First Order Assessment of the Indian Ponds
(Mystic Lake, Middle Pond, and Hamblin Pond)

FINAL REPORT
March, 2006

for the
Indian Ponds Association and the Town of Barnstable

Prepared by:

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Prepared for

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This project was completed under contract by the Cape Cod Commission for the Indian Pond Association

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Executive Summary

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Mystic Lake, Middle Pond, and Hamblin Pond are collectively known as the Indian Ponds. These three ponds which are located in the Town of Barnstable are similar in area (each over 100 acres), but their depth, surrounding land use, and location in the regional aquifer system have resulted in a variety of conditions and public concerns. In order to help discuss and address these concerns, local homeowners formed the Indian Ponds Association (IPA) in 1958. Through a partnership with the Town, the IPA asked the Cape Cod Commission to complete a first order assessment of the ponds, including the development of a 2004 water quality sampling plan, the delineation and development of a water budget, interpretation of water quality data, the development of a phosphorus budget and recommendations for water quality restoration and management and monitoring. The Commission prepared an initial water budget report, which included information on the pond, groundwater, and area water uses and highlighted relevant water management issues concerning the herring run, cranberry irrigation and water supply development. The report that follows refines the water budget findings based on the water quality analysis and collectively summarizes all the assessment activities for a first order assessment of the ponds.

Groundwater is greater than 80% of the inflow portion of the water budget for all the ponds and nearly 90% of the annual flow through the ponds discharges back to the aquifer system. Watershed delineations completed by the US Geological Survey show that groundwater flows from the top of the Sagamore Lens, is captured by three wellfields in Sandwich, flows through Spectacle, Lawrence, and Triangle Ponds and is captured by Crooked Cartway wellfield in Barnstable or Mystic Lake. This water then flows into Middle Pond and then into Hamblin Pond. As would be expected by this close connection to the groundwater, water levels in the ponds move up and down in tandem with regional water table changes and short-term impacts, such as cranberry bog withdraws, releases through the Middle Pond herring run, or large precipitation events, are balanced by opposite changes in flow into or out of the ponds. Recharge from the watersheds causes a given volume of water to remain in Mystic, Middle, and Hamblin for an average of 1.1, 0.56, and 1.0 years, respectively.

Field measurements and water quality samples were collected 10 times between May and November 2004 based on a sampling plan coordinated with the Town of Barnstable and IPA volunteers. Samples were analyzed at the School of Marine Science and Technology (SMAST) water quality lab at the University of Massachusetts, Dartmouth in New Bedford for the following parameters: total phosphorus (TP), total nitrogen (TN), chlorophyll-*a*, alkalinity, and pH. Field measurements included temperature and dissolved oxygen profiles with measurements at one meter increments and Secchi depth readings.

Temperature and dissolved oxygen profiles generally show that Hamblin and Mystic form a warm, well-mixed upper layer or epilimnion overlying a colder deep layer or hypolimnion in a process known as stratification. Because Middle Pond is shallower, normal winds are generally enough to keep its entire water column well mixed. Because there is too much organic matter in the sediments of Hamblin and Mystic, oxygen in their hypolimnia is rapidly consumed once stratification occurs. These anoxic conditions allow phosphorus that is otherwise bound in the sediments to be released back into the overlying water. This release is the primary source of phosphorus in both Hamblin Pond and Mystic Lake.

There is a significant difference, however, between Hamblin and Mystic that allows Hamblin to be relatively less impacted; the upper portion of Hamblin's hypolimnion has high oxygen concentrations. Phosphorus released from the sediments encounters these high oxygen concentrations, is converted back to an insoluble form, and sinks back toward the sediments. Because of this, water quality data shows that the phosphorus released by the anoxic bottom conditions does not impact its upper waters. The phosphorus budget shows a balance between watershed phosphorus loads from properties upgradient and abutting the pond and the TP concentrations measured in the pond. This well oxygenated portion of the hypolimnion is the result of a 1995 alum treatment; comparison of existing conditions to those prior to 1995 not only show the improvement in hypolimnetic oxygen conditions, but also reduced surface TP concentrations (*e.g.*, current is 10 ppb, while 1993 pre-alum was 69 ppb), improved Secchi readings (0.91 m in 1948 compared to a current average of 6.4 m), and reduced hypolimnetic oxygen demand (current average of 182 mg/m2/d, pre-alum 1993 average of 860 mg/m2/d). Hamblin Pond is still somewhat impacted given its on-going sediment oxygen demand, but is much improved compared to its pre-alum treatment conditions.

Mystic Lake, on the other hand, is clearly impaired. It has the highest average surface TP concentrations among the Indian Ponds (16 ppb), the worst Secchi readings (3 m average or 22% of its total depth), and the highest hypolimnetic oxygen demand (358 mg/m2/d). Because the dissolved oxygen profiles show that anoxic conditions exist up to the bottom of the epilimnion, some of the TP released into the hypolimnion from the sediments can seep into the epilimnion. The phosphorus budget confirms this scenario; watershed sources are insufficient to balance the measured epilimnetic TP concentrations. In order to match these concentrations, internal regeneration of TP from the sediments must add 12 kg/yr or roughly a quarter of the budget.

Middle Pond is relatively unimpacted compared to the other two ponds. It has the highest relative Secchi average (60%), average TP concentration of 10.6 ppb throughout its water column, and generally well oxygenated conditions even down to the sediments. It does develop some low oxygen conditions late in the summer or, apparently, during fairly quiescent periods. The phosphorus budget for the pond shows that an additional source of TP must be added to the pond to balance measured concentrations; potential sources are either water flowing from Mystic Lake or phosphorus released from the sediments during these intermittent low oxygen conditions.

After reviewing the water quality data, it is clear that Mystic Lake is impaired. Water quality in the other two ponds shows some issues of concern, but water quality conditions are generally good. Mystic Lake's impairments will require addressing phosphorus loads from both the sediment regeneration and the watershed sources. If the Cape Cod 10 ppb TP threshold in the epilimnion of Mystic Lake is used as a planning target, ~35 kg/yr would be the acceptable load to this layer. If a phosphorus reduction occurred similar to that achieved by the alum treatment in Hamblin Pond, a layer of well-oxygenated water in the hypolimnion would effectively isolate the phosphorus regenerated by the sediments and remove this load from the epilimnion. This would reduce the current epilimnion mass to the 35 kg/yr target, but it is estimated that there is an additional 12 kg/yr already in the groundwater from existing development and an additional 3 kg/yr is projected from buildout around the shoreline.

Project staff recommends that the IPA and the Town consider a series of three parallel steps to remediate Mystic Lake. The first step would be to address the phosphorus regenerated from the sediments; this can be done a number of ways (*e.g*., alum application, hypolimnetic aeration, etc.) and the selected option will likely require a permit and associated public hearings from the town Conservation Commission. The second step would be a number of activities to address the watershed loading; based on the phosphorus budget, 15 kg of TP would have to be removed. Steps to address this reduction are discussed. A third step would be to review existing regulatory programs (*i.e.*, board of health, conservation commission, and planning board) and their regulations and bylaws to evaluate potential changes to better protect water quality and, eventually, preserve the benefits of whatever investment is made to reduce the sediment phosphorus regeneration.

It is further recommended that the town and/or the IPA continue to monitor all three ponds, albeit on a reduced frequency compared to the sampling completed during this assessment. The recommended monitoring program should include, at a minimum, the same parameters, detections limits, depths, and sampling procedures utilized during this project; sampling should occur, at a minimum, in early April and late August. The late August sampling could occur via the regular PALS Snapshot, if this project is still occurring. Regular review of the results from the sampling program can be used to monitor conditions in the ponds and allow whatever management strategies are selected to be adapted to address concerns that may arise.

The Cape Cod Commission staff is available to elaborate on these recommendations and assist the town and IPA in the development of strategies to address the long term remediation and protection of the Indian Ponds.

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1. Introduction

Mystic Lake, Middle Pond, and Hamblin Pond are collectively known as the Indian Ponds. These three ponds which are located in the Town of Barnstable are similar in area (each over 100 acres), but their depth, surrounding land use, and location in the regional aquifer system have resulted in a variety of conditions and public concerns. These concerns have included water quality conditions, fluctuations in water levels, herring run management, and how additional development in the area might impact the ponds and their use by the public.

In order to help discuss these concerns, local homeowners formed the Indian Ponds Association (IPA) in 1958. The IPA was initially formed to address concerns about overpopulation and the impacts on the ecology of the ponds. Currently, IPA has over 130 members, has incorporated, has a 501(c)(3) public charity status, produces a newsletter, and has members regularly collecting water quality data with the assistance of the Town of Barnstable.

Through this partnership with the Town, IPA recently asked the Cape Cod Commission to complete a first order assessment of the ponds, including the development of a 2004 water quality sampling plan, the delineation and development of a water budget, interpretation of water quality data, the development of a phosphorus budget, and recommendations for water quality restoration, management, and monitoring. The Commission prepared a draft water budget report, which included information on the pond, groundwater, and area water uses. The draft findings highlighted relevant water management issues concerning the herring run, cranberry irrigation and water supply development. The report that follows refines these findings and collectively summarizes all the assessment activities for a first order assessment of the ponds.

2. History and Characteristics of Mystic Lake, Middle Pond, and Hamblin Pond

The Indian Ponds are located in a broad gently sloping glacial outwash plain referred to as the Barnstable Outwash (Oldale, 1979). The outwash plain is a deltaic deposit of sand and gravel that is abutted by the Sandwich Moraine to the north and extends south to Nantucket Sound. The glacial sediments were deposited during the last deglaciation of Wisconsinan Stage of the Pleistocene Epoch that occurred in New England approximately 15,000 years ago. The sandy outwash deposits are highly permeable and capable of storing a vast amount of water in their pore spaces; water that fills these spaces is referred to as groundwater. The Cape's groundwater system was designated as the Cape Cod Sole Source Aquifer, by the U.S. Environmental Protection Agency; this designation acknowledges that the aquifer system is Cape Cod's only source of potable water. The Indian Ponds are located in the Sagamore Lens, the largest of six independent groundwater flow cells that comprise the Cape Cod aquifer (Figure 1). The aquifer is bounded by the water table at its surface, the surrounding marine waters at it margins, and bedrock below (LeBlanc, *et. al.* 1986). The aquifer within the Barnstable outwash is approximately 250 feet thick and the average groundwater flow rate is approximately one foot per day (Masterson, *et al*., 1996).

The ponds are freshwater-flooded kettle holes. As the glacial ice sheets melted and receded from southern New England, remnant "dead" ice blocks were buried beneath the sandy outwash deposits from the glacial melt water (Strahler, 1966). When these ice blocks later melted, large depressions in the landscape resulted. Pollen records from ponds on outer Cape

Cod show lake sediments were forming approximately 12,000 years ago (Winkler, 1985). Groundwater levels rose in response to the post-glacial rise in sea level, which is estimated to have attained its modern level approximately 6,000 years ago, (Ziegler, *et al*., 1965).

Mystic Lake is the largest (148 acres) of the three Indian Ponds and is situated to the north and west of Middle and Hamblin Ponds. Middle Pond is 105 acres and is located between Mystic Lake to its north and Hamblin Pond to its south. Hamblin Pond is the deepest and second largest of the Indian Ponds (115 acres) and is located to the south of Middle Pond and Mystic Lake. Hamblin Pond was the subject of a diagnostic/feasibility study in 1993 by Baystate Environmental Consultants in response to water quality concerns. BEC (1993) evaluated historic land use around Hamblin Pond, including a large duck farm with approximately 10,000 Muscovy ducks operated between the 1920's and 1950's at the southern end of the pond. In 1995, alum was applied pond-wide in order to begin to remediate the water quality impacts of the duck farm and other watershed activities.

3. Watershed Delineation and Water Budget

A pond water budget accounts for the volume of water in the pond and the flows of water entering and leaving the pond. In kettle hole ponds, typically groundwater enters the pond along one shoreline (*i.e.*, the upgradient side) and pond water reenters the aquifer system along the opposite shoreline (*i.e.*, the downgradient side). Hamblin Pond functions in this way. In some cases, kettle ponds have small streams entering or leaving them; Middle Pond has a herring run along its downgradient side and a small direct connection to Mystic Lake at the northern end of the land bridge between them. The pond surface is a reflection of the level of the water table. Groundwater flows according to the regional hydraulic gradient starting at the top of the mound where it is 60 feet above mean sea level to Hamblin Pond at 41 feet. A hydrogeologic cross section shows the relationship of the Indian Ponds to the groundwater system (Figure 2).

A. Physical Characteristics of the Ponds

Mystic Lake is the largest (148 acres) of the three Indian Ponds; Hamblin Pond is 115 acres, while Middle Pond is 105 acres (Table 1). Based on interpretation of the contours in Figure 1, Hamblin Pond contains the most water (1029 million gallons), while Mystic Lake contains 913 million gallons and Middle Pond contains 589 million gallons. Hamblin Pond is the deepest of the three ponds (62 feet), while Mystic Lake's deepest point is 42 feet and Middle Pond has a maximum depth of 31 feet (Figure 3).

Table 1. Physical Characteristics of Indian Ponds

Pond	PALS Pond unique ID	Area	Volume	Deepest Point
		Acres	Million gallons	Feet
Mystic Lake	BA-584	148	913	42
Middle Pond	BA-640	105	589	31
Hamblin Pond	BA-668	115	1029	62

Notes: 1) Volume based on interpolation of MA Division of Fisheries and Wildlife bathymetric contours (available at http://www.state.ma.us/dfwele/dfw/dfw_pond.htm), 2) PALS ID is a unique identification assigned to each pond by the Cape Cod Commission under the Pond and Lake Stewardship (PALS) program

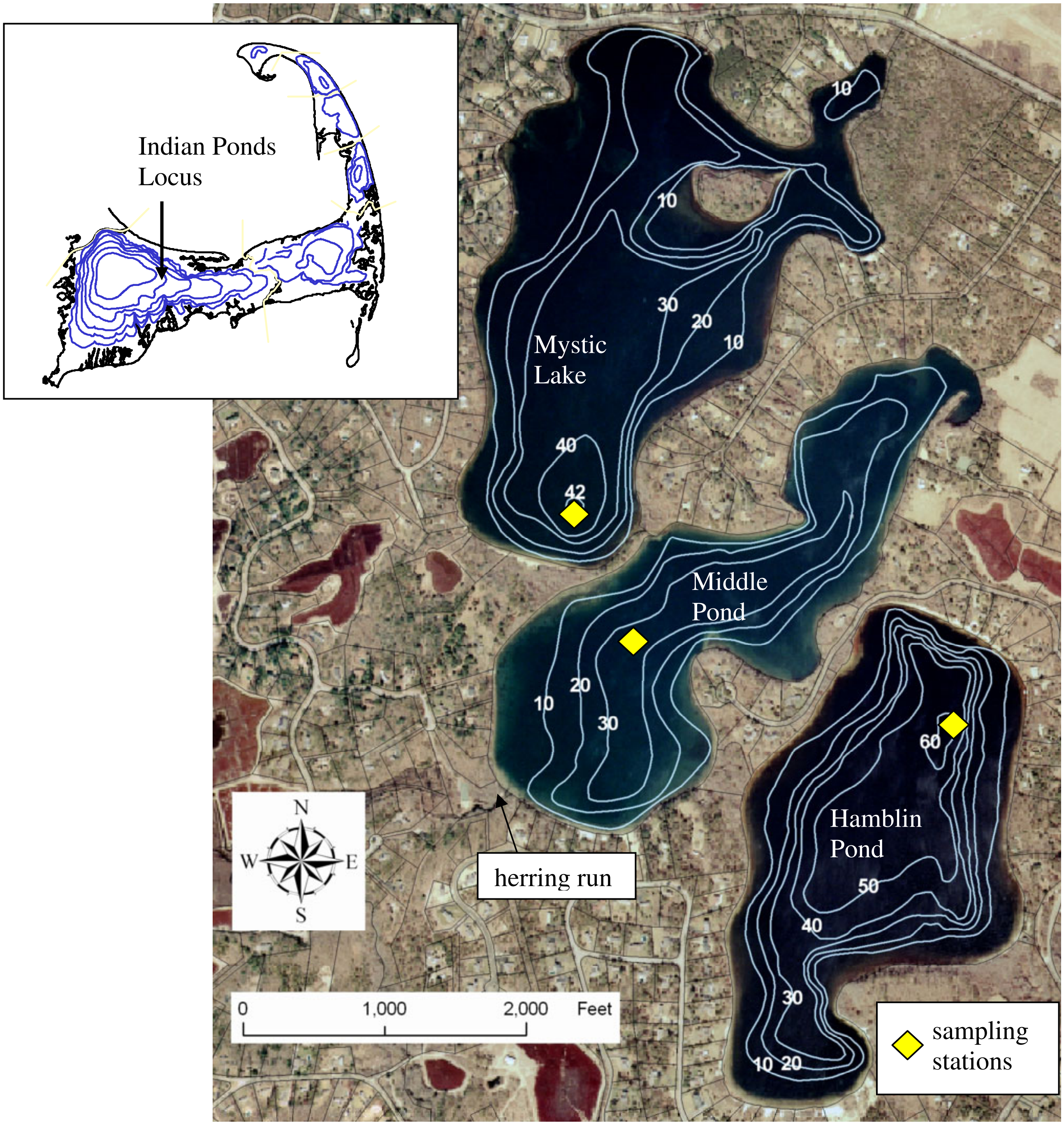
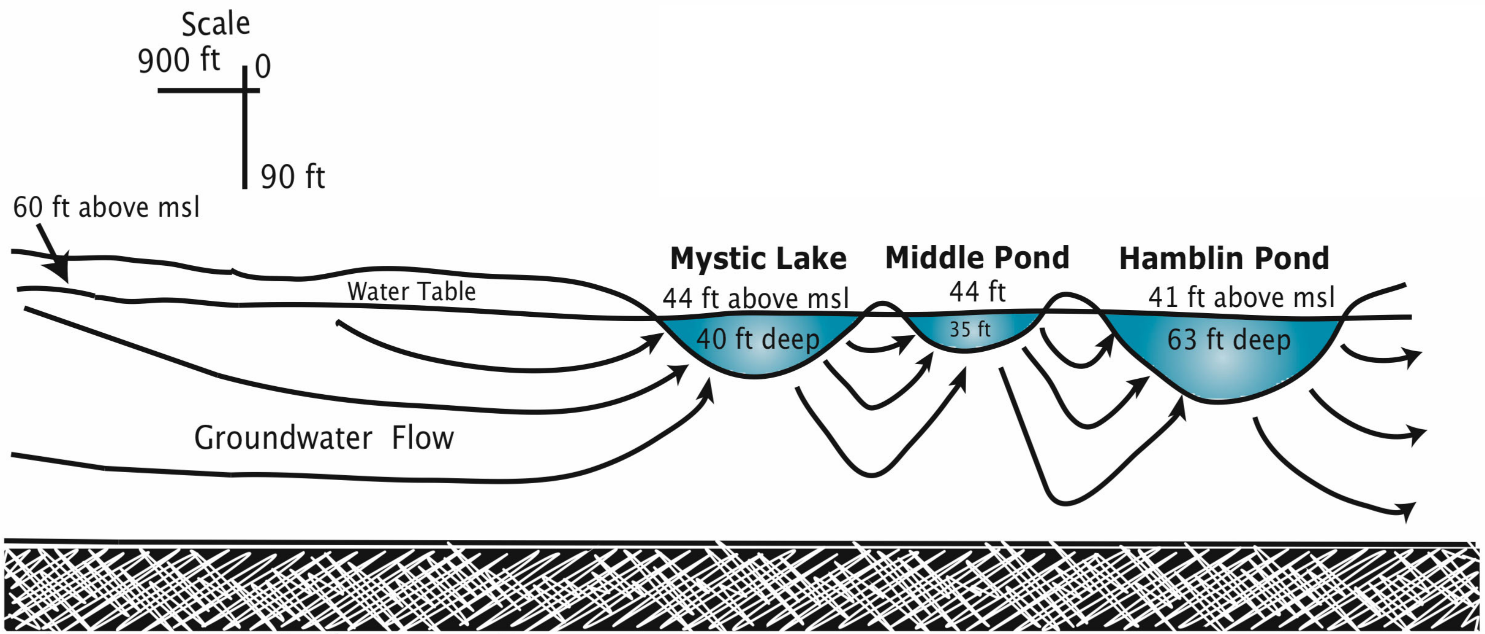
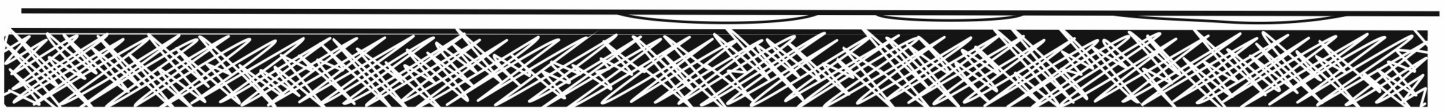


Figure 1. Locus, bathymetry, and water quality sampling stations for Indian Ponds
Bathymetry contours in feet; Bathymetry source: Massachusetts Division of Fisheries and Wildlife (http://www.state.ma.us/dfwele/dfw/dfw_pond.htm)



a) 1 to 10 vertical exageration



b)1 to 1 horizontal to vertical scale

Figure 2. Conceptual Hydrogeologic Cross Section in Indian Ponds area

Since the Indian Ponds are flow-through portions of the groundwater system, it is important to understand how surrounding groundwater levels fluctuate and how those fluctuations could impact water levels within the ponds. A previous study of Lake Wequaquet water levels has documented that pond and groundwater levels generally move in tandem, but the large surface area of a pond appears to result in a smaller fluctuation range for the pond than the surrounding groundwater (Eichner, *et al*., 1998).

