EcoLogic Memorandum

TO: Frank Sampson and Heinz Proft
FROM: Liz Moran and Kerry Thurston
RE: Harwich Ponds, 2009-2010 Data Review
DATE: April 18, 2011

The Town of Harwich, through its Water Quality Task Force, has requested advice from EcoLogic on limnological issues related to the municipality's fresh water ponds. This memo summarizes our review of the summer 2009 and 2010 water quality and habitat data from the annual monitoring program.

Twelve ponds within the Town were monitored in 2009 and 2010, including Aunt Edies, Bucks, Flax (East and West), Grass, Hawksnest, Hinckley's, John Joseph, Robbins, Sand, Skinequit, Walkers, and White. We offer the following data analysis and interpretation.

- **<u>Ecoregional Criteria assessment</u>** – Water quality in only one pond, Hawksnest, fully met the ecoregional criteria related to trophic state condition (chlorophyll-α, nitrogen and phosphorus) in both 2009 and 2010. The criteria are assessed on a summer average basis. In contrast, water quality conditions in four ponds (Aunt Edies, Hinckley's, Robbins and Skinequit Ponds) exceeded the three criteria in 2009 and 2010. Water quality conditions in the remaining ponds met some of the criteria some of the time.

- **<u>Trophic State</u>** – The Harwich ponds are classified as "mesotrophic", indicating an intermediate stage of productivity. Hinckley's and Skinequit Ponds are borderline eutrophic/mesotrophic, indicating a greater level of productivity.

- **<u>Shallow Ponds</u>** – The four shallow ponds (depths <3m) monitored in 2009 and 2010 were evaluated for long-term trends in nutrients, chlorophyll-α, and water clarity. For most of the ponds, nutrients, chlorophyll-α, and water clarity in 2009 and 2010 were consistent with previous years. Grass Pond's data set is not especially robust, given the small quantity of samples (4) collected since 2000.

	Concentrations Trends Over Time (+/-)			
Pond	***Phosphorus***	***Nitrogen***	***Chlorophyll-α***	***Secchi***
Aunt Edies	+	+ Significant	+	+
Flax-East	- Significant	- Significant	-	- Significant
Grass	-	-	-	+ Significant
Robbins	+ Significant	+ Significant	+	- Significant

+/- = indicates increasing/decreasing trend, 0 = indicates no trend direction
"Significant" = indicates the trend is statistically significant (90% chance the observations indicate a real trend)

- **<u>Deep Ponds</u>** – The nine deep ponds (depths >5m) monitored in 2009 and 2010 were evaluated for long-term trends in nutrients, chlorophyll-α, and water clarity. For most of the ponds, nutrients, chlorophyll-α, and water clarity in 2009 and 2010 were consistent with previous years. We also examined the potential magnitude and importance of internal phosphorus cycling within the deeper ponds. Skinequit Pond stood out in this analysis, as lower water TP concentrations were nearly an order of magnitude greater than surface water TP concentrations.

Pond	Concentrations Trends Over Time (+/-), Upper Waters			
	Phosphorus	*Nitrogen*	*Chlorophyll-α*	*Secchi*
Bucks	- Significant	+	-	-
Flax-West	- Significant	- Significant	- Significant	+
Hawksnest	+	+ Significant	- Significant	+
Hinckley	-	+	+	-
John Joseph	+	+	-	+
Sand	-	-	-	+
Skinequit	0	+ Significant	+	- Significant
Walkers	+ Significant	+ Significant	+	-
White	+	-	+	-

+/- = indicates increasing/decreasing trend, 0 = indicates no trend direction
"Significant" = indicates the trend is statistically significant (90% chance the observations indicate a real trend)

1 Water Quality Criteria and Trophic State Index

1.1 Ecoregional Criteria

The USEPA is taking an ecoregional approach to developing nutrient criteria for surface waters, considering the large variation in geology, soil conditions, climate, land cover, development, and recreational use across the nation. Eastern Massachusetts is an ecoregion, and criteria for nutrients (total N, and total P) and chlorophyll-*α* were calculated from results of a 2001 synoptic survey of 191 ponds - the vast majority of which were Cape Cod kettle ponds. EPA calculated the ecoregional criteria using the lowest 25th percentile of nutrient and chlorophyll-α measurements from the synoptic survey. The Cape Cod Commission calculated two ecoregional criteria for Cape Cod ponds. The more stringent (CC-Least) is based on nutrient and chlorophyll-*α* concentrations measured in the eight most pristine ponds in the sample, with undeveloped watersheds. The second (CC-All) is calculated using water quality conditions of all Cape Cod ponds sampled.

Results of 2009 and 2010 measurements in each of the Harwich ponds are compared with the EPA and Cape Cod Commission's ecoregional criteria (Table 1). Measurements exceeding the Cape Cod reference condition (CC-All) are highlighted. This analysis indicates the Harwich ponds exhibiting the highest ambient concentrations of nutrients and chlorophyll-α. Only Hawksnest Pond exhibited TN, TP, and chlorophyll-*α* concentrations below the Cape Cod ecoregional criteria for both years, while water quality conditions in four ponds (Aunt Edies, Hinckley, Robbins and Skinequit Ponds) exceeded the criteria for all three indicator parameters in both years.

Table 1. 2009 and 2010 Harwich Ponds summer average data compared with Cape Cod ecoregional criteria. Shaded cells exceed Cape Cod reference condition (CC-All).

Pond (upper waters)	Chlorophyll-α (µg/L)		Total Nitrogen (mg/L)		Total Phosphorus (µg/L)		Secchi Disk (m)	
EcoRegion14	*6*		*0.41*		*9*		*<2*	
CC-Least	*1*		*0.16*		*7.5*		*--*	
CC-All	*1.7*		*0.31*		*10*		*--*	
	2009	***2010***	***2009***	***2010***	***2009***	***2010***	***2009***	***2010***
Deep Ponds								
Bucks	2.2	0.81	0.39	0.42	11	7.5	4.1	5.8
Flax-West	2.7	2.4	0.56	0.60	10	9.5	3.7	2.9
Hawksnest	1.3	1.5	0.16	0.27	3.6	8.3	6.5	4.7
Hinckley	11	6.6	0.45	0.53	27	22	1.5	1.8
Hinckley East	8.1	*na*	1.7	*na*	160	*na*	*na*	*na*
John Joseph	1.7	1.5	0.36	0.45	8.3	13	5.9	6.0
Sand	1.9	1.3	0.32	0.43	8.0	18	3.9	3.7
Skinequit	26	12	0.89	0.57	40	23	1.2	1.5
Walkers	1.5	1.7	0.30	0.41	15	25	5.1	4.3
White	1.8	*na*	0.27	*na*	4.5	*na*	6.6	*na*
Shallow Ponds								
Aunt Edies	11	7.9	0.57	0.70	22	18	1.9	1.7
Flax-East	3.8	3.0	0.49	0.63	8.9	8.0	1.4	1.9
Grass	*na*	5.6	*na*	1.49	*na*	34	*na*	4.4
Robbins	3.3	3.9	0.46	0.58	19	29	2.2	2.2

Highlighted values indicate where pond data exceed the *CC-All* ecoregional criteria.
Upper waters defined as samples collected from 4.0 meters or less.
na – indicates no data were available.

1.2 Carlson Trophic State Index

The Carlson trophic state index (TSI) uses the chlorophyll-*α*, total phosphorus, and Secchi disk transparency measurements to classify a lake's trophic state. The TSI is useful for comparing lakes within a region, and assessing changes in trophic status over time. Trophic state is a continuum, and demarcations are not always clear. Oligotrophic lakes are low in productivity and generally have clear, well- oxygenated water. Many of these lakes are suitable for cold-water fish species such as trout, but often do not support a highly productive fish community. Eutrophic lakes are very productive and have high standing crops of phytoplankton that decrease water clarity. Eutrophic lakes may also have extensive beds of rooted aquatic vegetation. These lakes often have high standing crops of warm-water fish such as bass. Mesotrophic lakes are in an intermediate stage of productivity.

Of the 12 Harwich ponds sampled in 2009 and 2010, most are considered mesotrophic indicating moderate levels of productivity. Two ponds - Hinckley and Skinequit - exhibit TP, chlorophyll-*α* and Secchi disk transparency measurements consistent with borderline eutrophic conditions (Table 2).

Table 2. 2009 and 2010 Results of Trophic State Index (TSI) Calculations

Pond	Chlorophyll-α TSI		TP TSI		Secchi Disk TSI		Designated Trophic State	
	2009	*2010*	*2009*	*2010*	*2009*	*2010*	2009	2010
Deep Ponds								
Bucks	38	26	38	33	41	35	Mesotrophic	Mesotrophic
Flax-West	40	39	36	36	42	45	Mesotrophic	Mesotrophic
John Joseph	36	32	33	40	35	34	Mesotrophic	Mesotrophic
Hawksnest	33	34	22	34	32	43	Mesotrophic	Mesotrophic
Hinckley	52	48	50	48	56	52	Eutrophic	Mesotrophic
Sand	37	32	32	42	40	41	Mesotrophic	Mesotrophic
Skinequit	61	54	51	48	59	50	Eutrophic	Mesotrophic
Walkers	32	37	42	48	36	41	Mesotrophic	Mesotrophic
White	37	na	25	na	33	na	Mesotrophic	--
Shallow Ponds								
Aunt Edies	53	50	48	44	50	52	Mesotrophic	Mesotrophic
Flax-East	40	36	31	35	55	54	Mesotrophic	Mesotrophic
Grass	na	47	na	54	na	39	--	Mesotrophic
Robbins	40	40	46	51	49	49	Mesotrophic	Mesotrophic

TSI Divisions (http://www.secchidipin.org/tsi.htm) - Oligotrophic <30; Mesotrophic 30-50; Eutrophic 50-70.
TSI calculated for each sample date, and then TSI values are averaged for each pond.
na – no data were available.

2 2009 and 2010 Trends and Historical Comparisons

This section presents the results of the 2009 and 2010 Harwich Ponds monitoring program. Where possible, the results are discussed in context of recent conditions to evaluate trends. Only the ponds that were sampled in either 2009 or 2010 are evaluated. To simplify references to the historic dataset, the period "2000-2008" is cited, although for some parameters on some ponds there may not be data extending as far back as 2000. Metadata for the sample dataset, by pond and parameter, are included as Attachment 1. The data were typically collected during the summer months (June through September).

In evaluating the ponds data, it is necessary to understand that variability in water quality conditions is normal. Weather conditions and the timing of the sample collections contribute to fluctuations in the measurements. Minor deviations in measurements from year to year do not necessarily indicate improving or worsening conditions.

These data were evaluated in two ways:

1. Comparison of the historical (2000-2008) averages and standard error with the annual (2009 and 2010) averages and standard error, through which possible trends may be discerned;

2. Statistical significance testing, which corroborates whether long-term trends (increasing or decreasing) are significant.

Graphics showing the scatter plots and linear trend lines of pond data over time for phosphorus, nitrogen, chlorophyll-α and Secchi disk transparency are included as Attachment 2.

