Narragansett Bay
Research Reserve

Technical Report
2010:2

Water Quality, Nutrients, and Meteorology at the Narragansett Bay National Estuarine Research Reserve: 2008 Annual Report

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June 2010

Technical Report Series 2010:2

Executive Summary

The Narragansett Bay National Estuarine Research Reserve (NBNERR or Reserve) is part of the National Estuarine Research Reserve System (NERRS or Reserve System), which was established under Section 315 of the Coastal Zone Management Act of 1972. The Reserve System protects estuarine and coastal habitats and promotes science-based management of these habitats through research, education, stewardship, and training. The Reserve protects an estimated 1780 hectares of land and water (out to a depth of 5.5 m) on and around Prudence, Patience, Hope and Dyer islands in the middle of Narragansett Bay, Rhode Island. The mission of the Reserve is to practice and promote coastal and estuarine stewardship through innovative research and education.

The signature program 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 for tracking short-term variability and long-term changes in estuarine environments. Since 1995, the Reserve has collected SWMP data providing long-term datasets and scientific information to decision-making agencies and the private sector to effectively address coastal resource management issues. This is accomplished by collecting 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).

Water quality parameters have been collected since 1995 with the establishment of the first water quality monitoring station at Potter Cove. The remaining three water quality stations were brought online in subsequent years. Water temperature (^{o}C), salinity (ppt), dissolved oxygen (% saturation, and mg L^{-1}), pH, turbidity (NTU), and chlorophyll (μg L^{-1}) data are collected at each station. Data are collected every 15 minutes using data loggers that are calibrated and swapped out at each station approximately every two weeks.

Collection of meteorological data on Prudence Island began in 2001. Measured parameters include: air temperature (^{o}C), relative humidity (%), barometric pressure (mb), wind speed (m s^{-1}), wind direction (degrees), precipitation (mm), and photosynthetically active radiation (PAR, mmol m^{-2}). Data are collected every 5 seconds and averaged into 15-minute intervals. These data are stored by a central data logger and downloaded on an approximately monthly basis.

The nutrient monitoring component of SWMP began in 2002. The two sub-components of this program include monthly grab sampling at each of the four water quality stations, and diel sampling once a month at the T-Wharf Bottom station. All collected samples are analyzed for concentrations of PO_4, NH_4, NO_2, NO_3, NO_2+NO_3, DIN, SiO_4, and chlorophyll.

In this report we analyzed all available water quality, meteorological, and nutrient data, focusing on 2008 data and on long-term changes over time within each of the four seasons. To determine if significant changes occurred within seasons across years, linear regressions were performed using the seasonal means for each parameter and station.

The assessment of the long-term water quality data showed that winter water temperatures increased significantly over five years ($R^2>0.7$, $p<0.04$) at T-Wharf Surface and Bottom. The increase totaled approximately 2^{o}C, which agrees with other studies in Narragansett Bay and with the global trend of increasing sea surface temperatures. In 2008, anoxic (< 1 mg L^{-}) and hypoxic (≤ 2.9 mg L^{-1}) conditions were commonly recorded at Nag Creek; hypoxic conditions were also recorded at Potter Cove. At Potter Cove and T-Wharf Bottom, a significant increasing trend in pH ($R^2>0.5$, $p<0.01$) was found over time. We hypothesize that perhaps an increase in primary and secondary production might have contributed to the observed pH trend at Potter Cove and T-Wharf Bottom. In 2008, chlorophyll concentrations at the water quality stations were relatively low (< 18 µg L^{-1}); moreover, a significant decreasing trend in chlorophyll ($R^2>0.7$, $p<0.03$) over time was observed at Potter Cove and T-Wharf Bottom. These results agree with other studies in Narragansett Bay that document a decrease in 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.

Based on mean monthly data from 2002-2008, concentrations of most nutrient species and chlorophyll exhibited clear seasonal patterns. Phosphorous was lowest in late-winter and highest in mid-summer while nitrogen species were lowest throughout the spring and summer and highest in mid- to late-fall. Chlorophyll concentrations were generally low and exhibited a bimodal pattern with a peak in early winter and a second peak in August. Significantly decreasing trends were found in NO_3 and NO_2+NO_3 at Potter Cove, and in DIN, NO_3, and NO_2+NO_3 at T-Wharf Surface. If these trends continue over time, it may signal that true reductions in nutrient concentrations are occurring, perhaps in response to large-scale regulatory projects designed to reduce nutrient inputs into the Bay (e.g., nitrogen inputs from wastewater treatment facilities will be reduced by approximately 50% by 2014).

The meteorological data for 2008 also exhibited clear seasonal patterns typical of temperate latitudes. The preliminary assessment of the long-term meteorological data showed that 2008 was an average year when compared to previous years.

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GENERAL INTRODUCTION

The National Estuarine Research Reserves System (NERRS) includes 27 reserves that represent eleven biogeographic regions across the United States and its territories (Figure 1). These sites protect estuarine and terrestrial habitats and landscapes that are characteristic of each biogeographic region, and are being preserved and protected 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.

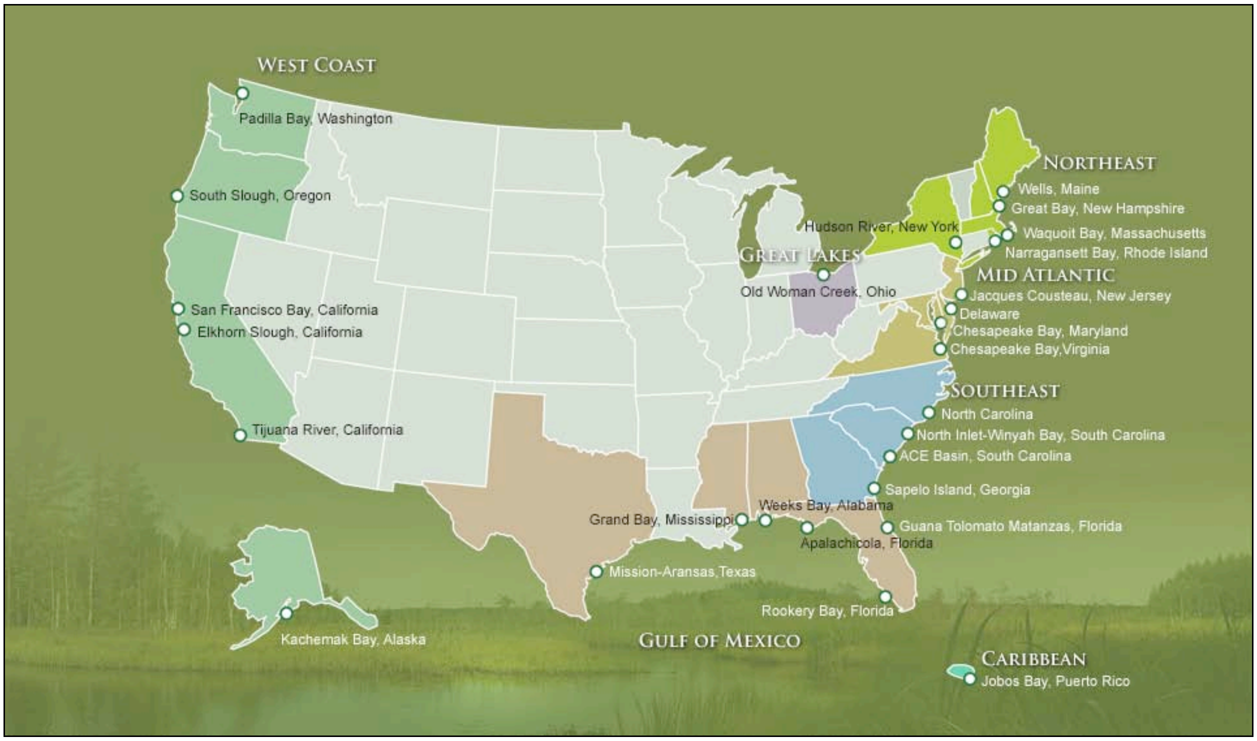

Figure 1. Biogeographic regions of the NERRS. A biogeographic region is a geographic area with similar dominant plants, animals and prevailing climate. Map from the NOAA / NERRS at http://www.nerrs.noaa.gov/ReservesMap.aspx.

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 is approximately located at the geographic center of Narragansett Bay in Rhode Island and it protects an estimated 1780 hectares of land and water (out to a depth of 5.5 m) on Prudence, Patience, Hope, and Dyer islands (Figure 2). 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 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 lots on Patience Island, which are privately owned.

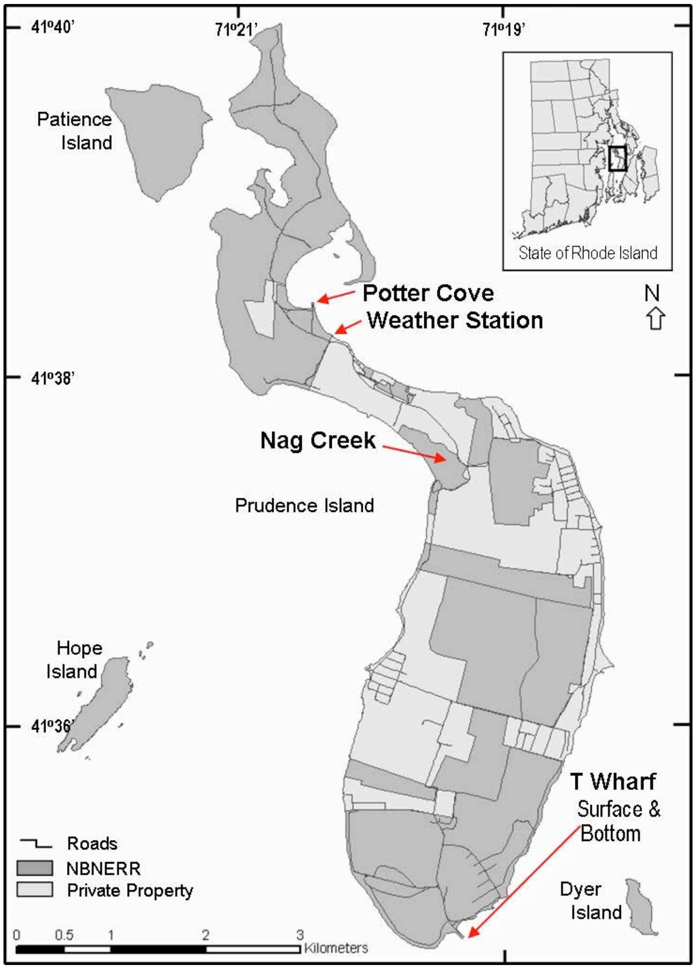

Figure 2. Location of the four islands included in the Narragansett Bay National Estuarine Research Reserve (Prudence, Patience, Hope, and Dyer), the four water quality stations (Potter Cove, Nag Creek, T-Wharf Surface, T-Wharf Bottom), and the weather station on Prudence Island.

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. In addition, the long-term collection of water quality and meteorological data at NBNERR provides information to decision-making agencies and private sectors 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.

A major program of the NERRS is the System-Wide Monitoring Program (SWMP), the goal of which is to develop long-term water quality and meteorological datasets in a coordinated manner at all 27 NERRS sites. All the Reserves within NERRS follow the same protocols for data collection, which is continuously revised for updates and improvements.

The SWMP was created and developed by the NERRS in 1995 as a nationally-coordinated long-term monitoring program. 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, the SWMP was established as a phased monitoring program to focus on three aspects of coastal ecosystem characteristics (National Estuarine Research Reserve System, 2005):

Phase 1 – Abiotic factors, including atmospheric conditions and water quality;
Phase 2 – Biological monitoring, including: biodiversity, habitat and population characteristics;
Phase 3 – Watershed and land use classifications, including: changes in human uses and land cover types.

Each of these three phases of SWMP is currently ongoing at NBNERR; however, the goal of this report is to provide a summary of Phase 1 abiotic monitoring. More specifically, this report will include sections on spatial and/or 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 2008, along with an analysis of longer-term interranual trends for each parameter.

Study Sites: Historical Notes

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.

Potter Cove

In 1995, Potter Cove (Figure 2) was selected as the initial NBNERR-SWMP monitoring station, and it was chosen to represent an impacted estuarine area as suggested by NERRS guidelines (NERRS 2007). Potter Cove has negligible developed land surrounding it and is relatively far from mainland metropolitan areas. However, the rationale for selecting it as an impacted site was based on suspected inputs of nutrient-rich waters flowing downstream from degraded areas in upper Narragansett Bay and from excessive discharges of boater wastes into the Cove. Recent research has demonstrated that Potter Cove has indeed been subjected to various sources of anthropogenic pollution dating back to the late 1800s (King et al. 2008). Recent impacts are mostly from large numbers of recreational boats, including elevated copper concentrations from antifouling paint and elevated carbon and nitrogen concentrations from the discharge of boater wastes (King et al. 2008).

Potter Cove is located along the northeastern shoreline of Prudence Island in the Upper East Passage segment of Narragansett Bay. It is approximately 40 ha in area, and water depths at the SWMP monitoring station on the south shore of the Cove range from approximately 2-4 m. Potter Cove is dominated by gravel and cobble beaches that support long stretches of fringing *Spartina alterniflora* marshes. Rooted submersed aquatic vegetation is absent, but dense pockets of drift macroalgae beds are present in some northern sections of the Cove throughout the summer (Russell and Raposa, unpublished data). Fine-grained organic sediments dominate subtidal benthic habitats of the Cove.

Potter Cove is a popular recreational destination, particularly during the warm summer months. Human-use surveys have found approximately 250 boats moored or anchored at one time in the Cove on ideal summer weekends (Raposa and Dalton unpublished data). Shellfishermen collect soft- and hard-shelled clams (*Mya arenaria* and *Mercenaria mercenaria,* respectively) in Potter Cove, and Save the Bay (a NBNERR partner) uses the Cove as an entry point to bring school groups to the Reserve. Selected research and monitoring projects in Potter Cove include an annual juvenile finfish survey dating back to 1990 (McNamee and Powell 2009), annual winter waterfowl surveys that began in 2005 (http://www.epa.gov/aed/html/research/fowl/index.html), a historical analysis of benthic chemistry in the Cove (King et al. 2008), the restoration of the adjacent Potter Pond salt marsh complex (Raposa 2008), and SWMP water quality, nutrient, and meteorological monitoring.

T-Wharf

The T-Wharf site is located along the southeastern shore of Prudence Island and is dominated by an approximately 170-m wooden T-shaped pier that was constructed by the Navy in the 1940s. As stated above, this location was originally selected in 1996 to represent a non-impacted or control site to compare with the impacted Potter Cove. T-Wharf was also selected because of the convenience the pier offers in terms of supporting water quality monitoring infrastructure.

In terms of winds, waves, and currents, T-Wharf is an exposed, high-energy site relative to Potter Cove and Nag Creek. General circulation patterns move bottom water from Rhode Island Sound north into Narragansett Bay past T-Wharf. In addition to the large pier, T-Wharf is dominated by gravel and cobble shorelines interspersed with a few small fringing *S. alterniflora* marshes. Subtidal habitats include one of the largest eelgrass (*Zostera marina*) beds in the mid-Bay area (Bradley et al. 2007), silty-organic bottoms, and dense blue mussel (*Mytilus edulis*) beds (Altieri and Witman 2006). T-Wharf is a primary haul-out site for overwintering harbor seals (*Phoca vitulina*) (Raposa and Dapp 2009), and is an important foraging area for a diverse winter waterfowl assemblage (http://www.epa.gov/aed/html/research/fowl/index.html) and for large numbers of Herring and Great Black-backed Gulls (*Larus argentatus* and *Larus marinus*, respectively) that arrive from the 350-pair gull rookery on nearby Dyer Island (Osenkowski unpublished data).

Similar to Potter Cove, T-Wharf is a popular recreational area for Prudence Island residents and visitors. Human-use surveys have recorded people using the small sandy beach directly to the north of the base of the pier for swimming, snorkeling, sunbathing, and for cook-outs (Raposa and Dalton unpublished data). T-Wharf is also used by recreational fisherman (both fin and shellfish), and as a summer field site for the NBNERR education program. Research and monitoring projects at T-Wharf include eelgrass mapping (Bradley et al. 2007), monitoring (Save The Bay unpublished data), and restoration; projects on harbor seal haul-out patterns (Norris 2007, Raposa and Dapp 2009); annual winter waterfowl surveys; invasive crab and tunicate research (Auker and Oviatt 2008; Raposa unpublished data); and NBNERR-SWMP water quality, nutrient monitoring, and telemetry.

Nag Creek

Nag Creek is located along the western side of Prudence Island along Prudence Neck, which is the narrow salt marsh-dominated stretch of land that connects the north and south ends of the island (Figure 2). Nag Creek is the colloquial name for the approximately 15-ha salt marsh that forms the western half of the Nag Marsh complex that stretches across the entire east-west length of Prudence Neck.

Nag Creek is a classic example of a well-developed New England meadow salt marsh. Tidal exchange between the marsh and Narragansett Bay is through a single inlet within a sandy beach on the west side of Prudence Island. Nag Creek habitats include a mosaic of vegetated intertidal marsh vegetation, tidal creeks, mosquito ditches, and tidal ponds. Nearly all of the ponds are connected to tidal creeks by man-made ditches, which eliminated most of the isolated marsh pools that are typical of natural marshes in New England. Vegetation is dominated by *S. alterniflora* in the regularly flooded zone; *S. patens*, *Distichlis spicata*, and *Juncus gerardii* in the salt meadow zone; and *Iva frutescens* along the marsh edge (Raposa and Weber 2009). Recent NBNERR restoration efforts have removed most of the invasive reed *Phragmites australis*, which was present in a few small areas along the marsh/upland edge.

Numerous research projects have been conducted in Nag Creek for over a decade. Most of this research has focused on salt marsh plant interactions, nutrient dynamics, and on examining marsh responses to sea level rise and warming temperatures (e.g., see Donnelly and Bertness 2001, Bertness et al. 2002, Bertness et al. 2008, among others). In 2007, Nag Creek was established by the NBNERR as a long-term reference or sentinel site for tracking marsh responses to climate change (Raposa and Weber 2009). In 2009, it was also selected as a study site for a three-year National Science Foundation study to examine nutrient dynamics in salt marshes (Sundareshwar, personal communication).

1. WATER QUALITY

1.1 Introduction

The NBNERR began collecting NERRS-SWMP water quality data at Potter Cove in 1995. By 2002, the Reserve was collecting data from each of the four current stations. 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 a strength of the SWMP, ensuring that the data collected from 27 different sites are comparable on regional and national scales. However, SWMP is also flexible at the site level, making it possible for each Reserve to address local and/or regional environmental issues as well. In this section, we examined and summarized the seasonal patterns in water quality data from 2008 at the four SWMP stations. We also (1) analyzed the long-term data by season to identify significant patterns or trends across years, (2) examined relationships between secchi depths and water column turbidity, and (3) quantified the degree and extent of hypoxic and anoxic events at each station.

1.2 Methods

1.2.1 Monitoring Infrastructure

Potter Cove

In 1995, sondes at Potter Cove were deployed in a PVC pipe that was mounted vertically on a piling located approximately 2 m west of the floating dock (41° 38.416' N, 71° 20.450' W). Sondes were maintained approximately 1 m off the bottom and, to facilitate water circulation, holes and large slits were drilled throughout the PVC pipe. The PVC was cleaned inside with a chimney brush on an approximately monthly basis during the summer to reduce the impact of biofouling on the data and a locking PVC cap was used to deter vandalism. Beginning in September 2006, the infrastructure changed to allow all sondes to be maintained in open water, free of any PVC pipes. The current design includes a short PVC pipe that extends from the deck of the floating dock down to just below the water's surface (Figure 3). 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.

Figure 3. Potter Cove water quality monitoring station (left) and deployment structure (right).

T-Wharf

From 1996 to 2002, this location supported a single SWMP water quality monitoring station (known simply as T-Wharf). This station was located approximately 75 m from the base of the pier and sondes were deployed in a fixed PVC pipe as previously described for Potter Cove. However it was later found that this location was generally in line with a summertime pycnocline (Kester unpublished data); this station was subsequently abandoned and two new stations (one at the surface and one at the bottom) were established further out on T-Wharf to examine patterns in stratification.

