Quartermaster Harbor Marine Water Quality Data Report 2007 – 2011

January 2014

King County

Department of Natural Resources and Parks
Water and Land Resources Division
Science and Technical Support Section
King Street Center, KSC-NR-0600
201 South Jackson Street, Suite 600
Seattle, WA 98104
206-477-4800 TTY Relay: 711
www.kingcounty.gov/EnvironmentalScience

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Quartermaster Harbor Marine Water Quality Data Report 2007 – 2011

Prepared for:

U.S. EPA West Coast Estuaries Initiative Grant
Quartermaster Harbor Nitrogen Management Study

Submitted by:

Kimberle Stark[1], Cheryl Greengrove[2], Nick Schlafer[2], Nannette Huber[2] and Julie Masura[2]

[1]Science and Technical Support Section
King County Water and Land Resources Division
Department of Natural Resources and Parks

[2] University of Washington-Tacoma

King County
Department of Natural Resources and Parks
Water and Land Resources Division

UNIVERSITY of WASHINGTON
TACOMA

Acknowledgements

Thanks especially to the field support provided by the King County Environmental Laboratory (Bob Kruger, Jim Devereaux, David Robinson, Christopher Barnes, and Stephanie Hess) and to the R/V WeeLander and her captain Dave Thoreson from the University of Washington. Also thanks to the King County Environmental Laboratory and to the University of Washington Oceanography Technical Services Marine Chemistry Laboratory for analytical support. Thanks to Curtis DeGasperi (Project Manager), project team members (Skip Albertson, Eric Ferguson, Larry Stockton, Jim Simmonds, and Sevin Bilir), and UWT students (Laura Nokes, Kelly Scholting, Audrey Hackett, Ashley Nepela, Ben Shetterly, Jeff Chrush, Carrie Hernandez, Julianne Ruffner, Sam Petrie, Kyra Gagliardi and a host of other student volunteers). Thanks also go to EPA Region 10 Project Officers past (Tony Fournier, Melisa Whitaker and Jill Gable) and present (Jayshika Ramrakha).

Thanks to Curtis DeGasperi, Eric Ferguson, Scott Mickelson, Wendy Eash-Loucks, Jim Simmonds, and Dave White for their review of this report.

Citation

King County. 2014. Quartermaster Harbor Marine Water Quality Data Report 2007-2011. Prepared by Kimberle Stark (King County Water and Land Resources Division), C. Greengrove, N. Schlafer, N. Huber, and J. Masura (University of Washington-Tacoma). Submitted by King County Dept. of Nat. Resources & Parks, Seattle, Washington.

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EXECUTIVE SUMMARY

In 2008, Region 10 of the United States Environmental Protection Agency (EPA) awarded King County a West Coast Estuaries Initiative grant to conduct the Quartermaster Harbor Nitrogen Management Study, which was funded through the end of 2013. The goal of this study was to support the protection and restoration of Quartermaster Harbor–a high value, coastal aquatic resource on Vashon-Maury Island in Puget Sound. Partners working with King County on this grant-funded study included the University of Washington-Tacoma (UWT) and the Washington Department of Ecology (Ecology). This project supported the enhancement of aquatic resource protection in an area threatened by population growth pressures and also added to the body of scientific knowledge regarding dissolved oxygen and nutrients in Puget Sound.

This report presents the marine water quality monitoring data collected as part of the Quartermaster Harbor Nitrogen Management Study and provides an overview of the findings. This monitoring effort assisted achievement of the project goals and outcomes by: characterizing existing water quality in Quartermaster Harbor; linking water properties and environmental conditions with nutrient patterns that influence water quality; assessing water quality variability on various temporal scales (e.g., daily and seasonally); and identifying areas of the highest water quality concern. The marine monitoring data collected in Quartermaster Harbor during this study will serve a multitude of purposes, including integration into King County's overall marine monitoring program as well as the programs of regional partners.

Dissolved oxygen (DO) levels below the Washington State marine water quality standard (Washington Administrative Code 173-201A) have been observed in Quartermaster Harbor over the last seven years by King County. DO values are typically the lowest between late August and October. DO is essential for fish and other marine life - when levels fall below critical thresholds marine life can become stressed, die, or forced to escape to more oxygenated waters if possible.

Nitrogen and phosphorus are essential nutrients for marine plants (seaweeds and seagrasses) and phytoplankton (plant-like organisms). Excess nutrients, nitrogen compounds in particular, can lead to excessive phytoplankton and/or plant growth which can deplete oxygen concentrations when the plants die and are decomposed by bacteria in the water column and sediments. Although phosphorus compounds are important for phytoplankton growth, nitrogen is generally considered to be the limiting nutrient in marine waters of Puget Sound and as such, is the nutrient of most concern.

During the course of this study, King County and UWT collected water data at multiple locations in Quartermaster Harbor. Most monitoring was conducted monthly, although continuous data collection occurred at 15-minute intervals via moored systems at four locations. The following parameters were measured: temperature, salinity, DO, density, fluorescence, transmissivity, nutrients (ammonia, nitrate/nitrite, total

phosphorus/orthophosphate, and silica), chlorophyll-*a*, pheophytin-*a*, Secchi disk water clarity, and fecal indicator bacteria. Phytoplankton samples were also collected at multiple locations.

