Cape Cod Regional Pond Data Analysis

CAPE COD FRESHWATER INITIATIVE

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Prepared by Cape Cod Commission Staff and Consultants

Cape Cod Regional Pond Data Analysis

A RESOURCE OF THE CAPE COD FRESHWATER INITIATIVE

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Executive Summary

Analysis of available data at the regional scale allows for several observations about changing nutrient loading, temperature, and pH, with implications for pond ecology. Cape Cod's ponds have generally become less acidic, with increases in alkalinity, since passage of the Clean Air Act. Alkalinity is a measure of the ability of a pond to neutralize acids and bases. An increase in alkalinity means a pond is better able to buffer against changes in pH, providing a more stable water chemistry, which in turn provides a healthier environment for aquatic plants and animals. The good news that Cape Cod's ponds have become less acidic, is overshadowed by changes in temperature and nutrient loading that creates changing and stressful conditions for pond life. Analysis of available data indicates that since 2001 there are statistically significant changes in temperature in ponds in the Sagamore and Monomoy lenses, ranging from approximately 1.6 – 2.4 degrees Celsius. Higher water temperatures, especially if they reflect warmer winter pond temperatures, will impact the timing, duration, and depth of pond stratification. Stronger and longer stratification of ponds can lead to extended low or no oxygen conditions in deeper waters, impacting aquatic life and altering the cycling of nutrients within a pond. Despite reductions in atmospheric nitrogen deposition, thanks to the positive effects of the Clean Air Act, nitrogen levels in ponds across the region are increasing. Similarly, and with more direct adverse effects, phosphorus levels in ponds have increased in every lens but the Pamet. Increasing levels of phosphorus in ponds is particularly concerning as it can remain cycling within a pond system indefinitely and have a lasting impact on pond biology. Together nitrogen and phosphorus, both necessary for plant growth and thereby affecting plant abundance in a pond, will influence the overall pond ecology. These observations allow for new insight into how Cape Cod's ponds have changed over the last twenty years, but ultimately still provide an incomplete picture. The historical data does not indicate whether warmer winters or hotter summers are driving changes in pond temperature, nor does it allow us to explore connections between internal phosphorus loads and summer algal growth. Analysis of the regional data set has shown there is real data behind many of the observed patterns in pond health, but also reinforced the need for more frequent monitoring throughout the growing season to better understand the drivers of change and determine appropriate courses of action.

Introduction

The glacial processes that formed modern-day Cape Cod left nearly 900 depressions in the landscape that are now freshwater ponds. Despite being formed in similar ways, these ponds vary widely in size, depth, and other physical characteristics and provide a variety of services in terms of habitat, recreation, drinking water, and their connection to the aquifer and other water resources.

While water quality is a defining feature of how well pond ecosystems are functioning, the physical characteristics of ponds and their watersheds also play important roles. Features such as pond depth, surface area, nearby topography, recharge area, and sediment thickness on the pond bottom factor into a pond's health. Similarly, the size of a pond's watershed, the ratio of watershed to pond volume, the land cover and land use activities in the watershed, as well as the amount of development, all may influence a pond's water quality and ecosystem health.

Because of their sometimes-small size and often geographically isolated nature, pond studies to assess water quality conditions and pond management actions often take place at a relatively small spatial scale, typically examining an individual pond or groups of ponds within a particular town or area. Several efforts have been made to better understand the condition of ponds throughout the entire region of Cape Cod, beginning with the creation of the Cape Cod Pond and Lake Stewards (PALS) program in 2000, followed by the 2003 publication of the Cape Cod Pond and Lake Atlas (2003 Pond Atlas).

The 2003 Pond Atlas gathered and summarized physical information about freshwater ponds on Cape Cod, implemented a numbering system that created unique identifiers for each water body, and presented a summary and analysis of the water quality results obtained during the sampling of 195 ponds in the 2001 PALS water quality snapshot. Included in that analysis was a discussion of the Environmental Protection Agency's (EPA) recent development of ecoregion thresholds, values of certain water quality parameters that serve as identifiers of water bodies "minimally impacted by human activities," and how they could be applied to Cape Cod's ponds and lakes.

The 2003 Pond Atlas found that based on 2001 sampling data approximately 74%, 75%, and 73% of monitored ponds were considered "impacted" by human activities, based respectively on Total Phosphorus, Total Nitrogen, and Chlorophyll a concentration. Other water quality parameters examined in the 2003 Pond Atlas included temperature, dissolved oxygen, pH, and alkalinity. The 2003 Pond Atlas presented the first region-wide analysis of Cape Cod's lakes and ponds, but also acknowledged significant need for additional monitoring, analysis, and planning resources to address human impacts and changing pond conditions.

Advancements in information and data collection, coupled with the need to reestablish a regional focus on pond health, led to the 2021 Cape Cod Pond and Lake Atlas (2021 Pond Atlas) and Data Viewer. The 2021 Pond Atlas built upon the 2003 Pond Atlas and included a review of the data, questions, and recommendations posed therein, as well as an exploration of new and updated information about land use, water quality monitoring, and management strategies. Comparisons of the number of ponds appearing on the State's List of Integrated Waters, trophic classifications of monitored ponds, and results of bathing beach bacterial sampling were added to the 2021 Pond Atlas. However, differences in the historical monitoring methods of data sampling, inconsistencies in the time-periods of data collection, and the availability of data stored in different locations and in different formats made in-depth analysis of data from a single pond or at the regional scale challenging. As such, the 2021 Pond Atlas began the launch of the Commission's Freshwater Initiative.

The Freshwater Initiative is a planning process to better understand and address threats to Cape Cod pond ecosystems. Among many elements (explore resources of the Freshwater Initiative), the Initiative provided for the development of ongoing data management processes to maintain accessible pond monitoring datasets and the creation of processing scripts for trend analyses.

To facilitate an updated regional analysis of pond data, the Commission compiled water quality data from historical monitoring activities spanning more than 20 years at over 200 ponds and lakes across Cape Cod, and converted it into a single format stored in the Regional Water Quality Database. Working with this new dataset and contractors from Anchor QEA and the Woods Hole Oceanographic Institution allowed for:

- The development of code and scripts to support data analyses
- Summarization of existing freshwater data and data characteristics in a standard format
- Presentation of regional data summaries, visualizations, and analyses.

As new data are received from various monitoring groups, they are entered into the Water Quality Database on a continuing basis and will be incorporated into future analyses.

Through this work, Commission staff and consultants were able to conduct a regional analysis of available freshwater pond monitoring data and investigate the current status of ponds. In response to anecdotal and observed changes to ponds visited on Cape Cod, this analysis posed numerous questions relating to whether Cape Cod's ponds are changing on a larger scale and why, which until this point could not be answered based on the data available. The newly assembled historical dataset along with new sampling data provides an opportunity to explore a number of questions such as:

- What are the present-day conditions and do pond water quality characteristics vary geographically?
- How have conditions in ponds changed since the 2003 Pond Atlas?
- Are ponds responding to the Clean Air Act in terms of nitrogen deposition and pH?
- How is climate change impacting ponds on Cape Cod?
- Are pond nutrient levels changing uniformly across the region?

Data and Methods

The regional pond data analysis described in this report utilizes all of the freshwater pond monitoring data collected on Cape Cod that was shared with or aggregated by the Commission at the time of publication, which includes data collected beginning in the early 2000s through the PALS program as well as data collected through the Freshwater Initiative's Cape Cod Regional Pond Monitoring (CCRPM) program beginning in 2023. The analysis dataset includes measurements from 3,031 individual sampling events: 2,515 PALS sampling events and 516 CCRPM program sampling events.

PALS data have been collected using consistent methods over the years, where samples were collected from the surface and bottom of each pond for water chemistry analysis including total nitrogen and phosphorus, pH, total alkalinity, and chlorophyll *a*. Secchi disk depth and profiles of temperature and oxygen with depth were also measured. Ponds in the PALS program were typically sampled once or twice each year, during late summer, with the goal of capturing a "worst case scenario" of water quality. Ponds in the CCRPM program are sampled monthly from spring to fall, including measurements generally similar and comparable to the PALS data. Despite the differences in schedule between programs, results from both could be combined into a single dataset for analysis since they utilized comparable sample collection and analysis methods. One exception is the 2023 Secchi disk data collected by the CCRPM program which, due to differences in methodology, were omitted from the analysis. For a detailed description of the sampling and analysis methods used by the PALS and CCRPM programs please see the respective Quality Assurance Project Plans (QAPPs) (Town of Orleans 2018, Town of Plymouth 2023, Cape Cod Commission 2024).

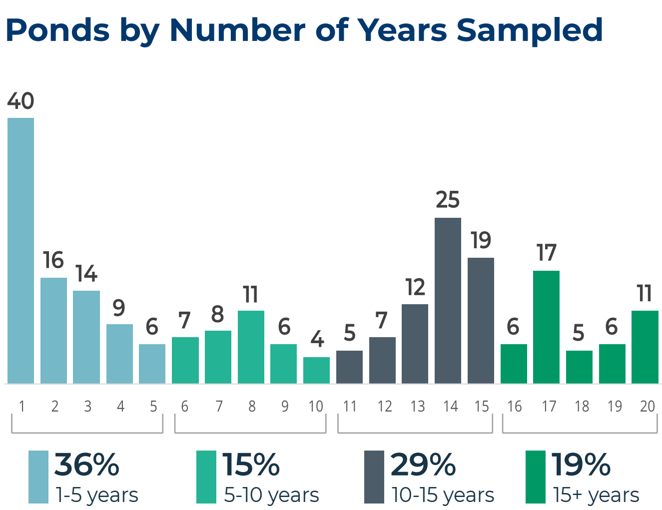
Overview of Available Data

One challenge with analyzing and interpreting patterns in the historical data is variation in the ponds sampled from year to year. If the collection locations making up the regional dataset change over time, there is potential for bias in long-term trend calculations when trying to assess multiple ponds within subregions (e.g. groundwater lenses) or the region as a whole. Therefore, even with this large dataset, it is important to recognize the limitations on the ability to calculate trends and the level of confidence associated with any trends that are observed. To better understand the types of analysis appropriate for the overall dataset, the scope, distribution, and frequency of data available for individual ponds were examined. ***Appendix A*** shows a summary of the ponds with monitoring data at the time of analysis, most recent and total years of data for each pond, and whether sufficient data was available to calculate individual pond trends.

Examining the distribution of data by pond, month, and year uncovered wide variation in the number of years each pond was monitored, samples per year, and the timing of those samples. ***Figure 1a*** illustrates the historical distribution of the years of monitoring data available for each pond. Many ponds were sampled only for a single year, which generally reflects locations where samples were only collected during the 2001 PALS snapshot sampling. The inset percentages in *Figure 1a* shows that 35% of the ponds have very limited data (less than five years) which is not sufficient for trend analysis, while nearly half (approximately 45%) have been monitored between five and 15 years, and approximately 20% have more than 15 years of data. Monitored ponds collectively represent only 26% of Cape Cod's 890 ponds, with the remainder having no monitoring data whatsoever.

Figure 1b shows that the vast majority of historical water quality monitoring occurred at the end of summer in August and September, with a small set of sampling events occurring during other months of the year. Sampling performed in other months can be mostly attributed to the CCRPM program that began in 2023, although certain towns and pond monitoring groups have previously included spring baseline sampling in April or May along with additional sampling during summer months. Given the focus of the historical data collection at the end of summer, information about pond behavior in the spring and throughout the summer is difficult to glean from this historical dataset and illustrates a critical data gap being filled by the CCRPM program.

Having data aggregated for the entire region also allowed for the examination of how the timing and duration of pond monitoring vary geographically. *Figure 2* illustrates the spatial variation in monitoring/data sharing and demonstrates some of the limitations in the historical dataset by showing, for each pond, the total number of years of data available for this analysis (*Figure 2a*) and in what year the most recent data were available (*Figure 2b*). The data characteristics for each pond are generally consistent within town boundaries as volunteer monitoring was typically



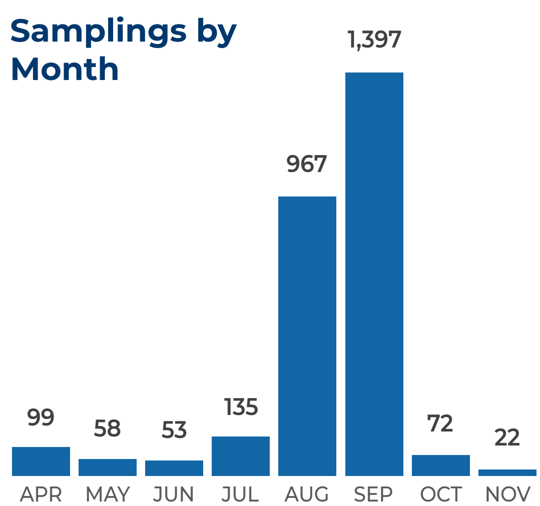


Figure 1. Left (a): Histogram illustrating the length of data record for individual ponds within the analysis data set, and proportion of ponds sampled 0-5 years, 6-10 years, 11-15 years, and >= 16 years. Right (b): Distribution of sampling events by month.

organized at the town level, though some individual ponds stand out from their surrounding peers. Unfortunately, many of the ponds that have extensive observations in the database do not have any data more recent than 2016 (***Figure 2b***). Despite this, there is sufficient data to evaluate temporal patterns in water quality indicators at many individual ponds, and there were a sufficient number of ponds sampled consistently [see below for more detail] throughout the overall data record to discern stronger regional trends emerging out of the natural variability that occurs throughout the dataset.

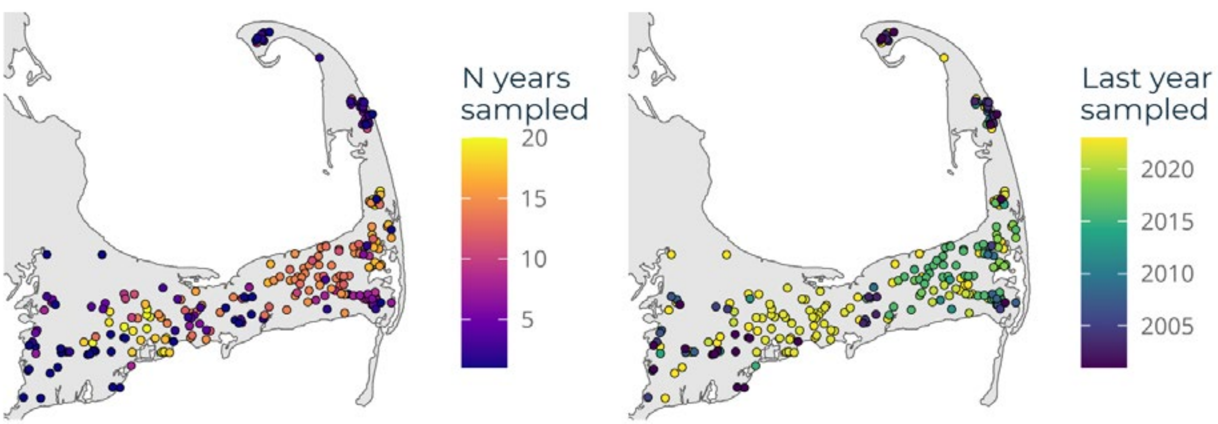


Figure 2. Geographic distribution of (a left) number of years sampled and (b right) most recent year of data, by individual pond.

Data Cleaning and Treatment

Data were processed in the following ways for use in the analyses described below.

PROCEDURES APPLIED TO ALL PONDS / PARAMETERS

Describing both spatial and temporal patterns in the analysis dataset required initial preparation that included data cleaning, outlier removal, and aggregation prior to analysis. First, data with erroneous values were removed from the overall dataset. Data reported as below the detection limit for each parameter were set to zero. The historical dataset was then filtered to data collected in only August and September for further analysis.

On the data collected during August and September (hereafter referred to as "the dataset"), values from discrete (grab sample) water measurements that deviated from the sampling station mean for a given parameter by more than three standard deviations were considered outliers and removed from further analysis.

DATA VARIABILITY WITH POND DEPTH

Ponds and lakes at this latitude undergo seasonal changes in water temperature, gaining heat in the spring, typically reaching their maximum temperature in late summer, and losing heat through the fall and winter. Ice cover of the ponds has become increasingly variable. In addition to water temperature change over the annual cycle, ponds exhibit temperature changes with depth. Heat added from solar radiation onto the pond surface is mixed deeper into the water column by wind-driven turbulence. Thermal stratification of lakes and ponds develops because the density of water varies with temperature; water has a maximum density at 4°C (39 °F) and warmer water is less dense. In deeper ponds, the density gradient between the warmer upper waters and the colder lower waters is strong enough to withstand turbulent mixing.

Once stable thermal stratification develops, typically by early summer, the ponds remain separated into the upper mixed layer (UML) and the isolated deeper waters (also referred to as the hypolimnion). The result is different water quality conditions in each layer. Photosynthetic organisms add oxygen to the UML (also referred to as the epilimnion); when they die, they settle to the pond bottom and are decomposed. Microbial decomposition draws down the limited supply of dissolved oxygen in the isolated hypolimnion. Oxygen depletion triggers chemical changes at the sediment-water interface. In consideration of these physical effects, the pond database differentiates between surface and bottom sample results to support analysis of these differences.

Annual mean August/September water quality parameters were then calculated separately for "surface" and "bottom" samples, where all samples collected at depths of one meter or less during the same sampling event were averaged as "surface" samples. Shallow ponds with depths less than three meters were not assigned a "bottom" sample and were assumed to be fully mixed, where the surface sample would be representative of the water column conditions. "Bottom" samples for deep ponds were determined by assigning the deepest sample collected each year as the "bottom" value. Because there was substantial variation in the depth at which bottom samples were collected, deepest samples had to be located within the bottom 25% of the pond, as determined by the greatest depth recorded in the dataset for that particular pond.

For each sampling event, a pond's mixed layer depth (MLD) was calculated using vertical temperature profiles with one-meter increments, by identifying the depth at which the change in temperature over one meter exceeds 1 degree Celsius[1]. If temperature measurements were available for at least the top 75% of the water column (based on maximum depth recorded for a pond) and no change in temperature fit the above criterion, the mixed layer depth was assumed to be the full water column recorded for each profile (not stratified). Ponds where the mixed layer depth is shallower than 75% of the maximum depth were further assumed to be stratified, while ponds with mixed layer depth deeper than 75% of the maximum depth were assumed to be mixed. All ponds with a maximum depth less than 5m were assumed to be fully mixed.

