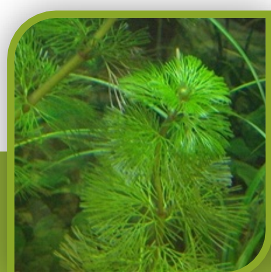
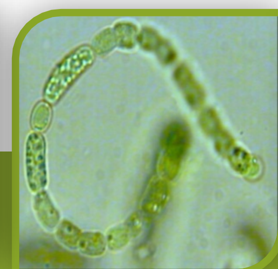
Lake Singletary
Trophic Status Model and Management Plan

March 2014



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Contents

Section 1: Introduction

In 2012, Geosyntec Consultants, Inc. (Geosyntec) was contracted by the Lake Singletary Watershed Association (LSWA) to conduct a study of 336-acre Lake Singletary and its watershed. The primary goals of this project were:

1. Assess the trophic status of Lake Singletary based on water quality data collected by the LSWA volunteer monitoring program;

2. Develop an estimated phosphorus budget for Lake Singletary, including external watershed sources and internal nutrient recycling;

3. Develop several in-lake phosphorus response models to characterize the lake's relationship between phosphorus loads and in-lake phosphorus concentration;

4. Conduct an evaluation of the Lake Singletary watershed to identify opportunities for stormwater management improvements to reduce pollutant loading to the lake;

5. Based on the results of the investigations listed above and other available information, provide recommendations for future watershed and in-lake management actions; and

6. Develop a "Field Guide to the Aquatic Plants of Lake Singletary", to aide in future volunteer vegetation monitoring efforts.

Lake Singletary (336 acres)
Sutton/Millbury, MA

Section 2: Literature Review

For reference purposes, this section presents excerpted findings and recommendations from previous studies related to the water quality and management of Lake Singletary its watershed.

Diagnostic Study of Singletary Lake (IEP, 1991)

- Bathymetry mapping revealed no notable loss of depth compared to historic bathymetric maps. Bottom sediments were nutrient rich and did not appear to be contaminated with heavy metals.
- Lake Singletary Lake water quality is fair, with moderate to high concentrations of nutrients and low bacteria levels. Oxygen concentrations in deep waters (hypolimnion) were depleted during summer stratification, indicating increased decomposition associated with lake eutrophication.
- Singletary Lake is mesotrophic bordering on eutrophic based upon trophic state modeling.
- Algae densities ranged from low to moderate, with peak densities observed in the spring and fall.
- The lake acts as a phosphorus sink, retaining 75 percent of the phosphorus entering the lake.
- Septic systems account for 27 to 35 percent of the total annual input of phosphorus to the lake.
- Aquatic vegetation has not reached problematic levels in most parts of the lake, although nuisance densities were observed in some localized areas.
- Recommended actions included:
    - Control localized nuisance weed growth, with consideration of the following techniques: mechanical harvesting, hydro-raking, herbicide/algaecide applications, and bottom barriers.
    - Reduce watershed nutrient sources, with consideration of stormwater management, watershed protection bylaws, wastewater management programs, and public education.

Singletary Lake Management Plan (Fugro East, 1995)

- This report provided recommendations on lake and watershed management actions, and provided estimates of associated pollutant load reductions and implementation costs.
- The maximum likely load reduction achieved by all recommended actions was approximately 30%, with an anticipated range of 21-30 % of existing loads. This estimate was below the recommended reduction of 35%, but was considered sufficient to provide observable improvement in lake conditions.
- Additional actions to achieve a greater load reductions were not deemed economically feasible.

Wastewater Facilities Plan for the Lake Singletary Watershed (BETA Group, 2000)

- A gravity sewer system in combination with low-pressure grinder pumps is the most cost effective method of nutrient load reduction for Lake Singletary. The system will convey wastewater to the Upper Blackstone Waste Water Treatment Facility via the Millbury collection system. The most cost effective method is Alternative 2 (*Figure 5-2 of the referenced report*). The most practical method, in terms of expansion, is Alternative 1 (*Figure 5-1 of the referenced report*).
- In both alternatives, Phase 1 and 2 are identical. These phases are the most important areas for surface water nutrient load reduction while Phase 3 differs in each alternative. Design and construction costs for both phases are estimated at $3.4 million. Funding limitations and construction across the town line may dictate the project progression. Phase 1 must be completed before Phase 2 and also services the lakefront homes located on small lots. The majority of Phase 1 construction will have to be financed by Millbury. Phase 2 is entirely within Sutton and can be constructed as soon as financing is available after the completion of Phase 1.

Stockwell Ponds Tributary System Water Quality Investigation (ACT, 2002)

- This investigation established baseline data for quantification of nutrient loading estimates. Based on the very low phosphorus levels obtained during base flow and storm flow sampling, further reduction of phosphorus levels through management of the Stockwell Ponds is questionable.
- ACT recommended that the study results and data set be used for further review, and as the basis for implementing additional sampling focusing on the direct storm water input (i.e. storm drains and direct overland flow) to Lake Singletary.

Lake Singletary Drawdown Evaluation (Geosyntec, 2010)

- Most rooted aquatic plants in Lake Singletary, including invasive fanwort, are exposed by a 6-foot drawdown. However, fanwort hand-harvesting efforts in 2009 resulted in observations that "fanwort was growing in 6-12 feet of water that was not visible from the surface".
- Each target drawdown depth (6, 8 and 10 feet) would require variances from the 31-day drawdown period and 31-day refill period recommended by DEP policy. Based on the lake's estimated inflow and refill rates, an 8-foot drawdown would pose technical and permitting challenges, but may be feasible. A 10-foot drawdown does not appear to be feasible.
- Geosyntec recommended, at a minimum, continuation of an annual 6-foot drawdown. Also recommended was consideration of requesting a drawdown permit allowing 6-foot and 8-foot drawdowns on alternating years. Based on the hydrologic calculations and the refill timing requirements, it is likely that the efficacy of drawdown for the 6- to 8-foot zone will vary considerably from year to year based on temperature, snow cover, and precipitation.

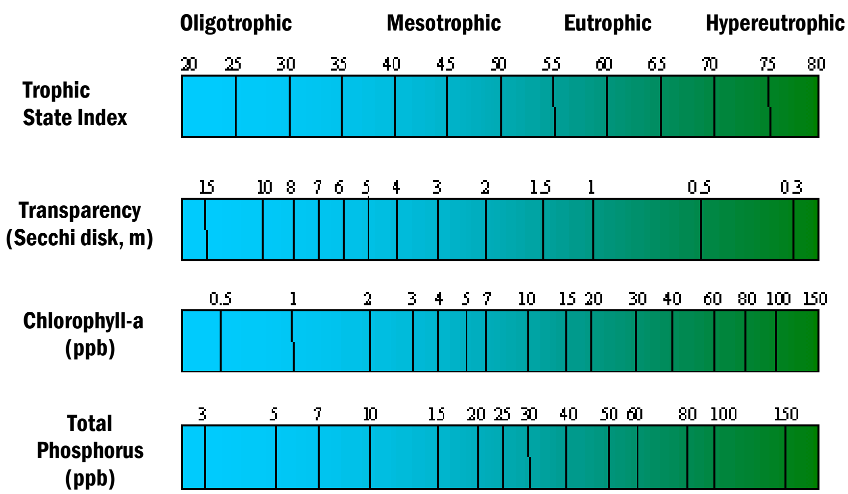
Section 3: Trophic Status Assessment

Lakes and ponds are typically categorized according to trophic state as follows:

- **Oligotrophic:** Low biological productivity. Oligotrophic lakes are very low in nutrients and algae, and typically have high water clarity and a nutrient-poor inorganic substrate. Oligotrophic water bodies are capable of producing and supporting relatively small populations of living organisms (plants, fish, and wildlife). If the water body is thermally stratified, hypolimnetic (deep water) oxygen is usually abundant.
- **Mesotrophic:** Moderate biological productivity and moderate water clarity. A mesotrophic water body is capable of producing and supporting moderate populations of living organisms (plant, fish, and wildlife). Mesotrophic water bodies may begin to exhibit periodic algae blooms and other symptoms of increased nutrient enrichment and biological productivity.
- **Eutrophic:** High biologically productivity due to relatively high rates of nutrient input and nutrient-rich organic sediments. Eutrophic lakes typically exhibit periods of oxygen deficiency and reduced water clarity. Nuisance levels of macrophytes and algae may result in recreational impairments.
- **Hypereutrophic:** Dense growth of algae throughout summer. Dense macrophyte beds, but extent of growth may be light-limited due to dense algae and low water clarity. Summer fish kills are possible.

Geosyntec calculated Lake Singletary's trophic status using the Carlson Trophic Status Index (TSI), one of the most commonly used means of characterizing a lake's trophic state. As illustrated in Figure 3.1, the TSI assigns values based upon logarithmic scales which describe the relationship between three parameters (total phosphorus, chlorophyll-*a*, and Secchi disk water clarity) and the lake's overall biological productivity. TSI scores below 40 are considered oligotrophic, scores between 40 and 50 are mesotrophic, scores between 50 and 70 are eutrophic, and scores from 70 to 100 are hypereutrophic.

Figure 3.1. Carlson Trophic State Index
(Figure adapted from 1988 Lake and Reservoir Restoration Guidance Manual. USEPA. EPA 440/5-88-002.)



TROPHIC STATUS	TSI	TP[1] (ppb)	Secchi Disk (m)	Chl-*a*[2] (ppb)
Oligotrophic	<40	<12	>4	<2.6
Mesotrophic	40-50	12-24	4-2	2.6-7.3
Eutrophic	51-70	25-96	2-0.5	7.4-56
Hypereutrophic	>70	>96	<0.5	>56

Notes:
1. For TP, parts per billion (ppb)=µg/L
2. For Chl-*a*, ppb=mg/m3

The TSI for Lake Singletary was calculated based on the data presented in Table 1, which represents summer data collected by the LSWA volunteer during the five-year period of 2009-2013.

		Secchi Disk (m)	Chl-a (µg/L)	TP (µg/L)
2013	June	3.5	0.5	12
	July	2.9	0.5	17
	Aug	4.9		16
2012	Jun	3.7	2.1	10
	July	3.2		10
	Aug	3.4		14
2011	Jun	3.3		16
	July	4.0		16
	Aug	3.8		15
2010	Jun	4.0		14
	July	4.3		10
	Aug	4.1		14
	Sept	2.5		16
2009	Jun	3.7		10
	July	4.5	4.0	10
	Aug	3.8		14
Average		**3.73**	**1.78**	**13.39**

Table 3.1.1. Carlson TSI Data for Lake Singletary: Summer 2009-Summer 2013

Transparency: Lake Singletary 2009-2013 mean summer Secchi disk (m) = 3.73m;
TSI = 60 - 14.41 ln Secchi Disk (m)
TSI = 41.0 (mesotrophic)

Chlorophyll-a: Lake Singletary 2009-2013 mean summer surface Chl-*a* = 3.05 µg/L;
TSI = (9.81) (ln Chlorophyll-a) + 30.6
TSI = 36.3 (oligotrophic)

Total Phosphorus*: Lake Singletary 2009-2013 mean summer surface TP =13.21 µg/L;
TSI = (14.42) (ln TP µg/L) + 4.15
TSI = 41.6 (mesotrophic)

** Phosphorus sampling results reported as below laboratory detection limits (10 µg/L) were conservatively assumed to be equal to the detection limit for the purpose of this calculation.*

- As shown in the calculations above, Lake Singletary has a TSI in the lower end of the mesotrophic range for both Secchi disk transparency and total phosphorus. The close agreement of the TSI scores for these parameters (41.0 and 41.6, respectively) adds confidence to the TSI classification of Lake Singletary as a lower mesotrophic lake.

- The TSI for chlorophyll-*a* (36.3) is in the upper end of the oligotrophic range, but this calculation is less reliable than the TSI for the other two parameters because it is based on only four measurements. Based on discussions with Karen Norlin of the LSWA, the LSWA has experienced some recent concerns with lab protocols and data reliability for chlorophyll-*a*. Incorporating a larger data set from a reliable lab to represent average conditions over the summer months will allow for greater confidence in the TSI assessment for this parameter.

Section 4: Lake Singletary Phosphorus Budget

Eutrophication is the gradual process of nutrient enrichment in aquatic ecosystems such as lakes. Eutrophication occurs naturally, as lakes become more biologically productive over geological time, but this process is often accelerated by human activities in the watershed. Nutrients that contribute to eutrophication can come from many natural and anthropogenic sources, such as fertilizers applied to residential lawns and agricultural fields; septic systems; deposition of nitrogen from the atmosphere; erosion of soil containing nutrients; and sewage treatment plant discharges. Land development not only increases the sources of nutrients, but also decreases opportunities for natural attenuation (e.g. uptake by vegetation) of such nutrients before they can reach a water body.

Nutrients such as phosphorus and nitrogen can stimulate abundant growth of algae and rooted plants in water bodies. Over time, this enhanced plant growth leads to reduced dissolved oxygen in the water, as plant material decomposes and consumes oxygen. Phosphorus is typically the "limiting nutrient" for freshwater lakes, which means that plant productivity is most often controlled by the supply of this nutrient. As such, increases in phosphorus load in a lake watershed are closely correlated with increases in plant productivity and accelerated eutrophication. To understand the magnitude of the role that phosphorus plays in the productivity of Lake Singletary, Geosyntec calculated an annual phosphorus budget by considering various phosphorus sources within the watershed, including non-point-source pollution from stormwater runoff, septic system discharge, aerial deposition, and internal loading.

4.1 Phosphorus in Stormwater Runoff

Phosphorus is transported to the lake through a variety of pathways during a storm event. Particulate phosphorus that has built up on impervious surfaces such as roads, parking lots, and rooftops is washed off by stormwater and conveyed through stormwater infrastructure or natural drainage pathways to the receiving body of water. Additionally, erosion causes phosphorus-containing soil particles to move from the surrounding watershed to the lake, via splash erosion during storm events, or subsequent rill and gully erosion as stormwater moves overland toward the lake.

A straightforward method of estimating the total phosphorus load entering the pond requires calculation of two values: the annual volume of stormwater runoff, and a typical concentration of phosphorus within that stormwater (referred to as an Event Mean Concentration, or EMC). One method for determining these two quantities and using them to calculate a pollutant load is known as the Simple Method. Annual stormwater runoff volume (Q_r) is calculated for a given area using precipitation depth (P), an assumed fraction of precipitation that contributes to runoff (P_r), impervious percentage (I), and area (A), as shown below:

$$Q_r = A \cdot P \cdot P_r(0.05 + 0.9I)$$

The annual pollutant load (L) is calculated by multiplying the stormwater runoff volume (Q_r) by the EMC (C).

$$L = Q_r \cdot C$$

Typical EMC values are presented in literature according to the land use type from which they originate. For example, runoff from a road or residential surface will generally exhibit a higher EMC value than runoff from a forested area. To calculate the total load for an entire watershed, the areal extent of each land use type is first calculated, and then the Simple Method equations shown above are applied to each individual land use. The sum of the pollutant loads from each individual land use is the total load for the watershed. Figure B3 (see Appendix B – Watershed Maps) displays the impervious cover within the Lake Singletary watershed, and Figure B4 shows the land uses present within the watershed. Table 4.1.1 shows the calculated annual loads for each land use type within the watershed, as well as the predicted total annual external load of 386 lb. P/yr.

Land Use Type	Annual Precipitation (in)	% of Precipitation Contributing to Runoff	Impervious Cover %	Area (ac)	Annual Stormwater Volume (ac-ft)	Event Mean Concentration (mg/l)	Annual Phosphorus Load (lb./yr)
	P	P_r	I	A	Q_r	C	L
High Density Residential	49	90%	26.4%	61.0	64.5	0.30	53
Low Density Residential			17.6%	394.3	302.5	0.18	148
Institutional/Commercial			35.3%	12.5	16.9	0.22	10
Agriculture/Pasture			3.7%	313.3	96.3	0.2	52
Forest/Open			3.7%	1272.2	390.8	0.11	117
Wetland			0.1%	139.9	26.3	0.08	6
						TOTAL:	**386**

Table 4.1.1. Simple Method Calculation of Phosphorus Load from Lake Singletary Watershed

A large portion of the watershed drains to Singletary Brook, which flows through the Stockwell Ponds before entering Lake Singletary. The land draining to Singletary Brook is estimated to contribute 182 lb P/yr, while areas proximal to Lake Singletary (those draining directly to the lake or to minor intermittent tributaries) are estimated to contribute 204 lb P/yr. Figure 4.1.1 shows the types of land uses present in these two regions as well as the phosphorus loads from each land use.

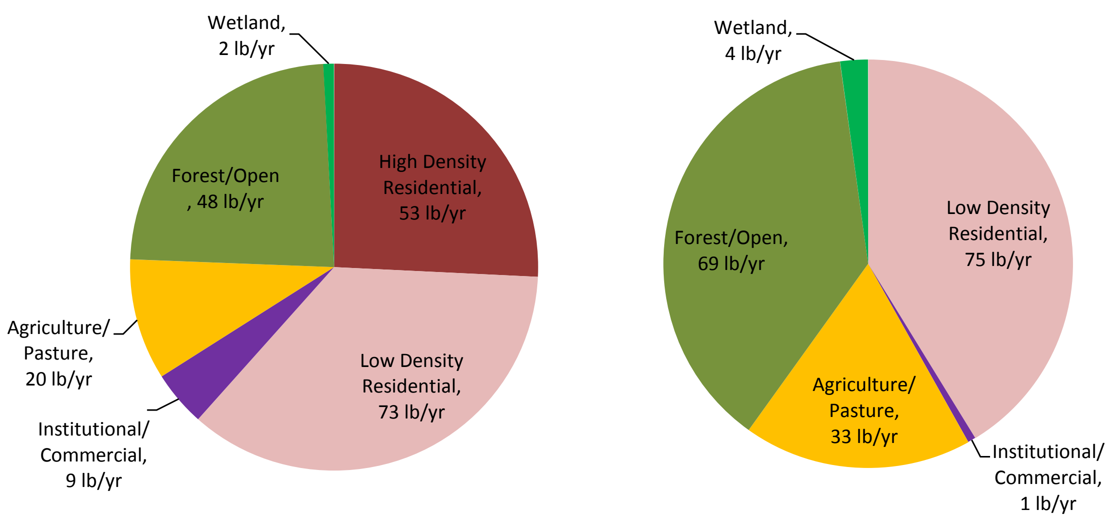


Figure 4.1.1. Land use and phosphorus loads from areas proximal to Lake Singletary (left) and areas draining to Singletary Brook (right).

4.2 Phosphorus from Septic Systems

Septic systems allow treated wastewater effluent, which is rich in phosphorus and other nutrient content, to leach into the groundwater and potentially migrate to the lake. Because phosphorus has a tendency to become bound to soil particles, the distance it can travel may be relatively short. For this reason, it is customary to only include septic systems in the near shore area (within 200 feet of shoreline) when calculating an annual septic system phosphorus load.

In order to quantify the number of homes with septic systems in the near shore area, LSWA volunteers conducted a survey to identify data relevant to each septic system, such as system volume, installation date, number of bedrooms, number of residents, etc. The survey results included 127 homes in the near shore area that are served by a septic system.

Based on the survey results, Geosyntec calculated an annual phosphorus load from septic systems of 17 lb. P/yr. This estimate was calculated using the following formula:

$$S = \sum_{i=0}^{h} B_i \cdot n_i \cdot Q_c \cdot m_i \cdot P_w \cdot \theta$$

Where:

S is the total P load from septic systems (lbs.);

h is the total number of homes considered in the inventory;

B_i is the number of bedrooms served by the system;

n_i is the average number of persons per bedroom (0.85, determined from a subset of homes that had information on both the number of bedrooms and the number of residents in the home);

Q_c is the per-capita daily water use (69.3 gal/person/day, from the USEPA Onsite Wastewater Treatment Systems Manual);

m_i is the number of months that the home is occupied (expressed as a number of months divided by 12);

P_w is the concentration of phosphorus in wastewater (10 mg/L, from the USEPA Onsite Wastewater Treatment Systems Manual);

θ is the fraction of phosphorus removal attributed to the septic system and leach field (0.94).

The 1991 "Diagnostic Study of Singletary Lake" reported approximately 412 lb P/yr resulting from near-shore septic system use. This result is significantly different from the annual load presented in this report. Both the 1991 study and this report agree on the per-capita generation of phosphorus from wastewater; the difference lies in the retention factor Θ.

In the 1991 "Diagnostic Study of Singletary Lake," a factor of 1 kg P/person/yr is used to represent the amount of phosphorus generated by each resident, which leaves the leach field.