For this review, we considered the Harwich ponds in two groups – deep ponds, with a maximum depth greater 5 m and shallow ponds, with a maximum depth less than 3 m. Deeper ponds are more likely to exhibit thermal stratification during the summer; the sun's energy warms the upper waters, and this warmer water layer rests on top of the cooler, denser waters below. Density differences caused by the thermal gradients are sufficient to prevent wind-induced mixing, and the deeper waters become isolated from exchange with the atmosphere, the primary source of dissolved oxygen (DO).

The upper sunlit region of the lake supports photosynthesis and algal growth, while the deep waters do not. Organic matter produced in the upper waters gradually settles through the water column, and is decomposed on the pond bottom. Water quality differences between the upper and lower waters become increasingly pronounced as the summer progresses. The supply of DO in the deep water is used up as microorganisms decompose organic material, and is not replenished until the waters cool in the fall and density gradients diminish sufficiently to allow wind mixing of the entire water column. If DO is depleted, chemical changes at the sediment surface can lead to the release of sediment-bound phosphorus to the overlying waters.

The monitoring program includes sampling the deeper Harwich ponds in both upper and lower waters, providing data to evaluate the potential for internal phosphorus cycling from sediments.

2.1 Shallow Ponds

The shallow ponds of Harwich, with a maximum depth less than 3m, do not exhibit stable thermal stratification. Those sampled in 2009 and 2010 and their depths were:

Aunt Edies (2.5m)	Flax-East (2m)
Grass (1m)	Robbins (2.5m)

Grass Pond had a very small data set relative to the other ponds, and therefore the statistical analyses are not robust. The number of samples for Grass Pond, as well as for the other shallow ponds, is detailed in the following sections.

2.1.1 Total Phosphorus in Shallow Ponds

Summer average concentrations of TP measured in the shallow Harwich ponds in 2009 and 2010 ranged from a low of 8.1 µg/l in Flax-East (2010) to a high of 34 µg/l in Grass Pond (2010). The highest individual measured value occurred in Robbins Pond at 46 µg/l on 7/15/2010. The number of samples in each data set is enumerated below:

Pond	***2000-2008***	***2009***	***2010***
Aunt Edies	24	2	2
Flax-East	20	4	3
Grass	6	4	3
Robbins	35	5	4

For the shallow Harwich ponds, 2009 and 2010 TP average concentrations were comparable to concentrations measured from 2000-2008 (Figure 1). Variability in water quality is normal, depending on weather conditions and the timing of the sample collections. Consequently, minor deviations do not necessarily indicate real change. For two ponds – Grass and Robbins – what appeared in Figure 1 to be a significant change warranted scrutiny.

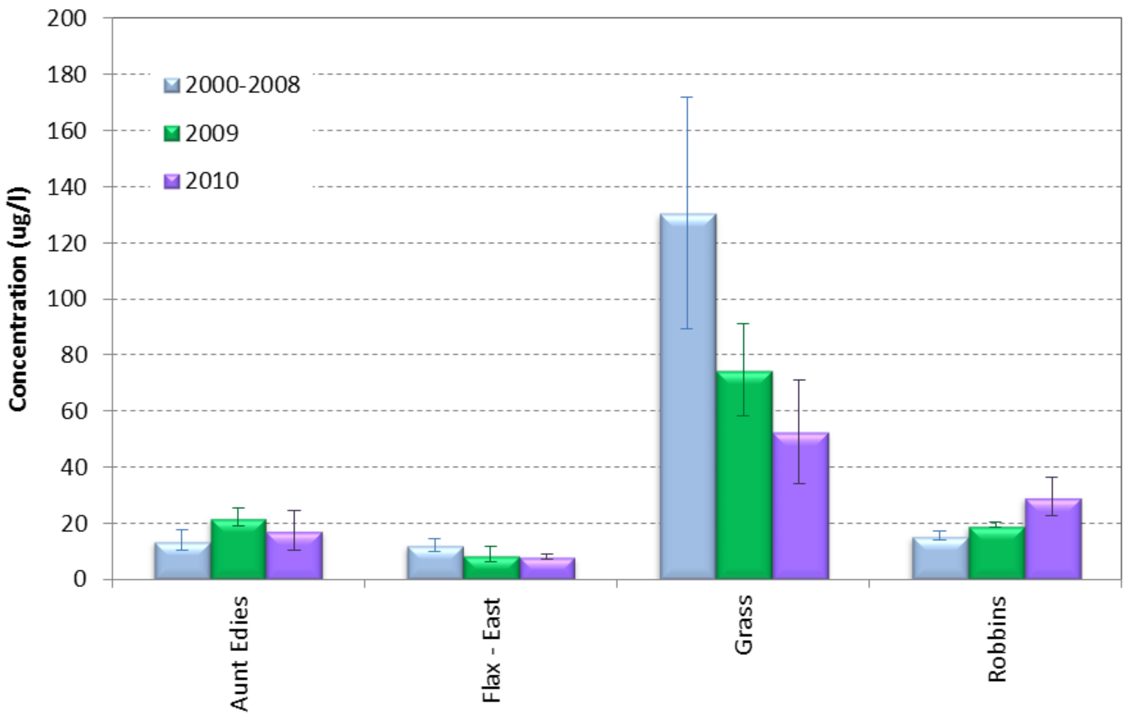


Figure 1. Comparison of 2009 and 2010 summer average total phosphorus concentration in upper waters (≤4m) for 4 shallow ponds in Harwich, with long-term average 2000-2008. Summer averages are shown with standard error.

- **<u>Grass Pond</u>** - Grass Pond exhibited consistently higher TP concentrations than the other Harwich ponds evaluated (Figure 1)[1]; however, the small sample set was not adequate for drawing conclusions about trends. The highest TP results in Grass Pond occurred in August and September of 2007 (260 µg/l and 254 µg/l, respectively). The data set is too small to conclude whether these values are outliers. The corresponding chlorophyll-α data for these two sample dates were:

Sample Date	TP (µg/l)	Chlorophyll-α (µg/l)
08/07/2007	260	5.3
09/18/2007	254	100

The relatively high chlorophyll-α value for 09/18/2007 may be related to high TP, or these higher values may reflect sampling, analytical or data entry errors.

[1] During evaluation of the upper waters TP in Grass Pond, EcoLogic noted that several sample results, particularly in 2009, were missing sample depth data. Based on available information, Grass Pond is a shallow water body – 3 ft deep - therefore, it was assumed that all samples from Grass Pond were taken at the same depth.

- **Robbins Pond** - Robbins Pond exhibited what appears to be an increasing trend in Figure 1, with the annual average for 2010 doubling the historical average for 2000-2008. The data for Robbins Pond does not show unusually high values for TP in 2010, which eliminates outliers as a possible cause of differences between the averages. At the same time, the averages for each of the three periods increase over time, suggesting TP concentrations in Robbins Pond may be slowly increasing. Long-term trend analysis may verify this assessment.

Long-term trends in total phosphorus were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 4). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 4. Long-term trend (positive or negative) and significance of trends for TP in shallow Harwich Ponds (2000-2010).

	Total Phosphorus	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Flax-East	-	0.035
Statistically significant increasing concentrations		
Robbins	+	0.00076
No statistically significant trends		
Aunt Edies	+	0.16
Grass	-	0.46

2.1.2 Total Nitrogen in Shallow Ponds

Summer average concentrations of total nitrogen (TN) measured in the shallow Harwich ponds in 2009 and 2010 varied from a low of 464 µg/l in Robbins Pond (2009) to a high of 1516 µg/l in Grass Pond (2010). The highest individual measured value occurred in Grass Pond at 1899 µg/l (8/17/2010). The number of samples in each data set is enumerated below:

Pond	***2000-2008***	***2009***	***2010***
Aunt Edies	24	2	2
Flax-East	18	4	3
Grass	6	4	3
Robbins	21	5	4

The 2009 and 2010 TN average concentrations were comparable to concentrations measured for the period 2000-2008 (Figure 2). As noted above, annual variability in water quality conditions is normal. In Figure 2, Aunt Edies and Robbins ponds both exhibit what appear to be increasing trends in TN, whereas Flax-East and Grass ponds appear to be more stable.

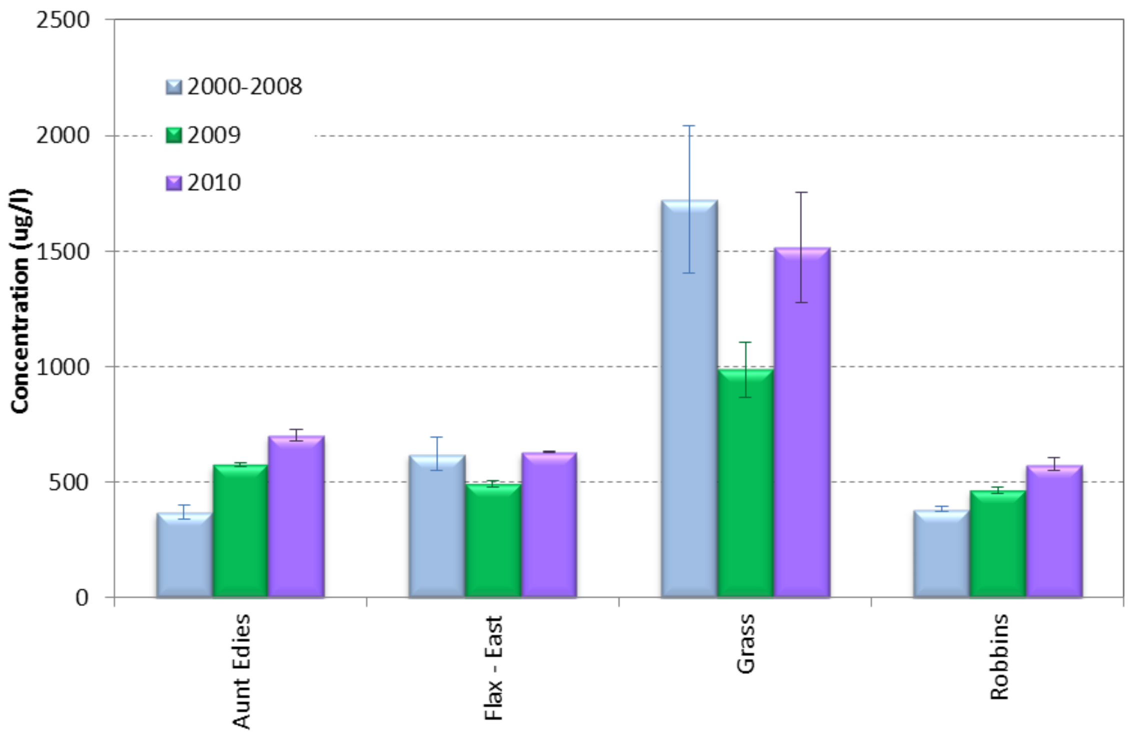


Figure 2. Comparison of 2009 and 2010 summer average total nitrogen concentration in upper waters (≤4m) for 4 shallow ponds in Harwich, with long-term average 2000-2008. Summer averages are shown with standard error.

Long-term trends in total nitrogen were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 5). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 5. Long-term trend (positive or negative) and significance of trends for TN in shallow Harwich Ponds (2000-2010).