PROCEDURES FOR DATA COLLECTED IN DEPTH PROFILES (TEMPERATURE AND DISSOLVED OXYGEN)

Dissolved oxygen measurements can be reported in concentration (mg/L) or as percent saturation (%), and current monitoring generally reports in both formats. Historical monitoring often reported only concentration, or only percent saturation, resulting in significant data gaps. Where temperature and pressure were known for a sampling event, a missing dissolved oxygen measurement (either concentration or percent saturation) was calculated using the reported measurement (percent saturation or concentration, respectively) with the equations of state and gas solubility found in the Gibbs Seawater Toolbox (McDougall and Parker, 2011). Because of the wide range in temperature and dissolved oxygen in stratified ponds, the outlier detection approach for discrete samples collected at the surface and bottom would not provide meaningful information. Instead, for each pond, water column profile data were first aggregated into 1-meter bins, and then the mean and standard deviation in temperature and dissolved oxygen for each depth bin over the entire data record was calculated. Outliers at each depth were excluded from further analysis if they deviated from the mean by more than three standard deviations. Following outlier removal, annual and overall August/September mean temperature and oxygen profiles were calculated for each pond, using the cleaned dataset.

1. Hutchinson, G. E. 1975. A Treatise on Limnology: Volume 1, Part 1- Geography and Physics of Lakes. John Wiley & Sons, New York. 540pp.

Data Analysis

Following the appropriate data preparation as described above, the resulting data were used to perform the analyses described below.

REGIONAL TRENDS

To prevent spatio-temporal biases from being introduced into the analysis because of changing sampling frequency through time, and to ensure that results across ponds were comparable, surface and bottom annual means were further grouped into ponds that were “consistently sampled” over the full data record. In order to be considered “consistently sampled,” ponds must have been sampled during the first and last 25% of the time period where data are available (2001-2006 and 2016-2023, respectively) and the ponds must have been sampled for at least 50% of the number of years in the data record (11 years). Note that 2016 was used as a lower bound for quantifying trends due to the large number of ponds with monitoring data that ends during this year.

ECOREGION THRESHOLDS

In the 2003 Cape Cod Pond and Lake Atlas, an assessment of key water quality variables was completed to identify threshold values that indicate conditions reflective of unimpacted ponds specific to Cape Cod. In this analysis, we repeat the calculations to determine if these thresholds have changed over time. The thresholds were quantified in two ways:

1. All August/September data collected from eight ponds identified as having limited anthropogenic impact in the 2003 Cape Cod Ponds Atlas were aggregated and thresholds for Total Nitrogen, Total Phosphorus, chlorophyll a, and Secchi disk depth were set at the 75th percentile of the full distribution of these data.
2. All August/September data from “consistently sampled” ponds were aggregated into annual means, and thresholds were determined, based on the 25th percentile in the data distribution, for Total Nitrogen, Total Phosphorus, chlorophyll a, and Secchi disk depth.

Cape Cod ecoregion thresholds were quantified for both the entire data distribution and for each year of data in the dataset.

DECADAL TREND SHIFTS IN THE DATA DISTRIBUTION

Broad scale shifts in the distribution of annual surface and bottom August/September means collected from “consistently sampled ponds” were evaluated. The data were first split into data collected during the 2001-2011 and 2012-2023 periods, and changes in the distributions were evaluated using two sample Kolmogorov-Smirnov tests. This statistical test is non-parametric, meaning it makes no assumptions about the structure of the data, and is designed to determine if two datasets are drawn from identical distributions.

TEMPORAL TREND ANALYSIS

Temporal trends in “consistently sampled” ponds were quantified for water quality variables at the surface and bottom by application of a Mann-Kendall trend analysis (Mann 1945, Kendall 1975, Gilbert 1987). Mann-Kendall trend analysis is a non-parametric analysis that documents whether a dataset has a monotonic increasing or decreasing trend by quantifying the number of concordant and/or discordant pairs in a given time series (pairs where a later value is greater or less than an earlier value, respectively), then assessing whether this number is significantly larger (or smaller) than zero. Trend magnitudes were quantified using the Sens slope method, which is defined as the median change in a parameter across all the concordant and/or discordant pairs in the dataset (Sen 1968). Trends were assessed across multiple sampling stations for ponds within the same groundwater lens, and for all ponds on Cape Cod, using Regional Mann-Kendall trends analysis. Regional Mann-Kendall trends combine each station’s Mann-Kendall test statistics into a grouped, combined value. The major benefit of the Regional Mann-Kendall test for trends is that within a group of sampling locations, there is no cross-location aggregation of individual measurements. The analysis determines non-parametric test statistics for each location individually, then groups the results together by region to determine if a common trend exists across the region.

PHYSICAL AND WATERSHED CHARACTERISTICS

Using data gathered during the 2021 Pond and Lake Atlas update, the following physical and watershed characteristics were used to group similar ponds together and explore whether data trends could be observed more clearly within those grouped ponds.

- Groundwater lens –Cape Cod’s aquifer system consists of six distinct mounds or lenses of groundwater: Sagamore, Monomoy, Nauset, Chequesset, Pamet, and Pilgrim lenses
- Regional location on Cape Cod – upper, mid, lower, and outer
- Total depth – determined as the maximum depth for which profile data were collected
- Stratification – the development of relatively stable, warmer and colder horizontal layers of water within a water body
- Surface area – a measure of the total area of a pond’s surface
- Watershed development – the level of development within 300 feet of a pond. “Developed” areas included impervious surfaces, building or roof areas, and managed turf. The percentage of developed buffer area was calculated for each pond, and ponds were grouped by quartiles denoted as low, medium, high, and very high development.

Results and Discussion

Present-Day Pond Conditions Throughout Cape Cod

Ponds across Cape Cod exhibit a range of water quality conditions related to their level of primary productivity, or trophic state. Primary productivity refers to the capacity of an aquatic ecosystem to support the growth of photosynthetic organisms, including rooted aquatic vegetation, algae, and cyanobacteria. Aquatic biota require suitable conditions of light, water temperature, and nutrients to thrive. With suitable light and temperature, nutrient availability is the primary determinant of primary productivity in lakes and ponds. The long-term dataset has been examined to evaluate nutrient concentrations in the monitored ponds and the ponds' response, as indicated by chlorophyll *a* (photosynthetic pigment in phytoplankton) and water clarity.

There are various methods to define thresholds for what constitutes a "healthy" pond. As ponds age, they naturally become more enriched in nutrients; the rate of change depends on both the nature of the ponds (depth, volume, water residence time) and the nature of the watershed (quality of water seeping in through groundwater and flowing in over the land surface). Water resource managers classify lakes and ponds based on their productivity; the scale ranges from oligotrophic (nutrient poor) to eutrophic (nutrient rich). Mesotrophic refers to moderate levels of nutrient supply and productivity. Both the process of nutrient enrichment and its impacts are referred to as eutrophication. While eutrophication is a natural process, it can be accelerated by human activities.

Water resource managers focus on identifying and controlling sources of nutrients (nitrogen and phosphorus) to manage the eutrophication process. The abundance of aquatic plants, algae, and cyanobacteria has a direct effect on aquatic habitat and recreational suitability. Nitrogen is the primary limiting nutrient for coastal and marine ecosystems, meaning that the supply of biologically available nitrogen governs the biomass of photosynthetic organisms, given suitable light and temperature conditions. Nitrogen enrichment has resulted in degradation of estuarine and marine water quality and habitat conditions, and wastewater is a major source of nitrogen.

In contrast, phosphorus is most frequently the limiting nutrient for inland freshwater lakes and ponds at this latitude, although there are some exceptions. Water quality assessment metrics focus on phosphorus as the causal variable and water clarity and abundance of phytoplankton (measured by chlorophyll *a*) as the response variables. The levels of these three variables are used to assess the trophic state of lakes and ponds. The Trophic State Index (Carlson and Simpson 1996) has been widely applied in lake and pond management.

Current pond conditions were evaluated by averaging the August and September data from 2016 to present for key water quality metrics. This timeframe was selected to reflect recent data, as some ponds have not been sampled since 2016 (or those data have not been provided to the

Commission). Key metrics evaluated include Secchi depth (meters, m) and mixed layer depth (m) (***Figure 3***); surface and bottom total alkalinity (Alk, mg/L) (***Figure 4***); surface and bottom total nitrogen (TN, mg/L) (***Figure 5***); surface and bottom total phosphorus (TP, mg/L) (***Figure 6***); surface TN:TP ratio and surface chlorophyll *a* (Chla, µg/L) (***Figure 7***); surface and bottom temperature (T, °C) (***Figure 8***); surface and bottom dissolved oxygen concentration (DO, mg/L) (***Figure 9***); and dissolved oxygen saturation (DO sat, %) (***Figure 10***).

Across all ponds and parameters, there is significant variation, even between nearby ponds within similar geographic or groundwater lens regions. Notably, although most ponds have Secchi depths that are relatively shallow and range between 2-4m, some ponds are remarkably clear, with Secchi depths approaching 8m on average and with individual measurements as high as 10m. Nutrients (TN, TP) and chlorophyll *a* concentration varied across ponds by several orders of magnitude in both surface and bottom waters, although bottom waters tended to have higher TN and TP than surface waters (***Figure 5*** and ***Figure 6***). TN:TP ratios, which can be indicative of limiting nutrients for phytoplankton species, were very high across most ponds, suggesting most ponds were phosphorus limited. However, two ponds (Cedar Pond in Orleans, and Dyer Pond in Wellfleet) had TN:TP ratios less than 16, suggesting that nitrogen limitation may be occurring in these two cases.

NUTRIENT LIMITATION

Aquatic primary producers, whether they are rooted plants or single cell plankton found in the water column, require nutrients to grow. Nitrogen and phosphorus are key essential nutrients, and research has found that plankton need these two nutrients in a ratio of 16:1 in order for growth to occur. When the ratios of these nutrients differ, one can become a factor that limits plankton growth. In freshwater systems, this ratio is often found to be greater than 16, indicating that more nitrogen than phosphorus is available to fuel plankton growth. In this case, phosphorus would be considered the "limiting nutrient." This differs from marine systems, where nutrient ratios are often found to be less than 16, indicating that more phosphorus than nitrogen is available, which would make nitrogen the limiting nutrient.

Summertime surface temperatures were consistent across the entire region, although bottom temperatures varied depending on whether a pond was stratified or well mixed. Stratified ponds were more than 5 degrees Celsius cooler at the bottom than at the surface, and some ponds varied by more than 10 degrees Celsius from surface to bottom conditions (***Figure 8***). Dissolved oxygen concentration and saturation also showed similar patterns: surface waters were relatively uniform in both concentration and saturation across the region, although two ponds experienced hypoxia (< 3 mg/L) in surface waters. In contrast, 72 ponds experienced hypoxia or anoxia in bottom waters.

Similarly, surface alkalinity was also consistent across ponds, although a cluster of ponds in the Mid-Cape and around the Town of Chatham had slightly higher alkalinity than the rest of the region. In contrast, bottom alkalinity was higher on average (14.32 versus 28.31 mg/L for surface and bottom, respectively) and much more varied (standard deviation of 15.95 versus 26.45 mg/L for surface and bottom, respectively). Bottom waters in stratified ponds tend to accumulate alkalinity sourced from metabolic processes occurring within sediments that are then oxidized once the pond turns over and stratification breaks down ([Kling et al. 1991](#)).

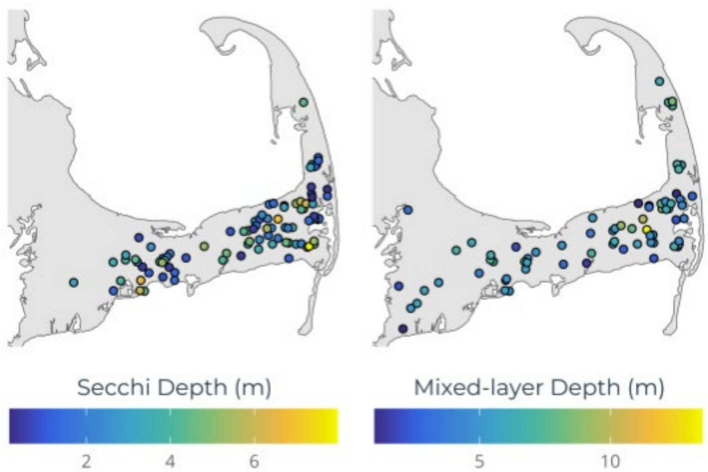


Figure 3. Current (based on 2016 - present data) pond water clarity (Secchi depth), and mixed-layer depth in deep stratified ponds.

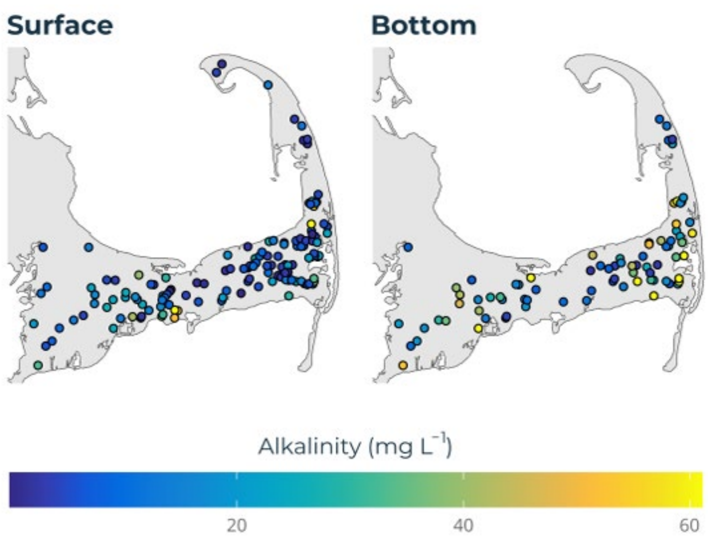


Figure 4. Current pond alkalinity (based on 2016 - present data) in surface waters for all ponds and bottom waters for ponds deeper than 3 meters.

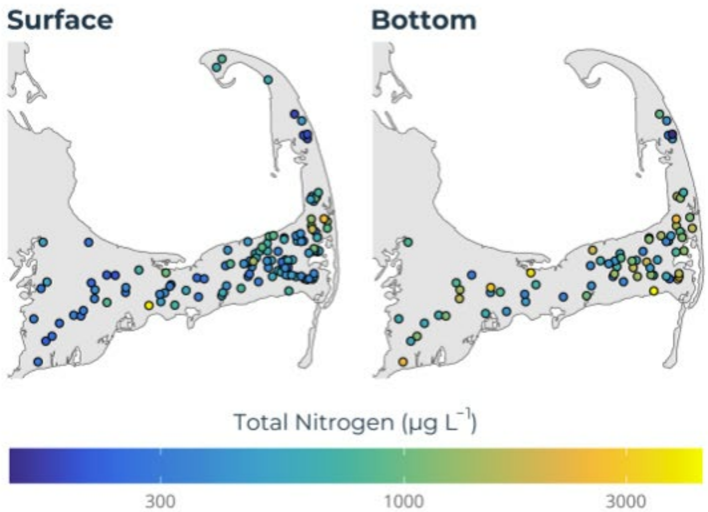


Figure 5. Current total nitrogen concentrations (based on 2016 – present data) in surface waters for all ponds and bottom waters for ponds deeper than 3 meters.

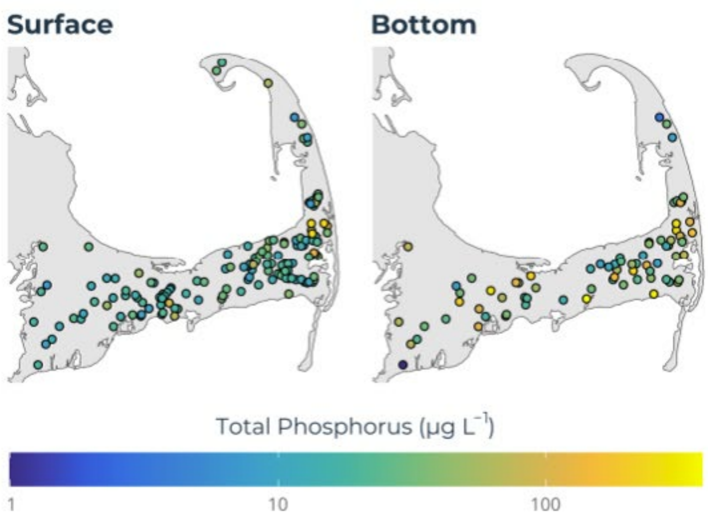


Figure 6. Current total phosphorus concentrations (based on 2016 – present data) in surface waters for all ponds and bottom waters for ponds deeper than 3 meters.

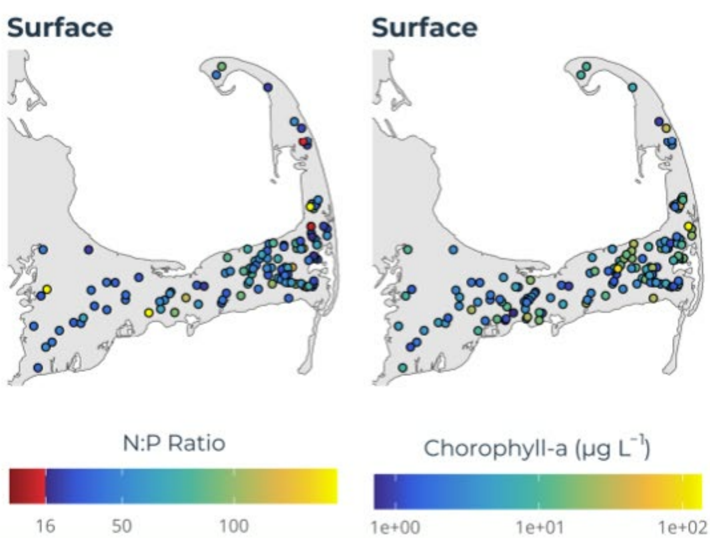


Figure 7. Current (based on 2016 – present data) pond nitrogen to phosphorus ratios (N:P) and chlorophyll a concentrations. N:P values less than 16 are shown in red and indicate potential nitrogen limitation.

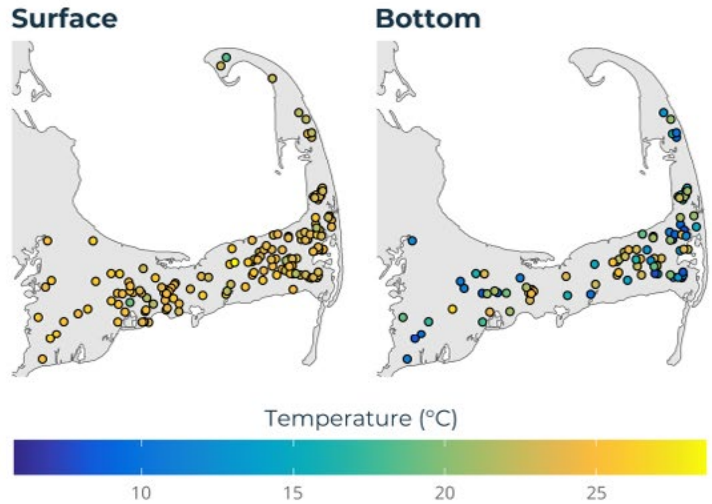


Figure 8. Current (based on 2016 - present data) summer average temperature measurements in surface waters for all ponds and bottom waters for ponds deeper than 3 meters.

