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

(CN 446.0)

COMMONWEALTH OF MASSACHUSETTS
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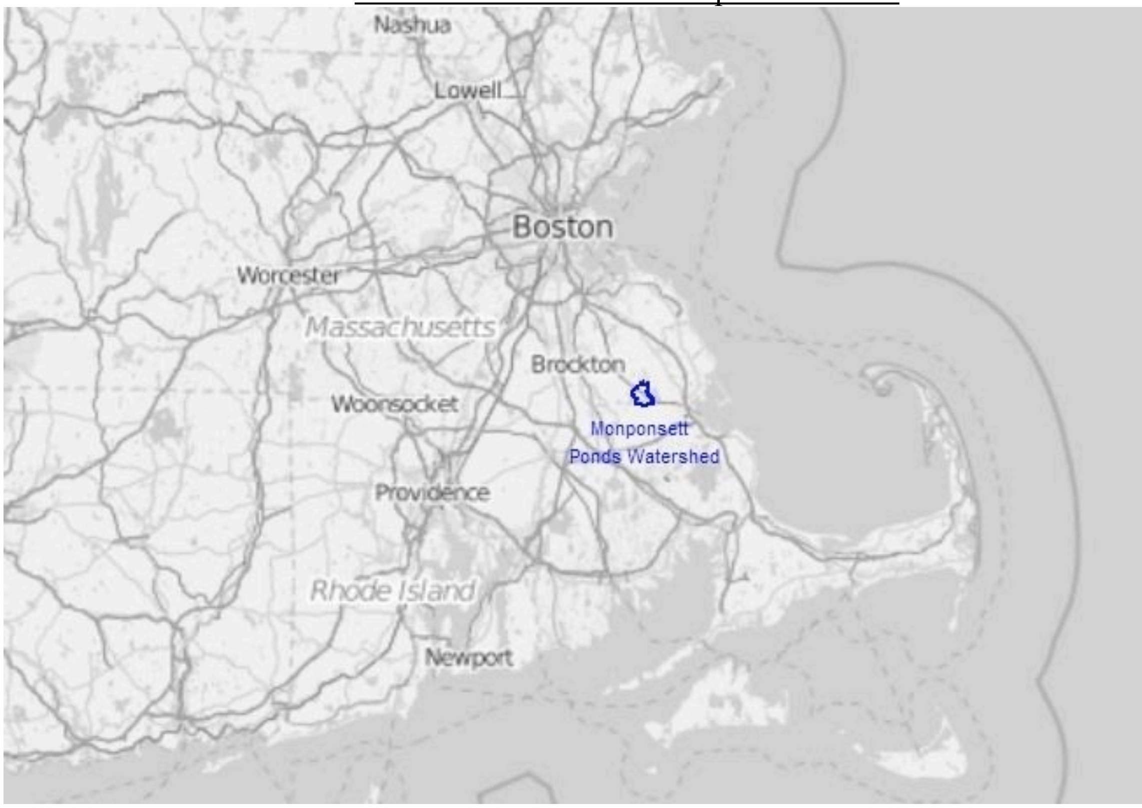
MassDEP DWM TMDL Report CN 446.0



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 Spgrades, Storm Water Management, Aluminum Treatment.

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

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Front Cover

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Cover photo credit: Police Chief Ted Broderick, Halifax, August 20, 2015.

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 TMDL report. The current and proposed integrated list and further explanation can be found at http://www.mass.gov/dep/water/resources/tmdls.htm.

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 Total Maximum Daily Load (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. West Monponsett Pond and Stetson Pond are listed as impaired (Category 5), on the "Massachusetts 2014 Integrated List of Waters" for nutrient related impairments (MassDEP, 2015). West Monponsett (Segment MA62119) is listed as impaired for Excess Algal Growth, Total Phosphorus and Secchi Disk Transparency. Stetson Pond (Segment MA62182) is listed as impaired for Dissolved Oxygen (DO) and Total Phosphorus (TP). East Monponsett Pond (Segment MA62218) and White Oak Reservoir (AKA Reservoir, Segment MA62157) were not previously listed as nutrient impaired, but are now determined to be impaired by excess algal growth and nuisance aquatic plants (duckweed), respectively, based on recent data analyzed in this report. Some of the ponds are listed for other non-nutrient 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 also listed for Mercury in Fish Tissue for which a TMDL exists (EPA#33880); West Monponsett Pond MA62119 is also listed for non-native aquatic plants. This report will satisfy the requirement of a phosphorus TMDL for all 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 are considered to be Class A and Outstanding Resource Waters (ORWs) and are tributary, 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-May) water flows regularly reverse direction and draw water 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, internal release from sediments, natural wetlands, and runoff from developed areas.

Ignoring sediment sources, the largest controllable watershed sources of phosphorous 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 and federal programs.

It is recommended to first reduce all external loads before addressing the internal loads, but due to health concerns regarding the potentially toxic cyanobacterial blooms in West Monponsett, the Town of Halifax funded a treatment with a light dose of aluminum in 2013 and 2015 and is continuing into 2016. Only a light aluminum dose was applied in small amounts over the summer months to avoid potential to impacts 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 will be encouraged. An additional aluminum treatment of West Monponsett Pond to bring the total applied dose up to 50 grams per square meter (g/m^2), and possibly treat the other ponds in the system.

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 71% as shown in Table ES-1 below. Although the TMDL must be expressed on a daily basis, the implementation and administrative decisions should rely on achieving the annual TMDL load which is more appropriate for these waterbodies.

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	20	207	0.57	40%
White Oak Brook Reservoir	50*	76	28	41	0.11	46%
West Monponsett	68	676	20	199	0.54	71%

*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. TMDLs 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 web at http://www.mass.gov/eea/agencies/massdep/water/.

The Massachusetts Surface Water Quality Standards (WQS) define conditions required to maintain designated uses. The standards are largely narrative as they apply to nutrients, however numeric thresholds for biological responses such as Secchi disk transparency and chlorophyll are detailed below. 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 to meet Massachusetts Surface Water Quality Standards (WQS) is selected and a target load of phosphorus is calculated for the lake. The phosphorus TMDL is established to control eutrophication in the water column, however additional plant management may be needed. A total phosphorus TMDL is established to meet WQS, and to generally 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 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). Details on the thresholds listed above can be found in MassDEP's Consolidated Assessment and Listing Methodology (CALM, see MassDEP, 2016a). 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 watershed grants listed in http://www.mass.gov/eea/agencies/massdep/water/grants/watersheds-water-quality.html.

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 of 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 to 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 fall and spring in deep lakes and also during the summer 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 particular 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 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 by the use of 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 completely 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, 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. Any unvegetated drainage way is a likely source of soil erosion. 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” 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 web at http://www.mass.gov/eea/agencies/massdep/water/grants/watersheds-water-quality.html

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 2014 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 sea level. West Monponsett Pond has been suffering the symptoms of a eutrophic lake with elevated chlorophyll a and cyanobacteria blooms and is on the 2014 Integrated List for Phosphorus (Total), Excess Algal Growth, Secchi disk transparency 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 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 above sea level. This waterbody is covered under 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 but has not previously been listed as impaired for nutrients.

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 2014 Integrated List (MassDEP 2015) for Phosphorus (Total), Oxygen, Dissolved 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 6 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. White Oak Reservoir, also known as 'Reservoir' was not listed as impaired by nutrients but in recent surveys by MassDEP it was noted that the pond exceeds the 25% threshold, as established in the CALM (MassDEP 2016a) for non-rooted macrophyte cover (duckweed) and will be listed as impaired for Nutrient/Eutrophication Biological Indicators. 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 2014 Integrated List information

Waterbody Name	Water Body Segment	Description and Location	Size (acres)[1]	Class	Qualifier	303d Cat.	Integrated List Nutrient Impairment Causes
Stetson Pond	MA62182	Pembroke	88.2	A	PWS\ORW	5	Phosphorus (Total), Oxygen, Dissolved,
Monponsett Pond[2]	MA62218	[East Basin] Halifax	244.6	A	PWS\ORW	4A	not applicable[3]
White Oak Reservoir	MA62157	Hanson	13.2	A	PWS\ORW	3	not applicable[3]
Monponsett Pond	MA62119	[West Basin] Halifax/ Hanson	282.8	A	PWS\ORW	5	Phosphorus (Total), Excess Algal Growth, Secchi disk transparency
Additional waters outside of study area							
Silver Lake	MA94143	Pembroke/ Plympton/ Kingston	617	A	PWS\ORW	4c	Other flow regime alterations[4]
Jones River	MA94-12	Kingston	4 mile	B		5	Fish-Passage Barrier, Low Flow Alterations, Aquatic Plants (Macrophytes), Excess Algal Growth, Oxygen dissolved, Turbidity
Stump Brook[5]	--	--	--	--	--	--	--

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)
3- Determined to be impaired in this report.
4-Not a pollutant, no TMDL required.
5-Stump Brook has not been officially 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 it's water supply as far back as 1899. In 1964 the Massachusetts Legislature approved Act 371 to allow a diversion from East 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 Ponponset 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 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 clean 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 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 East Monponsett Pond's use as a public water supply source. The use of East Monponsett Pond as a public water supply 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.

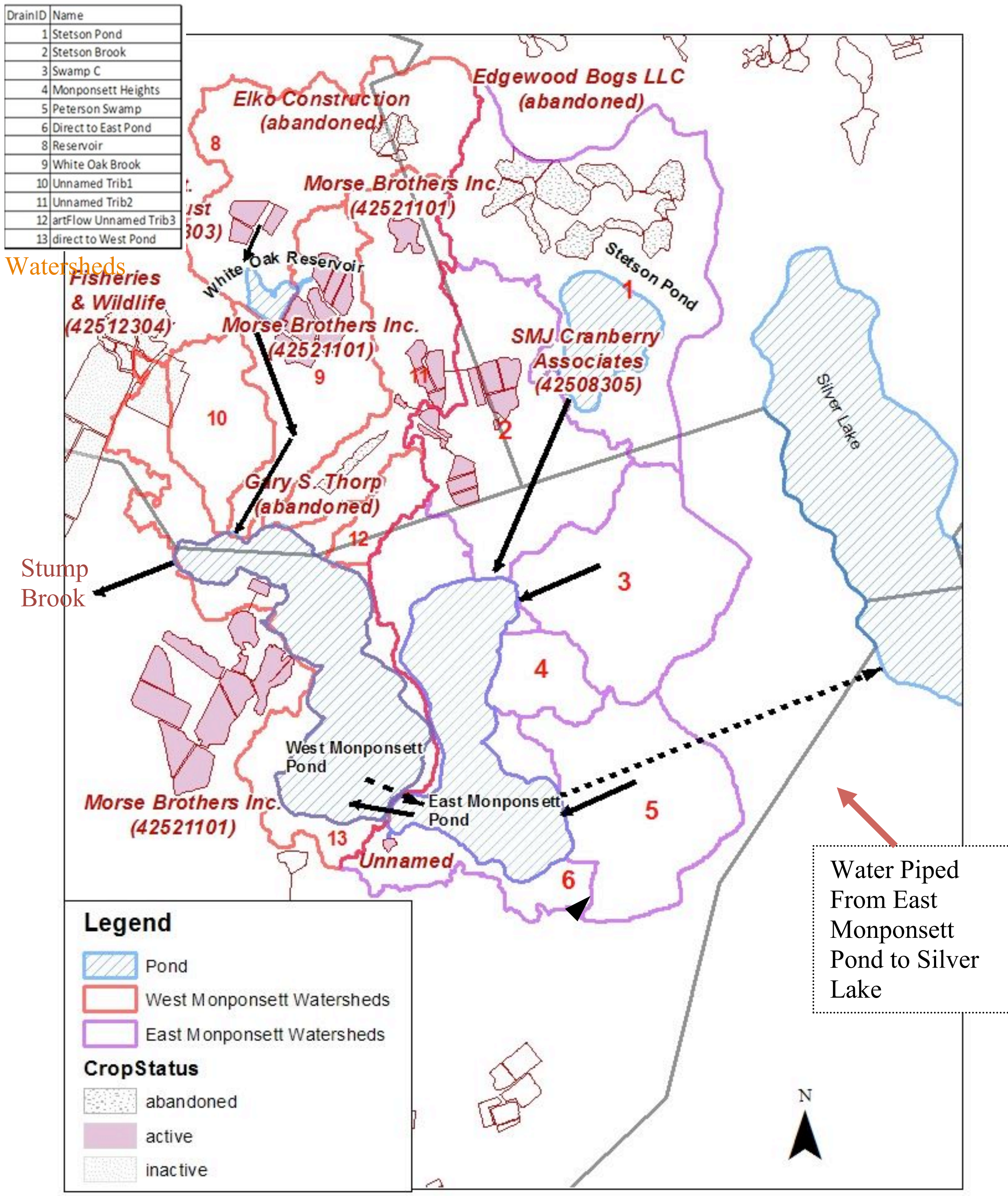

Figure 1: Flow Diagram for TMDL Study Area

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) datalayer, 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 of 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.

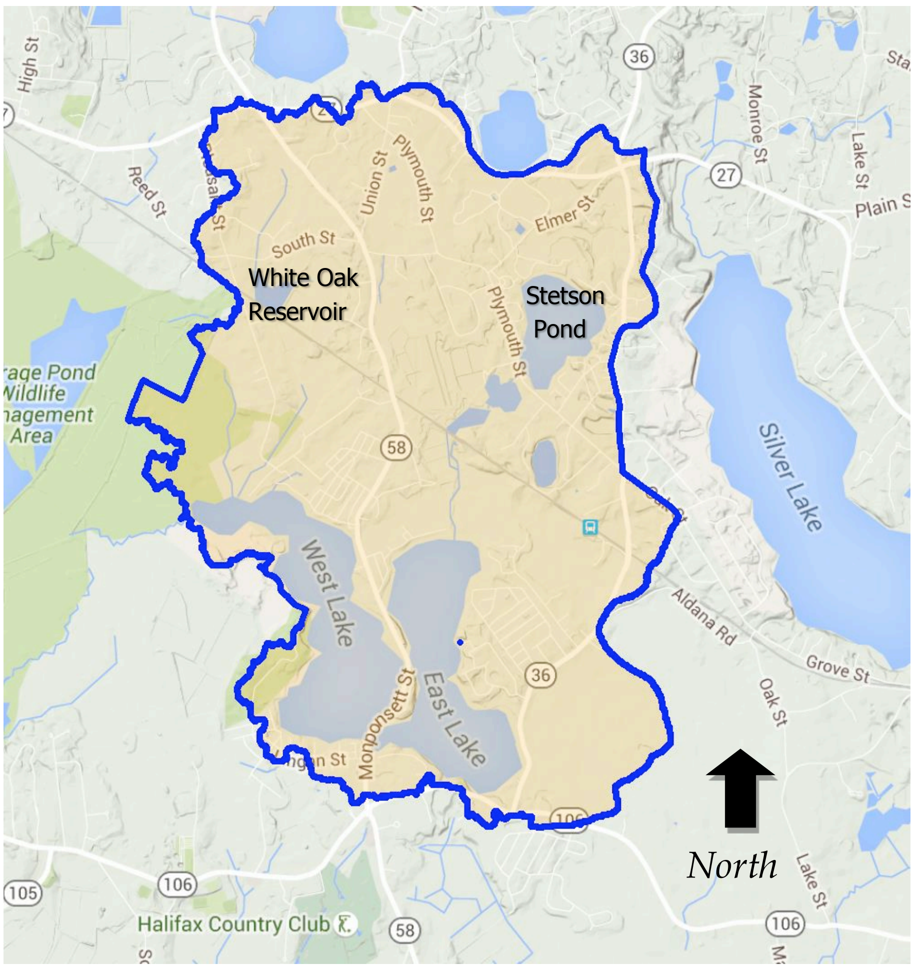

Figure 2. Monponsett Ponds Watershed and TMDL Study Area

Stetson Pond is also shown just east of Plymouth Street and White Oak Reservoir is also shown above West Monponsett just south of South Street. Silver Lake is shown to the right, outside of the catchment area. (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 x10^6 cubic meters (m^3) (BEC 1993) while East Monponsett Pond has an estimate volume of 2.1 E6 m^3. The White Oak Reservoir with an average depth of only 1.1 meters is estimated to only have a volume of approximately 66,000 m^3. The largest pond, West Monponsett Pond, has an estimated volume of 2.61x10^6 m^3 (Princeton Hydro, 2013). Given the shallow depths and ponds' inflows 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, 82 days for East Monponsett Pond, 21 days for White Oak Reservoir and 182 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
Morphometric Data						
	Symbol	units				
Lake Mean Depth	Z	meters	3.3	1.9	1.1	2.1
Maximum Depth	D_M	meters	9.80[1]	3.96[2]	2.33	6.84
Lake Surface Area	SA	hectares	38.1	109.9	6.0	124.6
Lake Volume	V	$meters^3$	1,259,265[1]	2,124,000	65,891	2,610,000
Width at widest point	W_D	meters	657	1143	326	1089
Maximum Length	L_M	meters	889	1957	414	2146
Shoreline Perimeter	S_L	meters	2719	6313	1476	7804
Physical Characteristics						
Retention Time	T	days	247	82	21	182
Flushing Rate	F	flushings/yr	1.5	4.4	17.4	2.0
Watershed Characteristics						
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)

Previous Analysis

A number of previous studies have been conducted on the Monponsett Ponds. Lycott (1987) conducted a comprehensive diagnostic/feasibility study of both East and West Monponsett Ponds. This study included significant sampling of a number of 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 of 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 quality 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 1057 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 to consists of the poorer quality 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 and 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 a number of management scenarios. They estimated in the absence of the Brockton water supply diversion, West Monponsett Pond would have a total phosphorus concentration of 0.057 mg/l while East Monponsett Pond would have a total phosphorus concentration of 0.019 mg/l. 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 0.037 mg/l and 0.029 mg/l. The estimated total phosphorus concentrations in West and East Monponsett Pond respectively were 0.064 mg/l and 0.004 mg/l 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.

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 Treatment	Key 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

In an effort to reduce the severity of cyanobacteria blooms in West Monponsett Pond the pond was treated with light doses of aluminum sulfate and sodium aluminate solutions in a 2:1 ratio during the summer of 2013 and 2015. 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 obsolete* (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^2. The monitoring study noted some increases and some decreases in mussel density before and after the treatment and no video evidence of obvious stress responses and the authors could not say that the treatment had any effect on the juveniles or adult mussels (Biodrawversity, 2014). Similarly, the same study examined emergence of the dragonflies over several years and found no evidence of any immediate adverse impacts on *N. obloseta* or the dragonfly community (Biodrawversity, 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^2). Thus the total dose of aluminum to the bottom for 2013 and 2015 was 12 g/m^2. Another set of alum treatments is being conducted in the summer months of 2016. The Town of Halifax has applied for permission to add additional alum to West Monponsett in 2017.

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 0.8m (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 (MacLaughlin, 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 (MassDEP, unpub. data). 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).

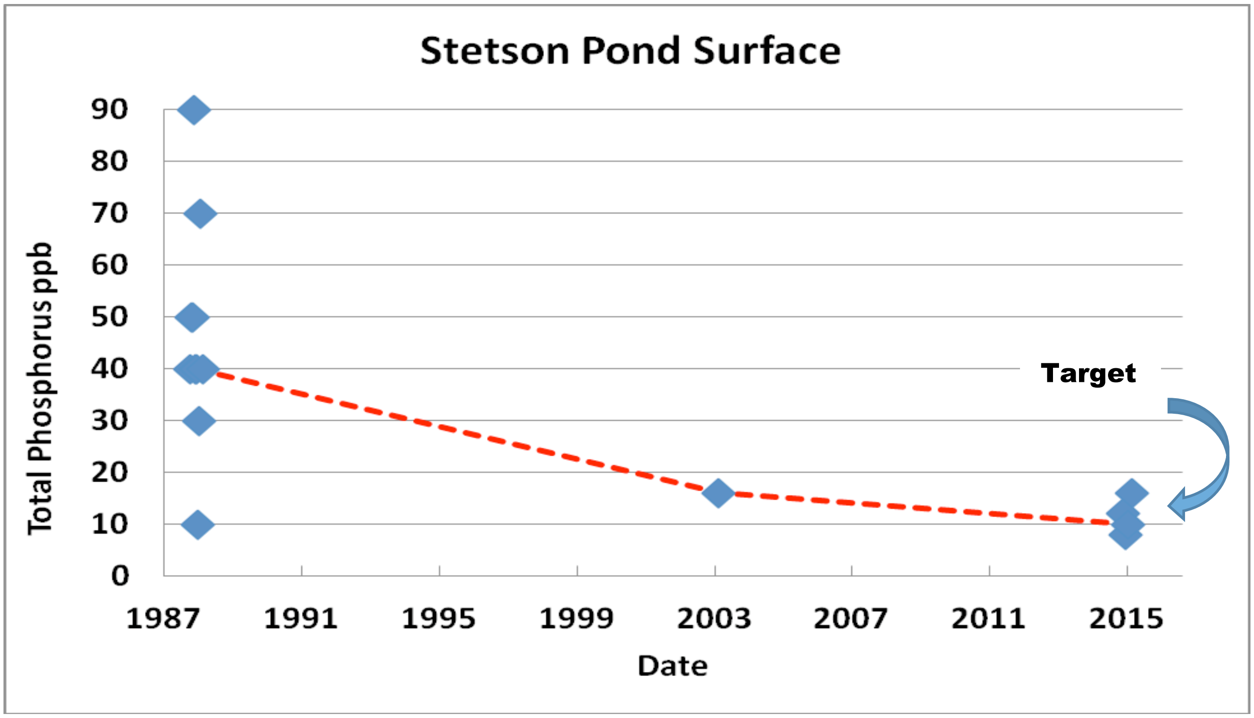

Figure 3. Stetson Pond Surface Total Phosphorus. Summer median values are indicated by the dashed line.

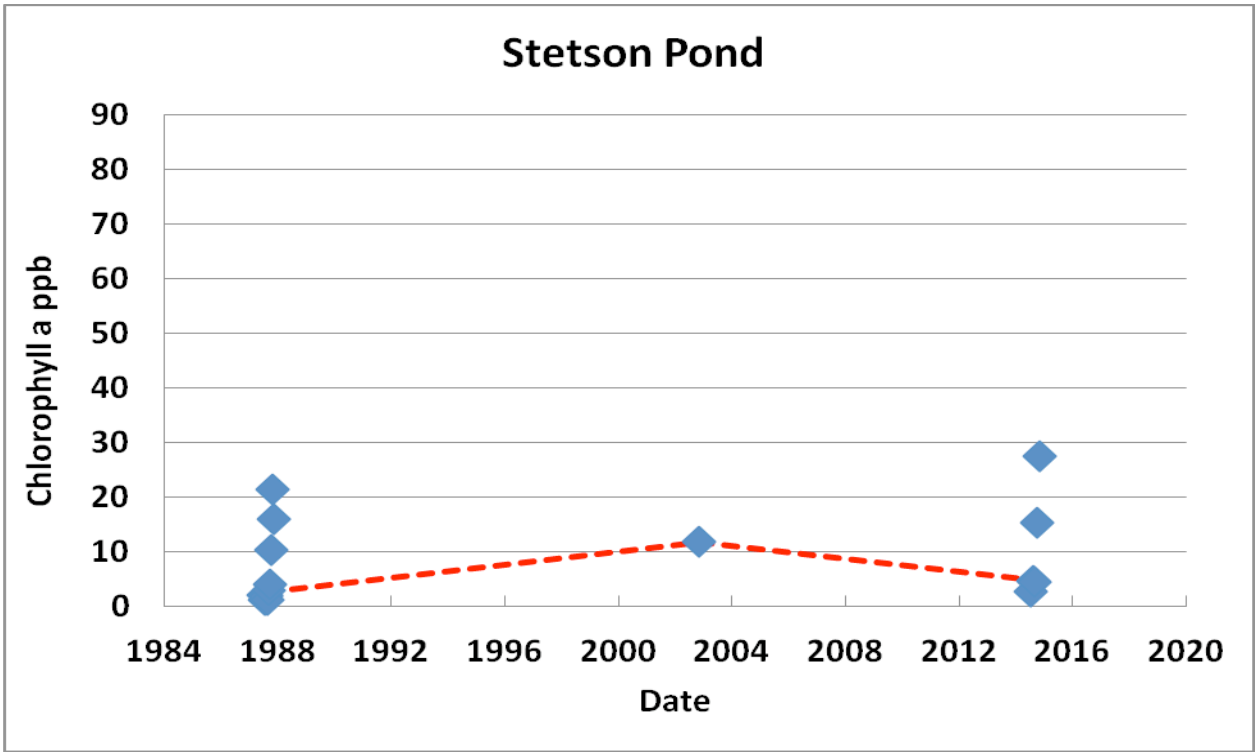

Figure 4. Stetson Pond Chlorophyll *a* . Summer median values are indicated by the dashed line.