	Total Nitrogen	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Flax-East	-	0.064
Statistically significant increasing concentrations		
Aunt Edies	+	0.00024
Robbins	+	0.0000082
No significant trends		
Grass	-	0.65

2.1.3 Chlorophyll-α in Shallow Ponds

In 2009 and 2010, average chlorophyll-α concentrations were generally low in most ponds (Figure 3), ranging from a low of 2.98 µg/l at Flax-East (2010) to a high of 17 µg/l in Grass Pond (2010). The highest individual measurement in 2009-2010 was 39 µg/l in Grass Pond on 8/3/2010. The number of samples in each data set is enumerated below:

Pond	***2000-2008***	***2009***	***2010***
Aunt Edies	24	2	2
Flax-East	18	4	3
Grass	7	4	3
Robbins	21	4	4

Elevated chlorophyll-α concentrations impart a greenish tinge to the water, making the waters less attractive for recreational use. In 2009 and 2010, Aunt Edies Pond exhibited chlorophyll-α concentrations associated with diminished suitability for recreational use, with summer average concentrations exceeding 7 µg/l in 2009 and 2010. By contrast, the average for the 2000-2008 period was about 4 µg/l. However, there were only two samples collected each year in 2009 and 2010, which is not a sufficiently robust dataset for identifying trends by averages in chlorophyll-α concentrations.

Grass Pond exhibited higher historical concentrations (2000-2008), in a range that could impair recreational use, as compared with 2009 and 2010; the sample set for this pond was too small to assess trends using Figure 3. Recent data for both Flax-East and Robbins ponds were comparable to historical values.

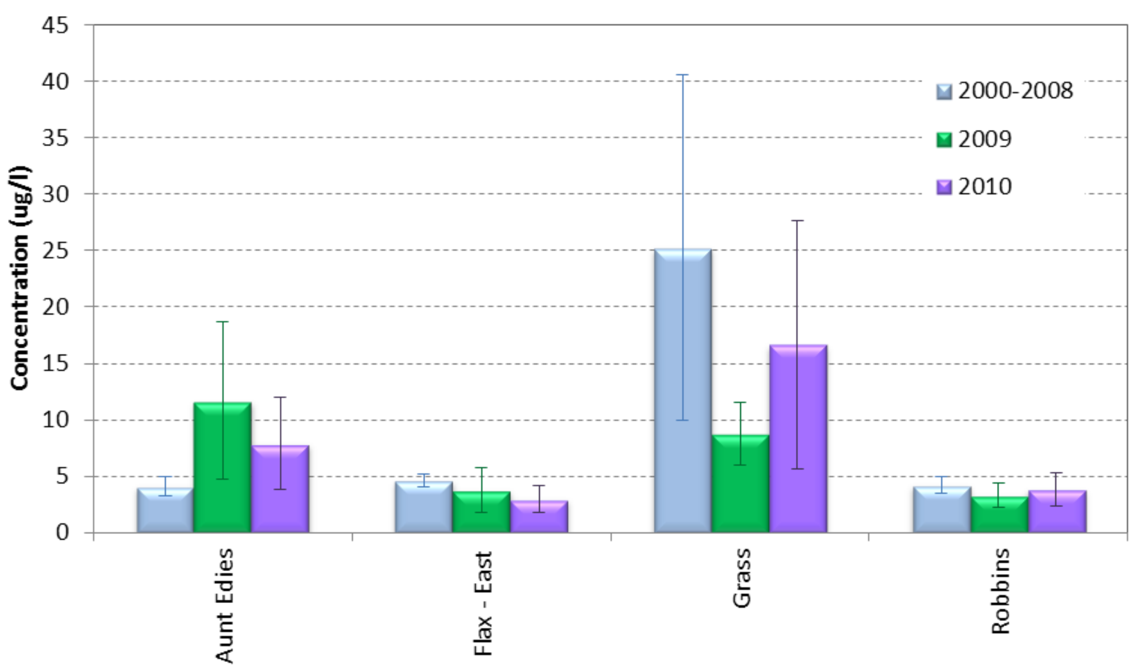


Figure 3. Comparison of 2009 and 2010 average chlorophyll-a concentration in upper waters (≤4m) for 4 shallow ponds in Harwich, with long-term average 2000-2008. *(Note: Average shown with standard error).*

Long-term trends in upper water chlorophyll-α were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 6). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 6. Long-term trend (positive or negative) and significance of trends for chlorophyll-α in upper waters of shallow Harwich Ponds (2000-2010).

	Chlorophyll-α	
	Trend	***Significance***
No statistically significant trends		
Aunt Edies	+	0.55
Flax-East	-	0.15
Grass	-	0.63
Robbins	+	0.21

2.1.4 Water Clarity in Shallow Ponds

The water clarity in the ponds for 2009 and 2010 appears generally comparable to conditions measured in previous years (Figure 4), with the exception of Grass Pond. According to available information, Grass Pond is approximately 1 meter deep. However, the one Secchi reading reported for 2010 was 4.4m. This appears to be a data entry error. One possibility is that the 4.4 value represents the Secchi depth in feet. If this is the case, then the appropriate value in meters would be 1.3, which would be more comparable to the historic data set. The number of samples in each data set is enumerated below:

Pond	***2000-2008***	***2009***	***2010***
Aunt Edies	40	5	4
Flax-East	30	5	3
Grass	2	0	1
Robbins	38	5	5

In Figure 4, the summer averages of most ponds are at or below the Health Department swimming value. Of the four shallow ponds, Robbins Pond appears to have the clearest water based on Secchi measurements. Grass Pond is likely not a representative data set, as it is comprised of 3 samples (2 collected in 2002, 1 collected in 2010).

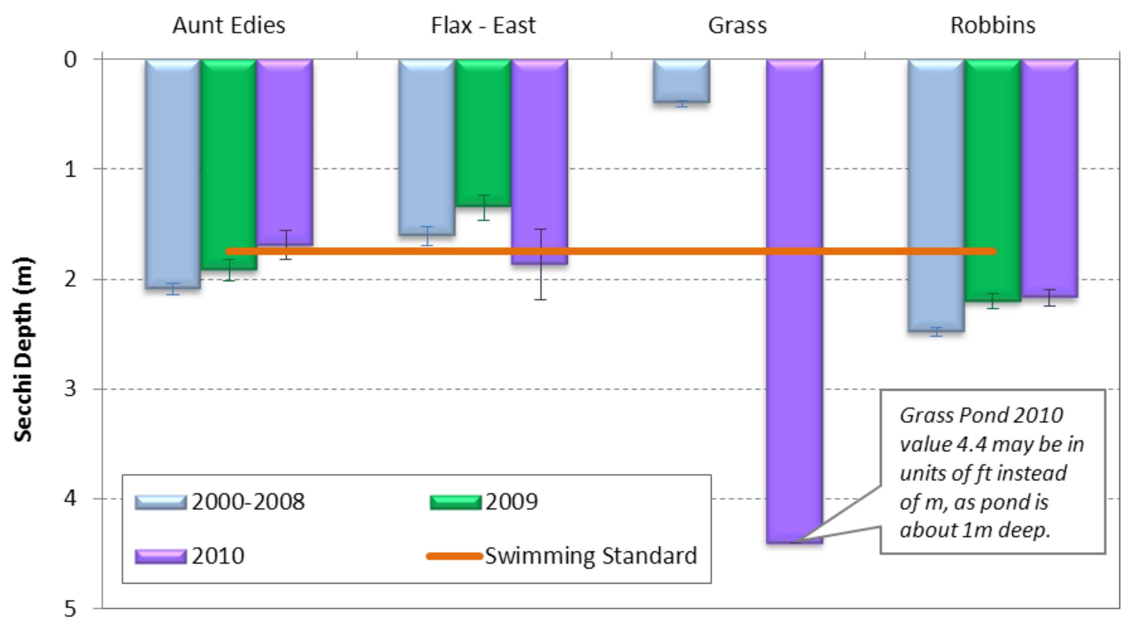


Figure 4. Comparison of 2009 and 2010 average secchi disk measurements for 4 shallow ponds in Harwich, with long-term average 2000-2008. Guidance value represents the Massachusetts Health Department swimming standard for bathing beaches (1.75 m). *(Note: Average shown with standard error).*

Long-term trends in Secchi disk transparency were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 7). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance. Grass Pond data set was too small to calculate this analysis.

Table 7. Long-term trend (positive or negative) and significance of trends for Secchi disk transparency in upper waters of shallow Harwich Ponds (2000-2010).

	Chlorophyll-α	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Flax-East	-	0.0072
Robbins	-	0.00000041
No statistically significant trends		
Aunt Edies	+	0.81

2.2 Deep Ponds

The deep ponds sampled in 2009 and 2010 were:

Bucks (10m),	Hinckley (8m)	Skinequit (10m)
Flax-West (6m),	John Joseph (18m)	Walkers (8m)
Hawksnest (8m),	Sand (6m)	White (6m)

In general, ponds the size of those in Harwich that are deeper than about 35 feet (10.7 m) will be resistant to mixing because of the small surface areas. Ponds as deep as Bucks, John Joseph, and Skinequit may become thermally stratified over the summer months. While thermally stratified, it is unlikely that significant quantities of nutrients would be mobilized from lower water to the surface waters. However, nutrients released from the sediments to the overlying lower waters eventually become available for algal growth as thermal stratification breaks down and mixing of upper and lower waters occurs. Given the long water residence time and the lack of surface outlets in kettle ponds, sediment phosphorus flux can be a significant factor affecting algal growth.

2.2.1 Total Phosphorus in Deep Ponds

Summer average concentrations of total phosphorus (TP) measured in the upper waters of the deep Harwich ponds in 2009 and 2010 varied from a low of 3.6 µg/l in Hawksnest Pond (2009) to a high of 40 µg/l in Skinequit Pond (2009). The highest individual measured value occurred in Hinckley East (160 µg/l on 7/29/2009); this location is not part of the Town's long-term monitoring program. The number of samples in each data set is as follows:

Pond	*2000-2008*	*2009*	*2010*
Bucks	29	3	4
Flax-West	28	4	3
Hawksnest	25	1	1
Hinckley	22	5	8
John Joseph	41	8	8
Sand	22	4	4
Skinequit	22	4	3
Walkers	22	4	4
White	17	1	0

2.2.1.1 Historical and Current Averages

For the majority of the Harwich ponds, 2009 and 2010 TP average concentrations were comparable to concentrations measured for the period 2000-2008 (Figure 5). As discussed, annual variability in water quality conditions is normal.