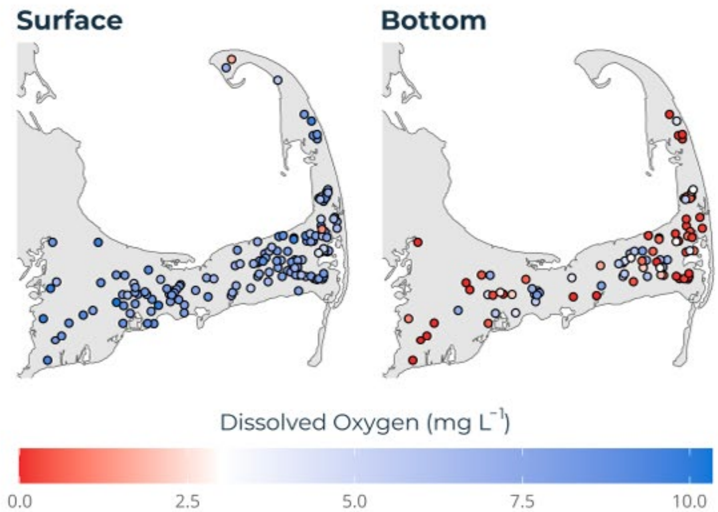


Figure 9. Current (based on 2016-present data) summer average dissolved oxygen in surface waters for all ponds and bottom waters for ponds deeper than 3 meters. Measurements below the Massachusetts Class C surface water standard of 3 mg/L dissolved oxygen are shown in red.

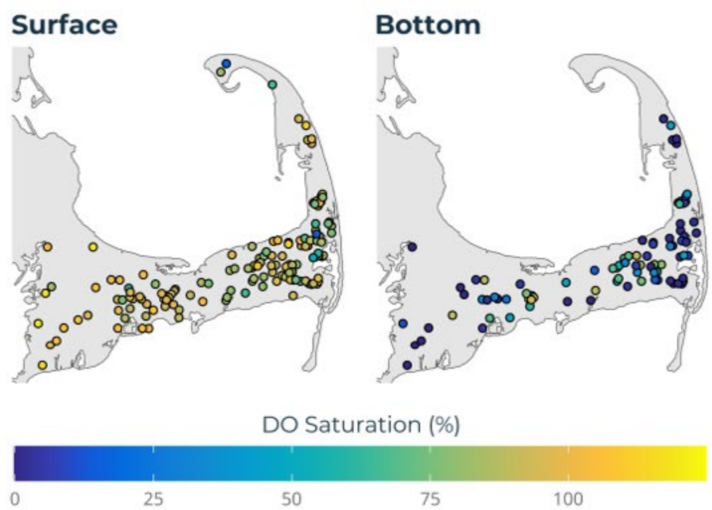


Figure 10. Current (based on 2016-present data) summer average dissolved oxygen saturation in surface waters for all ponds and bottom waters for ponds deeper than 3 meters.

How Pond Conditions Have Changed Since the 2003 Pond Atlas

The United States EPA developed methods and water quality criteria recommendations that rely on an evaluation of the statistical distributions of water quality parameters measured across the broader EPA regions and subregions. Cape Cod is part of ecoregion 14, and sub-ecoregion 84 (EPA 2000). These criteria better reflect representative conditions within the broad range of watershed geology, land use, climatic conditions, biological assemblages, and hydrology by focusing on localized data rather than uniform criteria applied to all water bodies. Ecoregion criteria identify threshold values for "impacted" and "unimpacted" waterbodies for key water quality parameters of TN, TP, Chla, and Secchi disk depth and represent starting points for states to develop more refined criteria and standards for nutrients. Results of this analysis were summarized in the 2003 Atlas (2003 Atlas Table 4). During development of the 2003 Atlas, the project team also applied the EPA methodology to data collected from Cape Cod ponds in 2001- 2003 to define a Cape Cod specific assessment of thresholds to define unimpacted ponds. This evaluation assessed whether local data provided more appropriate water quality indicators that better reflected natural variability at smaller spatial scales on Cape Cod. In this original assessment, chlorophyll *a* and TP were found to have lower thresholds than the recommended criteria from the EPA analysis. A further assessment of the data collected for the 2003 Pond Atlas identified eight ponds that were considered "unimpacted" due to their low nutrient, chlorophyll *a*, and pH values: Hathaway South and Micah in Barnstable; Slough and Pine in Brewster; Flax in Dennis; Slough in Truro; and Duck and Spectacle in Wellfleet (Cape Cod Pond and Lake Atlas, 2003). Specific criteria using only the data from these "unimpacted" ponds were developed by identifying the upper 25th percentile of the distribution of all data collected from this subset of ponds. Using this method resulted in lower thresholds than those determined for ecoregion 14 and sub-ecoregion 84, as well as the thresholds determined from the entire dataset collected for the 2003 Pond Atlas. Note that the reported Cape Cod ecoregional criteria (total phosphorus 10 µg/L, total nitrogen 0.31 mg/L, and chlorophyll a 1.7 µg/L, Table 4) reflected conditions in "unimpacted" ponds as measured in 2001 and are not regulatory standards or goals.

How Regional Thresholds Have Changed Over Time

The EPA criteria defining threshold water quality indicators of unimpacted ponds have not been updated since their publication (EPA 2000). With the new available data that has been compiled through the Cape Cod Freshwater Initiative, managers have more data to characterize change over time to understand if baseline water quality has changed over the decades. ***Table 1*** shows threshold values calculated from the 75th percentile for the "unimpacted" pond list quantified using all the data collected in August/September, from the lower 25th percentile for all ponds in August/September 2023, and from the lower 25th percentile for annual data from the entire data distribution for August/

September. This provides an assessment of the mean thresholds for the “unimpacted” ponds as well as the mean thresholds for all ponds compared to the thresholds for data collected in the most recent sampling year.

THRESHOLD VALUE COMPARISON	2003 Atlas Values	*Number of Ponds with Present Day Surface Conditions that Exceed 2003 Pond Atlas Threshold*	2003-2023 Values	*Number of Ponds with Present Day Surface Conditions that Exceed Updated Threshold*	Only 2023 Values
Unimpacted Cape Ponds 75 Percentile Threshold					
TN (mg/L)	**0.16**	*154 of 154*	**0.34**	*115 of 154*	**n/a**
Chla (µg/L)	**1**	*149 of 154*	**3.0**	*102 of 154*	**n/a**
Secchi (m)	**n/a**	*n/a*	**4.1**	*109 of 152*	**n/a**
TP (µg/L)	**7.5**	*149 of 154*	**12.4**	*124 of 154*	**n/a**
All Cape Ponds 25 Percentile Threshold					
TN (mg/L)	**0.31**	*125 of 154*	**0.328**	*120 of 154*	**0.247**
Chla (µg/L)	**1.7**	*133 of 154*	**1.78**	*131 of 154*	**2.6**
Secchi (m)	**n/a**	*n/a*	**4.15**	*112 of 152*	**n/a**
TP (µg/L)	**10**	*140 of 154*	**10.2**	*140 of 154*	**11.7**

EPA Reference Thresholds	EPA Ecoregion 14	Sub-ecoregion 84
TN (mg/L)	0.32	0.41
Chla (µg/L)	2	6
Secchi (m)	4.5	2
TP (µg/L)	9	9

Table 1. Ecoregion threshold values calculated from the full dataset, compared to those reported in the 2003 Pond Atlas. The term “4 List” ponds was given to the 8 ponds that were determined to be “unimpacted” in all four parameters evaluated (TN, TP, Chla, and pH) in the 2003 Pond Atlas. Note 75% 4 list ponds are not included for 2023 because only one pond was sampled in August/September.

For the “unimpacted” ponds, the thresholds for TN, chlorophyll a, and TP were 2.1, 3.0, and 1.7 times higher (respectively) than that reported in the 2003 Pond Atlas (***Table 1***), indicating nearly a doubling or more of water quality indicators compared to previous reference values for the region. For the thresholds calculated from all pond data available, values were nearly identical to those previously calculated in the 2003 Pond Atlas for all parameters assessed. Reference values using data from 2023 alone were slightly lower than those from all data for TN, but higher for chlorophyll a and TP. ***Figure 11*** shows how these thresholds have changed over time by applying the EPA calculation method to the distribution of each year’s August/September surface data. As discussed in the Introduction, only about 26% of Cape Cod ponds have been monitored; this limits managers’ ability to draw conclusions.

Several patterns are notable in this analysis. First, the 2003 Pond Atlas reported lower concentrations of nutrients and chlorophyll for thresholds determined from “unimpacted” ponds, which differs from what was observed in this analysis. Secchi disk depth is an exception to this observation; when evaluating the entire compiled dataset, annual thresholds determined using both methods were quite similar for Secchi disk depth. Note that Secchi disk depth was not reported for Cape Cod ponds in the 2003 Atlas due to the prevalence of observations of Secchi disk visibility to the pond bottom, although Secchi disk depth is reported for ecoregion 14 and sub-ecoregion 84. When comparing the annual thresholds from the “unimpacted” ponds to those from all ponds, TN and chlorophyll a thresholds were much more variable, with some year’s measurements much higher for “unimpacted” ponds than for the entire pond dataset. For TP however, the threshold quantified from “unimpacted” ponds was consistently higher than that quantified from all ponds.

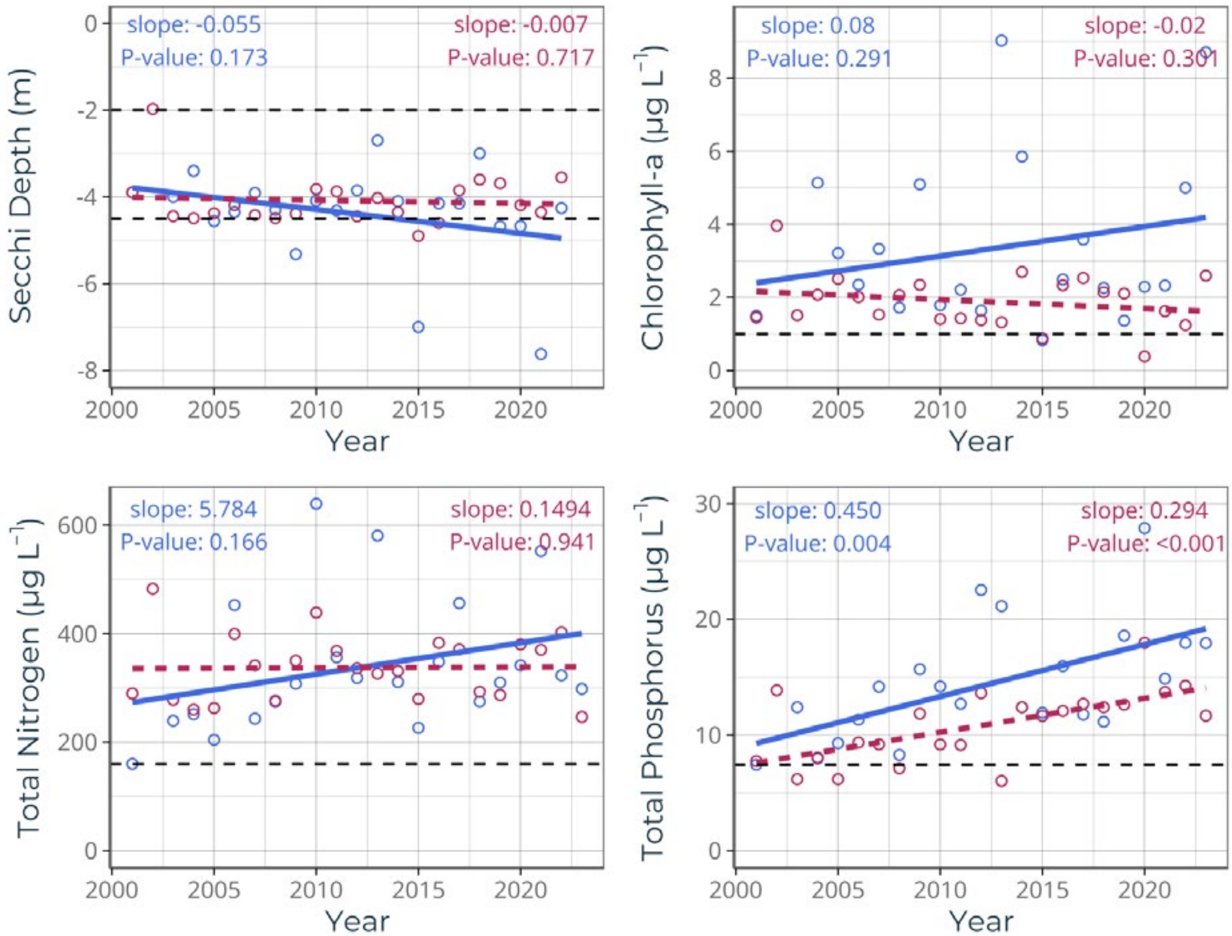


Figure 11. Ecoregion thresholds determined as in the 2003 Cape Cod Pond and Lake Atlas, shown for Secchi depth (top left), chlorophyll a (top right), total nitrogen (TN, bottom left), and total phosphorus (TP, bottom right). Annual thresholds determined from the entire August/September dataset are shown in red, and thresholds from the "unimpacted" 4 List ponds from the 2003 Atlas are shown in blue. Linear best fit trends, slopes, and p-values are shown as text on each plot. Black dashed lines indicate the threshold identified in the 2003 Atlas for "unimpacted" ponds.

Second, no statistically significant changes were observed in regional thresholds for Secchi disk depth, TN, or chlorophyll a quantified using either calculation method. Pond, lens, and regional trends were mixed for these parameters, and in fact, trends in chlorophyll a were actually declining for the Sagamore lens and region wide. This is in contrast to TP, which did display statistically significant increases in water quality indicator thresholds calculated from the entire Cape Cod pond dataset and those only from "unimpacted" ponds as identified in the 2003 Pond Atlas. This suggests that ponds identified as "unimpacted" in the 2003 Pond Atlas may in fact not be representative of unimpaired conditions in the region. Rather, 2001 may have been an anomalously low year for TP and chlorophyll a. Additionally, not only is the baseline TP increasing, quantified using either methodology, but the rate of increase in "unimpacted ponds is 1.5-fold faster than when quantified using the entire pond dataset. This suggests that the small subset of "unimpacted" ponds may actually have experienced a higher rate of localized phosphorus loading and water quality degradation than experienced overall across Cape Cod ponds. Further analysis may help elucidate whether this phenomenon is specific to the eight ponds selected in the 2001 Pond Atlas, or whether ponds with lower productivity (oligo- to mesotrophic) in general are experiencing higher rates of phosphorus loading relative to the overall pond population on Cape Cod.

Comparing the Distribution of Water Quality Observations between 2001-2011 and 2012-2023

In addition to identification of critical water quality thresholds, compilation and evaluation of distributions within an environmental dataset can also help discern if there have been subtle, large-scale shifts over time. This type of assessment has been crucial in evaluating how regional baseline conditions may shift over time, and the potential implications of those shifts. For example, as global temperatures rise due to climate change, shifts in the drivers and patterns of rainfall may lead to extreme events becoming more frequent (NCA 2023). With enough data, these changes can be quantified as shifts in the probability distribution of a given measurement over time (e.g., ***Figure 12***).

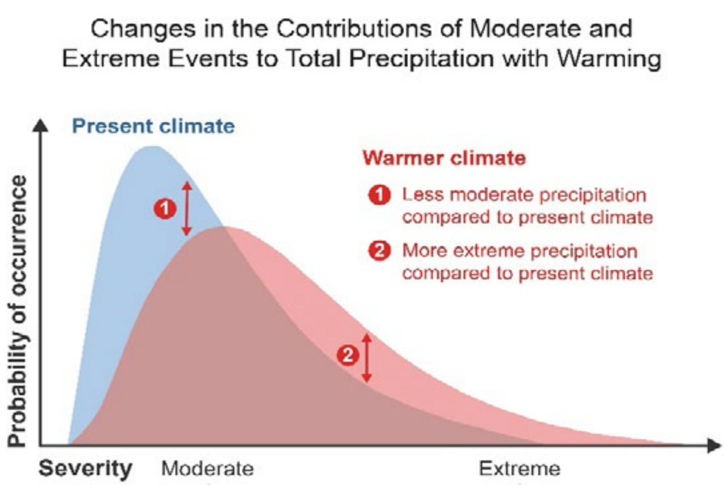


Figure 12. Example probability distribution illustrating changes to precipitation patterns under different climate conditions, from the 5th National Climate Assessment (NCA5, 2023).

WHAT IS A PROBABILITY DISTRIBUTION?

A probability distribution of observations describes how frequently an observation is likely to occur. The x-axis shows increasing values, and the y-axis describes the proportion of times that a value occurred in the dataset. In this example, in a present-day climate, moderate rainfall has a higher probability of occurrence. Warmer climates shift the distribution towards the right, or towards less moderate precipitation and more extreme rainfall events compared to the present climate.