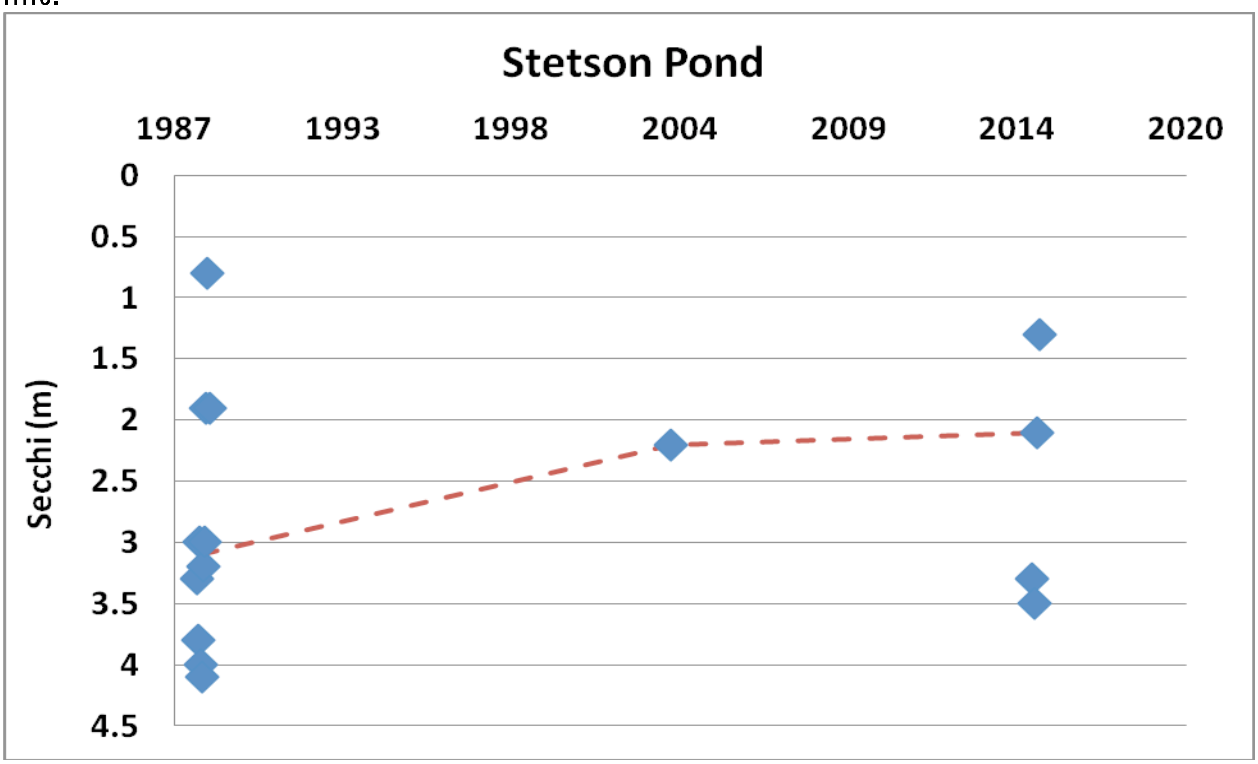

Figure 5. Stetson Pond Secchi disk transparency. (Note y axis reversed). Summer median values are indicated by the dashed line.

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 ug/l guidance threshold) in 2009-2014 (Figure 7). The most recent year, 2105 shows 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 with the exception of 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).

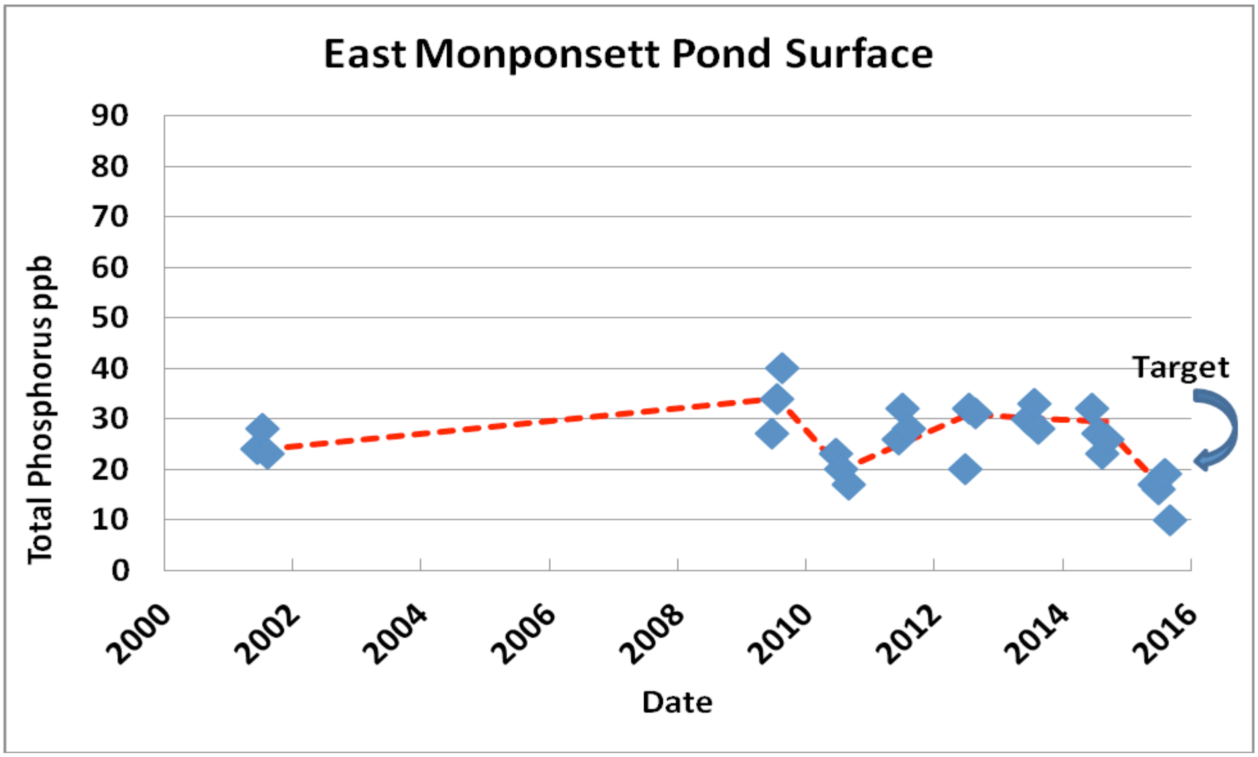

Figure 6. East Monponsett Pond Surface Total Phosphorus. Summer median values are indicated by the dashed line.

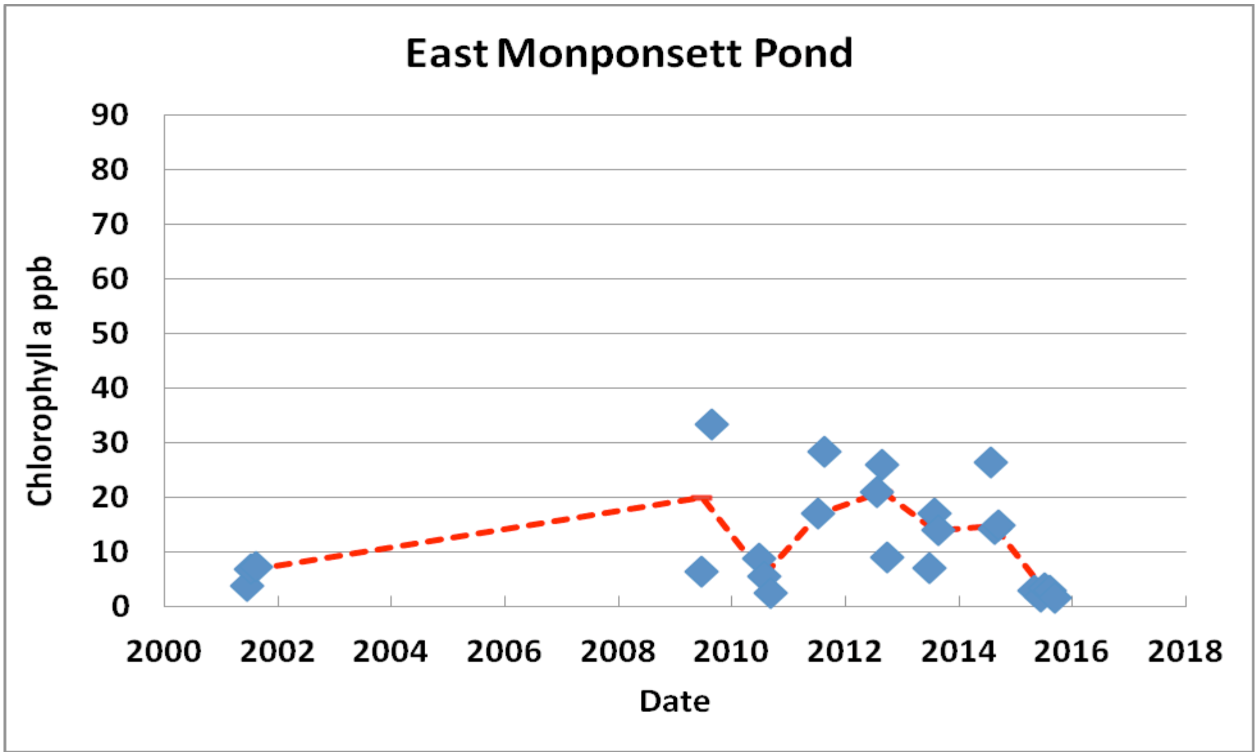

Figure 7. East Monponsett Pond Chlorophyll *a* . Summer median values are indicated by the dashed line.

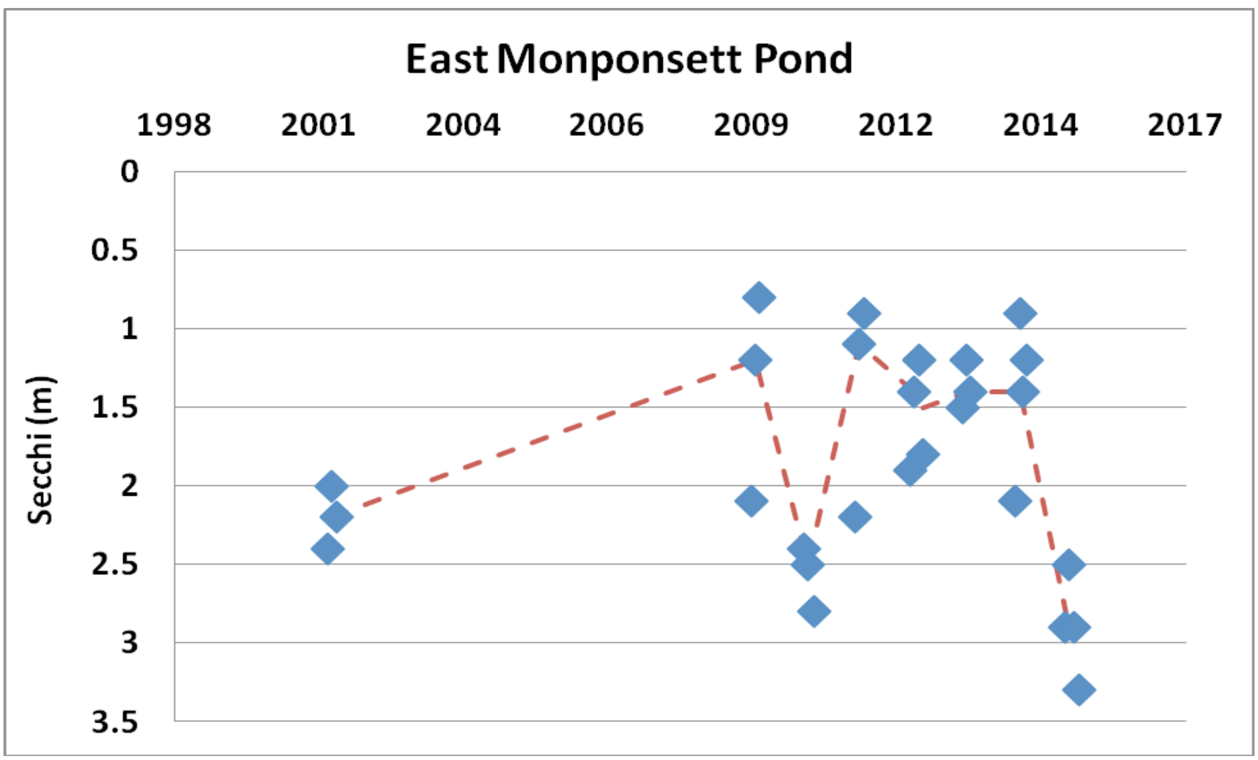

Figure 8. East Monponsett Pond Secchi disk transparency. (Note y axis reversed). Summer median values are indicated by the dashed line.

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 *Cerotophyllum.*, *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.

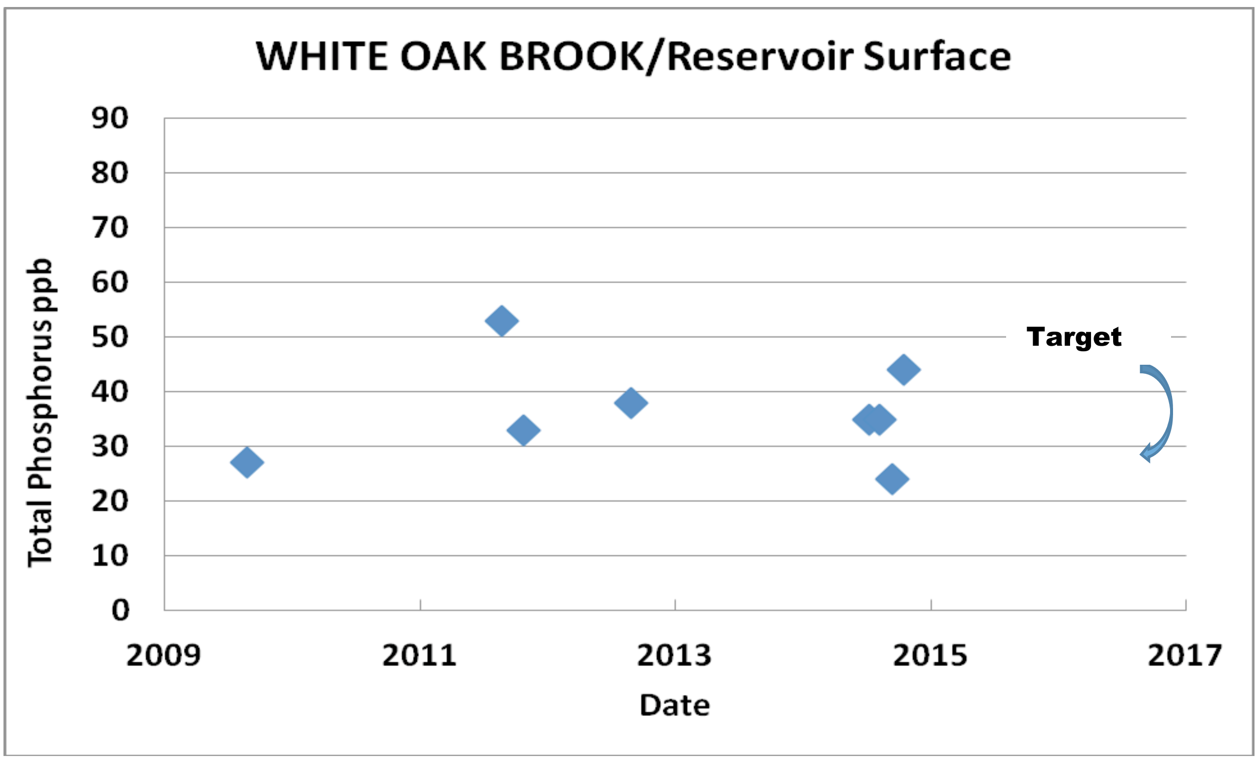

Figure 9. White Oak Reservoir Surface Total Phosphorus. Not enough data to compute summer median data.

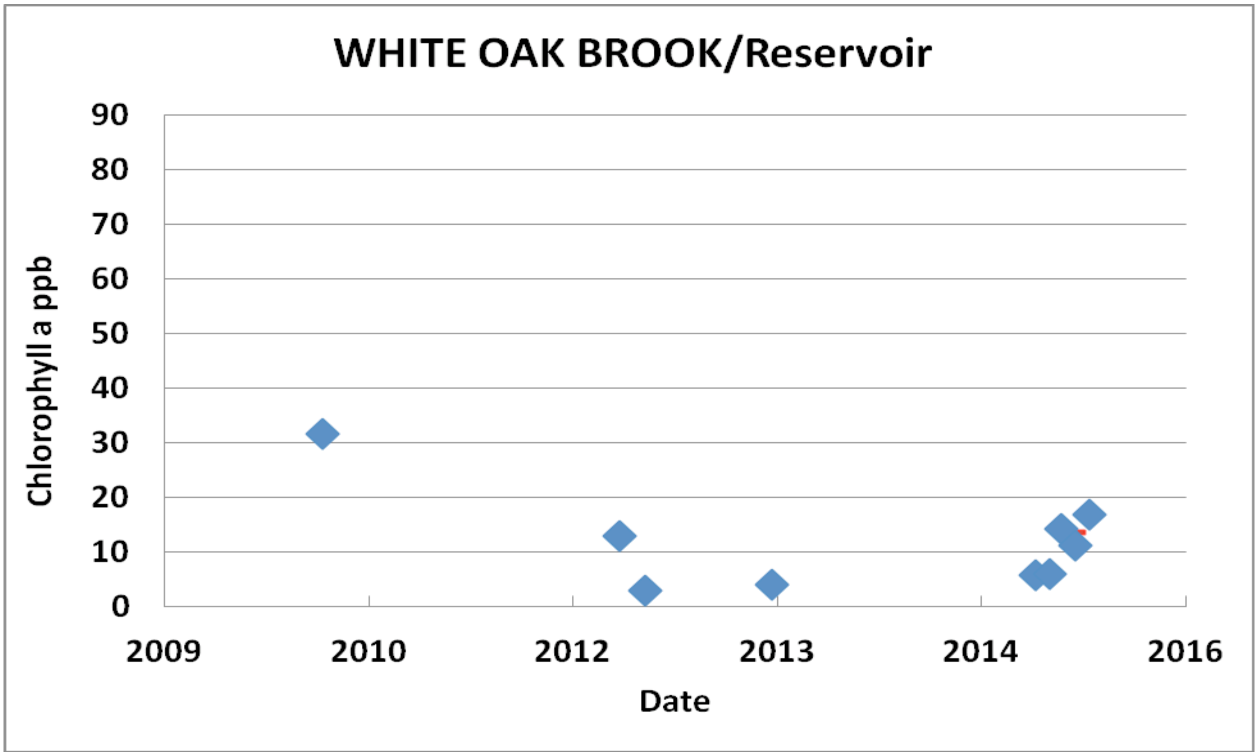

Figure 10. White Oak Reservoir Chlorophyll *a*. Not enough data to compute summer median.

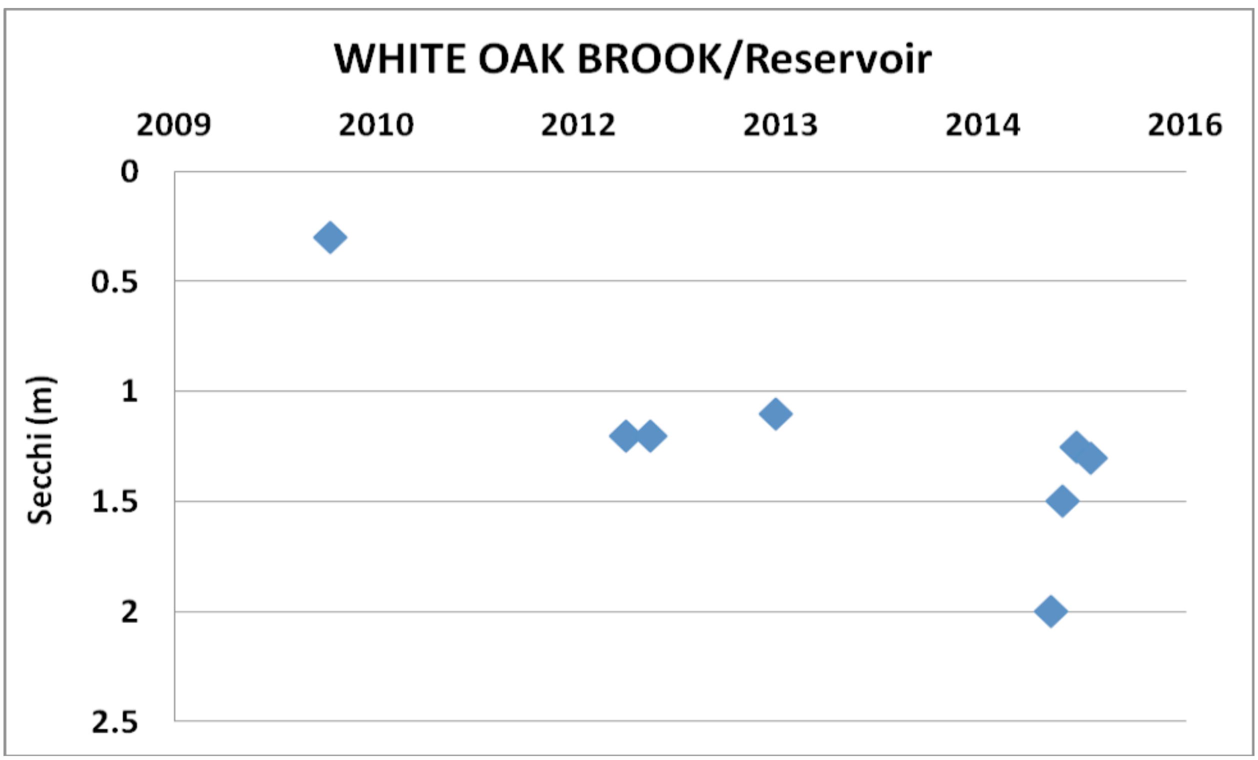

Figure 11. White Oak Reservoir Secchi disk transparency. (Note y axis reversed). Not enough data to compute summer median.

West Monponsett Pond was sampled in the summers of 1985 and again in 2007 by Lycott (1986, 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 54ppb 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 (a=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 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 of the summer and fall seasons during 2013 and 2014 (Appendix C). In 2015 cyanobacteria blooms continued to be an issue. A reduction in the frequency and severity of cyanobacteria blooms is a key restoration goal for this TMDL.

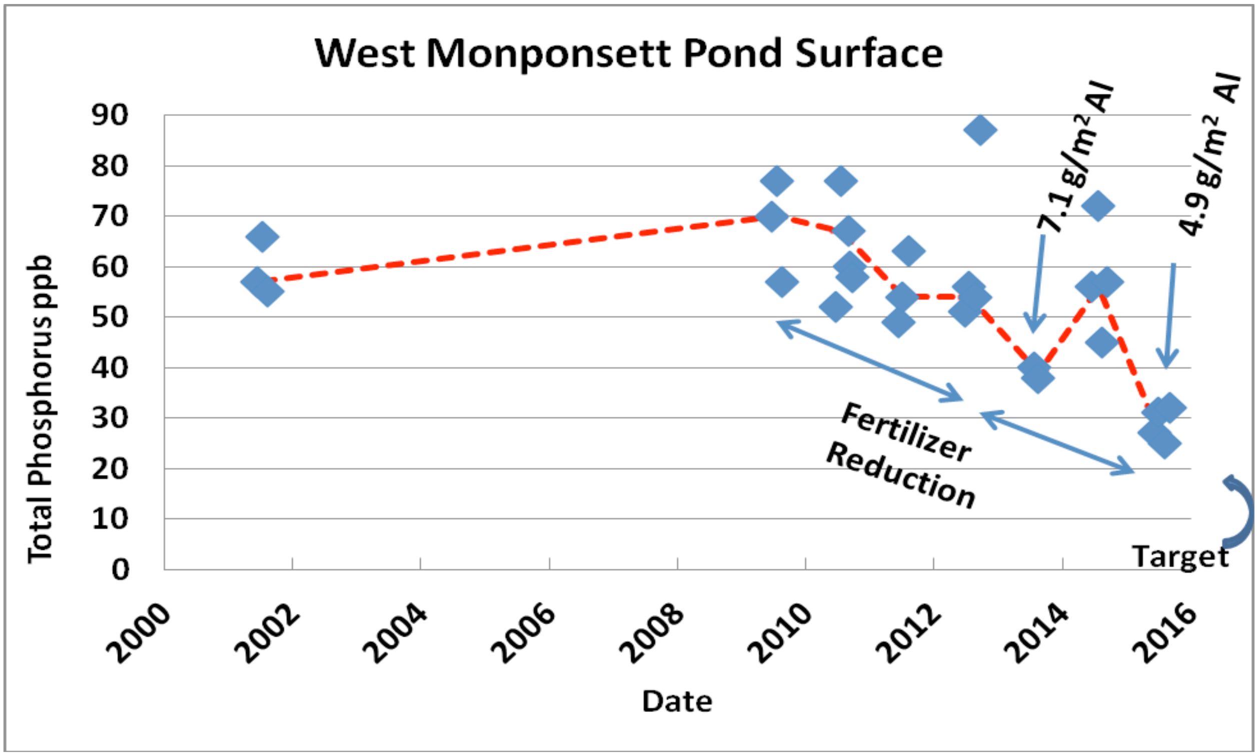

Figure 12. West Monponsett Pond Surface Total Phosphorus. Summer median values are indicated by the dashed line.

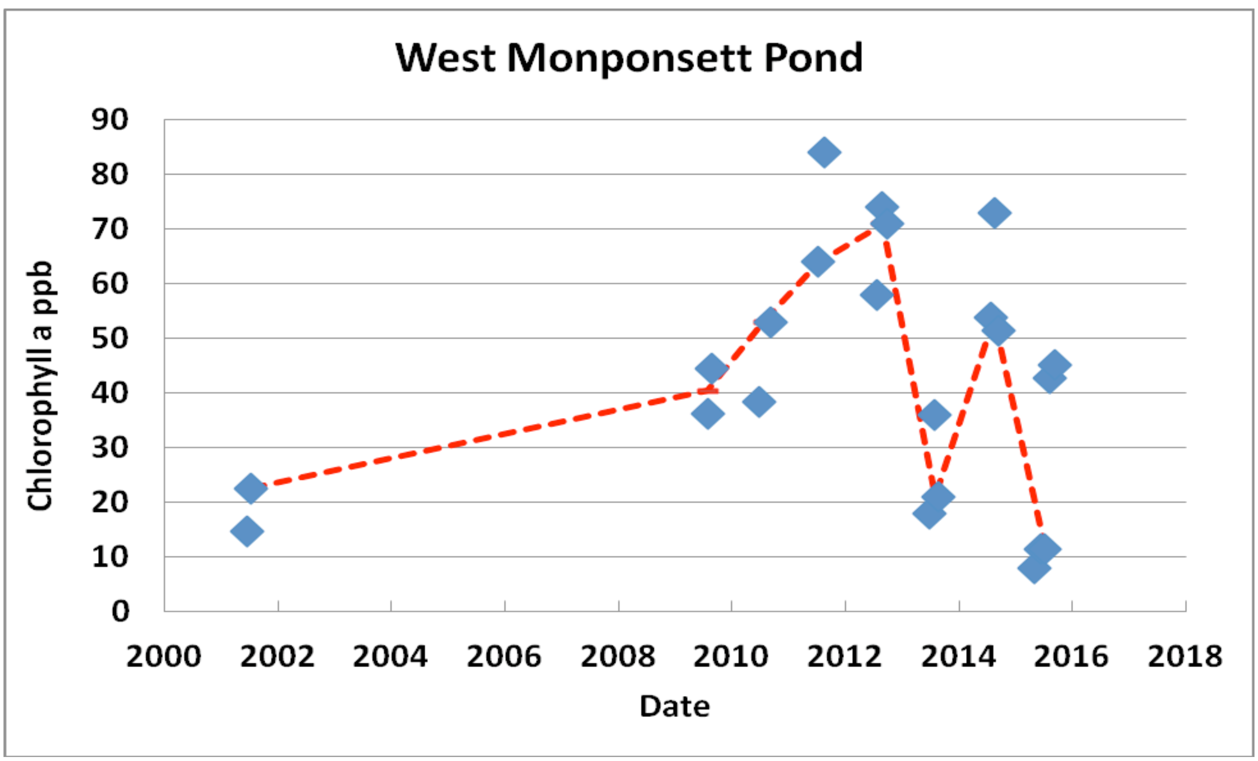

Figure 13. West Monponsett Pond Chlorophyll *a* . Summer median values are indicated by the dashed line.