The current T-Wharf Surface and T-Wharf Bottom stations 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.

Figure 4. Two water quality monitoring stations are located at T-Wharf: Surface and Bottom (left and right PVC pipes, respectively).

Nag Creek

The Nag Creek station was established in March 2002, and it utilized a metal cage which was tethered to the marsh bank for sonde deployments. A different structure was installed in December 2002, which consisted of a 0.1 m x 0.1 m pressure-treated post with a hinged 0.5 m x 0.1 m horizontal arm. The deployment structure changed again in September 2006 to include an L-shape wooden structure that is held in place by a large metal tripod sunk into the mud in the middle of the creek. The sonde is deployed from the arm into the water via a cleat, eye and line system and hangs approximately 0.5 m from the bottom of the creek (Figure 5). The station at Nag Creek can only be reached by kayak.

Figure 5. Deployment structure at Nag Creek (left) and the sonde in the water (right).

1.2.2 Data Collection

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 (Figure 6). They are equipped with self-cleaning optical sensors, anti-fouling wipers, optimal power management, and a built-in battery compartment which improve reliability and maintain high data accuracy during extended deployments. The sondes house multiple probes that simultaneously measure temperature, conductivity, dissolved oxygen (percent saturation, depth, pH, and turbidity. Other parameters are not measured directly but calculated by the sonde: salinity is calculated using specific conductivity and temperature; dissolved oxygen is calculated using temperature, salinity and dissolved oxygen percent saturation; chlorophyll is calculated from the measure of fluorescence. Beginning in 1995, data were originally collected at 30-minute sampling intervals; however, in May 2004, this was changed to a 15-minute sampling interval. At NBNERR, sondes are calibrated and deployed for two-week periods. At the end of the deployment period, the sondes are retrieved and replaced with recently calibrated sondes.

Figure 6. Physical and chemical parameters are measured simultaneously with a YSI 6600V2 automated datalogger (datalogger picture from www.ysi.com).

1.2.3 Quality Assurance Quality Control (QAQC)

After downloading the raw data obtained from the sonde to a computer in the laboratory, the data file is submitted to the Centralized Data Management Office (CDMO) where it goes through a careful process of quality assurance and quality control. After this primary QAQC process, the data are posted and available as provisional data on the CDMO online data information service

(ODIS) website (http://cdmo.baruch.sc.edu). Subsequently, the data are returned to the Reserve for a second QAQC process. After the secondary QAQC at the Reserve, the data are sent again to the CDMO, together with the corresponding metadata, as a completed annual dataset. The metadata is a document with information about the events that took place during the particular year that the sondes were collecting data (i.e., deployment and retrieval dates, post-calibration measures, instruments specifications, observations, etc.). This is important information that could help to explain temporal or spatial trends observed in the data. The CDMO examines the data and metadata during a final QAQC process; once it is authenticated, it becomes authoritative (i.e., the dataset that has gone through several layers of QAQC processes) on the CDMO-ODIS website. The dataset for 2008 is provisional due to the existing delay of over a year for submitted data to be finalized by CDMO. Nevertheless, we expect that the 2008 provisional dataset used for this report and the final authoritative dataset of CDMO will be similar. All other data used in this report are the authoritative datasets from CDMO.

The datasets used in this report can be downloaded by any interested party through the CDMO website. In every data file, each parameter contains an additional flag column. This column contains the quality control flag for that parameter. There are eleven QAQC flags ranging from 5 to -5, and are used, among others, when a data point is out of the sensor range, missing, or is several standard deviations (2-3) from the historical mean (Table 1). The water quality datasets from 1995 to 2007 used for this report were revised according to the QAQC flags in Table 1. Only data flagged as 0, 2, 3, and 4 were used for this report (datasets had no data flagged as 5=corrected data); in this report the resulting dataset will be called 'revised data' preceded by the corresponding year of the data (i.e. 2008 revised data), and were used for statistical analysis, tables, and graphs. For 2008 and subsequent datasets, CDMO is no longer using the 2 and 3 standard deviations flags; all other flags remain the same. Therefore, the dataset from 2008 was verified for outliers by calculating the 3rd standard deviation; data outside the 3rd standard deviation was not included in the 2008 revised data.

Table 1. QAQC flags used by CDMO during the automated primary QAQC process for data from 1995 to 2007.

QA/QC	Flag description
-5	Outside High Sensor Range
-4	Outside Low Sensor Range
-3	Data Rejected due to QAQC
-2	Missing Data
-1	Open – reserved for later flag
0	Good Data
1	Suspect Data
2	Data Outside 2 Standard Deviations from the historical seasonal mean
3	Data Outside 3 Standard Deviations from the historical seasonal mean
4	Historical Data: Pre-Auto QAQC
5	Corrected Data

1.2.4 Water Quality Telemetry

In July 2006, telemetry equipment was installed at the T-Wharf to allow for the near-real-time transmittal of water quality from the T-Wharf Bottom sonde to the internet (Figure 7). This equipment includes a Sutron Sat-Link2 transmitter, which is connected to the T-Wharf Bottom water quality sonde by a cable that transmits the collected data on an hourly basis to the NOAA GOES satellite. The near-real-time data are posted and available online at the CDMO website.

Figure 7. The telemetry station transmits water quality data from the T-Wharf Bottom station via satellite. The near-real time data collected can be accessed and downloaded online at http://cdmo.baruch.sc.edu/QueryPages/googlemap.cfm.

Water quality data collected at the T-Wharf Bottom station is 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. With this information, scientists can work on developing a more complete characterization of our oceans and coasts and improve our knowledge of climate and environmental changes. All 27 Reserves within the NERRS contribute SWMP data to IOOS.

1.2.5 Data Analysis

2008 Data

The 2008 revised data comprised between 70-98% of the original datasets 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 (W) included the months of January, February, March; spring (Sp) - April, May, June; summer (Su) - July, August, September; fall (F) - October, November, and December. The percentage of data used per season for all the stations and parameters is presented in Appendix II.

Long-term Seasonal Trends

Each of the long-term datasets from 1995 to 2008 were revised as described in section 1.2.3 (Data Collection – QAQC), and the percentage of data used for the seasonal means calculations for all the stations and parameters is presented in Appendix II. To calculate long-term seasonal means, the criteria mentioned in the above section (2008 Data) were used. For Nag Creek, no winter data are presented in this report 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 computer software version 3.5.

2008 Secchi Depth-Sonde Turbidity Correlation

The collection of secchi depth data was added to the NBNERR-SWMP protocols in 2008. Beginning on July 3, 2008, secchi depth readings were collected during water quality sonde deployment/retrieval events at Potter Cove and T-Wharf (secchi readings were not taken at the shallow Nag Creek station). Spearman rank order correlation analysis was used to determine if secchi depth readings were significantly correlated with water quality sonde turbidity readings in order to determine if each of the two water clarity datasets could serve as check for the other. The nonparametric Spearman rank order correlation test was used since most of the sonde turbidity data were not normally distributed. Since secchi depth readings integrate water clarity throughout the overlying water column, correlations tests were run using sonde turbidity data that were integrated (averaged) over varying intervals of time. These time intervals included instantaneous (the data points immediately before and after the secchi depth reading), ± 1 h, ± 3h, ± 5h, and ± 12 h from the secchi depth reading. During the analyses, it seemed that during some deployments, turbidity data began to drift by the end of the previous deployment; to account for this, correlation analyses were also conducted using the same time intervals, but only using data from the deployment immediately after the secchi depth reading (i.e., instantaneous, +1h, +3h, +5h, and +12h).

1.3 Results

1.3.1 Temperature

Water temperatures in 2008 ranged from -1.2 to 26.7^{o}C at Potter Cove, from -1.5 to 38.6^{o}C at Nag Creek, from 1.8 to 26.2^{o}C at T-Wharf Surface, and from 2.0 to 24.8^{o}C at T-Wharf Bottom (Appendix I). Minimum monthly means were recorded in January at Potter Cove (3.0 ^{o}C), in February at T-Wharf Surface and Bottom (3.5 and 3.7^{o}C, respectively), and in December at Nag Creek (4.7^{o}C; no data were collected in January or February due to ice) (Figure 8). The maximum monthly means were recorded in July at Potter Cove (23.9^{o}C), Nag Creek (25.9^{o}C), T-Wharf Surface (22.8^{o}C) and T-Wharf Bottom (21.2^{o}C) (Figure 8).

Seasonal patterns in water temperature in 2008 were similar among the monitoring stations over the entire year (Figure 9). Temperatures peaked in summer, were coldest in winter, and were generally similar in spring and fall.

Patterns were generally similar among stations when considering long-term seasonal water temperature means (Figure 10). Water temperature increased significantly in winter across years at the T-Wharf Surface (R^2=0.663, p=0.01) and Bottom (R^2=0.663, p=0.04) stations. In Nag Creek, a significant increase was observed in fall from 2002 to 2006 (R^2=0.95, p=0.005). However, no significant patterns were found over the long-term for Potter Cove.

1.3.2 Salinity

In 2008, salinity ranged from 20.6 to 32.2 ppt at Potter Cove, 10.7 to 35.2 ppt at Nag Creek, 21.3 to 33.2 ppt at T-Wharf Surface, and 25.4 to 33.0 ppt at T-Wharf Bottom (Appendix I). Minimum monthly means were recorded in February at Potter Cove (24.1 ppt), in March at Nag Creek and T-Wharf Surface (21.1 and 26.6 ppt, respectively) and in January at T-Wharf Bottom (27.7 ppt) (Figure 8). The maximum monthly means were recorded in June at Potter Cove (30.4 ppt), in August at Nag Creek (30.6 ppt), and at T-Wharf Surface and Bottom in September and July, respectively (31.4 ppt at both stations) (Figure 8).

Seasonal patterns in salinity in 2008 were similar among all stations with a peak observed in summer and lowest values observed in winter (although no data were available for Nag Creek in winter, Figure 9). Across all seasons, salinities were highest at the two T-Wharf stations and lowest at Nag Creek.

Long-term seasonal means for salinity were slightly different among stations and across seasons (Figure 10). At T-Wharf Bottom salinity decreased significantly over time in both fall (R^2=0.71, p=0.02) and winter (R^2=0.97, p=0.02), while no significant differences were observed at either T-Wharf Surface, Potter Cove or Nag Creek.

1.3.3 Dissolved Oxygen (percent saturation)

Dissolved oxygen (DO) measured as percent saturation (% sat.) for 2008 ranged from 35 to 167% at Potter Cove, 0 to 177% at Nag Creek, 35 to 133% at T-Wharf Surface, and 35 to 145% at T-Wharf Bottom (Appendix I). Minimum monthly means were observed in July at Potter Cove (81% sat.), in June at Nag Creek (65%) and T-Wharf Surface (86%), and in August at T-Wharf Bottom (74%) (Figure 8). Maximum monthly means were recorded in January and February at Potter Cove (115%), in April at Nag Creek (95%), and in January at T-Wharf Surface and Bottom (110% and 108%, respectively) (Figure 8).

Seasonal means for DO % sat. in 2008 were higher in Potter Cove than at the other stations, except for summer when T-Wharf Surface had the highest DO % sat (Figure 9). The lowest DO % sat. was recorded at Nag Creek each season that data were available.

Summertime dissolved oxygen % sat. was generally lowest at Nag Creek across most years, while Potter Cove had the highest DO % sat. during most of the winters (Figure 11). T-Wharf Bottom DO % sat. increased significantly across the years during winter (R^2=0.98, p=0.01), but significant changes over time were not observed in any other case.

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

Dissolved oxygen concentration (mg L^{-1}, DOc) in 2008 ranged from 1.1 to 7.4 at Potter Cove, 0.0 to 15.2 at Nag Creek, 3.0 to 14.9 at T-Wharf Surface, and 1.1 to 15.5 at T-Wharf Bottom (Appendix I). Minimum monthly means were observed in July at Potter Cove (5.7 mg L^{-1}) and Nag Creek (4.6 mg L^{-1}), in June at T-Wharf Surface (6.7 mg L^{-1}) and in August at T-Wharf Bottom (5.3 mg L^{-1}) (Figure 8). The maximum monthly DOc was recorded in February at Potter Cove (13.2 mg L^{-1}), in December at Nag Creek (10.2 mg L^{-1}), and in January at T-Wharf Surface and T-Wharf Bottom (11.9 and 11.4 mg L^{-1}, respectively) (Figure 8).

In 2008, anoxic conditions (DO < 1.0 mg L^{-1}.) were not recorded at Potter Cove, T-Wharf Surface or T-Wharf Bottom. At Nag Creek, however, anoxic conditions were recorded during the months of June (21 days), July (21 days), August (22 days), and September (15 days). The duration of the anoxic events varied from one reading up to 23 consecutive readings in one particular day, implying that some anoxic episodes might have lasted approximately up to six hours.

Hypoxic conditions (DO ≤ 2.9 mg L^{-1}) were recorded at Potter Cove, Nag Creek and T-Wharf Bottom, but not at T-Wharf Surface. At Potter Cove, hypoxic conditions were recorded during the months of July (15 days), August (13 days), September (3 days), and October (1 day). The duration of the hypoxic events varied from one reading up to 24 consecutive readings in one particular day, implying that some hypoxic episodes might have lasted approximately up to six hours. At Nag Creek, hypoxia was recorded with more frequency and duration during the months of June (29 days), July (27 days), August (31 days), September (28 days), and October (10 days) (no information was available in January or February). For March, April, May, October, and November dissolved oxygen levels were sporadically hypoxic over fewer days (1, 2, 5, 10, and 1 days, respectively). The duration of the hypoxic events varied from one reading up to 20 consecutive readings in one particular day, implying that some hypoxic episodes might have lasted approximately up to five hours. At T-Wharf Bottom, hypoxic conditions were recorded during the months of July (6 days), August (12 days), and September (9 days). The duration of the hypoxic events varied from one reading up to 16 consecutive readings in one particular day, implying that some hypoxic episodes might have lasted approximately up to four hours. At T-Wharf Bottom, these hypoxic events occurred when the sonde was found to have dropped one meter in depth, being in close proximity to the bottom sediment; however, once the depth was corrected, no other events of hypoxia were recorded during 2008.

Seasonal means for DOc in 2008 were similar among stations over the entire year (Figure 9). Among the seasons, concentrations were lowest in summer for all stations; among stations, Nag Creek had the lowest DOc across all seasons when data were available.

Long-term seasonal means for DOc plotted for all stations showed that Nag Creek had low DO concentrations consistently across years for all seasons (Figure 11). In Potter Cove, DOc was highest during most winters when compared to the other stations; concentrations were lowest in Nag Creek during all summers. T-Wharf DOc increased significantly (R^2=0.99, p=0.02) in fall across years, although this station was removed in 2002. No other significant trends over time were observed at either T-Wharf Surface or Bottom for any season.

1.3.5 pH

In 2008, pH ranged from 7.2 to 8.8 at Potter Cove, 6.2 to 8.6 at Nag Creek, 7.3 to 8.5 at T-Wharf Surface, and 6.9 to 8.6 at T-Wharf Bottom (Appendix I). Minimum monthly means were recorded in July at Potter Cove (7.7), in June and August at Nag Creek (7.2), in December at T-Wharf Surface (7.7), and in August at T-Wharf Bottom (7.5) (Figure 8). Maximum monthly means were observed in February at Potter Cove (8.4), in April at Nag Creek (7.8), in January to March at T-Wharf Surface (8.2), and in January at T-Wharf Bottom (8.4) (Figure 8).

Seasonal patterns in mean pH in 2008 were similar across all stations, except for Nag Creek, where pH was noticeably lower than the other stations from spring through fall (Figure 9). In summer, pH was lowest at all stations except T-Wharf Surface, where it was low in both summer and fall.

Long-term seasonal means for pH showed similar concentrations among all stations except for Nag Creek, which had lower pH concentrations than the other stations (Figure 12). A significant increase in pH was found across years at Potter Cove and T-Wharf Bottom. At Potter Cove, pH increased significantly in spring (R^2=0.47, p=0.01), summer (R^2=0.49, p=0.01) and fall (R^2=0.44, p=0.01) across years; at T-Wharf Bottom it increased in spring (R^2=0.97, p=0.01) and fall (R^2=0.90, p=0.01).

1.3.6 Turbidity

Turbidity (NTU) during 2008 ranged from 0 to 36 at Potter Cove, 0 to 183 at Nag Creek, 0 to 62 at T-Wharf Surface, and 0 to 18 at T-Wharf Bottom (Appendix I). Minimum monthly means were recorded in November at Potter Cove (0.1 NTU), in May at Nag Creek and T-Wharf Bottom (2.0 and 1.0 NTU, respectively), and in August T-Wharf Surface (0.0 NTU) (Figure 8). Maximum monthly means were observed in February at Potter Cove (2.3 NTU), in November at Nag Creek (11.3 NTU), in September at T-Wharf Surface and T-Wharf Bottom (3.0 and 3.6 NTU, respectively) (Figure 8).

Seasonal means for turbidity in 2008 varied among stations over the entire year (Figure 8), but were relatively low (< 7 NTU) for all stations (Figure 9). Trends in turbidity through the year were not clear at Potter Cove, T-Wharf Bottom or T-Wharf Surface, but at Nag Creek turbidity clearly increased from spring though late fall (Figures 8 and 9).

Long-term seasonal means were low for turbidity (< 7 NTU) when all years, stations and seasons were considered, except for spring and fall of 1999 at T-Wharf (Figure 12). A significant decreasing trend in turbidity was found at Potter Cove (R^2=0.60, p=0.01) in summer across years.

Significant correlations were found between secchi depth readings and sonde turbidity values when the sonde data were averaged ± 1h (correlation coefficient [cc] = -0.591, p=0.02), ± 3h (cc=-0.593, p=0.02), and ± 5h (cc=-0.558, p=0.02) from the secchi reading. Similar results were found when considering sonde data only after the secchi reading (+ 1h, cc=-0.512, p=0.03; + 3h, cc=-505; p=.04). All other correlative tests were not significant (p>0.05). These results suggest that strong relationships exist between secchi depth and sonde turbidity readings only when sonde data are averaged from 1-5 hours around the time of the secchi reading. Interestingly, the relationships were stronger when using data from the sondes deployed before and after the secchi reading even though it appeared that some turbidity data had drifted by the end of the prior deployment (Figure 13; A perfect negative correlation between two variables results in a correlation coefficient of -1; therefore lower correlation values indicate stronger negative relationships as occurs when using data from both the prior and subsequent sonde deployments).

1.3.7 Chlorophyll

Chlorophyll concentrations (µg L^{-1}) during 2008 ranged from 0 to 123 at Potter Cove, 0 to 20 at Nag Creek, 0 to 29 at T-Wharf Surface, and 0 to 143 at T-Wharf Bottom (Appendix I). Minimum monthly means were recorded in November and December at Potter Cove (0.8 µg L^{-1}), in November at Nag Creek (2.5 µg L^{-1}), and in June at T-Wharf Surface and Bottom (0.8 and 0.1 µg L^{-1}, respectively) (Figure 8). Maximum monthly means were recorded in January at Potter Cove (24.4 µg L^{-1}), in July at Nag Creek (7.1 µg L^{-1}), in March at T-Wharf Surface (12.0 µg L^{-1}) and in January at T-Wharf Bottom (13.1 µg L^{-1}) (Figure 8).

Seasonal chlorophyll concentration means showed no distinct pattern among stations within each season in 2008 (Figure 9). Chlorophyll was generally low for all stations (< 12 µg L^{-1}) and T-Wharf Surface and Bottom showed the highest chlorophyll concentration in winter.

Long-term seasonal means for chlorophyll showed low concentrations (< 13 µg L^{-1}) when all years, stations and seasons were combined (Figure 14). Across years at Potter Cove, a significant and strong decreasing trend (R^2=0.98, p<0.001) was found in summer, while a significant increasing trend (R^2=0.99, p=0.04) was found in winter.