In this report, average daily water use and typical wastewater phosphorus concentrations are used in place of the per-capita P generation factor. The resulting per-capita generation of phosphorus is:

$$\left(\frac{69.3\ gal}{person \cdot day}\right)\left(\frac{365\ day}{1\ yr}\right)\left(\frac{3.785\ L}{1\ gal}\right)\left(\frac{10\ mg}{L}\right)\left(\frac{1\ kg}{1000000\ mg}\right) = 0.96\ \frac{kg\ P}{person \cdot yr}$$

From this, it appears that amount of per-capita generation of phosphorus agrees between the two reports. The primary difference in the estimates of phosphorus loading to Lake Singletary arises from the soil retention factor used. The 1991 report appears to assume that approximately 75% of the phosphorus generated from septic systems reaches the lake. This assumption appears to be related to factors presented in the 1980 paper "Modeling phosphorus loading and lake response under uncertainty" by Reckhow and Simpson, which states that Θ may range from 0% to 100%, but that "…because of the complexities involved, the modeler's estimation of [Θ] still must be based on his/her knowledge of the soil conditions present in the watershed, past experience with similar watersheds, and his/her professional intuition".

We believe, based on our experience developing multiple phosphorus budgets for other lakes, that the fraction of phosphorus that makes it to the lake from the leach field is significantly lower, at only around 6%. Our arrival at this soil retention factor is based on literature review as well as calibration of several lake response models. Below is a list of literature references that have helped us reach this conclusion:

- Gillion and Patmont (1983*). "Lake Phosphorus Loading from Septic Systems by Seasonally Perched Groundwater."* This report states that "movement of diluted effluent to nearby lakes was common, but phosphorus transport from newer systems was usually less than 1%" and that "removal of more than 95% of phosphorus from wastewater is common after passing through a few meters of soil."

- Jones and Lee. (1979). *"Septic Tank Wastewater Disposal Systems and Phosphorus Sources for Surface Waters."* "Previous field studies have demonstrated that most soils... exhibit substantial ability to reduce phosphate concentrations. Reductions found were typically in excess of 95% within a few meters of the tile fields studied." Using wells installed downgradient of a septic system, they observed that septic effluent was moving through the groundwater, but that the effluent had very little phosphorus concentration. "No evidence for phosphate transport from septic tank effluent was found in any of the monitoring wells, even though this was a sand aquifer with a relatively high groundwater velocity."

- Kerfoot and Skinner (1981). *"Septic leachate surveys for lakeside sewer needs evaluation."* In a study of leach field effluent plumes, the authors found that "analysis of the observed ratios of total phosphorus found in groundwater plumes indicated a high of 2% and a low of 0.2% breakthrough of phosphorus content."

4.3 Phosphorus from Aerial Deposition

Atmospheric deposition of phosphorus is an estimate of the load of phosphorus delivered through wet or "dryfall" precipitation depositing phosphorus-containing particles directly on the surface of Lake Singletary. Deposition rates were determined from published literature (Reckhow, 1980). The annual atmospheric deposition load was calculated assuming a deposition rate of 0.24 lb. P/ac/yr, for a total atmospheric load of 82 lb. P/yr.

4.4 Internal Phosphorus Loading

Internal recycling of phosphorus can be a significant source of overall phosphorus load to a pond. Lake sediments contain phosphorus that is bound to the sediment particles. During periods of anoxia (oxygen concentration $\leq$ 1 mg/l), phosphorus can be released into the water from lake sediments in soluble form, making it biologically available to fuel increased algal productivity.

Geosyntec estimated internal phosphorus loading by assuming that the hypolimnion did not exchange significant amounts of phosphorus with the epilimnion during summer stratification. The difference in hypolimnion phosphorus concentration between the beginning of the sampling season (May) and the time of the highest observed hypolimnion concentrations (September-October) was multiplied by the estimated volume of the hypolimnion. The resulting mass of phosphorus was assumed to derive from internal loading.

The volume of the hypolimnion was estimated using dissolved oxygen profiles observed by LSWA and lake bathymetry. Figure 4.4.1 shows the observed (colored) and average (black, dashed) dissolved oxygen profiles during the height of stratification from 2005-2012. These profiles were collected during the months of June and August. The profiles indicate that the hypolimnion typically extends from the lake bottom up to a depth of approximately 6.5 m. Additionally, Figure 4.4.1 shows that the dissolved oxygen profile at the height of stratification remains fairly consistent from year to year. There does not appear to be a trend of decreasing dissolved oxygen levels at any particular depth. For instance, the hypolimnetic dissolved oxygen concentrations for 2008 and 2010 are slightly higher than the years before or after, which would not be expected if oxygen conditions at depth were decreasing from year to year.

A more detailed analysis of Lake Singletary's historic dissolved oxygen levels from 1998 to 2013 is provided in Appendix C.

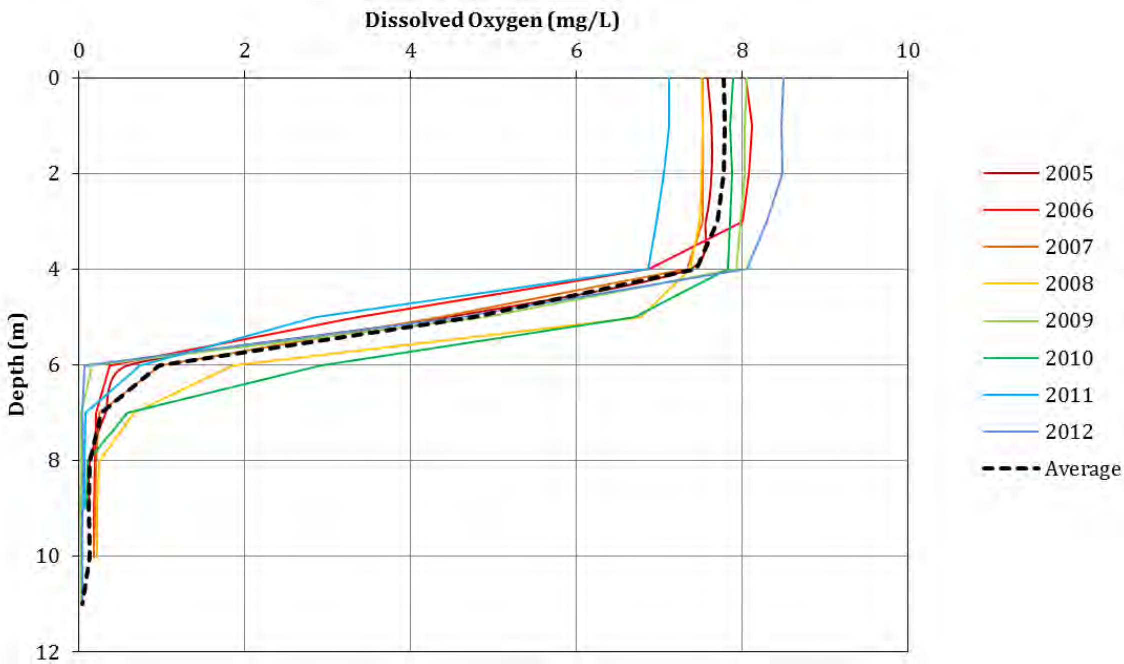


Figure 4.4.1: Observed and average (2005-2012) dissolved oxygen profile at height of stratification.

The average hypolimnetic total phosphorus concentrations over the course of the summers of 2005-2012 are shown in Figure 4.4.2. Each point on this curve represents the average of deep (approx. 10m) total phosphorus grab samples obtained during that month from 2005 to 2012. This curve shows behavior typical of a lake experiencing internal loading. On average, hypolimnion total phosphorus concentrations increased by approximately 53 µg/L from the onset of stratification in early summer to the peak of stratification in late August. Assuming that this increase in concentration resulted entirely from internal load, the average annual internal load can be calculated by multiplying the increase in concentration by the hypolimnion volume (the volume of water below 6.5m). The resulting estimated internal load for Lake Singletary is 156 lb./yr.

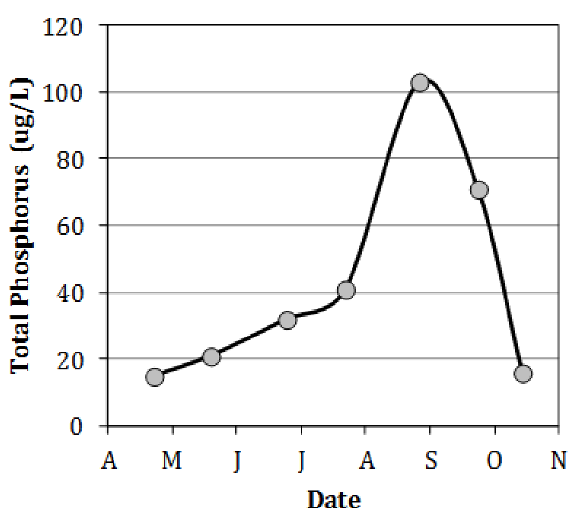


Figure 4.4.2. Monthly average (2005-2012) hypolimnetic total phosphorus concentrations.

4.5 Current Phosphorus Load

Based on the estimated sources of phosphorus presented in Sections 4.1 – 4.4, the total estimated annual phosphorus load to Lake Singletary is 639.8 pounds per year (290.3 kg/year). This estimated current load and its components are presented below in Figure 4.5.1.

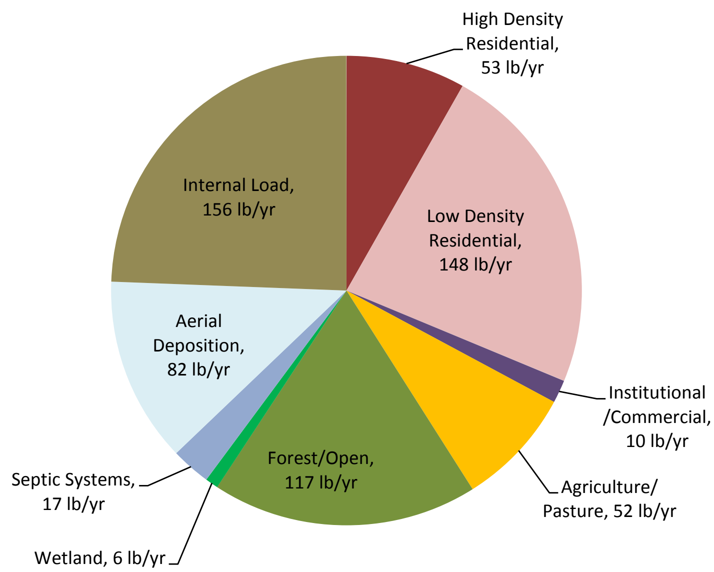


Figure 4.5.1. Estimated current phosphorus load to Lake Singletary.

The annual phosphorus load estimate presented in this report differs from those presented in the previous 1991 "Diagnostic Study of Singletary Lake" (1527 lb P/yr) and the 1995 "Singletary Lake Management Plan" (844 lb P/yr). The largest cause of the discrepancy between the various estimates is the annual load from near-shore septic systems, discussed in section 4.2.

When judging the validity of an annual phosphorus budget, it is important to note what the predicted in-lake concentrations would be, given the budget in question. The 1995 Management Plan contains some in-lake modeling which predicts average concentrations of 47 ug/L. Sampling data obtained by LSWA suggests an average in-lake concentration of approximately 15 ug/L. Because the earlier modeling efforts seem to overestimate in-lake concentrations, we believe that earlier phosphorus budgets have been likewise overestimated. Section 5 provides further discussion of Geosyntec's in-lake modeling, and demonstrates that our estimate of an annual external phosphorus budget of 484 lb P/yr leads to predictions of in-lake concentrations very similar to those obtained by LSWA water quality sampling data.

4.6 Future Conditions Analysis

Geosyntec estimated the extent of future development using population and developed land projections presented in the Central Massachusetts Regional Planning Commission (CMRPC) report, "2020 Growth Strategy for Central Massachusetts." The growth trends discussed in the report are shown in Figure 4.6.1, and these trends have been projected forward to 2030 by Geosyntec. We estimate that by 2030, Millbury's population will have grown by an estimated 415 people, with 401 additional acres of developed land. Sutton's population will have grown by an estimated 1032 people, with 484 additional acres of developed land.

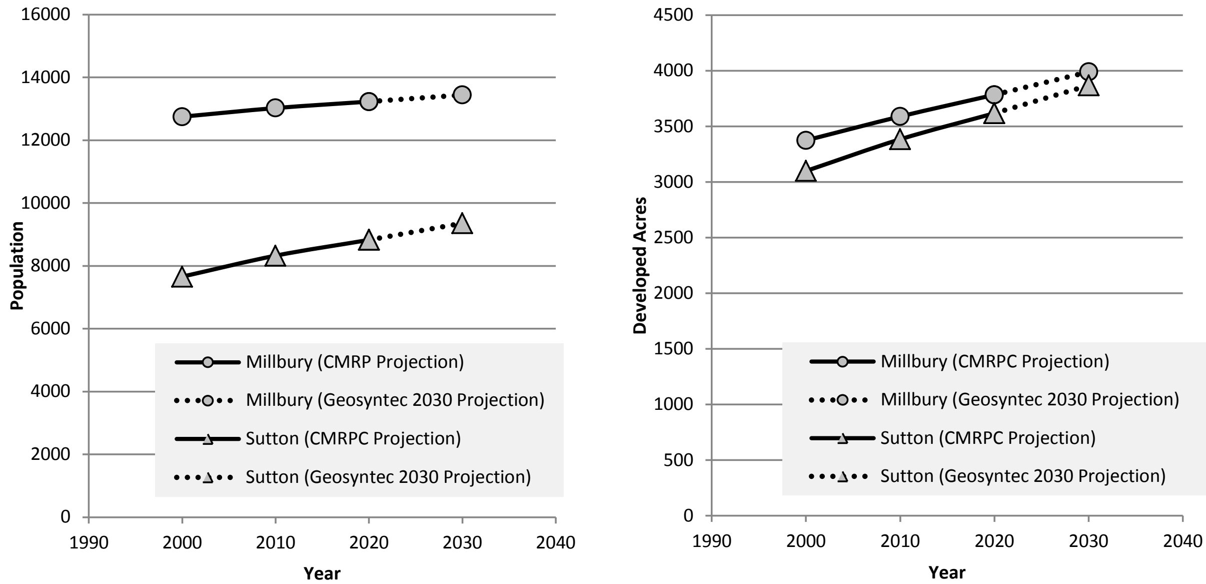


Figure 4.6.1. Central Massachusetts Regional Planning Commission (CMRPC) 2020 Population and Developed Land Projections, and Geosyntec 2030 Population and Developed Land Projections.

To apply these projections to the Lake Singletary watershed, the location of developable lands must be known. CMRPC provides a map of land suitable for development, as shown in Figure B5. According to this map, almost none of the Lake Singletary watershed contains land that CMRPC expects to be developed by 2020. This indicates that the Lake Singletary watershed may already be close to fully developed. For the sake of this analysis, we conservatively assumed that the projected additional development would occur uniformly through each town. The population and developed area projections are multiplied by the proportion of each town within the watershed, which contains 2.1% of the total area of Millbury and 10.8% of the total area of Sutton. The resulting estimates of additional population and developed area are 9 persons and 8.3 developed acres for Millbury, and 112 persons and 52.5 developed acres for Sutton.

The addition of 60.8 acres of residential land is expected to cause an increase in annual phosphorus loading of 22.8 lb P/yr. The new residential land is assumed to replace land that was previously forest and which generated an estimated 5.6 lb P/yr. The resulting conversion of 60.8 acres of forest to residential development is projected to increase Lake Singletary's total annual phosphorus load by 17.2 lb. P/yr.

The additional homes projected to be built in the watershed could potentially increase the annual phosphorus loading from septic systems. However, in the case of Lake Singletary, we believe the nearshore area (within 200 feet of shoreline) to be nearly built out. For the purpose of Geosyntec's buildout projection, we assumed that any additional homes in the watershed would occur far enough from the lake so as not to increase phosphorus loading from septic systems.

As discussed in Section 6.3, regulatory and land planning tools such as zoning bylaws, watershed protection districts and Low Impact Development bylaws are recommended and can be effective tools for protecting lakes from adverse impacts due to future land development.

Section 5: Phosphorus Concentration Modeling

In-lake phosphorus response models are commonly used to predict in-lake phosphorus concentrations as a function of annual phosphorus loading (Section 4), mean lake depth, and hydraulic residence time. The models are useful for understanding the relationships between current phosphorus loading and in-lake concentration, as well as for estimating in-lake concentrations under hypothetical scenarios, such as future buildout. One of the most commonly used in-lake response models is the Vollenweider model, which predicts an average annual in-lake phosphorus concentration. A second model, the Nurnberg Model, is a more refined response model that considers seasonal effects and internal phosphorus loading. The following sections discuss the results of these two models for Lake Singletary.

5.1 Mean Lake Depth and Hydraulic Residence Time

Geosyntec developed a bathymetric map for Lake Singletary in 2009, based on depth measurements provided by the LSWA. The bathymetry was processed using GIS tools to determine a total lake volume of 2,191 million gallons (8.29×10^6 m^3). Given the lake area of 340 acres, the average depth (volume divided by area) is 19.8 feet (6.0 m).

Hydraulic residence time is the average amount of time for the entire volume of water in a lake to be replaced. Residence time is estimated by dividing the lake volume by the average annual discharge of the lake. Average annual discharge is calculated by estimating a hydrologic budget for the watershed, which can be performed in several ways. Ideally, the optimal method involves direct measurement, such as installation of stream and precipitation gages to construct a full annual water budget. When time or budget prevents the use of direct measurement, other methods can be used. Geosyntec has performed two separate calculations of an annual water budget, presented below. The hydrologic budget is calculated as:

$$Q = Q_w + Q_d - Q_e = Q_w + (P \cdot A_s) - (\rho \cdot E_{pan} \cdot A_s)$$

Where Q is the annual discharge from the lake, Q_w is the annual discharge entering the lake from the watershed, Q_d is the water resulting from direct precipitation to the lake, and Q_e is the amount of water removed from the lake via evaporation, P is the annual precipitation, A_s is the lake surface area, E_{pan} is the pan evaporation rate (32 in/yr for New England), and ρ is the pan evaporation coefficient necessary to adjust pan evaporation to lake evaporation (0.75 for New England).

Watershed discharge, Q_w, was calculated using two separate methods. The first method involved using a map of annual runoff amounts prepared by USGS (Randall, 1996). For the Lake Singletary region, the Randall mean annual runoff value is approximately 26 inches. In this case, the term 'runoff' refers to all water that remains after interception, evaporation, and transpiration, including any water that infiltrated and enters the lake via groundwater. Multiplying this runoff depth by the watershed area results in an estimated Q_w of:

$$Q_w = \left(26\ \frac{in}{yr}\right)\left(\frac{1\ ft}{12\ in}\right)(2267\ ac)\left(\frac{43{,}560\ ft^2}{ac}\right) = 213.95 \cdot 10^6\ \frac{ft^3}{yr} = 6.06 \cdot 10^6\ \frac{m^3}{yr}$$

The second method incorporated USGS stream gaging results from 94 New England stream gages (a total of 942 water-years) to develop a discharge-area relationship (Figure 5.1.1). Linear regression of these data resulted in:

$$\log[Q_{da}] = 0.9096 \cdot \log[A_w] - 2.2943$$

Where Q_{da} is an average daily discharge in ft^3/s and A_w is the watershed area in acres. For Lake Singletary,

$$Q_{da} = 10^{[0.9096 \cdot \log[2267] - 2.2943]} = 5.72\ \frac{ft^3}{s}$$

$$Q_w = Q_{da} \cdot \left(3.17\ \cdot \frac{10^7 sec}{yr}\right) = 180.56 \cdot 10^6\ \frac{ft^3}{yr} = 5.11 \cdot 10^6\ \frac{m^3}{yr}$$

Geosyntec used an average of the two methods to determine an estimated of Q_w $5.59 \cdot 10^6$ m^3/yr.

Based on the water balance equation above, the total annual discharge, Q, is estimated to be approximately 6,494,460 m^3/yr, which equates to a hydraulic residence time of 1.27 years, or a flushing rate of 0.78 yr^{-1}.