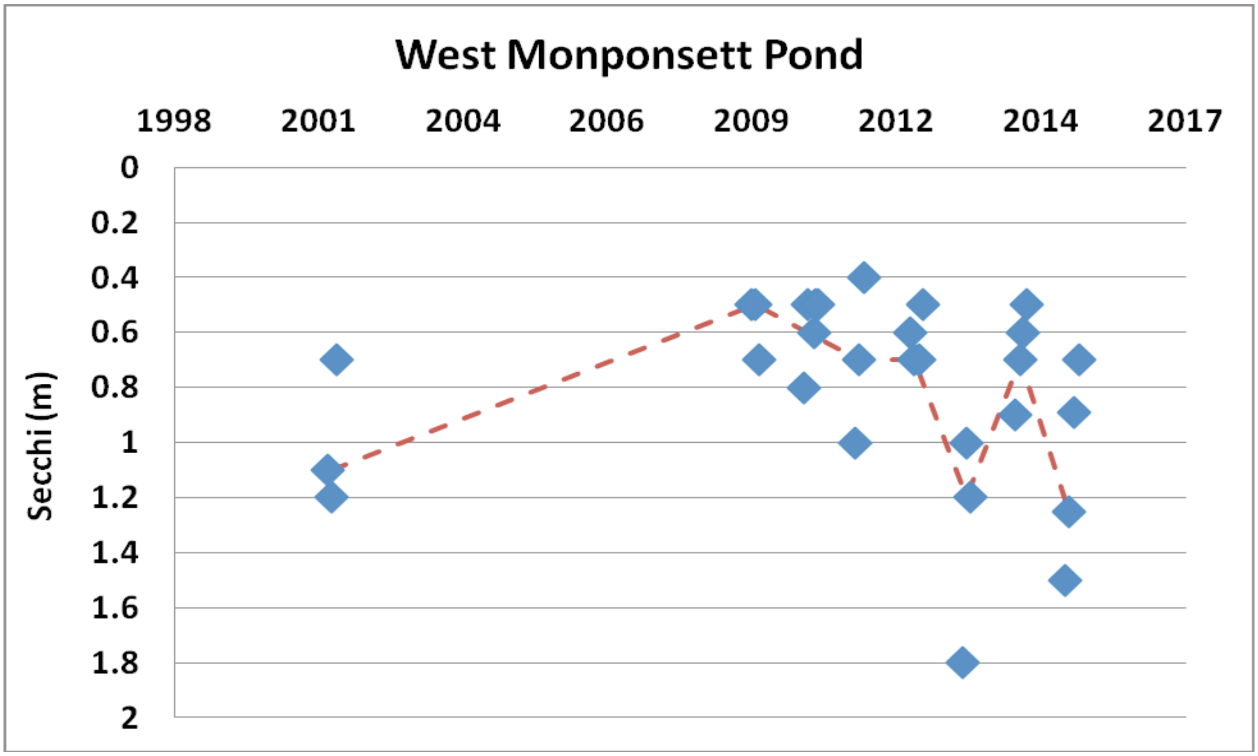

Figure 14. West Monponsett Pond Secchi disk transparency. Summer median values are indicated by the dashed line. (Note y axis reversed).

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 (MassDEP, 2016b).

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 Wittten (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; MassDEP 2016b).

Numeric Water Quality Target

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, 2016a) all of these lakes should generally meet the 1.2 meter Secchi disk transparency, the 16 ppb chlorophyll *a* concentration, 5 mg/l dissolved oxygen concentration, have less than 25% non-rooted macrophytes and be free from frequent cyanobacteria blooms (>70,000 cells/ml) to be free of nutrient impairment unless the exceedence 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 some times when the biological thresholds are exceeded.   The target TP concentrations for each waterbody in the system are listed on Table 9.

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 0.023 mg/l total phosphorus for clear (not tea colored) lakes that are dominated by groundwater seepage and 0.048 mg/l 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 clearwater lakes (MassDEP 2003, 2004, 2007a, 2007b, 2009, 2013).

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. 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 was not listed as impaired in the 2014 Integrated List of waters (MassDEP, 2015) but comparing the recent data on *Lemna* (duckweed) percent cover on the pond to our CALM assessment threshold of 25%, leads us to conclude the pond is in fact impaired by nutrients. 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 28 ppb which represents a reduction in loading of about 55 percent. This target is appropriate based on previous MassDEP lake surveys (MassDEP 2003, 2004, 2007a, 2007b, 2009, 2013). Furthermore, relatively high color in the impoundment which averages about 55 PCU of true color suggests a higher TP concentration may be appropriate. Given that this impoundment is tributary to a water supply a target of 28 ppb was chosen.

East Monponsett Pond is a lake 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 lake has been declining, 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. A compromise target of 20 ppb TP was 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 pond averaged 20 ppb TP the lake met the CALM thresholds for chlorophyll a and Secchi disk transparency (see Figure 7 and Figure 8).

West Monponsett Pond is equally complex in hydrology as 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 the pond in recent years). During times of diversion, this basin may also supply water to Silver Lake which is used for the City of Brockton's water supply (via East Monponsett Pond), and therefore a more restrictive TP concentration target is appropriate. The target concentration for West Monponsett is 20 ppb based on the LLRM model estimates that chlorophyll a will meet the target of 16 ppb approximately 96% of the time. 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 LRRM model was used to estimate each pond's target load for total phosphorus based on the target concentrations 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 LRRM 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, 207 kg/yr, 41 kg/yr and 199 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 ug/L, 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 threshold loads will have predicted peak chlorophyl *a* values of approximately 27 ug/L and 25 ug/L respectively. In the future, peak chlorophyll a values may occasionally exceed the 16 ug/L criterion. The goal though of this TMDL is to reduce the extent and severity of current algae blooms and ensure that all water quality standards are met.

Pollutant Load Allocations

Waste Load Allocation

Based on estimated current stormwater loads of TP phosphorus to East Monponsett Pond and West Monponsett Pond a 50% reduction in stormwater loads has been allocated in this TMDL. Although this approaches the limit of technology for stormwater treatment systems, there are treatment systems which can obtain this level of nutrient removal. In addition when a number of technologies are used and best management practices are followed, it should be possible to achieve these reductions. The allocated Waste Load Allocations for East Monponsett Pond and West Monponsett Pond watersheds are 18.6 kg/yr and 10.5 kg/yr respectively.

Load Allocation

In order to reach the target threshold for Stetson Pond, a 50% reduction in total phosphorus loads is required from the watershed loads from low and medium intensity land use categories while 90% reduction in internal loading (Table 5). Watershed load reductions could come from reduction in loads from fertilizer use and stormwater runoff.

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). A 50% reduction in loads from developed land categories will be necessary. 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.

The White Oak Reservoir will require reductions in total phosphorus loading from the landuse categories cranberry bogs (~88%); the same as described above for East Monponsett Pond. In addition a 25% reduction in loads from developed land categories will be necessary (Table 7).

The West Monponsett Pond will require an approximate 71% reduction in its total phosphorus loading in order to meet the threshold load of 198.9 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. Loads from developed land categories will need to be reduced by 50%.

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 71% as shown in Table 9.

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

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	7.6	7.6	0.0	0%
Internal	6.9	0.7	6.2	-90%
Septic System	10.8	10.8	0.0	0%
Watershed Load				
Low Intensity Development	16.3	8.1	8.1	-50%
Medium Intensity Development	13.2	6.6	6.6	-50%
Natural	6.3	6.3	0.0	0%
Abandoned Cranberry Bogs	4.4	4.4	0.0	0%
Forested Wetland	1.6	1.6	0.0	0%
Non-Forested Wetland	1.3	1.3	0.0	0%
Low Intensity Agriculture	0.9	0.9	0.0	0%
Total Watershed Load	44.1	29.4	14.7	-33%
Total Load Allocation	69.3	48	21	-30%

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

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	22.0	21.99	0.00	0%
Internal	30.0	30.00	0.00	0%
Septic System	16.2	16.24	0.00	0%
Watershed Load				
High Intensity Ag. (bog)	100.0	11.6	88.3	-88%
Medium Intensity Development	33.5	16.8	16.8	-50%
Forested Wetland	40.4	40.4	0.0	0%
Low Intensity Development	23.5	11.8	11.8	-50%
Natural	23.3	23.3	0.0	0%
High Intensity Development	5.4	2.7	2.7	-50%
Non-Forested Wetland	5.6	5.6	0.0	0%
Low Intensity Agriculture	4.7	4.7	0.0	0%
Abandoned Cranberry Bogs	3.4	3.4	0.0	0%
Total Watershed Load	239.7	120.2	119.5	-50%
Total Load Allocation	308.0	188.4	119.5	-39%
Stormwater Load By Landuse				
High Intensity Development	3.2	1.6	1.6	-50%
Medium Intensity Development	19.9	10.0	10.0	-50%
Low Intensity Development	14.0	7.0	7.0	-50%
Wasteload Allocation	37.2	18.6	18.6	-50%
Total Load	345	207	138	-40%

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

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	1.2	1.2	0.0	0%
Internal	0.0	0.0	0.0	0%
Septic System	0.0	0.0	0.0	0%
Watershed Load				
High Intensity Ag. (bog)	32.7	3.8	28.9	-88%
Low Intensity Development	17.0	12.7	4.3	-25%
Forested Wetland	8.9	8.9	0.0	0%
High Intensity Development	5.2	3.9	1.3	-24%
Natural	4.8	4.8	0.0	0%
Medium Intensity Development	3.1	2.3	0.8	-25%
Non-Forested Wetland	2.9	2.9	0.0	0%
Abandoned Cranberry Bogs	0.5	0.5	0.0	0%
Low Intensity Agriculture	0.1	0.1	0.0	0%
Total Watershed Load	75.1	39.9	35.2	-47%
Total Load Allocation	76	41	35	-46%

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

Source	Total Phosphorus Load (kg/yr)			% Reduction
	Current	Allocated	Reduction	
Atmospheric	24.9	24.9	0.00	0%
Internal	293.5	29.4	264.18	-90%
Septic System	13.0	13.0	0.00	0%
Watershed Load				
High Intensity Ag. (bog)	198.0	23.0	174.9	-88%
Forested Wetland	42.6	42.6	0.0	0%
Medium Intensity Development	25.1	12.6	12.6	-50%
Low Intensity Development	24.5	12.2	12.2	-50%
Natural	15.3	15.3	0.0	0%
Non-Forested Wetland	11.8	11.8	0.0	0%
High Intensity Development	5.6	2.8	2.8	-50%
Abandoned Cranberry Bogs	0.8	0.8	0.0	0%
Low Intensity Agriculture	0.1	0.1	0.0	0%
Total Watershed Load	323.7	121.2	202.5	-63%
Total Load Allocation	655.1	188.4	466.7	-71%
Stormwater Load By Landuse				
High Intensity Development	2.1	1.1	1.1	-50%
Medium Intensity Development	9.5	4.8	4.8	-50%
Low Intensity Development	9.3	4.6	4.6	-50%
Wasteload Allocation	20.9	10.5	10.5	-50%
Total Load	676.1	198.9	477.2	-71%

Table 9. 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	20	207	0.57	40%
White Oak Brook Reservoir	50*	76	28	41	0.11	46%
West Monponsett	68	676	20	199	0.54	71%

*Measured TP was 35 ppb (see text).

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.

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 (http://www.mass.gov/eea/waste-mgnt-recycling/air-quality/green-house-gas-and-climate-change/climate-change-adaptation/climate-change-adaptation-report.html). 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. In light of 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. As noted above 20 ppb summer average in 2010 and 2015 in East Monponsett has been shown to meet all designated uses so this appears to be a conservative target 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 clearwater groundwater seepage lakes. The 20 ppb TP target for these lakes has 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 (28 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 meet 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 accounting 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 is of particular concern because it is also listed as impaired on the 2014 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 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 sewering 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 filter bed to filter and absorb 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 (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 no impacts to the rare mussels was reported (Biodrawversity, 2014). The estimated total buffered alum treatment through 2015 is approximately 12 g/m^2 Al. An estimated additional 38 g/m^2 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 controls 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 sufficient. 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 sufficient 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 0.05 mg/l (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_2O_5 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 sufficient nitrogen to the crop while reducing phosphorus applications to a target of 10 lb/ac/year phosphorus 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. Doing so will ensure that excess nitrogen does not 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 water of 3.5 feet of water per acre bog at a concentration of 0.05 mg/l 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 results in increased water discharged through the spillway with resulting excess 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.

Control of Other Sources

The control of septic system inputs is recommended. Older homes with cesspools may be contributing disproportionate amounts of phosphorus to the groundwater near the lake.

Much of the data presented in this report is based upon accepted values from the scientific literature for phosphorus contribution rates. For septic system contributions, the report uses the accepted values. However, a septic system (a.k.a., Title 5 system) can be functioning in accordance with Massachusetts Title 5 requirements, yet still fail to control phosphorus. Iron in the soil of the leaching field and downgradient of the system binds to the phosphorus in the wastewater, stopping its movement. Over time, as the iron becomes saturated with phosphorus, it cannot bind more phosphorus. This may be problematic with septic systems close to water bodies where there is little soil for the wastewater to flow through before it reaches the water body.

When the soil between the septic system and the water body reaches its phosphorus saturation point, phosphorus in septic system wastewater can pass through the Title 5 system and reach the water body. While the TMDL does not recommend a specific phosphorus input reduction from the septic systems around Monponsett Pond, MassDEP strongly encourages the Towns of Hanson and Halifax to better evaluate the potential impact of septic systems on Monponsett Pond and implement steps to minimize the impacts where possible. Replacement of old Title 5 systems with systems that are located further from the pond and designed to meet today's standards, could lower the impact that septic systems in Hanson and Halifax are having on the system. It should be noted that, in certain cases, replacement of the soils downgradient of and below the leaching field can significantly improve the phosphorus absorptive capacity between the wastewater discharge into the septic system and the pond, possibly providing significant phosphorus reductions.

In addition, 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 sewering 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 sewering and this would completely eliminate the septic system phosphorus loads to the lake from those homes.

With the exception of Peterson Swamp and the wetlands northwest of West Monponsett Pond, the TMDL study area is considered an urbanized area and will be included in the EPA issued NPDES Phase II stormwater permit. 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 the stormwater permits are available at: http://www.mass.gov/eea/agencies/massdep/water/wastewater/stormwater-programs.html. In addition to these measures substantial reduction in TP loads (50%) from stormwater will be required for select East Monponsett 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 a number of technologies used in combination.

Stormwater is targeted for a 50% reduction 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) (http://www.mass.gov/eea/docs/agr/pesticides/docs/plant-nutrient-regs-ag-land-factsheet-pd.pdf, http://www.mass.gov/eea/agencies/agr/pesticides/plant-nutrient-management.html).

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 a large number of 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). See the web site http://www.mass.gov/dep/water/resources/watershed.htm for many of these publications. In Addition, MassDEP 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 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.

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 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% reduction in stormwater loads to East Monponsett Ponds (Watersheds 2-7) and West Monponsett Pond (Watersheds 9-13)	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

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 possible based on known science. Massachusetts Executive Office of Energy and Environmental Affairs 2011 Climate Change Adaptation Report: http://www.mass.gov/eea/waste-mgnt-recycling/air-quality/green-house-gas-and-climate-change/climate-change-adaptation/climate-change-adaptation-report.html 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 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 past 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 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 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. The MassDEP will propose modifications to the TMDL analysis only in the event that 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 to improve water quality may be needed. One such methodology, micro-floc aluminum addition, may be necessary should watershed load reductions prove elusive.

Public Participation

The draft TMDL will be publicly announced and released for public comment at a date to be scheduled. Response to comments to be completed before the final TMDL is delivered to EPA.

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Appendix A: Landuse Analysis

Table A1: Landuse in Stetson Pond

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
1	Stetson Pond	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%
	Stetson Pond Total		204.0	100%

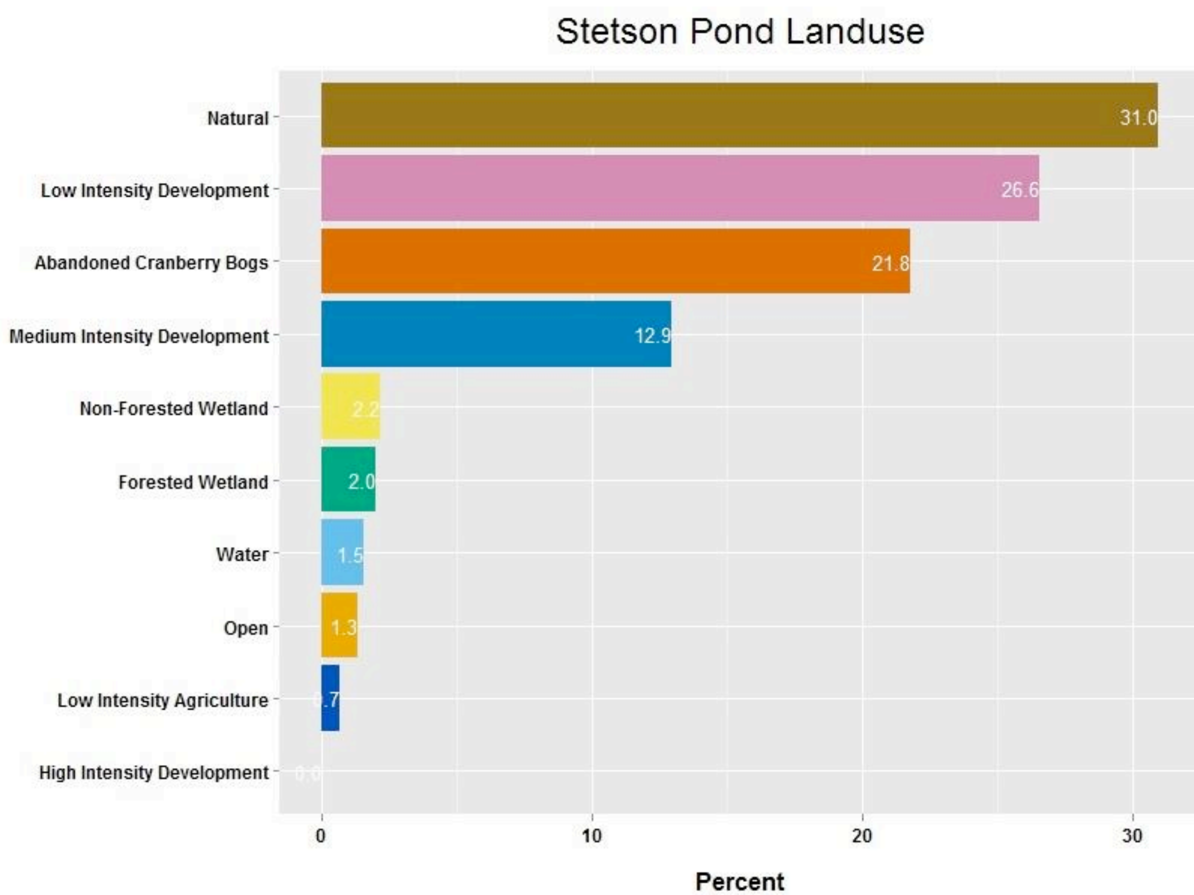


Figure A 1: Landuse in the Stetson Pond Watershed by %

Table A2: Landuse in Stetson Brook

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
2	Stetson Brook	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%
	Stetson Brook Total		154.09	100%

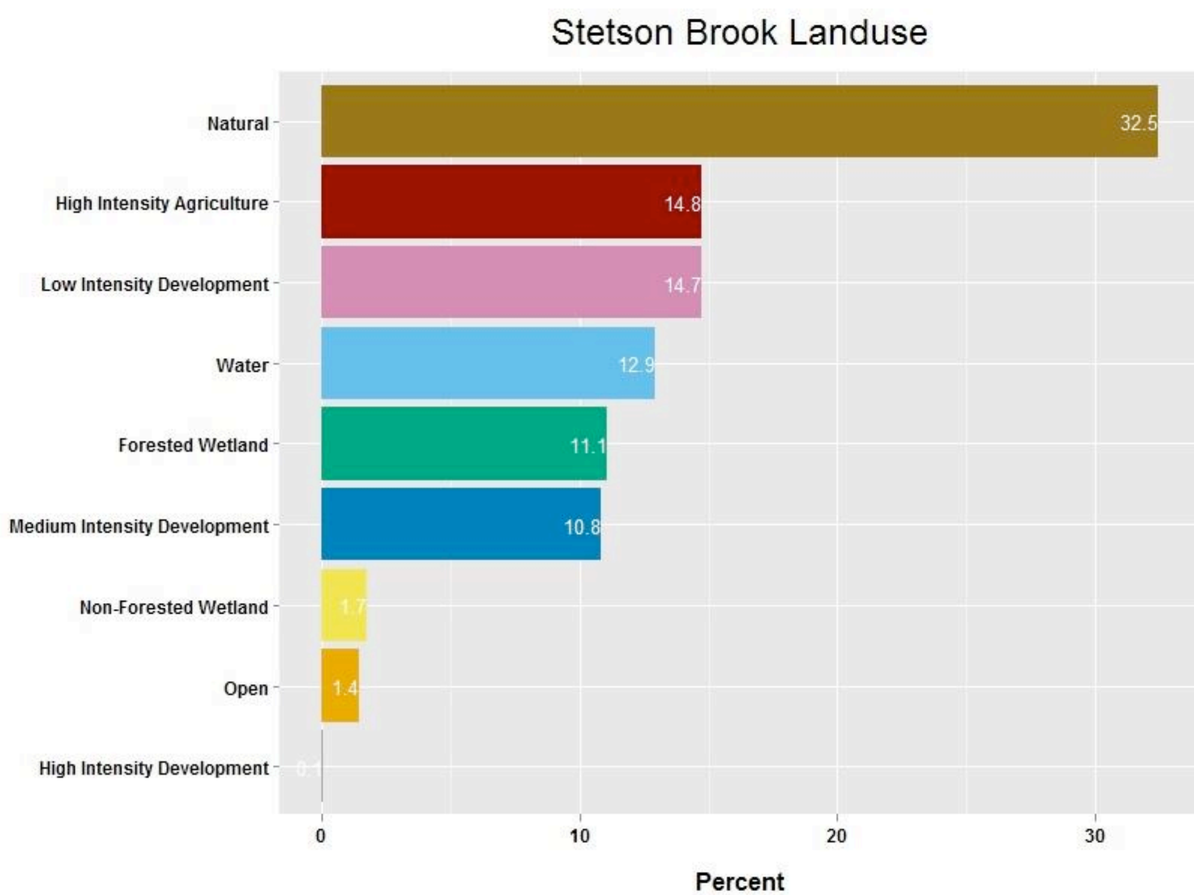


Figure A 2: Landuse in the Stetson Brook Watershed by %

Table A3: Swamp C Landuse

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
3	Swamp C	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%
	Swamp C Total		129.43	100%

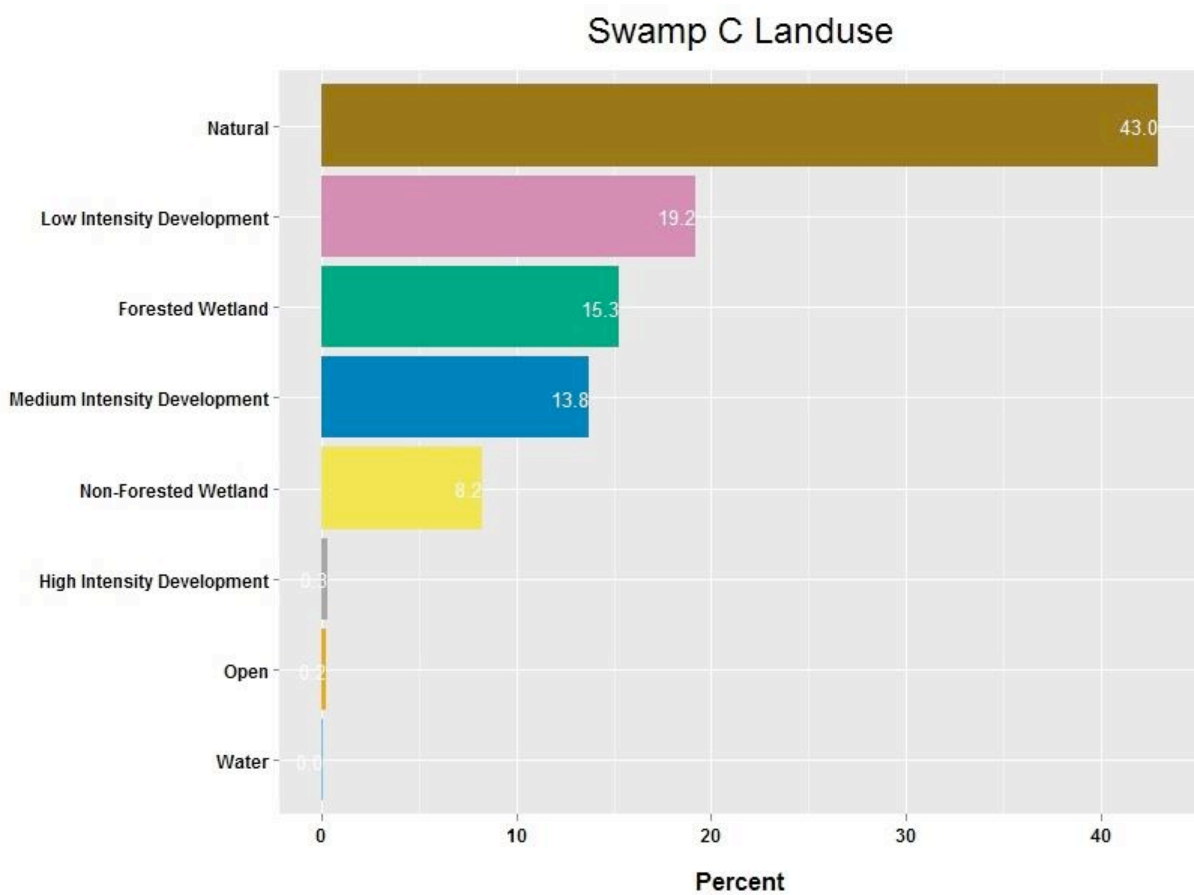


Figure A 3: Landuse in the Swamp C Watershed by %

Table A4: Monponsett Heights Landuse

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
4	Monponsett Heights	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%
	Monponsett Heights Total		31.57	100%

