Narragansett Bay
Research Reserve

Technical Report 2011:1

Water Quality, Nutrients, and Meteorological Trends at the Narragansett Bay National Estuarine Research Reserve in 2009

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Executive Summary

The Narragansett Bay National Estuarine Research Reserve (NBNERR or Reserve) is situated approximately in the center of Narragansett Bay, Rhode Island. It is located on Prudence, Patience, Hope and Dyer islands and it protects an estimated 1780 hectares of land and water (out to a depth of 5.5 m) within the 2667 km^2 Narragansett Bay Watershed. The Reserve is part of the National Estuarine Research Reserve System (NERRS), established under Section 315 of the Coastal Zone Management Act of 1972. Our mission is to preserve, protect and restore coastal and estuarine ecosystems of Narragansett Bay through long-term research, education and training (NBNERR Management Plan 2010-2015).

One of the signature programs of the NERRS is the System-Wide Monitoring Program (SWMP). The SWMP was established to collect a broad suite of water quality and meteorological parameters in order to track short-term variability and long-term changes in estuarine environments. Since 1995, the Reserve has collected near-continuous water quality and meteorological data along with monthly nutrient and chlorophyll data at four stations around Prudence Island. These stations represent a gradient in habitat types that range from salt marsh (Nag Creek station) to shallow cove (Potter Cove) to open Bay water (T-Wharf Surface and T-Wharf Bottom).

The purpose of this report is to analyze all available water quality, meteorological, and nutrient datasets since the programs inception through 2009 in order to examine short-term and long-term patterns and trends. Several findings were revealed after analyzing these datasets. In 2009, dissolved oxygen, anoxic (< 1 mg L^{-1}) and hypoxic (≤ 2.9 mg L^{-1}) events occurred slightly less frequently but over a longer duration than in previous years. However, no detrimental effects to fauna or flora (i.e. fish kills, die-offs of marine plants) were observed during any of these events. All nitrogen species had very low concentrations (approaching zero) during most of the year; while for meteorology, precipitation was highest during the fall with concomitantly low photosynthetically active radiation levels. At T-Wharf Bottom, salinity showed a significant decreasing trend in winter across years (R^2=0.97, P=0.016). At Potter Cove, pH data from 2009 continued the increasing trend found in the previous report for spring, summer, and fall (R^2>0.4, P<0.020), and at T-Wharf Bottom in fall (R^2=0.83, P=0.004). The reasons for these latter findings are unknown, although changes in primary and/or secondary productivity at these sites could lead to changes in pH (D'Hondt et al. personal communication). A significant decrease in springtime chlorophyll concentrations over time was also found at T-Wharf Bottom (R^2=0.59, P=0.043). This agrees with other studies in Narragansett Bay that document a decrease in the intensity and duration of the winter-spring bloom and may be a response to global climate change and/or recent large-scale nutrient reductions into the Bay. Significant decreases in nitrate (NO_3) and nitrite + nitrate (NO_2 + NO_3) were found at all stations in fall across years; this is perhaps a consequence of the large-scale regulatory projects designed to reduce nutrient inputs into the Bay. Barometric pressure also decreased significantly over time in both spring (R^2=0.860, P<0.001) and summer (R^2=0.833, P=0.002); the causes of these trends are unknown. However, the analysis of five years of data (2006-2010) from five northeast Reserves, showed a decreasing trend in barometric pressure for all seasons across years (Two-Way ANOVA, P<0.05), except for summer. Although it is unclear how this might affect the weather at these locations, changes in barometric pressure over time could be associated with different weather systems when other meteorological parameters are associated with these changes, i.e. changes in air temperature.

At NBNERR, our efforts are directed towards obtaining high-quality data to develop a robust long-term dataset in water quality, nutrients, and meteorology. By frequently analyzing these datasets we will be able to elucidate any trends and patterns in these physiochemical parameters that might affect biological and ecological processes in Narragansett Bay.

Acknowledgements

We would like to thank everyone who has helped with SWMP since 1995
and the NBNERR staff for their help and support
during the production of this report.

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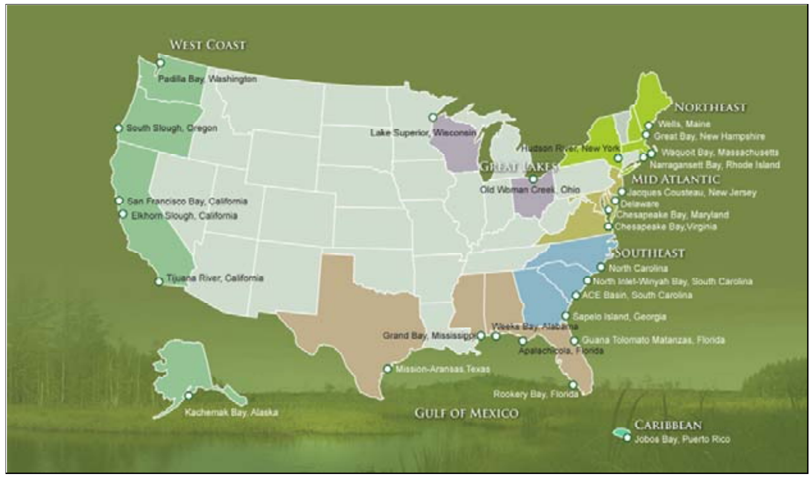
1.0 General Introduction

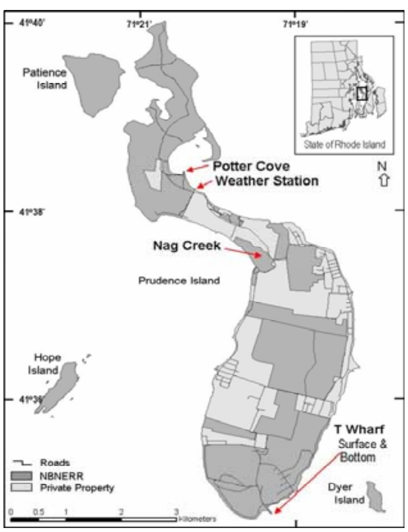
1.1 Background

The National Estuarine Research Reserves System (NERRS) is a network of 28 reserves that represent eleven biogeographic regions (areas with similar dominant plants, animals and prevailing climate) across the United States and Puerto Rico. The most recent designation was the Wisconsin Lake Superior NERR in November 2010, and another reserve has been proposed in Connecticut. All these sites protect estuarine and terrestrial habitats and landscapes that are characteristic of each biogeographic region for long-term research, water-quality monitoring, education, and coastal stewardship. The NERRS is a partnership program between the National Oceanic and Atmospheric Administration (NOAA) and the coastal states, as established by the Coastal Zone Management Act of 1972. NOAA provides financial support, national guidance, and technical assistance.



Map of NERRS biogeographic regions (http://www.nerrs.noaa.gov).

The Narragansett Bay National Estuarine Research Reserve (NBNERR or Reserve) was the 7th site selected to become part of the NERRS. The NBNERR was designated in 1980 through a partnership between NOAA and the Rhode Island Department of Environmental Management (RIDEM), which is responsible for the overall management of the Reserve. The NBNERR protects an estimated 1780 hectares of land and water (out to a depth of 5.5 m) on Prudence, Patience, Hope, and Dyer islands. The NBNERR headquarters, lab, and learning center are located at the south end of Prudence Island, which is approximately 11.3 km long and 1.6 km across at its widest point. About 86% of Prudence Island's land area is currently protected, either as part of the Reserve (68%) or by local conservation groups (11% and 8% of Prudence is protected by the Prudence Conservancy and the Audubon Society of Rhode Island, respectively). The three other islands that are also part of the Reserve are much smaller than Prudence; Patience, Hope, and Dyer islands are approximately 68 ha, 28 ha, and 11 ha, respectively. In relation to Prudence Island, Patience Island is approximately 0.16 km off the northwest point, Hope Island is 2.4 km to the west, and Dyer Island is 1.1 km to the southeast. Each of these three islands is uninhabited except for three privately-owned lots on Patience Island.



Map of Prudence, Patience, Hope, and Dyre Islands, and of the water quality and meteorological stations at the Reserve.

The NBNERR's principal mission is to preserve, protect and restore coastal and estuarine ecosystems of Narragansett Bay through long-term research, education and training (NBNERR Management Plan 2010-2015). The long-term collection of water quality and meteorological data at NBNERR provides information to decision-makers in public agencies and the private sector in RI to effectively address coastal resource management issues. The Reserve also enhances public awareness and understanding of the Narragansett Bay watershed and estuarine areas in the region through K-12 and teacher education programs as well as public education and outreach.

1.2 The System-Wide Monitoring Program

A major program of the NERRS is the System-Wide Monitoring Program (SWMP). It was created and developed by the NERRS in 1995 as a nationally-coordinated monitoring program to develop comparable long-term water quality and meteorological datasets in a coordinated manner. This program ensures that data collection, synthesis, and analysis are consistent across all the Reserves within NERRS. The primary mission of the NERRS-SWMP is to:

> *Develop quantitative measurements of short-term variability and long-term changes in the water quality, biotic diversity, and land-use / land -cover characteristics of estuaries and estuarine ecosystems for the purposes of contributing to effective coastal zone management (National Estuarine Research Reserve System 2007).*

To achieve this mission, a suite of standard methods are used to collect data on different environmental parameters grouped according to their nature and products they produce in abiotic, biotic, mapping, data analysis, and education (National Estuarine Research Reserve System 2010).

As part of SWMP, all water quality, nutrient (which includes chlorophyll) and meteorological monitoring occurs at three locations around Prudence Island: Potter Cove, Nag Creek, and T-Wharf (Figure 2). In terms of water quality and nutrients, the T-Wharf location supports two individually-recognized stations (T-Wharf Surface and T-Wharf Bottom) for a total of four monitoring stations at these three locations. Potter Cove and T-Wharf were the two original water quality monitoring locations at NBNERR and they were chosen to represent an impacted site and a control site, respectively. Nag Creek was added in 2002 and the study design changed from a comparison of an impacted and a control site into an analysis of data along a gradient in habitat types that range from salt marsh to shallow cove to open water. Detailed historical notes for each of the water quality station sites were included in the previous report (Durant and Raposa 2009).

1.3 Goal of this Report

The goal of this report is to provide a summary of the data obtained in 2009 using the NERRS-SWMP abiotic toolkit at NBNERR (National Estuarine Research Reserve System 2010). More specifically, this report will include sections on spatial and temporal patterns in (1) estuarine water quality, (2) nutrients and chlorophyll, and (3) meteorology. Each section will include a summary of all data collected in 2009, along with an analysis of longer-term inter-annual trends for each parameter.

1.4 Literature Cited

Durant, D., and K. Raposa. 2009. Water quality, nutrients and meteorology at the Narragansett Bay National Estuarine Research Reserve: 2008 Report. Narragansett Bay National Estuarine Research Reserve Tech Series 2010:2. Available at http://www.nbnerr.org/techreports.htm.

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National Estuarine Research Reserve System. 2007. The National Estuarine Research Reserve's System-Wide Monitoring Program (SWMP): A scientific framework and plan for detection of short-term variability and long-term change in estuaries and coastal habitats of the United States (2002; Revised August 2007). Available at http://nerrs.noaa.gov/pdf/SWMPPlan.pdf.

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2.0 Temporal and Spatial Variability in Water Quality

2.1 Introduction

Although the SWMP is carried out by each Reserve locally, support and national coordination of the program comes from the NERRS. This national coordination is the strength of the SWMP, ensuring that the data collected from 28 different sites are comparable on regional and national scales. In this section, we examined and summarized the monthly and seasonal water quality data from each SWMP station in 2009. We also analyzed the long-term data within each season to identify significant patterns or trends across years.

2.2 Methods

2.2.1 Monitoring Infrastructure

A brief description of the monitoring infrastructure at each water quality station will follow. However, a more detailed description can be found in Durant and Raposa (2009).

Potter Cove

The water quality station at Potter Cove (41° 38.416’ N, 71° 20.450’ W) was established in 1995. The sonde is deployed in a short PVC pipe that extends from the deck of the floating dock down to just below the water’s surface. A nylon line runs from within this pipe to a sonde that is fixed between a small mushroom anchor and a float at a depth of approximately 0.75 m off the bottom.

PVC deploying structure on floating dock.

T-Wharf

PVC deploying structure at T-Wharf

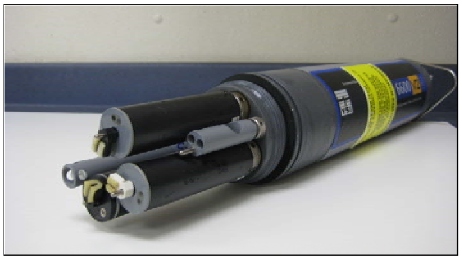
The T-Wharf Surface and T-Wharf Bottom stations (41° 34.700’ N, 71° 19.266’ W) were both established in July 2002 and both use a fixed PVC pipe to deploy sondes as described previously (Figure 4). Sondes at T-Wharf Surface are maintained just below the surface at approximately 0.5 m by means of a buoy attached by rope to the adjacent wharf. The pipe at T-Wharf Bottom extends approximately 6.1 m into the water column, allowing the sonde to be maintained approximately 1 m off the bottom.

Nag Creek

The Nag Creek station (41° 37.483’ N, 71° 19.450’ W) was established in March 2002. The deployment structure is a tripod wooden structure that is held in place by sinking it into the mud approximately in the middle of the creek. The sonde is deployed from the tripod into the water via a line system and hangs approximately 0.3 m from the bottom of the creek (Figure 5).

Deploying structure and sonde at Nag Creek

2.2.2 Data Collection



YSI 6600V2 automated data logger

Physical and chemical water quality parameters are collected at each station using Yellow Spring Instruments (YSI) 6600 EDS and 6600 V2 multi-parameter automated data loggers, also known as sondes. They are equipped with self-cleaning optical sensors, anti-fouling wipers, optimal power management, and a built-in battery compartment which improves reliability and maintains high data accuracy during extended deployments. The sondes house multiple probes that simultaneously measure temperature, specific conductivity, dissolved oxygen (percent saturation, depth, pH, and turbidity. Other parameters are not measured directly but calculated by the sonde include salinity (calculated using specific conductivity and temperature), dissolved oxygen concentration (calculated using temperature, salinity and dissolved oxygen percent saturation), chlorophyll (calculated from fluorescence). Data are collected at 15-minute sampling intervals. Sondes are calibrated and deployed for two-week periods. At the end of each deployment period, the sondes are retrieved and replaced with recently calibrated ones.

2.2.3 Water Quality Telemetry

Since 2006, T-Wharf Bottom water quality data has been transmitted on an hourly basis to the NOAA GOES satellite. These near-real-time data are posted and available online at the Centralized Data Management Office (CDMO) website. Water quality data collected at the T-Wharf Bottom station are also part of the Integrated Ocean Observing Systems (IOOS, http://ioos.noaa.gov), which is a coordinated effort to generate, disseminate, and make available to scientists continuous data from the Great Lakes, coastal waters, and oceans. All Reserves within the NERRS contribute SWMP data to IOOS.

Telemetry station at T-Wharf

2.2.4 Data Analysis

After downloading the raw data obtained from the sonde to a computer in the laboratory, the data file is submitted to the (CDMO) where it goes through a careful process of quality assurance and quality control (QAQC). After several levels of QAQC, the data are authenticated and become authoritative. The datasets are available through the CDMO website (http://www.nerrsdata.org/) and are accompanied by a metadata document, which contains important information to help interpret the data. Due to the existing delay of over three years for submitted data to be finalized by CDMO, all data used in this report previous to 2007 (inclusive) are the authoritative datasets from CDMO, and datasets after 2007 are provisional. Nevertheless, we expect these provisional datasets to be similar to the final authoritative dataset of CDMO. The datasets used in the report were revised according to the flagging system established by CDMO (Durant and Raposa 2009), and verified for outliers by calculating the 3rd standard deviation; data outside the 3rd standard deviation were not included. In this report, the resulting dataset used for statistical analysis, tables, and graphs will be called 'revised data'.

2009 Data

The 2009 revised dataset comprised between 76-100% of the original data from each station (see Appendix I). The revised data were used to calculate monthly and seasonal means for temperature

(^{o}C), salinity (ppt), dissolved oxygen (% saturation, and mg L^{-1}), pH, turbidity (NTU) and chlorophyll (µg L^{-1}) for all stations. In order to make valid comparisons, only datasets with 2/3 of data or more (> 67%) were used for monthly and seasonal comparisons (following Heffner 2009). Seasonal means were calculated based on the following: winter included the months of January, February, March; spring - April, May, June; summer - July, August, September; fall - October, November, and December. The percentage of data used per season for all the stations and parameters is presented in Appendix I.

Long-term Seasonal Trends

Long-term seasonal means were calculated following Heffner (2009). The percentage of data used for calculating long-term seasonal means for each parameter at all stations up to 2008 is presented in Durant and Raposa (2009). No winter data are presented in this report for Nag Creek since the sonde had to be retrieved for most of the season due to ice in the creek; the only exception was the winter of 2006. To determine if significant changes occurred at each station within seasons across years, linear regressions were performed using the seasonal means for each parameter as dependent variables and year as the independent variable. All regressions were performed using Sigma Stat version 3.5.

