

# **Final Draft West and East Monponsett Pond System Total Maximum Daily Loads For Total Phosphorus**

**(CN 446.1)**



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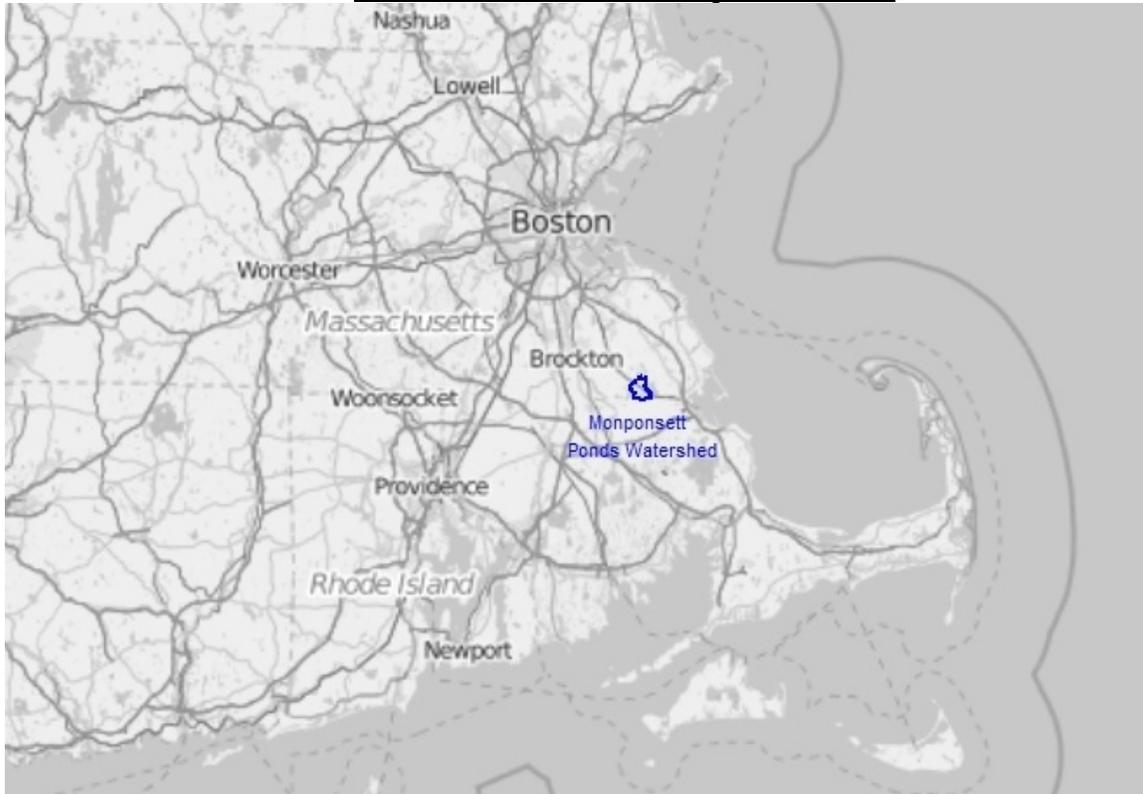
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# Final Draft West and East Monponsett Ponds, Stetson Pond and White Oak Reservoir Total Maximum Daily Loads for Total Phosphorus

MassDEP DWM TMDL Report CN 446.1



- Key Features:** Total Phosphorus TMDL for West Monponsett Pond (Segment ID #MA62182), and East Monponsett Pond (MA62218), Stetson Pond (MA62182) and White Oak Reservoir (MA62157) in Halifax, Hanson, and Pembroke MA
- Data Sources:** MassDEP data, MassGIS landuse,
- Data Mechanism:** Massachusetts Surface Water Quality Standards, Ambient Data, Landuse, and LLRM suite of Models
- Control Measures:** Cranberry Bog BMPs, Septic System Upgrades, Stormwater Management, Aluminum Treatment.

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<http://www.mass.gov/dep/water/resources/tmdls.htm>

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## Executive Summary

The Massachusetts Department of Environmental Protection (MassDEP) is responsible for monitoring the waters of the Commonwealth, identifying those waters that are impaired, and developing a plan to bring them back into compliance with the Massachusetts Surface Water Quality Standards. The list of impaired waters also referred to as Category 5 of the State Integrated List of Waters or the “303d list” identifies river, lake, and coastal waters and the cause for impairment. All impaired waters listed in Category 5 require the development of a Total Maximum Daily Load (TMDL) report.

Once a water body is identified as impaired, MassDEP is required by the federal Clean Water Act (CWA) to essentially develop a “pollution budget” designed to restore the health of the impaired body of water. The process of developing this budget, generally referred to as a TMDL, includes identifying the source(s) of the pollutant from direct discharges (point sources) and indirect discharges (non-point sources), determining the maximum amount of the pollutant that can be discharged to a specific water body to meet water quality standards, and developing a plan to meet that goal.

This report develops total phosphorus TMDLs for an interconnected set of four waterbodies (West and East Monponsett Pond, Stetson Pond and White Oak Reservoir) in the towns of Hanson, Halifax, and Pembroke Massachusetts. East and West Monponsett Pond, Stetson Pond, and White Oak Reservoir are listed as impaired (Category 5), on the "Massachusetts 2016 Integrated List of Waters" for nutrient related impairments (MassDEP, 2019). East Monponsett Pond (Segment MA62218) is listed as impaired for Chlorophyll-a and Harmful Algal Blooms. West Monponsett (Segment MA62119) is listed as impaired for Chlorophyll-a, Harmful Algal Blooms, Total Phosphorus and Transparency/Clarity. Stetson Pond (Segment MA62182) is listed as impaired for Dissolved Oxygen (DO), Harmful Algal Blooms, and Total Phosphorus (TP). White Oak Reservoir (Segment MA62157) is listed as impaired for Nutrient/Eutrophication Biological Indicators.

Stetson Pond and White Oak Reservoir were determined to be impaired by excess algal growth and nuisance aquatic plants (duckweed), respectively, based on data analyzed in this report. Some of the ponds are listed for other non-pollutant related impairments (TMDL not required) and these include Stetson Pond which is listed for non-native aquatic plants; East Monponsett Pond listed for non-native aquatic plants and has a completed TMDL for Mercury in Fish Tissue (EPA#33880); West Monponsett Pond MA62119 is listed for non-native aquatic plants. This report will satisfy the requirement of a phosphorus TMDL for each of the above waterbodies. In order to prevent further degradation in water quality and to ensure that each lake meets state water quality standards, the TMDL establishes phosphorus limits for the lakes and outlines actions to achieve that goal.

All four waterbodies covered in this TMDL are classified as Class A waterbodies as well as having been designated Public Water Supply and Outstanding Resource Waters (ORWs) (MassDEP 2007). The four waterbodies flow, via an underground pipe, from East Monponsett to Silver Lake (Pembroke, MA) which is the surface water supply for the City of Brockton. During diversions (mainly in October through May) water flows regularly in the reverse direction and

flows backward from West Monponsett to East Monponsett, potentially drawing the cyanobacteria and nutrients into Silver Lake. Action is being taken to address the cyanobacterial blooms observed in West and East Monponsett Ponds and the upstream waterbodies that are tributary to those ponds.

The Lake Loading Response Model (LLRM) suite of lake models was used for this TMDL. The LLRM is a spreadsheet based model which uses an annual steady state suite of models to estimate nutrient loadings. These estimated nutrient loadings along with pond morphometric and physical characteristics are then used to predict in-pond nutrient concentrations using a suite of well accepted lake models for phosphorus predictions. The successful calibration of the model was based on relatively high nutrient export rates from specific landuses that discharge directly to surface waters (cranberry bogs, stormwater and natural forested wetlands), combined with estimates of export from septic systems and internal sediment recycling of phosphorus. These estimates for each waterbody were simultaneously adjusted with the Lake Loading Response Model (LLRM) suite of lake models until they approximated the observed in-lake surface concentrations in each lake. The major sources of phosphorus to the lakes were cranberry bogs, runoff from developed areas, internal release from sediments, and natural wetlands.

Ignoring sediment sources, the largest controllable watershed sources of phosphorus are cranberry bog inputs and runoff associated with residential development. In the case of West Monponsett Pond, internal loading or recycling of phosphorus from lake sediments is a major source of phosphorus during the summer growing season. Implementation is already underway to address the cranberry bog inputs. The large commercial bogs north of Stetson Pond were retired in 2008 and that pond already shows a reduction in TP concentrations. The Morse Brothers Winebrook bogs and “bog #19” near West Monponsett Pond and White Oak Reservoir have implemented reduced phosphorus fertilizer rates as recommended by the University of Massachusetts (UMass) Cranberry Experiment Station. West Monponsett Pond has also shown significant reductions in TP concentrations coincident with the fertilizer reductions. In addition, a Section 319 grant (#12-02/319) was previously awarded in 2012 to assist in implementation and monitoring of new experimental filters for cranberry bog discharge waters, with monitoring being conducted by the UMass Cranberry Station. Funding support to aid implementation of this TMDL is available on a competitive basis under various state programs including the U.S. Environmental Protection Agency (EPA) Section 319 Grant Program administered by MassDEP.

It is recommended to first reduce external loads to the extent possible before addressing the internal loads, but due to health concerns regarding the potentially toxic cyanobacterial blooms in West Monponsett, the Town of Halifax funded treatments with a light dose of aluminum in 2013, 2015, and 2016. With 319 funding, the Town of Halifax applied aluminum doses in 2017, 2018 and 2019. Light aluminum doses were applied in small amounts over the summer months to avoid potential impacts to the rare state listed freshwater mussels in the pond. The sediment source of phosphorus is presumably due to historic inputs of phosphorus, largely from anthropogenic sources.

Implementation will include continued effort to reach out to remaining cranberry growers to use the most current recommended practices on their bogs. Implementation can be achieved by a combination of best management practices (BMPs) including reducing the phosphorus fertilizer

rates, reducing volumes of discharge water and reducing concentrations of total phosphorus in the discharge water. Further implementation of stormwater and septic system upgrades are encouraged. Aluminum treatment of West Monponsett Pond totals an applied dose of 50 g/m<sup>2</sup>. Treatment of the other ponds in the system is also encouraged with potential funding through the Section 319 Grant Program. The Town of Halifax received a Section 319 grant in 2017 to help fund alum treatment of West Monponsett through 2019.

Additionally, a substantial reduction in TP loads (50% - 60%) from stormwater will be required for Stetson Pond, East Monponsett, White Oak Reservoir, and West Monponsett Pond watersheds to meet this TMDL. These substantial reductions in TP loads from stormwater will be implemented through MS4 permits associated with designated urban areas in the towns of Halifax, Hanson and Pembroke.

In summary, the four waterbodies were modeled with a mass balance approach using a combination of landuse areas multiplied by phosphorus export coefficients and the resulting phosphorus loads for each pond were modeled using a suite of lake models to match the observed (2009 or 2015) TP concentrations. Target TP concentrations were chosen to attain recovery of the ponds and a set of TMDL loads were established to meet those targets. The reductions in loads required to reach the targets ranged from 30% to 73% as shown in Table ES-1 below. Although the TMDL must be expressed as a daily load, the implementation and administrative decisions should rely on achieving the annual TMDL load which is more appropriate for these waterbodies.

Table ES-1 Summary of Targets and Load Reductions for Ponds

Waterbody	Current TP ppb used in model	Current TP Load kg/yr	Target TP ppb	TMDL Load kg/yr	TMDL Load kg/day	Percent TP Load Reduction
Stetson Pond	15	69	13	48	0.13	30%
East Monponsett	34	345	18	182	0.53	47%
White Oak Brook Reservoir	50*	76	23	35	0.10	54%
West Monponsett	68	676	18	186	0.50	73%

\*Measured TP was 35 ppb (see text).

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## Programmatic Background and Rationale

Section 303(d) of the Federal Clean Water Act requires each state to (1) identify waters for which effluent limitations normally required are not stringent enough to attain water quality standards and (2) to establish Total Maximum Daily Loads (TMDLs) for such waters for the pollutants of concern. TMDLs may also be applied to waters threatened by excessive pollutant loadings. The TMDL establishes the allowable pollutant loading from all contributing sources that is necessary to achieve the applicable water quality standards. TMDL determinations must account for seasonal variability and include a margin of safety (MOS) to account for uncertainty of how pollutant loadings may impact the receiving water's quality. This report will be submitted to the USEPA as a TMDL under Section 303d of the Federal Clean Water Act, 40 CFR 130.7. After public comment and final approval by the USEPA, the TMDL can be used as a basis for state and federal permitting and regulatory decisions. The report will also serve as a general guide for future implementation activities such as grant funding of best management practices (BMPs). Information on watershed planning in Massachusetts is available on the MassDEP website at <https://www.mass.gov/guides/watershed-planning-program>.

The Massachusetts Surface Water Quality Standards (WQS), 314 CMR 4.0, define conditions required to maintain designated uses. The standards are largely narrative as they apply to nutrients. The Water Quality Standards are described in the Code of Massachusetts Regulations under sections:

314CMR 4.05 (3) b: These waters are designated as a habitat for aquatic life, and wildlife, and for primary and secondary contact recreation...These waters shall have consistently good aesthetic value.

1. Dissolved Oxygen: a. Shall not be less than 6.0 mg/l in cold water fisheries nor less than 5.0 mg/l in warm water fisheries unless background conditions are lower;
- b. natural seasonal and daily variations above this level shall be maintained...

and

314CMR 4.05 (5)(a) Aesthetics- All surface waters shall be free from pollutants in concentrations or combinations that settle to form objectionable deposits; float as debris, scum or other matter to form nuisances; produce objectionable odor, color, taste or turbidity; or produce undesirable or nuisance species of aquatic life.

and

314CMR 4.05 (5)(c) Nutrients. Unless naturally occurring, all surface waters shall be free from nutrients in concentrations that would cause or contribute to impairment of existing or designated uses and shall not exceed the site specific criteria developed in a TMDL or as otherwise established by the Department pursuant to 314 CMR 4.00. Any existing point source discharge containing nutrients in concentrations that would cause or contribute to cultural eutrophication, including the excessive growth of aquatic plants or algae, in any surface water shall be provided with the most appropriate treatment as determined by the Department, including, where necessary, highest and best practical treatment (HBPT) for POTWs and BAT

for non POTWs, to remove such nutrients to ensure protection of existing and designated uses. Human activities that result in the nonpoint source discharge of nutrients to any surface water may be required to be provided with cost effective and reasonable best management practices for nonpoint source control.

Section 314 CMR 4.05(3)(b) 6 also states:

Color and Turbidity- These waters shall be free from color and turbidity in concentrations or combinations that are aesthetically objectionable or would impair any use assigned to this class.

In addition to the criteria above the WQS also include an anti-degradation policy under 314 CMR: 4.04:

#### 4.04: Antidegradation Provisions

(1) Protection of Existing Uses. In all cases existing uses and the level of water quality necessary to protect the existing uses shall be maintained and protected.

(2) Protection of High Quality Waters. High Quality waters are waters whose quality exceeds minimum levels necessary to support the national goal uses, low flow waters, and other waters whose character cannot be adequately described or protected by traditional criteria. These waters shall be protected and maintained for their existing level of quality unless limited degradation by a new or increased discharge is authorized by the Department pursuant to 314 CMR 4.04(5). Limited degradation also may be allowed by the Department where it determines that a new or increased discharge is insignificant because it does not have the potential to impair any existing or designated water use and does not have the potential to cause any significant lowering of water quality.

(3) Protection of Outstanding Resource Waters. Certain waters are designated for protection under this provision in 314 CMR 4.06. These waters include Class A Public Water Supplies (314 CMR 4.06(1)(d)1.) and their tributaries, certain wetlands as specified in 314 CMR 4.06(2) and other waters as determined by the Department based on their outstanding socio-economic, recreational, ecological and/or aesthetic values. The quality of these waters shall be protected and maintained.

(a) Any person having an existing discharge to these waters shall cease said discharge and connect to a Publicly Owned Treatment Works (POTW) unless it is shown by said person that such a connection is not reasonably available or feasible. Existing discharges not connected to a POTW shall be provided with the highest and best practical method of waste treatment determined by the Department as necessary to protect and maintain the outstanding resource water.

(b) A new or increased discharge to an Outstanding Resource Water is prohibited unless:

1. the discharge is determined by the Department to be for the express purpose and intent of maintaining or enhancing the resource for its designated use and an authorization is granted as provided in 314 CMR 4.04(5). The Department's determination to allow a new or increased discharge shall be made in agreement with the federal, state, local or private entity recognized by the Department as having direct control of the water resource or governing water use; or
2. the discharge is dredged or fill material for qualifying activities in limited circumstances, after an alternatives analysis which considers the Outstanding Resource Water designation and further minimization of any adverse impacts. Specifically, a discharge of dredged or fill material is allowed only to the limited extent specified in 314

CMR 9.00 and 314 CMR 4.06(1)(d). The Department retains the authority to deny discharges which meet the criteria of 314 CMR 9.00 but will result in substantial adverse impacts to the physical, chemical, or biological integrity of surface waters of the Commonwealth

(4) Protection of Special Resource Waters. Certain waters of exceptional significance, such as waters in national or state parks and wildlife refuges, may be designated by the Department in 314 CMR 4.06 as Special Resource Waters (SRWs). The quality of these waters shall be maintained and protected so that no new or increased discharge and no new or increased discharge to a tributary to a SRW that would result in lower water quality in the SRW may be allowed, except where:

(a) the discharge results in temporary and short term changes in the quality of the SRW, provided that the discharge does not permanently lower water quality or result in water quality lower than necessary to protect uses; and

(b) an authorization is granted pursuant to 314 CMR 4.04(5).

(5) Authorizations.

(a) An authorization to discharge to waters designated for protection under 314 CMR 4.04(2) may be issued by the Department where the applicant demonstrates that:

1. The discharge is necessary to accommodate important economic or social development in the area in which the waters are located;

2. No less environmentally damaging alternative site for the activity, receptor for the disposal, or method of elimination of the discharge is reasonably available or feasible;

3. To the maximum extent feasible, the discharge and activity are designed and conducted to minimize adverse impacts on water quality, including implementation of source reduction practices; and

4. The discharge will not impair existing water uses and will not result in a level of water quality less than that specified for the Class.

(b) An authorization to discharge to the narrow extent allowed in 314 CMR 4.04(3) or 314 CMR 4.04(4) may be granted by the Department where the applicant demonstrates compliance with 314 CMR 4.04(5)(a)2. through 314 CMR 4.04(5)(a)4.

(c) Where an authorization is at issue, the Department shall circulate a public notice in accordance with 314 CMR 2.06. Said notice shall state an authorization is under consideration by the Department and indicate the Department's tentative determination. The applicant shall have the burden of justifying the authorization. Any authorization granted pursuant to 314 CMR 4.04 shall not extend beyond the expiration date of the permit.

(d) A discharge exempted from the permit requirement by 314 CMR 3.05(4) (discharge necessary to abate an imminent hazard) may be exempted from 314 CMR 4.04(5) by decision of the Department.

(e) A new or increased discharge specifically required as part of an enforcement order issued by the Department in order to improve existing water quality or prevent existing water quality from deteriorating may be exempted from 314 CMR 4.04(5) by decision of the Department.

(6) The Department applies its Antidegradation Implementation Procedures to point source discharges subject to 314 CMR 4.00.

(7) Discharge Criteria. In addition to the other provisions of 314 CMR 4.00, any authorized discharge shall be provided with a level of treatment equal to or exceeding the requirements of the Massachusetts Surface Water Discharge Permit Program (314 CMR 3.00). Before

authorizing a discharge, all appropriate public participation and intergovernmental coordination shall be conducted in accordance with Permit Procedures (314 CMR 2.00).

The programmatic background summary given below is intended to be general in nature and the issues described may or may not apply to the specific water body in question. The management of eutrophic freshwater lakes is typically based on a study of the nutrient sources and loads to the lakes and usually focuses on phosphorus as the important (or limiting) nutrient (Cooke et al., 2005). For TMDLs, the phosphorus loads estimated from the study can be compared to total phosphorus loadings estimated from a suite of different published lake models. A target concentration is selected, and a target load of phosphorus is calculated for the lake to control eutrophication in the water column, however additional plant management may be needed. A total phosphorus TMDL is established to meet Massachusetts narrative WQS. Although nutrient criterion does not exist in Massachusetts, water quality parameters which respond to nutrients can be used to assess the health of a water body. Guidance values for these parameters are detailed in MassDEP's Consolidated Assessment and Listing Methodology (CALM, see MassDEP, 2016). The CALM is used to translate the narrative nutrient criteria. As detailed in the CALM, lakes and pond should maintain a minimum of 4-foot visibility in surface waters for safe recreational use (which is equivalent to the 1.2 m Secchi disc transparency), a 16 ppb max monthly chlorophyll *a* concentration (a measure of algae and cyanobacterial biomass), limiting non-rooted macrophyte (i.e. duckweed) to 25% or less coverage, maintaining minimum dissolved oxygen (generally 5 mg/l for warm water) and to limit potentially toxic cyanobacterial blooms (less than 70,000 cells/mL).

The successful implementation of this TMDL will require cooperative support from the public including lake and watershed associations, local officials and municipal governments in the form of education, funding and local enforcement. In some cases, additional funding support is available under various state programs including the MassDEP Section 319 Grant Program (nonpoint source grants) and the State Revolving Fund Program (SRF); see Water Resources Grants and Financial Assistance on MassDEP web site.

**Nutrient Enrichment:** Nutrients are a requirement of life, but in excess they can create water quality problems. Lakes are ephemeral features of the landscape and over geological time most tend to fill with sediments and associated nutrients as they make a transition from lake to marsh to dry land. However, this natural successional (“aging”) process can be and often is accelerated through the activities of humans, especially through development in the watershed. For some highly productive lakes with developed watersheds, it is not easy to separate natural succession from “culturally induced” effects. Nonetheless, all feasible steps should be taken to reduce the impacts from cultural activities. The following discussion summarizes the current understanding of how nutrients influence the growth of algae and macrophytes (aquatic plants), the time scale used in the studies, the type of models applied, and the data collection methods used to create a nutrient budget. A brief description of the rationale for choosing a target load (the TMDL) as well as a brief discussion of implementation and management options is presented. A more detailed description of fertilizer and water usage in commercial cranberry bogs is provided in Appendix D, *Guidelines for Total Maximum Daily Loads of Phosphorus from Commercial Cranberry Bog Discharges in Massachusetts*.

A detailed description of the current understanding of limnology (the study of lakes and freshwaters) and management of lakes and reservoirs can be found in Wetzel (2001), Cooke et al., (2005) and Holdren et al., (2001). To prevent cultural enrichment it is important to examine the nutrients required for growth of phytoplankton (algae) and macrophytes. The limiting nutrient is typically the one in shortest supply relative to the nutrient requirements of the plants. The ratio of nitrogen (N) to phosphorus (P) in both algae and macrophyte biomass is typically about 7 by weight or 16 by atomic ratio (Vallentyne, 1974). Observations of relatively high N/P ratios in water suggests P is most often limiting and careful reviews of numerous experimental studies have concluded that phosphorus is a limiting nutrient in most freshwater lakes (Likens, 1972; Schindler and Fee, 1974). Most diagnostic/feasibility studies of Massachusetts lakes also indicate phosphorus as the limiting nutrient. Even in cases where excess phosphorus has led to nitrogen limitation, previous experience has shown that it is easier, more cost-effective and more ecologically sound to control phosphorus than nitrogen. The reasons include the fact that phosphorus is related to terrestrial sources and does not have a significant atmospheric source as does nitrogen (e.g., nitrates in precipitation). Thus, non-point sources of phosphorus can be managed more effectively by best management practices (BMPs). In addition, phosphorus is relatively easy to control in point source discharges. Finally, phosphorus does not have a gaseous phase, while the atmosphere is a nearly limitless source of nitrogen gas that can be fixed by some blue-green algae, (i.e. cyanobacteria) potentially resulting in toxic blooms. For all the reasons noted above, phosphorus is chosen as the critical element to control freshwater eutrophication, particularly for algal dominated lakes or in lakes threatened with excessive nutrient loading.

There is a direct link between phosphorus loading and algal biomass (expressed as chlorophyll *a*) in algae dominated lakes (Vollenweider, 1975). The situation is more complex in macrophyte-dominated lakes where the rooted aquatic macrophytes may obtain most of the required nutrients from the sediments. In organic, nutrient-rich sediments, the plants may be limited more by light or physical constraints such as water movement than by nutrients. In such cases, it is difficult to separate the effects of sediment deposition, which reduce depth and extend the littoral zone, from the effects of increased nutrients, especially phosphorus, associated with the sediments. In Massachusetts, high densities of aquatic macrophytes are typically limited to depths less than ten feet and lakes where organic rich sediments are found (Mattson et al., 2004). Thus, the response of rooted macrophytes to reductions in nutrients in the overlying water will be much weaker and much slower than the response of algae or non-rooted macrophytes, which rely on the water column for their nutrients. In algal or non-rooted macrophyte dominated systems, nutrient reduction in the water column can be expected to control growth with a lag time related to the hydraulic flushing rate of the system. In lakes dominated by rooted macrophytes, additional, direct control measures such as harvesting, herbicides or drawdowns will be required to realize reductions in plant biomass within a reasonably short time scale. In both cases, however, nutrient control is essential since any reduction in one component (either rooted macrophytes or phytoplankton) may result in a proportionate increase in the other due to the relaxation of competition for light and nutrients. In addition, it is critical to establish a TMDL so that future development around the lake will not impair water quality. It is far easier to prevent nutrients from causing eutrophication than to attempt to restore a eutrophic lake. The first step in nutrient control is to calculate the current nutrient loading rate or nutrient budget for the lake.

**Nutrient budgets:** Nutrient budgets and loading rates in lakes are determined on a yearly basis because lakes tend to accumulate nutrients as well as algal and macrophyte biomass over long time periods compared to rivers which constantly flush components downstream. In cases of short retention time reservoirs (less than 14 days), nutrient budgets may be developed on a shorter time scale (e.g. monthly budgets from wastewater treatment plants) but the units are expressed on a per year basis in order to be comparable to nonpoint sources estimated from land use models. Nutrients in lakes can be released from the sediments into the bottom waters during the winter and summer and circulated to the surface during mixing events (typically spring and fall in deep lakes and spring, summer and fall in shallow lakes). Nutrients stored in shallow lake sediments can also be directly used by rooted macrophytes during the growing season. In Massachusetts lakes, peak algal production, or blooms, may begin in the spring and continue during the summer and fall, while macrophyte biomass peaks in late summer. The impairment of uses is usually not severe until summer when macrophyte biomass reaches the surface of the water interfering with boating and swimming. Also, at this time of year the high daytime primary production and high nighttime respiration can cause large fluctuations in dissolved oxygen with critical repercussions for sustaining aquatic life. In addition, oxygen is less soluble in warm summer water as compared to other times of the year. The combination of these factors can drive oxygen to low levels during the summer and may cause fish kills. For these reasons the critical period for use impairment is during the summer, even though the modeling is done on a yearly basis for the reasons explained above.

There are three basic approaches to estimating current nutrient loading rates: the measured mass balance approach; the land use export modeling approach; and modeling based on the observed in-lake concentration. The measured mass balance approach requires frequent measurements of all fluvial inputs to the lake in terms of flow rates and phosphorus concentrations. The yearly loading is the product of flow (liters per year) times concentration (mg/l), summed over all sources (i.e., all streams and other inputs) and expressed as kg/year. The land use export approach assumes phosphorus is exported from various land areas at a rate dependent on the type of land use. The yearly loading is the sum of the product of land use area (Ha) times the export coefficient (in kg/Ha/yr). In some cases a combined or modified approach using both methods is used. In-lake phosphorus models provide an indirect method of estimating loading but do not provide information on the sources of input; however, this approach can be used in conjunction with other methods to validate results. Although the mass balance method is more time consuming and more costly due to the field sampling and analysis, it is generally considered to be more accurate. For this reason, the mass balance results are used whenever possible. If a previous diagnostic/ feasibility study or mass balance budget is not available, then a land use export model, such as Reckhow et al., (1980) or the NPSLAKE model (Mattson and Isaac, 1999) can be used to estimate nutrient loading.

**Target Load:** Once the current nutrient loading rate is identified, a new, lower rate of nutrient loading must be established which will meet surface water quality standards for the lake. This target load or TMDL can be set in a variety of ways. Usually a target concentration in the lake is established and the new load must be reduced to achieve the lower concentration. This target nutrient concentration may be established by a water quality model that relates phosphorus concentrations to water quality required to maintain designated uses. Alternatively, the target concentration may be set based on concentrations observed in background reference lakes for

similar lake types or from concentration ranges found in lakes within the same ecological region (or sub-ecoregion). In cases of impoundments or lakes with rapid flushing times (e.g., less than 14 days), somewhat higher phosphorus targets may be used because the planktonic algae and nutrients are rapidly flushed out of the system and typically do not have time to grow to nuisance conditions in the lake or accumulate in the sediments. In the case of seepage lakes (with no inlet streams) they may naturally have lower phosphorus targets, particularly if the lakes are clear water rather than dark or tea colored lakes.

Various models (equations) have been used for predicting productivity or total phosphorus concentrations in lakes from analysis of phosphorus loads. These models typically take into consideration the water body's hydraulic loading rate and some factor to account for settling and storage of phosphorus in the lake sediments. Among the more well-known metrics are those of Vollenweider (1975), Kirchner and Dillon (1975), Chapra (1975), Larsen and Mercier (1975) and Jones and Bachmann (1976). These models are used to calculate the Total Maximum Daily Load or TMDL, in kilograms of the nutrient per day or per year that will result in the target concentration in the lake being achieved. The TMDL must account for the uncertainty in the estimates of the phosphorus loads from the sources identified above by including a "margin of safety". The margin of safety can be specifically included, and/or included in the selection of a conservative phosphorus target, and/or included as part of conservative assumptions used to develop the TMDL. In addition, a simple mass balance equation (model) of total load divided by total water input, may also be used to establish the minimum load (assuming no settling or loss of phosphorus) that could explain the observed concentration in the lake.

After the target TMDL has been established, the allowed loading of nutrients is apportioned to various sources that may include point sources as well as non-point sources such as private septic systems and runoff from various land uses within the watershed. In Massachusetts, few lakes receive direct point source discharges of nutrients. In cases where significant point sources regulated through the National Pollutant Discharge Elimination System (NPDES) program exist upstream of a lake or impoundment, the point source will in most cases be required to use the Highest and Best Practical Treatment (HBPT) to reduce total phosphorus loading. The existing loads for NPDES point sources are calculated based on current data, not on the permitted discharge loading. New discharge mass loading limits at a treatment plant may be computed by applying the percent reduction required to meet the TMDL to the current loads. The new permitted concentrations of total phosphorus can then be calculated based on total mass loading divided by permitted flow rate for the discharge.

The nutrient non-point source analysis generally will be related to land use that reflects the extent of development in the watershed. This effort can be facilitated using geographic information systems (GIS) digital maps of the area that can summarize land use categories within the watershed. This is then combined with nutrient export factors which have been established in numerous published studies. The targeted reductions must be reasonable given the reductions possible with the best available technology and Best Management Practices (BMPs). The first scenario for allocating loads will be based on what is practicable and feasible for each activity and/or land use to make the effort as equitable as possible.

**Seasonality:** As the term implies, TMDLs must be expressed as maximum daily loads. However, as specified in 40 CFR 130.2(I), TMDLs may be expressed in other terms as well. For most lakes, it is appropriate and justifiable to express a nutrient TMDL in terms of allowable annual loadings. The annual load should inherently account for seasonal variation if it is protective of the most sensitive time of year. The most sensitive time of year in most lakes occurs during summer, when the frequency and occurrence of nuisance algal blooms and macrophyte growth are typically greatest. The phosphorus TMDL was established to be protective of the most environmentally sensitive period (i.e., the summer season), therefore it will also be protective of water quality during all other seasons. Additionally, the targeted reduction in the annual phosphorus load to lakes will result in the application of phosphorus controls that also address seasonal variation. For example, certain control practices such as stabilizing eroding drainage ways or maintaining septic systems will be in place throughout the year while others will be in effect during the times the sources are active (e.g., application of lawn fertilizer).

**Implementation:** The implementation plan or watershed management plan to achieve the TMDL reductions will vary from lake to lake depending on the type of point source and non-point source loads for a given situation. For non-point source reductions the implementation plan will depend on the type and degree of development in the watershed. While the impacts from development cannot be eliminated, they can be minimized by prudent “good housekeeping” practices, known more formally as best management practices (BMPs). Among these BMPs are control of runoff and erosion, well-maintained subsurface wastewater disposal systems and reductions in the use of fertilizers in residential areas, parks, cemeteries and golf courses and agriculture. Activities close to the water body and its tributaries merit special attention for following good land management practices. In addition, there are some statewide efforts that provide part of an overall framework. These include the legislation that curbed the phosphorus content of many cleaning agents, regulate application of plant nutrients on agricultural lands, turf, and lawns (330 CMR 31.0), revisions to regulations that encourage better maintenance of subsurface disposal systems (Title 5 septic systems), and the Rivers Protection Act that provides for greater protection of land bordering water bodies. In some cases, structural controls, such as detention ponds, may be used to reduce pollution loads to surface waters.

Although the land use approach gives an estimate of the magnitude of typical phosphorus export from various land uses, it is important to recognize that non-point source phosphorus pollution comes from many discrete non-point sources within the watershed. Perhaps the most common phosphorus sources in rural areas are associated with soil erosion and use of phosphorus fertilizers. Soils tend to erode most rapidly following land disturbances such as construction, gravel pit operations, tilling of agricultural lands, overgrazing, and trampling by animals or vehicles. Erosion from unpaved roads is also a common problem in rural areas. Soils may erode rapidly where runoff water concentrates into channels and erodes the channel bottom. This may occur where impervious surfaces such as parking lots and roadways direct large volumes of water into ditches which begin to erode from either excessive water drainage or poorly designed ditches and culverts. An unvegetated drainage way is a likely source of soil erosion. Cesspools or home septic systems that do not meet Title 5 requirements may also be a source if located close to surface waters.

Discrete sources of nonpoint phosphorus in urban, commercial and industrial areas include a variety of sources that are lumped together as ‘urban runoff’ or ‘stormwater’ and may be considered as point sources under wasteload allocations. As many of these urban sources are difficult to identify the most common methods to control such sources include reduction of impervious surfaces, infiltration, street sweeping and other non-structural BMPs as well as treatment of stormwater runoff by structural controls such as detention ponds when this becomes necessary.

Other sources of phosphorus include phosphorus-based lawn fertilizers used in residential areas, parks, cemeteries and golf courses and fertilizers used by agriculture. Manure from animals, especially dairies and other confined animal feeding areas, is high in phosphorus. In some cases, the manure is inappropriately spread or piled on frozen ground during winter months and the phosphorus can wash into nearby surface waters. Over a period of repeated applications of manure to local agricultural fields, the phosphorus in the manure can saturate the ability of the soil to bind phosphorus, resulting in phosphorus export to surface waters. In some cases, cows and other animals including wildlife such as flocks of ducks and geese may have access to surface waters and cause both erosion and direct deposition of feces to streams and lakes.

Perhaps the most difficult source of phosphorus to account for is the phosphorus recycled within the lake, from the lake sediments. In most stratified north temperate lakes, phosphorus that accumulated in the bottom waters of the lake during stratification is mixed into surface waters during spring and fall turnover when the lake mixes. Phosphorus release from shallow lake sediments may be a significant input for several reasons. These reasons include higher microbial activity in shallow warmer waters that can lead to sediment anoxia and the resultant release of iron and associated phosphorus. Phosphorus release may also occur during temporary mixing events such as wind or powerboat caused turbulence or bottom feeding fish, which can resuspend phosphorus rich sediments. Phosphorus can also be released from nutrient ‘pumping’ by rooted aquatic macrophytes as they extract phosphorus from the sediments and excrete phosphorus to the water during seasonal growth and senescence (Cooke et al., 2005; Horne and Goldman, 1994). Shallow lakes also have less water to dilute the phosphorus released from sediment sources and thus the impact on lake water concentrations is higher than in deeper lakes.

The most important factor controlling macrophyte growth appears to be light (Cooke et al., 2005). Due to the typically large mass of nutrients stored in lake sediments, reductions in nutrient loadings by themselves are not expected to reduce macrophyte growth in many macrophyte-dominated lakes, at least not in the short-term. In such cases additional in-lake control methods are generally recommended to directly reduce macrophyte biomass. Lake management techniques for both nutrient control and macrophyte control have been reviewed in “Eutrophication and Aquatic Plant Management in Massachusetts. Final Generic Environmental Impact Report” (GEIR) and the accompanying “Practical Guide” (Mattson et al., 2004; Wagner, 2004) <http://www.mass.gov/eea/agencies/dcr/water-res-protection/lakes-and-ponds/eutrophication-and-aquatic-plant-management.html>.

The MassDEP will support in-lake remediation efforts that are cost-effective, long-term and meet all environmental concerns, however, instituting such measures will be aided by continued Federal (via U.S. Environmental Protection Agency, or EPA), and State grant support.

Financial support for various types of implementation is potentially available on a competitive basis through both the non-point source (319) grants and the State Revolving Fund (SRF) loan program. The 319 grants require a 40 percent non-federal match of the total project cost although the local match can be through in-kind services such as volunteer efforts. Other sources of funding include the 604b Water Quality Management Planning Grant Program and the Community Septic Management Loan Program. Information on these programs is available on the MassDEP website: Water Resources Grants and Financial Assistance.

Because the lake restoration and improvements can take a long period of time to be realized, follow-up monitoring is essential to measure interim progress toward meeting the water quality goal and guide additional BMP implementation. This can be accomplished through a variety of mechanisms including volunteer efforts. Recommended monitoring may include Secchi disk readings, lake total phosphorus, macrophyte mapping of species distribution and density, visual inspection of any structural BMPs, coordination with Conservation Commission and Board of Health activities and continued education efforts for citizens in the watershed.

## **Description of Waterbodies and Problem Assessment**

All waterbodies covered in this study are classified by MassDEP as public water supplies and outstanding resource waters. The waterbodies in the study area, their class and 2016 Integrated List information are presented in Table 1. West Monponsett Pond is a 125 Ha (308 acre) *hypereutrophic* pond located in Halifax/Hanson, MA. The pond is at an elevation of 52 feet above mean sea level (AMSL). West Monponsett Pond has been suffering the symptoms of a eutrophic lake with cyanobacteria blooms and is on the 2016 Integrated List for Chlorophyll-a, Harmful Algal Blooms, Phosphorus (Total), Transparency/Clarity and Non-Native Aquatic Plants (a non-pollutant). The high levels of total phosphorus (TP) result in excessive algal growth and impair designated uses of the waters. The lake is naturally tea colored due to the high amount of dissolved organic material in the lake, presumably due to the large areas of wetlands and forested wetlands in the watershed. The federal Clean Water Act requires that such waters be listed on the 303d list in Category 5 (impaired) and that a Total Maximum Daily Load report be developed and submitted to the EPA. The modeling approach and implementation in this report follow the approach used in the previously approved TMDL for White Island Pond (MassDEP, 2010a).

East Monponsett Pond is a 110 Ha (272 acre) pond also located in the Town of Halifax, MA at an elevation of 52 feet (AMSL). This waterbody is included in the TMDL for mercury in fish tissue (Northeast States, 2007). East Monponsett Pond is a mesotrophic tea colored pond that is experiencing some cultural eutrophication but is generally in better condition than the west basin. It also suffers from occasional blooms and is listed as impaired for Chlorophyll-a, Harmful Algal Blooms, and Non-Native Aquatic Plants (a non-pollutant, not requiring a TMDL)

Stetson Pond is a 38.1 hectare pond located in Pembroke, MA. Stetson Pond is tributary to East Monponsett Pond via Stetson Brook, and as such is part of the Monponsett Pond system. The pond is at an elevation of 61 feet (AMSL). The pond was listed on the 2016 Integrated List (MassDEP 2019) for Dissolved Oxygen, Harmful Algal Blooms, Phosphorus (Total), and Non-

Native Aquatic Plants (a non-pollutant). The Massachusetts Department of Public Health (MassDPH) posted signage warning people to avoid contact with the water for 37 days in 2010 due to elevated concentrations of cyanobacteria.

White Oak Reservoir, an impoundment along White Oak Brook, is 6 hectares in size, a maximum depth of 2.3m (7.5 feet) and is located at an elevation of approximately 60 feet (AMSL). The stream was impounded sometime in the early 20th century to provide water for nearby cranberry bogs. In surveys of White Oak Reservoir by MassDEP it was noted that the pond exceeds the 25% threshold, as established in the CALM (MassDEP 2016) for non-rooted macrophyte cover (duckweed). White Oak Reservoir is listed as impaired for Nutrient/Eutrophication Biological Indicators in the 2016 Integrated List (MassDEP 2019). This TMDL will include loading limits for White Oak Reservoir, which is tributary, via White Oak Brook to West Monponsett Pond.

**Table 1. Description of waterbodies in study area and 2016 Integrated List information**

Waterbody Name	Water Body Segment	Description and Location	Size (acres) <sup>1</sup>	Class	Qualifier	303d Cat.	2016 Integrated List Impairment Causes
Stetson Pond	MA62182	Pembroke	88.0	A	PWS\ORW	5	Harmful Algal Blooms, Oxygen, Dissolved, Phosphorus (Total), (Non-native Aquatic Plants <sup>3</sup> )
Monponsett Pond	MA62218	[East Basin] Halifax	247	A	PWS\ORW	5	Chlorophyll-a, Harmful Algal Blooms, Mercury in Fish Tissue <sup>2</sup> , (Non-native Aquatic Plants <sup>3</sup> )
White Oak Reservoir	MA62157	Hanson	13.00	A	PWS\ORW	5	Nutrient/Eutrophication Biological Indicators
Monponsett Pond	MA62119	[West Basin] Halifax/Hanson	283.00	A	PWS\ORW	5	Chlorophyll-a, Harmful Algal Blooms, Phosphorus (Total), Transparency/Clarity
Additional waters outside of study area							

Waterbody Name	Water Body Segment	Description and Location	Size (acres) <sup>1</sup>	Class	Qualifier	303d Cat.	2016 Integrated List Impairment Causes
Silver Lake	MA94143	Pembroke/ Plympton/ Kingston	616.00	A	PWS\ORW	4c	Flow Regime Modification <sup>3</sup>
Jones River	MA94-12	Headwaters, outlet Silver Lake, Kingston to former dam (NATID:MA003 96) near Wapping Road, Kingston.	4.10 mile	B		5	(Dewatering <sup>3</sup> ) (Fish-Passage Barrier <sup>3</sup> ), Algae, Aquatic Plants (Macrophytes), Dissolved Oxygen Turbidity
Stump Brook <sup>4</sup>	--	--	--	--	--	--	--

1- note these sizes are regulatory sizes used by MassDEP in the 303d list, for purposes of TMDL modeling the 1:25,000 Hydrography layer areas were used.

2 -TMDL approved for mercury in fish (Northeast States 2007). EPA TMDL #33880.

3-Not a pollutant, no TMDL required.

4-Stump Brook has not been assessed.

## **Flow Issues**

The natural surface water flow pattern is from Stetson Pond south via Stetson Brook to East Monponsett Pond and then west through a culvert under Route 56 to West Monponsett Pond (Figure 1). In the northwest part of the watershed, White Oak Brook flows into White Oak Reservoir, then continues south to West Monponsett Pond. Stump Brook is the outlet on the west side of West Monponsett Pond (Figure 1).

The City of Brockton was authorized to use Silver Lake as a public water supply (PWS) as far back as 1899. In 1964 the Massachusetts Legislature approved Act 371 to allow a diversion from Monponsett Pond to Silver Lake (Figure 1) to supplement the water supply with some restrictions. Diversions occur generally only in the fall, winter and spring between October and June. During times of diversion the natural flow direction between the ponds (from East Monponsett Pond to West Ponponset Pond) may be reversed (West Monponsett Pond to East Monponset Pond). There are concerns that the potentially toxic cyanobacterial blooms and excess nutrients in West and East Monponsett Ponds will flow into Silver Lake and the altered hydrology may impact both West and East Monponsett Ponds as well as their downstream outlet, Stump Brook which suffers from low flows (Princeton Hydro, 2013; Horsley Witten, 2015). In addition, the use of Silver Lake as a PWS results in only brief outflows to the Jones River (Princeton Hydro, 2013). The hydraulic diversions result in less Silver Lake water to be discharged to the headwaters of the Jones River, which itself is listed as impaired on the 303d list of impaired waters due to low flows. In 1995 MassDEP and the City of Brockton signed an

Administrative Consent Order (ACO) which required the City to develop a Comprehensive Water Management Plan and a strategy to reduce environmental impacts. Both ponds are highly influenced by both their surrounding landuse and the ponds use as a public water supply source. The diversion of water from East Monponsett Pond affects the hydrology of both West and East Monponsett Ponds and increases the risk of introducing cyanobacteria to the public water supply source, Silver Lake.

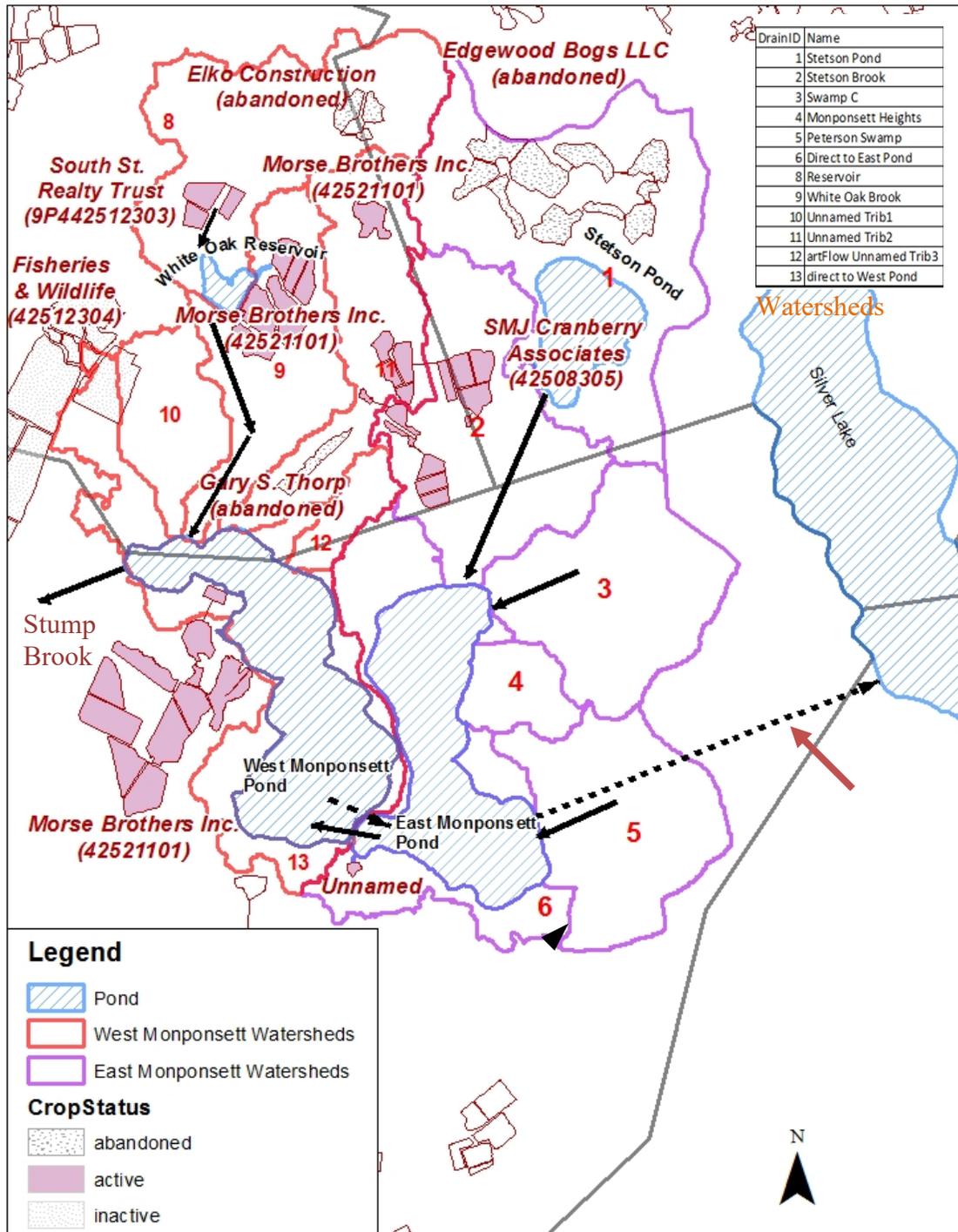
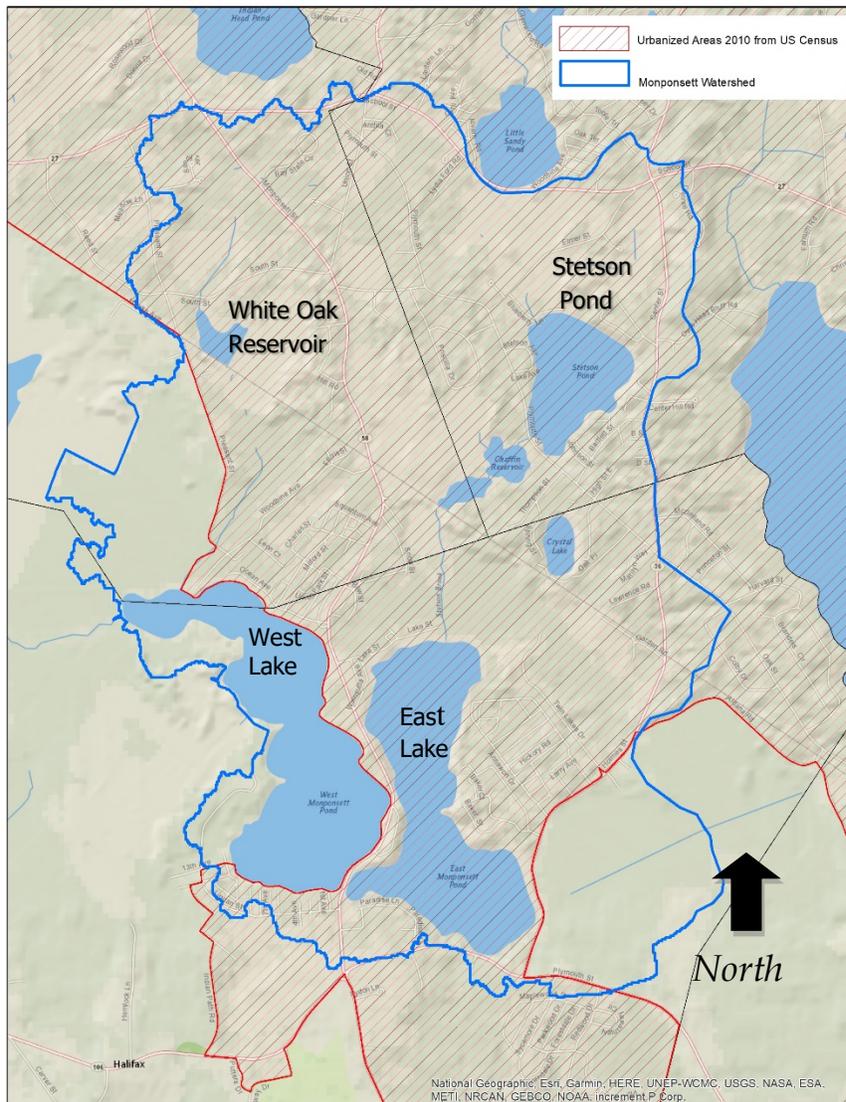


Figure 1: Flow Diagram for TMDL Study Area

## Watershed Characterization

The East and West Monponsett Ponds watershed area is 1,555 hectares (including the ponds' surface area) (Figure 2). Using the MassGIS Landuse (MassGIS 2005) data layer, the landuse in the TMDL study area was analyzed. The most common landuse categories are forest, water (including ponds) and low density residential which compromise approximately 26%, 20% and 15% of the overall TMDL study area, respectively. Also of note, are forested wetland, cranberry bog and non-forested wetland which compromise approximately 13%, 8% and 4% of the overall study area, respectively. Landuse categories in the TMDL study area are summarized in Table 2. All the waterbodies covered in this TMDL are part of the Taunton River watershed. Detailed information on the watershed and the lakes are included in Table 3.