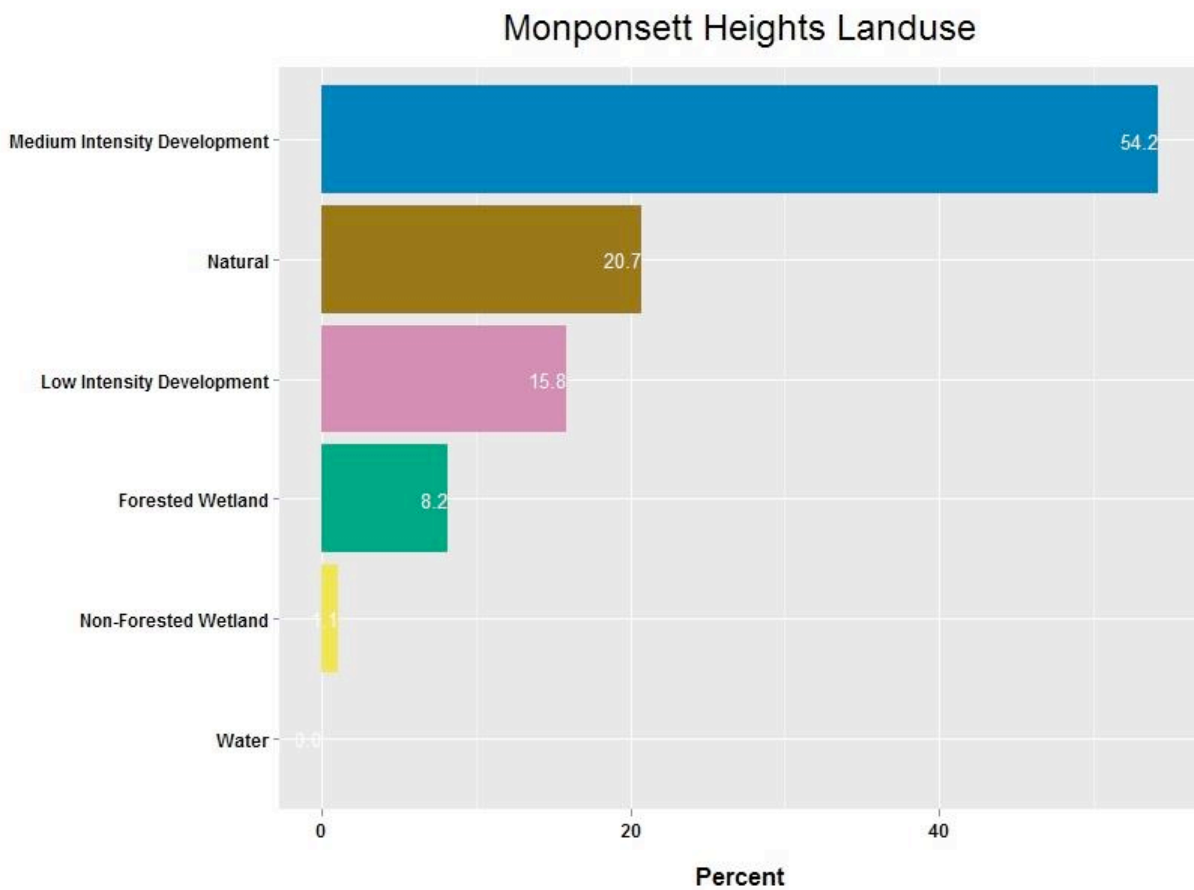


Figure A 4: Landuse in the Monponsett Heights Watershed by %

Table A5: Peterson Swamp Landuse

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
5	Peterson Swamp	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	Peterson Swamp Total		122.07	100%

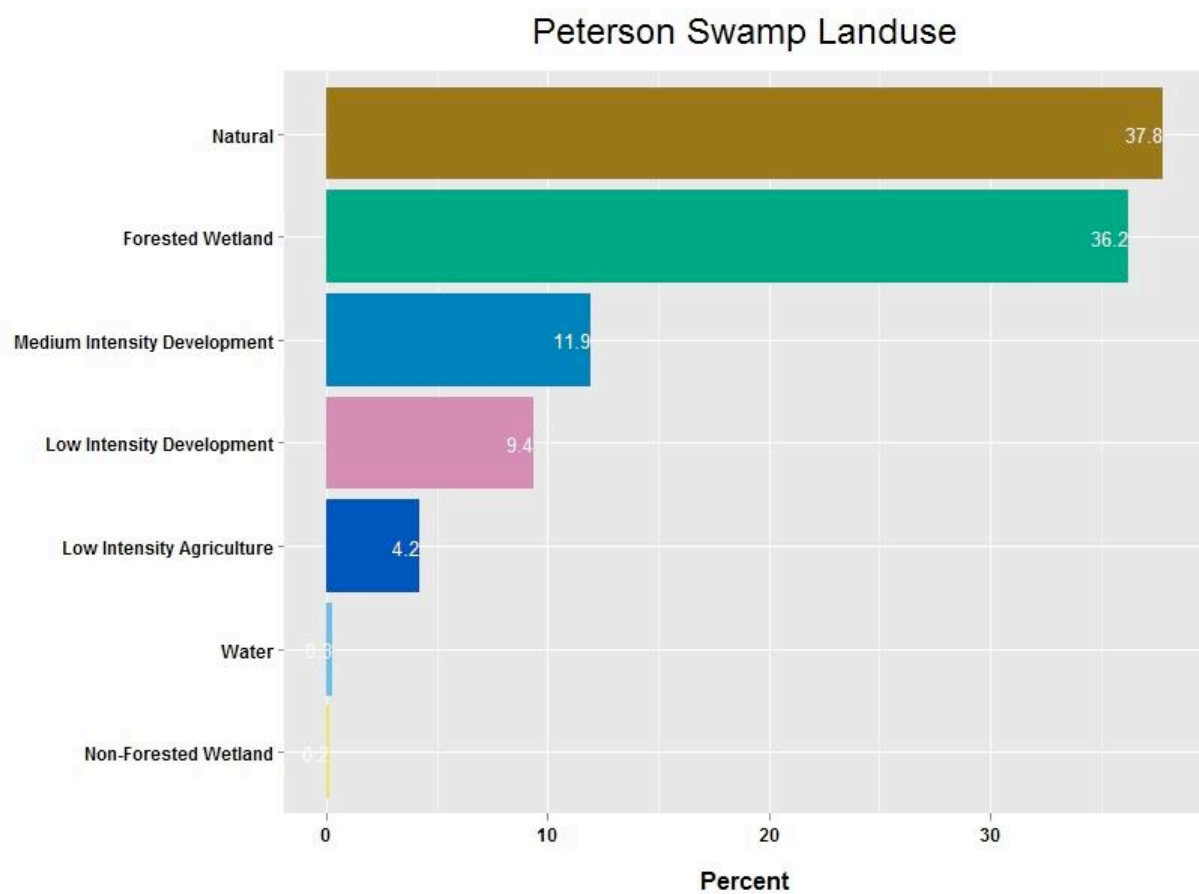


Figure A 5: Landuse in the Peterson Swamp Watershed by %

Table A6: Direct to East Pond Landuse

Shed #	Shed	Group	Area (Hectares)	% of Total Watershed Area
6	Direct to East Pond	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%
	Direct to East Pond Total		90.73	100%

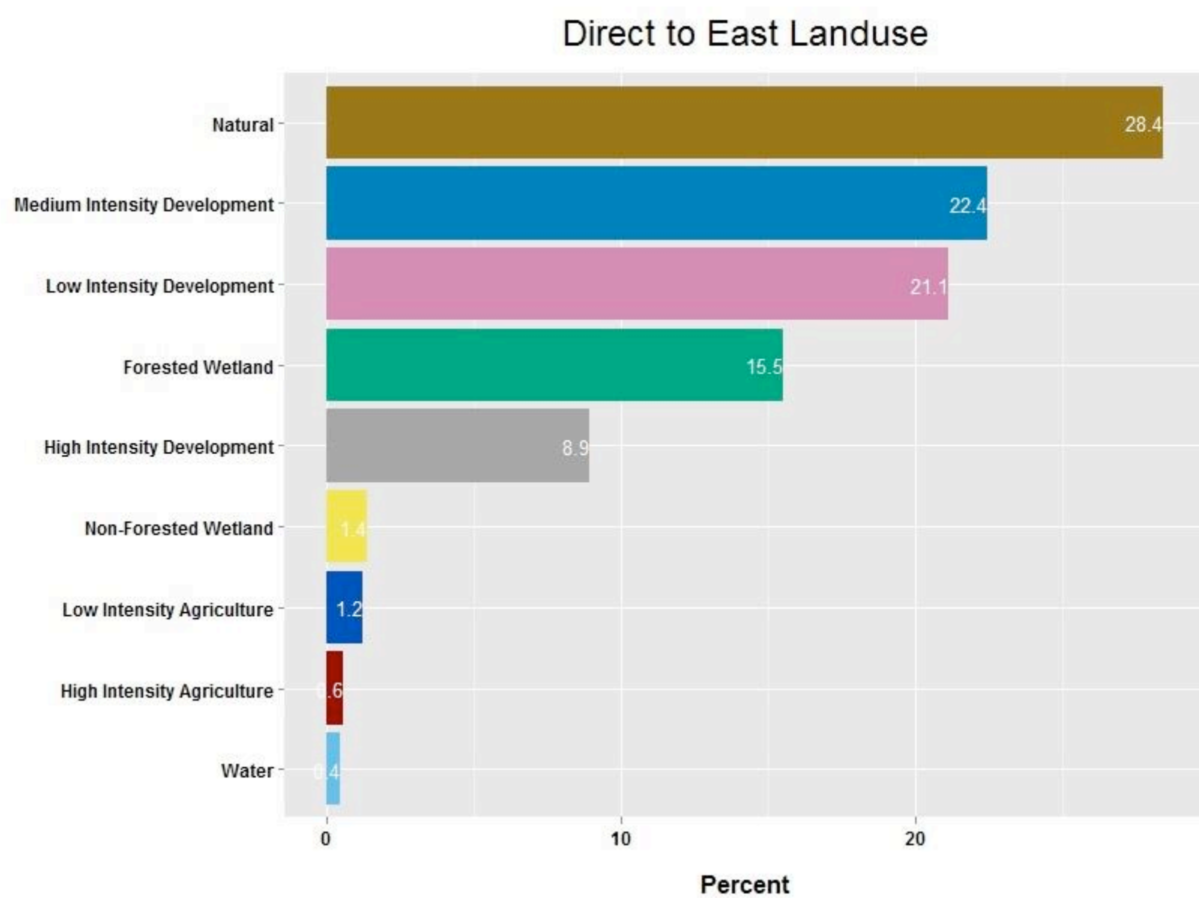


Figure A 6: Landuse in the Direct to East Pond Watershed by %

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%
All Landuse East Pond Total	769.98	100.0%

** 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%
	White Oak Reservoir Total		166.53	100%

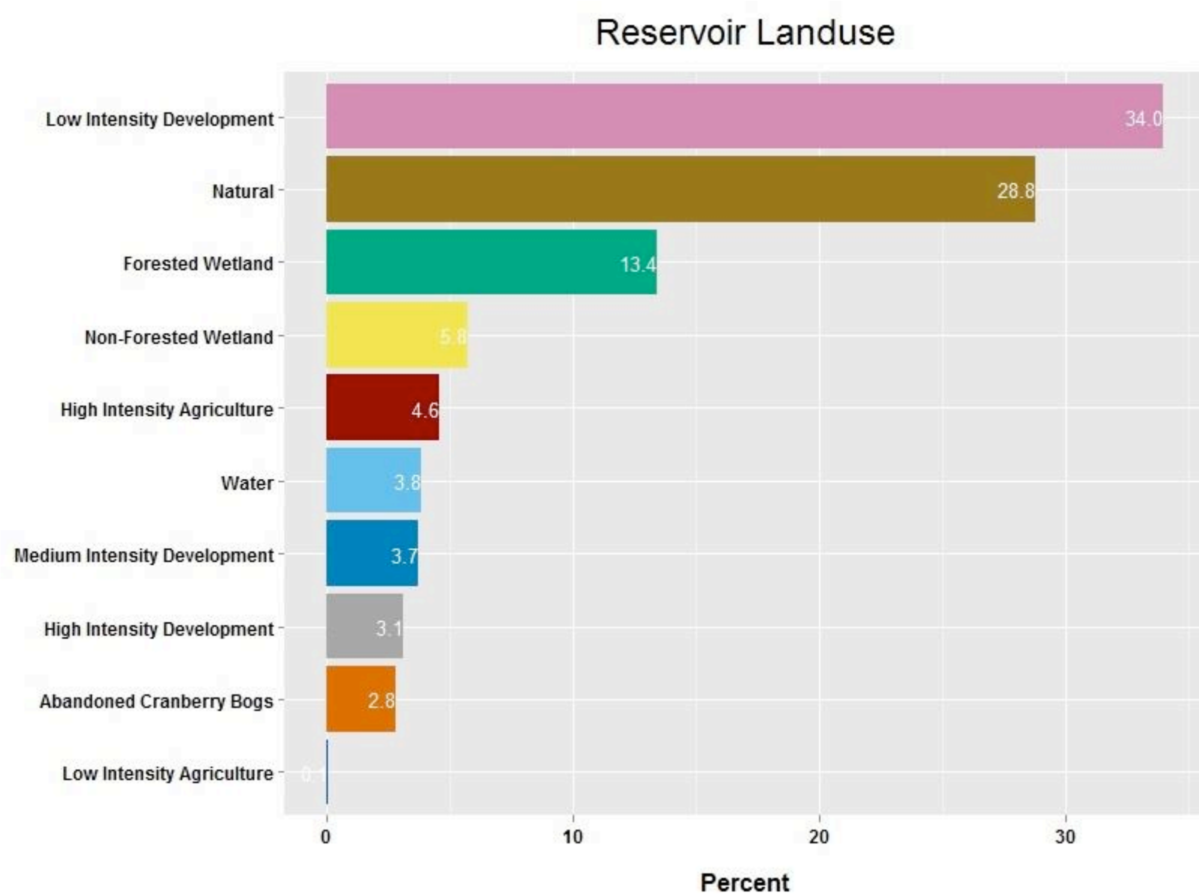


Figure A 7: Landuse in the White Oak Reservoir Watershed by %

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%

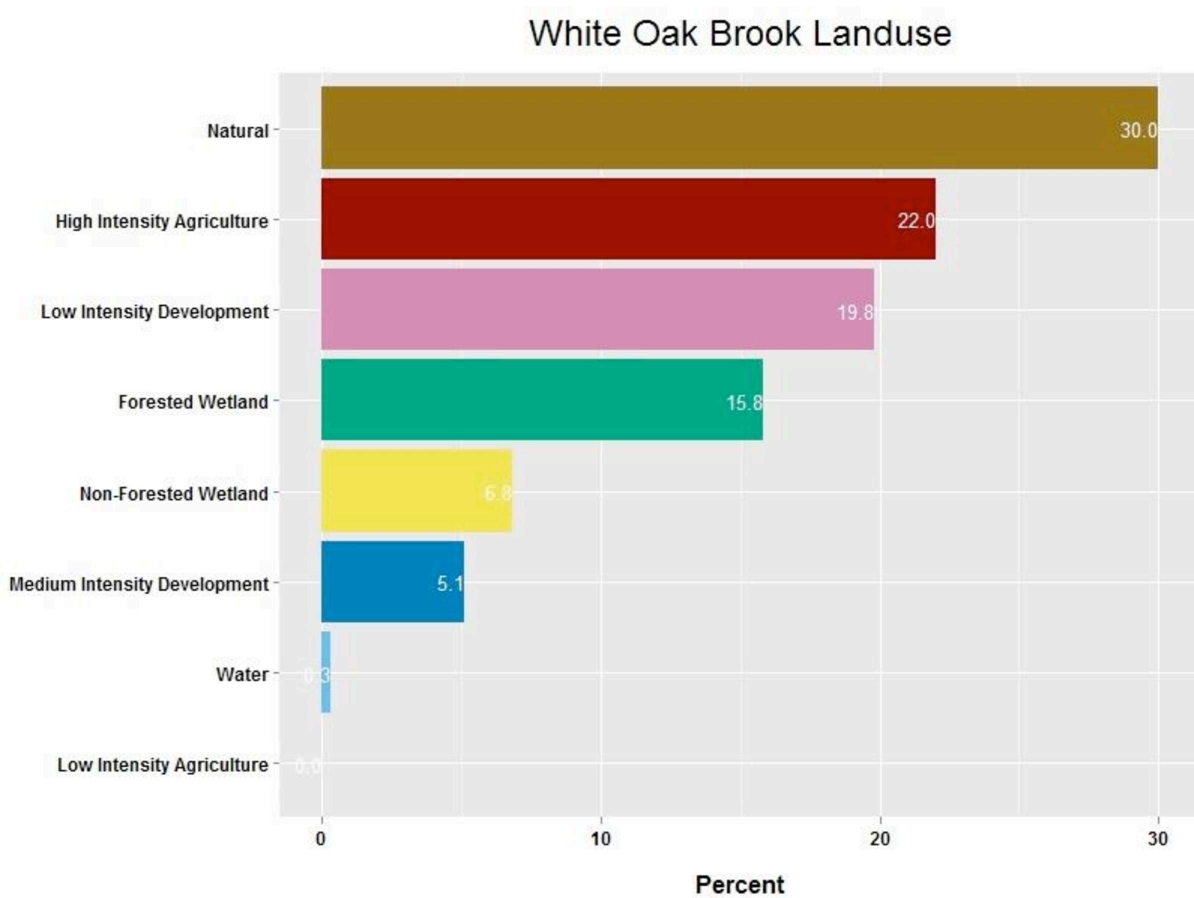


Figure A 8: Landuse in the White Oak Brook Watershed by %

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%

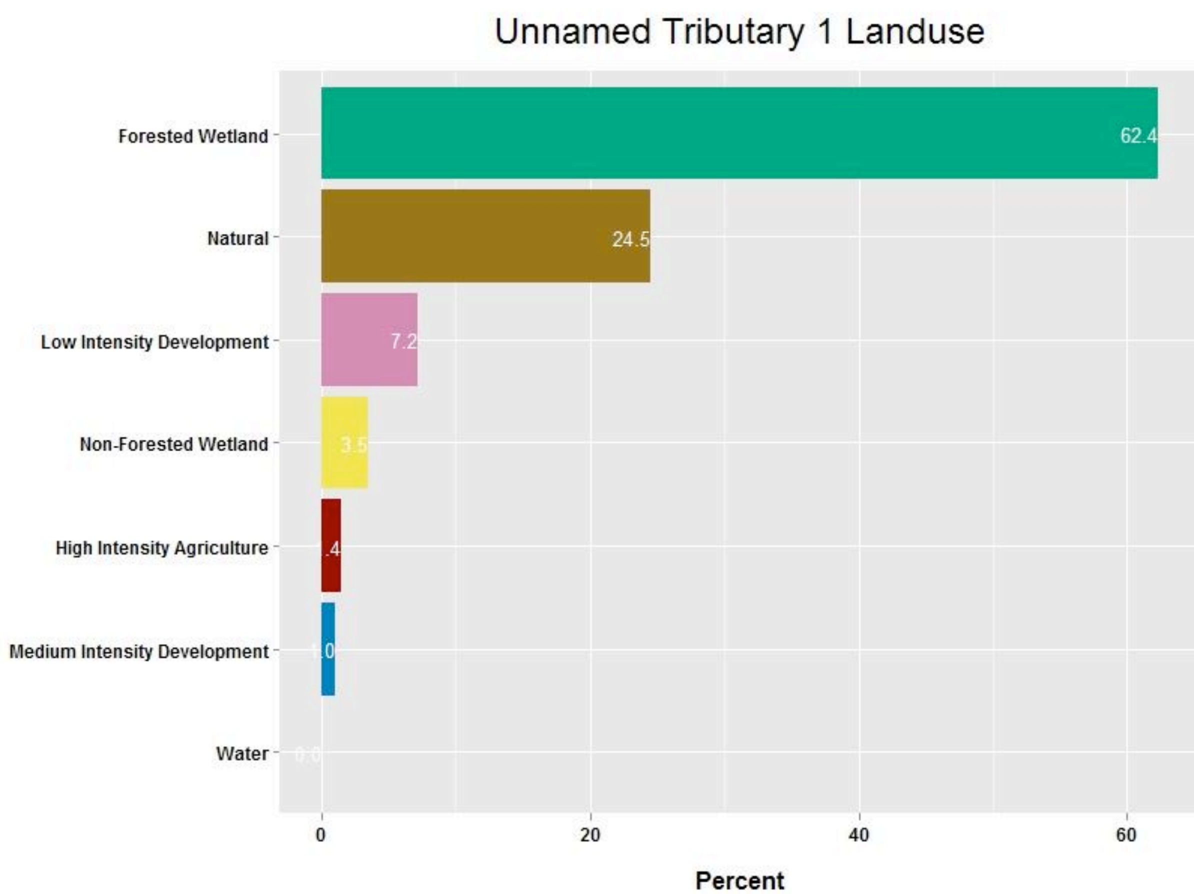


Figure A 9: Landuse in the Unnamed Tributary 1 Watershed by %

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%
	Unnamed Tributary2 Total		**108.65**	100%

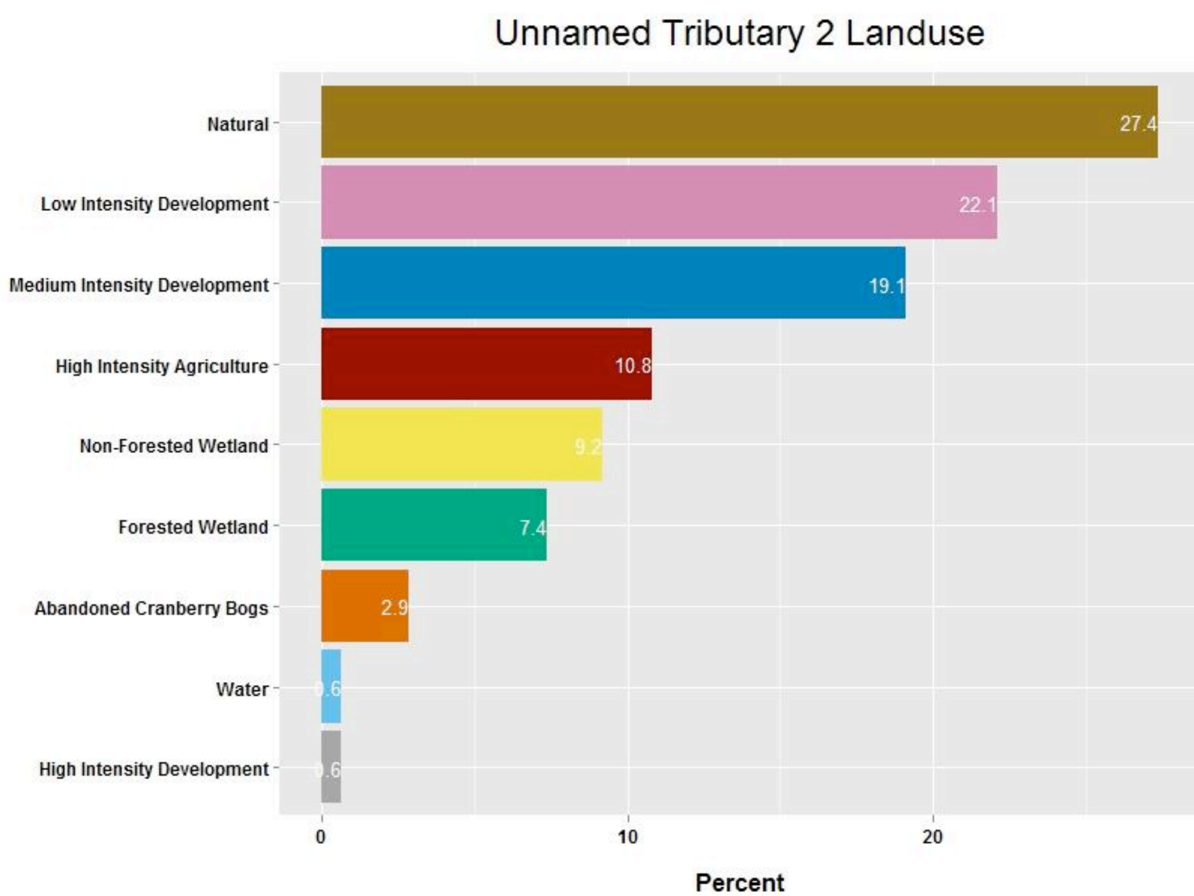


Figure A 10: Landuse in the Unnamed Tributary 2 Watershed by %

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%
	ArtFlow Unnamed Tributary3 Total		**21.44**	100%