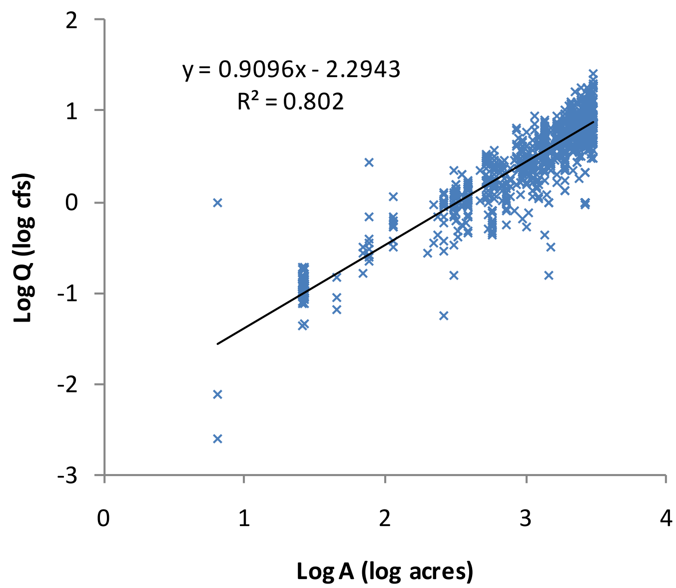


Figure 5.1.1. Area-Discharge Relationship for New England USGS Stream Gages (<3000 acres).

The 1991 "Diagnostic Study of Singletary Lake" estimated a flushing rate of 2.8 yr^{-1} (and a corresponding residence time of 0.36 years). The previous estimate suggests that water is flushed through the lake at a rate much faster than we have calculated. By investigating the hand calculations included in Appendix C of the Diagnostic Study, we believe this flushing rate was overestimated due to a 10-fold underestimate in lake volume. Table 1 of the Diagnostic Study states that lake volume is 2,715 million gallons and 1,026,270 m^3. 2,715 million gallons is actually equal to 10,277,392 m^3 (i.e. the metric value reported in the Diagnostic Study is approximately 10% of the correct conversion). The estimate, as presented in gallons, agrees well with Geosyntec's estimate of lake volume (2,191 million gallons), so we believe the value presented in cubic meters to be erroneous. Unfortunately, the metric value was carried forward in the hand-calculations. Apart from that, many of the key hydrologic and morphometric parameters presented in the diagnostic study (volume, evaporation, precipitation, runoff, etc.) agree with, or are very near to, those calculated by Geosyntec.

5.2 Vollenweider Model

The Vollenweider model is commonly used to predict in-lake phosphorus (P) concentrations as a function of annual phosphorus loading, mean lake depth and hydraulic residence time. Phosphorus concentrations predicted by the Vollenweider equation are based on an assumption that the lake is uniformly mixed, such as at spring turnover. The Vollenweider model is based on a five-year study of about 200 waterbodies in Europe, North America, Japan and Australia.

The Vollenweider Equation is provided below, with calculations for Lake Singletary based on the phosphorus loading estimate discussed in Section 4, including phosphorus from stormwater runoff, septic systems, and aerial deposition. Internal loading is not included in the Vollenweider phosphorus load because the model is an empirical relationship between in-lake phosphorus concentration and external load only. As stated in Section 4, Geosyntec estimates annual external phosphorus loading to Lake Singletary to be 484 lb. P/yr (219 kg P/yr). The equation parameters and the values specific to Lake Singletary are presented in Table 5.2.1.

The Vollenweider Equation is:

$$p_v = \frac{L_p}{\left(q_s\left(1 + \sqrt{\tau_w}\right)\right)}$$

where:

p_v = mean in-lake phosphorus concentration (mg/L) estimated by Vollenweider equation;

L_p = annual phosphorus load/lake area, (grams/m2/year);

τ_w = hydraulic residence time (yr);

q_s = hydraulic overflow rate=mean depth /hydraulic residence time (m/yr)= z/τ_w;

z = average depth (m)

Vollenweider Model Parameters			
Parameter		Value	Units
W	Total P Loading Rate	219	Kg/yr
V	Volume	8,294,000	m^3
z	Average Lake Depth	6.0	m
Q	Annual Discharge	6,494,460	m^3/yr
As	Lake Area	1,357,900	m^2
L	Areal Loading Rate	159.5	mg/m^2
q_s	Hydraulic Overflow Rate	4.72	m/yr
τ_w	Hydraulic Residence Time	1.27	yr

Table 5.2.1: Vollenweider Model Parameters

In-lake P concentration = $\frac{L_p}{\left(q_s\left(1+\sqrt{\tau_w}\right)\right)} = \frac{159.5}{4.72\left(1+\sqrt{1.27}\right)} = 15.9\ \mu\text{g/L}$

Based on the estimated annual external phosphorus load of 484 lb./yr (219 kg/yr), the Vollenweider equation predicts an in-lake phosphorus concentration of 15.9 µg/L. LSWA water quality sampling data indicates an average annual phosphorus concentration of 15 µg/L, indicating that the annual phosphorus load and Vollenweider equations have provided an accurate representation of in-lake phosphorus dynamics. As presented in Figure 5.4.1, the slope of the Vollenweider model line for Lake Singletary estimates that a 31 pound per year change (increase or decrease) in annual phosphorus load will result in a corresponding 1 µg/L change to in-lake phosphorus concentration.

5.3 Nürnberg Model

The Vollenweider model estimates an average annual in-lake P concentration that represents the lake in a fully mixed state (e.g. spring turnover). The Nürnberg model provides a more nuanced estimation of phosphorus concentrations that reflect seasonal changes related to internal loading. Nürnberg's model utilizes a parameter, R, which describes the fraction of sediment retained by the lake each year. This fraction is then applied to different subsets of the annual P load to determine an in-lake phosphorus concentration at various times of the year. Nürnberg estimates the value of R to be:

$$R = \frac{15}{18 + q_s}$$

The Nürnberg model uses the following three equations to calculate an annual average P concentration (p_{ann}), a summer epilimnion P concentration (p_{epi}), and a fall P concentration (p_{fall}):

$$p_{ann} = \left[\frac{(L_{ext} + L_{int})}{q_s}\right](1 - R)$$

$$p_{epi} = \left[\frac{(L_{ext})}{q_s}\right](1 - R)$$

$$p_{fall} < \left[\frac{(L_{ext})}{q_s}\right](1 - R) + \frac{L_{int}}{q_s}$$

For an annual average, the retention factor is applied to the complete annual load, as the internal load will be able to mix throughout the year and be available for uptake, settling, and flushing. The retention factor is applied to the external load only to obtain a summer epilimnion concentration, when any internal P loading is sequestered in the hypolimnion during stratification and is not available for uptake, settling, and flushing. Finally, the internal load is added to the epilimnion concentration and only subjected to flushing (by being divided by q_s, the hydraulic overflow rate) to represent the relatively rapid mixing of the pulse of soluble phosphorus from the hypolimnion into the epilimnion during fall turnover. This model is particularly useful in characterizing and developing management goals for lakes that experience late summer/early fall algae blooms when epilimnetic P concentrations are predicted to be peak, such as Lake Singletary. The Nürnberg model parameters and results for current (2010) conditions are provided below:

Nürnberg Model Parameters			
Parameter		Value	Units
W_{ext}	External P Loading Rate	219	kg/yr
W_{int}	Internal P Loading Rate	71	kg/yr
V	Volume	8,294,000	m^3
Q	Annual Discharge	6,494,460	m^3/yr
As	Lake Area	1,357,900	m^2
L_{ext}	External Areal Loading Rate	159.5	mg/m^2
L_{int}	Internal Areal Loading Rate	51.5	mg/m^2
R	Retention Factor	0.66	
q_s	Hydraulic Overflow Rate	4.72	m/yr

Table 5.3.1. Nürnberg Model Parameters

$$p_{ann} = \left[\frac{(L_{ext} + L_{int})}{q_s}\right](1 - R) = \left[\frac{(159.5 + 51.5)}{4.72}\right](1 - 0.66) = 15.2\ \mu g/L$$

$$p_{epi} = \left[\frac{(L_{ext})}{q_s}\right](1 - R) = \left[\frac{(159.5)}{4.72}\right](1 - 0.66) = 11.5\ \mu g/L$$

$$p_{fall} < \left[\frac{(L_{ext})}{q_s}\right](1 - R) + \frac{L_{int}}{q_s} = \left[\frac{(159.5)}{4.72}\right](1 - 0.66) + \frac{51.5}{4.72} = 22.4\ \mu g/L$$

Figure 5.3.1 shows the median observed phosphorus concentrations from 2008-2012 and the Nürnberg model results. The observed concentration data show the expected seasonal pattern of dropping slightly during summer, when stratification is in effect, and then rising in late fall during lake turnover, when P-rich water from the hypolimnion is mixed with the surface waters. The Nürnberg model p_{ann} result of 15.2 µg/L agree with the LSWA average concentration of 15 µg/L, and the seasonal p_{epi} and p_{fall} results provide a realistic bracketing of the observed seasonal fluctuations.

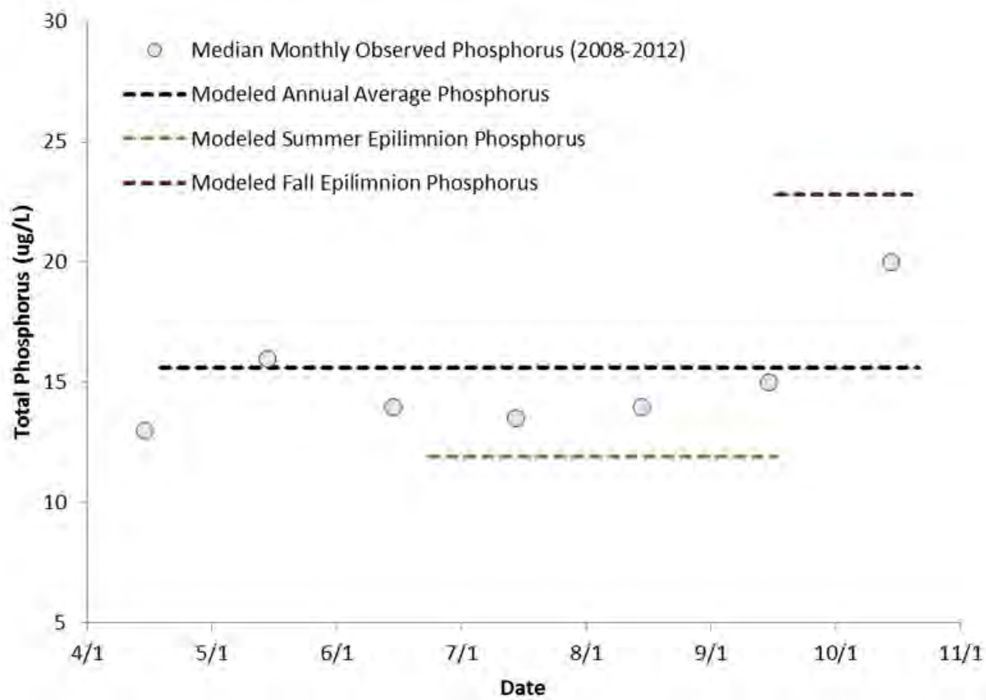


Figure 5.3.1. Median observed in-lake phosphorus concentrations (2008-2012) and Nürnberg model results.

5.4 Analysis of In-lake Phosphorus Modeling

The results presented in sections 5.2 and 5.3 demonstrate that both the Vollenweider and Nurnberg models produce realistic estimates of in-lake phosphorus concentrations for current conditions. These models were next used to analyze Lake Singletary phosphorus dynamics under varying land use scenarios.

The two scenarios to be investigated are the future conditions buildout scenario discussed in Section 4.5, and a pre-development, "pristine" scenario to understand what the best-case conditions for the lake might be. The future conditions buildout scenario indicated an expected total increase in annual phosphorus loading of 32 lb. P/yr, for a total annual phosphorus load of 516 lb./yr. The pristine condition was modeled by assuming all developed land use within the watershed is converted to forest. Under the pristine condition, there is no input from septic systems and internal load is not considered. The estimated annual phosphorus load for the pristine condition is 276 lb. P/yr (a 43% decrease from current loading).

Scenario	Annual External Phosphorus Load (lb. P/yr)	Annual Internal Phosphorus Load (lb. P/yr)	Vollenweider In-lake P (µg/L)	Nurnberg In-lake P (µg/L)		
				p_{ann}	p_{epi}	p_{fall}
Pristine	276	0	9.0		6.6	
Current (2012)	484	71	15.9	15.2	11.5	22.4
Buildout (2030)*	500	71	16.4	15.6	11.9	22.8

Table 5.4.1. Phosphorus Loading Scenario Results

* As discussed in Section 4.5, the 2030 buildout scenario is based on a conservative assumption that (1) new development will be evenly distributed throughout the towns and (2) that rates of new development projected through 2020 would remain consistent through 2030.

Figure 5.4.1 shows the relationship between annual phosphorus load and in-lake phosphorus concentration, as predicted by the Vollenweider model. Plotted on this figure are the three scenarios presented in Table 5.4.1 above, along with the threshold phosphorus concentrations for oligotrophic (12 µg/L) and eutrophic (25 µg/L) status. The slope of the Vollenweider model line for Lake Singletary estimates that a 31 lb./year change (increase or decrease) in annual phosphorus load will result in a corresponding 1 µg/L change to in-lake phosphorus concentration.

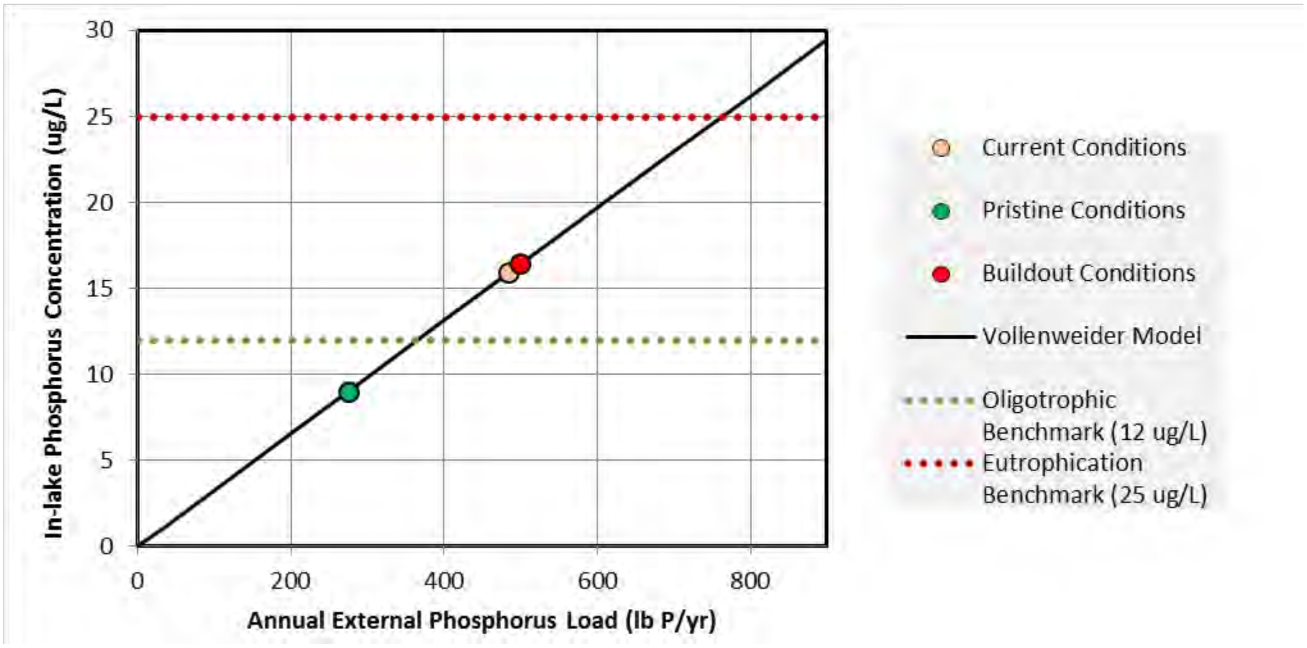


Figure 5.4.1. Vollenweider Model with Current Conditions and Scenario Results

Section 6: Lake and Watershed Management Recommendations

6.1 Watershed Management Recommendations

Geosyntec and members of LSWA conducted a field watershed investigation on December 18, 2012. Based on the field investigation results, this section provides a discussion of potential phosphorus reduction best management practices (BMPs) that relate to storm water management. The following pages describe sites identified during the field investigation and recommended improvements, along with estimates of cost and nutrient load reduction when applicable. It is important to note that the sites discussed in this section are not intended to be an all-inclusive listing of potential stormwater improvements in the Lake Singletary watershed. Rather, these sites are representative examples of potential stormwater improvements and retrofits that could be implemented at numerous sites throughout the watershed.

Recommendation 1: Crestview Lane

A large forested parcel is located just northwest of the intersection of Main Street and Crestview Lane. Runoff from approximately 4.5 acres surrounding Crestview Lane appears to drain north from the road through this parcel to a small, unnamed tributary to Lake Singletary.

View north along Crestview Lane.

The undeveloped land could be used to create a small constructed wetland or stormwater detention basin. This area could collect runoff currently flowing down Crestview Lane. Runoff can be directed to the new basin by repaving Crestview Lane so that runoff from the road drains to the north via overland flow, or by installing a pair of catch basins near the intersection of Crestview Lane and Main Street. Vegetated swales could be installed along Crestview Lane to promote the collection and direction of runoff to the new wetland or basin. Additionally, it may be possible to connect existing storm drains SD12-15 to the wetland or basin depending on the actual invert of the basin. These storm drains collect runoff from Singletary Road.

Potential discharge point to proposed constructed wetland.

The wetland or basin should be sized to the maximum extent practicable for the area. The final design should incorporate a pre-treatment forebay to facilitate maintenance, and a circuitous flow path through the basin to enhance settling of suspended sediment and the uptake of nutrients through plants. Bedrock outcrops that may limit the excavation depth of the proposed wetland or basin were observed within the site.

Prior to conceptual design, a site survey and wetland delineation should be performed, as well as several borings (at least 3) to establish groundwater elevation. The location of the existing adjacent wetland, as established by a wetland delineation, will serve to dictate the size of the constructed wetland, as well as the outlet elevation, which should be tied into the existing wetland grade.

A conceptual schematic of the proposed constructed wetland is presented in Figure B6. Construction costs may vary significantly depending on the extent of bedrock and any issues associated with land ownership.

Estimated Cost: $69,000 - $82,000

Estimated Pollutant Reduction: 0.33 lb. P/yr

Recommendation 2, Option A:
West Main Street and Singletary Road, Traffic Island Bioretention

A 1,350 square foot traffic island is located at the intersection of West Main Street and Singletary Road. This grassed traffic island could be retrofitted into an attractive, landscaped bioretention cell that would treat runoff from approximately 1 acre of surrounding road and residential area.

The traffic island would be excavated and refilled with a mixture of sand and loam such that the finished grade forms a depression relative to the surrounding road surfaces. Underdrain and overflow structures could be connected to the nearby SD26, which appears to drain to outfall OF07B approximately 300 feet south.

A critical component to this retrofit would include repaving of the surrounding sections of W. Main Street and Singletary Road such that the road surfaces pitch inwards toward the new bioretention cell.

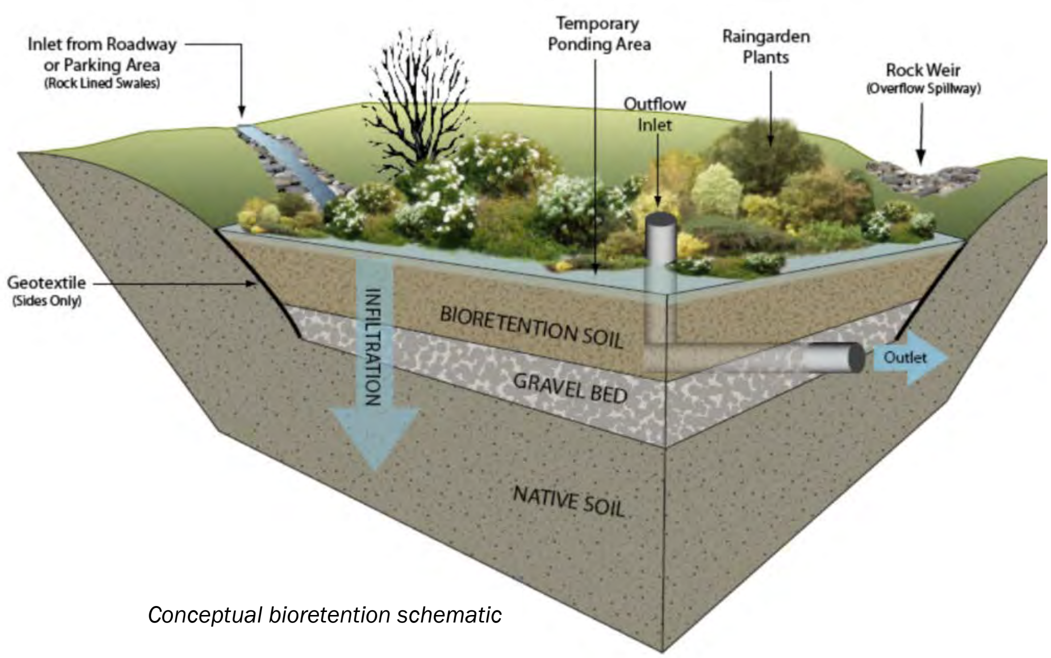
Catch basins in the surrounding area appeared to be unmaintained and clogged with sediment and debris. This may allow the proposed bioretention cell to capture runoff from the western portion of W. Main Street that bypasses clogged catch basins, potentially increasing its catchment area to several acres.