**Figure 2. Monponsett Ponds Watershed and TMDL Study Area**

Stetson Pond is just east of Plymouth Street and White Oak Reservoir is above West Monponsett just south of South Street. Silver Lake is to the right, outside of the catchment area. Urbanized areas subject to MS4 stormwater permit are shown as hatched. (Map made via ggmap, courtesy Kahle and H. Wickham 2013, base map data© 2016 Google)

**Table 2. Summary of the Landuse in the TMDL study area**

Landuse Code	Frequency	2005 Landuse Description	Area (hectares)	% Total Study Area
3	82	Forest	400.3	26%
20	19	Water	303.8	20%
13	71	Low Density Residential	239.5	15%
37	99	Forested Wetland	208.4	13%
12	27	Medium Density Residential	131.8	8%
23	18	Cranberry Bog	121.6	8%
4	66	Non-Forested Wetland	58.8	4%
18	2	Transportation	24.7	2%
15	11	Commercial	14.2	1%
10	6	Multi-Family Residential	13.5	1%
38	36	Very Low Density Residential	8.5	1%
11	2	High Density Residential	7.4	<1%
2	4	Pasture	6.8	<1%
6	5	Open Land	5.2	<1%
31	4	Urban Public/Institutional	3.6	<1%
17	5	Transitional	2.1	<1%
16	2	Industrial	2.1	<1%
7	3	Participation Recreation	1.5	<1%
36	1	Nursery	1.0	<1%
		Total	1554.7	

### **Lake Morphometry**

The ponds in this TMDL study are all shallow with maximum depths that range between 2.33 meters in White Oak Reservoir and 9.88 meters in Stetson Pond. Stetson Pond is estimated to have a lake volume of  $1.26 \times 10^6 \text{ m}^3$  (BEC 1993) while East Monponsett Pond has an estimated volume of  $2.1 \times 10^6 \text{ m}^3$ . White Oak Reservoir with an average depth of only 1.1 meters is estimated to have a volume of approximately  $66,000 \text{ m}^3$ . The largest pond, West Monponsett Pond, has an estimated volume of  $2.61 \times 10^6 \text{ m}^3$  (Princeton Hydro, 2013). Given the shallow depths and inflows to the ponds, all the ponds are well flushed with flushing rates that range from 1.5 lake volumes/year for Stetson to 17.4 lake volumes/year for White Oak Reservoir. It is important to note the modeled flushing rates correspond to an annual time step and do not account for seasonal variations. The diversion was included in the model calibrations but is averaged over the year. The estimated retention time of water measured in days is 247 days for Stetson Pond, 117 days for East Monponsett Pond, 21 days for White Oak Reservoir and 178 days for West Monponsett Pond. A summary of morphometric data, physical characteristics and watershed characteristics for ponds in the study area can be found in Table 3.

**Table 3. Select morphometric data, physical characteristics and watershed characteristics for ponds in study area**

Parameters			Stetson	East Monponsett	White Oak Reservoir	West Monponsett
<b>Morphometric Data</b>						
	Symbol	units				
Lake Mean Depth	Z	meters	3.3	1.9	1.1	2.1
Maximum Depth	D <sub>M</sub>	meters	9.80 <sup>1</sup>	3.96 <sup>2</sup>	2.33	6.84
Lake Surface Area	SA	hectares	38.1	109.9	6.0	124.6
Lake Volume	V	meters <sup>3</sup>	1,259,265 <sup>1</sup>	2,124,000	65,891	2,610,000
Width at widest point	W <sub>D</sub>	meters	657	1143	326	1089
Maximum Length	L <sub>M</sub>	meters	889	1957	414	2146
Shoreline Perimeter	S <sub>L</sub>	meters	2719	6313	1476	7804
<b>Physical Characteristics</b>						
Retention Time	T	days	247	117	21	178
Flushing Rate	F	flushings/yr	1.5	3.1	17.4	2.1
<b>Watershed Characteristics</b>						
Watershed Area	WA	hectares	242.1	1042.4	166.5	675.4
Watershed: Lake Ratio			6.4	9.5	27.7	5.4
% Watershed Occupied By Lake			16%	11%	4%	18%
Primary Landuse (By%)			Natural	Natural	Low Intensity Development	Natural
Secondary Landuse (By%)			Low Intensity Development	Low Intensity Development	Natural	Low Intensity Development
Tertiary Landuse (By%)			Abandoned Cranberry Bogs	Forested Wetland	Forested Wetland	Forested Wetland

1- BEC (1993), 2 –Princeton Hydro (2013)

### **Summary of Previous Analysis**

Several previous studies have been conducted on the Monponsett Ponds. Over the last few decades while these studies have yielded useful information that contributes to management decisions, some of the information conflicts. Lycott (1987) conducted a comprehensive diagnostic/feasibility study of both East and West Monponsett Ponds. This study included significant sampling of several tributary waterbodies for streamflow, water quality, stormwater outfall sampling, groundwater test well sampling, seepage sampling, macrophyte mapping, and in-lake sampling. In addition, using a mass balance model, an estimate of total phosphorus loading of 793 kg/yr for both East and West Monponsett Ponds was calculated (Lycott 1987, pg. 5-10). This loading included an estimated 378 kg/yr from septic systems or 47.7% of the total load. The next three largest sources of loading included 177 kg/yr from forest land, 168 kg/yr

from diffuse residential including stormwater and 53 kg/yr from precipitation. Lycott (1987) estimated outputs from the Monponsett Pond system of 61 kg/yr to Stump Brook and 45 kg/yr to Silver Lake via drinking water diversion.

Princeton Hydro (2013) conducted analysis of water management for the Monponsett Ponds, Furnace Pond and Silver Lake in order to recommend options to improve water quality as well as provide more sustainable flows in Stump Brook. As part of their work they estimated the hydrology of the Monponsett Pond system and modeled both current water quality and water quantity under various management scenarios. Princeton Hydro estimated a current total phosphorus load of 2,431 kg to both ponds and 1,374 kg/yr and 1,057 kg/yr to West and East Monponsett Ponds, respectively. Princeton Hydro also found that for West Monponsett Pond approximately 70% of the entire outflow is routed through the diversion to the east basin (on an annual basis). As a result, approximately 40% of the inflow to East Monponsett Pond consists of the higher nutrient water from West Monponsett Pond.

Horsley Witten (2015) conducted an evaluation of the management of the Stump Brook dam and its effects on the brook's flows and Monponsett Pond levels. As part of their work they modified USGS Modflow groundwater model to predict groundwater flows and model the hydrology of the system. In addition to determining the hydrological effects of different Stump Brook dam management options, they modeled water quality in the ponds based on their possible dam management scenarios using the Lake Loading Response Model (LLRM). Horsley Witten estimated a total phosphorus load of 727 kg/yr to both ponds (185 kg/yr and 542 kg/yr to East and West Monponsett Ponds, respectively). Horsley Witten estimated internal loads during their model calibration process. They estimated internal loading was 381 kg/yr in West Monponsett Pond or approximately 49% of load inputs. Watershed land use loads were 292 kg/yr or approximately 38% of load inputs. Atmospheric deposition and septic loads were estimated to be 50 kg/yr and 53 kg/yr respectively. Export of phosphorus via transfers out of West Monponsett Pond was estimated to be 235 kg/yr.

In addition to estimating current loading to the Monponsett Ponds, Horsley Witten (2015) evaluated several management scenarios. They estimated in the absence of the Brockton water supply diversion, West Monponsett Pond would have a total phosphorus concentration of 57 ppb while East Monponsett Pond would have a total phosphorus concentration of 19 ppb. The impact of diversion is discussed later in this report. The modeled effects of no internal nutrient loading were even more pronounced with estimated total phosphorus concentrations in West and East Monponsett Pond of 37 and 29 ppb. The estimated total phosphorus concentrations in West and East Monponsett Pond respectively were 64 and 4 ppb under the 50% reduction in land loads scenario.

The three previous water quality model attempts for the Monponsett Ponds used a variety of different assumptions and arrived at somewhat different loading estimates as described above and as shown in Table 4. For example, Princeton Hydro (2013) and Lycott (1987) considered Wine Brook Bogs to be part of the West Monponsett Pond watershed while Horsley Witten (2015) did not. There are likely many differences between the different previous water quality modeling efforts. A comprehensive comparison of previous model efforts is beyond the scope of this document but a summary of the three previous water quality modeling efforts, loadings,

estimated major loading sources and key model assumptions is provided in Table 4. Previous work has indicated the importance of internal loading and cranberry bogs. Both sources are identified as significant in this TMDL. This TMDL builds on prior work and supports management decisions for nutrient control.

**Table 4. Comparison of Previous Water Quality Modeling Efforts for Monponsett Pond.**

Previous Work	Model Type	Total Loading (kg/yr)	Top Loading Sources	Septic System Modeling Approach	Key Model Assumptions
Lycott (1987)	Mass Balance	793 (Both Ponds)	Septic Systems, Forest Land, Diffuse Residential (including stormwater), Precipitation	Included houses within twice the average septic system setback (271 houses total)	No internal loading, cranberry bog export coefficient of 0.16 kg/ha/yr, estimated hydraulic discharges for Stump Brook and diversion
Princeton Hydro, LLC (2013)	Various Mass Balance, Unit Area Load for landuse loads	2431 (Both Ponds), 1057 (East), 1374 (West)	Land use, Atmosphere, Septic	Houses within 100 ft included, Estimated per capita loading	Modeled both with current diversion and with no diversion. No internal loading, cranberry bog export coefficient of 9.9 kg/ha/yr
Horsley Witten Group, Inc. (2015)	Mass Balance (Lake Loading Response Model)	727 (Both Ponds), 185 (East), 542 (West)	Internal Loading, Watershed Landuse, Septic, Atmospheric	Houses within 100 ft (151 Houses total)	Includes diversion and net TP transfer out of West Monponsett Pond of 235 kg/yr

## Recent aluminum treatments for West Monponsett Pond

To reduce the severity of cyanobacteria blooms in West Monponsett Pond, the pond was treated with light doses of aluminum sulfate and sodium aluminate (alum) solutions in a 2:1 ratio during the summer of 2013, 2015, 2016, 2017 and 2018 with additional applications planned. Due to concerns about three state listed aquatic species of concern, additional testing was required as part of the Wetland Protection Act Order of Conditions. The freshwater mussels *Leptodea orchracea* (Tidewater mucket) and *Ligumia nasuta* (Eastern Pondmussel) are rare species that are listed by the Massachusetts Natural Heritage and Endangered Species Program (NHESP) as “Special Concern”. The dragonfly *Neurocordulia obsoleta* (Umber Shadowdragon) is also rare species listed as “Special Concern” by the NHESP.

The aluminum dose was applied over a period of days between June 4 and June 7, 2013 using 1,300 gallons of alum plus 6,500 gallons of sodium aluminate (Lycott, 2014). Assuming the treatment spread across the bottom of West Monponsett Pond the effective concentration of aluminum would be about 3.4 mg/l or 7.1 g/m<sup>2</sup>. The monitoring study noted some increases and

some decreases in mussel density before and after the treatment. A video showed no evidence of obvious stress responses and the authors could not say that the treatment had any effect on the juveniles or adult mussels (Biodrawiversity, 2014). Similarly, the same study examined emergence of the dragonflies over several years and found no evidence of any immediate adverse impacts on *N. oblosea* or the dragonfly community, in general (Biodrawiversity, 2014). A similar study on mussels in 2015 determined that conclusions were difficult to draw but short-term impacts appeared to be minimal (ACT, 2015).

The pond did not have any aluminum treatments in 2014. A second year of light dose treatments occurred over two months from June 2, 2015 to July 23, 2015 in West Monponsett Pond. This time the dose was 9,000 gallons of aluminum sulfate and 4,500 gallons of sodium aluminate resulting in an effective dose of about 2.3 mg/l (4.9 g/m<sup>2</sup>). Thus the total dose of aluminum to the bottom for 2013 and 2015 was 12 g/m<sup>2</sup>. An additional alum treatment of 3.2 g/m<sup>2</sup> was conducted in the summer months of 2016. Using EPA 319 grant funding the Town of Halifax received permission to add additional alum to West Monponsett in 2017. For 2017 the total dose of aluminum to the bottom was 17 g/m<sup>2</sup>, in 2018 it was 10 g/m<sup>2</sup>, and in 2019, 8 g/m<sup>2</sup>. The estimated total buffered alum treatment through 2019 for West Monponsett Pond is approximately 50 g/m<sup>2</sup> Al. Preliminary water quality data for 2018 from West Monponsett Pond shows a continued downward trend in total phosphorus.

## Water Quality Trends

As described above the general thresholds that are noted in the CALM document are a target of 1.2 m Secchi disk transparency, dissolved oxygen of 5 mg/l, 16 ppb chlorophyll *a*, 25% or less coverage of duckweed and cyanobacteria densities less than 70,000 cells/mL. The trends in the data will be discussed in downstream order, from Stetson Pond, East Monponsett Pond, White Oak Reservoir and West Monponsett Pond.

Stetson Pond was sampled in 1988 for a diagnostic feasibility study and they reported *Anabaena* blooms lowering the Secchi disk transparency to 0.8 m (BEC, 1993). MassDEP sampled the pond on one visit in late summer of 2003 and sampled the pond again in the summer of 2015 during 4 monthly visits. Total Phosphorus for all three surveys, is shown in Figure 3. Note the high TP concentrations reported in Stetson Pond in 1987 (BEC, 1993). A large decline in TP was observed following the sale of the bogs to the town and later abandonment of cranberry operations at the 85.4 acre Edgewood Bogs to the north of Stetson Pond (McLaughlin, 2016). Despite the reductions in TP, the chlorophyll *a* concentrations show no improvement (Figure 4) with the highest chlorophyll *a* concentrations found during the September 2015 sampling date. Stetson Pond was also monitored for cyanobacteria and records indicate the pond was posted with a warning of a cyanobacteria bloom that lasted 37 days in late summer of 2010 (MassDPH, 2014) The median Secchi disk transparency shows slightly less transparency in 2015, but the range of readings show the recent Secchi disk transparencies are maintaining transparency greater than the 1.2 m threshold (Figure 5). A hypolimnion was noted on August 2015 sampling date and temperature stratification was found during the summer (Appendix C, Figure C11-C12).

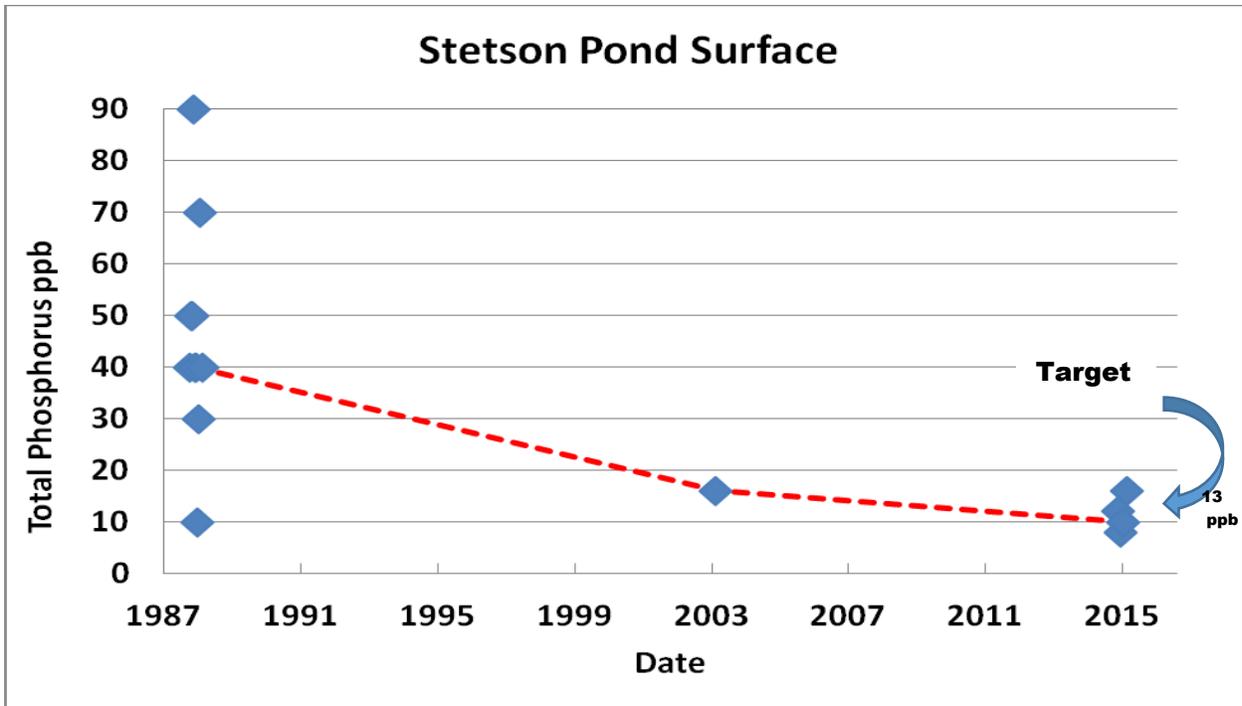


Figure 3. Stetson Pond Surface Total Phosphorus. Summer median values are indicated by the dashed line.

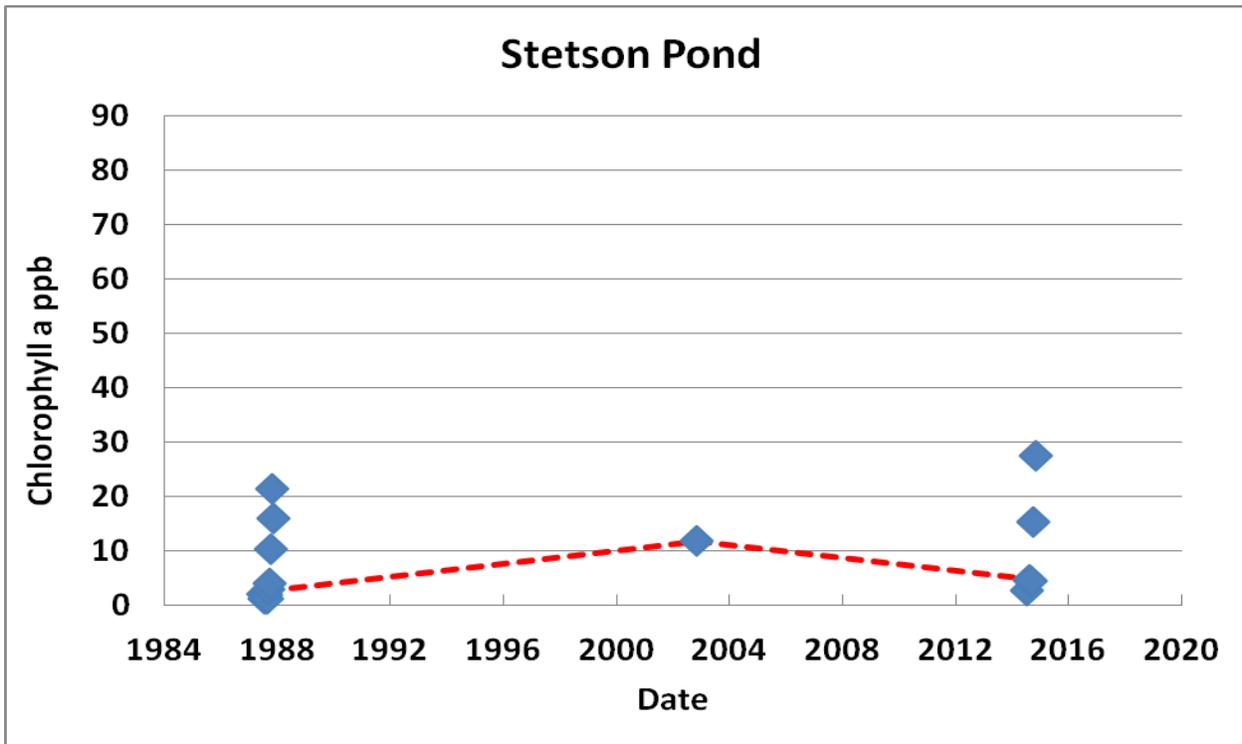
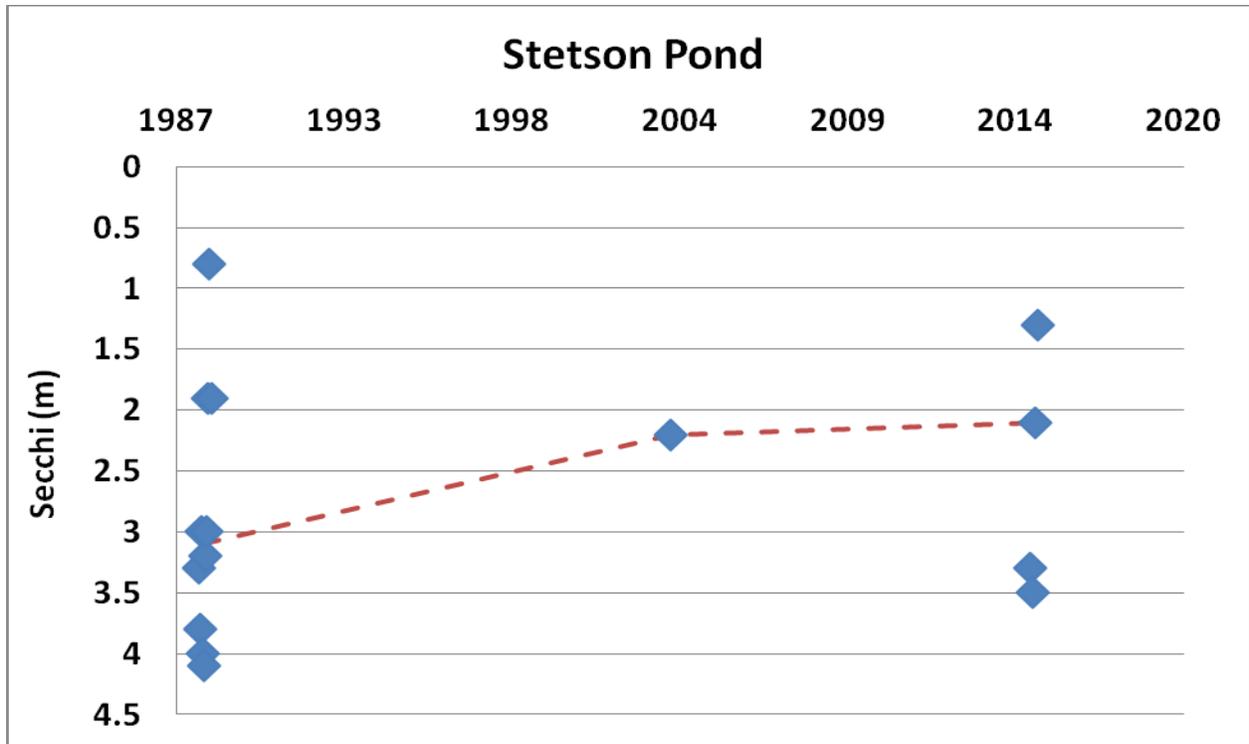


Figure 4. Stetson Pond Chlorophyll *a*. Summer median values are indicated by the dashed line.



**Figure 5. Stetson Pond Secchi disk transparency. (Note y axis reversed). Summer median values are indicated by the dashed line.**

East Monponsett Pond was sampled by MassDEP during the summers of 2001 and 2009 through 2015. The TP concentrations have been relatively constant but with a recent decline since 2013 (Figure 6). A slight drop in concentration was also noted in 2010 and is associated with a dry summer. The chlorophyll *a* concentration shows more variability with generally higher concentrations (above the 16 ppb guidance threshold) in 2009-2014 (Figure 7). In 2015, there was a marked improvement. Secchi disk transparency in East Monponsett (Figure 8) follows the trends in chlorophyll *a*, noted above. The mean transparency was near the 1.2 m threshold in 2009-2010 except for 2010 discussed above. Note that the transparency was markedly improved to nearly 3 meters in 2015. East Monponsett Pond was generally not noted to be hypoxic at depth and did not exhibit temperature stratification (Appendix C, Figures C13-C15). The pond also had frequent and/or prolonged algal blooms between 2011 and 2014 and was posted between 28 and 81 days each bathing season (MA DPH, 2014).

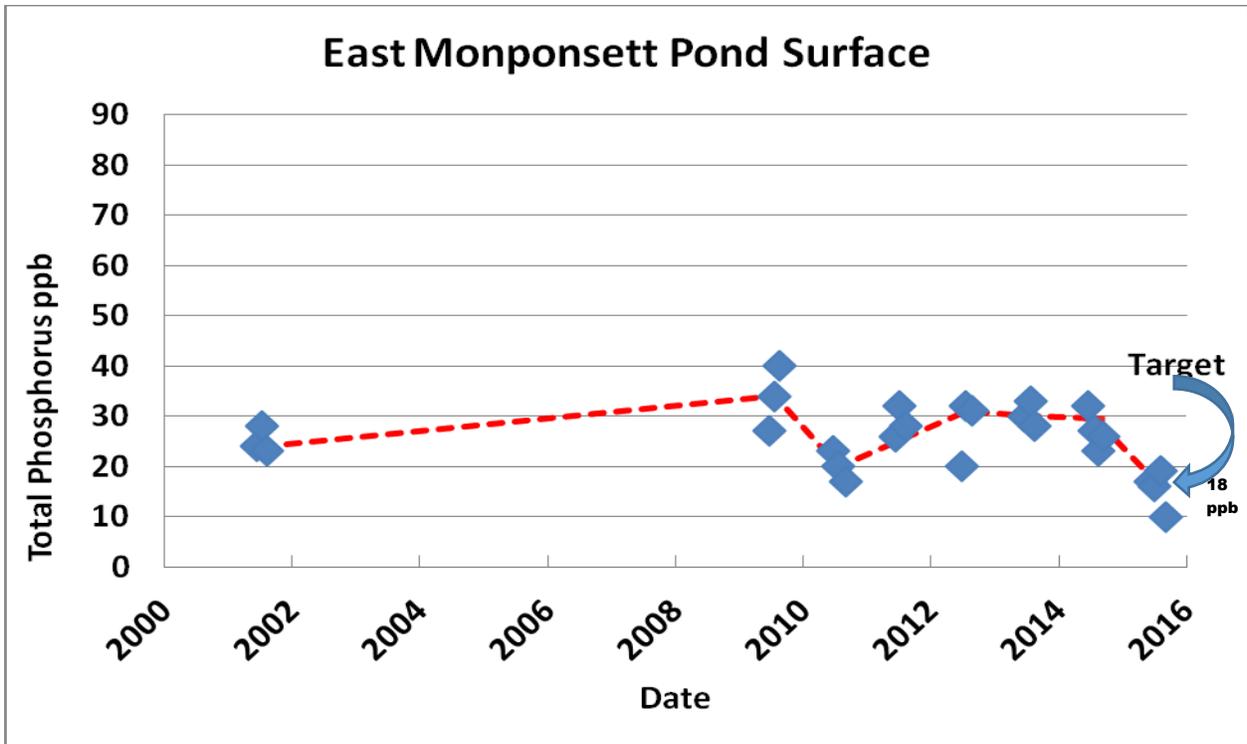


Figure 6. East Monponsett Pond Surface Total Phosphorus. Summer median values are indicated by the dashed line.

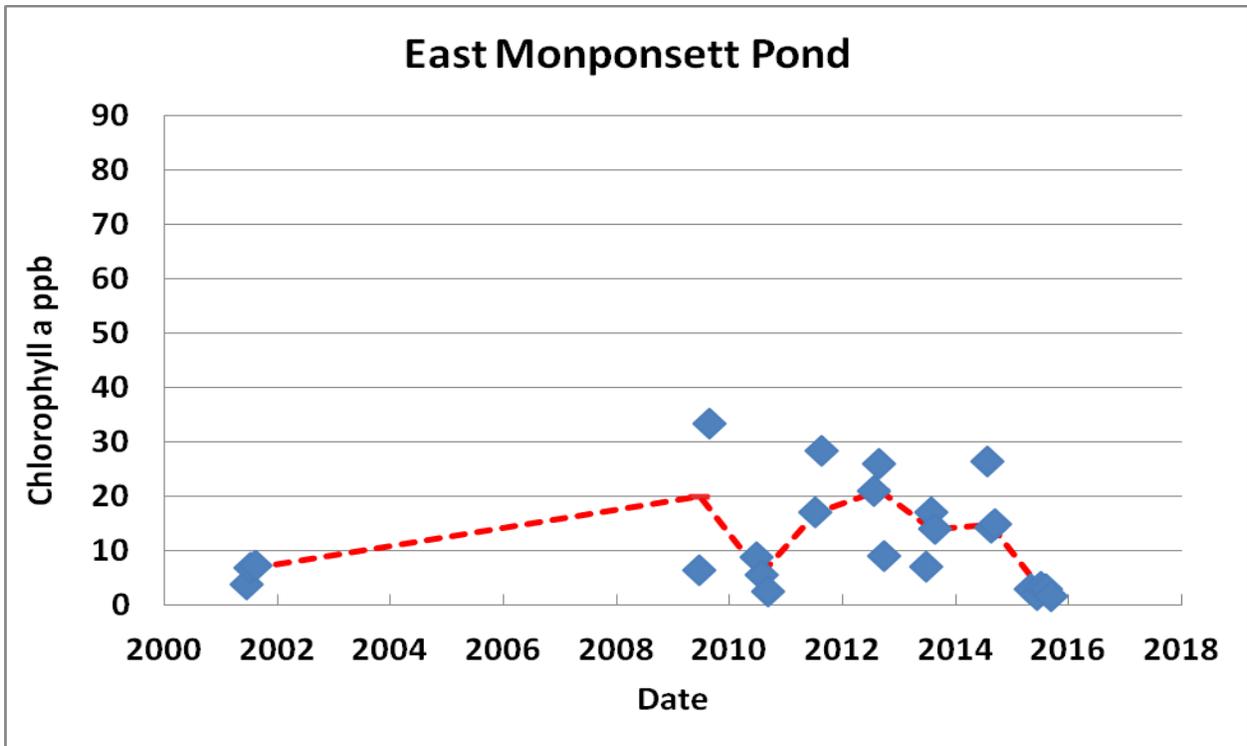
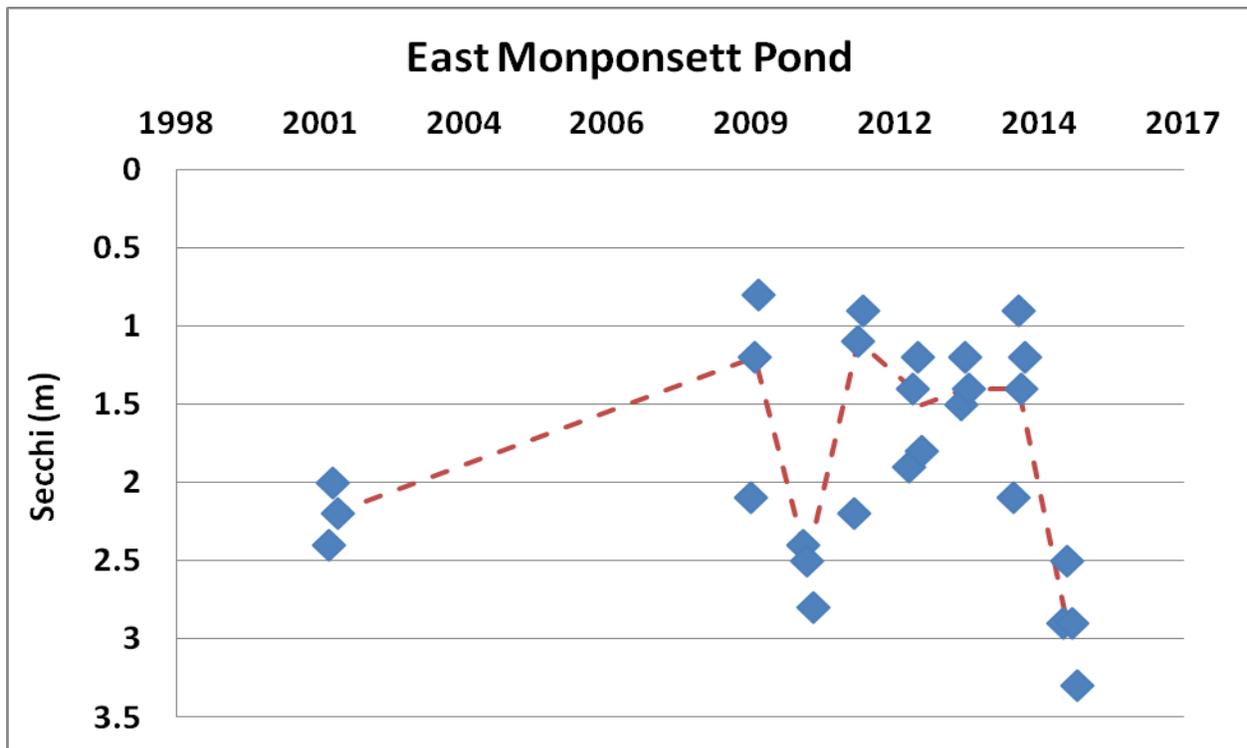


Figure 7. East Monponsett Pond Chlorophyll *a* . Summer median values are indicated by the dashed line.



**Figure 8. East Monponsett Pond Secchi disk transparency. (Note y axis reversed). Summer median values are indicated by the dashed line.**

White Oak Reservoir was sporadically sampled for various parameters in 2009-2015 with no clear trends in TP or chlorophyll *a* (Figure 9, Figure 10). Median Secchi disk transparency did improve to 1.5 m ( just above the 1.2 m threshold) in 2015 (Figure 11). The White Oak Reservoir was often noted in 2015 to have a dense whole lake plant coverage which consisted of *Ceratophyllum*, *Cabomba caroliniana*, *Wolffia* and *Lemna minor*. In past years the *Lemna minor* (duckweed) coverage was observed to be an impairment (>25%) to aquatic life support and a candidate for listing on the impaired waters list in need of a TMDL. In 2011 for example the White Oak Reservoir was observed to be 30%, 75% and 40% covered by duckweed on visits in June, July and August, respectively. During the 2015 sampling season duckweed cover began around 1% of the surface area of the White Oak Reservoir in May and by the end of the sampling season in September covered approximately 35% of the reservoir’s surface area. Steffenhagen *et al.* (2012) have found that *Lemna minor* and *Ceratophyllum* can incorporate a significant amount of in pond phosphorus in their standing stock. For this reason, even though the median summer TP was only 35 ppb in 2015 (Figure 9), the true concentration may be as high as 50 ppb if the mass of non-rooted macrophytes is included.

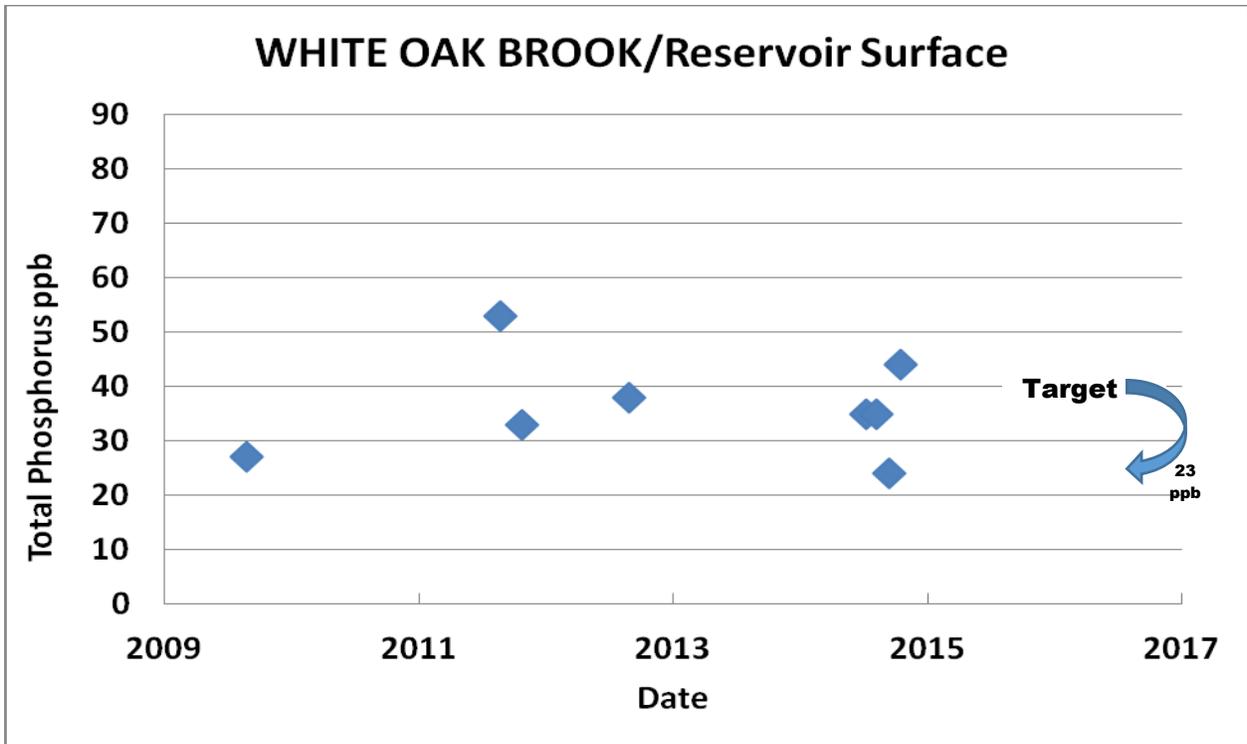


Figure 9. White Oak Reservoir Surface Total Phosphorus. Not enough data to compute summer median data.

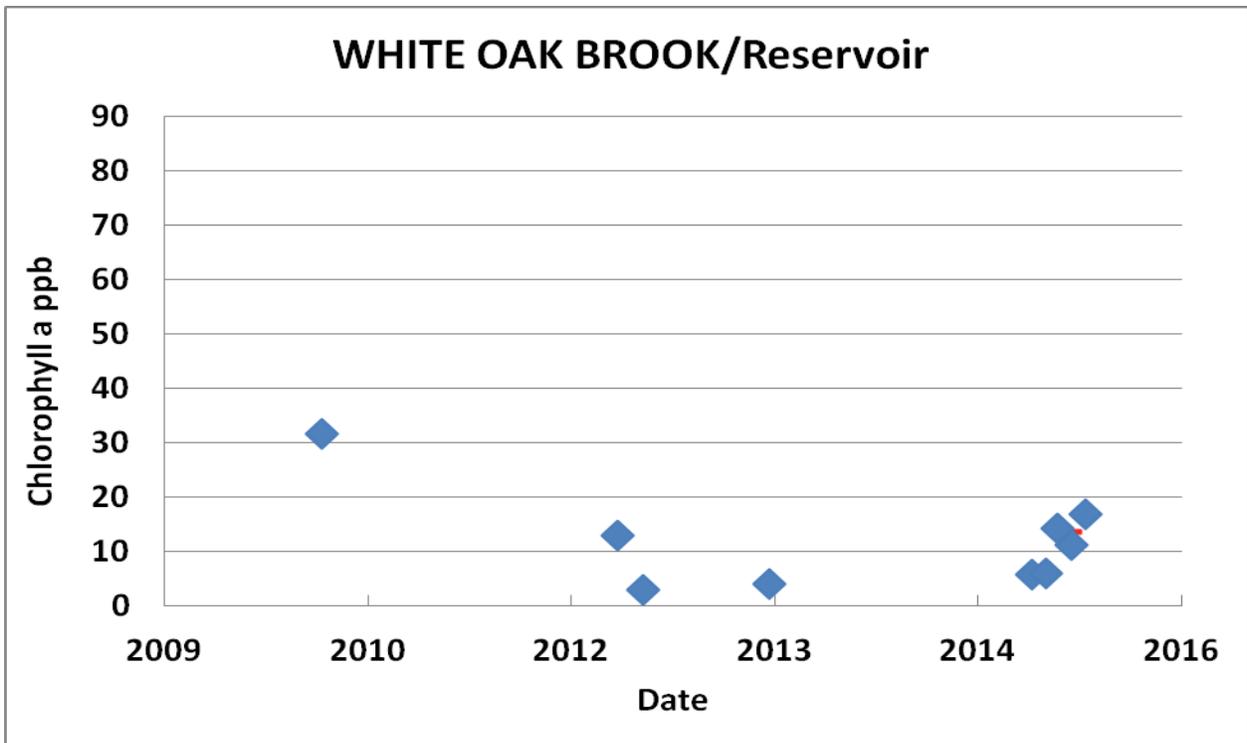
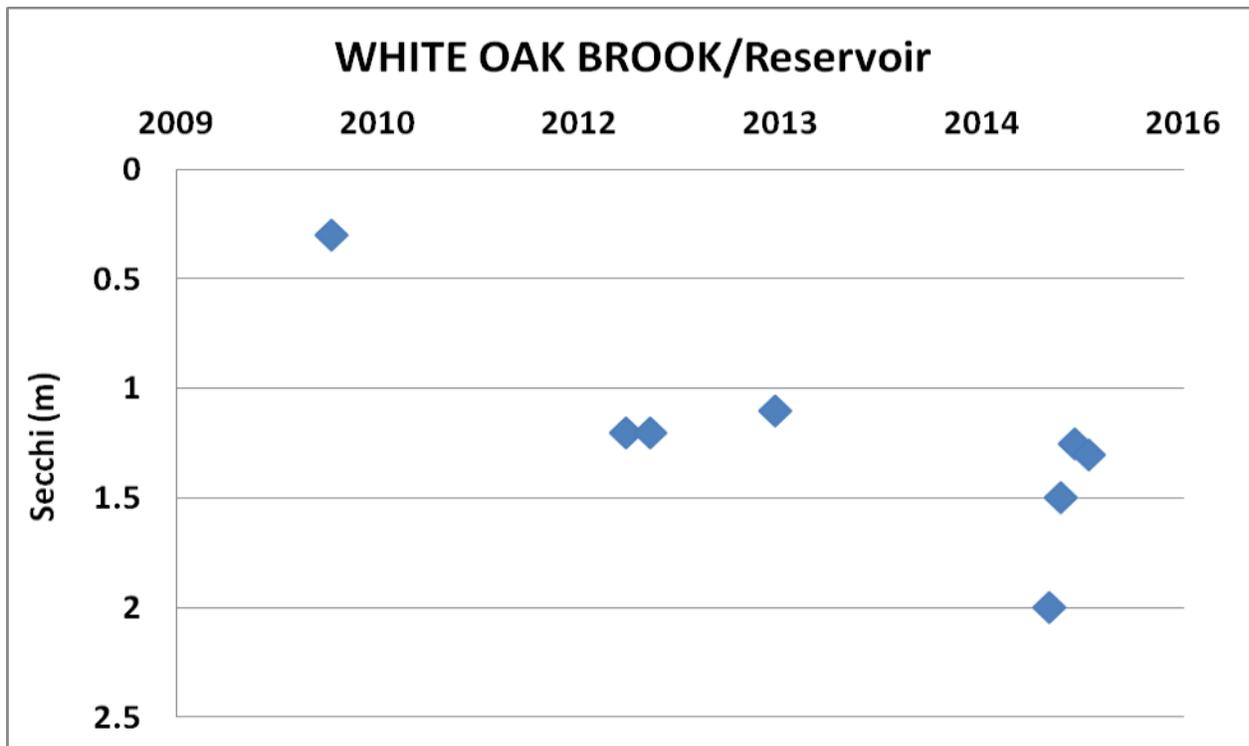


Figure 10. White Oak Reservoir Chlorophyll *a* . Not enough data to compute summer median.



**Figure 11. White Oak Reservoir Secchi disk transparency. (Note y axis reversed). Not enough data to compute summer median.**

West Monponsett Pond was sampled in the summers of 1985 and again in 2007 by Lycott (1987, 2007) and both sets of data are summarized in Lycott (2007). Unfortunately, Lycott sampled at both the surface and one foot off the bottom (indicated as deep), but the report cites the exact same results in Table A as Surface and in Table B as Deep so it is unclear where the samples came from (Lycott, 2007) but in either case the results were very high TP with one sample exceeding 1,000 ppb.

MassDEP sampled West Monponsett Pond on the same days as East Monponsett Pond in the summers of 2001 and 2009 through 2015. The June-August median TP concentration was 57 ppb in 2001 and was 70 ppb in 2009 (Figure 12). TP concentrations dropped after 2009 and the medians were 54 ppb in both 2011 and 2012. A t-test on the mean summer TP from the combined 2009 and 2010 data compared to the combined 2011 and 2012 data show a significant decline of 12.2 ppb ( $\alpha=0.026$ ). The 23 percent decline in median lake TP is coincident with a 71 percent reduction in phosphorus fertilizer rates (from 28.6 lb/acre to 8.2 lb/acre) at upstream Morse Brothers cranberry bog #19 and a 61 percent reduction (from 17.3 lb/acre to 6.8 lb/acre) at the small, 2 acre section of their Winebrook Bog next to the lake over the years 2008-2014 (DeMoranville, 2016b). An additional drop in TP concentrations can be seen in 2013 and 2015 that is coincident with the aluminum treatment described above. Some recovery in TP concentrations can be seen in 2014 during a year with no aluminum treatment (Figure 12).

Despite the reductions in West Monponsett TP concentrations between 2009 and 2013, the chlorophyll *a* concentrations appeared to increase during that time period as shown in Figure 13

reaching a median of just over 70 ppb in 2013, greatly exceeding the target of less than 16 ppb. The chlorophyll *a* concentrations tracked the TP concentrations and the June-August 2015 median chlorophyll *a* concentration declined to 11.5 ppb. A large bloom occurred in August-September that exceeded 40 ppb (Figure 13) resulting in the bloom shown on the cover of this report. The Secchi disk transparency also tracks the TP and chlorophyll *a* trends but the median summer values have generally been less than the 1.2 m target (Figure 14). Transparency improved following the aluminum treatment in 2015 and resulted in the June-August median slightly beating the target. Again, the late bloom in August and September resulted in poor transparencies for those months.

West Monponsett Pond was generally not noted to be hypoxic at depth and did not exhibit temperature stratification (Appendix C, Figures C15-C16). This pond has been found to consistently exceed the Massachusetts Department of Health (MA DPH) Advisory level of 70,000 cells/mL. The pond exceeded this level for substantially all the summer and fall seasons during 2013 and 2014 (Appendix C). Cyanobacteria blooms continued to be an issue during the summers of 2015, 2016 and 2017. A reduction in the frequency and severity of cyanobacteria blooms is a key restoration goal for this TMDL. The pond was not posted due to cyanobacteria blooms in 2018 while draft results indicate total phosphorus concentrations remained below the target threshold.

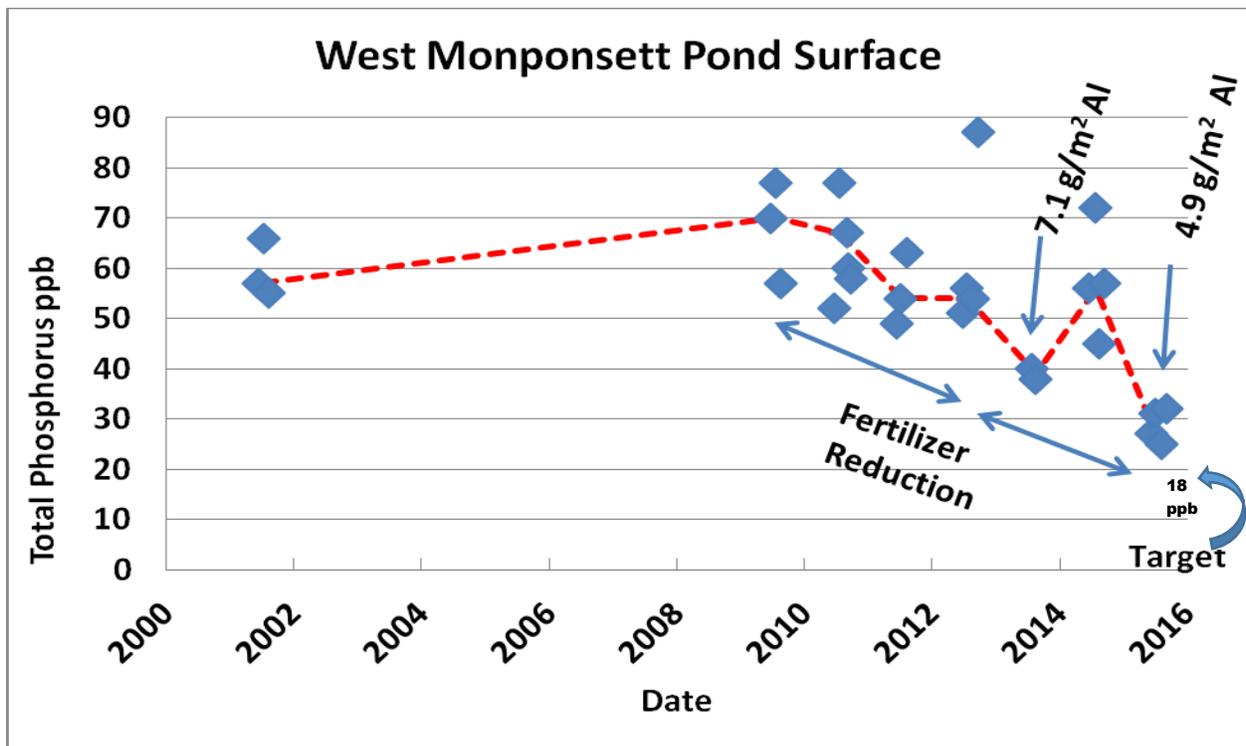


Figure 12. West Monponsett Pond Surface Total Phosphorus. Summer median values are indicated by the dashed line.

