EVALUATION OF HINCKLEYS POND, HARWICH, MASSACHUSETTS

BY WATER RESOURCE SERVICES, INC. AND CDM SMITH

Water Quality Harwich

JULY 2012

Contents

Tables

Figures

Executive Summary

Hinckleys Pond has suffered impairment of uses, including swimming and fish and wildlife habitat, for at least a decade as a consequence of algal blooms, many dominated by cyanobacteria. Phosphorus levels are excessive and the ratio of nitrogen to phosphorus is variable, with values in deeper water low enough to favor cyanobacteria during summer. Examination of available data and investigations to fill knowledge gaps have revealed a high potential for internal phosphorus loading, which is recycling of previous phosphorus inputs from the watershed under low oxygen conditions. This is a common problem for Cape Cod ponds, which have been subject to agricultural and residential inputs for many decades. The inputs from any one year are not overwhelming, but a portion of each phosphorus input is incorporated into the sediment under the pond, much of it bound to iron. The iron releases some of that phosphorus back into overlying waters under low oxygen conditions, which are brought on by periodic temperature stratification resulting in inadequate mixing and elevated oxygen demand by organic material in the sediment. With enough release of iron-bound phosphorus, algal blooms are supported, and the normally low ratio of nitrogen to phosphorus associated with that release favors cyanobacteria.

Actions are needed to improve the condition of Hinckleys Pond, and these should specifically seek to reduce the phosphorus concentration in the pond and raise the nitrogen:phosphorus ratio to discourage noxious cyanobacteria blooms. A comparison of pond management alternatives was performed using the available data. These data are not sufficient to provide a comprehensive and conclusive evaluation with firm recommendations, but options are presented that could result in improved pond conditions and recommendations are provided based on the available information. Selection of options requires input on economic and social factors that is beyond the scope of this study.

Hinckleys Pond in northwest Harwich covers 174 acres to an average depth of 13 ft with a maximum depth of 28 ft. Pond volume is about 2,270 acre-feet, just under 100 million cubic feet or 2.8 million cubic meters. Detention time averages about 157 days, equating to replacement of the water in the pond about 2.3 times per year, a more rapid flushing rate than for many Cape Cod ponds. Hinckleys Pond receives most of its water from Long Pond to the east via overflow that constitutes the start of the Herring River and from Seymour Pond to the north, through a canal dug to connect the lakes and provide water for cranberry farming in the 1850s. There are two active bogs adjacent to Hinckleys Pond, and these bogs use water from the pond, particularly for fall harvest flooding, after which the water is returned to Hinckleys Pond. Most of the rest of the watershed is either low density residential land or water (Long and Seymour Ponds), although a portion of Cape Cod Community College drains runoff to the pond through the Jenkins cranberry bog on the eastern side. Stormwater collection and treatment systems are minimal in this watershed, and a lot of runoff percolates into soil before reaching the pond, but evidence of stormwater inputs has been observed near the pond. Residential land is served by on-site Title 5 wastewater disposal systems.

The entire watershed covers about 2,422 acres, including 740-acre Long Pond and 182-acre Seymour Pond. The direct drainage area to Hinckleys Pond is about 190 acres. Groundwater inflowing to Hinckleys Pond has two main sources: the runoff that infiltrates into the land between the ponds (the

190-acre groundwatershed to Hinckleys Pond alone) and subsurface flow that discharges from Long Pond and enters Hinckleys Pond. Groundwater flowing in the upper portion of the aquifer along the predominant northeast-southwest flow path will likely be captured by the much deeper Long Pond upgradient of Hinckleys Pond. Surface water overflow from Long Pond appears to be much greater than groundwater outseepage, but detailed quantification is lacking. It appears that surface water inflows are more important at Hinckleys Pond than most other kettlehole ponds on Cape Cod.

From a technical perspective, examination of pond management alternatives suggests that the phosphorus concentration in Hinckleys Pond should be reduced by at least a third (from 30 ug/L to no more than 20 ug/L) to sufficiently lower the probability of nuisance algal blooms and achieve desirable water clarity. A reduction to 10 ug/L is preferred, but may not be practical in light of current land uses and incoming water quality. Calculations indicate that a 90% reduction in the internal load would achieve more than the minimum reduction (reducing phosphorus by at least a third), and such a reduction could be obtained through treatment with aluminum, which binds phosphorus more permanently than iron. Reducing the internal load of phosphorus will also help raise the nitrogen:phosphorus ratio and discourage cyanobacteria blooms.

Lack of oxygen near the interface of muck sediments and the overlying water drives the release of phosphorus from those sediments and creates the problematic internal load. This happens sporadically in Hinckleys Pond as a function of the competing forces of oxygen demand and mixing, with periods of low oxygen and elevated phosphorus release during summer. Increasing the amount of oxygen at the bottom of the pond would also keep the phosphorus bound in the sediment, and in deeper lakes oxygen can be added to the bottom layer without disrupting stratification. However, the depth of Hinckleys Pond is marginal for non-destratifying approaches. It is more likely that air or mechanically driven systems would be used to keep the water moving during calm periods and facilitate re-aeration from the atmosphere. This prevention of stratification could maintain adequate oxygen levels at the sediment-water interface and greatly reduce phosphorus release. However, experience indicates that this process is not as effective as directly inactivating the phosphorus in the target sediments; a 75% reduction of internal load is predicted. Artificial circulation may also disrupt algal growth cycles and tends to minimize cyanobacterial dominance, independent of nutrient management, and could provide the desired level of improvement in pond condition. Artificial circulation would have to be implemented every summer, but would not be subject to gradual diminishment of benefits with ongoing external loading. It may not consistently achieve desired conditions, however.

It is possible to combine artificial circulation and inactivation with aluminum to maximize the probability of success and provide a flexible operating system. Such a system would have chemical pumps and chemical feed lines in addition to compressors and air lines for the circulation system, and could inject aluminum compounds at the same time as the air to inactivate phosphorus. The air is needed to enhance mixing and the inactivation process. This would increase the initial operational cost substantially (chemical application as well as air release), but over time the need for aluminum injection should decline.

Other in-lake options were evaluated but not pursued as a function of inapplicability, cost, or lack of documented success.

If the internal load is inactivated with aluminum application, watershed inputs are expected to gradually re-establish the internal load, possibly within a decade. A 10-20% reduction in external loading to go with the 90% reduction in internal loading would be expected to provide enhanced conditions for multiple decades. With a current loading of about 351 kg/yr (772 lbs/yr), and 46% of that load derived internally from release from sediments, the recommended magnitude of reduction in phosphorus load from the watershed is 10-20% of 191 kg/yr, or 19.1-38.2 kg/yr (42-84 lbs/yr), which is equivalent to 1-2 five gallon pails of phosphorus as a powder. This is not a large mass to consider, but it is spread over the entire watershed and year such that most actions can only address a fraction of the load at any point in time or space.

Possible approaches to reducing the external load could focus on stormwater, wastewater, cranberry bog discharges, or the surface overflows from Long and Seymour Ponds. Only the inflow from Long Pond is large enough to provide the desired level of external loading reduction by itself, but achieving such a major reduction would be very difficult. A combination of actions directed at all watershed sources is needed. Actions that the Town of Harwich is encouraged to take include stormwater improvements at two identified areas near Hinckleys Pond and anywhere else in the watershed where problems become evident, encouragement of residents to reduce phosphorus use and implement runoff control on their properties with low impact development techniques, and enforcement of Title 5 wastewater regulations (including maintaining setback distances of leaching fields from the pond shore). These are actions that represent proper management to protect the pond, even though they do not represent major individual decreases in loading.

To achieve more substantial loading reductions to complement phosphorus inactivation, more aggressive and potentially controversial actions would be needed. These could include performing phosphorus inactivation at Seymour Pond, pursuing watershed management around Seymour Pond, and pushing for better water quality management in the cranberry bogs. One or more of these actions may be needed to achieve loading reductions that would prolong the benefits of a phosphorus inactivation for multiple decades.

The timing of the internal load and high availability of the associated phosphorus suggest that internal loading may be even more important than suggested by model analysis, so internal load control may provide benefits for longer than postulated under current external loading. Yet some measure of external load control is highly recommended to protect the substantial investment that might be made in internal load inactivation. The inactivation of internal phosphorus reserves will provide benefits for as long as it takes to replace those reserves, and modeling suggests that with the current loading the duration of desirable conditions is unlikely to last more than a decade.

If a commitment to watershed management can be made by the Town of Harwich, a phosphorus inactivation project is recommended, and is expected to cost on the order of $550,000, although further testing could lower that estimate. If adequate watershed management does not seem possible, installation of an artificial circulation system with the capacity to inject inactivating compounds to lower phosphorus levels and more gradually inactivate surficial sediment reserves of available phosphorus is recommended. Such a system would cost on the order of $250,000 with an annual operating cost around $30,000 and a lifespan of about 20 years.

Financial sources for supporting a project to improve Hinckleys Pond beyond the Town of Harwich are limited at this time. State and federal programs that have aided lake management in the past are either underfunded or provide insufficient funds for a project of the magnitude envisioned. Some monies might be obtained, but the vast majority of funding will likely have to come from local sources. The Community Preservation Act provides the most viable option of funding lake projects these days, and has been used in multiple Commonwealth communities to make improvements.

Introduction

Hinckleys Pond is in the northwest portion of Harwich, close to the border with Brewster off Route 124 (Figure 1). It is downstream of both Seymour Pond and Long Pond, each of which is partly in Harwich and partly in Brewster; both have surface water outlets that flow a short distance to Hinckleys Pond. The public can access Hinckleys Pond but there are no developed public facilities. Most of the shoreline is private property, with homes around much of the pond, although very few are close to the pond and there is a 100-ft setback in place that prevents future development close to the pond. Two cranberry bogs are adjacent to the pond, one at the northwest end and one at the southeast end, each of which uses water from and discharges water to Hinckleys Pond. Surface water leaves Hinckleys Pond through an outlet structure with flashboards that control the water level over a range of about 5 ft, discharging to the Herring River. Alewife travel up the Herring River each spring to spawn in Hinckleys, Seymour and Long Ponds. Hinckleys Pond is a visual, recreational and habitat amenity for the Town of Harwich and visitors to Cape Cod.

Concern over algal blooms, particularly of cyanobacteria, in recent years prompted the Town of Harwich to pursue an investigation into the causes of overfertility. Experience with the Long Pond study and rehabilitation project was generally positive, and the benefits now enjoyed at Long Pond were desired for Hinckleys Pond. The precise approach to achieving desired conditions may vary by pond, however, and an assessment of conditions and potential causative agents at Hinckleys Pond is needed before a management plan can be developed. Considerable data were available from Town monitoring and investigative programs, and from other studies on Cape Cod, so only a limited amount of additional study was viewed as necessary.

The Town of Harwich contracted with CDM Smith, with Water Resource Services (WRS) as a sub-consultant, to perform the additional investigative work and overall assessment of Hinckleys Pond, with development of management options for further consideration. This report provides the results of that effort.

Study Approach and Methods

Existing data were gathered from a variety of sources, and mostly provided by the Town of Harwich. Additional investigations, undertaken cooperatively between WRS, the Town of Harwich, and interested shoreline residents at Hinckleys Pond, included a check of water depths and soft sediment distribution, supplemental sampling of sediment quality, shoreline condition assessment, distribution of on-site wastewater disposal systems, plankton characteristics, water level fluctuations, and cranberry bog discharge quantity and quality.

Figure 1. Location and general area features of Hinckleys Pond. (Red arrows indicate surface water flows)

Water depths were checked with an electronic fathometer, while the presence of muck sediments was ascertained visually with the aid of a Marcum underwater video system operated from a pontoon boat making transects across the pond. Sediment was sampled with an Ekman dredge, which is a stainless steel device that has jaws that snap shut and collect a sample of surficial sediment when the spring-loaded mechanism is triggered. Collected material was gently placed in a plastic pan and a sample of the upper 10 cm of sediment was placed in labeled glass jars with a lexan spoon. The invaluable aid of local volunteers Richard King and Peter de Bakker and Environmental Science Director Heinz Proft in this field effort is acknowledged. Samples were placed on ice and transported to Spectrum Laboratories in Agawam, MA for analysis of percent solids, percent moisture, volatile solids (organic content), total phosphorus, iron-bound phosphorus, and loosely sorbed phosphorus. Assays were conducted to determine the amount of aluminum needed to inactivate the available phosphorus in the samples.

A shoreline condition assessment was conducted from a pontoon boat, simply by making a lap around the lake, viewing and photographing shoreline parcels on the way. Possible problem areas were then investigated by car and foot from land.

Environmental Science Director Heinz Proft supplied the distribution of on-site Title 5 wastewater disposal systems using the Assessor's maps and GIS support.

Plankton samples were collected by Chris Miller, Natural Resource Officer of Brewster, in August 2011 and by Ken Wagner of WRS in September and October 2011. Samples were preserved with gluteraldehyde, concentrated by settling, and viewed quantitatively under phase contract microscope optics at 400X to assess types of algae and zooplankton present and the abundance of each.

Water levels were determined from staff gauges placed at two docks and the outlet in September 2011. Water levels were made daily. The invaluable aid of local volunteer Peter de Bakker in this field effort is acknowledged. Peter de Bakker also collected water samples from cranberry bog discharges on October 10 and 11, 2011, in acid-washed containers provided by WRS. Samples were frozen until pick up, after which they were transported to Berkshire Enviro-Labs of Lee, MA for analysis of total and dissolved phosphorus, and nitrate, ammonium and total Kjeldahl nitrogen by standard methods. Cranberry bog discharge was determined by both volumetric assessment of the flooded bogs and by change in water level over the area of Hinckleys Pond during withdrawal and discharge.

The Lake Loading and Response Model (LLRM) was applied to evaluate phosphorus and nitrogen loading to Hinckleys Pond, resulting pond conditions including phosphorus and nitrogen concentration, water clarity by Secchi depth, and chlorophyll levels. This model has been developed by Ken Wagner and colleagues over two decades and is detailed in a manual produced by AECOM (2009). A second model, predicting the trajectory of loading after available sediment phosphorus inactivation, was developed by Ken Wagner in association with the Long Pond project in 2007, and was applied to Hinckleys Pond as well. This is a relatively simple spreadsheet model, but there is no manual for its use.

Lake Features

Physical Attributes and History

Hinckleys Pond is an atypical kettlehole pond, formed by a leftover block of ice at the end of the last ice age over 10,000 years ago, but with inflowing streams and an outlet; most kettlehole ponds are simply substantial depressions in the landscape that intersect the groundwater table. Having surface water inflow decreases detention time and the importance of direct groundwater inputs, although a significant portion of inflowing surface water from Seymour Pond (which was not naturally connected to Hinckleys Pond) and Long Pond (which forms the headwaters of the Herring River) was originally groundwater that entered those ponds.

The history of Harwich in general and Hinckleys Pond specifically has clear significance to the current configuration and condition of the pond. Hinckleys Pond, which was also known as Herring Pond and Pleasant Lake, received its name from Thomas Hinckley, a farmer who lived on the east side of the pond (Tunison, undated, ca. 2000). Two industries were dominant in the 1800s in the Herring River basin in Harwich, herring (alewife) harvest and cranberry growing (Tunison, undated, ca. 2000). Alewife supplied food and fertilizer, and even raw materials for buttons and other products, and elaborate weirs were constructed to corral alewife during spawning season in the spring. Weirs were also built to control water levels, allowing alewife access to and from the ponds, including structures on Hinckleys Pond and Long Pond. Harvest rights were sold to the highest bidder and barrels of alewife were sent off the Cape by rail. Herring Pond was a breeding ground for alewife, and therefore an important resource for this industry, although most harvesting occurred downstream. Alewife still run through Hinckleys Pond today, but huge harvests are gone. Still, the presence of alewife has pronounced effects on biological structure and energy and nutrient flow in the pond, and the management of weirs at Hinckleys and Long Ponds affects water levels and nutrient loading.

Cranberry farming has played a very important role in Hinckleys Pond since the mid-1800s. In the early 1800s cranberries were valued as a source of vitamin C for long sailing voyages, and the industry took off from there. Cranberry growing occurred all along the Herring River, with that stream providing a ready source of water for irrigation and flooding (Tunison, undated, ca. 2000). Even so, unreliable supply and occasional floods damaged bogs and the harvest, and means were sought for better control of water supplies and levels. Seymour Pond was found to be 2 ft higher in elevation than Hinckleys Pond, and the Cahoon family dug a canal between the two ponds in the early 1850s to allow use of Seymour Pond as a water supply to bogs around Hinckleys Pond. This resulted in a great expansion of the cranberry industry around Hinckleys Pond, with at least half a dozen major bogs linked to this water source. Two active bogs remain (Thatcher and Jenkins), but the remnants of other bogs are still observable in woods and wetlands near the lake. Consequently, cranberry farming has had a presence at Hinckleys Pond for over 150 years, pre-dating nearly all residential dwellings and recreational uses.

The water level in Hinckleys Pond was controlled at its outlet, which was altered to facilitate more control, and may have raised the water level of the pond slightly. The outlet structure has been modified on multiple occasions, but has apparently always involved an earthen berm supported by wood or concrete and a flashboard structure to regulate the water level. About 100 years after that control was established, a worker panicked during a big storm and pulled the flashboards at Hinckleys Pond, sending a wall of water downstream that destroyed dikes and related cranberry structures. The combination of this damage and sagging prices for cranberries resulted in the demise of a substantial portion of the cranberry industry in Harwich. A couple of active bogs remain downstream, but the Thatcher and Jenkins bogs and one on Long Pond are the only remaining active bogs in the study area. The current configuration of the outlet (Figure 2) is a concrete walled earthen berm with a double outlet chamber with flashboards, and allows both water level control and alewife access.

State publications (MA DFW 1990, CCC 2003) list Hinckleys Pond at 171 to 174 acres with a volume of 73,654,000 cubic feet, suggesting a mean depth of 9.7 to 9.9 ft. However, the bathymetric map available previously from the Division of Fisheries and Wildlife and widely reproduced since its construction not more recently that the early 1980s shows considerably more irregular water depth contours than encountered in 2011, with shallower water on the northeastern side and sand “spits” that nearly pinch the pond into two basins. We found no evidence of the northern sand spit and the water was considerably deeper along the northeastern shore in the fall of 2011. The reason for the discrepancy is unknown, but this affects volumetric and mean depth calculations.

As assessed in the fall of 2011, the morphometry of Hinckleys Pond (Figure 3) reflects a typical kettlehole bowl. Sand associated with a stranded glacial block of ice collapsed into the depression as the ice melted. Along the gradient of kettlehole lake configurations, Hinckleys Pond has a very characteristic shape, but appears to be at the shallow end of the depth range. Hinckleys Pond bathymetry, as evaluated in 2011, exhibits a maximum depth of about 28 ft. The distribution of pond area over depth (Table 1) indicates a total volume of 2270 acre-feet, or just under 100 million cubic feet of water in the pond. Calculations from these data result in an average depth estimate of 13 ft. We believe the bathymetry presented in Figure 3 and related calculations of volume and depth to be correct, and apply them to further analysis in this report.

The shoreline of Hinckleys Pond is sandy. A few areas of rocky bottom were encountered at depths between 5 and 15 feet, but most substrate was sand to depths of between 11 and 16 ft. Organic muck covers the sand from water depths of 11 ft in some areas (the southwest side), and completely covers the sand at all depths of 16 ft or more (Figure 4). The depth at which soft sediment completely covers the sand is shallower on the southwest side of the pond but further from shore than the northeast side, owing to more gradual slopes on the southwest side. The bottom area of the pond completely covered by organic muck sediment is approximately 90 acres, just over half the total pond area. Pockets of organic sediment can be found in shallower water, but muck accumulations appear very thin and mostly transient in those areas.

Figure 2. Outlet of Hinckleys Pond in 2011. See Figure 1 for location on pond.

Figure 3. Bathymetric map of Hinckleys Pond.
(all contours are in feet)

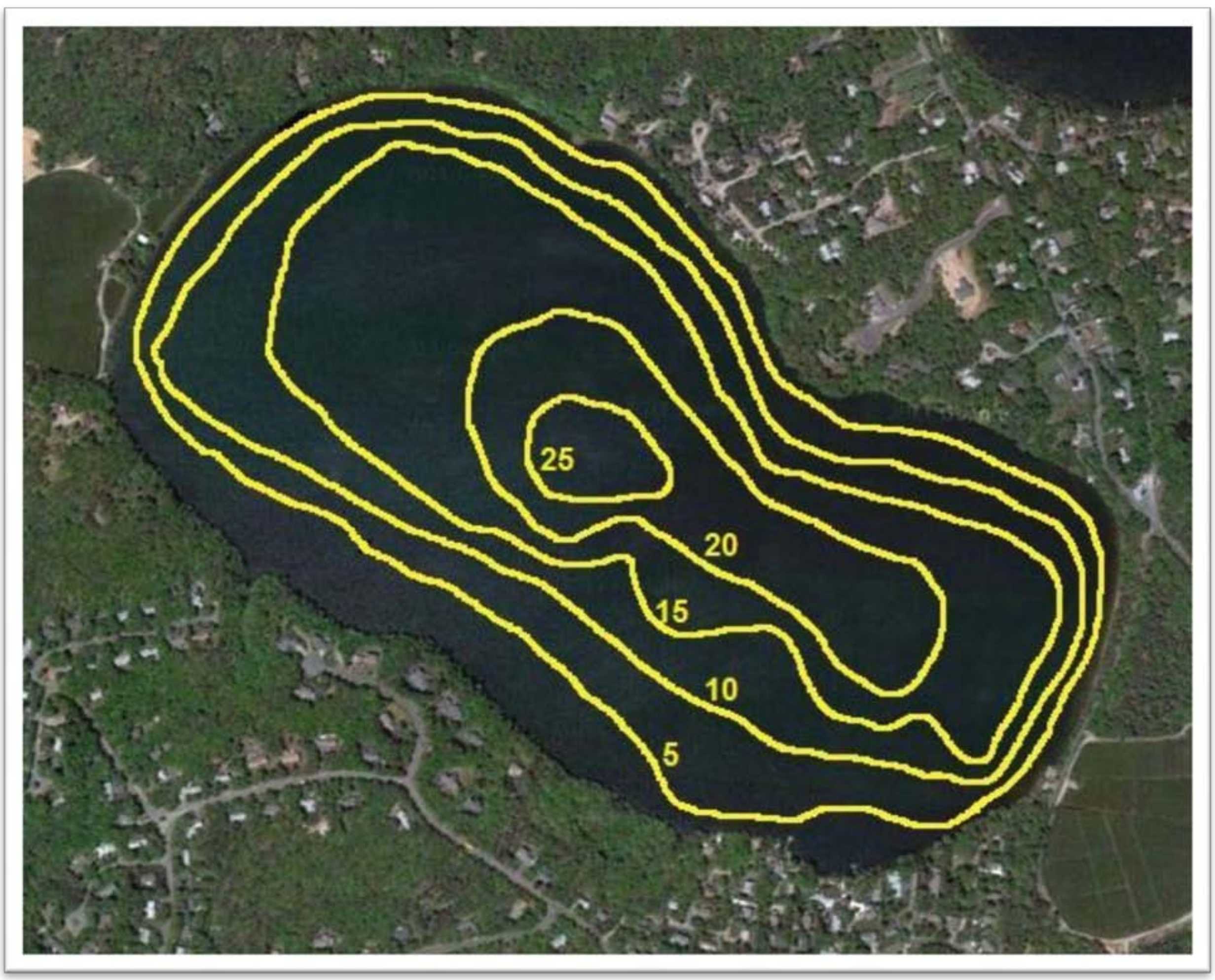
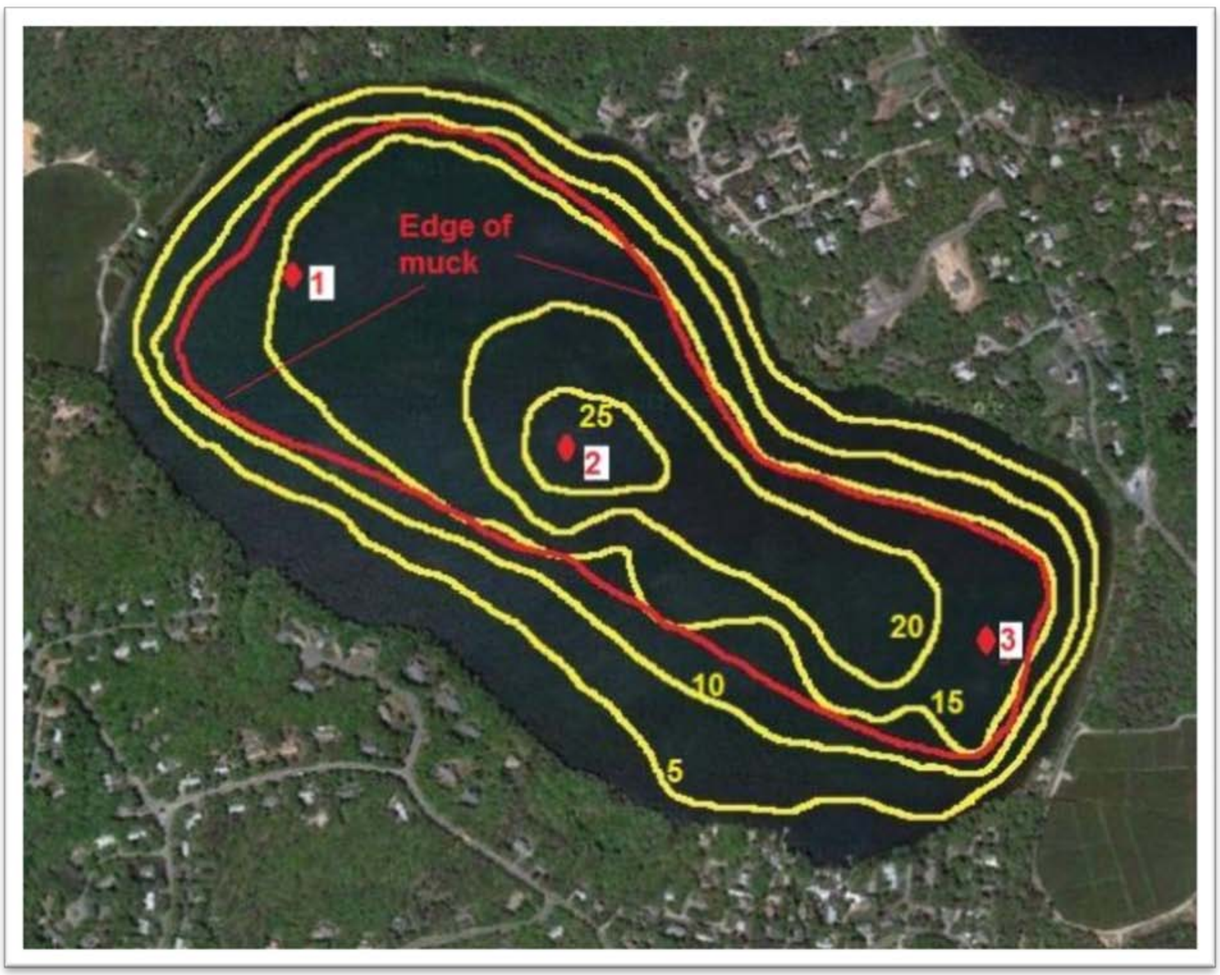


Table 1. Bathymetric features of Hinckleys Pond.

Depth (ft)	Area (ac)	Area (ha)	Volume (ac ft)	Volume (ft3)	Volume (m3)
0-5	174.0	70.2	800.3	34860565	987551
5-10	146.1	58.9	647.9	28220458	799446
10-15	113.0	45.6	476.8	20770581	588402
15-20	77.7	31.3	258.4	11255792	318861
20-25	25.7	10.3	75.3	3279565	92906
25-28	4.5	1.8	11.2	485862	13764
Total			2269.8	98872823	2800930

Figure 4. Defined edge of muck accumulations that completely cover the bottom of Hinckleys Pond.
(all contours are in feet, diamond shapes indicate sediment sampling locations)



Water Chemistry

A review of available water chemistry data (CCC 2003) indicates that a temperature-oxygen profile was collected in 1948 and again in 1989 by state agencies, with additional and more expanded monitoring by volunteers under the Pond And Lake Stewards (PALS) program supported by the School for Marine Science and Technology (SMAST) at UMASS Dartmouth starting in 2001. The August 1948 profile suggested well mixed conditions and oxygen levels near saturation at the top and bottom. The July 1989 profile indicated mixed conditions but depressed oxygen at about 69% saturation near the bottom. Assessment in August 2001 revealed oxygen at <1 ppm at water depths >20 ft (6 m). As the depth of Hinckleys Pond is such that temporary or weak stratification is possible, variations in weather could affect that stratification and related water chemistry, so the progression of oxygen levels in deep water may not be quite so definitive as the limited data make it sound. However, it has been a typical progression for Cape Cod lakes to have had high deep water oxygen prior to the 1950s transition to lower oxygen levels more recently, with attendant increases in internal phosphorus recycling from iron-bound accumulations in the organic surficial bottom sediments. This certainly appears to be what has happened at Hinckleys Pond.