2.3 Results

2.3.1 Temperature

Water temperature ranged from -2.4 to 26.9°C at Potter Cove, -1.3 to 32.6°C at Nag Creek, 0.9 to 25.3°C at T-Wharf Surface, and 1.2 to 30.1°C at T-Wharf Bottom (Appendix I). A slight thermocline was observed from April to August at T-Wharf (Fig. 1a). Seasonal patterns in mean water temperature were similar among the monitoring stations, except in spring when it was slightly warmer at Nag Creek (Fig. 1b) than at the other stations.

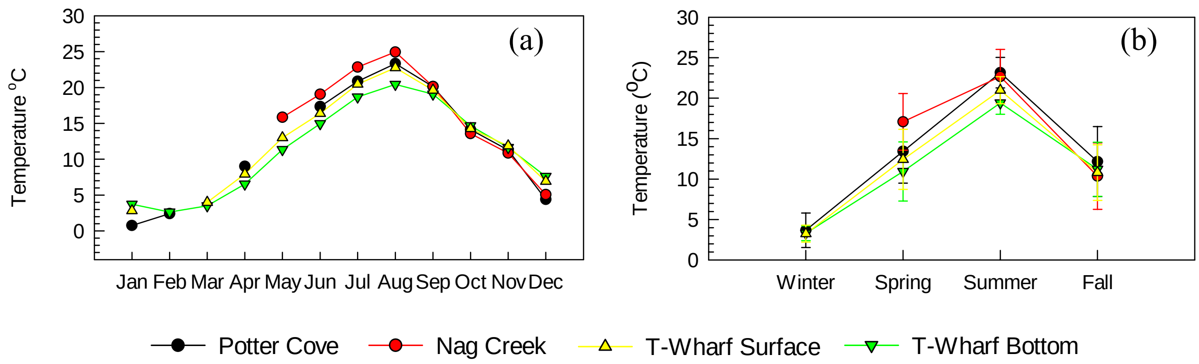


Figure 1. Monthly (a) and seasonal (± one standard deviation) (b) mean water temperature in 2009 at each of the four SWMP stations. Error bars on the monthly graph were omitted for clarity.

Long-term seasonal mean water temperatures followed no distinctive trend across years for all stations (Fig. 2).

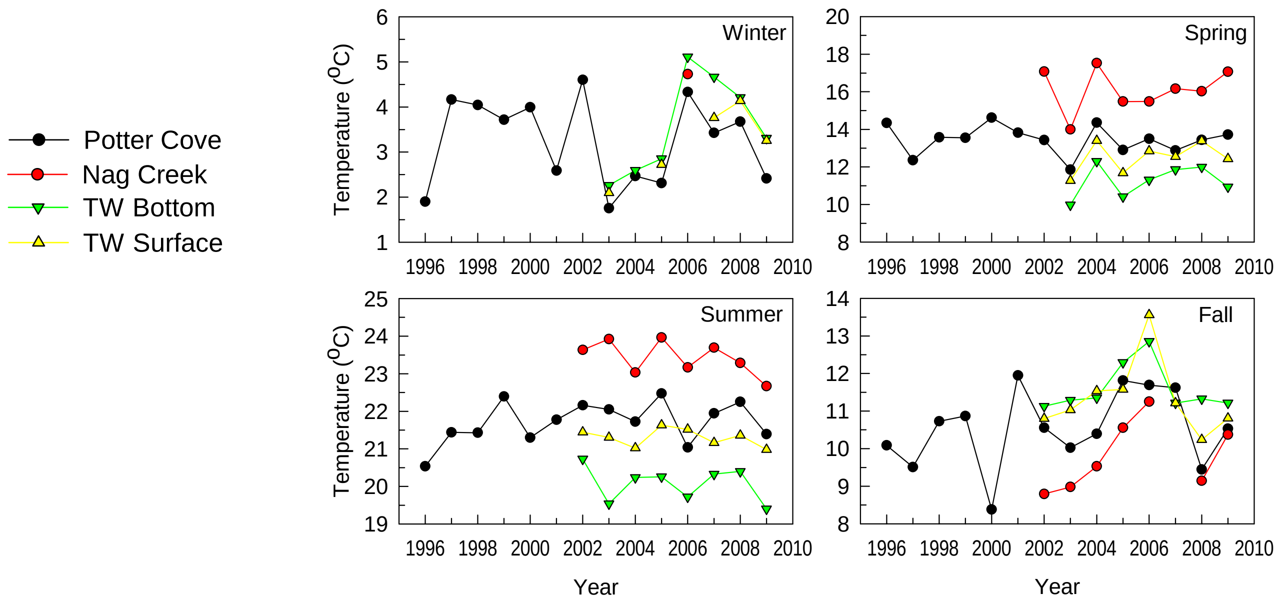


Figure 2. Long-term seasonal mean water temperature for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.3.2 Salinity

Salinity ranged from 14.6 to 34.4 ppt at Potter Cove, 13.8 to 34.3 ppt at Nag Creek, 24.8 to 33.3 ppt at T-Wharf Surface, and 26.4 to 33.3 ppt at T-Wharf Bottom (Appendix I). Salinity was slightly higher from October to December than during the rest of the year (Fig. 3a) for all stations. Salinity at Nag Creek had higher seasonal variability than at the other stations (Fig. 3b).

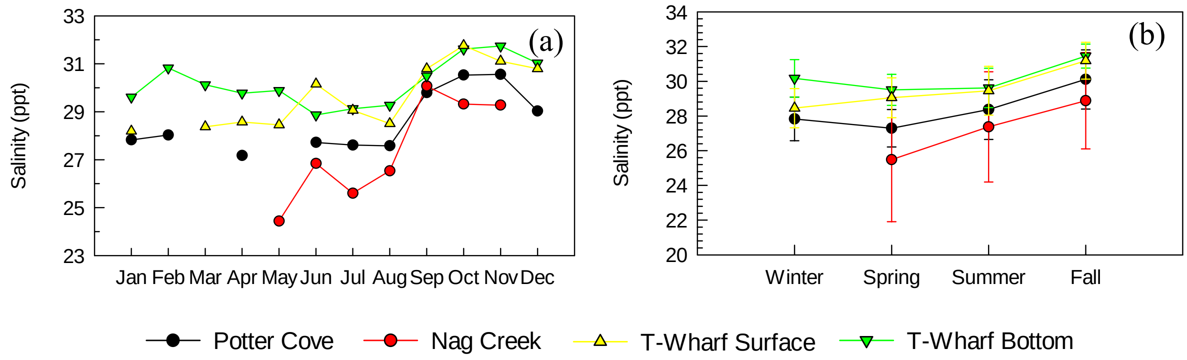


Figure 3. Monthly (a) and seasonal (b) mean salinity for 2009 water quality data at each of the four SWMP stations. Error bars on the monthly graph were omitted for visual clarity.

Long-term seasonal salinity means were slightly different among stations and across seasons (Fig. 4). In 2009, salinity was lower than previous years during summer and spring, and higher than previous years during winter and fall. At T-Wharf Bottom, salinity has been decreasing significantly over time in winter (R^2=0.97, P=0.016).

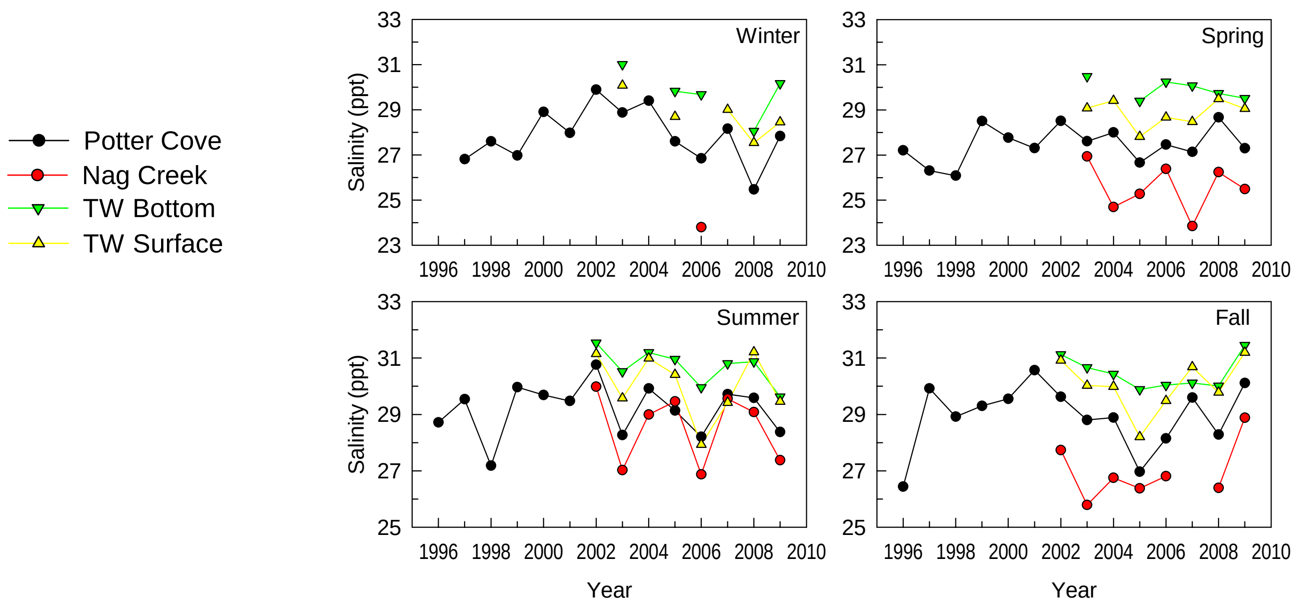


Figure 4. Long-term seasonal mean salinity for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.3.3 Dissolved Oxygen (percent saturation)

Dissolved oxygen (DO) measured as percent saturation (% sat.) ranged from 39 to 146% at Potter Cove, 0 to 173% at Nag Creek, 72 to 168% at T-Wharf Surface, and 51 to 132% at T-Wharf Bottom (Appendix I). Potter Cove and Nag Creek had the lowest DO concentrations in August (Fig. 5a). Seasonal DO % sat. was more variable at Nag Creek than at the other stations (Fig. 5b).

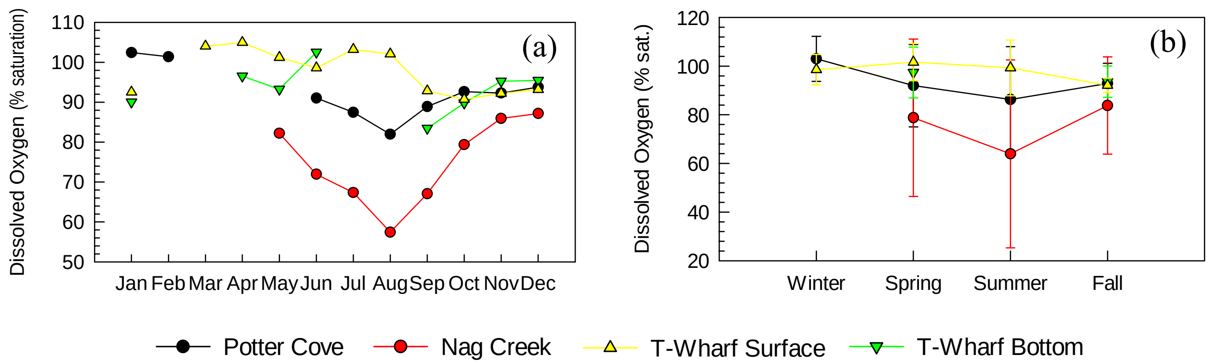


Figure 5. Monthly (a) and seasonal (b) mean dissolved oxygen percent saturation for 2009 water quality data at each of the four SWMP stations. Error bars on the monthly graph were omitted for visual clarity.

When considering the long-term seasonal data, there were no significant long-term trends in DO in any season, and Nag Creek had the lowest DO levels every season that data are available (Fig. 6).

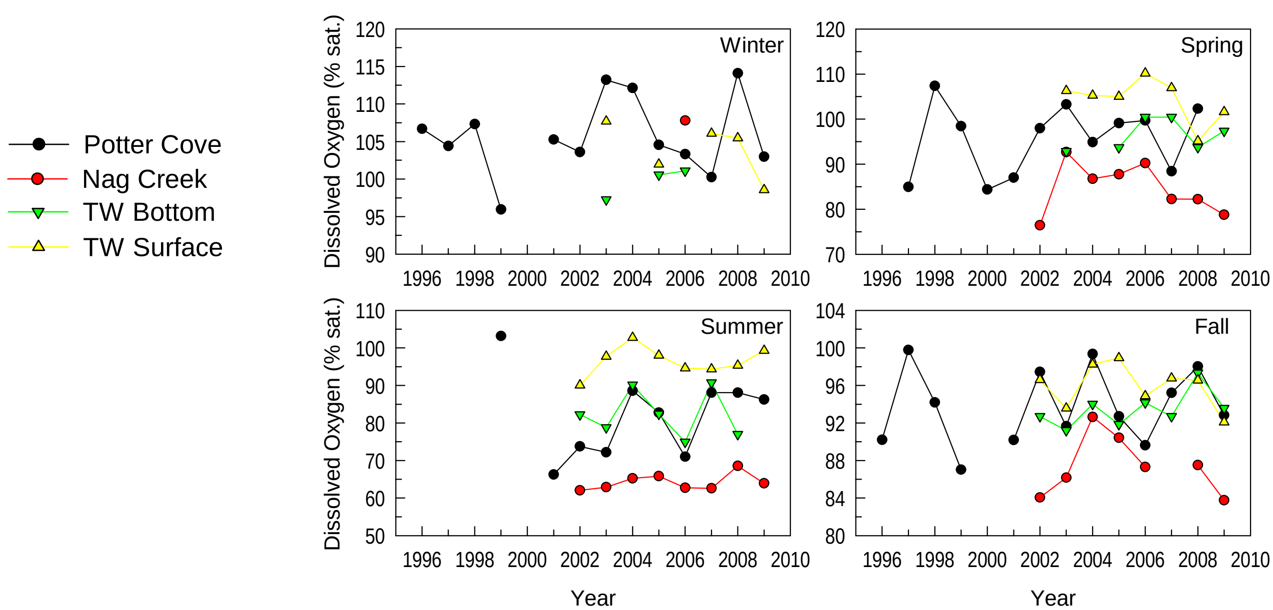


Figure 6. Long-term seasonal mean dissolved oxygen percent saturation for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.3.4 Dissolved Oxygen Concentration (mg L^{-1})

Dissolved oxygen concentration (mg L^{-1}, DOc) ranged from 0.7 to 15.9 at Potter Cove, 0.0 to 14.9 at Nag Creek, 4.5 to 13.2 at T-Wharf Surface, and 3.3 to 13.0 at T-Wharf Bottom (Appendix I). Monthly mean DOc at all stations was lowest in August or September, and the lowest overall was observed at Nag Creek in August (≈ 4 mg L^{-1}; Fig. 7a). Seasonal mean DOc followed a typical pattern for temperate zones, where the concentration of dissolved oxygen is lower during the warm summer months and higher during the rest of the year (Fig. 7b). Nag Creek exhibited much more variability and lower DOc than the other stations (Fig. 7b).

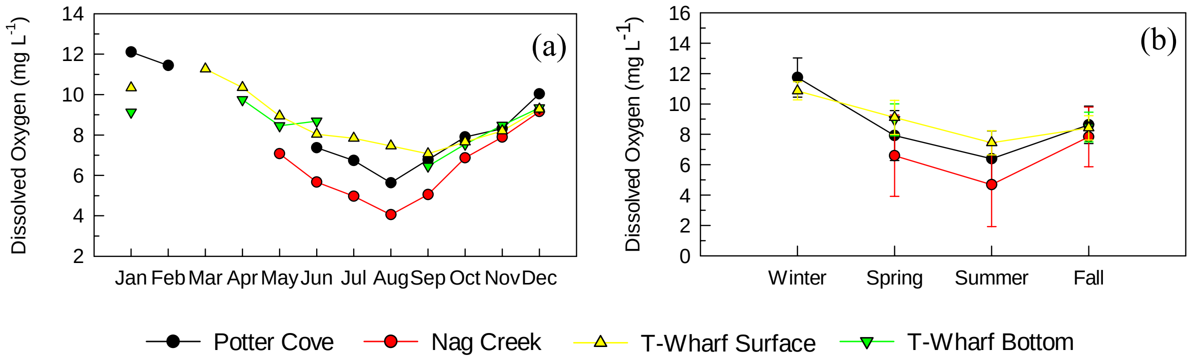


Figure 7. Monthly (a) and seasonal (b) mean dissolved oxygen concentration for 2009 water quality data at each of the four SWMP stations. Error bars on the monthly graph were omitted for visual clarity.