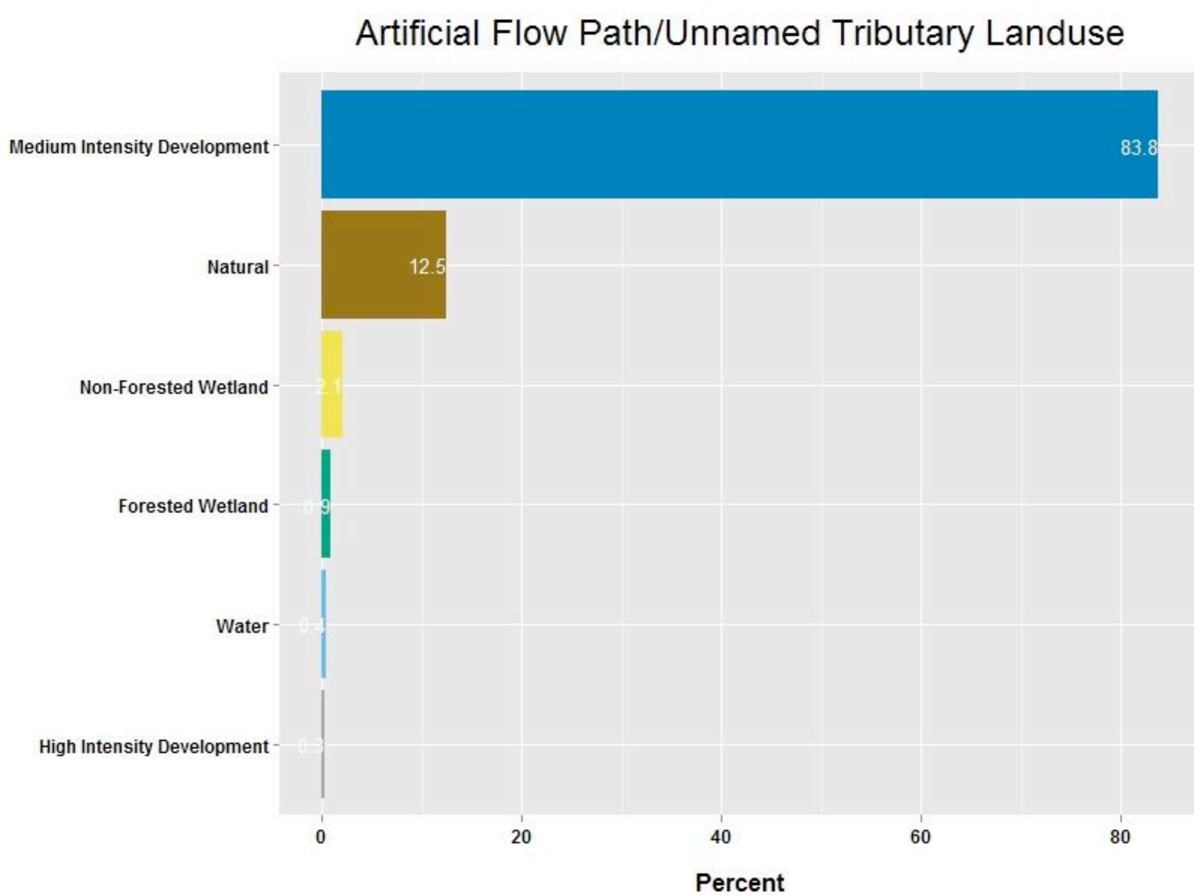


Figure A 11: Landuse in the Artificial Flow Path/Tributary Watershed by %

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%
	Direct to West Pond Total		94.21	1

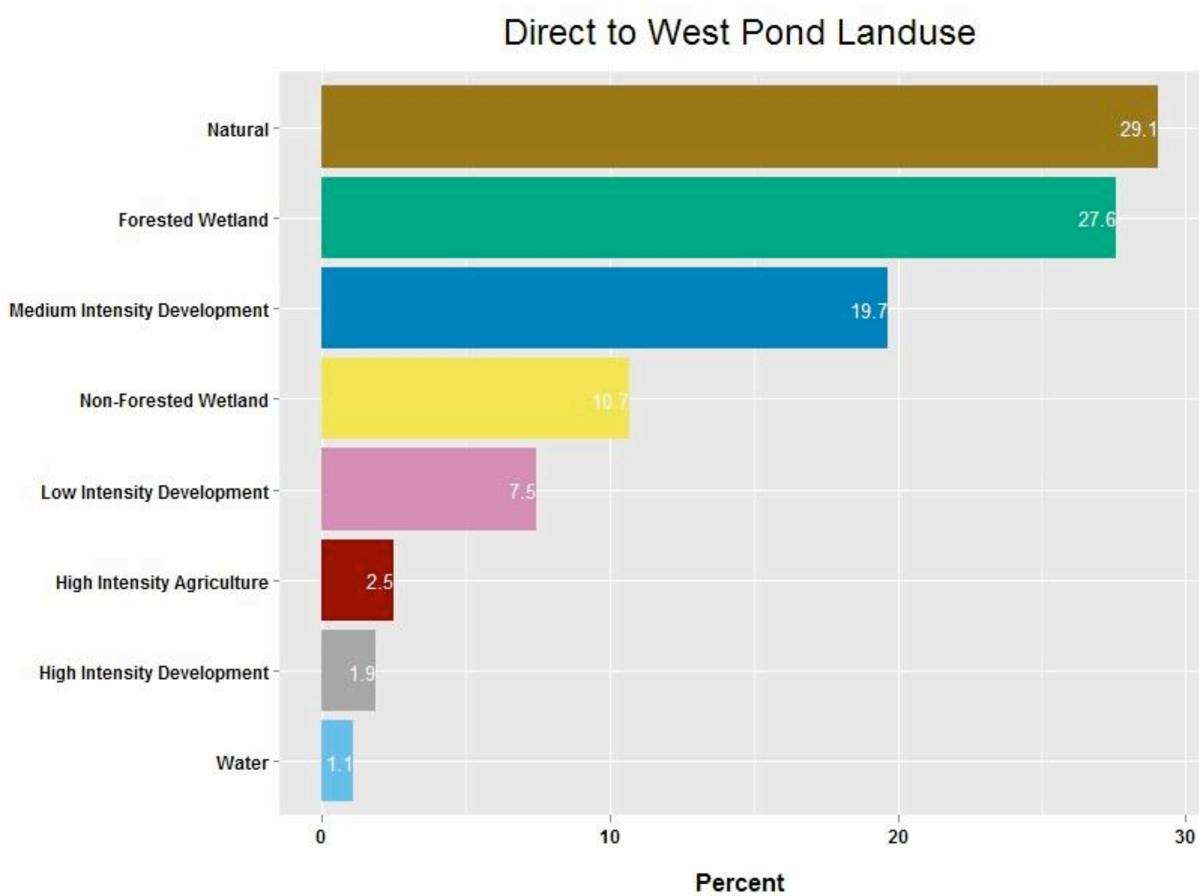


Figure A 12: Landuse in the Direct to West Pond Watershed by %

Appendix B: Select LLRM Information

Table B1: Water and TP Landuse Export Coefficient used for current condition LRRM 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/m2/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	m3/yr	From export model
A	Lake Area	m2	From data
V	Lake Volume	m3	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	((Vs+13.2)/2)/(((Vs+13.2)/2)+Qs)
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 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 this cell density 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, 4th Avenue Beach and Ocean Avenue Beach. Total cyanobacteria counts at the 4th 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 counts at the 4th 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 4th Avenue sampling site in 2013 and the bloom timing pattern was slightly different. During the period where total cyanobacteria counts exceeded the MA DPH Advisory Level, counts were on average 5.2 times the Advisory Level. The two highest cyanobacteria counts at this location in 2013 occurred on September 16 and November 18th 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 4th Avenue Beach, the boat launch and the Ocean Avenue Beach. The 4th 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 29th 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 1st (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 where total cyanobacteria counts exceeded the MA DPH Advisory Level, 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.

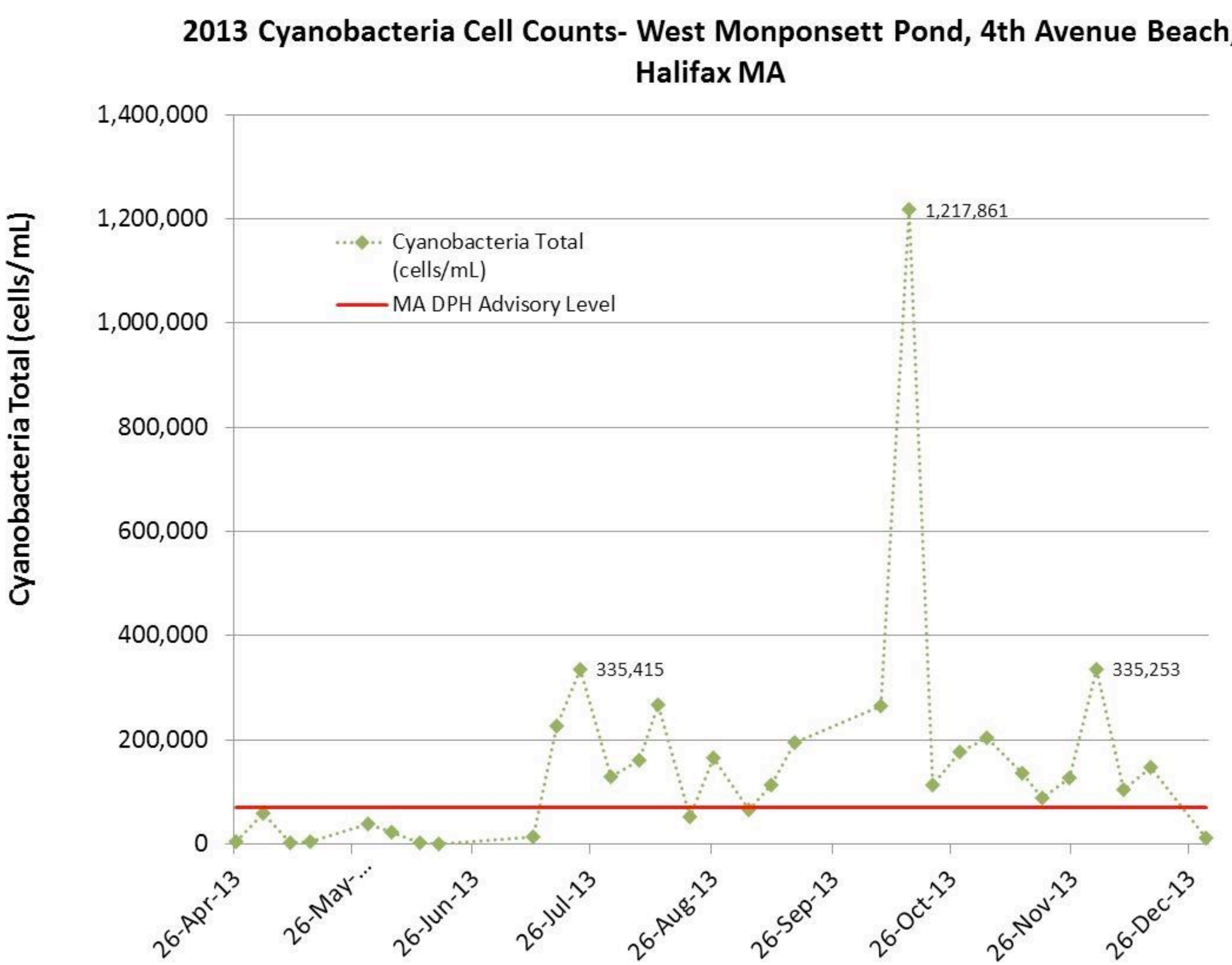


Figure C 1: West Monponsett Pond, 4th Avenue Beach, 2013 Cyanobacteria Cell Counts

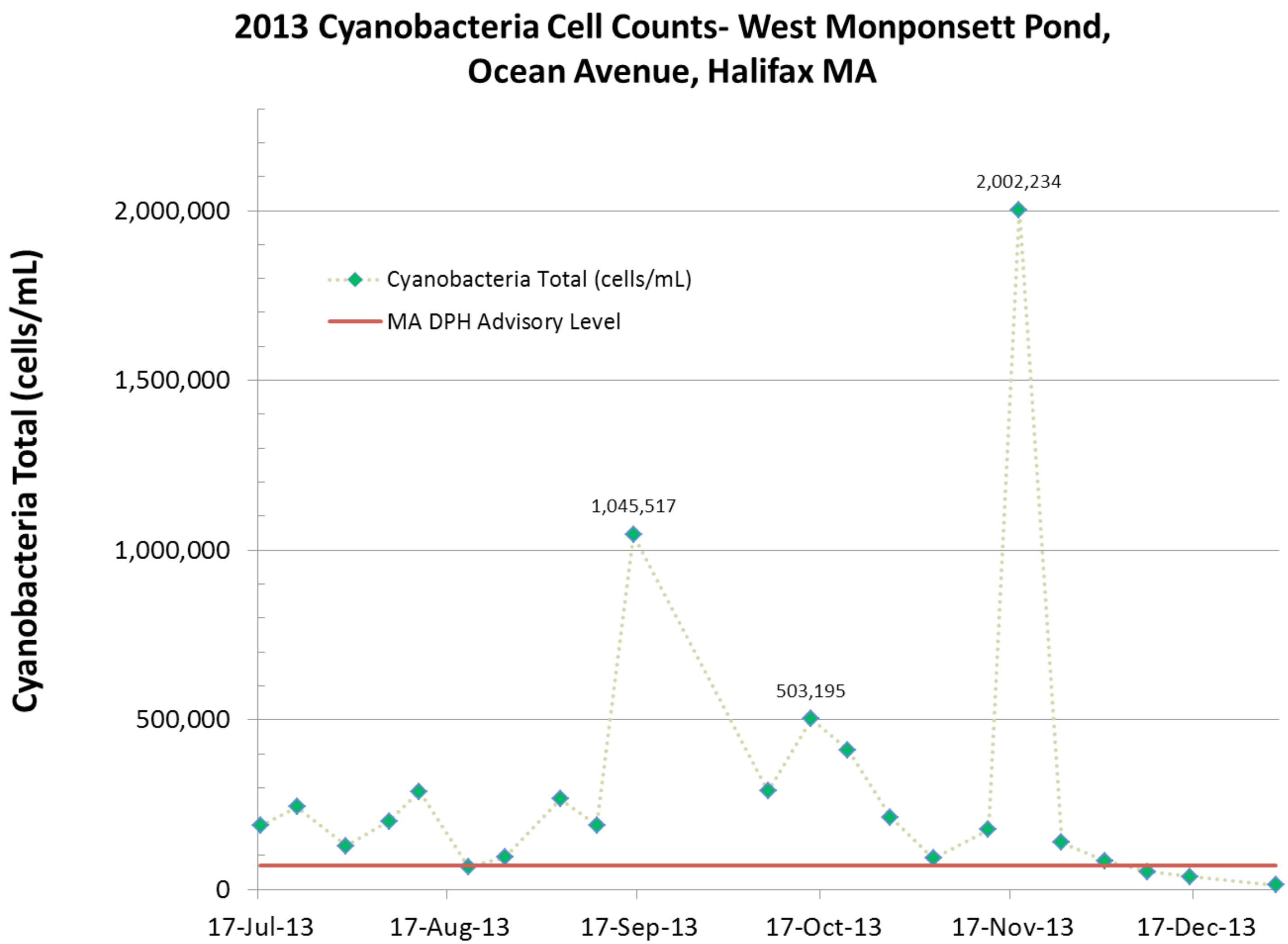


Figure C 2: West Monponsett Pond, Ocean Avenue Beach, 2013 Cyanobacteria Cell Counts

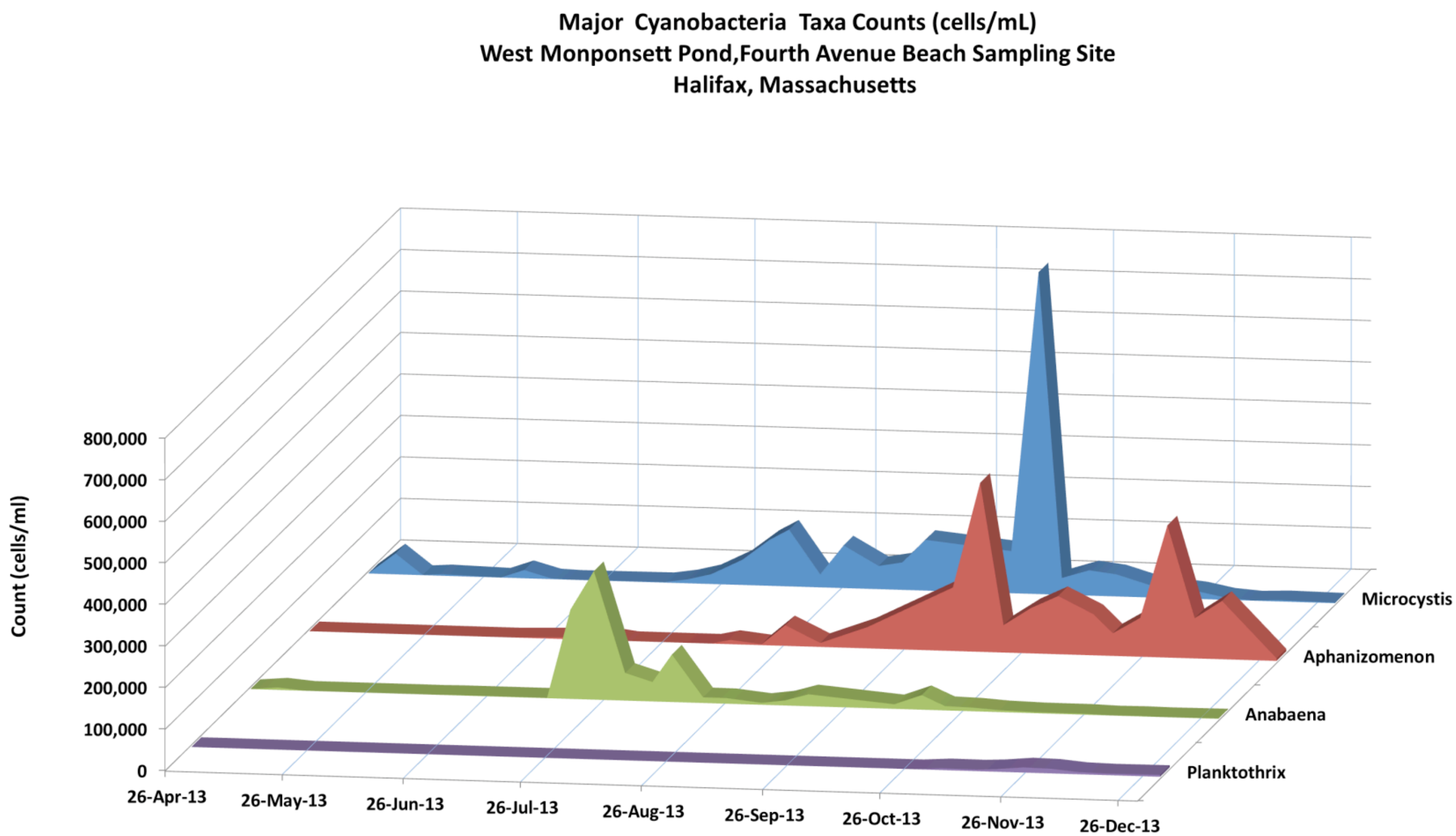


Figure C 3: West Monponsett Pond, 4th Avenue Beach, 2013 Major Cyanobacteria Taxa Counts (cells/mL)

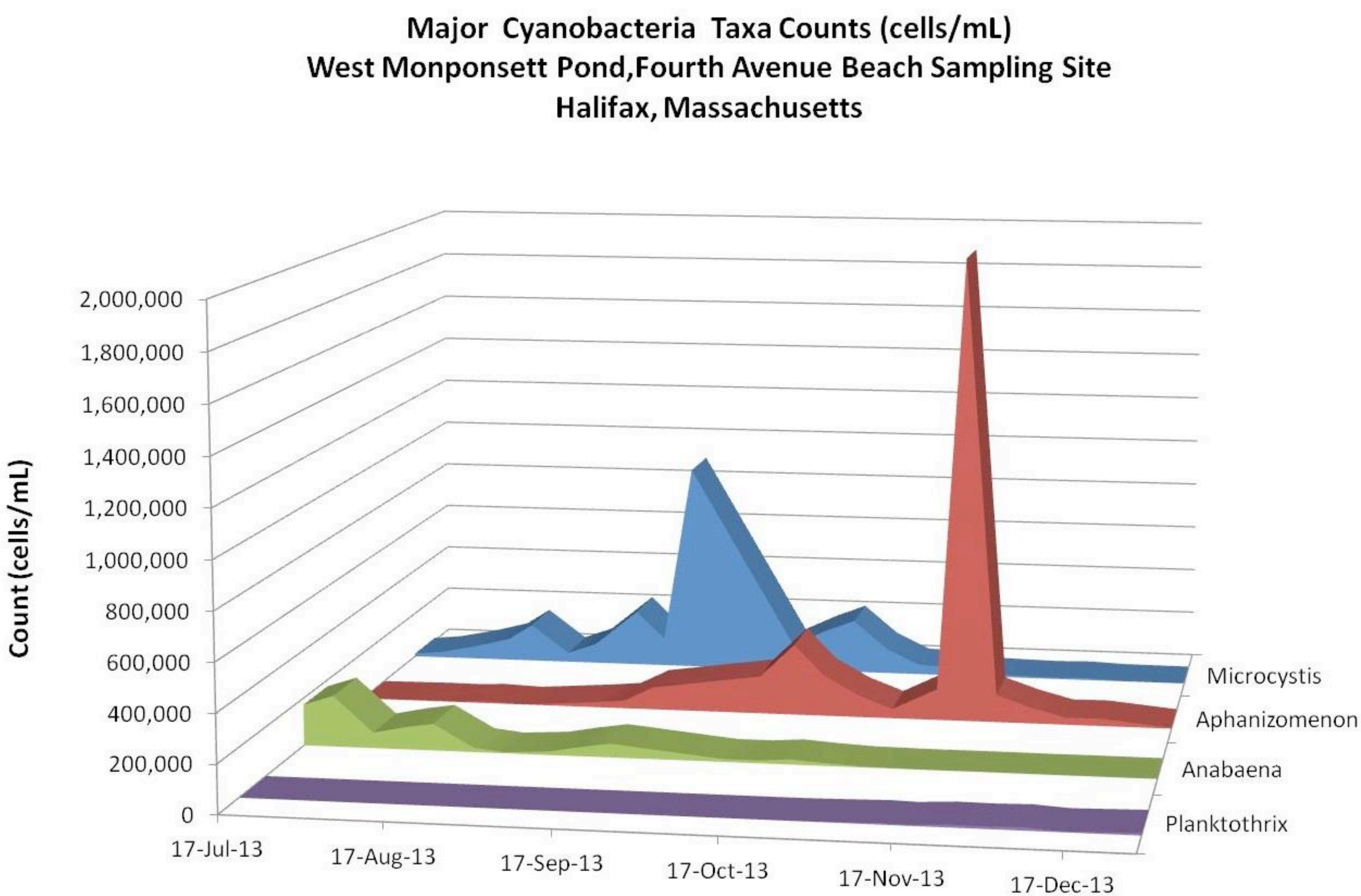


Figure C 4: West Monponsett Pond, Ocean Avenue Beach, 2013 Major Cyanobacteria Taxa Counts (cells/mL)

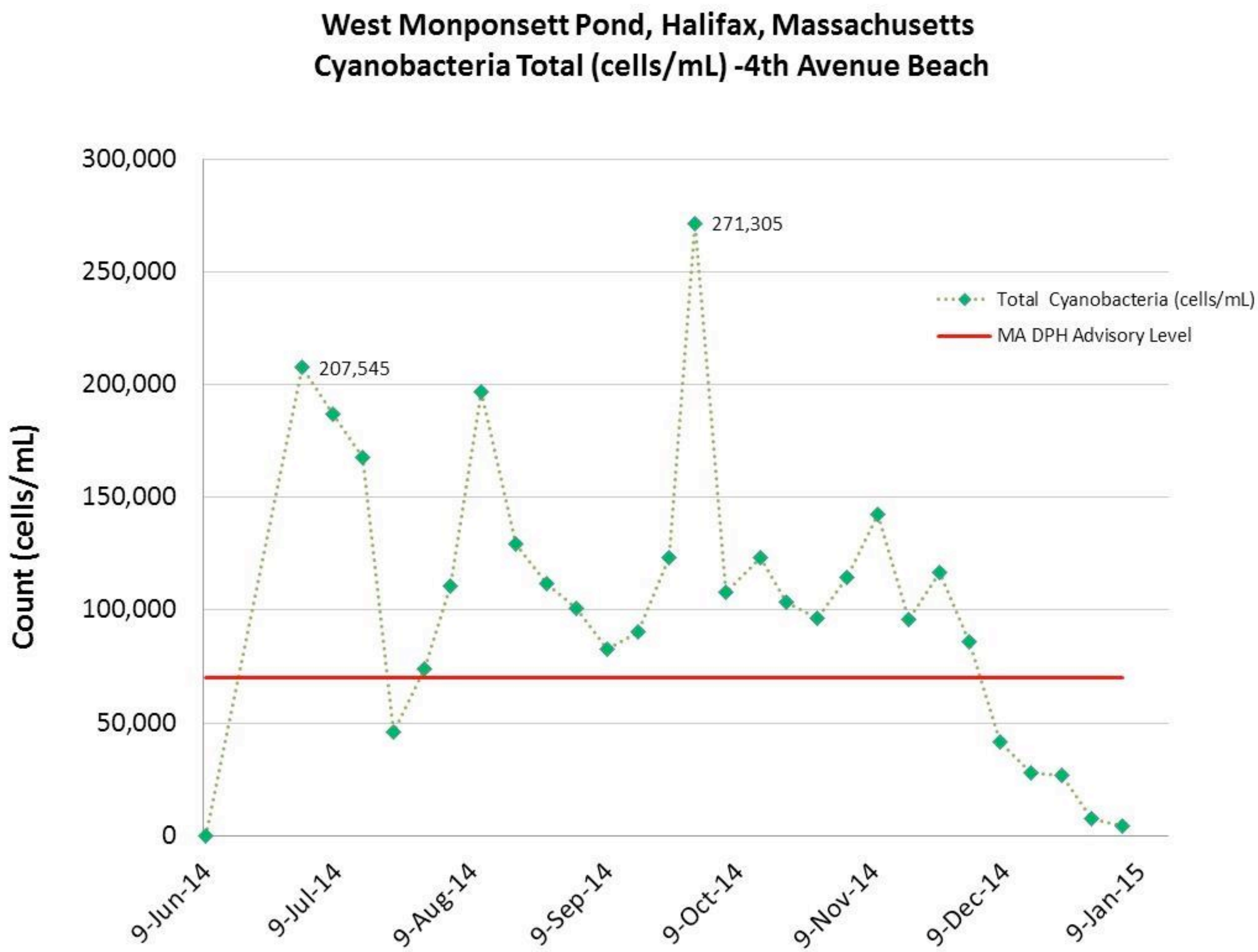


Figure C 5: West Monponsett Pond, 4th Avenue Beach, 2014 Cyanobacteria Cell Counts