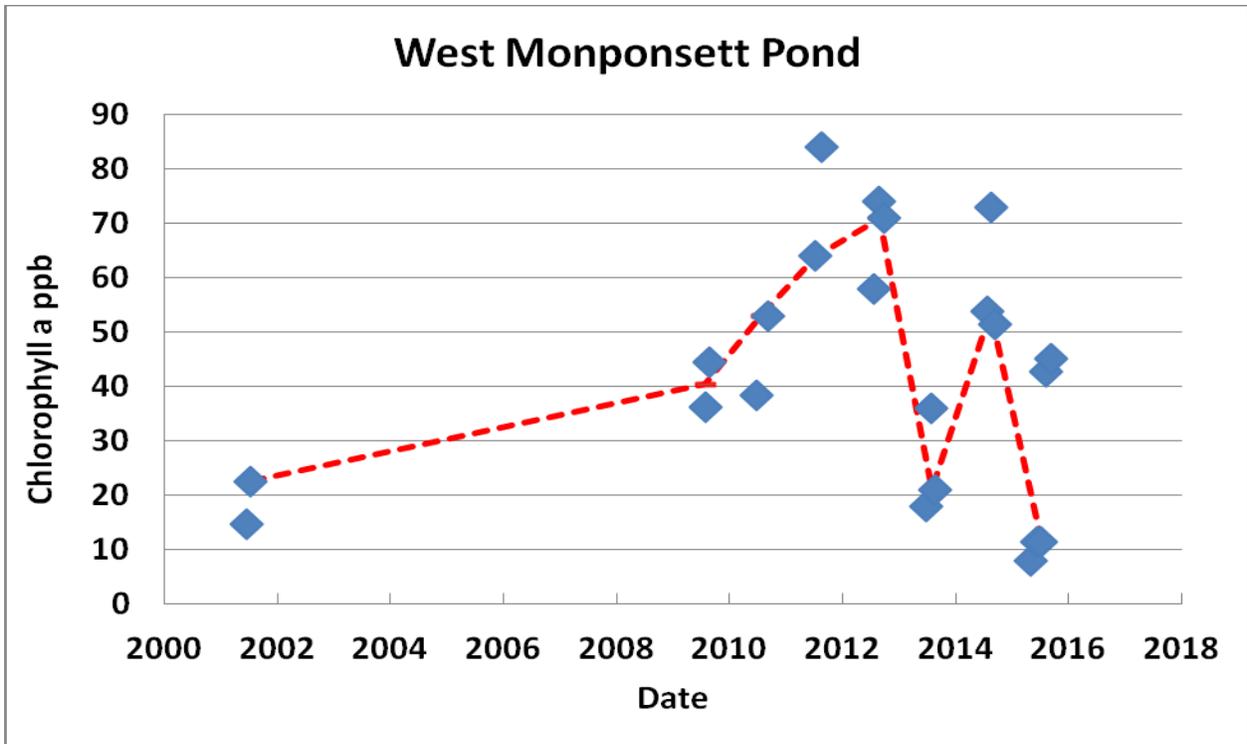


Figure 13. West Monponsett Pond Chlorophyll *a* . Summer median values are indicated by the dashed line.

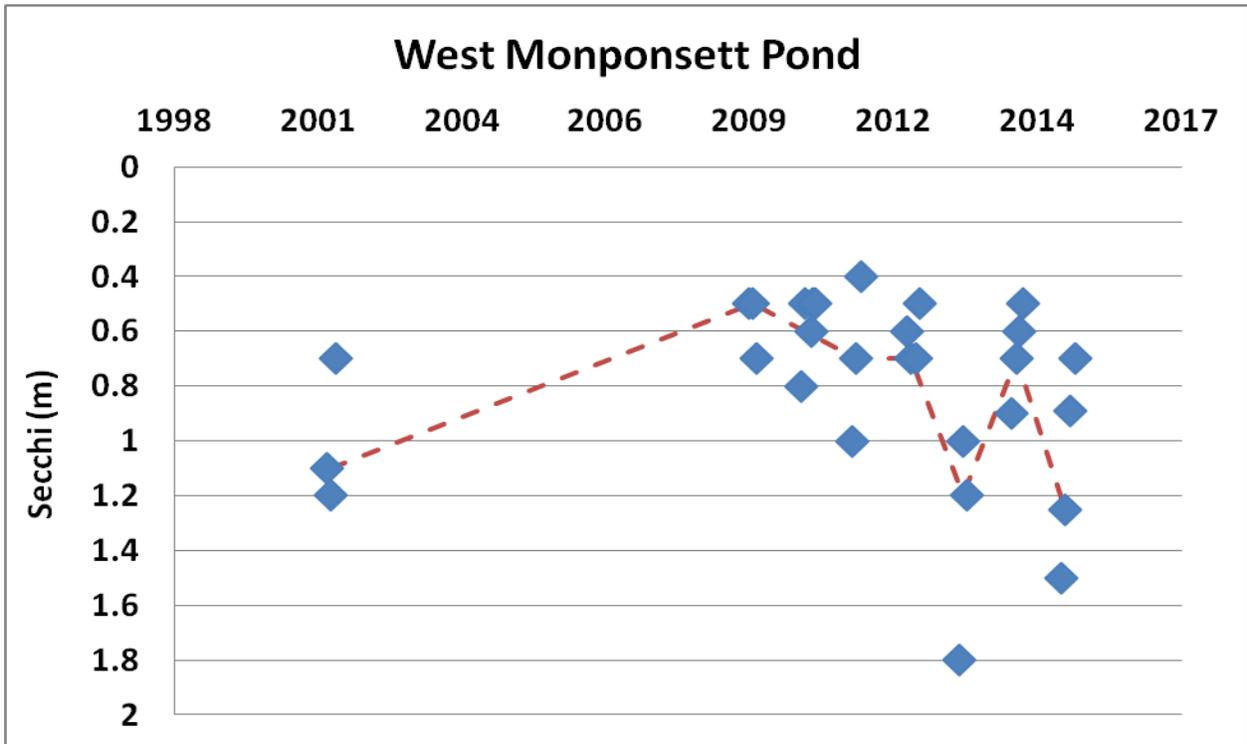


Figure 14. West Monponsett Pond Secchi disk transparency. Summer median values are indicated by the dashed line. (Note y axis reversed).

## Source Assessment

In order to estimate the current phosphorus loadings to the TMDL study ponds, the Lake Loading Response Model (AECOM 2009) was used. The Lake Loading Response Model (LLRM) is a spreadsheet based model which uses an annual steady state suite of models to estimate nutrient loadings. These estimated nutrient loadings along with pond morphometric and physical characteristics are then used to predict in-pond nutrient concentrations using a suite of well accepted lake models for phosphorus predictions (Kirchner-Dillon 1975, Vollenweider 1975, Larsen-Mercier 1976, Jones-Bachmann 1976 and Reckhow 1977). Details of models and notes on calibration of the models for the Monponsett Ponds can be found in the Monponsett Pond TMDL Modeling Documentation (Appendix E).

The LLRM model uses inputs for estimated nutrient loadings from landuse, septic systems, waterfowl, internal loading, areal deposition and point sources. The model was calibrated and used to estimate current loading to the ponds in the TMDL study area. An initial attempt was made to simply use the areas corresponding to landuse categories and multiply them by conventional phosphorus export coefficients to obtain nutrient loadings, but this approach resulted in very high loadings compared to estimates of loading based on lake concentrations and flushing rates. The phosphorus loadings appear to be greatly attenuated in the groundwater transport in this system as noted in discussion of calibration of the LLRM in Horsley Witten (2015). A similar issue was previously noted by another researcher in modeling the Pembroke Ponds which include Stetson Pond (BEC, 1993). Following the approach used by BEC (1993) we focused on direct fluvial inputs such as cranberry bogs discharges, inputs from streams draining forested wetlands and relatively direct inputs of lake sediment phosphorus recycling and stormwater inputs. MassDEP staff collected a series of sediment cores from West Monponsett Pond and aerobically incubated the cores in the lab to measure phosphorus release to the overlying water headspace. From these measurements an aerobic phosphorus release rate was determined and later used in calculations of summer release rates (MassDEP, 2010b; Appendix E).

## Numeric Water Quality Target

The waterbodies in the TMDL study area are all classified as Class A in the Massachusetts Surface Water Quality Standards (Table 1). Class A waterbodies are designated as a source of public water supply as well as “designated as excellent habitat for fish, other aquatic life and wildlife, including for their reproduction, migration, growth and other critical functions, and or primary and secondary contact recreation, even if not allowed” (MassDEP, 2007).

Massachusetts’ narrative criteria for nutrients is “Unless naturally occurring, all surface waters shall be free from nutrients in concentrations that would cause or contribute to impairment of existing or designated uses and shall not exceed the site specific criteria developed in a TMDL or as otherwise established by the Department pursuant to 314 CMR 4.00” (MassDEP, 2007).

In order to assess waterbodies in the Massachusetts uses the CALM (MassDEP, 2016) as part of 305b and 303d listing for Clean Water Act purposes. As referenced above this document has guidance threshold values which allow the characterization of whether a waterbody is supporting its designated uses. Lacking a nutrient criterion, a numeric target total phosphorus concentration

must be chosen which should meet certain CALM guidance thresholds for lakes and allow for the meeting of designated uses and therefore meeting SWQS. The target total phosphorus concentration must be chosen to be low enough for all designated uses to be attained. In the case of nutrients the uses include primary and secondary contact recreation, aquatic life and aesthetics. Based on MassDEP's CALM document (MassDEP, 2016) all of these lakes should generally meet the 1.2 meter Secchi disk transparency, 5 mg/l dissolved oxygen concentration, the maximum monthly chlorophyll *a* concentration should not exceed 16 ppb, have less than 25% non-rooted macrophytes and be free from frequent cyanobacteria blooms (>70,000 cells/mL) to be considered free of nutrient impairment (unless the exceedance is a natural condition). There is always uncertainty in the data collected, the modeling assumptions and modeling error in the loads. In addition there is temporal variability that is not included in the steady state models used here. As such there may be sometimes when the biological thresholds are exceeded. The rationale for MassDEP's selection of these target TP concentrations for each waterbody is described in the following sections.

Generally, all uses for typical warm water lake fisheries (including swimming, boating and aesthetics) can be met at the USEPA "Gold Book" recommendation of 0.025 mg/l (USEPA, 1986). A further refinement of total phosphorus targets utilizes concentrations of phosphorus in lakes within uniform ecological regions (the ecoregion approach). The phosphorus ecoregion map of Griffith et al. (1994) indicates the lake is in an ecoregion with concentrations of 15-19 ppb, based on spring/fall concentrations, while the phosphorus ecoregion map of Rohm et al., (1995) suggests that typical lakes in this ecoregion would have concentrations between 30 and 50 ppb, based on summer concentrations. The United States Environmental Protection Agency (USEPA) has proposed a lower TP concentration for lakes in Ecoregion XIV of 8 ppb (<https://www.epa.gov/sites/production/files/documents/rivers14.pdf>). MassDEP reviewed EPA's ecoregion approach and concluded that Massachusetts water quality data was not represented in the EPA analysis which calls into question the validity of directly applied EPA criteria to Massachusetts' waters.

Clear water seepage lakes tend to have lower total phosphorus concentrations than typical lakes with inlet streams. The median summer surface total phosphorus concentration in other relatively unimpacted clear water seepage lakes in southeastern Massachusetts is very low ranging from 6 to 16 ppb (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013).

The total phosphorus concentration expected to attain the biological thresholds of the CALM listed above may vary between types of lakes. In this case the lakes in question are quite different and are expected to respond differently to total phosphorus. Previous MassDEP sampling in lakes in Massachusetts suggests a target of 23 ppb total phosphorus for clear (not tea colored) lakes that are dominated by groundwater seepage and 48 ppb total phosphorus for clear impoundments is appropriate (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013). However, in colored lakes with high concentrations of dissolved carbon, as indicated by true color measurements exceeding 57 PCU, the natural total phosphorus is expected to be higher than in otherwise similar clear water lakes (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013). Using professional knowledge and a weight of evidence the pond's target concentrations were determined.

In the case of Stetson Pond, the data show that the lake has largely recovered from impairment in recent years (see Figure 3). There was a large reduction in TP concentrations from a surface median of 40 ppb down to near 15 ppb between the 1988 study and the recent 2015 data, respectively. This reduction is associated with the sale of the upstream cranberry bogs (Edgewood Bogs) to the town and subsequent abandonment of the cranberry production in 2008. The large reduction in TP is also associated with a general reduction in the nuisance algal blooms which caused impairment in 1988, yet the median chlorophyll *a* and median Secchi disk transparency did not change significantly (see Figure 4 and Figure 5). The lake is now attaining the minimum water quality response thresholds for chlorophyll *a* and duckweed but the lake still has brief oxygen depletion in the bottom waters as shown for the sample collected on 8/13/15 in Figure C-12. Such brief oxygen depletions near the bottom of the lake are expected as natural conditions in mesotrophic lakes.

Stetson Pond is a shallow, clear water lake with the longest residence time of the ponds in the TMDL study area. The TP concentration target is set at 13 ppb, just below the current volume weighted average of 15 ppb. The lake is a clear water lake and is expected to be relatively low in TP. The LLRM is basically a phosphorus model and does not predict hypolimnetic dissolved oxygen. MassDEP believes the target of 13 ppb TP will result in natural levels of dissolved oxygen in the lake and should attain all uses related to nutrient impairment. Even very low phosphorus, oligotrophic, similar sized lakes such as Mirror Lake in New Hampshire do not maintain oxygen in the deep hypolimnion and this is not a reasonable expectation (Winter and Likens, 2009).

White Oak Reservoir is listed as impaired for Nutrient/Eutrophication Biological Indicators in the 2016 Integrated List of waters (MassDEP, 2019). Comparing the data on *Lemna* (duckweed) percent cover on the pond to our CALM assessment threshold of 25%, supports this impairment. MassDEP sampling protocol generally excluded duckweed fragments from the phosphorus sample. MassDEP believes the TP concentrations reported for the water do not include the TP taken out of the water by the floating duckweed and we made adjustments to the loading models previously described. Because so much of the current phosphorus loading is quickly taken up in the duckweed, future reductions in phosphorus loadings may not be reflected in proportional reductions in TP as measured by traditional whole water total phosphorus samples. Instead, we expect the mass and percent cover of duckweed on the pond to diminish until the pond is less than 25% covered by duckweed and meets the biological threshold within the MassDEP CALM. The nominal target is thus set to 23 ppb which represents a reduction in loading of about 54 percent. This target is appropriate based on previous MassDEP lake surveys (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013).

White Oak Reservoir is a very shallow, well flushed and colored impoundment and this is expected to influence its response to nutrients. Most lakes nutrient budgets are calculated on an annual basis, as it is generally believed that they respond slowly to changes in nutrient loadings due to the long residence time. White Oak Reservoir, however, has a very short residence time of about 21 days due to the shallow mean depth of 1.1 m. This fast flushing time is expected to limit the growth of the algae and unattached macrophytes which are expected to be flushed downstream before growing to levels otherwise expected from the TP concentrations. Leesville Pond, a shallow pond with fast flushing time in central Massachusetts has an approved TMDL

with a target TP concentration of 40 ppb (MassDEP, 2002). Note that according to the Carlson Trophic State analysis (Carlson, 1977) a lake should have total phosphorus concentrations of about 40 ppb to meet the 4-foot transparency requirement for swimming beaches in Massachusetts. Furthermore, relatively high color in the impoundment (which averages about 55 PCU of true color) suggests a higher TP concentration may be appropriate. Despite the justification for a higher target total phosphorus concentration a lower target of 23 ppb was chosen. This conservative value was selected as the impoundment is tributary to a public water supply and it will provide some margin of safety for White Oak Reservoir, while also protecting downstream resources in West Monponsett Pond.

East Monponsett Pond is a shallow, moderately flushed and colored pond with complex hydrology. It combines surface water flows with groundwater inputs as well as reverse flows from West Monponsett Pond during periods of diversion to Silver Lake. This waterbody had moderately high median color of 61 PCU in 2009 which is associated with higher TP (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013). (Note that true color and TP in the East Monponsett Pond has been declining (i.e. improving), possibly due to implementation of Best Management Practices at the upstream cranberry bogs). However, East Monponsett Pond is also classified as Class A and is tributary to the public water supply, Silver Lake, and thus a lower target TP concentration should be considered as a measure to protect the water supply use of the Monponsett Ponds. A target of 20 ppb TP was initially selected because even at the higher current concentrations, no obvious impact to Silver Lake water quality has been observed and based on the LLRM model estimates that the chlorophyll *a* will meet the target of 16 ppb approximately 96% of the time. In the two years (2010 and 2015) that the East Monponsett Pond averaged 20 ppb TP it met the CALM thresholds for chlorophyll *a* and Secchi disk transparency (see Figure 7 and Figure 8). To add an additional margin of safety and to match the target of West Monponsett Pond the final TMDL target is set to 18 ppb.

West Monponsett Pond is also a shallow and colored pond and is equally complex in hydrology as East Monponsett Pond. This pond has a flushing rate greater than Stetson Pond but less than East Monponsett Pond. In addition to the flows and diversions mentioned above, West Monponsett Pond also has variable elevations and downstream flows due to changes in the dam gates by the City of Brockton. While the nominal target would be 23 ppb as above, the lake is also tea colored with a median color of 57 PCU in 2009 and thus a higher natural TP concentration target would be expected (note as above, color and TP have been declining (i.e. improving) in the pond in recent years). During times of diversion, water from West Monponsett Pond may flow (via East Monponsett Pond) to Silver Lake which is used for the City of Brockton's water supply, and therefore a more restrictive TP concentration target is appropriate. Given the pond's lower flushing rate when compared to East Monponsett Pond a more conservative target is also warranted. The target concentration for West Monponsett was initially set to 20 ppb. However, data collected in the summer of 2016 and 2017 indicated that West Monponsett surface waters continued to bloom with cyanobacteria and exceeded the CALM guidance value of 16 ppb chlorophyll *a* in 2016 and did not meet the Secchi disc CALM threshold of 1.4 meters. Based on this information the final TMDL target is set 10 percent lower to 18 ppb. In 2018 cyanobacteria blooms remained below the 70,000 cells/ml MA DPH advisory level while draft data indicate the total phosphorus threshold was met. It is important to note that West Monponsett Pond may not be in a stable state after recent alum applications.

This target is also supported by the Carlson Trophic State index or TSI (Carlson, 1977) as described in the GEIR (Mattson et al., 2004). The Carlson TSI predicts a trophic state of 57 based on the target Secchi of 1.2 m and a trophic state of 58 based on a maximum chlorophyll *a* of 16 ppb. The selected total phosphorus target of 18 ppb has a trophic state index of 45.8, which is expected to result in biomass approximately 50% below the biological response targets listed above. In addition, the previously approved TMDL for nearby White Island Pond has similar loading issues (dominated by cranberry bogs and internal loading) and has a target of 19 ppb. After the last alum treatment at that pond the lake is just below 19 ppb and has completely recovered from severe cyanobacteria blooms (MassDEP, 2010a; Mattson, 2015). Thus the targets are conservatively set to meet MassDEP's Water Quality Standards. Historically, records indicate that West Monponsett Pond was consistently more highly colored and was more eutrophic than East Monponsett Pond, but the two TMDL targets have been set the same given the fact both are Class A-ORW waterbodies.

## **Determination of Loading Capacity**

### **Linking Total Phosphorus to the Numeric Water Quality Target**

The LLRM model was used to estimate each pond's target load for total phosphorus based on the target concentrations in the water column described above. The total phosphorus load was adjusted for each pond until its predicted total phosphorus concentration matched the target phosphorus concentration. The predicted concentration used in the LLRM model was an average of all the prediction models excluding the Mass Balance equation (see Appendix B, Table B2, B3).

The estimated allowable total phosphorus load was 48 kg/yr, 182 kg/yr, 35 kg/yr and 186 kg/yr for Stetson Pond, East Monponsett Pond, White Oak Reservoir and West Monponsett Pond, respectively (Tables 5-8, below). The lake models used in this TMDL have a yearly time step. This along with the fact that ponds store phosphorus in the water column and sediments means water quality responds to inputs on a yearly basis. The use of annual loads in TMDLs is a generally accepted method for lake and pond TMDLs and is in accordance with EPA Guidance (EPA 1986 and 1990). Further details on the LLRM modeling are available in Appendix E.

Meeting the threshold loads for each pond will result in reduced algal blooms. All the ponds had a predicted probability of chlorophyll *a* >16 ppb, less than 10% of time. It is important to note White Oak Reservoir is currently dominated by duckweed and aquatic plants. Reduction in duckweed cover is the restoration target for this waterbody. East Monponsett Pond and West Monponsett Pond at their target loads will have predicted peak chlorophyll *a* values of approximately 21 ppb and 23 ppb, respectively, less than 2.5% annually (Appendix E, Table 18). In the future, peak chlorophyll *a* values may occasionally exceed the 16 ppb criterion. The goal of this TMDL is to reduce the extent and severity of current algae blooms and ensure that all surface water quality standards are met.

## **Pollutant Load Allocations**

### **Waste Load Allocation**

Based on estimated current stormwater loads of TP phosphorus to the waterbodies covered in this TMDL generally a 50% to 60% reduction in stormwater loads has been allocated in this TMDL for all affected waterbodies. The total Waste Load Allocations (WLA) for Stetson Pond, East Monponsett Pond, White Oak Reservoir and West Monponsett Pond watersheds are 19.24 kg/yr, 76.58 kg/yr, 21.63 kg/yr and 70.36 kg/yr, respectively. For complete details on the estimation of current stormwater loads and the procedure to allocate a wasteload allocation see Appendix E (pg. 122-128).

In order to reach the target threshold for Stetson Pond a 50% percent reduction in stormwater load will be required from the low intensity development, medium intensity development and natural landuse categories (MassGIS landuse categories: Low Density Residential, Medium Density Residential, Transitional, Forest; Table 5). (Note; reductions in “natural” areas refer to roads and other impervious areas within undeveloped areas.) Similar reductions in stormwater loads will be necessary to meet the target threshold for East Monponsett Pond (Table 6). A 60% reduction in stormwater loads will be necessary from the low intensity development, medium intensity development and high intensity landuse categories while a 50% reduction in the natural category is required (MassGIS landuse categories: Commercial, High Density Residential, Industrial, Low Density Residential, Medium Density Residential, Multi-Family Residential, Participation Recreation, Transportation, Urban Public/Institutional, Very Low Density Residential and Forest). For both ponds the necessary stormwater loading reductions would be associated with impervious areas. Additionally for the two ponds it is recommended to focus on reducing stormwater loads where impervious surfaces exist in any of the landuse categories.

Significant reductions in stormwater loads are also required in White Oak Reservoir and West Monponsett Pond (Table 7, 8 respectively). In order to reach the target threshold for White Oak Reservoir a 60% reduction in stormwater loads from the low intensity development, medium intensity development, high intensity development and natural land use categories is required (MassGIS landuse categories: Commercial, Industrial, Low Density Residential, Medium Density Residential, Multi-Family Residential, Transportation, Urban Public/Institutional, Very Low Density Residential and Forest; Table 7). West Monponsett Pond will also require a 60% reduction in stormwater loads from the high intensity agriculture, medium intensity development, high intensity development and natural land use categories (MassGIS landuse categories: Commercial, Cranberry Bog, Forest, Low Density Residential, Medium Density Residential, Multi-Family Residential, Participation Recreation, Transitional, Transportation, Urban Public/Institutional, Very Low Density Residential; Table 8). For both ponds the necessary stormwater loading reductions would be associated with impervious areas (including within “natural” areas. Additionally, for the two ponds it is recommended to focus on reducing stormwater loads where impervious surfaces exist in any of the landuse categories.

## **Load Allocation**

In order to reach the target threshold for Stetson Pond, a 90% reduction in internal loading will be required (Table 5). In addition watershed load reductions of 25% are necessary from the low intensity development and medium intensity development land use categories. Reduction could come from reduction in loads from residential fertilizer use.

In order to reach the target thresholds for the East Monponsett Pond in this TMDL, a large reduction in internal loading and current watershed loading is required for East Monponsett Pond (Table 6). The largest source of watershed land use load reductions (88%) will need to come from cranberry bogs (high intensity agriculture). The phosphorus export coefficient target of 0.5 kg/ha/yr successfully used at White Island Pond cranberry bogs (MassDEP, 2010a, Mattson, 2015) can be used to attain the target loads in the bogs located in the greater Monponsett Pond watershed. Additionally 50% reduction in watershed loads from the low intensity development, medium intensity development, and high intensity development land use categories will be necessary.

The White Oak Reservoir will require reductions in total phosphorus loading from cranberry bogs (~88%); the same as described above for East Monponsett Pond (Table 7). In addition a 25% reduction in watershed loads from the low intensity development land use category is necessary.

The West Monponsett Pond will require an approximate 73% reduction in its total phosphorus loading in order to meet the threshold load of 185 kg/yr (Table 8). The reduction in loading will need to come from two of the principal loads, internal sediment recycling and cranberry bogs. Total phosphorus loads from internal loading will require a 90% reduction, principally by aluminum addition. Similarly an 88% reduction in total phosphorus loads from cranberry bogs is also necessary via fertilizer reductions and other BMPs. Finally, watershed loads from the low intensity development, medium intensity development and high intensity land use categories will require a 50% reduction.

In summary, the four waterbodies were modeled with a consistent set of export coefficients and current (2009 or 2015) TP loads were estimated. Target TP concentrations were developed and a new set of TMDL loads were established to meet those targets. The reductions in loads required to reach the targets ranged from 30 to 73% as shown in Table 9.

## **Margin of Safety**

An explicit MOS quantifies an allocation amount separate from other Load and Wasteload Allocations. An explicit MOS can incorporate reserve capacity for future unknowns, such as population growth or effects of climate change on water quality. An implicit MOS is not specifically quantified but consists of statements of the conservative assumptions used in the analysis. The MOS for these TMDLs is implicit. MassDEP used conservative assumptions to develop numeric model applications that account for the MOS. These assumptions are described below, and they account for all sources of uncertainty, including the potential impacts of changes in climate.

**Table 5. Current TP Loads and Allocated TP Loads for Stetson Pond**

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	7.62	<b>7.62</b>	0.00	0%
Internal	6.87	<b>0.69</b>	6.19	90%
Septic System	10.77	<b>10.77</b>	0.00	0%
<b>Watershed Load</b>				
Low Intensity Development	6.16	<b>4.62</b>	1.54	25%
Medium Intensity Development	3.63	<b>2.72</b>	0.91	25%
Forested Wetland	1.09	<b>1.09</b>	0.00	0%
Non-Forested Wetland	0.75	<b>0.75</b>	0.00	0%
Low Intensity Agriculture	0.22	<b>0.22</b>	0.00	0%
<i>Total Watershed Load</i>	11.85	<b>9.40</b>	2.45	21%
<b>Total Load</b>	37.11	<b>28.48</b>	8.63	23%
<b>Stormwater Load By Landuse</b>				
Low Intensity Development	10.10	<b>5.05</b>	5.05	50%
Medium Intensity Development	9.56	<b>4.78</b>	4.78	50%
Natural	6.32	<b>3.16</b>	3.16	50%
Abandoned Cranberry Bogs	4.45	<b>4.45</b>	0.00	0%
Forested Wetland	0.53	<b>0.53</b>	0.00	0%
Non-Forested Wetland	0.59	<b>0.59</b>	0.00	0%
Low Intensity Agriculture	0.68	<b>0.68</b>	0.00	0%
<b>Total Wasteload</b>	32.23	<b>19.24</b>	12.99	40%
<b>Totals Maximum Yearly Load<sup>1</sup></b>	69	<b>48<sup>1</sup></b>	22	31%

1- (Total Maximum Yearly Load = Total Load Allocation plus Total Wasteload Allocation, rounded to nearest kg/year)

**Table 6. Current TP Loads and Allocated TP Loads for East Monponsett Pond**

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	21.99	<b>21.99</b>	0.00	0%
Internal	30.00	<b>15.00</b>	15.00	50%
Septic System	16.24	<b>16.24</b>	0.00	0%
<b>Watershed Load</b>				
High Intensity Agriculture	89.79	<b>11.00</b>	78.79	88%
Medium Intensity Development	5.24	<b>2.62</b>	2.62	50%
Forested Wetland	26.71	<b>26.71</b>	0.00	0%
Low Intensity Development	13.53	<b>6.76</b>	6.76	50%
High Intensity Development	1.53	<b>0.77</b>	0.77	50%
Non-Forested Wetland	3.10	<b>3.10</b>	0.00	0%
Low Intensity Agriculture	1.19	<b>1.19</b>	0.00	0%
<i>Total Watershed Load</i>	141.09	<b>52.15</b>	88.94	63%
<b>Total Load</b>	209.32	<b>105.38</b>	103.94	50%
<b>Stormwater Load By Landuse</b>				
High Intensity Agriculture	13.61	<b>13.61</b>	0.00	0%
Medium Intensity Development	48.22	<b>19.29</b>	28.93	60%
Forested Wetland	13.66	<b>13.66</b>	0.00	0%

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Low Intensity Development	24.01	<b>9.60</b>	14.40	60%
Natural	23.31	<b>11.65</b>	11.65	50%
High Intensity Development	7.04	<b>2.82</b>	4.23	60%
Non-Forested Wetland	2.47	<b>2.47</b>	0.00	0%
Abandoned Cranberry Bogs	3.48	<b>3.48</b>	0.00	0%
Low Intensity Agriculture	0.00	<b>0.00</b>	0.00	0%
<b>Total Wasteload</b>	135.80	<b>76.58</b>	59.22	44%
<b>Total Maximum Yearly Load<sup>1</sup></b>	345	<b>182<sup>1</sup></b>	163	47%

1- (Total Maximum Yearly Load = Total Load Allocation plus Total Wasteload Allocation. Total load is rounded to nearest kg/year)

**Table 7. Current TP Loads and Allocated TP Loads for White Oak Reservoir**

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	1.20	<b>1.20</b>	0.00	0%
Internal	0.00	<b>0.00</b>	0.00	0%
Septic System	0.00	<b>0.00</b>	0.00	0%
Watershed Load				
High Intensity Agriculture	26.80	<b>3.22</b>	23.58	88%
Low Intensity Development	1.57	<b>1.17</b>	0.39	25%
Forested Wetland	5.94	<b>5.94</b>	0.00	0%
Non-Forested Wetland	1.59	<b>1.59</b>	0.00	0%
Abandoned Cranberry Bogs	0.47	<b>0.47</b>	0.00	0%
<i>Total Watershed Load</i>	36.37	<b>12.39</b>	23.97	0%
<b>Total Load</b>	37.57	<b>13.59</b>	23.97	64%
Stormwater Load By Landuse				
High Intensity Agriculture	5.91	<b>5.91</b>	0.00	0%
Low Intensity Development	15.40	<b>6.16</b>	9.24	60%
Forested Wetland	2.99	<b>2.99</b>	0.00	0%
High Intensity Development	5.16	<b>2.07</b>	3.10	60%
Natural	4.79	<b>1.92</b>	2.87	60%
Medium Intensity Development	3.07	<b>1.23</b>	1.84	60%
Non-Forested Wetland	1.29	<b>1.29</b>	0.00	0%
Low Intensity Agriculture	0.06	<b>0.06</b>	0.00	0%
<b>Total Wasteload</b>	38.68	<b>21.63</b>	17.06	44%
<b>Total Maximum Yearly Load<sup>1</sup></b>	76	<b>35<sup>1</sup></b>	41	54%

1- (Total Maximum Yearly Load = Total Load Allocation plus Total Wasteload Allocation, rounded to nearest kg/year)

**Table 8. Current TP Loads and Allocated TP Loads for West Monponsett Pond**

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	24.92	<b>24.92</b>	0.00	0%
Internal	293.54	<b>14.68</b>	278.86	95%
Septic System	12.96	<b>12.96</b>	0.00	0%
<b>Watershed Load</b>				
High Intensity Agriculture	172.05	<b>20.65</b>	151.40	88%
Forested Wetland	28.29	<b>28.29</b>	0.00	0%
Non-Forested Wetland	6.51	<b>6.51</b>	0.00	0%
High Intensity Development	0.18	<b>0.09</b>	0.09	50%
Natural	0.00	<b>0.00</b>	0.00	0%
Medium Intensity Development	7.55	<b>3.77</b>	3.77	50%
Abandoned Cranberry Bogs	0.68	<b>0.68</b>	0.00	0%
Low Intensity Agriculture	0.02	<b>0.02</b>	0.00	0%
Low Intensity Development	5.75	<b>2.88</b>	2.88	50%
<i>Total Watershed Load</i>	221.03	<b>62.89</b>	158.14	72%
<b>Total Load</b>	552.45	<b>115.45</b>	437.00	79%
<b>Stormwater Load By Landuse</b>				
High Intensity Agriculture	25.91	<b>19.43</b>	6.48	25%
Forested Wetland	14.30	<b>14.30</b>	0.00	0%
Non-Forested Wetland	5.27	<b>5.27</b>	0.00	0%
High Intensity Development	7.49	<b>2.99</b>	4.49	60%
Natural	15.28	<b>6.11</b>	9.17	60%
Medium Intensity Development	27.14	<b>10.86</b>	16.29	60%
Abandoned Cranberry Bogs	0.10	<b>0.10</b>	0.00	0%
Low Intensity Agriculture	0.08	<b>0.08</b>	0.00	0%
Low Intensity Development	28.04	<b>11.21</b>	16.82	60%
<b>Total Wasteload</b>	123.61	<b>70.36</b>	53.24	43%
<b>Total Maximum Yearly Load<sup>1</sup></b>	676	<b>186<sup>1</sup></b>	490	-73%

1- (Total Maximum Yearly Load = Total Load Allocation plus Total Wasteload Allocation, rounded to nearest kg/year)

**Table 9. Summary of Targets, Total Maximum Daily Load and Load Reductions for Ponds**

Waterbody	Current TP ppb used in model	Current TP Load kg/yr <sup>1</sup>	Target TP ppb	TMDL Load kg/yr <sup>1</sup>	TMDL Load kg/day	Percent TP Load Reduction
Stetson Pond	15	69	13	48	<b>0.13</b>	30%
East Monponsett	34	345	18	182	<b>0.50</b>	47%
Reservoir	50*	76	23	35	<b>0.10</b>	54%
West Monponsett	68	676	18	186	<b>0.51</b>	73%

\*Measured TP was 35 ppb (see text)

1-all loads rounded to nearest kg/yr

While the general vulnerabilities of coastal areas to climate change can be identified, specific impacts and effects of changing conditions are not well known at this time

(<https://www.mass.gov/files/documents/2016/08/qz/eea-climate-adaptation-report.pdf>). Because the science is not yet available, MassDEP is unable to analyze climate change impacts on streamflow, precipitation, and nutrient loading with any degree of certainty for TMDL development. Considering these uncertainties and informational gaps, MassDEP has opted to address all sources of uncertainty through an implicit MOS. MassDEP does not believe that an explicit MOS approach is appropriate under the circumstances or will provide a more protective or accurate MOS than the implicit MOS approach, as the available data simply does not lend itself to characterizing and estimating loadings to derive numeric allocations within confidence limits. Although the implicit MOS approach does not expressly set aside a specific portion of the load to account for potential impacts of climate change, MassDEP has no basis to conclude that the conservative assumptions that were used to develop the numeric model applications are insufficient to account for the lack of knowledge regarding climate change.

The margin of safety is set by establishing targets for East and West Monponsett Pond that are below a nominal target of 23 ppb TP. Previous lake sampling (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013) has shown this target generally meets all CALM thresholds. The TMDL is based on annual loads and it is anticipated that excursions based on certain conditions during short duration events will exceed standards. Although we generally need several years of data after implementation to determine if uses are met, the 20 ppb summer average TP in East Monponsett Pond in 2010 and 2015 met relevant CALM thresholds. This indicates standards will be met and therefore the target appears conservative for these ponds. These two ponds are colored, influenced by both surface water and groundwater, and upstream wetlands. These characteristics make the ponds atypical of lakes fed by clear groundwater seepage. The 18 ppb TP target for these lakes has also been set conservatively given that both East and West Monponsett Ponds are classified as Class A waters (public water supply).

Similarly, the target concentrations for Stetson Pond (13 ppb) and White Oak Reservoir (23 ppb) were also conservatively set. Stetson Pond received a target concentration below its current in-pond concentration to both protect its water quality as well as the water quality of downstream water resources. The lake already meets Secchi disk thresholds and does not suffer from frequent cyanobacteria blooms. The lower TP target should help improve oxygen conditions in the hypolimnion but there is uncertainty in the relationship between TP and hypolimnetic oxygen depletion rates (Borowiak *et al.*, 2011). The White Oak Reservoir target concentration was set well below a nominal target of 48 ppb. Previous sampling of similar clear water impoundments (MassDEP 2003, 2004, 2007a, 2007b, 2009, 2013) has shown this target generally meets CALM thresholds for this waterbody type. This level is expected to reduce duckweed coverage, which is causing the impairment, and should also help restore the principal downstream waterbody, West Monponsett Pond.

### **Critical Conditions**

The effects of yearly total phosphorus loading have their most severe effects in the summer. This effect is captured by the LLRM model which was calibrated to average summer in-pond TP concentrations.

## **Seasonal Variations**

This TMDL captures seasonal variations in water quality with its calibration to summertime in-pond TP concentrations as noted above. Seasonal variations are also accounted for by using the average of several years of rainfall to estimate runoff flows.

## **Impact of Diversions**

As noted in the recent hydrologic evaluations of the diversion of East Monponsett waters to Silver Lake, the hydrology of the system is very complex (Princeton Hydro, 2013; Horsley Witten, 2015). The diversion occurs on a seasonal basis and with complex spatial mixing that can't be completely simulated with any well mixed, steady state model such as LLRM. The steady state models can be used to make estimates of how the system is likely to respond. For example, if the diversion of water and associated nutrients to Silver Lake did not occur then our model estimates that TP concentrations in West Monponsett Pond would decrease by 24%. This is in close agreement with the previous studies that found a 'no diversion' scenario would reduce TP concentrations in the pond by 23% to 32% (Horsley Witten, 2015 and Princeton Hydro, 2013, respectively). The improvement in water quality would be due to increased flushing with relatively clean East Monponsett Pond water. It should be noted that the above reports, as well as this report, conclude that stopping the diversion alone would not solve the cyanobacteria bloom problem. The watershed BMPs and aluminum treatment of West Monponsett are required to meet the TMDL.

There are additional impacts of the diversion on waters outside of the ponds that should be noted here. Both the Princeton Hydro (2013) report and the Horsley Witten (2015) report noted impacts to both Stump Brook and to the Jones River. The Jones River (segment MA94-12) is of concern because it is also listed as impaired for Aquatic Plant Macrophytes on the 2016 Integrated List (see Table 1) and requires a separate TMDL. The excess algae and dissolved oxygen problems noted may be alleviated if more water from relatively clean (less nutrient-rich) Silver Lake were to flush naturally downstream. All reasonable efforts should be made to reduce the reliance on Silver Lake so that impacts to all waters in the region are minimized.

## **Implementation**

Implementation of the TMDL will focus on the largest sources including the sediment recycling of phosphorus during the summer and the cranberry bog BMPs. Additional implementation will include upgrading Title 5 septic systems as required by regulations (310 CMR 15.00) or by sewerage areas as development increases. There are no reasonable BMPs available to significantly reduce atmospheric precipitation and dryfall inputs.

In the case of the Monponsett Ponds, Stetson Pond and White Oak Reservoir much of the above implementation has been underway since 2009. As noted previously the major bog owners have already reduced the fertilizer rates by 60-70% (DeMoranville, 2016a) and West Monponsett Pond exhibited a 23% reduction in TP concentrations coincident with those fertilizer reductions as shown in Figure 12. As more bog operators continue to reduce phosphorus fertilizer

applications and begin additional bog water BMPs (such as holding floodwater less than ten days and diverting discharges to detention ponds and upland areas as recommended in the UMass Cranberry bog BMPs) additional reductions in lake TP concentrations are expected. Such efforts were successful in restoring White Island Pond (Mattson, 2015). In addition, MassDEP has awarded Section 319 grant monies to the University of Massachusetts Cranberry Experiment Station to test additional BMPs. One of the tests involves the use of an iron enriched sand filterbed to remove phosphorus from water discharged from the Winebrook bogs on West Monponsett Pond. Initial testing resulted in clogging of the filter but additional prefilters and a gravel layer are expected to alleviate the clogging problems and provide additional TP removal (DeMoranville, 2016b).

### **Internal Loads**

For West Monponsett Pond to meet its target TP concentration will require a 90% reduction in TP loads from the sediments. The origin of this large amount of sediment phosphorus was due to historically high anthropogenic phosphorus inputs that have transferred and settled to the sediments over many years. The control of summer sediment phosphorus release in this lake can be treated with a buffered alum and sodium aluminate treatment; iron treatment combined with aeration; or by dredging the sediments after the major surface discharges are controlled. Aluminum treatment generally has been most cost effective (Mattson et al., 2004). There is a concern regarding rare species impacts with any of the treatment methods. Coordination with the Massachusetts NHESP staff is required to develop a treatment plan that will protect the rare freshwater mussel species. West Monponsett Pond was treated with low doses of buffered alum in the summer of 2013 and 2015 (Figure 12) and later in 2016, with no impacts to the rare mussels reported (Biodrawiversity, 2014). Additionally, alum treatments were conducted in 2017 and 2018 with no reported impacts to rare mussels. The estimated total buffered alum treatment through 2018 is approximately 42 g/m<sup>2</sup> Al. An estimated additional 8 g/m<sup>2</sup> Al is needed to treat the internal loading of 293.5 kg/yr for West Monponsett Pond.

East Monponsett Pond may also require an aluminum treatment of sediment phosphorus sources if further implementation of watershed control fails to stop cyanobacterial blooms in the pond. If treatment is required, a lighter dose than that used for West Monponsett Pond is likely to be enough. The same is true for Stetson Pond. Although TP concentrations were low in Stetson Pond surface waters in 2015, a cyanobacterial bloom occurred in late summer (August and September). Blooms also resulted in posting swimming bans by the local Board of Health in 2010 for 37 days. A lighter dose would probably be enough for this lake to meet water quality standards and eliminate the blooms. White Oak Reservoir may not need aluminum treatment to control the duckweed problem. The recommended approach is to implement cranberry bog BMPs upstream first and monitor the reservoir.

### **Cranberry Bogs**

A key to the success of this TMDL is the reduction of TP load from local cranberry bogs whose discharge is tributary to the lake. The cranberry bog discharge must be limited to 0.5 kg/ha/yr (0.45 lb/ac/yr), the same as recommended in Mattson (2009) and used in White Island Pond (Mattson, 2015). This level of phosphorus export can be achieved by limiting water discharge

rates to 3.5 acre-feet per acre of bog (see below) with average total phosphorus concentrations of 50 ppb (the acceptable concentration of inputs to lakes from EPA, 1986 “Gold Book”). A recent review of phosphorus export versus phosphorus fertilizer use suggests that exports can be dramatically reduced with reductions in phosphorus fertilizer application while maintaining crop yields (DeMoranville et al., 2009). In fact, some bogs can show zero export or even negative phosphorus export (uptake of phosphorus) while maintaining good yields by reducing phosphorus fertilizers (DeMoranville and Howes, 2005; DeMoranville et al., 2008). The key to maintaining yield is to supply the correct amount of nitrogen (generally the limiting nutrient for cranberries) while reducing the phosphorus in the fertilizer. This is accomplished by switching from low ratios of N:P:K to higher N fertilizers with proportionately less P. Commercial cranberry growers have used high ratios in the past (bags labeled 10-12-24, 10-20-20 or even 5-15-30) where the ratio of N to P<sub>2</sub>O<sub>5</sub> on the bag is 1:1.2 or 1:2 or 1:3 (Howes and Teal, 1995). This supplies excess phosphorus for plant growth needs. The recent UMass study recommends products with bag ratios of 18-8-12 or 15-15-15 (DeMoranville and Howes, 2005). For example, in order to deliver enough nitrogen to the crop while reducing phosphorus applications to a target of 10 lb/ac/year phosphorus, a fertilizer with a N:P ratio of 2:1 such as 18-8-12, or even lower P fertilizer would be required. Caution needs to be exercised so that the amount of nitrogen applied does not exceed the crop needs. Excess nitrogen would likely migrate from the site and contribute to nitrogen enrichment in down gradient embayment systems.

Manipulation of water usage is also critical for reducing the phosphorus loading to receiving waters. In order to meet the TMDL loading target of 0.5 kg/ha/yr the yearly discharge of 3.5 feet of water per acre of bog at a concentration of 50 ppb TP or less would satisfy the TMDL requirements. Other combinations of discharge and concentrations are also acceptable if they are demonstrated to meet the TMDL load. Increased public water supply demand requires an increase in water discharged through the spillway, increasing the leaching of phosphorus from the bogs. Irrigation water should be recycled from water stored in the bog ditches or in storage ponds to the greatest extent possible. Harvest water should also be recycled from section to section rather than flooding the entire bog complex at one time. After cranberry harvest the water should be retained in the bog complex for at least 1 to 3 days to allow particulate matter to settle out, but always less than 10 days to avoid excess release from sediments. Water should be discharged slow enough to minimize turbulence and erosion within the bogs. When possible, the discharge should be directed away from sensitive surface waters, particularly in the growing season. It is recommended that the small Winebrook bog currently discharging to West Monponsett Pond be further treated or diverted away from the pond. Winter floods should be withdrawn beneath newly formed ice within 10 days to avoid anoxic injury to plants and anoxic release of phosphorus from the flooded soils. Additional treatment and alternatives to winter flood discharges should be considered to meet the TMDL loading requirements. For a more comprehensive list of efforts to reduce total phosphorus from commercial cranberry bogs see Mattson, 2009.

Because of the large build-up of excess phosphorus in cranberry bog soils, soil tests often show very high TP concentrations that do not relate to crop yields and plant tissue tests may be more appropriate for determining fertilizer needs (DeMoranville and Davenport, 1997). Because of the high phosphorus in the soils, there may be a delayed response to the reductions in phosphorus fertilizer inputs and water discharges from the bogs. It is recommended that after fertilizers have

been reduced to 10 lbs/acre/year and the water reuse BMPs have been initiated and the watershed source TMDL are largely met before any further and potentially more expensive in-lake BMPs be initiated. Recent studies on commercial cranberry bogs have shown that reduced phosphorus fertilizer application led to increased yield of cranberries while reducing expensive fertilizers and reducing TP concentrations in discharge water (DeMoranville et al., 2009). Additional studies on plots have shown there was no justification for using high phosphorus fertilizers. Even the zero phosphorus plots showed no signs of deficiency after 6 years of study (Roper, 2009), but tissue tests are recommended to monitor plant health. For further background information and recommendations to reduce total phosphorus loading from cranberry bogs see Appendix D: Guidelines for Total Maximum Daily Loads of Phosphorus from Commercial Cranberry Bog Discharges in Massachusetts.

### **Flow Management**

MassDEP acknowledges the diversions “lessen the pond’s nutrient absorptive capacity by reducing new water additions to West Monponsett Pond that otherwise would improve flushing and reduce stagnation” (MassDEP 2017). MassDEP has issued an Administrative Consent Order to the City of Brockton. This administrative consent order requires that the City of Brockton take action to reduce the likelihood of water going from the West to East Monponsett Pond during diversion by altering their diversion transfer rate (MassDEP 2017, Provision 28). The ACO (MassDEP 2017) requires a minimum flow of 900,000 gallons/day to leave West Monponsett Pond both during diversion periods and beginning June 1, 2017 to be released at all times unless as stipulated in the consent order (Provisions 30,32). The ACO also requires the City of Brockton to create a Resource Management Plan that will “based on scientific data and evaluation that will include recommended metrics and procedures for Silver Lake Diversions and Stump Brook Dam operations intended to improve Monponsett Pond’s water quality and ecosystem while maintaining Brockton’s drinking water supply system reliability” (Provisions 33). In order to study possible dam management regimes it is recommended that the potential for increased flushing based on cyanobacteria counts be investigated.

### **Control of Septic Loads and Stormwater Loads**

The control of septic system inputs is recommended, although not currently required to meet the TMDL. Older homes with cesspools may be contributing disproportionate amounts of phosphorus to the groundwater near the lake. A septic system inspection program and bylaw to insure Title 5 compliance could be instituted in the local towns as part of general lake nutrient management activities.

Another possibility for reducing the loading from septic systems is to sewer the area and thus divert phosphorus loadings to a wastewater treatment plant where it can be removed prior to discharge outside the watershed. Opportunities for sewerage may occur if developers are required to reduce nutrient loadings to compensate for additional loadings of new home construction. The densely populated area along the shores of the West and East Monponsett Ponds is a potential area for sewerage and this would eliminate the septic system phosphorus loads to the lake from those homes.