Anoxic conditions (DOc < 1.0 mg L^{-1}) were not recorded at T-Wharf Surface or Bottom during 2009. At Potter Cove, brief events of anoxia (one to two consecutive readings) were recorded on two days during August. At Nag Creek, however, anoxic conditions were recorded during the months of June (5 days), July (15 days), August (28 days) and September (11 days). The duration of the anoxic events varied from one reading up to 42 consecutive readings (over 10 hours) in one particular day.

Hypoxic conditions (DOc 1.0 ≤ 2.9 mg L^{-1}) were recorded only at Potter Cove, and Nag Creek. At Potter Cove, hypoxic conditions were recorded during the months of July (3 days) and August (17 days). During these two months, the extent of the hypoxic events varied from one reading up to 26 consecutive readings (6 to 7 hours) in one particular day. At Nag Creek, hypoxia was recorded with more frequency and duration in 2009 compared to 2008 during the months of May (17 days), June (27 days), July (29 days), August (31 days), and September (28 days) (no information was available from January through most of April). In October and December, dissolved oxygen levels were sporadically hypoxic over fewer days (5 and 1 day, respectively), where the duration varied from one up to 31 consecutive readings (eight hours) in one particular day.

Long-term seasonal means for DOc plotted for all stations showed different trends among stations across years (Fig. 8). A decreasing trend may be occurring in spring across years at Nag Creek, but no significant differences were found. DOc is consistently low every summer in Nag Creek.

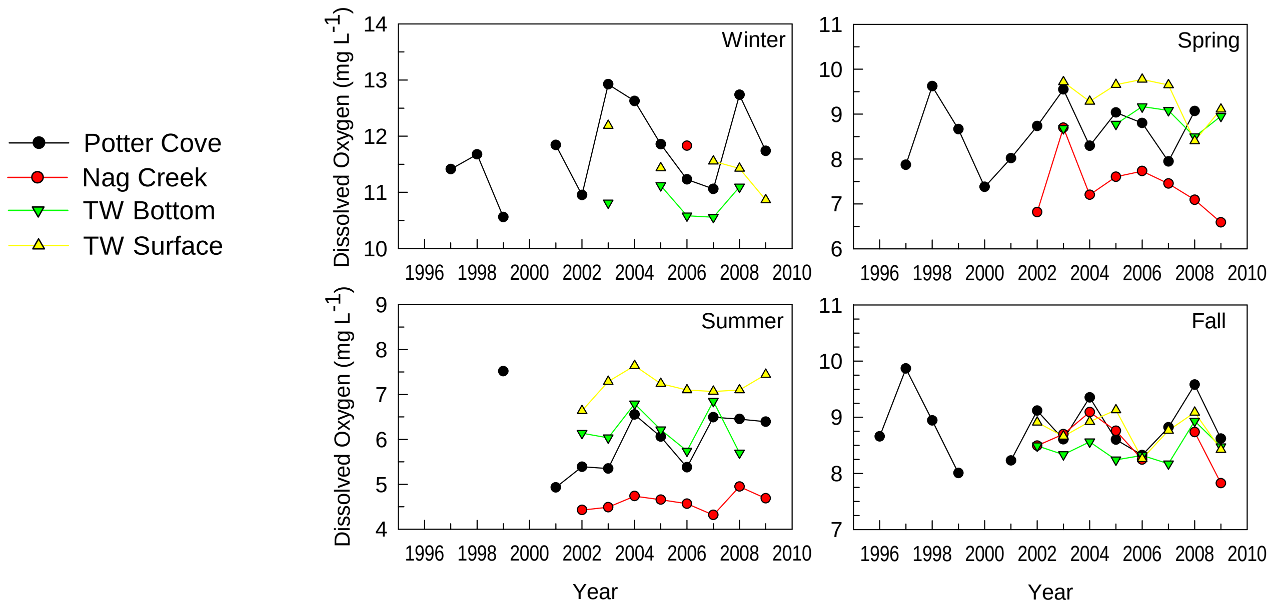


Figure 8. Long-term seasonal mean dissolved oxygen concentration for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.3.5 pH

In 2009, pH ranged from 7.2 to 7.9 at Potter Cove, 6.4 to 8.6 at Nag Creek, 7.4 to 8.7 at T-Wharf Surface, and 7.1 to 9.2 at T-Wharf Bottom (Appendix I). Monthly mean pH was similar among all stations except Nag Creek (Fig. 9a). Seasonal patterns in mean pH showed lower means and higher variability in Nag Creek for all seasons (no information was obtained for winter due to freezing of the creek) (Fig. 9b). T-Wharf Bottom had the highest pH during winter and fall, while Potter Cove and T-Wharf Surface were similar during all four seasons.

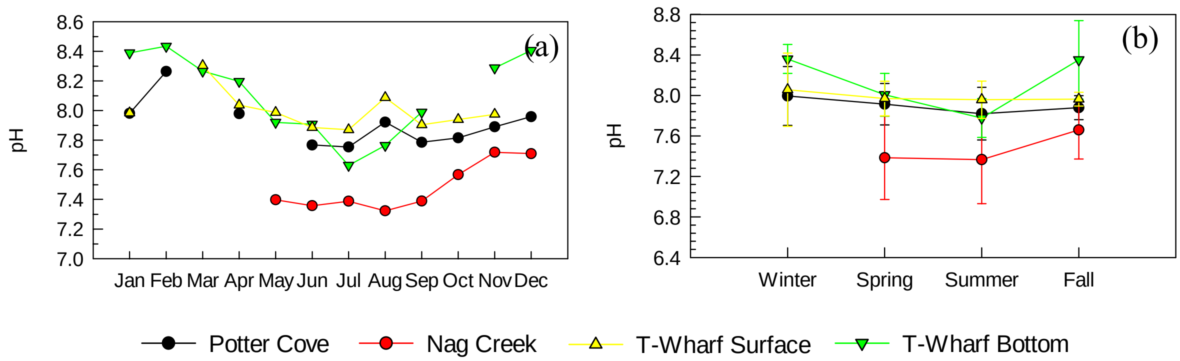


Figure 9. Monthly (a) and seasonal (b) mean pH for 2009 water quality data at each of the four SWMP stations. Error bars on the monthly graph were omitted for visual clarity.

Long-term seasonal pH patterns were similar among all stations except for Nag Creek, where pH was lower than the other stations (Fig. 10). A significant increase in pH across years was found at Potter Cove in spring (R^2=0.39, P=0.017), summer (R^2=0.56, P=0.002) and fall (R^2=0.37, P=0.020), and at T-Wharf Bottom in fall (R^2=0.83, P=0.004).

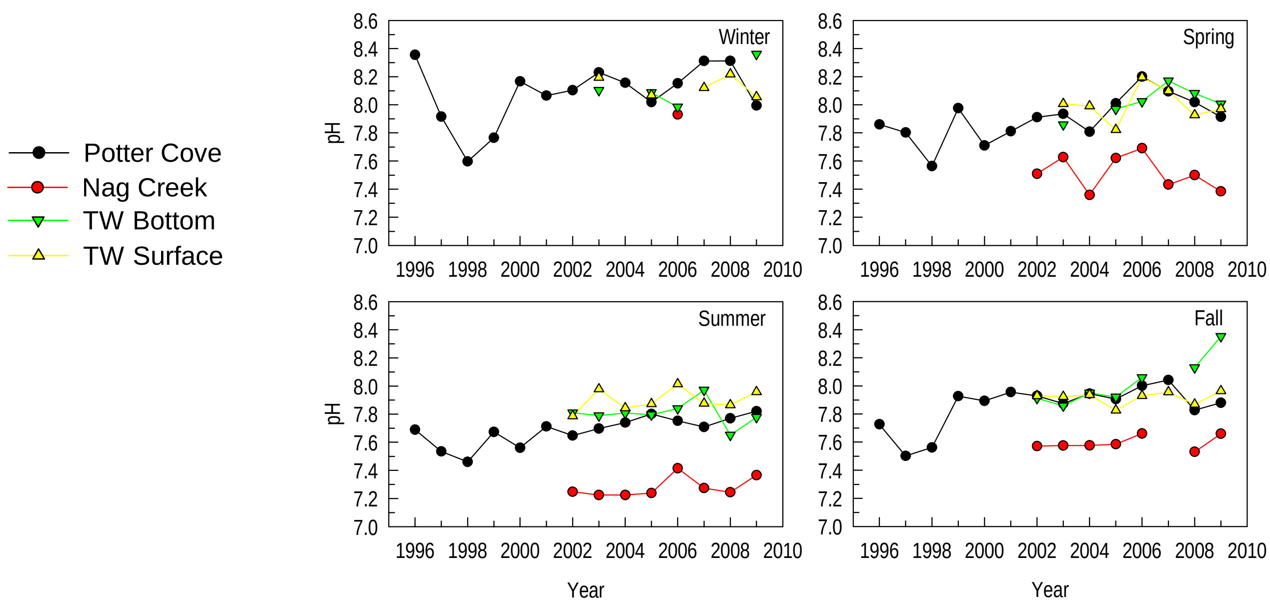


Figure 10. Long-term seasonal mean pH for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.3.6 Turbidity

Turbidity (NTU) ranged from 0 to 14 at Potter Cove, 0 to 33 at Nag Creek, 0 to 8 at T-Wharf Surface, and 0 to 29 at T-Wharf Bottom (Appendix I). Monthly mean turbidity was low at all stations; at T-Wharf Surface it was less than 1 NTU throughout the year, and a peak in turbidity was observed at T-Wharf Bottom in August (Fig. 11a). Seasonal turbidity means varied among stations. They were, however, generally low overall (< 10 NTU) and highly variable during the summer at T-Wharf Bottom and Nag Creek (Fig. 11b).

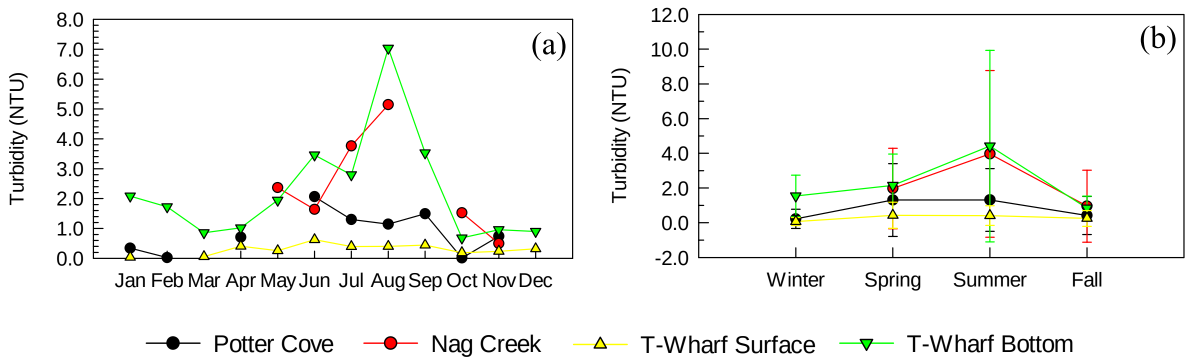


Figure 11. Monthly (a) and seasonal (b) mean turbidity for 2009 water quality data at each of the four SWMP stations. Error bars on the monthly graph were omitted for visual clarity.

Long-term seasonal turbidity means were low (< 8 NTU) when all years, stations and seasons were considered, and summer of 2002 at Nag Creek (Fig. 12). A significant decreasing trend in turbidity was found at Potter Cove (R^2=0.64, P=0.003) in summer across years.

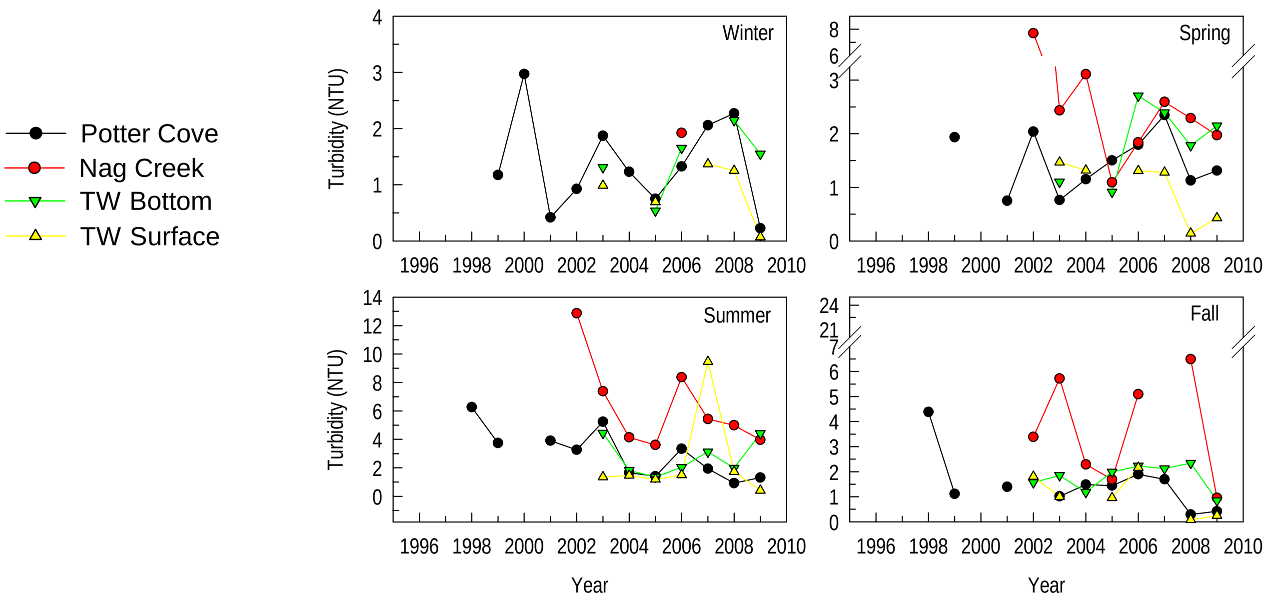


Figure 12. Long-term seasonal mean turbidity for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.3.7 Chlorophyll

Chlorophyll concentrations (µg L^{-1}) ranged from 0 to 16.1 at Potter Cove, 0 to 18.4 at Nag Creek, 0 to 17 at T-Wharf Surface, and 0 to 12 at T-Wharf Bottom (Appendix I). Monthly mean chlorophyll was very similar across all stations, although a small peak was observed at Nag Creek and T-Wharf Surface in August (Fig. 13a). Seasonal mean chlorophyll concentrations were generally low for all stations (< 10 µg L^{-1}) and showed no distinct pattern among stations within each season (Fig. 13b).

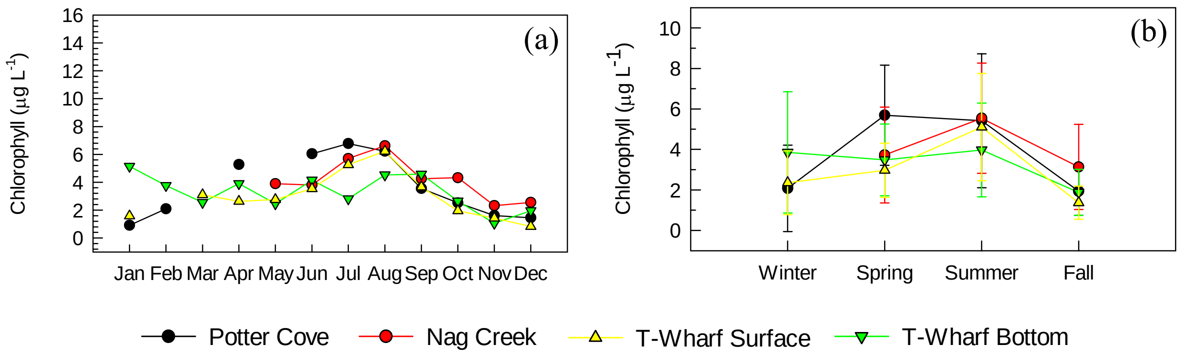


Figure 13. Monthly (a) and seasonal (b) mean chlorophyll for 2009 water quality data at each of the four SWMP stations. Error bars on the monthly graph were omitted for visual clarity.

Long-term seasonal mean chlorophyll concentrations were low (< 13 µg L^{-1}) across all years, stations and seasons (Fig. 14). A decreasing trend may be occurring in summer and fall across years at Potter Cove, but no significant differences were found.