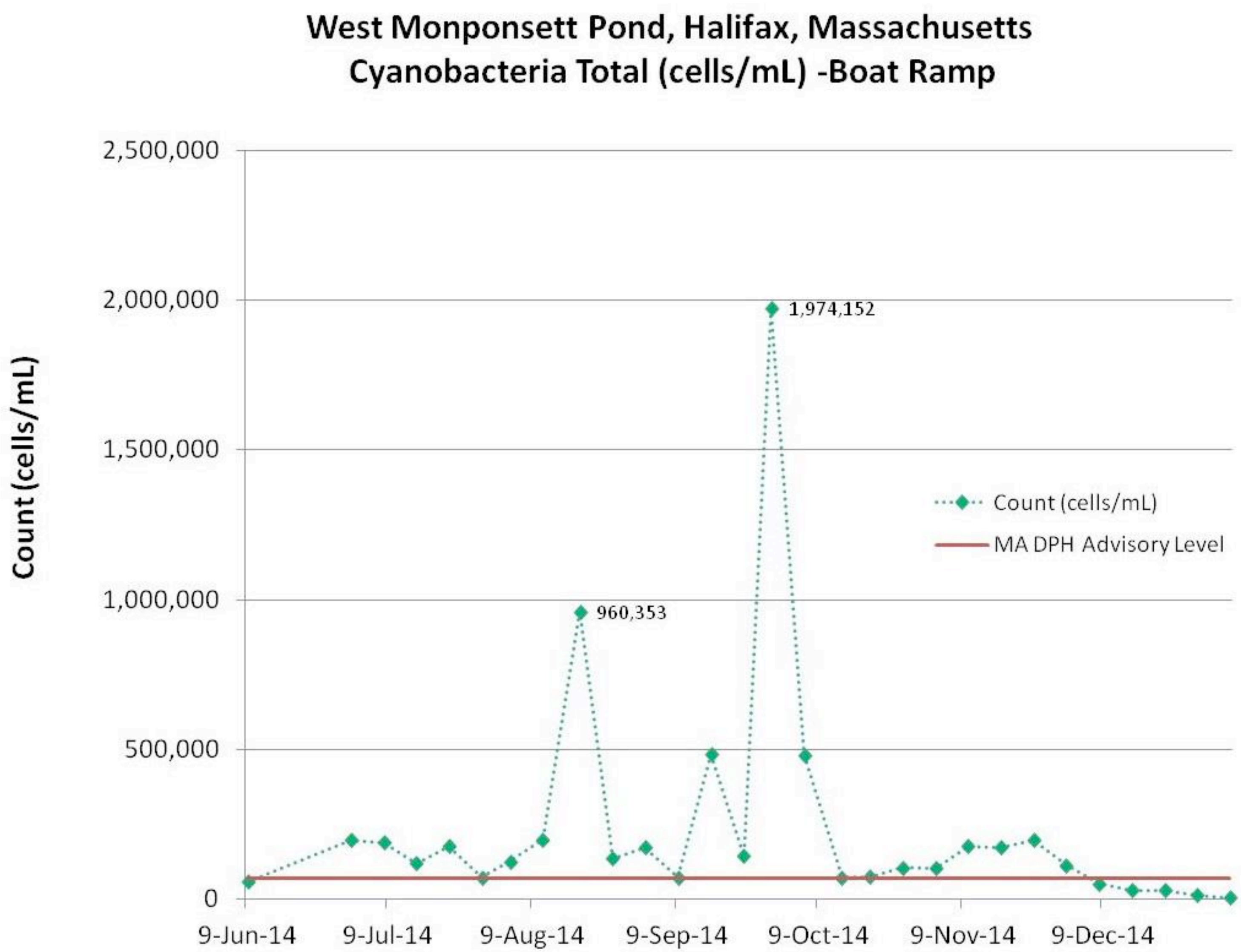


Figure C 6: West Monponsett Pond, Boat Ramp 2014 Cyanobacteria Cell Counts

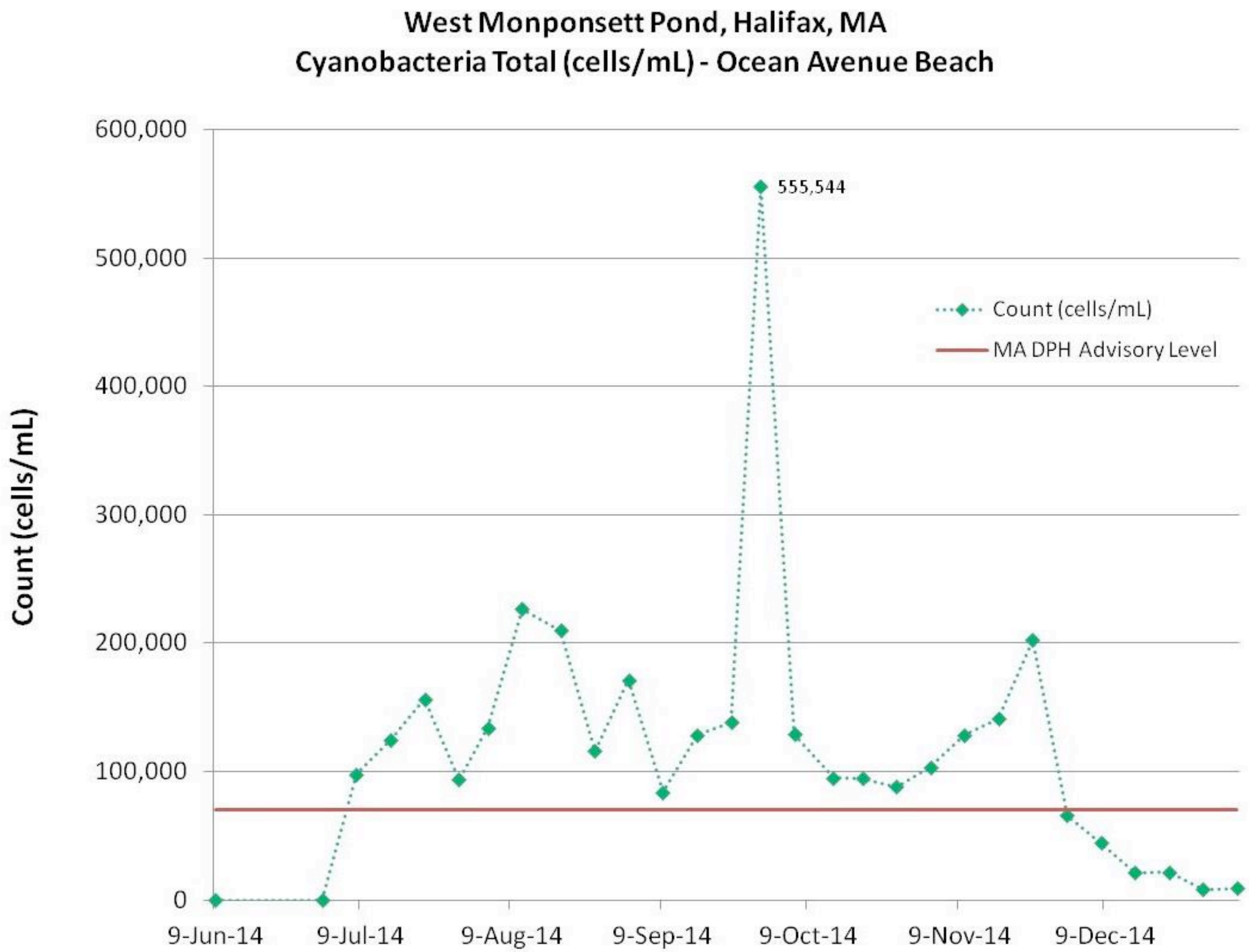


Figure C 7: West Monponsett Pond, Ocean Avenue Beach 2014 Cyanobacteria Cell Counts

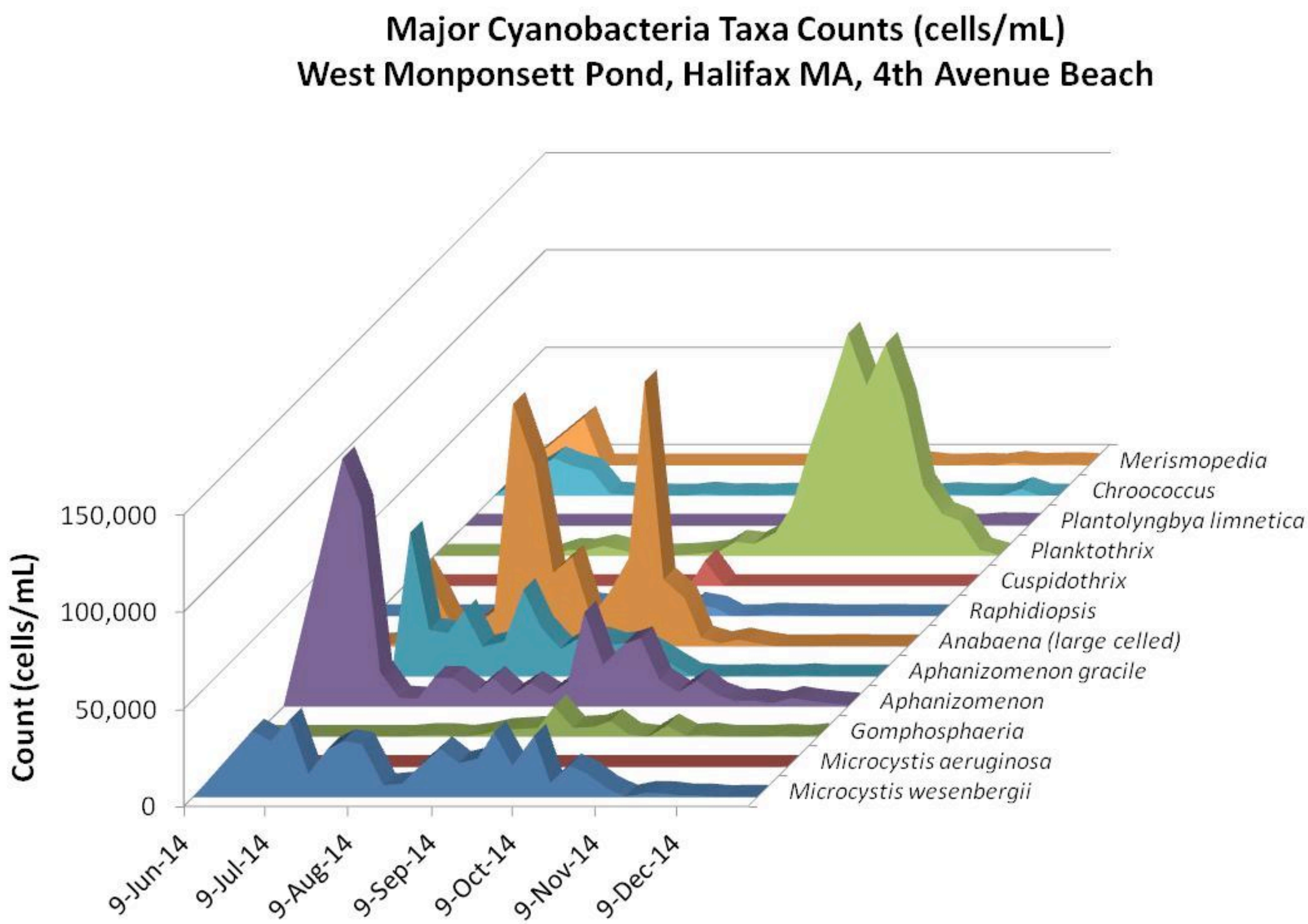


Figure C 8: West Monponsett Pond, 4th Avenue Beach, 2014 Major Cyanobacteria Taxa Counts (cells/mL)

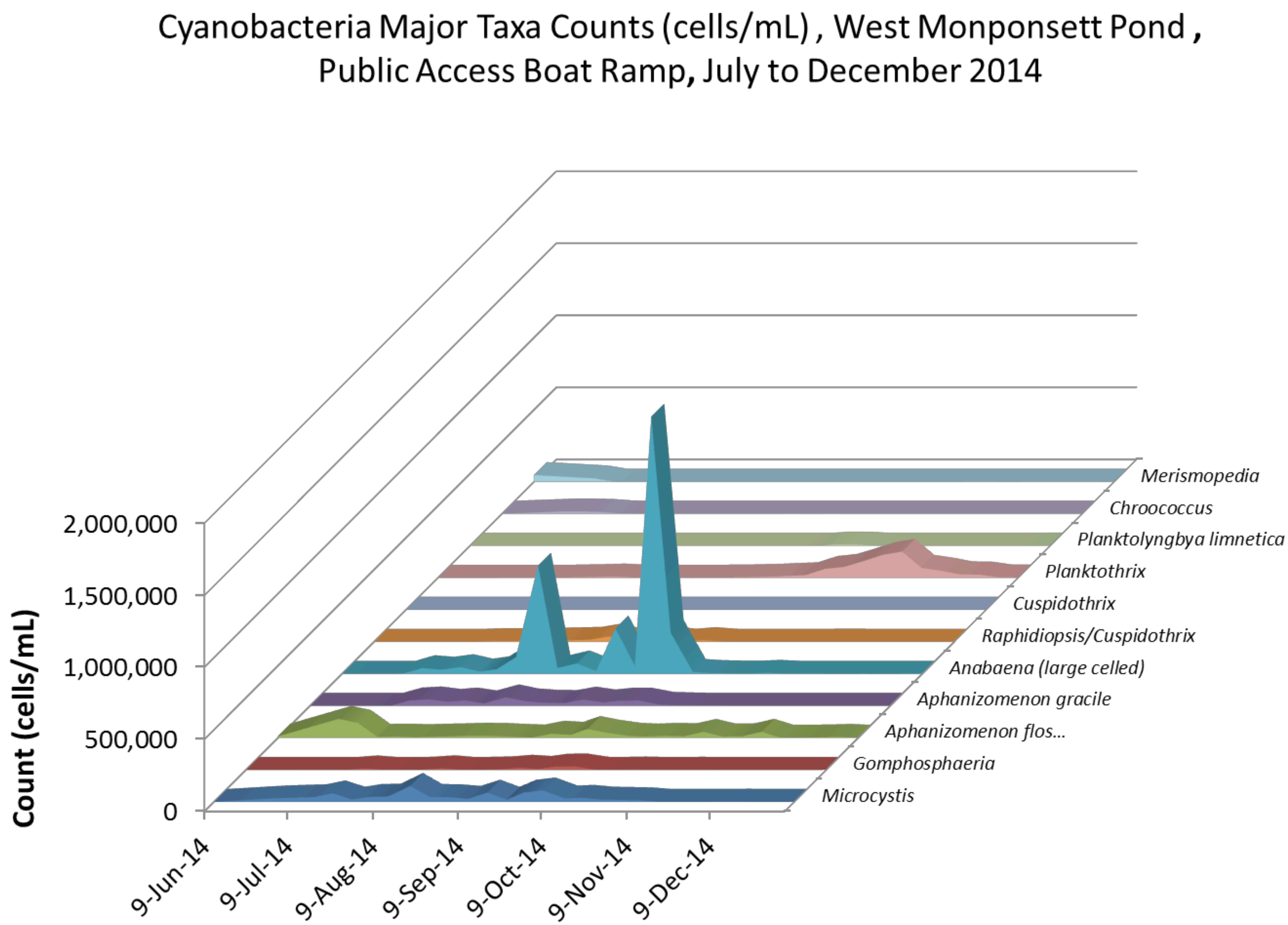


Figure C 9: West Monponsett Pond, Boat Ramp, 2014 Major Cyanobacteria Taxa Counts (cells/mL)

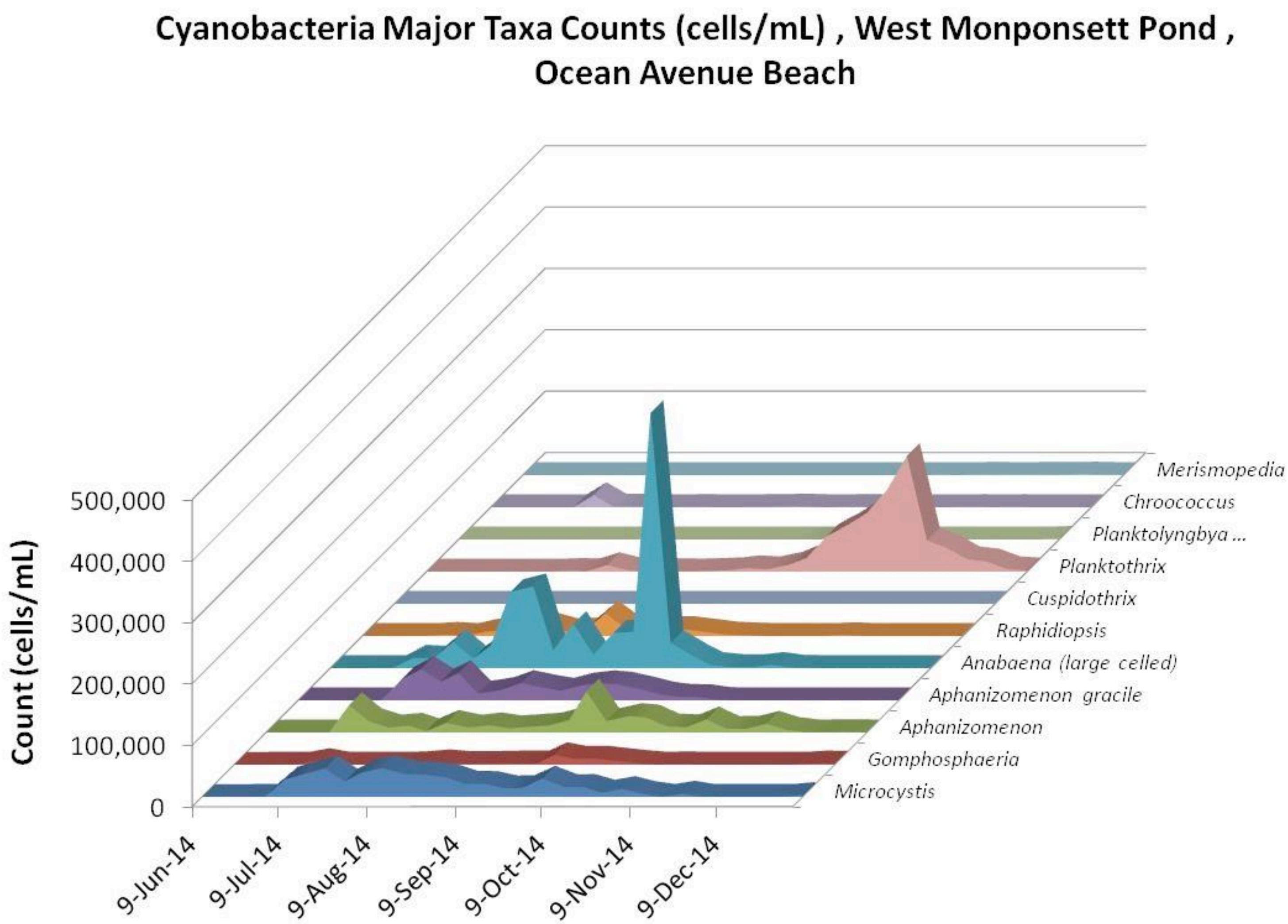


Figure C 10: West Monponsett Pond, Ocean Ave. Beach, 2014 Major Cyanobacteria Taxa Counts (cells/mL)

Dissolved Oxygen Profiles

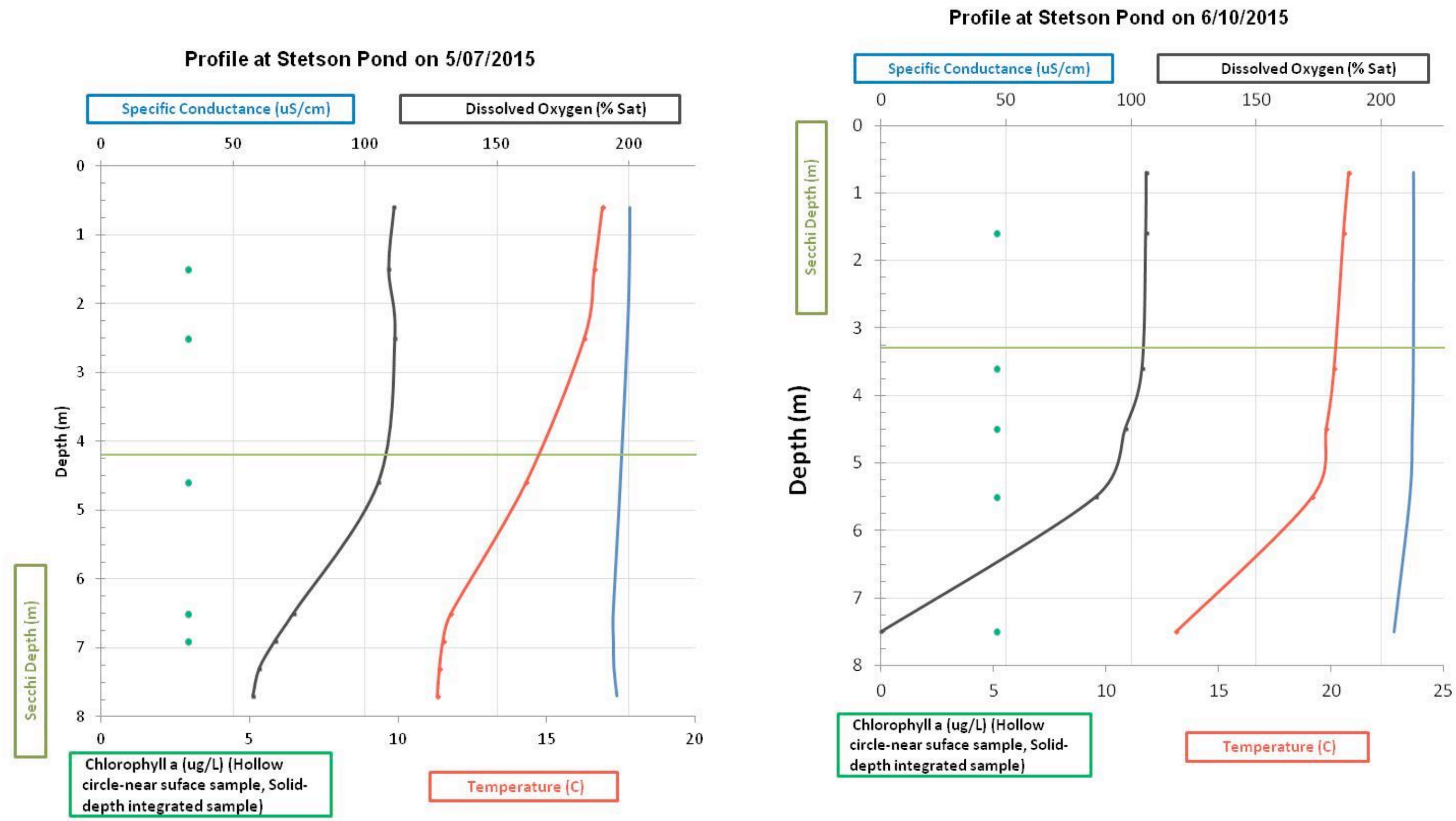
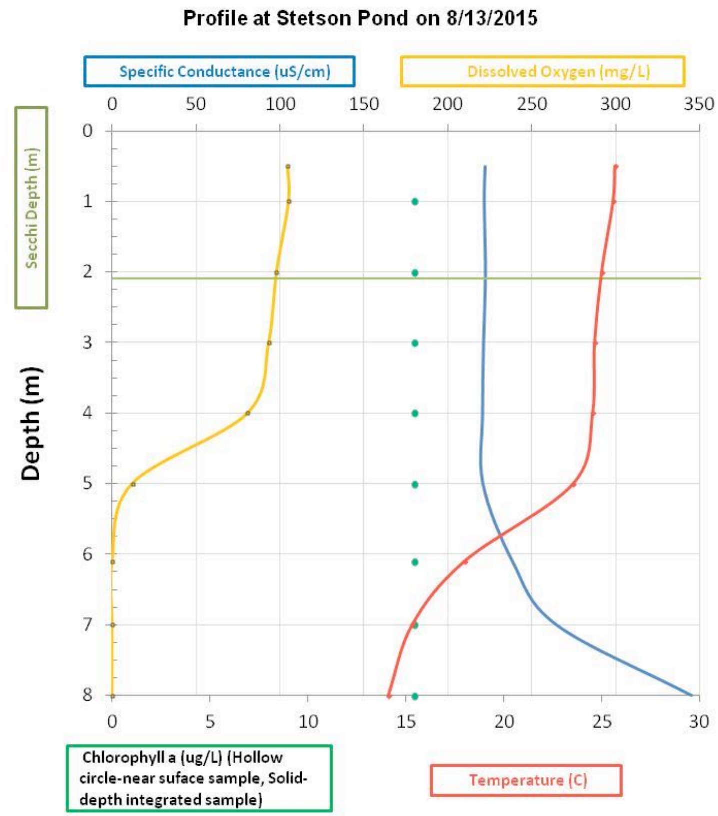


Figure C 11: Stetson Pond DO Profile May 2015 (left) and Stetson Pond DO Profile June 2015 (right)