Except for Peterson Swamp and the wetlands northwest of West Monponsett Pond, the TMDL study area is considered an urbanized area and are included in the jointly issued EPA- MassDEP NPDES Phase II stormwater permit. The 2016 Massachusetts MS4 General Permit will become effective July 1, 2018. Until that time, the 2003 General Permit is in effect. The NPDES permits require six minimum control measures including public education, public participation, illicit discharge detection and elimination, construction site runoff control, post construction runoff control, and good housekeeping at municipal operations. The latter ‘good housekeeping’ control should include BMPs and a schedule of activities to control pollution. The permits also require the development of a stormwater management plan that must include mapping outfalls to receiving waters. Details on Massachusetts stormwater program are available at: <https://www.mass.gov/info-details/stormwater>.

In addition to these measures, substantial reduction in TP loads (50% - 60%) from stormwater will be required for Stetson Pond, East Monponsett, White Oak Reservoir, and West Monponsett Pond watersheds to meet this TMDL. These reductions will not be easily achieved with any one single technology but are more likely to be achieved with several technologies used in combination.

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Necessary stormwater reductions in the TMDL study area which will be targeted by appropriate MS4 stormwater permits. Due to uncertainties in the sources and the lack of precision in watershed models these limits should not be disaggregated into smaller individual outfall limits, but rather applied as a basis for percent reduction targets for the watershed.

## **Responsibilities for Implementation**

MassDEP has authority to enforce existing water laws and regulations that relate to water use and water quality. The Commonwealth has provided a strong framework to encourage watershed management through on-site septic system regulations under Title 5, by legislation requiring low phosphorus detergents, and restrictions on the use of fertilizers on non-agricultural turf and lawns. Agricultural fertilizer rates and BMPs are also enforceable under the Massachusetts Department of Agriculture (MDAR) Plant Nutrient Regulations, <https://www.mass.gov/service-details/plant-nutrient-management>.

The MassDEP will be responsible for obtaining public comment and support for this TMDL. The proposed tasks and responsibilities for implementing the TMDL are shown in Table 10. The local citizens within the watershed will be encouraged to locate and describe additional sources of erosion and phosphorus within the watershed following methods described in the MassDEP guidebook “Surveying a Lake Watershed and Preparing an Action Plan” (MassDEP, 2001) available at: <http://bit.ly/MassLakeVolunteerGuide>.

Responsibility for remediation of each identified source will vary depending on land ownership, local jurisdiction and expertise. For example, the local lake associations or the Towns may organize a septic tank pumping and inspection program for all lakeside homeowners. Usually a discount for the pumping fee can be arranged if many homeowners apply together. Cranberry growers can apply for money to implement BMPs as part of the NRCS programs in soil conservation. Town public works departments will generally be responsible for reduction of

erosion from town roadways and urban runoff. The local conservation commissions and building inspectors will generally be responsible for ensuring the BMPs are being followed to minimize erosion from construction sites within their town. BMPs for general nonpoint source pollution control are described in a manual by Boutiette and Duerring (1994), BMPs for erosion and sediment control are presented in MassDEP (1997, reprinted 2003). See the MassDEP web site <http://www.mass.gov/eea/agencies/massdep/water/watersheds/erosion-and-sedimentation-control-guidelines.html> for Erosion and Sediment Control Guidelines. MassDEP also has an Unpaved Roads BMP Manual and general information on nonpoint source BMPs at <http://bit.ly/MassUnpavedRoads>. A description of potential funding sources for these efforts is provided in the Program Background section, above.

The City of Brockton is required to complete several tasks as outlined in the recent Administrative Consent Order (MassDEP 2017). The local towns of Halifax, Pembroke and Hanson will be required to comply with their relevant stormwater permits. The costs of in-lake treatments including aluminum treatment should be equitably shared by the responsible parties with the City of Brockton, the towns of Halifax, Hanson and Pembroke as well as cranberry growers with additional funding provided by matching state and federal grants, as available

A proactive approach to protecting the waterbodies in the TMDL study area may include implementation of local bylaws limiting development, particularly in areas near the lake, changes in zoning laws and lot sizes, requirements that new developments and new roadways include BMPs for runoff management and more stringent regulation of septic systems. As new housing development expands within the watershed, additional measures are needed to minimize the associated additional inputs of phosphorus. Although over fertilization of lawns was not apparent based on visual examination, homeowners should be aware of the Massachusetts Law limiting the use of phosphorus fertilizers on lawns (MGL Ch. 128 S. 65A). Additional BMPs are presented in the Nonpoint Source Management Manual by Boutiette and Duerring (1994) that was distributed to all municipalities in Massachusetts. Other voluntary measures may include encouraging the establishment of a native plant, vegetative buffer around the lake. Such BMPs provide enhancements that residents should find attractive and, therefore, should facilitate voluntary implementation.

Portions of the towns of Halifax, Hanson and Pembroke are designated urbanized areas and are therefore subject to regulation under Massachusetts Small MS4 General Stormwater Permit (effective date July 1, 2018). The 50-60 percent reductions in TP in stormwater required under this TMDL will be included in the next amendment of the MS4 General Permit (expected issue date 2021). Municipalities discharging stormwater to waters with a TP TMDL are required to prepare a Lake Phosphorus Control Plan (LPCP) as required in Appendix F, A: II (pg. 18-26) of the permit.

The town of Halifax has recently mapped and investigated several stormwater outfalls around East and West Monponsett Pond and investigated possible control measures (GHD 2017). The towns are encouraged to investigate the feasibility of treating as much of the impervious watershed area using smaller capacity low-tech controls (e.g., 0.2 to 0.4 inches of runoff) than treating less impervious area with larger capacity controls (e.g., 1.0 inch) as EPA research in the

Upper Charles River Watershed indicates this can be a more cost effective approach (USEPA 2011).

MassDEP is recommending that the East and West Monponsett Pond be monitored on a regular basis with emphasis on cyanobacteria monitoring to protect public health. If the ponds do not meet water quality standards additional implementation measures including sewerage may be required. For example, if phosphorus concentrations remain high after watershed controls are in place, then control of other sources may be considered and efforts to increase flushing may be investigated.

As phosphorus concentrations in the ponds in the TMDL study area are reduced and transparency of the lake increases, increased light reaches the sediments, then an increase in the growth of rooted aquatic plants is expected. Reducing the supply of nutrients will not in itself result in achievement of all the goals of the TMDL and continued macrophyte monitoring and appropriate management is an essential part of the implementation plan.

**Table 10. TMDL Tasks and Responsibilities**

Tasks	Responsible Group
TMDL development	MassDEP
Develop Cranberry Farm Plan, fertilizer type and rates and water management BMPs that meet TMDL requirements	Cranberry Growers in concert with NRCS, Soil Conservation Service, the Cape Cod Cranberry Growers Association and the UMass Cranberry Station.
Ensure that noncompliant septic systems are upgraded to meet Title 5 requirements and consider inspections for compliance	Local Boards of Health and homeowners
Use lesser amounts of lawn fertilizers, particularly no phosphorus fertilizers	Homeowners and lake association
Monitor chlorophyll, Secchi disk transparency and total phosphorus in lake	MassDEP and lake association
Organize and implement TMDL education, outreach programs, write grant and loan funding proposals	Local lake association and Towns working with consultants
After discharges are controlled implement sediment phosphorus controls	Cranberry growers, lake associations and towns with consultation with MassDEP
50% to 60% reduction in stormwater loads to Stetson Pond, East Monponsett Pond, White Oak Reservoir and West Monponsett Pond	Towns of Halifax, Pembroke and Hanson
Implement Phase II BMPs, twice yearly road sweeping, catchbasin inspection and maintenance, install infiltration or other BMPs	Towns of Halifax, Hanson and Pembroke in urbanized areas

Pass town bylaws to control development, erosion from all lands, driveways and limit fertilizers on non-agricultural land.	Town Selectmen, town meeting
Coordination of municipalities within the Central Plymouth County Water District with regards to relevant water issues	Central Plymouth County Water District
Compliance with Administrative Consent Order, Watershed and water supply management plan that focuses on efforts to improve water quality in Monponsett Ponds	City of Brockton

**Reasonable Assurances**

Reasonable assurances that the TMDL will be implemented include both enforcement of current laws and regulations, availability of financial incentives, and the various local, state and federal program for pollution control. Active cooperation of the cranberry growers and the Cape Cod Cranberry Growers Association, homeowners, the towns of Halifax, Hanson and Pembroke, City of Brockton, EPA, NRCS and the UMass Cranberry Station is required for this TMDL to be effective in returning the lake to an unimpaired status.

MassDEP is responsible for the implementation and enforcement of the laws related to discharges of pollution, including any nonpoint sources, under authority of Massachusetts General Laws M.G.L. c.21§ 26-53, the Massachusetts Surface Water Quality Standards at 314 CMR 4.00 and the Groundwater Discharge Permit Program at 314 CMR 5.00. MassDEP is also responsible for the implementation and enforcement of M.G.L. c.91 and the Waterways Regulations at 310 CMR 9.00. Enforcement of regulations may include USEPA enforcement of the MS4 Phase II permit conditions under NPDES. The Commonwealth of Massachusetts also oversees the implementation of 310 CMR 15.00 (Title 5) regulations of onsite septic systems by the local boards of health.

Financial incentives include Federal monies available under the 319(b) NPS program and the 604(b) and 104(b) programs, which are provided as part of the Performance Partnership Agreement between MassDEP and the EPA. Additional financial incentives include state income tax credits and low interest loans for Title 5 septic system upgrades, Clean Water Act State Revolving Fund loans, and cost sharing for agricultural BMPs under the Federal NRCS program.

**Climate Change**

MassDEP recognizes that long-term (25+ years) climate change impacts to southeastern Massachusetts, including the area of this TMDL, are occurring based on known science. Massachusetts Executive Office of Energy and Environmental Affairs 2011 Climate Change Adaptation Report: <https://www.mass.gov/service-details/2011-massachusetts-climate-change-adaptation-report> predicts that by 2100 the sea level could be from 1 to 6 feet higher than the current position and precipitation rates in the Northeast could increase by as much as 20 percent.

However, the details of how climate change will affect sea level rise, precipitation, streamflow, sediment and nutrient loading in specific locations are generally unknown. The ongoing debate is not about whether climate change will occur, but the rate at and the extent to which it will occur, and the adjustments needed to address its impacts. EPA's 2012 Climate Change Strategy [http://water.epa.gov/scitech/climatechange/upload/epa\\_2012\\_climate\\_water\\_strategy\\_full\\_report\\_final.pdf](http://water.epa.gov/scitech/climatechange/upload/epa_2012_climate_water_strategy_full_report_final.pdf) states: "Despite increasing understanding of climate change, there still remain questions about the scope and timing of climate change impacts, especially at the local scale where most water-related decisions are made." For TMDLs in Massachusetts, MassDEP recognizes that this is particularly true, where water quality management decisions and implementation actions are generally made and conducted at the municipal level on a sub-watershed scale.

EPA's Climate Change Strategy identifies the types of research needed to support the goals and strategic actions to respond to climate change. EPA acknowledges that data are missing or not available for making water resource management decisions under changing climate conditions. In addition, EPA recognizes the limitation of current modeling in predicting the pace and magnitude of localized climate change impacts and recommends further exploration of the use of tools, such as atmospheric, precipitation and climate change models, to help states evaluate pollutant load impacts under a range of projected climatic shifts.

In 2013, EPA released a study entitled, "Watershed modeling to assess the sensitivity of streamflow, nutrient, and sediment loads to potential climate change and urban development in 20 U.S. watersheds." (<https://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=256912>). The initial "first order" conclusion of this study is that, in many locations, future conditions, including water quality, are likely to be different from experience. However, most significantly, this study did not demonstrate that changes to TMDLs (the water quality restoration targets) would be necessary for the region. EPA's 2012 Climate Change Strategy also acknowledges that the Northeast, including New England, needs to develop standardized regional assumptions regarding future climate change impacts. EPA's 2013 modeling study does not provide the scientific methods and robust datasets needed to predict specific long-term climate change impacts in the southeastern Massachusetts region to inform TMDL development.

MassDEP believes that impacts of climate change should be addressed through TMDL implementation with an adaptive management approach in mind. Adjustments can be made as environmental conditions, pollutant sources, or other factors change over time. Massachusetts Coastal Zone Management (CZM) has developed a StormSmart Coasts Program to help coastal communities address impacts and effects of erosion, storm surge and flooding which are increasing due to climate change. The program, [www.mass.gov/czm/stormsmart](http://www.mass.gov/czm/stormsmart) offers technical information, planning strategies, legal and regulatory tools to communities to adapt to climate change impacts.

As more information and tools become available, there may be opportunities to make adjustments in TMDLs in the future to address predictable climate change impacts. When the science can support assumptions about the effects of climate change on the loadings to the TMDL can be reopened, if warranted.

## **Water Quality Standards Attainment Statement**

The proposed TMDL, if fully implemented, will result in the attainment of all applicable water quality standards, including designated uses and numeric criteria for each pollutant named in the Water Quality Standards violations noted above. In addition to the margin of safety within the context of setting the TP threshold levels as described above, a programmatic margin of safety also derives from continued monitoring of these waterbodies to support adaptive management. This monitoring effort provides the ongoing data to evaluate the improvements that occur over the multi-year implementation of the TMDL. This will allow refinements to ensure that the desired level of restoration is achieved.

## **Monitoring**

The cyanobacteria numbers have been monitored in the past by MassDEP and the Massachusetts Department of Public Health will continue as needed. As resources allow, future lake surveys by MassDEP, should include Secchi disk transparency, nutrient analyses, temperature and dissolved oxygen profiles and aquatic vegetation maps of distribution and density. With additional data, the strategy for restoration of the water resources in this TMDL study area and reducing total phosphorus concentrations can be re-evaluated and the TMDL modified if necessary. Monitoring of total phosphorus concentrations and transparency by local volunteer groups is encouraged when possible.

## **Provisions for Revising the TMDL**

The MassDEP reserves the right to modify this TMDL as needed to account for new information or data made available during the implementation of the TMDL. Modification of the TMDL will only be made following an opportunity for public participation and be subject to the review and approval of the EPA. New information, which will be generated during TMDL implementation includes monitoring data, climate change, new or revised State or Federal regulations adopted pursuant to Section 303(d) of the Clean Water Act, and the publication by EPA of national or regional guidance relevant to the implementation of the TMDL program. MassDEP uses an adaptive management approach to observe implementation results over time and allow for adjustments. If water quality targets are met and yet guidance threshold values and other habitat indicators indicate impaired water quality, total phosphorus water quality targets may be revised and TMDL loadings adjusted accordingly. MassDEP will propose modifications to the TMDL analysis only if a review of the new information or data indicates that such a modification is warranted and is consistent with the anti-degradation provisions in the Massachusetts Water Quality Standards. The subject waterbodies of this TMDL analysis will continue to be included on the State of Massachusetts Integrated List of Waters, in the appropriate category.

If the nutrient load reductions required in this TMDL are not achieved, other methodologies and technologies to improve water quality may be considered. One such methodology, a shore based micro-floc aluminum injection pump, may be necessary to control remaining watershed sources into the future while providing more flexibility in application rates. In theory this type of system

can control the dose of alum applied daily each summer to more precisely regulate TP and transparency. It has the potential advantage of being able to influence the amount of sunlight reaching the bottom and opening the possibility for controlling the maximum depth of nuisance plant populations. Further details on such a system can be found in Moore *et al.* (2009).

## **Public Participation**

The draft TMDL was announced in the Massachusetts Environmental Monitor and held December 15, 2016 in the Halifax Town Hall, Halifax, MA. Kimberly Groff provided an overview of TMDLs and the work of the MassDEP Watershed Planning Program. Mark Mattson and Matthew Reardon (MassDEP) summarized the draft TMDL and described its findings. Other MassDEP staff in attendance included David Johnston, Jon Hobill and Barbara Kickham. Comments received at the public meeting and received in writing within a 30-day comment period following the public meeting were considered by MassDEP. This final version of the TMDL report includes both a summary of the public comments together with MassDEP's response to the comments and scanned images of the attendance sheets from the meeting (Appendix F).

As a result of EPA comment and review of the Draft TMDL, changes were made to the Wasteload Allocations in the Final Draft, which necessitates providing an additional 30-day public comment period via the Massachusetts *Environmental Monitor*. Responses to any additional comments on received on this TMDL will also be included in Appendix F.

## References

ACT, 2015. Western Basin of Monponsett Pond. Halifax and Hanson, Massachusetts. 2015 year end Alum Treatment Report. Aquatic Control Technology. Shrewsbury, MA.

AECOM (2009). *LLRM – Lake Loading Response Model Users Guide and Quality Assurance Project Plan*. AECOM, Willington, CT.

Baystate Environmental Consultants, 1993. *Diagnostic/Feasibility Study for the management of the Pembroke Ponds: Oldham, Furnace, Little Sandy Bottom and Stetson, Pembroke, MA*. BEC Inc., East Longmeadow, Massachusetts.

Biodrawiversity, 2014. Report: Monitoring the Effects of a Low-dose Alum Treatment on *Leptodea ochracea*, *Ligumia nasuta*, and *Neurocordedulia obsoleta* in the Western Basin of Monponsett Pond (Halifax, Massachusetts). Prepared for Lycott Environmental. Biodrawiversity LLC. Amherst MA.

Boutiette, L.N. Jr., and C.L. Duerring. 1994. Massachusetts Nonpoint Source Management Manual. “The MegaManual” A Guidance Document for Municipal Officials. Mass. Dept. Environmental Protection, Boston, MA.

Borowiak, D. and others, 2011. Relationship between areal hypolimnetic oxygen depletion rate and the trophic stat of five lakes in northern Poland. *Limnol. Rev.* 11(4):135-142.

Carlson, R.E. (1977) A trophic state index for lakes. *Limnology and Oceanography*. 22:2 361-369.

Chapra, S. 1975. Comment on “An Empirical method of estimating the retention of phosphorus in lakes.” By W.B. Kirchner and P.J. Dillon. *Water Resources Research*. 11:1033-1034.

Cooke, G.D., E.B. Welsh, S.A. Peterson, S.A. Nichols. 2005. *Restoration and Management of Lakes and Reservoirs*. 3<sup>rd</sup> Ed. Lewis Publishers. Boca Raton.

DeMoranville, C.J. and J.R. Davenport. 1997. Phosphorus forms, rates and timing in Massachusetts Cranberry Production. *Acta, Hort.* 446:381-388.

DeMoranville C. and B. Howes. 2005. Phosphorus dynamics in cranberry production systems: Developing information required for the TMDL process for 303d water bodies receiving cranberry bog discharge. UMass Cranberry Station, E. Wareham, MA and UMass Dartmouth, New Bedford, MA, prepared for MassDEP and USEPA. 137pp.

DeMoranville, C., B. Howes, D. Schlezinger and D. White. 2009. Cranberry Phosphorus Management: How changes in practice can reduce output in drainage water. *Acta Hort* 810: 633-640.

DeMoranville C. 2016a. Re: Monponsett Pond Working Group - News from Carolyn DeMoranville 319 cranberry UMass Cranberry Station, E. Wareham, MA. Email attachment Sand Filter Experiment.pdf of 1/21/2016 to Mark Mattson, MassDEP Worcester MA.

DeMoranville C. 2016b. Re: Monponsett Pond Working Group - News from Carolyn DeMoranville 319 cranberry UMass Cranberry Station, E. Wareham, MA. Email attachment MorseBogP.xlsx of 1/25/2016 to Mark Mattson, MassDEP Worcester MA.

GHD Inc. 2017. Stormwater Outfall Assessment for the East and West Monponsett Ponds: Town of Halifax, Massachusetts. Hyannis, MA.

Griffith, G.E., J.M. Omernik, S.M. Pierson, and C.W. Kiilsgaard. 1994. Massachusetts ecological regions project. EPA/600/A-94/111. U.S. EPA, Environmental Research Laboratory, Corvallis, OR. 58p.

Holdren, C.W., W. Jones and J. Taggart. 2001. Managing Lakes and Reservoirs. N. Am. Lake Manage. Soc. And Terrene Inst. In coop. With Off. Water Assess. Watershed Prot. Div. U.S. Environ. Prot. Agency, Madison, WI.

Horne, A.J. and C.R. Goldman. 1994. Limnology. 2<sup>nd</sup> Ed. McGraw-Hill Inc. New York.

Horsley Witten. 2015. Stump Brook/Monponsett Pond. Hydrologic and Water Quality Assessment. June 30, 2015.

Howes, B.L. and J.M. Teal. 1995. Nutrient Balance of a Massachusetts Cranberry Bog and Relationships to Coastal Eutrophication. Environmental Sci. & Tech. 29(4):960-974.

Jones, J.R. and R.W. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. JWPCF 48:2176-2184.

Kirchner, W.B. and P.J. Dillon. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resources Research. 11:182-183.

Larsen, D.P. and H.T. Mercier. 1976. Phosphorus retention capacity of lakes. J. Fish. Res. Bd. Canada. 33:1742-1750.

Likens, G.E. 1972. Nutrients and Eutrophication.: The Limiting-Nutrient Controversy. Limnology and Oceanography, Special Symposia Volume I. 328pp.

Lycott Environmental Research Inc. (1987). East and West Monponsett Ponds Diagnostic/Feasibility Study Halifax And Hanson, Massachusetts Final Report. Prepared for Town of Halifax, Massachusetts Division of Water Pollution Control.

Lycott Environmental Inc. (2007). Phosphorus/phytoplankton study of West Monponsett Pond. Halifax/Hanson. Prepared for Town of Halifax, Massachusetts.

Lycott Environmental Inc. (2014). Low-Dose Alum Treatment Monitoring Report. Wes Basin of the Monponsett Ponds. Halifax/Hanson. Prepared for Town of Halifax, Massachusetts. Plus Appendices.

McLaughlin, J. (James.M.McLaughlin@.mass.gov), 2016. *RE: cranberry bogs in Monponsett Pond watershed*. Massachusetts Department of Environmental Protection, Southeast Regional Office, Lakeville, MA. Email to Matthew Reardon, Massachusetts Department of Environmental Protection, Division of Watershed Management, Worcester, MA dated January 1, 2016.

MassDEP. 1997 (reprint 2003). Massachusetts Erosion and Sediment Control Guidelines for Urban and Suburban Areas. A Guide for Planners, Designers and Municipal Officials. Massachusetts Dept. Environmental Protection., EOE, State Commission for Conservation of Soil, Water and Related Resources, Natural Resources Conservation Service USDA.

MassDEP. 2001. Massachusetts Volunteers Guide for Surveying a Lake Watershed and Preparing an Action Plan. Department of Environmental Protection, Boston MA.

MassDEP. 2002. CN 117.0 Total Maximum Daily Load for Total Phosphorus for Leesville Pond, Auburn-Worcester, MA (MA51087). Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2003. CN 161.0 Baseline Lake Survey 2000 Technical Memo. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2004. CN 167.0 Baseline Lake Survey 2001 Technical Memo. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2007. *Massachusetts Surface Water Quality Standards (314 CMR 4.00)*. Massachusetts Department of Environmental Protection, 1 Winter Street, Boston, MA.

MassDEP. 2007a. CN 204.0. Baseline Lake Survey 2002 Technical Memo. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2007b. CN 205.1. Baseline Lake Survey 2003 Technical Memo. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2009. CN 209.1. Baseline Lake Survey 2004 Technical Memo. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 20013. CN 224.5. Baseline Lake Survey 2005 Technical Memo. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2010a. CN 330.2. Final Total Maximum Daily Load of Total Phosphorus for White Island Pond, Plymouth/Wareham, MA, Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA (available online at:

[http://bit.ly/WhiteIslandPond\\_TMDL](http://bit.ly/WhiteIslandPond_TMDL)) <http://www.mass.gov/eea/docs/dep/water/resources/n-thru-y/whisland.pdf>.

MassDEP. 2010b. CN 199.0. Sampling & Analysis Protocol for Sediment Core Phosphorus Release. June 2010 (draft). Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MassDEP. 2016. *Massachusetts Consolidated Assessment and Listing Methodology (CALM) Guidance Manual for the 2016 Reporting Cycle*. CN445.0. Massachusetts Department of Environmental Protection, Worcester, MA.

MassDEP. 2017. *Administrative Consent Order, In the Matter of the City of Brockton, File Number 0000101, Signed By All Parties, Last Signed March 22, 2017*. Massachusetts Department of Environmental Protection, Southeast Region Office, Lakeville, MA.

MassDEP. 2019. CN 470.1. *Massachusetts Year 2016 Integrated List of Waters: Final Listing of the Condition of Massachusetts' Waters Pursuant to Sections 305(b), 314 and 303(d) of the Clean Water Act*. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA.

MA DPH. 2014. *MA DPH Beach Posting Information 2005 to 2013*. Excel Spreadsheet dated June 12, 2014. Massachusetts Department of Health, Boston, MA.

MassGIS. 2005. *Land Use (2005)*. Office of Geographic Information (MassGIS), Commonwealth of Massachusetts, MassIT. Datalayer available online: <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/>

Mattson, M.D. and R.A. Isaac. 1999. Calibration of Phosphorus Export Coefficients for Total Maximum Daily Loads of Massachusetts Lakes. *Lake and Reservoir Man.* 15(3):209-219.

Mattson, M.D., P.J. Godfrey, R.A. Barletta and A. Aiello. 2004. Eutrophication and Aquatic Plant Management in Massachusetts. Final Generic Environmental Impact Report. Edited by Kenneth J Wagner. Department of Environmental Protection and Department of Conservation and Recreation, Executive Office of Environmental Affairs, Commonwealth of Massachusetts.

Mattson, M.D. 2009. Guidelines for Total Maximum Daily Loads of Phosphorus from Commercial Cranberry Bog Discharges in Massachusetts. Massachusetts Department of Environmental Protection, Division of Watershed Management. Worcester, MA (available online at Appendix III in: [http://bit.ly/WhiteIslandPond\\_TMDL](http://bit.ly/WhiteIslandPond_TMDL)) <http://www.mass.gov/eea/docs/dep/water/resources/n-thru-y/whisland.pdf>.

Mattson, M.D. 2015. Managing phosphorus loads from agricultural cranberry bogs to restore White Island Pond. *Lake and Res. Man.* 31:281-291.

Moore, B.C., D. Christensen, and A.C. Richter. 2009. Newman Lake Restoration: A case study. Part II. Microfloc alum injection. *Lake and Res. Man.* 25:4(351-363).

Northeast States. 2007. *Northeast Regional Mercury Total Maximum Daily Load*. Connecticut Department of Environmental Protection, Maine Department of Environmental Protection, Massachusetts Department of Environmental Protection, New Hampshire Department of Environmental Services, New York State Department of Environmental Conservation, Rhode Island Department of Environmental Management, Vermont Department of Environmental Conservation, New England Interstate Water Pollution Control Commission. October 24, 2007.

Princeton Hydro, LLC, 2013. Monponsett Pond and Silver Lake Water Use Operations and Improvement. Sustainable Water Management Initiative Report for Project No. BRP 2012006. Prepared for the Town of Halifax, Massachusetts, by Princeton Hydro, Ringoes, NJ.

Reckhow, K. 1977. Phosphorus Models for Lake Management. Ph.D. Dissertation, Harvard University, Cambridge, MA.

Reckhow, K.H., M.N. Beaulac, J.T. Simpson. 1980. Modeling Phosphorus Loading and Lake Response Under Uncertainty: A Manual and Compilation of Export Coefficients. U.S.E.P.A. Washington DC. EPA 440/5-80-011.

Rohm, C.M., Omernik, J.M., Kiilsgard, C.W. 1995. Regional Patterns of Total Phosphorus in Lakes of the Northeastern United States. *Lake and Reservoir Management*, 11(1):1-14.

Roper, T.R. 2009. Mineral Nutrition of Cranberry: What we know and what we thought we knew. *Acta Hort.* 810:613-625.

Schindler, D.W. and E.J. Fee. 1974. Experimental Lakes Area: Whole-Lake Experiments in Eutrophication. *J. Fish. Res. Bd. Can.* 31:937-953.

Steffenhagen, P. D. Zak, K. Shulz, T. Timmermann, S. Zerbe. 2012. Biomass and nutrient stock of submerged and floating macrophytes in shallow lakes formed by rewetting of degraded fens. *Hydrobiologia*, Vol. 692, pg. 99-109.

USEPA. 1986. Technical Guidance Manual for Performing Wasteload Allocations, Book IV: Lakes, Reservoirs and Impoundments, Chapter 2: Eutrophication. EPA 440/4-84-019, p. 3-8.

USEPA. 1990. The Lake and Reservoir Restoration Guidance Manual. 2nd Ed. and Monitoring Lake and Reservoir Restoration (Technical Supplement). Prepared by North American Lake Management Society. EPA 440/4-90-006 and EPA 440/4-90-007.

USEPA. 2011. Summary of Important Points Related to Construction Cost Estimates for Storm Water Controls to Achieve Charles River Phosphorus TMDL in the Communities of Milford, Bellingham and Franklin, MA (Draft). United States Environmental Protection Agency, Boston, MA.

Vallentyne, J.R. 1974. The Algal Bowl – Lakes and Man. Ottawa, Misc. Spec. Publ. 22. Dept. of the Environ. 185pp.

Vollenweider, R.A. 1975. Input-Output Models with Special Reference to the Phosphorus Loading Concept in Limnology. Sch. Zeit. Hydrologic 37:53-84.

Wagner, K.J. 2004. The Practical Guide to Lake Management in Massachusetts. Massachusetts Department of Environmental Protection and Massachusetts Department of Conservation and Recreation.

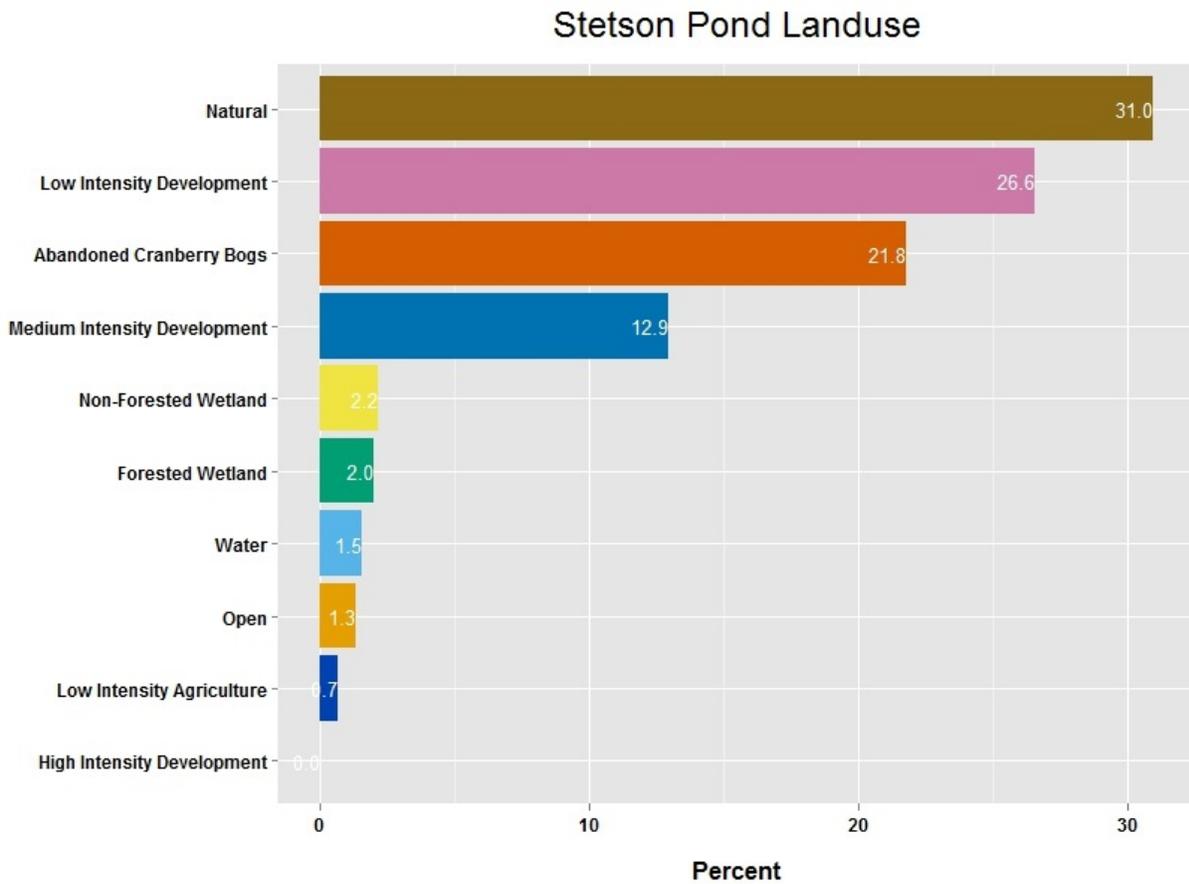
Wetzel, R.G. 2001. Limnology. Lake and River Ecosystems. 3<sup>rd</sup> Ed. Saunders College Publishing. New York.

Winter, T.C. and G.E. Likens. 2009. Mirror Lake: Interactions among Air, Land, and Water. Univ. Calif. Press. 384pp.

## Appendix A: Landuse Analysis

**Table A1: Landuse in Stetson Pond**

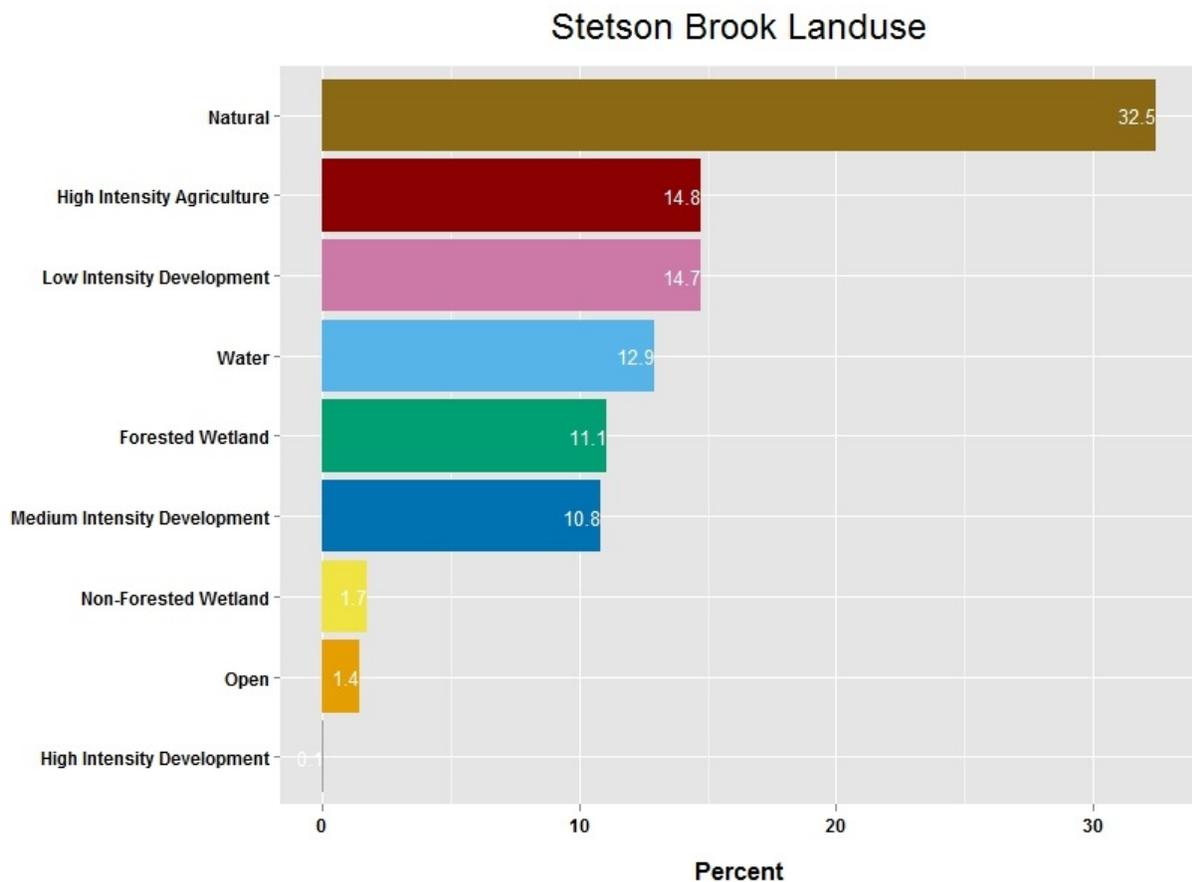
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area	
1	<b>Stetson Pond</b>	Natural	63.21	31%	
1		Low Intensity Development	54.18	27%	
1		Abandoned Cranberry Bogs	44.47	22%	
1		Medium Intensity Development	26.39	13%	
1		Non-Forested Wetland	4.44	2%	
1		Forested Wetland	4.07	2%	
1		Water	3.14	2%	
1		Open	2.72	1%	
1		Low Intensity Agriculture	1.41	1%	
1		High Intensity Development	0.00	0%	
<b>Stetson Pond Total</b>			204.0	100%	



**Figure A 1: Landuse in the Stetson Pond Watershed by %**

**Table A2: Landuse in Stetson Brook**

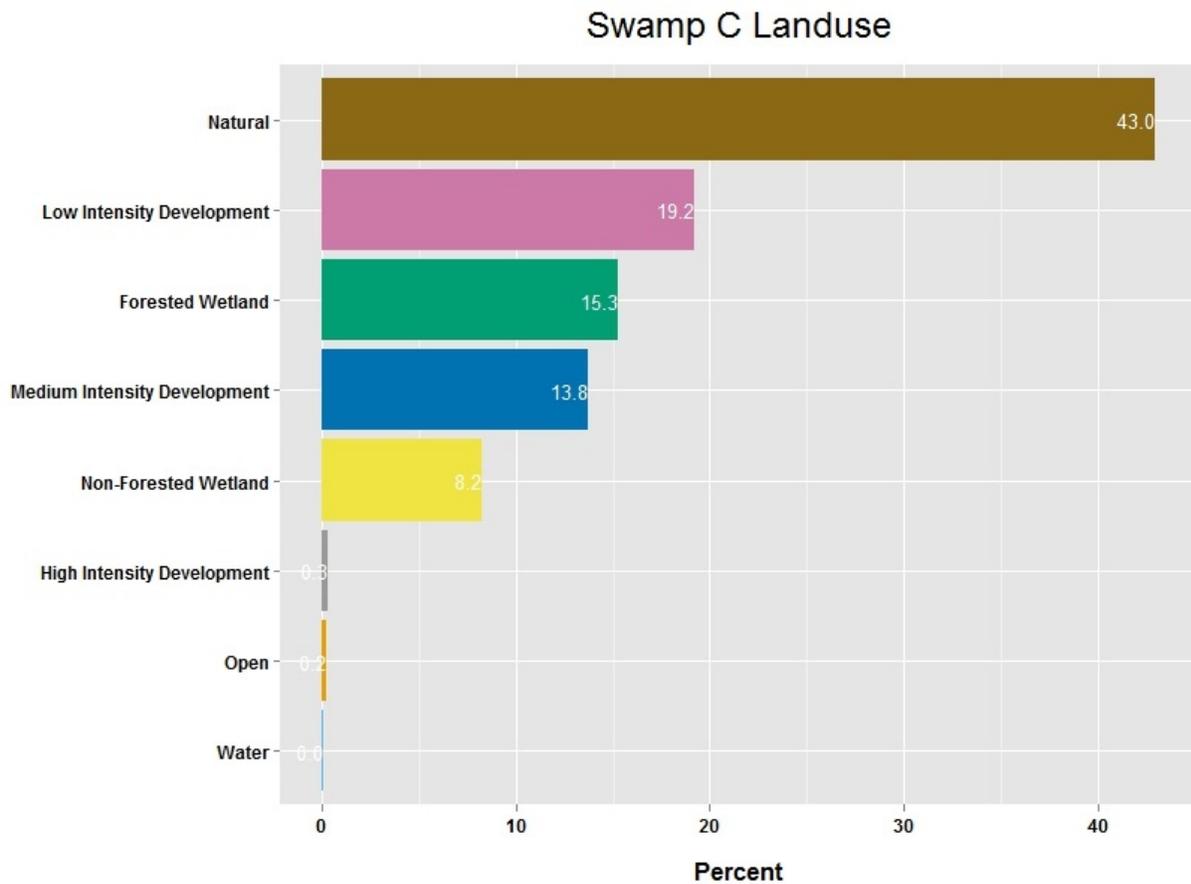
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
2	<b>Stetson Brook</b>	Natural	50.01	32%
2		High Intensity Ag. (bog)	22.74	15%
2		Low Intensity Development	22.67	15%
2		Water	19.91	13%
2		Forested Wetland	17.09	11%
2		Medium Intensity Development	16.66	11%
2		Non-Forested Wetland	2.68	2%
2		Open	2.23	1%
2		High Intensity Development	0.09	0%
<b>Stetson Brook Total</b>			154.09	100%



**Figure A 2: Landuse in the Stetson Brook Watershed by %**

**Table A3: Swamp C Landuse**

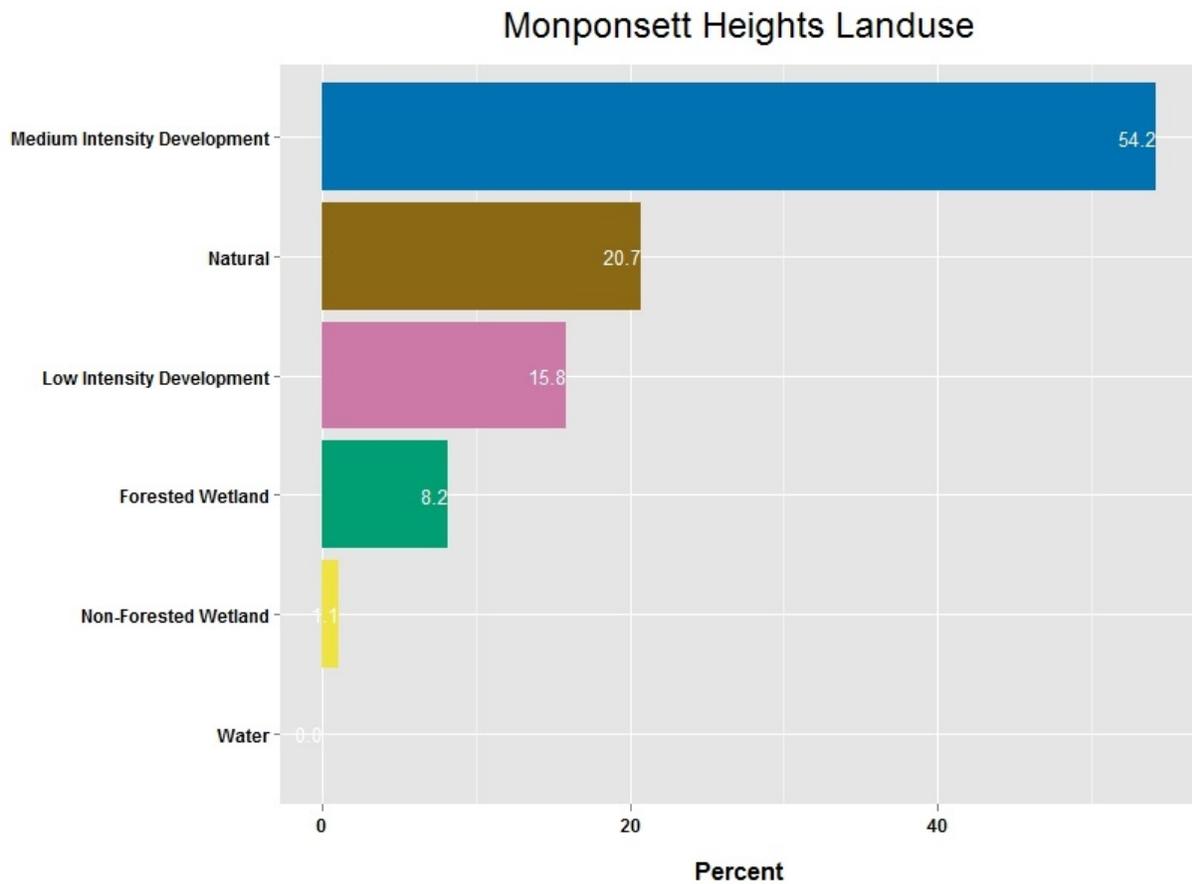
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
3	<b>Swamp C</b>	Natural	55.60	43%
3		Low Intensity Development	24.89	19%
3		Forested Wetland	19.76	15%
3		Medium Intensity Development	17.80	14%
3		Non-Forested Wetland	10.66	8%
3		High Intensity Development	0.40	0.3%
3		Open	0.25	0.2%
3		Water	0.07	0.1%
<b>Swamp C Total</b>			129.43	100%



**Figure A 3: Landuse in the Swamp C Watershed by %**

**Table A4: Monponsett Heights Landuse**

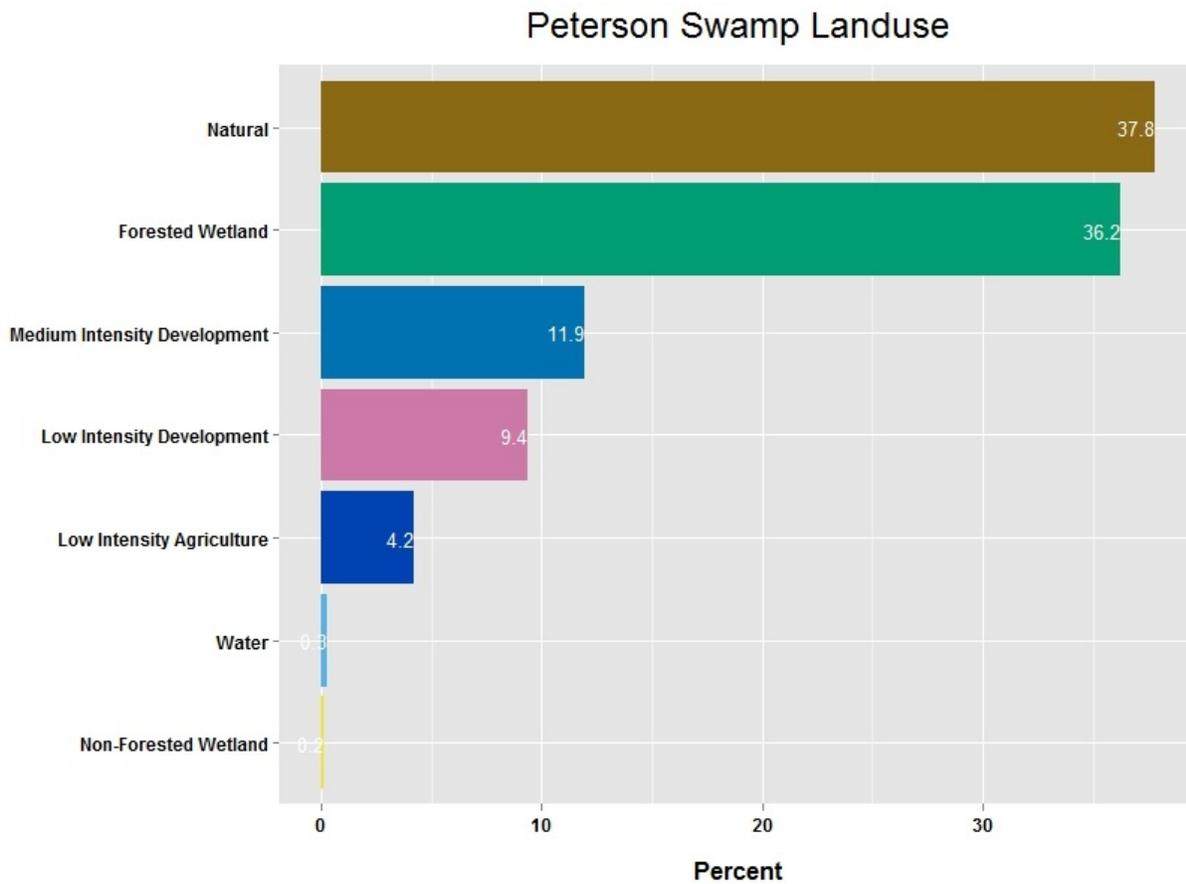
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
4	<b>Monponsett Heights</b>	Medium Intensity Development	17.11	54%
4		Natural	6.53	21%
4		Low Intensity Development	5.00	16%
4		Forested Wetland	2.58	8%
4		Non-Forested Wetland	0.34	1%
4		Water	0.01	0%
<b>Monponsett Heights Total</b>			31.57	100%