Estimated Cost: $13,000 - $15,600

Estimated Pollutant Reduction: 0.25 lb. P/yr

Traffic Island at intersection of W. Main Street and Singletary Road.

Parking lot bioretention facility, Harrisville NH



Conceptual bioretention schematic

Recommendation 2, Option B:
West Main Street and Singletary Road, Traffic Island Subsurface Sand Filter

The traffic island located at West Main Street and Singletary Road is situated near the downstream end of a line of stormwater infrastructure capturing runoff from approximately 5 acres of land surrounding West Main Street. The stormwater pipes from West Main Street could be redirected to a subsurface sand filter installed below grade within the footprint of the existing traffic island.

Sand filters consist of large underground vaults that contain pretreatment (trash grate, particle settling, etc.) and filtration areas. The filtered effluent can be discharged via an underdrain or allowed to infiltrate into the native soil, depending on the infiltration capacity of the native soil and depth to seasonal high groundwater.

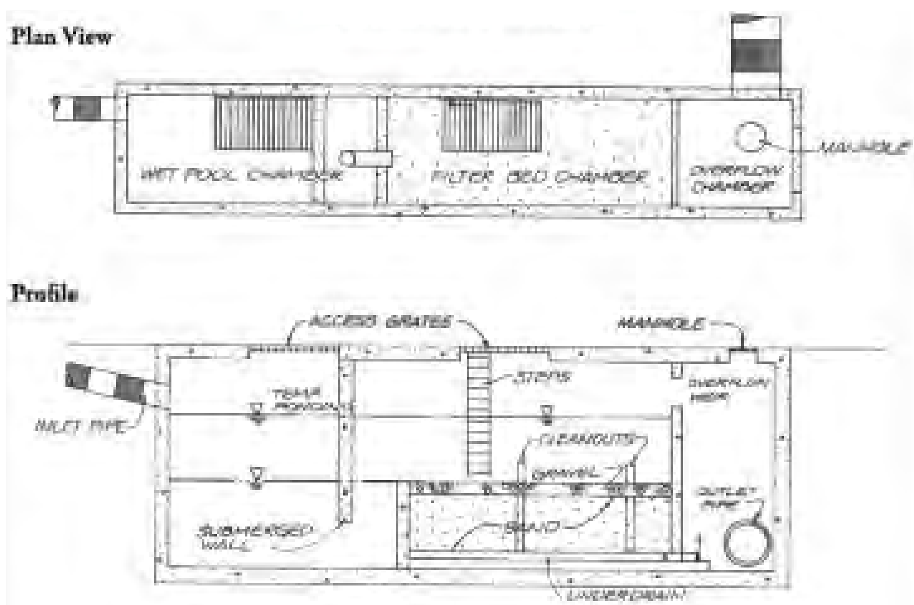
One advantage of this system relative to Recommendation 2, Option A (bioretention) is that the capture area includes the entire drainage system of West Main Street (west of the intersection) in addition to portions captured in the Option B scenario (i.e., runoff from the areas directly adjacent to the island). The disadvantage is that clogging and blockage of the existing catch basins will severely reduce the volume of water treated by the sand filter. Proper catch basin cleaning and maintenance is integral to the success of this recommended BMP.

Estimated Cost: $11,000 - $17,000

Estimated Pollutant Reduction: 1.0 lb. P/yr

Installation of subsurface storage/infiltration facility, Congamond Lake, MA.

Traffic Island at intersection of W. Main Street and Singletary Road.



Example sand filter design, NH Stormwater Manual, Vol. 2

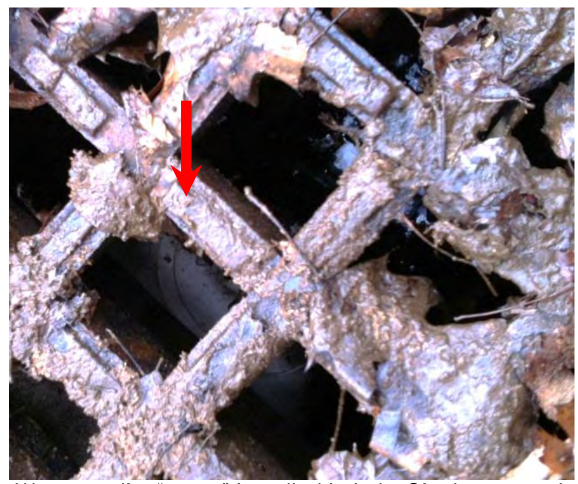
Recommendation 3: Catch Basin Maintenance

A system of catch basins and associated stormwater infrastructure collects drainage along the northwest shore of Lake Singletary. These catch basins are located along West Main Street and Singletary Road.

During a watershed investigation and site walk, Geosyntec observed that the majority of these catch basins were blocked with debris, leaf litter, and sediment. Blocked catch basins cause stormwater runoff to continue flowing overland, potentially across uncontrolled and easily erodible material. This can increase the occurrence of gullies and rills, and increase the load of sediment and nutrients discharged to Lake Singletary via stormwater.

Properly maintained and cleaned catch basins within Lake Singletary watershed.

Some existing catch basins have been fitted with water quality 'snouts,' which trap floating debris and trash by altering the catch basin's outlet configuration. These snouts provide additional stormwater treatment, but are not effective when the catch basin is clogged or blocked.



Water quality "snout" installed in Lake Singletary catch basin.

By working with the local DPW (in particular, Millbury), a more aggressive catch basin cleaning schedule could be implemented. Local residents can also contribute by clearing catch basin grates of accumulated debris/sediment after large storm events. To maintain sump capacity for proper catch basin performance, it is preferable to clean catch basins before they have accumulated sediment to half of capacity.

If contracted out to a private firm, catch basin cleaning will typically cost \$20 to \$30 per catch basin. The water quality benefits (i.e., pollutant reduction) of catch basin cleaning will vary considerably, depending on site-specific conditions such as the size of the drainage area contributing to each basin, catch basin sump volume, extent of localized erosion, time elapsed since last cleaning, etc. Without additional investigations beyond the scope of this project (e.g., catch basin sediment chemistry sampling, subwatershed-scale modeling), it is not possible to accurately estimate the quantity of additional pollutant removal per additional catch basin cleaning.

Example of sediment and debris-laden catch basin, West Main Street.

Although literature on this topic is relatively scarce, a frequently cited study of the benefits of catch basin cleaning (Mineart, P. & S. Singh. 1994. *Storm Inlet Pilot Study*) found that monthly cleaning yielded the best results in terms of pollutant removal per cleaning. This study concluded that the pollutant removal benefit of more frequent clean outs should be balanced against the associated increases in municipal costs.

Estimated Cost (for Millbury): \$960 - \$1,440, based on two extra cleanings per year for 24 catch basins

Recommendation 4:
Rain Garden Demonstration Program

A raingarden demonstration program could be implemented to educate Lake Singletary watershed residents about Low Impact Development (LID) stormwater management practices and to promote this approach throughout the watershed. Raingardens will vary in size depending on drainage area and property owner preference, and typically range between 50 to 200 square feet. These rain gardens would help improve water quality and provide pretreatment for stormwater that would otherwise runoff directly into the lake. For the cost and load reduction estimates below, five (5) 100-square foot raingardens were assumed as part of the raingarden demonstration program.

Soils in the majority of the nearshore area of the Lake Singletary watershed are generally favorable for implementation of raingardens and other infiltration practices as recommended in this report (see attached soils map, Figure B2). Soils classified in hydrologic soils groups A and B, such as those bordering the western, northern, and northeastern shores, have rates of infiltration conducive to practices such as raingardens. However, proper design can allow raingardens to function well in areas with less favorable native soils. As such, the raingarden demonstration program could be used to promote a broader, long-term effort to implement raingardens at numerous locations throughout the watershed.

Estimated Cost: $6,600 - $7,800

Estimated Pollutant Reduction: 0.1 lb. P/yr

Typical rain garden installation along road shoulder (Silver Lake watershed, Wilmington, MA)

Lakeside rain garden providing storage during a rain storm (Lake Shirley, Lunenburg, MA).

Newly planted rain garden with shrub planting scheme (Mirror Lake watershed, Tuftonboro, NH).

Recommendation 5:
Enhancement of Boat Ramp Parking Lot Redesign

Plans developed by the Massachusetts Department of Fish and Game proposed improvements to the public boat ramp and parking lot located off of West Main Street. The plans indicate that approximately half of the paved parking area will drain west to a water quality swale and onward to a 660 square foot raingarden along the south edge of the parking area.

The incorporation of stormwater BMPs in this proposed parking area redesign will likely have a positive impact on the quality of the runoff entering the lake at this location. However, some simple enhancements could be considered to maximize the effectiveness of the proposed system.

We recommend the installation of one deep sump catch basin across the street from the parking area entrance. This catch basin will collect runoff from West Main Street and two nearby residential parcels. This catch basin would effectively increase the catchment area of the proposed rain garden BMP by approximately a factor of 7.

Incorporation of this recommendation would require some limited survey to determine the feasibility of routing runoff from the proposed catch basin to the parking lot water quality swale. Additionally, the increased drainage area may require the proposed raingarden to have a slightly larger footprint.

Estimated Cost: $6,500 – $7,800

Estimated Pollutant Reduction: 0.30 lb. P/yr

Public Boat Ramp Parking Lot

Location of proposed catch basin and stormwater pipe.

Recommendation 6:
Installation of Hydrodynamic Separators

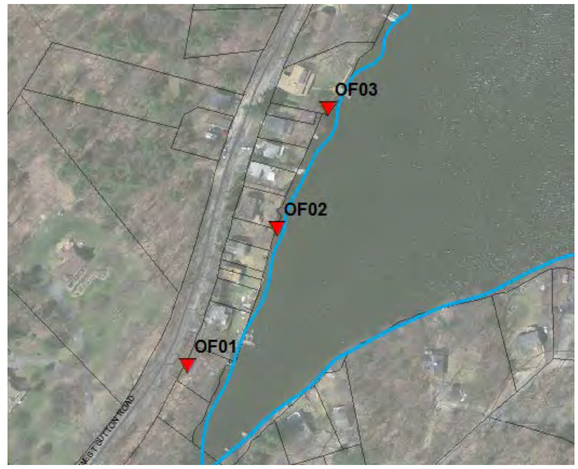
Recent installation of storm drainage infrastructure along West Sutton Road in Sutton has improved the collection of stormwater runoff in the area adjacent to the lake's western shore. As noted in Recommendation 3, some water quality 'snouts' were observed in drop inlet structures, which will aid in trash separation. However, performance of this drainage system could be improved by the installation of several hydrodynamic separators, such as BaySeparators or similar units.

We recommend installing three BaySeparator units upstream of outfalls OF01, OF02, and OF03, which discharge runoff from sections of West Sutton Road. These units would be able to treat approximatley 17.6 acres of runoff originiating on road surfaces, residential areas, and forested land. BaySeparators are typically installed in the road in-line with existing stormwater outfall pipes.

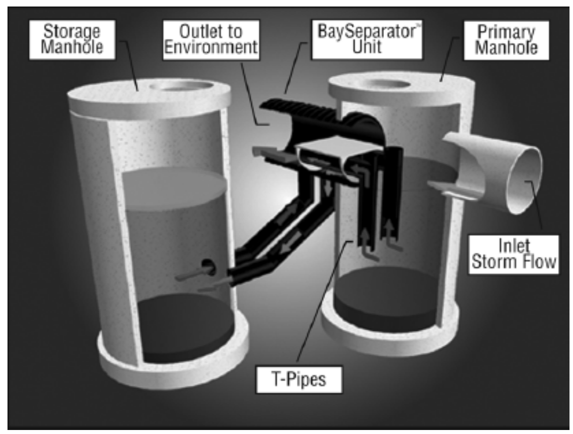
Hydrodynamic separators such as BaySeparators act similar to water quality 'snouts' in that they discharge runoff from the middle of the water column within an adjacent manhole structure. This allows heavy particles to settle to the bottom of the unit, and light, floatable material to remain above the outlet of the separator. Maintenance requirements for these systems are similar to those of catch basins or manhole structures that exist through the watershed.

Estimated Cost: $26,400 - $31,200

Estimated Pollutant Reduction: 1.47 lb. P/yr



Location of OF01-03, West Sutton Road



BaySeparator schematic, BaySeparator Technical Manual


BaySeparator installation

Recommendation 7:
Agricultural Best Management Practices

A pasture area used for raising horses is located within the watershed along Singletary Avenue. The pasture is located adjacent to an intermittent tributary that flows directly to Lake Singletary.

Several agricultural best management practices could be considered for use at this site such as:

- Vegetated Filter Strips
- Manure Management /Composting
- Barn Runoff Management

Cooperation with the property owner will be essential to the success of these or any other appropriate BMPs. The property owner and LSWA could obtain technical support and funding funding to support the implementation of these practices through the U.S. Department of Agriculture – Natural Resources Conservation Services (USDA-NRCS) Environmental Quality Incentives (EQIP) Program. The EQIP Program is a voluntary program that provides financial and technical assistance to agricultural land owners to meet a variety of environmental goals, including water quality and the reduction of nonpoint source pollution. Information about EQIP grants can be obtained from the Worcester County NRCS field office in Holden, MA (413-253-4350).

More information related to water quality protection at horse farms can be found through the following resources prepared by the Massachusetts Department of Environmental Protetcion's (MassDEP)

Aerial view of horse farm on Singletary Avenue.

Example of a manure composting shed located next to a horse barn.

- *Horsekeeping & Water Quality: A Horse Owner's Guide to Protecting Massachusetts Natural Resources:*

  www.mass.gov/eea/agencies/massdep/water/watersheds/a-horse-owner-guide-to-protecting-ma-natural-resources.html

- Horsekeeping and Water Quality Fact Sheets

  http://www.mass.gov/eea/agencies/massdep/water/watersheds/horsekeeping-and-water-quality.html

6.2 Discussion: Dam Removal at Stockwell Ponds

The Stockwell Ponds are comprised of a series of small, shallow impoundments and associated emergent wetlands along Singletary Brook, the primary tributary to Lake Singletary. Singletary Brook flows through these ponds from south to north towards the lake. Currently, the ponds and wetlands are slowing and storing incoming water, allowing for sediment and nutrients to settle in particulate form and be removed from the water that ultimately discharges to Lake Singletary. This type of wetland/impoundment system can typically play an important role in protecting the water quality of downstream receiving waters. For this reason, the design of many drinking water reservoirs includes a series of smaller upstream impoundments, each providing settling and pollutant removal and allowing for progressively improved water quality as water flows to the final reservoir.

The stockwell Ponds and their associated wetlands are likely lined with a layer of nutrient rich sediment that, in the event of dam removal, would be exposed to the surface and subject to erosive forces. This may cause a high temporary pulse of phosphorus-rich sediment to the lake for up to several years until a new equilibrium is reached. Additionally, due to the effects of internal loading, the presence of a large quantity of fresh sediment to the lake floor could potentially compound the severity of any late-summer algal blooms. Without a detailed study of the sediment chemistry, hydrology, and hydraulics of these ponds, the effects of dam removal from any specific pond in the sysytem are difficult to estimate. However, some recent studies of nutrient dynamics following dam removal provide some findings that could be applicable to Lake Singletary and the Stockwell Ponds. These studies, which generally indicate that dam removal may have a negative temporary impact on Lake Singletary, are summarized below.

- *Bushaw-Newton, K., J. Ashley, et al. (2001). "The Manatawny Creek Dam removal: Biogeochemical processes and sediment contaminants."*: This study examined the effects of a small dam removal in southeastern PA. This study found no significant difference in nutrient loading before and after the dam removal.

- *Stanley, E. and M. Doyle (2001). "Phosphorus transport before and after dam removal from a nutrient-rich creek in southern Wisconsin."*: This study examined the water quality impacts of a dam removal from a Wisconsin stream that was heavily impacted by agricultural uses. The study found that when the dam was in place, phosphorus concentrations downstream of the dam were reduced by 10-30%. After the dam removal, downstream phosphorus concentrations were significantly elevated, primarily due to the migration of nutrient-rich sediments.

- *Ahearn, D. S. and R. A. Dahlgren (2005). "Sediment and nutrient dynamics following a low-head dam removal at Murphy Creek, California."*: This study found that, after a dam removal, phosphorus export from the impoundment area occurred primarily during large storm events. The area typically acted as a phosphorus sink during periods of low flow.

- *Muskopf, S. A. (2007). The effect of beaver (Castor canadensis) dam removal on total phosphorus concentration in Taylor Creek and Wetland."*: This study addressed the effect of beaver dams in the vicinity of Lake Tahoe. The study found that phosphorus concentrations after the dam removal were approximately 25% higher.

- *Riggsbee, J. A., R. Wetzel, et al. (2012). "Physical and plant community controls on nitrogen and phosphorus leaching from impounded riverine wetlands following dam removal."*: This study investigated a dam removal site in North Carolina and found significant levels of nutrient export from the exposed sediments post-removal. The study also investigated the effect of vegetative controls and determined that stabilization of the sediments with vegetation was not an effective means to prevent nutrient export.

The LSWA should consider periodic monitoring of the aquatic vegetation in the Stockwell Ponds. These ponds can act as a source of plant fragments from invasive species that later take root in Lake Singletary. Understanding the abundance of invasive species in these ponds will allow the LSWA to make informed decisions about the use of control measures to limit their potential for downstream spread.

6.3 Regulatory and Land Planning Tools

Regulatory and land planning tools such as zoning bylaws, watershed protection districts and Low Impact Development bylaws are recommended and can be effective tools for protecting lakes from adverse impacts due to land development. The Town of Windham, New Hampshire recently adopted the Cobbett's Pond Watershed Protection Ordinance, which could serve as an excellent model for a municipal regulatory tool to protect and preserve Lake Singletary. This ordinance can be found at: www.cobbettspond.org/images/CobbettsPondOrdinance.pdf. Other model bylaws can be found on the website for the Citizen Planner Training Collaborative, a training and education service provided to planning boards and local officials from the University of Massachusetts and collaborative partners (www.umass.edu/masscptc/examplebylaws.html).

6.4 Aquatic Vegetation and Algae Management

When evaluating an aquatic plant and algae management strategy for Lake Singletary, it is important to consider the current condition of the lake and the goals of the LSWA with regard to maintenance of the lake's ecological and recreational values. Based on Geosyntec's field investigations and discussions with members of the LSWA, the primary goals for Lake Singletary Lake include:

1. Continued efforts to prevent the spread and proliferation of non-native fanwort (*Cabomba caroliniana*), Eurasian milfoil (*Myriophyllum spicatum*) and variable milfoil (*Myriophyllum heterophyllum*);
2. Restoration and preservation of conditions suitable for sustainable in-lake recreational uses, including swimming, boating, swimming, and fishing; and
3. Preservation and improvement of the overall water quality and ecological values of Lake Singletary.

A majority of Lake Singletary exhibits sparse growth of an aquatic plant community that is predominantly comprised of beneficial native species. Shallow areas at the southern end of the lake several other cove and near-shore areas exhibit moderate to dense growth. A diverse native plant community plays an important role in maintaining a healthy lake ecosystem and its recreational values. For example, the role of macrophytes in maintaining lake water clarity has been well documented, and native plant beds are critical as forage and protective cover for fish.

The presence of the three non-native species listed above represents a challenge that will require an adaptive and flexible approach to plant management. The optimal approach, or combination of approaches, is likely to change over time. The best approach for one area of the lake is likely to be inappropriate for another area, depending on plant growth density, species composition, and depth. It will be important to continually re-assess the effectiveness of invasive species control efforts and the overall condition of the lake's ecological and recreational values. Fanwort is the most prevalent of the non-native species, particularly in the southern end of the lake. Fanwort is capable of spreading rapidly in shallow water, outcompeting native species and impairing recreation by growing in dense beds that can extend to the water surface. The challenge lies in implementing a plant management strategy that properly balances the three goals listed above.

A discussion of aquatic vegetation techniques that could be implemented as part of a long-term strategy for Lake Singletary is provided below.

Diver Hand–Harvesting / Diver Assisted Suction Harvesting (DASH)

For new and relatively small areas of infestation, diver hand harvesting can be an effective and low-cost control technique. DASH has proven to be an effective technique for somewhat larger areas. The risk of plant fragmentation associated with DASH boat operation can be reduced by incorporating the following controls:

1. Water and plants pumped to the collection boat should be filtered through a mesh with a maximum opening size no greater than 0.125 inches (1/8 inch) to separate plant material from water discharged off the boat. The screen should be cleared regularly as needed to prevent clogging and allow return water flow. No plant fragments should be discharged back to the lake.