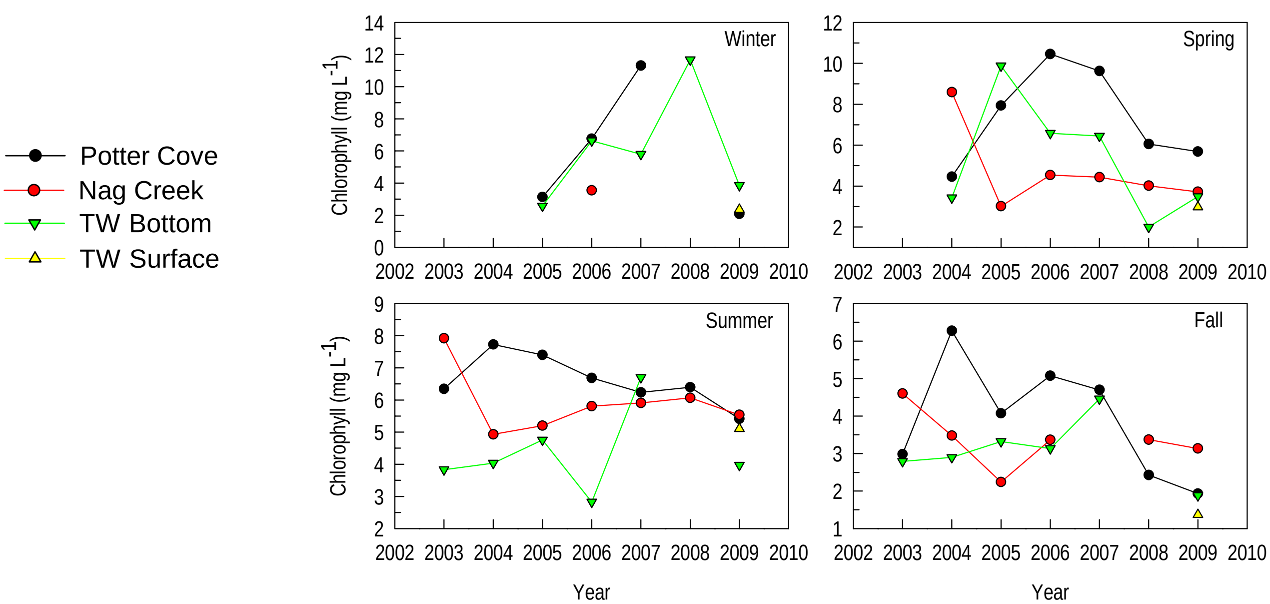


Figure 14. Long-term seasonal mean turbidity for each of the four SWMP stations. Error bars were omitted for visual clarity.

2.4 Discussion

In this section, the SWMP water quality data from 2009 were analyzed by month and season. In addition, the long-term water quality dataset that begins in 1995 was updated to include 2009 data, and then analyzed within each season to determine if any patterns or trends exist across years. With this analysis of inter- and intra-annual patterns and trends in water quality, we hope to improve our understanding of estuarine process in Narragansett Bay.

Scientists are becoming increasingly concerned with ongoing increases in oceanic sea surface temperatures (Levitus et al. 2009). Estuarine water temperatures are also increasing, in part due to climate change and the dynamic exchange of water between estuaries and warming oceans. Increasing estuarine water temperatures are well documented for some of New England's estuaries (for Narragansett Bay see Nixon et al. 2003, for Woods Hole, MA see Nixon et al. 2004; Durant and Raposa 2009). Durant and Raposa (2009) documented a significant increase in winter water temperatures of approximately 0.29^{o}C/year since 2002 using the Reserve's long-term SWMP water quality dataset (through 2008). However, when updating and analyzing the NBNERR long-term database with the 2009 data, no significant increase in winter water temperatures were found due to the slightly lower winter water temperatures recorded during this latest year.

The analysis of the long-term water temperature data showed that some degree of water column stratification has been occurring at least since 2002 at T-Wharf due to thermocline formation during spring and summer, while a halocline has been sporadically present during the same time period. No substantial stratification of the water column was observed during the winter/fall months, perhaps due to high wind speeds during these two seasons (see section 4 of this report), which together with tidal mixing, helps maintain a well-mixed water column.

Low dissolved oxygen concentrations are considered a critical coastal management issue, both locally (Saarman et al. 2008) and worldwide (Diaz and Rosenberg 2008). Low dissolved oxygen (i.e., hypoxia) is an ongoing issue in parts of Narragansett Bay, particularly in the Upper Bay region (Deacutis et al. 2005; Saarman et al. 2008). Physical and biological factors such as dense macroalgal biomass and phytoplankton blooms, that are exacerbated by anthropogenically-driven eutrophication, are believed to be a major factor leading to low dissolved oxygen conditions (Deacutis 2008; Hamburg et al. 2008). At Nag Creek, our data showed that anoxic events occurred with slightly less frequency but over a longer duration than last year; anoxic episodes lasted up to ten consecutive hours in 2009 and up to six hours in 2008 (Durant and Raposa 2009). A similar trend was found for hypoxic events at Nag Creek and Potter Cove, most of which occurred during low tide periods. Hypoxia also frequently occurred overnight in part due to respiration (D'Avanzo and Kremer, 1994).

The frequency and duration of hypoxic events is critical to different life stages of fish and other invertebrates. An exposure to 2.3 mg L^{-1} of dissolved oxygen for less than 24 hours is considered safe for marine organisms (USEPA 2000). At the Reserve, the majority of the hypoxic events were sporadic readings, although a few lasted up to eight consecutive hours. However, no detrimental effects to fauna or flora (i.e. fish kills, die-offs of marine plants) were noticed during weekly site visits in 2009 (Bertrand personal observations).

pH, a measure of oceanic and estuarine acidity, is mostly controlled by the equilibrium of the inorganic carbon system. For example, the continuous increase in atmospheric carbon dioxide (CO^2) is contributing to a concomitant decrease in oceanic pH (i.e., ocean acidification) (Caldeira and Wickett, 2003). Ocean acidification can adversely affect marine fauna (particularly calcifying species such as shellfish and corals), and ecosystem processes (Fabry et al. 2008), and has been highlighted as a potential indicator of climate change (Harrould-Kolied et al. 2010). At a smaller scale, the opposite has been happening across years at the Potter Cove and T-Wharf Bottom stations where a slight increasing trend in pH has been observed. The reason for an increase in pH at these two stations across years remains unknown. However, we hypothesize that perhaps an increase in photosynthesis by macroalgae, and/or an increase in calcification by bivalves (e.g., mussel beds, quahogs), phytoplankton, and zooplankton might be contributing to the increase in pH by fixing carbon; however, this remains speculative since no information is available at this time on the population dynamics of these groups at these two water quality stations.

Monthly turbidity means among all stations in 2009 were variable and ranged between 0 and 33 NTU. Nag Creek had the highest turbidity recorded among the four water quality stations. In general, turbidity was the lowest during fall and the highest in summer. High turbidity can result from factors such as resuspension of bottom sediments, waste discharge, and urban run-off, among others. In the case of Nag Creek, drift macroalgae was frequently spotted in the creek which might have contributed for the high turbidity at this station.

Chlorophyll concentrations were generally low ($< 8\ \mu g\ L^{-1}$) at all stations throughout 2009. Concentrations at NBNERR tend to be low every year and are comparable to values recorded elsewhere in the Bay (Oviatt et al. 2002). Across years, a decreasing trend may be occurring in the spring, summer and fall at Potter Cove, but this trend is not statistically significant. These results might be related to a decrease in the intensity, duration, and occurrence of the winter–spring bloom at Narragansett Bay (Oviatt 2004), which in turn is related to an increase in winter water temperatures in the Bay (Keller et al. 1999, Oviatt 2004).

In summary, the analysis of the 2009 NBNERR-SWMP water quality data provides a snapshot of the status of important physiochemical parameters in Narragansett Bay estuarine waters during the year. We found that anoxic and hypoxic events were less frequent but of a longer duration in 2009 than in 2008. The long-term seasonal analyses, updated with the 2009 data, provides an indication of how each of these water quality parameters is changing over time, which in turn provides useful information for the general public, scientists, and decision makers.

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3.0. Nutrients and Chlorophyll Trends

3.1 Introduction

In order to complement the long-term water quality monitoring program described in the previous section, the National Estuarine Research Reserve System (NERRS) began a new nutrient and chlorophyll monitoring program in 2002. This program consists of two components, the 'grab' and 'diel' programs (hereafter referred to as the nutrient monitoring program). Both programs require all participating NERR sites to analyze water samples for concentrations of a suite of dissolved nutrient parameters and chlorophyll. The grab sampling program requires duplicate water samples every month at each of the water quality stations. The goal of this program at the Narragansett Bay National Estuarine Research Reserve (NBNERR or Reserve) is to quantify seasonal patterns in nutrient and chlorophyll concentrations in different estuarine habitats (marsh creek, cove, open water surface, open water bottom). The diel program requires the collection of a series of samples from one station over an approximately 24-hour period each month. The goal of this program at NBNERR is to document changes in nutrient and chlorophyll concentrations in response to tidal forcing.

Although the temporal resolution of the nutrient program is limited (i.e., monthly sampling), the collection of data over the long-term will lead to an increasingly robust dataset. As with any long-term monitoring program, the true benefit is recognized once the data have been analyzed and synthesized. Thus, the goal of this section is to conduct a basic synthesis of eight years (2002-2009) of nutrient and chlorophyll data collected at NBNERR as part of the NERR nutrient monitoring program.

3.2 Methods

Grab Sampling Program

Grab samples were collected from Potter Cove, Nag Creek, T-Wharf Bottom and T-Wharf Surface monitoring stations each month around low tide. All grab samples were taken on the same day within the three-hour window before predicted slack low-water. No distinction was made between neap and spring tide conditions. Each month, replicate samples (n=2) were collected by hand at Nag Creek or with a small Niskin bottle at the other three stations. All samples were collected from the approximate depth of the water quality sonde at each station and transferred to wide-mouth amber plastic bottles. Prior to sampling, all bottles were washed in a 10% HCl solution acid bath, rinsed three times with distilled-deionized water, dried, and labeled. In the field, each bottle was rinsed again twice with ambient tidal water. Samples were immediately placed in a cooler with ice and returned to the NBNERR laboratory.

NBNERR staff collecting water with the grab sampler.

Diel Sampling Program

Deploying the ISCO

Diel samples were collected monthly from the T-Wharf Bottom station only using a pre-programmed automated ISCO 6712 sampler deployed on the pier in a secure enclosure (hereafter referred to as the ISCO). The ISCO is programmed to begin sampling at the approximate time of predicted low tide and to collect a 500-ml water sample every 2 hours, 15 minutes over a 24 hour-45 minute diel cycle for a total of 12 water samples. All diel samples were collected from approximately 1 m above the bottom.

Laboratory Procedures

In the laboratory, reserve staff members perform the initial filtering process for all the samples (please see Durant and Raposa 2009). After filtering, the samples were transported to the Marine Ecosystems Research Laboratory (MERL) for chlorophyll analysis, and to Dr. Scott Nixon's laboratory where each nutrient sample was analyzed for phosphate (PO_4), ammonium (NH_4), nitrite (NO_2), nitrite + nitrate ($NO_2 + NO_3$), and dissolved silica (SiO_4) concentrations; nitrate{ NO_3=($NO_2 + NO_3$)-(NO_2)} and dissolved inorganic nitrogen {DIN=($NO_2 + NO_3$)+(NH_4)} are then calculated.

3.2.1 Data Analysis

The nutrient and chlorophyll data from the grab and diel sampling were subjected to NERR and CDMO-QA/QC procedures. After several levels of QAQC, the data were authenticated by CDMO and became authoritative on the CDMO-ODIS website. The data are accompanied by a metadata document, which contains important information that might help to explain any temporal or spatial trends in the data. Due to a lag of over two year for submitted data to be finalized by the CDMO, data used in this report have been run through the CDMO QA/QC procedures but are not the authoritative dataset. However, few differences, if any, are expected between the dataset used in this report and the CDMO authoritative dataset.

2009 Data Analysis

Grab sample data were used to graphically illustrate nutrient and chlorophyll concentrations over an annual cycle. The data were used to calculate monthly and seasonal mean concentrations for each parameter at each station. Seasons were defined as: winter = January through March; spring = April through June; summer = July through September; and fall = October through December. If more than one month of data was missing from a season, the corresponding seasonal mean was not included in any analyses (following Heffner 2009).

Diel sample data were used to examine the effects of tide stage on nutrient and chlorophyll concentrations at T-Wharf Bottom. A series of simple linear regressions were run between water depth (a proxy for tidal stage) and standardized concentrations for each parameter. For each parameter, all concentrations were standardized (i.e., each population was converted to a mean of zero with a standard deviation of one) within each month in 2009 and then pooled across all months (maximum *n* of 144 for each nutrient species). This was done because concentrations in many cases changed across months and seasons. Water depth data for every nutrient and chlorophyll sample were obtained from the Reserve's SWMP water quality monitoring station at T-Wharf Bottom. Concentration data as the dependent variable were then regressed against water depth as the independent variable to examine if nutrient and chlorophyll concentrations changed with water depth (i.e., tide stage).

Long-term Seasonal Trends

All available grab sample data from 2002-2009 were used to graphically illustrate annual nutrient and chlorophyll concentrations over time. For each parameter, monthly concentrations were averaged across years. To examine how seasonal patterns vary by year and to observe how data from 2009 compare with past years, data from each year were combined into one of four seasons and plotted by station over the duration of the grab sampling program. Seasons were defined as mentioned in the section above (2009 Data Analysis). To determine if significant trends had occurred at each station within seasons across years, linear regressions were performed using the seasonal means for each parameter as the dependent variable and year as the independent variable. All regressions were performed using Sigma Stat version 3.5.

3.3 Results

Ninety water samples were collected for nutrient and chlorophyll analysis from the four stations as part of the monthly NBNERR grab program during 2009. An additional 141 samples were collected during the year at T-Wharf Bottom as part of the NBNERR diel program. From both of these programs combined, a total of 240 samples should have been collected (96 from the grab sampling program; 144 from the diel program); therefore 96.3% of all expected samples were collected in 2009. The six missing grab samples were due to ice conditions at Nag Creek in January, February and March; while three missing diel samples were due to problems with the ISCO.

2009 Data

Grab sampling

Monthly mean nutrient and chlorophyll concentrations at each of the four SWMP stations showed, in general, very low (approaching zero) concentrations for all nitrogen species (NH_4, NO_2, NO_3, NO_2 + NO_3, DIN) from April to September (Fig. 15). Phosphate concentrations peaked in September at Potter Cove and Nag Creek, and steadily increased from May to December at both T-Wharf stations. Silica concentrations were similar at both T-Wharf stations, higher at Potter Cove than at the other stations, and peaked at Nag Creek from September to December. Two distinct peaks in chlorophyll were observed in March and August at Nag Creek, and in April and August at T-Wharf Surface. Seasonal patterns in phosphate were similar among all stations except Nag Creek; similar patterns in nitrogen species were observed at all stations in each season except fall; similar patterns in silica were observed among all stations except Nag Creek, and similar seasonal patterns in chlorophyll were observed among all stations except Potter Cove (Fig. 16).

Diel sampling

Based on linear regressions, it was found that there were no significant relationships ($P>0.05$) between nutrient and chlorophyll concentrations and water depth (used as proxy for tidal stage).

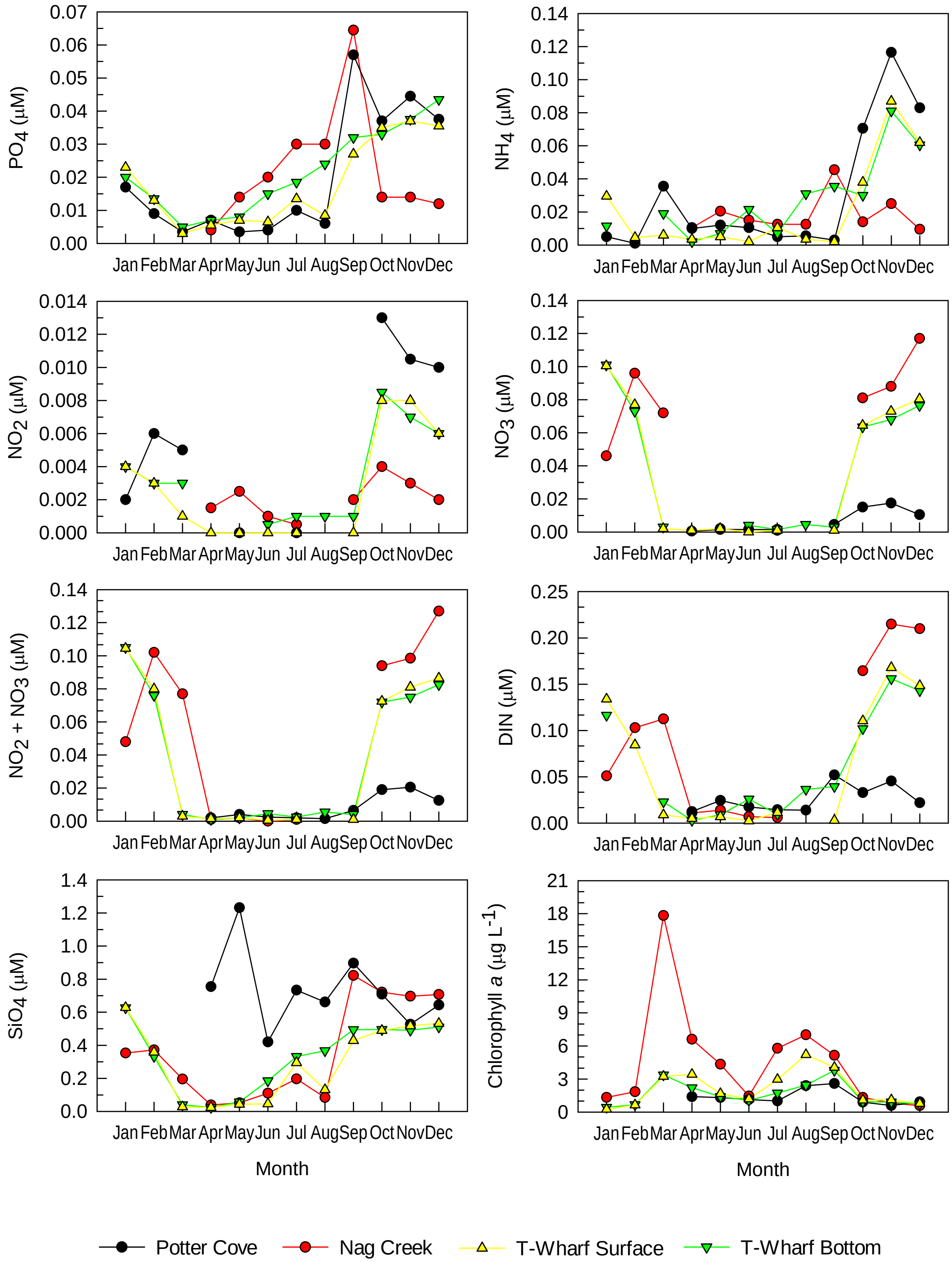

Figure 15. Monthly means for 2009 nutrient and chlorophyll concentrations at each of the four SWMP stations. Error bars were omitted for visual clarity.