**Figure A 4: Landuse in the Monponsett Heights Watershed by %**

**Table A5: Peterson Swamp Landuse**

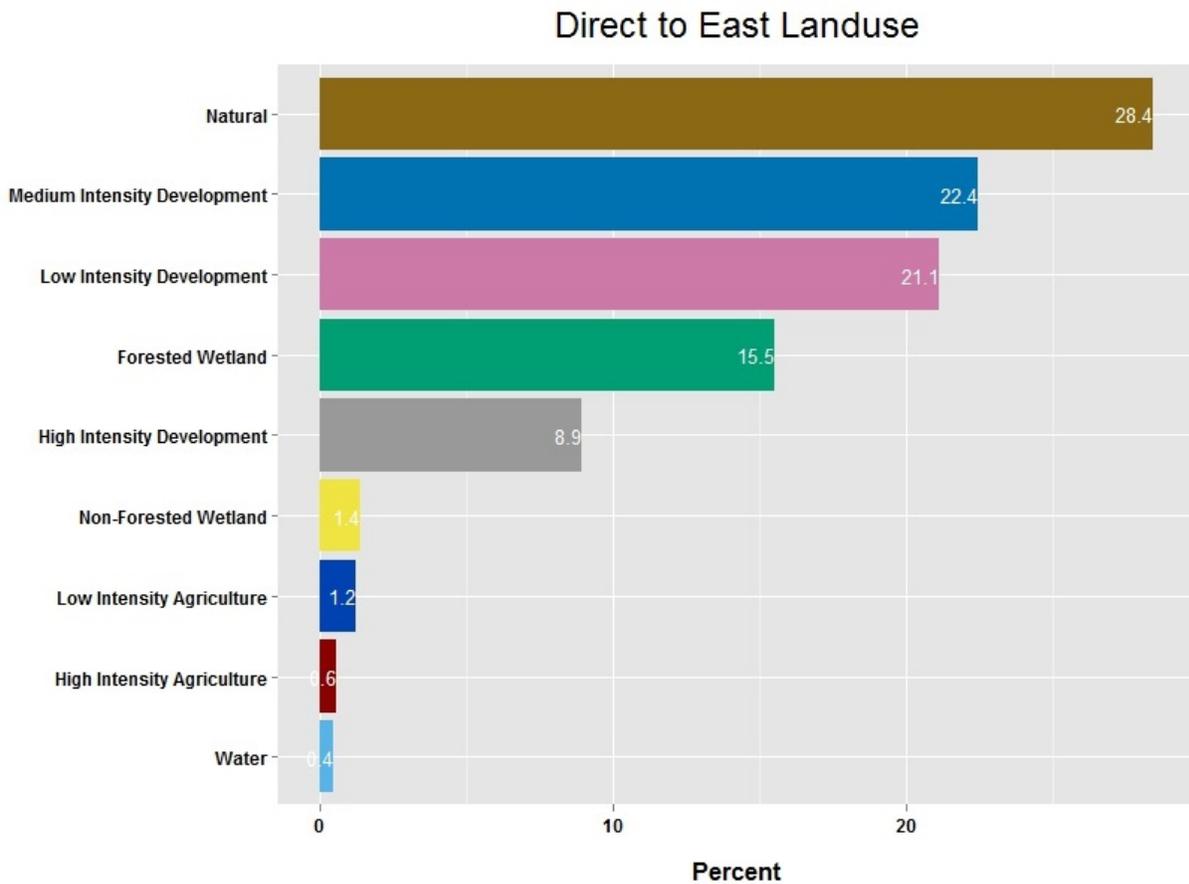
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
5	<b>Peterson Swamp</b>	Natural	46.16	38%
5		Forested Wetland	44.25	36%
5		Medium Intensity Development	14.56	12%
5		Low Intensity Development	11.42	9%
5		Low Intensity Agriculture	5.11	4%
5		Water	0.37	0.3%
5		Non-Forested Wetland	0.20	0.2%
5	<b>Peterson Swamp Total</b>		122.07	100%



**Figure A 5: Landuse in the Peterson Swamp Watershed by %**

**Table A6: Direct to East Pond Landuse**

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
6	<b>Direct to East Pond</b>	Natural	25.82	28%
6		Medium Intensity Development	20.36	22%
6		Low Intensity Development	19.16	21%
6		Forested Wetland	14.07	16%
6		High Intensity Development	8.09	9%
6		Non-Forested Wetland	1.23	1.4%
6		Low Intensity Agriculture	1.10	1.2%
6		High Intensity Ag. (bog)	0.51	0.6%
6		Water	0.40	0.4%
<b>Direct to East Pond Total</b>			<b>90.73</b>	<b>100%</b>



**Figure A 6: Landuse in the Direct to East Pond Watershed by %**

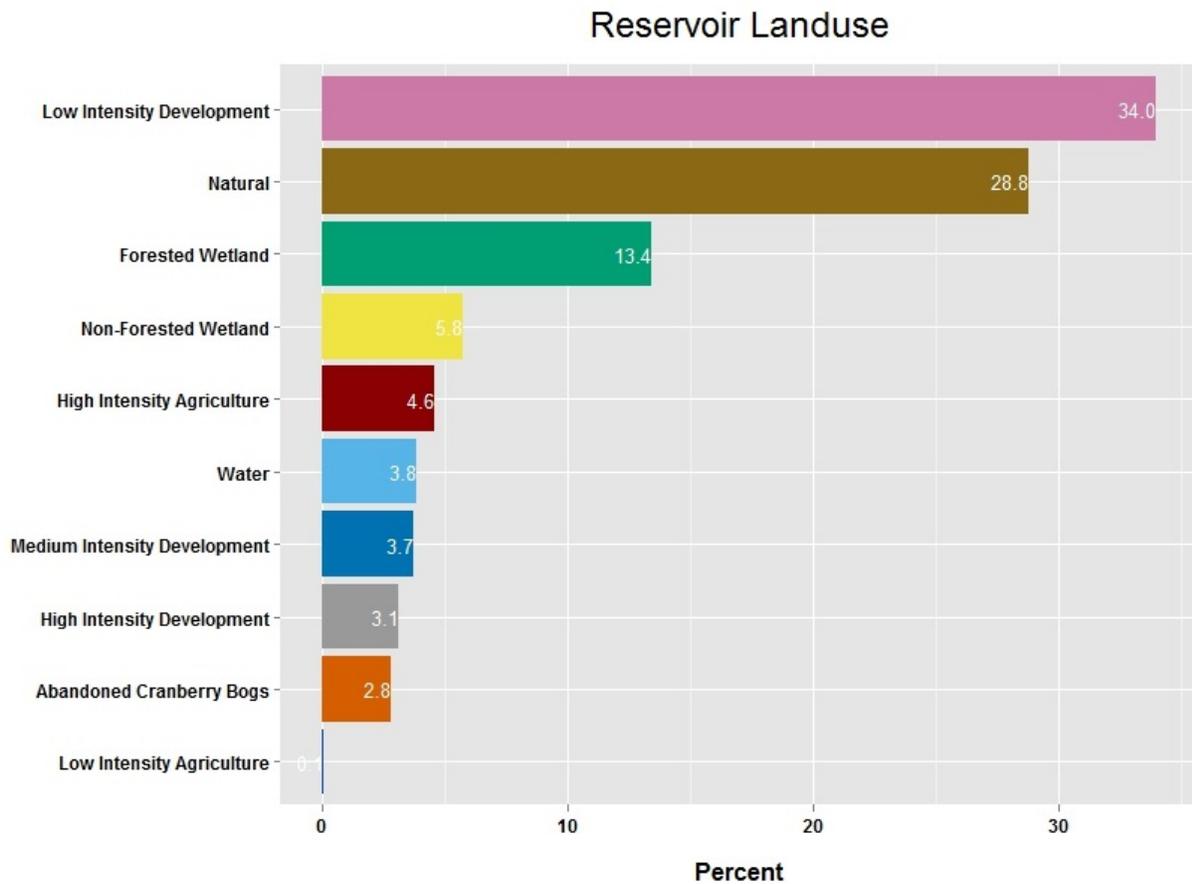
**Table A7: Summary of All Landuse in East Monponsett Pond**

Group	Area (Hectares)	% of Total Watershed Area
Natural	247.33	32.1%
Low Intensity Development	137.32	17.8%
Medium Intensity Development	112.88	14.7%
Forested Wetland	101.83	13.2%
High Intensity Ag. (bog)	67.71	8.8%
Water**	61.96	8.0%
Non-Forested Wetland	19.55	2.5%
High Intensity Development	8.58	1.1%
Low Intensity Agriculture	7.62	1.0%
Open	5.20	0.7%
<b>All Landuse East Pond Total</b>	<b>769.98</b>	<b>100.0%</b>

\*\* does not include surface area of Stetson Pond and East Monponsett Pond

**Table A8: White Oak Reservoir Landuse**

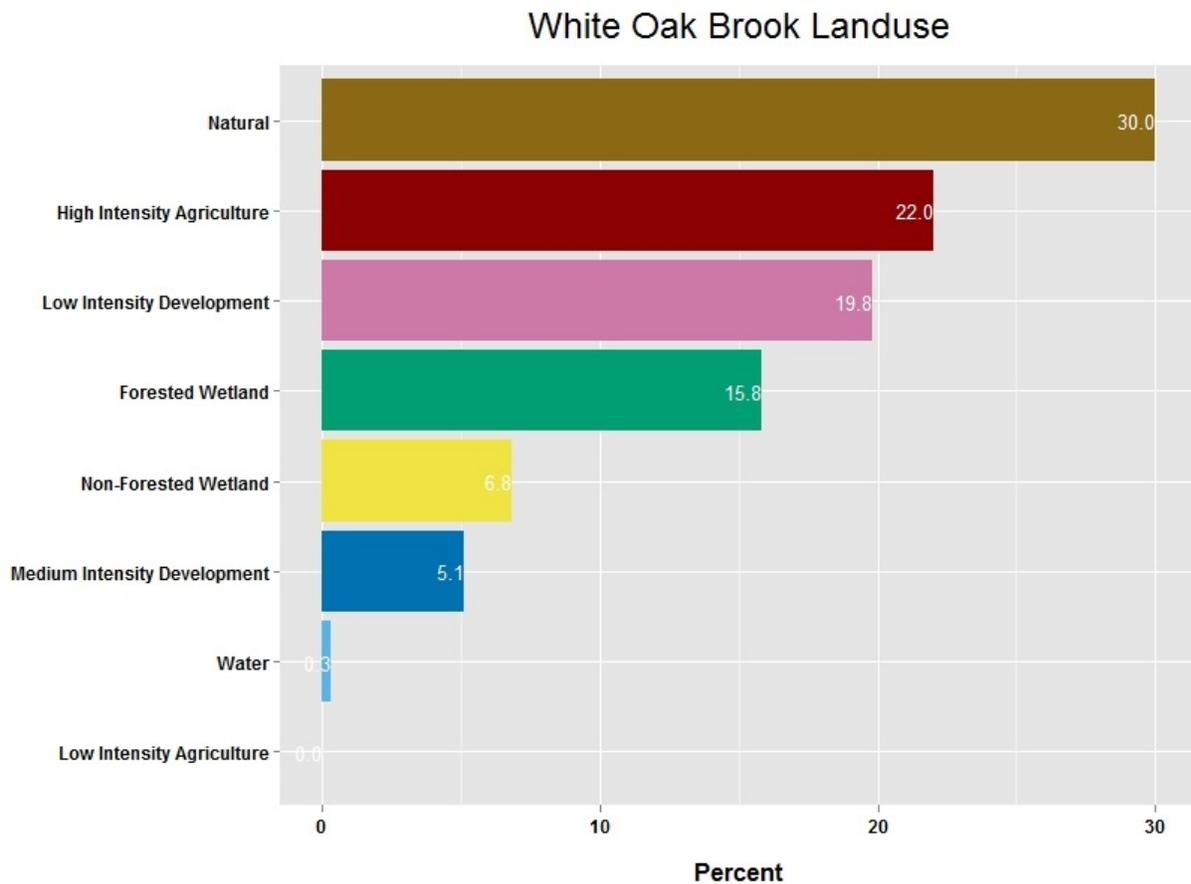
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
8	White Oak Reservoir	Low Intensity Development	56.56	34%
8		Natural	47.91	29%
8		Forested Wetland	22.34	13%
8		Non-Forested Wetland	9.58	6%
8		High Intensity Ag. (bog)	7.61	5%
8		Water	6.38	4%
8		Medium Intensity Development	6.14	4%
8		High Intensity Development	5.16	3%
8		Abandoned Cranberry Bogs	4.71	3%
8		Low Intensity Agriculture	0.13	0.1%
	<b>White Oak Reservoir Total</b>		<b>166.53</b>	<b>100%</b>



**Figure A 7: Landuse in the White Oak Reservoir Watershed by %**

**Table A9: White Oak Brook Landuse**

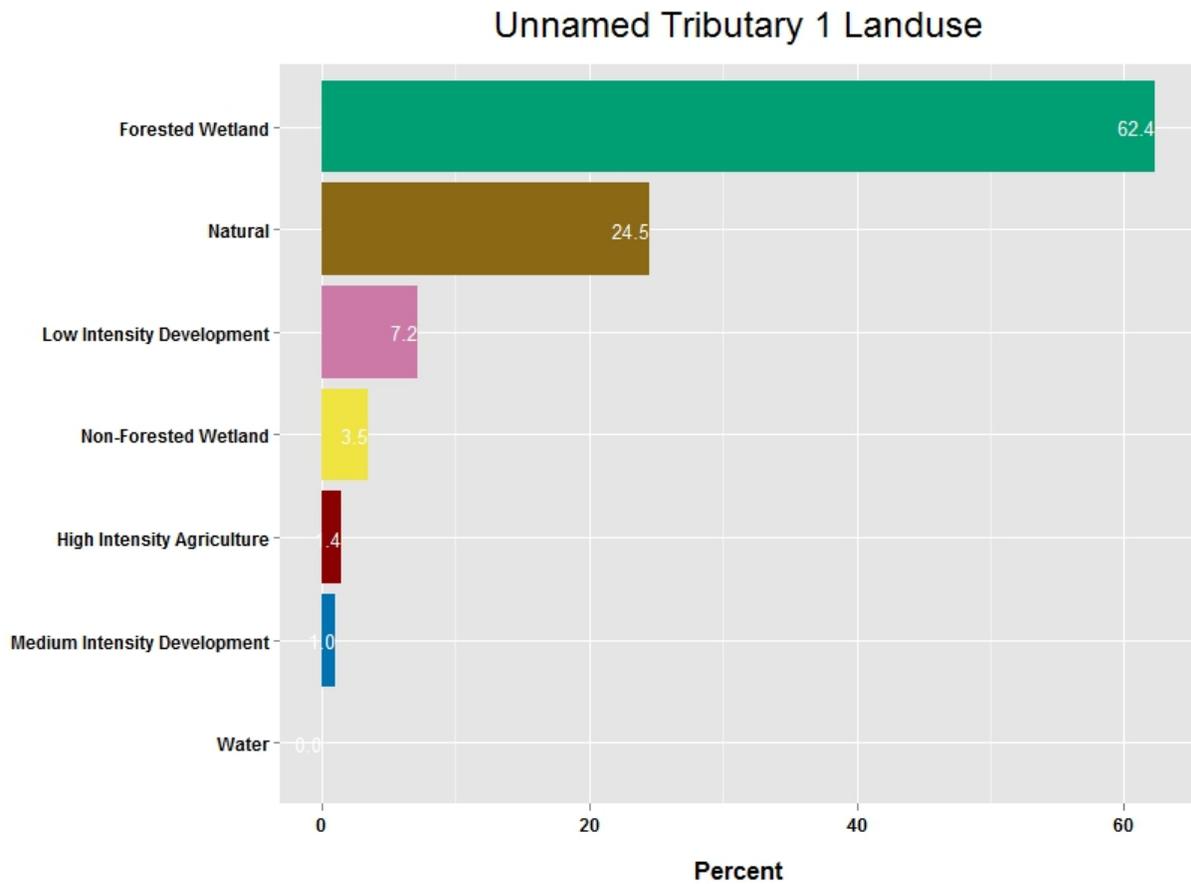
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
9	White Oak Brook	Natural	32.12	30%
9		High Intensity Ag. (bog)	23.59	22%
9		Low Intensity Development	21.24	20%
9		Forested Wetland	16.97	16%
9		Non-Forested Wetland	7.34	7%
9		Medium Intensity Development	5.47	5%
9		Water	0.34	0%
9		Low Intensity Agriculture	0.03	0%
	White Oak Brook Total		107.09	100%



**Figure A 8: Landuse in the White Oak Brook Watershed by %**

**Table A10: Unnamed Tributary 1 Landuse**

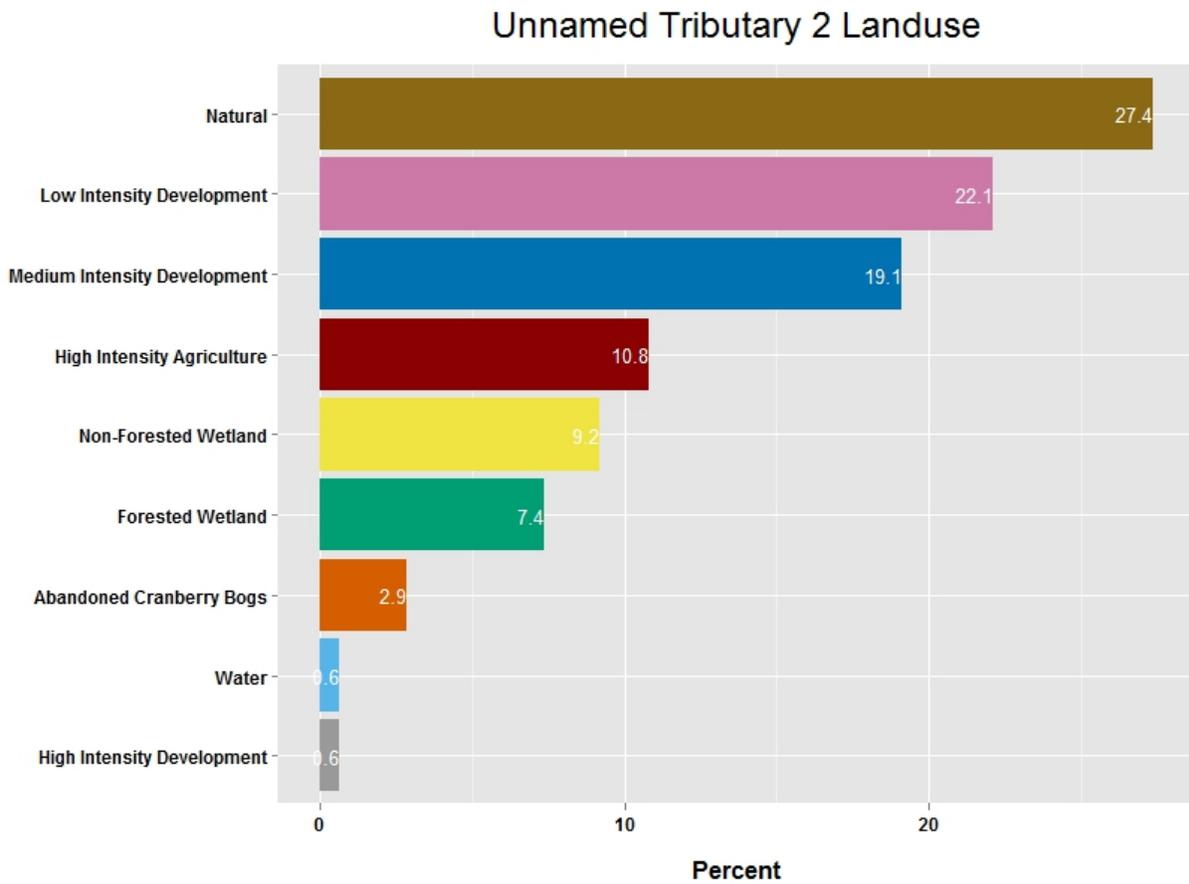
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
10	Unnamed Tributary1	Forested Wetland	32.96	62%
10		Natural	12.96	25%
10		Low Intensity Development	3.80	7%
10		Non-Forested Wetland	1.85	3%
10		High Intensity Ag. (bog)	0.74	1%
10		Medium Intensity Development	0.54	1%
10		Water	0.01	0%
Unnamed Tributary1 Total			52.86	100%



**Figure A 9: Landuse in the Unnamed Tributary 1 Watershed by %**

**Table A11: Unnamed Tributary 2 Landuse**

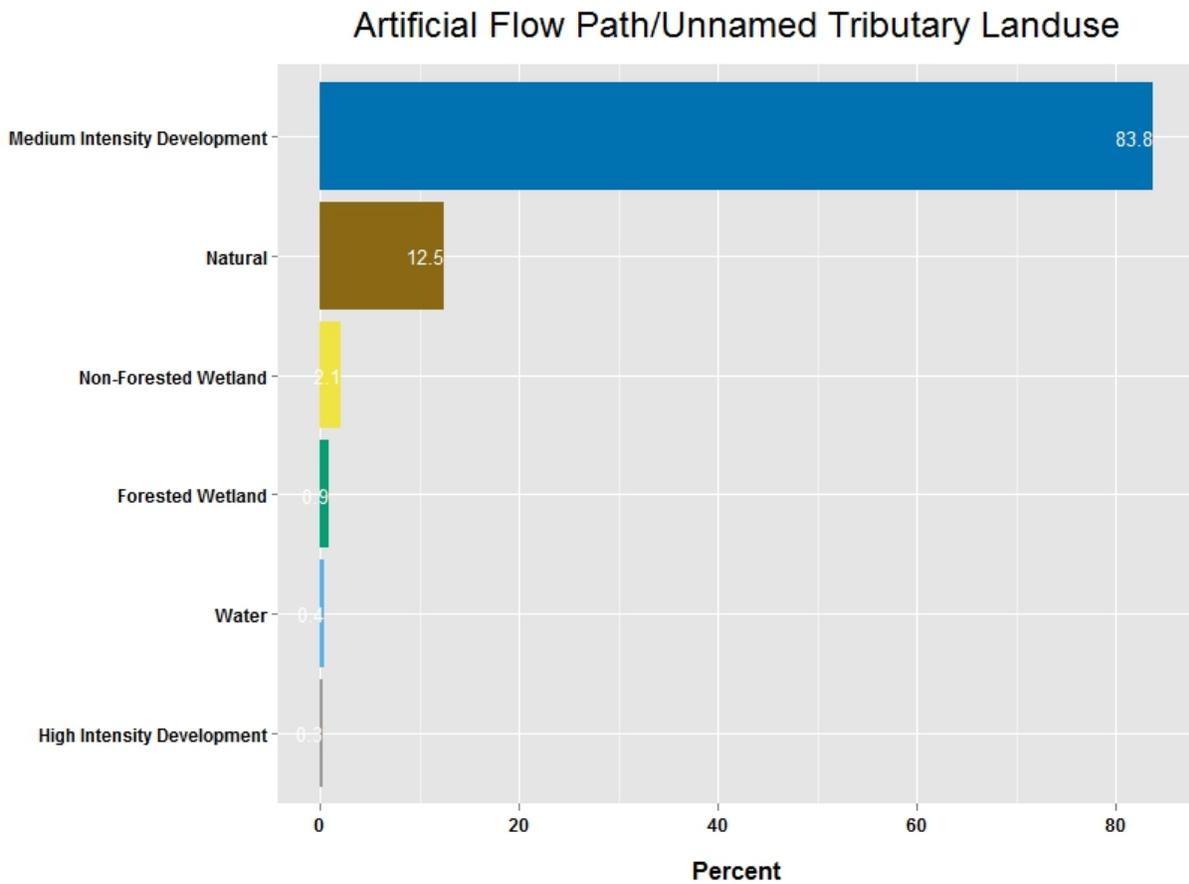
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
11	Unnamed Tributary2	Natural	29.74	27%
11		Low Intensity Development	23.99	22%
11		Medium Intensity Development	20.75	19%
11		High Intensity Ag. (bog)	11.73	11%
11		Non-Forested Wetland	9.96	9%
11		Forested Wetland	8.01	7%
11		Abandoned Cranberry Bogs	3.12	3%
11		Water	0.69	1%
11		High Intensity Development	0.67	1%
<b>Unnamed Tributary2 Total</b>			<b>108.65</b>	<b>100%</b>



**Figure A 10: Landuse in the Unnamed Tributary 2 Watershed by %**

**Table A12: Artificial Flow Path/Unnamed Tributary Landuse**

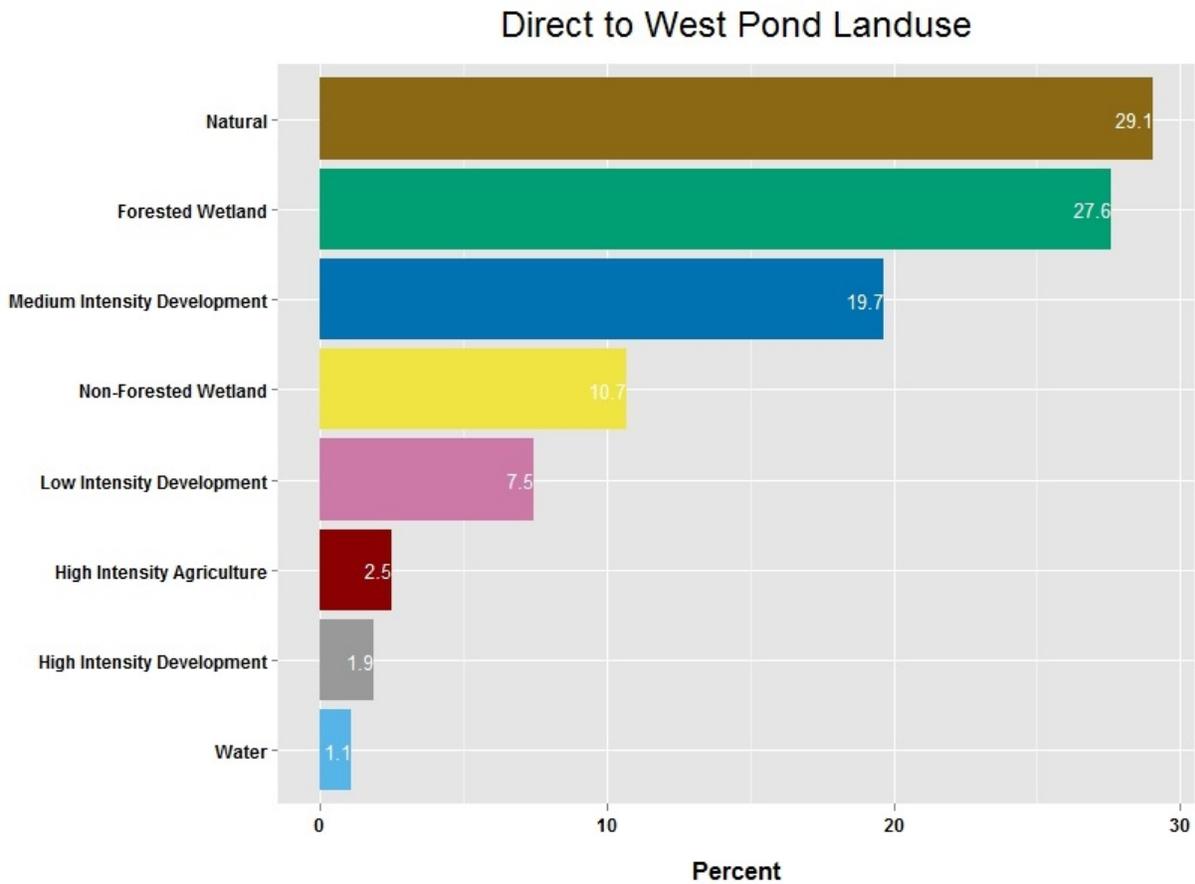
Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
12	ArtFlow Unnamed Tributary3	Medium Intensity Development	17.96	84%
12		Natural	2.68	12%
12		Non-Forested Wetland	0.46	2%
12		Forested Wetland	0.20	1%
12		Water	0.08	0.4%
12		High Intensity Development	0.06	0.3%
<b>Artificial Flow Unnamed Tributary3 Total</b>			<b>21.44</b>	<b>100%</b>



**Figure A 11: Landuse in the Artificial Flow Path/Tributary Watershed by %**

**Table A13: Direct to West Pond Landuse**

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
13	Direct to West Pond	Natural	27.38	29.1%
13		Forested Wetland	26.00	28%
13		Medium Intensity Development	18.53	19.7%
13		Non-Forested Wetland	10.08	11%
13		Low Intensity Development	7.05	7%
13		High Intensity Ag. (bog)	2.37	3%
13		High Intensity Development	1.77	2%
13		Water	1.04	1%
<b>Direct to West Pond Total</b>			<b>94.21</b>	<b>1</b>



**Figure A 12: Landuse in the Direct to West Pond Watershed by %**

## Appendix B: Select LLRM Information

**Table B1: Water and TP Landuse Export Coefficient used for current condition LLRM model calibration**

Landuse Grouping	TP (kg/ha/yr)	Flow Coeff (%)
Natural	0.10	0.50
Low Intensity Agriculture	0.64	0.50
Medium Intensity Agriculture	1.50	0.50
High Intensity Ag. (bog)	4.30	0.50
Forested Wetland	0.40	0.50
Non-Forested Wetland	0.30	0.50
Low Intensity Development	0.30	0.50
Medium Intensity Development	0.50	0.50
High Intensity Development	1.00	0.50
Open	0.00	0.50
Water	0.00	0.50
Abandoned Cranberry Bog	0.10	0.50

**Table B2: LLRM TP Prediction Equations**

Name	Formula
Mass Balance (Maximum Conc.)	$TP=L/(Z(F))*1000$
Kirchner-Dillon 1975 (K-D)	$TP=L(1-Rp)/(Z(F))*1000$
Vollenweider 1975 (V)	$TP=L/(Z(S+F))*1000$
Larsen-Mercier 1976 (L-M)	$TP=L(1-Rlm)/(Z(F))*1000$
Jones-Bachmann 1976 (J-B)	$TP=0.84(L)/(Z(0.65+F))*1000$
Reckhow General (1977) (Rg)	$TP=L/(11.6+1.2(Z(F)))*1000$

(see table B3 for symbol definitions and value derivations, see references above for citations)

**Table B3: Symbols Used In LLRM Model**

Symbol	Parameter	Units	Derivation
TP	Lake Total Phosphorus Conc.	ppb	From in-lake models
KG	Phosphorus Load to Lake	kg/yr	From export model
L	Phosphorus Load to Lake	g P/m <sup>2</sup> /yr	KG*1000/A
TPin	Influent (Inflow) Total Phosphorus	ppb	From export model
TPout	Effluent (Outlet) Total Phosphorus	ppb	From data, if available
I	Inflow	m <sup>3</sup> /yr	From export model
A	Lake Area	m <sup>2</sup>	From data
V	Lake Volume	m <sup>3</sup>	From data
Z	Mean Depth	m	Volume/area
F	Flushing Rate	flushings/yr	Inflow/volume
S	Suspended Fraction	no units	Effluent TP/Influent TP
Qs	Areal Water Load	m/yr	Z(F)
Vs	Settling Velocity	m	Z(S)
Rp	Retention Coefficient (settling rate)	no units	$((V_s+13.2)/2)/(((V_s+13.2)/2)+Q_s)$
Rlm	Retention Coefficient (flushing rate)	no units	$1/(1+F^{0.5})$

## Appendix C: Select MassDEP Sampling Data

### Algal Sampling

Given human health impacts MassDEP has monitored West Monponsett Pond since 2013 for total cyanobacteria counts and speciation. Massachusetts Department of Health (MA DPH) Advisory Level (AL) state that cyanobacteria cell counts greater than 70,000 per mL indicate a moderate risk level for adverse human health effects from potentially toxic cyanobacteria. At 70,000 cells/mL and above MA DPH will advise communities to post signage at waterbodies warning people to avoid contact with the water. Children and pets are most susceptible to the cyanotoxins because of the amount of time they are in the water and the amount of water they typically ingest in play. Dermal, liver or neurological effects may result from contact or ingestion of these waters.

In 2013 MassDEP conducted algal sampling at two locations on West Monponsett Pond, 4<sup>th</sup> Avenue Beach and Ocean Avenue Beach. Total cyanobacteria count at the 4<sup>th</sup> Avenue Beach sampling location were greater than 70,000 cells/mL, the MA DPH Advisory Level for contact recreation, for a substantial portion of the summer and high counts lasted into December of 2013 (Figure C1). During the period where total cyanobacteria counts exceeded the MA DPH Advisory Level, counts were on average 3.4 times the Advisory Level. The highest cyanobacteria count at the 4<sup>th</sup> Avenue Beach were found on October 15, 2013. On this date, the total cyanobacteria count was approximately 1.2 million cells/mL with the sample dominated by *Microcystis* and *Aphanizomenon* (Figure C3).

MassDEP sampling at the Ocean Avenue Beach found prolonged exceedance of the MA DPH advisory level for cyanobacteria cells counts (Figure C2). High total cyanobacteria counts were found beginning in July of 2013 and with exception of a slight dip in August continued into December of 2013. In general total cyanobacteria counts at this location were generally higher than the 4<sup>th</sup> Avenue sampling site in 2013 and the bloom timing pattern was slightly different. During the period, counts were on average 5.2 times the Advisory Level. The two highest cyanobacteria count at this location in 2013 occurred on September 16 and November 18<sup>th</sup> with counts of 1,045,517 and 2,002,234 (cells/mL). The September bloom was largely composed of *Microcystis* while the November bloom was principally composed of *Aphanizomenon* (Figure C4).

In 2014 MassDEP sampled at three locations on West Monponsett Pond, the 4<sup>th</sup> Avenue Beach, the boat launch and the Ocean Avenue Beach. The 4<sup>th</sup> Avenue Beach was found to have elevated total cyanobacteria counts beginning in July and lasting into December of 2014 (Figure C5). During the period where total cyanobacteria counts exceeded the MA DPH Advisory Level, counts were on average 1.8 times the Advisory Level. On September 29<sup>th</sup> the highest total cyanobacteria count (271,302 cells/mL) was found at this location and the dominant taxa on this date was *Anabaena*. MassDEP sampling at the boat launch in 2014 documented elevated total cyanobacteria counts on dates between July 1 and December 1<sup>st</sup> (Figure C6). Samples during this period were always greater than the

MA DPH Advisory Level. The samples during this period were on average approximately 4 times the Advisory Level. The highest total cyanobacteria count at the boat launch sampling station was 1,974,152 and occurred on September 29th. During this bloom the *Anabaena (large celled)* made up the majority of the total cell count (Figure C9).

In 2014 MassDEP sampling at the Ocean Avenue Beach documented elevated total cyanobacteria counts which exceed the MA DPH Advisory Level on dates between July 8 and November 24 (Figure C7). During the period, counts were on average 2.2 times the Advisory Level. The highest total cyanobacteria count of 555,544 (cells/mL) was found on September 29th and was dominated by *Anabaena (large celled)* (Figure C10).

MassDEP sampling has documented a severe impairment of the recreational use of West Monponsett Pond due to harmful algal blooms, namely cyanobacteria. In order to restore this resource a significant reduction in nutrient loading in this system will be required.

### 2013 Cyanobacteria Cell Counts- West Monponsett Pond, 4th Avenue Beach, Halifax MA

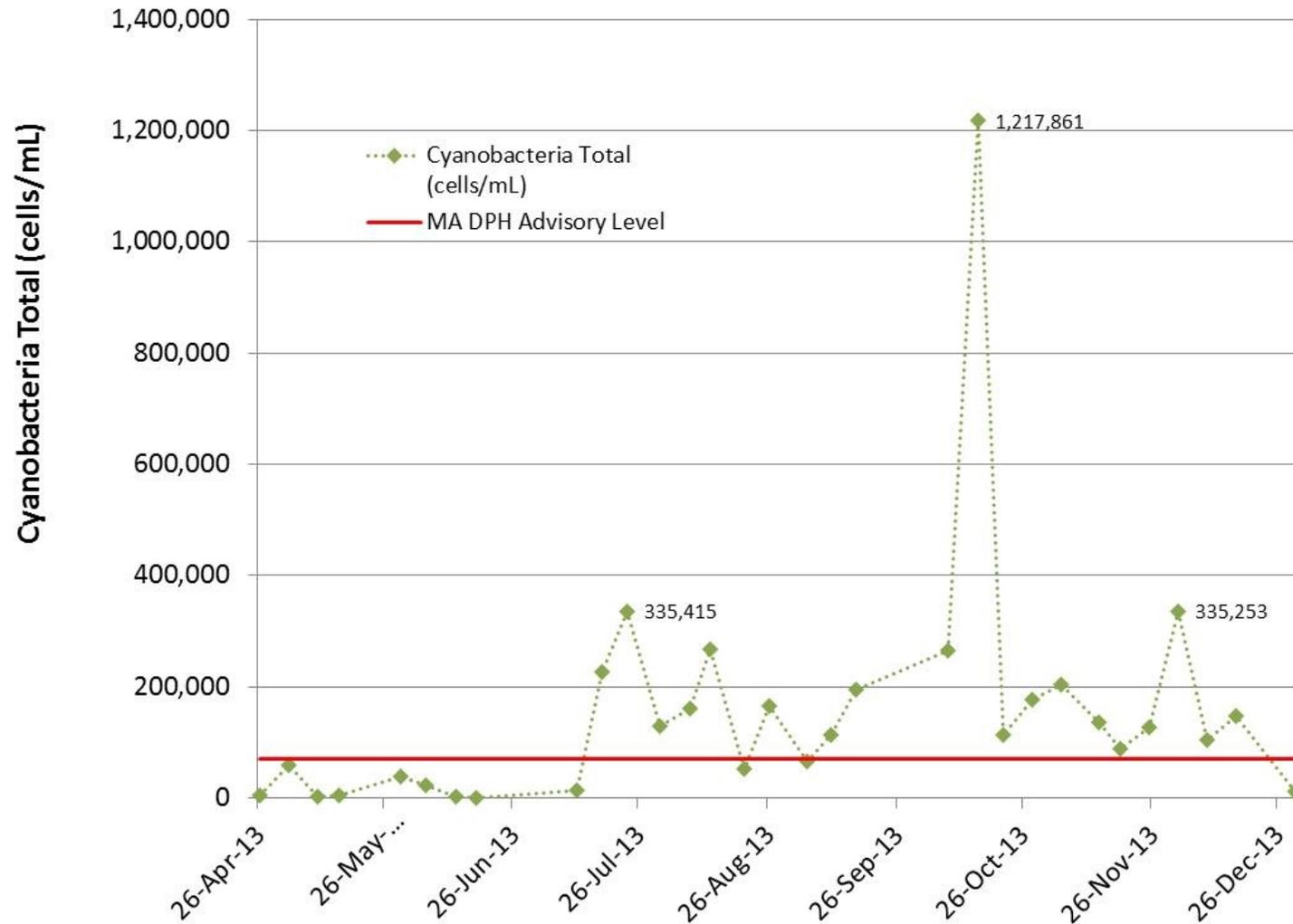


Figure C 1: West Monponsett Pond, 4th Avenue Beach, 2013 Cyanobacteria Cell Counts

### 2013 Cyanobacteria Cell Counts- West Monponsett Pond, Ocean Avenue, Halifax MA

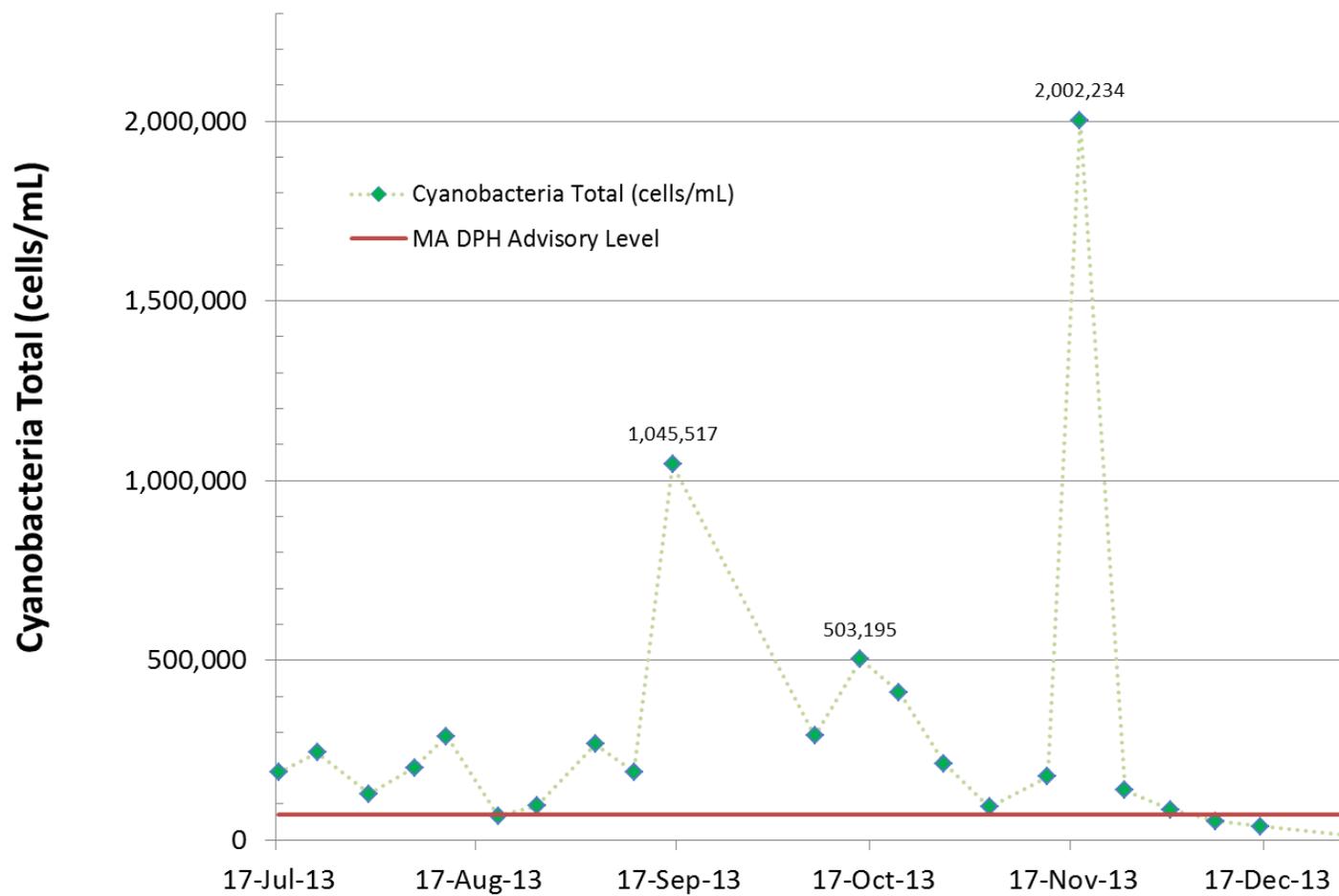
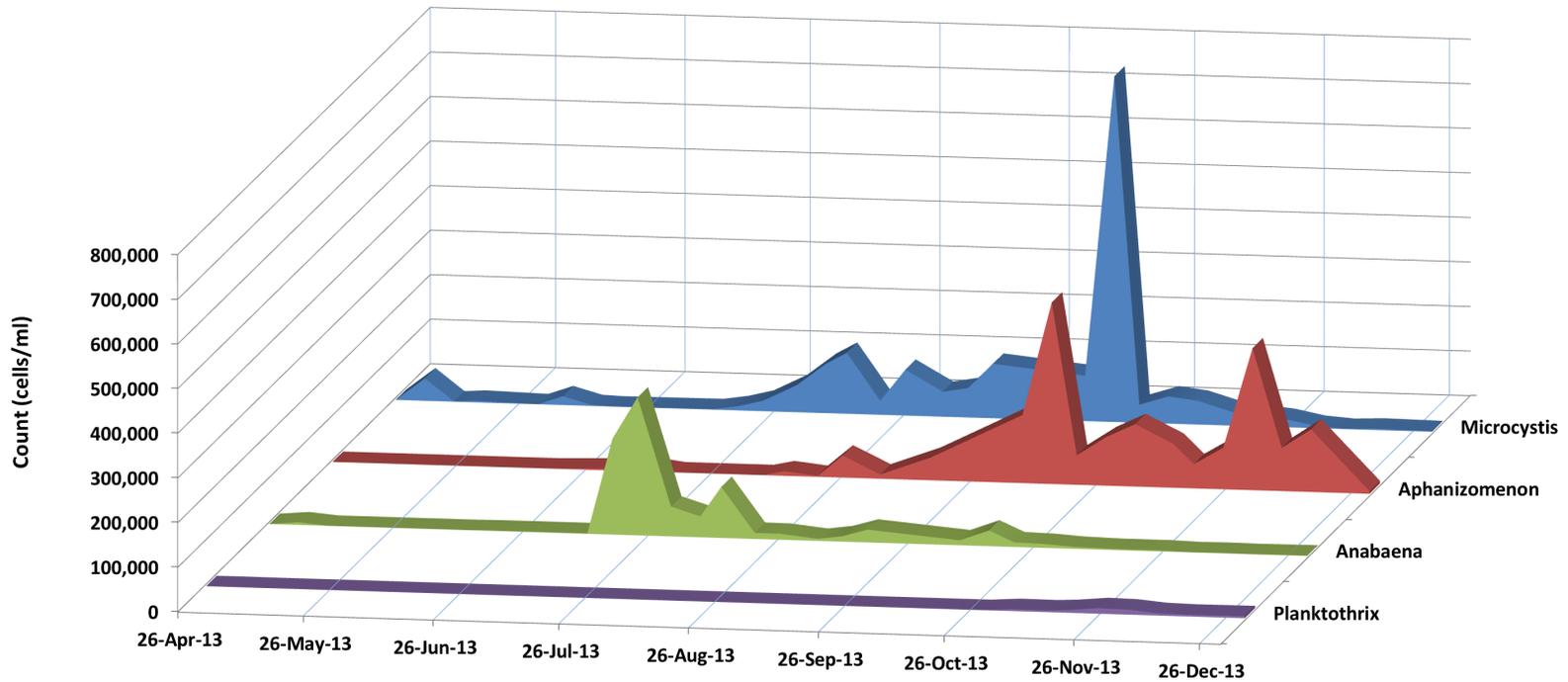


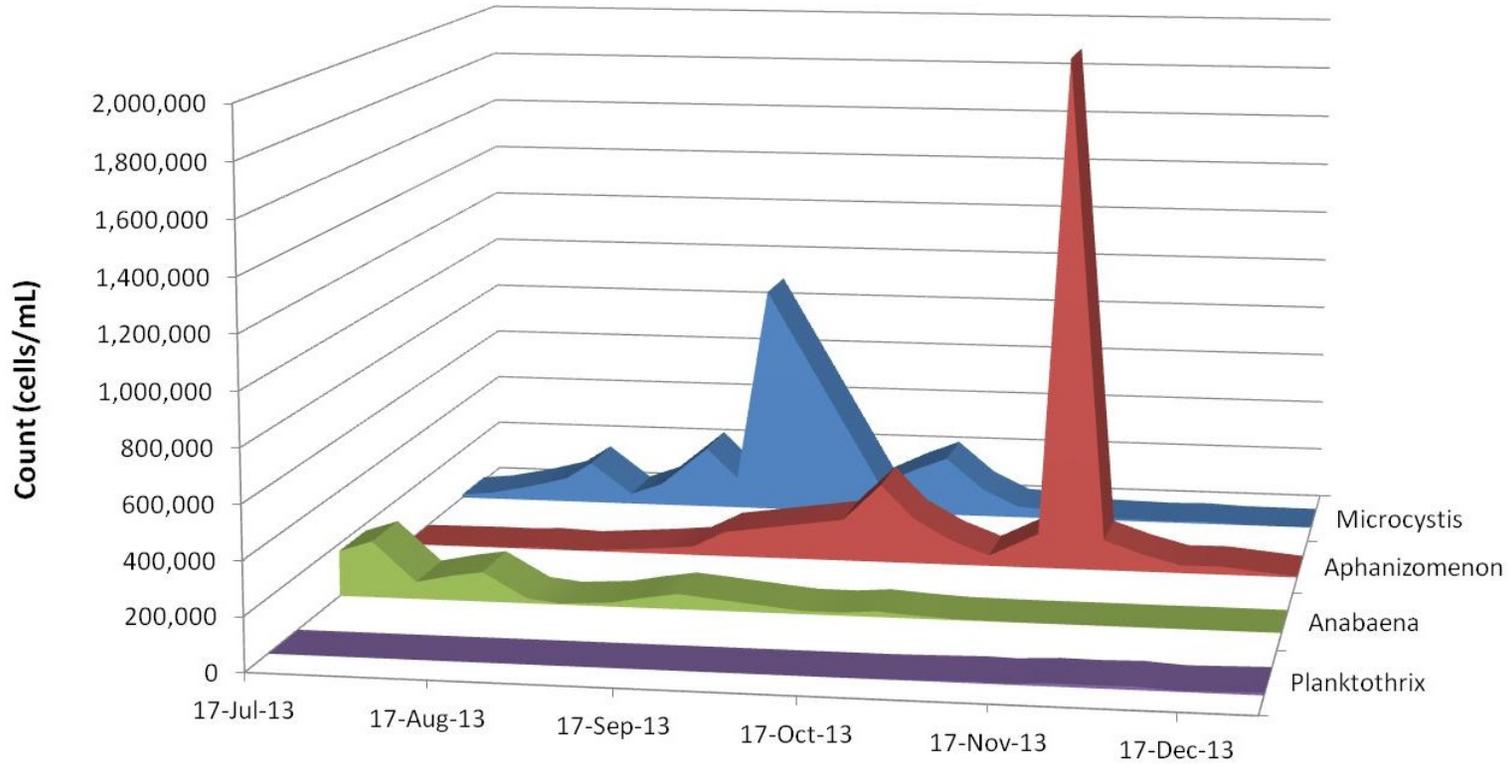
Figure C 2: West Monponsett Pond, Ocean Avenue Beach, 2013 Cyanobacteria Cell Counts

**Major Cyanobacteria Taxa Counts (cells/mL)  
West Monponsett Pond, Fourth Avenue Beach Sampling Site  
Halifax, Massachusetts**



**Figure C 3: West Monponsett Pond, 4th Avenue Beach, 2013 Major Cyanobacteria Taxa Counts (cells/mL)**

**Major Cyanobacteria Taxa Counts (cells/mL)  
West Monponsett Pond, Fourth Avenue Beach Sampling Site  
Halifax, Massachusetts**



**Figure C 4: West Monponsett Pond, Ocean Avenue Beach, 2013 Major Cyanobacteria Taxa Counts (cells/mL)**

### West Monponsett Pond, Halifax, Massachusetts Cyanobacteria Total (cells/mL) -4th Avenue Beach



Figure C 5: West Monponsett Pond, 4th Avenue Beach, 2014 Cyanobacteria Cell Counts