A review of PALS data from September 2001 from water <13 ft (4 m) deep, provided in the CCC (2003) summary, lists low alkalinity (5.6 mg/L), moderately elevated phosphorus (30-33 ug/L), nitrogen levels in the low to moderate transition zone (440-450 ug/L), and somewhat elevated chlorophyll *a* concentration (9.2-9.6 ug/L). Deep water values were not provided, but the surface values suggest that available phosphorus was supporting excessive algal production at that time, late in the summer. It appears that degraded conditions began at least a decade ago.

Examination of summer PALS data secured by the Town (Table 2) indicates that the pond stratifies only weakly and temporarily during summer, but normally exhibits some oxygen depression below depths of 16.5 to 20 ft (5-6 m), usually with oxygen depletion deeper than 20 to 23.5 ft (6-7 m). Yet there is variability that indicates influence by the weather; colder, windier periods tend to preclude or break down stratification and minimize deep water oxygen depression. In all summers, however, there are periods when low oxygen near the sediment-water interface in deep water would be expected to promote release of phosphorus from iron-bound forms in organic sediments. When iron is plentiful, it will recombine with the phosphorus and precipitate out of solution when exposed to oxygen in shallower water, minimizing phosphorus availability. Yet some phosphorus will become available, and we do not have data for iron levels, and scavenging of iron by sulfides under low oxygen conditions is a well-known mechanism whereby iron is removed and phosphorus availability is increased in Cape Cod lakes. With multiple processes at work, it is likely that there will be variation in phosphorus availability and a range of conditions in Hinckley Pond over sequential summers.

The PALS phosphorus data for summer sampling (Table 2) reflect the mechanisms and variability discussed above, with surface water (0-13 ft, or 0-4 m depth) values generally lower than mid-depth (point of weak stratification, 16.5 -20 ft, or 5-6 m depth) values, which in turn are lower than deepest water (> 20 ft or >6 m depth) values (Figure 5). There is considerable scatter, more than would be expected if the pond was a little deeper and a bottom water layer was present all summer. As it is,

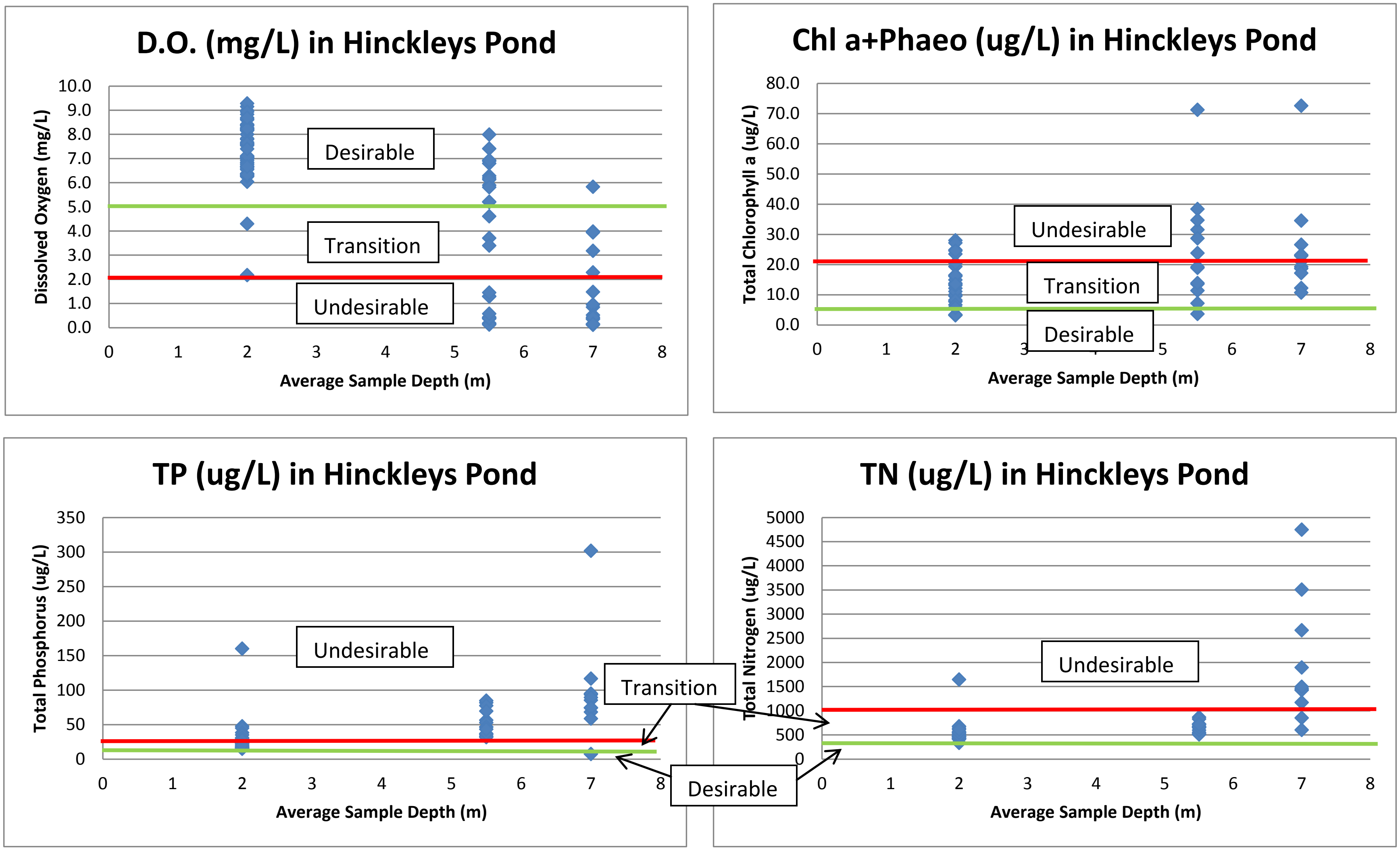
Table 2. Water quality data for Hinckleys Pond collected by the PALS program, 2005 – 2010.

Date	Sample Depth (m)	Pond Depth (m)	Secchi Depth (m)	Temp (C)	D.O. (mg/L)	pH (SU)	Alk (mg/L CaCO3)	TP (uM)	TP (ug/L)	TN (uM)	TN (ug/L)	Chl a (ug/L)	Phaeo (ug/L)	Chl a + Phaeo (ug/L)
6/14/2005	0.5	8.1	3.5	23.2	8.4	6.4	7.9	0.66	20.4	24.11	337.5	4.9	4.7	9.6
6/14/2005	6.0			13.5	0.2	6.0	16.1	1.50	46.5	47.34	662.8	7.2	4.1	11.3
8/24/2005	0.5	6.8	1.7	25.1	8.2	6.7	10.5	0.60	18.6	23.82	333.5	9.9	2.2	12.1
8/24/2005	5.5					6.2	13.3	1.19	36.9	36.33	508.6	26.7	4.8	31.5
7/5/2006	1.0	8.0				6.5	10.1	0.82	25.2	33.30	466.2	3.1	<0.05	3.1
7/5/2006	2.5					6.8	10.3	0.76	23.6	30.56	427.9	2.6	0.7	3.2
8/16/2006	0.5	8.0	1.1	24.0	7.0									
8/16/2006	1.0			24.0	7.0	6.6	13.1	0.99	30.6	47.89	670.4	16.9	3.5	20.5
8/16/2006	2.0			24.0	7.0									
8/16/2006	3.0			24.0	6.9									
8/16/2006	4.0			24.0	6.8									
8/16/2006	5.0			23.9	6.9	6.5	13.1	1.06	32.9	48.49	678.9	15.8	3.1	18.9
8/16/2006	6.0			23.8	5.9									
8/16/2006	6.5			23.6	0.9									
6/21/2007	0.5					6.3	7.3	0.80	24.7	35.59	498.3	6.0	4.0	10.0
6/21/2007	6.0					6.0	12.1	1.50	46.3	51.85	726.0	4.8	9.0	13.9
8/7/2007	0.5					6.3	9.3	0.90	27.7	33.13	463.9	10.7	8.6	19.3
8/7/2007	6.9					6.1	21.6	3.02	93.4	60.75	850.6	6.7	12.6	19.3
8/21/2007	0.5	8.0	1.0	22.7	7.0	6.1	10.3	1.53	47.4	40.39	565.4	21.9	2.8	24.8
8/21/2007	1.0			22.7	7.1									
8/21/2007	2.0			22.7	7.1									
8/21/2007	3.0			22.7	7.1									
8/21/2007	4.0			22.7	7.1									
8/21/2007	5.0			22.6	6.8									
8/21/2007	6.0			22.6	6.2									
8/21/2007	7.0			22.5	4.0									
8/21/2007	7.5			22.5	1.5									
8/21/2007	8.0					6.0	11.7	1.89	58.6	42.89	600.5	18.2	5.0	23.1
9/18/2007	0.5					6.6	12.3	1.44	44.6	45.41	635.7	18.7	9.3	28.0
9/18/2007	6.0					6.6	12.3	1.39	43.1	51.85	726.0	19.9	8.8	28.7
7/9/2008	0.5	8.4	2.2	26.0		6.6	35.5	0.56	17.4	24.03	336.5	5.5	2.2	7.7
7/9/2008	2.0			26.0										
7/9/2008	3.0			25.9										
7/9/2008	4.0			24.8										
7/9/2008	5.0			22.6	1.3									
7/9/2008	6.0			20.1	1.5									
7/9/2008	7.0			18.0	1.0	6.3	37.1	3.76	116.4	83.46	1168.4	5.3	13.4	18.7
7/24/2008	0.5	8.0	1.0	26.5	8.4	6.6	6.8	0.48	14.9	30.36	425.0	12.5	3.9	16.4
7/24/2008	2.0			26.4	8.4									
7/24/2008	3.0			26.3	8.2									
7/24/2008	4.0			26.2	8.2									
7/24/2008	5.0			26.1	8.0									
7/24/2008	6.0			22.1	0.2									
7/24/2008	7.0			21.5	0.5	6.4	47.6	0.23	7.1	190.44	2666.1	5.5	6.7	12.2
8/7/2008	0.5	8.1	1.0	24.4	6.6	6.4	7.2	1.23	38.2	39.90	558.7	21.9	5.2	27.1
8/7/2008	1.0			24.7	6.6									
8/7/2008	2.0			24.7	6.7									
8/7/2008	3.0			24.7	6.0									
8/7/2008	4.0			24.7	6.3									
8/7/2008	5.0			24.6	5.2									
8/7/2008	6.0			23.3	0.2									
8/7/2008	7.0			18.9	0.1									
8/7/2008	7.2					6.4	38.5	2.88	89.3	135.37	1895.1	10.2	12.7	22.8
8/26/2008	0.5	8.1	1.5	23.9	7.0	6.5	7.6	0.56	17.4	32.52	455.2	10.4	3.3	13.8
8/26/2008	1.0			23.9	7.0									
8/26/2008	2.0			24.0	7.1									
8/26/2008	3.0			23.9	7.0									
8/26/2008	4.0			23.9	6.4									
8/26/2008	5.0			23.6	1.3									
8/26/2008	6.0			23.3	0.1									
8/26/2008	7.0			22.3	0.1	6.8	67.9	3.06	94.8	250.54	3507.5	7.7	13.3	21.0
9/9/2008	0.5	8.2	1.6	23.4	9.0	6.7	7.0	0.75	23.3	30.16	422.2	10.1	4.8	14.9
9/9/2008	2.0			23.5	8.8									
9/9/2008	4.0			23.4	8.2									
9/9/2008	6.0			23.1	6.1									
9/9/2008	7.5					6.2	7.0	9.74	301.8	102.13	1429.9	16.8	55.8	72.6
9/9/2008	8.0			23.0	3.9									

Table 2. continued

Date	Sample Depth (m)	Pond Depth (m)	Secchi Depth (m)	Temp (C)	D.O. (mg/L)	pH (SU)	Alk (mg/L CaCO3)	TP (uM)	TP (ug/L)	TN (uM)	TN (ug/L)	Chl a (ug/L)	Phaeo (ug/L)	Chl a + Phaeo (ug/L)
7/14/2009	0.5	7.9	2.5	22.1	6.7	6.2	5.6	0.92	28.6	30.65	429.1	5.5	2.3	7.8
7/14/2009	2.0			22.0	6.7									
7/14/2009	4.0			22.2	6.5									
7/14/2009	6.0			18.4	0.4	6.1	8.5	2.50	77.4	47.05	658.6	71.2	<0.05	71.2
7/28/2009	0.5					6.3	5.9	1.13	35.0	29.29	410.0	10.3	5.8	16.1
7/28/2009	7.5					6.6	21.5	2.40	74.3	106.85	1495.9	11.3	15.2	26.5
7/29/2009	0.5					5.6	3.4	5.16	159.9	117.47	1644.6	8.1	2.9	11.0
8/12/2009	0.5	8.5	0.7	25.8	8.4	6.9	5.9	0.72	22.3	30.35	424.9	3.5	19.9	23.5
8/12/2009	2.0			25.8	8.2									
8/12/2009	3.0					6.0	6.0	0.88	27.1	30.05	420.6	10.0	6.3	16.3
8/12/2009	4.0			24.6	4.3									
8/12/2009	5.5					6.3	6.2	1.70	52.8	42.80	599.1	4.6	2.5	7.1
8/12/2009	6.0			21.5	0.4									
8/26/2009	0.5	8.2	1.2	26.4	7.6	6.3	5.9	0.73	22.8	39.15	548.1	20.6	4.0	24.5
8/26/2009	1.0			26.4	7.6									
8/26/2009	2.0			26.4	7.6									
8/26/2009	3.0			26.2	6.8									
8/26/2009	4.0			24.7	2.2									
8/26/2009	5.0			23.6	0.4	6.6	21.5	2.64	81.7	61.62	862.6	8.4	10.8	19.2
8/26/2009	6.0			22.5	0.4									
8/26/2009	7.0			21.7	0.4									
9/8/2009	0.5	8.1	1.7	22.8	9.2									
9/8/2009	1.0			22.5	9.3									
9/8/2009	2.0			21.0	8.9									
9/8/2009	3.0			22.0	8.3									
9/8/2009	4.0			21.9	7.6									
9/8/2009	5.0			21.7	7.4									
9/8/2009	6.0			21.6	6.9									
9/8/2009	7.0			21.6	3.2									
7/1/2010	0.5	7.9	2.8	24.9	7.8	6.9	6.0	0.52	16.1	33.90	474.5	3.2	0.1	3.3
7/1/2010	2.0			24.9	7.8									
7/1/2010	3.0			24.9	7.7	7.0	6.0	0.51	15.9	32.72	458.1	3.4	<0.05	3.4
7/1/2010	5.0			22.0	3.7	6.5	9.8	1.82	56.3	59.09	827.3	20.9	2.9	23.7
7/1/2010	6.0			20.2	0.4									
7/1/2010	7.0			18.7	0.4	6.7	23.9	2.75	85.2	101.57	1422.0	10.7	<0.05	10.7
7/15/2010	0.5	6.5	1.7	27.1	7.5	6.9	6.3	0.92	28.5	32.43	454.0	8.2	<0.05	8.2
7/15/2010	2.0			27.1	8.0									
7/15/2010	3.0					7.0	6.4	0.82	25.3	34.04	476.6	6.5	0.1	6.6
7/15/2010	4.0			27.0	7.4									
7/15/2010	5.0			24.1	0.4	6.6	9.7	2.73	84.4	46.49	650.9	30.4	8.0	38.3
7/15/2010	6.0			21.7	0.6	6.4	13.2	2.24	69.3	51.18	716.5	20.7	14.0	34.6
8/3/2010	0.5	7.6	1.8	25.2	8.3	7.1	6.8	0.97	30.2	37.41	523.8	9.6	3.5	13.1
8/3/2010	2.0			25.1	8.2									
8/3/2010	3.0					7.0	6.6	0.88	27.3	38.88	544.3	10.3	3.1	13.4
8/3/2010	4.0			24.9	8.2									
8/3/2010	5.0					6.9	6.9	1.15	35.7	37.12	519.7	8.1	5.5	13.6
8/3/2010	6.0			24.4	5.2									
8/3/2010	6.5					6.6	17.3	2.20	68.1	103.92	1454.8	20.8	13.7	34.5
8/3/2010	7.0			21.5	0.4									
8/17/2010	0.5	8.0	1.1	24.6	6.4	6.9	6.7	0.52	16.1	48.25	675.5	5.8	<0.05	5.8
8/17/2010	1.0			24.6	6.4									
8/17/2010	2.0			24.6	6.3									
8/17/2010	3.0			24.6	6.3	6.9	6.7	0.65	20.0	43.56	609.9	5.7	<0.05	5.7
8/17/2010	4.0			24.6	6.3									
8/17/2010	5.0			24.6	6.3	6.9	6.7	1.02	31.6	39.32	550.4	3.6	<0.05	3.6
8/17/2010	6.0			24.4	4.6									
8/17/2010	7.0			22.3	0.2	6.7	55.8	2.39	74.0	339.21	4749.0	17.2	<0.05	17.2
8/xx/2010	0.5	7.8	2.2	26.5	8.6									
8/xx/2010	2.0			24.7	8.6									
8/xx/2010	4.0			22.3	8.7									
8/xx/2010	6.0			22.0	3.4									
8/xx/2010	7.0			21.8	2.3									
9/6/2010	0.5	8.0	1.6	23.0	6.8									
9/6/2010	2.0			23.0	6.8									
9/6/2010	4.0			22.9	6.7									
9/6/2010	6.0			22.8	5.8									
9/6/2010	7.0			22.8	5.8									

Figure 5. Selected water quality of Hinckleys Pond, 2005 – 2010, expressed for three depth ranges.
Green lines represent highly desirable threshold values, while red lines represent very undesirable thresholds.



phosphorus is released by bottom sediments in deeper water, accumulates if there is weak stratification, but is periodically mixed with overlying waters, raising surface water values above desirable levels (<25 ug/L, preferably <10 ug/L). The pattern is not as striking for total nitrogen, with high bottom values suspected to be a function of ammonium build-up near the bottom during periods of anoxia (no oxygen), but is still apparent. The chemical processes are driven by oxygen, which also shows a strong surface – mid-depth – bottom pattern of decline, but with enough variation to indicate that phosphorus release and ammonium build-up will not occur every day during summer, and indicating that weather patterns (particularly wind) will be important determinants of conditions in the pond.

Algal abundance in Hinckleys Pond was assessed using available data for total chlorophyll *a*, which is the sum of chlorophyll *a* and phaeophytin, two pigments common to all algae. The PALS data (Figure 5) show relatively high levels of total chlorophyll *a* found throughout the water column. Chlorophyll *a* degrades into phaeophytin, and the two values are usually combined as total chlorophyll *a* in analyses like this, as the phaeophytin still represents algal biomass, and it is often uncertain whether the degradation of chlorophyll is occurring in the lake or in the samples before processing. As the one pigment that all algae have in common, chlorophyll *a* is often used as an indicator of algal abundance and productivity potential. However, the quantity of chlorophyll *a* per unit of algal biomass varies among major algal groups, with a low ratio of about 50:1 for green algae and a high ratio of about 300:1 for cyanobacteria. So the same amount of chlorophyll *a* present as cyanobacteria will represent a much higher biomass than if the chlorophyll *a* is in green algae. Total chlorophyll *a* is, however, still useful as a general indicator of algal abundance.

The values for the three depth ranges represented in Figure 5 are not significantly different in a statistical sense, but with cyanobacteria there are often surface scums that form and result in very high surficial values. Yet the Hinckleys Pond data for chlorophyll *a* suggest that deep values are at least as high as surface values based on limited sampling. It appears that wind, settling, or other factors are vertically distributing the algae, which are known to include many cyanobacteria during summer. It is also possible that the high values deep in the pond may be indicative of algal growths stationed at the transition zone, where available phosphorus and nitrogen are more abundant.

The average values for the displays in Figure 5 are provided in Table 3, as well as values for pH, alkalinity and Secchi depth (water clarity). Water clarity averages 5.6 ft (1.7 m), not an unsafe value for visibility, but not desirable either. However, as an average, this value indicates that lower values will often occur, and these may indeed be unsafe for swimming due to poor visibility. The September 2011 Secchi value was also 1.7 m. That the low clarity is related to algal blooms, many of which are dominated by cyanobacteria and may produce toxins, detracts further from contact recreation safety. The pH is slightly acidic, typical of Cape ponds. Alkalinity is low near the surface, but increases with depth and is fairly high for Cape ponds in deeper water; this indicates a build-up of dissolved solids.

Table 3. Average values for water quality features of Hinckleys Pond, 2005-2010.
Green highlighted values raise no concerns; yellow highlighted values raise some concern; red highlighted values cause considerable concern for water quality and pond condition.

Average values over specified depth ranges for mid-June to early September samples												
Sample Depth (m)	Secchi Depth (m)	Temp (C)	D.O. (mg/L)	pH (SU)	Alk (mg/L CaCO3)	TP (uM)	TP (ug/L)	TN (uM)	TN (ug/L)	Chl a (ug/L)	Phaeo (ug/L)	Chl a + Phaeo (ug/L)
0-4	1.7	24.4	7.3	6.6	8.5	1.0	30.3	37.5	524.7	9.5	4.5	13.2
5-6		22.4	3.3	6.4	11.5	1.7	53.4	47.7	668.3	18.6	6.7	24.3
6.5-8.0		21.5	1.6	6.4	31.8	3.1	96.6	137.9	1930.9	11.9	16.5	25.3

Overall, water quality in Hinckleys Pond is not good, but it is tempered by wind mixing that prevents lower oxygen for longer duration and limits surface scum formation. Still, low oxygen does occur in deeper waters and algal blooms do develop, often involving cyanobacteria with the potential for surface scums during summer. Phosphorus concentrations are elevated on average, promoting high algal growth; unless those algae are consumed by zooplankton (which are scarce in Hinckleys Pond), high algal biomass can be expected. The algae will accumulate in the water column while they are growing and will settle to the bottom when they die, adding to the organic muck layer and oxygen demand that it exerts. Nitrogen to phosphorus (N:P) ratios are not routinely low, but are sometimes low enough to favor cyanobacteria, some forms of which can make use of dissolved nitrogen gas instead of the measured inorganic forms.

Sediment Assessment

As noted previously (see Figure 4 and nearby text), organic muck sediments completely cover the natural sandy bottom of the pond over the 90 deepest acres of the pond. Significant muck deposits can be found in water as shallow as 11 ft deep on the southwest side and as deep as 16 ft on the northeast side of the pond, the differences being related to variable slope of the pond bottom. Over those 90 acres, the veneer of organic muck interacts with the overlying water and can release certain compounds under low oxygen conditions that might otherwise stay bound in the sediment.

Of particular concern is phosphorus, which tends to be mostly in organic compounds or bound to iron in the organic sediment. Only some of the organic matter decays, and that portion tends to release phosphorus slowly, so it is less of a threat than the iron-bound phosphorus, which can be released by chemical reactions under anoxia at a rate that will change the phosphorus concentrations in the overlying water. Loosely sorbed phosphorus is another readily available form of sediment phosphorus, but this source is usually minimal in Cape ponds. The total sediment phosphorus level is worth knowing, but is not useful for calculation of likely seasonal internal recycling. Such internal recycling is often one of the major sources of phosphorus in kettlehole ponds, and has been determined to be the primary cause of algal blooms in many other Cape ponds.

Data for two samples collected by the Town of Harwich on December 14, 2009, produced minimal loosely sorbed phosphorus in both samples, very low total and iron-bound phosphorus from one sample, but very high total and iron-bound phosphorus from the other sample (Table 4). The east sample was collected in shallower water and is clearly sandy (based on solids content), so it is no surprise that this sample has relatively low levels of any form of phosphorus. The west sample is from deeper water and is a loose organic muck, with about 10% solids, and had an iron-bound phosphorus level that is of definite concern for potential release under anoxia.

Table 4. Sediment quality data from the December 2009 sampling.

Station	Total P (mg/kg)	% Solids	Fe-P (mg/kg)	Loose-P (mg/kg)
West	6720	10.2	1380	0.45
East	95.4	75.8	34.2	0.21

Sampling of three locations (Figure 4) in September of 2011 yielded all muck samples, by intent, and those results were fairly similar for all stations (Table 5). Solids content was low, at 11 to 14%, while organic content (volatile solids) was relatively high at 33 to 34%; all material is typical pond muck sediment. Total phosphorus levels were elevated, but most of this is tied up in organic matter, much of which is likely to be refractory. Loosely sorbed phosphorus was minimal, as has been the case in every Cape pond sample examined to date. Iron-bound phosphorus, while only 8 to 13% of the total phosphorus value, is high in an absolute sense; if all the iron-bound phosphorus in just 10 vertical centimeters of a square meter was released at once, the overlying water in the deepest part of the pond could experience a phosphorus increase of over 1 mg/L (1000 ug/L, with an undesirable threshold of 25 ug/L). A smaller release from a thinner slice of surficial sediment would be adequate to support algal blooms; the potential for significant internal loading is very high.

All of the iron-bound phosphorus is not released at once, and various mechanisms tend to keep the effective release to <20% of the total, but the potential for major phosphorus increase is obvious. In terms of the values for iron-bound phosphorus concentration in Tables 4 and 5, values >50 mg/kg are cause for some concern, and values >200 mg/kg suggest a high potential for impact through internal loading. Except for the one sandy sample collected in December 2009, all samples exhibited high potential for phosphorus release. It follows that all areas of muck sediment in the pond represent a threat to pond condition. Actual release is very difficult to measure in a pond that does not strongly stratify, but values up to about 165 kg P/yr (representing just 5% of the available P reserves) are entirely plausible with intermittent anoxia and mixing.

Table 5. Sediment quality data from the September 2011 sampling.

Green highlighted values raise no concerns; yellow highlighted values raise some concern; red highlighted values cause considerable concern for possible phosphorus release.

					Initial Concentration		Fe-P (mg/kg) at Aluminum Dose =			
Station	Total P (mg/kg)	% Solids	% Moisture	% Volatile Solids	Fe-P (mg/kg)	Loose-P (mg/kg)	25 g/m2	50 g/m2	75 g/m2	100 g/m2
HS-1	6560	11.0	91.8	33.4	733	<6.8	184	268	126	68.5
HS-2	6350	11.8	91.8	32.6	806	<6.4	462	832	361	155
HS-3	5930	14.2	91.6	33.8	504	<5.3	139	104	48.9	ND

Phytoplankton

Historic information on phytoplankton in Hinckleys Pond is limited to chlorophyll measurements and anecdotal reports of algal blooms. Cyanobacterial blooms have been reported for at least a decade, and have been observed by reliable sources in each of the last three years. Chlorophyll data suggest that problems with algal blooms have existed for over a decade, consistent with observations by long-term residents and town officials. Yet actual plankton data are limited to three samples in summer 2011 (Tables 6 and 7, Figure 6). Numerically, cyanobacteria were most abundant in all samples, but their small cell size limits biomass dominance to the August sample. Green algae comprised the greatest fraction of biomass in the September and October samples, a common occurrence in many overfertile Cape ponds. Declining temperatures and shifting nutrient ratios (increased N:P in particular) tend to foster this shift. The primary algae present include the filamentous nitrogen-fixing and potential toxin producing cyanobacteria *Anabaena* and *Aphanizomenon*, the filamentous but non-nitrogen-fixing cyanobacteria *Planktolyngbya* and *Pseudanabaena* (common late season forms), and a variety of chlorococcalean green algae (very common bloom formers in many Cape ponds). A few diatoms were moderately abundant, as was the dinoflagellate *Peridinium*. All forms are commonly associated with overly fertile ponds. It is reasonable to assume that recent summer blooms include the same or similar cyanobacteria, with shifts to chlorococcalean greens when N:P ratios are high. It is notable that the common coccoid bloom formers Microcystis and Woronichinia were absent, but these may have been present earlier in the season before samples were collected.

Zooplankton

Historic information on zooplankton is minimal, but from the longstanding presence of an alewife population, it is very likely that Hinckleys Pond has had a low density of only small bodied forms for many years. The situation is much the same in Long Pond and other Cape ponds where alewife spawn, as the young of the year fish essentially strain all larger zooplankton from the water column. Cape ponds that support alewife runs often have denser winter zooplankton, with larger bodied forms depositing resting eggs prior to the spring hatch of alewife, allowing the population to resurge after the alewife young leave the pond in the fall. We have only one sample for Hinckleys Pond, and it exhibits (Table 8) the expected summer zooplankton population; there are few zooplankton and only small bodied forms. Biomass is <10 ug/L, a very low value, and average crustacean zooplankton body length is 0.42 mm, consistent with heavy size selective predation. There is no reason to believe that a denser, larger bodied zooplankton population exists in any summer in Hinckleys Pond. This is not by itself a problem, but it does mean that there will be no substantial zooplankton grazing capacity to offset algal production. The level of algal biomass accumulation will be as large as the base fertility of the system allows. For Hinckleys Pond, with elevated phosphorus and at least moderate nitrogen levels, that base fertility is high.

Table 6. Phytoplankton data for Hinckley Pond.