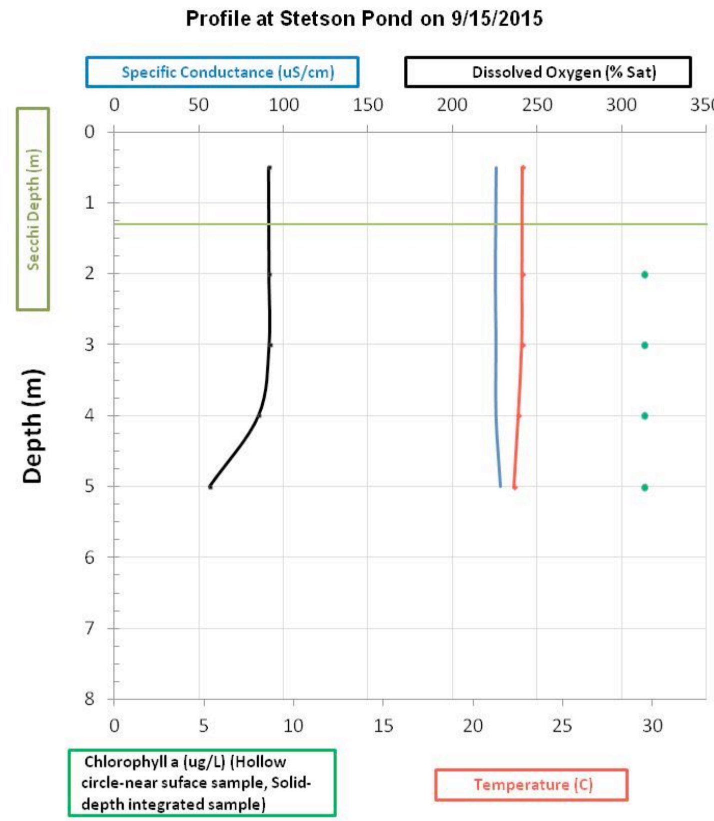
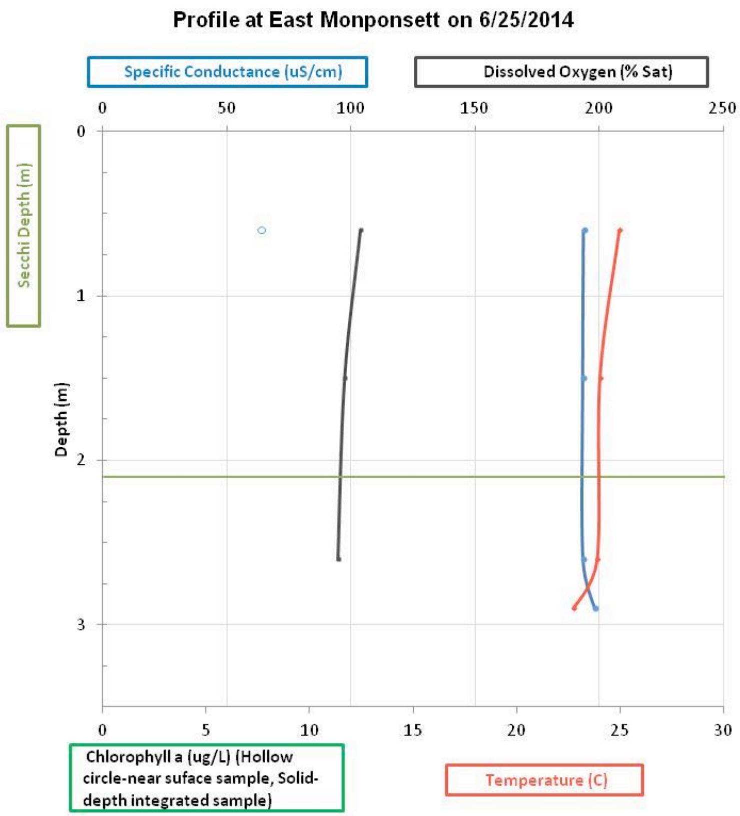


Figure C 12: Stetson Pond DO Profile August 2015 (left) and Stetson Pond DO Profile Sept. 2015 (right)



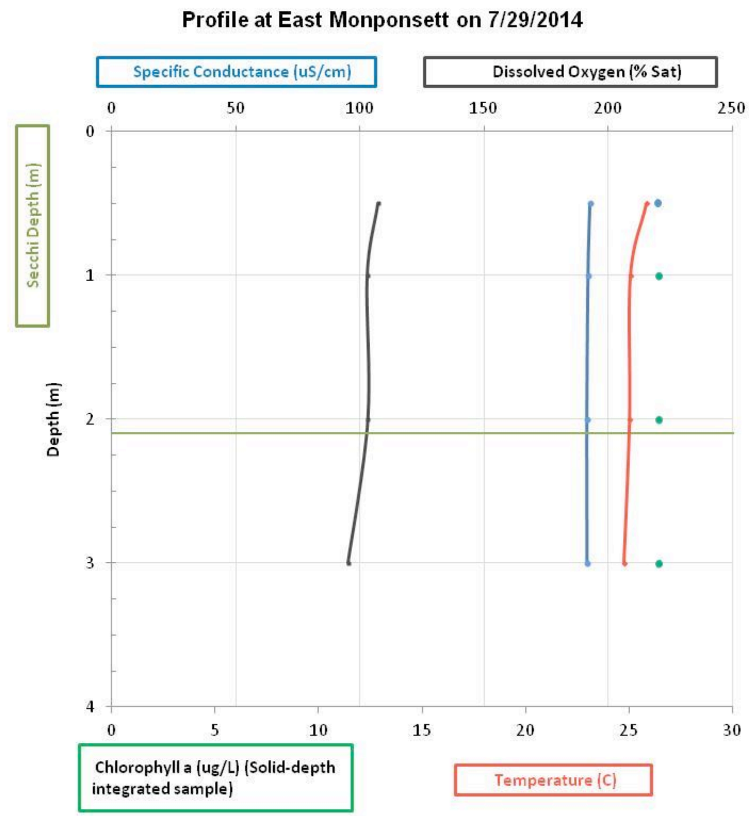
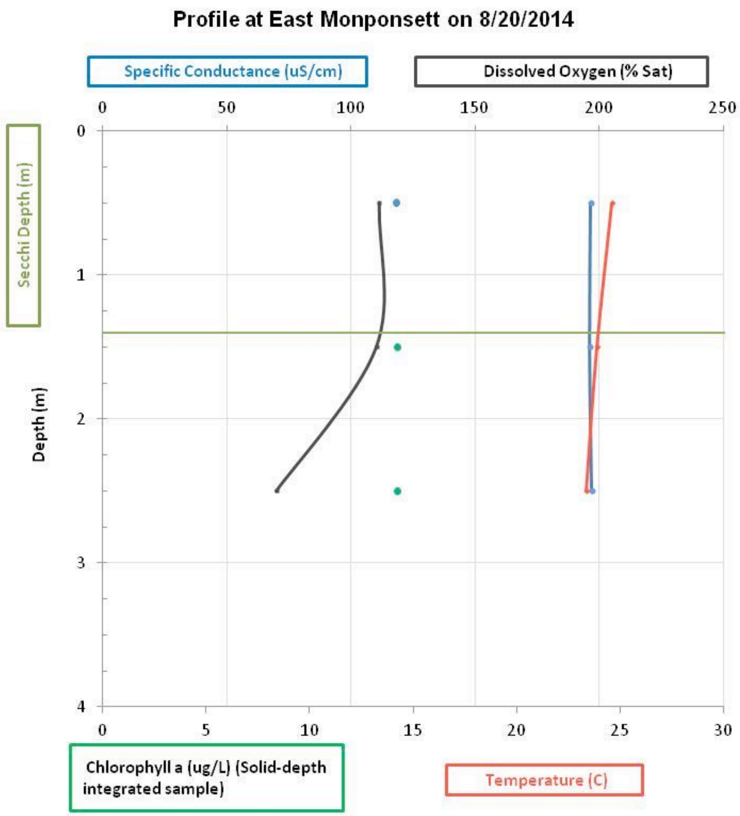


Figure C 13: East Monponsett Pond DO Profile June 2014 (left) and East Monponsett Pond DO Profile July 2015 (right)



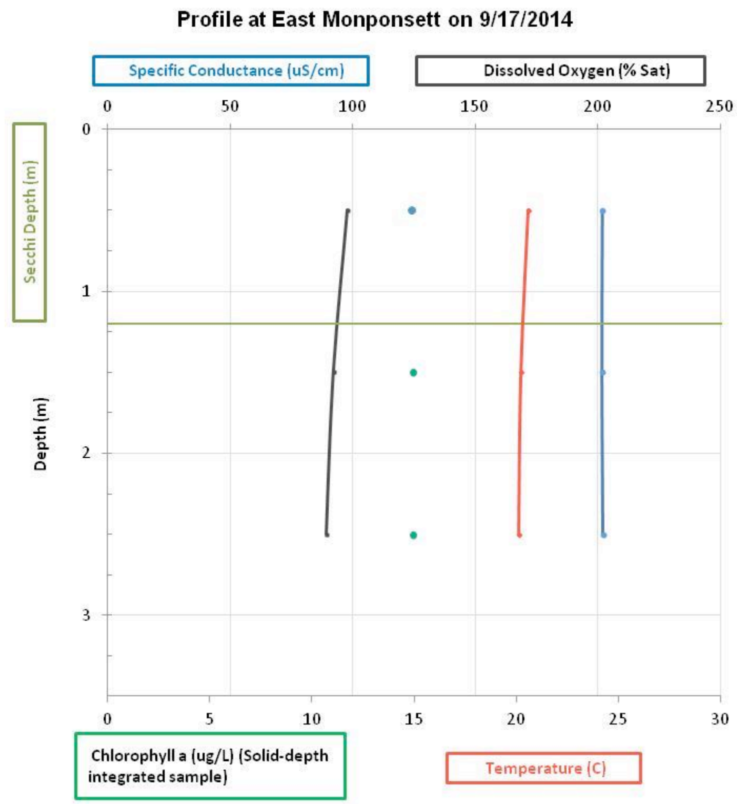
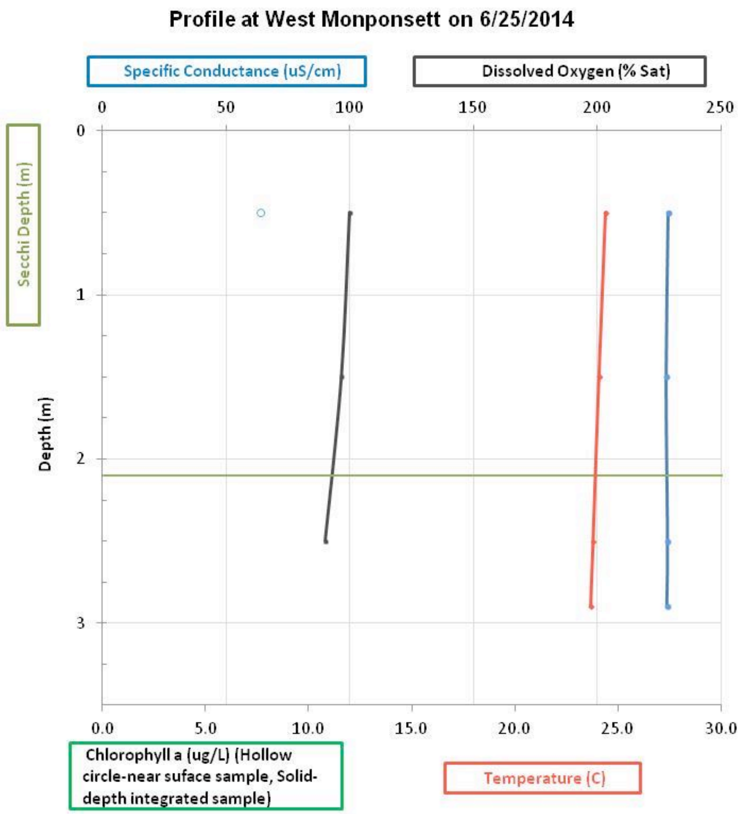


Figure C 14: East Monponsett Pond DO Profile August 2014(left) and East Monponsett DO Profile Sept. 2014 (right)



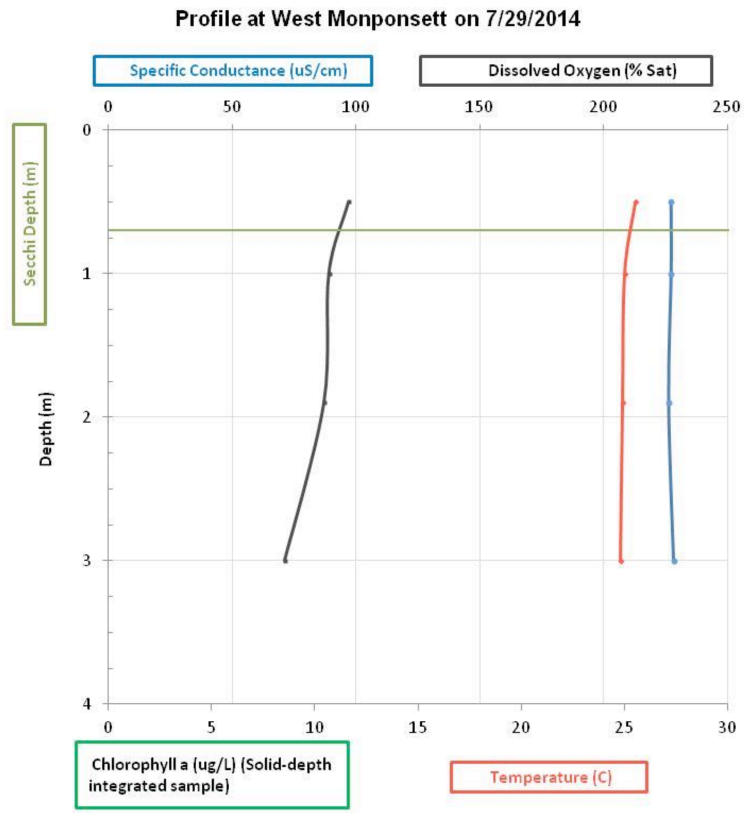
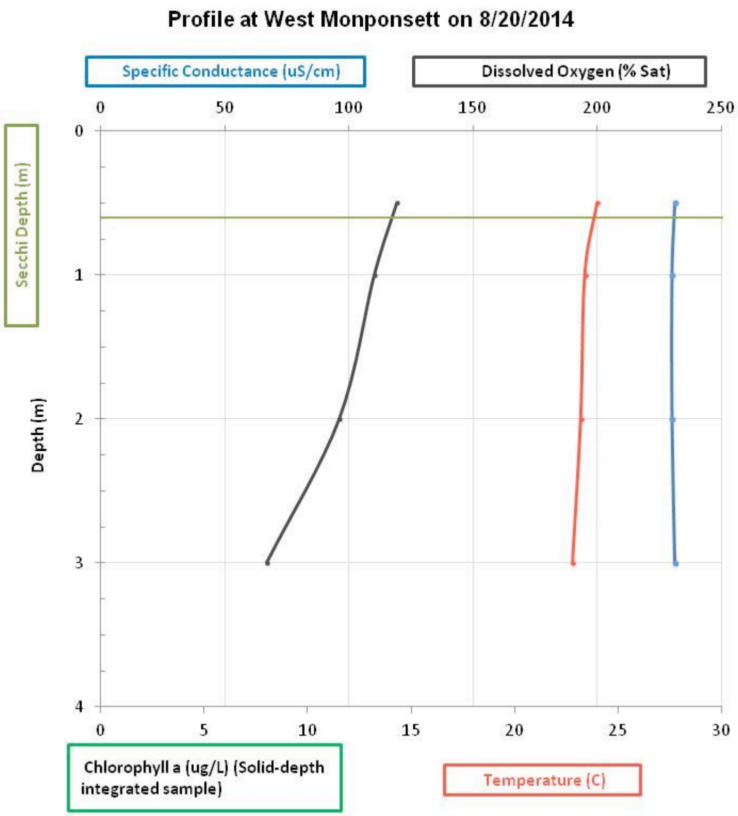


Figure C 15: West Monponsett Pond DO Profile June 2014 (left) and West Monponsett Pond DO Profile July 2014 (right)



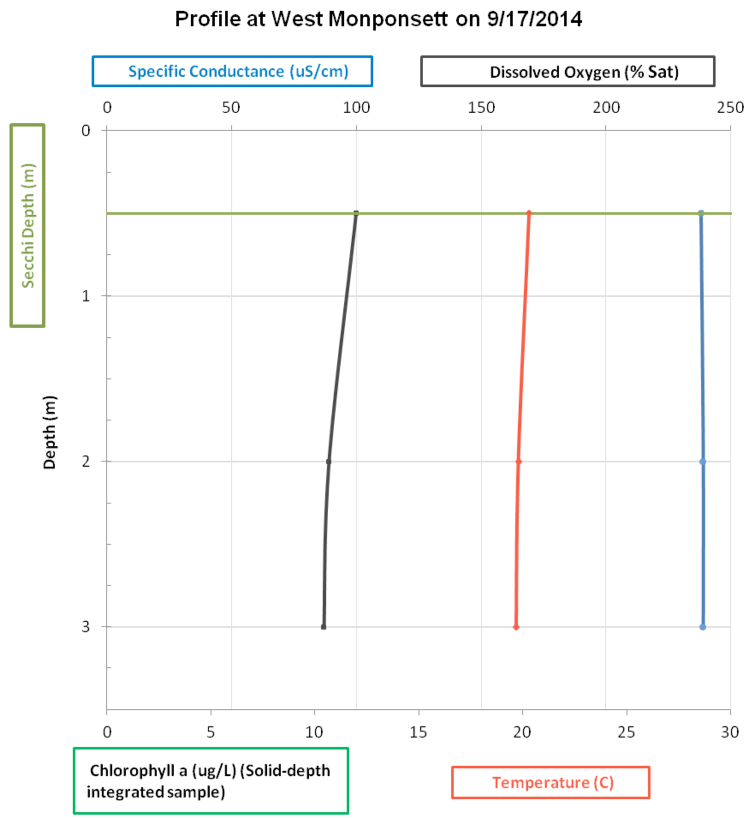
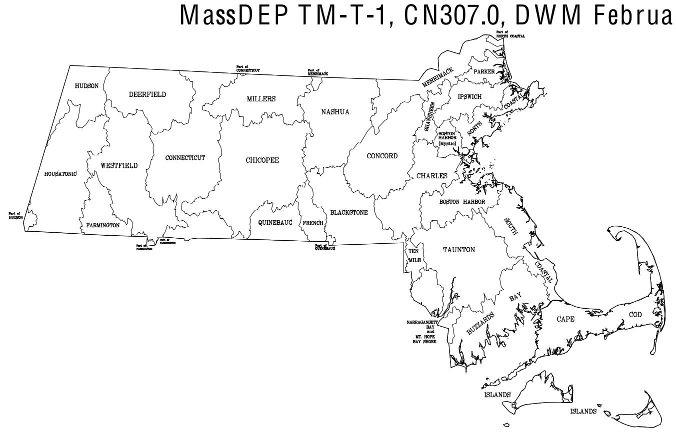


Figure C 16: West Monponsett Pond DO Profile August 2014 (left) and West Monponsett Pond DO Profile Sept. 2014 (right)

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

Mark D. Mattson

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



<u>NOTICE OF AVAILABILITY</u>

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Division of Watershed Management
627 Main Street
Worcester, MA 01608

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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).

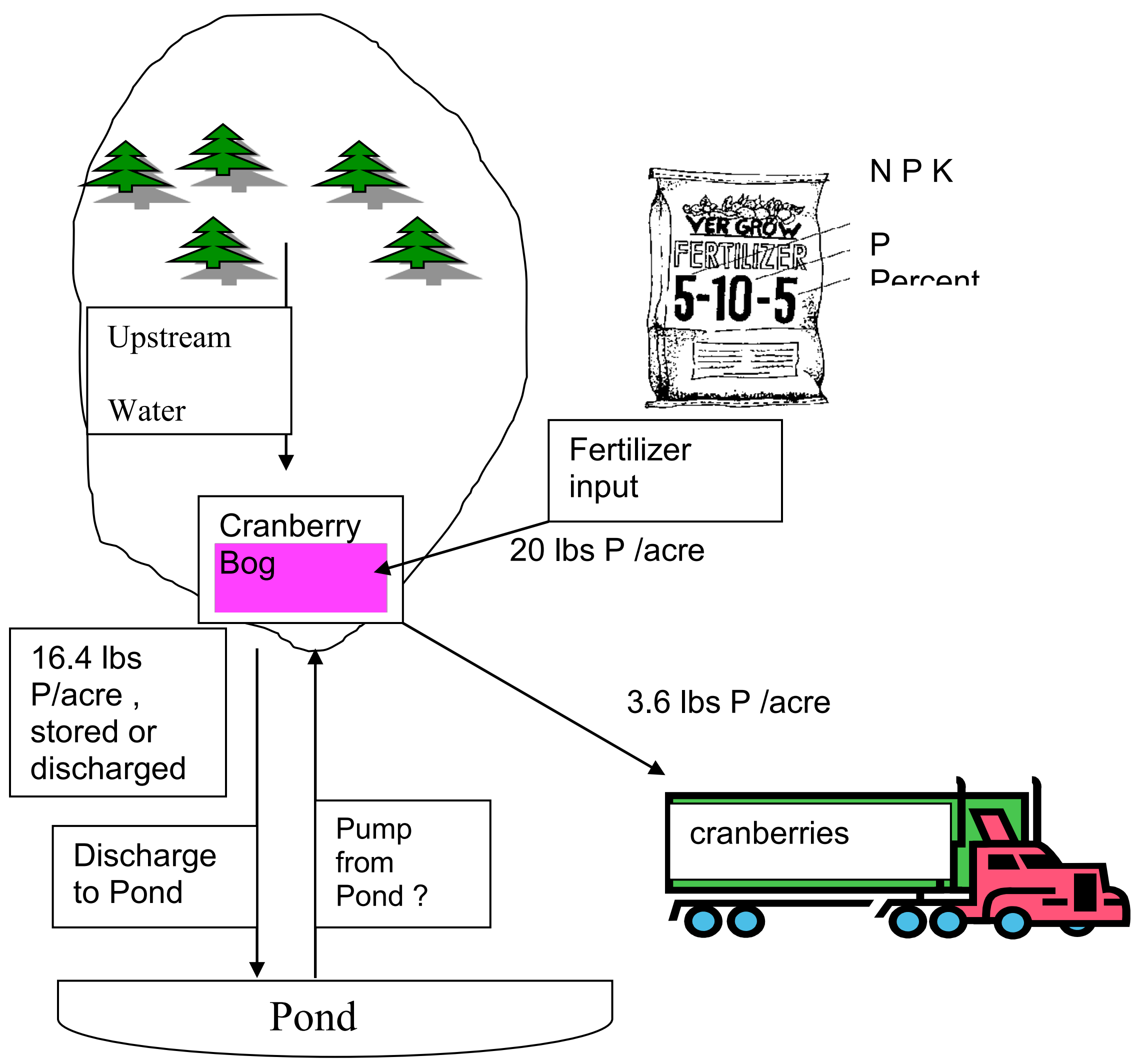

Figure 1. Schematic Diagram of a Phosphorus Budget for a Cranberry Bog.

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).

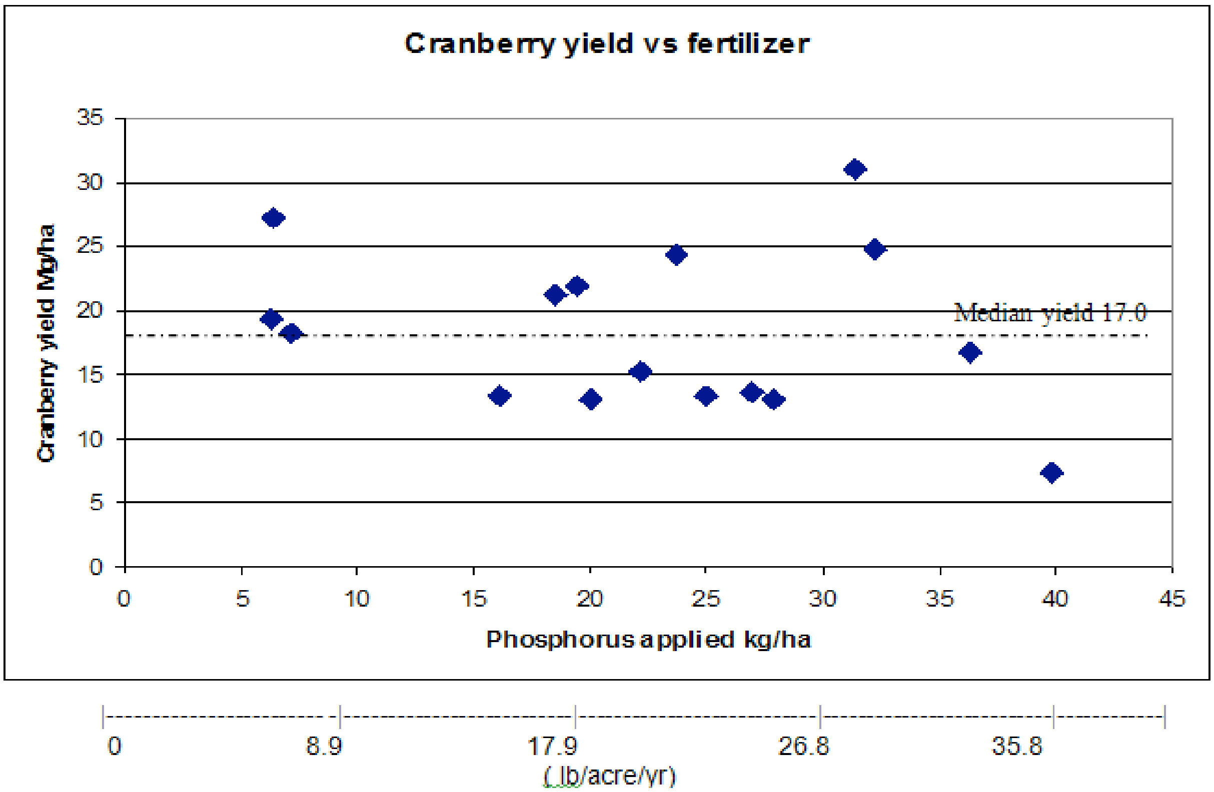

Figure 2. Cranberry yield vs. Fertilizer Rates (Data from DeMoranville et al., 2009).

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 0.1 mg/l 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 0.15 and 0.5 mg/l 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*Conc. (mg/l), N=18, r^2=0.47, α=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 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).