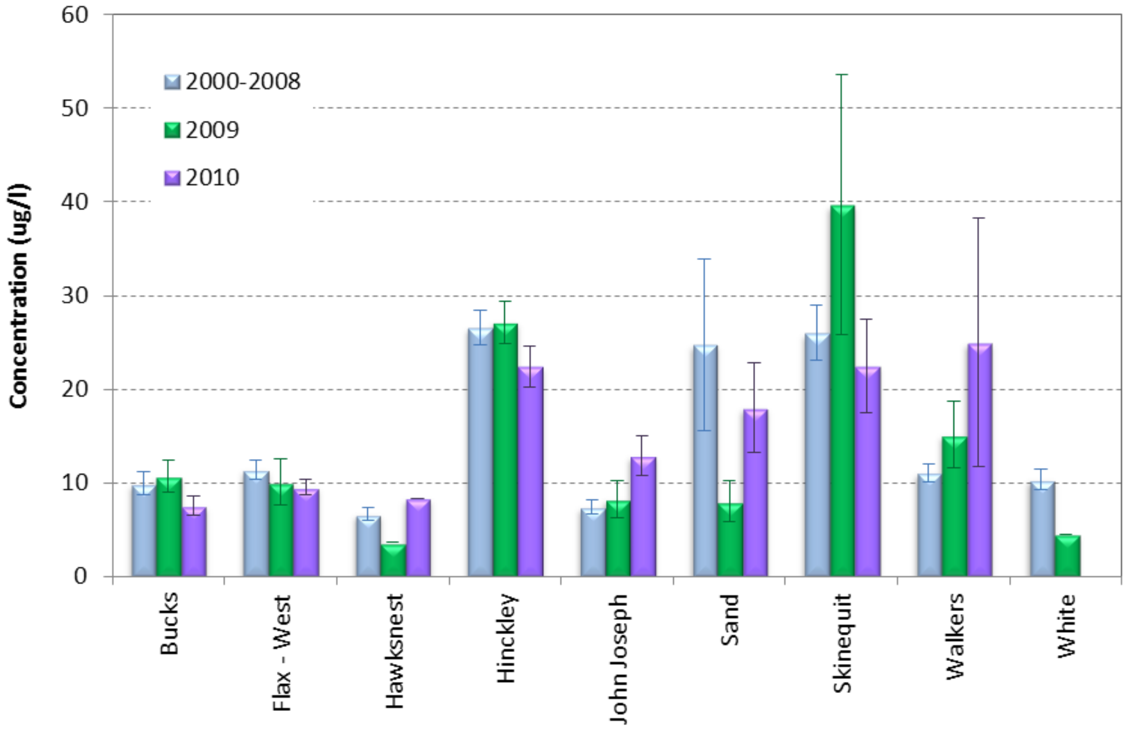


Figure 5. Comparison of 2009 and 2010 summer average total phosphorus concentration in upper waters (≤4m) for 9 deep ponds in Harwich, with long-term average 2000-2008. Summer averages are shown with standard error.

For several of these ponds – Sand, Skinequit and Walker – the data presented in Figure 5 suggest there are possibly significant changes happening over time in the upper waters. The data sets for these three ponds were evaluated more closely:

- **Sand Pond** - Sand Pond exhibited a historical (2001-2008) average higher than the averages for 2009 and 2010. A high TP measurement was identified as a possible outlier. This data point - 215 µg/l (8/21/02) - skewed the historical average higher:

	Average	Median	N Samples
2001-2008 with high values:	25 µg/l	13 µg/l	20
2001-2008 without high value:	15 µg/l	13 µg/l	19
2009:	8 µg/l	8 µg/l	4
2010:	18 µg/l	17 µg/l	4

When the outlier was excluded, the averages for 2009 and 2010 were comparable to the historical average. This outlier, at 215 µg/l, was an order of magnitude higher than the next highest measurement (30 µg/l), and did not appear to be associated with an algal bloom; chlorophyll-α concentration at the 0.5 m depth on 8/21/2002 was relatively low at 2.4 µg/l. The unusually high TP result in 2002 may reflect sampling, analytical or data entry errors.

- **Skinequit Pond** - Skinequit Pond exhibited a higher summer average in 2009, almost double relative to the historical average and the average for 2010:

	Average	Median	N Samples
2001-2008:	25 µg/l	24 µg/l	20
2009 with high value:	40 µg/l	38 µg/l	4
2009 without high value:	28 µg/l	33 µg/l	3
2010:	23 µg/l	22 µg/l	3

  One relatively high value of 70 µg/l (8/12/09) was reported for one of the four upper water samples collected in 2009. This measurement of 70 µg/l was made on the same date as the maximum chlorophyll-α concentration measured in 2009 (39 µg/l). With the exception of the one relatively high measurement in 2009, the TP results for Skinequit Pond in 2009 and 2010 appear to be consistent with historical data.

- **Walkers Pond** – Walkers Pond exhibited what appears to be an increasing trend in Figure 5, based on the averages:

	Average	Median	N Samples
2001-2008:	11 µg/l	10 µg/l	22
2009:	15 µg/l	16 µg/l	4
2010 with high value:	25 µg/l	13 µg/l	4
2010 without high value:	12 µg/l	11 µg/l	3

  Closer examination of the data revealed a high concentration measured in 2010 (65 µg/l on 8/3/10), which was more than 4 times the next highest measurement of 14.7 µg/l. Chlorophyll-α concentrations on 8/3/10 were not elevated (2.13 µg/l). With the high value in 2010 excluded, the 2010 average is comparable to 2009 and the historical average. Variability in Walker's Pond TP concentrations may be attributable to natural variability rather than an increasing trend.

2.2.1.2 Statistical Significance of Trends

Long-term trends in upper water total phosphorus were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year, and the outliers identified above were excluded. A statistical test of the regression line (the best fit through the data) was also completed (Table 8). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 8. Long-term trend (positive or negative) and significance of trends for TP in upper waters of deep Harwich Ponds (2000-2010).

	Total Phosphorus	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Bucks	-	0.053
Flax-West	-	0.021
Statistically significant increasing concentrations		
Walkers*	+	0.015
No statistically significant trends		
Hawksnest	+	0.132
Hinckley	-	0.91
John Joseph	+	0.12
Sand*	-	0.48
Skinequit*		0.61
White	+	0.52

*Outliers were excluded.

As shown in Table 8, the apparent increasing trend for Walkers Pond - identified in the discussion of Figure 5 – was verified as statistically significant, even when the outlier sample points were excluded from the analysis.

2.2.1.3 Internal Phosphorus Cycling

As discussed in Section 2.2, deep ponds are susceptible to sediment phosphorus flux. We used measured differences in water temperature to evaluate whether stable thermal stratification developed in Bucks, John Joseph, and Skinequit Ponds. As shown in Figure 6, the difference between lower and upper water temperatures is, on average, less pronounced for Hawksnest, Hinckley, and White. The most pronounced gradient occurs in John Joseph, Sand and Skinequit Ponds.

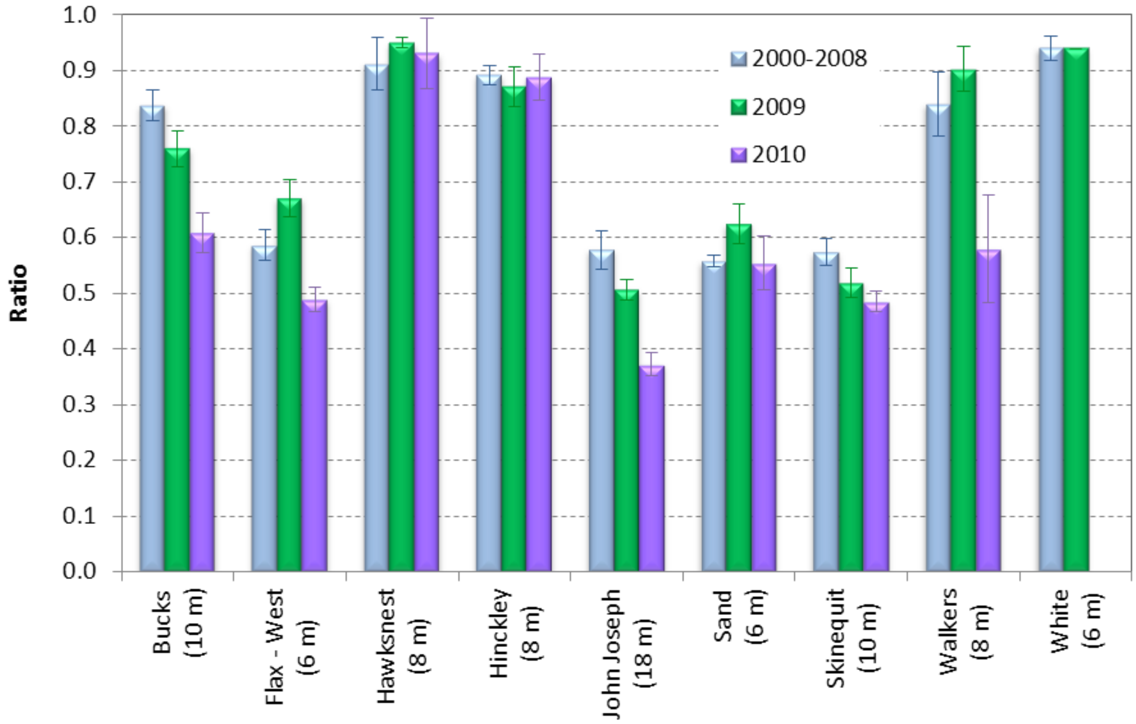


Figure 6. Ratio of temperature (°C) in lower waters (>5 m) and upper waters (<4m) of nine deeper ponds in Harwich, for the historical period (2000-2008) and recent years (2009 and 2010). The lower the value, the greater the temperature gradient between lower and upper waters. *Average shown with standard error.*

Dissolved oxygen (DO) saturation represents the DO concentration normalized to the water temperature and atmospheric pressure. In the lower waters (Figure 7), DO saturation in the nine deeper ponds ranges from as low as 0% to as high as 142%. On average, for the period 2000-2010, the ponds Flax-West, Hinckley, Sand and Skinequit exhibit less than 30% DO saturation in lower waters, while in the remaining ponds, average DO saturation ranges from 52% to 70%. By comparison, the upper waters of the nine ponds average from 71% to 97% saturation.

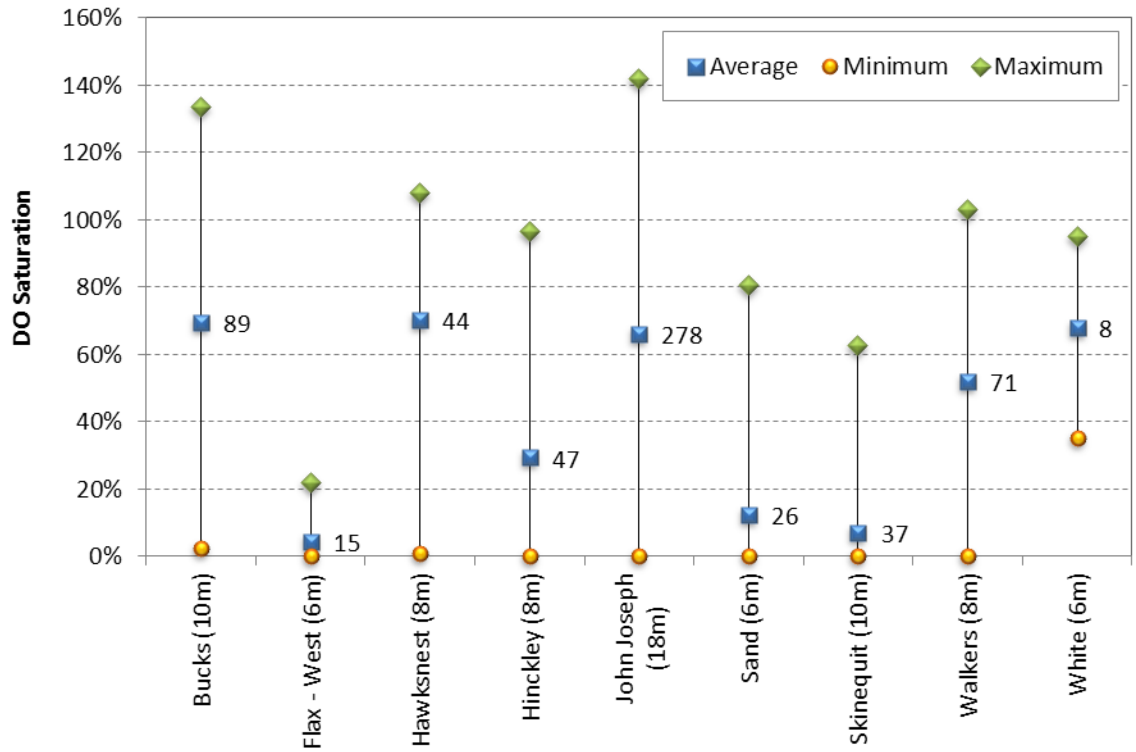


Figure 7. Dissolved oxygen percent saturation in lower waters (>5 m) of nine deeper ponds in Harwich. Average with maximum and minimum for the period of record (2000-2010), with number of samples shown.