	PHYTOPLANKTON DENSITY						
	(CELLS/ML)				(UG/L)		
	Hinckley	Hinckley	Hinckley		Hinckley	Hinckley	Hinckley
TAXON	08/15/11	09/21/11	10/14/11		08/15/11	09/21/11	10/14/11
BACILLARIOPHYTA							
Centric Diatoms							
Aulacoseira	0	650	890		0.0	195.0	267.0
Cyclotella	0	130	20		0.0	13.0	2.0
Araphid Pennate Diatoms							
Synedra	25	364	550		20.0	291.2	584.0
Tabellaria	0	52	0		0.0	41.6	0.0
Monoraphid Pennate Diatoms							
Biraphid Pennate Diatoms							
Nitzschia	25	0	0		20.0	0.0	0.0
CHLOROPHYTA							
Flagellated Chlorophytes							
Coccoid/Colonial Chlorophytes							
Ankistrodesmus	0	780	230		0.0	78.0	23.0
Coelastrum	0	416	200		0.0	83.2	40.0
Golenkinia	0	624	120		0.0	124.8	24.0
Micractinium	200	1300	60		600.0	3900.0	180.0
Pediastrum	0	208	400		0.0	41.6	80.0
Scenedesmus	600	416	640		60.0	41.6	64.0
Schroederia	50	260	80		125.0	650.0	200.0
Filamentous Chlorophytes							
Desmids							
Staurastrum	0	312	840		0.0	249.6	672.0
CHRYSOPHYTA							
Flagellated Classic Chrysophytes							
Mallomonas	25	78	30		12.5	39.0	50.0
Synura	300	0	0		240.0	0.0	0.0
Non-Motile Classic Chrysophytes							
Haptophytes							
Tribophytes/Eustigmatophytes							
Raphidophytes							
CRYPTOPHYTA							
Cryptomonas	200	52	40		40.0	10.4	8.0
CYANOPHYTA							
Unicellular and Colonial Forms							
Aphanocapsa	0	0	2400		0.0	0.0	24.0
Filamentous Nitrogen Fixers							
Anabaena	27750	0	0		5550.0	0.0	0.0
Aphanizomenon	10500	4680	5200		1365.0	608.4	676.0
Filamentous Non-Nitrogen Fixers							
Planktolyngbya	47500	23400	11250		475.0	234.0	112.5
Pseudanabaena	1500	1560	8500		15.0	15.6	85.0
EUGLENOPHYTA							
Trachelomonas	25	52	40		25.0	52.0	40.0
PYRRHOPHYTA							
Peridinium	0	26	80		0.0	54.6	597.0

Table 7. Summary of phytoplankton data for Hinckleys Pond.

	PHYTOPLANKTON FEATURE								
	(CELLS/ML)			(UG/L)			(Taxonomic Richness)		
	Hinckley	Hinckley	Hinckley	Hinckley	Hinckley	Hinckley	Hinckley	Hinckley	Hinckley
Phytoplankton Group	08/15/11	09/21/11	10/14/11	08/15/11	09/21/11	10/14/11	08/15/11	09/21/11	10/14/11
BACILLARIOPHYTA	50	1196	1510	40.0	540.8	981.0	2	4	8
Centric Diatoms	0	780	930	0.0	208.0	282.0	0	2	4
Araphid Pennate Diatoms	25	416	550	20.0	332.8	584.0	1	2	1
Monoraphid Pennate Diatoms	0	0	0	0.0	0.0	0.0	0	0	0
Biraphid Pennate Diatoms	25	0	30	20.0	0.0	115.0	1	0	3
CHLOROPHYTA	850	4316	2570	785.0	5168.8	1283.0	3	8	8
Flagellated Chlorophytes	0	0	0	0.0	0.0	0.0	0	0	0
Coccoid/Colonial Chlorophytes	850	4004	1730	785.0	4919.2	611.0	3	7	7
Filamentous Chlorophytes	0	0	0	0.0	0.0	0.0	0	0	0
Desmids	0	312	840	0.0	249.6	672.0	0	1	1
CHRYSOPHYTA	325	78	30	252.5	39.0	50.0	2	1	1
Flagellated Classic Chrysophytes	325	78	30	252.5	39.0	50.0	2	1	1
Non-Motile Classic Chrysophytes	0	0	0	0.0	0.0	0.0	0	0	0
Haptophytes	0	0	0	0.0	0.0	0.0	0	0	0
Tribophytes/Eustigmatophytes	0	0	0	0.0	0.0	0.0	0	0	0
Raphidophytes	0	0	0	0.0	0.0	0.0	0	0	0
CRYPTOPHYTA	200	52	40	40.0	10.4	8.0	1	1	1
CYANOPHYTA	87250	29640	27350	7405.0	858.0	897.5	4	3	4
Unicellular and Colonial Forms	0	0	2400	0.0	0.0	24.0	0	0	1
Filamentous Nitrogen Fixers	38250	4680	5200	6915.0	608.4	676.0	2	1	1
Filamentous Non-Nitrogen Fixers	49000	24960	19750	490.0	249.6	197.5	2	2	2
EUGLENOPHYTA	25	52	40	25.0	52.0	40.0	1	1	1
PYRRHOPHYTA	0	26	80	0.0	54.6	597.0	0	1	1
TOTAL	88700	35360	31620	8547.5	6723.6	3856.5	13	19	24
CELL DIVERSITY	0.48	0.59	0.78	0.52	0.72	1.04			
CELL EVENNESS	0.43	0.46	0.56	0.47	0.56	0.76			

Figure 6. Graphic summary of algal biomass in Hinckleys Pond.

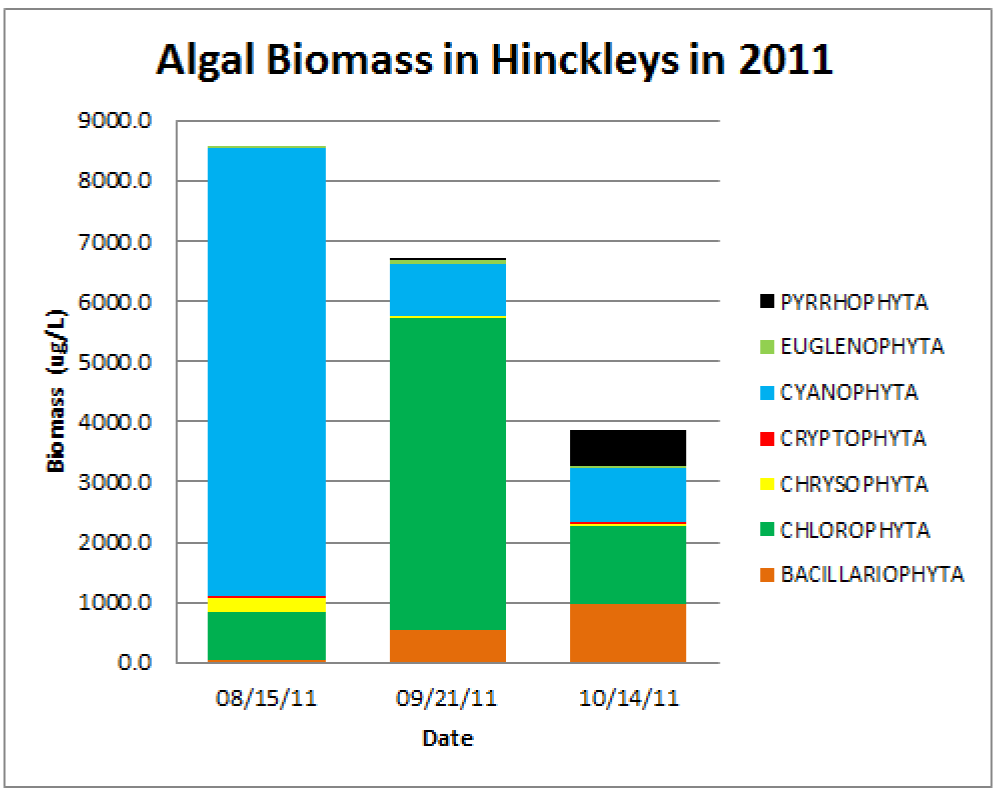


Table 8. Zooplankton of Hinckleys Pond.

	ZOOPLANKTON DENSITY		
	(#/L)		(UG/L)
	Hinckleys		Hinckleys
TAXON	9/21/11		9/21/11
PROTOZOA			
Ciliophora	0.0		0.0
Mastigophora	0.0		0.0
Sarcodina	0.0		0.0
ROTIFERA			
Asplanchna	3.2		4.8
Conochilus	0.2		0.0
Filinia	0.2		0.0
Keratella	0.7		0.1
Polyarthra	0.1		0.0
Trichocerca	0.1		0.0
COPEPODA			
Copepoda-Cyclopoida			
Cyclops	0.2		0.5
Copepoda-Calanoida			
Copepoda-Harpacticoida	0.0		0.0
Other Copepoda-Adults	0.0		0.0
Other Copepoda-Copepodites	0.0		0.0
Other Copepoda-Nauplii	0.5		1.3
CLADOCERA			
Bosmina	0.3		0.3
Holopedium	0.1		0.8
OTHER ZOOPLANKTON			
SUMMARY STATISTICS			
DENSITY			
PROTOZOA	0.0		0.0
ROTIFERA	4.5		4.9
COPEPODA	0.7		1.8
CLADOCERA	0.4		1.1
OTHER ZOOPLANKTON	0.0		0.0
TOTAL ZOOPLANKTON	5.6		7.8
TAXONOMIC RICHNESS			
PROTOZOA	0		
ROTIFERA	6		
COPEPODA	2		
CLADOCERA	2		
OTHER ZOOPLANKTON	0		
TOTAL ZOOPLANKTON	10		
S-W DIVERSITY INDEX	0.66		
EVENNESS INDEX	0.66		
MEAN LENGTH (mm): ALL FORMS	0.33		
MEAN LENGTH: CRUSTACEANS	0.42		

Rooted Plants

There has been no systematic survey of rooted aquatic plants in Hinckleys Pond. Based on visual examination using an underwater video system in September 2011, the rooted aquatic plant community of Hinckleys Pond is not a dominant biological component of this system. There are a few pondweeds (*Potamogeton* spp.) present, along with water celery (*Vallisneria americana*), some waterweed (*Elodea canadensis*), and some naiad (*Najas flexilis*), but growths are not expansive and are limited to water between about 2 and 10 ft deep. Water level fluctuations and limited light penetration are controlling factors, along with sandy substrate in the shallower portions of the pond. Rooted plants are not a major consideration for management issues at Hinckleys Pond.

Fish

Unpublished information from the Division of Fisheries and Wildlife and discussion with fishermen at Hinckleys Pond reveals fish populations that include alewife (*Alosa pseudoharengus*), largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dolomieui*), chain pickerel (*Esox niger*), white perch (*Morone americana*), yellow perch (*Perca flavescens*), white sucker (*Catostomus commersoni*), pumpkinseed (*Lepomis gibbosus*), brown bullhead (*Ameiurus nebulosus*) tessellated darter (*Etheostoma olmstedii*), banded killifish (*Fundulus diaphanus*), bridle shiner (Notropis bifrenatus) and American eel (*Anguilla rostrata*). Reports that Hinckleys Pond has provided an excellent warmwater fishery for an extended period of years have been noted, but there is no recent data to corroborate such statements. No recent survey data have been encountered, but the bridle shiner is a state listed species of concern. Unlike many listed species, it is not habitat destruction that threatens this species, but rather competition from released bait fish and predation from stocked predators in most ponds.

Watershed Features and Loads

Watershed Size and Boundary

The surface watershed for Hinckleys Pond includes the area draining to Long Pond and Seymour Pond, both of which overflow to Hinckleys Pond through short channels, plus the direct drainage to Hinckleys Pond itself. That watershed is somewhat difficult to define, given the very porous nature of area soils, but is believed to cover about 2422 acres in the immediate area of the three ponds (Figure 7), including 1500 acres of land as well as the 740-acre Long Pond and 182-acre Seymour Pond. Land use in this area has the potential to impact Hinckleys Pond, but the vast majority of this area drains first into Long Pond or Seymour Pond, each of which has substantial detention time and allows contaminant loads from the watershed to be diminished. The direct drainage area to Hinckleys Pond is about 190 acres, and includes two cranberry bogs and generally low density residential development.

Groundwater flow is a major consideration for most Cape ponds, and the direction of flow is often more important to determining the contributory land area than the surface land contours. The area contributing groundwater to Hinckleys Pond is reduced by the location of Long Pond at the groundwater divide of the Monomoy lens. Long and Seymour Ponds are believed to intercept most shallow groundwater originating at the divide. Long Pond then contributes flow to Hinckleys Pond both through the surface water connection and, to a much lesser extent, outseepage of water from Long Pond some of which becomes inseepage to Hinckleys Pond. Seymour Pond, on the other hand, only contributes upgradient groundwater through its surface water connection to Hinckleys Pond; groundwater leaving Seymour Pond travels toward the west, flowing north of Hinckleys Pond.

Groundwater flows were interpreted from a representation of the Monomoy lens aquifer developed from the USGS groundwater model (Walter and Whealan 2005). The model simulations represented 2003 average input conditions (such as rainfall/recharge and water supply well pumping rates). Under this scenario, the high point for the groundwater table in the area affecting Hinckleys Pond is northeast of Long Pond (Figure 8). Groundwater flow from this high point will both travel downward to create deep groundwater flow in the aquifer and will also travel outward to create shallow groundwater flow. The shallow groundwater originating from this high point and traveling to the southwest will likely be groundwater intercepted by the deeper Long Pond, and then either returned to the aquifer along Long Pond's southern and western shorelines or transmitted the rest of the way as surface water overflow or subsurface flow from Long Pond to Hinckleys Pond. Some groundwater leaving Long Pond's western shoreline may enter Seymour Pond and then be transmitted through the dug channel to Hinckleys Pond.

It is important to emphasize, however, that groundwater paths on Cape Cod (and especially in the vicinity of the groundwater divide) are even more difficult to know exactly than surface water drainage, and may vary over time with both natural and anthropogenic factors. Based on available data and modeling, it appears that Hinckleys Pond has a small direct groundwater contribution zone (Figure 9).

Land Uses

Land use in the vicinity of Hinckleys Pond (Figure 10) is dominated by just two uses: residential development and cranberry bogs. There is some wooded wetland adjacent to the pond on the west side, south of the Thatcher Bog, and residential development is not dense, but most parcels other than the two bog properties are privately held and have dwellings on them. Many of those dwellings are seasonal, but many are year round residences for retired couples as well. The user population swells in the summer, but is not negligible in the winter. The bogs have a typical annual cycle of activity, with frost management, sanding and other maintenance activities in the winter, irrigation during the growing season, and flooding for harvest in early October. Landscaping on individual properties is variable, ranging from natural to highly altered conditions. Roads have few stormwater control structures; most runoff infiltrates into the adjacent sandy soil, but in a few cases there are paved or even natural slopes that create significant runoff and possible erosion hazards. Issues relating to land uses are covered in separate sections of this report.

Figure 7. Surface watershed of Hinckleys Pond.

Figure 8. Groundwater contours in the Hinckleys Pond area. Data from USGS model of the Monomoy Lens (Walter and Whealan 2005) using average pumping conditions

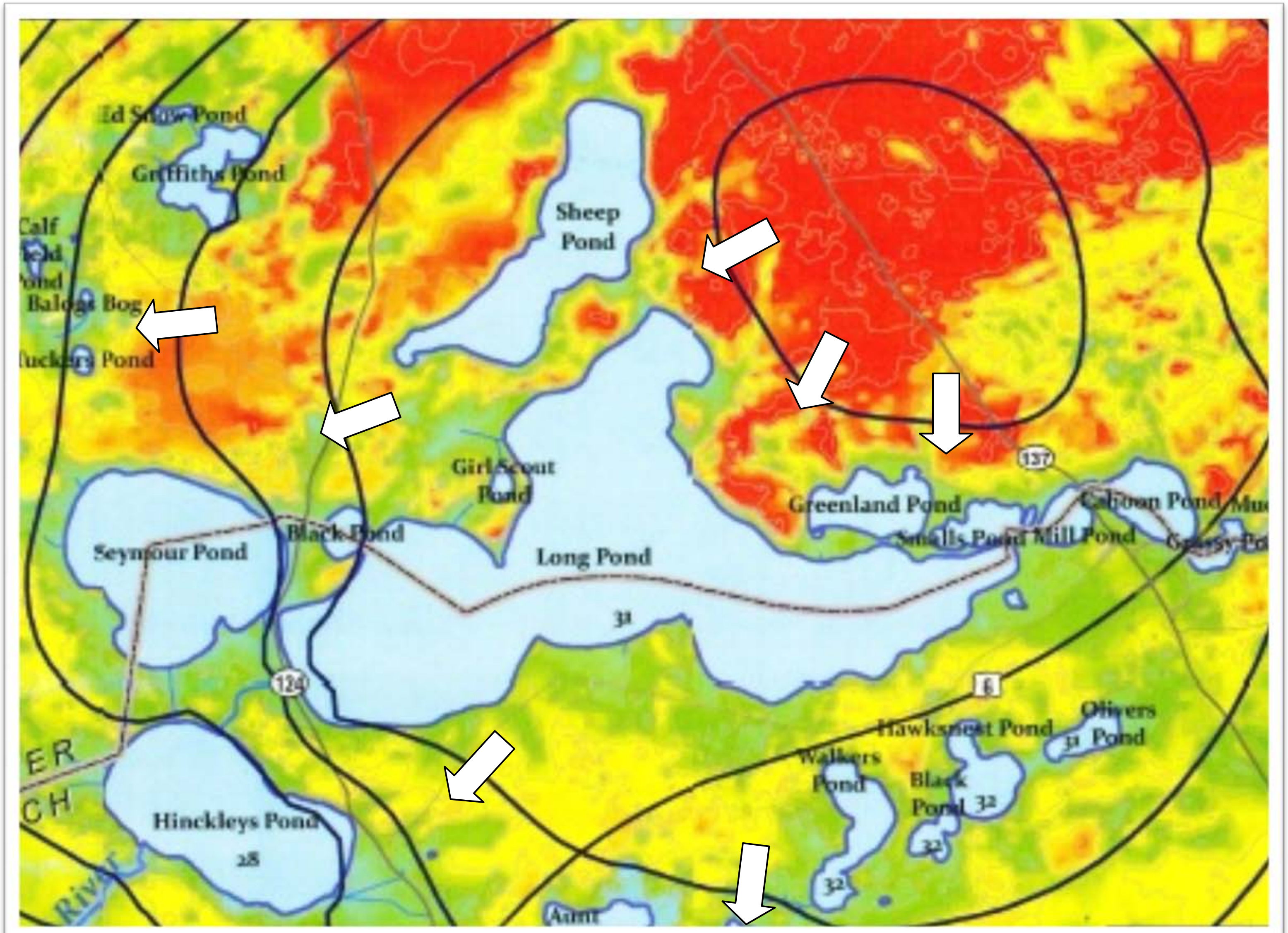


Figure 9. Approximate direct groundwater contribution zone for Hinckleys Pond. (brown line indicates approximate boundary of direct contributory zone)

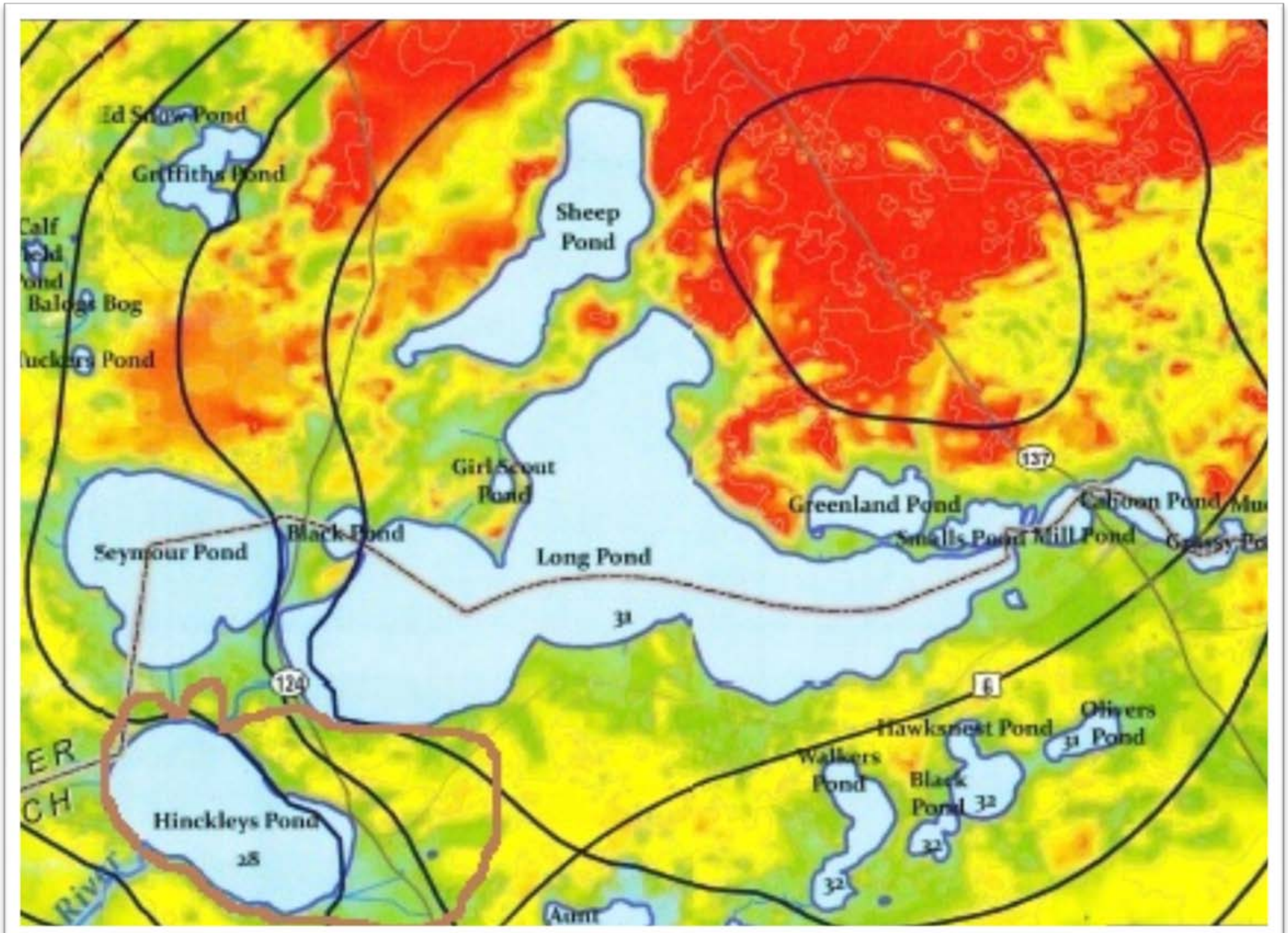


Figure 10. Land use around Hinckleys Pond, Harwich, Massachusetts.

Surface Water Drainage Issues

Based on a visual shoreline survey, there are no direct entry storm drainage pipes in the Hinckleys Pond watershed and the vast majority of the shoreline is well vegetated. A few residences are close to the pond, and some recent development has resulted in more clearing that might be advisable, but for the most part the shoreline is not a major contributor of sediment, nutrients, or other contaminants to the pond. Sample shoreline photos are provided in Figure 11.

Two stormwater runoff and erosion hazards were identified and investigated, both related to boat access areas at the ends of roads that point downhill and have no stormwater runoff control structures (Figures 12 and 13). On the south side of the lake, the final portion of James Road is unpaved and is used as an informal boat launch by some area residents (Figure 12). Stormwater runs down the road, across the unpaved area, and has cut a notch in the shoreline. Erosion is not severe, but there is no containment or treatment of runoff entering the pond at this point. On the northeast side of the lake, portions of Captain Jack and Duke Ballem Roads drain to Catherine Rose Road, which carries much of this stormwater east with no stormwater control structures, turning downhill toward the pond as a long approach to a boat ramp (Figure 13). Runoff is discharged directly into the lake at this point. Erosion is not severe, as the entire pathway is paved, but there is no attenuation of any contaminant loads and the shoreline area does suffer some sediment input and erosion in larger storms. No sampling has been performed on either of these runoff areas, so the level of nutrient input threat is not easily quantified.

One additional source of stormwater runoff is the Jenkins cranberry bog at the east end of Hinckleys Pond. The Thatcher bog at the west end reportedly holds all precipitation and stormwater that it receives (Wick 2010), but the Jenkins bog is subject to runoff inputs from area roads and the Cape Cod Community College property to the east. While the Jenkins bog provides substantial detention and possible treatment of that water, some of it must be passed into Hinckleys Pond to avoid bog flooding during the growing season. This water would not represent an erosion hazard at the pond, but may contain large concentrations of nutrients, both from the original runoff and as a consequence of passing through a fertilized bog.

Assuming that all land sloping to the pond produces runoff equivalent to the difference between the generally acknowledged levels for total precipitation (46 inches) and groundwater recharge (as much as 27 inches), approximately 19 inches of runoff would be generated over 190 acres of land, or about 13.1 million cubic feet. Not all of this will actually reach the pond as surface water, with some incorporated into shallow groundwater (some of which will discharge to the pond, mainly on the east side of the lake) or consumed by vegetation (much of this water being evapotranspired). We have no real data for runoff generation; a range of 25 to 33% of the non-recharge precipitation fraction is postulated for further calculations. This translates into 3.3 to 4.3 million cubic feet of runoff entering an almost 100 million cubic foot pond, a relatively minor amount.

There are no water quality results for any runoff entering Hinckleys Pond, but concentrations in runoff from developed land average about 0.42 mg/L for total phosphorus and 2.8 mg/L for total nitrogen (USEPA 1983, supported by many site specific studies in MA since that time). Dissolved nutrient levels

Figure 11. Shoreline photos from Hinckleys Pond during fall 2011.

Figure 12. Runoff and erosion hazard at James Road.

Figure 13. Runoff and erosion hazard at Catherine Rose Road.

are lower (averaging 0.15 mg/L for phosphorus and 0.86 mg/L for nitrogen), and for the level of landscaping observed in the Hinckleys Pond watershed, overall nutrient levels are likely to be in the lower portion of the developed land range. Assuming that nutrient concentrations in runoff are at national average levels for developed land suggests a total phosphorus input of 39.6 to 51.7 kg P/yr (3.3 to 4.3 million ft^3 X 28.6 L/ft^3 X 0.42 mg/L) and a total nitrogen input of 260 to 339 kg N/yr (3.3 to 4.3 million ft^3 X 28.6 L/ft^3 X 2.76 mg/L). Applying the lowest concentrations expected from the observed land use conditions (0.1 mg P/L and 0.8 mg N/L) would yield ranges of 9.4 to 12.3 kg/yr for phosphorus and 76 to 98 kg/yr for nitrogen. Based on experience on the Cape, and given that some of the stormwater will pass through the Jenkins cranberry bog (potentially picking up nutrients in that fertilized agricultural system), concentrations of 0.2 for phosphorus and 1.5 mg/L for nitrogen are suggested as best estimates. These yield stormwater loading ranges of 18.9 to 24.6 kg P/yr and 142 to 184 kg N/yr.

On-Site Wastewater Disposal Assessment

As with many Cape ponds, wastewater discharge from residential development represents a threat to Hinckleys Pond. The spatial distribution of septic systems is important, as the discharge must pass through soil to reach the pond and both the vertical distance down to groundwater and the horizontal distance to the pond affect how much phosphorus will be removed. Nitrogen is not effectively adsorbed to soils after discharge, and concentrations in groundwater reaching the pond depend on dilution. However, phosphorus adsorbs readily to positively charged soil particles. Although the adsorption capacity of sand is much lower than that of most other soil components, phosphorus can still be effectively removed, given enough distance under oxygenated soil (or groundwater) conditions.

Although long-term loading and the level of diffusion in wastewater plumes may influence the effective distance that phosphorus may travel before being adsorbed, it is generally assumed that systems farther than 300 ft from a pond will not contribute significant phosphorus. This is an assumption worth testing at some point, but will be adopted for the purpose of this analysis. The Town of Harwich provided the distribution of on-site Title 5 wastewater disposal systems, based on the Assessor's data base and GIS processing. Some of these systems may in fact be outside the groundwater drainage area to the west and south of Hinckleys Pond, and some further than 300 ft to the east might actually make some contribution, but for further calculations it will be assumed that all identified systems will adequately represent wastewater discharge to groundwater that will reach Hinckleys Pond. Town personnel found that there were 43 systems within 100 ft of the pond, 18 systems between 100 and 200 ft from the pond, and 24 systems between 200 and 300 ft from the pond.

A number of assumptions have to be made in the absence of data, but experience estimating inputs from on-site wastewater disposal systems is embodied in the Lake Loading and Response Model (LLRM, AECOM 2009), which provides a simple spreadsheet by which to itemize values and calculate inputs. For a "best case scenario" for Hinckleys Pond (Table 9A), the model assumes 180 days of average occupancy by 2.5 people using 66 gallons (0.25 m^3) of water each per day that goes to the disposal system, average system output concentrations of 4 mg P/L and 20 mg N/L, and attenuation factors (portion reaching the pond) for the <100 ft, 100-200 ft, and 200-300 ft groupings of 0.1, 0.05 and 0.01 for phosphorus and 0.7, 0.6 and 0.5 for nitrogen. For phosphorus, the input of greatest concern here, the total is 2.4 kg/yr. Greater removal (low attenuation factors when multiplying) would be linked to great depth of aerated soil above the groundwater table and relatively young age of disposal systems, factors that may indeed be applicable to parts of the Hinckleys Pond watershed, but not all inputs of phosphorus will be diminished so well.