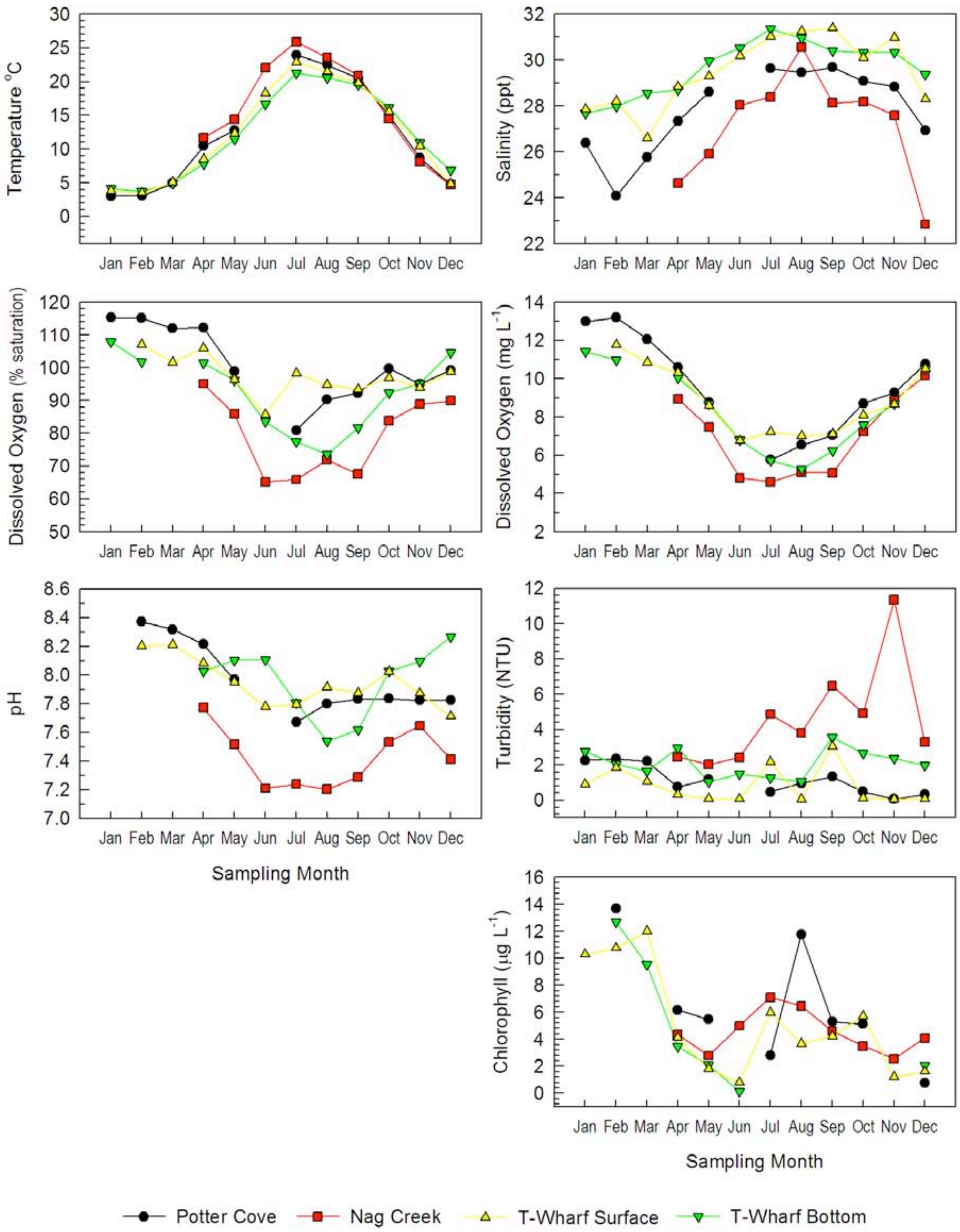

Figure 8. Monthly means calculated for water quality parameters for 2008, all stations included. Error bars omitted for clarity.

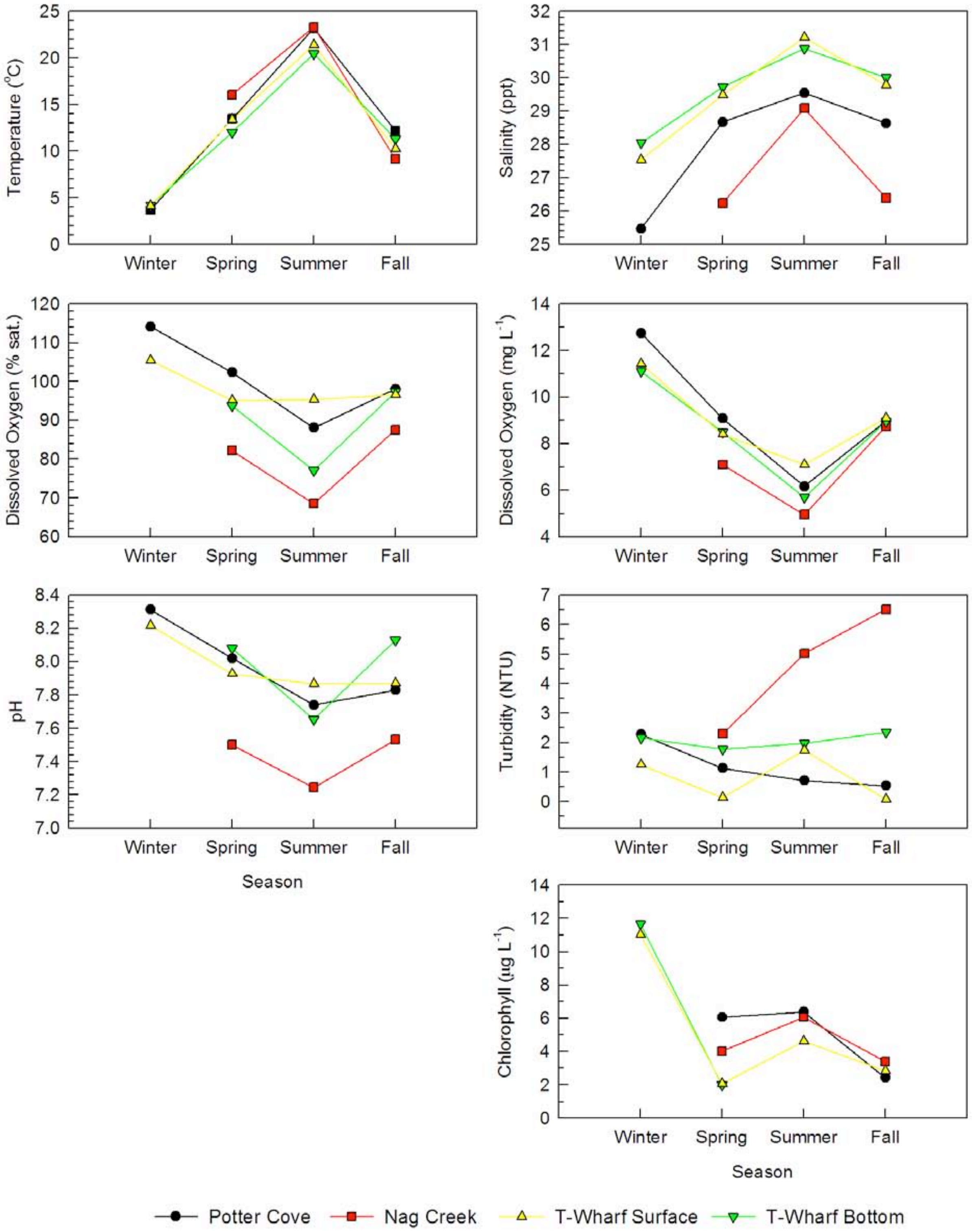

Figure 9. Seasonal means calculated for water quality parameters for 2008, all stations included. Error bars omitted for clarity.

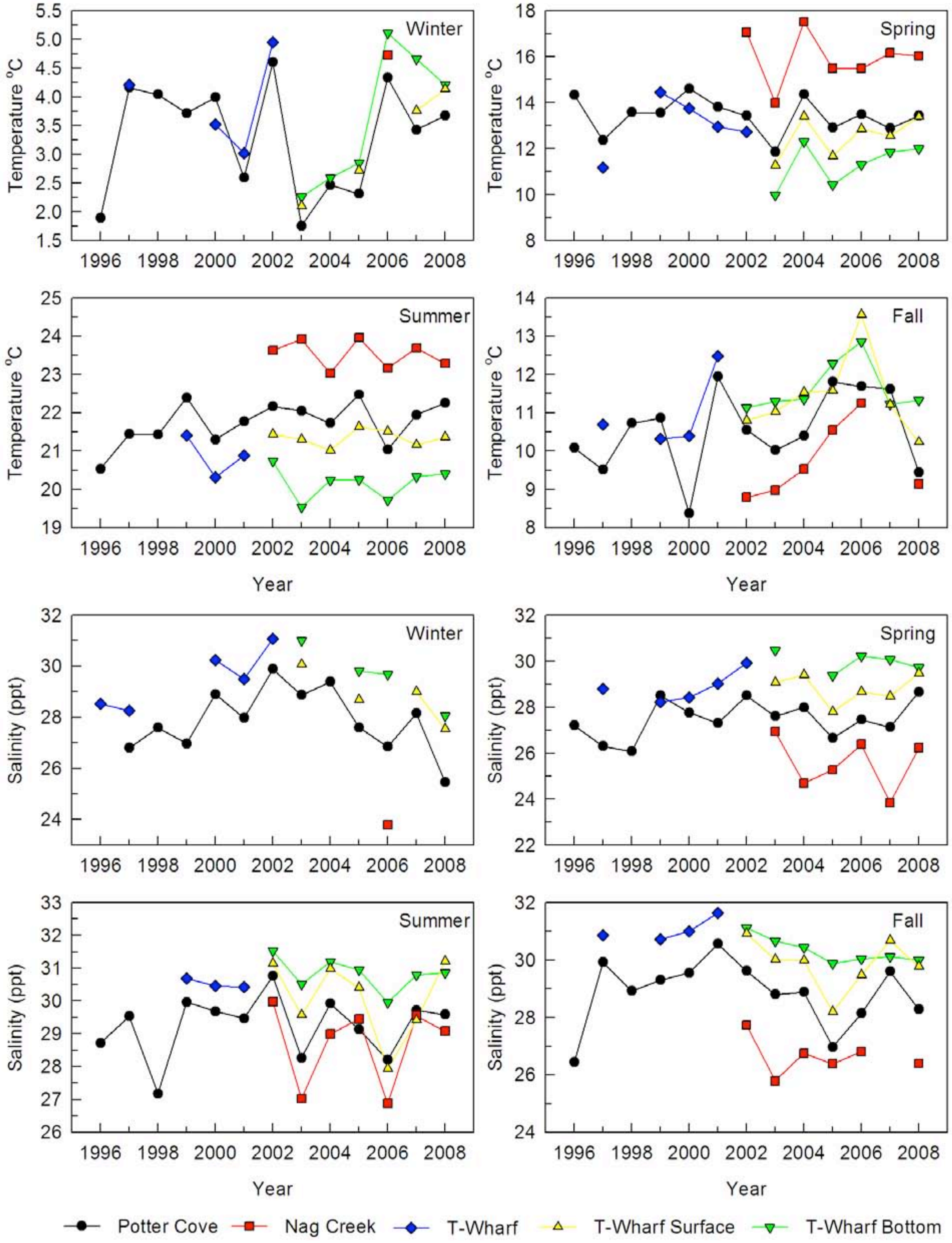

Figure 10. Long-term seasonal means calculated for water temperature (^{o}C) and salinity (ppt). Error bars omitted for clarity.

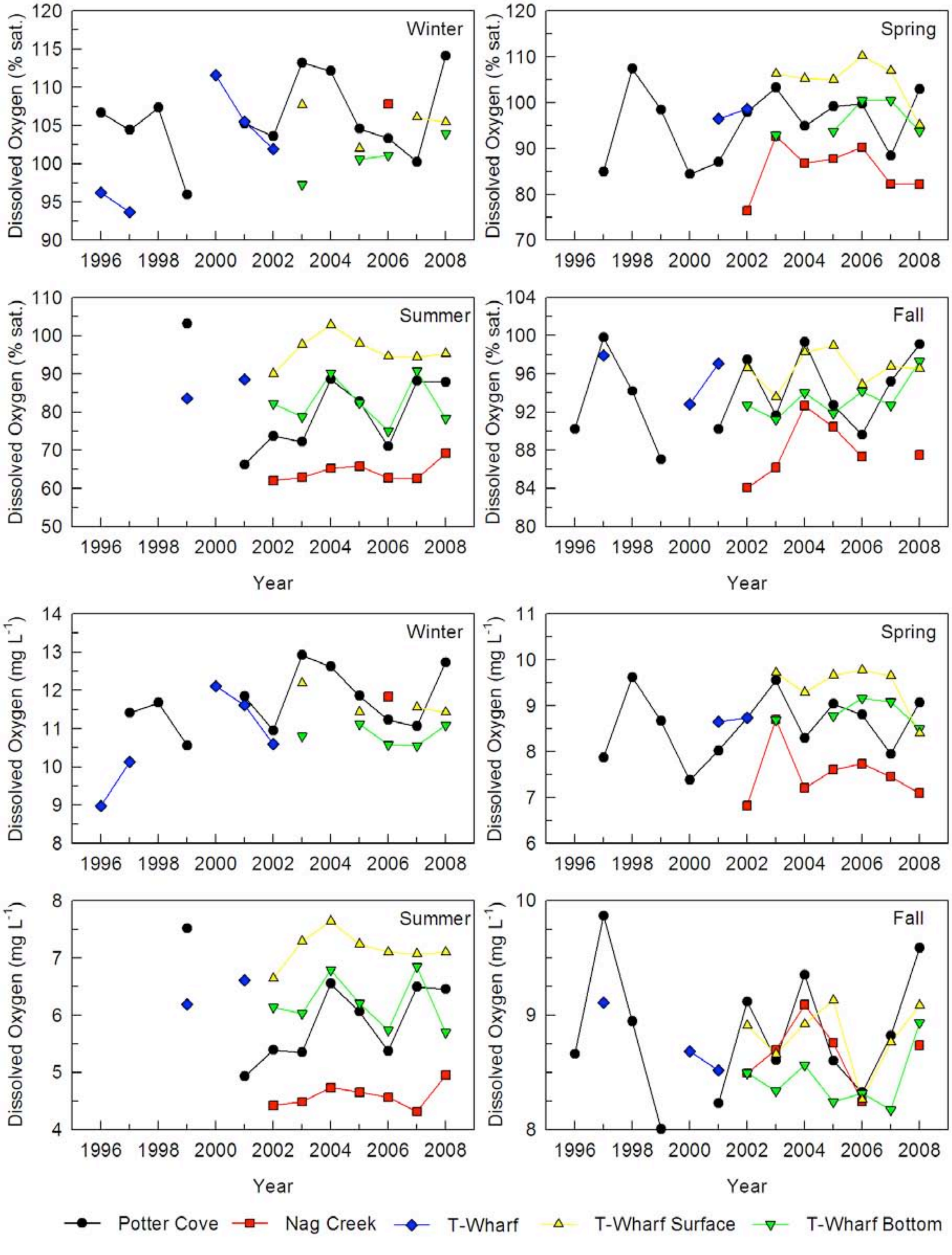

Figure 11. Long-term seasonal means calculated for dissolved oxygen percent saturation and concentration (mg L^{-1}). Error bars omitted for clarity.

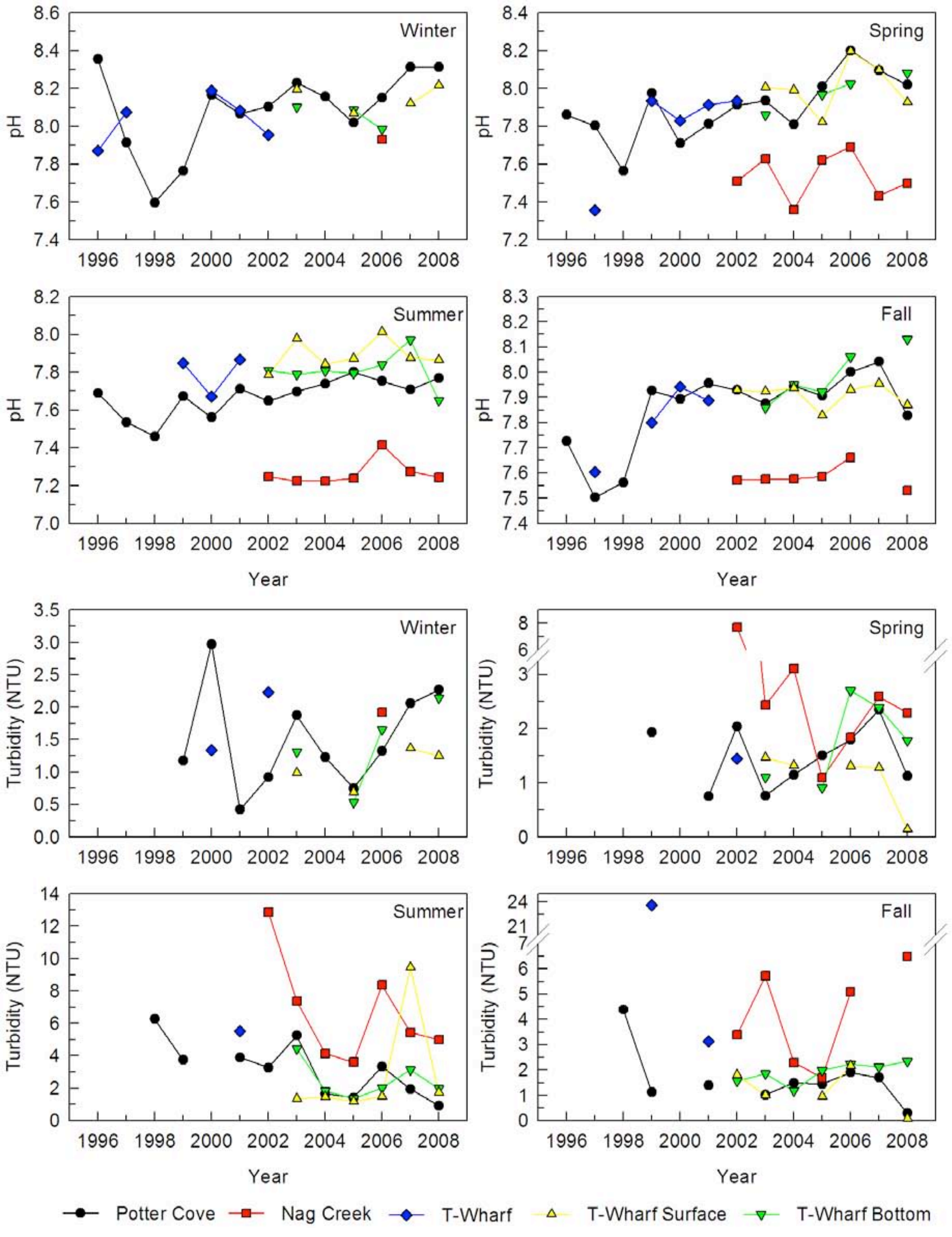

Figure 12. Long-term seasonal means calculated for pH (pH units) and turbidity (NTU). Error bars omitted for clarity.

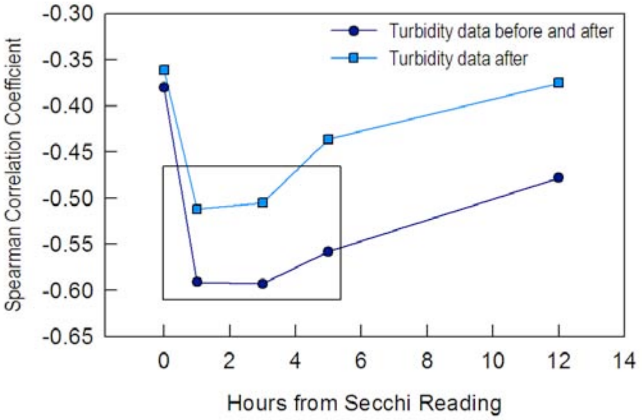

Figure 13. Spearman rank order correlation coefficients between secchi depth readings and data sonde turbidity values integrated over varying intervals of time. One plot in the graph includes sonde data averaged before and after the secchi depth reading and the other includes data only from after the secchi depth reading. Coefficients within the shaded box are all statistically significant ($p<0.05$).