The ratio of phosphorus in deep water compared to shallow water for nine of the deeper ponds is displayed in Figure 8; this Figure shows the 2009 and 2010 results compared to average values from the last nine years (2000-2008). Higher values of the ratio indicate probable release of phosphorus from the sediments.

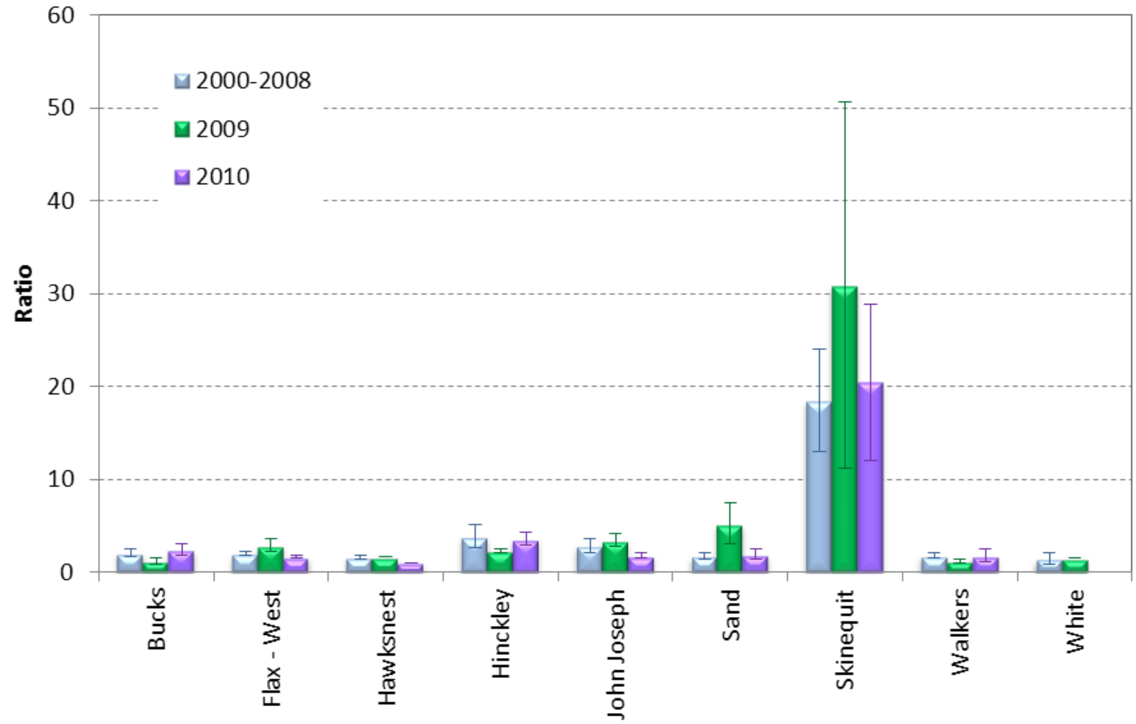


Figure 8. Ratio of deep water (>5m) phosphorus to surface water (≤4m) phosphorus in nine ponds in Harwich for long-term average (2000-2008) and recent years (2009, 2010). Higher numbers indicate increased P release from sediments. *Note: Ratios calculated for each sample date, then averaged for each year. Annual summer averages were used to calculate average for period 2000-2008. Shown with standard error.*

With few exceptions, as discussed below, the level of internal phosphorus release is consistent with past years. However, there is a great deal of variability in this dataset. Results are strongly influenced by the date of sample collection, because phosphorus accumulation in the lower waters increases over the period of stratification.

- **Sand Pond** - The ratios in Sand Pond were less than 2 for 2000-2008 and 2010, but exceeded 5 for 2009. One unusually high ratio (11.6) was identified, which occurred on 8/26/2009. The lower water TP concentration for this date was 36 µg/l, which is well within the range of historic data. The upper waters were measured at 3.1 µg/l, which is the lowest concentration measured in Sand Pond upper waters for the period of record evaluated. This very low concentration in the upper waters resulted in the higher ratio for this sample date, and contributed to the higher average ratio for 2009 observed in Figure 8.

- **Skinequit Pond** - The highest ratios of the Harwich Ponds were observed in the Skinequit Pond dataset. These higher ratios suggest that a significant component of the water column TP concentrations originate in the sediments. Concentrations of TP in lower waters during 2008 (ranging from 40 µg/l to 414 µg/l) were observed[2] to be

[2] EcoLogic, LLC, 2009. Harwich Ponds Memorandum, revised November 17, 2009.

somewhat lower than concentrations in previous years (average 456 µg/l), and may have been attributable to the action of the solar-powered mixing device (SolarBee). The SolarBee, installed in 2008, may limit the duration of the stratified period, or may mix oxygenated water deeper into the water column. However, lower water concentrations of TP returned to historic levels in 2009 and 2010 (Figure 9). Upper water concentrations of TP have been consistent over time, although levels were somewhat higher in 2009 (Figure 9).

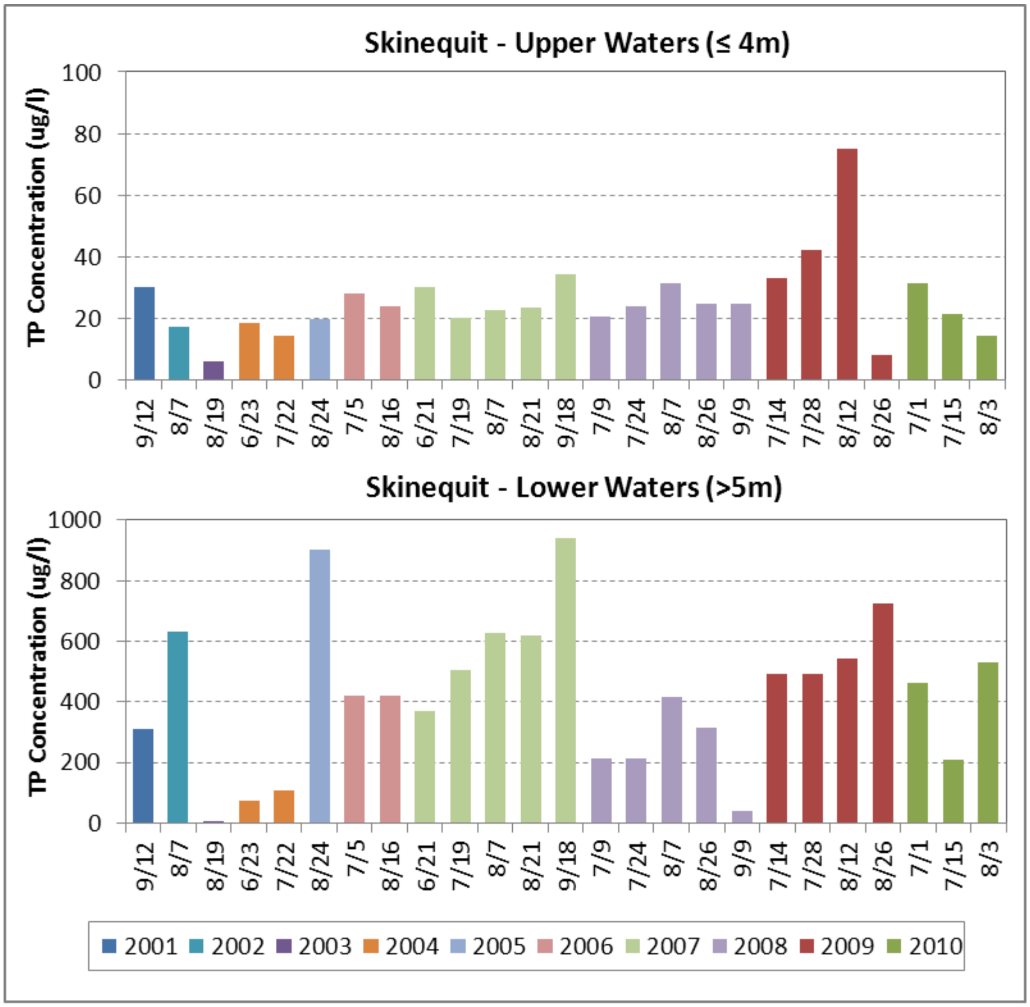


Figure 9. Phosphorus concentrations in upper and lower waters of Skinequit Pond over time. Lower water concentrations are generally close to an order of magnitude greater than upper water concentrations for the same date.

2.2.2 Total Nitrogen in Deep Ponds

Summer average concentrations of total nitrogen (TN) measured in the deeper Harwich ponds in 2009 and 2010 varied from a low of 159 µg/l in Hawksnest Pond (2009) to a high of 889 µg/l in Skinequit Pond (2009). Note that the low summer average actually represents a sample size of 1, and therefore is also the minimum individual measurement for 2009-2010. The maximum individual measurement was 1645

μg/l, measured in Hinckley East on 7/29/2009, which is not a routinely sampled location. The number of samples in each data set is enumerated below:

Pond	2000-2008	2009	2010
Bucks	23	3	4
Flax-West	23	4	3
Hawksnest	23	1	1
Hinckley	21	5	8
John Joseph	19	8	8
Sand	20	4	4
Skinequit	20	4	3
Walkers	23	4	4
White	13	1	0

For the majority of the Harwich ponds, 2009 and 2010 TN average concentrations were comparable to concentrations measured for the period 2000-2008 (Figure 10). Annual variability in water quality conditions is normal, depending on weather conditions and the timing of the sample collections. Consequently, minor deviations do not necessarily indicate improving or worsening conditions.