For a “worst case scenario”, it is assumed that occupancy is higher (270 days for 4 people per dwelling) and that phosphorus attenuation is about as poor as is ever observed (0.5, 0.3 and 0.1 for systems <100, 100-200, and 200-300 ft from the pond, respectively). The resulting phosphorus load (Table 9B) would be 31.6 kg/yr. This is much higher than would be expected under the conditions observed in the Hinckleys Pond watershed, but provides an upper end estimate for possible inputs.

An estimate based on best professional judgment would revert to 180 days average occupancy by 2.5 people and apply phosphorus attenuation factors of 0.3, 0.15 and 0.05 for systems <100, 100-200, and 200-300 ft from the pond, respectively (Table 9C). This results in a phosphorus load of 7.6 kg/yr.

The same approach for nitrogen suggests a high-end input estimate of 418 kg/yr, a low-end estimate of 119 kg/yr, and a best estimate of 157 kg/yr (Table 9).

To get a more accurate estimate of direct wastewater inputs, one would need much more data than are currently available and/or would need to apply a more complicated model for nutrient transport through watershed soils to the pond. This is indeed worthwhile for the greater Long Pond area and probably the entire Town of Harwich, but is beyond the scope defined for this work on Hinckleys Pond. Such an effort is in progress for nitrogen entering estuaries as part of the Massachusetts Estuaries Program. The potential inputs from on-site wastewater systems will be put into context with loading from other sources in the nutrient loading section, but do not appear to be a dominant source for this pond.

Table 9. Estimation of nutrient inputs from Title 5 wastewater disposal systems to Hinckleys Pond.

A: Low end estimate of waste water loading												
Septic System Grouping (by occupancy or location)	Days of Occupancy /Yr	Distance from Lake (ft)	Number of Dwellings	Number of People per Dwelling	Water per Person per Day (cu.m)	P Conc. (ppm)	N Conc. (ppm)	P Attenuation Factor	N Attenuation Factor	Water Load (cu.m/yr)	P Load (kg/yr)	N Load (kg/yr)
Group 1 Systems	180	<100	43	2.5	0.25	4	20	0.1	0.7	4838	1.9	67.7
Group 2 Systems	180	100 - 200	18	2.5	0.25	4	20	0.05	0.6	2025	0.4	24.3
Group 3 Systems	180	200-300	24	2.5	0.25	4	20	0.01	0.5	2700	0.1	27.0
B: High end estimate of waste water loading												
Septic System Grouping (by occupancy or location)	Days of Occupancy /Yr	Distance from Lake (ft)	Number of Dwellings	Number of People per Dwelling	Water per Person per Day (cu.m)	P Conc. (ppm)	N Conc. (ppm)	P Attenuation Factor	N Attenuation Factor	Water Load (cu.m/yr)	P Load (kg/yr)	N Load (kg/yr)
Group 1 Systems	270	<100	43	4	0.25	4	20	0.5	0.95	11610	23.2	220.6
Group 2 Systems	270	100 - 200	18	4	0.25	4	20	0.3	0.9	4860	5.8	87.5
Group 3 Systems	270	200-300	24	4	0.25	4	20	0.1	0.85	6480	2.6	110.2
C: Best professional estimate of waste water loading												
Septic System Grouping (by occupancy or location)	Days of Occupancy /Yr	Distance from Lake (ft)	Number of Dwellings	Number of People per Dwelling	Water per Person per Day (cu.m)	P Conc. (ppm)	N Conc. (ppm)	P Attenuation Factor	N Attenuation Factor	Water Load (cu.m/yr)	P Load (kg/yr)	N Load (kg/yr)
Group 1 Systems	180	<100	43	2.5	0.25	4	20	0.3	0.9	4838	5.8	87.1
Group 2 Systems	180	100 - 200	18	2.5	0.25	4	20	0.15	0.8	2025	1.2	32.4
Group 3 Systems	180	200-300	24	2.5	0.25	4	20	0.05	0.7	2700	0.5	37.8

Cranberry Bog Assessment

There are two active bogs associated with Hinckleys Pond: the Thatcher Bog at the west end and the Jenkins Bog at the east end (Figure 10). There was no direct contact with cranberry growers associated with the Thatcher or Jenkins Bogs during this project, at their request, but the Cape Cod Cranberry Growers' Association (via Mr. Brian Wick) and UMASS Cranberry Station (via Dr. Carolyn DeMoranville) provided input. The Jenkins Bog has about 19 acres of active growing area, while the Thatcher Bog has about 10.5 acres of cranberries. The bogs are largely dormant in the winter, and some drainage work, sanding for better soil conditions, and related maintenance are performed then. If it is a very cold winter, many growers put a layer of water on the bogs to limit frost damage; it is not known if the Jenkins and Thatcher Bogs apply this practice regularly, but the water for frost control would come from Hinckleys Pond and be returned to it later. More active weed control and fertilization occur in the spring, and irrigation is usually necessary in spring and summer. Both are wet pick bogs; they flood the bogs and collect floating berries for processing. The water comes from Hinckleys Pond and is returned to it. This fall flooding results in the greatest return flow to the pond, and assessment of associated inputs will provide the best estimate of bog impact on the pond.

Minimized impacts can be accomplished by limiting water return or cleaning the water before return to the pond, along with care in the use of fertilizers and pesticides on the bogs themselves. It is reported that both growers have up to date conservation farm plans for their properties (Wick 2010). A conservation farm plan is a detailed tool set to help a farming operation remain profitable while protecting natural resources on the farm. It is used to schedule improvements, document conservation practices, identify environmental resources and to help growers remain in regulatory compliance, among other uses. These plans are developed by certified agriculture planners and are approved by the Natural Resources Conservation Service, a division of the United States Department of Agriculture. Each plan is custom written for the individual property.

Nitrogen is the limiting factor in cranberry bog management and nearly all fertilizer applications are based on delivering the required amount of nitrogen (Wick 2010). Traditionally, the fertilizer used by cranberry farmers had a N:P ratio of 1:2, which provides considerably more phosphorus than needed. Recent research conducted by the University of Massachusetts Cranberry Station showed that a N/P ratio of 1:1 or 2:1 is what is required (Wick 2010), although this is still very rich in phosphorus. The research has shown that no more than 20 pounds of actual P is needed per year per acre to attain adequate nutrition for producing cranberry bogs. Kept in the bog, this is no threat to the pond, but the potential for movement if too much phosphorus is applied is an issue, and the fertilizers being used still contain a lot of phosphorus.

The growers on Hinckley Pond both routinely take tissue and soil tests to help determine their nutrient management program (Wick 2010). The growers are also following the reduced P management program that the latest research has proven to be successful. This involves a N:P ratio of 1:1 to 2:1. The Thatchers started using the aforementioned "Low P" fertilizer regime in 2007, with the Jenkins starting in 2008 (Wick 2010). The Jenkins have achieved up to a 52% reduction in phosphorus application while the Thatcher's have been able to attain up to an 84% reduction in total phosphorus applied. Reportedly, for many years prior to these reduced rates, the growers were already at or only slightly above the recommended 20 lbs total P applied per year (Wick 2010). At 20 lb/ac for 29.5 ac of bog, that is a phosphorus application rate of 590 lbs of phosphorus per year, or 268 kg P/yr. The amount actually leaving the bog will be considerably less, but the amount applied is large enough to be a threat to the pond health.

According to Mr. Wick, the Jenkins apply their fertilizer with a ground rig (i.e., a machine that drives onto the bog and drops the fertilizer, not unlike a drop spreader that a homeowner would use on their lawn, only larger). The Thatchers have traditionally used a helicopter to deliver their fertilizer applications. However, they have recently purchased a ground rig and will utilize this machine for future fertilizer applications. Helicopter applications are known for allowing deposition outside the targeted zone, but it is unknown how this may have affected loading to Hinckleys Pond in the past.

Water management is one of the critical aspects of successful cranberry bog management. Bogs involve a system of moving and managing water via ditches, pumps, flumes, and ponds. Bogs by their nature are collection points for precipitation, surface water runoff and groundwater. The bogs at Hinckleys Pond are typical low-lying, peat-based bogs that collect water. According to Mr. Wick, the Jenkins' bog can hold and use substantial water during the growing season, but does occasionally have to release water into the pond. Bog ditches are supposedly cleaned 3-4 times per season to help remove sediments so more capacity can be maintained, but discharges still occur. A charcoal filter was installed at the flume outlet to help screen out particulate matter and polish the water as much as possible before release. According to area residents, however, this filter has been removed when flows are high and clogging occurs. An exact account of releases from the bog is unavailable, leaving planned and actual practices open to speculation.

The Jenkins follow the UMass Cranberry Station Best Management Practices for harvest flood water, which states that after harvest is complete, some settling time is allowed and the water is slowly released, keeping the water on the bog for no more than 10 days (Wick 2010). The Jenkins have a non-migratory Canada Goose problem on the bog and as such, always try to minimize how long flood water stays on the bog as this attracts the geese and encourages them to stay. Geese are notorious for uprooting vines and providing unneeded excrement to the bog. The Jenkins hold a Chapter 91 Waterways license for the pumping structure on the pond and overall use of water is allocated under their up-to-date Water Management Act registration.

The bog that the Thatchers manage is able to hold all in-season water, barring some major storm (Wick 2010). For instance, even with the heavy rains of summer 2009, there was no reported discharge to the pond. The Thatchers also follow the UMass Chart Book recommendation for release of harvest water discharge. The Thatchers hold a Chapter 91 license for the pump house on the pond and an active Water Management Act registration for water use allocation.

Integrated Pest Management (IPM) is a method by which a grower determines the level of a pest on his farming operation and opts to treat that pest only when it meets or exceeds a pre-determined economic threshold for damage caused by that pest. IPM involves looking at all alternatives for treating a pest, using a mixture of treatment options, including not only chemical but biological and cultural practices wherever possible. Cranberries were one of the first crops is in the country to establish formal IPM protocols for pest control (Wick 2010). Growers routinely walk the bogs with an insect net, collecting samples of insects and then making management decisions. Prior to IPM programs being developed, growers in all segments of agriculture would often treat for pests based on pre-determined dates on the calendar or when other plants were in bloom, but now growers only treat for pests when necessary. Sanding the bog also aids pest control, but is not applied to any area more often than about every three years. A sand layer provides a rooting medium for new plant roots and covers insect eggs, weed seeds and fungal spores, thereby reducing the need for chemical applications. According to Mr. Wick, both growers utilize IPM principals on their bog operations.

Based on this input, practices appear to have changed substantially at these bogs over many decades, and current impacts may not be the same as historic ones. Management practices at the bogs appear up to date, and the greatest threat appears to be large applications of phosphorus, from the perspective of pond management, not bog management. While some of that phosphorus may enter the pond during any season as runoff passed through the bogs, such runoff discharge is reportedly minimal for these bogs. The fall flooding for harvest and subsequent return of water to the pond would appear to represent the greatest input, and an investigation was undertaken to evaluate that input.

The UMASS Cranberry Station has been collecting data for inflow to and discharges from bogs to evaluate the net transfer of phosphorus to associated ponds, this practice being recognized as an issue for pond management. Results from testing in 2009 and 2010 (DeMoranville unpublished data, Figure 14) suggest considerable variability, but averages of 174 (2010) and 396 (2009) ug/l were obtained for bog discharges of harvest water. Inflowing water had phosphorus concentrations of 46 (2010) and 96 (2009) ug/L, so the net discharge concentration was 128 ug/L in 2010 and 300 ug/L in 2009 for the tested waters. These are large values, relative to a desirable threshold of <25 ug/L for phosphorus in a pond, and a preferred level of <10 ug/L to minimize the probability of nuisance algal blooms. These high concentrations may be mitigated to some degree, however, by lesser availability of particulate forms of phosphorus and dilution in the receiving waters of the pond. Each of these factors can be significant, so some site-specific data are helpful in assessing potential impacts.

Given the low N:P ratio in applied fertilizer and the tendency of nitrogen to be the limiting nutrient in cranberry bogs, the N:P ratio in the discharge water is expected to be low, favoring cyanobacteria in the receiving waters if the bog discharge is a significant source of nutrients. How significant a source will be dependent upon the volume of discharge relative to the volume of the pond and its background nutrient levels.

With high variation in the bog study results provided by the UMASS Cranberry Station, some knowledge of local discharge conditions at Hinckleys Pond was considered important to impact assessment. Volunteer monitors therefore collected three samples from the discharge from each of the two bogs over a two-day period of discharge for each. Those samples were collected in acid-cleaned containers and frozen until pick-up, with subsequent thawing and analysis at Berkshire Enviro-Labs of Lee, MA. Resulting concentrations for forms of phosphorus and nitrogen (Table 10) suggest high total levels of each nutrient, although nearly all nitrogen was in particulate forms (i.e., dissolved inorganic nitrogen as

Figure 14. Results from cranberry bog testing by the UMASS cranberry station.

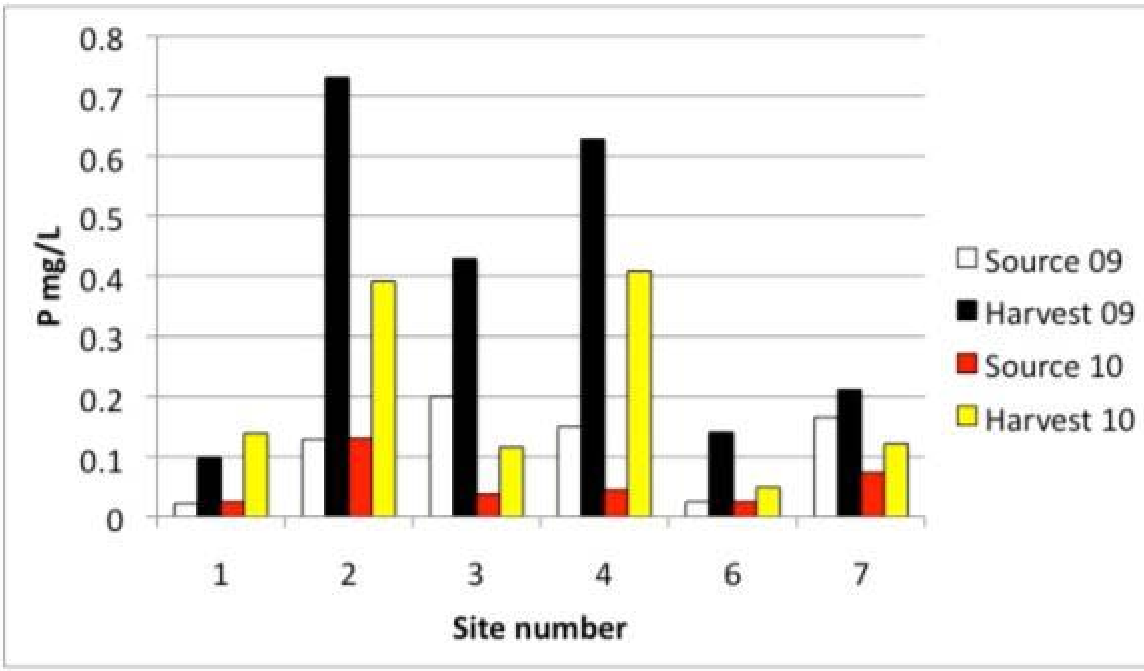


Table 10. Results from bog discharge testing at Jenkins and Thatcher Bogs, October 2011.

Bog	Date	Time	Ammonium N (ug/L)	Nitrate N (ug/L)	TKN (ug/L)	Dissolved P (ug/L)	Total P (ug/L)
Thatcher	10/10/2011	10:00	<20	<10	760	303	380
Thatcher	10/10/2011	16:00	<20	<10	800	424	477
Thatcher	10/11/2011	9:00	<20	<10	1150	612	740
		Mean	<20	<10	903	446	532
Jenkins	10/10/2011	9:30	<20	<10	620	131	143
Jenkins	10/10/2011	15:25	<20	<10	600	209	242
Jenkins	10/11/2011	8:30	<20	<10	1300	1125	6110
		Mean	<20	<10	840	488	2165

ammonium or nitrate were below detection levels in all samples, leaving organic particulates as the main nitrogen source).

Dissolved phosphorus comprised over 75% of the total phosphorus in five of six samples, with the one non-conforming sample having the highest dissolved phosphorus concentration but a very high total phosphorus level, leading to a dissolved phosphorus fraction of 18%. Dissolved phosphorus would be immediately available to support algal growth in Hinckleys Pond, while the particulate fraction (smaller but not insignificant in five of six samples) could become part of the sediment base. Any settled particulate fraction would be mostly organic matter and would be subject to possible release through decay over an extended period of time (years). Some of the dissolved phosphorus would be incorporated into algae and eventually could also add to the organic bottom sediment. Another portion would pass through the pond into the Herring River. Based on detention time in Hinckleys Pond and the processes that act on phosphorus in ponds, a substantial fraction of that dissolved phosphorus would be expected to bind with iron and become part of the available sediment phosphorus fraction discussed in relation to internal recycling within Hinckleys Pond.

The load of phosphorus from the bogs is a function of both concentration and water volume, the concentration having been evaluated above. Each bog is filled to a depth of 1.0 to 1.5 ft overall, which can be multiplied by bog area to get a flood water volume if one ignores any sequential harvesting and movement of water among bog sections and also the extra volume represented by the ditches that must be filled. Photographs from the 2011 harvest suggest that all bog areas were flooded at the same time, so no reduced volume for moving harvest water among bog sections appears appropriate. The channels will add little enough additional volume to be ignored. The volume of water involved in the Jenkins bog harvest would therefore be between 0.81 to 1.24 million ft^3 (23,500 to 35,200 m^3), while that for the Thatcher bog would be between 0.46 to 0.69 million ft^3 (12,900 to 19,400 m^3). Together, these bogs would discharge 1.27 to 1.93 million ft^3 (36,400 to 54,600 m^3) of water to Hinckleys Pond, not more than 2% of the pond volume.

An alternative approach to determining the volume of water used by the bogs involves tracking the water level in Hinckleys Pond, which was done over the period of September 21 through October 19, 2011 (Table 11). During a period of active bog pumping of water from Hinckleys Pond (Oct 1 – Oct 7), the water level dropped 0.24 ft over 174 acres of pond area, equating to 1.82 million ft^3. This was a period of minimal precipitation following a rainy period (Sept 23-24) when the water level rose by 0.15 ft and several dry days when the water level declined by approximately 0.05 ft before bog pumping commenced. With the pond level apparently not far out of equilibrium with the groundwater, the equilibration process is relatively slow (2-3 days to change by 0.01 ft just before pumping started), while the pumping process is fairly fast. Assuming that the entire water level decline of 0.24 ft was due to pumping, that equates to 1.82 million ft^3 (51,560 m^3). This is within the range estimated from calculated floodwater volume, and incorporating a small amount of inseepage or outseepage from the pond would not move the estimate from water level change outside of the range of estimates from the previous volumetric approach.

Table 11. Hinckleys Pond water level.

Day	Date	Water Level (ft)	Notes
Wednesday	21-Sep	1.64	
Thursday	22-Sep	1.64	
Friday	23-Sep	1.64	
Saturday	24-Sep	1.79	Rain for 2 days prior
Sunday	25-Sep	1.76	
Monday	26-Sep	1.76	Not much rain 9/25 & 9/26. Water clear on south side.
Tuesday	27-Sep	1.75	
Wednesday	28-Sep	1.75	
Thursday	29-Sep	1.74	
Friday	30-Sep	1.74	
Saturday	1-Oct	1.74	
Sunday	2-Oct	1.72	Pumps running at Thatcher bog. Jenkins bog not pumping.
Monday	3-Oct	1.70	Thatcher bog stopped pumping. Jenkins bog started pumping.
Tuesday	4-Oct	1.65	
Wednesday	5-Oct	1.55	
Thursday	6-Oct	1.50	Harvest in progress in Thatcher bog
Friday	7-Oct	1.50	Thatcher bog almost done harvesting. Jenkins bog started.
Saturday	8-Oct	1.54	Harvest in progress in Jenkins bog
Sunday	9-Oct	1.61	Jenkins bog begins discharge after noon.
Monday	10-Oct	1.68	Samples taken at both bogs. Jenkins bog discharging "full flow"
Tuesday	11-Oct	1.70	Samples taken at both bogs.
Wednesday	12-Oct	1.75	
Thursday	13-Oct	1.83	
Friday	14-Oct	1.84	
Saturday	15-Oct	1.85	
Sunday	16-Oct	1.90	
Monday	17-Oct	1.88	
Tuesday	18-Oct	1.87	
Wednesday	19-Oct	1.86	

During the subsequent discharge period for the bogs, the water rose by 0.29 ft. During the interim period (between apparent cessation of pumping and initiation of discharge) the water level rose by between 0.04 and 0.11 ft, believed to be a function of groundwater inseepage moving the pond back to an equilibrium level with groundwater. Uncertainty in the precise water level change relates to the timing of discharges, as measurements were made only once per day. Assuming an increase of 0.07 ft in water level due to groundwater during discharge, the change in water level due to bog discharge would be 0.22 ft, which equates to 1.67 million ft^3 (47,260 m^3). This estimate of water used in the bogs is also within the volume range estimated from the bog flooding geometry.

Applying a range of 36,400 to 54,600 m^3 of withdrawal or discharge water and dividing between the bogs based on area (64.4% Jenkins, 35.6% Thatcher), estimates of loading to Hinckleys Pond from cranberry bogs can be derived (Table 12). The range for Jenkins bog is wide, given one very large phosphorus value that skews the load if included. Applying either the mean value from the Thatcher bog or the mean from the UMASS Cranberry Station data yields a much lower load. The range for the Thatcher bog is much narrower, given fairly similar results among samples. Except for the load estimates derived from the mean 2011 discharge phosphorus value for Jenkins bog, influenced by one very high value, phosphorus loads from the bogs do not appear all that large. While phosphorus concentrations are high, the actual quantity of discharge water is small compared to pond volume or inputs from Long and Seymour Ponds.

The same analysis for nitrogen suggests very little nitrogen output from the bogs (Table 12), consistent with the nitrogen limitation normally experienced by bogs.

Table 12. Estimation of loading to Hinckleys Pond from cranberry bogs.

Bog	Volume (m3)	Inflow TP (ug/L)	Discharge TP (ug/L)	TP Load (kg)	Assumptions	Inflow TN (ug/L)	Discharge TN (ug/L)	TN Load (kg)
Jenkins	23442	30	2165	50.0	Low end volume and actual mean P concentration	525	840	7.4
Jenkins	23442	30	532	11.8	Low end volume and Thatcher mean P concentration			
Jenkins	23442	30	285	6.0	Low end volume and UMASS mean P concentration			
Jenkins	35162	30	2165	75.1	High end volume and actual mean P concentration	525	840	11.1
Jenkins	35162	30	532	17.7	High end volume and Thatcher mean P concentration			
Jenkins	35162	30	285	9.0	High end volume and UMASS mean P concentration			
Jenkins	29300	30	532	14.7	Mean volume estimate and Thatcher mean P concentration	525	840	9.2
Thatcher	12958	30	532	6.5	Low end volume and actual mean P concentration	525	903	4.9
Thatcher	12958	30	285	3.3	Low end volume and UMASS mean P concentration			
Thatcher	19438	30	532	9.8	High end volume and actual mean P concentration	525	903	7.3
Thatcher	19438	30	285	5.0	High end volume and UMASS mean P concentration			
Thatcher	16200	30	532	8.1	Mean volume estimate and actual mean P concentration	525	903	6.1

Hydrologic Loading

Water Inputs and Outputs

Inputs include direct precipitation, surface inflows from Long and Seymour Ponds, groundwater inflow that originates in Long Pond, direct stormwater runoff, discharges from cranberry bogs, and direct groundwater inputs, with wastewater from on-site disposal systems separable from natural groundwater. Many of these inputs have been addressed in previous sections of this report, but some have not and some additional description of the best available estimates is in order. Table 13 summarizes ranges and best estimates of values for hydrologic inputs.

Direct precipitation to Hinckleys Pond is about 46 inches per year, equating to 1.16 m on 70.2 hectares, or 813,900 m3/yr. Precipitation can vary by about 25% on an annual basis, yielding the range in Table 13.

Flow from Long Pond is addressed as part of the water budget for Long Pond (ENSR 2001), and averages 5 million m^3/yr, all of which travels a short distance in what is then the Herring River to Hinckleys Pond. On an annual basis that flow will vary mainly in proportion to precipitation.

No flow data are available for Seymour Pond, so average flow has been estimated based on the proportion of Seymour Pond and its watershed to Long Pond and its watershed. This is one of the more speculative estimates, and gauging of the stream between Seymour and Hinckleys Ponds is recommended for future management.

Direct stormwater inputs have been discussed in detail. The best estimate is simply the average of the estimated extremes (ends of the range of estimates). Likewise, cranberry discharge has been addressed previously and the average in Table 13 is the mean of the reported ends of the expected range of water discharge. It should be noted, however, that the water discharged from the bogs after harvest came from Hinckleys Pond in the first place; nutrient inputs are higher than what was withdrawn, but the water intake and output should be roughly in balance.

Direct groundwater seepage into Hinckleys Pond is difficult to estimate, as we have no data for actual seepage and much of the groundwater that might come from further away from the pond would likely be intercepted by Long Pond. Assuming that the 190-acre watershed associated directly with Hinckleys Pond is the primary source of groundwater, estimates were derived based on the proportion of Hinckleys Pond to Long Pond (23.5%) and the proportion of the watershed of each (16.8%). Reasonably reliable estimates of groundwater flow into Long Pond are available (ENSR 2001), but the extension of that relationship to Hinckleys Pond is speculative at 530,500 to 573,200 m^3/yr).

Another way to estimate subsurface inflow involves Darcy's law, which is represented as Q (flow) = K (hydraulic conductivity) * I (groundwater gradient) * A (cross sectional area through which water enters Hinckleys Pond). This quantifies the flow moving from the Long Pond area and being intercepted by Hinckleys Pond. With K at 100 to 200 ft/day, I at 4 ft over a 0.25 mile distance (0.003 ft/ft), and A at about 52,000 square feet (4000 ft long by 13 ft deep), subsurface flow from Long Pond to Hinckleys

Pond would be between 156,000 to 312,000 m3/yr. This range is less than the amount estimated by simply scaling the Long Pond inseepage to Hinckleys Pond by pond area or contributing groundwatershed area.

Wastewater inputs have been discussed previously, and while there may be error associated with the number and spatial distribution of systems linked to Hinckleys Pond, the range of inputs and best estimate of average input as calculated from a simple spreadsheet model are consistent with expectations based on other Cape Cod pond projects.

Waterfowl and internal loading are nutrient flux components, providing negligible amounts of water, so these do not figure into the hydrologic assessment.

The total hydrologic input to Hinckleys Pond is therefore estimated at just under 6.6 million m^3/yr, with almost 76% entering as overflow from Long Pond (Table 13). Flows from Seymour Pond and direct precipitation are the next largest contributions, at 16.2 and 12.4%, respectively. At the estimated average inflow, the detention time of Hinckleys Pond is calculated at 0.43 years, or about 157 days. The flushing rate is therefore 2.3 times per year, substantially faster than many Cape ponds, mainly as a function of surface water connection to Long and Seymour Ponds.

Table 13. Water and nutrient loads to Hinckleys Pond.

Source	Est. Range of Flow (cu. m/yr)	Best Est. of Flow (cu.m/yr)	% of Total Flow	Est. Range of TP Load (kg/yr)	Best Est. of TP Load (kg/yr)	% of Total P Load	Est. Range of TN Load (kg/yr)	Best Est. of TN Load (kg/yr)	% of Total N Load	TN:TP Load Ratio
Direct Precipitation	651,000 to 1,017,000	813,900	12.4	6.5 to 25.4	13.8	3.9	407 to 814	570	11.9	41.3
Flow from Long Pond	4,000,000 to 6,667,000	5,000,000	75.9	62.5 to 150	90.0	25.5	1500 to 2810	2155	45.1	23.9
Flow from Seymour Pond	900,000 to 1,230,000	1,065,000	16.2	21.3 to 42.7	28.8	8.2	799 to 1385	1144	23.9	39.8
Direct Stormwater Drainage to Hinckleys Pond	59,500 to 147,300	103,400	1.6	9.4 to 51.7	21.8	6.2	76 to 339	163	3.4	7.5
Cranberry Bog Discharge	36,400 to 54,600	45,500	0.7	9.3 to 84.9	22.8	6.5	12.3 to 18.4	15	0.3	0.7
Direct Groundwater Drainage to Hinckleys Pond (without Wastewater from within 300 ft)	156,000 to 573,200	364,600	5.5	1.6 to 11.5	3.6	1.0	78 to 287	182	3.8	50.6
Wastewater via Groundwater to Hinckleys Pond (within 300 ft)	9,600 to 23,000	9,600	0.1	2.4 to 31.6	7.6	2.2	119 to 418	157	3.3	20.7
Waterfowl	0	0	0.0	2.0 to 8.0	4.0	1.1	15 to 26	19	0.4	4.8
Internal Load	0	0	0.0	76.2 to 261	160.0	45.4	229 to 522	376	7.9	2.4
Total		6,588,100	100.0	0	352.4	100.0		4781	100.0	13.6

Nutrient Loading

Nutrient Inputs and Outputs

As with hydrologic inputs, nutrient inputs have been discussed in some detail already, but certain elements have received less attention and some additional discussion of other elements is warranted, leading to the summary in Table 13.