### West Monponsett Pond, Halifax, Massachusetts Cyanobacteria Total (cells/mL) -Boat Ramp

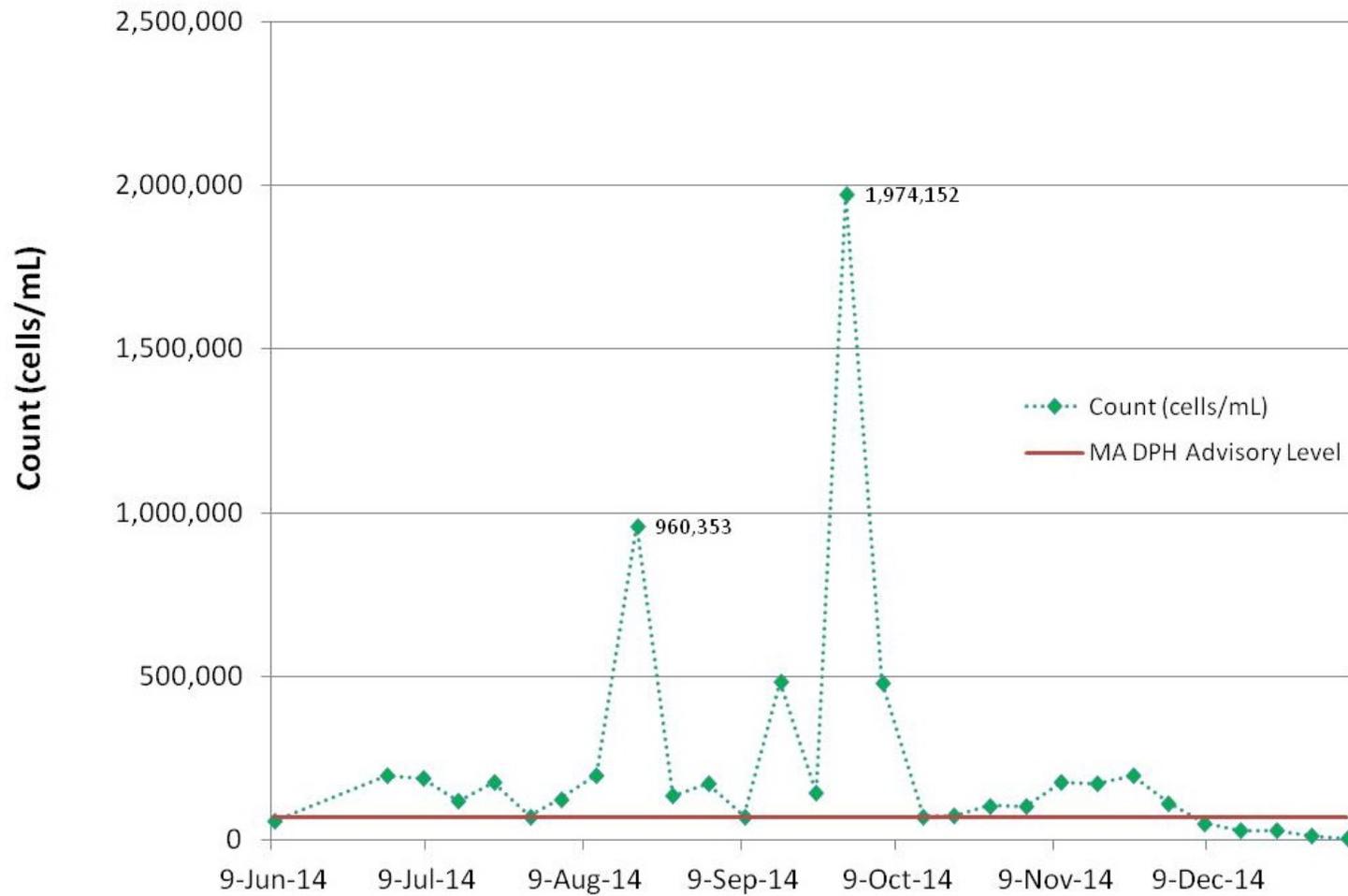


Figure C 6: West Monponsett Pond, Boat Ramp 2014 Cyanobacteria Cell Counts

West Monponsett Pond, Halifax, MA  
Cyanobacteria Total (cells/mL) - Ocean Avenue Beach

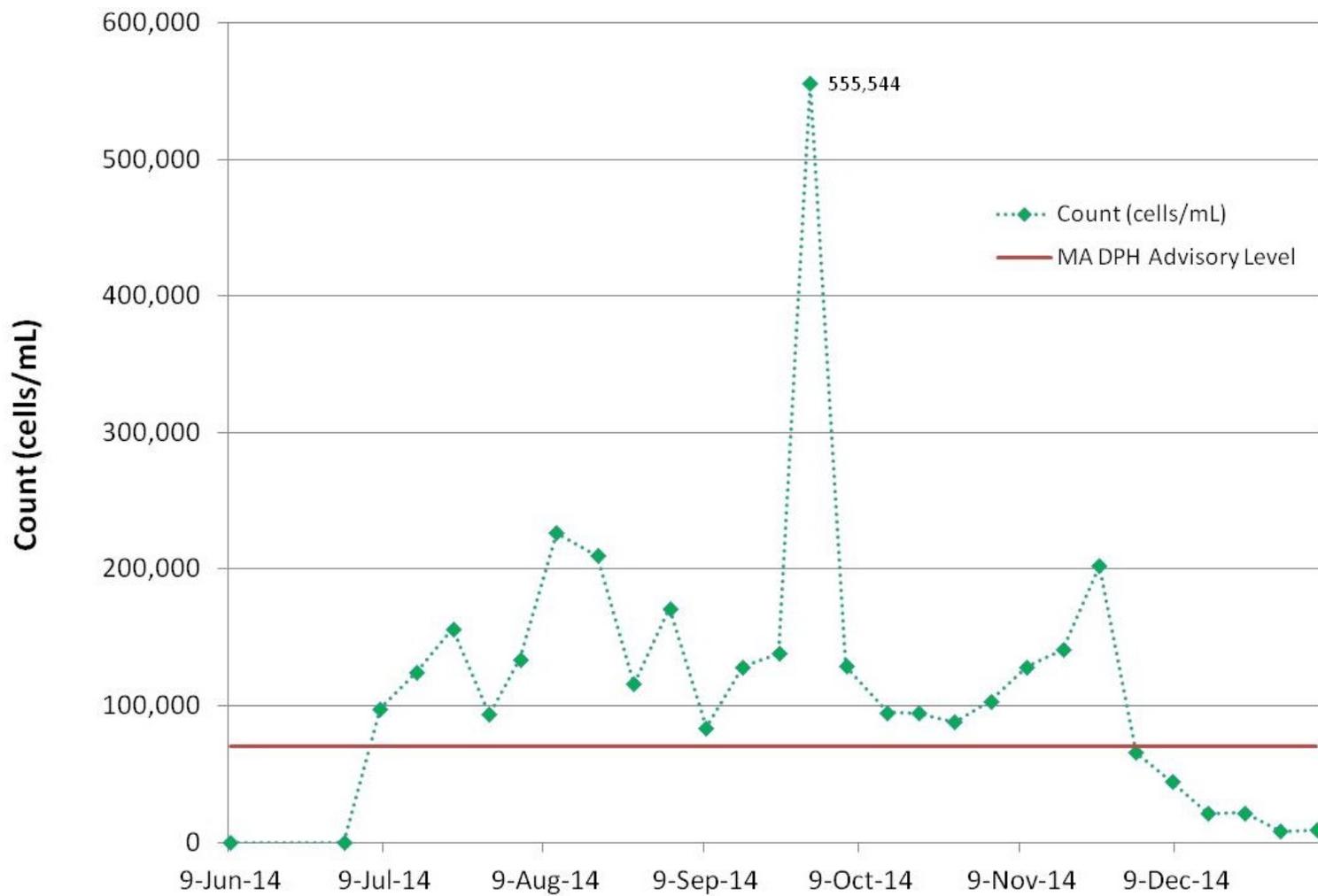
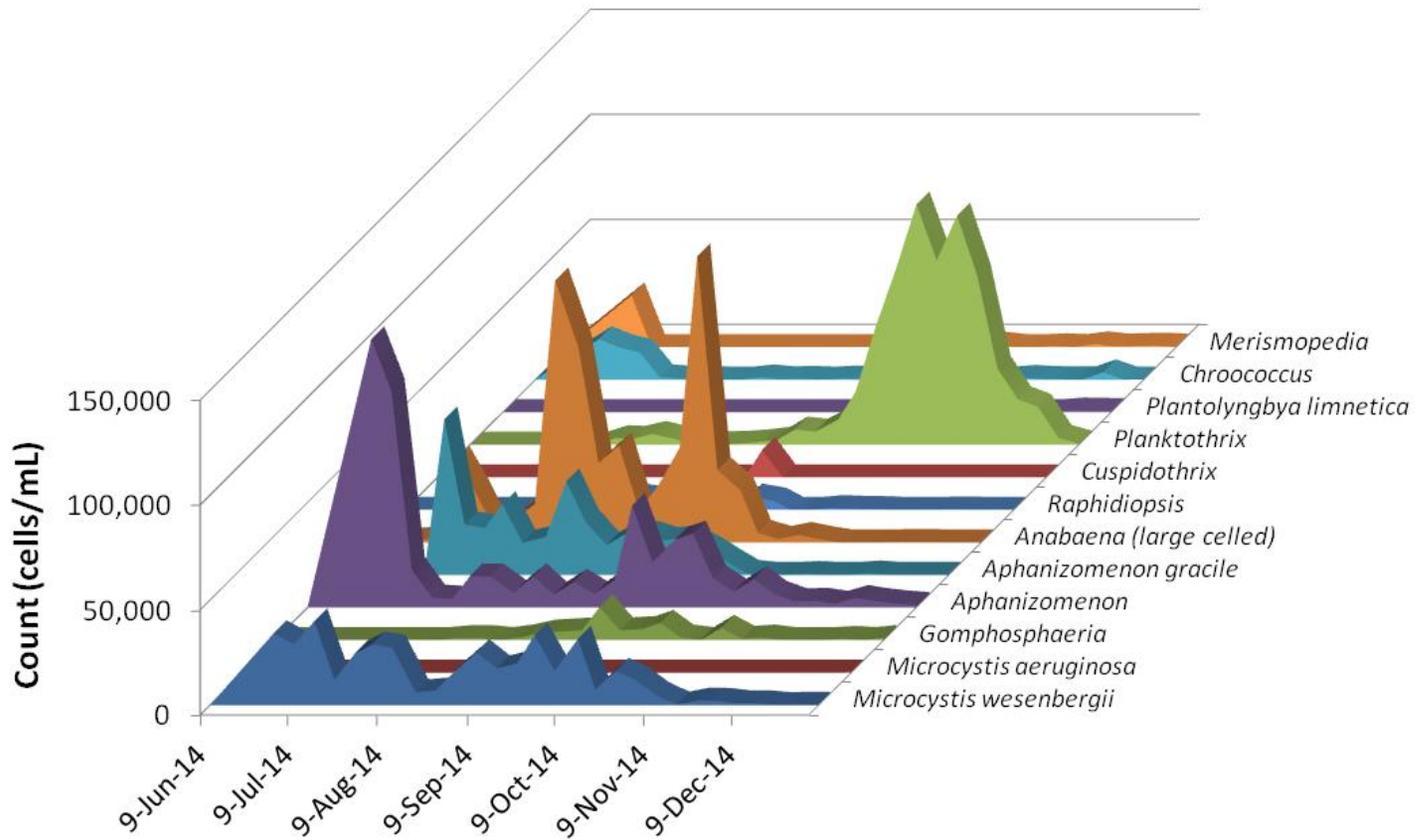


Figure C 7: West Monponsett Pond, Ocean Avenue Beach 2014 Cyanobacteria Cell Counts

**Major Cyanobacteria Taxa Counts (cells/mL)  
West Monponsett Pond, Halifax MA, 4th Avenue Beach**



**Figure C 8: West Monponsett Pond, 4th Avenue Beach, 2014 Major Cyanobacteria Taxa Counts (cells/mL)**

Cyanobacteria Major Taxa Counts (cells/mL), West Monponsett Pond,  
Public Access Boat Ramp, July to December 2014

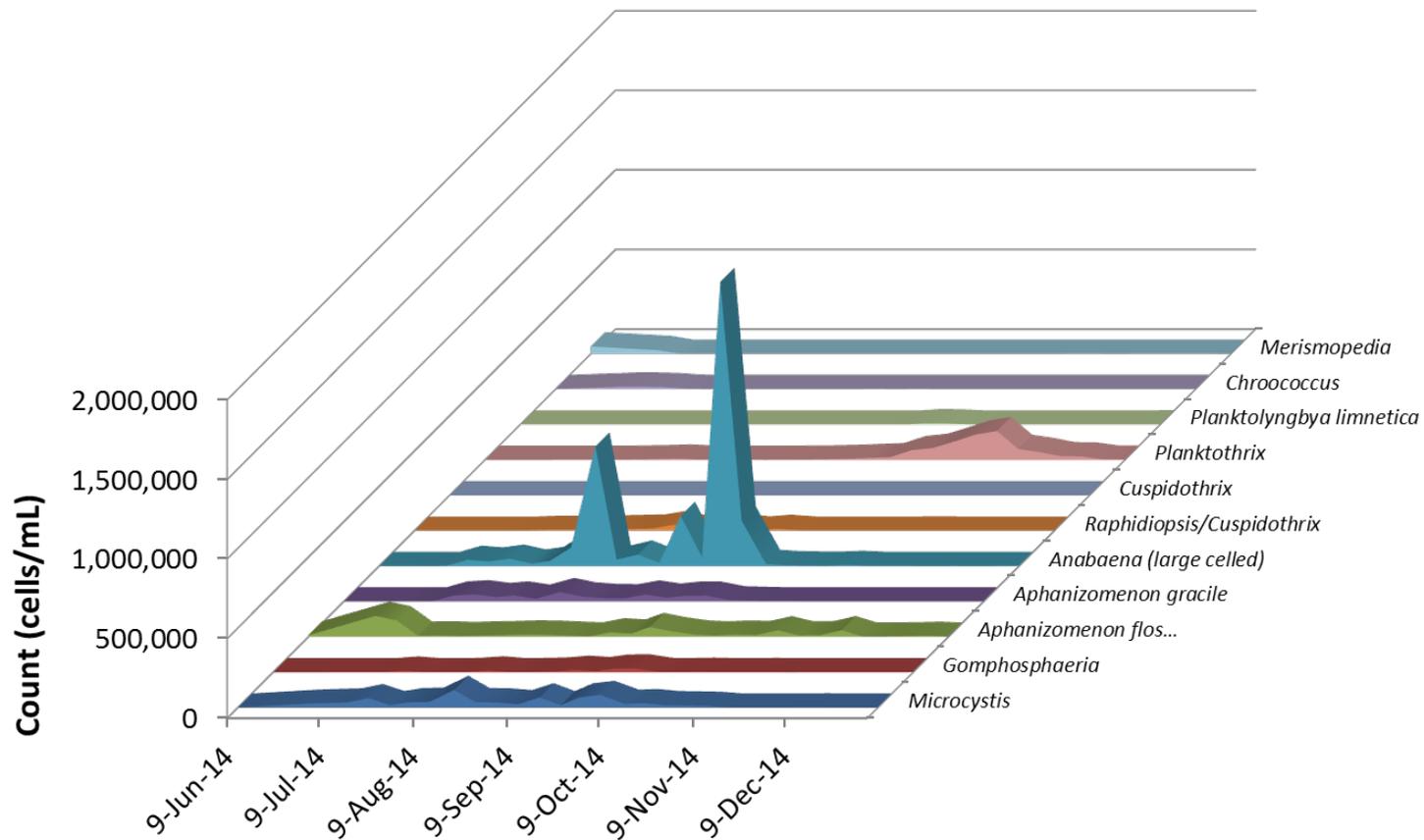
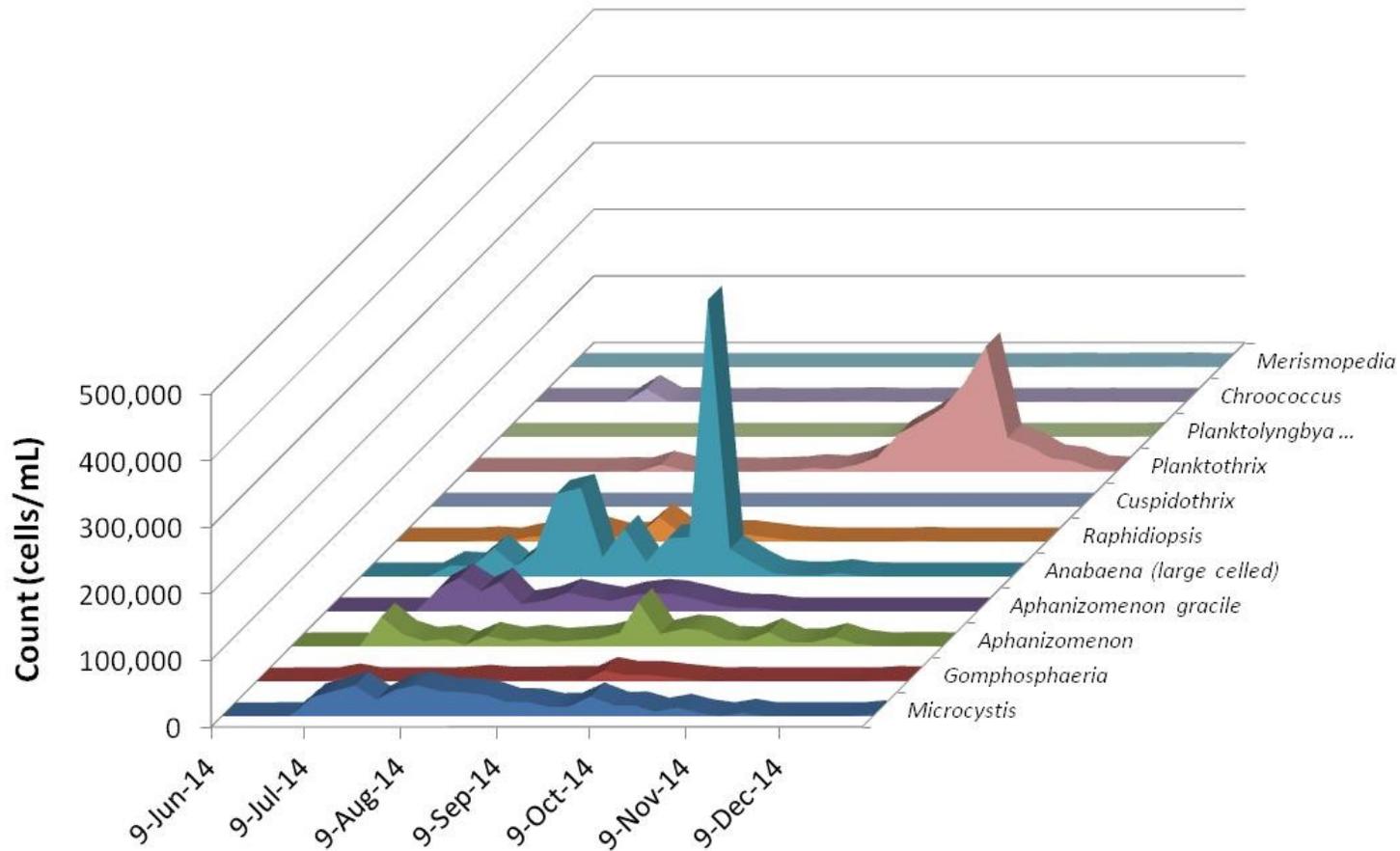


Figure C 9: West Monponsett Pond, Boat Ramp, 2014 Major Cyanobacteria Taxa Counts (cells/mL)

### Cyanobacteria Major Taxa Counts (cells/mL) , West Monponsett Pond , Ocean Avenue Beach



**Figure C 10: West Monponsett Pond, Ocean Ave. Beach, 2014 Major Cyanobacteria Taxa Counts (cells/mL)**

## Dissolved Oxygen Profiles

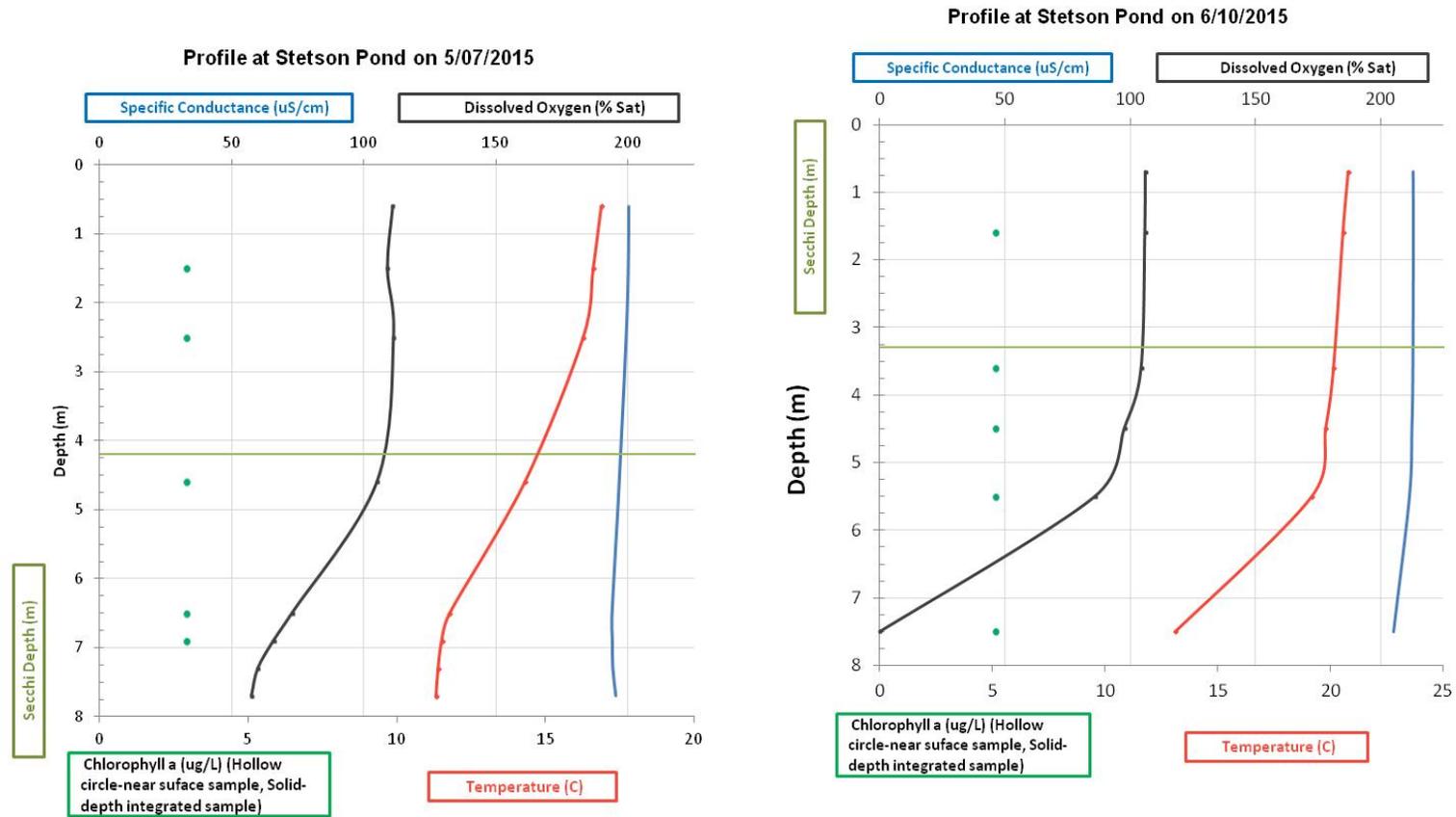
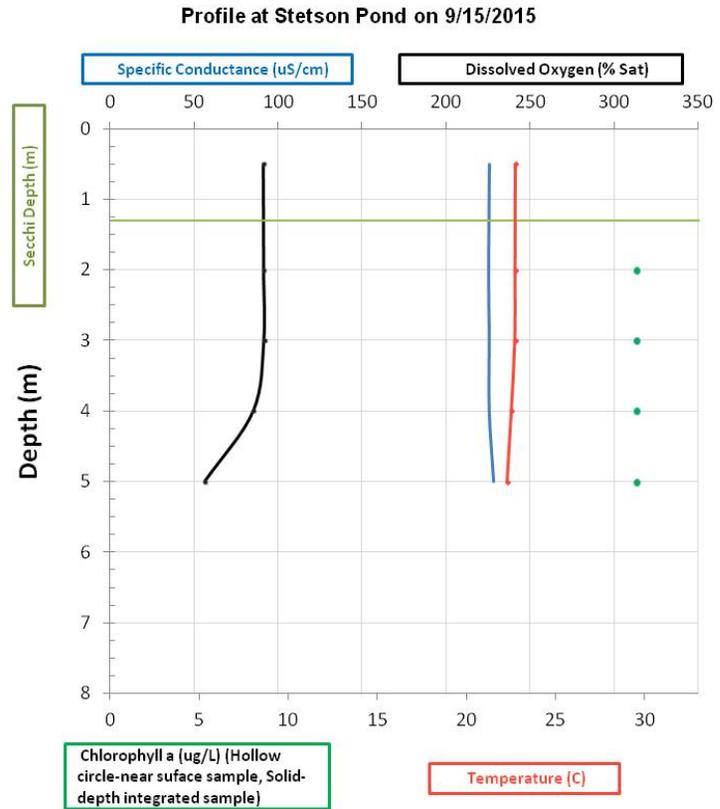
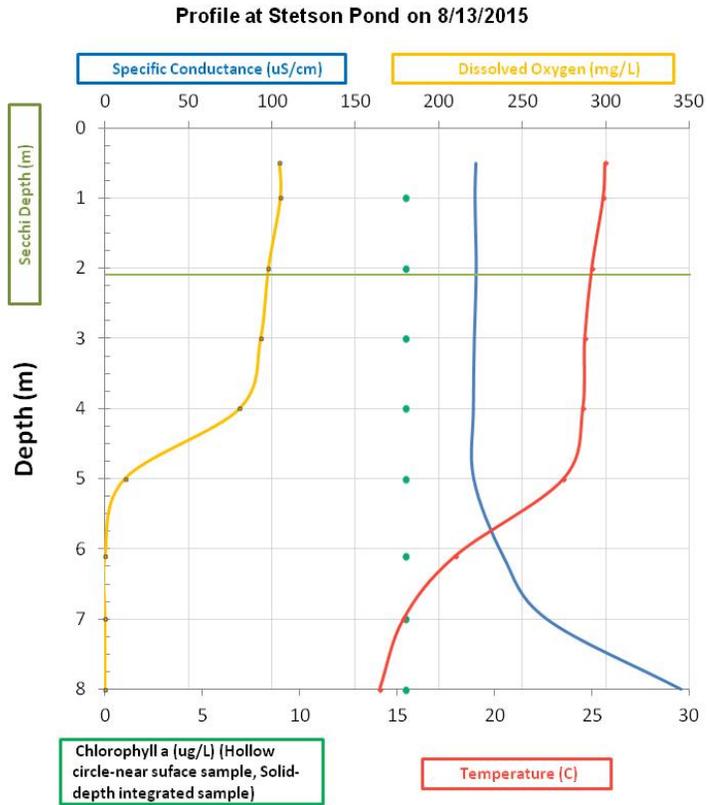
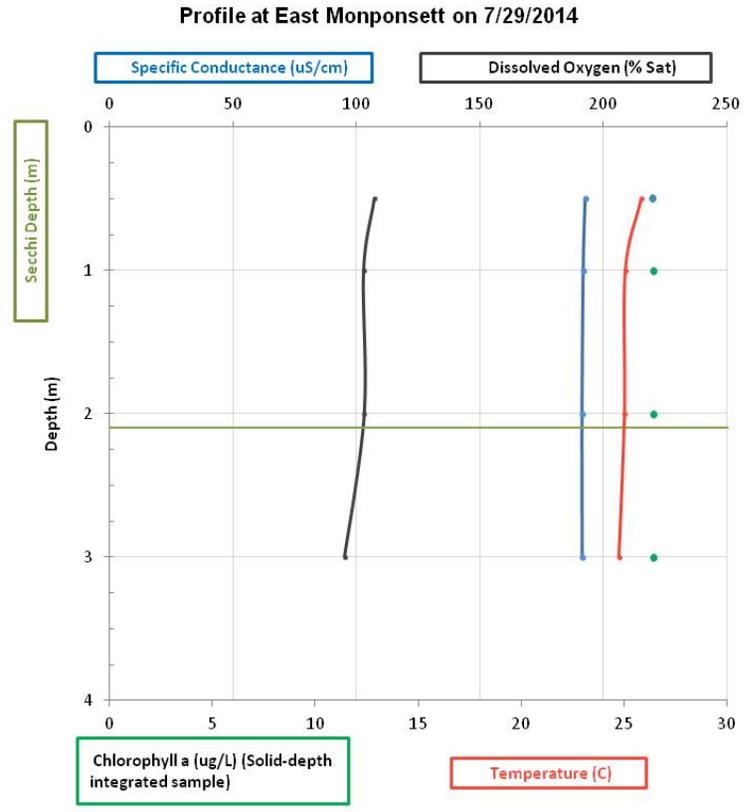
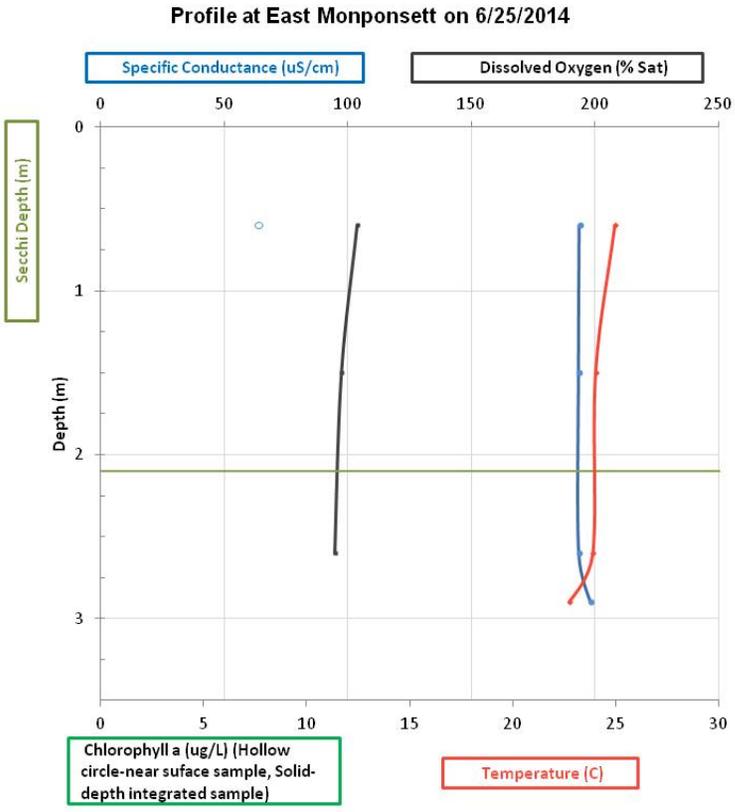


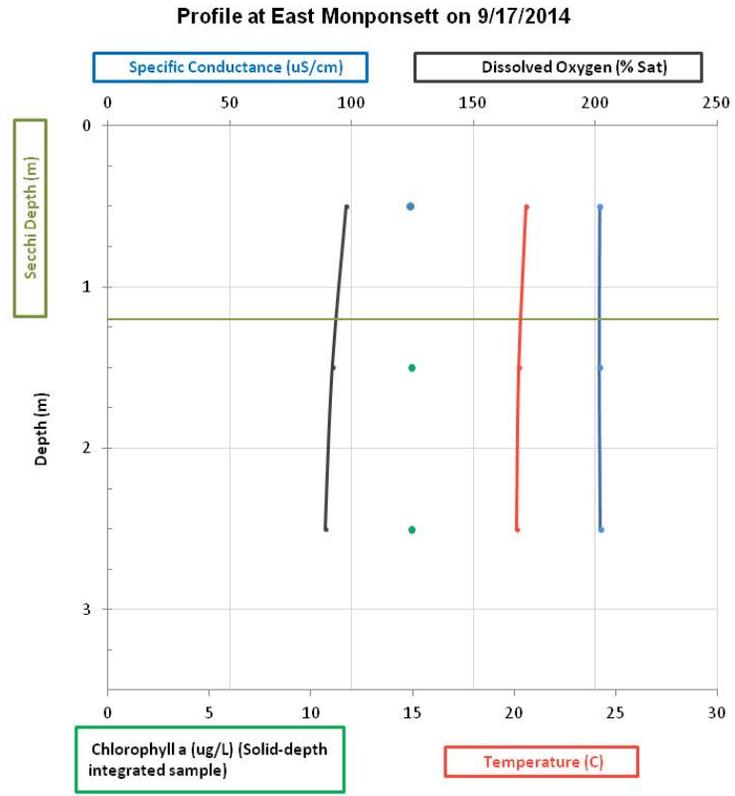
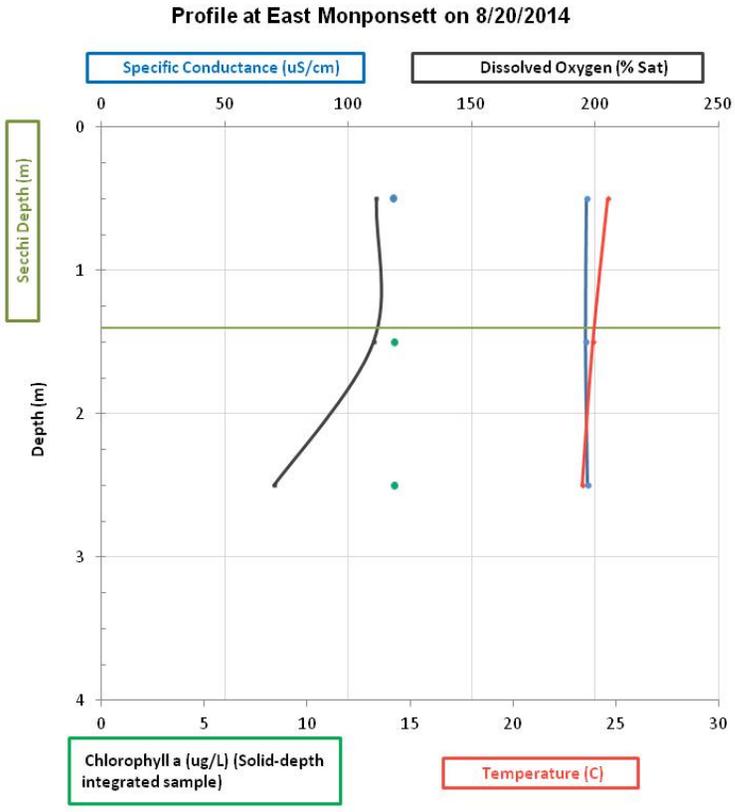
Figure C 11: Stetson Pond DO Profile May 2015 (left) and Stetson Pond DO Profile June 2015 (right)



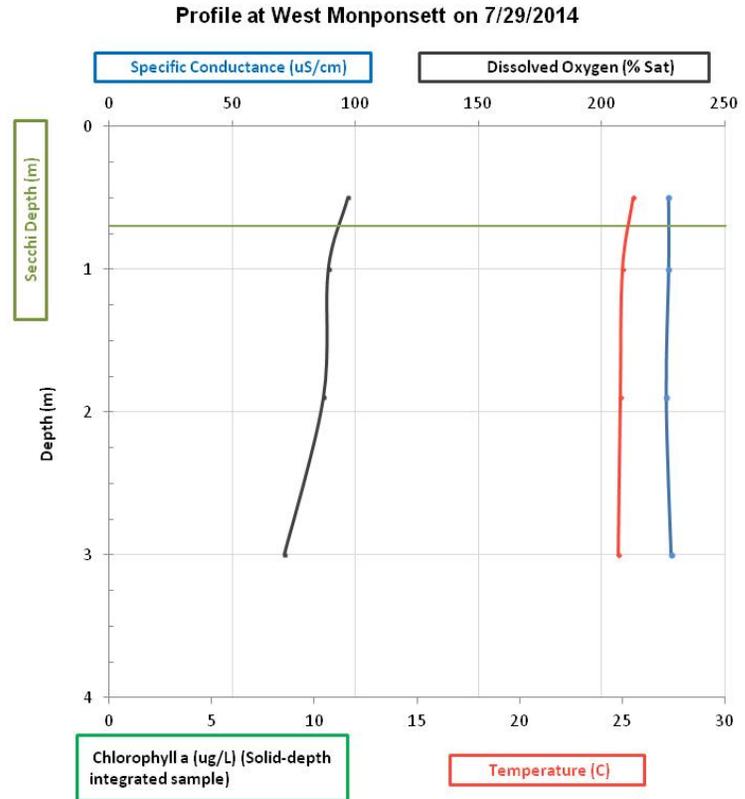
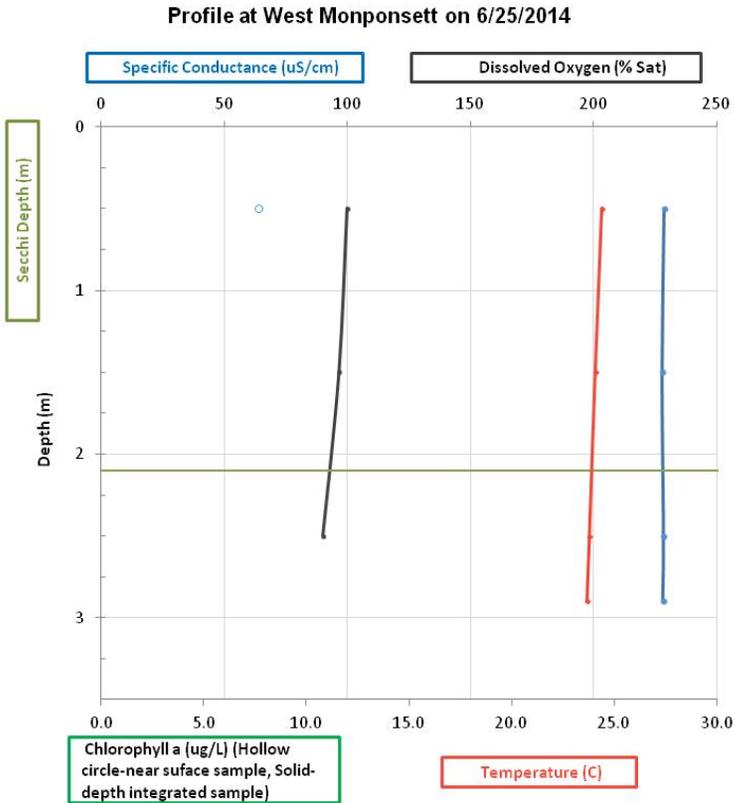
**Figure C 12: Stetson Pond DO Profile August 2015 (left) and Stetson Pond DO Profile Sept. 2015 (right)**



**Figure C 13: East Monponsett Pond DO Profile June 2014 (left) and East Monponsett Pond DO Profile July 2015 (right)**



**Figure C 14: East Monponsett Pond DO Profile August 2014(left) and East Monponsett DO Profile Sept. 2014 (right)**



**Figure C 15: West Monponsett Pond DO Profile June 2014 (left) and West Monponsett Pond DO Profile July 2014 (right)**

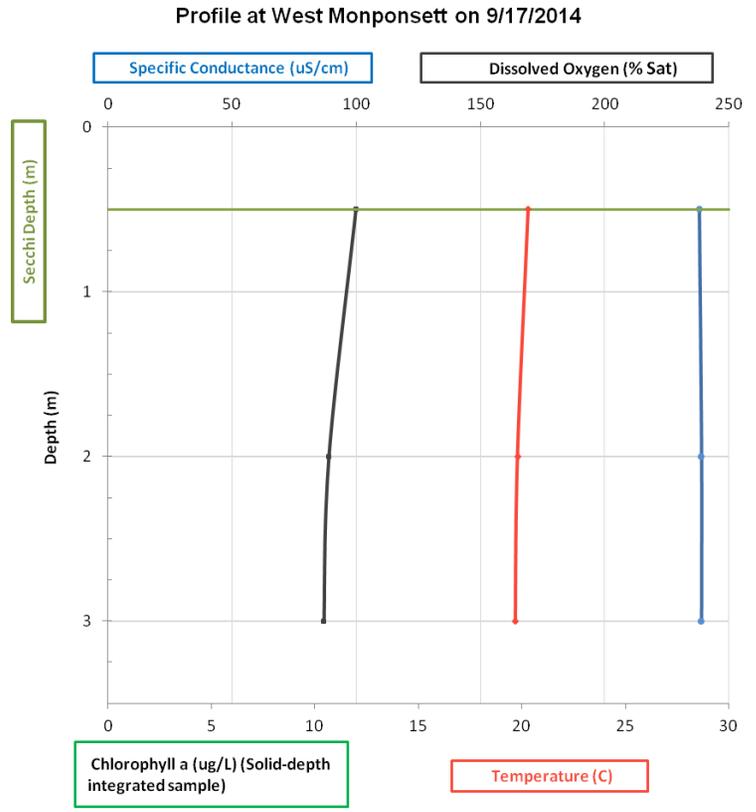
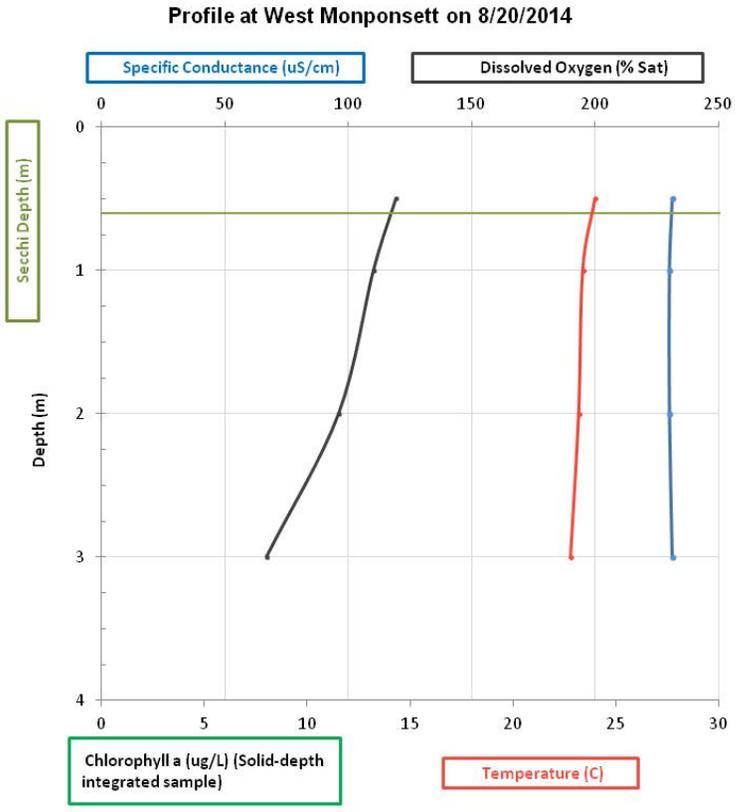
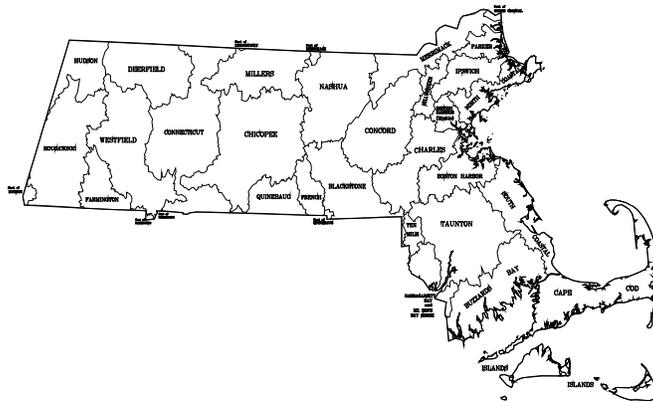


Figure C 16: West Monponsett Pond DO Profile August 2014 (left) and West Monponsett Pond DO Profile Sept. 2014 (right)

## Appendix D. Guidelines for Total Maximum Daily Loads of Phosphorus from Commercial Cranberry Bog Discharges in Massachusetts.

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MassDEP TM-T-1, CN307.0, DWM February 9, 2009



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## Introduction

The purpose of this document is to evaluate available information on the operation of commercial cranberry bogs in relation to discharges of nutrients, particularly phosphorus, into sensitive receiving waters such as freshwater lakes. The current operation of water use and fertilizer use is summarized to estimate the annual discharge of phosphorus from commercial bogs. In addition, the available information from the literature is summarized to establish new Best Management Practices for both water use, reuse and discharge as well as phosphorus fertilizer rates that are expected to result in receiving waters attaining all relevant Water Quality Standards.

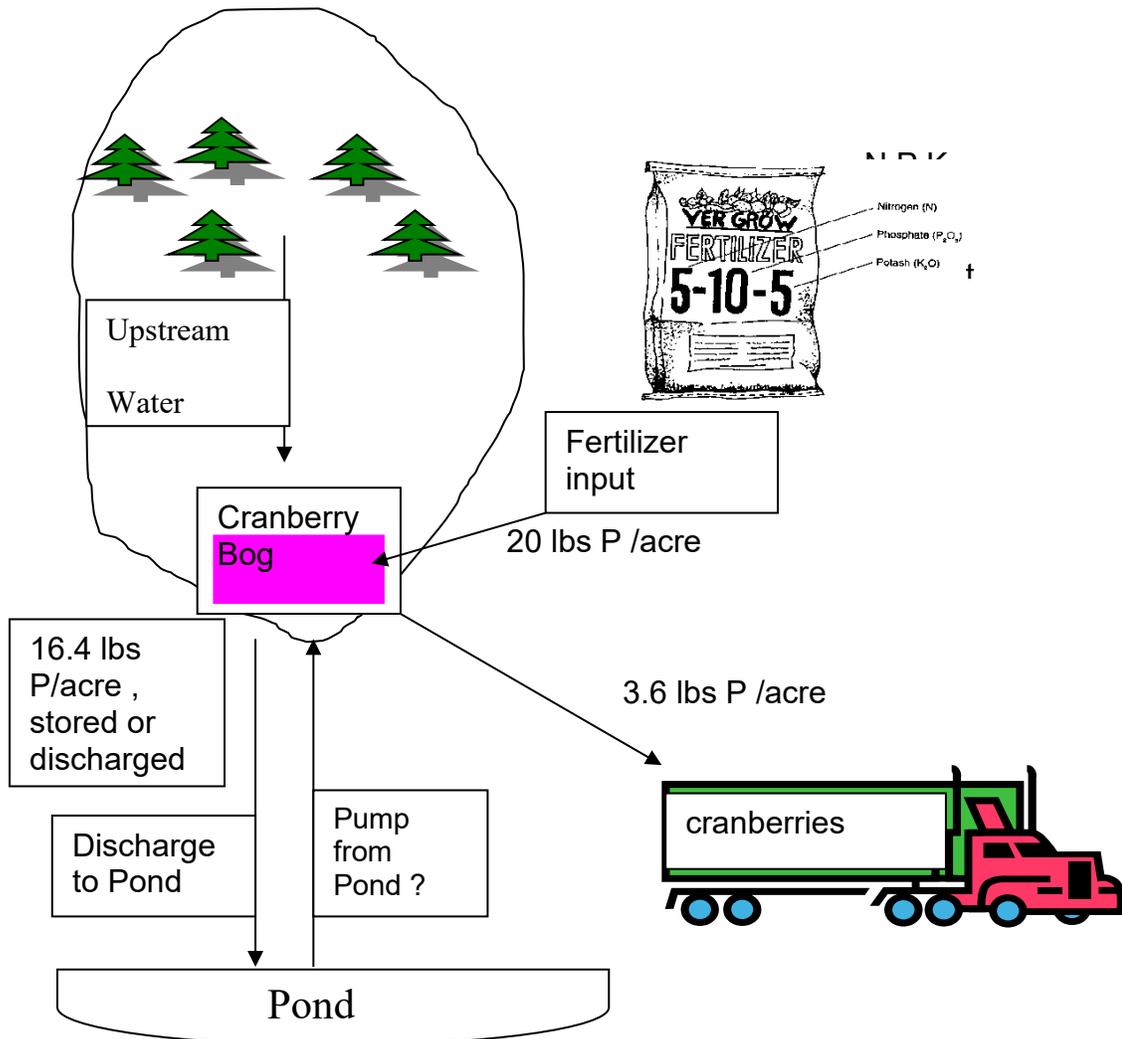
Commercial cranberry production is a major crop in southeastern Massachusetts. The cranberry is a native wetland plant (*Vaccinium macrocarpon*) that is planted into bogs and fertilized like other crops. But unlike other crops, cranberries require frequent irrigation and seasonal flooding. The discharge of waters from the bogs, from excessive rain or groundwater inputs, return flows from irrigation during the growing season or due to discharge of the flood waters allows nutrients such as phosphorus and nitrogen, to be discharged from the bogs to nearby or downstream surface waters. It is this large discharge of nutrient rich water that is a concern to local water quality because the nutrient can stimulate the growth of nuisance aquatic plants and algae.

Currently, many of the large recreational lakes in southeastern Massachusetts are impaired by various combinations of nutrients, noxious aquatic plants (includes algae), turbidity (due to algae blooms) and impairments of low dissolved oxygen and organic enrichment. Many of these lakes receive large discharges of water from nearby commercial bogs and these lakes are listed in the Massachusetts 2006 Integrated list (MassDEP, CN 262.1, 2007; <http://www.mass.gov/dep/water/resources/2006il4.pdf>) as impaired (Category 5) under Section 303d of the Federal Clean Water Act: New Bedford Reservoir in Acushnet, Noquochoke Lake in Dartmouth, Parker Mills Pond and Tihonet Pond in Wareham, White Island Pond and Billington Sea in Plymouth and Wareham, Furnace Pond and Stetson Pond in Pembroke, Wampatuck Pond in Hanson, Lower Mill Pond, Upper Mill Pond and Walkers Pond in Brewster, Santuit Pond in Mashpee, West Monponsett Pond in Halifax/Hanson.

According to the Federal Clean Water Act, the state must develop allowable nutrient budgets or Total Maximum Daily Loads (TMDLs) for these waters such that they fully support all designated uses. In addition to these there are numerous streams and coastal embayments downstream of the bogs that are also listed as impaired by nutrients. Many of the smaller lakes and streams in the region have not been assessed but may be threatened by excess nutrients because they are also located near the discharge areas of the commercial bog operations. Similar problems with lake eutrophication have been seen in Wisconsin (the leading producer of cranberries) where cranberry production was implicated as the major source of nutrients (Garrison and Fitzgerald, 2005). This report reviews the operation of the bogs and reviews the literature on fertilizer use and nutrient export from commercial bogs and natural wetlands and provides guidance for the development of total phosphorus Total Maximum Daily Loads for freshwater lakes.