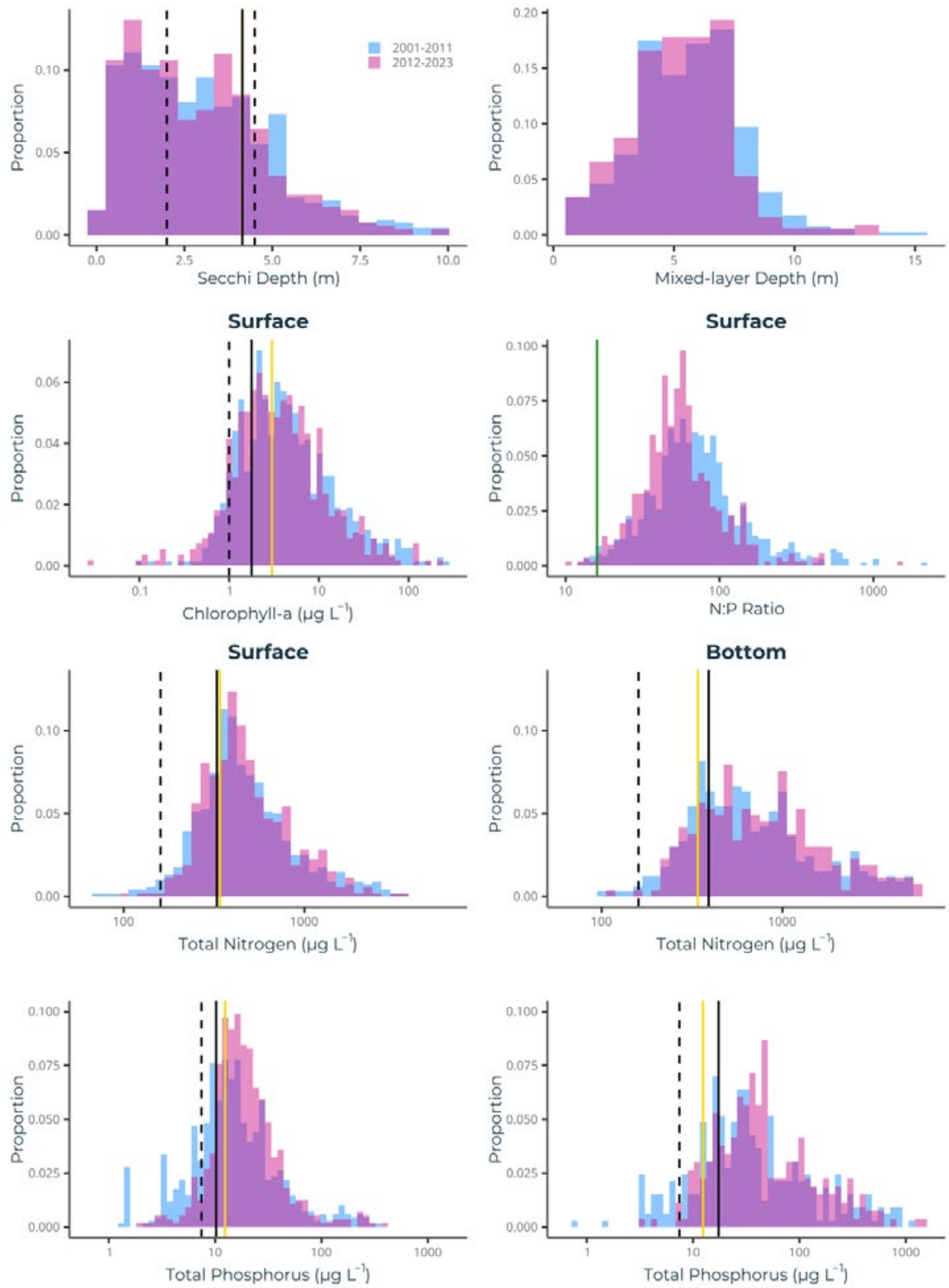


Figure Key: Blue bars illustrate the 2001-2011 data distribution, while pink bars illustrate the 2012-2023 data distribution. The overlap between the two distributions can be seen as a purple color. Dashed black vertical lines are the Cape Cod ecoregion Thresholds for "4 List" Cape Cod Ponds reported in the 2003 Pond Atlas (Secchi disk depth shows the values for both ecoregion 14 and sub-ecoregion 84), yellow vertical lines are the 25th percentile thresholds identified from the "4 List" ponds quantified from all data in the new dataset, and solid black vertical lines are the thresholds identified from the 75th percentile of entire new dataset (values are also reported in ***Table 1***). The green line on the N:P ratio plot shows 16:1.

Figure 13. Probability distributions of Secchi disk depth, mixed layer depth, surface chlorophyll a (Chla), surface total nitrogen to total phosphorus ratio (N:P) ratio, and surface and bottom total nitrogen (TN) and total phosphorus (TP). Chla, N:P, TN, and TP are shown with the x-axis on a log10 scale.

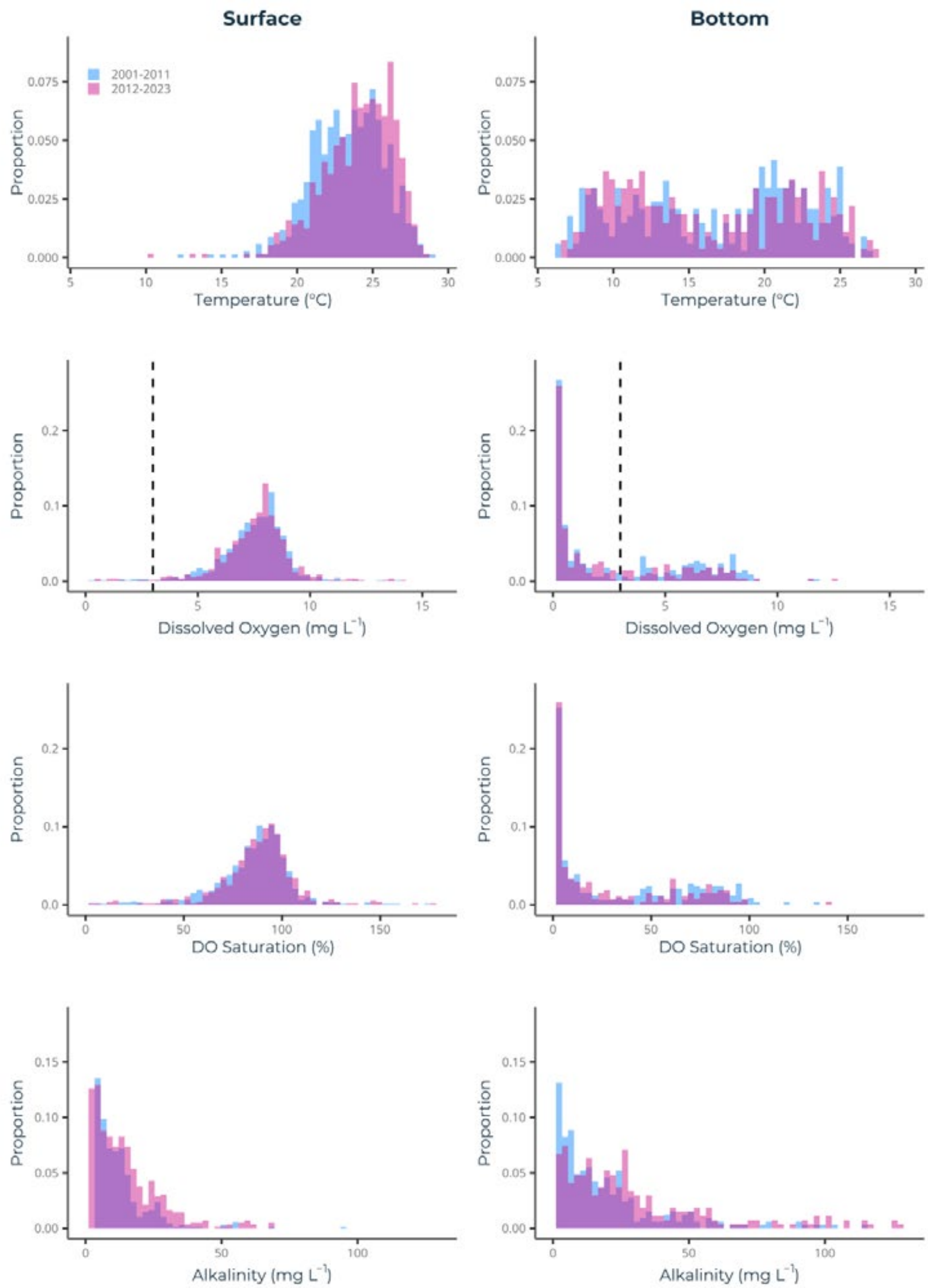


Figure Key: Blue bars illustrate the 2001-2011 data distribution, while pink bars illustrate the 2012-2023 data distribution. The overlap between the two distributions can be seen as a purple color. The vertical dashed black line shows the 3 mg/L hypoxia threshold for dissolved oxygen.

Figure 14. Probability distributions of surface and bottom temperature, dissolved oxygen concentration (DO), dissolved oxygen saturation (DO Saturation) and alkalinity.

	SURFACE		BOTTOM	
	Ks-stat	*p*	Ks-stat	*p*
Secchi	0.043	*0.657*	NA	*NA*
Chla	0.059	*0.228*	NA	*NA*
TN	0.058	*0.261*	**0.113**	***0.047***
TP	**0.216**	***<0.0001***	**0.158**	***0.001***
Temp	**0.149**	***<0.0001***	0.089	*0.186*
DO	0.053	*0.361*	**0.126**	***0.017***
DOsat	0.056	*0.282*	**0.13**	***0.013***
MLD	**0.103**	***0.048***	NA	*NA*
N:P	**0.214**	***<0.0001***	NA	*NA*

Table 2. Kolomogorov-Smirnov statistics and statistical significance for the two sample KS-tests evaluating whether the 2001-2011 and 2012-2023 data are from different distributions for surface and bottom samples. Parameters with $p < 0.05$ are shown in bold for visualization. Secchi results exclude CCRPM data collected in 2023.

Comparison of probability distributions between the first decade of the dataset and the second illustrates subtle shifts in the overall data structure for some parameters (***Figure 13*** and ***Figure 14***). No statistical difference was observed between the two time periods for Secchi disk depth, chlorophyll a, surface total nitrogen, surface dissolved oxygen, dissolved oxygen saturation, or bottom temperature (***Table 2***). In contrast, distributions of bottom total nitrogen, surface and bottom total phosphorus, surface temperature, bottom dissolved oxygen concentration and saturation, mixed layer depth, and N:P ratio were statistically different when comparing the 2001-2011 and 2012-2023 periods (***Table 2***).

Frequency distributions demonstrate not only differences in pond characteristics and hydrography but also provide clear examples of conditions illustrating a warming region along with worsening water quality. For example, surface temperature conditions clearly illustrate that warmer waters have become more frequent in the latter half of the dataset, with increasing frequency of temperatures above 25 degrees Celsius, and less frequent observations of cooler temperatures (***Figure 14***). Although the distribution of bottom temperatures did not change between the two decades, the data structure clearly illustrates a bimodal distribution (***Figure 14***). The two peaks observed show that some ponds are fully mixed in the summertime with warmer bottom temperatures that track surface temperatures, while other ponds are clearly stratified and maintain cooler temperatures in bottom waters despite warmer surface temperatures. The cooling of bottom waters in stratified ponds may be indicative that onset of stratification is occurring earlier in the year when the water column is cooler. Shallower mixed layers have also become more frequent (***Figure 13***), which is consistent with warming water temperatures and stronger stratification regimes. Although no differences in the distributions of surface oxygen concentration or saturation were noted (***Figure 14***), bottom waters did display statistically significant differences in data distributions (***Table 2***), reflected as a shift to the left towards lower frequencies of higher oxygen concentration and saturation. This was consistent with regional trends and declining water quality over time.

Nutrient concentrations displayed striking differences between decadal distributions, illustrating increasing frequency of higher TN and TP concentrations along with lower TN:TP ratios that agreed with the pond, lens, and Cape-wide trends (***Figure 13***, ***Table 1***). Although no changes in the decadal distributions of surface TN were observed, bottom TN and surface and bottom TP both displayed rightward shifts, indicating increasing concentrations, with very low to no observations at low concentrations in the 2012-2023 period (***Figure 13***). The maximum observed values did not change when comparing the two periods; rather, middle-to-high range concentrations became more common. This pattern, with consistent or small increases in surface TN concentration combined with strong increases in surface TP has led to a strong shift towards lower TN:TP ratios in the latter decade (***Figure 13***). Decadal shifts in TN:TP ratios combined with pond, lens, and regional trends in concentrations (***Table 1***) are suggestive of differences in the rates of nutrient loading over time between the two key nutrients. This pattern is likely caused by faster and more widespread increases in watershed phosphorus loads than nitrogen loads. That pond nitrogen levels are increasing in bottom waters, despite progress toward lower rates of atmospheric deposition discussed below, further implicates watershed loading as a primary nitrogen source to Cape Cod ponds.

Understanding the Influences of Federal Regulation, Climate Change, and Nutrients

This regional dataset can improve understanding of pond responses regionally to factors such as the Clean Air Act and nitrogen deposition, the effects of climate change, and nutrients in general.

Pond Response to The Clean Air Act

The Clean Air Act (CAA) was passed in 1970 and provided a framework for the EPA to regulate air quality nationally. Due to a lack of progress by many states in meeting the National Air Quality Standards set by the CAA, the act was further amended in 1990 to set more stringent regulatory thresholds for urban pollution, motor vehicle emissions, airborne toxics, and drivers of acid rain, among others. National air quality improvements have followed, and here on Cape Cod, declines in deposition of nitrate and total nitrogen have been documented through the National Atmospheric Deposition Program and led to reductions in atmospheric nitrogen loading to the marine environment (Lloret and Valiela 2016, Williamson et al. 2017, Valiela et al. 2023).

As shown in ***Figure 15***, local monitoring of rainfall chemistry has indicated that, in addition to reductions in nitrogen deposition, rainfall pH has increased by nearly one unit (which represents a ten-fold reduction in acidity), while sulfate (SO_4) concentration has decreased to approximately 25% of concentrations observed in the 1980s and 1990s.

Cape Cod's freshwater ponds have responded strongly to reductions in atmospheric deposition of chemicals that acidify rainfall and freshwater ecosystems. Significant increases in pond alkalinity, a measure of the pond's ability to buffer against changes in pH, were evident across the entire region. Statistically significant increases in alkalinity were observed in the surface waters at 50 ponds, and

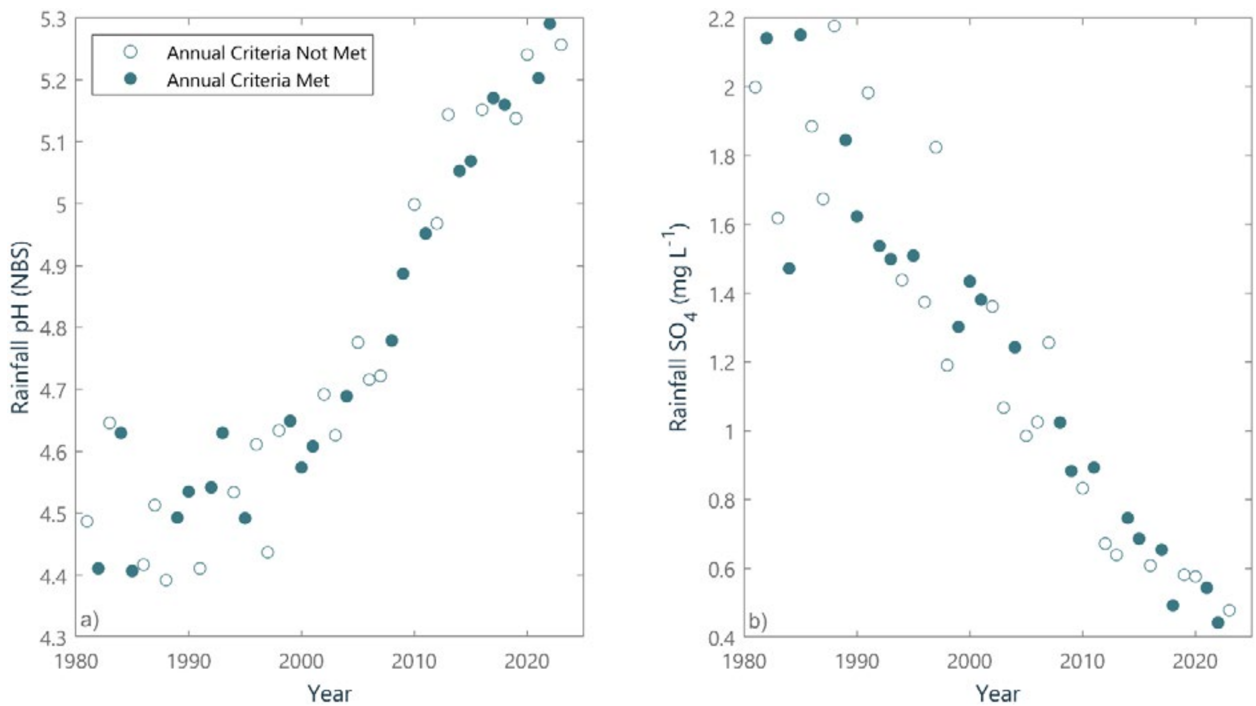


Figure 15. Annual average rainfall pH (a) and sulfate (b) concentrations as documented by the National Atmospheric Deposition Program from Station MA01, located near Provincetown, MA. When reporting annual averages, the NADP considers three criteria: 1) samples must be valid for 75% of the time period, 2) samples must be valid for 90% of the precipitation amount annually, and 3) precipitation data must have been collected for 75% of the time period. All annual average data are shown, but if annual criteria are not met, averages are shown as open circles.

in bottom waters at 19 ponds, while decreasing alkalinity was only observed in the bottom waters of one pond. Trends were more prominent at the groundwater lens and regional level, with the Monomoy, Nauset, and Sagamore lenses as well as Cape-wide showing strong increasing trends in both surface and bottom waters. Bottom water alkalinity has increased at rates more than 2-fold faster than surface waters, which is consistent with increasing primary productivity of the ponds. In the poorly buffered kettle ponds, microbial decomposition of organic matter at the sediment surface can release ammonium and bicarbonates of magnesium and iron. These compounds increase measured alkalinity which accumulates in the deeper waters of stratified ponds.

This Cape-wide increasing trend in alkalinity is a great success story highlighting how broader scale environmental management at national and regional levels can lead to significant water quality improvements at the local level.

The Impacts of Climate Change

Physical conditions in the Cape Cod regional setting have undergone large shifts over the past several decades, including changes in air (Smith et al. 2018a) and ocean water temperatures (Scully et al. 2022), wind speeds and direction (Scully et al. 2022, Smith et al. 2018a), and precipitation patterns (Smith and Medeiros 2019) (***Figure 16*** illustrates shifts in air temperature and wind speed). Recent studies have identified these factors as major drivers in shifts in both coastal and freshwater water quality indicators (Scully et al. 2022, Smith et al. 2018a) as changes can have impacts on circulation, stratification, overturning and mixing as well as influencing groundwater inputs and pond water levels (Smith and Medeiros 2019). A series of studies on temporal trends in freshwater ponds in the Cape Cod National Seashore has documented the impacts of climate change on a subset of Cape Cod freshwater ponds (Smith et al. 2016, 2017, 2018a, 2018b, Smith and Medeiros 2019). Here, that effort is expanded to document change in pond conditions more broadly across the region.

There have been broad changes in Cape Cod freshwater ponds that are consistent with other assessments of regional climate change. Sixteen out of 80 ponds consistently sampled for surface temperature had statistically significant increasing trends, while two had significant declining trends. The remaining 62 ponds had no statistical change in temperature, although many displayed weakly positive yet insignificant trends (***Figure 17***). Most ponds had no significant change in bottom temperature, with the exception of four ponds with decreasing trends and three ponds with increasing trends. However, when combining ponds together by region or across all of Cape Cod, weak or insignificant trends in surface temperature at individual ponds coalesce into strong, statistically significant trends for the Monomoy (0.08 degrees C/year) and Sagamore (0.122 degrees C/year) lenses and show summertime freshwater pond warming of 0.073 degrees C/year across all of Cape Cod (***Table 3***). Bottom temperature in deep ponds was more varied, and regional trend analysis revealed a weak but significant warming pattern in the Nauset lens, but no consistent patterns across other regions analyzed.