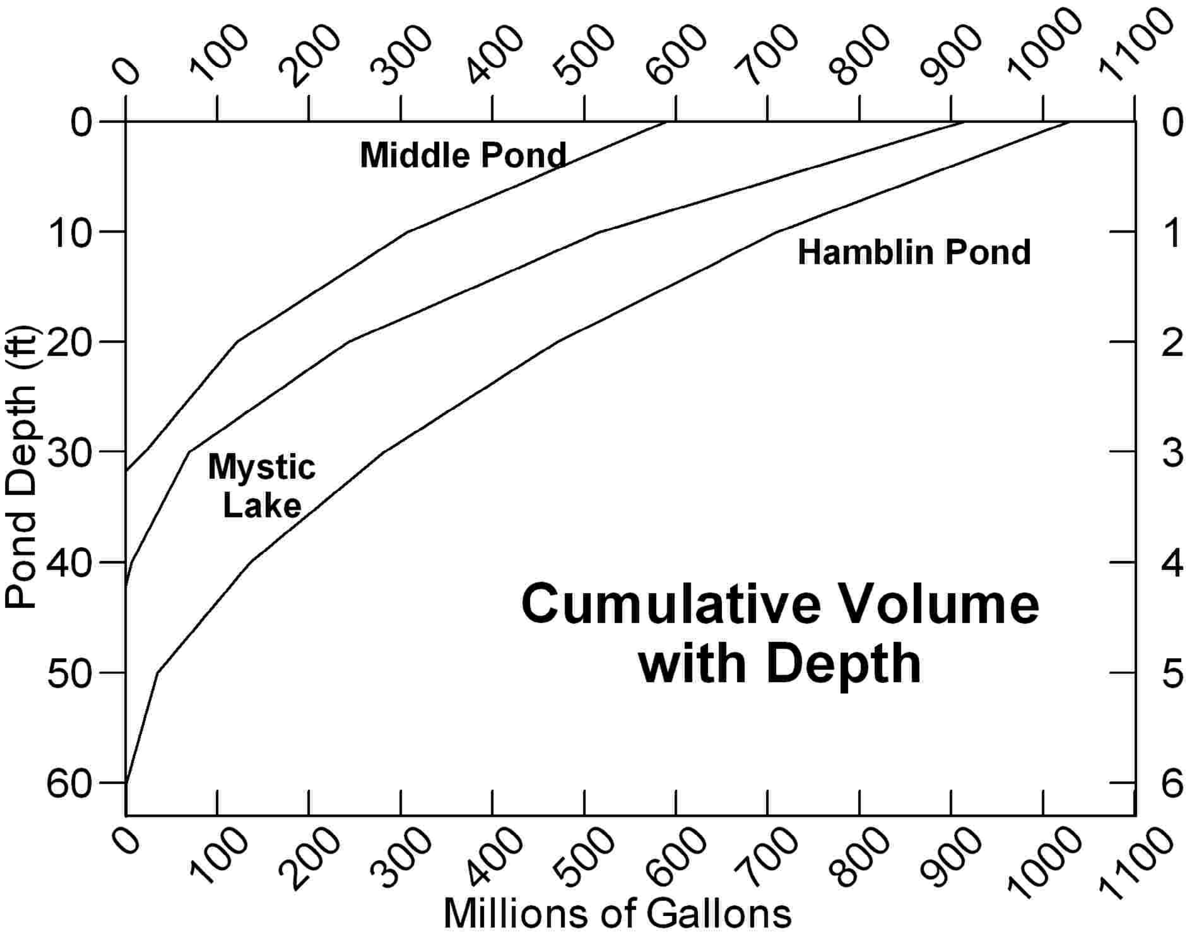


Figure 3. Hypsographic Curves of Mystic Lake, Middle Pond, and Hamblin Pond. As indicated, Hamblin Pond is the deepest and has the greatest volume. These curves also indicate that all the ponds have relatively gradual changes in depth.

The US Geological Survey (USGS) has installed over 60 monitoring wells throughout the Cape for the purpose of measuring fluctuations in groundwater levels; some of these wells have been monitored for over 50 years. Staff of the Cape Cod Commission have collected these water level readings and managed the well network for more than 20 years. Four of these monitoring wells with long-term records are located in the area around the Indian Ponds: SDW253, A1W314, A1W254, and SDW 258. As noted in Figure 4, the range between the highest and the lowest recorded groundwater elevations at SDW253 is approximately 9.3 ft, 7.5 ft at A1W314, 4 ft at A1W254, and 3.5 ft at SDW258. Based on these observations and the location of the ponds in the aquifer system, the likely maximum range in pond level elevations would be 4 to 6 ft without accounting for any reduction in the range as observed at Lake Wequaquet (Eichner, *et al.*, 1998). When the ponds are at average water levels conditions, the high end of a 4 to 6 ft range would result in a 2 to 3 ft increase. A 2 to 3 ft increase in water levels would increase the volumes of the ponds between 7 to 11% in Hamblin Pond, 11 to 16% in Mystic Lake, and 12 to 18% in Middle Pond.

In order to explore the potential interaction between the water levels in the ponds and nearby groundwater levels, staff gauges were installed in Mystic Lake, Middle Pond, and Hamblin Pond at locations shown in Figure 5. The Town of Barnstable's Engineering Division determined the elevations of the gauges so pond water levels could be accurately measured. Water-level information was measured and recorded by resident volunteers from May to October 2004 at the new gauges and by staff at an existing stream gauge from May to August 2004 (data is included in Appendix A).

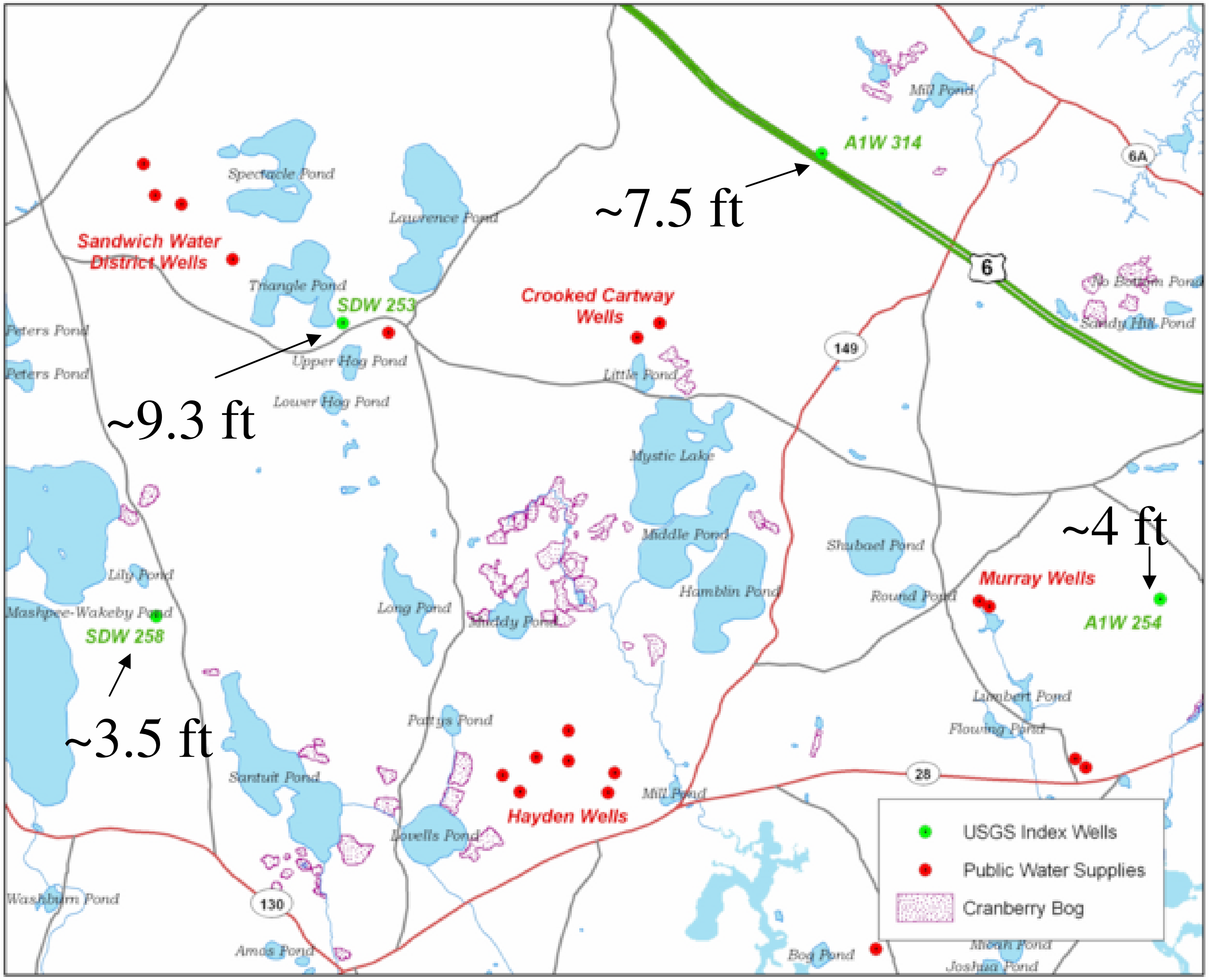


Figure 4. US Geological Survey Index Wells and Range of Groundwater Level Fluctuations near Indian Ponds

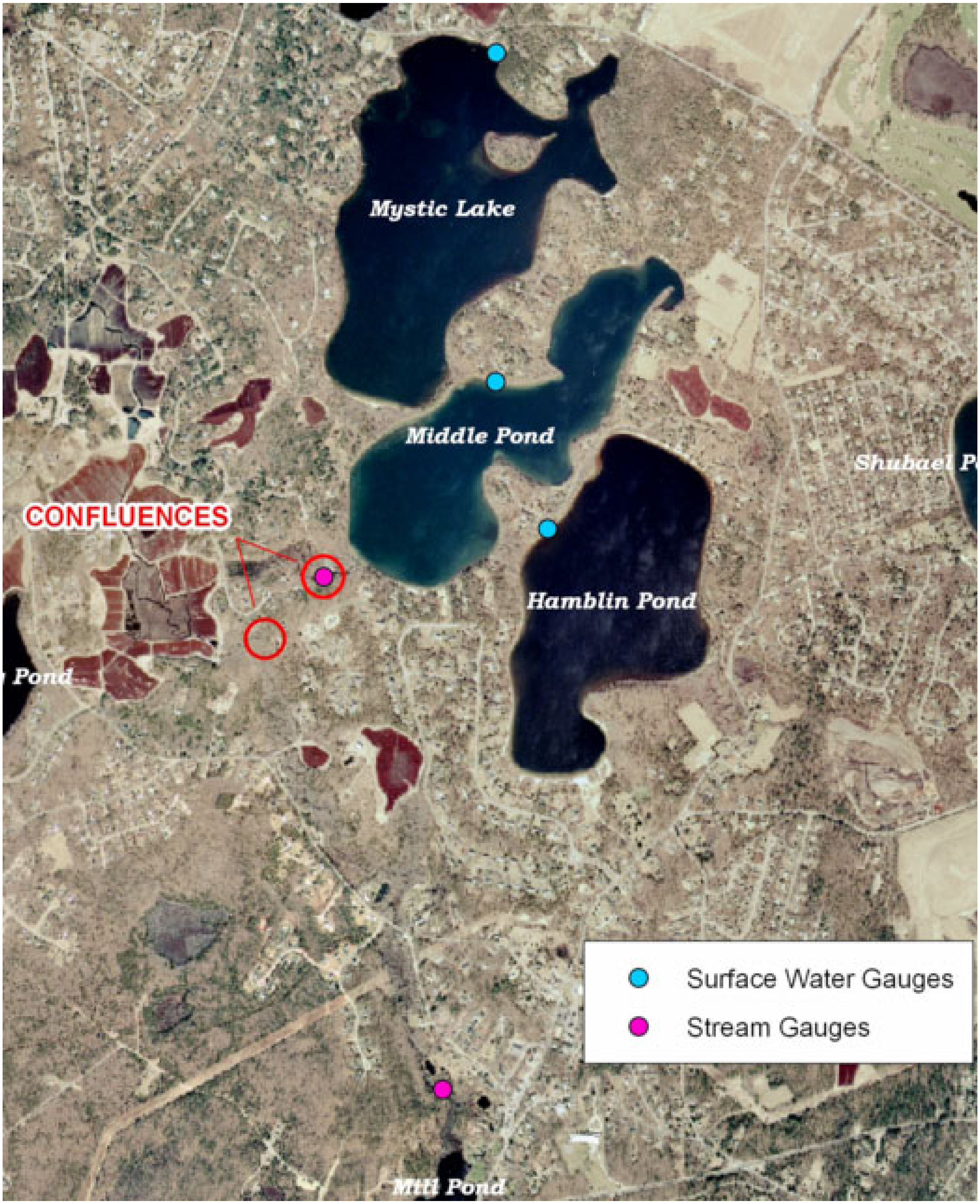


Figure 5. Stream and pond water level gauges in the Indian Pond study area.

Figure 6 shows the changes in water levels in the ponds and a comparison to groundwater levels at USGS index well SDW253 (see Figure 4 for location) during the period of record for water-level measurements in the Indian Ponds (May - October 2004). Water levels in the ponds dropped by a total of 0.8 feet. By comparison, groundwater levels measured in index wells around the ponds dropped from between 0.7 feet to 1.1 feet during the same period, which suggests that water levels in the ponds and the surrounding groundwater move in tandem without any dampening in the overall range. More frequently measured data collected at the Middle Pond stream gauge on the cranberry bog flume during 2001 shows similar congruence, as well as short-term impacts of rain events and the natural building of an obstructing beach or berm at the mouth of the channel from Middle Pond to the herring ladder (Figure 7).

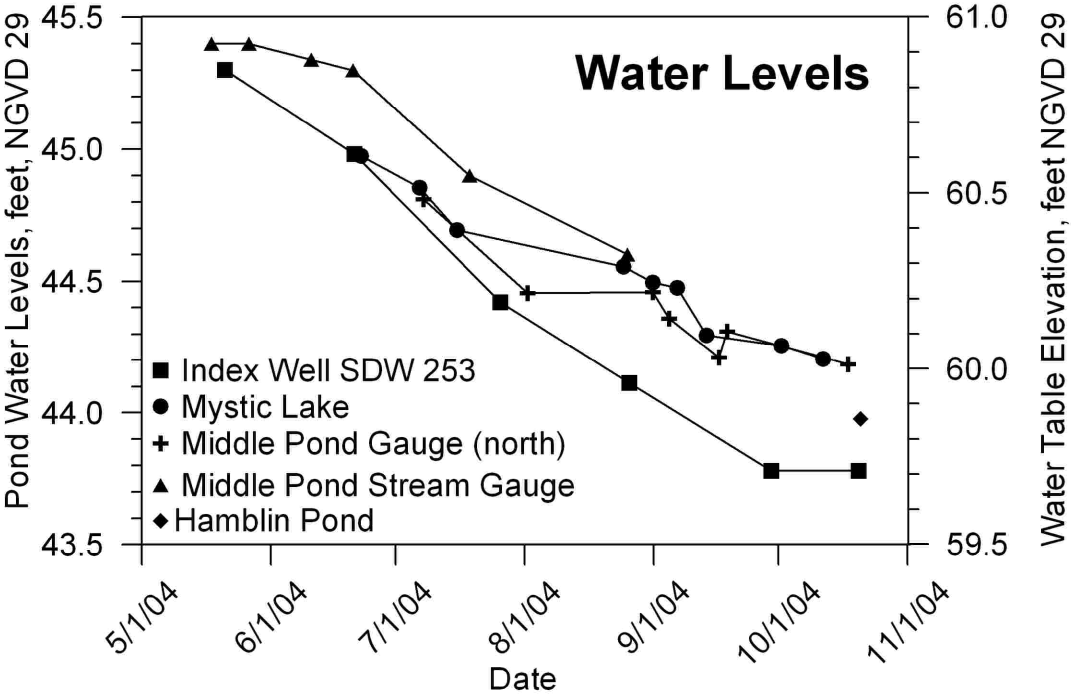


Figure 6. Groundwater and Pond Water Level Fluctuation in the Indian Ponds Study Area (May to October 2004).

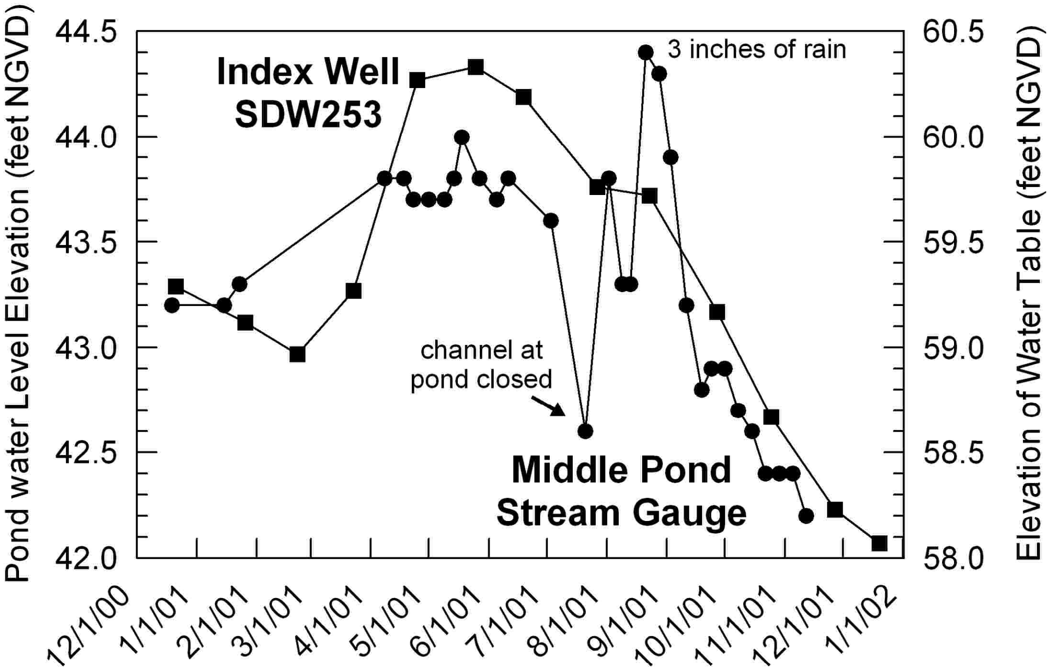
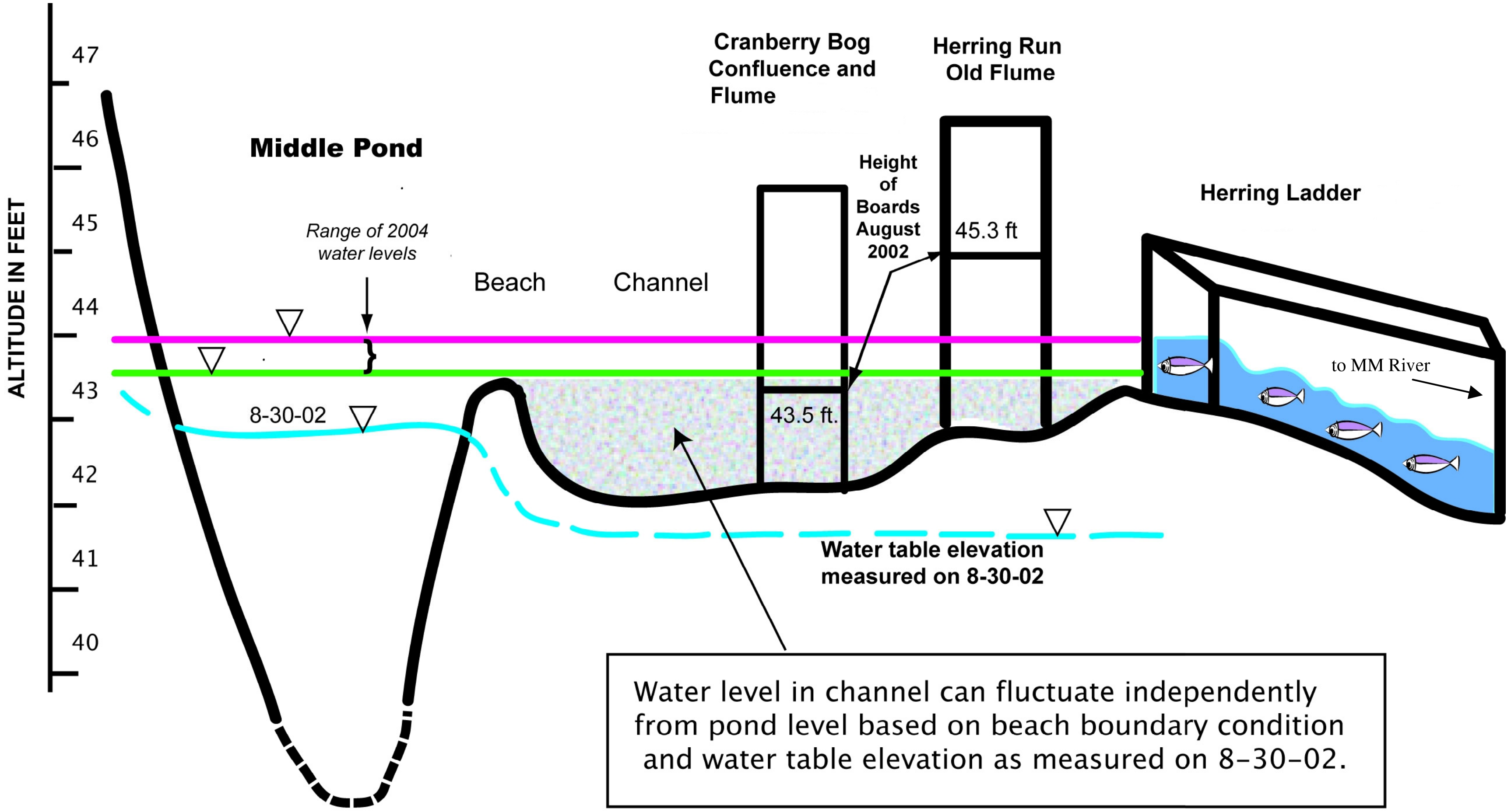


Figure 7. 2001 Hydrograph of SDW253 and water levels at the Middle Pond stream gauge. Water levels generally move in tandem except for extreme rain events and beach elevation changes.