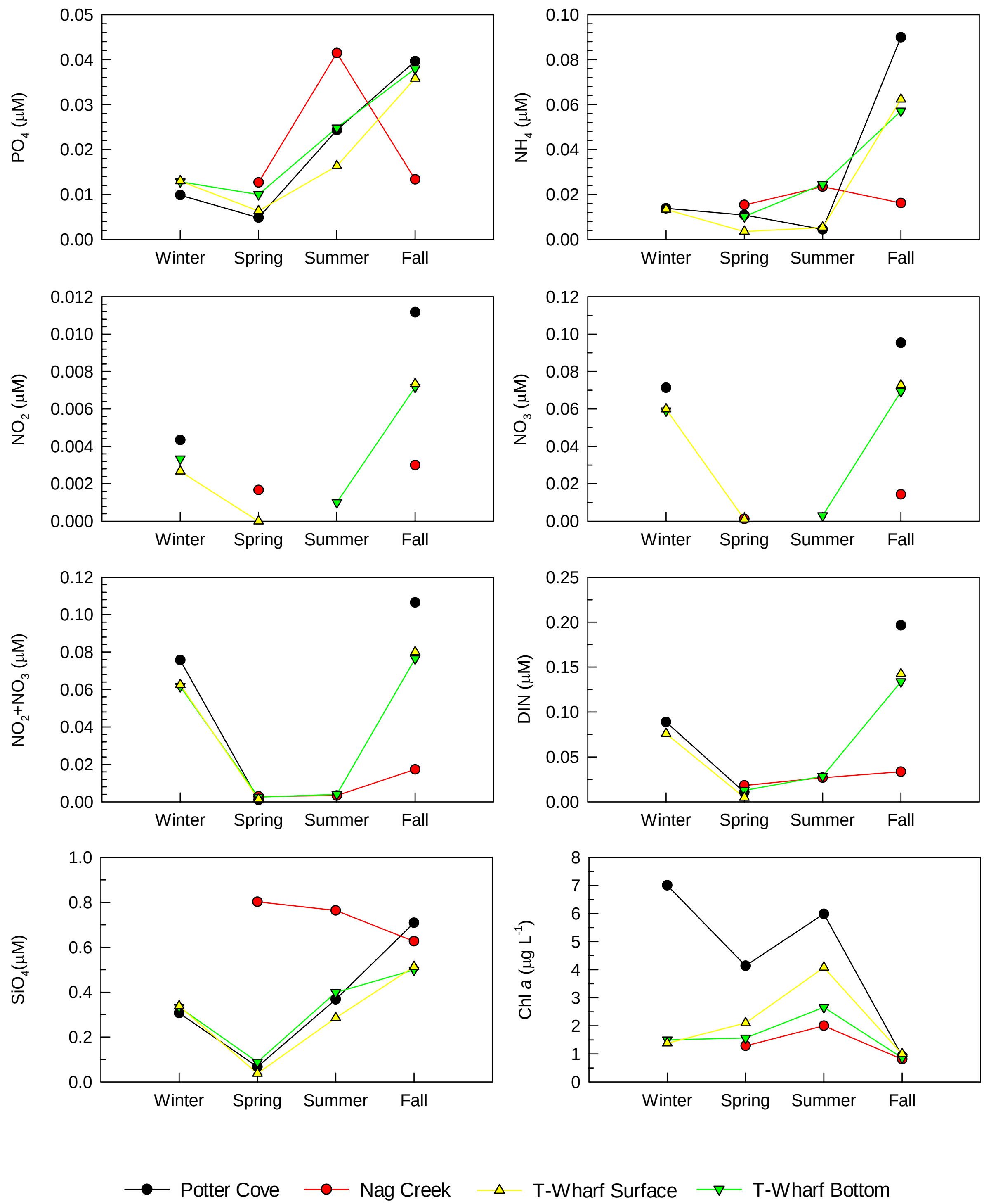

Figure 16. Seasonal means for 2009 nutrient and chlorophyll concentrations at each of the four SWMP stations. Error bars were omitted for visual clarity.

Long-term Data

Long-term seasonal graphs illustrated different patterns and trends for nutrients and chlorophyll across years (Figs. 17-20). Phosphate and ammonium tended to have higher concentrations during summer and fall across years at all stations (Fig. 17). All nitrogen species (nitrite, nitrate, nitrite + nitrate, and dissolved inorganic nitrogen) were present in higher concentrations in winter and fall across years (Figs. 18, 19). Silica concentrations were higher in summer and fall at all stations, and at Nag Creek a higher concentration was observed in spring across years (Fig. 20). Chlorophyll was high across years during winter and summer (Fig. 20). At Potter Cove, a steady increase in chlorophyll was observed in winter, although this was not significant (Fig. 20). Table 2.1 shows all the statistically significant decreasing trends in nutrient concentrations that were found during this analysis.

Table 2.1 Results from linear regression analyses performed on long-term nutrient and chlorophyll data from grab sampling. Only results that were significant ($P<0.05$) are presented. All parameters in the table had a significantly decreasing trend across years

Parameter	Season	Site	P	R^2
DIN	Fall	T-Wharf Surface	0.027	0.585
NO_2	Fall	Nag Creek	0.036	0.548
$NO_2 + NO_3$	Fall	Nag Creek	0.035	0.552
$NO_2 + NO_3$	Fall	Potter Cove	0.023	0.607
$NO_2 + NO_3$	Fall	T-Wharf Bottom	0.037	0.543
$NO_2 + NO_3$	Spring	T-Wharf Bottom	0.032	0.634
$NO_2 + NO_3$	Fall	T-Wharf Surface	0.008	0.718
NO_3	Fall	Nag Creek	0.035	0.551
NO_3	Fall	Potter Cove	0.021	0.614
NO_3	Fall	T-Wharf Bottom	0.038	0.540
NO_3	Fall	T-Wharf Surface	0.006	0.736
PO_4	Summer	Nag Creek	0.021	0.619
PO_4	Spring	T-Wharf Bottom	0.034	0.626
PO_4	Spring	T-Wharf Surface	0.033	0.631

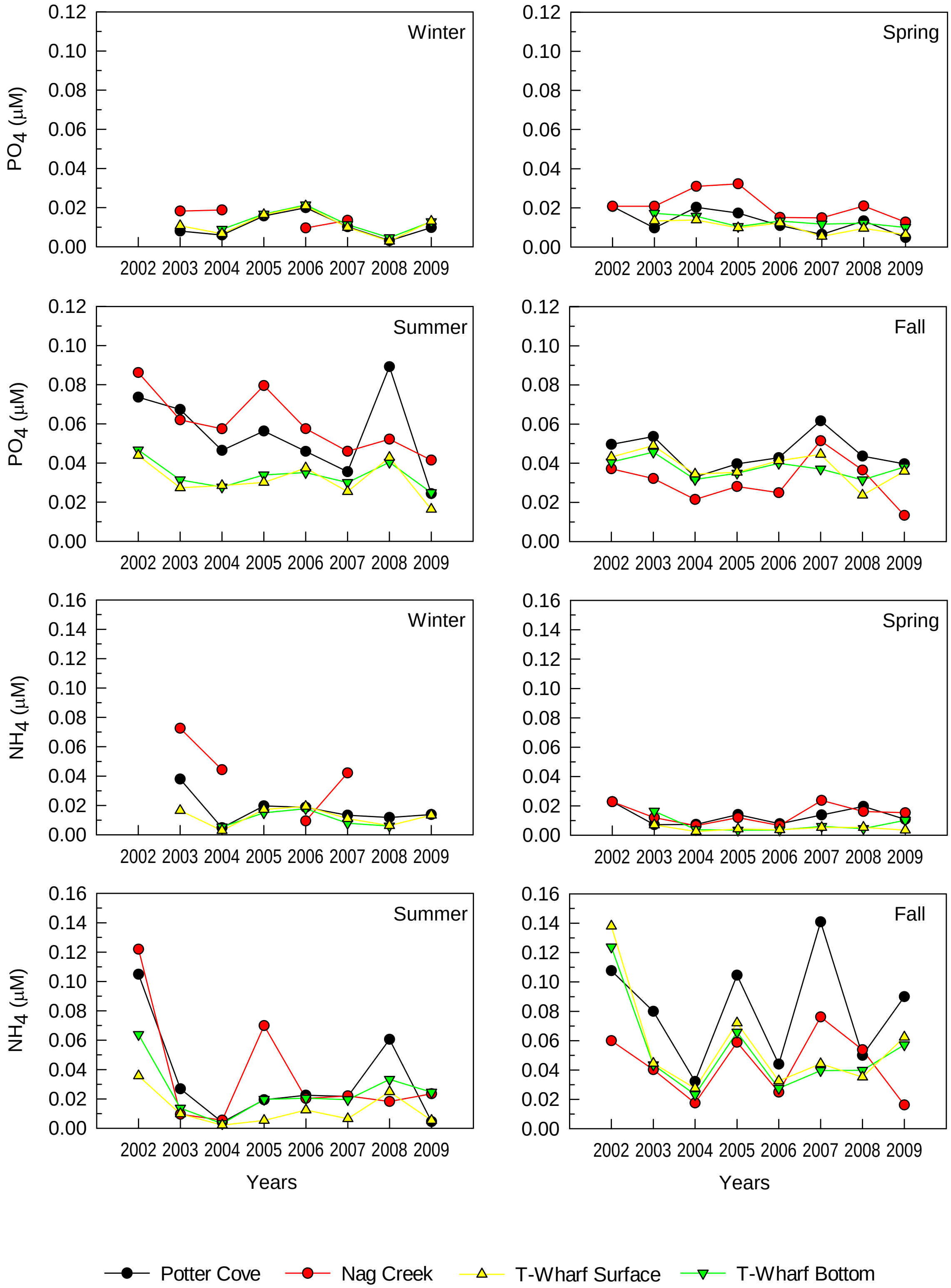

Figure 17. Seasonal means of phosphate (PO_4) and ammonia (NH_4) concentrations at each of the four SWMP stations from 2002 to 2009. Error bars were purposefully omitted for visual clarity.

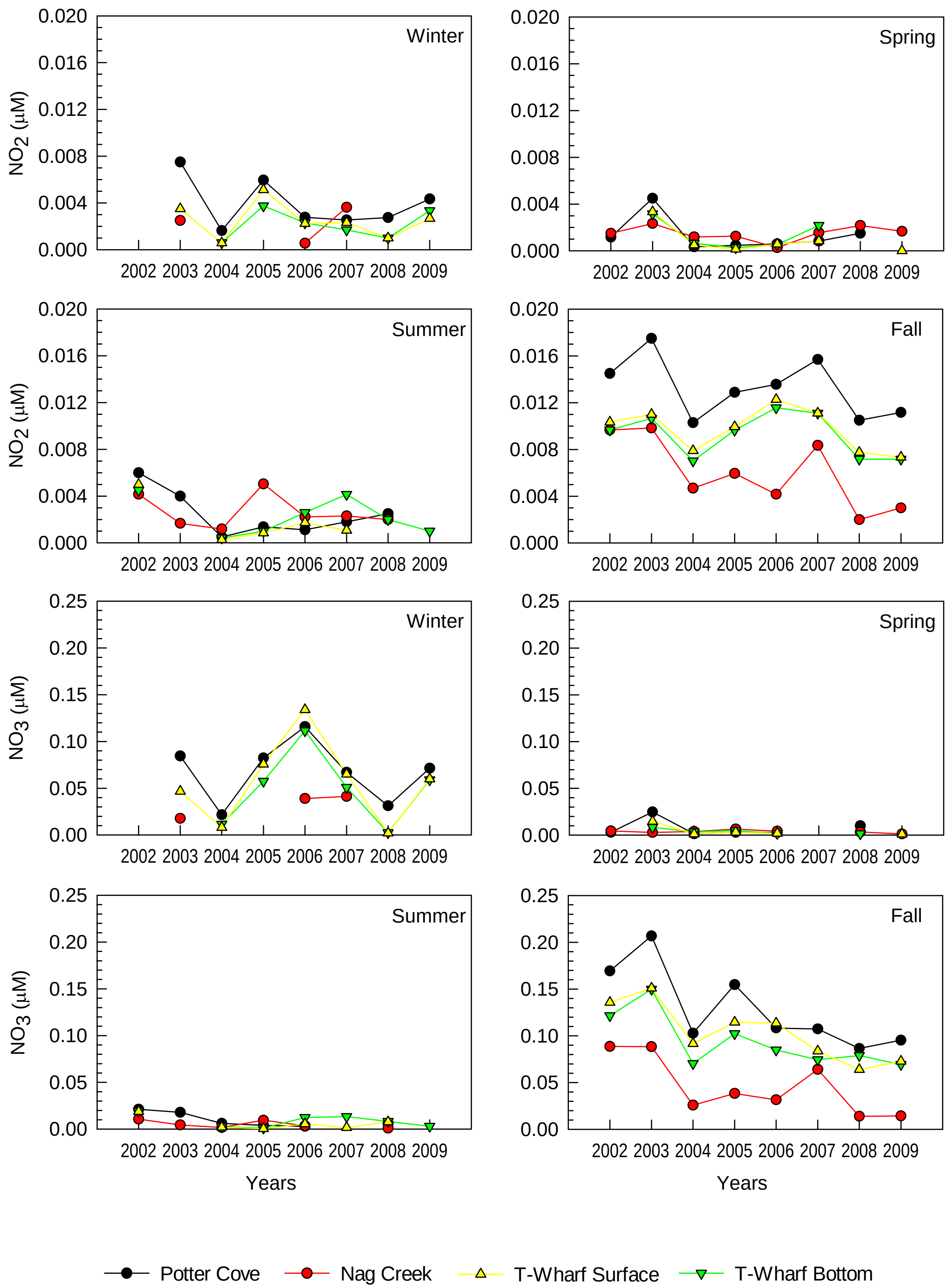

Figure 18. Seasonal means of nitrite (NO_2) and nitrate (NO_3) concentrations at each of the four SWMP stations from 2002 to 2009. Error bars were purposefully omitted for visual clarity.