Direct precipitation inputs of phosphorus and nutrients are based on the estimated inflow and literature values derived from and used for New England pond studies over the last decade. Phosphorus in area rain averages about 17 ug/L, while the range is about 10 to 25 ug/L. Nitrogen levels average about 0.7 mg/L with a range of 0.5 to 1.0 mg/L. One could adjust these values based on more local data, but only an unrealistically severe increase would result in precipitation being a major loading factor.

The flows for Long and Seymour Ponds were multiplied by the high, low and average values from PALS program monitoring from the past few years, with slight adjustment since samples are not actually collected from the outlets, where concentrations should be slightly lower. Long Pond nutrient chemistry has changed since the aluminum treatment in 2007; therefore, only more recent data were applied.

Direct stormwater inputs were discussed and estimated previously. This is another area where potential variability is high and lack of site specific data limits analysis, but associated inputs are not extreme.

Considerable effort went into assessment of cranberry bog input from harvest water discharge, and results have been discussed in detail already. Concentrations of phosphorus are very high, but the relatively low quantity of water involved results in a relatively small proportionate load. The load shown in Table 13 represents the mean value estimated in Table 12 (last line for each bog). This ignores the one very high phosphorus value from the Jenkins Bog and any inputs from frost protection water or irrigation water return flow. Consequently, inputs from cranberry bogs to Hinckleys Pond could be larger than estimated here; we simply do not have adequate data to further the analysis at this time. Nitrogen from cranberry bogs appears to be a negligible influence on Hinckleys Pond. All estimates of possible nitrogen inputs are relatively small, consistent with expectations for cranberry bog systems, which tend to conserve nitrogen.

Direct groundwater inputs are very difficult to assess with no local data, but the inflow estimates were multiplied by plausible background concentrations (10 to 20 ug/L for P, 500 ug/L for N) to derive estimates of nutrient inputs. Background levels for phosphorus are expected to be low, so this is not a major source to Hinckleys Pond, but the “background” nitrogen entering the Hinckleys Pond system includes possible wastewater inputs from outside the direct contributing area. That is, while phosphorus does not travel well through groundwater, nitrogen does, and what is considered background for groundwater moving into the Hinckleys Pond direct drainage area may include diluted wastewater from land around Long Pond, elevating that load somewhat. Even then, the groundwater nitrogen load is not large relative to surface water sources.

Wastewater can be a much more significant source, despite modest associated water quantities, as a function of potentially very high concentrations. The derivation of loading from wastewater has been discussed previously, but is also speculative and may warrant further investigation before making final management decisions. Note that the estimated wastewater phosphorus input from the 300 ft upgradient zone of assumed contribution is substantially more than the background contribution from a much larger area that is further from the pond, while the nitrogen load from within the 300 ft zone is slightly less than the postulated background for all areas contributing groundwater, some of which will also contribute nitrogen from wastewater. Again, phosphorus is greatly reduced by transport over long distances through soil, while nitrogen levels are much less attenuated.

Waterfowl are not a dominant feature of Hinckleys Pond, and simple estimation based on 20 birds at the pond on an annual basis with standard literature values for input per bird was applied. Most birds at Hinckleys Pond appear to be gulls, but ducks, geese and swans could be found at times. The distribution of birds at the pond over time is undoubtedly not uniform, but this estimate is an annual average.

The internal load is difficult to estimate when a pond is not strongly stratified; calculation of the amount of phosphorus or nitrogen in each defined water layer is possible at any time, but the flux over time is not readily determinable. There is an obvious increasing gradient in phosphorus concentration from top to bottom in summer (Table 3), but the flux is not easily calculable since stratification breaks down periodically. Based on the large amount of available sediment phosphorus bound to iron in Hinckleys Pond, the potential for a very high internal load exists. Realization of this potential is limited by a maximum pond depth of 28 ft, not deep enough to maintain low oxygen at the sediment-water interface throughout the summer under typical Cape Cod conditions. The presence of oxygen limits the chemical reactions that release iron and phosphorus into the overlying water, and promotes recombination of iron and phosphorus once released and exposed to oxygen, forming a precipitate that sinks back to the bottom.

It would be usual for 10% of the available sediment phosphorus to be released in a stratified pond, which would equate to 658 kg/yr in Hinckleys Pond. Long Pond is much deeper and subject to greater release as a function of continual strong anoxia at the bottom during summer, and had an even higher release rate prior to aluminum treatment. A lower release rate is expected in Hinckleys Pond, where stratification is not stable and the affected volume is lower. We have inadequate data to quantify the release with any degree of precision, but from professional experience with a range of ponds suffering from internal loading, the release rate is likely to be about half that for deeper systems like Long Pond and the period of release is also likely to be about half that experienced by more strongly stratified systems. This suggests an internal load on the order of 165 kg/yr.

Another approach to estimating sediment phosphorus release rates involves application of literature values for release per unit area per unit time to the expected release area over the expected duration of anoxia at the sediment-water interface. Typical release rates found applicable to Cape ponds are from 6 to 20 $mg/m^2/day$ under anoxia. Exposure to anoxia ranges from 30 to 120 days. For Hinckleys Pond, an area of 363,000 m^2 appears to be exposed to anoxic conditions for 35 to 60 days each year, with an expected range of release of 6 to 12 $mg/m^2/yr$. The range of predicted release would therefore be 76.2

to 261.4 kg/yr. As the best estimate of average internal load that we can offer at this time, a rate of 12 mg/m^2/day seems appropriate in light of the very high available sediment phosphorus values, but a duration of only 35 to 40 days seems appropriate in light of wind mixing and observed oxygen status in the pond; this suggests an internal load of about 160 kg/yr. Actual internal load may vary substantially among and within years, based on weather pattern.

Internal loading of nitrogen is less a straight function of anoxic releases. Ammonium builds up under anoxia, as oxygen is necessary for conversion to nitrite and then nitrate, and evidence of that build up is observed in the PALS data. Nitrogen loading from internal sources is usually about two to three times the phosphorus release, which is typically a minor component of overall nitrogen loading to a pond.

Lake Loading Response Model

The Lake Loading and Response Model (LLRM) is used both to corroborate the itemized loading discussed above and to provide a mechanism to explore how changes in loading might affect other pond features such as chlorophyll *a* and water clarity expressed as Secchi depth. It is a spreadsheet model that relies on precipitation, land use, and export coefficients to derive loads for various components and predict in-lake conditions as a result of those loads (AECOM 2009).

Model Inputs

Precipitation of 1.17 m/yr (46 inches) is used to drive hydrologic inputs. Only three land uses are applied, and then only to the direct drainage area of Hinckley Pond, as the inputs from Long and Seymour Ponds are treated as point sources (flow times concentration). Export coefficients for those land uses are provided in Table 14. There are 60.6 ha of residential areas, 4.0 ha of forested wetland, and 11.9 ha of cranberry bogs. A pond area of 70.2 ha with a potential contributory area for internal loading of 36.3 ha is applied. Site-specific data and related information for wastewater, internal load, and waterfowl are added as previously described.

Table 14. Export coefficients applied in LLRM for Hinckleys Pond.

	RUNOFF EXPORT COEFF.			BASEFLOW EXPORT COEFF.		
LAND USE	Precip Coefficient (Fraction)	P Export Coefficient (kg/ha/yr)	N Export Coefficient (kg/ha/yr)	Precip Coefficient (Fraction)	P Export Coefficient (kg/ha/yr)	N Export Coefficient (kg/ha/yr)
Urban 1 (LDR)	0.15	0.40	5.50	0.30	0.050	5.50
Forest 2 (Wetland)	0.05	0.20	2.00	0.40	0.010	0.50
Cranberry Bog	0.15	1.20	2.00	0.20	0.050	0.50

Model Calculations

The model processes the inputs, generating loads and attenuating them on their way to the pond. The result is an itemized and summed load to the pond (Table 15) that reasonably matches the itemized load generated in Table 13, albeit with less detail and no ranges. The watershed load includes the inputs from Long and Seymour Ponds as well as the direct drainage area, and combines surface and groundwater sources except for septic systems.

Table 15. LLRM load summary for Hinckleys Pond.

DIRECT LOADS TO LAKE	P (KG/YR)	N (KG/YR)	WATER (CU.M/YR)
ATMOSPHERIC	14.0	561.6	814320
INTERNAL	159.9	399.7	0
WATERFOWL	4.0	19.0	0
SEPTIC SYSTEM	7.6	157.3	9563
WATERSHED LOAD	166.0	3898.4	5764044
TOTAL LOAD TO LAKE	351.5	5036.0	6587927
TOTAL INPUT CONC. (MG/L)	0.053	0.764	

Model Predictions

Generating a believable model for further use depends on being able to match predictions with actual data without adjusting the model outside the normal bounds for input parameters. For the application of LLRM to Hinckleys Pond, the match was very close with no adjustment. Limited fine tuning helps match parts of the model with the available data, and the result (Table 16) appears to reasonably represent Hinckleys Pond under current conditions. The current average phosphorus value and the mean and peak chlorophyll *a* levels for upper pond waters are just slightly less than the corresponding values predicted by the model. The mean nitrogen level for the pond and the average Secchi disk value are just slightly larger than predicted. The distribution of predicted chlorophyll *a* is slightly skewed to lower values than the actual data suggest, but the data available for constructing the distribution are limited and differences are not extreme. The LLRM for Hinckleys Pond appears to adequately represent processes and conditions in the pond and its watershed.

The LLRM model applies a mass balance equation that provides the maximum possible phosphorus and nitrogen values; under mass balance, no nutrients settle to the bottom or are flushed from the pond. As nutrients do indeed settle or are flushed from the system, the empirical equations that are applied provide various representations of those processes based on studies of many other systems. The average of those empirical models is taken as the best available representation of the Hinckleys Pond system.

While there could be multiple versions of the model that might reasonably match current conditions, the model as set up here is a logical representation of the Hinckleys Pond system and can be used to test the relative results of management scenarios. Given the simplicity of the model, the direction and magnitude of change are accorded higher value than precise numbers that result from management scenarios.

Table 16. LLRM predictions for current conditions with actual data for comparison.

Shaded boxes indicate values from actual data.

THE MODELS					PREDICTED CHL AND WATER CLARITY			
	PHOSPHORUS	PRED.	PERMIS.	CRITICAL				
		CONC.	CONC.	CONC.				
NAME	FORMULA	(ppb)	(ppb)	(ppb)	MODEL	Value	Mean	Measured
Mass Balance	TP=L/(Z(F))*1000	53						
(Maximum Conc.)					**Mean Chlorophyll (ug/L)**			
Kirchner-Dillon 1975	TP=L(1-Rp)/(Z(F))*1000	29	18	36	Carlson 1977	13.4		
(K-D)					Dillon and Rigler 1974	11.2		
Vollenweider 1975	TP=L/(Z(S+F))*1000	43	26	53	Jones and Bachmann 1976	13.0		
(V)					Oglesby and Schaffner 1978	15.6		
Larsen-Mercier 1976	TP=L(1-Rlm)/(Z(F))*1000	32	20	39	Modified Vollenweider 1982	15.7	13.8	13.2
(L-M)					**Peak Chlorophyll (ug/L)**			
Jones-Bachmann 1976	TP=0.84(L)/(Z(0.65+F))*1000	35	21	43	Modified Vollenweider (TP) 1982	49.2		
(J-B)					Vollenweider (CHL) 1982	42.0		
Reckhow General (1977)	TP=L/(11.6+1.2(Z(F)))*1000	22	13	27	Modified Jones, Rast and Lee 1979	47.2	46.1	43.8
(Rg)					**Secchi Transparency (M)**			
					Oglesby and Schaffner 1978 **(Avg)**	1.6		1.7
Average of Model Values		32	20	40	Modified Vollenweider 1982 **(Max)**	3.7		
(without mass balance)								
Measured Value		30.3			**Bloom Probability**			
(mean, median, other)					Probability of Chl >10 ug/L **(% of time)**	65.4%		75.0%
					Probability of Chl >15 ug/L **(% of time)**	33.9%		51.9%
From Vollenweider 1975, 1982					Probability of Chl >20 ug/L **(% of time)**	16.1%		34.6%
Permissible Load (g/m2/yr)	Lp=10^(0.501503(log(Z(F)))-1.0018)	0.31			Probability of Chl >30 ug/L **(% of time)**	3.6%		11.5%
Critical Load (g/m2/yr)	Lc=2(Cp)	0.61			Probability of Chl >40 ug/L **(% of time)**	0.9%		3.8%
	NITROGEN							
Mass Balance	TN=L/(Z(F))*1000	764						
(Maximum Conc.)								
Bachmann 1980	TN=L/(Z(C1+F))*1000	519						
Bachmann 1980	TN=L/(Z(C2+F))*1000	556						
Bachmann 1980	TN=L/(Z(C3+F))*1000	484						
Average of Model Values		520						
(without mass balance)								
Measured Value		525						
(mean, median, other)								

Management Goals

Current Uses

The current uses of Hinckleys Pond include water supply for cranberry bogs, swimming, boating, fishing, and habitat for fish and wildlife support, including support of an active alewife run. These have been the uses of Hinckleys Pond for many years. No clear priority has been established, and it appears possible for all of these uses to co-exist with limited interference. However, alewife in the pond minimizes zooplankton populations and associated grazing on algae, allowing the highest algal biomass supported by the fertility level of the pond, which is high. Return of water used to flood cranberry bogs to the pond represents nutrient inputs that add to that fertility. Watershed activities of concern include stormwater and wastewater generation and routing. These activities do not result in immediate impairment, but rather contribute to the long-term build-up of phosphorus reserves, with the internal load generating the primary impairment through support of algal blooms during summer.

Use Impairment

Low clarity, algal blooms, and deep water anoxia affect all uses but boating. Use of the water in cranberry bogs is not functionally impaired, but the image of berries picked in water with cyanobacterial blooms is not good for marketing. Hinckleys Pond experiences common but not continual algal blooms, many of them dominated by cyanobacteria, particularly in summer. There has been no toxicity testing of water from Hinckleys Pond, and hazardous levels of toxins are actually fairly rare in occurrence (Lindon and Heiskary 2009, Graham and Jones 2009, Bigham et al. 2009), but the threat exists and is most commonly associated with high concentrations of cyanobacteria that coincide with surface scum formation or wind-blown shoreline accumulations. Both of these occur in the pond. Hinckleys Pond is rendered unaesthetic by algal blooms, and much of the algal production winds up in the sediment, impairing oxygen through decay. Additionally, the movement of primary productivity (algae) to the sediment instead of through zooplankton into fish alters the flow of energy in a way that lowers desirable fish production.

Rehabilitation Objectives

Improving water clarity is the most apparent objective, and requires algal biomass reduction, which is best achieved by phosphorus reduction. The current average chlorophyll *a* concentration for surface waters in the lake is 13.2 ug/L, and the average concentration in deep water is even higher (24.3 and 25.3 ug/L for 5-6 m and >6 m layers, respectively). The deeper chlorophyll values may represent sinking of algae produced closer to the surface or populations of algae adapted to low light that thrive on the higher nutrient levels in deeper water. Reducing chlorophyll levels to no more than about half the current concentrations would be desirable; systems with chlorophyll *a* <10 ug/L tend to have more desirable biological structure, lower oxygen demand in deep water, and fewer cyanobacterial blooms (Watson et al. 1997, Holdren et al. 2001, Heiskary and Wilson 2008).

Increased deep water oxygen levels are also highly desirable. Increased oxygen may be achieved by algal biomass reduction, since the settling and decay of algae is one of the factors creating the oxygen demand. However, inputs of organic matter from cranberry bogs and surface water inflows from Long Pond and Seymour Pond are factors as well, and deep water anoxia may persist with reduced algal production. Hamblin Pond in Marstons Mills experienced a pronounced increase in oxygen below the thermocline (stratification boundary) after inactivation of internal load in 1995 (PALS unpublished data), but Long Pond just upstream of Hinckleys Pond has not shown such an increase following internal load reduction in 2007 (PALS unpublished data). There are multiple sources of oxygen demand for Hinckleys Pond, and if not countered at the source, some form of in-lake oxygenation system might be needed to maintain desirable deep water oxygen levels.

Possible Loading Targets

For most contact uses, phosphorus of <10 ug/L will minimize the probability of algal blooms, usually defined as chlorophyll *a* levels in excess of 10, 15 or 20 ug/L; there is no strict definition of a bloom, but low clarity is rarely a problem at phosphorus levels <10 ug/L. For fish production, somewhat higher phosphorus levels are desirable, and may be maintained without excessive problems with algae at phosphorus levels <25 ug/L. A target somewhere between 10 and 25 ug/L would therefore be desirable, while the current phosphorus level averages 30 ug/L in the surface water of Hinckleys Pond and considerably higher in water more than 20 ft (6 m) deep. To provide some margin of safety, a target of no more than 20 ug/L is suggested. A value of 20 ug/L is predicted by the LLRM as the concentration below which blooms should be infrequent, and corresponds to an annual load of approximately 225 kg of phosphorus. This matches the average surface water phosphorus level in Long Pond since the aluminum treatment, and this has provided acceptable water clarity while still supporting fishing uses. The new Long Pond phosphorus level has not eliminated deep water anoxia, however. A logical target for oxygen is no less than 2 mg/L near the sediment-water interface. Although the state standard of 5 mg/L applies throughout the pond, low oxygen at the sediment-water interface is naturally common and values of >2 mg/L will minimize internal loading.

Management Options

A wide range of approaches exist for reducing algal biomass and increasing oxygen in aquatic systems (Table 17). Extensive discussion of most options can be found in Mattson et al. (2004), Cooke et al. (2005) and NYSFOLA (2009). Options with applicability to Hinckleys Pond include:

- Stormwater management – Anything that can be done to reduce nutrients and other contaminants in stormwater reaching Hinckleys Pond is a step in the right direction. However, stormwater within the direct drainage area represents only 6.2% of the phosphorus load and 3.4% of the nitrogen load to Hinckleys Pond (Table 13) based on the analysis of available data. Managing stormwater should be an integral part of town water management planning, but cannot solve the current problems of Hinckleys Pond by itself. Stormwater is not known to be a pressing issue for upstream Long or Seymour Ponds, although the quality of water entering Hinckleys Pond from those ponds is partly dependent on stormwater management at those ponds. Infiltration of stormwater is quite practical on Cape Cod, but the state stormwater policy creates some complications for implementation.

Table 17. Algae management options review

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
WATERSHED CONTROLS				
1)Management for nutrient input reduction	♦ Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake ♦ Essential component of algal control strategy where internal recycling is not the dominant nutrient source, and desired even where internal recycling is important	♦ Acts against the original source of algal nutrition ♦ Creates sustainable limitation on algal growth ♦ May control delivery of other unwanted pollutants to lake ♦ Facilitates ecosystem management approach which considers more than just algal control	♦ May involve considerable lag time before improvement observed ♦ May not be sufficient to achieve goals without some form of in-lake management ♦ Reduction of overall system fertility may impact fisheries ♦ May cause shift in nutrient ratios to favor less desirable algae	♦ Highly applicable, but not easy. Key targets would include stormwater, wastewater and cranberry bogs in the immediate watershed, plus inputs to Long and Seymour Ponds.
1a) Point source controls	♦ More stringent discharge requirements ♦ May involve diversion ♦ May involve technological or operational adjustments ♦ May involve pollution prevention plans	♦ Often provides major input reduction ♦ Highly efficient approach in most cases ♦ Success easily monitored	♦ May be very expensive in terms of capital and operational costs ♦ May transfer problems to another watershed ♦ Variability in results may be high in some cases	♦ There are no true point sources in this watershed; cranberry bogs and stormwater discharges can be treated as point sources, but really represent non-point sources with focused discharges.
1b) Non-point source controls	♦ Reduction of sources of nutrients ♦ May involve elimination of land uses or activities that release nutrients ♦ May involve alternative product use, as with no phosphate fertilizer	♦ Removes source ♦ Limited ongoing costs	♦ May require purchase of land or activity ♦ May be viewed as limitation of “quality of life” ♦ Usually requires education and gradual implementation	♦ Best management practices have been specified for cranberry bogs, and possible purchase of all or part of the bogs might be considered. The town is evaluating wastewater and stormwater management options.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
1c) Non-point source pollutant trapping	♦ Capture of pollutants between source and lake ♦ May involve drainage system alteration ♦ Often involves wetland treatments (det./infiltration) ♦ May involve stormwater collection and treatment as with point sources	♦ Minimizes interference with land uses and activities ♦ Allows diffuse and phased implementation throughout watershed ♦ Highly flexible approach ♦ Tends to address wide range of pollutant loads	♦ Does not address actual sources ♦ May be expensive on necessary scale ♦ May require substantial maintenance	♦ Actions to minimize pollutant inputs through stormwater or bog discharges are appropriate.
IN-LAKE PHYSICAL CONTROLS				
2) Circulation and destratification	♦ Use of water or air to keep water in motion ♦ Intended to prevent or break stratification ♦ Generally driven by mechanical or pneumatic force	♦ Reduces surface build-up of algal scums ♦ May disrupt growth of blue-green algae ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Can eliminate localized problems without obvious impact on whole lake	♦ May spread localized impacts ♦ May lower oxygen levels in shallow water ♦ May promote downstream impacts	♦ Highly applicable; it appears that current problems result from temporary loss of circulation and short-term development of stratification.
3) Dilution and flushing	♦ Addition of water of better quality can dilute nutrients ♦ Addition of water of similar or poorer quality flushes system to minimize algal build-up ♦ May have continuous or periodic additions	♦ Dilution reduces nutrient concentrations without altering load ♦ Flushing minimizes detention; response to pollutants may be reduced	♦ Diverts water from other uses ♦ Flushing may wash desirable zooplankton from lake ♦ Use of poorer quality water increases loads ♦ Possible downstream impacts	♦ Inapplicable; no adequate source of water available.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
4) Drawdown	♦ Lowering of water over autumn period allows oxidation, desiccation and compaction of sediments ♦ Duration of exposure and degree of dewatering of exposed areas are important ♦ Algae are affected mainly by reduction in available nutrients.	♦ May reduce available nutrients or nutrient ratios, affecting algal biomass and composition ♦ Opportunity for shoreline clean-up/structure repair ♦ Flood control utility ♦ May provide rooted plant control as well	♦ Possible impacts on non-target resources ♦ Possible impairment of water supply ♦ Alteration of downstream flows and winter water level ♦ May result in greater nutrient availability if flushing inadequate	♦ Inapplicable; limited drawdown capacity, and shallow areas that might be exposed do not represent a problem.
5) Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering ♦ Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system ♦ Nutrient reserves are removed and algal growth can be limited by nutrient availability	♦ Can control algae if internal recycling is main nutrient source ♦ Increases water depth ♦ Can reduce pollutant reserves ♦ Can reduce sediment oxygen demand ♦ Can improve spawning habitat for many fish species ♦ Allows complete renovation of aquatic ecosystem	♦ Temporarily removes benthic invertebrates ♦ May create turbidity ♦ May eliminate fish community (complete dry dredging only) ♦ Possible impacts from containment area discharge ♦ Possible impacts from dredged material disposal ♦ Interference with recreation or other uses during dredging	♦ Applicable but very difficult; dredging would need to occur in >15 ft of water (rarely done in ponds), and complete testing of sediments for a large suite of contaminants would be necessary to assess disposal options. Costs could be prohibitive, but dredging would represent a truly restorative approach, setting the pond back in time.
5a) "Dry" excavation	♦ Lake drained or lowered to maximum extent practical ♦ Target material dried to maximum extent possible ♦ Conventional excavation equipment used to remove sediments	♦ Tends to facilitate a very thorough effort ♦ May allow drying of sediments prior to removal ♦ Allows use of less specialized equipment	♦ Eliminates most aquatic biota unless a portion left undrained ♦ Eliminates lake use during dredging	♦ Inapplicable; no way to control that much groundwater.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
5b) "Wet" excavation	♦ Lake level may be lowered, but sediments not substantially exposed ♦ Draglines, bucket dredges, or long-reach backhoes used to remove sediment	♦ Requires least preparation time or effort, tends to be least cost dredging approach ♦ May allow use of easily acquired equipment ♦ May preserve aquatic biota	♦ Usually creates extreme turbidity ♦ Normally requires intermediate containment area to dry sediments prior to hauling ♦ May disrupt ecological function ♦ Use disruption	♦ Possible but very disruptive; unlikely to be a preferred approach under current regulatory system.
5c) Hydraulic removal	♦ Lake level not reduced ♦ Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area ♦ Slurry is dewatered; sediment retained, water discharged	♦ Creates minimal turbidity and impact on biota ♦ Can allow some lake uses during dredging ♦ Allows removal with limited access or shoreline disturbance	♦ Often leaves some sediment behind ♦ Cannot handle coarse or debris-laden materials ♦ Requires sophisticated and more expensive containment area	♦ Applicable; would require specialized equipment and a containment area for material, quantity and quality not determined in this study. A very expensive option, but highly restorative.
6) Light-limiting dyes and surface covers	♦ Creates light limitation	♦ Creates light limit on algal growth without high turbidity or great depth ♦ May achieve some control of rooted plants as well	♦ May cause thermal stratification in shallow ponds ♦ May facilitate anoxia at sediment interface with water	♦ Inapplicable; dyes not usually allowed where an outlet is present, clarity already low. Covers would impair access.
6.a) Dyes	♦ Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth ♦ Dyes remain in solution until washed out of system.	♦ Produces appealing color ♦ Creates illusion of greater depth	♦ May not control surface bloom-forming species ♦ May not control growth of shallow water algal mats ♦ Altered thermal regime	♦ Light limits and greater temperature in surface waters may favor surface blooms of cyanobacteria.
6.b) Surface covers	♦ Opaque sheet material applied to water surface	♦ Minimizes atmospheric and wildlife pollutant inputs	♦ Minimizes atmospheric gas exchange ♦ Limits recreation	♦ Would prevent swimming, boating and fishing.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
7) Mechanical removal	♦ Filtering of pumped water for water supply purposes ♦ Collection of floating scums or mats with booms, nets, or other devices ♦ Continuous or multiple applications per year usually needed	♦ Algae and associated nutrients can be removed from system ♦ Surface collection can be applied as needed ♦ May remove floating debris ♦ Collected algae dry to minimal volume	♦ Filtration requires high backwash and sludge handling capability ♦ Labor and/or capital intensive ♦ Variable collection efficiency ♦ Possible impacts on non-target aquatic life	♦ Inapplicable; algae are not amenable to any but a very sophisticated and expensive filtration system; would be like running a pool filter for the entire pond.
8) Selective withdrawal	♦ Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels ♦ May be pumped or utilize passive head differential	♦ Removes targeted water from lake efficiently ♦ May prevent anoxia and phosphorus build up in bottom water ♦ May remove initial phase of algal blooms which start in deep water ♦ May create coldwater conditions downstream	♦ Possible downstream impacts of poor water quality ♦ May promote mixing of remaining poor quality bottom water with surface waters ♦ May cause unintended drawdown if inflows do not match withdrawal	♦ Possible but not advisable, as poor quality water would be discharged to the Herring River. Could be attempted with treatment, but expense rises and benefits uncertain.
9) Sonication	♦ Sound waves disrupt algal cells	♦ Supposedly affects only algae (new technique) ♦ Applicable in localized areas	♦ Unknown effects on non-target organisms ♦ May release cellular toxins or other undesirable contents into water column	♦ Possible but not usually applied on the needed scale; would need many units, does not work on all algal types.
IN-LAKE CHEMICAL CONTROLS				
10) Hypolimnetic aeration or oxygenation	♦ Addition of air or oxygen provides oxic conditions ♦ Maintains stratification ♦ Can also withdraw water, oxygenate, then replace	♦ Oxic conditions reduce P availability ♦ Oxygen improves habitat ♦ Oxygen reduces build-up of reduced compounds	♦ May disrupt thermal layers important to fish community ♦ Theoretically promotes supersaturation with gases harmful to fish	♦ Applicable to a degree, but no stable hypolimnion; would be more appropriate to use a circulation system.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
11) Algaecides	♦ Liquid or pelletized algaecides applied to target area ♦ Algae killed by direct toxicity or metabolic interference ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid elimination of algae from water column , normally with increased water clarity ♦ May result in net movement of nutrients to bottom of lake	♦ Possible toxicity to non-target species ♦ Restrictions on water use for varying time after treatment ♦ Increased oxygen demand and possible toxicity ♦ Possible recycling of nutrients	♦ Applicable, but will not address the source of the problem and would require repeated additions.
11a) Forms of copper	♦ Cellular toxicant, disruption of membrane transport ♦ Applied as wide variety of liquid or granular formulations	♦ Effective and rapid control of many algae species ♦ Approved for use in most water supplies	♦ Possible toxicity to aquatic fauna ♦ Accumulation of copper in system ♦ Resistance by certain green and blue-green nuisance species ♦ Lysing of cells releases nutrients and toxins	♦ Applicable but may have some regulatory resistance for possible impacts to juvenile alewife. Ongoing application expected but not desirable.
11b) Peroxides	♦ Disrupts most cellular functions, tends to attack membranes ♦ Applied as a liquid or solid. ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid action ♦ Oxidizes cell contents, may limit oxygen demand and toxicity	♦ Much more expensive than copper ♦ Limited track record ♦ Possible recycling of nutrients	♦ Less disruptive than copper, but more expensive. Tends to work best on cyanobacteria, but unlikely to prevent all blooms in fertile system.
11c) Synthetic organic algaecides	♦ Absorbed or membrane-active chemicals which disrupt metabolism ♦ Causes structural deterioration	♦ Used where copper is ineffective ♦ Limited toxicity to fish at recommended dosages ♦ Rapid action	♦ Non-selective in treated area ♦ Toxic to aquatic fauna (varying degrees by formulation) ♦ Time delays on water use	♦ Few available, not likely to be acceptable in this situation.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
12) Phosphorus inactivation	♦ Typically salts of aluminum, iron or calcium are added to the lake, as liquid or powder ♦ Phosphorus in the treated water column is complexed and settled to the bottom of the lake ♦ Phosphorus in upper sediment layer is complexed, reducing release from sediment ♦ Permanence of binding varies by binder in relation to redox potential and pH	♦ Can provide rapid, major decrease in phosphorus concentration in water column ♦ Can minimize release of phosphorus from sediment ♦ May remove other nutrients and contaminants as well as phosphorus ♦ Flexible with regard to depth of application and speed of improvement	♦ Possible toxicity especially by aluminum ♦ Possible release of phosphorus under anoxia or extreme pH ♦ May cause fluctuations in water chemistry, especially pH, during treatment ♦ Possible resuspension of floc in shallow areas ♦ Adds to bottom sediment	♦ Highly applicable; internal load is a major source of phosphorus, inactivation with aluminum is possible and proven effective in other Cape ponds, including Long Pond immediately upstream.
13) Sediment oxidation	♦ Addition of oxidants, binders and pH adjustors to oxidize sediment ♦ Binding of phosphorus is enhanced ♦ Denitrification is stimulated	♦ Can reduce phosphorus supply to algae ♦ Can alter N:P ratios in water column ♦ May decrease sediment oxygen demand	♦ Possible impacts on benthic biota ♦ Longevity of effects not well known ♦ Possible source of nitrogen for blue-green algae	♦ Applicable but not commonly applied; technology not fully developed. Not as reliable yet as direct phosphorus inactivation.
14) Settling agents	♦ Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too ♦ Lime, alum or polymers applied, usually as a liquid or slurry ♦ Creates a floc with algae and other suspended particles ♦ Floc settles to bottom of lake ♦ Re-application typically necessary at least once/yr	♦ Removes algae and increases water clarity without lysing most cells ♦ Reduces nutrient recycling if floc sufficient ♦ Removes non-algal particles as well as algae ♦ May reduce dissolved phosphorus levels at the same time	♦ Possible impacts on aquatic fauna ♦ Possible fluctuations in water chemistry during treatment ♦ Resuspension of floc possible in shallow, well-mixed waters ♦ Promotes increased sediment accumulation	♦ Applicable but will not prevent recurring blooms unless coupled with a phosphorus inactivator.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
15) Selective nutrient addition	♦ Ratio of nutrients changed by additions of selected nutrients ♦ Addition of non-limiting nutrients can change composition of algal community ♦ Processes such as settling and grazing can then reduce algal biomass	♦ Can reduce algal levels where control of limiting nutrient not feasible ♦ Can promote non-nuisance forms of algae ♦ Can improve productivity of system without increased standing crop of algae ♦ Used more for fish production that algal community management	♦ May result in greater algal abundance through uncertain biological response ♦ May require frequent application to maintain desired ratios ♦ Possible downstream effects	♦ Increased nitrate levels tend to reduce frequency of cyanobacterial blooms. No data for nitrate available, adding nitrate likely to promote green algal blooms, which are less objectionable than cyanobacteria but still not desirable.
IN-LAKE BIOLOGICAL CONTROLS				
16) Enhanced grazing	♦ Manipulation of biological components of system to achieve grazing control over algae ♦ Typically involves alteration of fish community to promote growth of grazing zooplankton	♦ May increase water clarity by changes in algal biomass or cell size without reduction of nutrient levels ♦ Can convert unwanted algae into fish ♦ Harnesses natural processes	♦ May involve introduction of exotic species ♦ Effects may not be controllable or lasting ♦ May foster shifts in algal composition to even less desirable forms	♦ Highly applicable but not feasible without depression of alewife population, the support of which is a current use of the pond.
16.a) Herbivorous fish	♦ Stocking of fish that eat algae	♦ Converts algae directly into potentially harvestable fish ♦ Grazing pressure can be adjusted through stocking rate	♦ Typically requires introduction of non-native species ♦ Difficult to control over long term ♦ Smaller algal forms may be benefited and bloom	♦ None available that effectively consume and control the target algae.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
16.b) Herbivorous zooplankton	♦ Reduction in planktivorous fish to promote grazing pressure by zooplankton ♦ May involve stocking piscivores or removing planktivores ♦ May also involve stocking zooplankton or establishing refugia	♦ Converts algae indirectly into harvestable fish ♦ Zooplankton response to increasing algae can be rapid ♦ May be accomplished without introduction of non-native species ♦ Generally compatible with most fishery management goals	♦ Highly variable response expected; temporal and spatial variability may be high ♦ Requires careful monitoring and management action on 1-5 yr basis ♦ Larger or toxic algal forms may be benefitted and bloom	♦ Highly applicable, but zooplankton size and biomass are depressed by alewife feeding.
17) Bottom-feeding fish removal	♦ Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion	♦ Reduces turbidity and nutrient additions from this source ♦ May restructure fish community in more desirable manner	♦ Targeted fish species are difficult to control ♦ Reduction in fish populations valued by some lake users (human/non-human)	♦ Bottom feeding fish not known to be a dominant component of fish community, unlikely to improve conditions.
18) Microbial competition	♦ Addition of microbes, often with oxygenation, can tie up nutrients and limit algal growth ♦ Tends to control N more than P	♦ Shifts nutrient use to organisms that do not form scums or impair uses to same extent as algae ♦ Harnesses natural processes ♦ May decrease sediment	♦ Minimal scientific evaluation ♦ N control may still favor cyanobacteria ♦ May need aeration system to get acceptable results	♦ Applicable, but very limited scientific evaluation of mechanisms involved. Would require and experimental approach.
19) Pathogens	♦ Addition of inoculum to initiate attack on algal cells ♦ May involve fungi, bacteria or viruses	♦ May create lakewide "epidemic" and reduction of algal biomass ♦ May provide sustained control through cycles ♦ Can be highly specific to algal group or genera	♦ Largely experimental approach at this time ♦ May promote resistant nuisance forms ♦ May cause high oxygen demand or release of toxins by lysed algal cells ♦ Effects on non-target organisms uncertain	♦ No commercial products available, would not address source of problem, the nutrients.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
20) Competition and allelopathy by plants	♦ Plants may tie up sufficient nutrients to limit algal growth ♦ Plants may create a light limitation on algal growth ♦ Chemical inhibition of algae may occur through substances released by other organisms	♦ Harnesses power of natural biological interactions ♦ May provide responsive and prolonged control	♦ Some algal forms appear resistant ♦ Use of plants may lead to problems with vascular plants ♦ Use of plant material may cause depression of oxygen levels	♦ Limited plant growths due to low light. Enough plants to limit algal growth would likely constitute a different problem, and pond is too deep to get growth in all needed areas.
20a) Plantings for nutrient control	♦ Plant growths of sufficient density may limit algal access to nutrients ♦ Plants can exude allelopathic substances which inhibit algal growth ♦ Portable plant "pods" , floating islands, or other structures can be installed	♦ Productivity and associated habitat value can remain high without algal blooms ♦ Can be managed to limit interference with recreation and provide habitat ♦ Wetland cells in or adjacent to the lake can minimize nutrient inputs	♦ Vascular plants may achieve nuisance densities ♦ Vascular plant senescence may release nutrients and cause algal blooms ♦ The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes	♦ Inputs appear too great and too sporadic for this approach, getting plants in the area of internal releases is not feasible. Largely experimental.
20b) Plantings for light control	♦ Plant species with floating leaves can shade out many algal growths at elevated densities	♦ Vascular plants can be more easily harvested than most algae ♦ Many floating species provide waterfowl food	♦ Floating plants can be a recreational nuisance ♦ Low surface mixing and atmospheric contact promote anoxia	♦ Inapplicable; pond too deep to address key areas, would impair other uses.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO HINCKLEYS POND
20c) Addition of barley straw	♦ Input of barley straw can set off a series of chemical reactions which limit algal growth ♦ Release of allelopathic chemicals can kill algae ♦ Release of humic substances can bind phosphorus	♦ Materials and application are relatively inexpensive ♦ Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	♦ Success appears linked to uncertain and potentially uncontrollable water chemistry factors ♦ Depression of oxygen levels may result ♦ Water chemistry may be altered in other ways unsuitable for non-target organisms	♦ Limited applicability; some success with cyanobacteria achieved, but not a licensed algaecide and will not address source of problem – nutrients. Would require repeated addition, adds to oxygen demand.