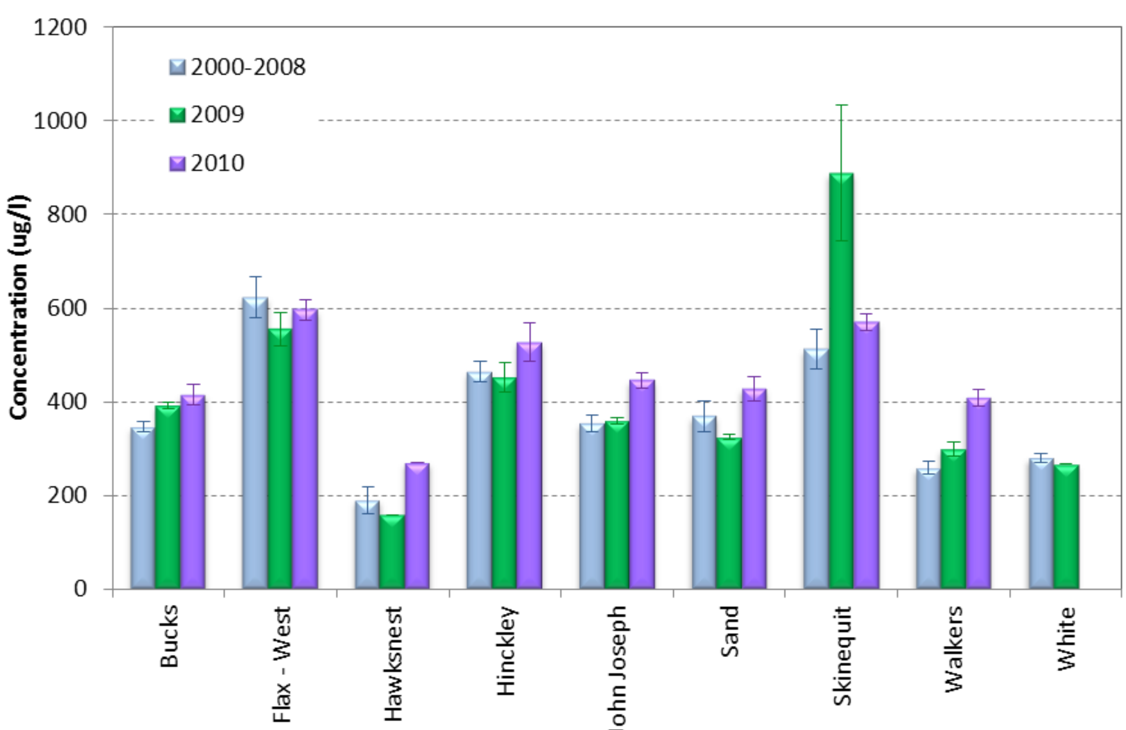


Figure 10. Comparison of 2009 and 2010 summer average total nitrogen concentration in upper waters (≤4m) for 9 deep ponds in Harwich, with long-term average 2000-2008. Summer averages are shown with standard error.

For Skinequit Pond, the data presented in Figure 10 suggest an increase in TN in upper waters for 2009. The data set was evaluated more closely, and there was one high measurement of 1263 μg/l (8/12/2009), which may be an outlier that is skewing the annual average for 2009.

	Average	Median	N Samples
2001-2008:	513 µg/l	431 µg/l	20
2009 with high value:	889 µg/l	861 µg/l	4
2009 without high value:	764 µg/l	804 µg/l	3
2010:	570 µg/l	581 µg/l	3

Overall, the TN data for 2009 appear to be higher than either historical or 2010 data even excluding the possible outlier.

Long-term trends in upper water total nitrogen were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 9). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 9. Long-term trend (positive or negative) and significance of trends for TN in Harwich Ponds (2000-2010).

	Total Nitrogen	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Flax-West	-	0.0023
Statistically significant increasing concentrations		
Hawksnest	+	0.033
Skinequit	+	0.033
Walkers	+	0.000051
No statistically significant trends		
Bucks	+	0.48
Hinckley	+	0.14
John Joseph	+	0.11
Sand	-	0.13
White	-	0.54

2.2.3 Chlorophyll-α in Deep Ponds

Chlorophyll-α concentration is an indicator of algal abundance. The amount of algal production in a waterbody is largely a function of the concentration of the limiting nutrient (usually phosphorus), light and water temperature. Because algal blooms vary in frequency, intensity and duration, the annual measurements of peak and average chlorophyll-α concentrations will vary as well. The number of samples in each data set is enumerated below:

Pond	2000-2008	2009	2010
Bucks	22	3	4
Flax-West	23	4	3
Hawksnest	24	1	1
Hinckley	21	4	4
John Joseph	19	4	4
Sand	20	4	4
Skinequit	20	4	3
Walkers	21	4	4
White	13	1	0

In 2009 and 2010, average chlorophyll-α concentrations were generally low in most ponds (Figure 11), ranging from a low of 0.81 µg/l at Bucks Pond (2009) to a high of 26 µg/l in Skinequit Pond (2009). Elevated chlorophyll-α concentrations impart a greenish tinge to the water, making the waters less attractive for recreational use. In 2009 and 2010, Skinequit Pond exhibited chlorophyll-α concentrations associated with diminished suitability for recreational use.

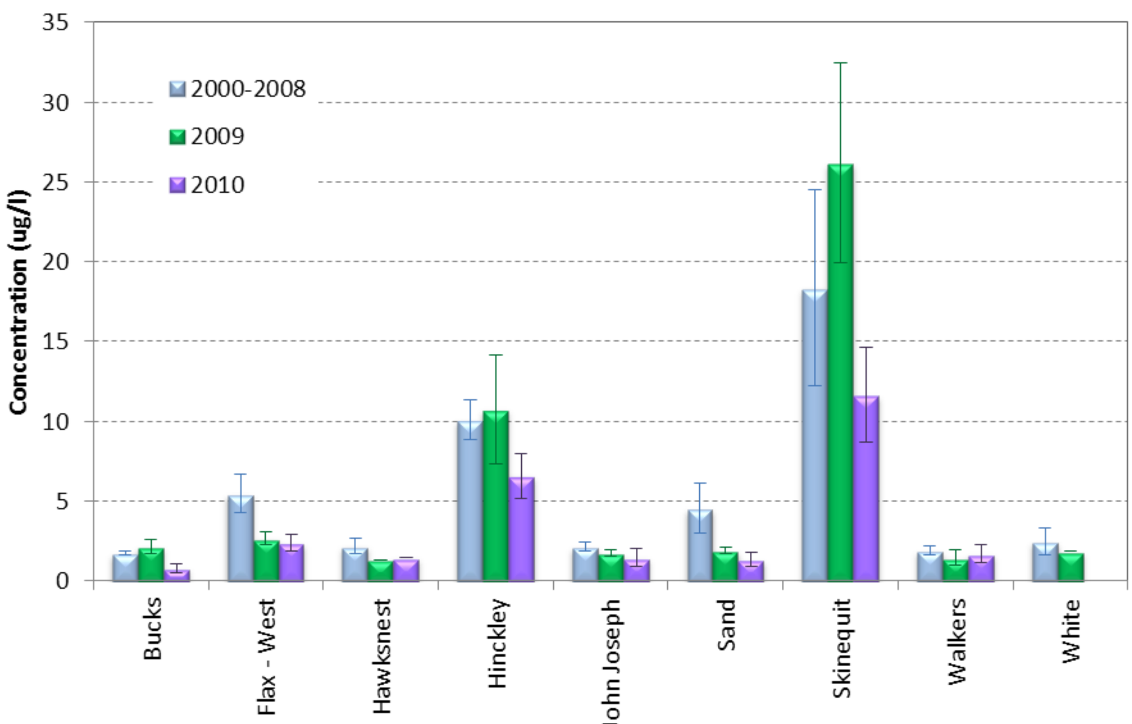


Figure 11. Comparison of 2009 and 2010 average chlorophyll-a concentration in upper waters (≤4m) for 9 deep ponds in Harwich, with long-term average 2000-2008. *(Note: Average shown with standard error).*

Most of the deeper ponds in 2009 and 2010 had average chlorophyll-α concentrations comparable to those measured in previous years, with the exception of Flax-West, Sand and Skinequit Ponds. The

datasets for these three ponds were evaluated more closely to assess whether outliers may skew the averages.

- **Flax Pond (West)**, - Flax West exhibited a summer average chlorophyll-α concentration for the 2000-2008 period that was double the average concentrations for 2009 and 2010.

	Average	Median	N Samples
2000-2008 with high value:	5.5 µg/l	7.0 µg/l	23
2000-2008 without high value:	4.4 µg/l	3.9 µg/l	22
2009:	2.7 µg/l	2.4 µg/l	4
2010:	2.4 µg/l	2.1 µg/l	3

  Closer examination of the data revealed that the highest concentration from this sampling location was measured on 7/17/2003 (30 µg/l); otherwise, concentrations over time were consistently less than 10 µg/l. Excluding this outlier, the historic average was still slightly higher than 2009 and 2010, so there may be a slight, decreasing trend of chlorophyll-α.

- **Sand Pond** – Similar to Flax West, Sand Pond's average historical chlorophyll-α concentration was substantially higher than the averages for 2009 and 2010.

	Average	Median	N Samples
2000-2008 with high value:	4.6 µg/l	3.0 µg/l	20
2000-2008 without high value:	3.0 µg/l	2.9 µg/l	19
2009:	1.9 µg/l	1.9 µg/l	4
2010:	1.3 µg/l	1.1 µg/l	4

  Closer examination of the data revealed that the highest concentration (34 µg/l) was measured on 8/29/2006; otherwise, concentrations ranged from 1.26 µg/l to 6.9 µg/l for the 2000-2008 period. There may be a slight, decreasing trend of chlorophyll-α for 2009 and 2010 as compared with the period 2000-2008.

- **Skinequit Pond** – Skinequit Pond exhibited chlorophyll-α average concentrations much higher than the other Harwich Ponds examined. There was a high degree of variability in the dataset. The highest measurement of 128 µg/l occurred on 9/18/2007.

	Average	Median	N Samples
2000-2008 with high value:	18 µg/l	8.8 µg/l	20
2000-2008 without high value:	13 µg/l	8.8 µg/l	19
2009:	26 µg/l	25 µg/l	4
2010:	12 µg/l	14 µg/l	3

  The 2009 dataset exhibits somewhat higher concentrations; based on the four samples collected, concentrations ranged from 15 to 39 µg/l. These higher concentrations may be attributed to natural variability.

Long-term trends in upper water chlorophyll-α were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 10). Trends with a significance value less than 0.10 indicate a 90% probability that

the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 10. Long-term trend (positive or negative) and significance of trends for chlorophyll-α in upper waters of deep Harwich Ponds (2000-2010).

	Chlorophyll-α	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Flax-West	-	0.017
Hawksnest	-	0.0034
No statistically significant trends		
Bucks	-	0.45
Hinckley	+	0.39
John Joseph	-	0.20
Sand	-	0.24
Skinequit	+	0.54
Walkers	+	0.93
White	+	0.60

2.2.4 Water Clarity in Deep Ponds

Water clarity, as measured by Secchi disk transparency over the June-September period, is another important indicator of water quality conditions and trophic state. In ponds where algal cells are the primary class of particulate material suspended in the water column, chlorophyll-α and Secchi disk transparency are correlated. This is the case for the Harwich ponds. In general, the ponds with the lowest TP and chlorophyll-α concentrations exhibit the highest Secchi disk transparency. The number of samples in each data set is enumerated below:

Pond	***2000-2008***	***2009***	***2010***
Bucks	47	4	5
Flax-West	33	5	5
Hawksnest	33	3	2
Hinckley	40	4	5
John Joseph	52	5	5
Sand	40	5	5
Skinequit	40	4	5
Walkers	43	4	5
White	21	1	0

The water clarity in the ponds for 2009 and 2010 appears generally comparable to conditions measured in previous years (Figure 12).