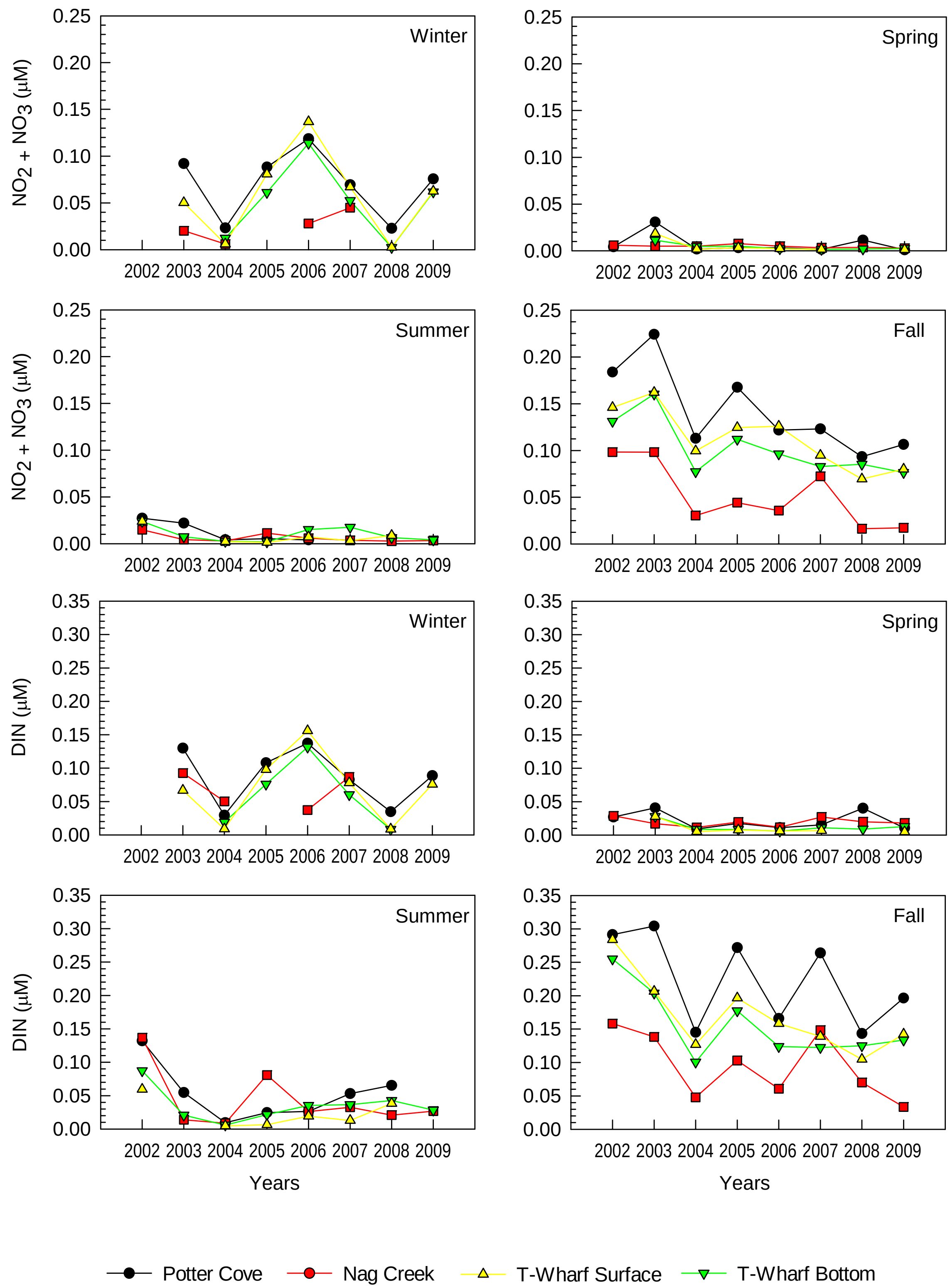

Figure 19. Seasonal means of nitrite and nitrate (NO_2 + NO_3) and dissolved inorganic nitrogen (DIN) concentrations at each of the four SWMP stations from 2002 to 2009. Error bars were purposefully omitted for visual clarity.

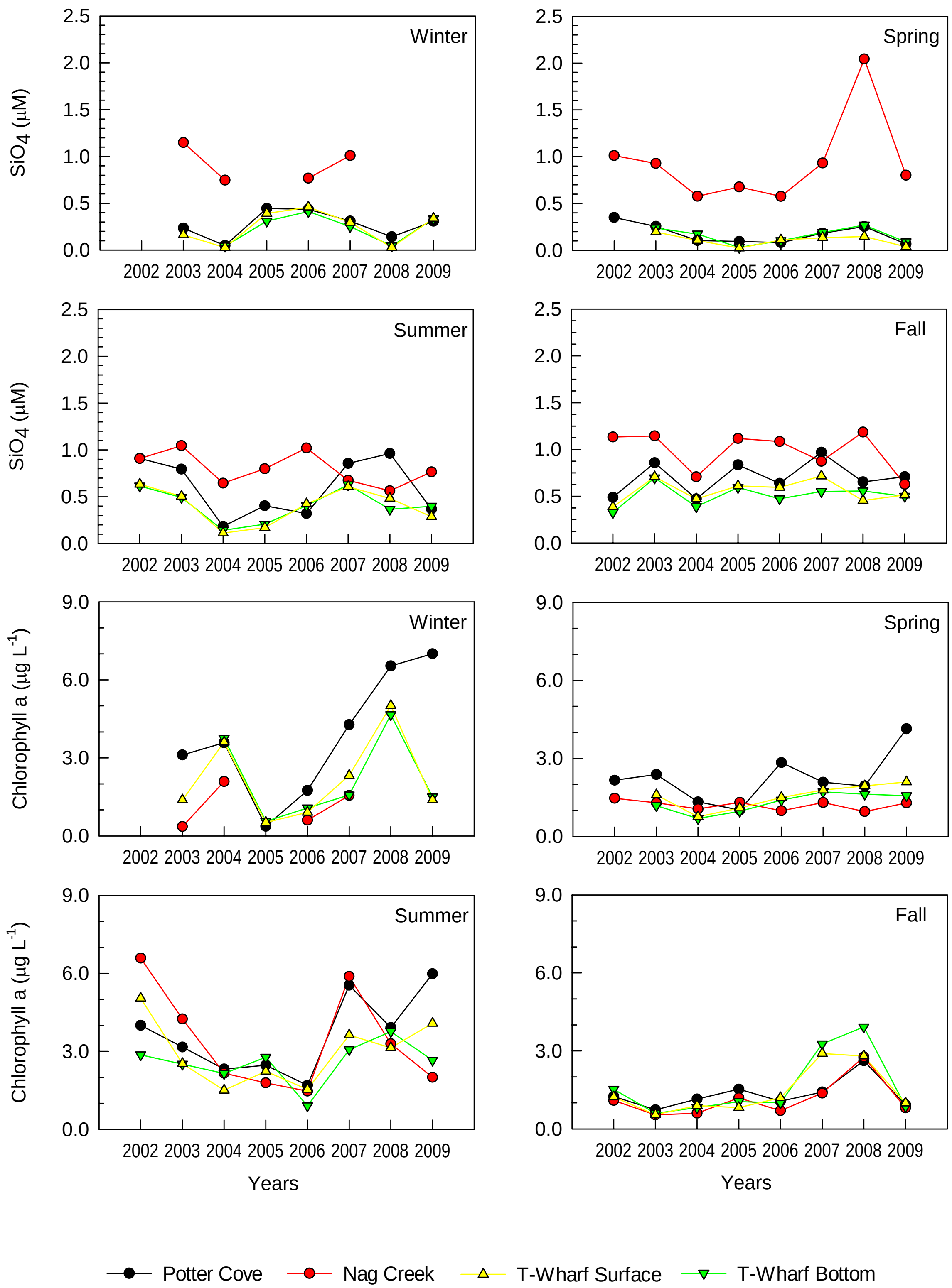

Figure 20. Seasonal means of dissolved silica (SiO_4) and chlorophyll *a* concentrations at each of the four SWMP stations from 2002 to 2009. Error bars were purposefully omitted for visual clarity.

3.4 Discussion

The SWMP nutrient and chlorophyll data from 2009 were analyzed by month and season in this section. The long-term water quality dataset that began in 2002 was also updated to include 2009 data and analyzed within each season across years. The analyses conducted here will help identify any trends in nutrient and chlorophyll concentrations in the Reserve over time.

Based on all of the nutrient and chlorophyll data analyzed from the grab sampling program, concentrations of most nutrient species and chlorophyll exhibited clear seasonal patterns. Phosphate patterns are likely driven by seasonal changes in anthropogenic inputs (e.g., increased fertilizer use in summer) and precipitation patterns. For instance, peaks in phosphate concentration and precipitation were both observed in summer 2008 (see section 4 of this report) implying that the increase in phosphate concentration during this time of year might have been due in part to surface runoff. The proximity of the Potter Cove water quality station to an active farm might also increase phosphate concentrations in this area of the Reserve. Nitrite, nitrate, nitrite + nitrate, and dissolved inorganic nitrogen concentrations have been consistently low in spring and summer across years. This reflects the fact that nitrogen becomes limited in summer in part due to the uptake of the available dissolved nitrogen in the water column by primary producers such as phytoplankton (Kinney and Roman 1998). However, a significant decreasing trend over time was observed for all nitrogen species (NO_2, NO_3, $NO_2 + NO_3$, DIN) in fall when most nitrogen uptake from phytoplankton has ceased. This decreasing trend for most nitrogen species might be due in part to the large-scale regulatory projects that are designed to reduce nutrient inputs into the Bay. One of these projects includes the development of a 10-m wide, 4.8-km long combined-sewer-overflow tunnel under Providence to hold untreated sewage overflows from heavy rains. Another project requires a reduction of approximately 50% of nitrogen inputs into the Bay from selected wastewater treatment facilities.

Silica concentrations were found to be generally lower in winter and spring than in summer and fall at all stations, except in spring at Nag Creek. These results might reflect the effects of a winter-spring bloom that is dominated by diatoms, which use dissolved silica for their frustules during winter and spring (Pratt 1959, Durbin and Durbin 1981).

Chlorophyll concentrations are an excellent indicator of phytoplankton biomass. Seasonal patterns have been described previously (Pilson 1985, Li and Smayda 1998, Oviatt et al. 2002) and are driven by factors such as light, temperature, nutrient availability and grazing pressure exerted by zooplankton (Hargraves 1988, Smayda 1998). Across years, chlorophyll concentrations have been low ($< 8\ \mu g\ L^{-1}$) at the Reserve but comparable to levels from other areas of the Bay (Oviatt et al. 2002). The low concentration in chlorophyll observed here might be related to a decrease in the intensity, duration, and occurrence of the winter–spring bloom at Narragansett Bay (Oviatt 2004), which is correlated with an increase in winter water temperatures in the Bay (Keller et al. 1999, Oviatt 2004).

The analysis of the 2009 diel samples showed absolutely no effect of tidal stage on nutrient and chlorophyll concentrations in the bottom waters at T-Wharf. The same results were found when the long-term data (2002-2008) were analyzed in a previous report (Durant and Raposa 2009). The diel sampling location at T-Wharf Bottom is located approximately in the lower mid-Bay region where there are no substantial direct nutrient inputs; concentrations here therefore remain relatively constant over small time-scales (e.g., over tidal cycles). In light of these results, the NBNERR diel sampling station will be relocated to Potter Cove starting in January 2011 in order to examine the effects of tidal forcing on these parameters in another location. Since Potter Cove is an attractive site for boaters during warm months, diel sampling in the cove would help in isolating the effects of boater wastes on nutrient concentrations in the Cove.

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4.0 Meteorology

4.1 Introduction

Meteorological data have been continuously collected at the Reserve since 2001. These data have been used to support ongoing water quality and biological monitoring efforts, and to assist with scientific research projects around the Bay. Here we analyzed each meteorological parameter collected during 2009 by month and season. In addition, the long-term meteorological dataset was analyzed to determine whether any significant environmental changes or trends are occurring over time in the Reserve.

4.2 Methods

4.2.1 Monitoring Infrastructure

The weather station is located in grassland on the east side of Prudence Island (41° 38.216’ N, 71° 20.350’ W), approximately 389 m south of the Potter Cove water quality monitoring station. A large wooden platform has housed some of the instruments for approximately 17 years. This structure was built by the U.S. Environmental Protection Agency (EPA) to house atmospheric deposition equipment, which is no longer in use. A 10-m aluminum tower is used to mount both the wind sensor and the temperature and humidity sensor.

Weather station on Prudence Island.

4.2.2 Data Collection

At the NBNERR weather station, a CR1000 data logger is used to collect data from sensors that record air temperature, relative humidity, wind speed, wind direction, barometric pressure, precipitation, and photosynthetically active radiation (PAR). The CR1000 is enclosed in a Campbell housing unit that is situated under the aforementioned wooden platform. The housing unit also contains all associated hardware and the barometric pressure sensor. Other associated equipment including a GPS antenna, solar panel, rain gauge, PAR meter, and beam antenna are located on top of the platform. A 10-m aluminum tower is used to mount both the wind sensor and the temperature and humidity sensor (Figure 29). All sensors were located in accordance with manufacturer recommendations.

Meteorological data are sampled at 5-second intervals under the control of the Centralized Data Management Office (CDMO)/Campbell Scientific LoggerNet program. The data are output to memory in 15 minute intervals (an average from the 5-second interval data). The data are downloaded from the CR1000 on an approximately monthly basis to a laptop computer via a RS-232 serial cable connection. The meteorological data are uploaded to CDMO to undergo the same rigorous and careful QAQC process as described for the water quality data (see section 2.2.4-Data Analysis).

4.2.3 Meteorological Telemetry

In July 2006, Campbell Scientific data telemetry equipment was installed at the weather station to transmit collected data on an hourly basis to the NOAA GOES satellite. The near real-time data collected are available online as first-draft data at the CDMO website http://cdmo.baruch.sc.edu/QueryPages/googlemap.cfm. The near real-time telemetry data from the weather station are also considered by CDMO as provisional data and do not comprise an authenticated dataset.

4.2.4 Data Analysis

The data obtained from the datalogger at the weather station is submitted to the CDMO where it goes through several levels of QAQC. After the final QAQC, data are authenticated and posted as authoritative on the CDMO-ODIS website. The data are also accompanied by a metadata document that contains information that could help to explain any potential temporal or spatial trends. Due to the existing delay of over two years for submitted data to be finalized by CDMO, all the data used in this report prior to 2007 (inclusive) are the authoritative datasets from CDMO. Consequently, the datasets after 2007 are provisional although we expect them to be similar to the final authoritative CDMO datasets.

The data can be downloaded by any interested party through the CDMO website (http://www.nerrsdata.org/). Datasets were revised according to the flagging system established by CDMO (Durant and Raposa 2009). In addition, the provisional datasets were checked for outliers by calculating the 3rd standard deviation; data outside the 3rd standard deviation were not included. In this report the resulting dataset is referred to as 'revised data' and was used for statistical analysis, tables, and graphs.

2009 Data

The 2009 revised data comprised from 97-100% of the original dataset (see Appendix I). The revised data were used to calculate monthly and seasonal means for air temperature (^{o}C), relative humidity (%),barometric pressure (mb), wind speed (m s^{-1}), wind direction (degrees); for precipitation (mm) and photosynthetic radiation (mmol m^{-2}), monthly and seasonal totals were calculated. Seasonal means were calculated following Heffner (2009) and mentioned in section 2.2.4-Data Analysis. To calculate seasonal wind direction for 2009, the Lakes Environmental Software (1998-2010)-Wind Rose Plots for Meteorological Data (WRPLOT View, v 6.5.1) was used. This program generates wind rose plots using wind direction, wind speed, and precipitation information.

Long-term Seasonal Trends

The percentage of data used to calculate the long-term seasonal means for each parameter at each station up through 2008 is presented in detail elsewhere (Durant and Raposa, 2009). Long-term seasonal means for air temperature, relative humidity, wind speed, wind direction, barometric pressure, and seasonal totals for precipitation and photosynthetic active radiation were calculated following Heffner (2009). To determine if significant changes occurred within seasons across years, linear regressions were performed for each parameter using Sigma Stat v3.5.

A general decreasing trend in barometric pressure was found across years at NBNERR. To further investigate, five years of data (2006 to 2010) from the northeast NERRs (Narragansett Bay, Wells Bay, Great Bay, Waquiot Bay, and Hudson River) were obtained from the CDMO website to calculate the long-term seasonal means and determine if the decreasing trend in barometric pressure is a local or regional phenomenon. Seasonal means were calculated following Heffner (2009) and mentioned in the 2.2.4-Data Analysis section. Statistical comparison was made using Two-Way ANOVA for each season with Reserve and Year as factors, and the Holm-Sidak method for pair-wise comparison. All the data passed the normality and homogeneity of variance test (P>0.05). All statistical tests were performed using Sigma Stat v3.5.

Correlation Analyses

Correlation analyses were performed using the long-term meteorological and water quality datasets to explore relationships between meteorological parameters and water quality parameters at each of the SWMP stations. A Pearson Correlation was performed when the data passed the normality assumption ($P \geq 0.05$); a Spearman Correlation was used if the data did not pass the normality test ($P < 0.05$).

4.3 Results

4.3.1 Air Temperature

Monthly and seasonal mean air temperatures in 2009 at the Potter Cove weather station followed a distinct pattern that is typical of temperate latitudes (Fig. 21a). Air temperature ranged from -15.8 to 33.0 °C (Appendix I). The minimum monthly mean was recorded in January (-3.5 °C), while the maximum monthly mean was recorded in August (22.5 °C, Fig. 21a). In terms of seasonal means, the highest temperatures occurred in summer (21.4 °C), while the lowest occurred in winter (2.4 °C, Fig. 21b).