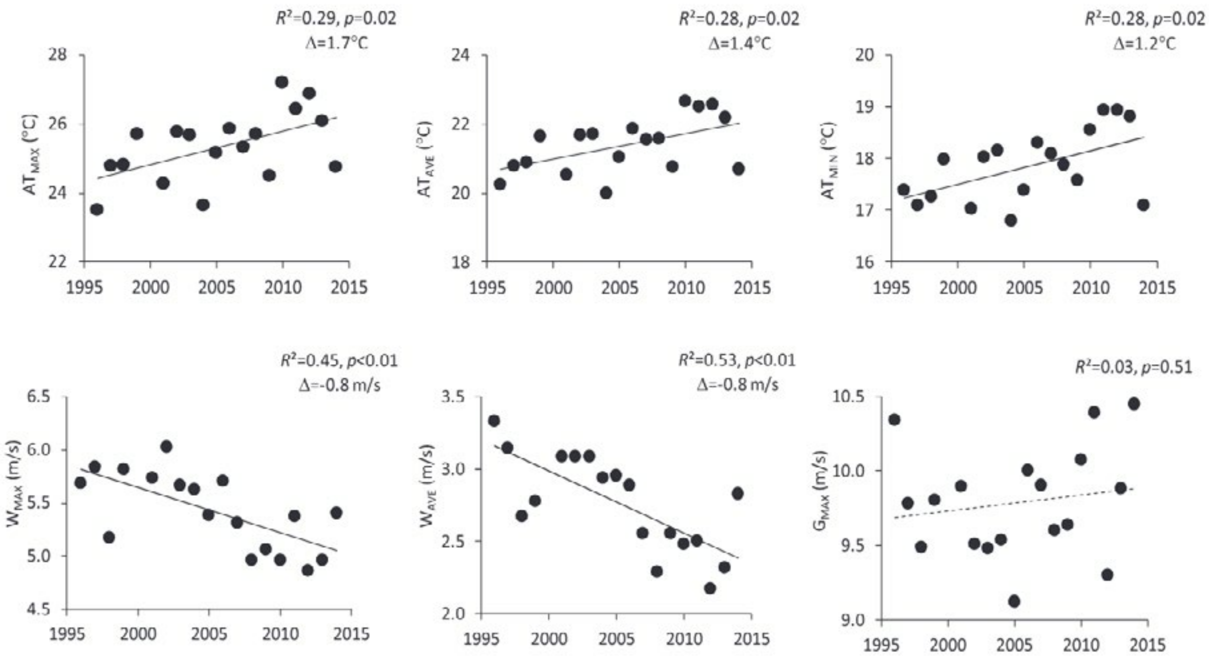


Figure 16. Trends in mean daily maximum (AT_{MAX}), average (AT_{AVE}), and minimum (AT_{MIN}) temperatures and mean daily maximum (W_{MAX}), average (W_{AVE}), and maximum gust (G_{MAX}) windspeeds during July-August from 1996 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are nonsignificant) (figure from Smith et al. 2018a).

Warming surface waters were also accompanied by changes to a few stratified ponds' mixed layer depth (MLD). Statistically significant decreasing trends in MLD were observed in five ponds (meaning that the mixed layer was becoming shallower over time) with increasing trends observed in two ponds. Weak but insignificant decreasing MLD trends were seen in 25 ponds and increasing trends in 11 ponds (***Figure 18***). When combining ponds together regionally, Monomoy, Sagamore, and all-Cape displayed significant regionally decreasing trends in MLD, while Nauset and Pamet lenses displayed no trend. This suggests that despite variability amongst ponds, regional metrics imply that depth of the surface mixed layer is becoming shallower across the region at a rate of –0.004 m/yr (***Table 3***).

HOW PONDS ARE RESPONDING TO CLIMATE CHANGE

Warming water temperatures directly affect the physical, chemical, and biological properties of ponds. In deeper ponds, the annual cycle of development and breakdown of thermal stratification can be extended by warmer spring and fall weather. As surface waters warm more quickly in the spring, density differences become stronger; stronger density differences then require more wind energy for complete mixing to occur. A consequence is colder water deep in the ponds and a prolonged period of isolation of the deep waters. This pattern was observed in several ponds at the Cape Cod National Seashore (Smith et al. 2018), and in several ponds in this dataset.

The extended period of isolation of the deeper waters affects the ponds' water chemistry. The annual cycle of oxygen depletion and internal phosphorus loading is prolonged as oxygen is used by the microbial community to decompose organic matter, which then can trigger release of phosphorus from the pond sediments.

Finally, the warming climate can affect the ponds biological community in multiple ways, many of them synergistic. An underlying factor is that warmer conditions increase the rate of biochemical reactions. This results in more rapid growth of aquatic biota, including cyanobacteria. The aquatic community composition can shift to favor organisms better adapted to thrive at higher water temperatures. Climate impacts are a factor in expanding the range of invasive species, both plants and animals. Loss of dissolved oxygen in deeper waters adversely impacts habitat for fish and macroinvertebrates.

The MLD divides a pond into thermally stratified layers referred to as the epilimnion, (the surface waters where the water mixes and dissolved oxygen is high), the metalimnion, (the transition zone), and the hypolimnion (the stagnant cooler bottom waters). When the hypolimnion is cut off from the rest of the pond by stratified layers, over time it can become low in oxygen as microorganisms decompose and consume the available dissolved oxygen. Low or no oxygen (anoxia) in the hypolimnion for extended periods of time is detrimental to a pond's ecosystem. In an anoxic environment, phosphorus that is bound to iron and manganese oxides in the sediment is released into the overlying water and becomes available for plant and algae growth, accelerating the eutrophication process.

Eighty ponds in total were sampled consistently enough over this timeframe to assess trends in surface water oxygen (***Figure 17***). The majority of these ponds did not display any trends in oxygen concentration. Six ponds showed statistically significant decreasing trends in oxygen concentration, while six showed increasing trends. Forty deep ponds were sampled consistently enough to evaluate temporal trends in bottom water dissolved oxygen. Across these ponds, eight had decreasing trends in oxygen concentration in bottom waters, while only one showed an increasing trend. Note that despite a relatively small number of declining trends in bottom water oxygen, many ponds are already experiencing severe hypoxia or even anoxia in bottom waters, particularly in deeper ponds that become stratified during the summertime.

Interestingly, when evaluating temporal trends in oxygen at broader spatial scales, no significant trends in surface oxygen concentration emerge at either the lens or Cape-wide scales (***Table 3***). Despite this, significant increases in oxygen saturation were observed in the Monomoy and Sagamore lenses, and Cape-wide. Oxygen saturation is calculated by comparing the observed oxygen concentration measurements to the oxygen saturation concentration at a given temperature and pressure. Because of the thermodynamics of dissolved gases, oxygen is less soluble with warming water temperatures, which means that as ponds warm, oxygen concentration would decrease naturally simply as a function of increasing water temperatures. Flat trends in oxygen concentration combined with increasing saturation and increasing surface temperatures suggest that natural declines in oxygen due to changes in oxygen solubility may be offset by other processes. Processes such as photosynthesis in surface waters and/or reduced gas exchange rates resulting from declines in regional wind speeds may be leading to relative increases in surface oxygen content. Confirming either of these theories, however, would require targeted projects at the pond scale.

In bottom waters, the opposite pattern is occurring for dissolved oxygen. Regionally, the Monomoy and Sagamore lenses and Cape-wide scales show strong decreases in both oxygen concentration and saturation. These trends are also not accompanied by strong temporal trends in bottom temperatures, suggesting that the declines observed may be due to increased consumption of oxygen via respiration occurring in the hypolimnion.

The deeper colder waters of ponds on Cape Cod provide habitat for cold-water fish. When deep waters remain isolated from the oxygen exchange that happens at the surface of a pond, the supply of oxygen can be depleted. Once the dissolved oxygen is depleted, the available fish habitat is minimized or lost. The warmer surface waters, while oxygen rich are not suitable for cold water fish, while the colder bottom waters lack sufficient oxygen for fish survival. The combination of MLD trending towards more shallow water and the extent of hypoxia/anoxia in bottom waters increasing, results in expanded volume or area of anoxic hypolimnion, creating a squeeze of available cold-water habitat for fish.

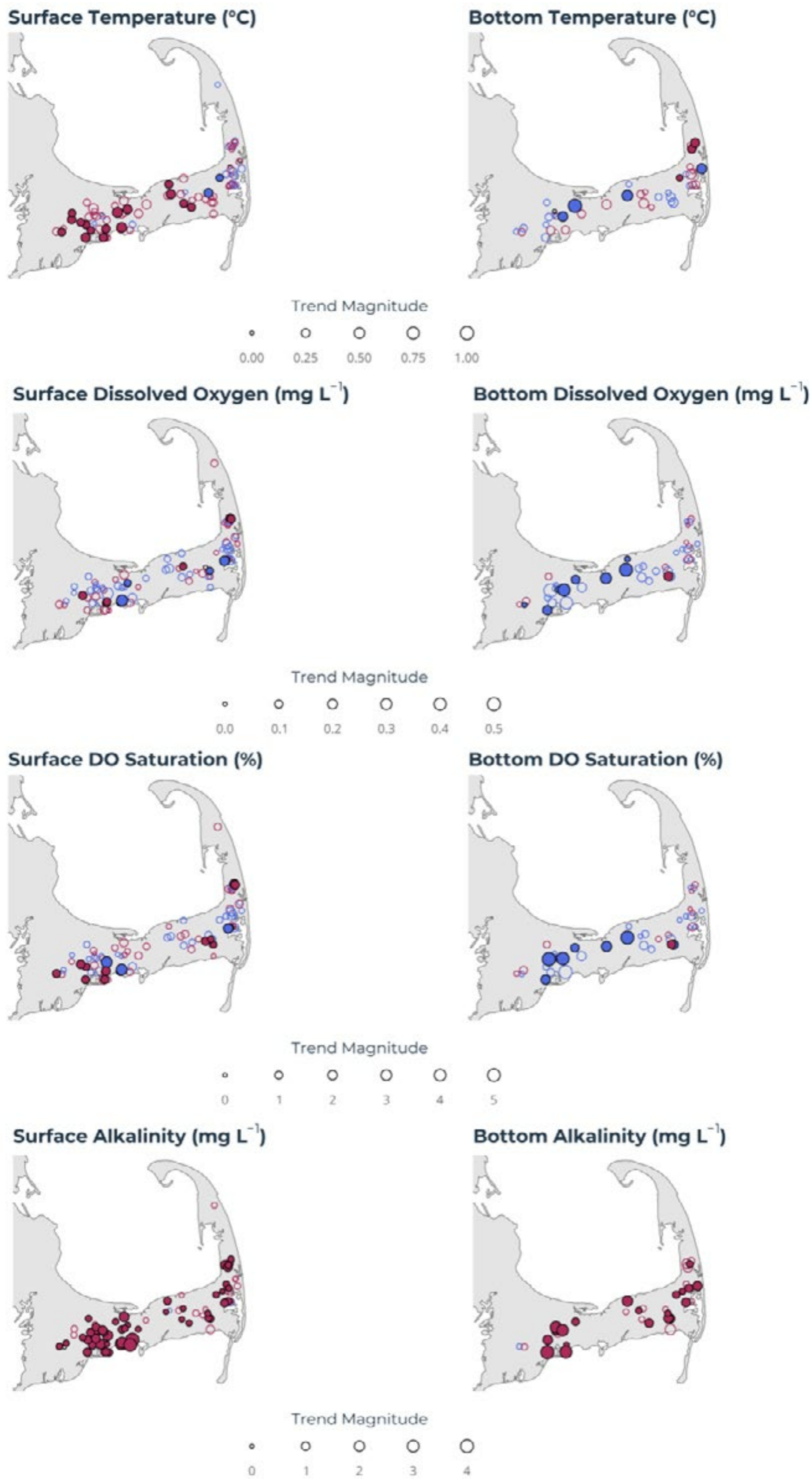


Figure 17. Maps illustrate the magnitude (change per year), direction, and significance of individual pond trends in temperature, dissolved oxygen concentration, dissolved oxygen saturation, and alkalinity for surface and bottom waters. Trends that were statistically significant at $p < 0.05$ are filled, while non-significant trends are open circles. Slopes > 0 (values increasing over time) are illustrated in red, while slopes < 0 (values decreasing over time) are illustrated in blue. The size of the circle reflects the magnitude of the trend, where larger circles reflect larger slope magnitude.

TRENDS IN WATER QUALITY INDICATORS BY GROUNDWATER LENS	Chequesset	Monomoy	Nauset	Pamet	Pilgrim	Sagamore	All-Cape
SURFACE							
Secchi (m/yr)	ND	-0.007	0	ND	ND	0.006	0
Temp (degC/yr)	ND	***0.08***	0	-0.012	ND	***0.122***	***0.073***
MLD (m/yr)	ND	*-0.014*	0	0.071	ND	***-0.008***	***-0.004***
DO (mg/L/yr)	ND	-0.005	-0.007	0.038	ND	0.001	-0.001
DO saturation (% sat/yr)	ND	*0.161*	-0.076	0.486	ND	***0.214***	**0.125**
Alkalinity	ND	***0.156***	***0.25***	0.093	ND	***0.4***	***0.292***
TN (µg/L/yr)	ND	***4.359***	0.673	2.881	ND	0.359	**1.396**
TP (µg/L/yr)	ND	***0.329***	***0.286***	-0.105	ND	***0.314***	***0.31***
Chla (µg/L/yr)	ND	*0.037*	-0.05	ND	ND	***-0.047***	***-0.029***
TN:TP ratio	ND	***-0.966***	**-0.615**	2.462	ND	***-1.074***	***-0.879***
BOTTOM							
Temp	ND	-0.024	*0.039*	ND	ND	-0.013	0.008
DO (mg/L/yr)	ND	**-0.019**	-0.003	ND	ND	***-0.019***	***-0.011***
DO saturation (% sat/yr)	ND	**-0.149**	-0.028	ND	ND	***-0.18***	***-0.098***
Alkalinity	ND	***0.422***	***0.579***	ND	ND	***1.102***	***0.621***
TN (µg/L/yr)	ND	***10.01***	6.33	ND	ND	3.698	***7.244***
TP (µg/L/yr)	ND	**0.42**	**0.864**	ND	ND	0.244	***0.435***

Table 3. Trends in water quality indicators by groundwater lens and Cape-wide, calculated with a Regional Mann-Kendall analysis illustrating change over the available data from 2001-2023. Slopes are shown for each parameter, and the level of statistical significance is indicated in the text, where $0.1 > p \geq 0.05$ is shown in italics, $0.05 > p \geq 0.01$ is shown in italics and underlined, and $p < 0.01$ is italicized and bolded.

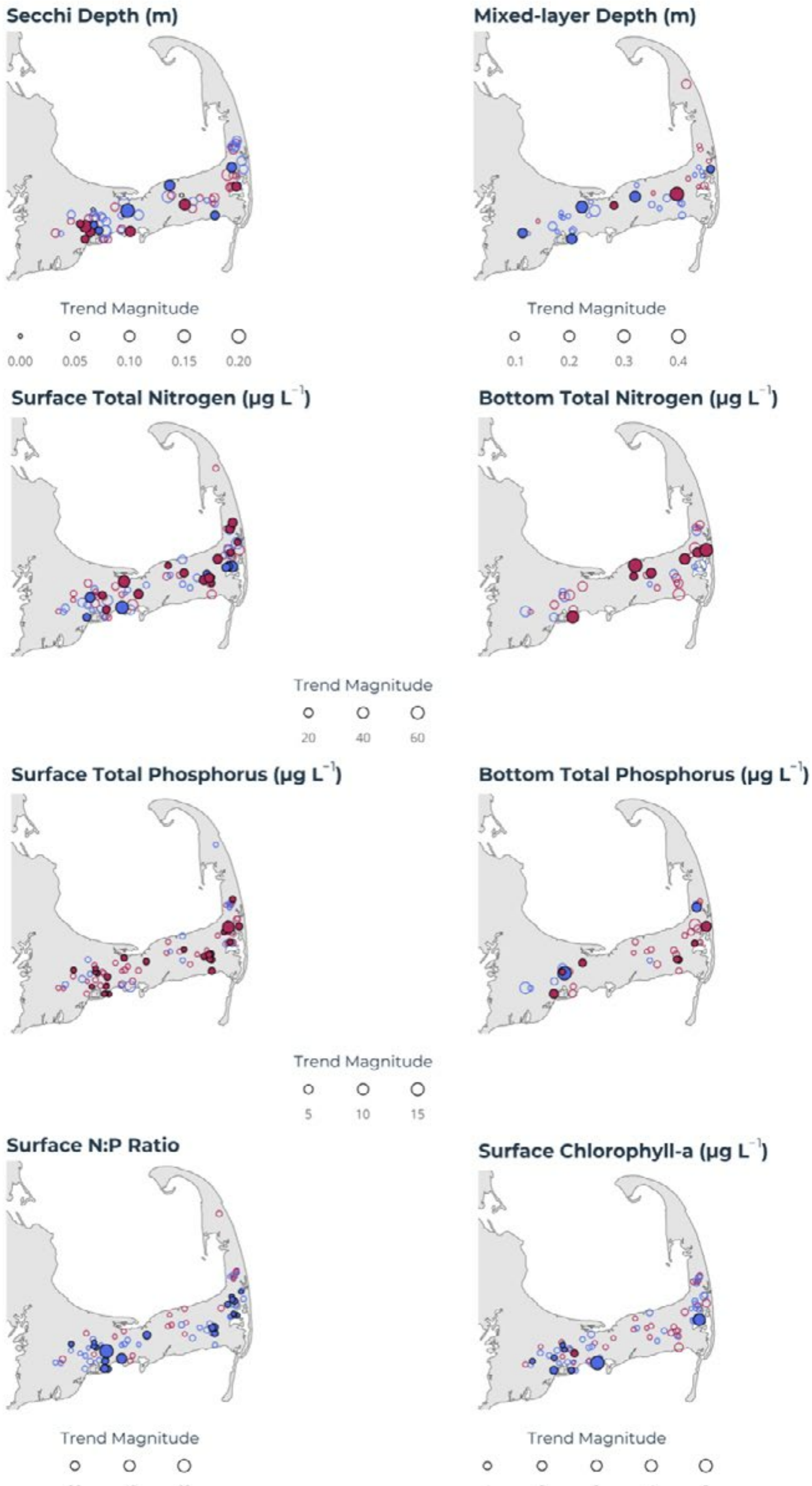
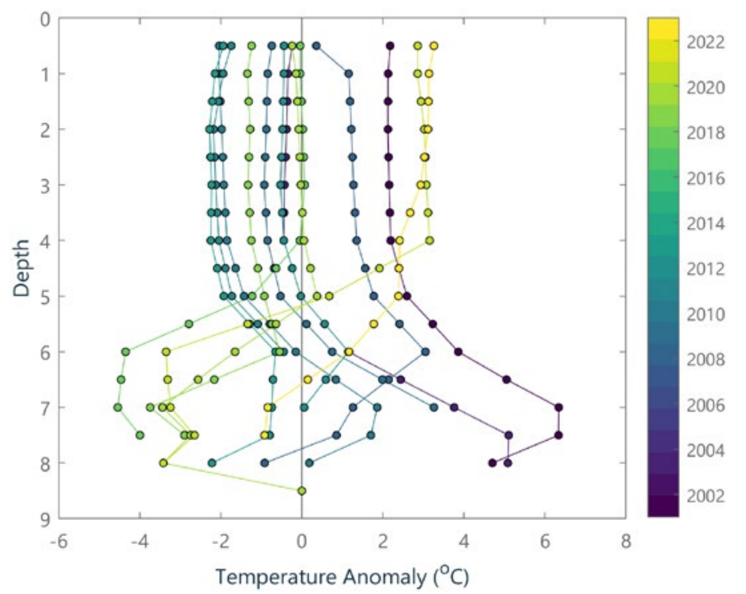


Figure 18. Maps illustrate the magnitude (change per year), direction, and significance of individual pond trends in Secchi disk depth, mixed layer depth, surface and bottom total nitrogen and total phosphorus, and surface N:P ratio and Chlorophyll a. Trends that were statistically significant at p < 0.05 are filled, while non-significant trends are open circles. Slopes > 0 (values increasing over time) are illustrated in red, while slopes < 0 (values decreasing over time) are illustrated in blue. The size of the circle reflects the magnitude of the trend, where larger circles reflect larger slope magnitude.