Since the pond water level and the surrounding groundwater move in tandem, the elevations of the pond bottom and the herring run outlet are important considerations for determining flow through the herring run, especially during low groundwater conditions. Figure 8 shows a cross-section displaying elevations of Middle Pond, the beach berm, the channel to the flume and fish ladder and the beginning of the herring run. Relatively high water levels during 2004 show that all the features are completely connected for most of the year. By comparison, low water levels during August 2002, when the level of the pond dropped below the elevation of the beach leading to the herring run, show that groundwater/pond levels are lower than the herring run. In this condition, there will not be any flow through the old flume or the cranberry bog confluence.

B. Watershed Delineation

The United States Geological Survey (USGS) has recently released a revised version of the regional Cape Cod groundwater model (Walter and Whealan, 2004). This model incorporates information characterizing groundwater levels, municipal drinking water supply pumping, stream flow measurements, and geologic information developed over a number of decades. The model relies on the USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) and the USGS particle-tracking program MODPATH4 (Pollock, 1994). MODPATH4 uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer and was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. The model



Water level in channel can fluctuate independently from pond level based on beach boundary condition and water table elevation as measured on 8-30-02.

Figure 8. Hydraulic Cross-section from Middle Pond to the herring ladder flowing to the Marstons Mills River. Elevations were established by the Town Barnstable Engineering Division. Purple and green lines show water level elevation range in 2004 indicating that pond and groundwater levels were sufficient to allow water to pass through to the herring ladder. The light blue line shows water level readings in August 2002 indicating that obstruction caused by the natural beach growth would not allow pond water to leave the pond and groundwater levels on this downgradient side of the pond were lower than the bottom of the channel leading to the herring run.

simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information. Average pumping rates (1995 to 2000) for the public water wells in the Indian Ponds area are used as part of the dataset for the development of the model (Table 2).

In isotropic aquifer systems, groundwater flows perpendicular to water table contours or lines of equal water table elevation. On Cape Cod, groundwater flow lines may be projected upgradient from ponds, perpendicular to these water table contours, to delineate recharge areas to the ponds. Assuming uniformly distributed groundwater recharge across watersheds, watershed areas are directly proportional to the flux through those watersheds. Therefore, the areal extent of the upgradient watershed is a function of how much water is flowing into a pond.

Table 2. Average Pumping Rates (1995 – 2000) for Public Water Supply Wells in the Indian Ponds Watershed. Data supplied by USGS ((D. Walter, personal communication).

Water District	Well field	Million Gallons per Year
Cotuit-Osterville-Marstons Mills Water District	Crooked Cartway	263
	Hayden	333
	Murray # 12 & 13	102
	Lumbert Mill # 9 & 5	80
Sandwich Water District	Pinkham Road # 4 & 6 / # 10 & 11	319
	20-87 # 8	55

Note: these pumping rates were used by the USGS in the construction of the Sagamore Lens groundwater model

Since the Indian Ponds are part of the groundwater system and, as discussed above, have water levels that generally fluctuate in tandem with the surrounding groundwater, groundwater discharges into these ponds along the upgradient shoreline and pond water discharges back to the groundwater along the downgradient shoreline. The regional groundwater model incorporates the ponds and can reasonably model this “flow-through” characteristic of Cape Cod ponds. With this in mind, the USGS model was used to delineate watersheds to the Indian Ponds, as well as watersheds to the other ponds and public water supplies upgradient of the Indian Ponds (Figure 9). These watershed delineations show that groundwater flows from the top of the Sagamore Lens, is captured by three wellfields in Sandwich, flows through Spectacle, Lawrence, and Triangle Ponds and is captured by Crooked Cartway wellfield in Barnstable or Mystic Lake. This water then flows into Middle Pond and then into Hamblin Pond.

Since the downgradient shorelines of the ponds in Sandwich are only partially within the watershed to the Indian Ponds, a portion of the flow out of these ponds flows out of the Indian Ponds watershed. In order to calculate the amount of recharge or annual flow out of each pond, project staff determined the length of the downgradient shoreline to each pond. Discharge out of the pond was then split among all the downgradient watersheds receiving flow based on the percentage of the total shoreline length. For example, 23% of the shoreline and groundwater flow from Lawrence Pond is discharged to the watershed to the Crooked Cartway wellfield, while 59% of the Pond discharge is out of the Indian Ponds watershed and the remainder discharges into the Mystic Lake watershed (see Figure 9). Table 3 summarizes the division of the recharge among the ponds in the Indian Ponds watershed.

Since recharge drives movement of groundwater within the aquifer system, annual recharge within each watershed is equivalent to the flow of groundwater discharge out of each watershed. This recharge was then compared with the volume of each pond and a residence time for water in each of the ponds was determined. This data was compared to observed nutrient concentrations; this analysis found that the recharge associated with the wellhead contributing areas should be removed from the water budget in order to better balance observed concentrations. Volumes in Table 3 reflect these corrections.

The preceding analyses are based on output from the USGS groundwater flow model. Parameters and assumptions imposed on the model result in a simulation that suggests that water does not underflow the pond system, i.e. all upgradient groundwater flows into the pond system. This scenario would mean that groundwater at bedrock, hundreds of feet below the water table, would surface into the ponds. Addition of new water supply wells in the area would have the potential to alter watershed delineations and these alterations could be evaluated using the model.

Earlier watershed delineations for the Indian Ponds completed by the Cape Cod Commission (CCC, 1991) have utilized an annual depression rate method. This method determines the maximum depth of a pond and uses available water table information to determine the flowpath that would meet this depth. The location at which this flowpath intersects the top of the water table is the maximum extent of the watershed to the pond; the land area between the maximum extent and the pond is the estimated watershed. Watersheds determined using this method generally are significantly smaller than the results of the USGS modeling. For example, the recharge flow to Mystic Lake using this method is 0.82 MGD compared to the 2.08 MGD determined from the USGS model. Water quality data analysis suggests that the depression rate volume is insufficient to produce the observed concentrations. Additional site-specific hydrogeologic data collection would be necessary to further refine groundwater flowpaths in this area.

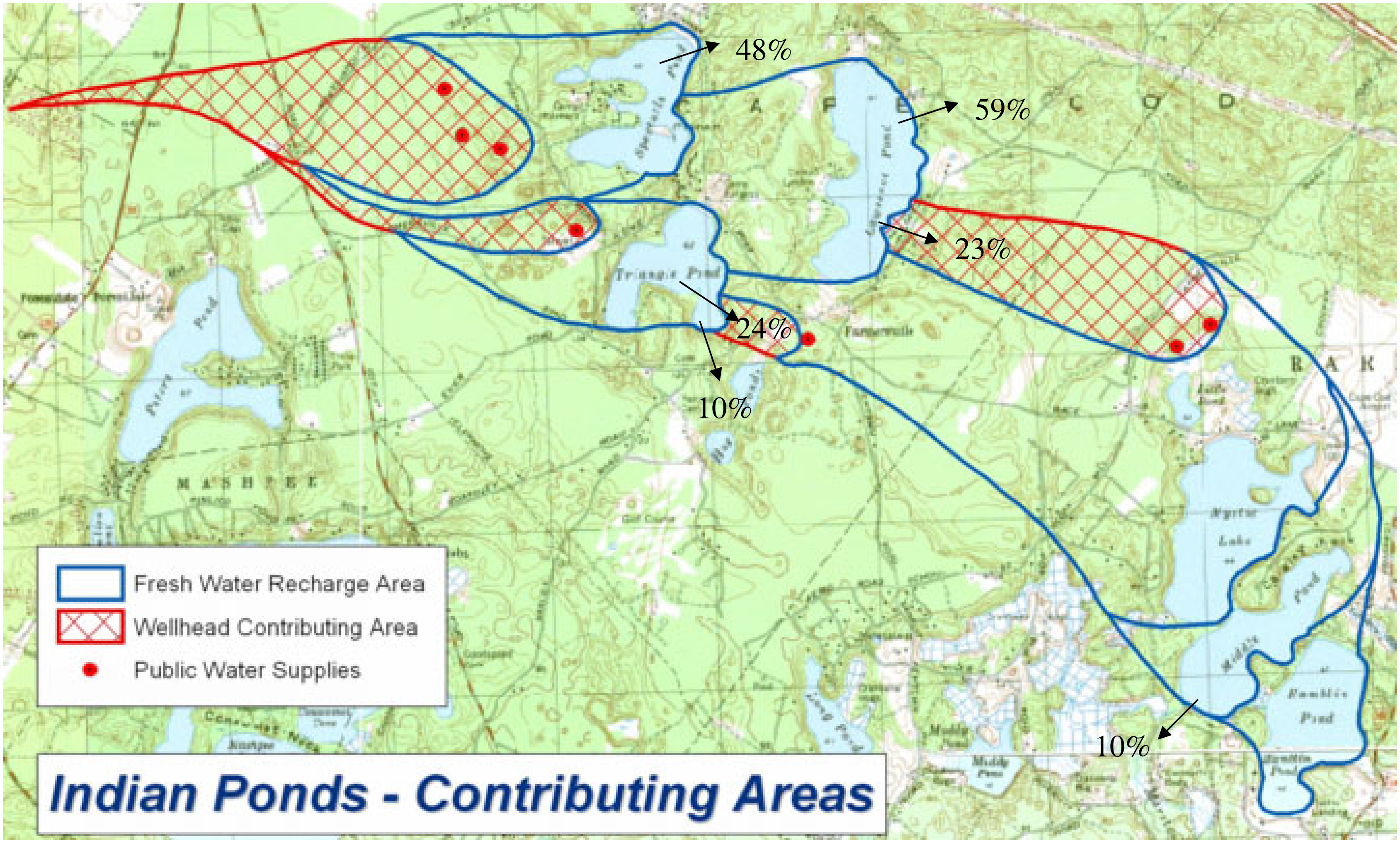


Figure 9. Indian Pond Watersheds

Watersheds based on US Geological Survey model outputs (Walter and Whealan, 2004). Percentage of ponds downgradient shoreline that flows out of overall Indian Pond watershed are indicated; recharge within wellhead areas is removed from watershed flows based on an analysis of residence times related to measured water quality data.

Table 3. Contributions of Subwatershed Areas to Indian Ponds

Receiving pond for Spectacle, Triangle, and Lawrence is Mystic Lake, while Middle Pond receives 100% of Mystic Lake flow. Hamblin Pond only receives 90% of flow from Middle Pond since 10% of the downgradient shoreline discharges into the Marstons Mills River watershed. Watersheds to public water supply wells are not included in these calculations based on analysis of water quality that shows residence times without recharge within these areas better match observed nutrient concentration in the ponds.

Watershed	(A) Watershed Area in Figure 8 (acres)	(B) Percent to Receiving Pond	(C) Watershed Recharge (in/yr)	(A) x (B) x (C) Watershed Flow to Receiving Pond (MGD)	(D) Cumulative Flux (MGD)	(E) Net Recharge to Pond (MGD)	(F) = (D) - (E) Groundwater Inflows (MGD)	(G) Pond Volume (MG)	(H) = (G) / (F) Average Residence Time (months)
Spectacle Pond	313	9%	27.25	0.06	-	-	-	-	-
Triangle Pond	226	22%		0.10	-	-	-	-	-
Lawrence Pond	405	18%		0.15	-	-	-	-	-
Mystic Lake	1,021	100%		2.07	2.38	0.30	2.08	909	13.3
Middle Pond	247	100%		0.50	2.88	0.21	2.67	572	6.7
Hamblin Pond	162	100%		0.33	2.92	0.23	2.69	1028	12.0

MGD = million gallons per day; MG = million gallons

C. Herring Run

In order to complete a water budget for a pond system, it is necessary to calculate all inputs and outputs of water. While Mystic Lake and Hamblin Pond inputs and outputs are via groundwater, Middle Pond includes a stream outflow through a herring run and flume located on its southeastern shore (see Figure 5). Water from the herring run discharges into the Marstons Mills River and, eventually, into the Three Bay estuary system. The Barnstable Natural Resources Division manages the herring run under a draft management plan that the town has developed with the Massachusetts Division of Marine Fisheries and the Indian Ponds Association. The plan specifies time frames during which flow through the herring run is allowed and requires the use of v-notched boards to limit flow through a stream weir while providing adequate passage to herring (Michaud, *et al.*, 2005).

As discussed above, the water fluctuations in Middle Pond and the surrounding groundwater can limit flow through the herring run during low groundwater conditions. In order to provide some basis for establishing the quantity of flow through the herring run, Commission staff asked town staff to provide notification of openings of the run. During a year and a half of monthly observations, Commission staff only observed streamflow through the herring run on one occasion (May 18, 2004). At this time, discharge over the fish ladder weir was measured as approximately 500 gpm, or 0.74 mgd using a pygmy meter in the channel downgradient of the fish ladder. The water-level elevation was 45.4 feet NGVD. Further discussion with town staff indicated that additional releases were not anticipated during the Fall 2004 season.

Since this flow was the only measurement recorded in at least a year, this flow could be divided by 12 to estimate an annualized streamflow. An annualized streamflow on this basis would be 0.06 mgd. Based on the groundwater flow modeling, the maximum discharge through this section of Middle Pond's downgradient shoreline would be 0.29 mgd or approximately five times the annualized herring run flow.

As demonstrated in Figure 7, instantaneous discharges through the herring run or large precipitation events are likely to create short-term changes in the water level of Middle Pond that the interconnected nature of the aquifer and the ponds will then bring back into a regional equilibrium in the longer term. Any herring run losses are eventually balanced by greater groundwater flow into the pond from upgradient sources. Given the interconnected nature of the aquifer, pond levels, and streamflows, it is likely that if the herring run was enhanced to maximize flow, the maximum expected flow would approximate the downgradient shoreline maximum of 0.29 mgd. More refined and frequent monitoring of the herring run, possibly involving a variety of streamflow rates, and pond water levels would be necessary to better characterize their relationship as discussed in Michaud, *et al.* (2005).

D. Cranberry Bog Irrigation

Cranberry bog managers on Cape Cod often use pond water to flood the bogs during harvest or for protection of the plants when temperatures are below freezing. Cranberry bogs are located to the west of Middle Pond and to the north of Mystic Lake. The industry standard for cranberry bog irrigation is 10 ft water per year. This amount used by policy under the Massachusetts Water Management Act with irrigation of bogs over 4.6 acres may be considered a non-consumptive use by Massachusetts Department of Environmental Protection if it is determined that the bogs have surface water flowing through them.

On February 8, 2005, Commission staff interviewed John Hamblin, who manages the approximately 30 acres of cranberry bogs southwest of Mystic Lake and west of Middle Pond. Mr. Hamblin indicated that these bogs are flooded with water withdrawn from the ponds during autumn harvest operations, but the bogs are not irrigated using pond water during the growing season. Water is released from Mystic Lake and Middle Pond into these bogs annually over a period of 2 to 3 days in October to flood approximately 9-1/2 acres of bog with 3 to 4 inches of water (total volume between 0.77 and 1 million gallons) and then recycled to flood additional downstream bogs. The water is eventually discharged to the Marstons Mills River. No water quality analysis of bog discharge water is available.

At one time, Mr. Hamblin also operated approximately 10 acres of bog immediately north of Mystic Lake and was able to provide some insight into their management. During Mr. Hamblin's tenure, the bogs were irrigated with groundwater pumped from on-site wells and flooded with water derived from Mystic Lake during the harvest season and returned to Mystic Lake following the harvest. In previous years, water diverted from Little Pond (see Figure 1) was used to flood the bogs.

The withdrawals of irrigation water have the potential to cause short term changes in pond water levels, similar to the temporary release of water through the herring run in Middle Pond, that are eventually balanced by the water levels in the surrounding aquifer. The maximum bog flood waters (one million gallons) is 12% of groundwater inflow over three days into Middle Pond or only 0.18% of the pond's total volume. These relatively small volumes and the temporary nature of their withdrawals, it is understandable that the impacts should be relatively transitory as further discussed in Michaud, *et al*. (2005).

E. Water Budget

A water budget summarizes all the water inputs and outputs of a pond and, because the pond volume is relatively stable, makes sure that the inputs and outputs balance. In the case of the Indian Ponds, the predominant input and output is groundwater with additional inputs from precipitation and additional outputs from evaporation and, in the case of Middle Pond, streamflow. In equation form, a water budget is typically represented as:

$$\text{IN} = \text{OUT} + \Delta\text{S}, \tag{1}$$

Where,
IN = groundwater inflow + precipitation
OUT = groundwater discharge + stream flow + evaporation
Δ S = the amount of water storage gained or lost as water levels increase or decrease, respectively.

As mentioned above (Section 2A), groundwater levels and pond levels of the Indian Ponds tend to fluctuate together; so long-term decreases in the volume of the pond tend to be accompanied by equivalent changes in the amount of groundwater inflow and outflow. Shorter term events, such as individual storms, can change the storage, but in a way that is quickly assimilated by the aquifer and has little impact on the overall annual water budget. Because of this relationship, the storage component of the water budget equation is removed and equation (1) is simplified to:

$$\text{IN} = \text{OUT} \qquad (2)$$

Groundwater is greater than 80% of the inflow portion of the water budget for all the ponds (Table 4). The "IN" portion of the budget is determined by the recharge within the watersheds shown in Figure 8 and the precipitation on the surface of the ponds. Walter and Whealan (2004) evaluated recharge rates on land surfaces and ponds as part of the activities to prepare the recent USGS groundwater model for Cape Cod. This included an evaluation of precipitation between 1941 and 1995 at Hatchville, MA. This evaluation showed annual precipitation ranging between 26 inches in 1965 and 74 inches in 1972 with an average of 44 inches. Using available hydrogeologic data, Walter and Whealan (2004) estimated annual recharge to groundwater through land surfaces to be 27.25 inches and through ponds to be 15.8 inches. Ponds have higher evapotranspiration because of the exposure of the water surface to sunlight and wind; these systems also tend to have a greater density of plant biota. In the preparation of a budget, the difference between precipitation and the net pond recharge is the amount of evapotranspiration. The land surface recharge rate and the precipitation on pond surfaces were applied to their respective areas to calculate the "IN" portion of the ponds water budgets.

Table 4. Water budget for the Indian Ponds.

			IN		OUT			Storage
	PALS #	Area	Groundwater	Precipitation	Groundwater	Evaporation	Stream	Volume
		acres	m3/y	m3/y	m3/y	m3/y	m3/y	m3
Mystic	BA-584	148.4	2,872,364	671,182	3,113,379	430,167	0	3,439,736
Middle	BA-640	104.6	3,685,760	473,173	3,772,780	303,261	82,892	2,163,671
Hamblin	BA-668	115.4	3,710,864	521,866	3,898,261	334,469	0	3,892,004
							max	

			IN		OUT		
	PALS #	Area	Groundwater	Precipitation	Groundwater	Evaporation	Stream
		acres	%	%	%	%	%
Mystic	BA-584	148.4	81%	19%	88%	12%	0
Middle	BA-640	104.6	89%	11%	91%	7%	2%
Hamblin	BA-668	115.4	88%	12%	92%	8%	0

note: PALS# is unique identifier developed for each pond on Cape Cod by the Cape Cod Commission under the Pond and Lake Stewardship (PALS) program

Groundwater is the primary component of the "OUT" portion of the water budget; it is approximately 90% of the flow out of each of the ponds. The "OUT" portion of the water budget is determined by reviewing the "IN" portion of the budget and adjusting with collected and available data. As stated above, average annual recharge on pond surfaces has been estimated by the USGS as 15.8 inches; the difference between precipitation and recharge on these surfaces is 28.2 inches per year. This value was assigned to calculate the evapotranspiration off the pond surfaces. As mentioned previously, the streamflow out of

Middle Pond is some portion of the downgradient flow out of the pond and into the Marstons Mills River watershed. The estimated flow through the stream is included in Table 4 as 82,892 m3/yr; this flow is based on the annualized flow of 0.06 mgd, which is discussed above.

Additional description and details of field measurements is contained in the Commission's Water Budget Report (Michaud, *et al.*, 2005).

4. Pond Water Quality

The other major component of this First Order Assessment of the Indian Ponds is a review of water quality in the ponds; this data was coordinated and informed by the preceding water watershed and water budget estimates. In order to begin to characterize the water quality in the system, project staff in coordination with town staff and IPA volunteers developed a sampling plan, ensured adequate volunteer training, reviewed field sampling results as they became available, ensured that proper chain-of-custody procedures were followed for the samples, and reviewed laboratory results. Laboratory and field data results are discussed in this section.

A. Water Quality Sampling Plan

Project staff developed a sampling plan in coordination with the Town of Barnstable and IPA volunteers. Samples to be analyzed in laboratory tests were collected at the following depths in each of the ponds: Mystic (0.5 m, 3 m, 9 m, and one meter off the bottom), Middle (0.5 m, 3 m, and one meter off the bottom), and Hamblin (0.5 m, 3 m, 9 m, and one meter off the bottom). These sampling depths are the same as utilized in the annual Cape Cod Pond and Lake Stewardship (PALS) snapshots, so snapshot results could easily be compared to results from the samples collected during this project. The sampling plan led to water quality sampling on the following dates in 2004: May 19/20, June 9, June 24, July 8, July 22, August 5, August 24, September 7, September 21, and November 2. Samples were collected with Niskin samplers and stored in dark brown acid-washed Nalgene bottles, which were transported in coolers with ice packs. Samples were delivered on the same day as they were collected to the School of Marine Science and Technology (SMAST) water quality lab at the University of Massachusetts, Dartmouth in New Bedford. Laboratory procedures are described in the SMAST Coastal Systems Analytical Facility Laboratory Quality Assurance Plan (2003).