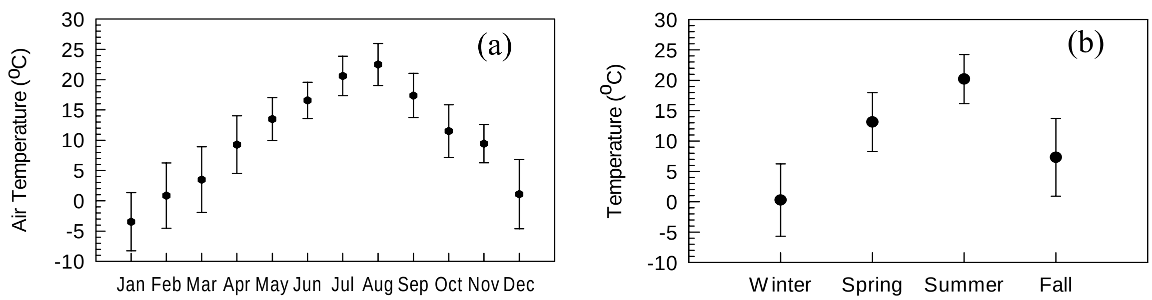

Figure 21. Monthly (a) and seasonal (b) mean air temperature (± 1 standard deviation) for 2009 meteorological data.

Long-term seasonal temperature means exhibited very similar seasonal patterns across years; consequently, no significant trends were found over time for any season (Fig. 22). In 2009, seasonal mean air temperatures were generally similar to most previous years.

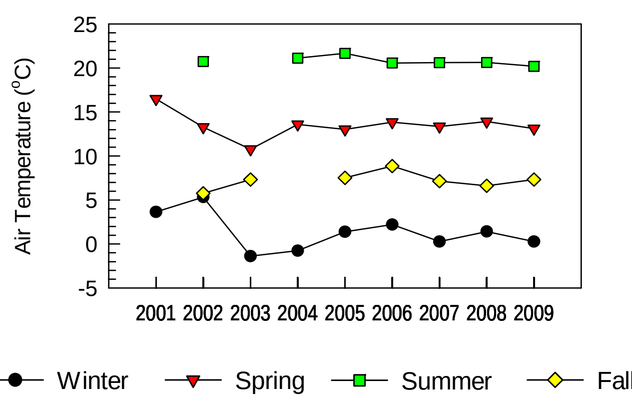

Figure 22. Long-term seasonal means calculated for air temperature recorded at the weather station. Error bars were omitted for visual clarity.

4.3.2 Relative Humidity

Relative humidity ranged from 16 to 100% (Appendix I). The minimum monthly mean was observed in February (67%) and the maximum in June (88%, Fig. 23a). In terms of seasonal means, the highest humidity levels occurred in summer (82%), and the lowest in winter (68%, Fig. 23b). Nevertheless, there was a relatively high amount of variability within each month and season during 2009.

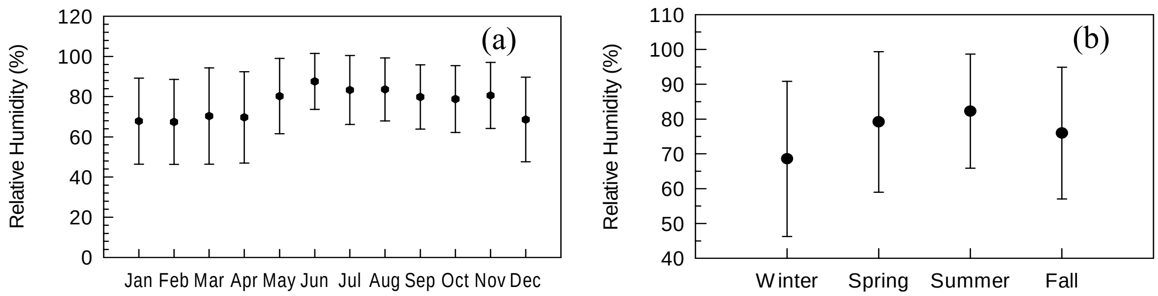

Figure 23. Monthly (a) and seasonal (b) mean relative humidity (± 1 standard deviation) for 2009 meteorological data.

Long-term seasonal relative humidity means exhibited comparable seasonal patterns across years and no significant trends over time were found for any season (Fig. 24). In 2009, seasonal mean relative humidity was generally similar to most previous years.

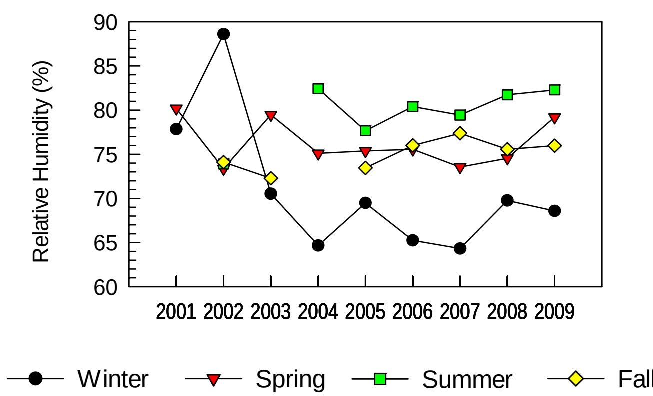

Figure 24. Long-term seasonal means calculated for relative humidity recorded at the weather station. Error bars were omitted for visual clarity.

4.3.3 Barometric Pressure

Barometric pressure ranged from 988 to 1034 mb (Appendix I). The minimum monthly mean was recorded in June (1008 mb), while the maximum was recorded in March (1019 mb, Fig. 25a). In terms of seasonal means, the highest barometric pressure values were recorded during winter (1016 mb) and the lowest were recorded during spring (1012 mb, Fig. 25b).

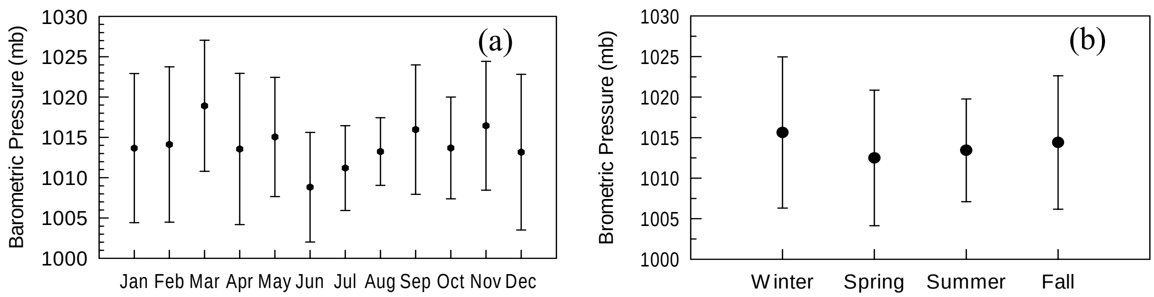

Figure 25. Monthly (a) and seasonal (b) mean barometric pressusre (± 1 standard deviation) for 2009 meteorological data.

Long-term seasonal barometric pressure means decreased significantly over time in spring (R^2=0.860, P<0.001) and summer (R^2=0.833, P=0.002) although the causes of this decrease remain unknown (Fig. 26). Except for winter, seasonal mean barometric pressure was lowest in 2009 relative to all other years.

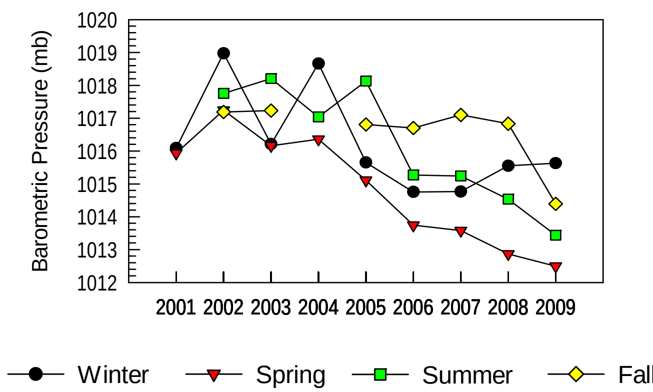

Figure 26. Long-term seasonal means calculated for barometric pressure recorded at the weather station. Error bars were omitted for visual clarity.

The Two-Way ANOVA found that barometric pressure did not differ among Reserves (F=2.85, P=0.059) but decreased significantly across years in winter (F=11.83, P<0.001); for fall, no significant differences were found among Reserves (F=2.36, P=0.100) but a significant decrease was found across years (F=14.53, P<0.001); for spring, no significant differences were found among Reserves (F=0.53, P=0.717) but a significant decrease was found across years (F=3.41, P=0.036); for summer, no significant differences were found among Reserves (F=1.96, P=0.153) or across years

(F=2.69, P=0.07). The Holm-Sidak multiple comparison test found that for winter, spring, and fall, the barometric pressure was significantly lower in 2010 (P<0.05) when compared to the rest of the years. These results were also observed when the long-term seasonal barometric pressure data were plotted for all the Reserves (Fig. 27).

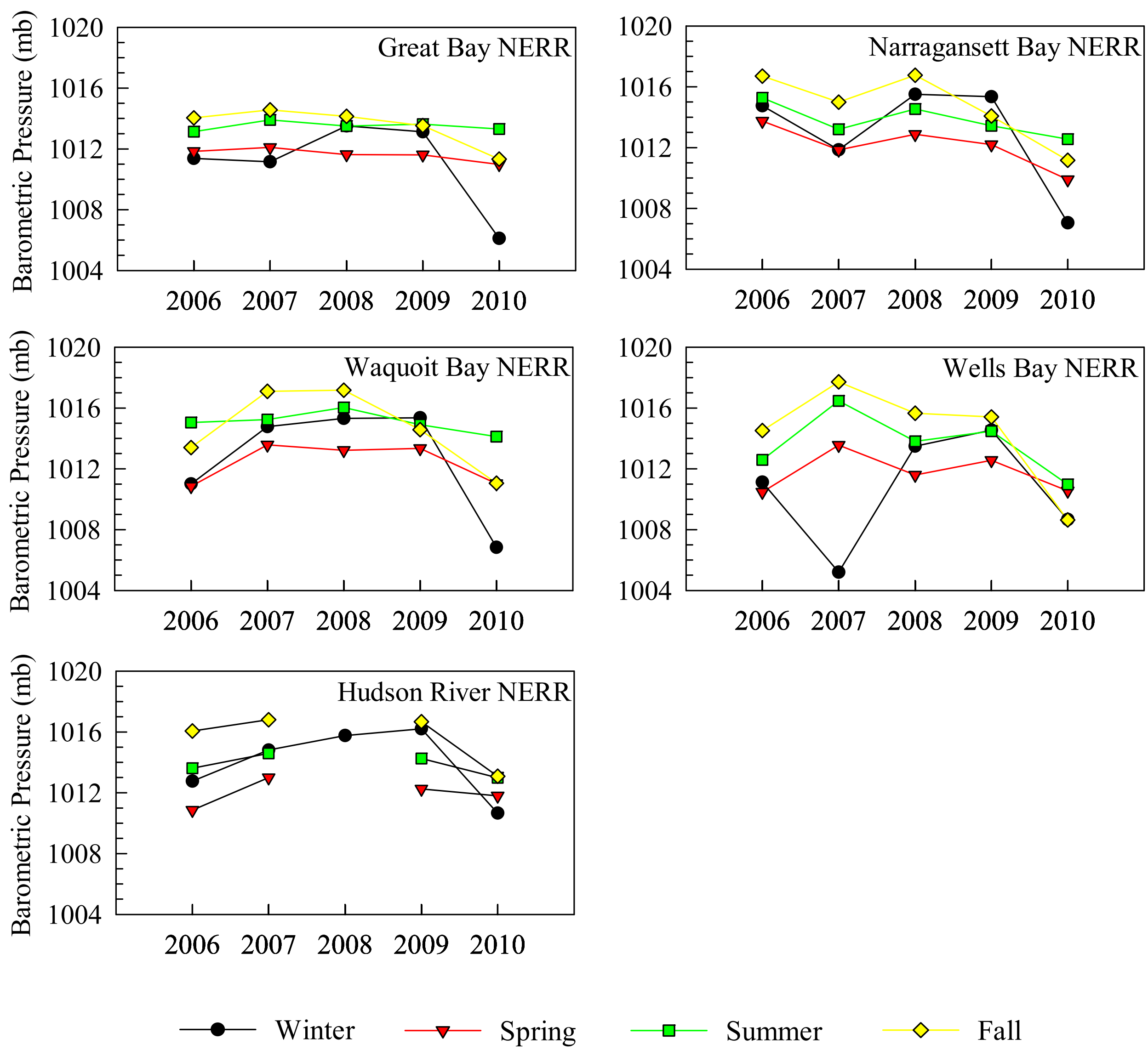

Figure 27. Long-term seasonal barometric pressure means calculated for Great Bay, Narragansett Bay, Waquoit Bay, Wells Bay, and Hudson River NERR.

4.3.4 Wind Speed

Wind speed ranged from 0 to 10.9 m s^{-1} (Appendix I). The minimum monthly mean was observed in August (2.8 m s^{-1}), while the maximum monthly mean was observed in November (4.5 m s^{-1}, Fig. 28a). In terms of seasonal means, the highest wind speeds were recorded in winter (4.3 m s^{-1}) and the lowest in summer (3.1 m s^{-1}, Fig. 28b).

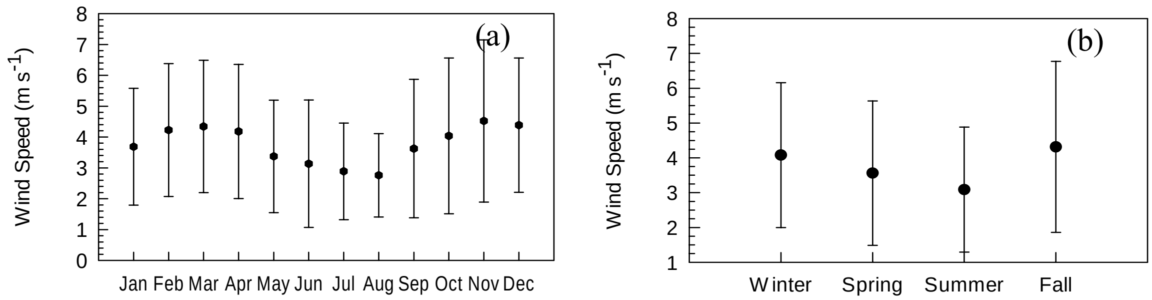

Figure 28. Monthly (a) and seasonal (b) mean wind speed (± 1 standard deviation) for 2009 meteorological data.

Long-term seasonal mean wind speeds exhibited no clear trends across years or among seasons (Fig. 29). In 2009, seasonal mean wind speeds were generally similar to most previous years.

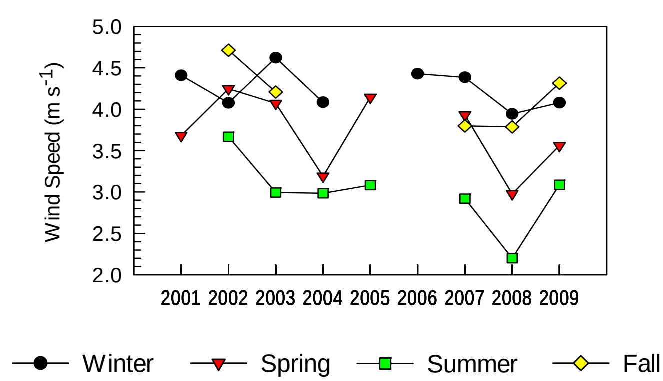

Figure 29. Long-term seasonal means calculated for wind speed recorded at the weather station. Error bars were omitted for visual clarity.

4.3.5 Wind Direction

Across all of 2009, winds blew mainly from the west to southwest in spring and summer and from the west to north in winter and fall (Fig. 30).

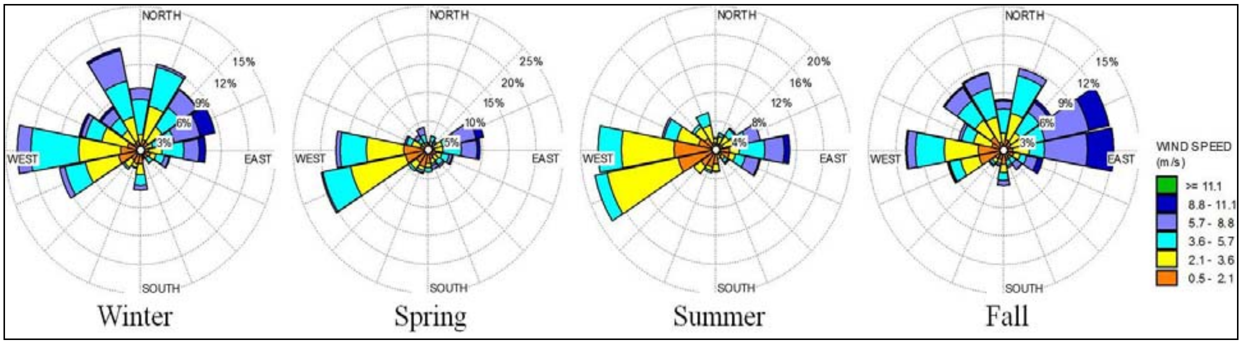

Figure 30. Seasonal mean wind direction for 2009 meteorological data. The wind rose was generated with the Lakes Environmental Software (1998-2010) - Wind Rose Plots for Meteorological Data.