Stormwater management actions will need to be evaluated with regard to level of contaminant load reduction, cost, and regulatory issues.

- Wastewater management – Like stormwater, wastewater represents only a small fraction of the nutrient loads to Hinckleys Pond, but the long-term health of the pond and any investment in immediate nutrient reduction will be best protected by proper wastewater management. Current Title 5 provisions push wastewater management through on-site systems in the right direction over time, and consideration of sewering for problem areas is appropriate, but wastewater is not a dominant threat to the pond within the zone of direct contribution. Wastewater is not known to be a pressing issue for Long or Seymour Ponds upstream, either, although the quality of water entering Hinckleys Pond from those ponds is partly dependent on wastewater management around those ponds. Proper siting, design and maintenance of systems would be the primary thrust of wastewater management in this case, unless there is sufficient impetus for a sewering and wastewater treatment project in the greater Long Pond area.
- Cranberry bog discharge management – The cranberry bogs represent an obvious and proximal source of nutrients to Hinckleys Pond, and the concentrations in water released from the bogs are quite high. However, the bogs do not use all that much water relative to pond volume, and the actual load of phosphorus is not appreciably greater than that estimated for stormwater from the direct drainage area. Since not all bog discharges were examined in this study, actual inputs may be somewhat higher, but the harvest discharge is normally the major output of phosphorus from cranberry bogs. The nitrogen input to the pond from the bogs is negligible compared to other sources to Hinckleys Pond. The issue with the bogs is the availability of the phosphorus in the discharge after harvesting (very high) and the likelihood that the load is incorporated into the iron-bound phosphorus fraction in the Hinckleys Pond sediment. Additionally, that load is delivered from a relatively small area, one that could be effectively targeted for improvements. Over time, phosphorus loading from the two bogs represents a substantial source for the internal load to the pond.

  Best management practices for the bogs have been specified in appropriate plans, and while closer adherence to the plans appears possible, the primary issue is a very low recommended N:P ratio for fertilizer. This ratio has been raised by recent research and application, and may be necessary for best growth by cranberries, but would appear to result in considerable excess phosphorus accumulation in the bogs. Water used to flood the bogs picks up this phosphorus, most of it in available form, and the concentrations in water discharged to the pond are over 25 times greater than desirable. Anything that can be done to limit the movement of phosphorus from the bogs to the lake is worth considering.

- Artificial circulation – Hinckleys Pond has a maximum depth near the boundary for seasonal stratification; that is, the pond is deep enough to undergo thermal stratification when there is little wind, but under conditions often experienced on Cape Cod, the water can be mixed from top to bottom. When mixed, atmospheric input of oxygen is increased and oxygen levels can remain high enough to limit the recycling of phosphorus, which is controlled in this case primarily by binding with iron. How often and how extensively the pond bottom goes anoxic will be a function of the weather, and is therefore not reliably predictable. However, mechanical or air driven systems are available that could maintain circulation and ensure desirable mixing from top to bottom. Such a system would decrease the release of phosphorus from muck sediments that cover about 90 acres of the pond and represent the largest single potential source of phosphorus to the pond.

Circulation can be maintained with air, but this air would not be the primary source of oxygen. There would be some transfer, but this mechanism is inefficient over relatively short vertical distances and without a very strong oxygen gradient. Rather, it would be the constant exposure of water to the atmosphere, with circulation throughout the pond that would raise oxygen levels by the greatest extent. Mechanical systems, whereby water is pumped up or down, sprayed into the air, or otherwise mixed by mechanical force, can also maintain circulation. Maintaining adequate oxygen at all times in all parts of the pond is difficult, but the current situation of periodic anoxia at the interface between the muck sediments and the overlying water could be greatly improved, lowering the release of phosphorus substantially.

- Hydraulic dredging – Actually removing the accumulated muck sediment would be the ideal solution to the internal load problem, would greatly decrease oxygen demand, would enhance habitat for many species, and would effectively set Hinckleys Pond back in time, possibly to the end of the last ice age, if done completely. Continued nutrient inputs would remain a concern for the long-term health of the pond, but the pond would experience major improvements in many conditions, including clarity and oxygen levels, and that improvement would last for a long time.

  However, dredging is a very expensive technique that requires considerable planning and permitting. It is rare to dredge a freshwater pond at depths greater than 15 ft, as a function of equipment limitations and perceived need, but that is where most of the needed dredging of Hinckleys Pond would have to occur. Sediment quantity and quality have not been assessed. Assuming only an average of 1 ft of soft sediment over 90 acres (comparable to assessed conditions in Long Pond), a thorough dredging would remove 90 acre-feet, or 145,000 cubic yards (cy) of sediment. This sediment is only 11 to 14% solids, and will dry to a smaller volume, but the cost of dredging is largely dependent on the in-place volume. With the cleanest of sediment, a rough cost of at least $30/cy would be postulated as a minimum price, suggesting a removal cost of about $4.4 million. With more sediment or contamination, the cost would rise. Where reclaiming water depth is not an issue, other approaches to dealing with sediment-water interactions are usually employed.

- Sonication – Devices that emit sonic waves that disrupt algal cell structure have been used to minimize algal biomass accumulation in ponds. Usually these are smaller ponds with less depth, but the application is extendable to larger systems. The technique depends on a “line of sight” concept; nothing can block the sound waves if they are to be effective, so systems with rooted plants, large rocks, or just an irregular shape may not be well suited to this approach. It is applicable to Hinckleys Pond, but many units would be needed, electric lines would have to enter the pond unless a solar-powered version was used, and not all algae are susceptible. While this technique has reduced algal biomass in a number of ponds, it has not created the level of clarity perceived as desirable for Hinckleys Pond and will not address the key issue, excessive phosphorus. Where inputs cannot be controlled (e.g., golf courses, waterfowl ponds), sonication is a viable maintenance technique, but for Hinckleys Pond it is assumed that a solution focused on phosphorus control would be preferred.

- Phosphorus inactivation – Iron is the dominant natural binder of phosphorus in Cape Cod ponds, but iron releases phosphorus under anoxic conditions, and can itself be permanently bound by sulfur, a reaction that occurs under strong anoxia over an extended period of time. Adding oxygen in the presence of sufficient iron can result in inactivation and precipitation of phosphorus, and this happens naturally but not continually in Hinckleys Pond and many other Cape Cod ponds. To more permanently bind phosphorus, aluminum is used in systems of near neutral or lower pH, as aluminum-phosphorus complexes are not subject to dissociation under low oxygen conditions. Calcium compounds may be used in high pH systems, but these do not exist on the Cape. Lanthanum has been used in Australia with results similar to those for aluminum, and is now available in the USA, but is considerably more expensive than aluminum.

  The amount of aluminum needed is mainly a function of the amount of iron-bound phosphorus in the surficial sediments at a depth at which anoxia can occur. The amount is usually calculated for sediment depths up to 10 cm, yielding a quantity of phosphorus per square meter that must be inactivated. Sampling in multiple places in a pond provides a measure of variability, and multiple treatment zones can be set up, each with its own assigned dose. Some phosphorus will be stripped from the water column during treatment, which usually involves application of the aluminum compounds near the surface, but this is not a very efficient reaction. It is the binding of formerly iron-bound phosphorus into aluminum compounds in the surficial sediment layer that then limits further phosphorus release and lowers the internal load drastically. Where the internal load is a dominant factor in phosphorus levels in the overlying water, this inactivation process can result in control of algal blooms, improved water clarity, and lower oxygen demand. There is indication that this would be an effective process in Hinckleys Pond, but the duration of benefits with continued phosphorus inputs at current levels must be further evaluated.

- Nitrate addition – While not widely known or commonly practiced, the presence of adequate nitrate deters cyanobacteria. Additions in several cases have eliminated cyanobacterial blooms that had occurred for multiple years (Kortmann pers. comm.). Nitrate levels in Hinckley Pond are not known, as only total nitrogen is sampled in the PALS program, but based on the dominance of nitrogen-fixing cyanobacteria in Hinckleys Pond blooms, it is likely that nitrate is negligible much of the time it the pond. However, while addition of nitrate might shift the algal community away from certain cyanobacteria, it is not likely to lower algal biomass, as phosphorus levels will still be elevated. There is also the issue that most Cape estuaries are overly fertile due to nitrogen loading and adding through the Herring River would not be perceived as appropriate overall environmental management. It is unlikely that nitrate addition could be permitted, and it would be preferable to raise the N:P ratio by lowering phosphorus.

- Algaecides and settling agents – Directly attacking algae is sometimes the only option left when prior planning and action have not occurred or have failed. Proper control of algae with algaecides or settling agents occurs as the algal populations are growing, not once excessive biomass has been accumulated. Problems with oxygen sag, release of toxins, and other water quality problems after treatments are routinely traced to treating excessive biomasses. Rather, the algae must be monitored, probably weekly, and treatment should be conducted when problem species begin their exponential growth phase. Yet for blooms that arise suddenly from resting stages in the sediment, even monitoring may fail to detect them until it is too late, so tracking is by no means a guarantee of success. Algaecides and settling agents do not typically attack the source of the problem, elevated phosphorus, but new formulations are incorporating phosphorus binders and may give longer lasting results. It would seem preferable in Hinckleys Pond to address the phosphorus excess before resorting to algaecides and settling agents.

- Microbial competition – There is a body of theory about microbial competition with algae for nutrients that suggests that given the right supplements, bacteria can outcompete algae and prevent blooms. It is less clear how this can work quickly or why the bacteria would not discolor the water and/or limit clarity, but anecdotal reports of success can be found. Microbial decomposition of bottom muck is also reported, usually aided by an aeration system for either circulation or oxygen input, but there is virtually no peer-reviewed scientific literature supporting these contentions. The products are not registered with the USEPA as algaecides, and there is speculation that the enzymes often added as part of the process are actually attacking algae, acting like algaecides. While there may be potential in such additives, especially if a circulation system is installed, a professional recommendation for this approach cannot be offered without more documentation of results, effectiveness, longevity, and non-target impacts.

- Enhanced zooplankton grazing – Zooplankton are the primary consumers of algae, so any adjustment that favors more zooplankton and especially larger bodied zooplankton (which are more efficient grazers of algae) would help minimize the build-up of algal biomass. However, the primary reason for depressed zooplankton biomass and body size in Hinckleys Pond is the presence of an alewife population. Adult alewife enter the pond from salt water and spawn in the spring, leaving young to feed and grow through the summer before migrating to salt water. Thus during the summer, when algal grazing by zooplankton is most needed, there are few zooplankton present. Other than somehow sequestering a portion of the pond as a zooplankton reserve, there is not much to be done about this, as alewife propagation is a current use of the pond. Feeding on zooplankton is less effective in dark zones, but with low oxygen those zones are not hospitable to zooplankton. This does suggest that an aeration or circulation system might be an aid to zooplankton survival through the summer, but in the presence of alewife it is very unlikely that zooplankton grazing will be great enough to control algal biomass.

It would therefore appear that the primary and feasible methods for achieving rehabilitation objectives at Hinckleys Pond include artificial circulation and/or phosphorus inactivation to reduce internal loading of phosphorus and oxygen demand, supported by watershed management to reduce external loads from stormwater, wastewater, cranberry bog discharges or surface inflows from Long and/or Seymour Ponds . None of these methods is mutually exclusive, and all may be needed to achieve lasting success.

Additional Information for Artificial Circulation

The key to artificial circulation is sufficient power to overcome thermal stability and resistance to mixing. This has been examined in great detail in a number of aeration studies, and the rule postulated by Lorenzen and Fast in 1977 has proven reliable (Cooke et al. 2005); to maintain circulation it requires 1.3 cubic feet per minute of air (cfm) per acre, measured at one atmosphere and termed a standard cubic foot per minute, or SCFM. Under some circumstances less air will work, especially when the distance travelled by the air is long (i.e., the diffuser is in a deep lake). In very shallow systems it is hard to distribute the air over each acre in a way that ensures uniform mixing. Yet time after time, failure of a circulation system applying air to maintain unstratified conditions is traced to inadequate airflow.

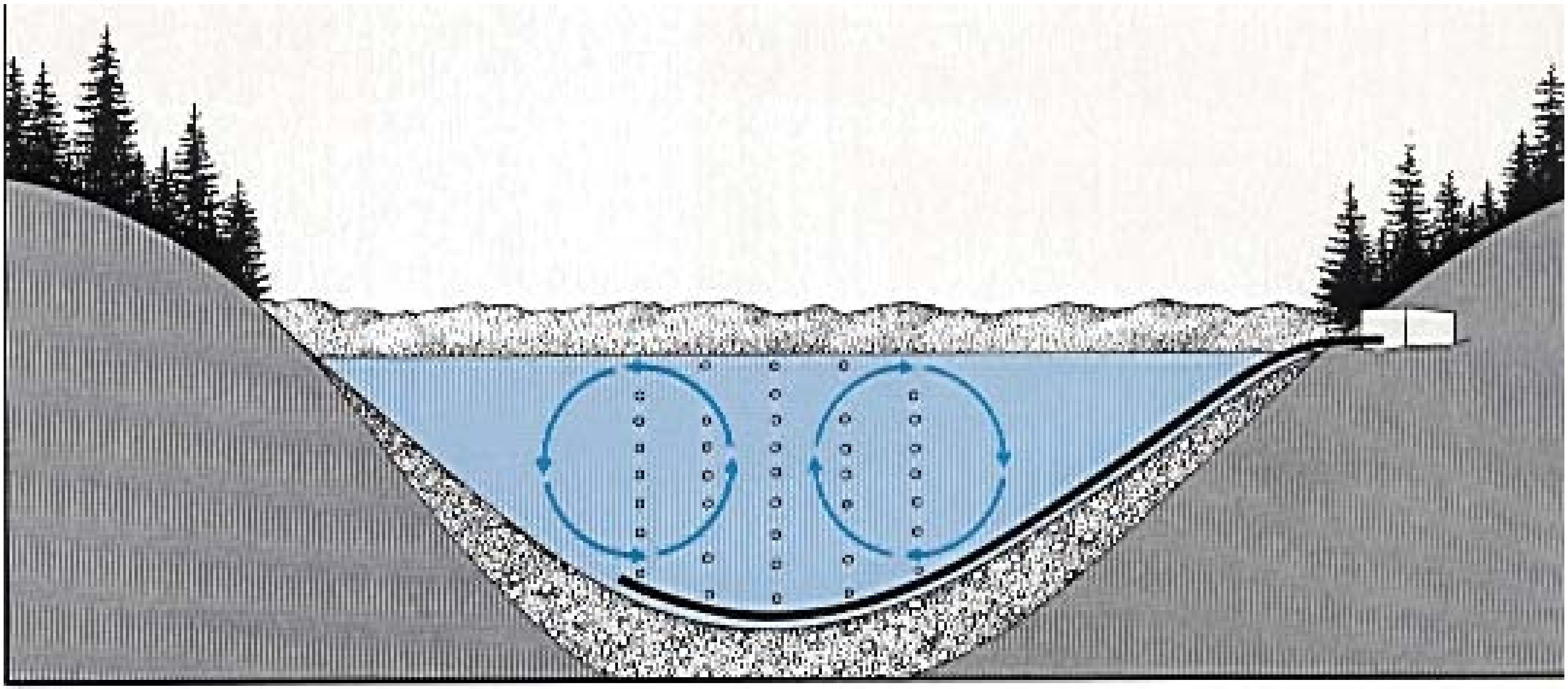
For Hinckleys Pond, an area of up to 90 acres should be mixed, representing the area with muck sediments in need of oxygen at times during the summer. However, it is possible that only the area deeper than 20 ft might need direct attention on a regular basis, lowering the target area to only 25.7 ac. Yet it is more likely that all areas deeper than 15 ft should be addressed in a mixing system, suggesting a target area of 77.7 ac. It is always better to overpower and overdistribute when designing a mixing system.

At a target area of 77.7 ac and an airflow rate of 1.3 scfm/ac, an input of just over 100 scfm is needed. This airflow may not be needed at all times, and it is customary to use two compressors to provide the desired airflow, allowing partial operation when appropriate and maintenance of one compressor without complete loss of airflow. Two 15 horsepower (hp) compressors would each typically provide 60 scfm, providing enough power to drive the circulation system. Slightly larger (20 hp) compressors might be considered to facilitate wider distribution of air and better mixing throughout the pond.

The layout of such as system can vary, but is usually relatively simple (Figure 15), and would include a shoreline housing for each compressor (they could be housed together with lines running into the pond, or could be run from separate areas, each covering part of the pond) and lines running to distribution points in the pond. Usually metal pipe is used from the compressor to the water, given more initial heat and pressure, but plastic hoses usually no more than 1 inch in diameter are used within the pond itself. The pipe may be perforated or may have diffusers at given intervals; the exact spacing and distribution of output points depends on the manufacturer and designer, and a variety of workable spatial alignments are possible.

No data for early season deep water oxygen are available; the earliest monitoring is in June, and indicates that there is a need for more oxygen by that time almost every year. It is likely that the system

Figure 15. Schematic of standard destratifying aeration system for pond circulation.



would be turned on in early to mid-May and would operate through September. More sporadic operation or partial operation (one compressor and selected target areas, like the deepest water) may be possible with more frequent tracking of pond oxygen levels, but most successful circulation projects let the system run through the summer. Based on similar systems installed in other lakes, the capital cost for such a system would be on the order of $150,000, possibly up to $200,000 for larger compressors, greater coverage, and top of the line materials. Operational costs vary mainly with power costs, but would be expected to be on the order of $10,000 per year.

Circulation does not have to be achieved through air input, however, and a number of mechanical systems are available. One brand of solar powered bottom to surface pump is the SolarBee, and there are a number of installations on Cape Cod. Water is pulled from the bottom of a pipe (can be set at any depth) by an impeller powered by photovoltaic cells, and the water is released in a laminar flow in all directions from the top (Figure 16). The actual amount of water pulled up through the tube is not especially large, but the process depends upon compensatory flow as the water moves, providing additional circulation farther from the unit. There is debate over how far the influence extends, and how well these units deal with vertical gradients of temperature, but the intent is to keep a pond mixed, not break existing stratification. If operated continuously, a proper installation should be able to maintain destratified conditions in a pond such as Hinckleys, with a maximum depth of 28 ft. More commonly, however, intake tubes are set at depths of 6 to 15 ft, mixing only the upper waters. This can create a stronger boundary zone near the lower water layer interface, and helps keep that water from being mixed during wind storms. It is not clear that this would work well in Hinckleys Pond, however, with a very thin lower water layer. Completely mixing Hinckleys Pond from mid-spring into autumn would seem to be more appropriate.

Given uncertainty over how far effects extend, determining how many SolarBee units are needed for an installation is not as straightforward as one might prefer. It appears that Hinckleys Pond would need about six units to mix the target area. A unit typically costs at least $35,000, with shipping and installation adding about another $5000, but there are fewer maintenance or operational costs than for electric systems. Rental is possible, allowing testing at reasonable cost if this option is appealing.

Another non-air driven circulation system is manufactured by WEARS of Australia, and is a downdraft pump system called ResMix (Figure 17). It too has a solar version, but the electric motor version is recommended by the manufacturer where power is available. These are large units – a single one would be adequate for Hinckleys Pond – and push large quantities of surface water to the bottom of the pipe. The warmer surface water will try to rise through the colder deeper water, creating currents in response to the pumping. These systems are typically installed in reservoirs used for potable supply, and maintain fairly uniform water quality over large areas very efficiently. More water is moved per unit of power applied than for an air driven circulation system, so long-term maintenance costs are lower. A unit appropriate for Hinckleys Pond would cost on the order of $200,000.

Figure 16. SolarBee circulation unit.

Figure 17. ResMix circulation system by WEARS.

Air driven, updraft and downdraft circulators have a mixed record of performance. Often there are inadequate data to evaluate performance, making assessment more subjective than it should be. Only about half of studied air mixing systems have reduced algae to the desired level, but in the vast majority of failed cases, inadequate airflow was applied. There are literally hundreds of SolarBee installations in the USA, but there are very few data available and only one peer reviewed paper on performance. There are many complaints about performance, as well as endorsements from users, and implementation failure (e.g., insufficient units, poor placement) is suspected in cases where performance was not satisfactory. The WEARS ResMix system has only been installed in one USA location, with another planned for summer 2012, but results from Australia and Europe appear promising. There are advantages to a downdraft system, including pushing algae into dark zones and not distributing poor quality bottom water at the surface, but local experience is limited to date.