Case Study: Climate Induced Cooling of Pond Bottom Waters



Changing temperature anomaly profiles over time in Garretts Pond in Barnstable

Ponds across Cape Cod exhibit strong seasonal variation in temperature. The impact of the warming climate is evident in the significant trend toward increased surface water temperature. However, water temperature is decreasing in the deep waters of some ponds. This phenomenon has been documented in lakes and ponds in many regions across the globe and is attributed to a shift in the timing and duration of thermal stratification. This shift toward earlier development and later breakdown of thermal stratification has implications for both water quality and aquatic habitat.

Thermal stratification results from the interaction of turbulence and heat exchange between the water surface and the atmosphere. More rapid warming in the spring creates a stronger density gradient between the upper, sunlit layers and the deep cold waters below. In some deep ponds, the density gradient between the warming upper waters and the deeper colder waters is strong enough to withstand turbulent mixing by the winds. Other factors, such as fetch, surface area, and watershed foliage also affect a pond's annual temperature and mixing regime.

Garretts Pond in Barnstable is an example of a pond that exhibits a significant trend of decreasing temperature in the deep waters, at the same time the upper water temperatures are increasing.

The figure above shows "anomalies" of late summer thermal profiles of Garretts Pond collected between 2001 and 2023. "Anomalies" show the difference in any given year's profile from the mean profile for Garrett's Pond, so anomalies that are greater than zero indicate warmer than average conditions, and anomalies that are less than zero indicate cooler than average conditions. Profiles in this graphic are colored by the year the data were collected. The trend toward diminished heat transfer from the atmosphere to the deep waters indicates that stable thermal stratification is developing earlier in response to warmer spring conditions. Air temperatures in the fall are increasing as well, leading to longer duration of thermal stratification. A prolonged period of isolation of the deep waters has implications on habitat and water chemistry, particularly in the more productive ponds, where decomposition of organic material consumes dissolved oxygen. Oxygen depletion can trigger chemical changes in pond sediments that release soluble phosphorus to the overlying waters.

Nutrient Level Changes Across the Region

Despite well documented decreases in atmospheric nitrogen deposition associated with improvements in air quality, studies have shown that land-based sources of nutrients have increased in many coastal watersheds of Cape Cod (Valiela et al. 2016, Williamson et al. 2017, Lloret et al. 2022). In some cases, strong declines in atmospheric sources have been offset or even overtaken entirely by increases in watershed-derived nutrients, namely from increasing development using on-site wastewater disposal systems, that, while compliant with local public heath requirements, are not designed to remove nitrogen. Here, temporal trends in nutrients and correlations across ponds are assessed to determine whether similar behavior is occurring in freshwater pond systems. Subsequent ecosystem response variables were assessed at several different spatial scales, including single ponds, groupings of pond by aquifer lens, and across the entire Cape Cod region.

As previously indicated by changing ecoregion Threshold results over time and changes to decadal-scale distributions, nutrient concentrations in many Cape Cod ponds have changed over the past several decades. Surface and bottom Total Nitrogen (TN) has increased significantly in 15 ponds, while decreasing significantly in eight ponds. Bottom TN has increased significantly in seven ponds and has not decreased significantly in any ponds. Despite a mix of surface water TN trends which included decreases in some ponds, no ponds displayed significant decreasing trends in Total Phosphorus (TP) while 26 ponds had statistically significant increases in surface TP. Trends in bottom water TP differed from those in surface water, with seven ponds showing increasing trends while two displayed decreasing trends. At broader spatial scales, weak but consistent, insignificant trends coalesce into common patterns, particularly for TP. In surface waters, the Monomoy, Nauset, and Sagamore lenses showed strong increasing trends, which was also reflected in the Cape-wide data, while increasing trends were also observed for bottom waters in the Monomoy and Nauset lenses, and Cape-wide data. Patterns in TN were more mixed, with increasing trends observed in both surface and bottom waters for the Monomoy lens and Cape-wide, while the Nauset and Sagamore lenses showed no regional trends.

HOW PONDS ARE RESPONDING TO CHANGING NUTRIENT INPUTS

Freshwater ponds are traditionally thought of as limited by available phosphorus in driving primary productivity. Interestingly, despite widespread increases in TP in many ponds, lenses, and the Cape-wide region, a corresponding increase in chlorophyll a concentration was not observed. In fact, only one pond displayed a significant increasing trend in chlorophyll *a*, while eight ponds actually displayed decreasing trends and the majority of ponds evaluated displaying no significant change in chlorophyll *a*. When combining data from multiple ponds with regional Mann-Kendall analysis at the lens and Cape-wide scales, results suggest consistent increasing chlorophyll *a* trends in the Monomoy lens, while the Sagamore lens and the Cape-wide region show consistent decreasing trends in chlorophyll *a*. Trends in Secchi disk depth were similar in overall scope to chlorophyll *a*, where 7 ponds displayed increasing Secchi disk depths, indicating improving water clarity, 6 ponds displayed decreasing trends, and 55 ponds displayed no statistical trends. All ponds with statistically significant decreasing trends in Secchi disk depth had no trend in chlorophyll *a*, suggesting that declines in water clarity in these ponds may be due to factors other than increased phytoplankton abundance. No change in Secchi disk depth was observed at the lens or regional level, which was consistent with the ecoregion thresholds and decadal patterns. Future biological monitoring may help to discern how changes to primary producer composition, balance between algae and rooted aquatic vegetation, and other ecological changes may reflect responses to changing conditions while also contributing to observed changes in water clarity.

The observed patterns in nutrient concentrations suggest that, similar to Cape Cod's marine embayments, the well-documented declines in regional atmospheric nitrogen deposition may be offset by increasing loads originating within the watersheds. The increased population in Barnstable County and the associated human activities on land contribute to increased nutrient loading in groundwater[2]. Many inland ponds by virtue of their connection to the aquifer act as windows to local groundwater conditions. Growing numbers of residents and visitors on Cape Cod require more septic systems, increased septic system density, and continued development adjacent to freshwater ponds. Approximately 85% of Cape Cod's watershed populations (residences and businesses) have individual septic systems for disposal of human waste, and housing densities are a good indicator of septic-derived nutrient inputs to groundwater (Persky 1986, Valiela et al. 1992). Traditional Title 5 septic systems have relatively low removal efficiencies for nitrogen and phosphorus and, when combined with the highly permeable sandy soils of Cape Cod, result in the discharge of wastewater with high nutrient concentrations, which can move through the soil to reach groundwater.

Nitrogen and phosphorus in wastewater do not move through soils at the same rate; and so their transport to, and behavior within ponds can be very different. Dissolved forms of nitrogen do not effectively adsorb to soil particles, readily seeping into and traveling with groundwater. This means nitrogen can both enter and exit ponds through groundwater inflows and outflows. In contrast, dissolved phosphorus readily binds to iron and aluminum oxides and hydroxides present in soil. However, once these binding sites are full, phosphorus will travel through the soil and into groundwater and ponds. Once in a pond, phosphorus may be consumed by primary producers or bind to pond sediments, but mechanisms for phosphorus to physically leave ponds are limited.

Increased development also brings an increase in impervious surfaces that facilitate stormwater runoff, carrying nutrients and pollutants to ponds. Land clearing and other human impacts related to development remove vegetated cover around ponds, increasing erosion and sedimentation. In addition to sediment being an impairment to water quality on its own, it often has phosphorus,

2. Cape Cod Commission (2015) Cape Cod Area Wide Water Quality Management Plan Update

metals, or other pollutants bound to it. Sediment acts as a phosphorus sink, forming complexes with phosphorus (Li et al.); however, chemical changes under anoxic conditions can release phosphorus bound to sediment into the overlying waters.

Many towns are implementing plans to reduce nutrient inputs to groundwater. Until those solutions are in place, continued nutrient inputs from septic systems and the environment generally (e.g., runoff from pavement, treatment of lawns using pesticides or fertilizers) into ponds and their upstream watersheds will remain a threat to pond water quality. Even after solutions have been put in place to reduce or eliminate nutrient contributions from septic systems, historic nutrients added to the watershed from septic systems and other sources can remain in the soil, groundwater, or pond sediments for decades. Legacy phosphorus from these reservoirs can continue to be released and fuel primary production in ponds. The various sources and reservoirs of nutrients that can exist throughout a pond and its watershed emphasize the need for integrated solutions that can address nutrients at different scales and locations.

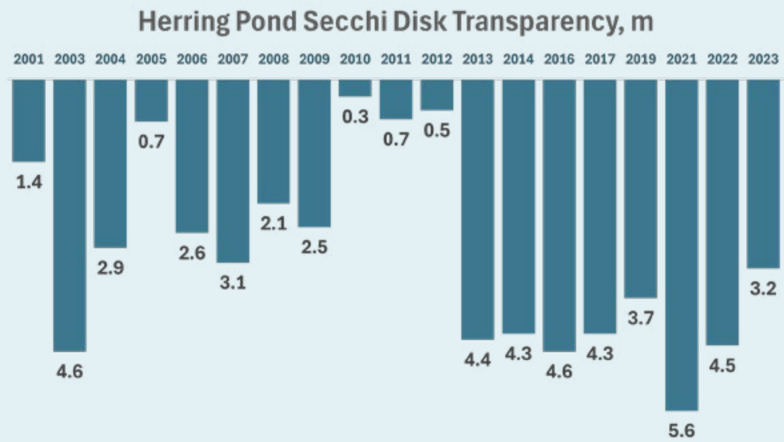
Case Study: Impacts of Nutrient Management Interventions on Water Quality (Herring Pond)

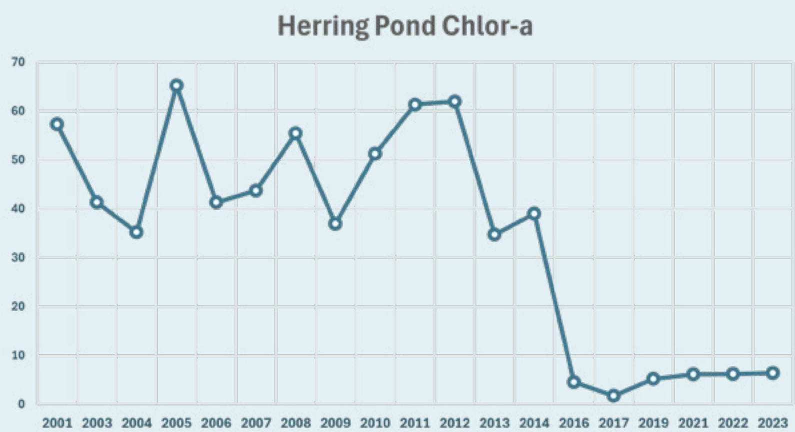
Even with concerted efforts to reduce external phosphorus loading, release of phosphorus stored in bottom sediments (internal loading) can cause elevated concentrations of phosphorus to persist. This is a particular challenge for the Cape Cod kettle ponds because most lack surface water outflows. Once phosphorus enters the pond system, it continues to cycle between the sediments, biota, and water column. In certain ponds, internal phosphorus loading reaches a level that threatens the ponds' desired uses. Several Cape Cod communities have implemented rehabilitation measures to reduce the magnitude of internal phosphorus loading. While these interventions are temporary, they may offer years of improved water quality conditions.

Herring Pond in Eastham is one example. In October 2012, Herring Pond underwent an alum treatment program. Certified applicators injected a mixture of aluminum sulfate and sodium aluminate below the water surface. The chemical mixture formed a floc that bound and precipitated phosphorus from the water column. As the floc settled onto the sediment surface, additional binding sites remained to prevent sediment phosphorus from reaching the overlying water column and affecting primary productivity.

Water clarity improved dramatically following the alum treatment, increasing from 0.5 m in summer 2012 to 4.5 m in summer 2013. The higher water clarity in the pond has persisted (see secchi disk transparency figure) as has the decrease in chlorophyll a (see chlor-a figure). As summarized in the table below, total phosphorus concentrations have decreased, most notably in the lower waters. The minimum DO concentration has increased in response to the reduced biomass of plankton decomposing each growing season.

Alum treatment is not a permanent solution. The Herring Pond treatment program was designed to provide an estimated 10 years of phosphorus binding capacity and allow time for the impact of watershed-related measures to be realized. Continued monitoring will inform the community regarding the need for and timing of a repeat alum treatment.





Herring Pond Late Summer Water Quality Measurements

PARAMETER	2007-2012	2013-2018	2019-2023
Upper waters Total P (µg/L)	33.6	19.5	14.3
Lower Waters Total P (µg/L)	80	25	56
Lower Waters Dissolved Oxygen (mg/L)	0.4	0.5	4.4

A NOTE ABOUT TRENDS: We use the term "trend" throughout this document, generally to indicate how a variable is changing over time. Each trend analysis looks at a specific time frame and group of water bodies, and may consequently have different results. Trends were calculated at spatial scales ranging from a single pond, to a geographic subregion (aquifer lenses), to the entire Cape Cod Region, looking both at annual changes (regional Mann-Kendall) as well as decadal shifts (regional histograms).

While nutrients garner much of the focus of pond planning effort, there are other drivers that contribute to changes in pond water quality, including physical characteristics of ponds, their watersheds, and the land use within a watershed. Using GIS and available data, relationships between water quality and pond physical attributes, as well as watershed properties, were analyzed. Potential indicators or drivers of change were identified, including watershed size and level of development, as well as characteristics that affect how a pond responds to inputs (area, depth, volume, residence time).

Many of these activities result in additional nutrient contribution and can also impact a pond's ability to cope with excess nutrients. In an earlier study conducted by the Commission the amount and type of land use was compared to pond water quality. It was expected that in highly developed watersheds, contaminants from upgradient land uses can readily make their way to ponds. Similarly, the density of septic systems within a pond's buffer was expected to be correlated with pond water quality. Septic density within 100-, 300-, and 500- foot buffer areas to ponds ultimately did not correlate with total phosphorus, dissolved oxygen, or trophic status index levels. Further, no clear or direct connections between any single pond stressor and pond water quality were observed, further confirming that the unique limnological makeup, physical attributes, and watershed characteristics of ponds on Cape Cod result in a unique set of factors contributing to changes in individual pond water quality.

One-to-one correlations between water quality and drivers of change can be difficult to discern because multiple drivers often co-depend on, influence, or even counter one another. As an example, ***Figure 19*** shows how cyanobacteria and microcystin abundance in lakes across the United States is influenced by complex relationships between numerous water column, landscape, climate, and lake characteristics.

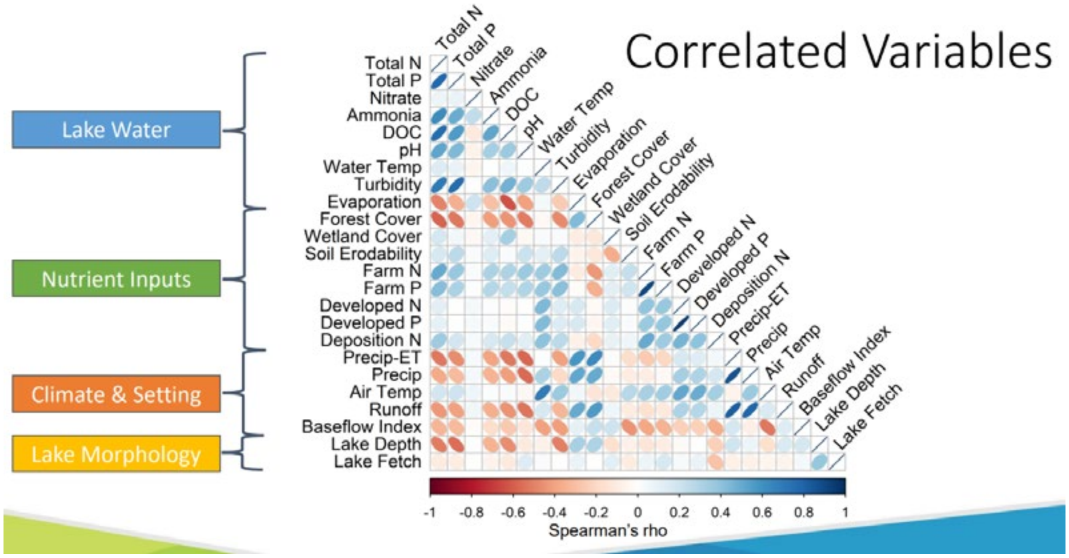


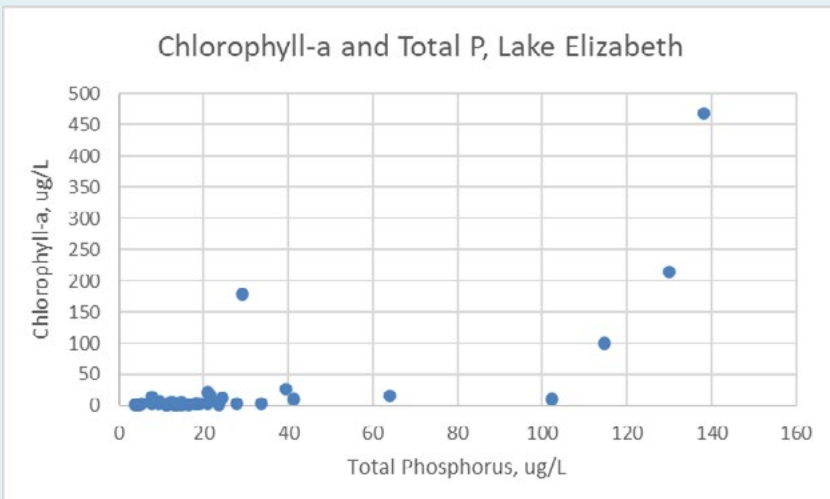
Figure 19. Correlation between lake, watershed, and climate characteristics and cyanobacteria/ microcystin distributions in the Continental United States. From Handler et al (2024)

Pond characteristic data are also useful to evaluate whether ponds with similar properties behave in similar ways. Pond depth (i.e., whether a pond is shallow or deep) is a key characteristic that distinguishes the response to nutrient enrichment in two important ways: light penetration and thermal stratification. Shallow ponds have a greater area of littoral habitat (defined as where light reaches the sediment surface) and provide more extensive habitat for rooted aquatic plants and algae (macrophytes). The macrophyte community competes with phytoplankton suspended in the upper waters for available phosphorus. Increases in overall primary productivity of ponds that are driven by the macrophyte community may not be associated with increased phytoplankton abundance. Consequently, in some shallow ponds, increasing TP does not exhibit a corresponding increase in chlorophyll a.