2. A moveable silt/fragment curtain (i.e., Brockton Equipment Type 2 SILTDAM turbidity barrier or equivalent) suspended in the water from the surface to the lake bottom could be used to prevent plant fragments from spreading beyond the locus of active plant removal areas. The silt/fragment curtain should be placed to either surround the DASH work area or in a horseshoe shape around the downstream side of the area.

A 1/8-inch polyethylene mesh screen installed in a DASH boat to filter plant fragments.

Ideally, the use of diver hand-harvesting and DASH would be used in combination with continued lake-level drawdown (discussed below). Drawdown will help to provide control within nearshore areas, allowing hand-harvesting and DASH efforts to focus on deeper areas that are not exposed to drawdown.

Lake-level Drawdown

Continued use of lake-level drawdown should be considered by the LSWA as part of long-term, sustainable plant management strategy. Lake–level drawdown is conducted during the winter months to control plant growth by exposing plant seeds and over-wintering structures to freezing conditions and desiccation. The effectiveness of drawdown depends on the susceptibility of the target species to drawdown. Fortunately, each of the three target non-native species in Lake Singletary are considered susceptible to drawdown and can be expected to decrease in abundance. As previously stated in Geosyntec's 2010 drawdown evaluation for Lake Singletary, continuation of an annual 6-foot (at minimum) drawdown is recommended.

Herbicide Treatment

The use of herbicides can be an appropriate and effective technique for short-term control of aquatic vegetation control in some settings. The LSWA should consider the following:

- For fanwort, Sonar (fluridone) is the only herbicide currently registered in Massachusetts that provides effective short-term control. Unfortunately, this broad-spectrum systemic herbicide requires a long exposure time (>60 days). Given the limited overall extent of fanwort in Lake Singletary, treating with Sonar is not practical or recommended because it would require treating virtually the entire lake. However, another broad-spectrum herbicide (Clipper, active ingredient flumioxazin) has been proven effective for short-term fanwort control. Clipper is currently pending registration based on a June 2013 recommendation from the Massachusetts Department of Environmental Protection (MassDEP). Because this "contact" herbicide requires a very short exposure time, it can be used for spot treatments in specific areas of infestation. As such, Clipper may provide a useful option for Lake Singletary. It is worth noting that the use restrictions for Clipper recommended by MassDEP include the following:

  "Treated areas may not be retreated with flumioxazin or any herbicide with a similar mode of action (i.e., light dependent peroxidizing herbicide) in consecutive years in order to prevent the development of herbicide resistance in treated plants.

Based on this recommended restriction, a strategy for Clipper use could involve herbicide application in one year to reduce plant abundance, followed by DASH or hand harvesting in the following year.

- Widespread use of broad-spectrum herbicides (e.g. Reward) to target native plants is generally not recommended. However, it is reasonable to consider such herbicides as a tool for control of nuisance growth in limited areas where recreational access is impaired and other recommended methods either do not provide relief or are impractical.

- Based on Geosyntec's review of Lake Singletary's water quality data, it seems unlikely for the near future that the lake will experience nuisance algae blooms on a frequent basis. Mesotrophic lakes may experience periodic algae blooms, but these tend to be less frequent, of shorter duration and less severe than those experienced by more biologically productive lakes. As stated in Section 4.5, buildout projections prepared by the Central Massachusetts Regional Planning Commission project very little new development for the Lake Singletary watershed by year 2020. This relative stability in the watershed is expected to correlate with relatively stable water quality and associated infrequent algae blooms.

  Copper-based algaecides provide effective control of algae blooms and are recommended only on an as-needed basis to control persistent blooms. As discussed in Section 5.3, nuisance algae blooms in lakes like Lake Singletary are most common in late summer or fall, when epilimnetic phosphorus concentrations are at their peak due to the effects of internal loading.

Phosphorus Inactivation

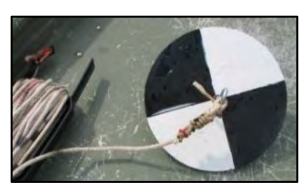
Phosphorus precipitation and inactivation are also commonly used to control algae. These techniques use chemical complexes to bind with soluble phosphorus and make it unavailable to fuel the growth of algae. Aluminum sulfate (alum) and sodium aluminate are currently the most commonly used products for this purpose. These products add acidity to the water, and must therefore be dosed carefully and combined with buffering agents (e.g., soda ash) to avoid impacts to fish and other aquatic organisms. A new alternative product is called Phoslock, which uses modified bentonite clay to bind with phosphorus without affecting pH. Phoslock is currently under review by the Massachusetts Department of Environmental Protection and is not currently available for use in Massachusetts.

Phosphorus precipitation provides very short-term algae control by using a relatively low dose of alum to bind with phosphorus in the water column. Phosphorus inactivation can provide multi-year control of phosphorus release from sediments by applying as much phosphorus binder as can be safely added to the lake.

Phosphorus inactivation may be a viable option for the LSWA to consider if future nuisance algal blooms are occurring on a regular basis and are severe enough and of sufficient duration to impair recreational use of the lake. Estimated costs for phosphorus inactivation using aluminum sulfate and sodium aluminate typically range from $1,000 to $2,000 per acre for lakes similar to Lake Singletary, with price variability mostly depending on the required dosage. A cost range of $300,000 to $600,000 is estimated for a whole-lake treatment, with the lower end of this range considered to be more likely.

As stated above, based on Geosyntec's review of Lake Singletary's water quality data, it seems unlikely for the near future that the lake will experience severe nuisance algae blooms on a frequent basis.

Monitoring



Water Quality Monitoring: The LSWA has an outstanding volunteer monitoring program, the results of which have been used by Geosyntec to support development of the trophic status assessment, phosphorus budget and phosphorus concentration modeling presented in this report. We strongly recommend continuation of this monitoring to track water quality trends. Of particular usefulness, and what sets the LSWA monitoring program apart from that of many similar lake associations, is the monthly data collection that extends from April through October. This allows for analysis of long term trends that are seasonally dependent, such as oxygen depletion in the lakes hypolimnion and associated internal phosphorus release from sediments.

As discussed in Section 3, we understand that the LSWA has experienced adjustments in its sampling program over the last two decades and has had recent concerns with lab protocols and data reliability for chlorophyll-*a*. Incorporating a larger data set from a reliable lab to represent average conditions over the summer months will allow for greater confidence in the TSI assessment for this parameter.

Sediment Sampling: To better understand the lake sediment quality and the impact of sediment chemistry on hypolimnetic oxygen depletion (see discussion in Appendix C), sediment grab samples (obtained with an Eckman sampler or similar device) should be collected and analyzed for organic content.

Aquatic Vegetation Monitoring: An aquatic vegetation survey of Lake Singletary is recommended annually, at minimum, to track the progression of invasive species and their response to control efforts. Regular monitoring also helps to ensure quick identification of new infestations of non-native species, allowing for rapid response actions before an infestation becomes widespread.

As previously stated in Section 6.2, the LSWA should also consider monitoring vegetation in the Stockwell Ponds. These ponds discharge to the lake's primary tributary (Singletary Brook), and can act as a source of plant fragments that later take root in Lake Singletary. Understanding the abundance of invasive species in these ponds will allow the LSWA to make informed decisions about the use of control measures to limit their potential for downstream spread.

Public Education and Outreach

Public information and education can be used to enhance public understanding of issues related to phosphorus loading, invasive species, and other threats to Lake Singletary's water quality. Public information and education about can be provided via the LSWA website, brochures, workshops, social media, and other media outlets such as local newspapers.

- **Field Guide to the Aquatic Plants of Lake Singletary:** To aid future volunteer monitoring efforts, Geosyntec developed a *Field Guide to the Aquatic Plants of Lake Singletary* as part of this project. This field guide, which is included as Appendix A to this report, includes information on each of the plant species observed during Geosyntec's 2009 aquatic vegetation survey.

- **Other Resources:** Homeowners in the Lake Singletary Watershed are encouraged to review the following educational resources:

    - **The Massachusetts Nonpoint Source Pollution Management Manual:** http://projects.geosyntec.com/NPSManual/

    - **Innovative Land Planning Techniques – A Handbook for Sustainable Development:** http://des.nh.gov/organization/divisions/water/wmb/repp/innovative_land_use.htm

    - **The Vermont Raingarden Manual:** http://nsgl.gso.uri.edu/lcsg/lcsgh09001.pdf

    - **A Shoreland Homeowner's Guide to Stormwater Management** http://des.nh.gov/organization/commissioner/pip/publications/wd/documents/nhdes-wd-10-8.pdf

- **Brochure:** General information geared to lake residents, which could be included on the LSWA website or adapted into an educational brochure, is provided on the following page.

Example website/brochure text:

"Just say No" to fertilizer. Lawn fertilizer is transported to Lake Singletary by storm water runoff, fueling algae blooms that reduce water clarity and can lead to beach closures and recreational contact advisories. Use natural alternatives to lawn and garden chemicals and establish low-maintenance, native vegetation on your property.

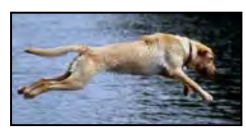
Build a **raingarden** to manage stormwater runoff from your property. Raingardens protect water quality while beautifying your home and neighborhood! For more information, see:
http://nsgl.gso.uri.edu/lcsg/lcsgh09001.pdf

Rain barrels are a great way to re-use rainwater from roofs for gardening and landscaping. A rain barrel will save most homeowners about 1,300 gallons of water during the peak summer months. Diverting this water from storm drains also decreases the impact of runoff to streams. Rain barrels can be purchased at many home and garden centers.

Have your **septic system** pumped out and inspected on a regular basis. The Lake Singletary Watershed Association recommends septic system pumping and inspection at least once every three years, or more frequently if recommended by the licensed septic service provider.

Keep **litter, leaves, and debris** out of street gutters and storm drains. Dispose of used **oil, antifreeze, paints**, and other household chemicals properly. Do not dump these products in storm drains. These outlets drain directly to Lake Singletary, local streams and wetlands.

Don't feed waterfowl! Bread and snack food are harmful to waterfowl Feeding discourages winter migration and encourages bird flocks that can degrade the Lake Singletary shoreline with droppings.



Pick up after your pet! Use biodegradable doggie bags to collect pet waste. Don't dispose of pet waste in storm drains.

Control soil erosion on your property by planting ground cover and stabilizing erosion-prone areas.

Appendix A:

Field Guide to the Aquatic Plants of Lake Singletary

Field Guide to the
Aquatic Plants of

LAKE SINGLETARY

Prepared for:
Lake Singletary Watershed Association

Prepared by:

Geosyntec consultants

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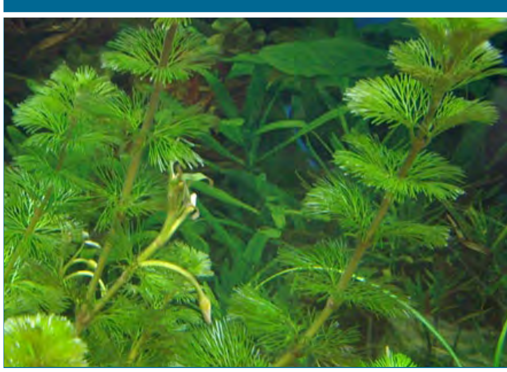


This Field Guide **to the Aquatic Plants of Lake Singletary has been developed to aide volunteer monitoring of aquatic vegetation in the lake.**

Massachusetts lakes and ponds host a great variety of aquatic plants. If you find a plant in Lake Singletary which is not included in this field guide, there are a number of more comprehensive field guides that can be used as a reference for species identification. Some recommended references include the following:

- A Guide to Aquatic Plants in Massachusetts. New England Aquarium and the Massachusetts Department of Environmental Management. 1999. (Available online at http://archive.org/details/guidetoaquaticpl00kell)
- Aquatic Plants & Algae of New Hampshire's Lakes and Ponds. New Hampshire Department of Environmental Services. (Available online at: www.des.nh.gov/organization/commissioner/pip/publications/wd/documents/wd-05-30.pdf)
- G.E. Crow and C.B. Hellquist. 2000. Aquatic and Wetland Plants of Northeastern North America. The University of Wisconsin Press.
- Fassett, N.C. 1940. A Manual of Aquatic Plants. The University of Wisconsin Press.

This field guide is based on the results of an aquatic vegetation survey of Lake Singletary conducted by Geosyntec Consultants in 2009. Emergent wetland plants were recorded only if they were rooted in standing water within the perimeter of Lake Singletary.

Fanwort
(Cabomba caroliniana)

This invasive, non-native plant has finely divided submerged leaves that are arranged in opposite pairs along the stem. Small floating leaves (1 cm long) can also be found at the water surface along with small white flowers that bloom in late summer.

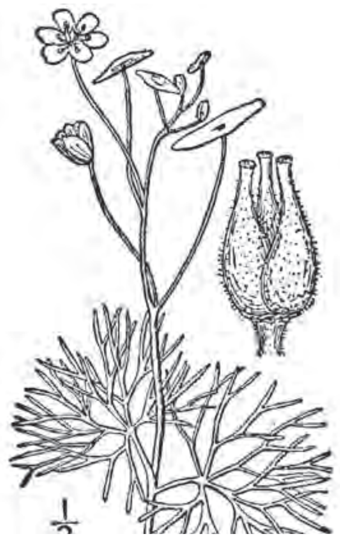


Illustration from: : USDA-NRCS PLANTS Database / Britton, N.L., and A. Brown. 1913. An illustrated flora of the northern United States, Canada and the British Possessions. 3 vols. Charles Scribner's Sons, New York. Vol. 2: 76.

Rough Stonewort
(Chara aspera)

Chara species are structured forms of algae rather than true vascular aquatic plants. *Chara aspera* is similar in structure to *Chara vulgaris* (page 5), but smaller.

Illustration from: Sowerby's English Botany 3rd Edition. Vol 12. Cryptogamia. 1886.

Musk Grass
(Chara vulgaris)

Musk grasses have a distinct musky odor and are brittle when crushed between two fingers. Similar-looking vascular plants such as Bushy Pondweeds (*Najas spp.*) and Coontail (*Ceratophyllum demersum*) do not produce an odor when crushed.

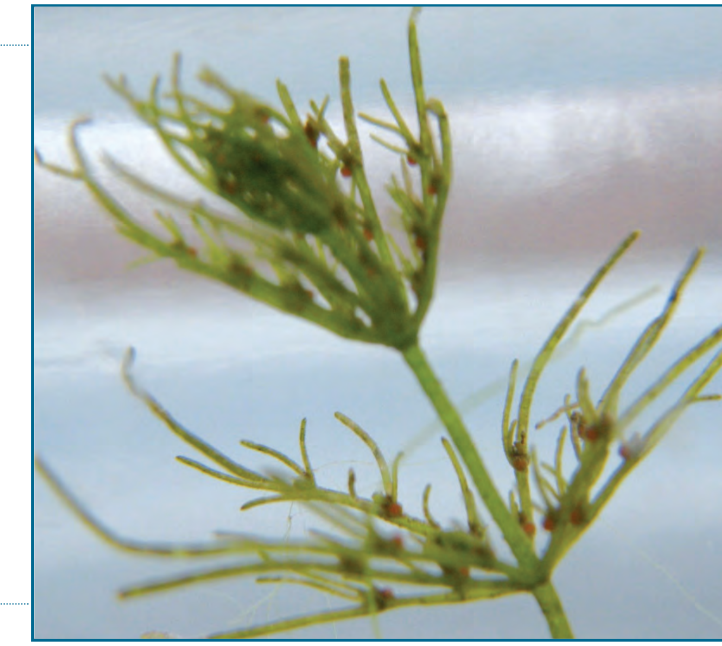


Illustration from: G.E. Crow and C.B. Hellquist. 1982. Aquatic Vascular Plants of New England. New Hampshire Agricultural Experiment Station.

Waterwort
(Elatine minima)

This tiny plant is typically found growing in shallow water. Its leaves are rounded at the tip and up to 4 mm long.

Quillwort

(Isoetes sp.)

The leaves of this plant become narrower from the base toward the sharply pointed tip. This plant looks similar to Pipewort, but does not have cross lines on its roots.

Variable Milfoil

(Myriophyllum heterophyllum)

This type of milfoil has a reddish 3 mm - 8 mm diameter stem and whorled submersed leaves. This plant flowers in green to reddish spikes which are raised above the water surface and 2 to 12 inches long.

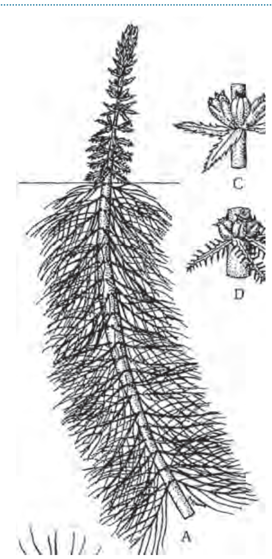


Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station.

Lowly Watermilfoil

(Myriophyllum humile)

Compared to variable milfoil and Eurasian milfoil, lowly watermilfoil is small and low growing. This type of milfoil has vegetative elongated stems and leaves that are alternately arranged.

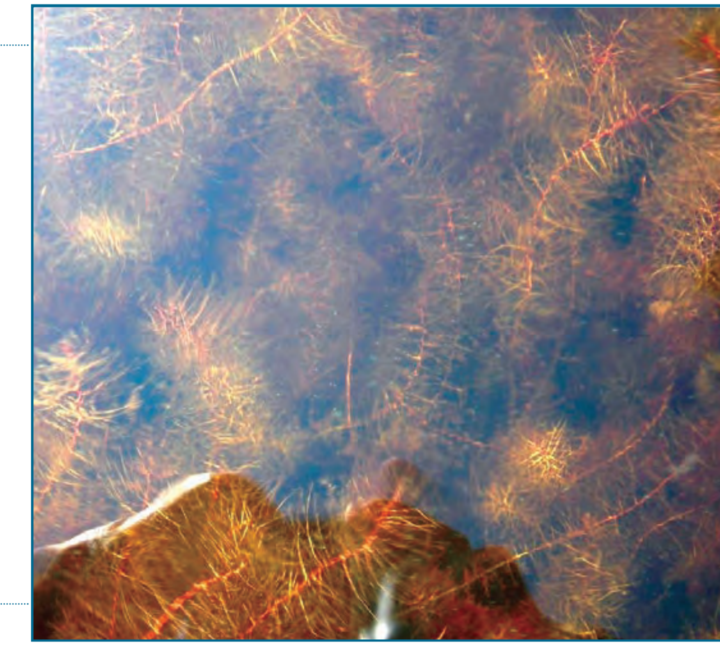


Illustration from: Crow, G.E. and Hellquist, C.B. 1982. Aquatic V*ascular Plants of New England.* New Hampshire Agricultural Experiment Station.

Eurasian Milfoil

(Myriophyllum spicatum)

This invasive, non-native plant has stems that are reddish-brown to whitish-pink. Its finely divided leaves are feather-like in appearance and arranged in whorls of three to six leaves around the stem. The leaves are blunt-ended, as if cut by scissors, and have 11 leaflets per side. This plant has tiny reddish flowers that appear on top of an emergent flower spike that is several inches long.

Illustration from: G.E. Crow and C.B. Hellquist. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station.

Bushy Pondweed
(Najas flexilis)

Bushy Pondweed can be distinguished from other *Najas* species by the pointed tips of its oppositely arranged leaves.

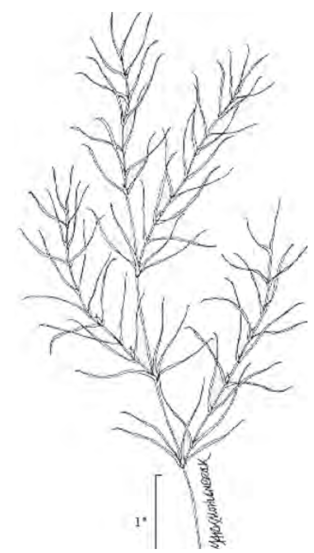
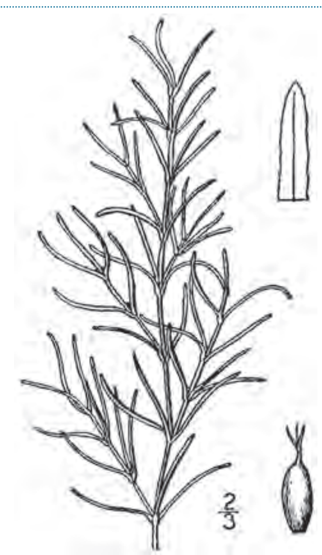


Illustration from: Crow, G.E. and Hellquist, C.B. 1982. Aquatic Vascular Plants of New England. New Hampshire Agricultural Experiment Station.