One appealing option is the combination of circulation with phosphorus inactivation. One can inject phosphorus inactivators into a circulation system, using the circulation as a mixing system for the aluminum. Phosphorus inactivation is discussed in more detail in the next section. This has been done mainly with air driven systems, and such systems have been installed in a number of temperate zone lakes, generally with positive results, although no detailed literature exists on this approach as of yet. Morses Pond in Wellesley, MA has used such a system with acceptable results for the last three years. A Florida company now markets a combination mixing and inactivation system with very flexible features. This approach is gaining rapid and widespread acceptance, but is still experimental to some degree. For Hinckleys Pond, this might add a capital cost of about $30,000 and an annual operating cost (mainly for chemicals) of $25,000. The need for chemical addition should decline over a period of years, but probably would remain for at least a decade.

The most common combined circulation-inactivation approach involves holding tanks for liquid aluminum sulfate and sodium aluminate, which are released at a 2:1 ratio by volume to achieve a pH neutral injection. That injection is made directly above diffusers, allowing the air to mix the chemicals in the water of the pond. Therefore, there are two hoses (one for each chemical) added to the air line for the circulation system, with an adjustable pump for each chemical feed line. The Wellesley system and the one now offered commercially out of Florida come on trailers, but underground installations have also been constructed. The circulation system can be run continuously in late spring and summer, with aluminum additions only as warranted. For existing installations, the chemical feed system is normally turned on in response to stormwater inputs or changes in water clarity that suggest the need for inactivation, but could be operated in a very flexible manner. However, such systems are not meant to be run just when it is convenient, and vigilant monitoring, operation and maintenance are essential; this is not a simple solution for algal blooms.

Additional Information for Nutrient Inactivation

If a circulation system is installed in Hinckleys Pond, adequate iron may be present to bind available phosphorus already, and if not, more iron could be added. However, more permanent binding is achieved by aluminum, and targeting the sediment reserves of iron-bound phosphorus would limit internal recycling independent of oxygen status. This involves a potentially much larger dose of aluminum than would be injected in a combined circulation-inactivation system, which would focus on stripping phosphorus only from the water column. A one-time inactivation of surficial sediment phosphorus reserves would seek to minimize the availability of phosphorus from iron compounds in the sediment, the main source of internal recycling. The data collected to assess the potential for internal loading and follow up lab assays for inactivation efficiency (Table 5) as part of this project are adequate to provide considerable input for planning such a treatment. Additional sediment collection and testing would be warranted prior to actual treatment, to fine tune areas and doses, but the three samples collected in September 2011 suggest similar conditions across the muck-covered portion of the pond. However, the results of simulated aluminum dosing in the lab varied considerably over the three samples, suggesting that additional testing is warranted.

The essential calculations are embodied in a spreadsheet (Table 18), and include two approaches. These apply the same basic data, but in the stoichiometric approach the dose is determined from an established (but changeable) ratio of aluminum to phosphorus. Doses are rarely <10:1 (Al:P by weight), and can exceed 20:1, but in MA treatments this is the typical range. A value of 15:1 was arbitrarily chosen as a starting point, but turns out to be a reasonable match for the results of the other approach, in which the dose is based on the dose response curve for phosphorus laden sediment treated in the lab with aluminum (Figure 18). In the dose-response lab assay method, there can be considerable variability in testing within samples and results among samples, and more samples may be advantageous when variability is high. For Hinckleys Pond sediment, the variability was moderate, and while additional sampling may be desirable prior to any treatment to fine tune the approach, these results were relatively uniform. However, the phosphorus content in muck in September 2011 differs quite a bit from the single applicable sample from December 2009 (Table 4 vs. Table 5), and the cost of different doses is significant, so more testing is recommended. Additionally, the target treatment area was evenly divided among the three samples collected; more samples would facilitate a more detailed distribution of doses among areas.

From the September 2011 samples and related calculations, it appears that the amount of phosphorus to be inactivated in the upper 10 cm of about 36.3 ha (90 ac) of muck sediment ranges from 7.9 to 10.5 g P/m^2, a relatively narrow range. At a set ratio of 15 Al:1 P by weight, that equates to doses of 118 to 157 g Al/m^2, at the high end of the application range from known projects. Using the dose response curves, the ratio that achieves sufficient phosphorus inactivation (generally taken as <50 mg/kg) varies from 10 to 17, yielding doses of 75 to 175 g/m^2, again at the high end of the scale. Other treatments on Cape Cod have ranged from 10 to 100 g/m^2, with an average around 50 g/m^2. Lesser doses could be applied, but inactivation of possible phosphorus reserves will be incomplete. Depending on how the sediment reacts, this could mean less initial reduction in internal loading or less duration of desirable effects. As noted previoulsy, additional testing would be appropriate before such a treatment was conducted, as the dose and associated cost can vary substantially.

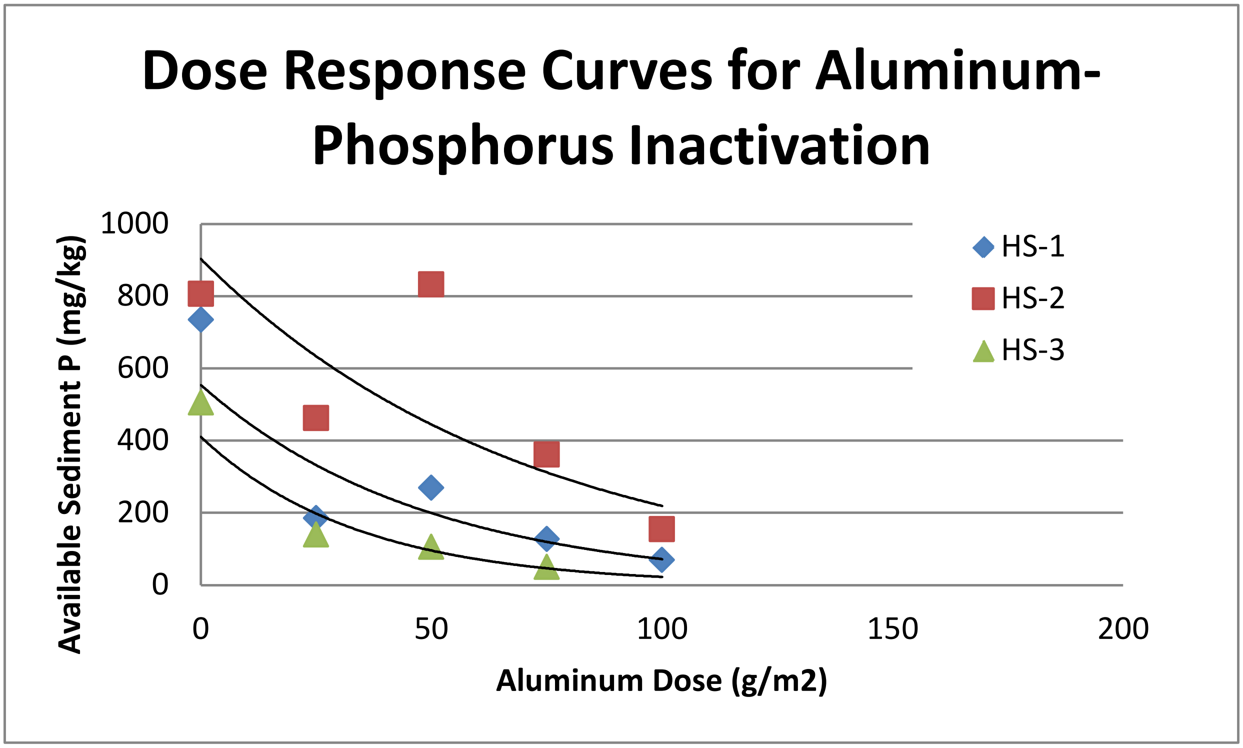
Where alkalinity is adequate, only aluminum sulfate (alum) need be applied, but where alkalinity is low (virtually all Cape Cod ponds), a compound that produces higher pH and balances the pH depression effect of alum is required. Options exist, but use of sodium aluminate (aluminate) allows addition of aluminum while balancing the pH. This tends to raise the cost of the treatment, but only slightly. The cost of a single treatment to inactivate most of the phosphorus in the upper 10 cm of muck sediment in

Table 18. Estimation of phosphorus inactivation dose and cost for Hinckleys Pond.

Shaded cells denote data input points; changes can be made in these cells to adjust for additional data.

	HINCKLEYS POND							
	From Stoichiometric Calculation				From Lab Assay			
Lake or Area	Area 1	Area 2	Area 3	Total	Area 1	Area 2	Area 3	Total
Mean Available Sediment P (mg/kg DW)	733	806	504		733	806	504	
Target Depth of Sediment to be Treated (cm)	10	10	10		10	10	10	
Volume of Sediment to be Treated per m2 (m3)	0.100	0.100	0.100		0.100	0.100	0.100	
Specific Gravity of Sediment	1.10	1.10	1.10		1.10	1.10	1.10	
Percent Solids (as a fraction)	0.110	0.118	0.142		0.110	0.118	0.142	
Mass of Sediment to be Treated (kg/m2)	12.1	13.0	15.6		12.1	13.0	15.6	
Mass of P to be Treated (g/m2)	8.87	10.46	7.87		8.87	10.46	7.87	
Target Area (ac)	30	30	30		30	30	30	
Target Area (m2)	120968	120968	120968		120968	120968	120968	
Aluminum sulfate (alum) @ 11.1 lb/gal and 4.4% aluminum (lb/gal)	0.4884	0.4884	0.4884		0.4884	0.4884	0.4884	
Sodium aluminate (aluminate) @ 12.1 lb/gal and 10.38% aluminum (lb/gal)	1.256	1.256	1.256		1.256	1.256	1.256	
Stoich. Ratio (ratio of Al to P in treatment)	15	15	15		14	17	10	
Resulting areal dose (g Al/m2)	133	157	118		125	175	75	
Ratio of alum to aluminate during treatment (volumetric)	2.00	2.00	2.00		2.00	2.00	2.00	
Aluminum Load								
Dose (kg/area)	16093	18983	14285	49361	15121	21169	9073	45363
Dose (lb/area)	35406	41763	31426	108595	33266	46573	19960	99798
Dose (gal alum) with Alum only	72493	85510	64346	222349	68112	95357	40867	204337
Application (gal/ac) for alum	2416	2850	2145		2270	3179	1362	
Dose (gal alum) @ specified ratio of Alum to Aluminate	31714	37409	28150	97273	29798	41717	17879	89393
Dose (gal aluminate) @ specified ratio of Alum to Aluminate	15857	18704	14075	48636	14899	20858	8939	44697
Application (gal/ac) for Alum in Alum+Aluminate Trtmt	1057	1247	938		993	1391	596	
Application (gal/ac) for Aluminate in Alum+Aluminate Trtmt	529	623	469		497	695	298	
Anticipated days of treatment in area (assumes 4000 gal alum/day)	8	10	8	26	8	11	5	24
Unit Cost								
Alum	$1.00	$1.00	$1.00		$1.00	$1.00	$1.00	
Aluminate	$3.00	$3.00	$3.00		$3.00	$3.00	$3.00	
Chemical Cost								
Alum only for entire aluminum dose	$72,493	$85,510	$64,346	$222,349	$68,112	$95,357	$40,867	$204,337
Alum + Aluminate combination	$79,285	$93,522	$70,374	$243,182	$74,494	$104,292	$44,697	$223,483
Labor Cost								
Application	$67,428	$78,818	$60,300	$206,545	$63,595	$87,434	$39,757	$190,786
Mobilization/Contingencies (assumes 1 day/20 ac)	$12,000	$12,000	$12,000	$36,000	$12,000	$12,000	$12,000	$36,000
Monitoring (assumes 1 day/trtmt day + 12 days + 20% for lab costs)	$24,514	$26,223	$23,445	$74,182	$23,939	$27,515	$20,364	$71,818
Cost Summary (alum only)	$176,436	$202,550	$160,090	$539,076	$167,647	$222,306	$112,988	$502,941
Cost Summary (alum + aluminate)	$183,228	$210,562	$166,119	$559,909	$174,029	$231,240	$116,817	$522,087

Figure 18. Response curves for aluminum inactivation of Hinckleys Pond sediment phosphorus.



Hinckleys Pond is estimated at $520,000 to $560,000. This is more than the treatment of 340 acres of Long Pond in 2007, but the necessary dose appears much higher based on testing to date and accounts for most of the difference. More sampling and testing might result in some change in doses and costs.

Although inactivation could be coupled with a circulation system and spread over time, the primary intent of the surficial sediment treatment is not maintenance, but a one-time inactivation of phosphorus in the surficial bottom sediments that interact with the overlying water. As such, and given the substantial cost, the primary question revolves around how long the benefits will last. The non-quantitative answer is that treatment benefits will persist for as long as it takes for surficial sediment phosphorus reserves to accumulate to the point where they can fuel a significant internal load. The quantitative answer has to be calculated, and a spreadsheet has been developed to facilitate this analysis (Table 19), with graphic representation of results (Figure 19). This spreadsheet incorporates the current external and internal loads and processes them to produce a roughly steady state condition by manipulating settling rates, refractory portions, and other variables in light of all available information from sampling and experience.

Table 19. Calculation of the longevity of phosphorus inactivation on phosphorus load to Hinckleys Pond.

Scenario 0 - current conditions

Below permissible		
Permissible load = 225 kg/yr	Between permissible and critical	
Critical load = 450 kg/yr	Above critical	

Scenario 0 - current conditions	Value	Unit	Note
Ext. Load	192.4	kg/yr	Total from itemized list in Table 13.
Fraction Ext. Load Avail:	0.50		About half of load from Long Pond is dissolved, main source after internal load.
Effective Ext. Load	96.2	kg/yr	
Int. Reserves	3450.0	kg	Calc from measured avail sed P, 10 cm active depth, 36.3 ha contributory area
Pre-trtmnt Fraction of ASP Avail:	0.05		Fraction limited by periodic aeration, chosen to match expected release rate
Int. Load	159.7	kg/yr	
Fraction Load Sedimented:	0.60		Partly from LLRM model calculations, partly adjusted to balance for near steady state
Int. Load Inactivated	0.00		No treatment
Post-trtmnt Fraction of ASP	0.05		No change in release rate for uninactivated P assumed
Non-refractory Portion of Sed Load	0.76		Partly from dissolved/total ratio, partly balances load for near steady state

		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4
Effective Ext. Load	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2
Int. Reserves	3450.0	3450.0	3450.8	3451.7	3452.5	3453.2	3454.0	3454.7	3455.4	3456.1	3456.8	3457.5	3458.1	3458.8	3459.4	3460.0	3460.6	3461.2	3461.7	3462.3	3462.8	3463.3	3463.8	3464.3	3464.8	3465.2	3465.7	3466.1
Int. Load	159.7	159.7	159.8	159.8	159.8	159.9	159.9	160.0	160.0	160.0	160.1	160.1	160.1	160.1	160.2	160.2	160.2	160.3	160.3	160.3	160.3	160.4	160.4	160.4	160.4	160.4	160.5	160.5
Total Load	352.1	352.1	352.2	352.2	352.2	352.3	352.3	352.4	352.4	352.4	352.5	352.5	352.5	352.5	352.6	352.6	352.6	352.7	352.7	352.7	352.7	352.8	352.8	352.8	352.8	352.8	352.9	352.9
Sedimented Load		211.3	211.3	211.3	211.3	211.4	211.4	211.4	211.4	211.5	211.5	211.5	211.5	211.5	211.5	211.6	211.6	211.6	211.6	211.6	211.6	211.7	211.7	211.7	211.7	211.7	211.7	211.7

Scenario 1 - No external reduction, 90% internal reduction

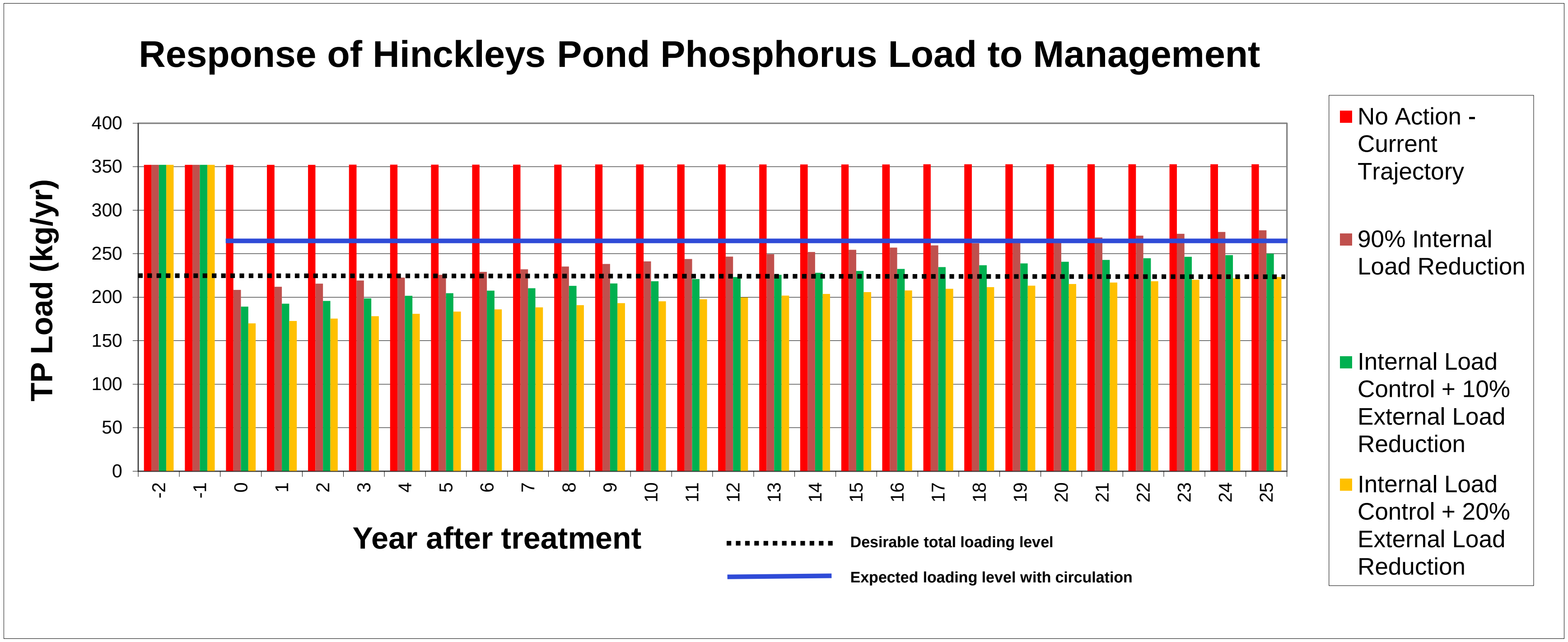
Scenario 1 - No external reduction, 90% internal reduction	Value	Unit	Note
Ext. Load	192.4	kg/yr	From itemized list in Table 13.
Fraction Ext. Load Avail:	0.50		From scenario 0
Effective Ext. Load	96.2	kg/yr	
Int. Reserves	345.0	kg	Current reserves reduced by 90%
Pre-trtmnt Fraction of ASP:	0.05		From scenario 0
Int. Load	16.0	kg/yr	
Fraction Load Sedimented:	0.60		From scenario 0
Post-trtmnt Fraction of ASP	0.05		From scenario 0
Non-refractory Portion of Sed Load	0.76		From scenario 0

		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4	192.4
Effective Ext. Load	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2
Int. Reserves	3450.0	3450.0	345.0	424.0	501.1	576.2	649.4	720.8	790.4	858.2	924.3	988.8	1051.6	1112.9	1172.6	1230.8	1287.5	1342.8	1396.7	1449.3	1500.5	1550.4	1599.1	1646.6	1692.9	1737.9	1781.9	1824.8
Int. Load	159.7	159.7	16.0	19.6	23.2	26.7	30.1	33.4	36.6	39.7	42.8	45.8	48.7	51.5	54.3	57.0	59.6	62.2	64.7	67.1	69.5	71.8	74.0	76.2	78.4	80.5	82.5	84.5
Total Load	352.1	352.1	208.4	212.0	215.6	219.1	222.5	225.8	229.0	232.1	235.2	238.2	241.1	243.9	246.7	249.4	252.0	254.6	257.1	259.5	261.9	264.2	266.4	268.6	270.8	272.9	274.9	276.9
Sedimented Load		211.3	125.0	127.2	129.4	131.4	133.5	135.5	137.4	139.3	141.1	142.9	144.7	146.4	148.0	149.6	151.2	152.7	154.2	155.7	157.1	158.5	159.9	161.2	162.5	163.7	164.9	166.1

Table 19. continued.

Scenario 3 - 10% external reduction, 90% internal reduction																												
Ext. Load			173.2	kg/yr	10% reduction from original external load																							
Fraction Ext. Load Avail:			0.50		From scenario 0																							
Effective Ext. Load			86.6	kg/yr																								
Int. Reserves			345.0	kg	Current reserves reduced by 90%																							
Pre-trtmnt Fraction of ASP:			0.05		From scenario 0																							
Int. Load			16.0	kg/yr																								
Fraction Load Sedimented:			0.60		From scenario 0																							
Post-trtmnt Fraction of ASP			0.05		From scenario 0																							
Non-refractory Portion of Sed Load			0.76		From scenario 0																							
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	192.4	192.4	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2	173.2
Effective Ext. Load	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6	86.6
Int. Reserves	3450.0	3450.0	345.0	415.3	483.8	550.6	615.7	679.2	741.1	801.4	860.2	917.5	973.4	1027.8	1080.9	1132.7	1183.1	1232.3	1280.2	1327.0	1372.5	1416.9	1460.2	1502.4	1543.6	1583.7	1622.8	1660.9
Int. Load	159.7	159.7	16.0	19.2	22.4	25.5	28.5	31.4	34.3	37.1	39.8	42.5	45.1	47.6	50.0	52.4	54.8	57.1	59.3	61.4	63.5	65.6	67.6	69.6	71.5	73.3	75.1	76.9
Total Load	352.1	352.1	189.2	192.4	195.6	198.7	201.7	204.6	207.5	210.3	213.0	215.7	218.3	220.8	223.2	225.6	228.0	230.3	232.5	234.6	236.7	238.8	240.8	242.8	244.7	246.5	248.3	250.1
Sedimented Load		211.3	113.5	115.5	117.4	119.2	121.0	122.8	124.5	126.2	127.8	129.4	131.0	132.5	133.9	135.4	136.8	138.2	139.5	140.8	142.0	143.3	144.5	145.7	146.8	147.9	149.0	150.1
Scenario 2 - 20% external reduction, 90% internal reduction																												
Ext. Load			153.9	kg/yr	20% reduction from original external load																							
Fraction Ext. Load Avail:			0.50		From scenario 0																							
Effective Ext. Load			77.0	kg/yr																								
Int. Reserves			345.0	kg	Current reserves reduced by 90%																							
Pre-trtmnt Fraction of ASP:			0.05		From scenario 0																							
Int. Load			16.0	kg/yr																								
Fraction Load Sedimented:			0.60		From scenario 0																							
Post-trtmnt Fraction of ASP			0.05		From scenario 0																							
Non-refractory Portion of Sed Load			0.76		From scenario 0																							
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	192.4	192.4	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9	153.9
Effective Ext. Load	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0	77.0
Int. Reserves	3450.0	3450.0	345.0	406.5	466.4	524.9	581.8	637.3	691.5	744.2	795.7	845.8	894.7	942.3	988.8	1034.0	1078.2	1121.2	1163.1	1204.0	1243.9	1282.7	1320.6	1357.5	1393.5	1428.6	1462.8	1496.1
Int. Load	159.7	159.7	16.0	18.8	21.6	24.3	26.9	29.5	32.0	34.5	36.8	39.2	41.4	43.6	45.8	47.9	49.9	51.9	53.9	55.7	57.6	59.4	61.1	62.9	64.5	66.1	67.7	69.3
Total Load	352.1	352.1	169.9	172.7	175.5	178.2	180.8	183.4	185.9	188.4	190.7	193.1	195.3	197.5	199.7	201.8	203.8	205.8	207.8	209.6	211.5	213.3	215.0	216.8	218.4	220.0	221.6	223.2
Sedimented Load		211.3	101.9	103.6	105.3	106.9	108.5	110.0	111.5	113.0	114.4	115.8	117.2	118.5	119.8	121.1	122.3	123.5	124.7	125.8	126.9	128.0	129.0	130.1	131.1	132.0	133.0	133.9

Figure 19. Predicted trajectories for phosphorus load to Hinckleys Pond under various management strategies.



Scenario 0 represents current conditions. Despite frequent algal blooms, the current load and that projected for the next 25 years remains between the permissible and critical loads. This may suggest that the calculated permissible and critical loads are not especially accurate for Hinckleys Pond; it is more important to look at the magnitude of the load over time relative to current conditions, which are not acceptable. Permissible and critical loads are based on equations developed by Vollenweider (1975, 1982), represent the level below which algal blooms should be rare (permissible) and above which blooms will be common (critical), but are only approximations based on empirical data for a group of lakes used to construct the relationships upon which the analysis is based. The permissible level as calculated here equates to a phosphorus concentration in Hinckleys Pond surface water of 20 ug/L, which should result in acceptable conditions most of the time; higher values would be undesirable.

Scenario 1 represents a 90% decrease in the internal load, achievable by phosphorus inactivation. There is a steep decline in the load in the year of treatment, as would be expected, then a gradual increase as new inputs arrive and are incorporated into sediment phosphorus reserves. The load would remain below the permissible threshold for only about five years, but would remain below the current load within the 25 year timeframe of this analysis. It is possible that this scenario underestimates the value of internal phosphorus load reduction, as this load occurs mainly during the summer and is highly available. The portion of the total surficial sediment load that becomes available was also estimated as only a small fraction of the total that is potentially available. Nevertheless, current inputs appear large enough to necessitate additional input reductions to maintain the conditions that are expected when the internal load is reduced.

Scenario 2 represents the 90% internal load reduction with an external load reduction of 10%. The total load would remain below the permissible level for 13 years. With a 20% reduction in external load as represented by scenario 3, the load remains below the permissible level for over 25 years. It would appear that some level of external load reduction would be desirable to protect the investment made in a major phosphorus inactivation treatment.

For comparison, the loading level expected from a circulation system is provided as a blue line on Figure 19. A circulation system would be expected to provide the same level of improvement in each year of operation, so it is a flat line. It appears from the graph that the phosphorus load after inactivation will remain below that expected from a circulation system for at least 20 years. However, the results from circulation may differ somewhat from those of phosphorus inactivation by aluminum, as circulation can provide some algal control independent of reduced phosphorus availability.

Prediction of Conditions Achievable Through Management

Consideration of the two in-lake management options and watershed management support efforts can be aided by the LLRM model. If a 90% reduction in internal loading was achieved through phosphorus inactivation, the expected in-lake surface water concentration would be 18 ug/L (Table 20) and the average Secchi reading would be 2.5 m. Average chlorophyll *a* would be 6.7 ug/L, with values higher than 10 ug/L occurring only 14% of the time with a peak of 23.1 ug/L. This would represent much improved pond condition, but it would not last indefinitely, as the internal load will eventually be re-established (Table 19, Figure 19). Just how long it would take for enough internal load to build up to

Table 20. Summary of LLRM output of predicted Hinckleys Pond water quality for various management scenarios.

Pond Variable (units)	Current Actual Value	Current Predicted Value	90% Internal Load Reduction (P inactivation by aluminum)	75% Internal Load Reduction (spring-summer circulation system)	90% Internal Load Reduction plus 20% Load Reduction from Long Pond	90% Internal Load Reduction plus 10% External Load Reduction	90% Internal Load Reduction plus 20% External Load Reduction
Total Phosphorus (kg/yr)	352.4	351.5	207.6	231.6	187.6	191.0	174.4
Total Phosphorus (ug/L)	30	32	18	21	16	17	15
Total Nitrogen (ug/L)	525	520	520	520	448	485	449
Secchi Depth (m)	1.7	1.6	2.5	2.3	2.7	2.7	2.9
Mean Chlorophyll a (ug/L)	13.2	13.8	6.7	7.8	5.8	5.9	5.2
Peak Chlorophyll a (ug/L)	43.8	46.1	23.1	26.7	20.2	20.7	18.3
Chlorophyll a >10 ug/L (%)	75.0%	65.4%	14.4%	22.5%	8.8%	9.7%	5.9%
Chlorophyll a >15 ug/L (%)	51.9%	33.9%	3.0%	5.9%	1.5%	1.7%	0.9%
Chlorophyll a >20 ug/L (%)	34.6%	16.1%	0.7%	1.6%	0.3%	0.4%	0.2%
Chlorophyll a >30 ug/L (%)	11.5%	3.6%	0.1%	0.2%	0.0%	0.0%	0.0%
Chlorophyll a >40 ug/L (%)	3.8%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%

support algal blooms at an unacceptable frequency is difficult to predict, but the timeframe appears to be between five and twenty years.

Use of a circulation system to reduce internal loading is not likely to achieve as large a reduction as phosphorus inactivation with aluminum, probably more on the order of 75%. This results in lesser improvement than the 90% reduction scenario (Table 20), but the improvement is still substantial and should continue indefinitely as long as the circulation system is used. Acceptability of this approach is largely dependent on auxiliary algal control mechanisms (effects of mixing beyond any nutrient control) which have not been clearly documented to date or studied adequately for Hinckleys Pond. Research to date suggests that blue-green algae are greatly reduced by circulation systems, but that overall algal abundance is not substantially depressed. Blue-greens tend to be replaced by diatoms in the spring and fall and green algae in the summer, but at similar or only slightly lower biomass levels. Without a dense zooplankton community to consume the diatoms or greens, the lake may not look much more appealing.