The second factor distinguishing response of deep and shallow ponds to nutrient enrichment is whether a pond develops stable thermal stratification. Isolation of deep water affects internal phosphorus cycling (see oxygen trend description, above, for additional discussion). Continued flux of legacy phosphorus, which may have entered the ponds over decades, from the sediment to the water column can promote phytoplankton growth as measured by chlorophyll a.

Case Study: Ecosystem Influences on Water Quality Measurements (Lake Elizabeth)

Ecosystem factors, particularly the abundance of rooted aquatic plants, can affect the relationship between phosphorus, chlorophyll, and water clarity. Lake Elizabeth, a small shallow pond in Barnstable connected to Red Lily Pond, is an example of a pond where rooted aquatic plants (macrophytes), not phytoplankton, dominate.



Property-property plot showing how chlorophyll a concentrations change with varying total phosphorus concentrations in Lake Elizabeth.

In 2021, scientists from UMASS Dartmouth's School for Marine Science and Technology (SMAST) noted that the pond exhibited lower chlorophyll concentrations than expected, given the elevated total phosphorus concentrations. The likely causes were cited as complex interactions between the watershed, pond sediments, flow from Red Lily Pond, and the macrophyte community. As displayed in the figure at right, which plots database measurements from 2001 – 2024, the wide variation in total P in the open waters does not translate to an increase in phytoplankton (indicated by chlorophyll a) until concentrations are very high (> 100 ug/L).

Despite the clear connection between human derived sources of nutrients and declining water quality in marine systems, Cape Cod's freshwater ponds are much more variable, and correlations are less clear between these expected drivers of change and resulting water quality. For example, pond watershed development, while often considered an indicator of whether a pond may have more risk of eutrophication sourced from the nearby landscape, was not clearly correlated with nutrient concentrations. In shallow ponds, ponds with increasing levels of development did display some increases in TN. However, this pattern was not uniform, and ponds falling within 50-75% of the distribution of watershed development actually displayed significantly lower mean TN than those within 25-50% of the development distribution. Neither TP nor chlorophyll a displayed a significant difference in surface concentrations across all levels of watershed development. Indeed, some ponds with very low levels of watershed development had some of the highest nutrient concentrations in the dataset.

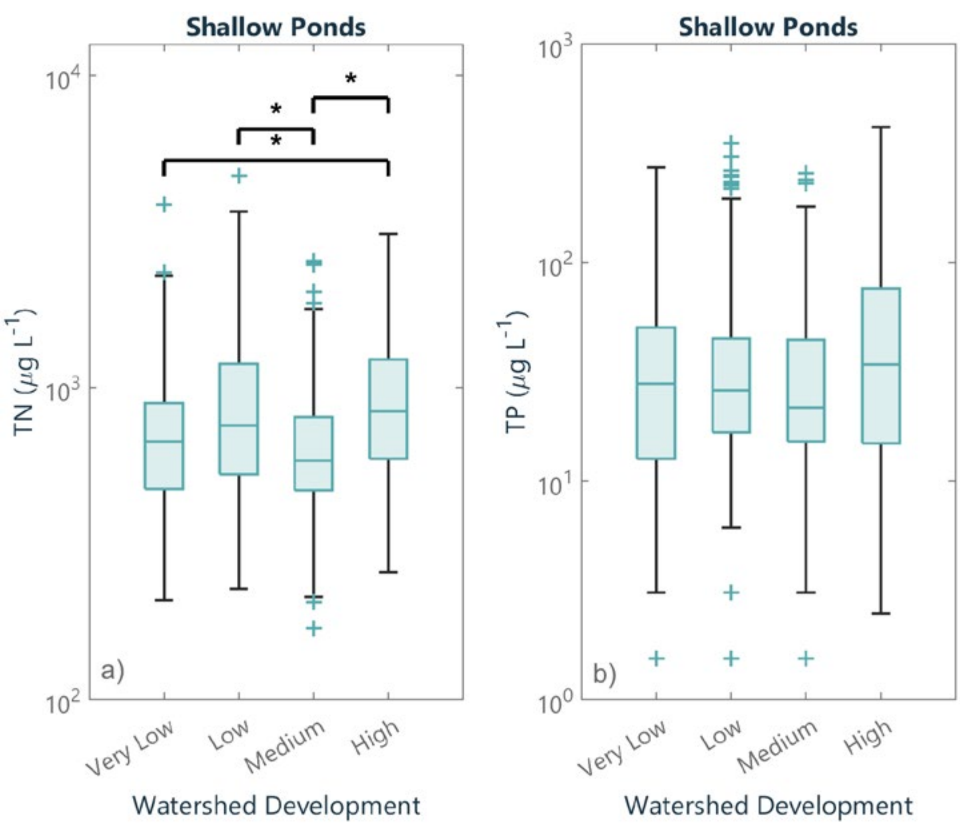


Figure 20. Boxplot distributions of TN (left) and TP (right) from ponds classified as "Shallow" (depth < 3m). Means of groups were tested using a non-parametric Kruskal-Wallis test and compared with pairwise post-hoc multiple comparison tests. Bars with asterisks above show pairs of groups with significantly different means.

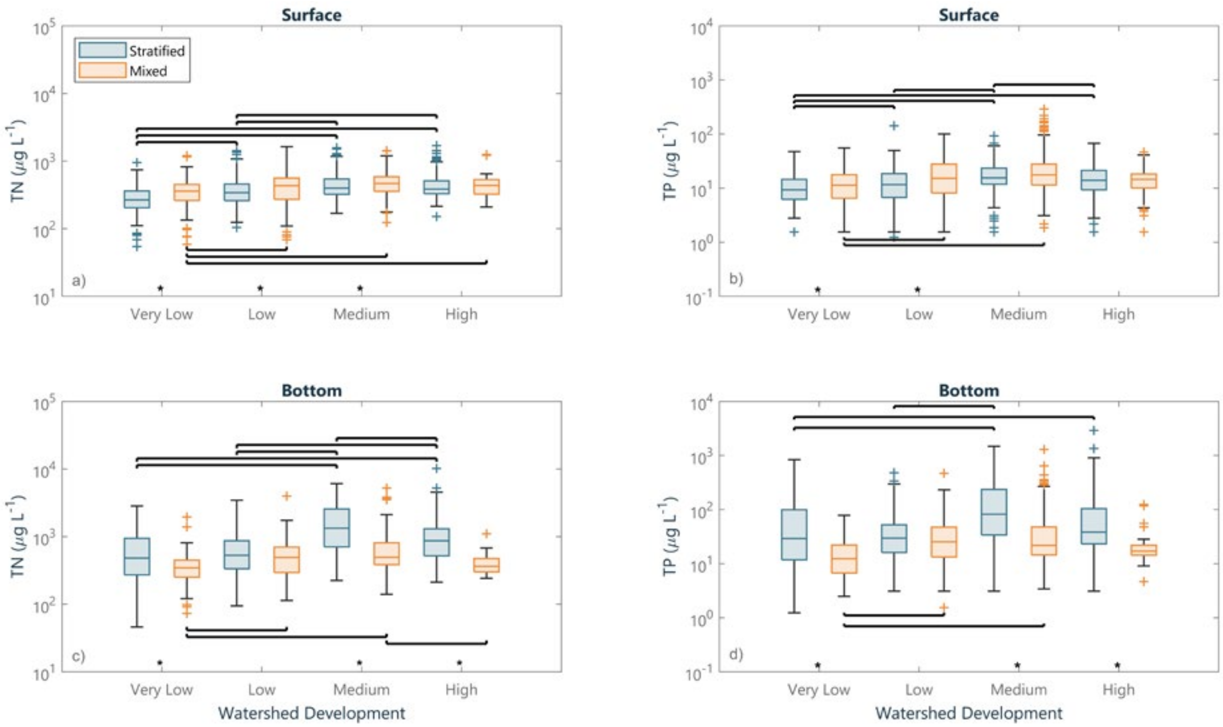


Figure 21. Distribution of annual mean August/September total nitrogen (TN) and total phosphorus (TP) in surface (top) and bottom (bottom) waters for deep ponds (depth > 3m) for four categories of development within the 300-foot buffer of a pond's watershed. Colors separate mixed (orange) vs. stratified (blue) ponds. Asterisks indicate statistically significant differences between mixed and stratified ponds at a given development level, and bars show pairs of distributions with significant differences in means.

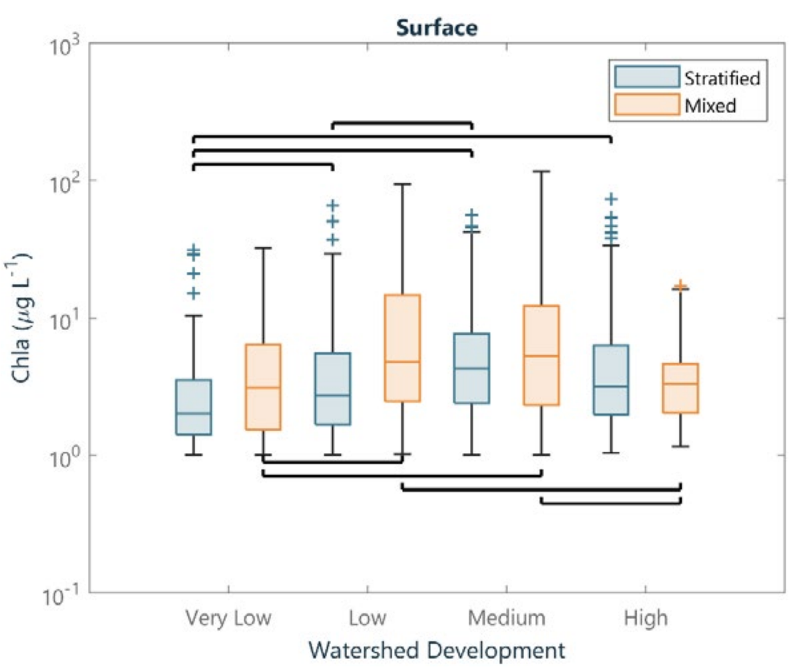


Figure 22. Distribution of annual mean August/September chlorophyll a in surface waters for deep ponds (depth > 3m) for four categories of development within the 300-foot buffer of a pond's watershed. Colors separate mixed vs. stratified ponds. Asterisks indicate statistically significant differences between mixed and stratified ponds at a given development level, and bars show pairs of distributions with significant differences in means.

Water quality patterns for increasing levels of watershed development were more consistent with expectations for ponds categorized as deep, defined as ponds with depths greater than three meters. Pond surface TN, TP, and chlorophyll a had very similar characteristics - distributions of all three parameters tended to increase with increasing levels of watershed development for both surface (TN, TP, Chla) and bottom waters (TN and TP). Across most levels of watershed development, in comparison to ponds that were well mixed, stratified ponds tended to have lower surface TN, TP, and chlorophyll a, but higher bottom TN and TP. This pattern may be driven by the fact that as respiration and anoxic microbial processes occur in waters trapped below the mixed layer, nutrients generated as byproducts can build up in bottom waters, while surface waters may become depleted.

When evaluating measurements collected across all ponds, there were correlations between many of the water quality parameters as shown in ***Figure 23***. Combined with a high degree of variability in measurements, parameters that covary can complicate interpretation and understanding of ecosystem drivers and response variables. For example, negative correlations were observed between Secchi disk depth and total alkalinity for both mixed and stratified ponds. Although these observations are correlated, they may not be a significant driver-response relationship. Water clarity and alkalinity may be changing in opposite directions over time due to other external factors. Despite this, some relationships can be informative.

For example, in both surface (for stratified ponds) and bottom (for both mixed and stratified ponds) waters, TN and TP were positively correlated (***Figure 23*** and ***Figure 24***), i.e. ponds with high TN also tend to have high TP, suggesting that increased loading of both nutrients is likely occurring simultaneously in watersheds. Across all ponds, TN and TP varied by nearly three and four orders of magnitude, respectively, and few ponds displayed surface measurements of TN:TP ratios less than 16, indicating that nitrogen limitation is not likely occurring in most places.

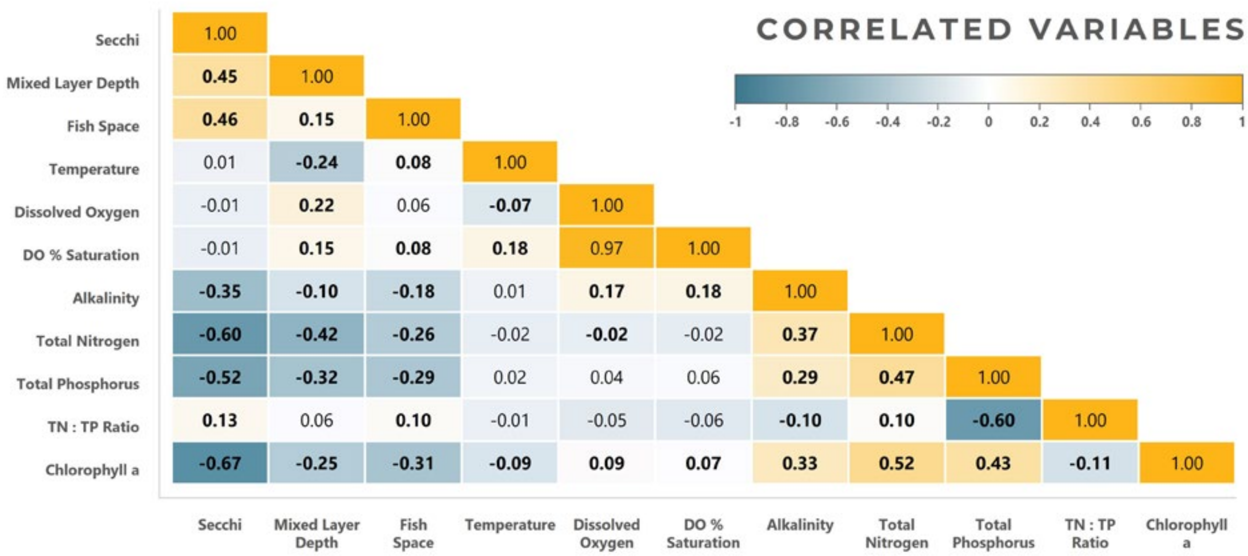


Figure 23. Correlations (color, numbers) across all water quality parameters evaluated and their statistical significance ($p < 0.05$ is shown in bold).

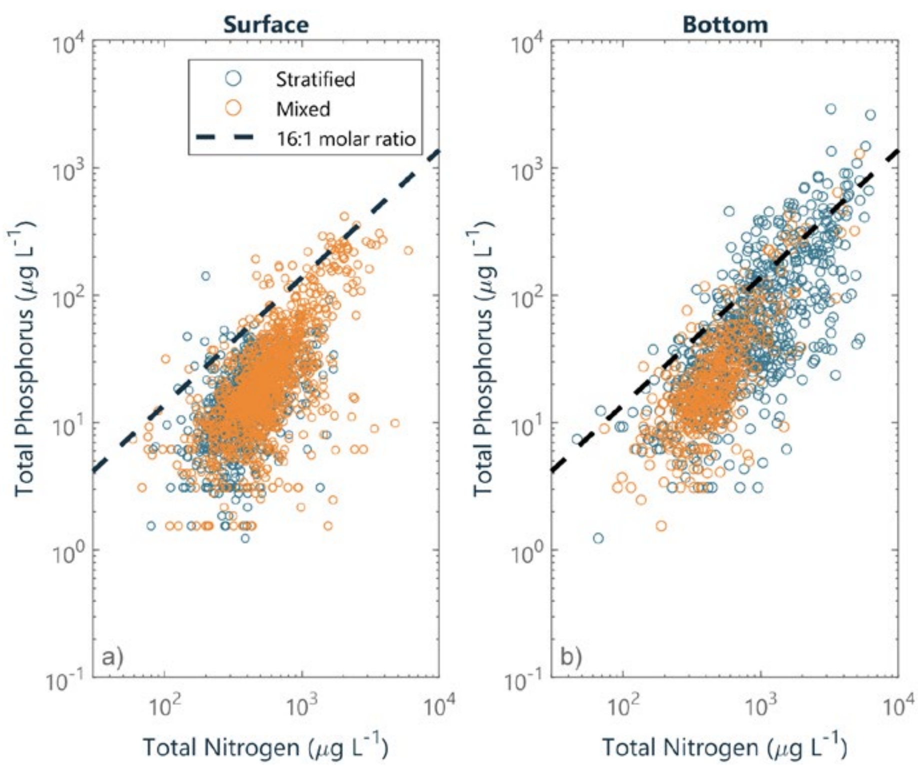


Figure 24. Total Nitrogen (TN) vs. Total Phosphorus (TP) for surface and bottom waters. Points are colored based on whether a pond was classified as mixed (orange) or stratified (blue). The 16:1 N:P molar ratio is shown as a dashed black line.

Chlorophyll a was also positively correlated with both TN and TP, suggesting that ponds with high surface nutrient concentrations also tended to have high chlorophyll a. Secchi disk depth was anticorrelated with water quality indicators of increased eutrophication, namely TN, TP, and chlorophyll a, which was true for ponds demonstrating a fully mixed water column or summer stratification. This is consistent with expectations of pond ecosystem response to increased eutrophication, where water clarity decreases as ponds become increasingly eutrophic and more phytoplankton and particulate matter lead to increased water column light attenuation.

Despite some correlations that are in agreement with expectations, further exploration of relationships amongst all the available water quality data and pond characteristic information did not lead to additional conclusions. For example, weak relationships with significant scatter were observed between climate drivers and ecosystem response variables (e.g. temperature, mixed layer depth, vs. chlorophyll a) and evaluating relationships by lens, pond size, or nutrient limitation did not yield additional clear patterns. This speaks to the complexity of Cape Cod's freshwater ponds and the significant limitations to even this long-term, relatively large dataset.

Summary And Future Data Recommendations

The Freshwater Initiative assembled a regional dataset from existing monitoring data, which facilitated an examination of regional pond chemistry and water quality, including how both have changed over the last twenty years, that was previously not possible. This analysis has reiterated that, despite many similarities in how they were formed and their placement within the landscape, Cape Cod's ponds are complicated individual water bodies that respond differently to environmental inputs and are evolving in distinct ways. While the impact of the Clean Air Act on ponds was relatively uniform throughout the region, ponds have responded to climate change and increasing air temperatures in different ways depending on their depth and other physical characteristics. Across the region, warmer water temperatures have been accompanied by increasing nutrient levels, and yet expected responses by algal and plant communities, such as increased chlorophyll a concentrations or decreased water clarity, were not clearly observed in a uniform manner throughout the current data set.