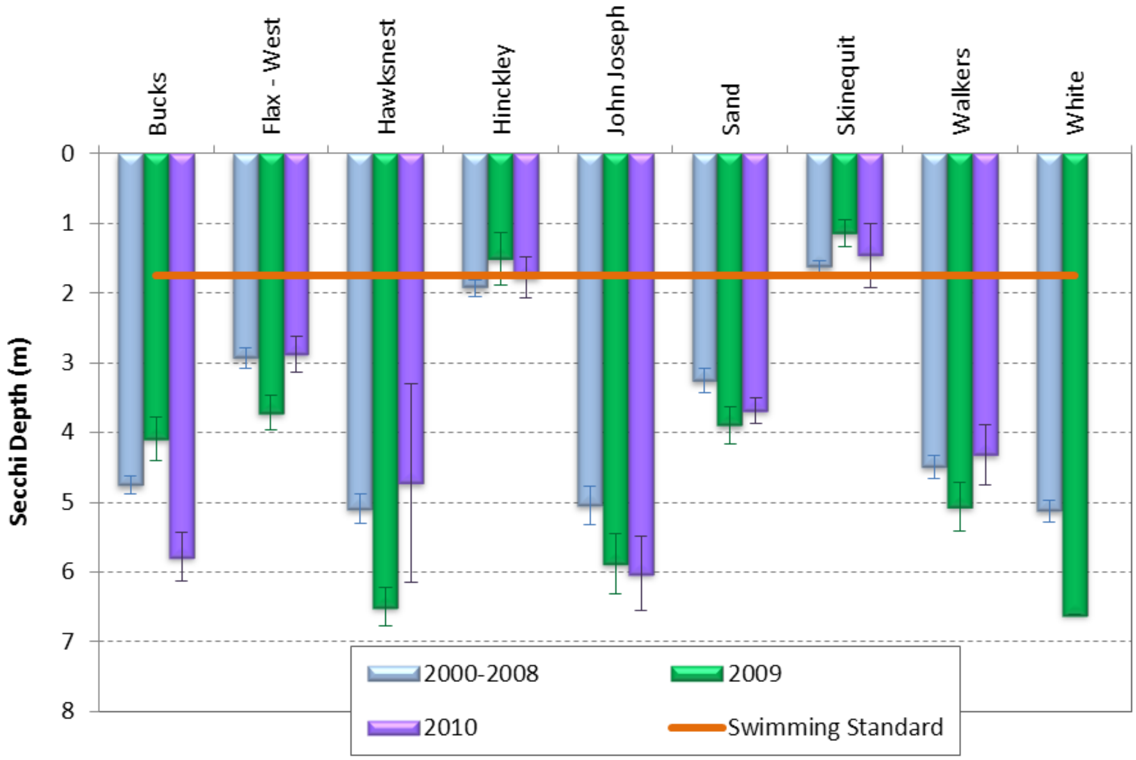


Figure 12. Comparison of 2009 and 2010 average secchi disk measurements for 9 deeper ponds in Harwich, with long-term average 2000-2008. Guidance value represents the Massachusetts Health Department swimming standard for bathing beaches (1.75 m). *(Note: Average shown with standard error).*

The average Secchi disk transparency in Hinckley and Skinequit Ponds were consistently low in 2009 and 2010, at or below the Massachusetts Health Department swimming standard for bathing beaches (Figure 12). Secchi disk transparency measurements for the remaining seven deeper Harwich ponds, on average, met the swimming standard. Ponds with measurements averaging more than 4m Secchi depth – Bucks, Hawksnest, John Joseph, Walkers and White - indicate exceptionally clear water.

Long-term trends in Secchi disk transparency were also evaluated for statistical significance. Individual samples were used in this analysis instead of annual averages in order to incorporate the inherent variability within each year. A statistical test of the regression line (the best fit through the data) was also completed (Table 11). Trends with a significance value less than 0.10 indicate a 90% probability that the trend is real. If the significance value is equal to or greater than 0.10, the variability in the data set is too large to evaluate whether an apparent trend is real or due to chance.

Table 11. Long-term trend (positive or negative) and significance of trends for Secchi transparency in Harwich Ponds (2000-2010).

	Secchi Transparency	
	Trend	***Significance***
Statistically significant decreasing concentrations		
Skinequit	-	0.00081
No statistically significant trends		
Bucks	-	0.82
Flax-West	+	0.93
Hawksnest	+	0.12
Hinckley	-	0.11
John Joseph	+	0.12
Sand	+	0.90
Walkers	-	0.12
White	-	0.99

Attachment 1
Number of Samples by Year and Parameter

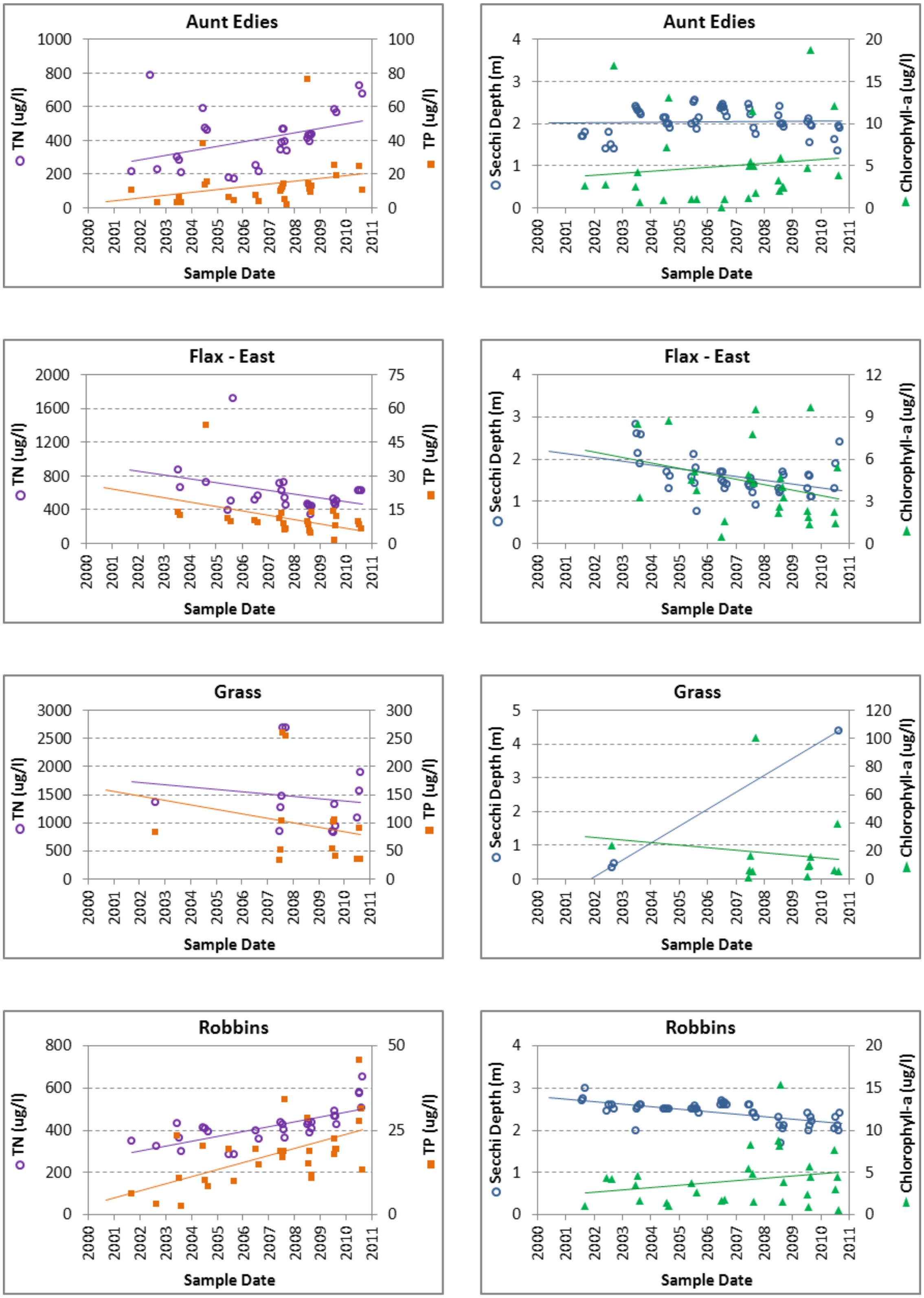
Attachment 1. Number of samples per year by parameter and pond.

		Number of Samples										
Pond		***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***	***2009***	***2010***
Aunt Edies												
	Total Phosphorus		1	2	3	4	2	2	6	5	2	2
	Total Nitrogen		1	2	3	4	2	2	6	5	2	2
	Chlorophyll-α		1	2	3	4	2	2	6	5	2	2
	Secchi disk		6	4	9	7	7	7	6	5	5	4
Bucks												
	Total Phosphorus	2	2	2	7	9	4	6	10	36	6	8
	Total Nitrogen	0	2	2	7	9	4	6	10	36	6	8
	Chlorophyll-α	0	2	2	7	9	4	4	10	36	6	8
	Secchi disk	4	22	13	26	31	34	46	30	36	4	5
Flax - East												
	Total Phosphorus				4	1	3	2	5	5	4	3
	Total Nitrogen				4	1	4	2	5	5	4	3
	Chlorophyll-α				4	1	4	2	5	5	4	3
	Secchi disk				10	6	12	6	6	5	5	3
Flax - West												
	Total Phosphorus				6	5	4	5	10	24	8	6
	Total Nitrogen				6	5	5	5	10	24	8	6
	Chlorophyll-α				6	5	5	5	10	24	8	6
	Secchi disk				15	14	22	22	18	24	5	5
Grass												
	Total Phosphorus			2					5		4	3
	Total Nitrogen			2					5		4	3
	Chlorophyll-α			4					5		4	3
	Secchi disk			5					0		0	1
Hawksnest												
	Total Phosphorus		2	6	6	6	4	5	9	30	2	2
	Total Nitrogen		2	6	6	6	4	5	9	30	2	2
	Chlorophyll-α		2	12	6	6	4	5	9	30	2	2
	Secchi disk		13	35	17	16	29	28	19	30	3	2
Hinckley												
	Total Phosphorus		2	2	6	6	4	4	8	36	9	16
	Total Nitrogen		2	2	6	6	4	4	8	36	9	16
	Chlorophyll-α		2	3	6	6	4	4	8	36	9	16
	Secchi disk		12	11	20	19	38	42	34	36	4	5