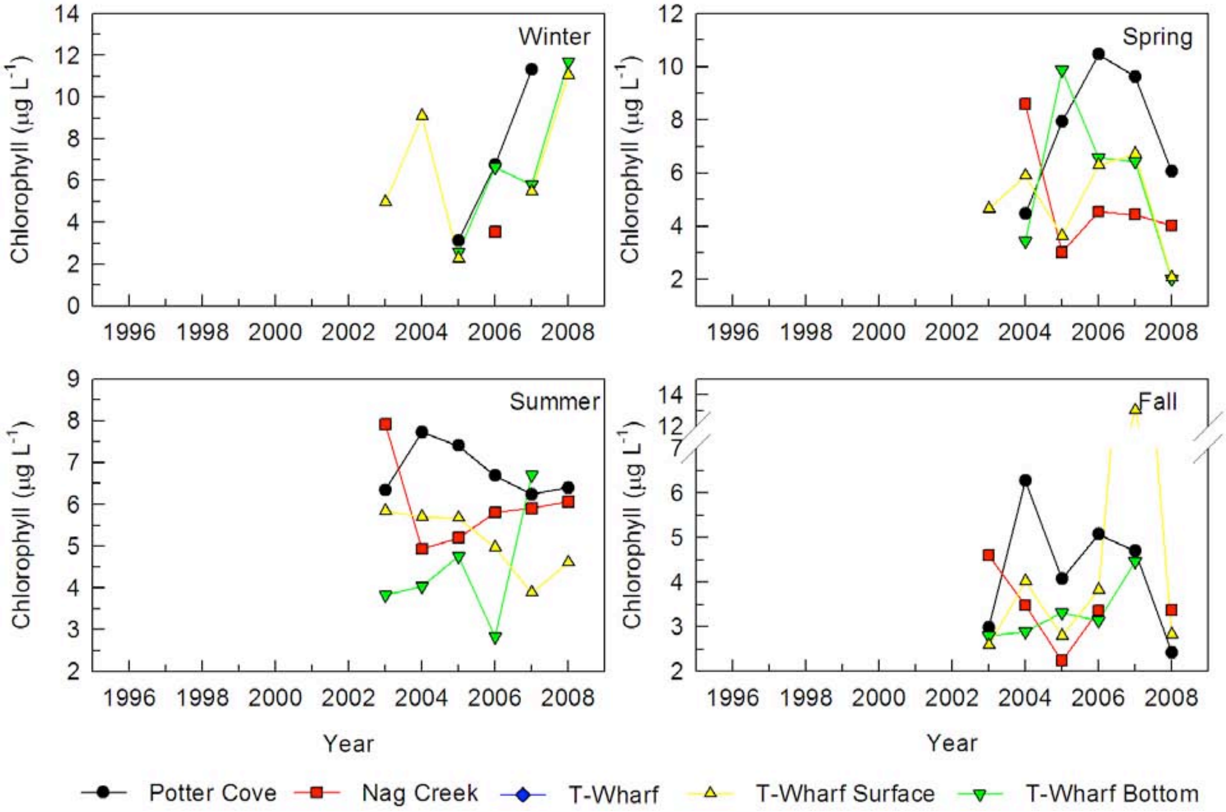

Figure 14. Long-term seasonal means calculated for chlorophyll concentration (μg L^{-1}). Error bars omitted for clarity.

1.4 Discussion

In this report, we analyzed and summarized 14 years of data (from 1995 to 2008) using graphs and statistical calculations. This will aid in the study and interpretation of inter- and intra-annual patterns and trends in water quality, which in turn will improve our understanding of estuarine processes in the Bay. In a previous report (Durant et al., 2009), we examined 13 years of water quality data (up to 2007) by calculating monthly and yearly means. However, in this report we included new SWMP data and conducted additional analyses. For example, we incorporated water quality data from 2008, analyzed the data within each season, included 2003-2008 chlorophyll data collected by the sondes, and included 2002-2008 data collected through the nutrient monitoring program.

The increase in sea surface temperature has been well documented worldwide (Levitus et al. 2009), as well as in a smaller scale, such as in New England waters (Narragansett Bay-Nixon et al. 2003, Woods Hole, MA-Nixon et al. 2004). For example, when analyzing seasonal means from 1970 to 2002 for Woods Hole, Nixon et al. (2004) found a significant increase in water temperature of 1.7°C in winter and of 1.0°C in summer. Similarly, in this report, an increase in winter water temperatures was found across years of approximately 2.1°C at both T-Wharf Surface and Bottom stations (i.e. winter water temperature means in 2003 and 2008 at T-Wharf Surface were 2.1 and 4.1°C; at T-Wharf Bottom they were 2.3 and 4.2°C, respectively).

The study of increasing sea surface temperatures is important since it can have negative ecological effects on marine plants and animals. For example, when using temperature treatment experiments, Bintz et al. (2003) found a negative correlation between increasing water temperatures and eelgrass density and rhizomes production, and a positive correlation with the time interval of the growth of new leaves, which adversely affected eelgrass health. Another example is the study by Collie et al. (2008) using long-term trawl survey datasets (1959-2005) from Narragansett Bay and adjacent Rhode Island Sound. The analysis of the data showed a transition from fish to invertebrate communities and a shift from benthic to pelagic species that correlated positively with the increase in sea water temperature in RI across years. They further predicted that if temperatures continue to increase, a shift toward a more warm-water and pelagic community will occur in RI, similar to estuaries such as Delaware Bay and Chesapeake Bay. Oviatt (2004) described how the increase of sea surface temperatures during the winter in the past decades in Narragansett Bay decreased the winter-spring bloom, and as a consequence, the zooplankton density increased, and nutrient concentrations remained high due to enhanced zooplankton grazing.

The analyses of the long-term data did not indicate that a thermocline is present at T-Wharf; however, a weak halocline was apparent through 2007 according to our salinity analyses. In 2008, the differences in salinity between T-Wharf Surface and Bottom were reduced when compared to previous years. This was due to a significant decrease in salinity at T-Wharf Bottom across years, which apparently weakened the halocline that previously existed. Factors contributing to the relatively well-mixed water column at the T-Wharf probably include strong tidal and wind-driven mixing.

Historical measures of dissolved oxygen in Narragansett Bay have shown low concentrations of oxygen, or hypoxic conditions, mainly in the upper part of the Bay (Upper Bay) (Deacutis et al.

2005, Saarman et al. 2008). In Narragansett Bay, oxygen decreases that lead to hypoxia are caused by a combination of physical and biological factors (i.e. dense macroalgal biomass, phytoplankton blooms; Deacutis 2008) exacerbated by anthropogenically-driven eutrophication (Hamburg et al. 2008). The prevailing decrease in dissolved oxygen is considered a critical coastal management issue, both locally (Saarman et al. 2008) and worldwide (Diaz and Rosenberg 2008). Our results showed no anoxic conditions in 2008 at Potter Cove, T-Wharf Surface and T-Wharf Bottom. However, anoxic conditions were recorded at Nag Creek, and hypoxic conditions were recorded at both Potter Cove and Nag Creek. The geophysiological characteristics of Nag Creek contributes to low oxygen conditions, since most of the events coincided with low tide (tidal hypoxia). The dataset at Nag Creek, and to a lesser extent at Potter Cove, also showed hypoxia occurring overnight, which might imply that oxygen was depleted overnight by respiration, but replenished by photosynthesis after dawn (also called diel hypoxia; D'Avanzo and Kremer, 1994).

The duration and frequency of hypoxia events are critical to different life stages of fish and other invertebrates. Consequently, the EPA established a conservative estimate of the safe dissolved oxygen concentration for exposures less than 24 hours to be 2.3 mg L^{-1} (USEPA 2000). At the Reserve, the majority of the hypoxic events were sporadic readings, although a few lasted up to six consecutive hours. At Potter Cove, only 19% of all the hypoxic readings were below 2.3 mg L^{-1}, while at Nag Creek 61% of the readings were below this level. No detrimental effects to fauna or flora (i.e. fish kills, die-offs of marine plants) were noticed during weekly visits in 2008 (Durant personal observations).

Monthly turbidity means across all stations were variable and ranged between 0 and 14 NTU. High turbidity readings could be the result of several factors such as resuspension of bottom sediments, waste discharge, and urban run-off, among others. The Reserve has incorporated in the water quality protocols secchi depth readings to serve as a complementary dataset. Secchi depth readings are an integrated measurement of water clarity in the entire water column overlying the secchi disc. In contrast, an individual datasonde turbidity reading is taken from within 5 centimeters from the probe and is therefore subject to much greater variability than an integrated secchi depth reading. Integrating sonde turbidity data over time can compensate for this and the significant relationships found in this study when the data were averaged from ± 1h to ± 5h from the secchi reading support this. The non-significant results observed when averaging over longer time frames may simply indicate that it is not appropriate to use sonde data taken more than 5 hours from the secchi reading, since these data may reflect conditions that are different from when the secchi disc was deployed. All of this suggests that supplemental secchi depth readings can serve in verifying datasonde turbidity values, but only when the latter are averaged from 1 to 5 hours (or conservatively from 1 to 3 hours) before and after the secchi depth reading.

Oceanic pH is a critical chemical indicator, and is mostly controlled by the equilibrium of its inorganic carbon system. For instance, the continuous increase in atmospheric carbon dioxide (CO^2) is believed to be the cause of ocean acidification (Caldeira and Wickett, 2003), or a decrease in the pH of the ocean, which can adversely affect marine fauna (Fabry et al. 2008). At a smaller scale, the opposite has been observed at Potter Cove and T-Wharf Bottom where a significant increasing trend in pH was found across years in spring, summer, and fall. The reason for an increase in pH at these two water quality stations at the Reserve remains unknown.

However, if an increase in CO^2 in the ocean causes a decrease in pH, perhaps an increase in alkalinity might be attributed to an increase in carbon fixation (i.e. decrease in CO^2). For example, an increasing trend in marine algae production (carbon fixation) in response to increased nutrient loading across years was inferred from the analysis of C/N ratios of sediment cores that dated from the 1800s at Potter Cove (King et al. 2008). This increase in nitrogen began after the industrial revolution reached Narragansett Bay and increased sewage inputs augmented the overall anthropogenic input of nitrogen in the Bay (Hamburg et al., 2008). We hypothesize that perhaps an increase in photosynthesis by macroalgae, and/or an increase in calcification by arthropods (mussel beds, quahog, crabs, etc.), phytoplankton, and zooplankton might be contributing to the increase in pH observed at these stations; however, this remains speculative since no information is available at this time on the population dynamics of these groups.

A peak in chlorophyll was observed in February and a then a lower peak was observed in July-August at Potter Cove and at the T-Wharf Surface and Bottom stations. Concentrations were generally low at all stations throughout 2008 and previous years, but they are comparable to results from Oviatt et al. (2002). Across years, a significant decreasing trend was observed in the winter and summer seasons at Potter Cove, and in summer at T-Wharf Surface. 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 has been found to be negatively correlated to an increase in winter water temperature (Keller et al. 1999, Oviatt 2004, this study).

The SWMP long-term water quality monitoring program is successfully developing a large database over time, making it possible to assess and study environmental changes in Narragansett Bay. Our efforts are directed towards obtaining high-quality data to study trends and patterns of physical and chemical variables that support scientific research, enhance public awareness and understanding of the Bay's watershed and estuarine areas, and promote educated management decisions and regulations.

2. NUTRIENTS

2.1 Introduction

In 2002, the National Estuarine Research Reserve System (NERR or NERRS) implemented a new nutrient and chlorophyll monitoring program to complement its existing long-term water quality monitoring program. This new program required all participating NERR sites to collect duplicate water samples every month from each of the four long-term water quality monitoring stations and to analyze these samples for concentrations of a suite of dissolved nutrient parameters and chlorophyll *a*. This program also required each NERR site to collect a series of samples from one station over an approximately 24-hour period each month to examine how nutrient and chlorophyll concentrations change over diel and tidal cycles. These two components of the NERR nutrient and chlorophyll monitoring program (hereafter referred to as the nutrient monitoring program) are the ‘grab’ and ‘diel’ programs, respectively. The goal of the grab program at the Narragansett Bay National Estuarine Research Reserve (NBNERR or Reserve) is to quantify seasonal patterns of nutrient and chlorophyll concentrations in different estuarine habitats (marsh creek, cove, open water surface, open water bottom). The goal of the diel program at NBNERR is to document changes in nutrient and chlorophyll concentrations in response to tidal forcing.

The NERR nutrient monitoring program differs from the water quality and meteorological components of the NERR System Wide Monitoring Program (SWMP), both of which use automated monitoring equipment to collect data at high temporal frequencies. Instead, the nutrient program relies on the simple field collection of water samples, which are brought back to appropriate laboratories for processing. This approach results in only 20 samples collected each month, but it was necessary due to cost, availability, and accuracy issues associated with using automated nutrient and chlorophyll sensors. However, the limited temporal resolution of the nutrient program has been at least partially offset by the long-term duration of the program; a robust nutrient and chlorophyll dataset up to 8 years in length now exists from each participating NERR site. As with any long-term monitoring program, the true benefit is realized once the data have been analyzed and synthesized. The goal of this section of the 2008 NBNERR-SWMP report is to conduct a basic synthesis of all 2002-2008 nutrients and chlorophyll data (focusing on 2008 data) collected at NBNERR as part of the NERR nutrient monitoring program.

2.2 Methods

The grab and diel components of the NBNERR nutrient monitoring program began in March and September 2002, respectively. Each month, grab samples are collected from Potter Cove, Nag Creek, T-Wharf Bottom and T-Wharf Surface monitoring stations; diel samples are collected from the T-Wharf Bottom station only (Figure 2). Samples are collected each month throughout the year except when the water column freezes in winter at Nag Creek.

2.2.1 Field and Laboratory Procedures

All grab samples are taken on the same day within the three-hour window before predicted slack low-water. No distinction is made between neap and spring tide conditions. Each month, replicate (n=2) samples are collected by hand at Nag Creek or with a small Niskin bottle at the other three stations. All samples are collected from the approximate depth of the water quality sonde at each station. All samples were collected in wide-mouth glass sample bottles until July 2008, after which wide-mouth amber plastic samples bottles were used. Prior to sampling, all bottles are washed in a 10% HCl solution acid bath, rinsed three times with distilled-deionized water, dried, and labeled. In the field, each bottle is rinsed again twice with ambient tidal water. Samples are immediately placed in a cooler on ice and returned to the NBNERR laboratory.

In the laboratory, each nutrient sample is filtered through a 0.45-µm disposable disk filter and stored at approximately –4°C until analysis. Exactly 20 ml of each chlorophyll sample is filtered onto a 25-mm GF/F filter. Two drops of magnesium carbonate are added to the filter, is then folded in half, wrapped in aluminum foil, and stored at –4°C until analysis. Samples are then transported as quickly as possible to the Marine Ecosystems Research Laboratory (MERL) and Dr. Scott Nixon's laboratory, both at the University of Rhode Island's Graduate School of Oceanography (URI-GSO) for processing.

Diel samples are collected at T-Wharf Bottom 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 approximately the 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 are collected from approximately 1 m above the bottom and all are processed in the NBNERR lab as described above for grab samples.

URI-GSO Laboratory Methods

At the Nixon Lab, each nutrient sample is analyzed for phosphate (PO_4), ammonium (NH_4), nitrite (NO_2), nitrate (NO_3), nitrite + nitrate (NO_{23}), dissolved inorganic nitrogen (DIN), and dissolved silica (SiO_4) concentrations. According to the Nixon Lab standard operation procedures, all nutrient analyses are run on a Lachat Quik Chem 8000 Flow Injection Analyzer by EPA approved methods. Acid washed tubes are used for all analyses. Glass tubes are used for all except silica analysis. Standards and blanks are made up in low nutrient Sargasso Sea water to match the salinity matrix. Calibration curves are run using a minimum of 4 standards, and a reagent blank. The correlation coefficient must be >0.99, otherwise, a new calibration is run. Precision and accuracy should be within 10%".

At MERL, chlorophyll filters are extracted with 90% buffered acetone and kept in the dark in a freezer for 20-24 hours. In preparation to be read on the fluorometer, they are centrifuged for 5 minutes and the supernate is poured off into a separate vial, mixed and poured into a fluorometer cuvette. The cuvette is then read on a Turner 10-AU fluorometer. The same vial is acidified with 10% HCl and read a second time to obtain a measure of phaeophytin.

2.2.2 Data Analysis

All concentration data that are sent to the Reserve from both URI-GSO labs are converted to units of µM for nutrients and µg L^{-1} for chlorophyll. The data are then subjected to NERR quality control/quality assurance (QA/QC) procedures before the final dataset is submitted to the NERR Centralized Data Management Office (CDMO) for approval (for details of QA/QC procedures see recent NBNERR nutrient metadata documentation available at http://cdmo.baruch.sc.edu/QueryPages/data_metadata_select.cfm). Since there is a lag of over one year for submitted data to be finalized by the CDMO, data used in this report have been run through the NERR QA/QC procedures but have not received final approval from the CDMO. However it is expected that there will be very few, if any, differences between the dataset used here and the final CDMO-approved dataset.

All available grab sample data from 2002-2008 were used to graphically illustrate nutrient and chlorophyll concentrations over an annual cycle. For each parameter, monthly concentrations were averaged across years and plotted individually for each sampling station. To examine how seasonal patterns vary by year and to observe how data from 2008 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. 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). Seasons are defined as: winter = January through March; spring = April through June; summer = July through September; and fall = October through December. In order to statistically compare each parameter among stations and over time, Two-way analysis of variance (ANOVA) tests were used with station and season as main factors. If significant differences were found, a post-hoc multiple comparison Tukey test was used to identify the specific stations and/or seasons that differed. Finally, simple linear regression was used to statistically determine if seasonal concentration peaks for each parameter have changed over the duration of the grab sampling program covered in this report.

Using 2008 data from the diel program, standardized nutrient and chlorophyll concentrations were plotted against standardized tide stage data in order to determine if concentrations are affected by tidal forcing. The data had to be standardized in order to combine data across all months since concentrations change throughout the year and since ISCO sampling was not always initiated at exactly the same time relative to low tide (NERRS guidance requires only that samples be taken within the 3-hour window before the time of predicted low tide). For each parameter, concentration data were standardized by determining the maximum value within each month and converting all data within that month to a percentage of the maximum value. Tide stage data were standardized by determining when each sample was taken relative to the initial low tide (i.e., the number of hours, rounded to the nearest hour, before or after the initial low tide). In order to serve as a check for the analyses described above that combined all standardized data, actual phosphate and ammonium concentrations were also plotted against actual tide levels during one month in each of the four seasons.

2.3 Results and Discussion

During 2008, 92 water samples were collected for nutrient and chlorophyll analysis from the four stations as part of the monthly NBNERR grab program. An additional 144 samples were collected during the year at T-Wharf Bottom as part of the NBNERR diel program. Ideally, a total of 240 samples would have been collected from both of these programs combined (96 from the grab sampling program; 144 from the diel program); therefore 98.3% of all expected samples were collected in 2008. The four missing grab samples were due to ice conditions at Nag Creek in January and February.

Based on mean monthly data from 2002-2008, concentrations of most nutrient species and chlorophyll exhibited clear seasonal patterns (Figure 15). In general, phosphorous was lowest in late-winter and highest in mid-summer while nitrogen species were lowest throughout the spring and summer and highest in mid- to late-fall. Seasonal patterns in dissolved silica concentration were the least defined and differed between Nag Creek (where a pattern was not observed) and the other three stations. Except for Nag Creek, dissolved silica was lowest in late-winter/early-spring and higher in summer and fall. Finally, chlorophyll concentrations exhibited a bimodal pattern with a peak in early winter and a second peak in August. Two-way ANOVA was used to statistically compare these observed concentrations among seasons and the results are presented in Table 2.