It is again worth noting that none of this analysis would have been possible without the ongoing pond monitoring conducted by the PALS program in conjunction with municipal staff and volunteer groups over multiple decades. Some of the limitations of the historical data have already helped to guide decisions on more recent monitoring to include additional sampling events ranging from a second spring baseline sampling to monthly samples throughout the spring, summer, and fall seasons. By expanding the monitoring season beyond the end-of-summer snapshot, it is possible to better understand how and when pond water temperatures are increasing (i.e. whether they stay warmer during winter, or simply warm faster in spring and summer); whether ponds stratify and for how long; and to gain insight into the relative contribution of internal phosphorus loads to individual ponds and how spring phosphorus loads can serve to predict summer algal growth potential.

Examining pond water quality data at the regional level has also highlighted how one-to-one correlations between water quality variables can be difficult to discern because multiple variables often co-depend on one another. This analysis is further complicated because the majority of the monitoring thus far has focused on water chemistry, which both influences and is influenced by the biological activity within a pond. By incorporating biological samples into future monitoring efforts, it may be possible to start unpacking how ecological change is unfolding in response to large scale drivers like climate change, localized drivers like development or pond management actions, and how those biological changes may better explain patterns observed in water chemistry variables.

New approaches to monitoring can help to address other data gaps identified through the regional data analysis. While variation in the consistency of ponds monitored from year to year complicated the time series analyses, current work using satellite imagery to estimate a limited set of water quality parameters will provide estimates for all ponds above a minimum size threshold every one to two weeks, using the same instrumentation and methods across the region. Establishing a small subset of ponds that receive enhanced monitoring, similar to Sentinel Lake programs in other states and regions, can add additional types of information (e.g. biological, meteorological, hydrographic) and/or higher frequency measurements with the goal of addressing data or knowledge gaps at a reasonable cost.

While outside the scope of this analysis, this same regional data set can be used to examine water quality trends and relationships for individual ponds via the Cape Cod Water Quality Portal (waterquality.capecodcommission.org). This resource also includes monitoring data from additional programs, and is updated with new data as it becomes available. Continuing to collect and display data through the portal will ensure that data access is no longer a barrier to planning and making efficient use of the resources dedicated to freshwater.

This analysis, and the larger Freshwater Initiative, are both meant to serve as starting points from which many future efforts can be launched. With a regional baseline for many of the freshwater initiative tasks, individual efforts and analyses can be re-evaluated as appropriate to gauge progress or take advantage of new information and technological advancements. Ongoing collaboration by multiple partner groups and agencies will build upon the resources created through the Freshwater Initiative to further improve our baseline understanding of Cape Cod’s ponds, to identify where management actions are needed, and to capture the effectiveness of those actions. As the nature of Cape Cod’s ponds and the data we use to understand them evolves, so too will our tools and approaches.

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Appendix A: Summary of Available Data and Trend Analysis by Pond

The analysis dataset includes all data available at time of publication from PALS and CCRPM 2001-2023

POND NAME (GIS ID)	Years of Data[1]	Last Year of Data[2]	Surface Trend Parameters[3]	Bottom Trend Parameters[4]
BARNSTABLE				
Aunt Bettys Pond (BA-756-01)	11	2022	3	0
Bearse Pond (BA-617-01)	13	2022	0	3
Bog Pond (BA-802-01)	16	2022	3	0
Coleman Pond (BA-819-01)	1	2001	0	0
Crystal Lake (BA-878-01)	14	2022	5	0
Dunns Pond (BA-723-01)	4	2022	0	0
Eagle Pond (BA-815-01)	14	2022	8	3
Fawcetts Pond (BA-748-01)	3	2022	0	0
Filends Pond (BA-750-01)	2	2022	0	0
Garretts Pond (BA-510-01)	11	2023	3	0
Hamblin Pond (BA-668-01)	17	2022	4	0
Hathaway Pond (North) (BA-565-01)	10	2023	10	0
Hathaway Pond (South) (BA-594-01)	2	2022	0	0
Hinckley Pond (BA-411-01)	12	2022	0	0
Joshua Pond (BA-807-01)	14	2022	3	3
Lake Elizabeth (BA-795-01)	11	2023	5	0
Lewis Pond (BA-881-01)	14	2022	7	3
Little Pond (BA-564-01)	13	2022	3	0
Long Pond (BA-675-01)	8	2022	0	0
Long Pond (BA-737-01)	4	2023	0	0
Lovells Pond (BA-759-01)	14	2023	4	2
Lumbert Pond (BA-719-01)	11	2022	7	0
Mary Dunn Pond (BA-646-01)	11	2022	8	0
Micah Pond (BA-797-01)	14	2023	2	0
Middle Pond (BA-640-01)	17	2022	8	3
Mill Pond (BA-391-01)	2	2022	0	0
Mill Pond (BA-746-01)	16	2022	3	0
Muddy Pond (BA-694-01)	12	2022	3	3
Mystic Lake (BA-584-01)	17	2022	10	3
Neck Pond (BA-874-01)	14	2022	5	0
No Bottom Pond (BA-523-01)	2	2022	0	0
Parker Pond (BA-875-01)	14	2023	5	0
Red Lily Pond (BA-782-01)	11	2022	5	0
Round Pond (BA-691-01)	13	2022	7	3
Rushy Marsh Pond (BA-914-01)	7	2015	0	0
Schoolhouse Pond (BA-806-01)	11	2022	7	0
Shallow Pond (BA-626-01)	11	2022	7	0
Shubael Pond (BA-664-01)	12	2022	8	2
Wequaquet Lake - Gooseberry Island (BA-605-04)	5	2022	0	0

1. Total number of years sampled (may not be consecutive). 2. Most recent year of data available in the regional database. 3/4. The different trend parameters indicate the total number of parameters where trends were able to be calculated for surface waters and for bottom waters.

POND NAME (GIS ID)	Years of Data[1]	Last Year of Data[2]	Surface Trend Parameters[3]	Bottom Trend Parameters[4]
Wequaquet Lake - Middle Basin (BA-605-02)	2	2022	0	0
Wequaquet Lake - North Basin (BA-605-01)	9	2022	0	0
Wequaquet Lake - South Basin (BA-605-03)	2	2022	0	0
BOURNE				
Fish and Game Pond (South) (BO-578-01)	1	2001	0	0
Flax Pond (BO-556-01)	5	2023	0	0
Lily Pond (BO-538-01)	4	2008	0	0
Queen Sewell Pond (BO-212-01)	1	2023	0	0
Red Brook Pond (BO-644-01)	6	2023	0	0
Shop Pond (BO-511-01)	3	2007	0	0
BREWSTER				
Black Pond (BR-316-01)	12	2016	0	0
Blueberry Pond (BR-180-01)	14	2016	0	0
Cahoon Pond (BR-299-01)	13	2016	0	0
Canoe Pond (BR-269-01)	14	2016	0	0
Cliff Pond (BR-1028-01)	14	2023	8	0
Cobbs Pond (BR-179-01)	14	2016	0	0
Eel Pond (BR-202-01)	6	2009	0	0
Elbow Pond (BR-357-01)	13	2016	0	0
Flax Pond (BR-168-01)	14	2016	0	0
Greenland Pond (BR-305-01)	13	2016	0	0
Griffiths Pond (BR-248-01)	14	2016	0	0
Higgins Pond (BR-194-01)	14	2016	0	0
Little Cliff Pond (BR-192-01)	14	2016	0	0
Long Pond (BR-279-01)	13	2023	9	3
Long Pond (BR-279-02)	3	2013	0	0
Lower Mill Pond (BR-245-01)	14	2016	0	0
Myricks Pond (BR-177-01)	13	2016	0	0
Owl Pond (BR-162-01)	12	2016	0	0
Pine Pond (BR-335-01)	14	2016	0	0
Schoolhouse Pond (BR-205-01)	14	2016	0	0
Sheep Pond (BR-240-01)	14	2016	0	0
Slough Pond (BR-321-01)	13	2023	9	3
Smalls Pond (BR-314-01)	13	2016	0	0
Smith Pond (BR-225-01)	11	2016	0	0
Sols Pond (BR-189-01)	11	2016	0	0
Upper Mill Pond (BR-272-01)	14	2016	0	0
Walkers Pond (BR-313-01)	14	2016	0	0
CHATHAM				
Barclay Pond (CH-479-01)	7	2023	0	0
Black Pond (CH-524-01)	7	2008	0	0
Black Pond (CH-550-01)	6	2008	0	0
Blue Pond (CH-543-01)	6	2008	0	0

1. Total number of years sampled (may not be consecutive). 2. Most recent year of data available in the regional database. 3/4. The different trend parameters indicate the total number of parameters where trends were able to be calculated for surface waters and for bottom waters.

POND NAME (GIS ID)	Years of Data[1]	Last Year of Data[2]	Surface Trend Parameters[3]	Bottom Trend Parameters[4]
Emery Pond (CH-491-01)	7	2016	0	0
Goose Pond (CH-458-01)	8	2023	0	0
Lovers Lake (CH-428-01)	9	2016	0	0
Marys Pond (CH-484-01)	6	2008	0	0
Meadow View Pond (CH-582-01)	2	2005	0	0
Mill Pond (CH-440-01)	8	2016	0	0
Minister Pond (CH-439-01)	7	2016	0	0
Newty Pond (CH-522-01)	1	2001	0	0
Ryders Pond (CH-481-01)	8	2016	0	0
Schoolhouse Pond (CH-463-01)	8	2016	0	0
Stillwater Pond (CH-396-01)	9	2016	0	0
Trout Pond (CH-425-01)	7	2008	0	0
White Pond (CH-516-01)	7	2016	0	0
DENNIS				
Bakers Pond (DE-342-01)	15	2018	6	3
Cedar Pond (DE-281-01)	13	2015	0	0
Coles Pond (DE-201-01)	14	2023	6	0
Eagle Pond (DE-447-01)	15	2018	10	3
Flax Pond (DE-355-01)	16	2023	9	3
Fresh Pond (DE-597-01)	14	2016	0	0
Northern Simmons Pond (DE-325-01)	14	2016	0	0
Run Pond (DE-348-01)	15	2018	8	0
Scargo Lake (DE-236-01)	16	2023	8	2
EASTHAM				
Bridge Pond (EA-98-01)	11	2023	8	0
Deborahs Pond (EA-97-01)	1	2001	0	0
Depot Pond (EA-96-01)	1	2022	5	3
Great Pond (EA-95-01)	15	2022	9	0
Herring Pond (EA-103-01)	15	2023	10	3
Jemima Pond (EA-100-01)	13	2022	8	0
Little Depot Pond (EA-99-01)	15	2022	0	0
Ministers Pond (EA-92-01)	15	2023	8	0
Molls Pond (EA-91-01)	15	2022	8	0
Muddy Pond (EA-102-01)	13	2014	0	0
School House Pond (EA-93-01)	13	2022	9	6
Widow Harding Pond (EA-101-01)	15	2017	0	0
FALMOUTH				
Cedar Lake (FA-761-01)	5	2007	0	0
Coonamessett Pond (FA-888-01)	1	2023	0	0
Crocker Pond (FA-893-01)	7	2014	0	0
Dam Pond (FA-832-01)	2	2005	0	0
Deep Pond (FA-857-01)	1	2001	0	0
Fresh Pond (FA-933-01)	2	2005	0	0

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POND NAME (GIS ID)	Years of Data[1]	Last Year of Data[2]	Surface Trend Parameters[3]	Bottom Trend Parameters[4]
Jenkins Pond (FA-918-01)	1	2023	0	0
Mares Pond (FA-938-01)	1	2023	0	0
Miles Pond (FA-993-01)	1	2005	0	0
Oyster Pond (FA-927-01)	1	2001	0	0
Pickerel Pond (FA-888-02)	1	2008	0	0
Potters Hole (FA-844-01)	1	2001	0	0
Round Pond (FA-882-01)	2	2008	0	0
Shivericks Pond (FA-996-01)	1	2023	0	0
Trout Pond (FA-780-01)	5	2007	0	0
Wing Pond (FA-845-01)	1	2023	0	0
HARWICH				
Andrews Pond (HA-442-01)	7	2021	0	0
Aunt Edies Pond (HA-376-01)	14	2021	8	0
Bucks Pond (HA-420-01)	14	2021	10	3
Cornelius Pond (HA-381-01)	7	2023	0	0
Flax Pond (HA-507-01)	8	2012	0	0
Grass Pond (HA-579-01)	2	2012	0	0
Hawksnest Pond (HA-354-01)	10	2023	9	0
Hinckleys Pond (HA-353-01)	14	2021	8	3
Josephs Pond (HA-416-01)	14	2021	8	3
Robbins Pond (HA-386-01)	13	2021	2	0
Sand Lake (HA-418-01)	1	2023	0	0
Sand Pond (HA-525-01)	14	2021	3	4
Seymour Pond (HA-306-01)	14	2016	0	0
Skinequit Pond (HA-629-01)	14	2021	9	4
Walkers Pond (HA-358-01)	11	2023	10	6
White Pond (HA-414-01)	10	2018	0	0
MASHPEE				
Amos Pond (MA-801-01)	1	2001	0	0
Ashumet Pond (MA-808-01)	17	2021	9	2
Cataquin Pond (MA-870-01)	1	2001	0	0
Coombs Pond (MA-804-01)	1	2001	0	0
Deans Pond (MA-957-01)	1	2001	0	0
Flashy Pond (MA-897-01)	1	2001	0	0
Flying Squirrel Pond (MA-895-01)	1	2001	0	0
Jim Pond (MA-960-01)	1	2001	0	0
Johns Pond (MA-818-01)	18	2023	4	4
Martha Pond (MA-871-01)	1	2014	0	0
Mashpee Lake (MA-634-01)	18	2021	4	0
Moody Pond (MA-793-01)	12	2023	8	3
Santuit Pond (MA-718-01)	17	2023	8	0
Trout Pond (MA-876-01)	1	2001	0	0
Wakeby Pond (MA-1039-01)	18	2021	0	0
Washburn Pond (MA-781-01)	1	2001	0	0

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POND NAME (GIS ID)	Years of Data[1]	Last Year of Data[2]	Surface Trend Parameters[3]	Bottom Trend Parameters[4]
ORLEANS				
Bakers Pond (OR-167-01)	16	2019	8	7
Bolands Pond (OR-136-01)	17	2019	5	4
Cedar Pond (OR-122-01)	15	2017	0	0
Chigger Pond (OR-171-01)	2	2005	0	0
Critchetts Pond (OR-129-01)	1	2016	0	0
Crystal Lake (OR-153-01)	15	2023	5	4
Deep Pond (OR-262-01)	17	2019	9	7
Gould Pond (OR-174-01)	17	2019	8	3
Ice House Pond (OR-113-01)	17	2019	0	0
Kettle Pond (OR-147-01)	12	2019	5	0
Meadow Bog Pond (OR-256-01)	16	2019	8	0
Pilgrim Lake (OR-176-01)	15	2023	10	0
Reubens Pond (OR-123-01)	14	2023	8	0
Sarahs Pond (OR-249-01)	17	2019	8	7
Shoal Pond (OR-253-01)	17	2019	9	0
Twinings Pond (OR-247-01)	17	2019	9	3
Uncle Harveys Pond (OR-142-01)	16	2019	5	4
Uncle Israels Pond (OR-228-01)	17	2019	8	0
Uncle Seths Pond (OR-264-01)	17	2019	8	0
Wash Pond (OR-203-01)	9	2009	0	0
PROVINCETOWN				
Bennett Pond (PR-22-01)	2	2003	0	0
Blackwater Pond (PR-2-01)	1	2023	0	0
Clapps Pond (PR-28-01)	8	2023	0	0
Clapps Round Pond (PR-25-01)	1	2001	0	0
Duck Pond (PR-26-01)	2	2004	0	0
Grassy Pond (PR-1-01)	1	2001	0	0
Great Pond (PR-9-01)	3	2004	0	0
Pasture Pond (PR-16-01)	1	2001	0	0
SANDWICH				
Lawrence Pond (SA-431-01)	10	2023	9	3
Peters Pond (SA-526-01)	4	2023	0	0
Pimlico Pond (SA-615-01)	4	2005	0	0
Shawme Lake (SA-210-01)	1	2023	0	0
Snake Pond (SA-568-01)	4	2005	0	0
Spectacle Pond (SA-409-01)	8	2023	0	0
Triangle Pond (SA-504-01)	10	2012	0	0
TRURO				
Great Pond (TR-48-01)	10	2023	9	0
Horseleech Pond (TR-51-01)	2	2004	0	0
Round Pond (East) (TR-49-01)	3	2004	0	0

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POND NAME (GIS ID)	Years of Data[1]	Last Year of Data[2]	Surface Trend Parameters[3]	Bottom Trend Parameters[4]
Round Pond (West) (TR-50-01)	2	2003	0	0
Ryder Pond (TR-54-01)	4	2013	0	0
Slough Pond (TR-53-01)	7	2009	0	0
Snow Pond (TR-52-01)	5	2013	0	0
Village Pond (TR-38-01)	1	2023	0	0
WELLFLEET				
Doanes Bog Pond (WE-60-01)	1	2001	0	0
Duck Pond (WE-76-01)	9	2023	0	0
Dyer Pond (WE-71-01)	4	2016	0	0
Grass Pond (WE-74-01)	1	2001	0	0
Great Pond (WE-67-01)	3	2023	0	0
Gull Pond (WE-59-01)	6	2009	0	0
Herring Pond (WE-56-01)	3	2023	0	0
Higgins Pond (WE-57-01)	3	2004	0	0
Kinnicum Pond (WE-61-01)	3	2004	0	0
Long Pond (WE-65-01)	5	2011	0	0
Northeast Pond (WE-66-01)	3	2004	0	0
Southeast Pond (WE-68-01)	3	2004	0	0
Spectacle Pond (WE-64-01)	3	2004	0	0
Turtle Pond (WE-70-01)	2	2004	0	0
Williams Pond (WE-55-01)	3	2004	0	0
YARMOUTH				
Big Sandy Pond (YA-711-01)	3	2006	0	0
Dennis Pond (YA-472-01)	12	2023	10	0
Elishas Pond (YA-493-01)	1	2003	0	0
Flax Pond (YA-569-01)	11	2016	0	0
Greenough Pond (YA-492-01)	10	2016	0	0
Horse Pond (YA-692-01)	2	2005	0	0
Jabez Neds Pond (YA-716-01)	1	2003	0	0
James Pond (YA-693-01)	1	2023	0	0
Long Pond (YA-657-01)	12	2016	0	0
Miss Thachers Pond (YA-478-01)	1	2003	0	0
Perch Pond (YA-483-01)	1	2003	0	0
Plashes Pond (YA-653-01)	1	2003	0	0
Tom Matthews Pond (YA-371-01)	6	2009	0	0
West Sandy Pond (YA-700-01)	1	2023	0	0

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