## Background on Commercial Bog Operations

Historically, commercial cranberry bogs were created over natural wetlands, but natural wetlands have been protected since the development and revisions of the Wetlands Protection Act in Massachusetts between 1963-1972. Any new commercial bogs created in Massachusetts since that time are required to be constructed in upland areas by grading the land level and adding sand as the plant bed. A series of dikes, ditches, pumps and flumes allows for periodic flooding and sand is added to the beds as a rooting medium. Water enters as rainfall and is pumped in for frequent irrigation. In some cases surface water runoff, a natural stream or groundwater seepage may add additional water to the bogs and is also discharged as needed (i.e., a flow-through bog; see Figure 1). The fall harvest occurs by flooding the bogs to allow the berries to be knocked loose and float into collection areas. After harvest the water is discharged to nearby surface waters. Flooding also occurs temporarily during winter to allow ice formation to protect vines from freezing. Flooding may also occur at other times for insect control. Typically, commercial cranberry bogs require about 10 acre-feet of water, including rainfall, each year for combined irrigation and flooding purposes (DeMoranville and Howes, 2005).



## Figure 1. Schematic Diagram of a Phosphorus Budget for a Cranberry Bog.

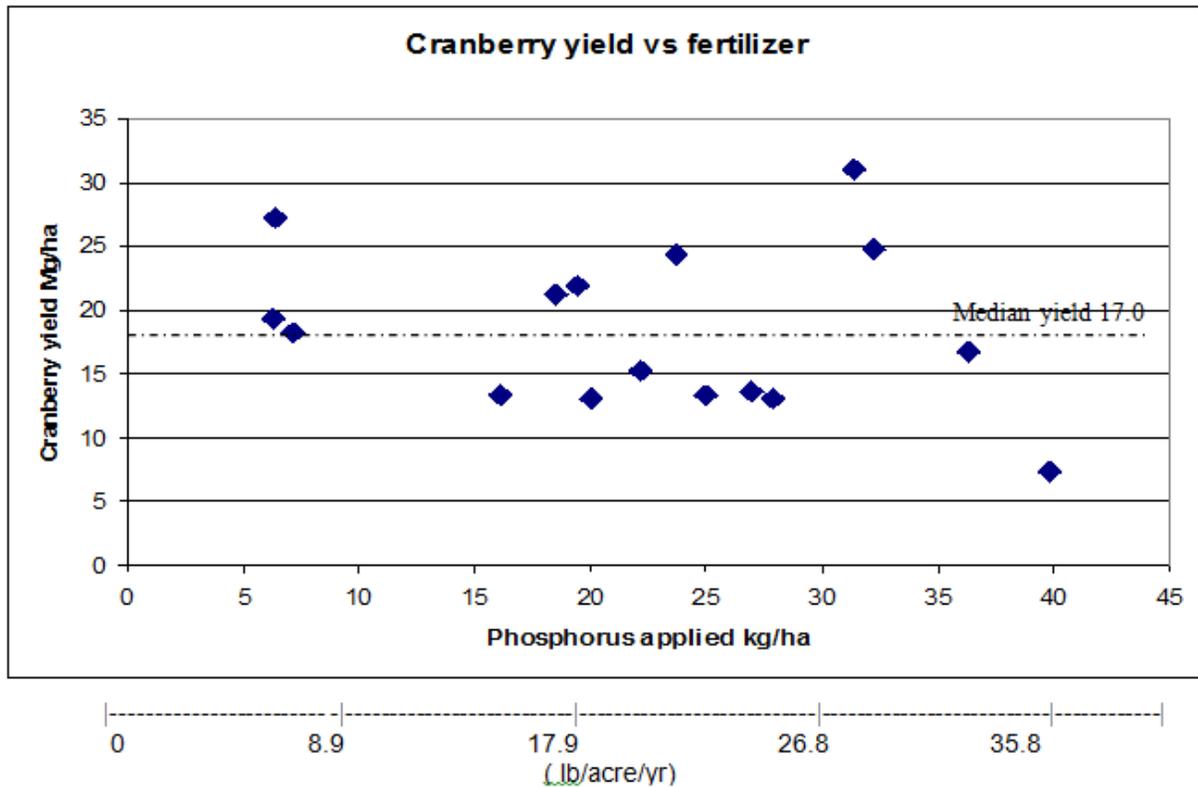
Up until recently, the recommended phosphorus fertilizer inputs for traditional cranberry bogs has been 20 pounds per acre per year, according to the University of Massachusetts Cranberry Station publications <http://www.umass.edu/cranberry/services/bmp/phosphorus.shtml> although higher rates are recommended in some cases. The Best Management Practices are under review by the University and by MassDEP. Typical commercial bogs often use higher rates than the recommended 20 lbs/ac/yr (22.4 kg/ha/yr) as shown in Table 16 in DeMoranville and Howes, (2005). In that study, half of the bogs were applying phosphorus fertilizer at rates of 31 to 45 lbs P/ac/yr (27.9-39.8 kg/ha/yr) in the first year of the study. These rates are similar to a study of a nearby bog where the rates of phosphorus fertilizer application were 29.2 lb P/ac/yr (Howe and Teal, 1995). The harvest of berries and associated leaves and twigs removes about 3.6 pounds of phosphorus per acre each year (DeMoranville and Howes, 2005). If a bog were fertilized at the recommended rate (20 lbs/ac/yr) it implies that 16.4 pounds per acre (18.3 kg/ha/yr) are potentially available for buildup in the soil or for downstream export (see Figure 1). Over many years of excess phosphorus application soils are expected to become saturated with excess phosphorus and may start to export more phosphorus over time.

### Review of Fertilizer Application and Crop Yield

Several lines of evidence are available on the phosphorus fertilizer requirements of cranberries. As noted in Roper et al., 2004, a number of early studies had identified that 22 kg/ha/yr (20 lbs/acre/yr) was sufficient for commercial cranberry operations, but the studies did not examine if lower fertilizer rates would also be sufficient. More recent studies in Massachusetts have found that yields of cranberry are not very responsive to phosphorus in fertilizer at any rate, presumably because of over fertilization in past years has built up a supply of phosphorus in the cranberry soils. These studies include the recent whole bog studies as well as smaller, but more detailed plot studies in Massachusetts (DeMoranville and Howes, 2005; DeMoranville, 2006) which found no reduction in cranberry yield as phosphorus was lowered to less than 20 lbs/acre/year and in some cases yields increased with lower or even no phosphorus applied at all. In the Eagle Holt bog fertilizer rates were reduced to 16.1 kg/ha and 6.3 kg/ha (14.3 lb/ac and 5.6 lb/ac) in 2003 and 2004, respectively, and yields actually increased by 31 percent over the previous two years (DeMoranville and Howes, 2005). The average yield for all six bogs in the first two years was 135 bbl/acre/yr, but the yield actually increased to 155 bbl./acre/yr during the next 2 years as fertilizer was reduced on the six bogs studied by DeMoranville and Howes (2005). The final recommendations of the DeMoranville and Howes (2005) study was that 20 lbs/acre/year of phosphorus fertilizer are sufficient and that typical native cranberries on organic soils may have lower targets of 10-15 lbs/acre/year unless tissue tests show deficiency (<0.1% in August).

An extended multiyear study of four of the experimental bogs also showed that the three lowest phosphorus fertilizer rates below 10 kg/ha/yr (averaging about 6 lb/ac/yr) produced cranberry yields greater than the median of all the treatments (Figure 2). These results are supported by recent work of Parent and Marchand (2006) who found there were year-to-year differences and site-to-site differences in cranberry production but found there was no benefit to adding phosphorus on the yield of cranberries in a Quebec study. Additional studies on plots have

shown there was no justification for using high phosphorus fertilizers to increase yields . Even the zero phosphorus plots showed no signs of deficiency after 6 years of study (Roper, 2009).



**Figure 2. Cranberry yield vs. Fertilizer Rates (Data from DeMoranville et al., 2009).**

### Export of Phosphorus from Commercial Cranberry Bogs

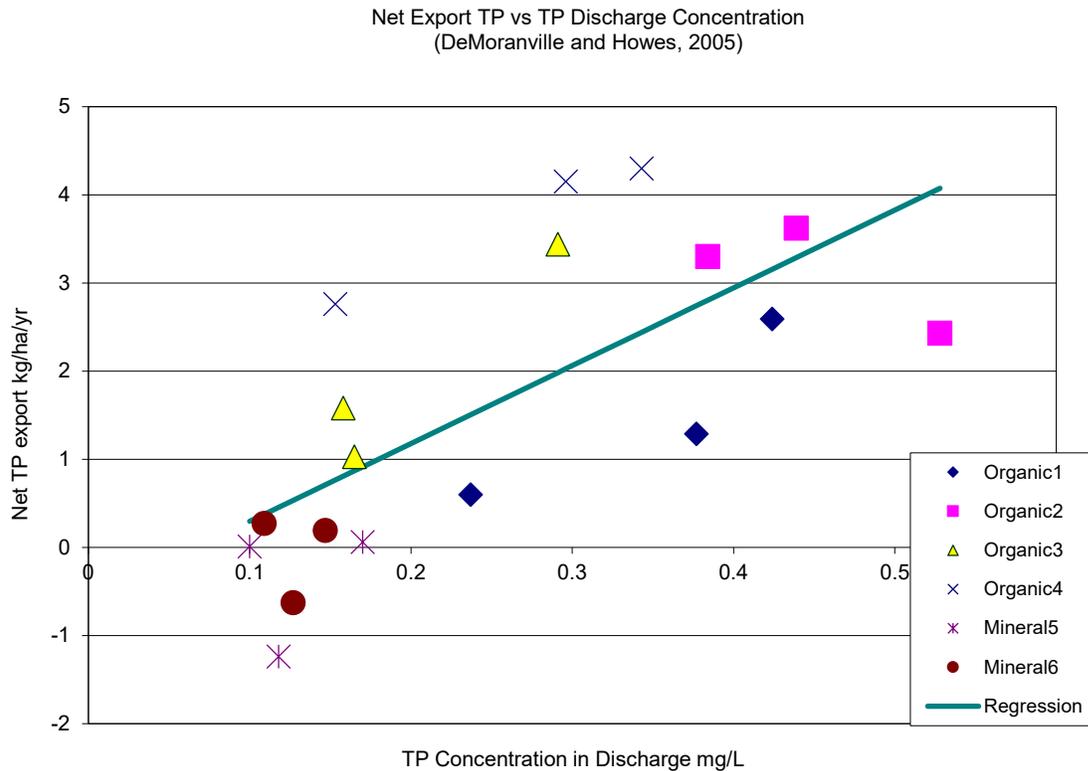
There have been two recent studies on nutrient export from commercial cranberry bogs in Massachusetts. The first study (Howes and Teal, 1995), focused on a flow-thru bog while the second study (DeMoranville and Howes, 2005), was more extensive and included varying fertilizer rates, and measuring cranberry yields along with both net and gross export of nutrients from six commercial bogs over several years. Much of the following discussion will focus on the more recent study (DeMoranville and Howes, 2005).

The bogs studied by DeMoranville and Howes (2005) showed variation in export related to soil type and fertilizer rates. The two upland bogs on mineral soils (Mineral 5 and 6 in Figure 3) with essentially no discharges other than harvest discharges had total phosphorus concentrations equal to or less than 100 ppb in discharge water, with resulting low export rates of about 0.5 kg/ha/yr. The four organic bogs studied by DeMoranville and Howes (2005), were established bogs on organic (wetland) soils with periodic discharges during the growing season as well as during

harvest or winter floods. These bogs tend to have concentrations of phosphorus between 15 and 50 ppb in the discharge water and tend to discharge about 3 kg/ha/yr (see Figure 3, Organic 1-4). The median of the organic bog net discharge in the first year (prior to major reductions in fertilizer application) was 3.4 kg/ha/yr and is the best estimate of typical organic cranberry bog export in Massachusetts. Because the total discharge of water (per unit area) was similar from the series of six bogs there is a linear relationship between the net discharge of phosphorus from the bogs and the concentration of phosphorus in the discharge water (Figure 3). Lacking other information the net export from bogs can be estimated from the average total phosphorus concentration as shown in Figure 3 as: net export (kg/ha/yr) =  $-0.59 + 8.83 * \text{Conc. (mg/l)}$ , N=18,  $r^2=0.47$ ,  $\alpha=0.001$ . The flow-thru bog was reported to export large amounts of phosphorus (9.9 kg/ha/yr) with the major discharge events having phosphorus concentrations averaging 530 ppb (0.53 mg/l) during winter floods (Howes and Teal, 1995). Recent studies on commercial cranberry bogs have shown that reduced phosphorus fertilizer application did not suppress the yield of cranberries, rather yields increased while reducing TP concentrations in discharge water (DeMoranville et al., 2009).

Much of the phosphorus exported from the bogs is associated with flood discharges. In particular, flood waters held for more than about 10 days leads to anoxia and the release of phosphorus (DeMoranville and Howes, 2005).

Export of total phosphorus from natural wetlands and forested watersheds was also reviewed by DeMoranville and Howes (2005). The literature suggests that freshwater wetlands such as beaver ponds, peat soil wetlands, and wetlands bordering streams export between 0.41 kg/ha/year and 0.68 kg/ha/year (median of 0.47 kg/ha/yr), while cypress swamps and tidal saltwater marshes export higher amounts. The forested wetland system in Westport Massachusetts had a gross export of 0.14 to 0.15 kg/ha/yr of phosphorus. This is in general agreement with a review of phosphorus export from various land uses that indicates forests export an average of 0.236 kg/ha/yr, while row crops export an average of 4.46 kg/ha/yr (Reckhow et al., 1980). Thus, the overall mean fluvial export of 1.65 and 3.02 kg/ha/yr (net and gross, respectively) reported for commercial cranberry bogs by DeMoranville and Howes (2005) indicates cranberries export much larger amounts of phosphorus than forests or typical freshwater wetlands, but generally export less than agricultural row crops. Note that net fluvial phosphorus exports are lower than gross fluvial exports if the bogs are using source water with high concentrations of phosphorus. Flow-through bogs may export higher amounts of phosphorus than most row crops (Howes and Teal, 1995).



**Figure 3. Net TP Export vs. TP Concentration.**

### Lake Nutrient Budgets

Nutrient budgets for impaired lakes require knowledge of nutrient export from local sources including point sources (discharges from pipes or other discrete sources as well as various land uses that discharge nonpoint source pollution). This report examines nutrient budgets from commercial cranberry operations within Massachusetts as diagramed in Figure 1. Nutrient budgets are typically presented both as net budgets and as gross discharge budgets and as ‘fluvial budgets’. The nutrient budgets measure (or estimate) all nutrients entering the bog and all nutrients leaving the bog as shown in the schematic diagram below. Generally, the two major nutrient inputs to a bog are nutrients in the irrigation water and nutrient in the fertilizers. The two major nutrient losses from a bog are nutrients discharged in released water, and nutrients in plant materials harvested from the bog (berries as well as leaves and twigs). From a water quality standpoint we are most interested in the ‘fluvial budget’, that is, the amount of nutrients delivered to a lake via natural water inputs compared to the additional nutrients in discharge water that enter the bog due to commercial bog operations. Other imports to the bogs (such as fertilizers) and exports from the bog, such as phosphorus in the crop of cranberries, are accounted for outside of the fluvial budget in the total budget.

From a lake water quality point of view there are two general types of bogs and associated nutrient budgets to consider: autochthonous nutrient sources and allochthonous nutrient sources. First, where the source of bog irrigation and floodwater is a tributary to the receiving pond or is

the receiving pond itself (autochthonous), the most appropriate nutrient flux is the net fluvial nutrient budget. In such bogs the original nutrients in the irrigation and flood waters was either in the lake or would have entered the lake in the absence of bog operations. In that case, the nutrients in the input source water are subtracted from the fluvial outputs to calculate the net difference. In other words the extra amount of nutrients entering the pond due to the cranberry bog operation is the net fluvial export from the bog. Corrections may be required if the source water is polluted from previous discharges from the same bog. The second case would be a bog that gets irrigation and flood water from an outside water source (allochthonous), that is, from a source that normally would not enter the receiving pond. Typically this is a groundwater well or stream or source pond that is not tributary to the receiving pond. In this case the gross fluvial export is calculated as the input to the receiving pond, because the input to the pond includes both the nutrients from the bog as well as nutrients in the original source water. The nutrients from both the water as well as nutrients derived from fertilizers are new inputs to the bog as a result of management operations.

### **Target loads and nutrients to maintain water quality standards.**

The Massachusetts Water Quality Standards 314CMR4.05 <http://www.mass.gov/dep/service/regulations/314cmr04.pdf>) state conditions for best available technology (BAT) for point and nonpoint sources including publicly owned treatment works (POTWs) and other sources:

Unless naturally occurring, all surface waters shall be free from nutrients in concentrations that would cause or contribute to impairment of existing or designated uses and shall not exceed the site specific criteria developed in a TMDL or as otherwise established by the Department pursuant to 314 CMR 4.00. Any existing point source discharge containing nutrients in concentrations that would cause or contribute to cultural eutrophication, including the excessive growth of aquatic plants or algae, in any surface water shall be provided with the most appropriate treatment as determined by the Department, including, where necessary, highest and best practical treatment (HBPT) for POTWs and BAT for non POTWs, to remove such nutrients to ensure protection of existing and designated uses. Human activities that result in the nonpoint source discharge of nutrients to any surface water may be required to be provided with cost effective and reasonable best management practices for nonpoint source control.

In addition, water withdrawals are regulated under the Water Management Act regulations <http://www.mass.gov/dep/service/regulations/310cmr36.doc>. These regulations allow for registration and/or permitting of water withdrawals for cranberry operations including regulations regarding water conservation, water quality, farming practices and reporting requirements to protect other water uses. Water withdrawals may be established under nonconsumptive use which means any use of water which results in its being discharged back into the same water source at or near the withdrawal point in substantially unimpaired quality and quantity.

As a general guideline, concentrations should not exceed 50 ppb in any stream entering a lake or pond (USEPA, 1986). The USEPA has issued guidance for water quality nutrient concentrations

of total phosphorus of 31 ppb l for rivers in southeastern Massachusetts (USEPA, 2000; [http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/rivers/rivers\\_14.pdf](http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/rivers/rivers_14.pdf).)

The lakes in southeastern Massachusetts may be considered as belonging to two general types: lakes with tributaries and seepage lakes with no tributaries. The seepage lakes are fed mainly by groundwater and direct precipitation and tend to be more oligotrophic, clear water lakes. Some seepage lakes are set in organic soils that may contribute dissolved organic compounds that color the water, and this may result in higher phosphorus levels. The clear water seepage lakes are thus more sensitive to nutrient inputs and generally should have lower total phosphorus concentrations. Clearwater seepage lakes in southeastern Massachusetts may reasonably be expected to have concentrations of total phosphorus of less than 20 ppb and possibly as low as 8 ppb (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013; USEPA, 2001; [http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/lakes\\_14.pdf](http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/lakes_14.pdf)).

Thus, inputs from external sources must be limited to meet the state's Water Quality Standards and to protect designated uses. The nutrient management requirements to meet Water Quality Standards may vary depending on the receiving water but at a minimum, discharges should not exceed the EPA guideline of 100 pb for streams and the 50 ppb for tributaries to lakes. By way of comparison, current National Pollutant Discharge Elimination System (NPDES) permits for typical wastewater treatment plant discharges in Massachusetts are set at 100 ppb in the discharges to sensitive receiving waters. Extensive Best Management Practices may be required in order to ensure receiving waters meet the state's Water Quality Standards.

### **Best Management Practices Protective of Water Quality**

The data from the six commercial cranberry bogs studies in the DeMoranville and Howes (2005) study was further analyzed to examine the relationship of fertilizer rates on cranberry yields, concentrations of phosphorus in discharge waters and downstream export of nutrients. The data indicate that if most protective BMPs recommended by DeMoranville and Howes (2005) are followed, export of phosphorus from commercial bogs can be reduced with little or no impact on crop yields.

For bogs that discharge to sensitive surface waters some combination of the following BMPs may be required. Specifically, no more phosphorus than the lower range of fertilizer rates of 10-15 lbs/acre/year recommended by DeMoranville and Howes (2005) may be required. In addition, the recommended best management of water use (using tailwater or retention ponds to remove phosphorus prior to discharge, holding floodwater 1-3 days, but less than 10 days, with slow discharge and winter flood control to minimize flood holding times to avoid anoxia) may be required. Fertilizers with ratios of N:P<sub>2</sub>O<sub>5</sub> of greater than 1:1 and preferably 2:1 such as commercial 18-8-12 or 12-6-8 may be required. If discharges are to a sensitive clear water seepage bog the additional BMPs recommended by DeMoranville and Howes (2005) of installing tailwater recovery or other physical barriers or filtration may be required to meet water quality standards.

If the recommended phosphorus fertilizer rates of 10-15 lb/acre/year are followed the data suggest commercial cranberry bogs will achieve net fluvial discharges of less than 1 kg/ha/year.

This can typically be achieved if total phosphorus concentrations in discharge waters are at or below 0.1 mg/l (Figure 3) and/or, if increase in phosphorus concentration between source water to discharge water is held to an increase of no more than 0.032mg/l (assuming 10 acre feet of water use and no reuse of source water). If the discharge is to sensitive waters then lower export rates may be required. A discharge of 0.5 kg/ha/yr (higher than forests but lower than row crops) may be required and this could be achieved if discharge concentrations follow than the EPA 'Gold Book' (EPA, 1986) guidelines of 0.050mg/l for discharges to lakes and discharge volumes are limited to 3.3 acre-feet per acre bog per year or less. Bogs discharging to less sensitive waters may be able to discharge 5 acre-feet or more as long as net nutrient loading rates are kept low by reuse of water or other BMPs.

## References

- DeMoranville, C.J. and B. Howes. 2005. Phosphorus dynamics in cranberry production systems: Developing the information required for the TMDL Process for 303D waterbodies receiving cranberry bog discharge. MassDEP 01-12/319. UMass Amherst Cranberry Station, E. Wareham, MA and UMass Dartmouth SMAST, New Bedford, MA. 137pp.
- DeMoranville, C.J. 2006. Cranberry Best Management Practice Adoption and Conservation Farm Planning. *HortTechnology* 16(3):393-397.
- DeMoranville, C., B. Howes, D. Schlezinger and D.White. 2009. Cranberry Phosphorus Management: How changes in practice can reduce output in drainage water. *Acta Hort* 810: 633-640.
- Garrison, P.J. and S.A. Fitzgerald. 2005. The role of shoreland development and commercial cranberry farming in a lake in Wisconsin, USA. *J. Paleolimnology* 33(2): 169-188.
- Howes, B.L. and J.M. Teal. 1995. Nutrient Balance of a Massachusetts Cranberry Bog and Relationships to Coastal Eutrophication. *Environmental Sci. & Tech.* 29(4):960-974.
- Parent, L.E. and S. Marchand. 2006. Response to Phosphorus of Cranberry on High Phosphorus Testing Acid Sandy Soils. *Soil Sci. Soc. Am. J.* 70:1914-1921.
- Reckhow, K.H., M.N. Beaulac, and J.T. Simpson. 1980. Modeling phosphorus loading and lake response under uncertainty: A manual and compilation of export coefficients. EPA 44/5-80-011. USEPA, Washington DC. 214pp.
- Roper, T.R. 2009. Mineral Nutrition of Cranberry: What we know and what we thought we knew. *Acta Hort.* 810:613-625.
- USEPA. 1986. Quality Criteria for Water 1986. United States Environmental Protection Agency, Washington, DC. EPA 440/5-86-001. (AKA "Gold Book").

USEPA. 2000 Ambient Water Quality Recommendations. Rivers and Streams in Nutrient Region XIV. United States Environmental Protection Agency, Washington, DC. EPA 822-B-00-022. [http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/rivers/rivers\\_14.pdf](http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/rivers/rivers_14.pdf)

USEPA. 2001 Ambient Water Quality Recommendations. Lakes and Reservoirs in Nutrient Region XIV. United States Environmental Protection Agency, Washington, DC. EPA 822-B-00-022. [http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/lakes\\_14.pdf](http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/lakes_14.pdf)

## **Appendix E: Monponsett Pond TMDL Modeling Documentation**

**COMMONWEALTH OF MASSACHUSETTS**  
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MATTHEW A. BEATON, SECRETARY  
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**BUREAU OF WATER RESOURCES**  
DOUGLAS FINE, ASSISTANT COMMISSIONER

October 2017

Stormwater Section Revised August 2019

CN 455.5.1

# **Monponsett Pond TMDL Modeling Documentation**

## **Introduction and Background**

The Monponsett Pond system which includes Stetson Pond, White Oak Reservoir, East Monponsett Pond and West Monponsett Pond is located in Southeast Massachusetts. A TMDL has been written for the four ponds in this system. A number of impairments have been identified in this system principally related to nutrient enrichment and specifically phosphorus loads. The TMDL was written to reduce phosphorus loading in this system and to restore all uses associated for the pertinent waterbodies. A principal restoration goal was West Monponsett Pond which has experienced harmful algal blooms in recent years.

The City of Brockton was allowed to use Silver Lake as it's water supply as far back as 1899. In 1964 the Massachusetts Legislature approved Act 371 to further allow a diversion from East Monponsett Pond to Silver Lake to supplement the water supply with some restrictions. Diversions occur generally only in the fall, winter and spring between October and June. During times of diversion the natural flow direction under the culvert between the ponds may be reversed. There are local concerns that the potentially toxic cyanobacterial blooms and excess nutrients in West and East Monponsett will flow into Silver Lake and the altered hydrology may impact both West and East Monponsett Pond as well as their downstream outlet, Stump Brook (Princeton Hydro, 2013; Horsley Witten, 2015). In addition, the diversion from Silver Lake results in only brief outflows to the Jones River (Princeton Hydro, 2013). As a result of hydrologic diversions the Jones River itself is listed as impaired on the 303d list of impaired waters.

East Monponsett Pond is diverted to Silver Lake, which is used by the City of Brockton for use as a public water supply (Figure 1). West Monponsett Pond is connected to East Monponsett Pond by a culvert under Route 58. When water is pumped from East Monponsett Pond to Silver Lake, water flows into East Monponsett Pond from West Monponsett Pond. Both ponds are highly influenced by both their surrounding landuse and the pond's use as a source of public water supply. The ponds use as a public water supply affects both their hydrology and consequently water quality. The high levels of total phosphorus (TP) result in excessive algal growth and impair designated uses of the waters. The federal Clean Water Act requires that such waters be listed on the 303d list in Category 5 (impaired) and that a Total Maximum Daily Load report be developed and submitted to the EPA. The modeling approach and implementation in this report follow the previously approved TMDL for White Island Pond (MassDEP 2010a).

## **Water Quality Model**

The purpose of the MassDEP modeling effort was to quantify the principal sources of phosphorus loading in this system and to determine the maximum allowable total phosphorus loads to the ponds in this system. The Lake Loading Response Model (LLRM) is a spreadsheet based model which allows the estimation of hydrologic input and nutrient inputs as well as allowing estimation of atmospheric deposition, septic loads, point source loads, internal loading and loading from waterfowl (AECOM 2009). This model was chosen as it provides a reasonable estimation of nutrient loads and requires less time, effort and expertise than more complex models (SWAT, BASINS, HSPF).

The watershed is described in “Watershed and Lake Characterization” of the TMDL. USGS StreamStats (USGS 2015) was used to delineate individual subbasins for streams and artificial flow paths. The StreamStats derived watersheds were then adjusted so that they did not overlap each other. In addition the StreamStats derived watersheds were adjusted so they did not extend beyond the GeoSyntec (2015) pond watersheds. The delineated watersheds are presented in Figure 2. Using the MassGIS Landuse (2005) data layer and a GIS system the landuse in the TMDL study area was analyzed. For land use analysis by subwatershed see Appendix A.

### **Scope and Approach for Model**

Annual precipitation from the Plymouth weather station for 2001, 2003 and 2008-2014 (years in which MassDEP sampled in the TMDL study area) were analyzed. The average annual precipitation for the period examined was 55.74 inches. This is slightly higher than the average annual rainfall in Plymouth of 52.36 inches. This annual average is similar to the 52.8 inches used in Horsley Witten (2015). Precipitation coefficients for each landuse were set at 50% in order to obtain a water yield of 26.2 inches per year. Only total flow was estimated in the LLRM model. Flows were not split between runoff flows and base flows.

The year 2009 was chosen as the target year for the LLRM model calibration for the entire Monponsett Pond system as this was before recent alum treatments in West Monponsett Pond. The year 2009 appears to have been typical for both yearly and summer precipitation (Figure 1) and therefore a good choice for modeling the system in terms of average water and phosphorus loading. The model was calibrated based on 2009 in-pond total phosphorus concentration for East and West Monponsett Pond as well as White Oak Reservoir.

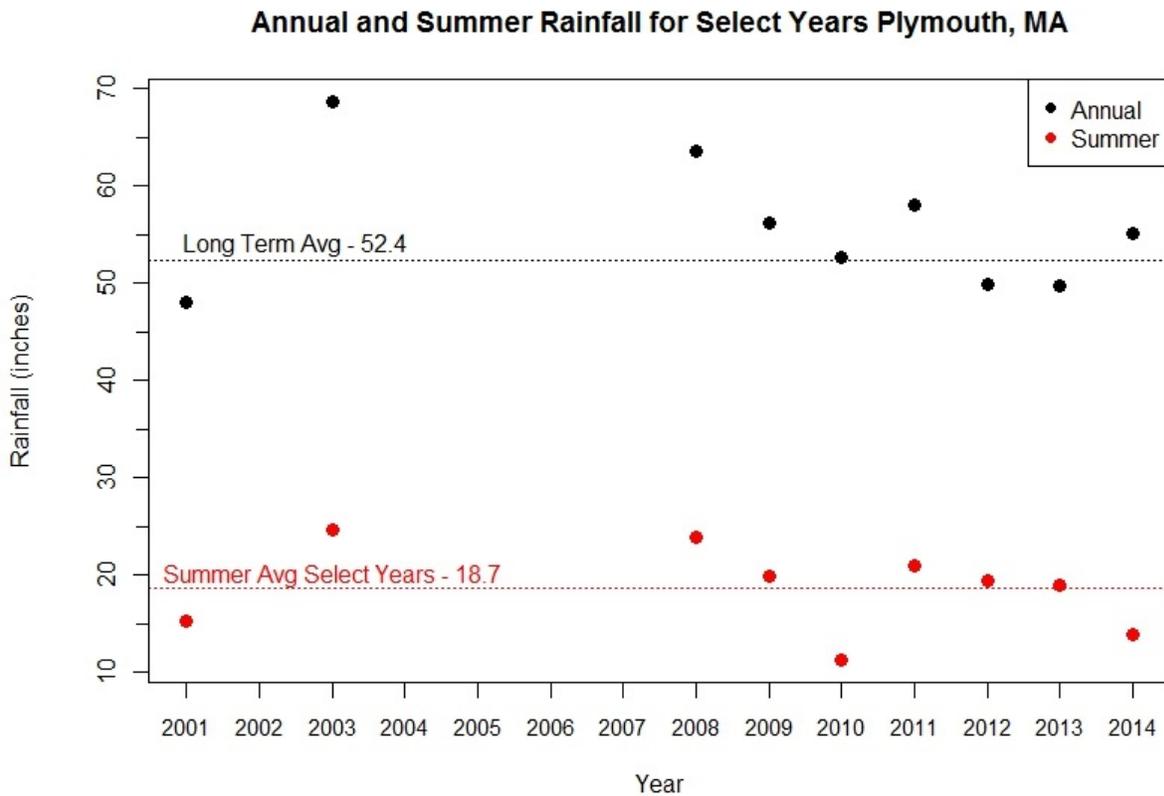


Figure 1: Annual and Summer Rainfall for Select Years Plymouth, MA (National Climatic Data Center 2016)

### Quality of Acquired Data

MassDEP has conducted water quality sampling in the TMDL study area for several years. A summary of the principal in-pond sampling data by years and the quality control status of the data see Table 1. For an overview of MassDEP data validation see MassDEP 2012. Recently acquired data that is considered “draft” in the quality control process was reviewed and checked before use in this TMDL and any modeling activity. No data were excluded from analysis due to quality control or quality assurance issues. Sampling of tributary streams by MassDEP and Lycott Environmental Inc. was conducted for validation of the LLRM model (2007).

Water Body	Sampling Site	Sampling Years	QC Status
Stetson Pond	W1086	2003, 2015	QC5, draft
East Monponsett Pond	W0930	2001, 2009, 2010, 2011, 2012, 2013, 2014, 2015	2001 and 2009 to 2012 - QC4, 2013 Lab and Attended Data - QC4, 2014 Attended Data QC4 (rest draft), 2015 draft
West Monponsett Pond	W0926	2001, 2009, 2010, 2011, 2012, 2013, 2014, 2015	2001 and 2009 to 2012 - QC4, 2013 Lab and Attended Data - QC4, 2014 Attended Data QC4 (rest draft), 2015 draft
White Oak Reservoir	W2173	2010, 2012, 2013, 2015	2010 & 2012 - QC4, 2013 Lab and Attended Data - QC4, 2015 draft

Table 1: MassDEP sampling by year and QC status for principal sampling stations

### Description of Model

The LLRM model is a mass balance type model. Required inputs are estimates of rainfall, nutrient loading, internal loading, point source loading, atmospheric deposition and other nutrient inputs. This model has been used in several TMDL studies in New England (AECOM 2009b, AECOM 2011, FB Environmental Associates, 2014). The model is documented in AECOM (2009a). The LLRM model is a spreadsheet model using Microsoft Excel software.

### Model Configuration

The LLRM model was applied to a delineated watershed for the TMDL study area. The principal model inputs are estimated hydrologic inputs for the water budget, nutrient inputs by subwatershed and other nutrient loading estimates. The general pattern of flow in this system is described in Figure 1. The equations that predict in-pond phosphorus concentrations rely on a steady state condition. The goal of the TMDL is to model the overall nutrient budget for this system so a steady state model and assumptions are satisfactory. Another key assumption of the calibration or base scenario model run as part of the TMDL process was that only water contributions from East and West Monponsett Ponds watersheds would go to each pond, respectively. No flow was modeled from East to West. Previous modeling efforts (Princeton Hydro, LLC, 2013) indicated that the volume of water withdrawn for water supply was equal to the total annual water yield to East Monponsett Pond as well as a portion of the annual hydrologic loading of water to West Monponsett Pond. Flows were not split between runoff flows and base flows.

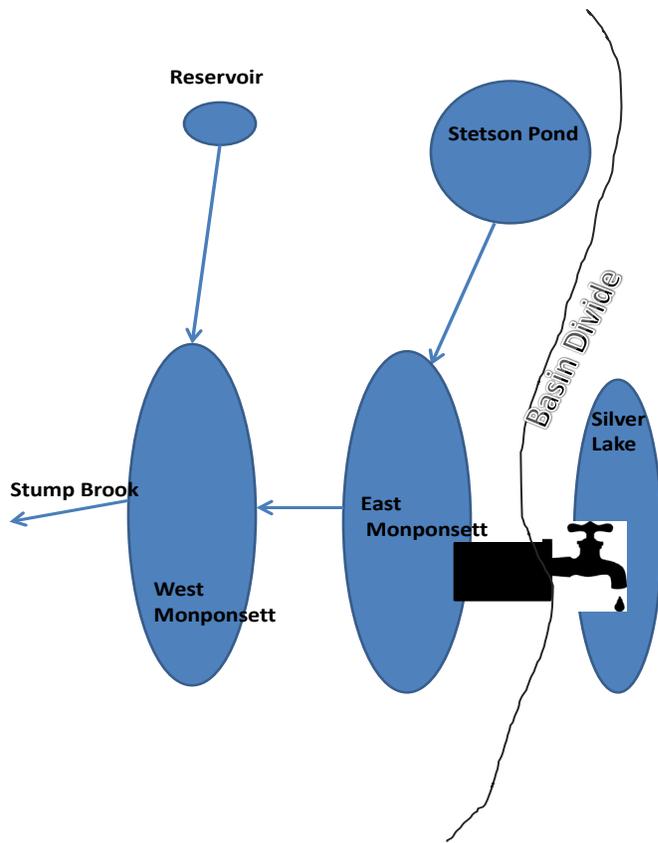


Figure 1: Model Schematic Showing Flow Patterns in TMDL study Area

### Watershed Delineations

In consultation with the GIS department at MassDEP, watersheds for each pond in the TMDL study area were obtained based on the work of Geosyntec (2015). Using a GIS system these watersheds were then adjusted to match the Taunton River watershed basin as appropriate. USGS StreamStats (USGS 2015) was used to delineate individual subbasins for streams and artificial flow paths. The StreamStats derived watersheds were then adjusted so that they did not overlap each other. In addition the StreamStats derived watersheds were adjusted so they did not extend beyond the Geosyntec (2015) pond watersheds. The delineated watersheds are presented in Figure 2. It is important to note that these watersheds are based on surface topology and may not reflect complex groundwater flow patterns that may exist in the study area.

## Model Load Inputs

### Landuse Analysis

Landuse in the delineated watersheds was analyzed based on the MassGIS Landuse (2005) datalayer. The landuses were then aggregated into logical categories for modeling purposes (Table 2). As part of landuse analysis, an investigation into current cranberry bog activities was conducted. An inventory of cranberry bog land use was created and in consultation with the MassDEP Southeast Regional Office (McLaughlin 2016) the current status of the cranberry bogs (active, inactive etc.) was determined (Figure 3). The Edgewood Bogs LLC located in the Stetson Pond watershed were abandoned in 2008 while the Gary S. Thorp Bogs in the unnamed tributary 2 watershed to the West Monponsett Pond were abandoned in 2006. The Elko Construction Bogs located in the White Oak Reservoir watershed were abandoned in 1994. For the purposes of nutrient loading modeling the abandoned bogs were given their own landuse category, “abandoned cranberry bog”. Based on MassDEP sampling which found elevated total phosphorus in samples from tributaries in the Swamp C and Peterson Swamp watersheds, the MassGIS landuse categories “Forested Wetland” and “Non-forested Wetland” were retained for modeling purposes. For a more detailed analysis of land use see MassDEP 2016, Appendix A.

### Parameterization (calibration) Input

The major parameterization (calibration) dealt with assigning land use export coefficients for phosphorus (see Table 3). Using the measured in-pond total phosphorus concentrations, these coefficients values were iteratively optimized to provide the best fit between predicted in-pond total phosphorus concentrations and measured in-pond concentrations in all four ponds simultaneously. The White Island Pond TMDL (MassDEP 2010) and the work of Mattson (2015) helped provide estimates of total phosphorus loading from cranberry bog areas which made up almost the entirety of the High Intensity Agriculture land use category. Based on MassDEP sampling in Stetson Brook, Swamp C tributary and the Peterson Swamp tributary where total phosphorus concentrations ranged from 0.032 mg/l to 0.098 mg/l, phosphorus export coefficients for the two major wetland landuse types, forested wetland and non-forested wetland were assigned. The forested wetland landuse category was assigned a phosphorus export coefficient of 0.40 kg/ha/yr while the non-forested wetland category was assigned a value of 0.30 kg/ha/yr. Although in-stream phosphorus values were elevated in some of the tributaries, especially the Peterson Swamp tributary, there is some uncertainty as to the water load from these areas. During sampling some of the tributaries were noted to be stagnant. The atmospheric deposition was estimated to be 0.2 kg TP/ha/yr based on the median value from the reference variables worksheet associated with the LLRM model.

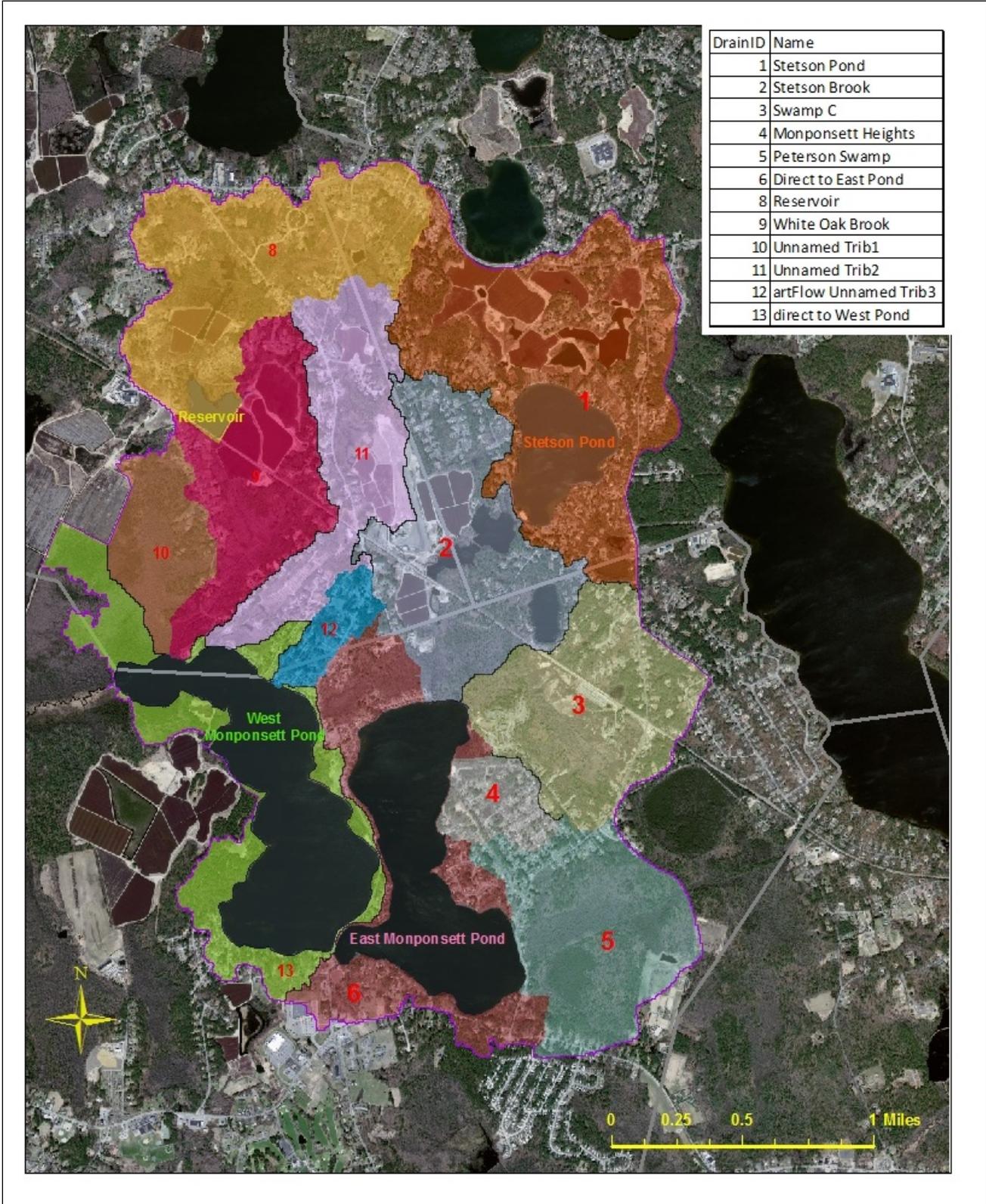


Figure 2. Watersheds in the TMDL study area.

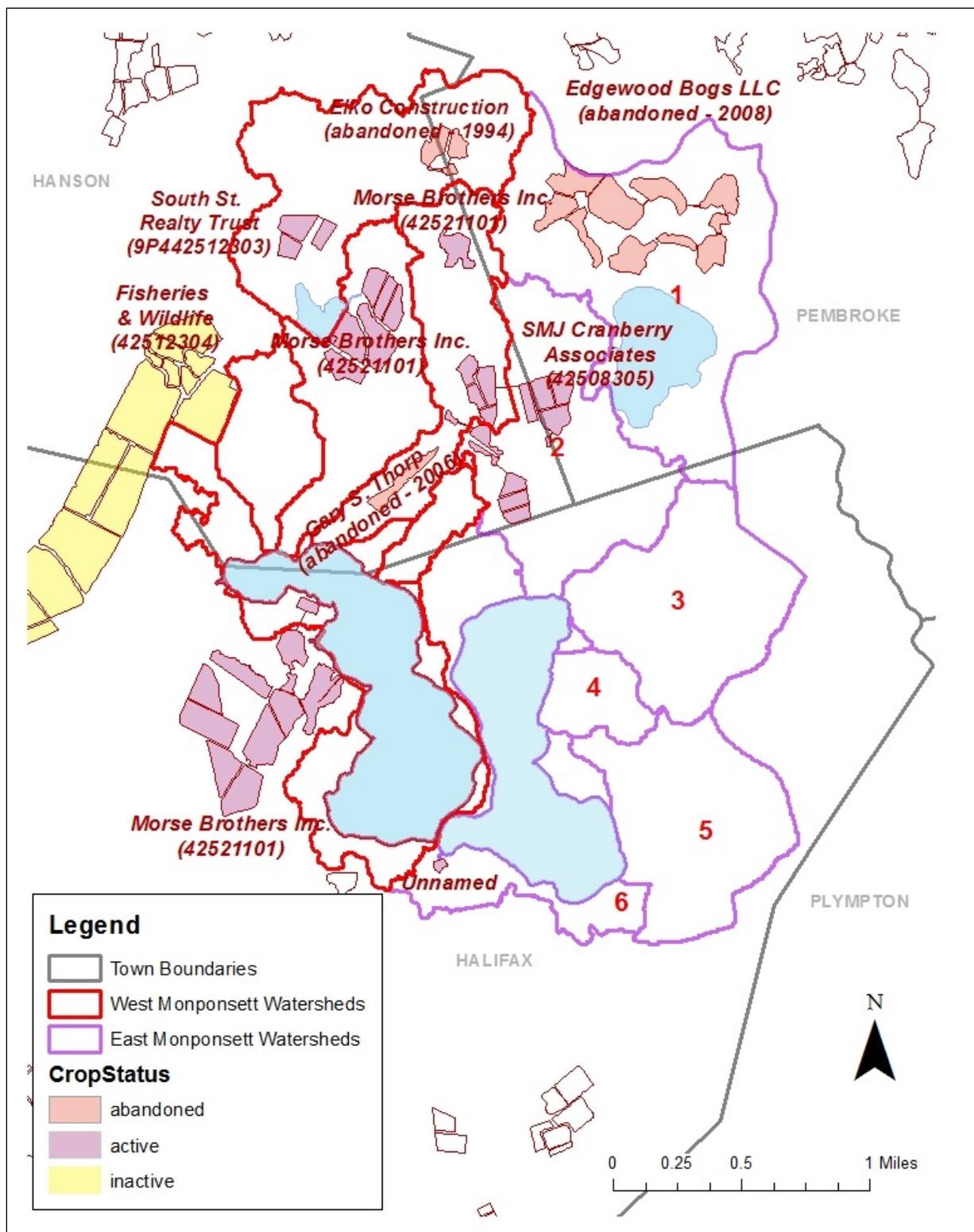


Figure 3. Cranberry Bogs and their Status in TMDL study area (if active water withdrawal Water Management Act (WMA) # in parenthesis)

Table 2: Mapping of MassGIS 2005 Landuse Categories to Aggregated Groups for Modeling

MassGIS 2005 Description Land Use	TMDL Grouping	EPA Designation Stormwater P Load Calculations
Brushland / Successional	Natural	Forest
Commercial	High Intensity Development	Commercial
Cranberry Bog	High Intensity Ag. (bog)	Agriculture
Cranberry Bog	Abandoned Cranberry Bog	Agriculture
Cropland	Medium Intensity Agriculture	Agriculture
Forest	Natural	Forest
Forested Wetland	Forested Wetland	Forest
High Density Residential	Medium Intensity Development	High Density Residential
Industrial	High Intensity Development	Industrial
Low Density Residential	Low Intensity Development	Low Density Residential
Medium Density Residential	Medium Intensity Development	Medium Density Residential
Multi-Family Residential	Medium Intensity Development	High Density Residential
Non-Forested Wetland	Non-Forested Wetland	Forest
Nursery	Low Intensity Agriculture	Agriculture
Open Land	Open	Open Land
Participation Recreation	Medium Intensity Development	Open Land
Pasture	Low Intensity Agriculture	Agriculture
Transitional	Low Intensity Development	Commercial
Transportation	Medium Intensity Development	Highway
Urban Public/Institutional	Medium Intensity Development	Open Land
Very Low Density Residential	Low Intensity Development	Low Density Residential
Water	Water	Water

The landuse export coefficients used in this study are within reasonable ranges and generally within ranges detailed in the LLRM model and Reckhow (1980). The ranges for some development landuse categories are slightly lower than the median values found in the LLRM. Lower export coefficients are believed to be warranted given the importance of groundwater in the TMDL study and attenuation. It is expected that given the sandy glacial soils in the study, high infiltration and low soil nutrient content should act to reduce pollutant loading. BEC (1993) found using their export coefficients overestimated loading to Stetson Pond and used a groundwater and surface water export model. In order to more reasonably approach both tributary and in-pond total phosphorus concentrations, landuse export coefficients slightly lower than median values found in the LLRM reference variables were used.

Grouping	TP (kg/ha/yr)	LLRM ranges*(kg/ha/yr)	Reckhow (1980) (kg/ha/yr) ranges**
Natural	0.10	0.02 - 0.83	0.019 – 0.830
Low Intensity Agriculture	0.64	0.1 - 2.9	0.1 – 2.90
Medium Intensity Agriculture	1.50	0.14 - 4.9	0.14 – 4.90
High Intensity Agriculture	4.30	0.29 - 18.6	0.29 - 18.6
Forested Wetland	0.40	0.02 - 0.83	--
Non-Forested Wetland	0.30	0.02 - 0.83	--
Low Intensity Development	0.30	0.19 - 6.3	0.19 – 2.7
Medium Intensity Development	0.50	0.19 - 6.3	0.88 – 1.7
High Intensity Development	1.00	0.19 - 6.3	0.56 – 1.1
Open	0.00	0.02 - 0.83	--
Water	0.00	0.02 - 0.83	--
Abandoned Cranberry Bog	0.10	--	--

Table 3: Landuse Categories and Assigned Total Phosphorus Export Coefficients

\*comparison based on most relevant LLRM landuse categories (note some LLRM ranges are based on Reckhow 1980)

\*\* comparison based on most relevant landuse in Reckhow (1980) export coefficients compilation

## Stormwater

Stormwater loadings was estimated using an analysis which included MassGIS landuse classifications (MassGIS 2005), analysis of directly connected impervious areas and hydrologic soil group classifications as well as individual TP export loading rates by landuse for directly connected impervious area and for pervious areas as provided by Table 1-2 in Appendix F of the 2016 Massachusetts MS4 permit.