Seasonal patterns in chlorophyll have been described previously (Pilson 1985, Li and Smayda 1998, Oviatt et al. 2002) and are driven by factors including light, temperature, nutrient availability and grazing pressure exerted by zooplankton (Hargraves 1988, Smayda 1998). The winter peak (known as the winter-spring bloom) is dominated by diatoms while the summer peak is likely an annual dinoflagellate bloom (Pratt 1959, Durbin and Durbin 1981). Since diatoms rely on dissolved silica for their frustules, the winter-spring bloom probably results in the simultaneous dip in silica seen at the open water stations (Figure 15). Phosphate patterns are likely driven by seasonal changes in anthropogenic inputs (e.g., increased fertilizer use in summer). While it would seem logical that nitrogen should also increase in summer due to increased human activities, the paradoxical summertime drop is likely due to uptake of most available dissolved nitrogen in the water column by phytoplankton macroalgae, the latter of which can become nitrogen limited in summer (Kinney and Roman 1998). These data provide a solid foundation for understanding the basic seasonal patterns of nutrients and chlorophyll concentrations within the Reserve. These data provide a baseline to which future seasonal patterns can be compared (e.g., to observe if any shifts occur due to changes in climate) and can serve as a reference for comparison with more eutrophic areas of Narragansett Bay or with other long-term nutrient datasets such as the one produced by MERL at URI-GSO (http://gso.uri.edu/merl/data.htm).

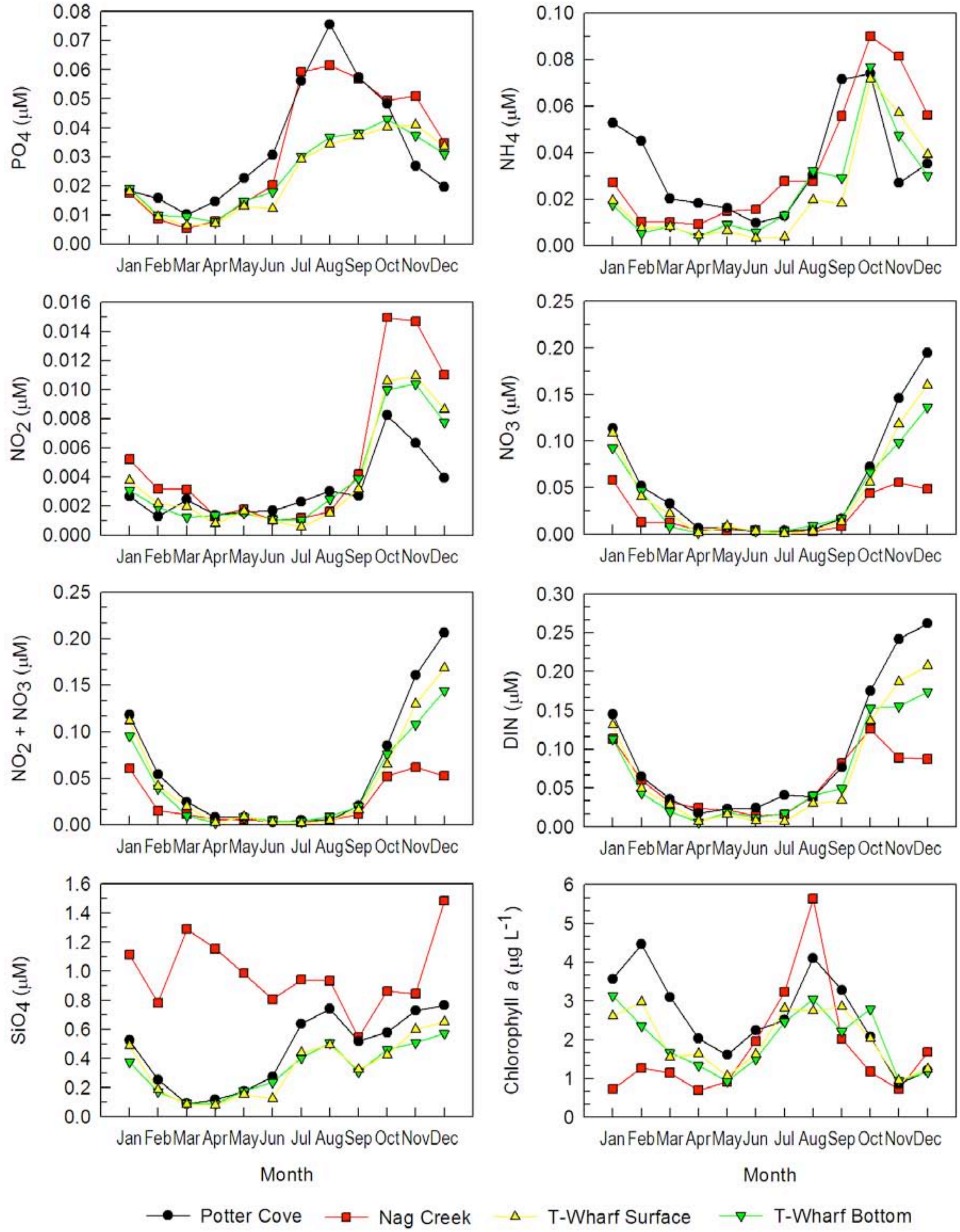

Figure 15. Monthly means of nutrient and chlorophyll concentrations at each of the four SWMP stations. Means were calculated from all available data between 2002 and 2008. Error bars were purposefully omitted for visual clarity.

Table 2. Two-way ANOVA to compare nutrient species and chlorophyll among seasons.

Phosphate (PO_4)

Source of Variation	DF	SS	MS	F	P
Season	3	7.037	2.346	94.089	<0.001
Station	3	0.421	0.14	5.625	0.001
Season x Station	9	0.574	0.064	2.556	0.012
Residual	87	2.169	0.025		
Total	102	10.394	0.102		

Ammonium (NH_4)

Source of Variation	DF	SS	MS	F	P
Season	3	9.256	3.085	31.57	<0.001
Station	3	1.989	0.663	6.785	<0.001
Season x Station	9	1.115	0.124	1.268	0.266
Residual	87	8.503	0.098		
Total	102	20.522	0.201		

Nitrite (NO_2)

Source of Variation	DF	SS	MS	F	P
Season	3	14.113	4.704	47.077	<0.001
Station	3	0.452	0.151	1.506	0.219
Season x Station	9	1.027	0.114	1.142	0.343
Residual	81	8.094	0.1		
Total	96	23.344	0.243		

Nitrate (NO_3)

Source of Variation	DF	SS	MS	F	P
Season	3	31.207	10.402	67.253	<0.001
Station	3	1.001	0.334	2.158	0.1
Season x Station	9	0.909	0.101	0.653	0.748
Residual	77	11.91	0.155		
Total	92	45.421	0.494		

Nitrite + Nitrate (NO_2+NO_3)

Source of Variation	DF	SS	MS	F	P
Season	3	30.965	10.322	73.078	<0.001
Station	3	0.998	0.333	2.355	0.078
Season x Station	9	0.952	0.106	0.749	0.663
Residual	84	11.864	0.141		
Total	99	44.908	0.454		

Table 2 (cont.). Two-way ANOVA to compare nutrient species and chlorophyll among seasons.

Dissolved Inorganic Nitrogen (DIN)					
Source of Variation	DF	SS	MS	F	P
Season	3	15.825	5.275	53.836	<0.001
Station	3	1.096	0.365	3.728	0.014
Season x Station	9	0.826	0.092	0.937	0.498
Residual	85	8.328	0.098		
Total	100	25.551	0.256		

Dissolved Silica (SiO_4)					
Source of Variation	DF	SS	MS	F	P
Season	3	4.321	1.44	18.79	<0.001
Station	3	5.431	1.81	23.611	<0.001
Season x Station	9	1.387	0.154	2.01	0.048
Residual	87	6.67	0.077		
Total	102	17.635	0.173		

Chlorophyll a					
Source of Variation	DF	SS	MS	F	P
Season	3	1.852	0.617	8.685	<0.001
Station	3	0.495	0.165	2.321	0.081
Season x Site	9	0.389	0.043	0.608	0.787
Residual	87	6.184	0.071		
Total	102	8.811	0.086		

These seasonal patterns are clearly superimposed within the 2002-2008 nutrient and chlorophyll concentration time series (Figure 16 to 19). Using peak seasonal concentrations for each parameter at each station, it was found that most are not trending significantly over time (linear regression; $p>0.05$ for each case). However, statistically significant exceptions include decreases in NO_3 ($F=7.57$; $p=0.04$) and NO_2+NO_3 ($F=7.34$; $p=0.04$) at Potter Cove and decreases in DIN ($F=9.99$; $p=0.03$), NO_3 ($F=11.61$; $p=0.02$), and NO_2+NO_3 ($F=10.24$; $p=0.02$) at T-Wharf Surface. Although these trends were statistically significant, only continued monitoring will indicate whether these nutrients are truly decreasing over the long-term since the current dataset spans less than eight years. However, if these trends continue, it may signal that true reductions in nutrient concentrations are occurring, perhaps in response to large-scale regulatory projects designed to reduce nutrient inputs into the Bay. These projects include excavating a 10-m wide, 4.8-km long combined-sewer-overflow tunnel under Providence to catch untreated sewage overflows from heavy rains, and enacting tertiary treatment at selected sewage treatment plants to induce an approximately 50% reduction in nitrogen inputs into the Bay from wastewater treatment facilities.

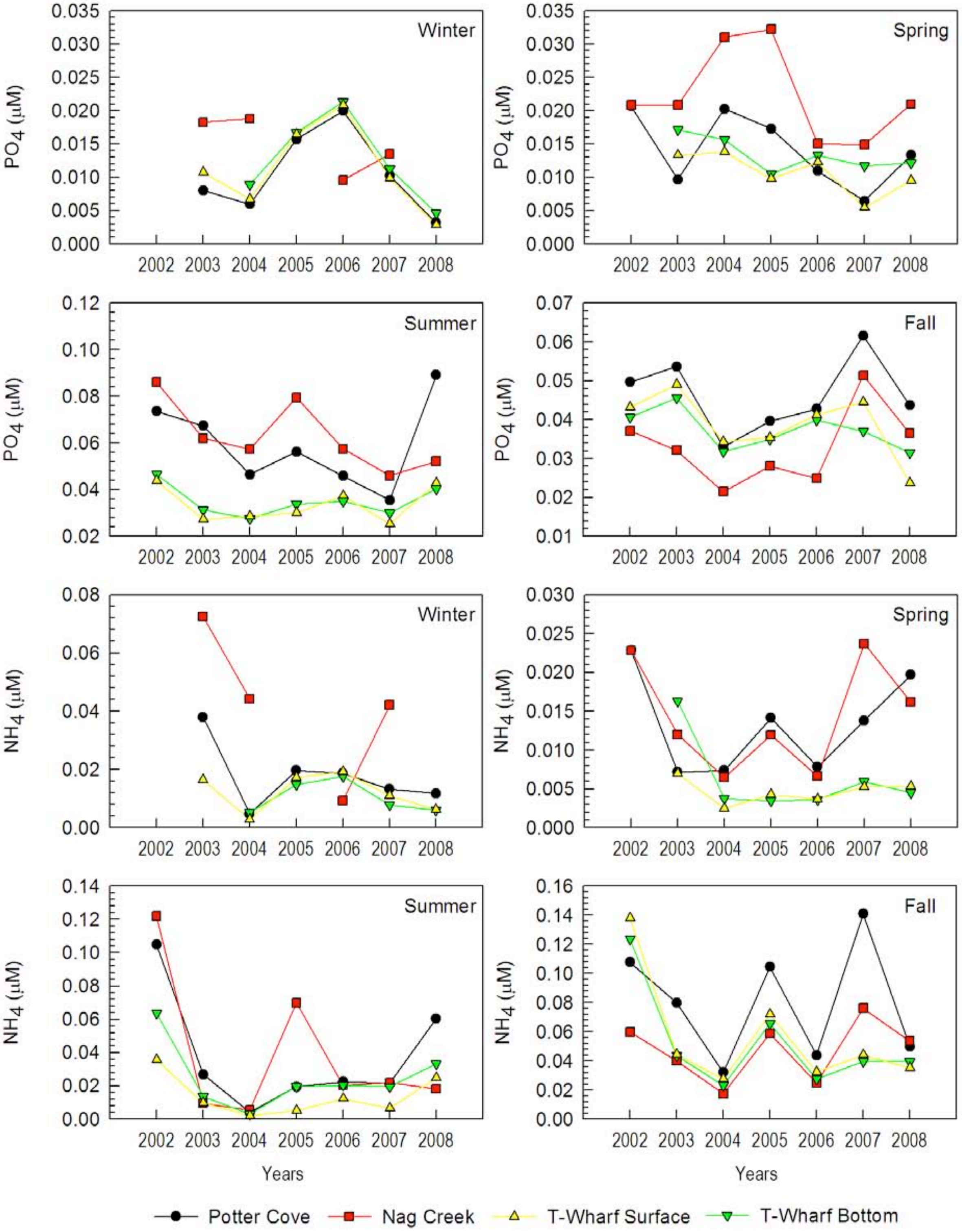

Figure 16. Seasonal means of phosphate (PO_4) and ammonia (NH_4) concentrations at each of the four SWMP stations from 2002 to 2008. Error bars were purposefully omitted for visual clarity. Winter = January-March; spring = April-June; summer = July-September; fall = October-December.

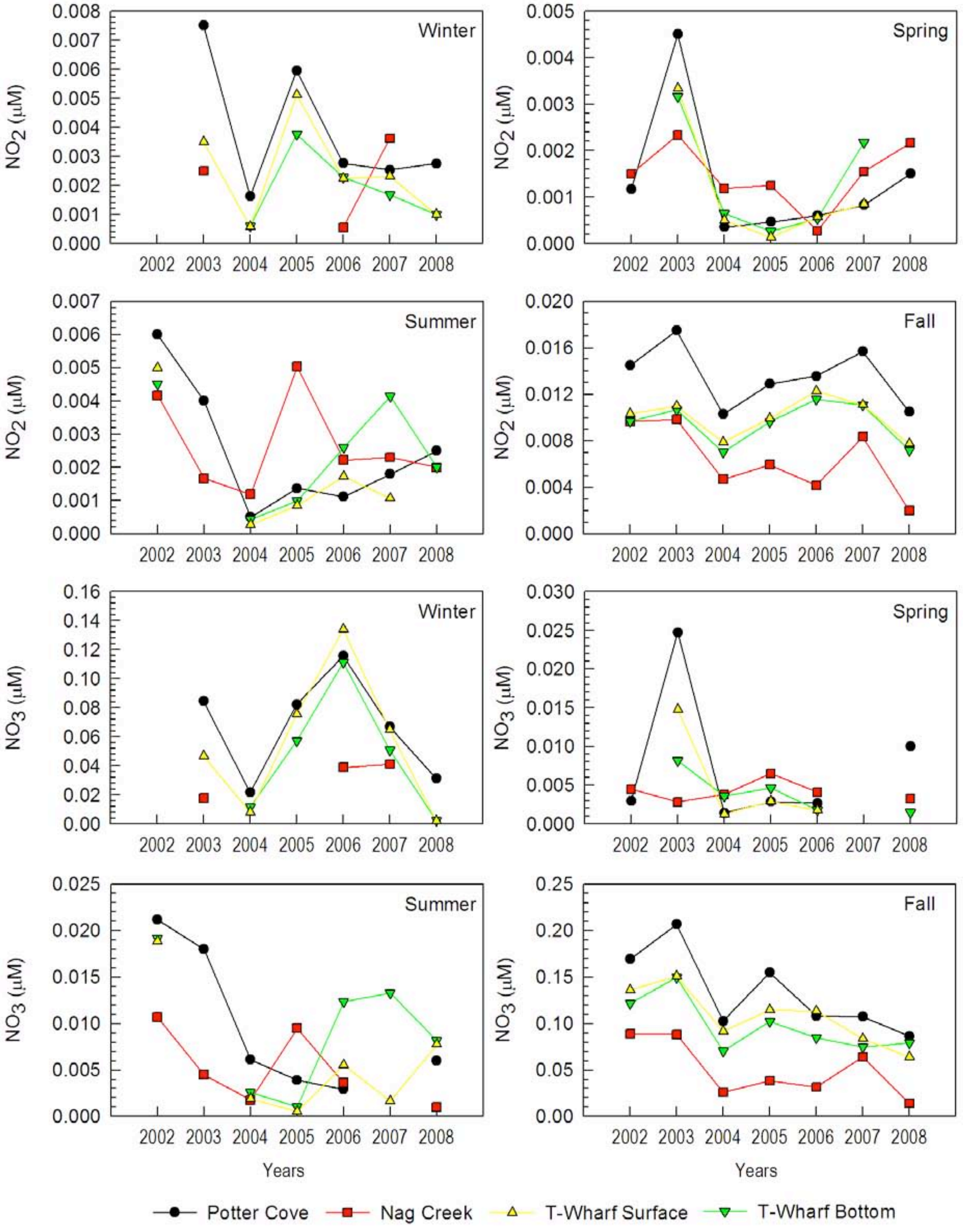

Figure 17. Seasonal means of nitrite (NO_2) and nitrate (NO_3) concentrations at each of the four SWMP stations from 2002 to 2008. Error bars were purposefully omitted for visual clarity. Winter = January-March; spring = April-June; summer = July-September; fall = October-December.

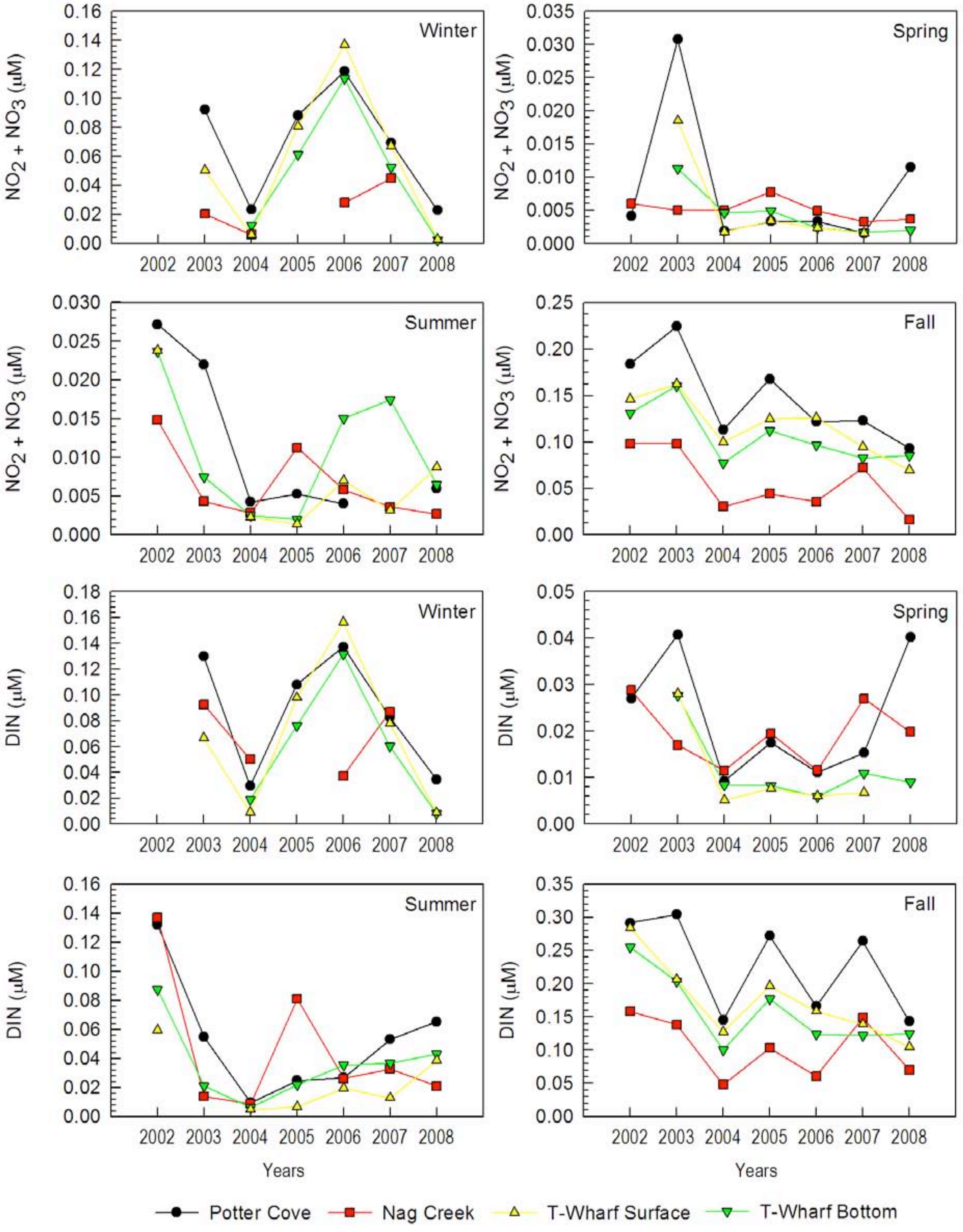

Figure 18. Seasonal means of nitrite and nitrate ($NO_2 + NO_3$) and dissolved inorganic nitrogen (DIN) concentrations at each of the four SWMP stations from 2002 to 2008. Error bars were purposefully omitted for visual clarity. Winter = January-March; spring = April-June; summer = July-September; fall = October-December.