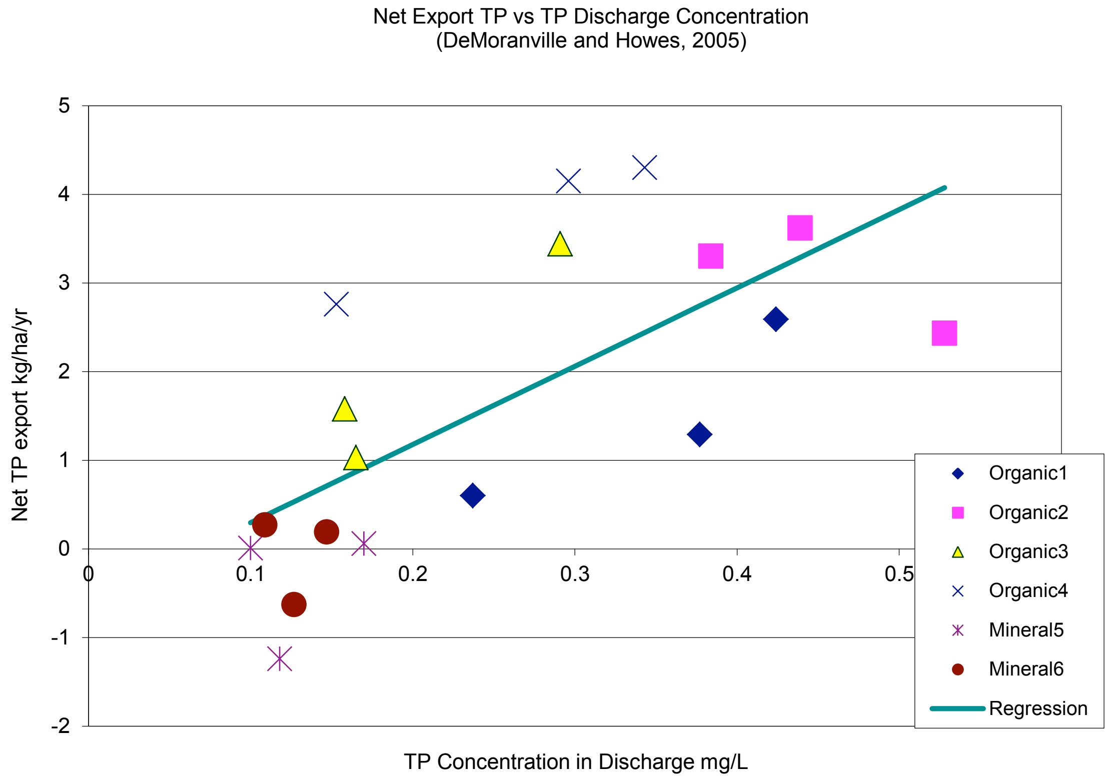

Figure 3. Net TP Export vs. TP Concentration.

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 0.050 mg/l in any stream entering a lake or pond (USEPA, 1986). The USEPA has issued guidance for water quality nutrient concentrations of total phosphorus of 0.031 mg/l for rivers in southeastern Massachusetts

(USEPA, 2000; 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 0.020mg/l and possibly as low as 0.008 mg/l (MassDEP, 2003, 2004, 2007a, 2007b, 2009, 2013; USEPA, 2001; 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 0.1 mg/l for streams and the 0.05 mg/l 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 0.1 mg/l 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 $N:P_2O_5$ 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.

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Appendix E: Draft Monponsett Pond TMDL Modeling Documentation

(CN 446.5)

COMMONWEALTH OF MASSACHUSETTS

EXECUTIVE OFFICE OF ENVIRONMENTAL AFFAIRS

MATTHEW BEATON, SECRETARY

MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION

MARTIN SUUBERG, COMMISSIONER

BUREAU OF WATER RESOURCES

DOUGLAS FINE, ASSISTANT COMMISSIONER

June 23, 2016

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 principally 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 as1899. 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. In 1995 MassDEP and the City of Brockton signed an Administrative Consent Order which required the city to develop a Comprehensive Water Management Plan and a strategy to reduce environmental impacts.

East Monponsett Pond is diverted to Silver Lake, which is used by the City of Brockton for as a public water supply (Figure 1). West Monponsett Pond is connected to East Monponsett Pond by a culvert under Route 56. 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 (MassDEP 2016). 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 where adjusted so they did not extend beyond the Geosyntec (2015) pond watersheds. The delineated watersheds are presented in Figure 16 of the TMDL (MassDEP 2017). Using the MassGIS Landuse (2005) datalayer and a GIS system the landuse in the TMDL study area was analyzed. For land use analysis by subwatershed see Appenidx A, MassDEP 2016.

Scope and Approach for Model

Annual precipitation of 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.

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. 2009 appears to be a typical year in 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.

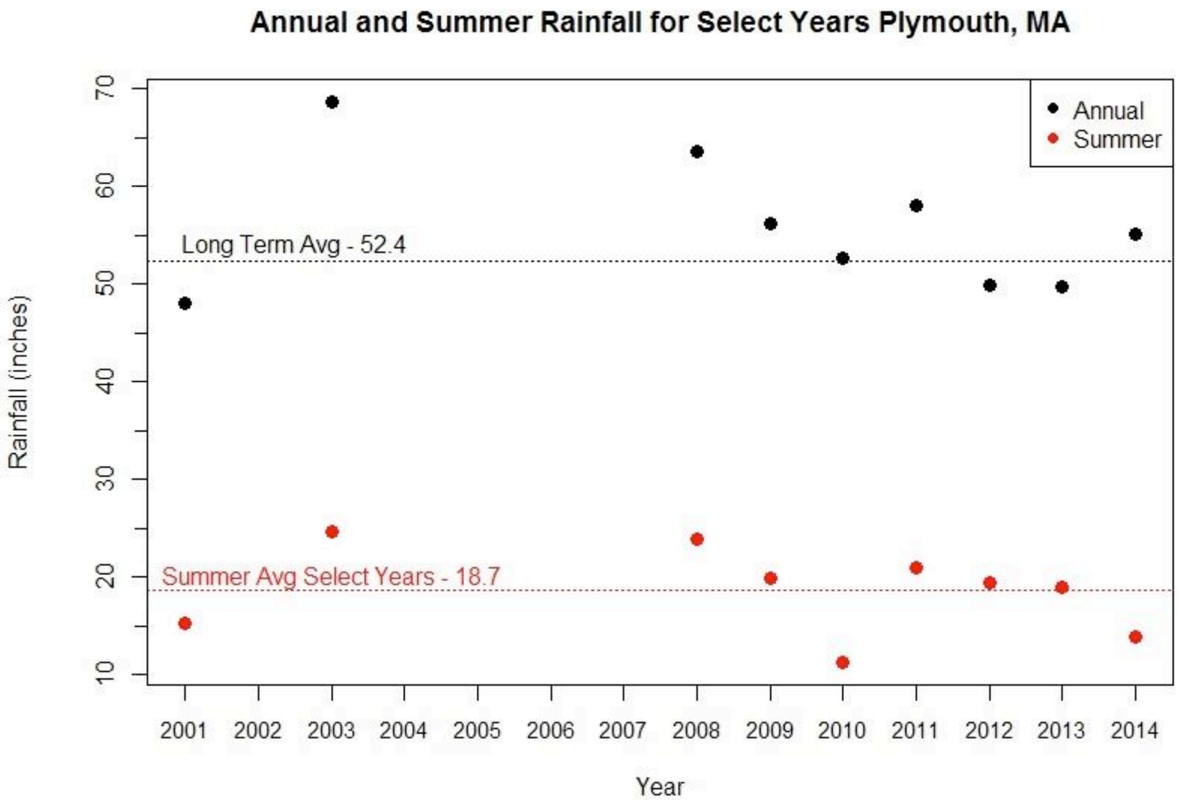

Figure 1: Annual and Summer Rainfall for Select Years Plymouth, MA (NCDC 2006)

Quality of Acquired Data

MassDEP has conducted water quality sampling in the TMDL study area of a number of 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.

Water Body	Sampling Site	Sampling Years	QC Status
Steston 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

In addition for validation of the LLRM model sampling of tributary streams by MassDEP and Lycott Environmental Inc. (2007).

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 a number of TMDL studie sin New England (AECOM 2009b, AECOM 2011, FB Environmental Associates, 2014)._The model is documented in AECOM (2009a). The LLRM model is a spreadsheet model and uses Microsoft Excel software.

Model Configuration

The LLRM model was applied to a delineated watershed for the TMDL study area. The principal model inputs for this are estimate hydrologic inputs, nutrient inputs by subwatershed and other nutrient loading estimates. The general pattern of flow in this system in 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 both East and West Monponsett Ponds watersheds respectively would go to each pond. 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.

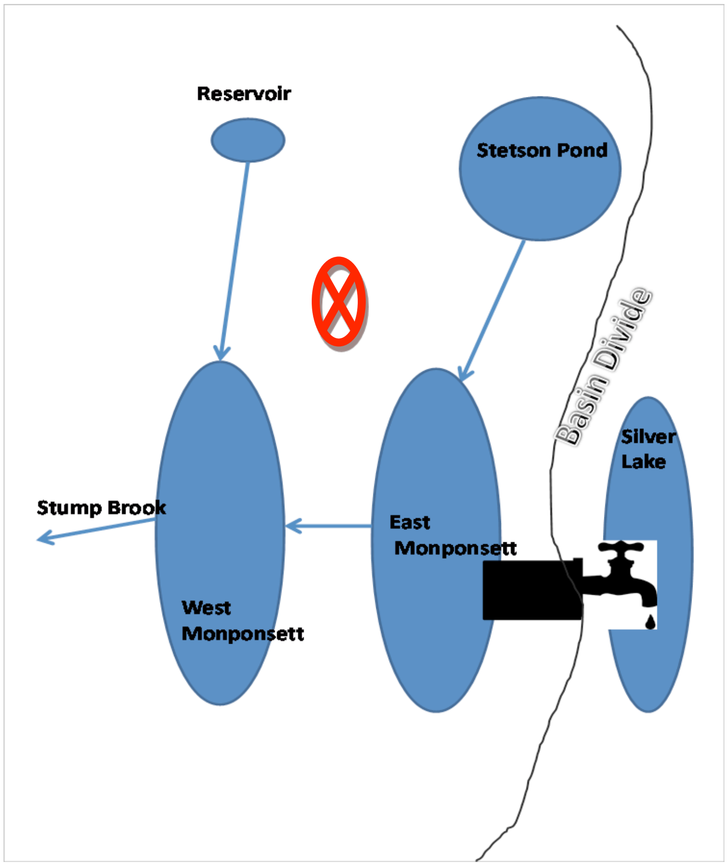

Figure 1: Model Schematic Showing Flow Patterns in TMDL study Area

Watershed Delineations

In consultation with the GIS department at MassDEP, watersheds for each pond in the TMDL study area were obtained based 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 where 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 (MacLaughlin 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.

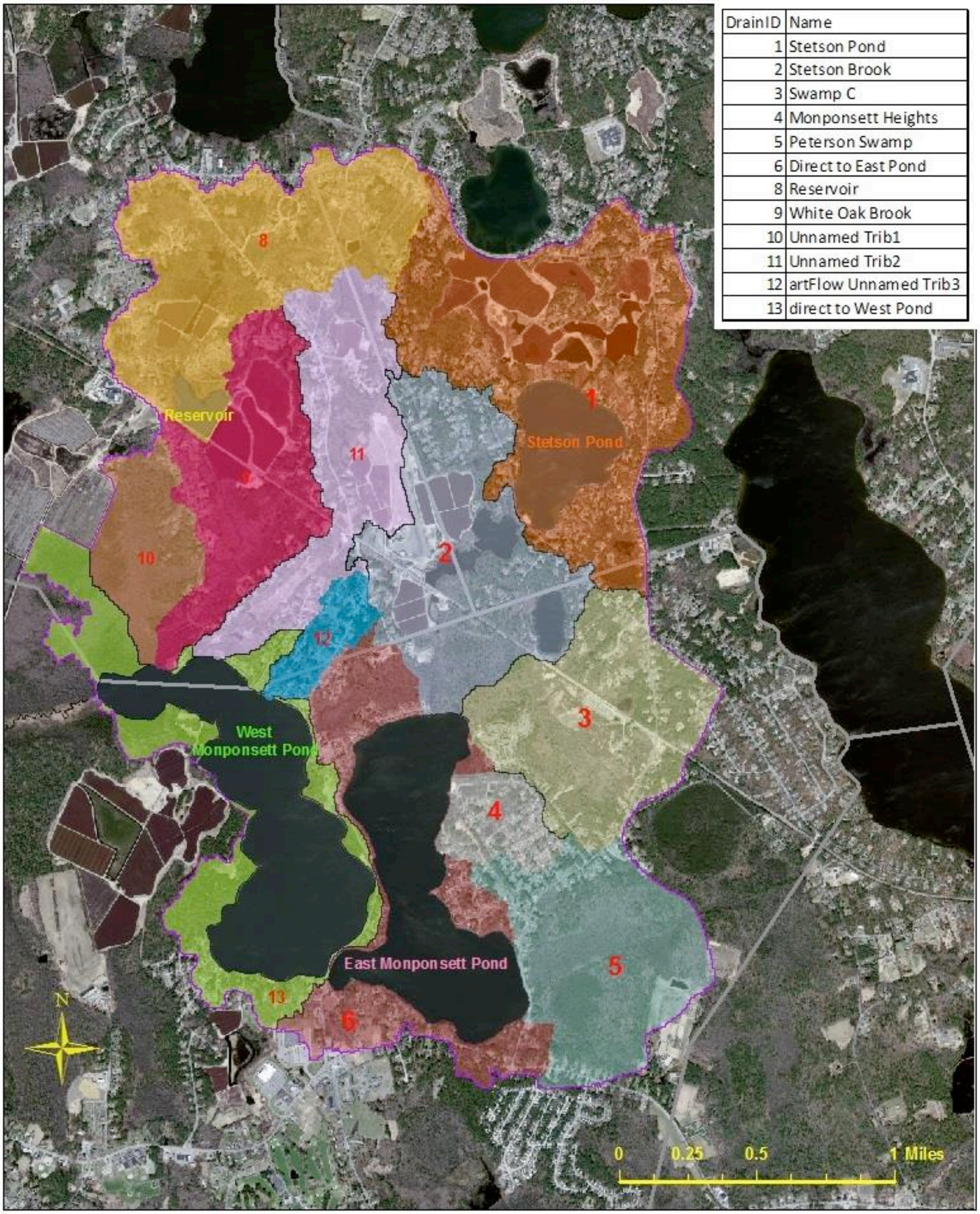

Figure 2. Watersheds in the TMDL study area.
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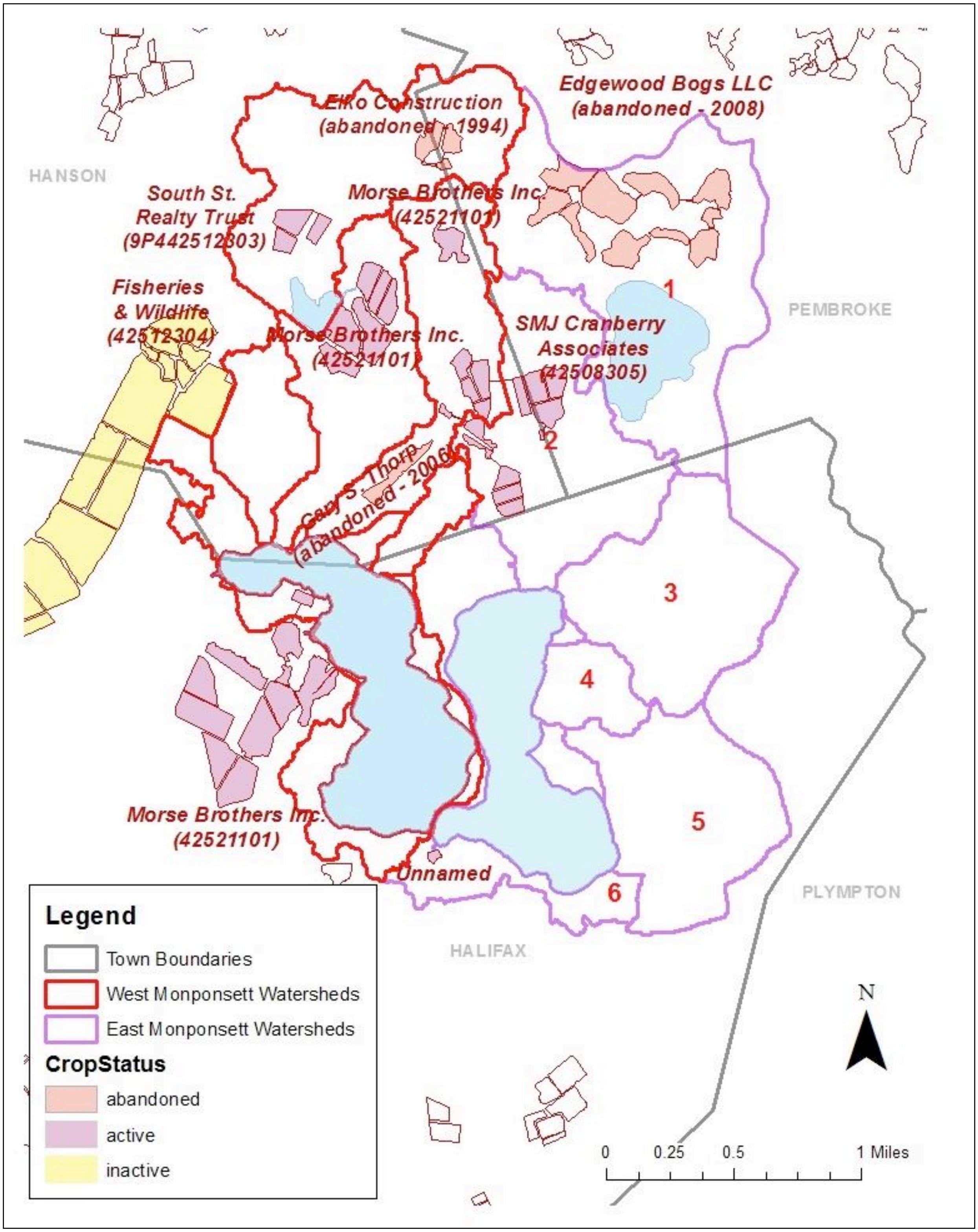

Figure3. Cranberry Bogs and their Status in TMDL study area (if active Water Management Act (WMA) # in parenthesis)

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

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

Parameterization (calibration) Input

The major parameterization (calibration) dealt with assigning land use export coefficients for phosphorus (see Table 3). Using predicted in pond total phosphorus concentrations, these values were iteratively optimized to provide the best fit between predicted in pond total phosphorus concentrations and measured in pond concentrations. 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 instream 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.

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 coefficient 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.

Stormwater

Stormwater loads were estimated for East Monponsett Pond and West Monponsett Pond based on the stormwater load estimates of Lycott (1987). By analyzing the development land use categories (low, medium and high intensity development) for the East Monponsett Pond and West Monponsett Ponds watersheds exclusive of the upstream Stetson Pond and White Oak Reservoir watersheds, the high estimate of total phosphorus loading of 58.1 kg TP/yr of Lycott (1987) was apportioned to the two pond's watersheds. The development categories in the East Monponsett Pond watershed were approximately 64% of the total development category in both ponds watersheds, therefore 64% of 58.1 kg TP/yr or 37.2 kg TP/yr were assigned as the stormwater load for East Monponsett Pond. The development category in West Monponsett Pond represented 36% of the total development category in both ponds watersheds, therefore 36% of 58.1 kg TP/yr or 20.9 kg TP/yr was assigned as the stormwater load for West Monponsett Pond.

Internal Loading

MassDEP sampling in 2015 found hypoxia in Stetson Pond below 6 meters in depth. Based on an estimated area below 6 meters of approximately 3.8 hectares and a sediment release rate of 2 mg/m^2/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 of 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/m2/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 293kg/year. This may be an underestimate because West Monponsett Pond does become anoxic durirng rare periods of calm conditions and phosphorus release may be much higher at those times. Between 2009 and 2015 MassDEP conducted 22 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/m2/day affecting approximately 25 hectares of the lake for 120 days.

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

Grouping	TP(kg/ha/yr)	LLRM ranges*(kg/ha/yr)	Reckhow (1980) (kg/ha/yr) ranges**	Flow Coeff (%)
Open	0.00	0.02 - 0.83	--	0.50
Water	0.00	0.02 - 0.83	--	0.50
Abandoned Cranberry Bog	0.10	--	--	0.50

Table 3: Landuse categories and Assigned Total Phoshporus 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

Septic Systems

In order to estimate septic system loading to each pond the number of houses with 100 feet of each water body and between 100 and 300 feet was estimated using a GIS system with orthophotos and parcel data (Table4) . For septic system loads, an average of 2.5 people for 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 5.

# 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 4: 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 5: 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 that 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 5 below is 1. So for example Stetson Pond (Basin 1) passes into Stetson Brook which then passes into East Monponsett Pond (Table 6). Routing was conducted similarly for all the ponds in this TMDL.

ROUTING PATTERN	(Basin in left hand column passes through basin in column below if indicated by a 1)					
1=YES 0=NO XXX=BLANK	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6
	Stetson Pond	Stetson Brook	Swamp C	Monponsett Heights	Peterson Swamp	Direct To East Pond
	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(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 6 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 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 coefficient throughout the study area and not depending 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 phosphrorus 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 unusal 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 7. The estimated watershed loads for the White Oak Reservoir watershed and all watersheds that contribute to West Monponsett Pond can be found in Table 8.

Table 7: Watershed Loads by Landuse for East Monponsett Pond Watersheds

	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
TOTAL	34.1	125.6	33.4	11.8	36.4	35.5	276.9

Table 8: Watershed Loads by Landuse for West 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

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. All of the predictions are based on empirical equations from literature across a range of ponds and lakes sizes and types with a large proportion located in North America. It should be noted that the models included were often developed in large deeper waterbodies with greater retention time. They are standard models though and their average is believed to given a reasonable result. An example of the predicted total phosphorus for West Monponsett Pond is given in Table 7 below. For the purposes of this modeling effort the the Mass Balance equation was 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 9: 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 seperately 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 discrepency 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 concentration and the observed concentrations in all the ponds ranged from 1.6% to 29% (Table 8). 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 10: 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 7 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 Resevoir 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 sensitivity to the high intensity agriculture landuse TP export coefficient likely due to its relatively small watershed size and small pond volume . West Monponsett Pond and East Monponsett Pond are the next most sensitive to changes in the high intensity agriculture landuse TP export coefficient.

Model Prediction Runs

MassDEP determined target TP concentrations for each pond in the TMDL study area (MassDEP 2016). 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 LRRM model was an average of all the prediction models excluding the Mass Balance equation.

The estimated allowable total phosphorus load for was 48 kg/yr, 213 kg/yr, 35 kg/yr and 199 kg/yr for Stetson Pond, East Monponsett Pond, White Oak Reservoir and West Monponsett Pond, respectively (Table 9). 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 11: 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 ug/L (as % of time) less than 10% (Table 10). 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 27 ug/L and 25 ug/L respectively. In the future peak Chlorophyll a values may not meet the 16 ug/L criterion. The goal though 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.

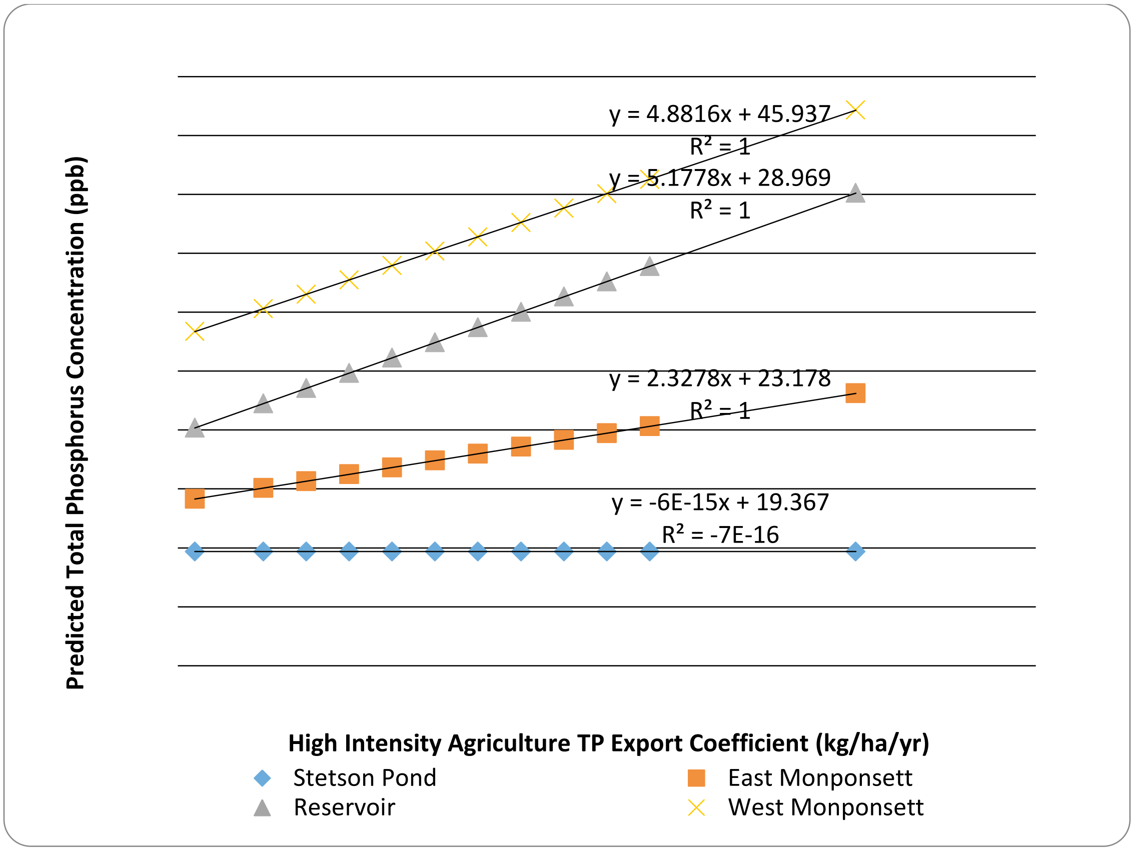

Figure 4: Comparison Predicted TP Concentration and High Intensity Agriculture TP Export Coefficient

Waterbody	Target TP Concentration (mg/l)	Load TP (kg/yr)	Predicted Mean Chlorophyll a (ug/L)	Predicted Peak Chlorophyll a (ug/L)	Probability of Chl >16 ug/L (% of time)
Stetson Pond	12	48	4	16	0.2%
East Monponsett	20	213	8	27	3.4%
White Oak Reservoir	23	35	9	31	8.4%
West Monponsett	20	199	7	25	3.4%

Table 12: Threshold Loads for Study Area Waterbodies

Model Summary

The LLRM model is 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 which aided in the estimation of internal loading for West Monponsett Pond. The complex hydrology of this system with monthly

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