Aside from the samples to be delivered to the SMAST lab, volunteers also collected field readings. These readings were recorded on field sheets; an example is included in Appendix B. Readings included a measurement of Secchi depth and dissolved oxygen and temperature profiles with readings recorded at every meter. Dissolved oxygen and temperature readings were recorded using YSI-55 meters calibrated prior to each sampling event. Laboratory and field data collected, along with detection limits, measurement ranges, and accuracy measurements, are shown in Table 5.

Table 5. Field and laboratory reporting units and detection limits for data collected for the Indian Ponds assessment

Parameter	Matrix	Reporting Units	Detection Limit	Accuracy (+\-)	Measurement Range
Field Measurements					
Temperature	Water	ºC	0.5°C	± 0.3 ºC	-5 to 45
Dissolved Oxygen	Water	mg/l	0.5 ppm	± 0.3 mg/l or ± 2% of reading, whichever is greater	0 – 20 mg/l
Secchi Disk Water Clarity	Water	meters	NA	20 cm	Disappearance
Laboratory Measurements - SMAST					
Alkalinity	Water	mg/l as $CaCO_3$	0.5	80-120% Std. Value	NA
Chlorophyll-*a*	Water	µg/l	0.05	80-120% Std. Value	0-145
Nitrogen, Total	Water	µM	0.05	80-120% Std. Value	NA
pH	Water	Standard Units	NA	80-120% Std. Value	0 - 14
Phosphorus, Total	Water	µM	0.1	80-120% Std. Value	NA

Note: All laboratory measurement information from SMAST Coastal Systems Analytical Facility Laboratory Quality Assurance Plan (January, 2003)

Additional water quality sampling including only the upper portions of the water column was completed in 2005. These results are generally not included or considered in this assessment. Sampling dates during 2005 were: June 28, July 13, July 27, August 11, August 25, September 13, September 27, and October 27 (Mystic Lake only).

B. Field Collected Water Quality Data

i. Dissolved Oxygen and Temperature

Pond and lake ecosystems are controlled by interactions among the physical, chemical, and biological factors within a given lake. The availability of oxygen determines distributions of various species living within a lake; some require higher concentrations, while others are more tolerant of occasional low oxygen concentrations. Oxygen concentrations also determine the solubility of many inorganic elements; higher concentrations of phosphorus, nitrogen, and iron, among other constituents, can occur in the deeper portions of ponds when anoxic conditions convert bound, solid forms in the sediments into soluble forms that are then released into the water column. Temperature is inversely related to dissolved oxygen concentrations (*i.e.*, higher temperature water holds less dissolved oxygen).

Oxygen concentrations are also related to the amount of biological activity in a pond. Since one of the main byproducts of photosynthesis is oxygen, a vigorous algal population can produce DO concentrations that are greater than the concentrations that would be expected based simply on temperature interactions alone. These instances of "supersaturation" usually occur in lakes with high nutrient concentrations, since the algal population would need readily available nutrients in order to produce these conditions. Conversely, as the algal populations die, they fall to the sediments where bacterial populations consume oxygen as they degrade the dead algae. Too much algal growth can thus lead to anoxic conditions and the release of recycled nutrients back into the pond from the sediments.

Shallow Cape Cod ponds [less than 9 meters (29.5 ft) deep] tend to have well mixed water columns because ordinary winds blowing across the Cape have sufficient energy to move deeper waters up to the surface. In these ponds, both temperature and dissolved oxygen readings tend to be constant from surface to bottom; Middle Pond profiles tend to have this characteristic (Figure 10). In deeper ponds on Cape Cod, mixing tends to occur throughout the winter, but rising temperatures in the spring heat upper waters more rapidly than winds can mix the heat throughout the water column. This leads to stratification of the water column with warmer waters continuing to be mixed and warmed throughout the summer and isolating cooler, deeper waters. The upper layer of warmer water is called the epilimnion, while the lower layer is called the hypolimnion; the transitional zone between them is called the metalimnion. Mystic Lake and Hamblin Pond profiles show stratification of temperature and dissolved oxygen (see Figure 10).

Since the lower layer in a stratified pond is cut off from the atmosphere by the epilimnion, there is no mechanism to replenish oxygen consumed by bacterial populations in the sediments as they consume organic matter falling onto the sediments. If there is extensive organic matter falling to the sediments, as one would expect with lakes with higher amounts of nutrients (*i.e.*, eutrophied lakes), the bacterial respiration can consume all of the oxygen before the lake mixes throughout the water column again in the fall. Highly eutrophied lakes can have low oxygen or anoxic conditions set up shortly after stratification occurs (*e.g.*, Eichner, *et al.*, 1999). The earliest profile collected on May 20, 2004 for Hamblin Pond shows low oxygen and anoxic conditions deep in the pond (see Figure 10); the conditions rise toward the bottom of the epilimnion as the summer progresses.

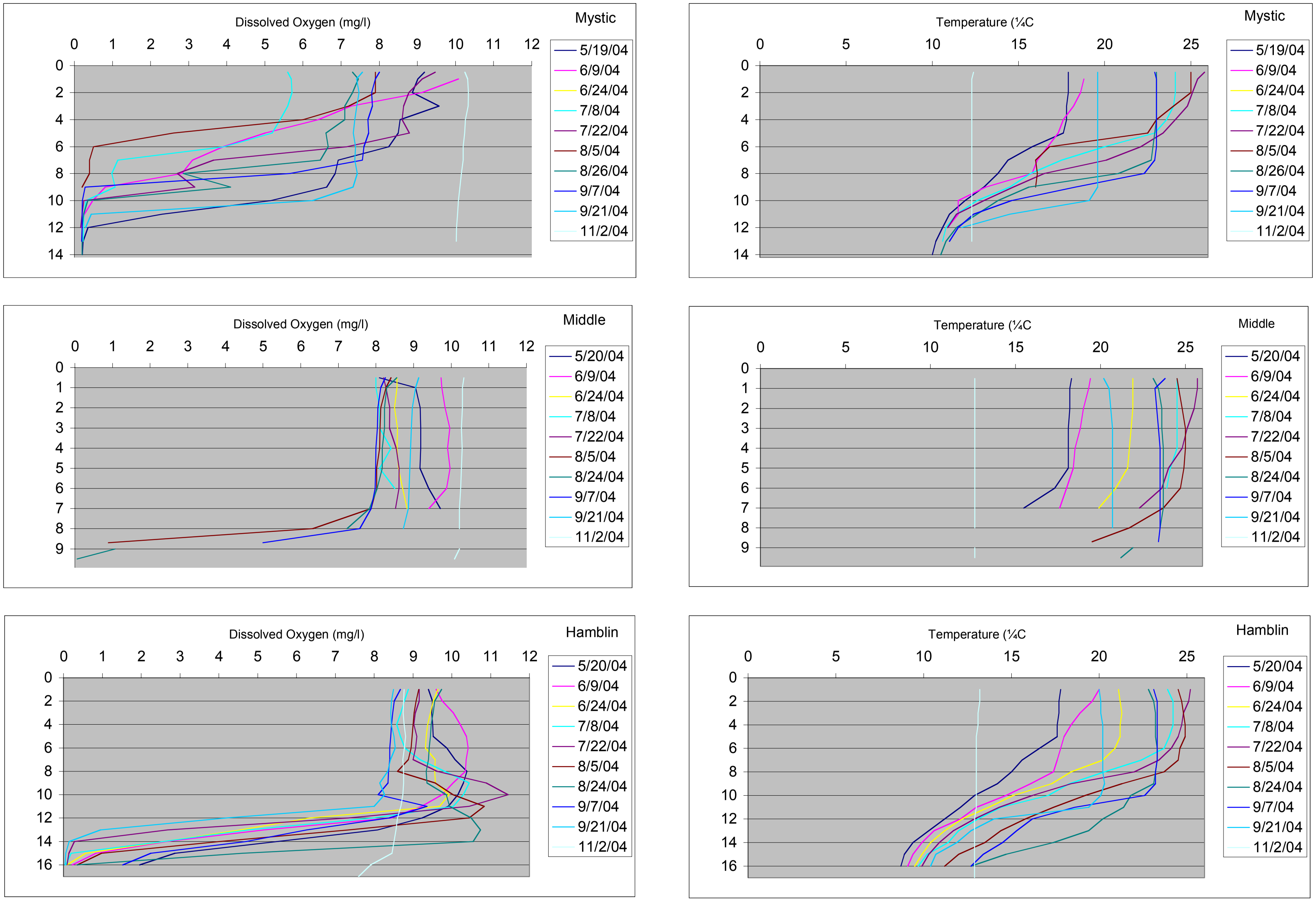


Figure 10. 2004 dissolved oxygen and temperature profiles for Mystic Lake, Middle Pond, and Hamblin Pond.

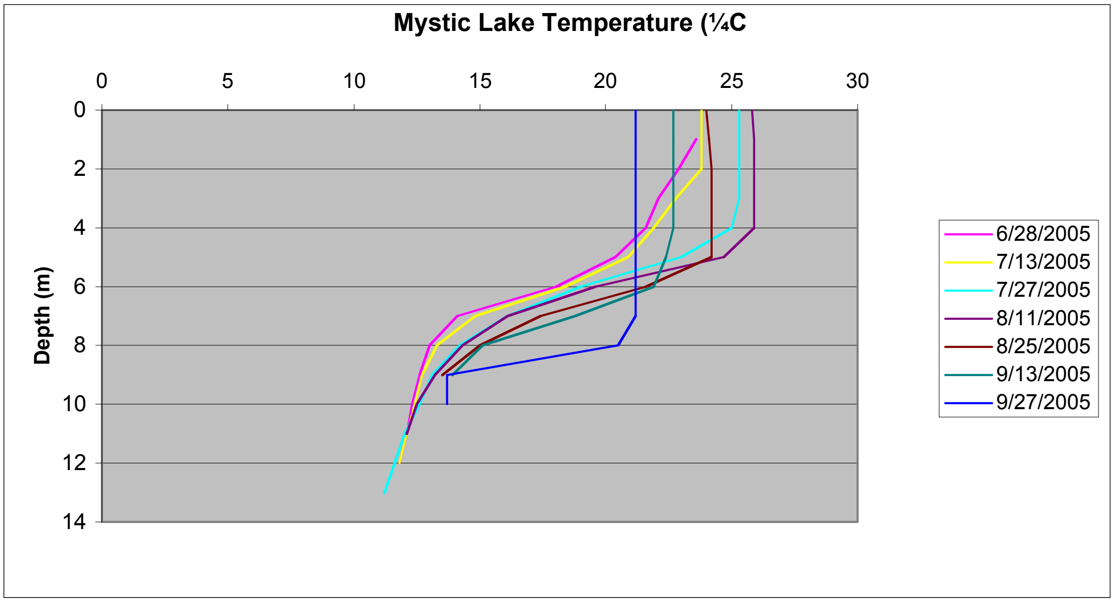
The dissolved oxygen profiles of Hamblin Pond also show what is called a positive heterograde curve with higher concentrations of dissolved oxygen measured near the metalimnion than in the waters above this zone. This metalimnion maximum is usually the result of a high concentration of phytoplankton utilizing light collected in shallower waters and phosphorus seeping from the hypolimnion (Wetzel, 1983).

Since dissolved oxygen and temperature profiles were not collected before the onset of low oxygen conditions in the hypolimnetic waters of Hamblin Pond, a definitive loss of oxygen to sediment demand cannot be determined. However, a reasonable estimate of oxygen demand by the sediments can be made. Staff assumed a March dissolved oxygen concentration of 11 ppm; this is the saturation concentration at 11ºC (temperatures in the November profile were around 13ºC). Based on this assumption, sediment oxygen demand in the hypolimnion ranges between 2,763 and 7,773 kg based on the profiles collected. If these demands are spread over the area of the hypolimnetic sediments (52 ac), which is assumed to be the area below 9 m, the daily oxygen demand varies between 84 and 325 mg/m2 with an average of 219 mg/m2. Similar values are seen in the 2005 data collected by IPA. Baystate Environmental Consultants (1993) estimated a daily sediment oxygen demand based on hypolimnetic concentrations of 860 mg/m2 prior to the alum treatment. This comparison suggests that the alum treatment of Hamblin Pond in 1995 reduced the sediment oxygen demand by approximately 75%

The impact of the oxygen demand in Hamblin Pond can be observed by comparing the November 2004 dissolved oxygen profiles in the three ponds (see Figure 10). Temperature profiles show that temperatures in the three ponds are generally the same and that all three ponds are well mixed, with similar temperatures from top to bottom. Given this, the dissolved oxygen concentrations should also be the same, but Hamblin Pond is approximately 1.5 ppm less than the other two. This difference is likely due to residual oxygen demand in the hypolimnetic waters that was mixed, probably within weeks of the November measurement, into the rest of the water column.

Temperature and dissolved oxygen profiles for Middle Pond show that the pond water column is generally well mixed with occasional slight isolation of waters below 7 m (see Figure 10). For example, the temperature profile from August 5 shows a drop of approximately 5ºC between 6 and 8.5 m; this "bend" in the profile is gone by the next profile measurement on August 24 and the temperature is relatively uniform from top to bottom. The transitory nature of the deep temperature isolation indicates that it is relatively weak and the pond can be fully mixed by normal winds in the area. These isolations may, however, have measurable impact on the amount of phosphorus in the water column. The low dissolved oxygen readings appear to allow phosphorus to be released from the sediments and mixed into the water column; further discussion of this is included in following sections.

The temperature profiles for Mystic Lake are similar to those for Hamblin Pond with a gradual deepening and warming of the epilimnion as the summer progressed (see Figure 10). The dissolved oxygen profiles, however, show a significant amount of variability from reading date to reading date. During the course of the summer, project staff requested clarification of volunteer calibration and sampling activities. Results of this type suggest that the system is notably unstable. Dissolved oxygen profiles collected during 2005 do not show this variability (Figure 11) and suggest that select profiles in the 2004 season should be disregarded.



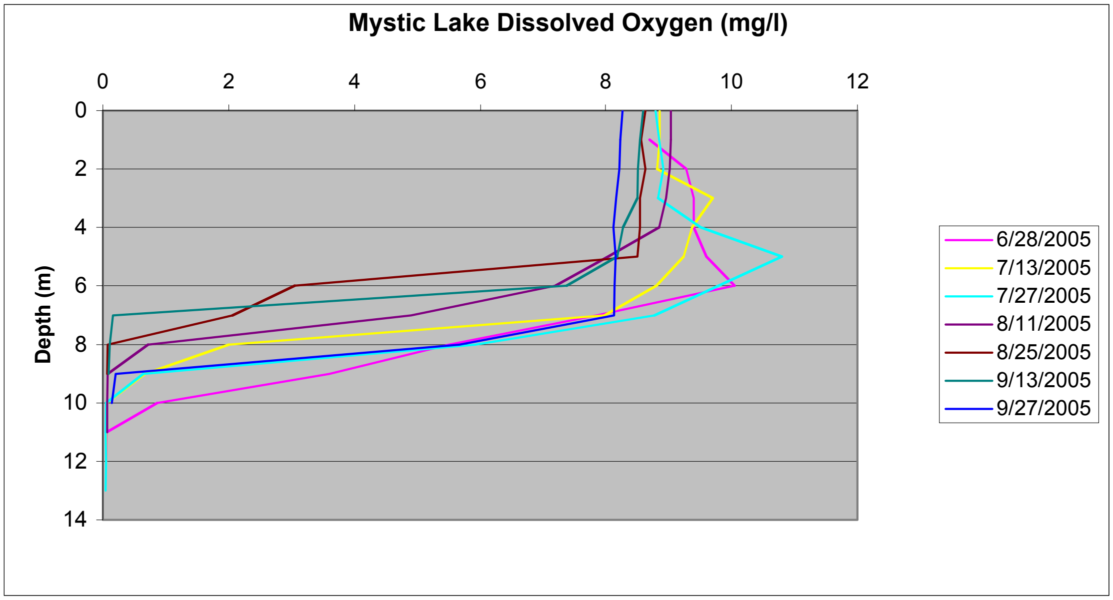


Figure 11. Mystic Lake 2005 Dissolved Oxygen and Temperature Profiles.
Data collected by IPA volunteers using a YSI-55 meter.

Using the 2005 data, Mystic Lake dissolved oxygen and temperature profiles can be used to estimate sediment oxygen demand using the same assumptions used for Hamblin Pond. Staff assumed a March dissolved oxygen concentration of 11 ppm. Based on this assumption, sediment oxygen demand ranges between 6,133 and 9,840 kg based on the profiles collected. If these demands are spread over the area of the hypolimnetic sediments (38 ac), which is assumed to be the area below 9 m, the daily oxygen demand varies between 230 and 424 mg/m2 with an average of 358 mg/m2. This average is 139 mg/m2/d higher than the 2004 average for Hamblin Pond; Hamblin Pond had a 219 mg/m2/d average in 2005 and a 182 mg/m2/d average in 2004. As mentioned previously, BEC (1993) estimated a hypolimnetic oxygen demand of 860 mg/m2/d in Hamlin Pond prior to the alum treatment; Mystic Lake hypolimnetic oxygen demand is roughly half of the pre-alum treatment Hamblin Pond.

ii. Secchi Depth

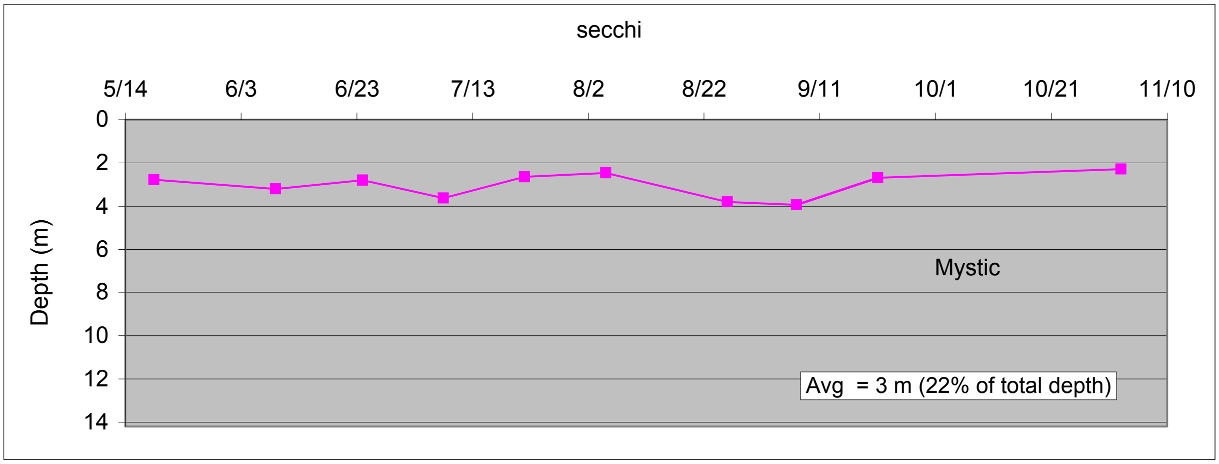
A Secchi disc is used to evaluate transparency, or light penetration, of water. Since fluctuations in Secchi depths are linked to fluctuations in concentrations of plankton or inorganic particles, a Secchi reading is an aggregate general measure of ecosystem condition. Because of this, Secchi readings have been linked through a variety of analyses to trophic status of lakes (*e.g.*, Carlson, 1977). Secchi depth is also related to the overall depth of a pond; if the pond is relatively shallow, the disk may be visible on the bottom even with significant algal densities. Relative Secchi readings compared to total depth of the sampling location have also been used to assess the condition of a pond ecosystem.

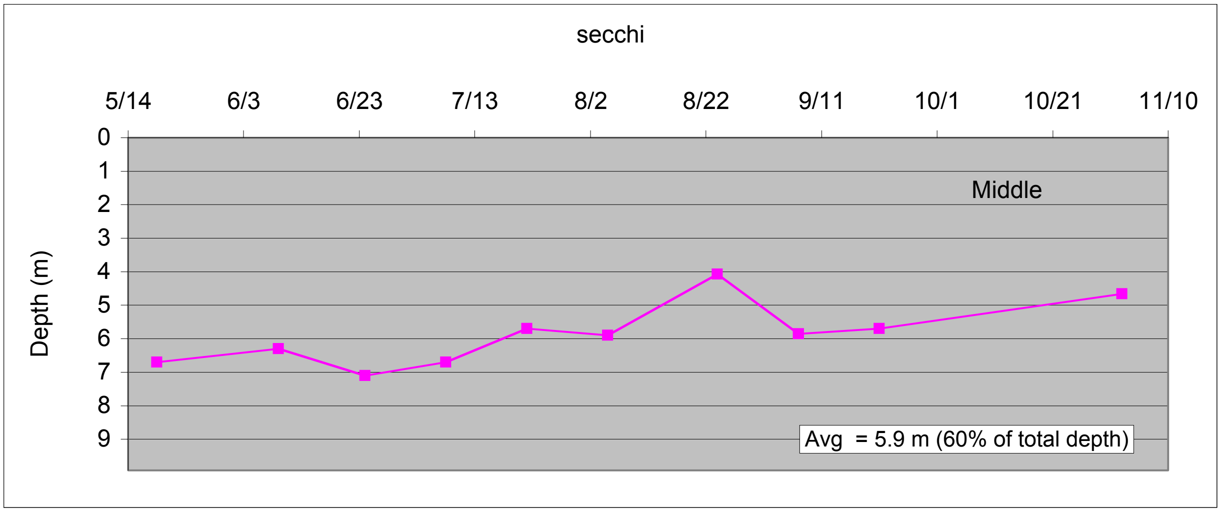
Secchi readings collected for Mystic Lake, Middle Pond, and Hamblin Pond during the 2004 sampling season are relatively stable, although readings from Middle Pond show a bit of an upward trend (Figure 12). Hamblin Pond has the deepest average (6.4 meters), while Middle Pond has the deepest relative average (60% of its total depth). Mystic Lake presents as the most impacted with an average Secchi depth of 3 meters and a relative average of 22% of its total depth. These readings are consistent with a qualitative assessment of the observed dissolved oxygen concentrations.

iii. Historic Field Measurements

Field measurements of Cape Cod ponds have not been extensively collected, but there are a select number of measurements that provide some historical context for readings in the Indian Ponds. A 1948 Massachusetts Division of Fisheries and Game (MADFG) survey of fifty-one Cape Cod lakes and ponds has transparency, dissolved oxygen, and temperature readings. Ahrens and Siver (2000) conducted a survey of sixty Cape Cod lakes and ponds. Hamblin Pond was the focus of a diagnostic feasibility study conducted prior to its 1995 alum application (BEC, 1993). Temperature and dissolved oxygen profiles and Secchi readings are part of the standard sampling protocol for the Cape Cod PALS snapshots that have been annually conducted between 2001 and 2005.