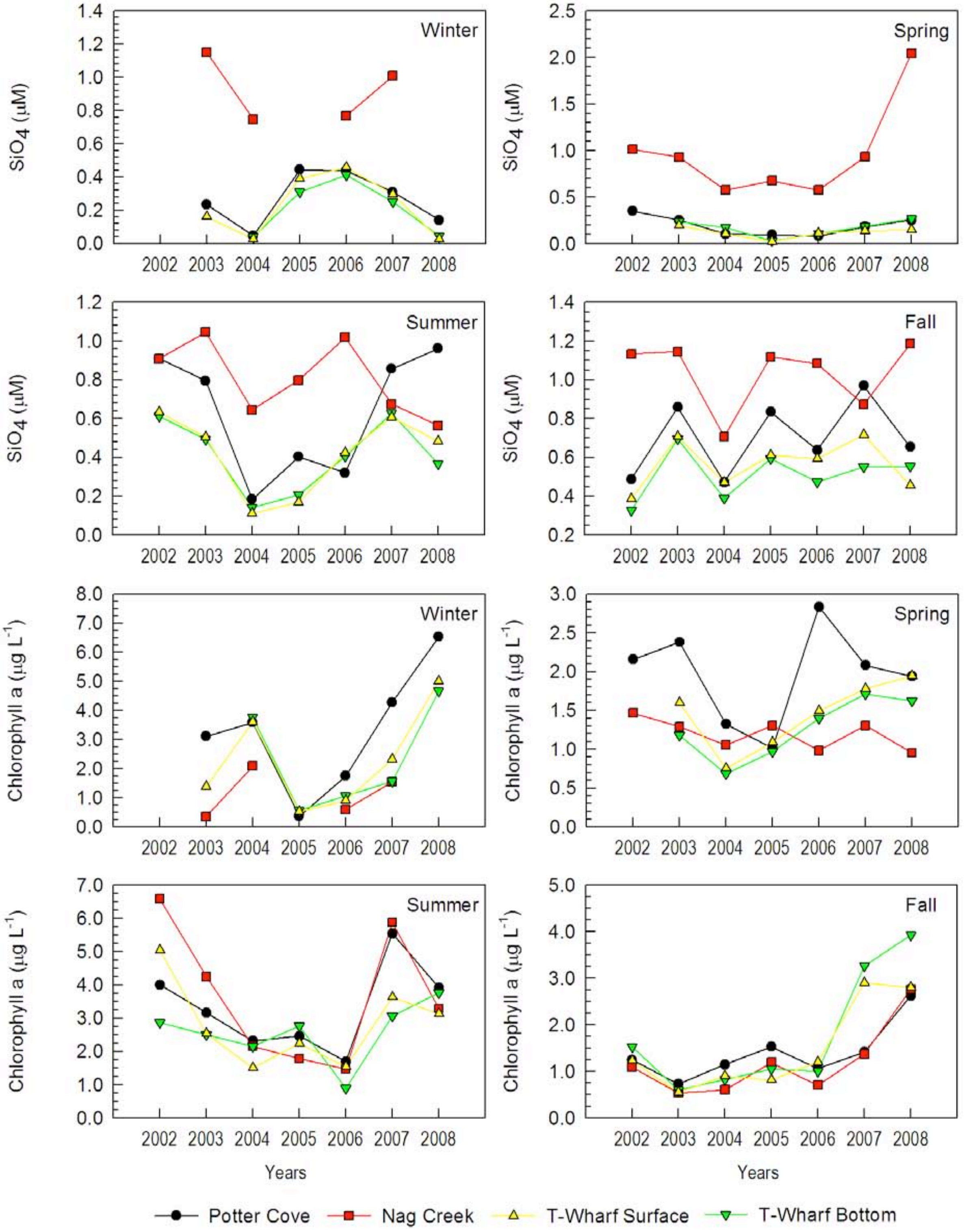

Figure 19. Seasonal means of dissolved silica (SiO_4) and chlorophyll concentrations at each of the four SWMP stations from 2002 to 2008. Error bars were purposefully omitted for visual clarity. Winter = January-March; spring = April-June; summer = July-September; fall = October-December.

It makes sense that concentrations of some nitrogen species may be declining at some NBNERR monitoring stations, but not others. Nag Creek cannot truly be considered as representative of the West Passage of Narragansett Bay proper; instead it is more likely that data from this station only reflect conditions within the small salt marsh system itself, rather than of the surrounding portions of the Bay. Since semi-enclosed salt marshes are likely to be mostly affected by nutrient inputs from the surrounding uplands, this station should not be expected to reflect larger-scale changes occurring in adjacent areas of Narragansett Bay. As previously stated, the T-Wharf Bottom station may not reflect conditions throughout much of Narragansett Bay proper since this station receives some of its signal from waters flowing in from Rhode Island Sound. The opposite is true of the T-Wharf Surface station, which is presumably influenced by surface waters flowing downstream from upper areas of the Bay. This might explain why decreases in the concentrations of some nitrogen species were observed at the surface and not the bottom station at T-Wharf.

Differences in concentrations among stations were also tested for using Two-way ANOVA. Ammonium, DIN, phosphate, and dissolved silica all differed among stations (Table 2). Ammonium concentrations were higher at Nag Creek compared to T-Wharf Surface and Bottom and at Potter Cove compared to T-Wharf Surface. Dissolved inorganic nitrogen was higher at Potter Cove than at T-Wharf Surface. Phosphate was higher at Nag Creek than at either T-Wharf Surface or Bottom. Finally, dissolved silica was higher at Nag Creek than at any other station. Without more information or carefully designed field experiments, it is only possible to speculate as to why differences in these concentrations were found among these stations. For example, concentrations of ammonium and DIN may be generally lower at T-Wharf simply because this station is located lower in the Bay and is probably flushed with relatively more nutrient-poor water from outside the Bay. In addition, phosphate may be relatively high at Potter Cove due to the active farm adjacent to the Cove, while salt marshes such as Nag Creek naturally sequester high concentrations of dissolved silica that can then be exported to support estuarine food webs (Hackney et al. 2000).

Using simple graphical interpretations, no relationships were found between tide stage and the concentrations of any parameter. This was true when plotting standardized tide stage against standardized concentrations (Figure 20), as well as when plotting examples of actual nutrient concentrations relative to actual water levels (Figures 21 and 22). As discussed previously, the T-Wharf Bottom station (where diel samples are collected) is probably mostly influenced by Rhode Island Sound waters as compared to relatively nutrient-rich waters from upper Narragansett Bay. This likely minimizes the influence of tide stage, especially relative to eutrophic areas further upstream in the Bay where concentrations might be expected to raise at lower tide stages when influences from land-based sources are relatively high. Although these results are based on 2008 data only, it is expected that patterns were the same for the previous years of the diel monitoring program.

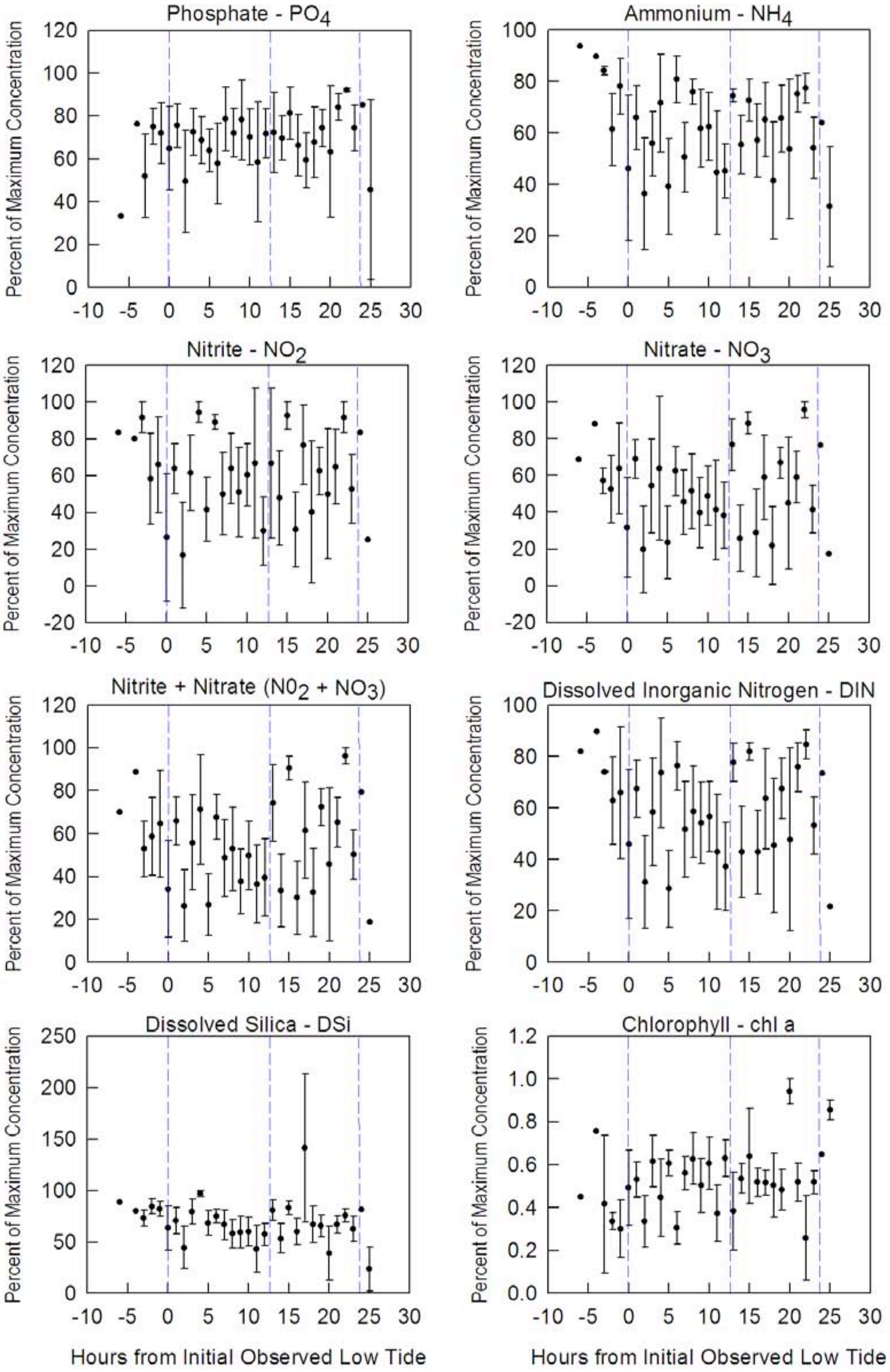

Figure 20. Relationships between standardized nutrient and chlorophyll concentrations and standardized tide stage. Vertical dashed lines represent the approximate time of slack low tides. Error bars represent ± 1 SE.

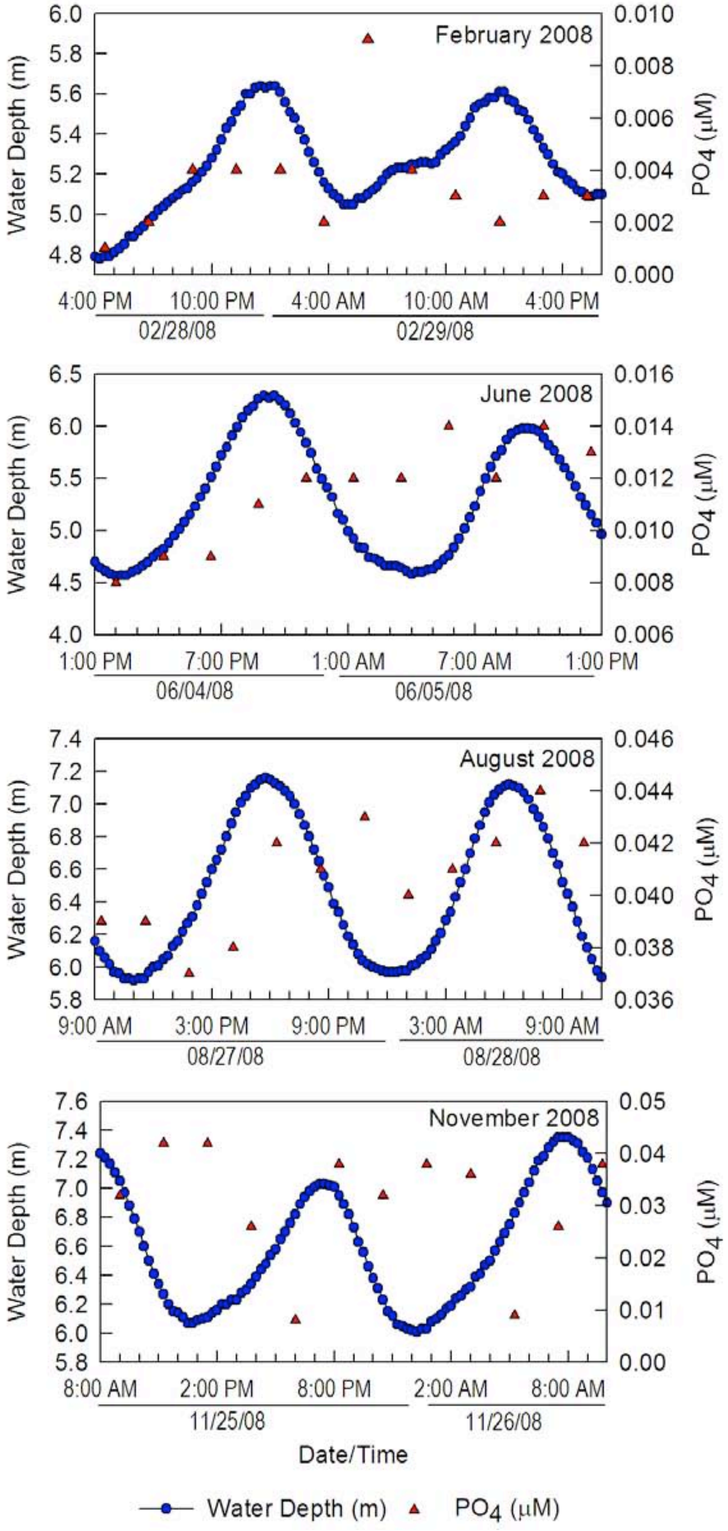

Figure 21. Examples of phosphate (PO_4) concentrations relative to water levels at the T-Wharf Bottom station during one month in each season in 2008.

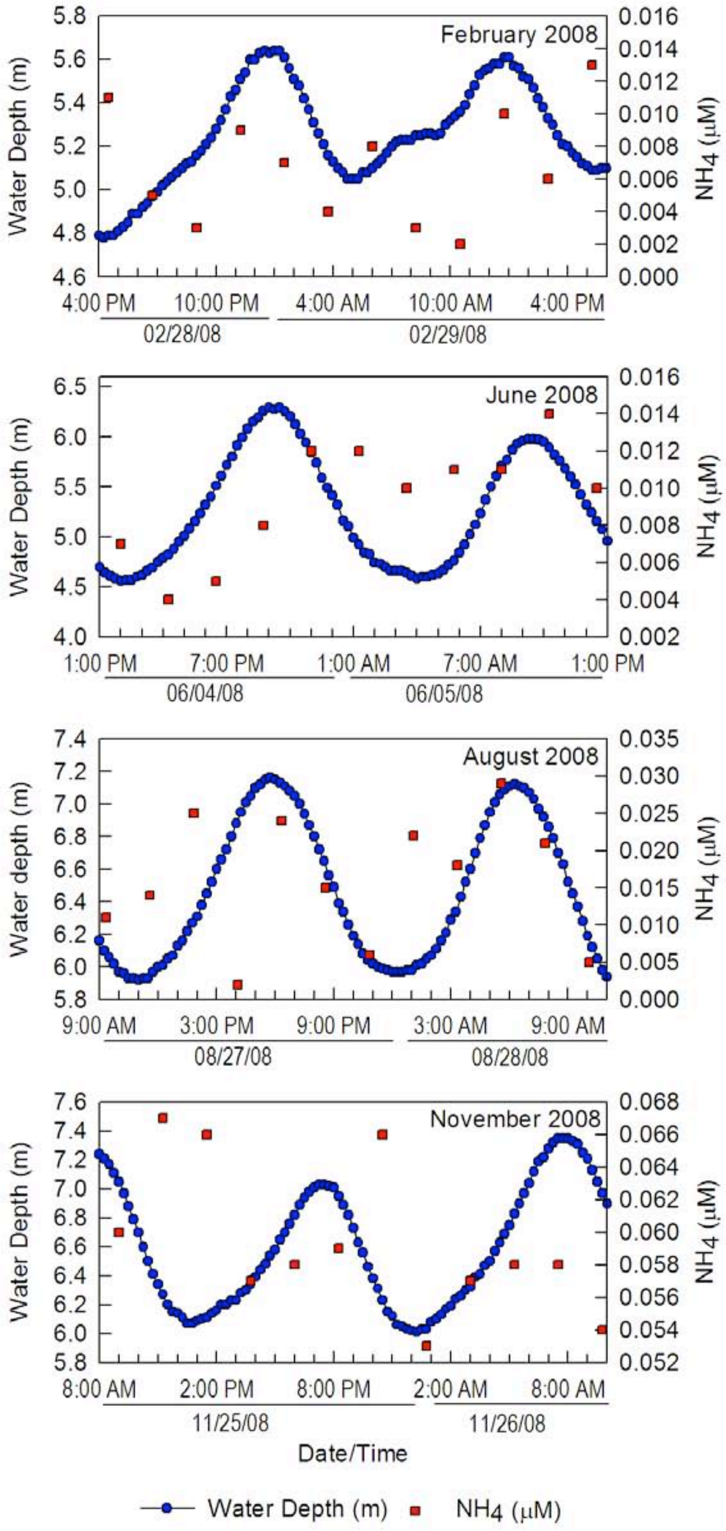

Figure 22. Examples of ammonium (NH_4) concentrations relative to water levels at the T-Wharf Bottom station during one month in each season in 2008.

The results found here suggest that some changes or improvements can be made to the NBNERR nutrient and chlorophyll monitoring programs. For example, no relationships were found between nutrient/chlorophyll concentrations and tide stage from the diel sampling program at T-Wharf Bottom. The overall goal of the NERR program is to examine the effects of tidal forcing on these parameters. Since tidal forcing was found to not have an affect at T-Wharf, and since the NERRS also allows for changing the location of the diel program, it is recommended here that the NBNERR diel sampling program be moved to Potter Cove. It may also be helpful to increase the spatial and/or temporal frequency of sampling at Potter Cove to try to isolate the effects of boater wastes on nutrient concentrations in the Cove. A program designed to collect samples before, during, and after multiple summer weekends throughout the Cove may be an effective start. Finally, the results presented here also suggest that it may be redundant to keep both the surface and bottom sampling stations at T-Wharf since concentrations in all parameters were statistically the same at both stations. It may be more effective to keep the bottom station at T-Wharf and move the surface station to another location that would provide an expanded spatial coverage, and therefore more information, of Bay-wide patterns in nutrient and chlorophyll concentrations.