Southern Waternymph
(Najas guadalupensis)

This submersed annual plant has opposite leaves that are often clustered near the stem tips. The leaf base is much wider than the rest of the leaf blade. The leaves are finely toothed, 1-3 cm long and 1-2 mm wide. The entire plant is eaten by waterfowl, for which it is an important food source.



USDA-NRCS PLANTS Database / Britton, N.L., and A. Brown. 1913. An illustrated flora of the northern United States, Canada and the British Possessions. 3 vols. Charles Scribner's Sons, New York. Vol. 1: 90.

Snailseed Pondweed
(Potamogeton bicupulatus)

This pondweed has submersed and floating leaves that are spirally arranged. The floating leaves, although not always present, have 3-7 veins.

Illustration from: Britton & Brown's Illustrated Flora of the Northern United States and Canada, 2nd ed.

Ribbonleaf Pondweed
(Potamogeton epihydrus)

The floating leaves of this pondweed, when present, range from 3/4"-3 3/16" long and up to 1 3/8" wide. The submerged leaves look wilted and have a lightly colored stripe down the center.

Illustration from: G.E. Crow and C.B. Hellquist. 1982. *Aquatic Vascular Plants of New England*. New Hampshire Agricultural Experiment Station.

Thinleaf Pondweed
(Potamogeton pusillus)

This pondweed has narrow leaves (about 2mm wide) with an inner midrib. Stipules are blunt or rounded.

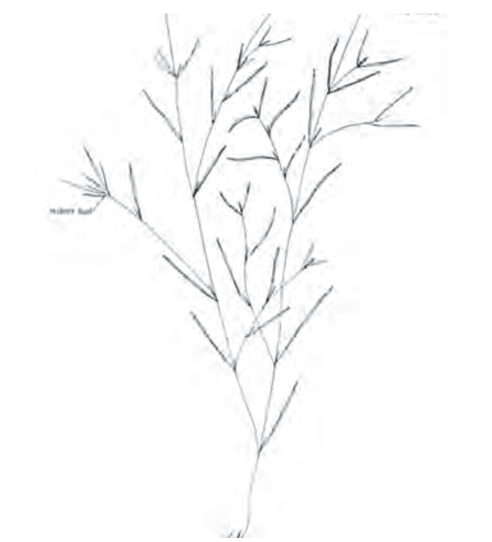


Illustration from: G.E. Crow and C.B. Hellquist. 1982. *Aquatic Vascular Plants of New England*. New Hampshire Agricultural Experiment Station.

Robbins' Pondweed
(Potamogeton robbinsii)

Also known as Fern-leaf Pondweed, this Potamogeton species has a fern-like appearance and leaves that are 3-8 mm wide.

Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England*. New Hampshire Agricultural Experiment Station.

Sago Pondweed
(Stuckenia pectinatus)

This submersed plant has very narrow leaves (1/32"-1/16" wide, 2"-12" long) that grow in bushy clusters and emerge from a sheath towards the end of the stem.

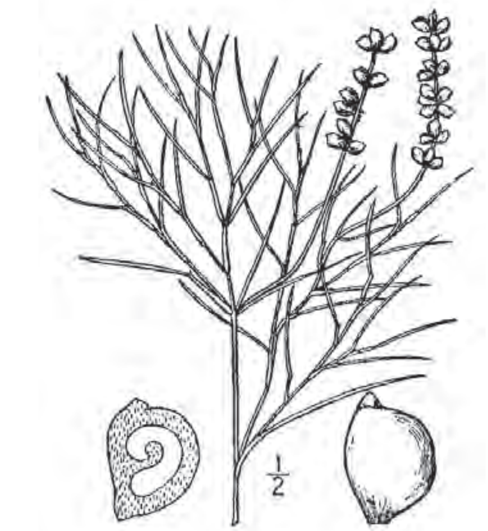


Illustration from: USDA-NRCS PLANTS Database / Britton, N.L., and A. Brown. 1913. An illustrated flora of the northern United States, Canada and the British Possessions. 3 vols. Charles Scribner's Sons, New York. Vol. 1: 87.

Common Bladderwort
(Utricularia vulgaris)

Bladderworts are carnivorous plants which capture and digest zooplankton (microscopic animals) in clusters of "bladders" for which they are named. When in bloom, common bladderwort has small yellow flowers.

Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England*. New Hampshire Agricultural Experiment Station.

floating leaf species

Tape Grass
(Vallisneria americana)

Tape grass (also known as water celery or wild celery) has ribbon-like leaves with bluntly rounded tips. A distinct light green stripe runs down the center of the leaves, which is most visible when the leaf is held up to light.

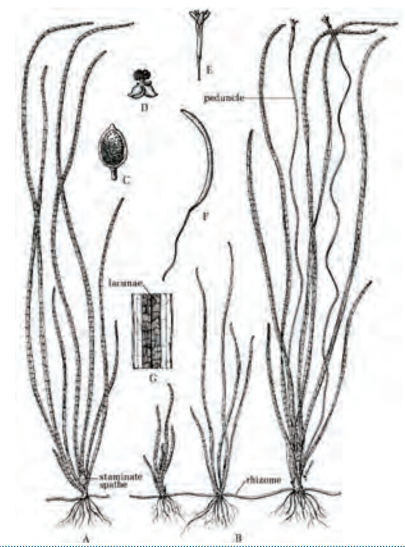


Illustration from: G.E. Crow and C.B. Hellquist. 1982. Aquatic Vascular Plants of New England. New Hampshire Agricultural Experiment Station.

Watershield
(Brasenia schreberi)

There is a jelly-like substance on the underside of this plant's oval-shaped leaves and also on the plant's stem. The leaves are 2"-3" long and there may be dull colored red flowers present.

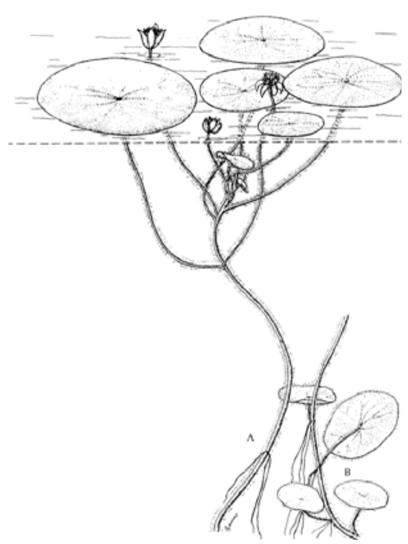
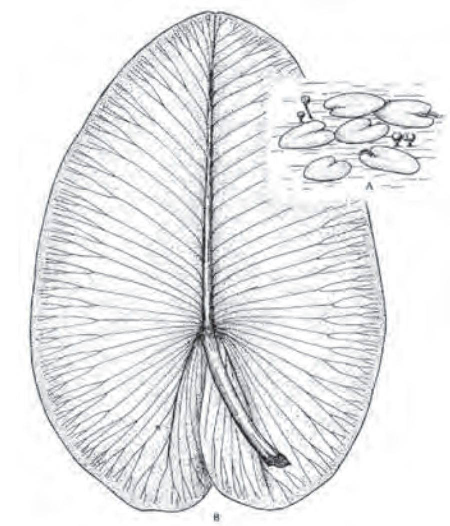


Illustration from: G.E. Crow and C.B. Hellquist. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station.

Yellow Water Lily
(Nuphar sp.)

Yellow water lilies have yellow flowers and large floating leaves with rounded lobes that frequently overlap.



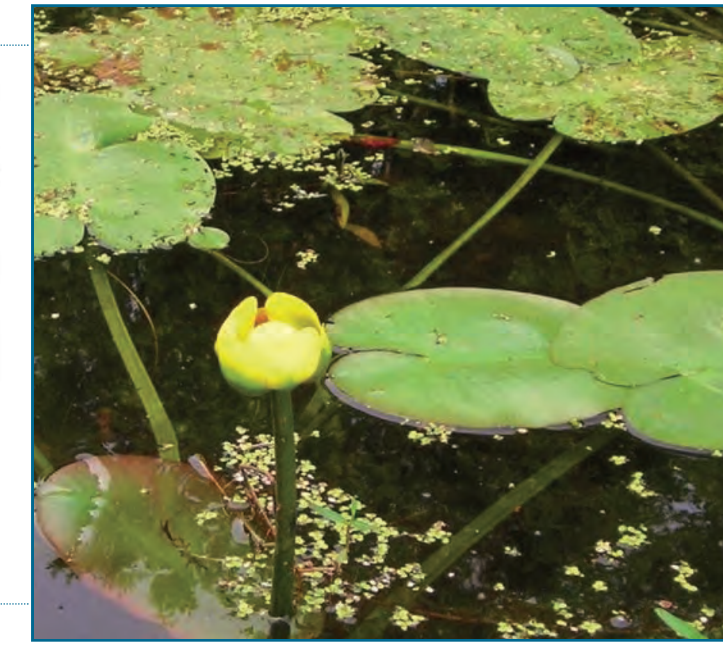
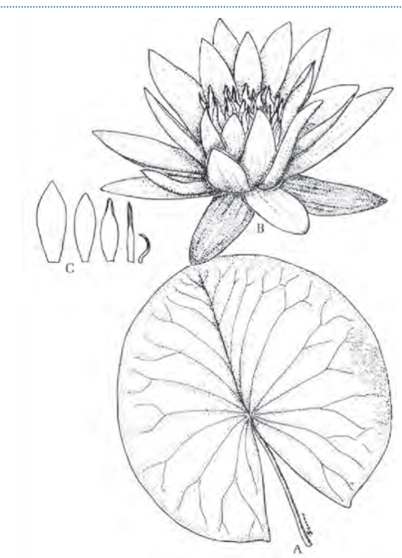


Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station.

White Water Lily
(Nymphaea spp.)

White water lilies have white flowers and floating leaves with pointed lobes that rarely overlap.



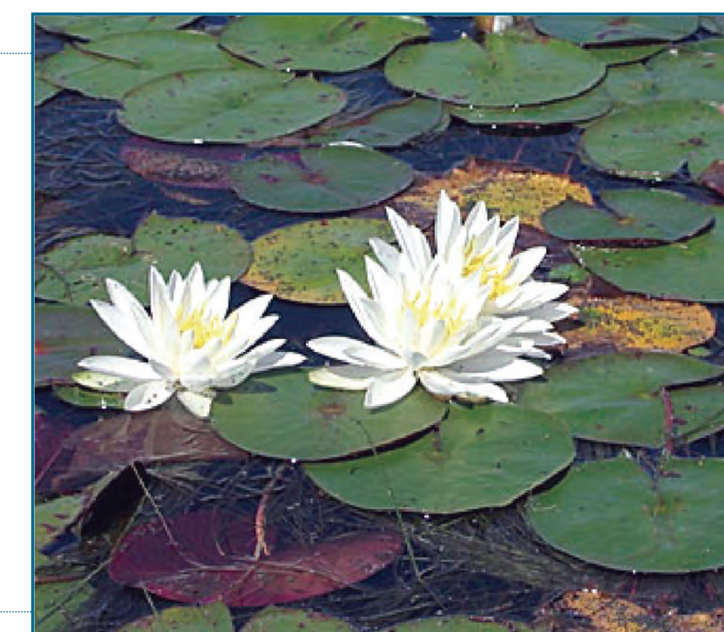
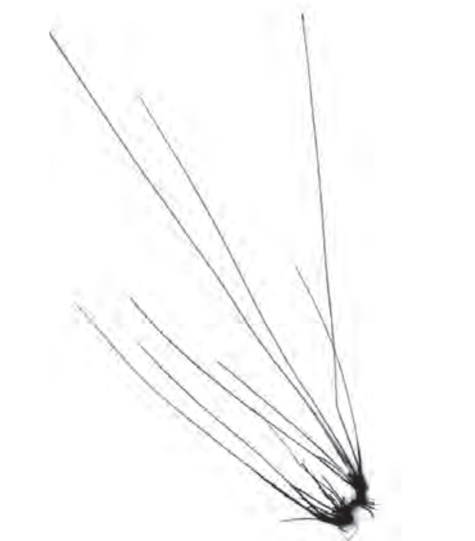
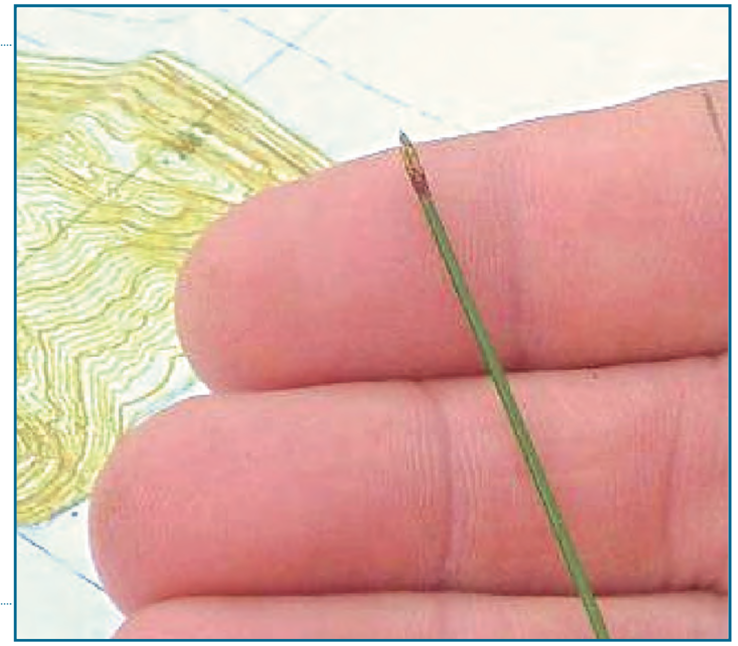


Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station

Spike Rush
(Eleocharis robbinsii)

The soft green stems of this plant often grow clumped together with oval shaped spikelets forming at the tips.





Golden Hedge Hyssop
(Gratiola aurea)

The oppositely arranged leaves of this plant are slightly toothed and are widest at the base. When flowers are in bloom they are a golden yellow color. In Lake Singletary, the sterile, submersed form of this plant can also be found in shallow water.

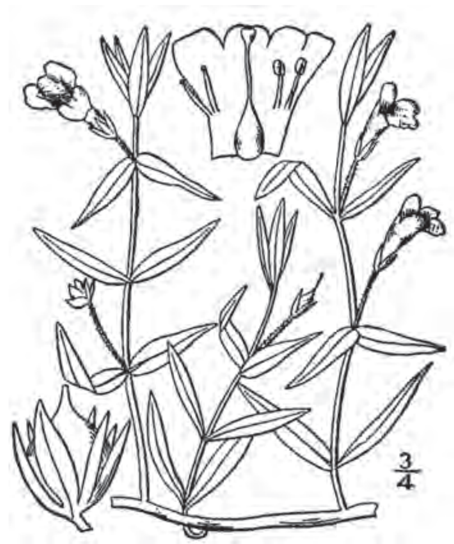


Illustration from: USDA-NRCS PLANTS Database / Britton, N.L., and A. Brown. 1913. *Illustrated flora of the northern states and Canada.* Vol. 3: 195.

Northern St. Johnswort
(Hypericum boreale)

The stems of this submersed plant are limp. The leaves have three strong veins that come out at the base of the leaf.

Illustration from: USDA-NRCS PLANTS Database/Britton, N.L., and A. Brown. 1913. Illustrated flora of the northern states and Canada. Vol. 2: 534.

Canada Rush
(Juncus canadensis)

This rush can grow up to 3' tall and tends to grow in small groups.

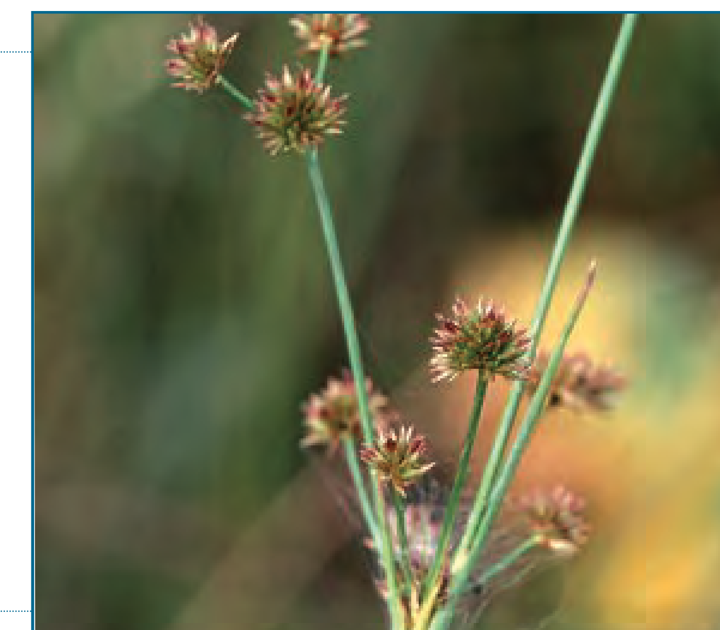


Illustration from: USDA-NRCS PLANTS Database / USDA NRCS. *Wetland flora: Field office illustrated guide to plant species.*

Purple Loosestrife

(Lythrum salicaria)

Purple loosestrife is an invasive perennial wetland plant with showy purple to magenta flowers that appear from June to September. The flowers are arranged on a spike that ranges from 2 inches to 3 feet long. This plant's leaves are typically in opposite pairs that alternate down the stem at 90 degree angles, but sometimes occur in whorls of three or four.

Illustration from: USDA-NRCS PLANTS Database / Britton, N.L., and A. Brown. 1913. An illustrated flora of the northern United States, Canada and the British Possessions. 3 vols. Charles Scribner's Sons, New York. Vol. 1: 444.

Arrow Arum

(Peltandra virginica)

This emergent wetland plant has bright green arrow- to heart-shaped leaves with rounded triangular lobes and veins that radiate from a central vein. This plant is often confused with arrowhead (*Sagittaria sp.*), which is distinguished by its pointed lobes and veins that radiate from one point.

Illustration from: USDA-NRCS PLANTS Database / Britton, N.L., and A. Brown. 1913. An illustrated flora of the northern United States, Canada and the British Possessions. 3 vols. Charles Scribner's Sons, New York. Vol. 1: 444.

Soft-Stemmed Bulrush

(Scirpus validus)

Soft-stemmed bulrush is an emergent wetland plant with soft stems that grows up to eight feet tall and 3/4" thick. Drooping oval spikelets covered in reddish-brown scales emerge in clusters just below the top of the stem.

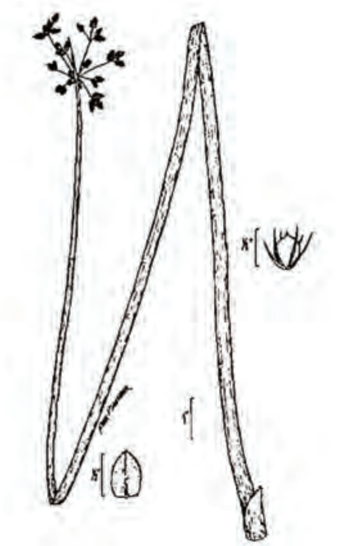


Illustration from: USDA, NRCS. 2011. The PLANTS Database (http://plants.usda.gov, 29 June 2011). National Plant Data Team, Greensboro, NC 27401-4901 USA.

Bur-reed

(Sparganium sp.)

Bur-reed is an emergent wetland plant that typically grows up to two feet tall. Its bright green, strap-like leaf blades grow up to 1 inch wide. Its spherical flower heads are green in early season, becoming brown and bur-like later.

Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station.

Broadleaf Cattail

(Typha latifolia)

Cattails are easily identified by their tall, sword-shaped leaves and fruiting spikes. Broad-leaved Cattail is distinguished from Narrow-leaved Cattail by its broader leaves and fruiting spikes that don't have a separation between the male and female sections.

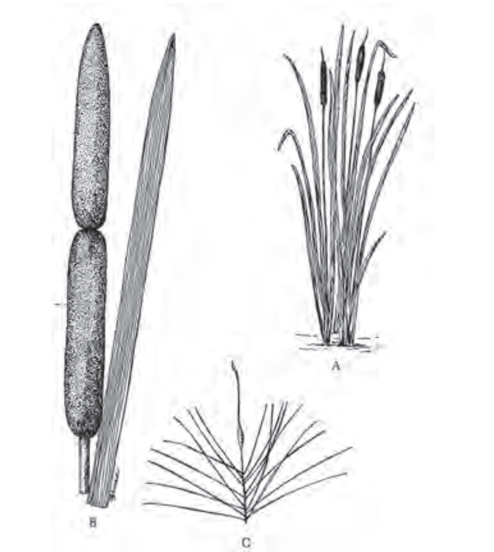


Illustration from: Crow, G.E. and Hellquist, C.B. 1982. *Aquatic Vascular Plants of New England.* New Hampshire Agricultural Experiment Station.