As the internal load is derived from longer term external loads, some control over those external loads is highly desirable to lower phosphorus inputs. This is considered especially important to limit the need for repeated inactivation of the internal load. We do not know just how long it took for the internal load to build to the point where unacceptable conditions resulted, but the longevity model for which results are displayed in Figure 19 suggests that current inputs could create problems within a decade if modest reductions in watershed loads of phosphorus are not accomplished. These do not have to occur prior to treatment, and it looks like a reduction between 10 and 20% of the current external load would be sufficient to maintain the benefits of a treatment for multiple decades. Thus, some watershed action appears desirable to protect the investment represented by a phosphorus inactivation project.

Watershed management options can realistically focus on reduction of loading from stormwater, wastewater, cranberry bog discharge, outflow from Long Pond, and outflow from Seymour Pond. If a target of 10 to 20% reduction of external phosphorus loading is set, the load from Long Pond represents a large enough portion of the external load (47%) to provide that reduction by itself, but then only with management at levels not likely to be feasible. Decreasing the load from Long Pond much further will be challenging; internal loading has already been reduced through the 2007 alum treatment and external loading is from stormwater, wastewater and one cranberry bog, setting up the same management issues as within the direct drainage area of Hinckleys Pond. Achieving a 20% reduction in phosphorus loading to Long Pond is about the most that could be rationally conceived, and would represent a 9.4% decrease in external load. Even elimination of any one other source of phosphorus to Hinckleys Pond would be insufficient to provide a 20% decrease in external phosphorus load; no other source represents even 10% of the total load or 20% of the external load (Table 13). A multi-pronged approach is therefore desirable to reduce external loading and prolong the benefits achievable from internal load control.

Recent nuisance algal blooms and available water quality data for Seymour Pond suggest that this pond probably needs the same level of attention as Hinckleys Pond, and improved condition of Seymour Pond would result in a lower load to Hinckleys Pond. Seymour Pond did not provide water and nutrients to

Hinckleys Pond before the canal between them was dug over 150 years ago. Eliminating that surface water connection would provide an additional 8.2% decrease in total phosphorus loading to Hinckleys Pond (Table 13) over inactivation alone, and represents 15% of the external load. Yet closing that connection is not really feasible based on the existence of an alewife run and potentially higher water levels in Seymour Pond. We have no detailed loading analysis for Seymour Pond, but assuming a similar internal load, its inactivation using aluminum could provide around a 4% decrease in total phosphorus loading to Hinckleys Pond and a 7% decrease in the external load. Work in Seymour Pond and its watershed is highly advisable to improve the condition of that waterbody, and would also help protect Hinckleys Pond.

Wastewater within the zone of contribution to Hinckleys Pond (not just within the 300 ft zone for which wastewater inputs were calculated) appears to have a nominal effect on phosphorus loading. It will be hard to justify a sewer project based on this simple analysis, especially since the sewage would require substantial treatment before discharge elsewhere.

Cranberry bog discharges represent about 6.5% of overall total phosphorus loading (Table 13), and represent at least 11% of the external load. It is possible to greatly reduce the current load by adjusting fertilization practices and/or treating the water prior to discharge, but these have economic consequences for the cranberry farming operations. Additionally, some phosphorus delivered to the pond through at least the Jenkins bog is related to stormwater runoff from nearby developed areas that passes through the bog, and is not directly a function of bog operation. The bogs were in place long before Hinckleys Pond hosted many homes in its watershed and before recreation on the pond was popular. Discussion with the growers is warranted before any final action plan can be generated. However, if the owners ever consider ceasing operation, the town should consider what it can do to alter use of these parcels to protect Hinckleys Pond.

It is not common to achieve more than a 50% reduction in stormwater loading through available best management practices, but a 50% reduction in the direct stormwater load of phosphorus to Hinckleys Pond would result in an overall reduction of a little over 3%. This would require substantial site management for virtually all parcels within the direct drainage watershed and some major engineering improvements to roadways by the town; this would not happen quickly or inexpensively. Some cases, like the two observed roads which discharge stormwater to the pond (Figures 12 and 13), should be addressed to limit erosion and pond filling as well as nutrient inputs. But the level of effort needed to counteract diffuse stormwater inputs throughout the direct drainage area will stretch town resources. Getting residents to apply low impact development techniques that minimize runoff (e.g., rain barrels and gardens, simple low cost methods to enhance infiltration) is highly advisable, but requires outreach effort and continued encouragement.

Of the above options for further reducing nutrient loading and prolonging the benefits of internal load reduction in Hinckleys Pond, the most appealing combination includes inactivating the internal load of Seymour Pond, local stormwater management (the obvious cases discussed previously and application of low impact development techniques on existing residential parcels), and strict adherence to nutrient management plans (which might need some adjustment) for the cranberry bogs. Each element presents challenges, however, and further discussion with all interested parties is needed before a more definitive plan can be developed.

Several factors point to increased importance of the internal load in determining conditions in Hinckleys Pond. Algal chlorophyll is greatest at greater depth, despite lower light, suggesting that nutrient availability in deep water (where the release occurs) is important to algal growth. While other loads to Hinckleys Pond are spread over the year (stormwater, wastewater, flow from upstream ponds) or are focused in a season other than summer (cranberry bogs), the internal load occurs coincident with the algal blooms. Additionally, most loading sources have relatively high N:P ratios (Table 13), while the internal load presents a very low N:P ratio that would favor cyanobacteria, the algae known at least anecdotally to be responsible for most summer blooms. Cranberry bog post-harvest discharge also has a low N:P ratio, but occurs out of season. Inflows from Long Pond are known to decline over summer, with water actually held back to ensure adequate outflow during the fall emigration period for juvenile alewife. The summer contribution from Long Pond, the largest phosphorus source after internal loading, is therefore diminished.

The LLRM model takes a long-term, steady state approach, and does not consider the seasonal aspect of loads; it appears likely that control of the internal load will provide greater benefits than suggested by the modeling exercise. However, the high cost of an inactivation treatment of the appropriate magnitude strongly suggests that the investment should be protected. Under current loading conditions as processed through the longevity model (Table 19, Figure 19), the benefits of internal load treatment alone persist for over 25 years, but the target loading level is achieved for only about five years. Even if there is underestimation of the importance of the internal load, it seems likely that some blooms would occur again within a decade of inactivation based on the expected post-treatment phosphorus concentration and the continued loading at current levels. With an elevated N:P ratio, there should be less cyanobacteria, but water clarity may not remain as high as desired throughout all summers. This would still represent a major improvement over current conditions, but at the high cost of inactivation in this case, any algal blooms would be disappointing. These can best be prevented by further reductions in loading from watershed sources.

Management Conclusions and Recommendations

It is apparent that the internal load must be addressed to measurably improve the condition of Hinckleys Pond, but it is equally apparent that the internal load will eventually be replaced by incorporation of a portion of external loads into the sediment. Estimation of the duration of benefits from a one-time internal load inactivation effort may have yielded a shorter timeframe than is suggested by the temporal importance of the internal load, but some measure of watershed load reduction is warranted to protect the considerable investment that might be made in that inactivation. It does not appear that any single source within the watershed can be reduced enough to provide the desired maximum margin of safety (20% reduction of external load), although achieving the practical maximum reduction for each source would be more than adequate collectively, and a reduction closer to 10% may be sufficient. Achieving a meaningful reduction of loading from the Hinckleys Pond watershed will still be a challenge, but if the investment in an appropriate phosphorus inactivation treatment can be protected through watershed management, such a treatment would provide lasting major improvement and would be recommended.

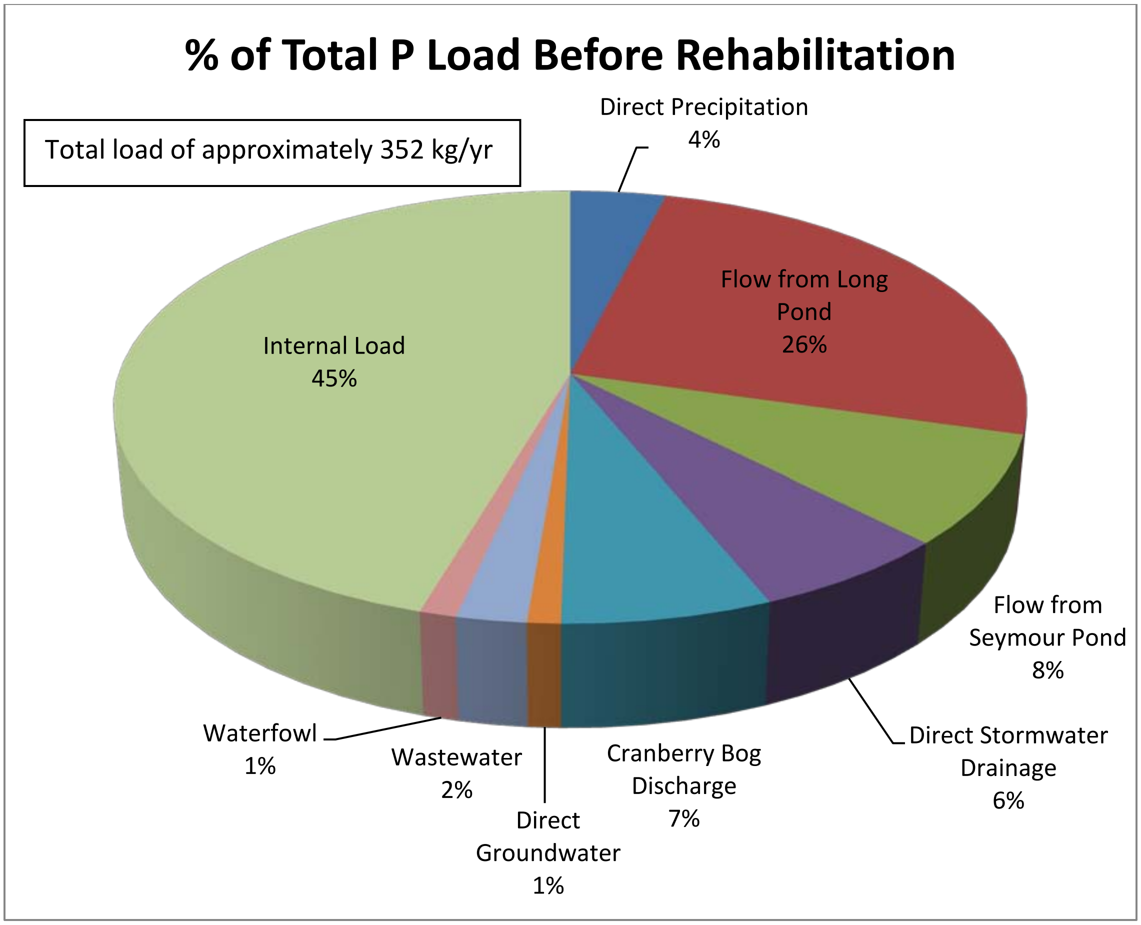
One plausible scenario is depicted in Figure 20. The current loading total of about 352 kg/yr has a breakdown among sources as shown, and the total load would be cut roughly in half (signified by the smaller pie chart), producing a new breakdown of loading among sources. The internal load would be greatly reduced, both in actual magnitude and as a percentage of the total load. The load from Long Pond would be reduced slightly, but would become the largest source by virtue of the large reduction in the internal load. Loads from stormwater runoff, cranberry bogs, and Seymour Pond would be reduced substantially relative to current loads, but the percentage that each represents of the desired future load would not be very different, as that future load would be considerably smaller than the current load. Loads from the atmosphere, waterfowl, wastewater, and direct groundwater would not be expected to change in magnitude, but would increase in percentage of the new total load.

Cost comparison of in-lake phosphorus and algae reduction options (Table 21) suggests that a major investment is needed, but a decision cannot be made based on these costs alone. Projecting the costs out to at least a 25 year horizon suggests that the costs are not so different, and the administrative aspects for repeat effort are not incorporated. Additionally, circulation systems may provide additional algal control independent of phosphorus limitations, but are unlikely to provide the degree of reduction in phosphorus availability achievable by inactivation. Permit acquisition, financing, and general public appeal must also be considered; these transcend the realm of science and move into economics and the socio-political climate within town, necessitating discussions beyond this report to reach a clear decision.

The inactivation treatment would involve the addition of aluminum compounds at doses ranging from 75 to 175 g/m^2 over an area of approximately 90 acres (36 ha) at a cost expected to be on the order of $550,000. Additional testing may allow fine tuning, but the high levels of available phosphorus in the sediment will necessitate a high dose and commensurate cost. To get the results to last over multiple decades, watershed loading should be decreased between 10 and 20%.

The alternative to internal load inactivation with aluminum is a circulation system that will keep oxygen elevated at the sediment-water interface and minimize release of large quantities of phosphorus from an iron-bound state. Air driven or mechanical circulation systems could be applied, but would not be expected to achieve the level of reduction obtained from inactivation with aluminum. The capital cost of a mixing system in this case is likely to be at least $200,000, but this is substantially less than than the cost of the aluminum treatment of surficial sediments, with a typical lifespan of about 20 years. Even incorporating annual power costs for a compressor driven system, the cost would be lower for circulation than inactivation over a 20-year timeframe, although the costs become much more similar on that time scale. Use of the circulation system from May through September each year should provide similar benefits in each year of operation, as opposed to the gradual diminishment of one-time inactivation benefits. While watershed management is still highly desirable, it is less critical if circulation

Figure 20. Pie chart representation of current and desired future loads of phosphorus.



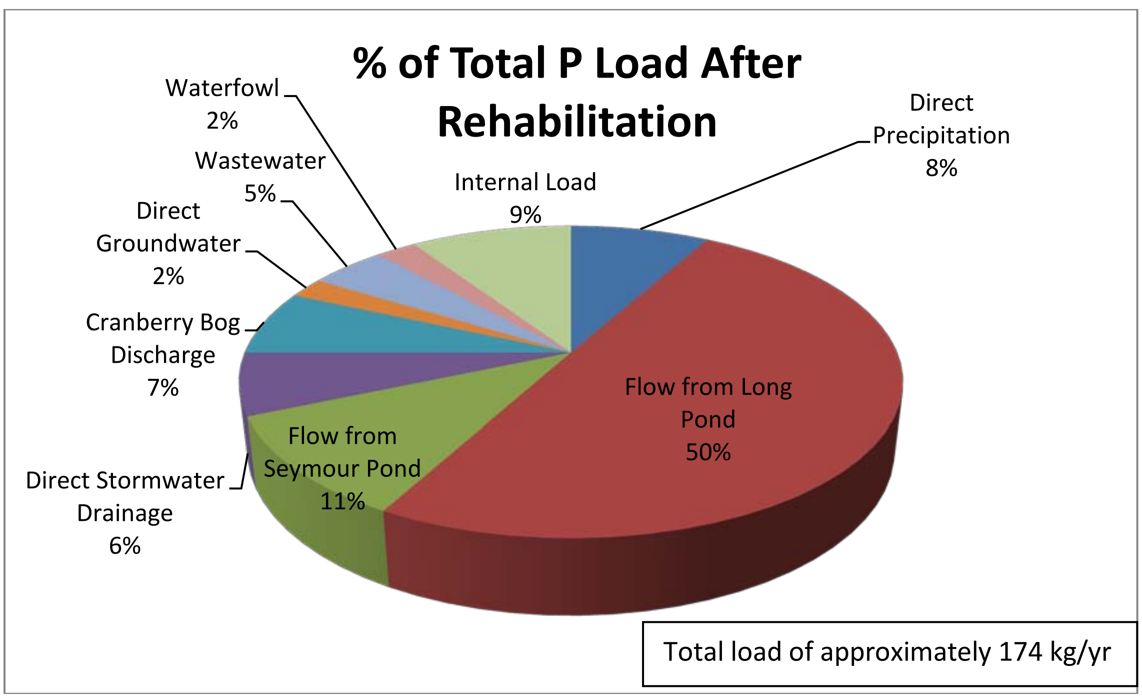


Table 21. Cost comparison of possible internal load reduction approaches.

Circulation System						Phosphorus Inactivation			
Air Driven		SolarBee		WEARS		Sediment		Water Column (with circulation)	
Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
200,000	10,000	240,000	2,000	200,000	3,000	550,000	0	50,000	25,000

is applied, since the thrust of this effort is toward limiting release of phosphorus from the sediments by elevating oxygen levels. Adding to the internal load through processing of external loads is less of a concern, although the direct impacts of the external load before incorporation into the internal load may require attention in some cases (e.g., high precipitation and runoff years).

The primary issue with circulation systems is their varied track record; there are as many failures as successes (Cooke et al. 2005) and maximizing success appears to require vigilance in system operation and maintenance. Use of circulation as an algal control technique is not as well understood as phosphorus inactivation, and greater variability in conditions with artificial circulation is to be expected. Even when properly designed and constructed, there is a human error factor in operation that has caused unsatisfactory performance in many cases. Towns and utilities have started systems too late in the spring, run only one of two compressors to save money, or failed to perform proper maintenance, leading to breakdowns and periods of non-operation. Hinckleys Pond appears to be an appropriate site for artificial circulation, but whether or not a system can be managed over many years to provide the desired conditions remains to be seen.

However, combined with an aluminum injection system, it would be possible to circulate water, maximize deep water oxygen, and inactivate phosphorus with one system. This would entail a substantial capital cost (on the order of $50,000) to add pumps and chemical feed lines to the air lines used for circulation, but would impart great flexibility of operation. Injection of aluminum over time would increase operating cost about $25,000 annually and would both strip phosphorus from the water column and gradually inactivate phosphorus in surficial sediments. The process would not be as rapid or efficient as the one-time intensive inactivation approach, but would be more flexible and would spread costs out over multiple years. Such systems have more complex operational issues than those described above for an aeration only system. They have been in use on a limited basis for about a decade, and enhancements are still being developed, but such a system would be appropriate for Hinckleys Pond.

If a workable plan for reduced loading from the watershed of at least 10% can be developed, the one-time intensive inactivation of available sediment phosphorus reserves in the muck sediments of Hinckleys Pond is recommended. A combined circulation-aluminum injection system is recommended as a viable alternative for consideration if sufficient watershed improvements do not seem feasible. Air driven systems have been better developed for this purpose, and running additional lines for chemicals is fairly straightforward. Injection pumps would be needed and the housing for on-shore equipment will have to be larger and more sophisticated to contain the necessary equipment and chemicals, but the flexibility of operation is attractive. A system would most likely be custom designed, making cost difficult to estimate precisely, but it would seem that an air driven circulation system with additional lines and a chemical feed system could be installed for about $250,000. Annual operational costs will depend on the amount of air and aluminum chemicals used, but are estimated at $25,000. The use of aluminum should decrease over time, as current internal load is inactivated; it took many years for that load to accumulate, so once inactivated, there should be less need for aluminum injection.

Aluminum injection could also be applied to the inlets to Hinckleys Pond from Long Pond and Seymour Pond, and in the discharges from the cranberry bogs, but this moves into an operational mode that is may not be desirable to the town. A single system for dosing the pond in conjunction with artificial circulation would be much easier to handle than four separate inlet stations. These do represent options, however, for incoming phosphorus load control.

Watershed management appears necessary to support longer term improvement of Hinckleys Pond. Actions that can be taken directly by Harwich to augment internal load control include:

- Capture the drainage off James Road south of the lake that currently runs unabated into the pond; a leaching catch basin or more likely a trench drain could be established near the lake.
- Capture the runoff from Catherine Rose Road (and associated residential streets) that currently runs unabated into the pond; a leaching catch basin could be installed at the top of the boat ramp access point, where Catherine Rose Road ends and a paved access proceeds downhill.
- Encourage reduction in phosphorus use (e.g., lawn fertilizer) and runoff abatement on individual private parcels through low impact development techniques such as rain barrels and rain gardens.
- Examine the drainage from Cape Cod Community College and Rt. 124 that currently enters the Jenkins Bog. Minimizing surface water runoff to that bog, which has considerable available phosphorus to be picked up during passage through the bog, would be desirable. Consider the use of rain gardens and other low impact development techniques at the college, both for effectiveness and as an educational tool.
- Aggressively pursue stormwater issues on the Harwich side of Long and Seymour Ponds as they become known.
- Aggressively enforce Title 5 regulations regarding wastewater disposal, including maintaining setback distances of new or replaced leaching fields from the pond shore. Educate residents about the importance of proper system maintenance both for minimum contaminant discharge and system protection.

The above actions will help, and represent beneficial management of land within the town, but additional, more extreme actions may be needed. More controversial or complicated actions that should be discussed include:

- Work with the Town of Brewster to investigate internal load inactivation within Seymour Pond, which could greatly reduce loading to Hinckleys Pond.

- Work with the Town of Brewster to investigate watershed loading to Seymour Pond and options for its reduction.
- Work with the Cape Cod Cranberry Growers Association to encourage growers to implement best management practices. Plans appear to be in place and a number of improvements have been made, but more can be done. In particular, further change in the N:P ratio appears warranted (the excess phosphorus in the bogs is washing out with flood waters and concentrations are higher than average), and better filtration, detention or other treatment of discharges is possible. This represents additional economic pressure on growers that is unlikely to be welcome, but the bogs represent the largest phosphorus contributor per unit of land area.

Monitoring is an integral part of lake management and should be supported at Hinckleys Pond and in Harwich in general. Monitoring through the PALS system has greatly supported this assessment and management planning project. Its continuation is strongly urged, and a few enhancements of the monitoring program are suggested:

Sampling earlier in spring would be very desirable. A complete testing by mid-May is preferred, but if laboratory testing is not possible at that time through SMAST, at least collect temperature and dissolved oxygen profiles, which require only a field meter available through the PALS program. Knowledge of the thermal and oxygen pattern over depth would be helpful in calculating the oxygen demand and knowing when to turn on a circulation system.

Nitrate nitrogen should be added to the total nitrogen testing currently performed. Loss of nitrate is a major factor promoting cyanobacterial dominance, and knowing the nitrate nitrogen level would help enhance predictive capacity and may provide an early warning system.

Qualitative algal analysis to go with the chlorophyll measurements would be a helpful improvement to the monitoring program. We know that cyanobacterial blooms have occurred but have data from only 2011 regarding what types of cyanobacteria comprise those blooms; the types of cyanobacteria vary enough to have implications for pond use impairment and possible management strategies. Such data will not likely change the focus on internal load control with watershed management to protect the investment, but may have influence on the value of circulation vs. inactivation or the timing of activities.

Flow monitoring of Long and Seymour inputs with automated equipment would be desirable. Inputs from these two upstream ponds represent almost 90% of the water input based on the analysis of available data, but we have only limited data from which to work. Manipulation of water levels in Long Pond to facilitate alewife immigration and emigration may provide opportunities to address inputs from Long Pond to Hinckleys Pond.

Funding Options

There are four main funding opportunity to address actions related to pond restoration, watershed improvements and non-point sources. Two are state grant programs: 604(b) Water Quality

Management Planning Grants and the 319 Non-Point Source Competitive Grants. The third is Massachusetts State Revolving Fund (SRF) program; and the fourth is the Harwich's Community Preservation Act.

Massachusetts Department of Environmental Protection (MDEP) administers the 604(b) Water Quality Management Planning Grants. For 2012, MDEP intends to focus grant funding towards watershed or subwatershed based nonpoint source assessment and planning projects. DEP states that "projects should lead to the development of updated watershed based plans for specific watersheds or subwatersheds, determination of the nature, extent and causes of water quality problems, assessment of impacts and determination of pollutant loads reductions necessary to meet water quality standards, green infrastructure projects that manage wet weather to maintain or restore natural hydrology, development of implementation plans that will address water quality impairments, and development of assessment and remediation strategies in impaired watersheds." Deadline for submittal for 2012 is in March. No local match of funds is required.

Section 319 of the Clean Water Act authorized a nonpoint source competitive grants program, which provides funding for implementation projects that address the prevention, control, and abatement of nonpoint source (NPS) pollution. In general, eligible projects must implement measures that address NPS pollution, target the major sources of NPS pollution within a watershed, contain an appropriate method for evaluating the project results, and address activities that are identified in the Massachusetts NPS Management Plan. Recently MDEP has determined that projects that are "required" by a draft MS4 permit cannot be funded through the 319 program. Since EPA has issued draft MS4 permits covering the entire Commonwealth any requirements of those permits applied to the MS4 regulated area in Harwich would be ineligible for funding. While most of the watershed area to Hinckleys Pond is included in Harwich's regulated MS4 area (http://www.epa.gov/region1/npdes/stormwater/ma/ic/MA_Imperv2010_Harwich.pdf) actions in the watershed should be eligible for 319 funding because the pond is not included in the Massachusetts impaired waters list and thus is not subject to a total maximum daily load (TMDL). To be eligible to receive funding, a 40% non-federal match is required from the grantee.

The SRF provides low-cost financing to help communities comply with federal and state clean water and water resource planning requirements. The loan covers planning and construction costs, but not design costs. Actions recommended in this report that could be eligible for SRF funds include in-lake treatment (either the alum treatment or the aeration system); an application for these improvements should highlight the water quality problems experienced by the pond and the potential public health issue associated with cyanobacteria algal blooms. In addition, the SRF program has recently been readily approving projects related to the MS4 program, and thus Harwich should consider filing an application for watershed improvements (such as the control of stormwater reaching the pond). The deadline for eligibility for the Project Evaluation Form is due in August, which would get a project the Funded Project List (the Intended Use Plan). If your project makes the list, additional paperwork needs to be completed the following year to obtain the funding.

The Harwich Community Preservation Committee recommends Community Preservation Act (CPA) projects to Town Meeting, which makes the final decision on uses of CPA funds. Funds are used in different areas of concentration: open space, historic preservation, affordable housing and outdoor recreation, with passive recreation being the latest area being accepted for community oversight. Other communities have used CPA funds to support the purchase of cranberry bogs; for example, the Town of Pembroke used funds toward the purchase of a 55-acre cranberry bog to provide open space, water protection and recreation use. As discussed above, purchase and possible re-purposing of a cranberry bog would improve water quality in the pond but is recognized as an action that requires input from the community. Applications are typical due in November for May town meeting.

References

AECOM. 2009. LLRM – Lake Loading Response Model Users Guide and Quality Assurance Project Plan. Prepared by AECOM, Willington, CT.

Bigham, D., M. Hoyer, and D. Canfield Jr. 2009. Survey of toxic algal (microcystin) distribution in Florida Lakes. Lake Reserv. Manage. 25:2264-275.

Cooke, G.D., E.B. Welch, S.A. Peterson, and S.A Nichols. 2005. Restoration and Management of Lakes and Reservoirs, Third Edition. Taylor and Francis, Boca Raton, Fl.

ENSR. 2001. Management Study of Long Pond, Brewster and Harwich, Massachusetts. ENSR International, Willington, CT.

Graham, J. and J. Jones. 2009. Microcystin in Missouri reservoirs. Lake Reserv. Manage. 25:240-252.

Heiskary, S. and B. Wilson. 2008. Minnesota's approach to lake nutrient criteria development. Lake Reserv. Manage. 24:282-297.

Holdren, G.C., W. Jones and J. Taggart (eds). 2001. Managing Lakes and Reservoirs. NALMS. Madison, WI.

Kortmann, R. 2010. Personal communication regarding experiences with nitrate loss and addition with the owner of ECS. NALMS conference, Spokane, WA.

Lindon, M and S. Heiskary. 2009. Blue-green algla toxin (microcystin) levels in Minnesota lakes. Lake Reserv. Manage. 25:240-252.

MA DFW. 1990. Cape Cod Pond Maps. Publication #16,235-77-250-3-90-C.R. Division of Fisheries and Wildlife.

Mattson, M., Godfrey, P.J., Barletta, R.A. and A. Aiello. (edited by K. Wagner). 2004. Generic Environmental Impact Report for Eutrophication and Aquatic Plant Management in Massachusetts. MADCR/MADEP, Boston, MA

NYSFOLA. 2009. Diet for a Small Lake. New York State Federation of Lake Associations, NY.

Pond And Lakes Stewards (PALS) program. Ongoing. Annual data reports supplied to participating towns by the School for Science and Marine Technology at UMASS Dartmouth.

Tunison, G. M. 2000? History of the Herring River. Harwich Natural Resources Department Special Report, prepared by G.M. Tunison of the University of Massachussets. Available at http://www.vsv.cape.com/~harharb/tunnison1.html

USEPA. 1983. Final Report of the National Urban Runoff Program. Office of Water Program Operations, USEPA, Washington, DC.

Vollenweider, R.A. 1975. Input-output models with special references to the phosphorus loading concept in limnology. Schweiz. Z. Hydrol. 37:53-62.

Vollenweider, R. 1982. Eutrophication of Waters: Monitoring, Assessment and Control. OECD, Paris.

Walter, D.A., and Whealan, A.T. 2005. Simulated water sources and effects of pumping on surface and ground water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004-5181, 85 p.

Watson, S.B., McCauley, E. and Downing, J.A. 1997. Patterns in phytoplankton taxonomic composition across temperate lakes of differing nutrient status. Limnol. Oceanogr. 42:487-495.

Wick, B. 2010. Letter from Cape Cod Cranberry Growers' Association detailing bog operations associated with Hinckleys Pond, dated March 17, 2010. CCCGA, Carver, MA.