The 1948 MADFG survey includes dissolved oxygen and temperature profiles collected in August for the Indian Ponds (Figure 13). Because the 1948 data is only one profile, comparisons to data collected under this project and the relatively recent PALS data have to be somewhat tentative, but the comparisons present some notable differences. Comparison of the 1948 readings to the PALS readings and August 2004 readings collected under this project (and 2005 for Mystic Lake) show that Mystic Lake appears to have worsened with low dissolved





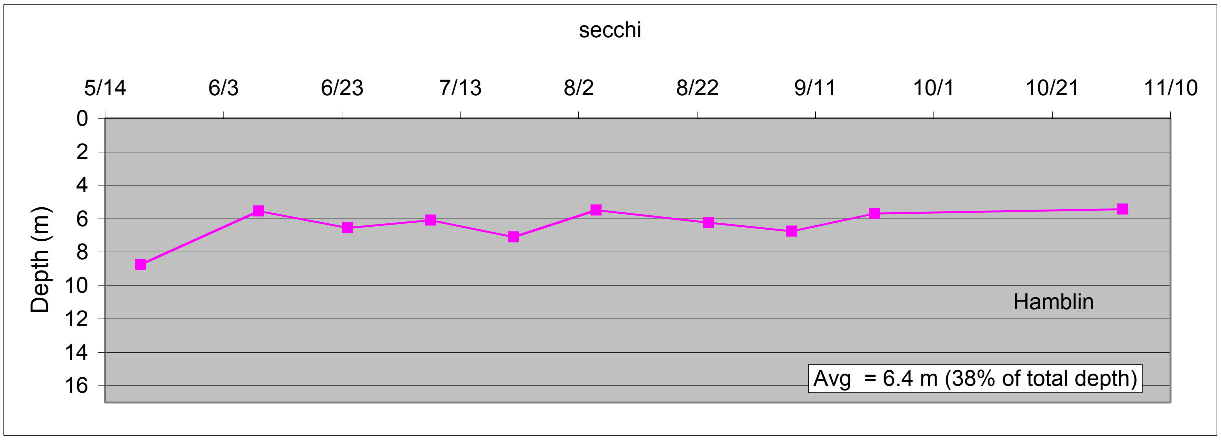


Figure 12. 2004 Secchi Depth readings for Mystic Lake, Middle Pond, and Hamblin Pond

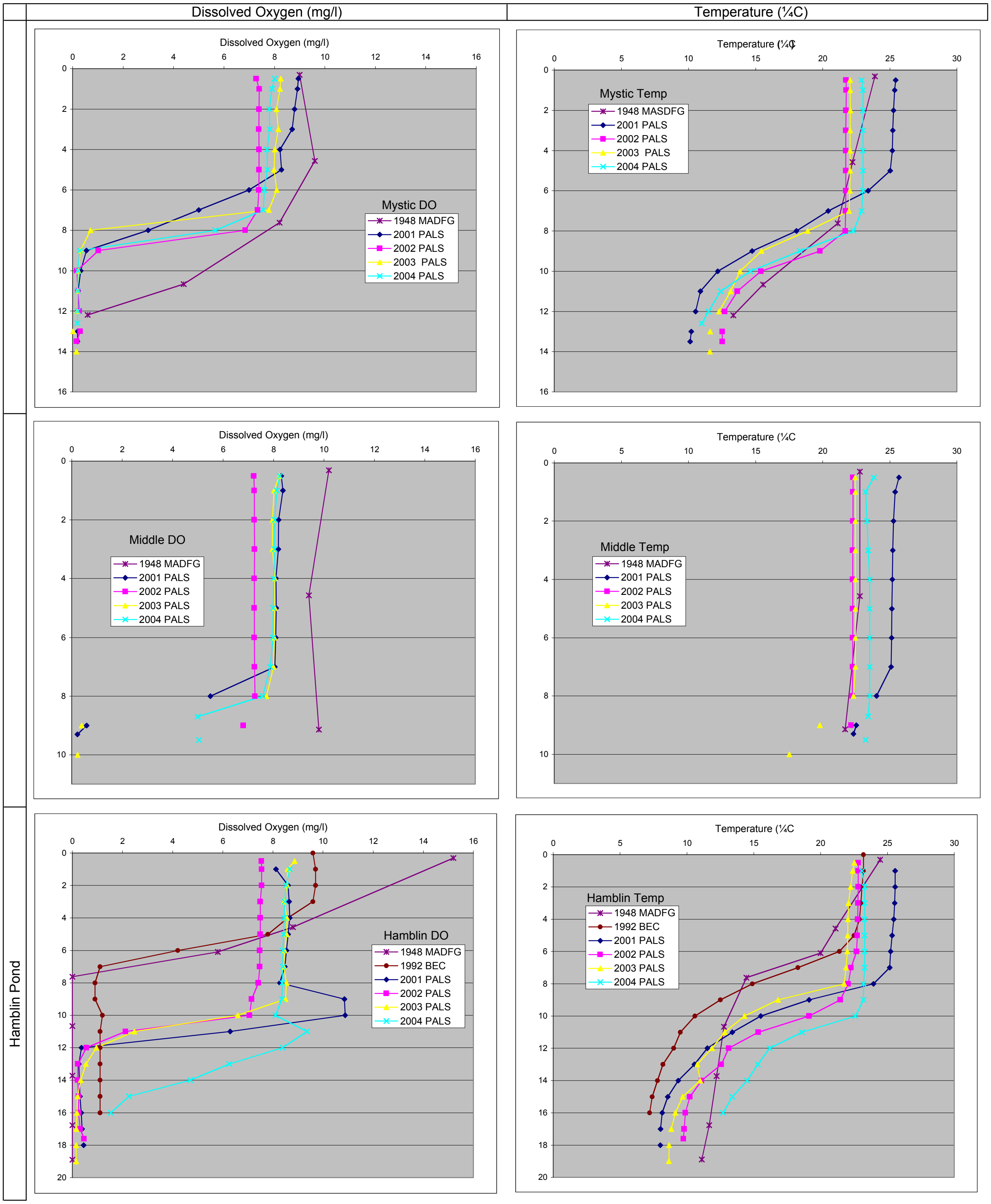


Figure 13. Historic Temperature and Dissolved Oxygen profiles for Indian Ponds.
1948 profile from August reading by MA Division of Fisheries and Game; 2001-2004 profiles from August 15 through September 30 Cape Cod Pond and Lakes Stewardship (PALS) Snapshot.

oxygen readings rising higher in the water column than in 1948 (anoxic conditions were encountered only at 12 m, while they are as shallow as 7 m in 2005) and Hamblin Pond has much improved deep dissolved oxygen concentrations (anoxic conditions existed at 8 m in 1948, while they rose only to 13 m in 2004). Secchi readings show similar effects: Mystic in 1948 was 15 ft (4.57 m), which has declined to 3.5 to 3.8 in readings collected for this study and PALS Snapshots; Hamblin in 1948 was 3 ft (0.91 m) and has improved to 4.2 to 8.1 m in readings collected for this study and PALS Snapshots. Although Middle Pond does not show any significant changes in dissolved oxygen concentrations, comparison of August Secchi readings seem to show some decline; Middle had a reading of 22 ft (6.71 m) in 1948, while readings collected for this study and PALS Snapshots are between 4.1 and 5.9 m.

C. Laboratory Water Quality Data

As mentioned above, unfiltered water samples were collected in the ponds at depths specified under the sampling plan. These depths match the protocols developed for the PALS Snapshot, so comparisons between previous data collected under the Snapshot and data collected as part of this analysis are facilitated. Water samples were analyzed at the SMAST Coastal Systems Analytical Facility Laboratory at UMASS, Dartmouth for the following constituents: pH, total nitrogen (TN), total phosphorus (TP), alkalinity, and chlorophyll *a* (Figure 14).

i. Total Phosphorus (TP)

Phosphorus is the key nutrient in ponds and lakes because it is usually more limited in freshwater systems than nitrogen. Typical plant organic matter contains phosphorous, nitrogen, and carbon in a ratio of 1 P:7 N:40 C per 500 wet weight (Wetzel, 1983). Therefore, if the other constituents are present in excess, phosphorus, as the limiting nutrient, can theoretically produce 500 times its weight in algae. Because it is more limited, 90% or more of the phosphorus occurs in organic forms (plant and animal tissue or plant and animal wastes) and any available inorganic phosphorus [mostly orthophosphate (PO_4^{-3})] is quickly reused by the biota in a lake (Wetzel, 1983). Extensive research has been directed towards trying to determine the most important phosphorus pool for determining the overall productivity of lake ecosystems, but to date, most of the work has found that a measure of total phosphorus is the best predictor of productivity of lake ecosystems (*e.g.*, Vollenweider, 1968). The laboratory analysis techniques for total phosphorus (TP) include ortho-phosphorus and all phosphorus incorporated into organic matter, including algae.

Most Cape Cod lakes have low phosphorus concentrations due to the lack of phosphorus in the surrounding glacially-derived sands. The median surface concentration of TP in 175 Cape Cod ponds sampled during the 2001 Pond and Lake Stewards (PALS) Snapshot is 16 ppb (or µg/l) (Eichner, *et al*., 2003). A more limited sampling of 60 Cape Cod lakes in 1997 and 1998 found a mean TP concentration in surface waters of 14 ppb (Ahrens and Siver, 2000). Using the US Environmental Protection Agency (2000) method for determining a nutrient criteria and the 2001 PALS Snapshot data, the Cape Cod Commission determined that unimpacted ponds on Cape Cod should have a surface TP concentration no higher than 10 ppb).

Mystic Lake has higher TP concentrations at depth, as would be expected due to the anoxic conditions of the sediments. The upper two sampling stations (0.5 and 3 m) are relatively

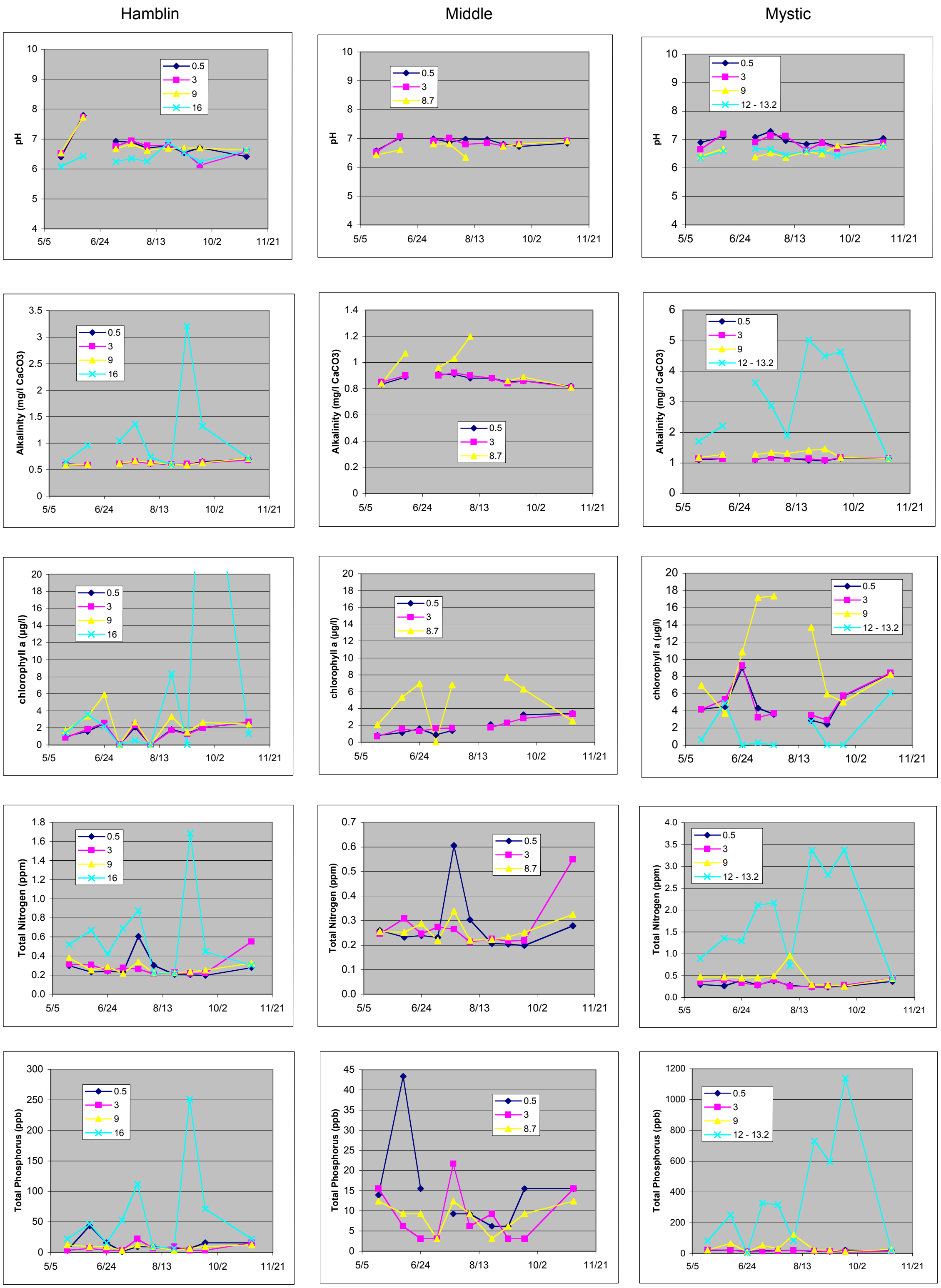


Figure 14. 2004 Laboratory water quality data for Indian Ponds for total phosphorus, total nitrogen, chlorophyll *a*, alkalinity, and pH.

constant and combined have an overall average over the sampling period of 15.9 ppb (Table 6). This is slightly higher than the 12 ppb average of the Mystic Lake PALS Snapshot data from 2001 through 2004 (Figure 15); this is one indication of how more refined data collection can give a better understanding of how conditions develop and fluctuate in a pond. The next deepest (9 m) station has an average concentration in this study of 38 ppb and the deepest station (12-13.2 m) has an average concentration of 355 ppb. Based on bathymetric information and examination of each sampling date, the average amount of TP in Mystic Lake water is 158 kg with a range of 35 to 375 kg.

Hamblin Pond also has higher TP concentrations at depth due to anoxic conditions in the sediments (see Figure 14). The upper concentrations, however, are lower than Mystic Lake with an average TP concentration across the upper three station depths (0.5, 3, and 9 m) of 9.8 ppb (Hamblin Pond PALS data from 2001 through 2004 results in an average of 5.1 ppb). At the deepest station (16 m), the average concentration in this study's data is 61 ppb (see Table 6). Based on bathymetric information and examination of each sampling date, the average amount of TP in Hamblin Pond is 91 kg with a range of 24 to 281 kg.

Table 6. Average Water Quality Concentrations in 2004 in Indian Ponds

	Mystic Lake			Hamblin Pond		Middle Pond	Cape Cod Surface Thresholds[1]	
Depth/ Constituent	0.5 and 3 m	9 m	12-13.2 m	0.5, 3, and 9 m	16 m	0.5, 3, and 8.7 m	All ponds	Unimpacted Ponds
Total Phosphorus (ppb)	15.9	38	355	9.8	61	10.3	10	7.5
Total Nitrogen (ppm)	0.31	0.46	1.85	0.28	0.6	0.27	0.31	0.16
Alkalinity (mg CaCO3/l)	1.1	1.3	3.1	0.6	1.2	0.9		
pH[2]	6.9	6.6	6.6	6.8	6.4	6.8	5.62	5.19
Chlorophyll *a* (µg/l)	5.1	9.9	1.6	2.0	6.6	2.9	1.7	1.0

[1] Thresholds determined based on surface samples collected during the 2001 PALS Snapshot (Eichner, *et al*., 2003); threshold for alkalinity has not been determined

[2] Threshold determination procedures were completed for pH in order to provide some analysis of impacted vs. unimpacted ponds, but the concept of a pH threshold for Cape Cod ponds needs additional analysis.

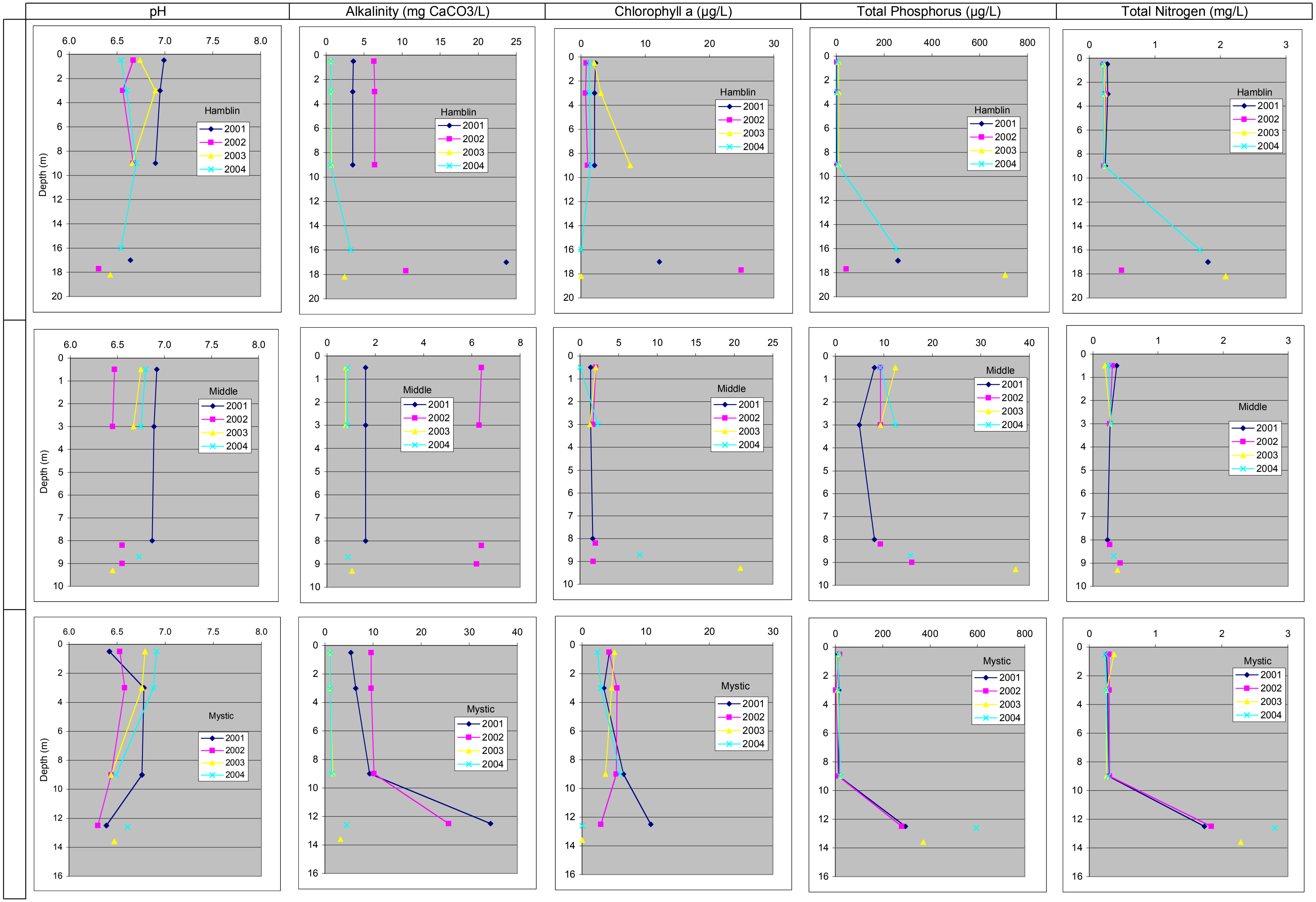


Figure 15. PALS Snapshot Laboratory Data for the Indian Ponds (2001-2004)

Middle Pond does not thermally stratify, so its water column was relatively well mixed throughout the 2004 sampling season and, accordingly, TP concentrations are relatively consistent at all sampling depths (0.5, 3, and 8.7 m) (see Figure 14). The average concentration in Middle Pond is 10.3 ppb, which is essentially the same concentration measured in the upper waters of Hamblin Pond (see Table 6). Middle Pond PALS data from 2001 through 2004 results in an average of 12.4 ppb across all sampling depths (see Figure 15). Based on bathymetric information and examination of each sampling date in this study, the average amount of TP in Middle Pond is 22 kg with a range of 4 to 42 kg.

ii. Total Nitrogen (TN)

Nitrogen is one of the primary nutrients in surface water systems (phosphorus and potassium being the other two). Nitrogen switches between a number of chemical species (nitrate, nitrite, ammonium, nitrogen gas, and organic nitrogen) depending on a number of factors, including dissolved oxygen, pH, and biological uptake (Stumm and Morgan, 1981). Nitrate-nitrogen is the fully oxidized form of nitrogen, while ammonium-nitrogen is the fully reduced (*i.e.*, low oxygen) form. Inorganic nitrogen generally enters ponds in the nitrate-nitrogen form, is incorporated into algae-forming organic nitrogen, and then is converted back to inorganic forms (nitrate- and ammonium-nitrogen) in the waste from algae or organisms higher up the food chain or by bacteria decomposing dead algae in the sediments. Total Kjeldahl nitrogen (TKN) is a measure of organic nitrogen and ammonium forms. Total nitrogen (TN) is generally reported as the addition of TKN and nitrate-nitrogen concentrations.