Prepared by:

Geosyntec consultants

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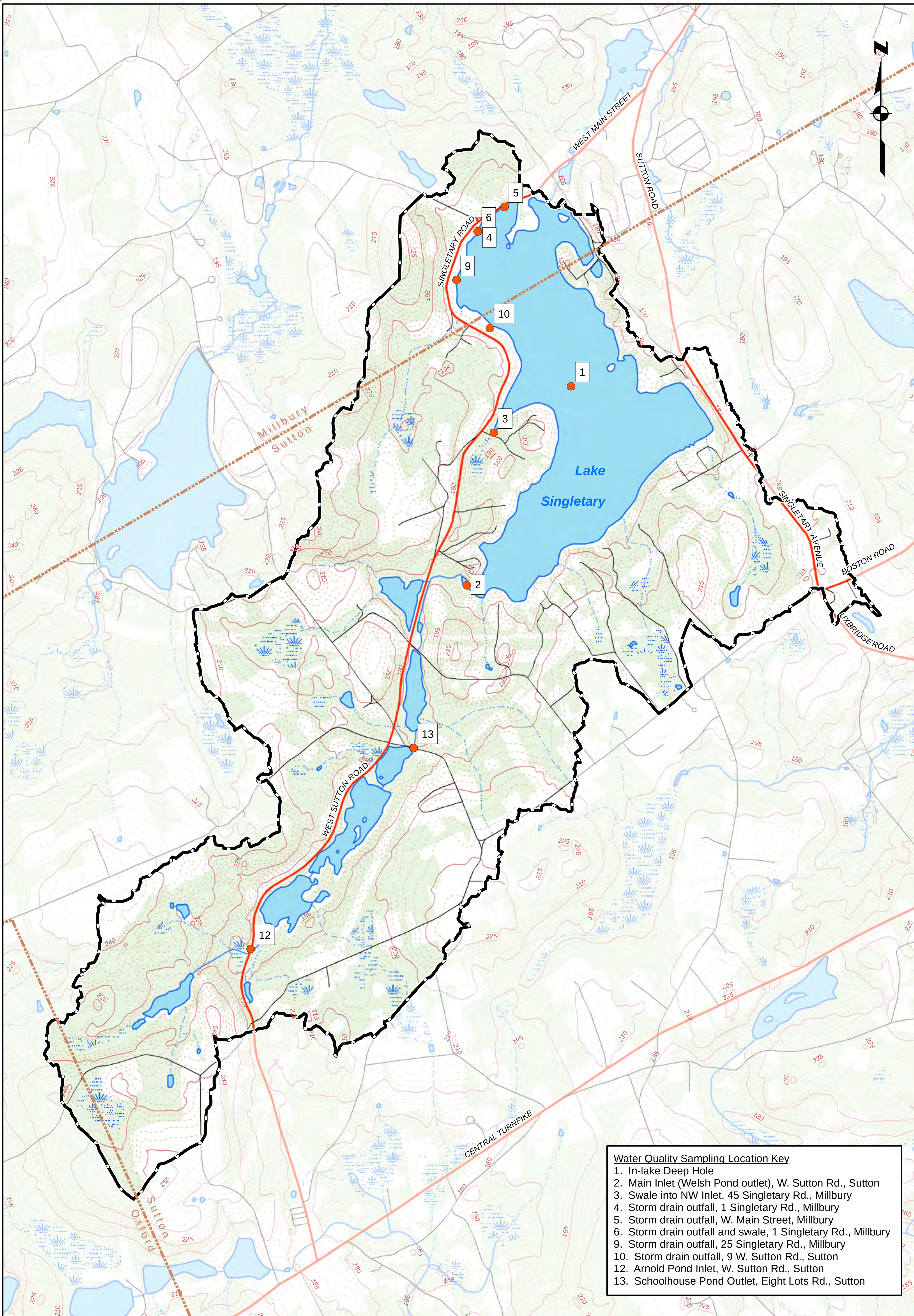
Prepared for:

Lake Singletary Watershed Association
http://www.lakesingletary.org

Appendix B:

Watershed Maps and Figures



0.5 0.25 0 0.5 1 Miles

Legend

- Lake Singletary Watershed Boundary
- Water Quality Sampling Location
- Town Boundary

Roads

- Major Road
- Local Road

Topographic Contour

- Minor Contour (3 m)
- Major Contour (15 m)

Watershed Topographic Map and Water Quality Sampling Locations

Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

Geosyntec consultants

Figure
B1

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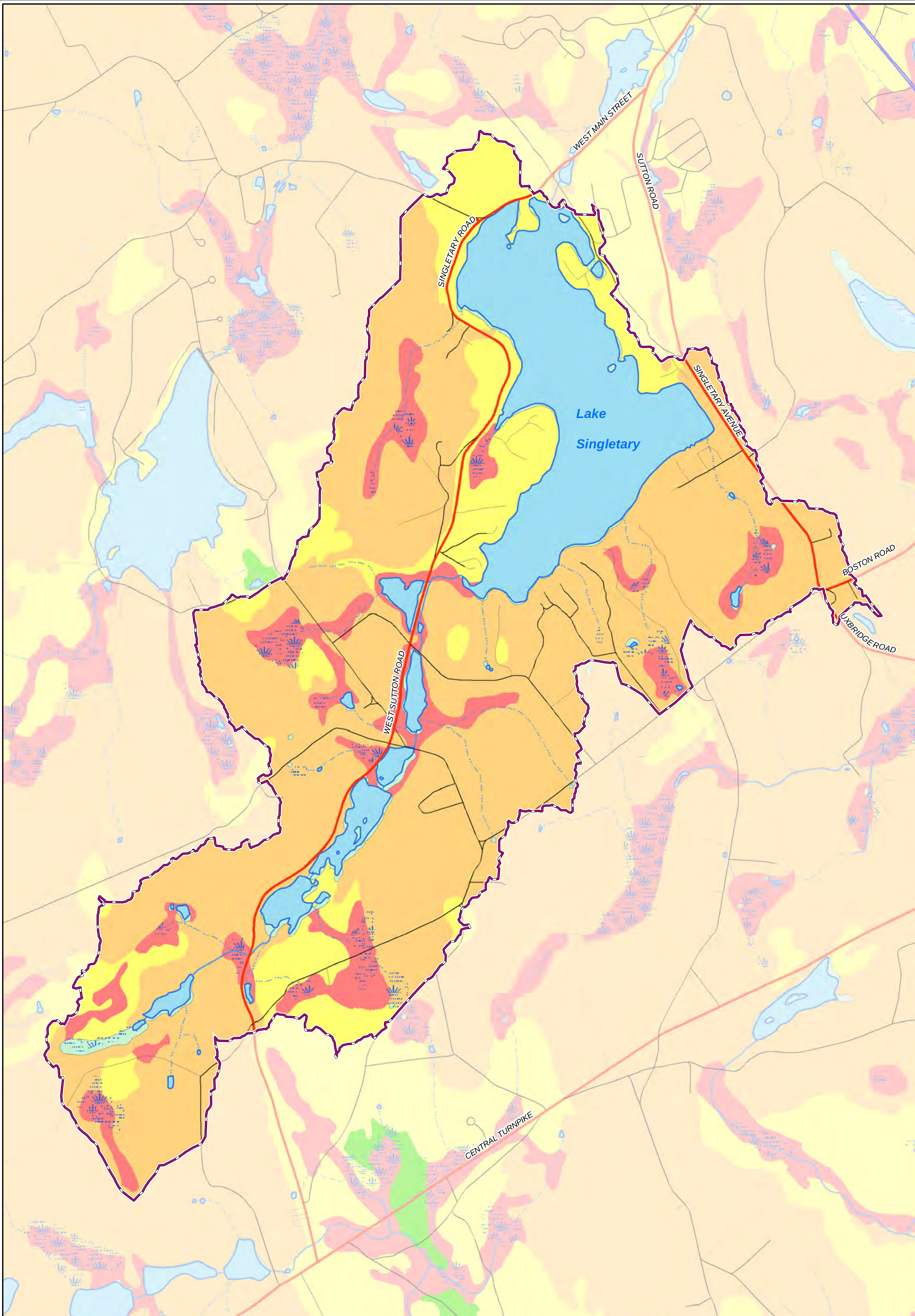

0.5 0.25 0 0.5 1 Miles

N

Legend

Lake Singletary Watershed Boundary

Hydrologic Soil Group

A B C D

Soils data from MassGIS 'NRCS SSURGO-Certified Soils' layer, Worcester - South. Hydrologic soil group represents ability for soil to infiltrate, with 'A' being the most favorable for infiltration.

Watershed Soils Map

Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

Geosyntec consultants

Figure
B2

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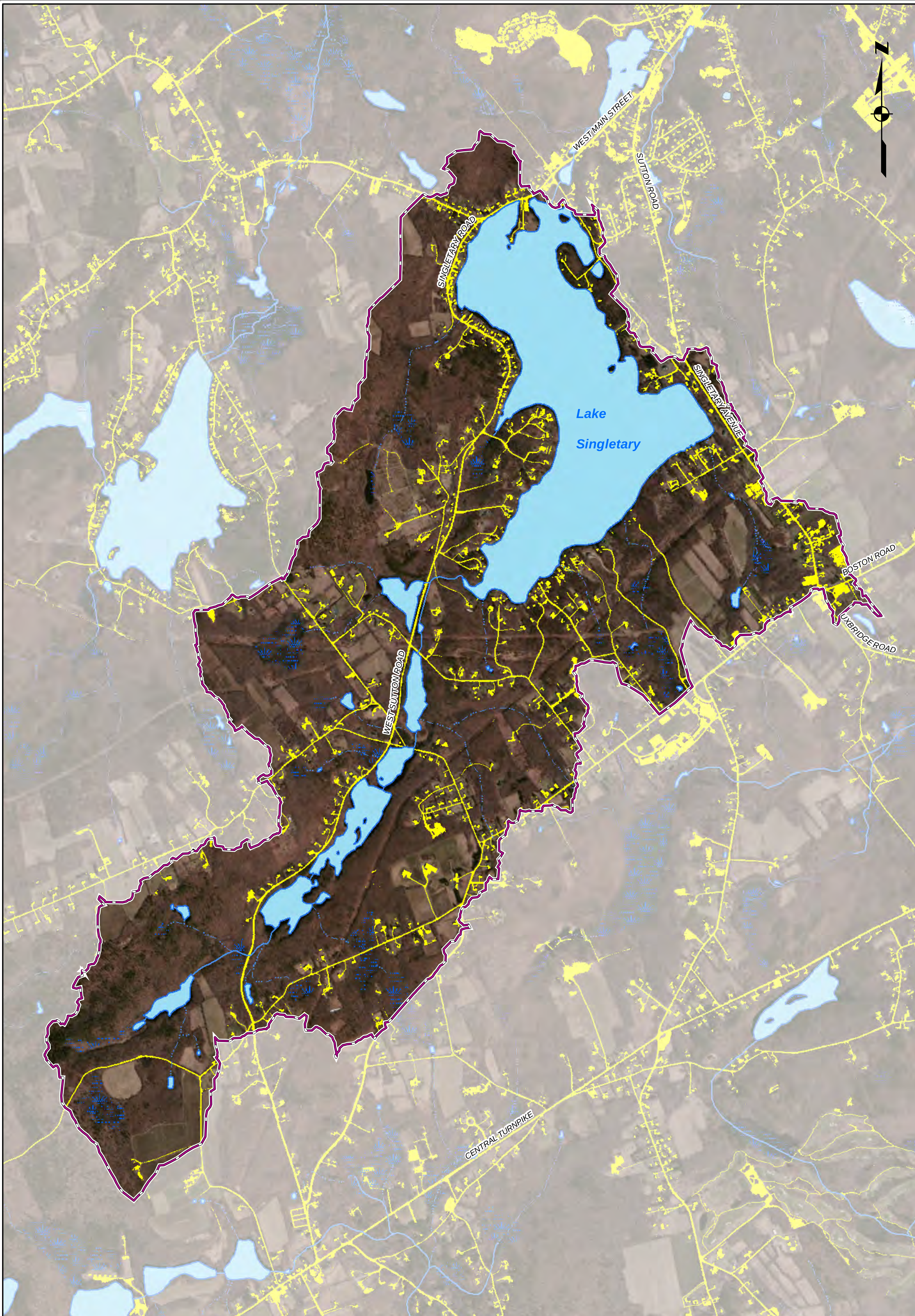

0.5 0.25 0 0.5 1
Miles

Legend

Lake Singletary Watershed Boundary

Impervious Surface

Impervious surface data from MassGIS 2005 Impervious Surface data layer. Imagery via ArcGIS Online Imagery basemap.

Impervious Surfaces

Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

Geosyntec consultants

Figure
B3

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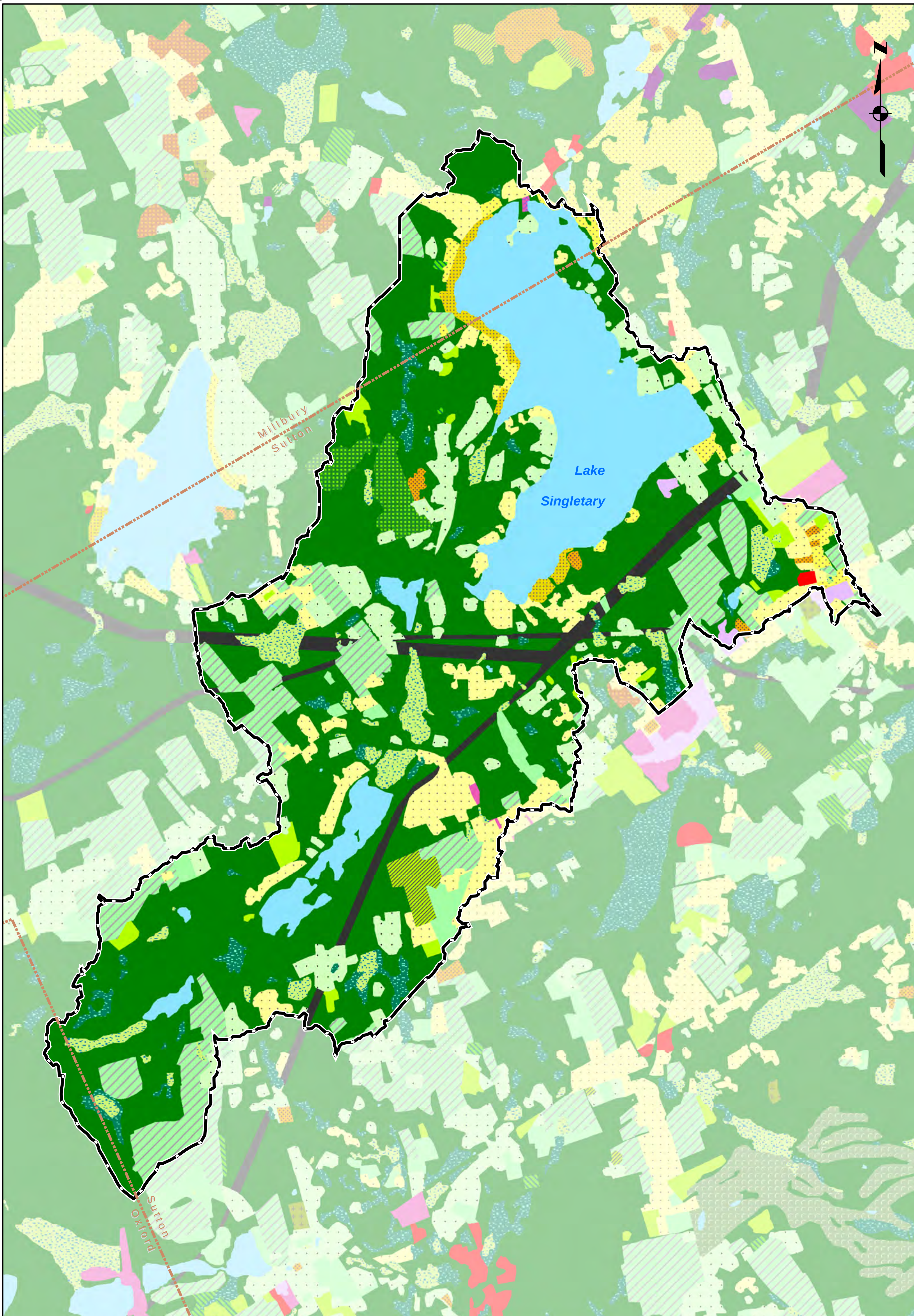

0.5 0.25 0 0.5 1 Miles

Legend

- Lake Singletary Watershed Boundary
- Forest
- Brushland/Successional
- Open Land
- Water
- Forested Wetland
- Non-Forested Wetland
- Orchard
- Nursery
- Cropland
- Pasture
- Cemetery
- Golf Course
- Participation Recreation
- Spectator Recreation
- Water-Based Recreation
- Marina
- Multi-Family Residential
- High Density Residential
- Medium Density Residential
- Low Density Residential
- Very Low Density Residential
- Transitional
- Urban Public/Institutional
- Commercial
- Industrial
- Transportation
- Powerline/Utility
- Mining
- Waste Disposal
- Junkyard

Land Use (2005)

Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

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consultants

Figure
B4

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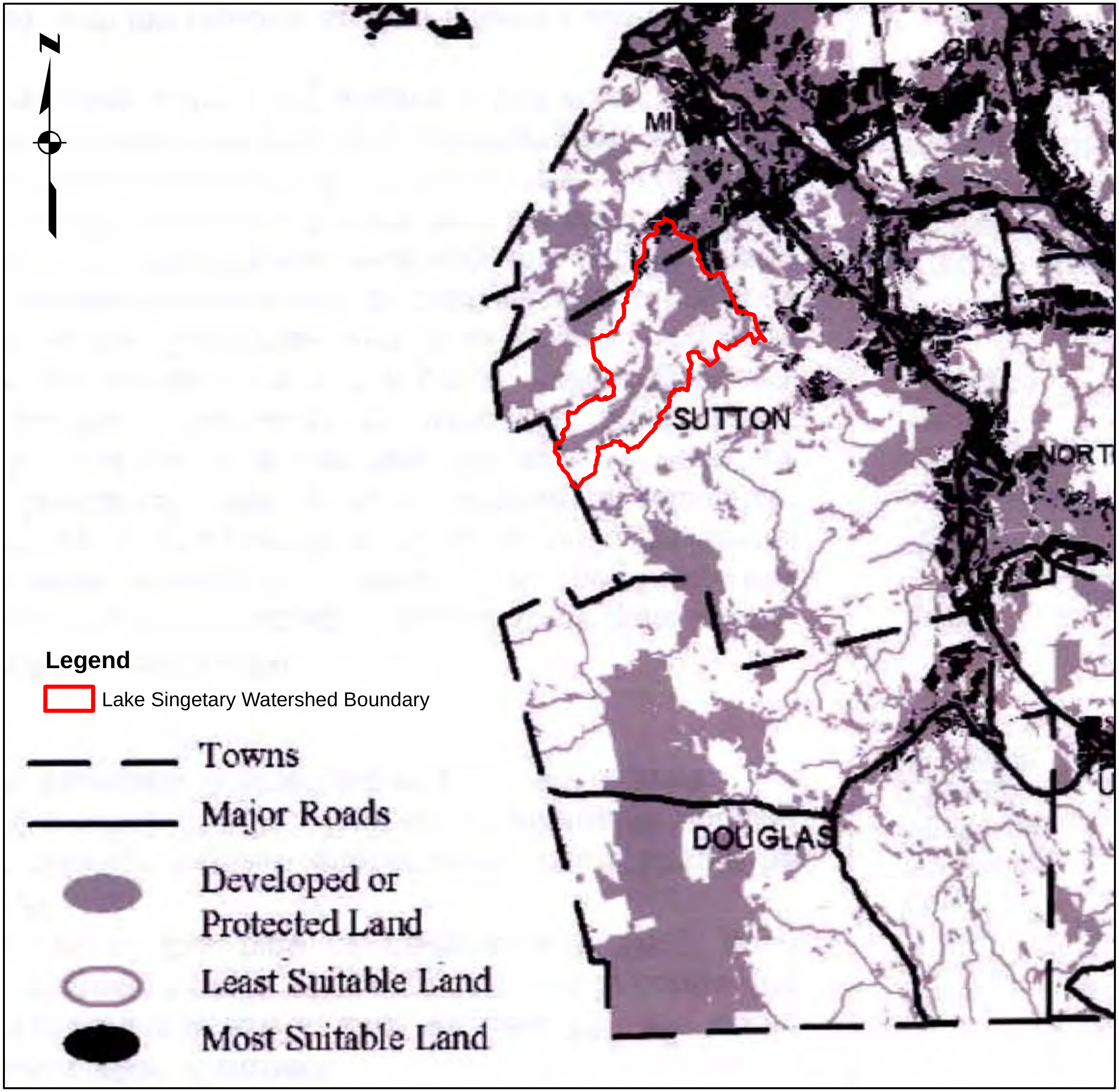

Base map of land suitable for development obtained from Central Massachusetts Regional Planning Commission (CMRPC) report, "2020 Growth Strategy for Central Massachusetts," 2000.