4.3.6 Precipitation

Total precipitation ranged from 0 to 18 mm during 2009 (Appendix I). The minimum total precipitation was observed in February (46 mm), while the maximum was observed in July (188 mm, Fig. 31a). In terms of seasonal totals, the highest amount of precipitation was recorded in fall (391 mm) and the lowest in winter (148 mm, Fig. 31b).

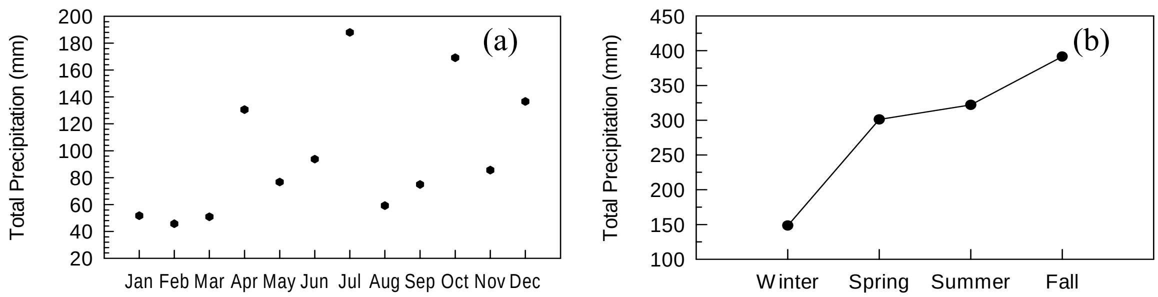

Figure 31. Monthly (a) and seasonal (b) totals for precipitation for 2009 meteorological data.

Long-term seasonal total precipitation did not exhibit any significant trends across years (Fig. 32). In 2009, seasonal precipitation totals were generally comparable with most prior years, except in fall, which had the second highest (391 mm) amount of precipitation for this season.

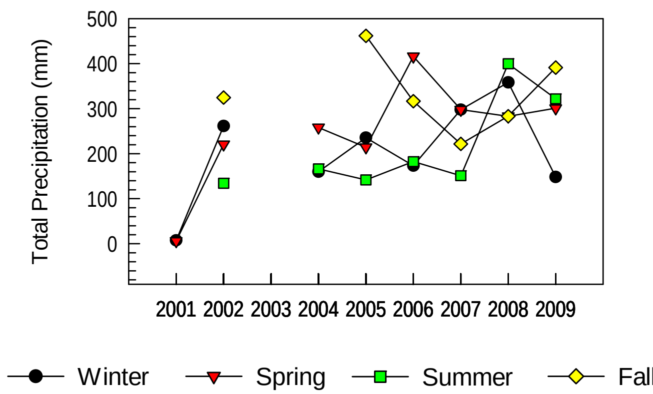

Figure 32. Long-term seasonal totals calculated for precipitation recorded at the weather station.

4.3.7 Photosynthetic Active Radiation

Total photosynthetic active radiation ranged from 0 to 1714 mmol m^{-2} (Appendix I) in 2009. The minimum monthly total PAR was observed in November (302435 mmol m^{-2}), while the maximum was observed in July (1086033 mmol m^{-2}, Fig. 33a). In terms of seasonal PAR totals, the highest totals occurred in summer and the lowest in fall (Fig. 33b).

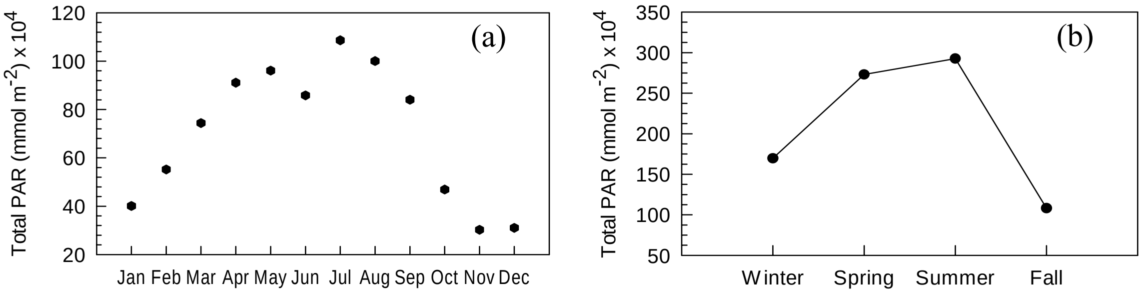

Figure 33. Monthly (a) and seasonal (b) totals for photosynthetic active radiation for 2009 meteorological data.

Long-term seasonal PAR totals exhibited very similar patterns across years; consequently, no significant trends were found over time for any season (Fig. 34). In 2009, seasonal PAR totals were generally similar to most previous years.

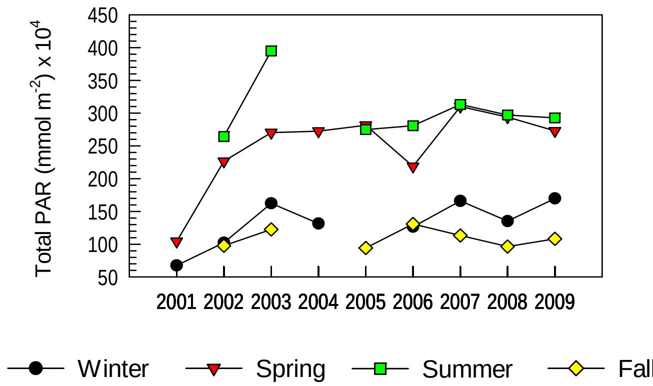

Figure 34. Long-term seasonal totals for photosynthetic active radiation recorded at the weather station.

4.3.8 Correlation Analyses

Results of the correlation analyses relating meteorological and water quality parameters are shown on Table 4.1. These results indicate that the T-Wharf Surface water quality is most affected by meteorological parameters in spring and Nag Creek in summer. In general across all seasons, the least affected station was Potter Cove (Table 4.1). The correlations indicate that air temperature is the most common meteorological parameter that affects water quality parameters among seasons. In turn, water temperatures and chlorophyll concentrations were the water quality parameters most often affected by meteorological conditions.

In general, some significant relationships between meteorological and water quality parameters were found, but no clear patterns or trends emerged (Table 4.1). The results show that different meteorological parameters can affect the same water quality parameter during the same season at different stations. For example, summer chlorophyll concentrations seem to increase significantly with increasing air temperatures at Potter Cove (R^2=0.86, P=0.03), but with increasing PAR at Nag Creek (R^2=0.97, P<0.001). Conversely, the same meteorological parameters can affect the same water quality parameter during different seasons. For example, water temperature increases significantly with increasing air temperature in spring at Potter Cove (R^2=0.69, P=0.04), in fall at Nag Creek (R^2=0.85, P=0.03), and in fall and spring at T-Wharf Surface (R^2=0.84, P=0.02, R^2=0.83, P=0.02, respectively) and Bottom (R^2=0.75, P=0.04, R^2=0.78, P=0.04, respectively).

Table 4.1. Correlation between the long-term meteorological (MET) and water quality (WQ) datasets for all water quality stations. Empty cells indicate that no significant correlation (P>0.05) was found.

Potter Cove		Fall			Spring			Summer			Winter		
MET	WQ	R^2	P	N	R^2	P	N	R^2	P	N	R^2	P	N
Air Temperature	Temperature				0.70	0.04	9						
Air Temperature	Chlorophyll							0.86	0.03	6			
Air Temperature	DO % sat.	-0.89	0.01	7									
Relative Humidity	Turbidity				-0.76	0.02	9						

Nag Creek		Fall			Spring			Summer			Winter		
MET	WQ	R^2	P	N	R^2	P	N	R^2	P	N	R^2	P	N
Air Temperature	pH							-0.89	0.03	6			
Air Temperature	Temperature	0.85	0.03	6									
Barometric Pressure	Temperature							0.75	0.03	8			
Relative Humidity	Temperature							-0.91	0.01	6			
Total PAR	Chlorophyll							0.97	0.00	6			

T-Wharf Surface		Fall			Spring			Summer			Winter		
MET	WQ	R^2	P	N	R^2	P	N	R^2	P	N	R^2	P	N
Air Temperature	Temperature	0.84	0.02	7	0.84	0.02	7						
Barometric Pressure	Turbidity				0.89	0.03	6						
Total PAR	Chlorophyll										-0.93	0.02	5
Total PAR	DO concentration	-0.85	0.02	7									
Total Precipitation	pH				0.89	0.02	6						
Wind Speed	DO concentration				0.89	0.02	6						
Wind Speed	Temperature				-0.91	0.01	6						
Wind Speed	Turbidity							-0.94	0.02	6			

T-Wharf Bottom		Fall			Spring			Summer			Winter		
MET	WQ	R^2	P	N	R^2	P	N	R^2	P	N	R^2	P	N
Air Temperature	Temperature	0.75	0.04	7	0.78	0.04	7						
Barometric Pressure	Temperature										-0.96	0.00	7
Relative Humidity	pH	0.83	0.04	6									
Total Precipitation	Turbidity							0.89	0.04	5			
Wind Speed	Chlorophyll	0.93	0.02	5									

4.4 Discussion

In this section, the SWMP meteorological data from 2009 were analyzed by month and season. The long-term dataset that begins in 2001 was updated with 2009 data and analyzed within each season to determine if any patterns or trends are present across years. By analyzing the meteorological data collected through the SWMP, we can improve our understanding of how meteorological parameters might affect estuarine water quality in Narragansett Bay.

The meteorological parameters analyzed in 2009 exhibited seasonal patterns that are characteristic of temperate zones. Although our long-term data did not show any significant trends, with the exception of barometric pressure, much longer datasets have shown a distinct warming trend in Narragansett Bay (Pilson 2008). It remains difficult to identify any meaningful trends from this relatively limited dataset. However, as the dataset grows over time it should be possible to detect other long-term meteorological trends that might emerge, which can then be related back to patterns in water quality.

The decreasing trend in barometric pressure observed for Narragansett Bay across years demonstrated to be a regional occurrence when the same trend was found for four other northeast Reserves. Narragansett Bay, Wells Bay, Great Bay, Waquiot Bay, and Hudson River NERR had a decreasing trend in barometric pressure for all seasons across years, except for summer. Even though it is unknown how this might affect the weather at these locations, changes in barometric pressure over time could be associated with different kinds of weather systems like snow storms, heavy precipitation, wind shifts, increase cloudiness, etc., when other meteorological parameters are associated with these changes, i.e. changes in temperature.

The correlation analyses between the long-term meteorological and water quality datasets demonstrate that the four SWMP water quality stations may be affected differently by different meteorological parameters. This in turn might be related to the gradient in habitat types that these stations represent, ranging from salt marsh (Nag Creek station) to shallow cove (Potter Cove) to open Bay water (T-Wharf Surface and T-Wharf Bottom). However, these water quality parameters might also be affected by factors other than the meteorological parameters discussed here. These could include other physiochemical parameters that are not currently being measured by the Reserve but could be added to its monitoring program in the future (i.e. sedimentation rates, surface runoff, anthropogenic disturbances, underwater PAR, light attenuation, total irradiance, atmospheric carbon, etc.).

4.4 Literature Cited

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Heffner, L. 2009. Nutrients in mid-Narragansett Bay: a spatial comparison of recent and historical data. Narragansett Bay Research Reserve. Technical Series 2009:1.

Pilson, M.E.Q. Narragansett Bay amidst a globally changing climate. In: Science for Ecosystem-based Management: Narragansett Bay in the 21st Century. A. Desbonnet and B.A. Costa-Pierce (eds.). Pages 35-46. Springer, New York, NY.35-46.

Appendix I. Descriptive Statistics for 2009 Water Quality and Meteorological Datasets

Potter Cove

	Temp. (°C)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (µg L^{-1})
Original Dataset	35040	35040	35040	35040	35040	35040	35040
Revised Dataset (No. Data points)	29865	29475	27476	27813	29828	26708	29444
% Data Used	85	84	78	79	85	76	84
Mean	12.30	28.41	93.14	8.53	7.90	0.86	3.78
Std Dev	7.59	1.81	16.40	2.47	0.24	1.64	2.99
Std. Error	0.044	0.011	0.099	0.015	0.001	0.010	0.017
C.I. of Mean	0.086	0.021	0.194	0.029	0.003	0.020	0.034
Range	29.24	19.8	107.1	15.23	1.42	14.5	16.1
Maximum	26.89	34.4	146.3	15.98	8.61	14.1	16.1
Minimum	-2.35	14.6	39.2	0.75	7.19	0.0	0.0
Median	12.38	28.38	93.8	8.31	7.9	0.4	3.1
25%	4.9	27.2	85.4	6.9	7.8	0.0	1.5
75%	19.1	29.5	102.7	10.5	8.0	1.0	5.3

Nag Creek

	Temp. (°C)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (µg L^{-1})
Original Dataset	35040	35040	35040	35040	35040	35040	35040
Revised Dataset (No. Data points)	23329	22722	23288	23249	23328	21370	23157
% Data Used	100	97	100	100	100	92	99
Mean	16.92	27.39	74.84	6.29	7.47	2.30	4.21
Std Dev	6.36	3.43	32.74	2.83	0.41	3.58	2.65
Std. Error	0.042	0.023	0.215	0.019	0.003	0.025	0.017
C.I. of Mean	0.082	0.045	0.421	0.036	0.005	0.048	0.034
Range	33.87	20.5	173.2	14.97	2.12	33	18.4
Maximum	32.6	34.27	173.2	14.96	8.57	33	18.4
Minimum	-1.27	13.77	0	0.0	6.45	0	0
Median	17.42	27.96	79	6.68	7.46	1.2	3.6
25%	12.4	25.8	51.7	4.2	7.1	0.1	2.3
75%	21.7	29.7	97.4	8.4	7.8	2.8	5.4

T-Wharf Surface

	Temp. (°C)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (μg L^{-1})
Original Dataset	35040	35040	35040	35040	35040	35040	35040
Revised Dataset (No. Data points)	32434	32385	32378	32396	31116	31599	32097
% Data Used	93	92	92	92	89	90	92
Mean	12.24	29.57	97.91	8.88	7.99	0.30	2.96
Std Dev	6.76	1.56	8.56	1.48	0.22	0.56	2.20
Std. Error	0.038	0.009	0.048	0.008	0.001	0.003	0.012
C.I. of Mean	0.074	0.017	0.093	0.016	0.002	0.006	0.024
Range	24.46	8.47	95.9	8.66	1.3	8.1	17
Maximum	25.32	33.31	168.1	13.19	8.66	8.1	17
Minimum	0.86	24.84	72.2	4.53	7.36	0.0	0.0
Median	12.33	29.56	95.8	8.57	7.95	0.0	2.4
25%	5.7	28.5	92.1	7.8	7.9	0.0	1.4
75%	18.6	30.7	103.3	10.2	8.1	0.4	3.9

T-Wharf Bottom

	Temp. (°C)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (μg L^{-1})
Original Dataset	35040	35040	35040	35040	35040	35040	35040
Revised Dataset (No. Data points)	34812	34679	27408	27792	32656	33916	33385
% Data Used	99	99	78	79	93	97	95
Mean	11.26	30.18	92.30	8.45	8.12	2.24	3.28
Std Dev	6.27	1.24	12.60	1.76	0.35	3.27	2.30
Std. Error	0.034	0.007	0.076	0.011	0.002	0.018	0.013
C.I. of Mean	0.066	0.013	0.149	0.021	0.004	0.035	0.025
Range	22.75	6.92	80.8	9.73	2.02	29.8	12
Maximum	23.92	33.32	131.7	13.03	9.17	29.4	12
Minimum	1.17	26.4	50.9	3.3	7.15	0.0	0.0
Median	11.38	30.23	95.3	8.54	8.06	1.3	2.9
25%	5.1	29.3	88.9	7.5	7.9	0.7	1.6
75%	17.3	31.2	99.5	9.6	8.4	2.5	4.4

Weather Station

	Air Temp. (^oC)	Relative Humidity (%)	Barometric Pressure (mb)	Wind Speed (m s^{-1})	Wind Direction (degrees)	Total Precip. (mm)	Total PAR (mmol s^{-1})
Original Dataset	35040	35040	35040	35040	35040	35040	35040
Revised Dataset (No. Data points)	35038	35038	34755	34583	35038	35038	35038
% Data Used	100	100	99	99	100	100	100
Mean	10.27	76.53	1013.98	3.75	190.07	0.03	240.69
Std Dev	9.10	20.19	8.20	2.17	112.27	0.25	382.73
Std. Error	0.049	0.108	0.044	0.012	0.600	0.001	2.045
C.I. of Mean	0.095	0.211	0.086	0.023	1.176	0.003	4.008
Range	48.844	84	46	10.9	360	18.03	1714.38
Maximum	33.044	100	1034	10.9	360	18.03	1714.33
Minimum	-15.8	16	988	0.0	0.0	0.0	0
Median	10.98	79.84	1014.14	3.32	236.59	0.0	5.85
25%	4.0	61.2	1008.9	2.1	79.0	0.0	0.0
75%	17.3	95.8	1020.0	5.0	279.4	0.0	356.2