Nitrogen is not usually the nutrient that limits growth in ponds, but ecosystem changes during the course of a year or excessive phosphorus loads can create conditions where it is the limiting nutrient. In very productive or eutrophic lakes, algae that can extract nitrogen directly from the atmosphere, which is approximately 75% nitrogen gas, often have a strong competitive advantage and tend to dominate the pond ecosystem. These blue-green algae, more technically known as cyanophytes, are generally indicators of excessive nutrient loads.

Nitrogen is a primary pollutant associated with wastewater. Septic systems, the predominant wastewater treatment technology on Cape Cod, generally introduce treated effluent to the groundwater with concentrations between 20 and 40 ppm: Massachusetts Estuaries Project watershed nitrogen loading analyses use 26.25 ppm as an effective TN concentration for septic system wastewater (*e.g.*, Howes, *et al*., 2004). As such, Cape Cod ponds and lakes tend to have relatively high concentrations of nitrogen; the 184 ponds sampled during the 2001 PALS Snapshot had an average surface water TN concentration of 0.58 ppm. Review of these sampling results established that unimpacted ponds have an average concentration of 0.16 ppm (Eichner, *et al*., 2003).

Mystic Lake has higher TN concentrations at depth, as would be expected due to the anoxic conditions of the sediments (see Figure 14). The upper two sampling stations (0.5 and 3 m) are relatively constant and combined have an overall average over the sampling period of 0.31 ppm (see Table 6). The next deepest (9 m) station has an average concentration of 0.46 ppm and the deepest station (12-13.2 m) has an average concentration of 1.85 ppm.

Hamblin Pond also has higher TN concentrations at depth due to anoxic conditions in the sediments (see Figure 14). The upper concentrations, however, are lower than Mystic Lake with an average TN concentration across the upper three station depths (0.5, 3, and 9 m) of 0.28 ppm. At the deepest station (16 m), the average concentration is 0.60 ppm.

Middle Pond does not thermally stratify, so its water column was relatively well mixed throughout the 2004 sampling season and, accordingly, TN concentrations are relatively consistent at all sampling depths (0.5, 3, and 8.7 m) (see Figure 14). The average concentration in Middle Pond is 0.27 ppm, which is essentially the same concentration measured in the upper waters of Hamblin Pond.

iii. Alkalinity and pH

pH is a measure of acidity; pH values less than 7 are considered acidic, while pH values greater than 7 are considered basic. pH is the negative log of the hydrogen ion concentration in water (*e.g.*, water with a H^+ concentration = $10^{-6.5}$ has a pH of 6.5). pH is determined by the interaction of all of the ions with carbon species, like carbon dioxide, carbonate, and bicarbonate, having the most direct effect (Stumm and Morgan, 1981). The pH of rainwater, in equilibrium with carbon dioxide in the atmosphere, is 5.65. Photosynthesis takes carbon dioxide and hydrogen ions out of the water causing pH to increase, so more productive lakes will tend to have higher pH measurements. Alkalinity is a measure of the compounds that shift pH toward more basic values, is mostly determined by the concentrations of bicarbonate, carbonates, and hydroxides, and is a measure of the capacity of waters to buffer acidic inputs. Consequently, pH and alkalinity are linked values.

Since the sand deposited as Cape Cod during the last glacial period does not have carbonate minerals, Cape soils have low alkalinity and little capacity to buffer the naturally acidic rainwater that falls on the Cape. Available groundwater data generally shows pH on Cape Cod between 6 and 6.5; Frimpter and Gay (1979) sampled groundwater from 202 wells on Cape Cod and found a median pH of 6.1. The average surface pH of 193 ponds sampled in the 2001 PALS Snapshot is 6.16 with a range of 4.38 to 8.92, while the average alkalinity is 7.21 mg/L as $CaCO_3$ with a range of 0 to 92.1 (Eichner, *et al*., 2003).

The three ponds all show relatively high pHs compared to most Cape Cod ponds (see Figure 14); Hamblin Pond has an average pH of 6.7, Middle Pond is 6.8, and Mystic is 6.8. Readings tend to drop slightly in all three ponds with increasing depth, likely due to the lower photosynthetic activity.

Average alkalinity in shallow waters of Mystic and Middle are similar (1.1 mg/L as $CaCO_3$ in Mystic and 0.9 mg/L as $CaCO_3$ in Middle), while Hamblin has a slightly lower average concentration (0.6 mg/L as $CaCO_3$) (see Table 6). Hamblin and Mystic have increased average concentrations at the deepest sampling locations (1.2 mg/L as $CaCO_3$ in Hamblin and 3.1 mg/L as $CaCO_3$ in Mystic). These increases are consistent with the anoxic conditions measured; lack of oxygen causes a number of elements to convert from insoluble to soluble forms and many of these soluble forms will increase buffering capacity (Stumm and Morgan, 1981).

iv. Chlorophyll *a* (CHL-a)

Chlorophyll is the primary photosynthetic pigment in plants, both algae and macrophytes (*i.e.*, any aquatic plants larger than microscopic algae, including rooted aquatic plants). Because of its prevalence, measurement of chlorophyll can be used to estimate how much algae is present in collected water samples. Chlorophyll *a* (CHL-a) is a specific pigment in the chlorophyll family and plays a primary role in photosynthesis (USEPA, 2000).

During the 2001 PALS Snapshot sampling, 191 ponds had surface CHL-a samples. The average of concentration of these samples is 8.44 µg/l with a range from 0.01 to 102.9 µg/l. Ahrens and Siver (2000) survey of sixty Cape Cod lakes and ponds found the mean CHL-a concentration to be 3.07 µg/l with a range of 0.51 to 19.25 µg/l. Review of the PALS 2001 sampling results established that unimpacted ponds have an average CHL-a concentration of 1.0 µg/l (Eichner, *et al*., 2003).

Hamblin and Middle Ponds have similar CHL-a profiles (see Figure 14). Both have average surface concentrations in the 1.7-1.9 µg/l range with higher concentrations deeper in the ponds; Hamblin's 16 m station has an average CHL-a concentration of 8.5 µg/l, while Middle's 8.5 m station has an average of 5.4 µg/l (see Table 6). While Hamblin concentrations do not have significant trends over the course of the sampling season, Middle Pond shallow water concentrations significantly increase ($R^2 = 0.87$ at the 0.5 m station and $R^2 = 0.89$ at the 3 m station).

Mystic Lake has a much higher average shallow CHL-a concentration than the other two ponds (5 µg/l at 0.5 m station and 5.2 µg/l at the 3 m station)(see Figure 13). These concentrations are similar to the concentration observed at the deepest sampling station in Middle Pond. The 9 m sampling station in Mystic Lake has an average concentration of 9.9 µg/l, while the deepest station (12-13.2 m) has an average concentration of 1.6 µg/l.

5. Overall Assessment: Ecosystem Status and Phosphorus Budget

A. Ecosystem Status Factors

Assessing the ecosystem status of a lake or pond usually starts from trying to develop an understanding what the system would be like if it did not have the impacts of watershed and surrounding land uses. This understanding usually has to be developed by looking at similar, unimpacted ponds and historic water quality measurements. On Cape Cod, developing this understanding is hindered a bit more than in other portions of the country since the Cape's geology and climatic environment are relatively unique.

Carlson (1977) developed a trophic status index based on water quality monitoring available at the time, mostly for ponds in Wisconsin and Minnesota. The trophic state of a pond is the total amount of living biological material (*i.e.*, biomass) in the ecosystem and Carlson's index uses various measures to provide a single index number that places ponds in various trophic categories (Table 7). Carlson designed the system to utilize one or another of the measures to classify the trophic state index (TSI) of a pond or lake on a scale of 0 to 100 (Carlson and Simpson, 1996). Although the Carlson indices were developed for use in northern temperate lakes and do not work well in lakes where macrophytes (i.e., rooted aquatic plants) dominate the ecosystem, use of this index provides a common touchstone for comparing the Indian Ponds.

During the course of preparing the Cape Cod Pond and Lake Atlas (Eichner, *et al*., 2003), 2001 PALS Snapshot data was reviewed using a USEPA method for developing nutrient limits (USEPA, 2000). The USEPA method has two approaches for setting a nutrient limit: 1) review all the available data and determine the 25th percentile and 2) look at the data from systems that are "unimpacted" and determine the 75th percentile. When these approaches were applied to the 2001 PALS Snapshot data, the surface water total phosphorus concentrations were 10 and 7.5 µg/l, respectively, while the total nitrogen concentrations were 0.31 and 0.16 ppm, respectively. Chlorophyll *a* concentrations were 1.7 and 1.0 µg/l, respectively. USEPA's determination of these same factors using the 25th percentile approach for all ponds in the ecoregion that includes Cape Cod, which extends from Maine to Georgia, had the following limits: chlorophyll *a*, 2.1 µg/l; TN, 0.32 ppm; and TP, 8 µg/l.

Table 7. – Carlson Trophic State Index (TSI)

TSI Calculations

$\mathrm{TSI(SD)} = 60 - 14.41 \ln(\mathrm{SD})$	SD = Secchi disk depth (meters)
$\mathrm{TSI(CHL)} = 9.81 \ln(\mathrm{CHL}) + 30.6$	CHL = Chlorophyll *a* concentration (µg/l)
$\mathrm{TSI(TP)} = 14.42 \ln(\mathrm{TP}) + 4.15$	TP = Total phosphorus concentration (µg/l)

TSI values and likely pond attributes

TSI Values	Chl a (µg/l)	SD (m)	TP (µg/l)	Attributes	Fisheries & Recreation
<30	<0.95	>8	<6	Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion	Salmonid fisheries dominate
30-40	0.95-2.6	8-4	6-12	Hypolimnia of shallower lakes may become anoxic	Salmonid fisheries in deep lakes only
40-50	2.6-7.3	4-2	12-24	Mesotrophy: Water moderately clear; increasing probability of hypolimnetic anoxia during summer	Hypolimnetic anoxia results in loss of salmonids.
50-60	7.3-20	2-1	24-48	Eutrophy: Anoxic hypolimnia, macrophyte problems possible	Warm-water fisheries only. Bass may dominate.
60-70	20-56	0.5-1	48-96	Blue-green algae dominate, algal scums and macrophyte problems	Nuisance macrophytes, algal scums, and low transparency may discourage swimming and boating.
70-80	56-155	0.25-0.5	96-192	Hypereutrophy: (light limited productivity). Dense algae and macrophytes	
>80	>155	<0.25	192-384	Algal scums, few macrophytes	Rough fish dominate; summer fish kills possible

after Carlson and Simpson (1996);
Note: Carlson TSI developed in algal dominated, northern temperate lakes

B. Phosphorus Budget Development

Biomass in pond and lake ecosystems is usually limited by a key nutrient; if more of the nutrient is available the biomass will increase. In ponds and lakes, the key nutrient is usually phosphorus; rapid introduction of phosphorus usually leads to algal blooms, while more gradual increases can prompt the change in the dominant plant community from one dominated by algae to one dominated by rooted plants. Overall, addition of phosphorus increases the biomass in a lake and excessive phosphorus leads to excessive plant growth the decay of which overwhelms natural regeneration processes and leads to anoxic sediment conditions (Wetzel, 1983). One way to assess whether a lake is limited by phosphorus is to review the balance between phosphorus and nitrogen; as a rule of thumb, if the ratio between nitrogen and phosphorus is greater than 16, phosphorus is the limiting nutrient (Redfield, *et al.*, 1963). Because phosphorus is usually the key nutrient, lake scientists usually develop a phosphorus budget to quantify the primary sources and, if there are water quality problems, to develop targeted strategies to reduce the loads from these sources.

As groundwater flows into Cape Cod ponds along the upgradient shoreline, it brings with it contaminants from the pond watershed, including phosphorus. Phosphorus is chemically more stable in well-oxygenated waters if it is bound with iron (Stumm and Morgan, 1981). Because of this, phosphorus associated with small sources, like septic systems, moves very slowly (~1 m/yr) in groundwater systems, like the Cape, where iron coats sand particles that make up most of our aquifer (*e.g.*, Robertson, *et al.*, 1998). By contrast, a general groundwater flow for Cape Cod is 1 ft/d (or 111 m/yr). Because of this slow movement for phosphorus, most of the sources of phosphorus entering Cape Cod ponds is from properties abutting the pond shoreline; previous analysis of Cape Cod ponds have focused on properties within 300 ft of the shoreline (*e.g.*, Eichner, *et al.*, 1999).

For the Indian Ponds complex, project staff began the development of the watershed portion of the phosphorus budget by looking at properties within 300 ft of the pond shoreline. The list of these properties was then adjusted to assign properties to a given lake only if they were on the upgradient side (Figure 16). Aerial photographs of the properties were reviewed and loads were only assigned to developed properties with houses or other structures within the 300 ft boundary. Properties included in the loading calculations were adjusted, as described below, based on best professional judgment of likely groundwater flow characteristics near the ponds and better balance between observed phosphorus concentrations and those estimated based on the calculated loads. Phosphorus loads were developed based on the factors in Table 8.

Table 8. Watershed Loading Factors for Phosphorus Budget

Factor	Value	Units	Source
Wastewater P load	1	lb P/septic system	MEDEP, 1989
Road surface P load	5.3	lb P/ac	MEDEP, 1989
Natural Areas P conc.	0.014	mg P/l	BEC, 1993
Recharge Rate	27.25	in/yr	Walter and Whealan, 2005
Building Area	Actual value	ft2	Town of Barnstable Assessor Information
Road Area	Actual value	ft2	Mass. Highway Information
Lawn Factors			
Area per residence	5,000	ft2	Eichner and Cambareri, 1992
Fertilizer lawn load	0.3	lb P/ac	MEDEP, 1989
Waterfowl Factors			
P load	0.156	g/m2/yr	Scherer, *et al.*, 1995
New P load	13	%	Scherer, *et al.*, 1995

i. Mystic Lake

Mystic Lake is an impacted pond with water quality problems. The lake thermally stratifies during the summer and the deeper waters are cut off from direct interaction with the atmosphere (see Figure 10). Oxygen in these deep waters is consumed by sediment oxygen demand relatively soon after stratification; these anoxic conditions were measured at the earliest readings collected during this study (May 19, 2004). The anoxic conditions indicate that more organic material is present in and falling to the sediments than can be digested (or broken down) by its bacterial population. Average hypolimnetic sediment oxygen demand is estimated at 358 mg/m2/d. These anoxic conditions create chemical conditions that cause nutrients that would otherwise be bound in the sediments to be released back into the overlying water column. Deep TN and TP concentrations increase relatively linearly throughout the summer (0.02 ppm TN per day and 7 ppb TP per day).

These increases are also seen at the 9 m interface between the upper, well-mixed epilimnion and the deep hypolimnion. The average TP concentration at 9 m is twice the concentrations seen at the 0.5 and 3 m sampling depths and the 9 m chlorophyll *a* average is nearly twice seen in the upper waters (see Figure 14). These 9 m concentrations suggest that nutrients from the hypolimnion are mixing into the epilimnion, but the relatively stable concentrations in the epilimnion suggest that the mass mixing is relatively constant. TP mass in the upper waters (0.5 and 3 m) fluctuates in a relatively constrained range between 31 and 62 kg and individual sampling date results show no trend throughout the summer.

The surface TP and chlorophyll *a* concentrations are high compared to other Cape Cod ponds and show that the system is clearly impacted. The average TP concentration of the upper two sampling depths is 16 ppb, which is higher than the 10 ppb developed as an impacted threshold for Cape Cod ponds (Eichner, *et al*., 2003). This TP concentration and the 5.1 ppb average chlorophyll *a* concentration place this lake in the mesotrophic category in the Carlson and Simpson (1996) trophic index. Lakes in this category are characterized as: "water moderately clear; increasing probability of hypolimnetic anoxia during summer" and fisheries are characterized as "hypolimnetic anoxia results in loss of salmonids." Secchi readings are consistent with other readings, showing that the average reading in the lake is 3 m or 22% of the total depth, both of which are the lowest among the three Indian Ponds (see Figure 12).

Nutrient concentrations are consistent with phosphorus limitation in Mystic Lake. TN to TP concentration ratios in the epilimnion average 42, which is more than twice the Redfield limit of 16, and solidly supports phosphorus limitation in Mystic Lake. Ratios of samples from deeper in the lake are also two to six times the Redfield limit.

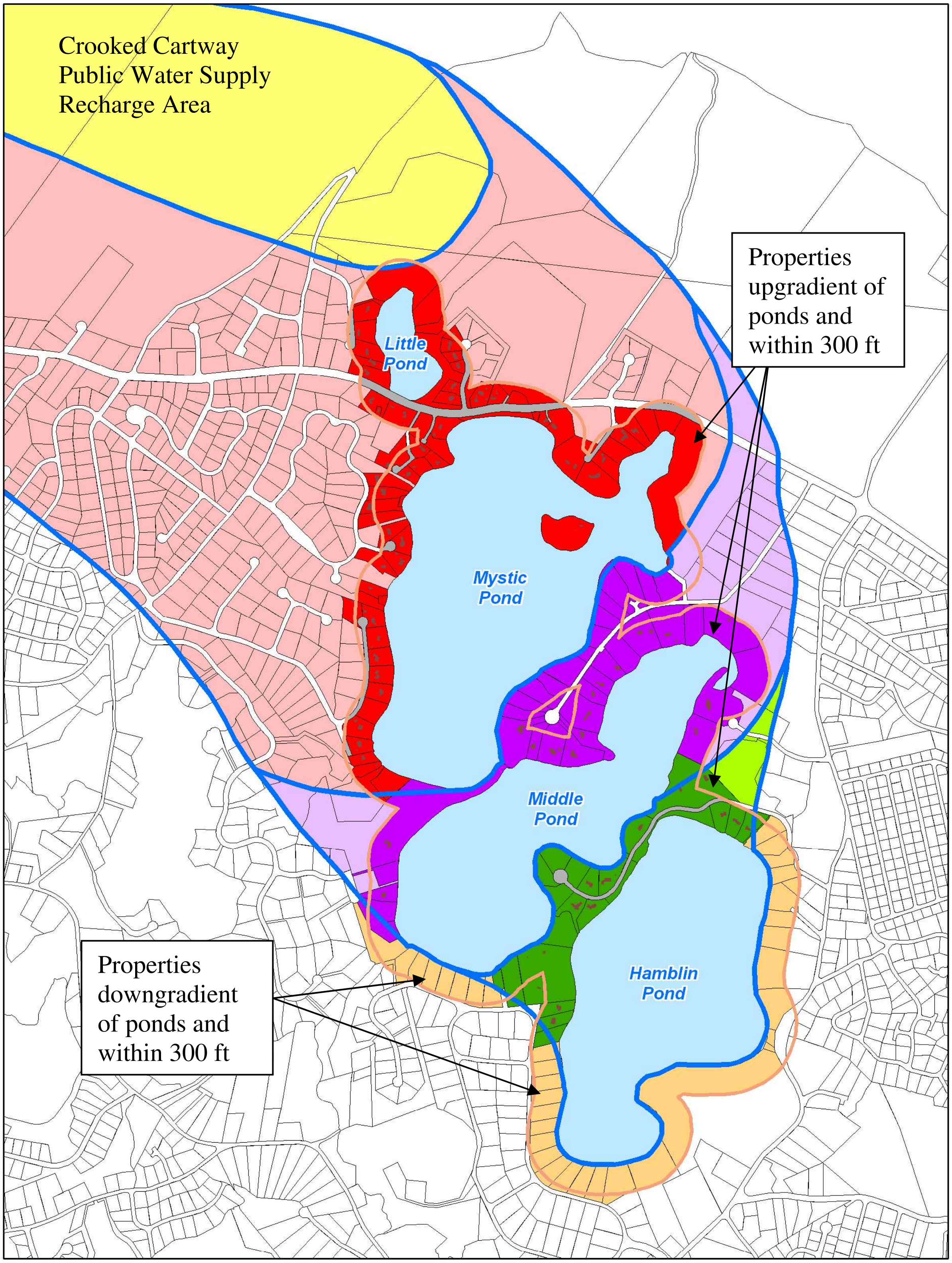


Figure 16. Properties considered in watershed phosphorus loading analysis for Indian Ponds

Although the 1948 MADFG data is the only significantly older data available, comparison of these dissolved oxygen and temperature profiles to data collected in August during this study and PALS snapshot profiles from the past four years seem to indicate that conditions in the Mystic Lake have become more impaired over the last 50 years (see Figure 13). The August 1948 temperature profile is similar to the ones collected during the PALS snapshot. However, the 1948 dissolved oxygen profile has anoxic conditions at a depth of 12 m, while the more recent data has anoxic conditions at 9 m. The recent readings are notable because this depth is the bottom of the epilimnion. This comparison means that sediment regeneration of nutrients in 1948 would not have reached the epilimnion because there would be a layer of well-oxygenated water between 9 and 12 m that would have essentially prevented the leaking of TP to the epilimnion that is seen in the 2004 data. This "bleed through" has been observed in other Cape Cod ponds that are similarly impaired (*e.g.*, ENSR, 2001).

The release of TP from the sediments is the primary source of phosphorus in Mystic Lake (Figure 17). This portion of the phosphorus budget is based on lake-specific water quality measurements; phosphorus in the hypolimnion increases throughout the summer, the TP load increasing from 30 kg in May to 330 kg in mid-September. Because of this, the sediment portion of the phosphorus budget increases from 34% to 88% and the total mass of TP increases from 88 to 375 kg. The average hypolimnetic mass was used to develop the internal regeneration portion of the phosphorus budget shown in Figure 17.

The rest of the phosphorus budget for Mystic Lake is the load that comes from its watershed and, mostly, the properties that abut the lake. The two primary constituents of the watershed phosphorus budget are wastewater and waterfowl (see Figure 17). The wastewater load (41% of the watershed budget) is based on septic systems on the properties within 300 ft (see Figure 16). The waterfowl load is based on a factor developed in a highly detailed study of bird feeding and phosphorus loading (Scherer, *et al*., 1995); similar site-specific data is not available. Long time IPA members remember significant gull populations gathering on Middle Pond, in particular; these flocks have largely disappeared following the capping of the town landfill. Further review of the factors used in the phosphorus load suggests that the simple budget could be refined, but this would require the collection of additional site-specific data.