3. METEOROLOGY

3.1 Introduction

Meteorological data have been continuously collected at the Reserve since 2001 and used to support ongoing water quality and biological monitoring efforts, and to assist scientific research projects around the Bay. In this section, we analyzed the meteorological parameters collected during 2008 by month and season, and also summarized the long-term data using a seasonal approach in order to identify any significant environmental changes or trends over time in the Bay.

3.2 Methods

3.2.1 Monitoring Infrastructure

The weather station is located on a grassland on the east side of Prudence Island (41° 38.216' N, 71° 20.350' W) (Figure 2), approximately 389 m South of the Potter Cove water quality monitoring station. A large wooden platform (2.4 m W x 1.8 m D x 2.1 m H) has housed some of the instruments for approximately 16 years (Figure 23). This structure was build by the U.S. Environmental Protection Agency (EPA) to house atmospheric deposition equipment, which is no longer in use. With EPA permission, the platform is being used for SWMP for the purpose of collecting meteorological data.

Figure 23. Meteorological station at Potter Cove showing the wooden platform and aluminum tower where the sensors are located for the collection of atmospheric data.

3.2.2 Data Collection

At the NBNERR weather station, a CR1000 data logger is used to collect data from sensors recording air temperature, relative humidity, wind speed, wind direction, barometric pressure, precipitation, and photosynthetically active radiation (PAR). The CR1000 is enclosed in the Campbell housing unit, 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 23). All sensors were located in accordance with manufacturer recommendations.

Meteorological data are sampled at 5-second intervals under the control of the CDMO/Campbell Scientific Logger Net 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 through the website (http://cdmo.baruch.sc.edu) and undergoes the same rigorous and careful QAQC process as described for the water quality data (see section 1.2.2-Quality Assurance Quality Control).

3.2.3 Quality Assurance Quality Control (QAQC)

The meteorological data used in this report are the authoritative datasets of CDMO, except for 2008. The dataset for 2008 is provisional due to the existing delay of over one year for submitted data to be finalized by CDMO. Nevertheless, we expect that the 2008 provisional dataset used for this report and the final authoritative dataset of CDMO will be similar. The data can be downloaded by any interested group or individual through the CDMO website at http://cdmo.baruch.sc.edu/QueryPages/csv_export.cfm. The downloaded meteorological file is similar to the water quality file described in section 1.2.3 (see Quality Assurance Quality Control), and the same eleven QAQC flags (Table 1) described in the aforementioned section apply to the meteorological data. The meteorological datasets from 1995 to 2007 used for this report were checked according to the QAQC flags in Table 1. Data flagged as 0, 2, 3, and 4 were used for this report (datasets had no data flagged as 5=corrected data); the resulting dataset was called 'revised data' preceded by the corresponding year of the data (i.e. 2008 revised data), and was used for statistical analysis, tables, and graphs. For 2008 and subsequent datasets, CDMO is no longer using the 2 and 3 standard deviations from the historical mean flags; all other flags remain the same. Therefore, the dataset from 2008 was verified for outliers by calculating the 3rd standard deviation; data outside the 3rd standard deviation were not included in the 2008 revised data.

3.2.4 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.

3.2.5 Data Analysis

2008 Data

The 2008 revised data comprised from 96-100% 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 using the same criteria mentioned in section 1.2.4 Data Analysis.

Long-term Seasonal Trends

At the Reserve, meteorological data have been collected from 2001 to 2008. After revising the long-term datasets as described in section 3.2.2 Data Collection, the percentage of data used for the seasonal mean calculations is presented in Appendix II. To calculate long-term seasonal means for air temperature, relative humidity, wind speed, wind direction, barometric pressure, and seasonal totals for precipitation and photosynthetic active radiation, the same criteria mentioned in the section 1.2.5 Data Analysis were used. Precipitation data from years 2002 and 2003 were not included due to the low availability of data (2 to 7%) due to equipment failure as described in the metadata documents of each year. To determine if significant changes occurred within seasons across years, a linear regression was performed for each parameter using Sigma Stat version 3.5.

3.3 Results

3.3.1 Air Temperature

Monthly and seasonal mean air temperatures recorded for 2008 at the Potter Cove weather station followed a distinct pattern that is typical of temperate latitudes (Figures 24 and 25). Air temperature ranged from -13.8 to 35.5 ^{o}C (Appendix I). The minimum monthly mean was recorded in February (0.2 ^{o}C), while the maximum monthly mean was recorded in July (23.0 ^{o}C; Figure 24). Summer was relatively high (21.0 ^{o}C), while the seasonal mean for winter approached zero (1.4 ^{o}C).

Long-term seasonal means for air temperature showed very similar seasonal patterns across years (Figure 26); consequently, no significant trends were found over time for any season. For 2008, the seasonal mean for air temperature was similar to previous years.

3.3.2 Relative Humidity

Relative humidity for 2008 at the weather station ranged from 15 to 100% (Appendix I). The minimum monthly mean was observed in March (66.2 %) and the maximum in October (82.9%, Figure 24). Seasonal means for relative humidity showed that the summer season had the highest mean relative humidity (82%), while winter had the lowest (70%, Figure 25). Nevertheless, there was a relatively high amount of variability within each season during 2008 (Figure 25).

Long-term seasonal means for relative humidity showed comparable seasonal patterns across years (Figure 26). No significant trends over time were found for any season.

3.3.3 Barometric Pressure

Barometric pressure recorded for 2008 at the weather station ranged from 989 to 1039 mb (Appendix I). The minimum monthly mean was recorded in May (1009 mb), while the maximum was recorded in April, September and October (1018 mb, Figure 24). Seasonal means for barometric pressure showed that the highest values were recorded during the fall season (1017 mb), while the lowest were recorded during spring (1013 mb, Figure 25).

Long-term seasonal means for barometric pressure showed a decreasing trend across years (Figure 26). A closer look at the data showed that the barometric pressure decreased significantly in spring (R^2=0.810, p=0.002) and summer (R^2=0.751, p=0.01) across years; however, we are not sure of the causes and/or implications of these trends. Spring and summer of 2008 had the lowest barometric pressure levels since 2001; winter and fall were very similar to previous years.

3.3.4 Wind Speed

Wind speed measured at the weather station for 2008 ranged from 0 to 10.3 m s^{-1} (Appendix I). The minimum monthly mean was observed in August (1.8 m s^{-1}), while the maximum monthly mean was observed in December (4.9 m s^{-1}, Figure 24). Seasonal means for wind speed were relatively low during 2008 (Figure 25). However, the highest speeds were recorded during the winter months (3.9 m s^{-1}), and the lowest during the summer (2.2 m s^{-1}).

Long-term seasonal means for wind speed showed a similar seasonal pattern across years except for summer, which showed a significant (R^2=0.708, p=0.036) decreasing trend across years (Figure 26). Spring and summer of 2008 had the lowest wind speed since 2001; winter and fall were very similar to previous years.

3.3.5 Wind Direction

Wind direction measurements at the weather station showed winds blowing from all directions (0-360^o, Appendix I) in 2008. During 2008, winds came mostly from the southeast (90-180^o) in April, August, September, and October, and from the southwest (181-270^o) the rest of the year (Figure 24). Seasonal means for wind direction showed the winds blowing mainly from the southwest; however, high variability is still present within seasons since wind direction changes constantly over the year (Figure 25).

Long-term seasonal means for wind direction consistently showed winds coming from the southwest in winter and fall and mostly from the southeast in spring and summer across years (Figure 27). For 2008, winter, spring and fall were similar to previous years. However, winds during the summer of 2008 were mainly from the southwest, which differed from previous years when winds were mainly southeast.

3.3.6 Precipitation

Precipitation measured at the Potter Cove weather station in 2008 ranged from 0 to 20.8 mm (Appendix I). The minimum total precipitation was observed in October (35 mm), while the maximum was observed in September (225 mm, Figure 24)). Seasonal totals showed that the highest amount of precipitation was recorded during the summer (400 mm) followed by winter (358 mm), while spring and fall were comparable (283 mm, Figure 25).

Long-term seasonal total precipitation did not show any significant seasonal patterns across years (Figure 27). However, the highest amount of precipitation since 2001 was recorded during the fall of 2005 (446 mm) followed by the spring of 2006 (416 mm). For 2008, precipitation in spring and fall was similar to previous years; however, winter (358 mm) and summer (400 mm) of 2008 had the highest precipitation recorded during these seasons for any year (Figure 27).

3.3.7 Photosynthetic Active Radiation

Photosynthetic active radiation measured at the Potter Cove weather station in 2008 ranged from 0 to 1652 mmol m^{-2} (Appendix I). The minimum monthly total PAR (Figure 24) was observed in December (28044 mmol m^{-2}), while the maximum was observed in July (1244306 mmol m^{-2}). Seasonal total PAR showed comparable values for spring and summer, while the lowest PAR was recorded during the fall (Figure 25).

Long-term seasonal PAR totals exhibited a cycle typical of temperate latitudes (Figure 27). There were no significant long-term trends in PAR.

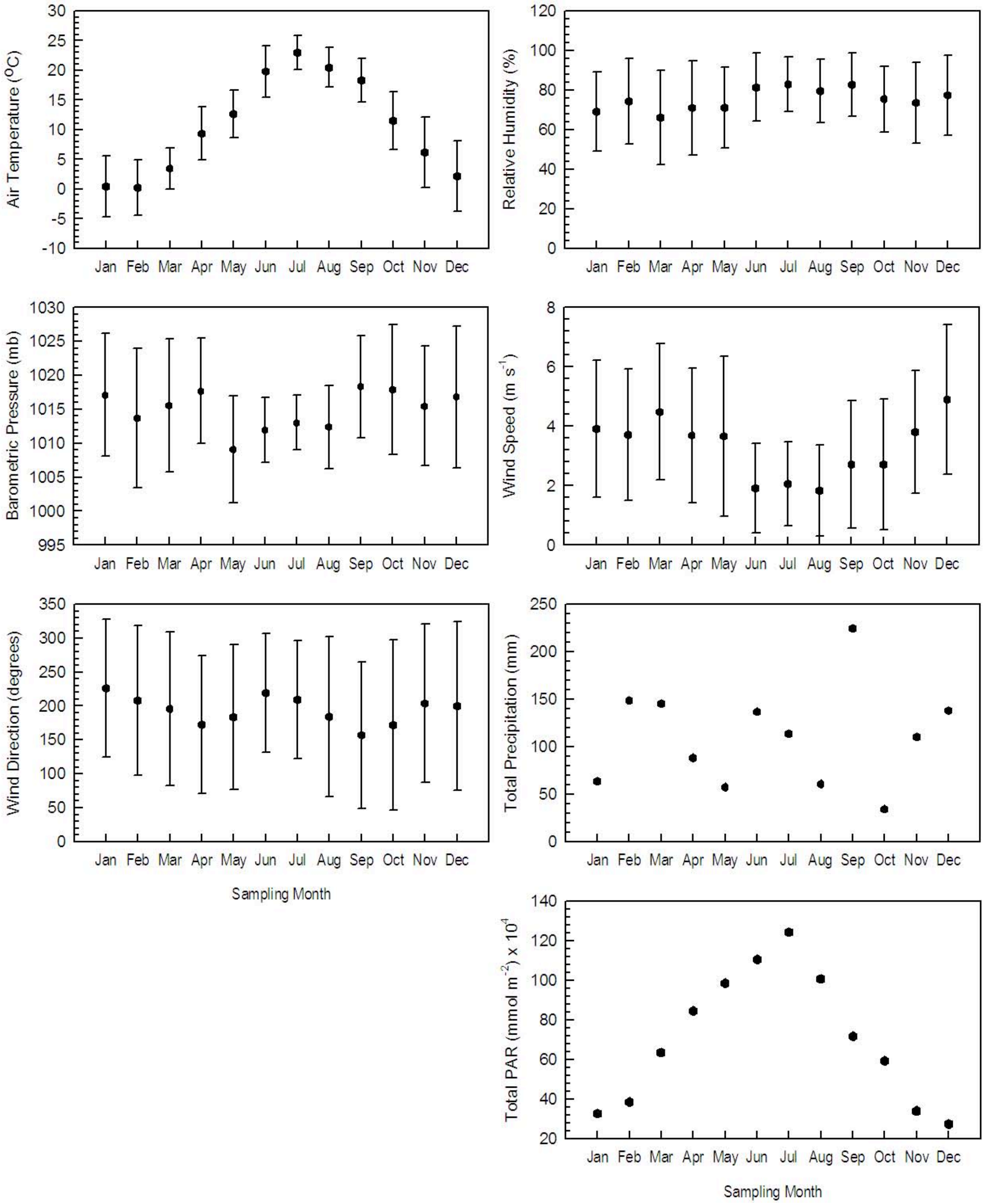

Figure 24. Monthly means (± 1 standard deviation) calculated for meteorological parameters recorded by the weather station in 2008. Precipitation and PAR are monthly totals.

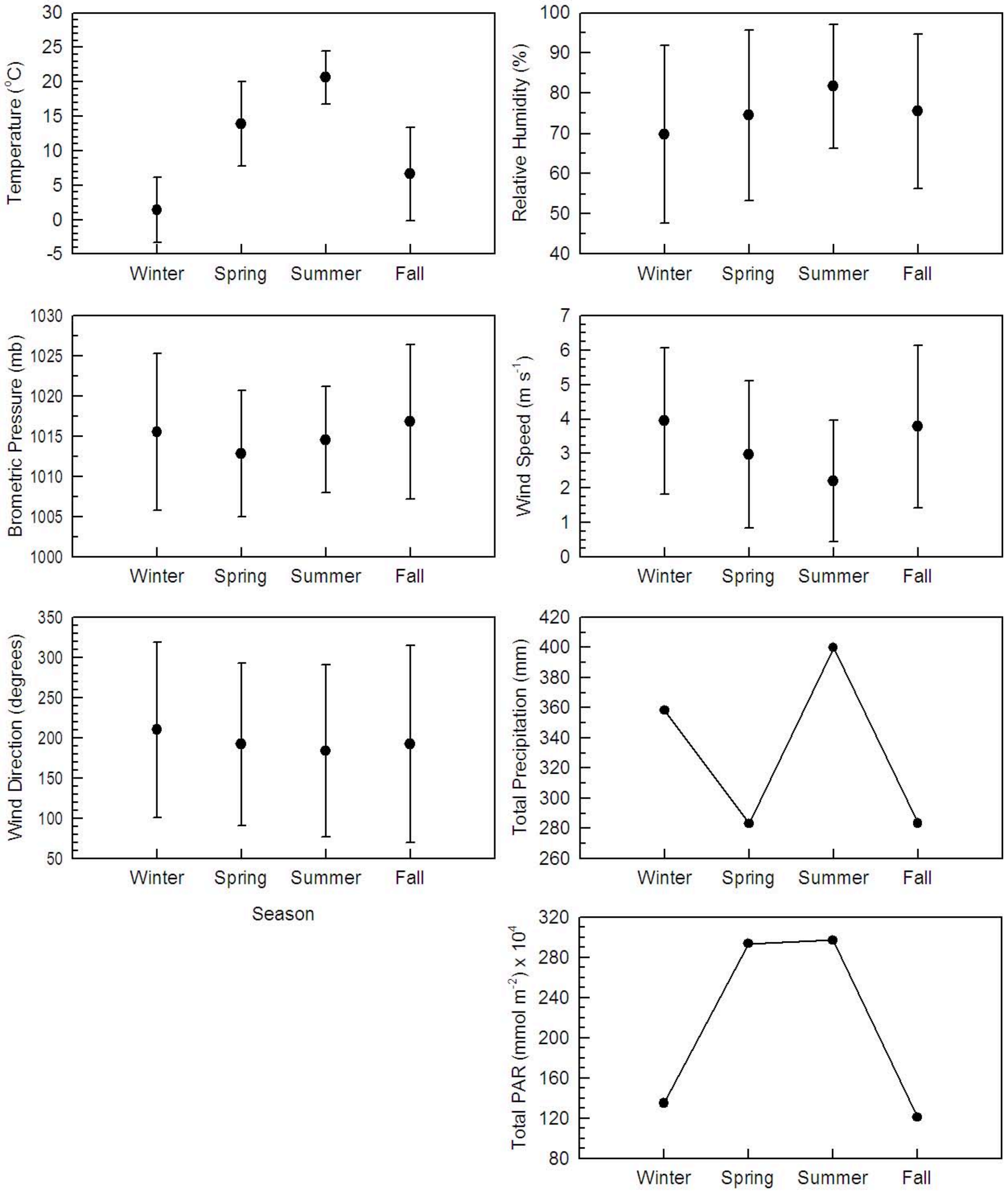

Figure 25. Seasonal means (± 1 standard deviation) calculated for meteorological parameters recorded by the weather station in 2008. Precipitation and PAR are monthly totals.

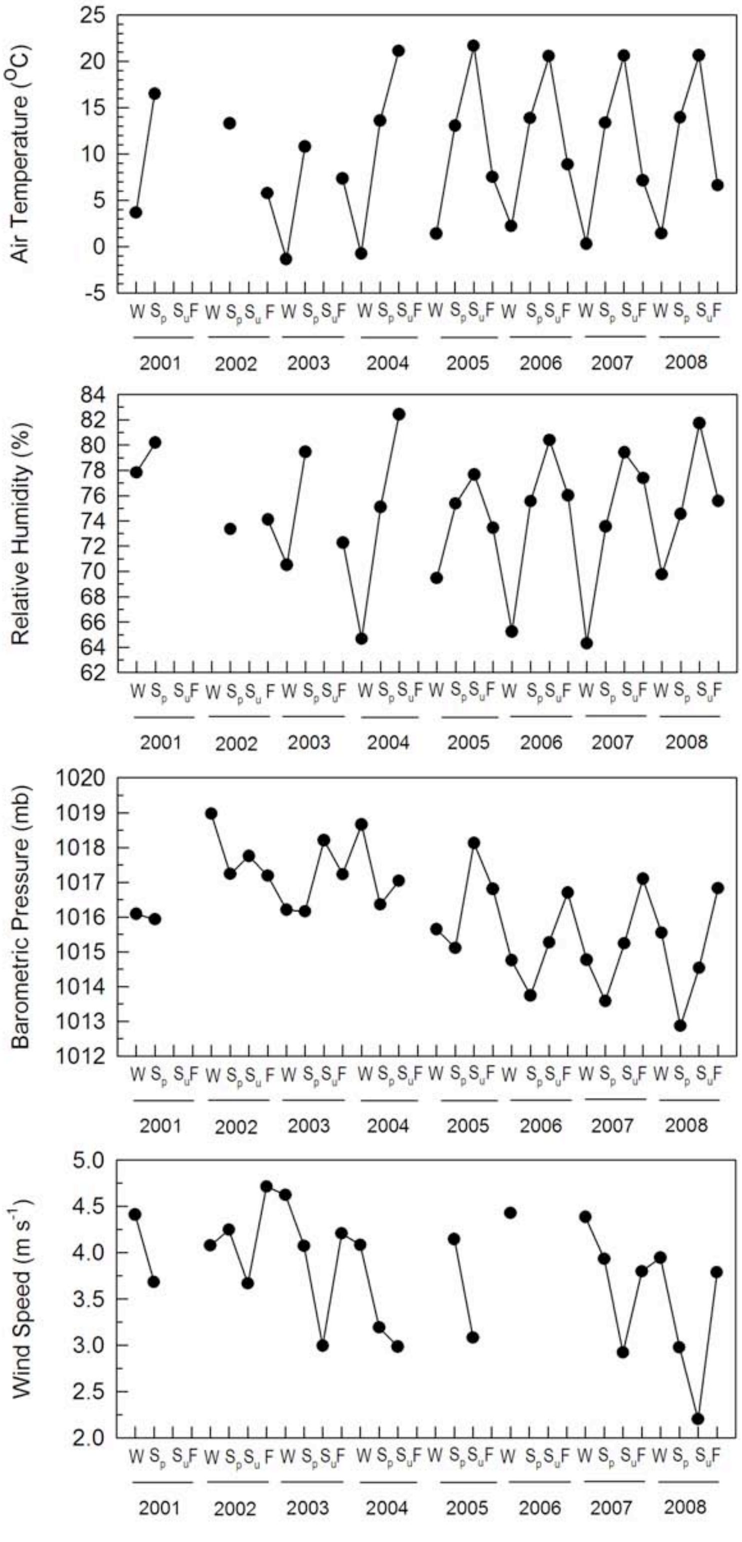

Figure 26. Long-term seasonal means calculated for air temperature, relative humidity, barometric pressure, and wind speed recorded at the weather station.