For each watershed the impervious area (MassGIS 2007) was intersected with the MassGIS landuse classification and directly connected impervious area percentages and loadings were calculated using EPA methodology (EPA 2010). Soil survey information for the TMDL study area was downloaded from Natural Resources Conservation Service web soil survey (Survey Staff, National Resources Conservation Service, 2018). The downloaded soils data was accessed with the use of NRCS Soil Data Viewer Software ArcMap add-in and the HSG classification was rated using the dominant condition aggregation method. MassGIS landuse classifications were summarized according to the MA Stormwater Permit, Appendix F, Attachment 1, Table 1-3. The landuse in areas without impervious surface was then intersected with hydrologic soil group

information from the NRCS web soil survey. In areas without a soil classification, the dominant soil classification for that landuse and watershed was assigned. Soil classifications that were split were assigned the first soil rating classification. The stormwater load from pervious areas was then calculated using the total phosphorus loading factors in Table 4 below for each landuse and hydrological soil group classification. Specifically the area for each landuse and hydrological soil group in Table 4 for each subwatershed was multiplied by the appropriate pervious landuse TP export rate (Table 4).

<b>Land Use &amp; Cover<sup>1</sup></b>	<b>TP (lb/acre/year)</b>	<b>TP (kg/hectare/yr)</b>
AGRICULTURE, HSG A	0.45	0.50
AGRICULTURE, HSG B	0.45	0.50
AGRICULTURE, HSG C	0.45	0.50
AGRICULTURE, HSG D	0.45	0.50
AGRICULTURE, IMPERVIOUS	1.52	1.70
COMMERCIAL, HSG A	0.03	0.03
COMMERCIAL, HSG B	0.12	0.13
COMMERCIAL, HSG C	0.21	0.24
COMMERCIAL, HSG D	0.37	0.41
COMMERCIAL, IMPERVIOUS	1.78	2.00
FOREST, HSG A	0.12	0.13
FOREST, HSG B	0.12	0.13
FOREST, HSG C	0.12	0.13
FOREST, HSG D	0.12	0.13
FOREST, HSG IMPERVIOUS	1.52	1.70
HIGH DENSITY RESIDENTIAL, HSG A	0.03	0.03
HIGH DENSITY RESIDENTIAL, HSG B	0.12	0.13
HIGH DENSITY RESIDENTIAL, HSG C	0.21	0.24
HIGH DENSITY RESIDENTIAL, HSG D	0.37	0.41
HIGH DENSITY RESIDENTIAL, IMPERVIOUS	2.32	2.60
HIGHWAY, HSG A	0.03	0.03
HIGHWAY, HSG B	0.12	0.13
HIGHWAY, HSG C	0.21	0.24
HIGHWAY, HSG D	0.37	0.41
HIGHWAY, IMPERVIOUS	1.34	1.50
INDUSTRIAL, HSG A	0.03	0.03
INDUSTRIAL, HSG B	0.12	0.13
INDUSTRIAL, HSG C	0.21	0.24
INDUSTRIAL, HSG D	0.37	0.41
INDUSTRIAL, IMPERVIOUS	1.78	2.00

Land Use & Cover <sup>1</sup>	TP (lb/acre/year)	TP (kg/hectare/yr)
LOW DENSITY RESIDENTIAL, HSG A	0.03	0.03
LOW DENSITY RESIDENTIAL, HSG B	0.12	0.13
LOW DENSITY RESIDENTIAL, HSG C	0.21	0.24
LOW DENSITY RESIDENTIAL, HSG D	0.37	0.41
LOW DENSITY RESIDENTIAL, IMPERVIOUS	1.52	1.70
MEDIUM DENSITY RESIDENTIAL, HSG A	0.03	0.03
MEDIUM DENSITY RESIDENTIAL, HSG B	0.12	0.13
MEDIUM DENSITY RESIDENTIAL, HSG C	0.21	0.24
MEDIUM DENSITY RESIDENTIAL, HSG D	0.37	0.41
MEDIUM DENSITY RESIDENTIAL, IMPERVIOUS	1.96	2.20
OPEN LAND, HSG A	0.03	0.03
OPEN LAND, HSG B	0.12	0.13
OPEN LAND, HSG C	0.21	0.24
OPEN LAND, HSG D	0.37	0.41
OPEN LAND, IMPERVIOUS	1.52	1.70
WATER, HSG	0	0.00
<sup>1</sup> MassGIS landuse category assigned per Appendix F, Attachment 1, Table 1-3 2016 MA MS4 Permit,; HSG = Hydrologic Soil Group		

Table 4: Landuse Categories and Assigned Total Phosphorus Export Coefficients for DCIA and pervious areas (per 2016 MA MS4 permit, Appendix F, Attachment 1, Table 1-2).

The total DCIA load and pervious stormwater load by watershed was calculated (Table 5). Except for Stetson Pond all stormwater loads were less than the calculated TMDL watershed load. For Stetson Pond this discrepancy is likely explained by the fact that the agricultural areas in this watershed are largely abandoned cranberry bogs and not active operations. The pervious agriculture TP export coefficient of 0.50 kg/hectare/yr (Table 4) is likely an overestimate in this watershed and 0.1 kg/hectare/yr TP was used as a more appropriate estimate. A crosswalk between the modeled watershed loading landuse groupings (Table 3) and EPA MA MS4 landuse groupings (EPA 2016, Appendix F, Attachment 1, Table 1-3) for each MassGIS landuse code was then constructed to allow the determination of stormwater loads for each modeled watershed loading landuse grouping.

As described above the total modeled watershed loading was calculated for each watershed. On occasion the calculated total stormwater load was greater than the modeled watershed load for a given modeled watershed landuse grouping, therefore for the purposes of the stormwater wasteload allocation (WLA) in the TMDL, the entirety of the modeled watershed load was assigned to the wasteload allocation for stormwater.

The calculated stormwater loads and the assigned stormwater wasteload allocation for Stetson Pond, East Monponsett Pond, White Oak Brook Reservoir and West Monponsett Pond can be found in Tables 6, 7, 8 and 9 respectively.

Watershed	DCIA TP Load (kg/yr)	Pervious TP Load (kg/year)	Total Stormwater TP Load <sup>1</sup> (kg/year)	Modeled TP Watershed Load (kg/yr)
Stetson Pond	18.0	33.1	51.0	44.1
East Monponsett	73.3 <sup>1</sup>	83.7 <sup>1</sup>	157.0 <sup>2</sup>	276.9
White Oak Reservoir	19.9	21.5	41.4	75.1
West Monponsett	54.8 <sup>2</sup>	74.8 <sup>2</sup>	129.6 <sup>3</sup>	344.6
Grand Total				740.7

1- Total Stormwater Load is the sum of the DCIA TP Load (column 1) and Pervious TP Load (column 2)

2- Includes unattenuated loads from Stetson Pond

3- Includes unattenuated loads from White Oak Reservoir

Table 5: Total Stormwater Load as the sum of DCIA TP Load and Pervious TP Load

(report continued next page)

TMDL Grouping	DCIA TP Load (kg/year)	Pervious TP Load (kg/year)	Total Stormwater Load <sup>1</sup> (kg/year)	Modeled Watershed Load (kg/yr)	Current Stormwater Waste Load (kg/yr) <sup>2</sup>
Forested Wetland	0.0	0.5	0.5	1.6	0.5
High Intensity Ag. (bog)	0.0	20.9	20.9 <sup>3</sup>	4.4	4.4
High Intensity Development	0.0	0.0	0.0	0.0	0.0
Low Intensity Agriculture	0.1	0.6	0.7	0.9	0.7
Low Intensity Development	8.5	1.6	10.1	16.3	10.1
Medium Intensity Development	8.9	0.6	9.6	13.2	9.6
Natural	0.2	8.1	8.3	6.3	6.3
Non-Forested Wetland	0.0	0.6	0.6	1.3	0.6
Open	0.3	0.1	0.4	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0
<b>Grand Total</b>					<b>32.2</b>

1- Total Stormwater Load is the sum of the DCIA TP Load (column 1) and Pervious TP Load (column 2)

2- The TMDL Stormwater WLA is the Total Stormwater Load or the Modeled Watershed Load, whichever is less.

3- Stormwater Load from pervious agriculture areas likely overestimate as majority of agricultural area is abandoned cranberry bogs

Table 6: Stormwater Loads for Stetson Pond

TMDL Grouping	DCIA TP Load (kg/year)	Pervious TP Load (kg/year)	Total Stormwater Load <sup>1</sup> (kg/year)	Stetson Attenuated Total Stormwater Load (kg/year)	Total Stormwater Load Included Attenuated Stetson Pond Stormwater Load (kg/yr)	Modeled Watershed Load (kg/yr)	Current Stormwater Waste Load (kg/yr) <sup>2</sup>
Forested Wetland	0.0	13.1	13.1	0.5	13.7	40.4	13.7
High Intensity Ag. (bog)	0.0	10.2	10.2	3.4	13.6	103.4 <sup>3</sup>	13.6
High Intensity Development	6.8	0.2	7.0	0.0	7.0	8.6	7.0
Low Intensity Agriculture	0.1	2.9	3.0	0.5	3.5	4.7	3.5
Low Intensity Development	13.2	3.0	16.2	7.8	24.0	37.5	24.0
Medium Intensity Development	38.3	2.5	40.8	7.4	48.2	53.5	48.2
Natural	0.5	23.9	24.4	4.9	29.3	23.3	23.3
Non-Forested Wetland	0.0	2.0	2.0	0.5	2.5	5.6	2.5
Open	0.6	0.2	0.8	0.0	0.8	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Grand Total</b>							<b>135.8</b>

- 1- Total Stormwater Load is the sum of the DCIA TP Load (column 1) and Pervious TP Load (column 2)
- 2- The TMDL Stormwater WLA is the Total Stormwater Load or the Modeled Watershed Load, whichever is less.
- 3- Includes the attenuated load from abandoned cranberry bogs in Stetson Pond  
(note all values rounded to the nearest tenth of a kilogram/yr)

Table 7: Stormwater Loads for East Monponsett Pond

TMDL Grouping	DCIA TP Load (kg/year)	Pervious TP Load (kg/year)	Total Stormwater Load <sup>1</sup> (kg/year)	Modeled Watershed Load (kg/yr)	Current Stormwater Waste Load (kg/yr) <sup>2</sup>
Forested Wetland	0.0	3.0	3.0	8.9	3.0
High Intensity Ag. (bog)	0.0	5.9	5.9	32.7	5.9
High Intensity Development	6.1	0.2	6.3	5.2	5.2
Low Intensity Agriculture	0.0	0.1	0.1	0.1	0.1
Low Intensity Development	11.1	4.4	15.4	17.0	15.4
Medium Intensity Development	2.7	0.4	3.1	3.1	3.1
Natural	0.1	6.3	6.3	4.8	4.8
Non-Forested Wetland	0.0	1.3	1.3	2.9	1.3
Water	0.0	0.0	0.0	0.0	0.0
<b>Grand Total</b>					<b>38.7</b>

1- Total Stormwater Load is the sum of the DCIA TP Load (column 1) and Pervious TP Load (column 2)

2- The TMDL Stormwater WLA is the Total Stormwater Load or the Modeled Watershed Load, whichever is less.  
(note all values rounded to the nearest tenth of a kilogram/yr)

Table 8: Stormwater Loads for White Oak Reservoir

TMDL Grouping	DCIA TP Load (kg/yr)	Pervious TP Load (kg/yr)	Total Stormwater Load <sup>1</sup> (kg/yr)	White Oak Reservoir WLA	Total Stormwater Load Including White Oak Reservoir WLA (kg/yr)	Modeled Watershed Load (kg/yr)	Current Stormwater Waste Load (kg/yr) <sup>2</sup>
Forested Wetland	0.0	11.3	11.3	3.0	14.3	42.6	14.3
High Intensity Ag. (bog)	0.0	20.0	20.0	5.9	25.9	198.7 <sup>3</sup>	25.9
High Intensity Development	2.2	0.2	2.3	5.2	7.5	7.7	7.5
Low Intensity Agriculture	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Low Intensity Development	10.2	2.4	12.6	15.4	28.0	33.8	28.0
Medium Intensity Development	22.2	1.9	24.1	3.1	27.1	34.7	27.1
Natural	0.3	13.6	13.9	4.8	18.7	15.3	15.3
Non-Forested Wetland	0.0	4.0	4.0	1.3	5.3	11.8	5.3
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Grand Total</b>							<b>123.5</b>

- 1- Total Stormwater Load is the sum of the DCIA TP Load (column 1) and Pervious TP Load (column 2)
- 2- The TMDL Stormwater WLA is the Total Stormwater Load or the Modeled Watershed Load, whichever is less.
- 3- Includes the load from abandoned cranberry bogs  
(note all values rounded to the nearest tenth of a kilogram/year)

Table 9: Stormwater Loads for West Monponsett

## Internal Loading

MassDEP sampling in 2015 found hypoxia in Stetson Pond below a depth of 6 meters. Based on an estimated area below 6 meters of approximately 3.8 hectares and a sediment release rate of 2 mg/m<sup>2</sup>/day for a period of 90 days, an estimated internal load of approximately 6.9 kg/yr was calculated for Stetson Pond. MassDEP sampling in White Oak Reservoir did not indicate internal loading was a source for total phosphorus therefore no internal load was estimated.

The internal load in West Monponsett Pond was estimated based on MassDEP sediment core sampling and laboratory incubation of the cores with oxic headspace lake water in September 2010 (MassDEP 2010c) following the methods of Nowlin et al., (2005). The average phosphorus loading from the set of four cores was found to be approximately 1.57 mg/m<sup>2</sup>/day (median 1.67). Using this areal phosphorus release rate over a period of 150 days for the entire surface of the pond, yielded an internal load of 293 kg/year. This may be an underestimate because West Monponsett Pond does become anoxic during rare periods of calm conditions and phosphorus release may be much higher at those times. Between 2009 and 2015 MassDEP conducted 24 dissolved oxygen profiles at the deep hole in West Monponsett Pond (Site ID W0926) between the months of May and September. On five occasions the dissolved oxygen was below 1 mg/l at the near bottom sampling depth, indicative of anoxia. Low dissolved oxygen at depth often occurred in the months of August and September, likely due to high phytoplankton biomass and warmer water temperatures often seen during these months.

For the East Monponsett Pond no sediment cores were taken with which to estimate internal loading directly. MassDEP estimated the internal loading to be 30 kg/yr using an estimated phosphorus release of 1 mg/m<sup>2</sup>/day affecting approximately 25 hectares of the lake for 120 days. A lower phosphorus release rate was chosen for East Monponsett Pond given the fact it has historically had a lower in pond total phosphorus concentrations.

## Septic Systems

In order to estimate septic system loading to each pond the number of houses within 100 feet of each water body and between 100 and 300 feet was estimated using a GIS system with orthophotos and parcel data (Table 10). For septic system loads, an average of 2.5 people per dwelling, a water use of 0.25 cubic meters per day per person and an effluent concentration of 8 mg/l and a phosphorus attenuation factor of 0.1 was used. An example of septic system loading calculations for East Monponsett Pond is provided in Table 11.

# Houses	Stetson Pond	East Pond	White Oak Reservoir	West Pond
within 100 feet	59	89	0	71
between 100 and 300 feet	44	73	6	80

Table 10: Estimate of Septic Systems near ponds in TMDL study area

**DIRECT SEPTIC  
SYSTEM LOAD**

Septic System Grouping (by occupancy or location)	Days of Occupancy/Yr	Distance from Lake (ft)	Number of Dwellings	Number of People per Dwelling	Water per Person per Day (cu.m)	P Conc. (ppm)	P Attenuation Factor	Water Load (cu.m/yr)	P Load (kg/yr)
Group 1 Septic Systems	365	<100	89	2.5	0.25	8	0.1	20303	16.2
Group 2 Septic Systems	365	100 - 300	73	2.5	0.25	8	0	16653	0.0
Totals								36956	16.2

Table 11: Estimated Septic Load for East Monponsett Pond

**Load Routing**

As part of the model, loads must be routing through different subbasins for each pond as appropriate. In the model each basin on the left of the spreadsheet passes into another basin in a column to the right is labeled with a 1. A zero value is otherwise the default. Each basin passes through itself so the first row in the Table 9 below is 1. So for example Stetson Pond (Basin 1) passes into Stetson Brook which then passes into East Monponsett Pond (Table 12). Routing was conducted similarly for all the ponds in this TMDL.

**ROUTING PATTERN**

1=YES 0=NO  
XXX=BLANK

(Basin in left hand column passes through basin in column below if indicated by a 1)

	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6
	Stetson Pond (CU.M/YR)	Stetson Brook (CU.M/YR)	Swamp C (CU.M/YR)	Monponsett Heights (CU.M/YR)	Peterson Swamp (CU.M/YR)	Direct To East Pond (CU.M/YR)
INDIVIDUAL BASIN	1	1	1	1	1	1
BASIN 1 OUTPUT	XXX	1	0	0	0	0
BASIN 2 OUTPUT	0	XXX	0	0	0	0
BASIN 3 OUTPUT	0	0	XXX	0	0	0
BASIN 4 OUTPUT	0	0	0	XXX	0	0
BASIN 5 OUTPUT	0	0	0	0	XXX	0
BASIN 6 OUTPUT	0	0	0	0	0	XXX
BASIN 7 OUTPUT	0	0	0	0	0	0
BASIN 8 OUTPUT	0	0	0	0	0	0
BASIN 9 OUTPUT	0	0	0	0	0	0
BASIN 10 OUTPUT	0	0	0	0	0	0

Table 12 Water Routing for East Monponsett Pond subwatersheds

**Load Routing and Attenuation**

Water load attenuation and phosphorus attenuation largely did not play a significant factor in this modeling effort. A small amount of attenuation was estimated for Stetson Pond. Based on a

predicted in-pond total phosphorus concentration 19.4 ppb and a measured concentration of 15 ppb, a 22.5% attenuation was estimated. Similarly 35% water load attenuation was estimated for Peterson Swamp given the large portion of wetlands in its watershed and to more closely match measured in-stream concentrations. In general this modeling effort relied on parameterizing land use export coefficients throughout the study area and not on subwatershed specific attenuation factors to bring loading into balance with measured conditions.

### Estimated Watershed Loads

The landuse export coefficients for phosphorus were based on ranges presented in Reckhow et al., 1980 and default values used in the LLRM model with some exceptions as noted below. Using the phosphorus export coefficients determined as part of the calibration of the LLRM model (Table 3), the watershed loads for each of the ponds in the TMDL study area were estimated. The high intensity agriculture (cranberry bogs) export coefficient of 4.3 kg/ha/yr was estimated. The forested wetland was broken out as a separate landuse due to the extensive area of this unusual forest type and the large observed concentrations in waters flowing out of the wetland areas. The estimated watershed loads for the Stetson Pond watershed and all watersheds that contribute to East Monponsett Pond can be found in Table 13. The estimated watershed loads for the White Oak Reservoir watershed and all watersheds that contribute to West Monponsett Pond can be found in Table 14.

	Basin 1	Basin 2	Basin 3	Basin 4	Basin 5	Basin 6	Total
	Stetson Pond	Stetson Brook	Swamp C	Monponsett Heights	Peterson Swamp	Direct To East Pond	
LAND USE	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)
High Intensity Ag. (bog)	0.0	97.8	0.0	0.0	0.0	2.2	100.0
Medium Intensity Development	10.2	8.3	8.9	8.6	7.3	10.2	53.5
Forested Wetland	1.3	6.8	7.9	1.0	17.7	5.6	40.4
Low Intensity Development	12.6	6.8	7.5	1.5	3.4	5.7	37.5
Natural	4.9	5.0	5.6	0.7	4.6	2.6	23.3
High Intensity Development	0.0	0.1	0.4	0.0	0.0	8.1	8.6
Non-Forested Wetland	1.0	0.8	3.2	0.1	0.1	0.4	5.6
Low Intensity Agriculture	0.7	0.0	0.0	0.0	3.3	0.7	4.7
Abandoned Cranberry Bogs	3.4	0.0	0.0	0.0	0.0	0.0	3.4
Medium Intensity Agriculture	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Open	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>TOTAL</b>	<b>34.1</b>	<b>125.6</b>	<b>33.4</b>	<b>11.8</b>	<b>36.4</b>	<b>35.5</b>	<b>276.9</b>

Table 13: Watershed Loads by Landuse for East Monponsett Pond Watersheds

	Basin 8	Basin 9	Basin 10	Basin 11	Basin 12	Basin 13	Total
	White Oak Reservoir	White Oak Brook	Unnamed Tributary 1	Unnamed Tributary 2	Artificial Flow/ Unnamed Tributary 3	Direct to West Pond	
LAND USE	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)
High Intensity Ag. (bog)	32.7	101.4	3.2	50.4	0.0	10.2	198.0
Forested Wetland	8.9	6.8	13.2	3.2	0.1	10.4	42.6
Medium Intensity Development	3.1	2.7	0.3	10.4	9.0	9.3	34.7
Low Intensity Development	17.0	6.4	1.1	7.2	0.0	2.1	33.8
Natural	4.8	3.2	1.3	3.0	0.3	2.7	15.3
Non-Forested Wetland	2.9	2.2	0.6	3.0	0.1	3.0	11.8
High Intensity Development	5.2	0.0	0.0	0.7	0.1	1.8	7.7
Abandoned Cranberry Bogs	0.5	0.0	0.0	0.3	0.0	0.0	0.8
Low Intensity Agriculture	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Medium Intensity Agriculture	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Open	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	75.1	122.7	19.6	78.1	9.5	39.5	344.6

Table 14: Watershed Loads by Landuse for West Monponsett Pond Watersheds

### Water Quality Predictions

Using spreadsheet values provided or generated as part of the nutrient load predictions the LLRM model can predict in-pond total phosphorus concentrations, mean and peak chlorophyll *a*, and Secchi disk depth. The model can also estimate bloom frequency (as % of time) above certain chlorophyll *a* concentrations. Each prediction is based on an empirical equation from literature obtained across a range of pond and lake sizes and types with a large proportion located in North America. It should be noted that the model results included were often developed in large, deep waterbodies with greater retention times. They are considered standard model equations however and the average of the results is considered reasonable. An example of the predicted total phosphorus for West Monponsett Pond is given in Table 15 below. For the purposes of this modeling effort the results of the Mass Balance equation were excluded from the average of the model values used to predict in-lake total phosphorus concentrations.

NAME	FORMULA	PRED. CONC. (ppb)
Mass Balance (Maximum Conc.)	$TP=L/(Z(F))*1000$	126
Kirchner-Dillon 1975 (K-D)	$TP=L(1-Rp)/(Z(F))*1000$	47
Vollenweider 1975 (V)	$TP=L/(Z(S+F))*1000$	100
Larsen-Mercier 1976 (L-M)	$TP=L(1-Rlm)/(Z(F))*1000$	74
Jones-Bachmann 1976 (J-B)	$TP=0.84(L)/(Z(0.65+F))*1000$	81
Reckhow General (1977) (Rg)	$TP=L/(11.6+1.2(Z(F)))*1000$	32
Average of Model Values		67

Table 15: West Monponsett - Prediction of in-lake total phosphorus based on model prediction equations

**Calibration Results**

The LLRM Model was calibrated based on average 2009 in-pond total phosphorus concentrations (as measured during MassDEP sampling) for White Oak Reservoir, West Monponsett Pond and East Monponsett Pond. Stetson Pond was not sampled until 2015 and therefore for Stetson Pond the model was calibrated to 2015 in-pond total phosphorus concentrations.

In general the calibrated LLRM model matched observed conditions in each of the ponds. Rather than calibrating each pond separately with different landuse coefficients and/or attenuations, we calibrated all the lakes with the same coefficients simultaneously, with minor adjustments to internal loading to obtain a more robust model for all ponds. Due to a discrepancy in the loading model predicted in lake TP concentration and the observed in lake concentration in White Oak Reservoir, the modeled calibration target was adjusted as follows. The median observed TP concentration in the White Oak Reservoir was observed to be 35 ppb (See MassDEP 2016, Figure 9). The calibration target was adjusted from 35 to 50 ppb to account for the phosphorus in the biomass of the *Lemna* (duckweed) on the surface. Once this adjustment was made the models calibrated fairly well. The % error between the predicted concentrations and the observed concentrations in all the ponds ranged from 1.6% in West Monponsett to 29% in Stetson (Table 16). The absolute error in Stetson is only 4.4 ppb and given the ponds disparate size, morphology and landuse, this fit is acceptable.

Name	Lake Predicted Concentration (ppb)	Observed (ppb)	Abs (error)	% Error
Stetson Pond	19	15	4.4	29.1
East Monponsett	33	34	0.8	2.4
White Oak Reservoir	51	50	1.2	2.5
West Monponsett	67	68	1.1	1.6

\*Actual observed TP in White Oak Reservoir was 35 ppb (see text MassDEP 2016).

Table 16: Comparison LLRM Predicted TP Concentration and Observed TP Concentration

### Sensitivity Analysis

It is likely the most sensitive landuse export coefficient for TP is for cranberry bog areas or high intensity agriculture. A comparison of landuse export coefficient for high intensity agriculture and predicted in-pond phosphorus concentrations is detailed in Table 17 below. Stetson Pond which no longer has active cranberry bog operations is insensitive to changing high intensity agriculture landuse TP export coefficient. East Monponsett, White Oak Reservoir and West Monponsett Pond are all sensitive to changing high intensity agriculture landuse export coefficient. It can easily be seen that White Oak Reservoir is the most sensitive to the high intensity agriculture landuse TP export coefficient likely due to its relatively small watershed size and small pond volume.

### **Model Prediction Runs**

MassDEP determined target TP concentrations for each pond in the TMDL study area (MassDEP 2016). The TP load was adjusted for each pond until its predicted TP concentration matched the target TP concentration. The predicted concentration used in the LLRM model was an average of all the prediction models excluding the Mass Balance equation.

The estimated allowable TP load for was 48 kg/yr, 183 kg/yr, 35 kg/yr and 186 kg/yr for Stetson Pond, East Monponsett Pond, White Oak Reservoir and West Monponsett Pond, respectively (Table 18). The lake models used in this TMDL have a yearly time step. This along with the fact that ponds store phosphorus in the water column and sediments means water quality responds to inputs on a yearly basis.

	Predicted Total Phosphorus Concentration (ppb)			
High Intensity Agriculture TP (kg/ha/yr)	Stetson Pond	East Monponsett	Reservoir	West Monponsett
2.2	19	28	40	57
3	19	30	45	61
3.5	19	31	47	63
4	19	32	50	65
4.5	19	34	52	68
5	19	35	55	70
5.5	19	36	57	73
6	19	37	60	75
6.5	19	38	63	78
7	19	39	65	80
7.5	19	41	68	83
9.9	19	46	80	94
Measured Values	15	34	50	68

Table 17: Comparison of Predicted Total Phosphorus Concentration for TMDL study ponds and high intensity agriculture TP export coefficient

Meeting the threshold loads for each pond will result in reduced algal blooms. All the ponds had a predicted probability of Chlorophyll *a* >16 ppb (typically considered a cause of impairment) less than 10% of the time (Table 18). It is important to note White Oak Reservoir is currently dominated by duckweed and aquatic plants. Reduction in duckweed cover is the restoration target for this waterbody. East Monponsett Pond and West Monponsett Pond at their threshold loads will have predicted peak Chlorophyll *a* values of approximately 21 ppb and 23 ppb, respectively. In the future peak Chlorophyll *a* values may exceed the 16 ppb criterion. The goal of this TMDL is to reduce the extent and severity of current algae blooms such that the Chlorophyll *a* criterion is predicted to be met over 90% of the time.

## Model Summary

The LLRM model although lacking the sophistication of more complex flow related models was adequate to identify the major sources of loading in the TMDL study area. It also provides a method to predict the results of management actions to reduce total phosphorus loading in this system. There is some uncertainty in the estimates of internal loading but this is the only modeling effort with measured nutrient flux measurements. Some uncertainty is unavoidable, however, given the Margin of Safety within the TMDL it is believed modeling efforts are sufficient to guide future management actions in this system.

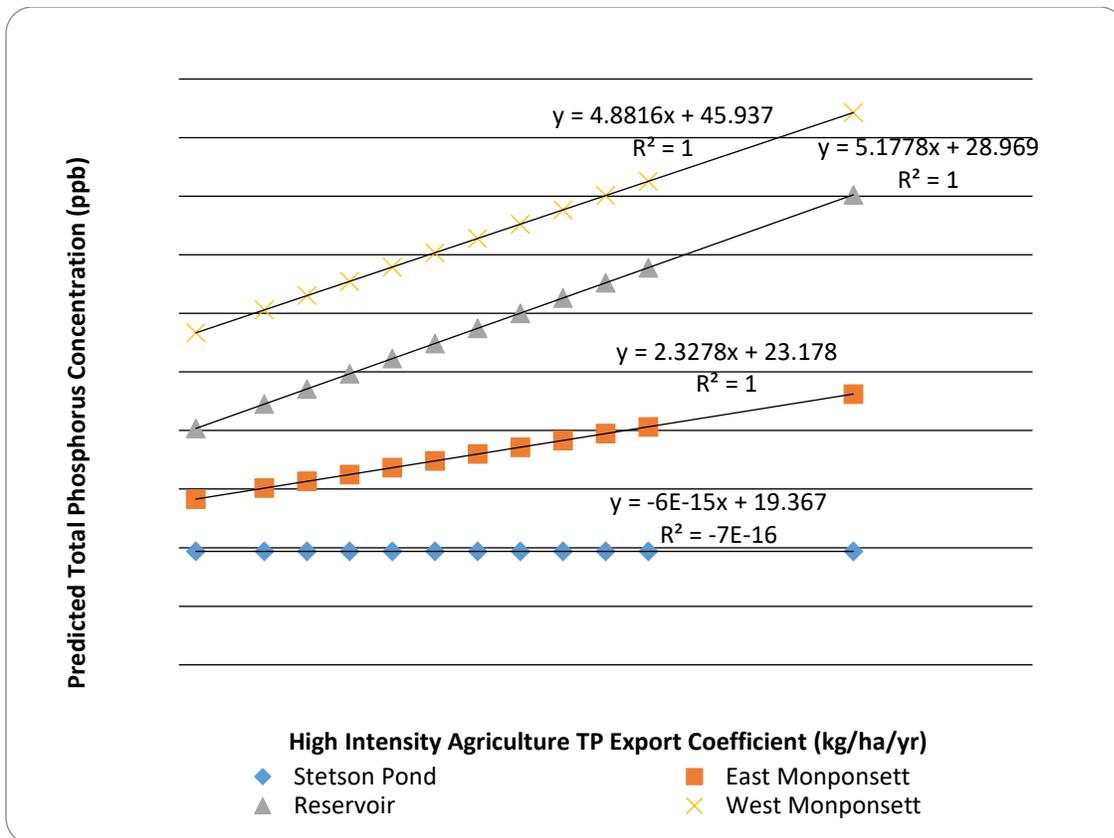


Figure 4: Comparison Predicted TP Concentration and High Intensity Agriculture TP Export Coefficient

Waterbody	Target TP Concentration (ppb)	Target Load TP (kg/yr)	Predicted Mean Chlorophyll <i>a</i> (ppb)	Predicted Peak Chlorophyll <i>a</i> (ppb)	Probability of Chl >16 ppb (% of time)
Stetson Pond	13	48	4	16	0.2%
East Monponsett	18	182	6	21	1.3%
White Oak Reservoir	23	35	9	31	8.4%
West Monponsett	18	186	7	23	2.3%

Table 18: Threshold Loads for Study Area Waterbodies  
(note all values rounded to the kilogram/yr)

## References

AECOM (2009a). *LLRM – Lake Loading Response Model Users Guide and Quality Assurance Project Plan*. AECOM, Willington, CT.

AECOM (2009b). *Use Of The Lake Loading Response Model (LLRM) In TMDL Development For Lake Pocotopaug, East Hampton, CT*. AECOM, Willington, CT.

AECOM (2011). *Total Maximum Daily Load for Forest Lake, Winchester, NH*. AECOM, Willington, CT.

Baystate Environmental Consultants, (1993). *Diagnostic/Feasibility Study for the management of the Pembroke Ponds: Oldham, Furnace, Little Sandy Bottom and Stetson, Pembroke, MA*. BEC Inc., East Longmeadow, Massachusetts.

Environmental Protection Agency (2010). *EPA's Methodology to Calculate Baseline Estimates of Impervious Area (IA) and Directly Connected Impervious Area (DCIA) for Massachusetts Communities*. Environmental Protection Agency, Boston, MA.

FB Environmental Associates (2014). *Province Lake Nutrient Modeling: Estimating Phosphorus Loads using Lake Loading Response Modeling For Province Lake*. FB Environmental Associates, Portland, ME.

Geosyntec (2015). *Lake and Pond Watershed Delineations as part of Watershed -Based Plans Project*. Geosyntec Inc., Acton, MA.

Lycott Environmental Inc. (2007). *Phosphorus/Phytoplankton Study of West Monponsett Pond, Halifax and Hanson, Massachusetts*. Lycott Environmental Inc, Charlton, MA.

Bureau of Geographic Information (MassGIS), Commonwealth of Massachusetts, Executive Office of Technology and Security Services (2007). *Impervious Surface 2005, GIS data layer dated February 2007*. Boston, MA. Available online at:  
<https://docs.digital.mass.gov/dataset/massgis-data-impervious-surface-2005>

McLaughlin, J. (James.M.McLaughlin@.state.ma.us), (2016). *RE: cranberry bogs in Monponsett Pond watershed*. Massachusetts Department of Environmental Protection, Southeast Regional Office, Lakeville, MA. Email to Matthew Reardon, Massachusetts Department of Environmental Protection, Division of Watershed Management, Worcester, MA dated January 1, 2016.

MassDEP (2012). *DWM WATER QUALITY DATA VALIDATION PROCESS (SUMMARY)*. CN 056.15, Massachusetts Department of Environmental Protection, Worcester, MA.

MassDEP(2016). *West and East Monponsett Pond System Total Maximum Daily Loads For Total Phosphorus (Draft)*.

National Climatic Data Center (2016). Monthly Rainfall for Plymouth, MA (COOP: 196486). Downloaded 2 February, 2016 from <https://www.ncdc.noaa.gov/>

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture (2018). Web Soil Survey. Available online at the following link: <https://websoilsurvey.sc.egov.usda.gov/>. Accessed [10/18/2018]

Nowlin, W.H., J.L. Evarts, and M.J. Vanni. 2005. Release rates and potential fates of nitrogen and phosphorus from sediments in an eutrophic reservoir. *Freshwater Biology* 50(2): 301-322

USGS 2015. USGS Stream Stats for Massachusetts. United States Geological Survey. Northborough MA. Accessed 12/7/15, 12/15/2015,12/24/2015. Available at <http://water.usgs.gov/osw/streamstats/massachusetts.html>

## Appendix G: Monponsett Pond Draft 2016 Water Quality Sampling Data

These raw data are currently being validated by MassDEP, Division of Watershed Management, and are considered DRAFT. As a result of DWM's data validation process, some of these data may be censored or qualified.

**Table G1: Draft 2016 Nutrients and Chlorophyll a Data**

Data Type	Waterbody	Unique ID	Date	Time	Sample Number	Lake Level	Sample Depth	Secchi Depth (m)	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)	Chlorophyll <i>a</i> (mg/m <sup>3</sup> )
draft_2016	Monponsett Pond [deep hole, center of southern portion of east basin, Halifax]	W0930	06/23/16	11:45	LB-5932		Depth Integrated (0-2)				4.16
draft_2016	Monponsett Pond[deep hole, center of southern portion of east basin, Halifax]	W0930	06/23/16	12:05	LB-5931	Normal	Surface	2.20	0.28	0.012	
draft_2016	Monponsett Pond [deep hole, center of southern portion of east basin, Halifax]	W0930	08/25/16	11:25	LB-5972		Depth Integrated (0-2.5)				1.92
draft_2016	Monponsett Pond[deep hole, center of southern portion of east basin, Halifax]	W0930	08/25/16	11:20	LB-5971	Low	Surface	3.00	0.38	0.014	
draft_2016	Monponsett Pond [East Basin, approximately 15 feet from shore at boat ramp west off Route 36, Halifax]	W2450	07/14/16	11:47	LB-5952		Surface				1.57
draft_2016	Monponsett Pond[East Basin, approximately 15 feet from shore at boat ramp west off Route 36, Halifax]	W2450	07/14/16	11:46	LB-5951	Low	Surface	**	0.32	0.012	

Data Type	Waterbody	Unique ID	Date	Time	Sample Number	Lake Level	Sample Depth	Secchi Depth (m)	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)	Chlorophyll <i>a</i> (mg/m <sup>3</sup> )
draft_2016	Monponsett Pond [deep hole, center of southern portion of west basin of pond, Halifax]	W0926	06/23/16	11:00	LB-5925		Depth Integrated (0-2.4)				29.91
draft_2016	Monponsett Pond[deep hole, center of southern portion of west basin of pond, Halifax]	W0926	06/23/16	11:24	LB-5922	Normal	Surface	0.80	0.54	0.021	
draft_2016	Monponsett Pond[deep hole, center of southern portion of west basin of pond, Halifax]	W0926	06/23/16	11:24	LB-5923	Normal	Surface	0.80	0.47	0.018	
draft_2016	Monponsett Pond [deep hole, center of southern portion of west basin of pond, Halifax]	W0926	08/25/16	10:42	LB-5965		Depth Integrated (0-1.5)				45.8
draft_2016	Monponsett Pond[deep hole, center of southern portion of west basin of pond, Halifax]	W0926	08/25/16	10:38	LB-5962	Low	Surface	0.50	0.85	0.019	
draft_2016	Monponsett Pond[deep hole, center of southern portion of west basin of pond, Halifax]	W0926	08/25/16	10:38	LB-5963	Low	Surface	0.50	0.82	0.02	
draft_2016	Monponsett Pond [West Basin, approximately 15 feet from shore at boat ramp west off Route 58, Halifax]	W2451	07/14/16	11:24	LB-5945		Surface				45.34
draft_2016	Monponsett Pond[West Basin, approximately 15 feet from shore at boat ramp west off Route 58, Halifax]	W2451	07/14/16	11:21	LB-5942	Low	Surface	0.50	0.59	0.027	

<b>Data Type</b>	<b>Waterbody</b>	<b>Unique ID</b>	<b>Date</b>	<b>Time</b>	<b>Sample Number</b>	<b>Lake Level</b>	<b>Sample Depth</b>	<b>Secchi Depth (m)</b>	<b>Total Nitrogen (mg/L)</b>	<b>Total Phosphorus (mg/L)</b>	<b>Chlorophyll <i>a</i> (mg/m3)</b>
draft_2016	Monponsett Pond[West Basin, approximately 15 feet from shore at boat ramp west off Route 58, Halifax]	W2451	07/14/16	11:22	LB-5943	Low	Surface	0.50	0.65	0.026	

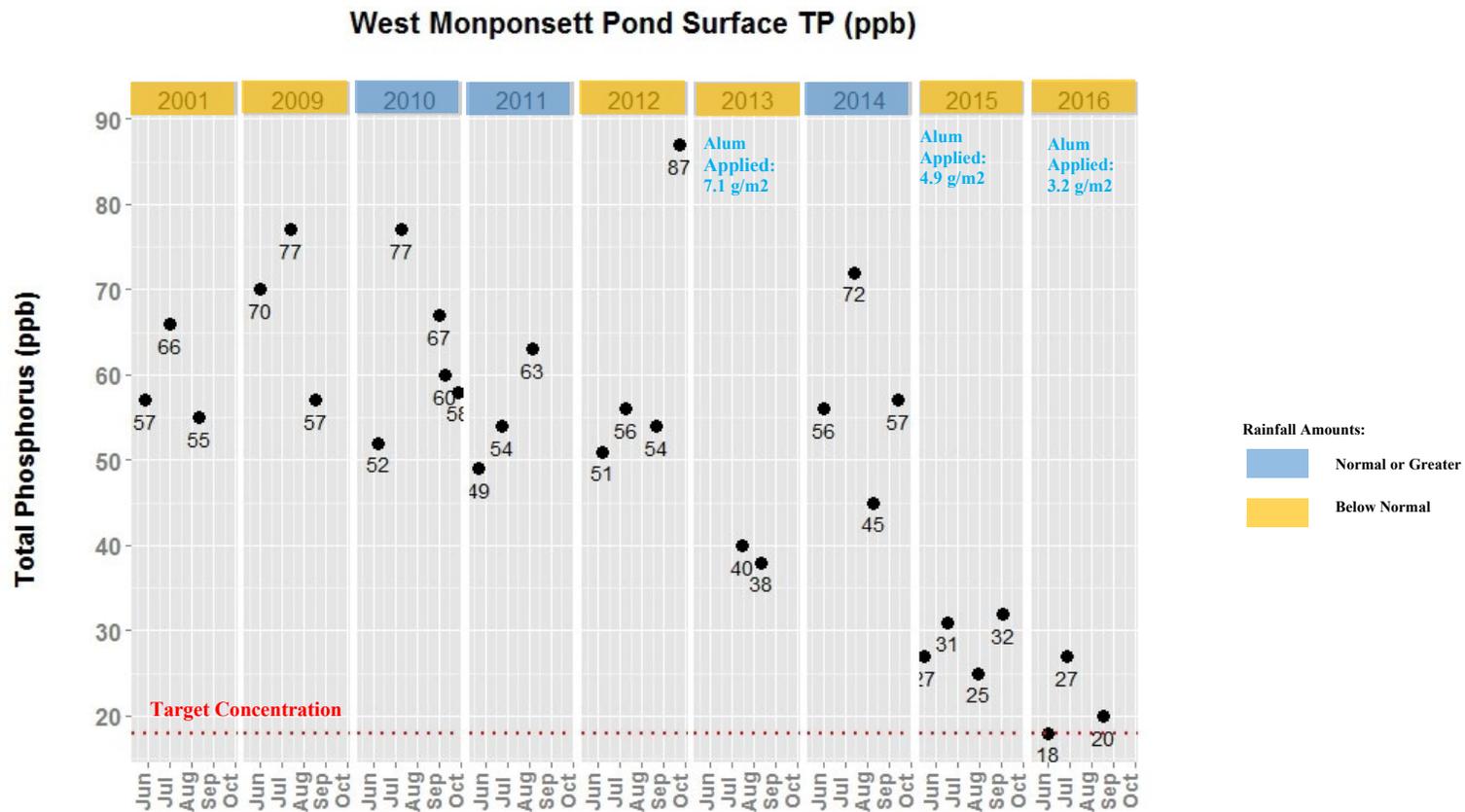


Figure G1. West Monponsett Pond Surface Total Phosphorus (updated, note 2014-2016 data are draft)

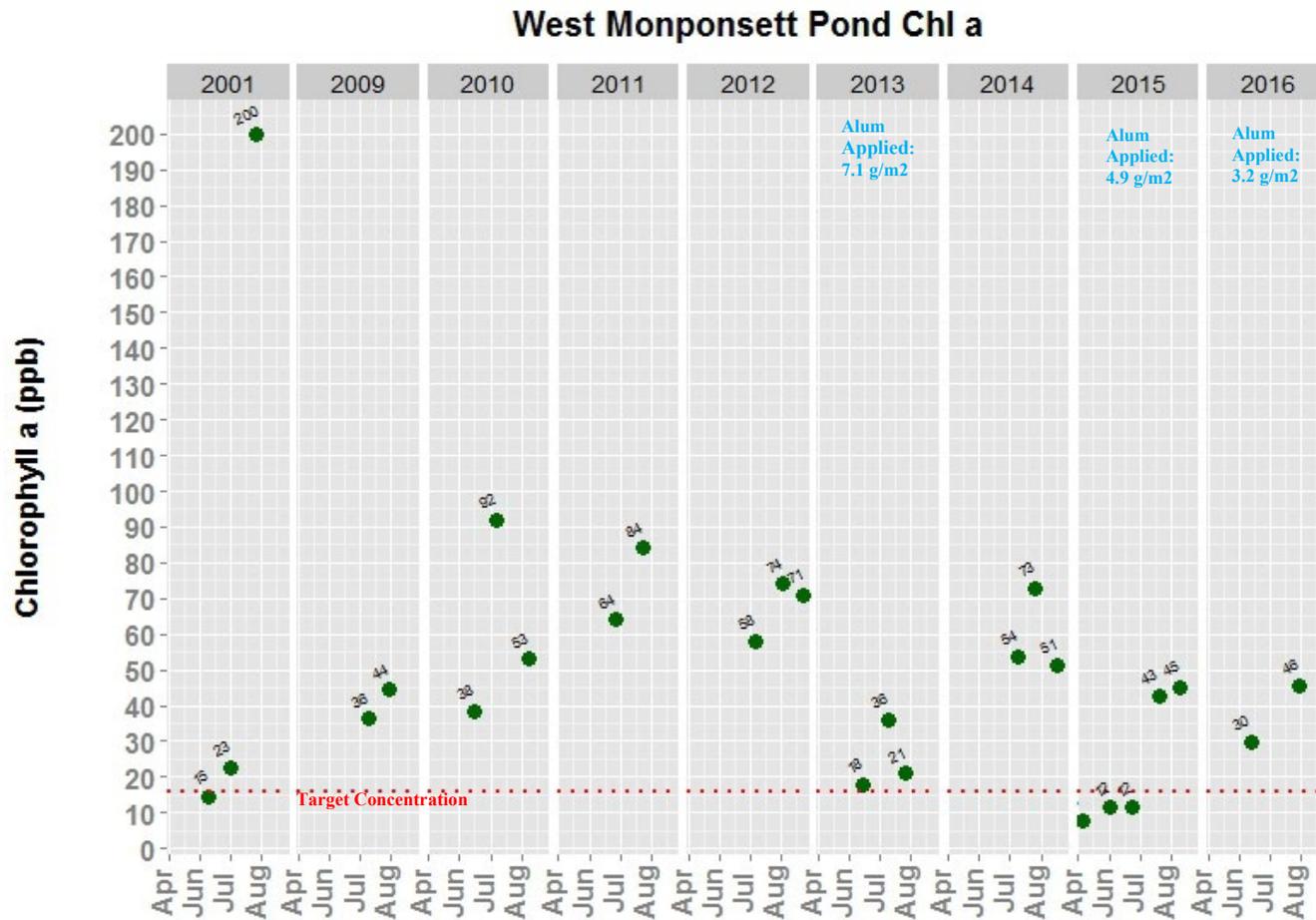


Figure G2. West Monponsett Pond Chlorophyll a Surface and Depth Integrated Samples (updated, note 2014-2016 data are draft)

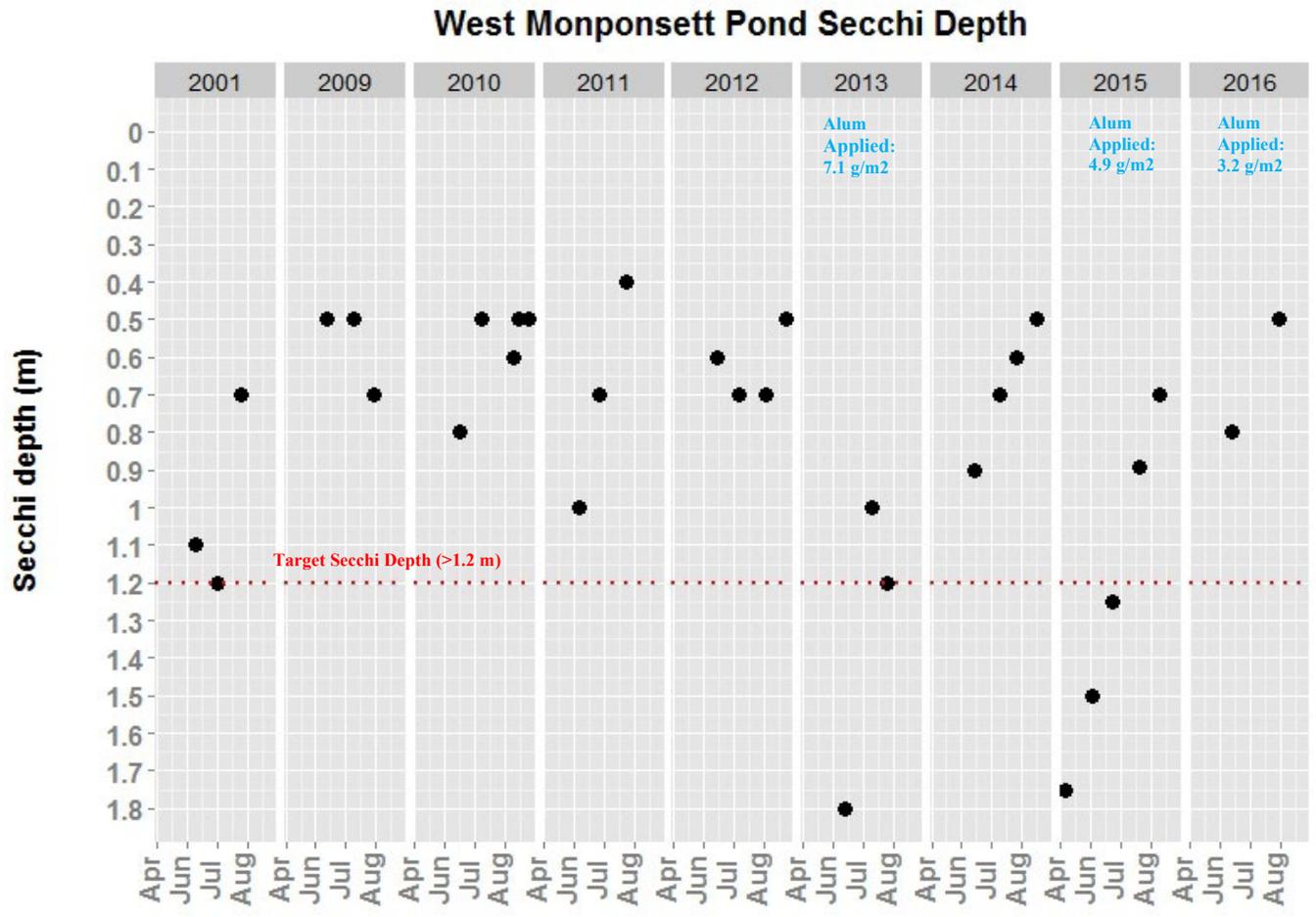


Figure G3. West Monponsett Pond Secchi Depth (updated, note 2014-2016 data are draft)