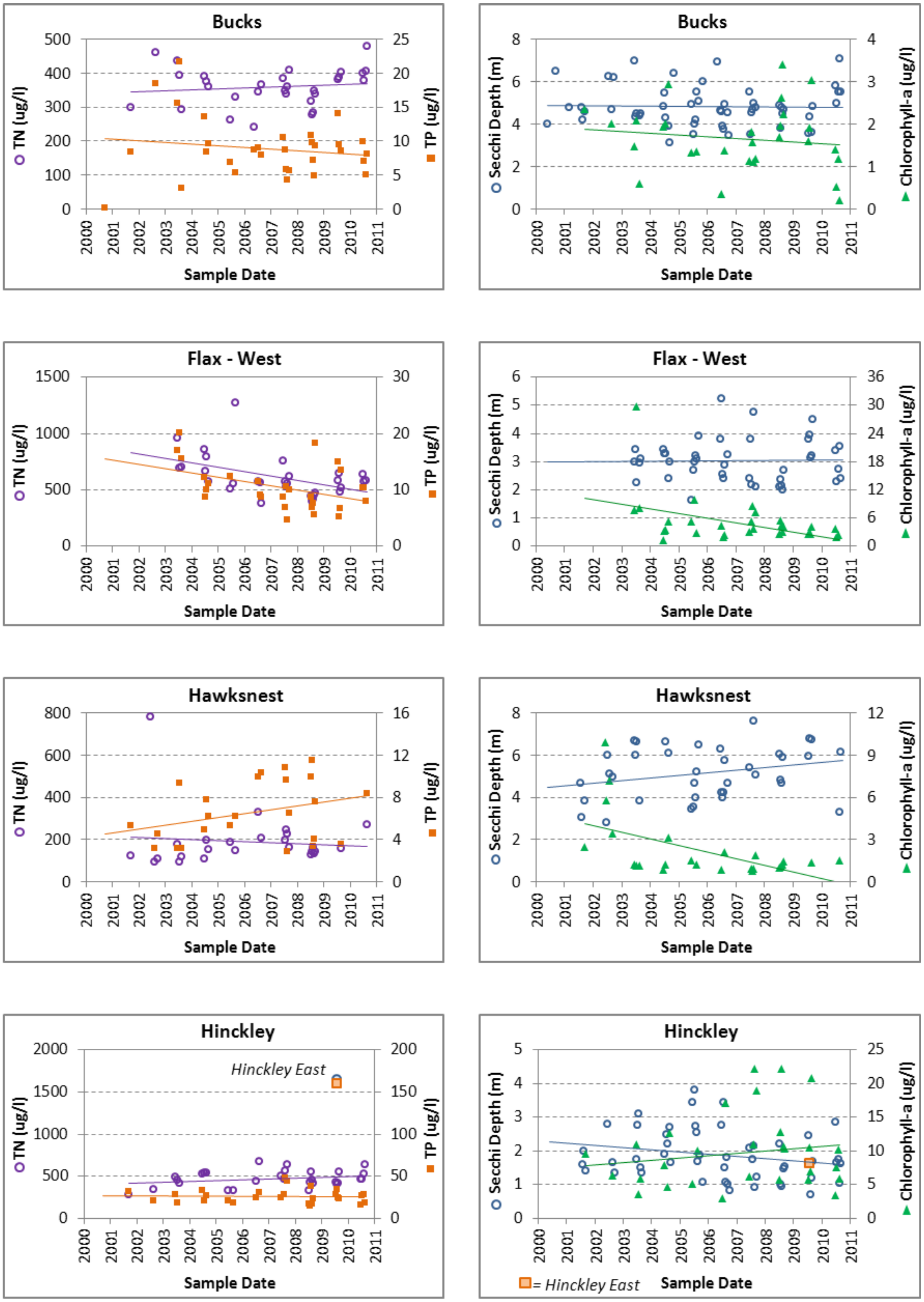
Attachment 1. Number of samples per year by parameter and pond (continued)

		Number of Samples										
Pond		***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***	***2009***	***2010***
Hinckley East												
	Total Phosphorus										1	
	Total Nitrogen										1	
	Chlorophyll-α										1	
	Secchi disk										0	
John Joseph												
	Total Phosphorus	2	4	3	3	7	8	12	21	54	16	16
	Total Nitrogen	0	4	3	3	7	8	12	21	54	16	16
	Chlorophyll-α	0	4	8	3	7	8	8	21	54	16	16
	Secchi disk	4	34	23	40	45	64	112	77	54	5	5
Robbins												
	Total Phosphorus		2	2	6	4	3	2	8	10	5	4
	Total Nitrogen		2	2	6	4	3	2	8	10	5	4
	Chlorophyll-α		2	4	6	4	3	2	8	10	5	4
	Secchi disk		10	11	10	10	12	13	12	10	5	5
Sand												
	Total Phosphorus		2	2	4	4	4	5	11	27	8	8
	Total Nitrogen		2	2	4	4	4	5	11	27	8	8
	Chlorophyll-α		2	2	4	4	4	5	11	27	8	8
	Secchi disk		11	10	12	24	26	20	22	27	5	5
Skinequit												
	Total Phosphorus		2	3	2	6	4	4	10	28	8	6
	Total Nitrogen		2	3	2	6	4	4	10	28	8	6
	Chlorophyll-α		2	3	2	6	4	4	10	28	8	6
	Secchi disk		13	18	20	25	31	31	19	28	4	5
Walkers												
	Total Phosphorus		3	2	6	6	4	4	12	27	8	8
	Total Nitrogen		3	2	6	6	4	4	12	27	8	8
	Chlorophyll-α		3	2	6	6	4	4	12	27	8	8
	Secchi disk		13	19	24	33	38	35	30	27	4	6
White												
	Total Phosphorus					6	2	3	8	12	2	
	Total Nitrogen					6	2	3	8	12	2	
	Chlorophyll-α					6	2	3	8	12	2	
	Secchi disk					26	22	16	14	12	1	

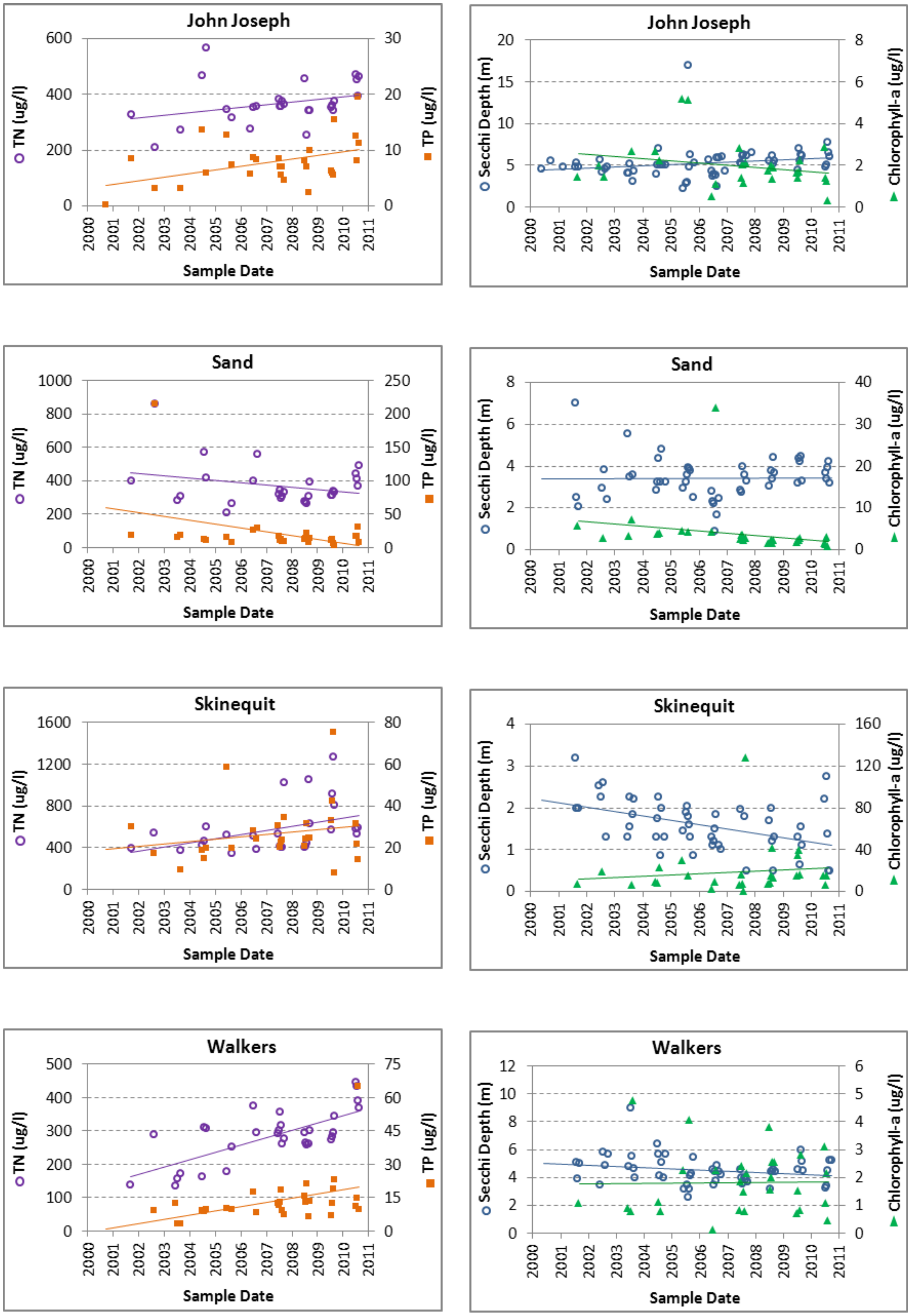
Attachment 2
Temporal scatter Plots of Harwich Ponds over Time



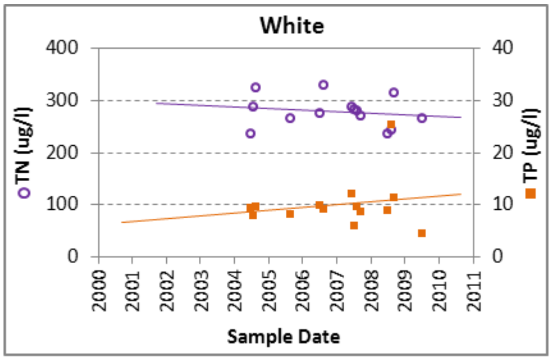
Attachment 2 (pg. 1 of 4). Total phosphorus, total nitrogen, Secchi and Chlorophyll-a temporal trends in shallow Harwich ponds.

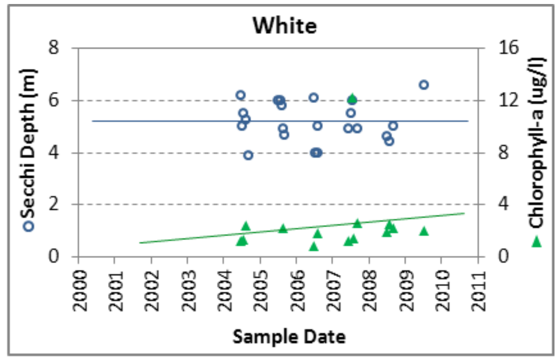


Attachment 2 (pg. 2 of 4). Total phosphorus, total nitrogen, Secchi and Chlorophyll-a temporal trends in deep Harwich ponds.



Attachment 2 (pg. 3 of 4). Total phosphorus, total nitrogen, Secchi and Chlorophyll-a temporal trends in deep Harwich ponds.





Attachment 2 (pg. 4 of 4). Total phosphorus, total nitrogen, Secchi and Chlorophyll-a temporal trends in deep Harwich ponds.