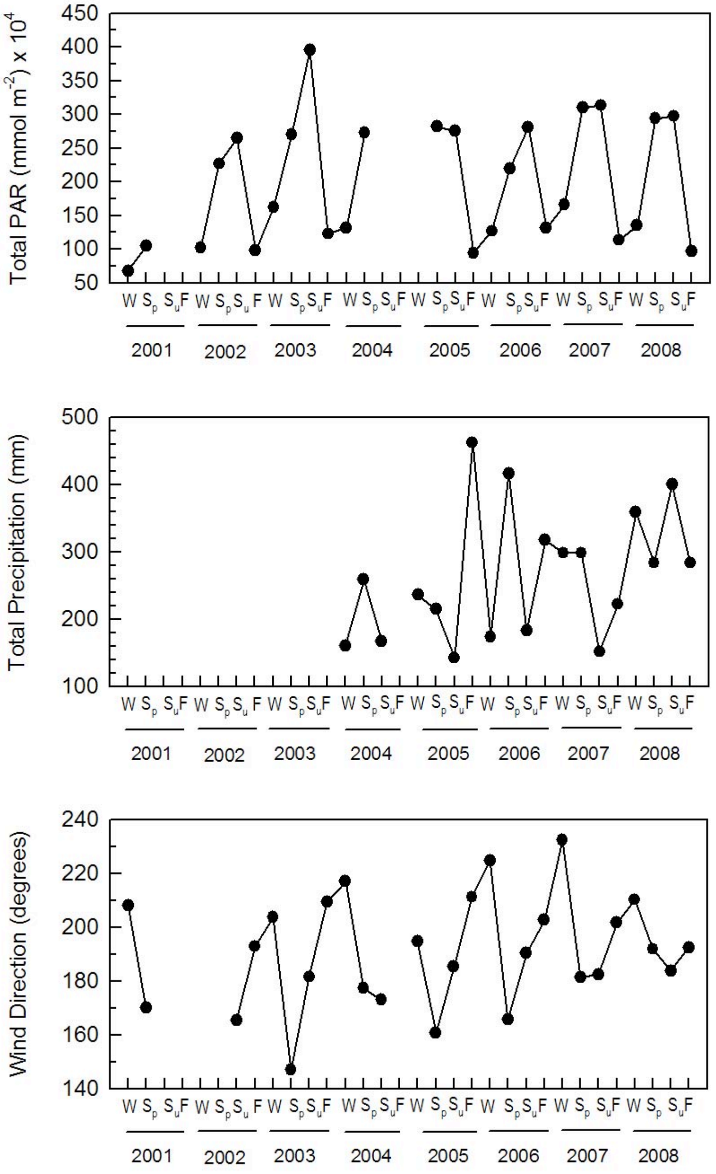

Figure 27. Long-term seasonal means calculated for wind direction recorded at the weather station. Precipitation and PAR are totals for each season.

3.4 Discussion

The NBNERR has been collecting meteorological data since 2001. In this section of the report we provided a summary of eight years of data, from 2001 to 2008. By analyzing and summarizing the data, inter and intra-annual patterns and trend can by identified. In a previous report (Durant et al. 2009), we analyzed seven years of meteorological data by examining monthly and yearly means. However, in this report we analyzed the long-term and 2008 data within each season. We believed that this method of analysis was more appropriate, informative, and effective since Narragansett Bay is a temperate estuary with strongly defined seasons.

The meteorological parameters analyzed for 2008 exhibited seasonal patterns that are characteristic of temperate zones. Air temperature followed a distinctive seasonal cycle during 2008; this same distinct pattern has been observed since 2001. Monthly mean relative humidity varied from ~15 to 100%; wind direction was mostly from the southwest, and low to moderate wind speeds (2-5 m s^{-1}) prevailed during 2008. Precipitation was low during 2008 but comparable to previous years, and photosynthetic active radiation was higher during summer months. It remains difficult to identify any meaningful trends from this relatively limited dataset; as the dataset grows over time it should be possible to detect long-term meteorological trends, which can then be related back to patterns in water quality.

4. ACKNOWLEDGEMENTS

We would like to thank the NBNERR staff for their help and support during the production of this report.

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APPENDIX I. DESCRIPTIVE STATISTICS FOR 2008

Potter Cove

	Temp. (°C)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (µg L^{-1})
Original Dataset	35136	35136	35136	35136	35136	35136	35136
Revised Dataset (No. Data points)	32649	32292	32193	32576	30536	32339	26293
% Data Used	93	92	92	93	87	92	75
Mean	12.07	27.97	100.66	9.50	7.96	1.15	6.80
Std Dev	7.67	2.28	20.58	2.93	0.30	1.65	7.91
Std. Error	0.04	0.01	0.12	0.02	0.00	0.01	0.05
C.I. of Mean	0.08	0.02	0.23	0.03	0.00	0.02	0.10
Range	27.9	11.6	132.4	16.3	1.6	36	123
Maximum	26.7	32.2	167.1	17.4	8.8	36	123
Minimum	-1.2	20.6	34.7	1.1	7.2	0	0
Median	11.9	28.4	101	9.3	8	1	4.3
25%	4.6	26.6	89.7	7.5	7.7	0	1.5
75%	19.5	29.7	113.3	12	8.2	2	9.5

Nag Creek

	Temp. (°C)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (µg L^{-1})
Original Dataset	35136	35127	35136	35136	35136	35136	35042
Revised Dataset (No. Data points)	26141	25411	25452	25493	26133	24848	26463
% Data Used	74	72	72	73	74	71	76
Mean	15.91	27.13	79.75	7.01	7.43	4.50	4.48
Std Dev	7.58	3.79	32.30	3.05	0.42	8.00	2.88
Std. Error	0.05	0.02	0.20	0.02	0.00	0.05	0.02
C.I. of Mean	0.09	0.05	0.40	0.04	0.01	0.10	0.03
Range	40.1	24.5	177.3	15.2	2.4	183	20.5
Maximum	38.6	35.2	177.2	15.2	8.6	183	20.5
Minimum	-1.5	10.7	-0.1	0	6.2	0	0
Median	16.2	28.1	84.7	7.5	7.4	2	3.8
25%	10	25.8	60.4	4.9	7.1	1	2.7
75%	22.2	29.6	100.1	9.3	7.8	5	5.4

T-Wharf Surface

	Temp. (^oC)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (µg L^{-1})
Original Dataset	35136	35136	35136	35136	35136	35136	35136
Revised Dataset (No. Data points)	34379	34379	32555	32690	32801	34228	33789
% Data Used	98	98	93	93	93	97	96
Mean	12.27	29.51	97.94	8.95	7.96	0.81	5.12
Std Dev	7.12	1.87	11.31	1.98	0.23	3.68	5.61
Std. Error	0.04	0.01	0.06	0.01	0.00	0.02	0.03
C.I. of Mean	0.08	0.02	0.12	0.02	0.00	0.04	0.06
Range	24.4	11.9	98.2	11.9	1.2	62	29.4
Maximum	26.2	33.2	133.2	14.9	8.5	62	29.4
Minimum	1.8	21.3	35	3	7.3	0	0
Median	11.9	29.9	98.4	8.8	8	0	2.9
25%	5	28.425	91.8	7.3	7.8	0	1.4
75%	19.3	30.8	104.7	10.7	8.1	1	6.8

T-Wharf Bottom

	Temp. (^oC)	Salinity (ppt)	DO (% sat.)	DO (mg L^{-1})	pH	Turb. (NTU)	Chl. (µg L^{-1})
Original Dataset	35136	35136	35136	35136	35136	35136	35136
Revised Dataset (No. Data points)	33124	33080	30194	31164	29165	32648	24458
% Data Used	94	94	86	89	83	93	70
Mean	12.20	29.72	92.76	8.46	7.97	2.06	4.77
Std Dev	6.35	1.40	14.96	2.34	0.31	2.09	6.45
Std. Error	0.03	0.01	0.09	0.01	0.00	0.01	0.04
C.I. of Mean	0.07	0.02	0.17	0.03	0.00	0.02	0.08
Range	22.8	7.6	109.7	14.4	1.7	18	143
Maximum	24.8	33	144.9	15.5	8.6	18	143
Minimum	2	25.4	35.2	1.1	6.9	0	0
Median	11.9	29.9	95	8.6	8	2	2.6
25%	5.8	28.7	84.6	6.7	7.8	1	0.9
75%	18.8	30.8	103.2	10.3	8.2	3	5.8

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	35136	35136	35136	35136	35136	35136	35136
Revised Dataset (No. Data points)	35127	35127	35093	34552	34855	35129	32389
% Data Used	100	100	100	98	99	100	92
Mean	10.7	75.4	1014.9	3.2	194.5	0.0	253.9
Std Dev	9.1	20.1	8.7	2.2	110.6	0.3	390.4
Std. Error	0.0	0.1	0.0	0.0	0.6	0.0	2.2
C.I. of Mean	0.1	0.2	0.1	0.0	1.2	0.0	4.3
Range	49.3	85	50	10.3	360	20.8	1657.1
Maximum	35.5	100	1039	10.3	360	20.8	1651.7
Minimum	-13.8	15	989	0	0	0	-5.4
Median	10.4	79	1015	2.9	231	0	10.3
25%	3.4	61	1009	1.6	79	0	0
75%	18.5	93	1021	4.5	279	0	397

APPENDIX II. PERCENT DATA USED

Potter Cove

YEAR	SEASON	PERCENT DATA						
		Temperature	Salinity	DO % sat.	DO Conc.	pH	Turbidity	Chl
1995	Winter	16	16	15	16	16	0	
	Spring	0	0	0	0	0	0	
	Summer	0	0	0	0	0	0	
	Fall	0	0	0	0	0	0	
1996	Winter	77	64	77	64	77	13	
	Spring	73	73	48	48	73	19	
	Summer	82	82	25	25	82	1	
	Fall	100	100	89	89	100	17	
1997	Winter	73	73	73	73	73	5	
	Spring	100	100	91	91	100	20	
	Summer	77	77	37	37	77	15	
	Fall	100	100	83	83	100	62	
1998	Winter	93	93	93	93	93	23	
	Spring	93	93	87	87	93	27	
	Summer	87	87	32	32	87	87	
	Fall	85	85	72	72	85	85	
1999	Winter	100	100	100	100	100	97	
	Spring	87	87	87	87	87	79	
	Summer	100	100	97	97	100	77	
	Fall	99	99	99	99	99	99	
2000	Winter	76	76	45	45	76	72	
	Spring	75	72	70	70	75	43	
	Summer	98	98	23	23	82	29	
	Fall	78	78	63	63	78	17	
2001	Winter	100	100	100	100	100	73	
	Spring	97	97	70	70	96	97	
	Summer	100	100	70	70	96	100	
	Fall	92	92	75	75	85	92	
2002	Winter	85	85	85	85	85	85	
	Spring	100	100	85	85	92	85	
	Summer	100	100	100	100	93	83	
	Fall	85	85	85	85	85	58	
2003	Winter	100	86	70	70	100	98	0
	Spring	100	85	100	100	100	100	7
	Summer	84	84	84	84	84	83	97
	Fall	100	100	77	77	100	100	75
2004	Winter	77	77	71	71	77	77	54
	Spring	100	100	100	100	100	94	100
	Summer	100	100	100	100	100	99	98
	Fall	85	85	85	85	85	74	85

Potter Cove (cont.)

YEAR	SEASON	PERCENT DATA						
		Temperature	Salinity	DO % sat.	DO Conc.	pH	Turbidity	Chl
2005	Winter	100	100	96	96	100	70	99
	Spring	100	100	100	100	100	100	98
	Summer	100	100	100	100	100	90	99
	Fall	89	89	89	89	89	88	87
2006	Winter	87	87	87	87	87	87	71
	Spring	100	100	100	100	100	94	100
	Summer	74	74	74	74	74	74	71
	Fall	100	100	89	89	100	77	89
2007	Winter	97	97	97	97	97	90	95
	Spring	99	99	99	99	99	97	100
	Summer	96	96	96	96	96	94	87
	Fall	81	81	81	81	81	80	77
2008	Winter	100	97	100	100	76	100	49
	Spring	75	75	74	74	75	73	75
	Summer	97	97	95	97	97	96	91
	Fall	100	99	98	99	100	99	85

Note: At the Reserve, the collection of chlorophyll data started in 2002. Empty cells = no data collected.

Nag Creek

YEAR	SEASON	PERCENT DATA						
		Temperature	Salinity	DO % sat.	DO Conc.	pH	Turbidity	Chl
2002	Winter	19	0	19	19	19	19	
	Spring	100	80	88	88	88	73	
	Summer	100	52	99	100	100	100	
	Fall	100	87	99	99	100	97	
2003	Winter	30	8.3	30	30	30	25	0
	Spring	100	75	100	85	100	100	7
	Summer	84	84	83	83	84	79	82
	Fall	100	100	100	100	100	100	89
2004	Winter	6	4.7	6	6	6	6	6
	Spring	96	96	96	96	96	80	77
	Summer	100	86	100	100	100	99	100
	Fall	98	98	98	98	98	98	98
2005	Winter	0.7	0.7	0.7	0.7	0.7	0.7	1
	Spring	100	100	100	100	100	94	99
	Summer	100	100	99	100	100	96	99
	Fall	100	100	100	100	100	99	100
2006	Winter	100	100	100	100	100	100	100
	Spring	100	100	100	100	100	100	97
	Summer	100	100	100	100	100	99	99
	Fall	81	81	81	81	81	80	79
2007	Winter	23	23	23	23	23	23	23
	Spring	89	74	88	88	89	89	85
	Summer	89	90	93	93	100	100	81
	Fall	61	46	61	60	65	50	65
2008	Winter	5	4.9	5	5	5	5	6
	Spring	100	97	100	100	100	100	100
	Summer	94	93	86	87	94	90	98
	Fall	98	94	98	98	98	88	98

T-Wharf

YEAR	SEASON	PERCENT DATA						
		Temperature	Salinity	DO % sat.	DO Conc.	pH	Turbidity	Chl
1996	Winter	86	86	72	72	86	24	
	Spring	0	0	0	0	0	0	
	Summer	0	0	0	0	0	0	
	Fall	12	12	12	12	12	0	
1997	Winter	100	100	100	100	100	40	
	Spring	96	96	39	39	96	32	
	Summer	55	55	47	47	55	24	
	Fall	100	100	90	90	100	23	
1998	Winter							
	Spring							
	Summer							
	Fall							
1999	Winter	14	14	5.8	5.8	14	14	
	Spring	78	78	23	23	78	70	
	Summer	98	98	92	92	98	57	
	Fall	71	71	62	62	71	71	
2000	Winter	100	100	100	100	89	93	
	Spring	75	71	66	66	75	51	
	Summer	87	67	45	45	87	48	
	Fall	100	100	92	92	100	32	
2001	Winter	100	100	100	100	100	12	
	Spring	89	89	89	89	89	39	
	Summer	100	100	100	100	100	100	
	Fall	98	98	98	98	98	98	
2002	Winter	93	93	93	93	93	93	17
	Spring	100	100	100	100	100	82	56
	Summer	25	25	25	25	25	7.7	25
	Fall	0	0	0	0	0	0	0

Blank cell = not data collected.

T-Wharf Surface

YEAR	SEASON	PERCENT DATA						
		Temperature	Salinity	DO % sat.	DO Conc.	pH	Turbidity	Chl
2002	Winter	0	0	0	0	0	0	0
	Spring	0	0	0	0	0	0	0
	Summer	88	81	88	88	88	53	16
	Fall	100	100	100	100	100	75	45
2003	Winter	100	100	94	94	100	68	83
	Spring	100	100	83	83	100	92	98
	Summer	100	100	100	100	100	99	98
	Fall	97	97	97	97	97	97	99
2004	Winter	50	50	31	31	50	37	100
	Spring	85	85	85	85	85	76	100
	Summer	99	99	99	99	99	95	100
	Fall	74	74	74	74	74	60	88
2005	Winter	100	100	90	90	100	100	100
	Spring	90	90	90	90	90	51	89
	Summer	93	93	93	93	93	90	90
	Fall	100	100	100	100	100	100	100
2006	Winter	52	52	52	52	52	52	49
	Spring	100	100	100	100	100	99	91
	Summer	92	92	92	92	92	87	92
	Fall	70	70	70	70	70	70	78
2007	Winter	87	87	87	87	87	87	87
	Spring	100	100	100	100	100	97	100
	Summer	100	100	100	100	100	84	89
	Fall	87	87	74	74	70	54	75
2008	Winter	100	100	86	86	88	100	95
	Spring	92	92	92	92	90	92	92
	Summer	100	100	93	94	95	98	99
	Fall	100	100	100	100	100	100	99

T-Wharf Bottom

YEAR	SEASON	PERCENT DATA						
		Temperature	Salinity	DO % sat.	DO Conc.	pH	Turbidity	Chl
2002	Winter	0	0	0	0	0	0	0
	Spring	0	0	0	0	0	0	0
	Summer	97	97	89	89	97	61	32
	Fall	80	80	80	80	66	70	15
2003	Winter	100	89	83	83	100	98	0
	Spring	100	100	93	93	92	99	0
	Summer	67	67	67	67	67	67	71
	Fall	99	99	99	99	84	99	85
2004	Winter	67	33	33	33	33	33	14
	Spring	70	55	55	55	55	55	100
	Summer	99	99	99	99	99	99	99
	Fall	92	92	92	92	90	92	92
2005	Winter	100	100	95	95	100	100	100
	Spring	95	95	95	95	95	90	100
	Summer	100	100	100	100	100	87	100
	Fall	94	94	94	94	94	94	93
2006	Winter	79	79	79	79	79	79	78
	Spring	76	76	76	76	76	75	76
	Summer	100	100	100	100	100	95	99
	Fall	89	89	89	89	89	89	100
2007	Winter	72	64	63	68	45	49	75
	Spring	85	85	85	85	59	85	85
	Summer	95	92	88	88	92	76	90
	Fall	98	75	71	78	47	84	69
2008	Winter	84	84	64	70	49	84	72
	Spring	99	99	99	99	96	97	94
	Summer	94	94	81	85	86	93	55
	Fall	100	100	100	100	100	98	57

Weather Station

YEAR	SEASON	PERCENT DATA						
		Air Temp.	Relative Humidity	Barometric Pressure	Wind Speed	Wind Direction	Total Precip.	Total PAR
2001	Winter	98	98	98	98	98	1	98
	Spring	76	76	76	76	76	0	76
	Summer	0	0	0	0	0	0	0
	Fall	0	0	0	0	0	0	0
2002	Winter	38	38	94	94	34	6	94
	Spring	81	81	81	81	0	4	81
	Summer	33	33	100	100	82	2	100
	Fall	94	94	95	95	95	7	95
2003	Winter	100	100	100	100	100	4	100
	Spring	83	83	96	96	96	6	96
	Summer	54	54	96	96	96	3	96
	Fall	100	100	100	100	100	5	100
2004	Winter	100	100	100	100	100	100	91
	Spring	100	100	100	100	100	100	91
	Summer	69	69	69	69	69	69	61
	Fall	58	58	58	54	58	58	41
2005	Winter	73	73	73	0	73	73	66
	Spring	99	99	99	94	99	99	93
	Summer	100	100	100	100	100	100	93
	Fall	100	100	100	4	100	100	85
2006	Winter	100	100	100	72	100	100	90
	Spring	100	100	100	59	100	100	84
	Summer	99	99	99	0	99	99	93
	Fall	100	100	100	14	86	100	100
2007	Winter	100	100	100	100	100	100	100
	Spring	100	100	100	100	100	100	100
	Summer	100	100	100	100	100	100	100
	Fall	100	100	100	100	100	100	100
2008	Winter	100	100	100	99	100	100	100
	Spring	100	100	100	99	100	100	100
	Summer	100	100	100	100	100	100	100
	Fall	100	100	100	96	97	100	69