CMRPC Estimation of Developable Land, Southeast Subregion

Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

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Figure
B5

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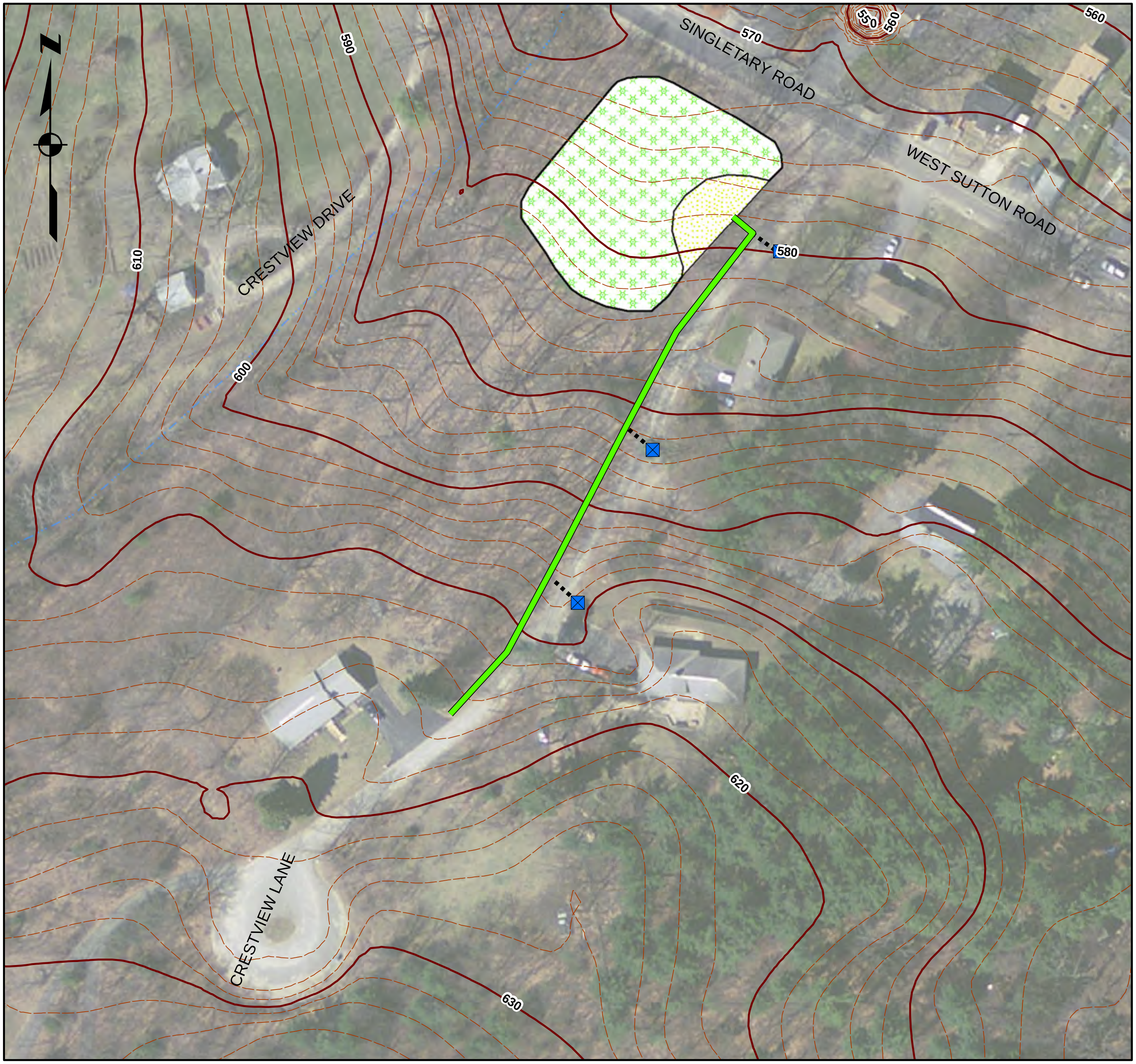


Legend

- Proposed Constructed Wetland
- Proposed Sediment Forebay
- Proposed Catch Basin
- Proposed Stormwater Pipe
- Proposed Vegetated Swale
- Topographic Contour (2')
- Topographic Contour (10')
- Tributary

0 50 100 200 300
Feet

Proposed Constructed Wetland BMP

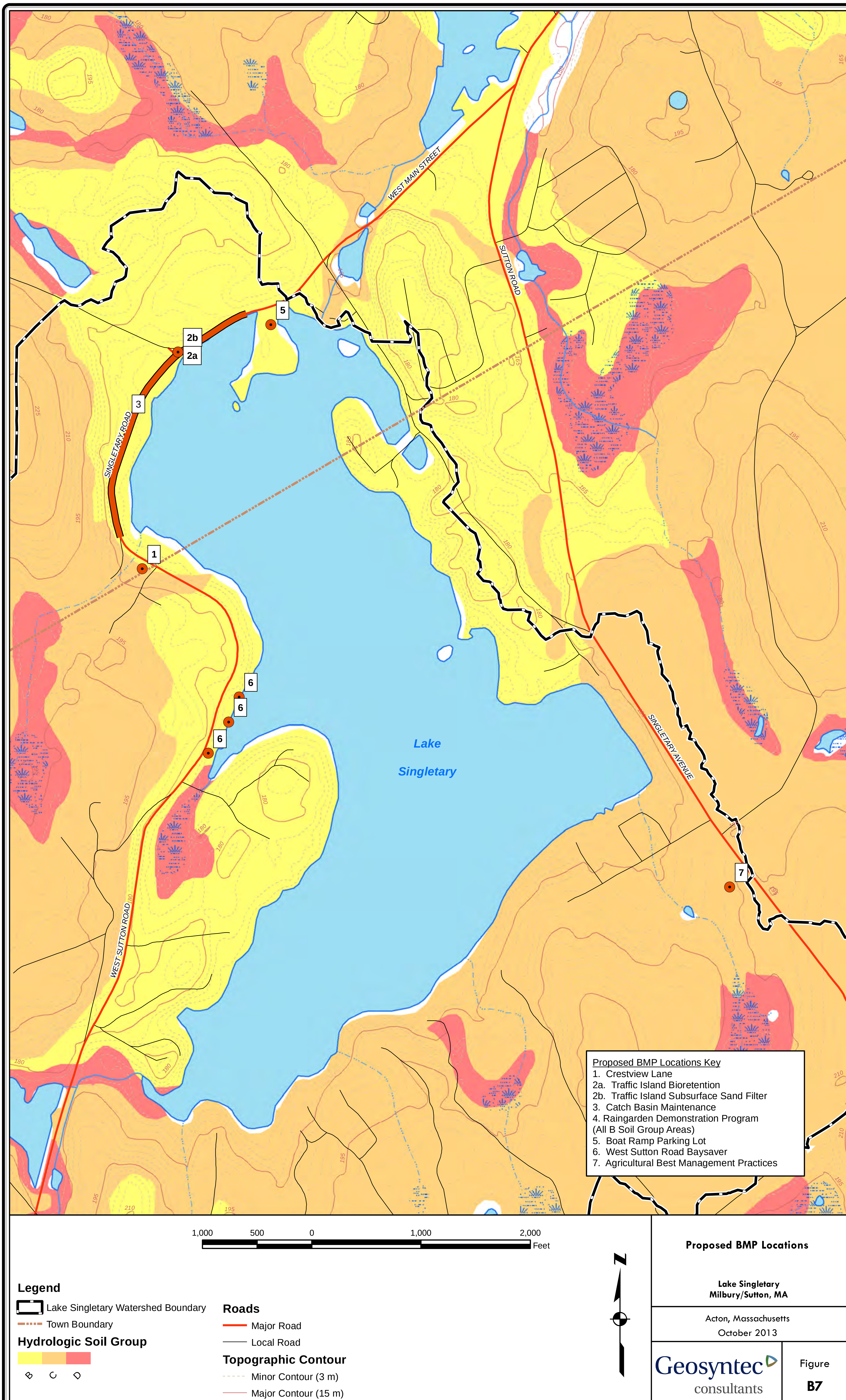
Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

Geosyntec consultants

Figure
B6

Q:\GISProjects\BW0221-Lake_Singletary\BMP_crestview.mxd



Proposed BMP Locations

Lake Singletary
Milbury/Sutton, MA

Acton, Massachusetts
October 2013

Geosyntec consultants

Figure
B7

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Appendix C:

Analysis of Historic Dissolved Oxygen Profiles

Analysis of Historic Dissolved Oxygen Profiles

The question of whether dissolved oxygen (DO) conditions within a lake are worsening over time is difficult to answer with the types of data typically collected as part of lake water quality sampling programs. Single DO measurements, or DO profiles collected once or intermittently during the year, will not provide sufficient data to identify trends or patterns.

The question itself also must be further clarified if any useful analysis is to be attempted. The statement "dissolved oxygen conditions are worsening" could mean several things:

1. Low dissolved oxygen concentrations are appearing at shallower depths within the water column;
2. The rate at which oxygen is consumed in the hypolimnion has increased; or
3. The period of time during which the hypolimnion experiences 'low oxygen' conditions is lengthening.

Monthly DO profiles cannot shed light on statement 1 above, as the time at which low oxygen concentrations have reached their shallowest depth within the water column is unlikely to correspond to any of the specific dates on which DO profiles were measured. Even with monthly measurements, the date of peak oxygen depletion (with regard to vertical extent of low oxygen conditions) could be off by several weeks. Additionally, the location of the boundary between the epilimnion and hypolimnion depend more on physical processes (wave action, mixing, lake morphometry, etc.) than on any water quality dynamics. In other words, degradation or improvement of water quality conditions is unlikely to influence the maximum vertical extent of low oxygen conditions. In this sense, question 1 above does not provide any useful insight into whether DO conditions are worsening over time.

Statements 2 and 3, however, can be answered (provided sufficient data exists) and do shed light on whether and how DO conditions are changing over time. Both questions may be answered if DO profiles have been measured at least monthly, and at least from the period between the onset of stratification (early spring) to fall turnover (late summer/early fall). In the case of Lake Singletary, such profiles have been recorded since 1998.

Consider a column of water in the lake that has a surface area of 1 m^2. A dissolved oxygen profile is measured along this water column, and each measurement indicates the concentration of dissolved oxygen in the 'slice' of the water column where the measurement was obtained. By multiplying the observed DO concentration by the volume of the 'slice' to which it applies, the total mass of dissolved oxygen within the water column can be estimated. Furthermore, by assuming that once stratification occurs, there is little to no mixing between the lake strata, the hypolimnion may be considered a closed system. The mass of hypolimnetic dissolved oxygen present at the onset of stratification is the maximum that will be available for the summer until DO supplies are replenished during fall turnover. Estimating the mass of DO in the hypolimnion for each month that a DO profile was measured, and plotting that mass over time will provide an estimate of the rate at which that limited supply of DO is consumed by biological processes in the sediment.

This rate of DO consumption, or "sediment oxygen demand" (SOD) is the most useful metric for understanding if DO conditions in a lake are worsening over time. Measuring SOD directly is a complex, costly, and difficult process beyond the capability of most water quality sampling programs. While not ideal compared to direct measurement, the method described above (using measured DO profiles to estimate oxygen mass) is an acceptable alternative to estimate SOD. SOD is described as grams of oxygen per square meter of sediment per day ($g/m^2/day$).

Geosyntec used monthly dissolved oxygen profiles collected by LSWA to estimate hypolimnetic oxygen mass for each month and to calculate a maximum sediment oxygen demand for each year. Figure C1 shows an example of the changes in calculated hypolimnetic oxygen mass for 1998-2000 (*Note: This subset of years is shown as an example to make the figure easier to view. Including the entire data set of 1998-2012 would result in many overlapping DO trend lines and would be difficult to view*). These patterns show that after stratification, the oxygen content in the lake's lower layer is gradually depleted due to biological processes in the sediment, until fall mixing ultimately causes DO content to increase later in the year.

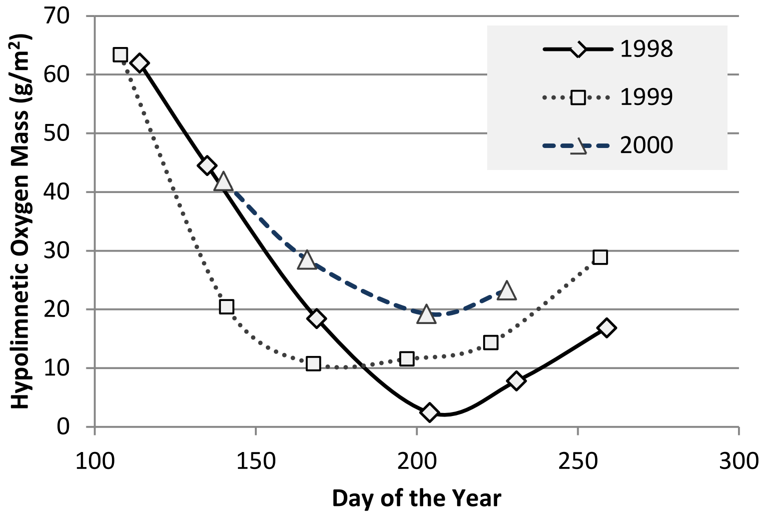

Figure C1. Monthly mass of hypolimnetic oxygen for 1998-2000. Values were calculated using observed DO profiles and are plotted on the day of the year on which the respective DO profile was measured.

The difference in hypolimnetic oxygen mass between any two sampling dates divided by the number of days between the sampling dates provides an estimate of SOD over that period. The maximum calculated SOD for each year (usually occurring just after stratification) is plotted in Figure C2. If dissolved oxygen conditions in the lake were worsening over time, we would expect to see an increase in the maximum rate of SOD over time. Figure C2 shows that this is not the case. While a trend (displayed as a dotted line in Figure C2) is shown and is weakly positive, the trend itself is not statistically significant (it does not pass a Student's t-test). In other words, assuming that SOD concentrations were not gradually increasing over time, one still might calculate such a trend as shown in Figure C2 by random chance. Continuing this type of calculation as future years' data becomes available could strengthen the significance of the calculated trend and help solidify conclusions with regard to hypolimnetic oxygen depletions trends.

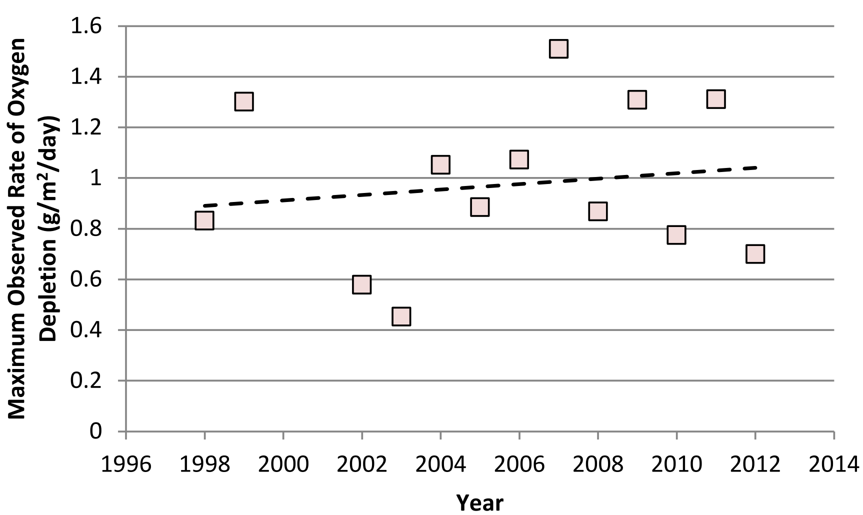

Figure C2. Maximum Rate of Hypolimnetic Oxygen Depletion, 1998-2012. (Note: years 2000 and 2001 did not have sufficient data to calculate SOD).

As a point of reference, sandy sediments typically exhibit a sediment oxygen demand of 0.2 $g/m^2/d$ to 1 $g/m^2/d$. "Enriched" sediments (those with higher organic matter content) typically exhibit SOD in the range of 1 $g/m^2/d$ to 10 $g/m^2/d$. The range of SOD values shown in Figure C2 indicate that Lake Singletary's sediment likely would be classified at the low end of "enriched" (Chapra, 1997). To better understand the lake sediment quality, sediment grab samples (obtained with an Eckman sampler or similar device) should be collected and analyzed for organic content.

Next, we attempt to answer the question of whether or not the period of time over which the hypolimnion experiences low oxygen conditions is lengthening. From Figure C1, it is apparent that there is some level of dissolved oxygen mass that the hypolimnion falls below sometime in the spring/early summer, and that it subsequently rises back above in late summer/early fall. The particular value of that level is arbitrary; for our purposes, we have chosen 15 g/m^2, as all but three years of record (2000, 2003, and 2007) pass through that level twice. This value converts to a concentration of 2.3 mg/l for Lake Singletary's hypolimnion. As a point of reference, the Massachusetts surface water quality standards for Class B waters use a DO standard of 5.0 mg/l for warm water fisheries. By choosing this 'low oxygen' level, we can estimate the number of days between the time when observed hypolimnetic DO mass fell below the level and the time at which DO mass rose back above that level. In this manner, the length of time that the hypolimnion experiences 'low oxygen' can be directly compared year to year.

Figure C3 shows the length of time during each year that the hypolimnion experienced 'low oxygen' content (containing less than 15 g/m^2 dissolved oxygen). A negative trend in this data is observed, meaning that the period of 'low oxygen' is shortening over time. However, as in the case of Figure C2, the trend is not statistically significant.

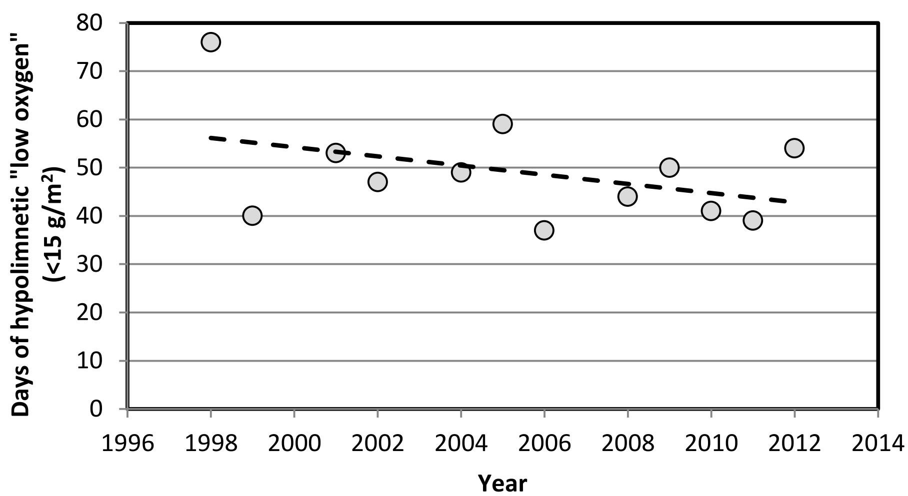

Figure C3. Length of time (in days) during which hypolimnion contained less than 15 g/m^2 DO.

In summary, we have investigated whether the rate of oxygen depletion in the hypolimnion is increasing over time, and whether the length of the period of depleted oxygen is increasing over time. The rate of oxygen depletion did appear to be increasing (worsening) over time, although the apparent trend was not statistically significant. The length of time over which the hypolimnion experiences depleted oxygen content was decreasing over time (improving), although that trend of improvement was also statistically insignificant. The statistical insignificance of these trends supports the conclusion that there is no real trend, either worsening or improving, of DO conditions over the period of record. One might argue that the statistical insignificance of the trends is due to the relatively short period of record, and that the data indicate a trend, even if it is a weak trend. The two measures of DO conditions presented in Figures C2 and C3, however, disagree on whether conditions are degrading or improving. As such, we believe the most prudent conclusion to reach from these results is that there has been no overall change in the DO conditions of Lake Singletary over the period of record from 1998-2012. Incorporating these types of calculations into future water quality analyses as new data becomes available will allow stronger conclusions to be reached.