Studies of septic system effluent have shown that the phosphorus portion of a system groundwater plume moves at approximately 1 m per year (e.g., Robertson, *et al*., 1998). This flow rate means that phosphorus would need 91 years to traverse 300 ft. Based on a review of town Board of Health and Building Department records by Holly Hobart of the IPA, the average age of residences within the 300 ft buffer is 35 years old (*i.e.*, built in 1970). The average distance for the septic system leachfields for these properties is 196 ft. Using the 1 m/y phosphorus travel time, the average time for phosphorus from the average property abutting Mystic Lake to reach the lake is ~60 years. Given that the average travel time is greater than the average age of the residences, this analysis suggests that the wastewater, fertilizer, and road portions of the phosphorus budget should be reduced by 42%. Further, this analysis also suggests that the observed nutrient concentrations in the pond are likely to increase as phosphorus already in the groundwater reaches the lake. The in-lake phosphorus budget shown in Figure 17 reflects an adjustment in these portions, so the budget is based on existing

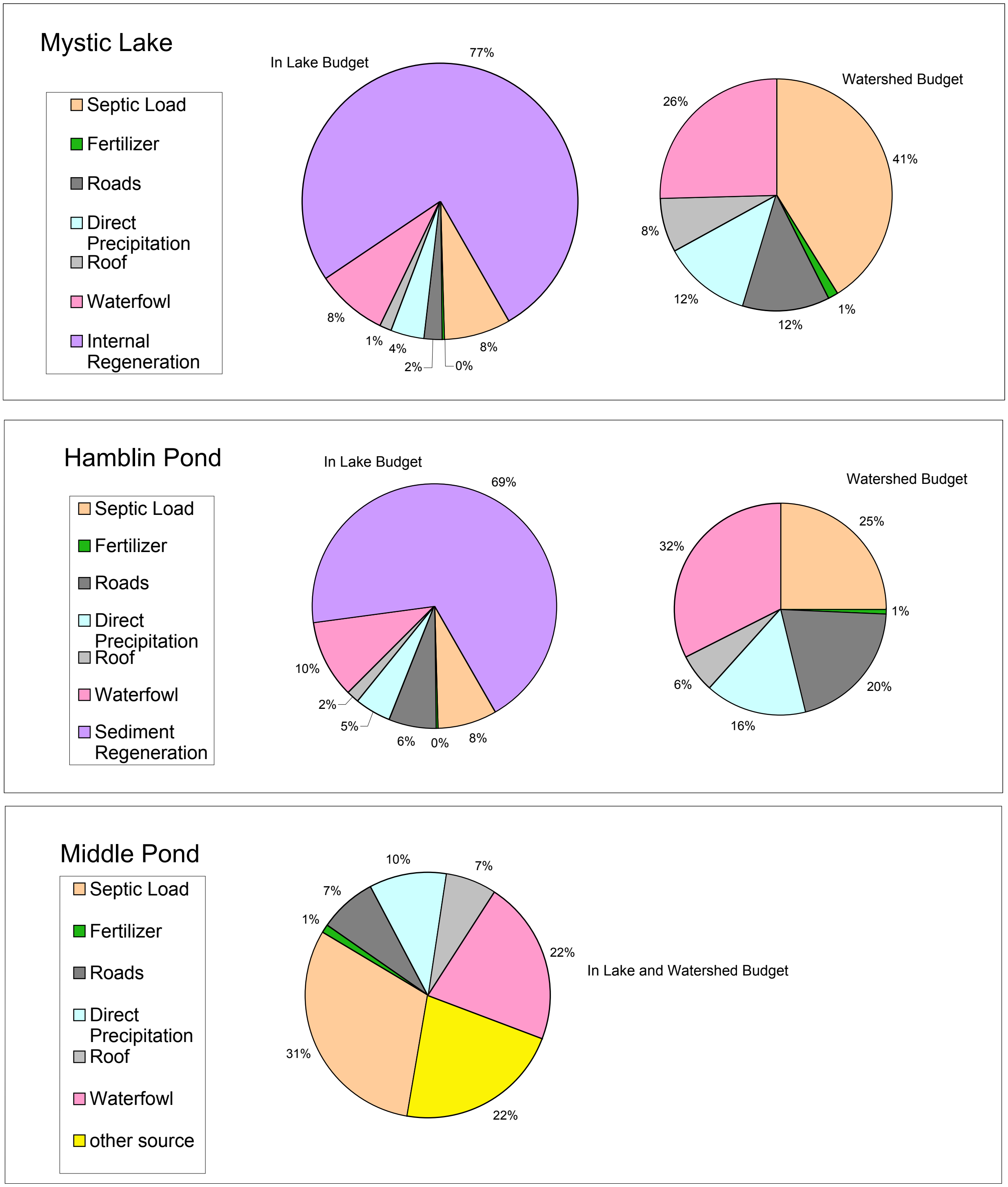


Figure 17. Phosphorus Budgets for the Indian Ponds.

Sediment regeneration is based on median phosphorus mass calculated from 2004 water quality data; watershed loads are estimated based on factors in Table 8 with adjustments to account for phosphorus time of travel.

conditions. The watershed budget is based on steady state conditions and does not include modification to account for phosphorus time of travel.

Project staff checked the balance between the modeled watershed recharge coming into the pond, the calculated phosphorus load, and the observed concentrations in the pond; this analysis suggested that observed concentrations in the pond were better matched if the recharge was reduced by removing the recharge within the watersheds to the public water supply wells. This analysis suggests that most of the water pumped by these wells is not discharged within the Indian Ponds watershed.

The average calculated TP mass in the epilimnion of Mystic Lake is 45.7 kg. The adjusted watershed load, incorporating modifications to account for delays in phosphorus travel time, accounts for 35.2 kg. In order to bring the lake TP budget into balance, 12.3 kg of TP would have to be added. Based on the observed TP data, the most likely source of this load is from the hypolimnion. Average TP and chlorophyll a concentrations at 9 m are close to double the concentrations above them; given that 9 m is generally in the metalimnion (*i.e.*, the transition zone between the upper and lower layers), these concentrations are consistent with a conclusion that nutrients are generally leaking up from the hypolimnion. This hypothesis is also consistent with the estimated sediment oxygen demand. Five additional houses are projected within the 300 ft buffer area at buildout; this will increase the annual steady state watershed TP load at buildout to 50.2 kg.

ii. Middle Pond

Middle Pond is a well-mixed pond with generally good water quality characteristics, but with concerns. The pond does not thermally stratify since its maximum depth is only slightly deeper than the stratification depth of most ponds on Cape Cod (~9m) and because of this normal wind energy is sufficient to keep the water column generally well mixed throughout the summer (see Figure 10). This mixing allows oxygen to be mixed into the water column on a regular basis, but even with this availability the pond occasionally develops anoxic conditions near the sediments. Average sediment oxygen demand is estimated at 109 mg/m2/d.

Concentrations of TP and TN are relatively stable during the summer, but chlorophyll *a* concentrations have a significant upward trend. Sampling at the shallowest station had an average TP concentration of 15 ppb, while lower concentrations deeper in the pond produce an overall average concentration of 10.6 ppb (see Figure 14). This overall concentration is approximately the same as the 10 ppb impacted threshold developed from a review of over 180 Cape Cod ponds (Eichner, *et al*., 2003). Average TN concentrations are similar at all depths (0.26 to 0.28 ppm) with an overall pond average of 0.27 ppm. Comparison of TN and TP concentrations on individual sampling dates and averages at all three sampling depths indicate that the pond is phosphorus limited; the average lake-wide ratio is 82.

Middle Pond's average surface TP and chlorophyll *a* concentrations place this lake in the high oligotrophic mesotrophic category in the Carlson and Simpson (1996) trophic index. Lakes in this category are characterized as: "hypolimnia of shallower lakes, may become anoxic" and fisheries are characterized as "salmonid fisheries in deep lakes only." These characterizations illustrate some of the issues with applicability of this index, in general, to shallower lakes that do not stratify and, specifically, to Cape Cod ponds and lakes.

Although the 1948 MADFG data is the only significantly older data available, comparison of these dissolved oxygen and temperature profiles to data collected in August during this study and PALS snapshot profiles from the past four years seem to indicate that conditions in the Middle Pond have become more impaired over the last 50 years (see Figure 13). The deepest dissolved oxygen reading (9 m) in the August 1948 profile has full saturated conditions, while all the more recent data has anoxic conditions at 9 m. This comparison suggests that the pond is receiving more nutrients than it did in the past and that the current load has exceeded the capacity of the sediments to process this load during oxygenated conditions.

Shallow (0.5 and 3 m) chlorophyll *a* concentrations average 1.9 µg/l, which is higher than the Cape Cod 1 µg/l impacted threshold (Eichner, *et al.*, 2003). In addition, these readings have a significant upward trend (R^2=0.89) as the summer progresses. This is inconsistent with the TP concentrations, which fluctuate somewhat but within a relatively constrained range. Secchi readings show a similar trend with a slightly weaker relationship (R^2=0.52; 13 mm reduction in Secchi depth per day), but this trend suggests that the chlorophyll readings are accurate. Further analysis of food chain dynamics (*e.g.*, variations in composition of phyto- and zooplankton populations) and chemical interactions would be necessary to resolve why there is an apparent disconnect between TP and chlorophyll *a* concentrations. The only likely sources of additional TP that could prompt chlorophyll *a* increases and Secchi depth decreases would be sediment regeneration or phosphorus coming from Mystic Lake.

When the phosphorus budget for Middle Pond is worked up, there is a deficiency after accounting for all the known sources (listed in Table 8). The primary accounted sources are waterfowl (22%) and septic systems (16%). TP from septic systems is from properties mostly abutting the pond, plus all the properties on the land bridge between Middle Pond and Mystic Lake (see Figure 16). The land bridge properties were included because, even though these properties are beyond the 300 ft buffer, groundwater from them would have to discharge to Middle Pond. In order to have the calculated TP sources balance the measured TP based on the water quality data, approximately 14 kg needs to be added; this is labeled “other source” in Figure 17.

This analysis of the budget includes an adjustment to account for delays of phosphorus reaching the pond from watershed sources. Studies of septic system effluent have shown that the phosphorus portion of a system groundwater plume moves at approximately 1 m per year (e.g., Robertson, *et al*., 1998). This flow rate means that phosphorus would need 91 years to traverse 300 ft. Based on a review of town Board of Health and Building Department records by Holly Hobart of the IPA, the average age of residences included in the watershed load to Middle Pond is 32 years old (*i.e.*, built in 1973). The average distance for the septic system leachfields for these properties is 187 ft. Using the 1 m/y phosphorus travel time, the average time for phosphorus from the average property abutting Middle Pond to reach the pond is ~57 years. Given that the average travel time is greater than the age of the residences, this analysis suggests that the wastewater, fertilizer, and road portions of the watershed phosphorus budget should be reduced by 44%. Further, this analysis also suggests that the observed nutrient concentrations in the pond are likely to increase as phosphorus already in the groundwater reaches the lake. The in-lake phosphorus budget reflects an adjustment in these portions (see Figure 17), so the budget is based on existing conditions. The watershed budget is based on steady state conditions and does not include modification to account for phosphorus time of travel.

Since Middle Pond's sediments and Mystic Lake were potential additional TP sources, staff reviewed the likelihood of these two sources supplying the TP necessary to balance the budget. The water budget has 3,113,379 m^3 annually discharging from Mystic Lake (see Table 4); if this volume is multiplied by the average epilimnetic TP concentration (17 ppb), 53 kg of TP would be available to be discharged to Middle Pond. The load needed to balance the phosphorus budget would be 26% of this mass. The length of the downgradient shoreline at the land bridge between Mystic Lake and Middle Pond is approximately 13% of the total shoreline, so an approximate calculation would estimate that half of what is needed would flow through this portion. The regular water connection between the ponds at the north edge of the land bridge could focus this mass transfer, although additional characterization of this connection would be necessary to quantify its impact. This connection, the low elevation of this land bridge, its width (no more than 10 feet across at the closest point between the ponds), and past observations that it has been submerged during high groundwater conditions suggest that the phosphorus mass crossing it may be greater than half of the load needed to balance the phosphorus budget. At the very least, it is fairly easy to justify Mystic Lake as a partial source to the phosphorus budget of Middle Pond.

Sediment regeneration is more constrained than transfer from Mystic Lake because it would need to occur during the limited period when anoxia occurs over the sediments in Middle Pond. Anoxic conditions are necessary to favor release of TP from the sediments; these conditions occur in late July through mid-September in both the 2004 and 2005 dissolved oxygen profiles. In order to generate ~14 kg worth of TP needed to balance the budget and sustain it in the pond, ~0.6 kg of TP would need to be released daily during the month and a half of deep water anoxia. Given that Mystic Lake's sediments can release TP at a rate of 4.1 kg/d over a similar time period, sediment regeneration is also a possible source of the additional phosphorus necessary to balance Middle Pond's phosphorus budget. However, water quality data do not show higher TP concentrations deep in the ponds (see Figure 14).

As with Mystic Lake, the wastewater and sediment/Mystic Lake portions of the Middle Pond phosphorus budget are more certain than the waterfowl portion (22% of the budget); this estimate is based on a highly detailed study (Scherer, *et al*., 1995). Long time IPA members remember significant gull populations gathering on Middle Pond; these flocks have largely disappeared following the capping of the town landfill. Additional site-specific study would be necessary to clarify how similar the waterfowl population at Middle Pond is to those used to develop the waterfowl phosphorus-loading factor.

With the addition of ~14 kg of TP, the overall phosphorus budget compares reasonably with the water quality data. The overall annual watershed load to Middle Pond is 39 kg. Two additional houses are projected within the 300 ft buffer area at buildout; this will increase the annual steady state watershed TP load at buildout to 40 kg. The existing load is nearly twice the observed load in the pond (22 kg) based on water quality data; the annual watershed load needs to be nearly twice as much as the load in the pond because the residence time of water in the pond is exchanged every 0.56 years (6.7 months) (see Table 3).

iii. Hamblin Pond

Hamblin Pond is an impacted pond with water quality problems, but much improved over the problems that existed prior to the 1995 alum treatment (BEC, 1993). Currently, the lake thermally stratifies during the summer and the deeper waters are cut off from direct interaction with the atmosphere (see Figure 10). Water quality data shows that oxygen in these deep waters is consumed by sediment oxygen demand relatively soon after stratification; the deepest DO concentrations were less than 2 ppm at the initial profile (May 20, 2004) and were anoxic (<1 ppm) when the next profile was measured (June 9). These conditions indicate that more organic material is present in and falling to the sediments than can be digested (or broken down) by its bacterial population. Average sediment oxygen demand is estimated at 219 mg/m2/d. These anoxic conditions create chemical conditions that cause nutrients that would otherwise be bound in the sediments to be released back into the overlying water column.

Review of nutrient and chlorophyll concentrations at the upper three sampling depths indicates, however, that the release of sediment nutrients does not significantly impact the upper waters of the pond during the summer. Concentrations of TP, TN, and chlorophyll *a* at these stations fluctuate, but do not show significant upward trends. Analysis of the mass of phosphorus in the upper waters also shows fluctuations in the total mass, but no upper trend.

The surface TP and chlorophyll *a* concentrations reflect some of the mix of good and impacted water quality that is seen in Hamblin Pond. The average surface TP concentration is 8.4 ppb, which is less than the 10 ppb impacted threshold developed by the Commission for Cape Cod ponds (Eichner, *et al*., 2003). The average chlorophyll *a* concentration, on the other hand, is 2.0 µg/l, which is twice the 1.0 µg/l threshold developed by the Commission. Both average concentrations place this lake in the upper oligotrophic category in the Carlson and Simpson (1996) trophic index. Lakes in this category are characterized as: “hypolimnia of shallower lakes, may become anoxic” and fisheries are characterized as “salmonid fisheries in deep lakes only.” Secchi readings are consistent with other readings, showing that the average reading in the lake is 6.4 m or 38% of the total depth; the depth reading is the deepest among the three Indian Ponds, while the relative reading is between the averages for Middle and Mystic (see Figure 12).

Nutrient concentrations are consistent with phosphorus limitation in Hamblin Pond. TN to TP concentration ratios in the epilimnion average 95, which is nearly six times the Redfield limit of 16, and solidly supports phosphorus limitation in Hamblin Pond. Ratios of samples from the deepest portion of the lake show the impact of phosphorus release from the sediments; the average ratio is 38 and some sampling dates the ratio dips slightly below the Redfield limit.

Comparison of dissolved oxygen and temperature profiles collected in 1948 by MADFG and in 1992 by BEC to data collected in August during this study and PALS snapshot profiles from the past four years indicate that conditions in the Hamblin Pond have improved as a result of the 1995 alum application, but that water quality impairments still persist (see Figure 13). The August 1948 and August 1992 dissolved oxygen profiles have anoxic conditions at a depth of 8 and 7 m, respectively. The more recent data have anoxic conditions at 12 m. This means that the alum application recovered ~6 m worth of oxygenated depth and 335 million gallons worth of oxygenated water. In addition, because oxygenated conditions now extend beyond 9 m (the thermal stratification boundary), there is now an oxygenated buffer that provides some protection from the deeper anoxia and the accompanying high TP concentrations. This is similar to the conditions that existed in Mystic Pond in 1948 (see Figure 13).

The release of TP from the sediments is the primary source (69%) of phosphorus in Hamblin Pond (see Figure 17). This portion of the phosphorus budget is based on the water quality measurements. Although this load fluctuates based on individual sampling dates, phosphorus in the hypolimnion generally has an increasing trend throughout the summer; the hypolimnetic TP load starts at 23 kg in May and climbs as high as 267 kg in early September. The sediment portion of the phosphorus budget fluctuates between 27 and 95% of the total mass of TP in the pond. Staff used the average hypolimnetic mass to develop the internal regeneration portion of the phosphorus budget shown in Figure 17.

The rest of the phosphorus budget for Hamblin Pond is the load that comes from its watershed. The watershed loads (*i.e.*, wastewater, fertilizer, road, roof, direct precipitation, and waterfowl loads) are developed using the factors common to all the ponds (see Table 8); the two primary constituents of the watershed phosphorus budget are wastewater (25%) and waterfowl (32%) (see Figure 17). As with the other two ponds, the wastewater and sediment regeneration portions of the phosphorus budget are more certain than the waterfowl portion; this estimate is based on a highly detailed study (Scherer, *et al*., 1995), but additional study would be necessary to clarify how similar the waterfowl population at Hamblin Pond is to the study lake. This analysis includes TP from septic systems on properties mostly abutting the pond, plus all the properties on the land bridge between Middle Pond and Hamblin Pond (see Figure 16). The land bridge properties were included because, even though these properties are beyond the 300 ft buffer, groundwater from them would have to discharge to Hamblin Pond. The good match between observed water quality and estimated TP loads suggests that phosphorus from Middle Pond does not traverse the land bridge between Middle Pond and Hamblin Pond. The sum of all these loads is 24 kg and this approximately matches the average load in the epilimnion of 26.9 kg developed based on water quality data. Based on the analysis of properties within the 300 ft buffer, there are no additional residences projected at buildout.

This analysis of the budget includes an adjustment to account for delays of phosphorus reaching the pond from watershed sources. Studies of septic system effluent have shown that the phosphorus portion of a system groundwater plume moves at approximately 1 m per year (e.g., Robertson, *et al*., 1998). This flow rate means that phosphorus would need 91 years to traverse 300 ft. Based on a review of town Board of Health and Building Department records by Holly Hobart of the IPA, the average age of residences included in the watershed load to Hamblin Pond is 31 years old (*i.e.*, built in 1974). The average distance for the septic system leachfields for these properties is 154 ft. Using the 1 m/y phosphorus travel time, the average time for phosphorus from the average property abutting Hamblin Pond to reach the pond is ~47 years. Given that the average travel time is greater than the age of the residences, this analysis suggests that the wastewater, fertilizer, and road portions of the watershed phosphorus budget should be reduced by 34%. Further, this analysis also suggests that the observed nutrient concentrations in the pond are likely to increase as phosphorus already in the groundwater reaches the lake. The in-lake phosphorus budget reflects an adjustment in these portions (see Figure 17), so the budget is based on existing conditions. The watershed budget is based on steady state conditions and does not include modification to account for phosphorus time of travel.

In summary, the apportionment of the watershed load into the various categories could require some additional work to refine and confirm, but the overall budget compares reasonably with the water quality data. This comparison also supports the assessment that deeper, hypolimnetic sediment regeneration of TP is not significantly impacting the upper, epilimnetic waters of Hamblin Pond.

6. Conclusions

After reviewing the water quality data, it is clear that Mystic Lake is impaired. Water quality in the other two ponds shows some issues of concern, but water quality conditions are generally good.

Mystic Lake's impairments are the result of total phosphorous entering the lake from its watershed and being regenerated from its sediments. Anoxic conditions in the hypolimnion that have occurred over the last 50 years allow TP to be released from the sediments back into the water; TP in the sediments originally came from the watershed, was utilized by phytoplankton in the lake, and fell to the sediments when the phytoplankton died. So much TP is being released from the sediments that it is leaking through the bottom of the epilimnion and prompting higher TP and chlorophyll *a* concentrations in this upper layer, as well as lower Secchi readings. Current phosphorus loading from the lake's watershed is approximately 35 kg/yr, while sediment regeneration is estimated as 12 kg/yr. Watershed loads are projected to increase to 47 kg/yr at steady state without any additional development along the shoreline and 50 kg/yr at full buildout. TP management activities should address the sediment regeneration and the existing and future watershed sources.

Middle Pond has surface water phosphorus concentrations that are just above the impacted threshold of 10 ppb determined by the Cape Cod Commission (Eichner, *et al*., 2003). Chlorophyll *a* concentrations and Secchi depth readings have significant summer-long trends indicating worsening conditions in the pond. Current watershed phosphorus loading is approximately 23 kg/yr plus an additional ~14 kg/yr from sediment regeneration and/or direct input from Mystic Lake. Watershed loads are projected to increase to 40 kg/yr at steady state without any additional development along the shoreline and two additional lots at buildout will increase this load less than one additional kilogram per year.

Hamblin Pond has surface water phosphorus concentrations that are just below the 10 ppb threshold, but anoxic conditions that allow sediment regeneration of phosphorus exist deeper in the pond. Fortunately, the 1995 alum treatment reduced sediment oxygen demand sufficiently to reestablish a fully oxygenated layer within the hypolimnion. The above analysis indicates that this oxygenated layer is preventing regenerated phosphorus from prompting phytoplankton growth in the epilimnion. Current watershed phosphorus loading is approximately 24 kg/yr. Watershed loads are projected to increase to 29 kg/yr at steady state without any additional development along the shoreline and there are no projected additions at buildout.

7. Recommendations for Future Activities

A. Mystic Lake

The sum of the above analysis indicates that the high phosphorus and low Secchi depth readings in Mystic Lake are the result of phosphorus loading from both its watershed and regeneration from its sediments. If the 10 ppb TP threshold in the epilimnion is used as a planning target, ~35 kg/yr would be the acceptable load to this layer. Attaining this target would require reductions in both watershed and sediment regeneration loading.

If a phosphorus reduction similar to that achieved in Hamblin Pond by the alum treatment occurred, a layer of well-oxygenated water in the hypolimnion would effectively isolate the phosphorus regenerated by the sediments and remove this load from the epilimnion. This would reduce the epilimnion mass to the 35 kg/yr target. While this is the projected current load, it is estimated that an additional 12 kg/yr are already in the groundwater from existing development and an additional 3 kg at buildout within the 300 ft buffer around the shoreline, so additional phosphorus reduction steps in the watershed will be necessary to accommodate the steady state loading and loading that is already coming from existing development, as well as buildout additions.

Project staff recommends that the IPA and the Town consider a series of three parallel steps to remediate Mystic Lake. The first step would be to address the phosphorus regenerated from the sediments; this can be done a number of ways (*e.g.*, alum application, hypolimnetic aeration, etc.); a complete list of remedial options is available in the state's Final Generic Environmental Impact Report on Eutrophication and Aquatic Plant Management (Mattson, *et al.*, 2003). Interim steps to determine the appropriate activity should include sampling of the sediments, analysis of their phosphorus content, and evaluation of various phosphorus forms to identify likely maximum regeneration. Whatever remedial activity is chosen will likely require a permit and associated public hearings from the town Conservation Commission.

The second step would be a number of activities to address the watershed loading; the two largest sources in the watershed portion of the phosphorus budget are wastewater (19.5 kg at steady state) and waterfowl (12.2 kg at steady state). Based on the phosphorus budget, 15 kg of TP would have to be removed. As mentioned previously, in order to better quantify the waterfowl loading, the town and/or IPA would need to initiate a site-specific waterfowl phosphorus loading project on Mystic Lake. The wastewater loading would require an evaluation of options to remove or reduce this component.

Reducing the wastewater component could be addressed by removing this source from the watershed via sewers; since this is likely a high cost proposition, additional analysis is warranted. Additional analysis should include review of: 1) alternative treatments that utilize existing or upgraded septic systems, 2) issues associated with design of a collection system, selection of a wastewater discharge site and evaluation of impacts of effluent discharge on other downgradient resources, and 3) cost evaluation of management, design, and financing of the various options.

A third step would be to review existing regulatory programs (*i.e.*, board of health, conservation commission, and planning board) and their regulations and bylaws to evaluate potential changes that would better protect water quality and preserve the benefits of whatever investment is made to reduce the sediment phosphorus regeneration. One recent example of this was the bylaw and regulation evaluation completed by the Cape Cod Commission staff at the request of the Brewster Board of Selectmen; this evaluation included recommendations to increase the minimum septic system leachfield setbacks from ponds and to enhance and better utilize existing requirements such as real estate transfer upgrades and required water quality reports (1/30/04 memo from Ed Eichner to Brewster Board of Health and Conservation Commission).

During the course of these activities, it is further recommended that the town and/or the IPA continue to monitor Mystic Lake. This monitoring program should include, at a minimum, the same parameters, detections limits, depths, and sampling procedures utilized during this project; sampling should occur, at a minimum, in early April and late August. The late August sampling could occur via the regular PALS Snapshot, if this project is still occurring.

B. Middle Pond

The sum of the above analysis indicates that Middle Pond has generally good water quality, but the summer-long upward trends for chlorophyll a concentrations and decrease in Secchi transparency and the late summer anoxia deep in the pond raise some concerns. These concerns have developed over the last 50 years.

Current average TP concentrations are just above the 10 ppb TP threshold for Cape Cod ponds; existing and buildout loads will increase this concentration by ~1.5 ppb. The total load into the pond needed to balance the observed water quality concentrations includes an addition from an undefined source. Based on the physical connection to Mystic Lake and the observed deep anoxia, this undefined source could be loads from Mystic Lake, sediment regeneration or a combination of the two sources.

If the recommended target of 10 ppb TP is met in Mystic Lake, as discussed above, and it is assumed that Mystic Lake contributes half of the undefined load, the resulting improvements in Mystic Lake would cause average existing Middle Pond TP concentrations to drop to 7.7 ppb and the average buildout TP concentration to drop to 9.8 ppb. This analysis indicates that if Mystic Lake is the undefined source needed to balance the TP budget in Middle Pond, effectively addressing Mystic Lake's TP concentrations would also address Middle Pond's water quality concerns.

If, on the other hand, internal sediment regeneration is the predominant source of the undefined TP, similar protections of Middle Pond would require activities to address the phosphorus or the sediment oxygen demand. Given that Middle Pond is shallower than Mystic Lake or Hamblin Pond and does not thermally stratify, there are additional options available. These options might include removal of the sediments, enhanced aeration near the sediments, or a phosphorus inactivation (*e.g.*, alum application); a complete list of potential options is available in the state's Final Generic Environmental Impact Report on Eutrophication and Aquatic Plant Management (Mattson, *et al.*, 2003).

Given that Middle Pond has generally good water quality, it is recommended that the IPA and the town focus on addressing the water quality problems in Mystic Lake while continuing to monitor water quality conditions in Middle Pond. The impact of implementating remedial activities in Mystic Lake should be observed in Middle Pond within five years if Mystic Lake is the undefined source of TP to Middle Pond. If monitoring does not show improvement after five years, the town and IPA should consider proceeding with remedial activities for the sediments in Middle Pond.

Since water quality monitoring is the key to realizing this recommended adaptive management strategy, a monitoring program should include, at a minimum, the same parameters, detection limits, depths, and sampling procedures utilized during this project. Sampling should occur, at a minimum, in early April and late August. The late August sampling could occur via the regular PALS Snapshot, if this project is still occurring.

C. Hamblin Pond

The sum of the above analysis indicates that Hamblin Pond has generally good surface water quality, including the best average TP concentrations among the Indian Ponds. The 1995 alum treatment has significantly improved all water quality measures and has created a layer of cold, well-oxygenated water that essentially isolates the persistent low dissolved oxygen and sediment TP regeneration found deeper in the pond. Water quality data and the phosphorus budget indicate that there is no significant leakage of high TP concentrations into the upper waters.

The phosphorus budget and water quality data indicates that the arrival of all phosphorus coming from existing development within the 300 ft buffer has not arrived at the pond. Once all of this arrives and steady-state is achieved, average TP concentrations should rise ~1.8 ppb and exceed the 10 ppb Cape Cod impacted threshold. Given that the pond has some concerns regarding chlorophyll *a* concentrations and Secchi transparency, this slight rise above the threshold should be closely watched.

It is recommended, therefore, that the town and IPA continue monitoring Hamblin Pond. This monitoring program should include, at a minimum, the same parameters, detection limits, depths, and sampling procedures utilized during this project. Sampling should occur, at a minimum, in early April and late August. The late August sampling could occur via the regular PALS Snapshot, if this project is still occurring. Monitoring data should be reviewed every five years; if additional concerns arise, remedial options to address the concerns should be reviewed at that time.

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Appendix A

Water-level information from May to October 2004 collected at sites in Figure 4

Pond Water Level Measurements

Gauge	Location	Elevation of Benchmark (feet NGVD)	Elevation of Measuring Point (feet NGVD)		Measurement (feet)	Date	Pond Elevation (feet NGVD)	Data Recorded by	Notes
			original gauge (June 1, 2004)	replacement gauge (Sept.1, 2004)					
Mystic Lake	1139 Race Lane	47.99	46.11	N/A	2.2	6/23/2004	45.0	N.Dawson, resident volunteer	Ź
					2.1	7/7/2004	44.9		Ź
					1.9	7/16/2004	44.7		Ź
					1.8	8/25/2004	44.6		Ź
					1.7	9/1/2004	44.5		Ź
					1.7	9/7/2004	44.5		Ź
					1.5	9/14/2004	44.3		Ź
					1.5	10/2/2004	44.3		Ź
					1.4	10/12/2004	44.2		Ź
Middle Pond (north)	380 Wheeler Road	49.32	**45.56**	46.66	**0.8**	7/8/2004	44.8	R. Frazee/A.Frazee, resident volunteer	Ź
					1.1	8/2/2004	44.5		Ź
					2.2	9/1/2004	44.5		Ź
					2.3	9/5/2004	44.4		Ź
					2.5	9/17/2004	44.2		Ź
					2.3	9/19/2004	44.3		Ź
					1.4	10/18/2004	44.2		confirmation measurement
					2.5		44.2		
Hamblin Pond	335 Hollidge Hill Road	46.27	45.67	N/A	1.6	10/21/2004	44.0	S.Sawyer, resident volunteer	Ź
Middle Pond (herring run)	Flume Avenue	-	-	N/A	45.4	5/18/2004	45.4	S.Michaud, CCC	Ź
					45.4	5/27/2004	45.4		Ź
					45.3	6/11/2004	45.3		Ź
					45.3	6/21/2004	45.3		Ź
					44.9	7/19/2004	44.9		Ź
					44.6	8/26/2004	44.6		Ź
					43.4	10/21/2004	-		Channel between herring run and Middle Pond sandbagged

Appendix B

Indian Ponds Water Quality/Sampling Field Sheet

CAPE COD COMMISSION

LAKE AND POND SAMPLING DATA SHEET

2004 Indian Ponds Sampling Project

LAKE/POND NAME: ____

TOWN: ____________________________ Sample Collector: __________________________

Date:__________ Time: _______ (AM or PM)

Observations (write in or circle as appropriate):

Water Color: ______________________ (blue, brown, green, blue/green, red/orange, white, etc)

Weather (circle):

1. Cloudless, 2. Pt. Cloudy, 3 Overcast, 4. Rain, 5. Fog/Haze, 6. Drizzle, 7. Intermit. Rain

Wind (circle): 1. Calm, 2. Light Breeze, 3. Steady Wind, 4. Strong Wind

Plants on Pond (check conditions):	Over 50%	25% to 50%	10% to 25%	up to 10%	less than 1% or None
Waterlilies coverage of pond surface:					
Floating Algae on pond surface:					
Emergent Grasses/Sedges of surface:					
Other plant #1_________________:					
Other plant #2_________________:					
Other Notes:					

TOTAL DEPTH: __________________________________meter

SECCHI READING: Disappearing: _______ meter Reappearing: _______ meter

DISSOLVED OXYGEN/TEMPERATURE PROFILE

Meter Manufacturer: _________________________ Model# _______________________

Record DO/Temp profile in one-meter increments except for the first surface reading which is taken at 0.5 m. If the pond is very shallow (3 meters or less), record readings at 0.5 meter increments.

Depth (m)	Temp (°C)	Dissolved Oxygen (mg/l)	Depth (m)	Temp (°C)	Dissolved Oxygen (mg/l)	Depth (m)	Temp (°C)	Dissolved Oxygen (mg/l)

LAKE/POND NAME: ____
TOWN: ____________________________ Sample Collector: _________________________

WATER QUALITY SAMPLING

!! FILL BOTTLE TO TOP and RECORD BOTTLE #'s !!

Hamblin Pond or Mystic Lake	
Sampling Depth	Bottle Number/Label
a. just below the surface	
b. 3 m down	
c. 9 m down	
d. 1 m above the bottom	

Middle Pond	
Sampling Depth	Bottle Number/Label
a. just below the surface	
b. 3 m down	
c. 1 m above the bottom	

TIME SAMPLING COMPLETED: ________ (AM or PM)

SAMPLE SIGNOFFS

	Signature	**Received**	**Delivered**
		Date/Time	**Date/Time**
Pond Monitor			
Sampling Coordinator			
SMAST			

Appendix C

Glossary of Pond and Lake Terms and List of Acronyms

Glossary and List of Acronyms

Aerobic:
Processes requiring oxygen.

Algae:
microscopic organisms/aquatic plants that use sunlight as an energy source (*e.g.*, diatoms, kelp, seaweed). One-celled (phytoplankton) or multicellular plants either suspended in water (Plankton) or attached to rocks and other substrates (periphyton). Their abundance, as measured by the amount of chlorophyll *a* (green pigment) in an open water sample, is commonly used to classify the trophic status of a lake. Numerous species occur. Algae are an essential part of the lake ecosystem and provide the food base for most pond and lake organisms, including fish. Phytoplankton populations vary widely from day to day, as life cycles are short.

Alkalinity:
The ability of water, or other substances, to absorb high concentrations of hydrogen ions. A measure of the amount of carbonates, bicarbonates, and hydroxide present in water. Increasing alkalinity is often related to increased algae productivity. Often expressed as milligrams per liter (mg/1) of calcium carbonate ($CaCO_3$).

Anoxic:
Lacking oxygen

CCC:
Cape Cod Commission

Chlorophyll *a*:
Green pigment present in all plant life and necessary for photosynthesis. The amount present in lake water depends on the amount of algae and is therefore used as a common indicator of water quality.

Chlorophyll:
a green pigment found in plants that is essential for the process of photosynthesis.

Concentration:
The amount of solute present in proportion to the total solution. More specifically, a measure of the average density of pollutants or other constituents, usually specified in terms of mass per unit volume of water or other Solvent (*e.g.*, milligrams per liter) or in terms of relative volume of solute per unit volume of water (*e.g.*, parts per million). Other common units of concentration are: parts per billion (ppb), micrograms per liter (µg/l), and micromoles per liter (µM).

Decompose:
breakdown of organic materials to inorganic materials.

Detritus:
partially decomposed (dead) organic matter.

Dissolved Oxygen (DO):

the amount of free oxygen absorbed by the water and available to aquatic organisms for respiration; amount of oxygen dissolved in a certain amount of water at a particular temperature and pressure, often expressed as a concentration in parts of oxygen per million parts of water.

Ecosystem:
a system formed by the interaction of a community of organisms with each other and with the chemical and physical factors making up their environment.

Epilimnion:
The upper layer of water during stratification. Stratification is caused by water’s temperature-related density differences. Water's greatest density occurs at 39 ºF (4 ºC). As water warms during the summer, it remains near the surface while colder water remains near the bottom. Wind mixing determines the thickness of the warm surface water layer (epilimnion), which on Cape Cod usually extends to a depth of about 9 m (29 ft).

Eutrophication:
the process by which surface waters are enriched by nutrients, and the resulting increase in plant and algae growth. The extent to which this process has occurred is reflected in a lake's trophic classification: oligotrophic (nutrient poor), mesotrophic (moderately productive), and eutrophic (very productive and fertile).

Flushing Rate/Residence Time:
The average length of time water resides in a pond or lake, ranging from several days in small ponds to many years in large lakes. Residence time is important in determining the impact of nutrient inputs. Long retention times result in recycling and greater nutrient retention in most lakes. Calculate retention time by dividing the annual volume of water passing through a pond by the pond volume.

Hypolimnion:
The lower layer of water during stratification. Stratification is caused by water’s temperature-related density differences. Water's greatest density occurs at 39 ºF (4 ºC). As water warms during the summer, it remains near the surface while colder water remains near the bottom. The cold bottom water is the hypolimnion.

IPA:
Indian Ponds Association

Insoluble:
incapable of dissolving in water.

Limiting nutrient/factor:
The nutrient or condition in shortest supply relative to plant growth requirements. Plants will grow until stopped by this limitation; for example, phosphorus in summer, temperature or light in fall or winter.

Limnology:
the study of inland lakes and waters.

Metalimnion:

The middle layer of water during stratification. Stratification is caused by water's temperature-related density differences. Water's greatest density occurs at 39 ºF (4 ºC). As water warms during the summer, it remains near the surface while colder water remains near the bottom. Wind mixing determines the thickness of the warm surface water layer (epilimnion), which on Cape Cod usually extends to a depth of about 9 m (29 ft). The narrow transition zone between the epilimnion and cold bottom water (hypolimnion) is called the metalimnion or thermocline.

Nitrogen:
Essential element for plant growth, comprising 78 percent of the atmosphere in gaseous (N_2) form, which is quite inert and unavailable to most plants in its natural form. Dissolved in water in ammonia (NH_4+), nitrate or nitrite or elemental forms. Nitrate is an inorganic form that is the stable form when oxygen is present. Nitrate often contaminates groundwater when water originates from lawns or septic systems. Nitrite (NO_2-) is rapidly converted to nitrate (NO_3-) and is usually included in the NO_3- analysis. Total Kjeldahl Nitrogen (TKN) is a measure of all organic and ammonium forms. Total Nitrogen (TN) is generally reported as TKN plus nitrate-nitrogen.

Nitrogen Cycle:
cyclic movement of nitrogen in different chemical forms from the environment to organisms and then back to the environment.

Nutrients:
elements or substances such as nitrogen and phosphorus that are necessary for plant growth. Large amounts of these substances can become a nuisance by promoting excessive aquatic plant growth.

Organic Matter:
elements or material containing carbon, a basic component of all living matter.

Destratification/Turnover:
Fall cooling of surface water on Cape Cod increases density, and gradually makes temperature and density uniform from top to bottom. This allows wind and wave action to mix the entire lake. Mixing allows bottom waters to contact the atmosphere, raising the water's oxygen content.

PALS:
Pond and Lake Stewards or Pond and Lake Stewardship program. Umbrella association of all organizations, groups, and individuals concerned with pond and lake issues on Cape Cod.

pH:
the numerical value used to indicate how acid or alkaline a solution is. The number is a measure of the concentration of hydrogen ions in the solution. The pH scale ranges from 1 to 14 with 7.0 being neutral; solutions with pH below 7 are acidic, while solutions with pH above 7 are alkaline.

Phosphorus:
Key nutrient influencing plant growth in Cape Cod ponds and lakes. Soluble reactive phosphorus is the amount of phosphorus in solution that is readily available to plants. Total phosphorus (TP) includes the amount of phosphorus in solution (reactive) and in particulate form.

Photosynthesis:

the process by which green plants convert carbon dioxide (CO_2) dissolved in water to sugar and oxygen using sunlight for energy. Photosynthesis is essential in producing a lake's food base, and is an important source of oxygen for many lakes.

Phytoplankton:
microscopic plants found in the water. Algae or one-celled (phytoplankton) or multicellular plants either suspended in water (plankton) or attached to rocks and other substrates (periphyton). Their abundance, as measured by the amount of chlorophyll *a* (green pigment) in an open water sample, is commonly used to classify the trophic status of a lake. Numerous species occur. Algae are an essential part of the lake ecosystem and provide the food base for most lake organisms, including fish. Phytoplankton populations vary widely from day to day, as life cycles are short.

Plankton:
small plant organisms (phytoplankton and nanoplankton) and animal organisms (zooplankton) that float or swim weakly though the water.

ppm:
parts per million; units per equivalent million units; equal to milligrams per liter (mg/l)

Precipitate:
A solid material which forms and settles out of water as a result of certain negative ions (anions) combining with positive ions (cations).

Secchi Disc:
An 8-inch diameter plate with alternating quadrants painted black and white that is used to measure water clarity (light penetration).

Sediments:
Accumulated organic and inorganic matter on the lake bottom. Sediment includes decaying algae and other organic matter collected from the lake and its watershed.

SMAST
School of Marine Science and Technology, University of Massachusetts, Dartmouth

Soluble:
capable of being dissolved.

Species:
A group of animals or plants that share similar characteristics such as can reproduce.

Stratification:
The layering of water due to differences in density. Stratification is caused by water’s temperature-related density differences. Water's greatest density occurs at 39 ºF (4 ºC). As water warms during the summer, it remains near the surface while colder water remains near the bottom. Wind mixing determines the thickness of the warm surface water layer (epilimnion), which on Cape Cod usually extends to a depth of about 9 m (29 ft). The narrow transition zone between the epilimnion and cold bottom water (hypolimnion) is called the metalimnion or thermocline.

Trophic State:
Eutrophication is the process by which ponds and lakes are enriched with nutrients, increasing the production of rooted aquatic plants and algae. The extent to which this process has occurred is reflected in a pond's trophic classification or state: oligotrophic (nutrient poor), mesotrophic (moderately productive), and eutrophic (very productive and fertile).

USGS:
United States Geological Survey

Watershed:
the land area draining into a specific stream, river, lake, estuary or other body of water. On Cape Cod, these areas are determined largely by the topography of the top of the groundwater system, known as the water table.

Zooplankton:
Microscopic or barely visible animals that eat algae. These suspended plankton are an important component of a pond or lake food chain and ecosystem. For many fish, they are the primary source of food.

Adapted from the following sources:

1. Libby McCann and "Understanding Lake Data" by Byron Shaw, Christine Mechenich and Lowell Klessig (http://dnr.wi.gov/org/water/fhp/lakes/laketerm.htm)
2. North American Lake Management Society Lake and Water Word Glossary (http://www.nalms.org/glossary/glossary.htm)