Quartermaster Harbor is a biologically-driven system with phytoplankton dynamics (e.g., abundance, growth rates, and mortality) having a considerable influence on nutrient and DO levels. The physical configuration of Quartermaster Harbor and, consequently, poor flushing rate exacerbates this influence. Unlike in open waters, phytoplankton are present at substantial levels throughout much of the year in Quartermaster Harbor, particularly in early spring and in the fall months. In early spring, phytoplankton abundance increases with increased daylight and, at the same time, surface stratification (layering) increases due to increased spring freshwater runoff, resulting in limited vertical and horizontal mixing of the water column. This is when the spring phytoplankton bloom (a rapid and distinct increase in the population) occurs in Quartermaster Harbor, typically in March. The spring bloom in Quartermaster Harbor occurs earlier than in open waters of the Puget Sound Central Basin.

The spring bloom is dominated by diatoms as this group of phytoplankton are efficient at nutrient uptake and have a fast growth rate. Dinoflagellates, the other main phytoplankton group, become more prevalent in late summer and fall. During the spring bloom, nutrients in both the upper and lower water column in Quartermaster Harbor are taken up by phytoplankton until nitrate/nitrite, and occasionally silica, are depleted below detectable levels. This depletion typically occurs between April and August until nutrients are replenished by freshwater input, mixing, and biogeochemical pathways. Nutrient depletion occurs earlier in the inner harbor (March) and can persist through September.

The phytoplankton community in Quartermaster Harbor differs from that observed in open Puget Sound waters in that phytoplankton abundances (number of organisms) generally appear to be higher, but diversity (number of different species) is lower. This may be indicative of a eutrophic (excessive nutrients) system as well as a dinoflagellate-based (microbial) food web, as dinoflagellates have lower species diversity than diatoms. Quartermaster Harbor is a documented hotspot for the occurrence of the dinoflagellate, *Alexandrium catenella,* which causes paralytic shellfish poisoning.

Once phytoplankton deplete nutrients, they die and sink to the seafloor where they are decomposed by bacteria. This decay process uses up oxygen leading to low bottom oxygen levels (<1.0 mg/L) as well as causing high ammonia values as a byproduct of decomposition. This was particularly discernible in the inner harbor which had lower DO values in bottom waters than the outer harbor. DO levels in the bottom layer typically decrease following the spring bloom and continue to drop throughout the summer until annual lows are reached in the fall months. During the large spring phytoplankton blooms, DO levels in the surface layer increase dramatically due to the increased oxygen production through photosynthesis. Both continuous monitoring and monthly sampling indicate that oxygen levels in the surface layer of inner Quartermaster Harbor are often supersaturated (>200%) during this time.

The sinking and decay of phytoplankton plays a critical role in the biogeochemical nutrient cycle. Sediments in the shallow inner harbor, in particular, are likely an important source of nutrients to the water column. Both high and low DO levels observed at various times throughout the year are connected with phytoplankton productivity. Thus, understanding nutrient availability during the spring through fall months and the associated effects on phytoplankton and DO levels is crucial for understanding stressors on the Quartermaster Harbor ecosystem. Key findings from this study are:

- the sediment biogeochemical cycle likely plays a large role in nutrient cycling;
- the shallow inner harbor is the area of most concern;
- the lowest DO values occur in the inner harbor usually in late August through September, occasionally in October;
- the inner harbor exhibits diurnal DO variations with nighttime levels sometimes falling below 1.0 mg/L;
- nitrate/nitrite is depleted below detectable levels in the water column for extended periods, up to five consecutive months, which suggests that the addition of more nutrients during this time could lead to even lower DO levels; and
- diatoms dominate phytoplankton species composition during the spring months and dinoflagellates during the late summer and early fall months.

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1.0 INTRODUCTION

Low dissolved oxygen levels were observed in Quartermaster Harbor starting in 2006 when King County began monthly sampling in the harbor. As a result, the U.S. Environmental Protection Agency (EPA) Region 10 awarded King County a West Coast Estuaries Initiative (WEI) grant in late 2008 to conduct a four-year Quartermaster Harbor Nitrogen Management Study. The grant was initially funded through 2012, but was subsequently extended through the end of 2013. The goal of this study was to support the protection and restoration of Quartermaster Harbor–a high value, coastal aquatic resource on Vashon-Maury Island (VMI) in Puget Sound. Partners working with King County (KC) on this study include the University of Washington-Tacoma (UWT) and the Washington State Department of Ecology (Ecology). This project supports the enhancement of aquatic resource protection in an area threatened by population growth pressures. This report is one of several project reports delivered to EPA as part of the overall study. It describes and presents results from marine water quality monitoring activities conducted in Quartermaster Harbor as part of UWT's and King County's marine monitoring programs. Results from 2007 through 2011 are presented in this report.

The report is organized into an introduction, a section describing the field and analytical methods (Methods), a section summarizing monitoring results (Results) and a discussion section. Appendices providing all water column profile data, time series graphic plots, and phytoplankton data are also included.

1.1 Project Overview

Dissolved oxygen (DO) levels below the Washington State "marine extraordinary" water quality standard of 7.0 milligrams per liter (mg/L) (Washington Administrative Code 173-201A) have been observed in Quartermaster Harbor since 2006 by both King County and UWT. DO values below 5.0 mg/L were often measured from August through October. Dissolved oxygen is essential for fish and other marine life and when levels fall below critical thresholds, marine life may become stressed, die, or forced to escape to more oxygenated waters if possible. Low dissolved oxygen levels combined with the high habitat value of Quartermaster Harbor and ongoing population growth, make this project a high priority for King County.

Quartermaster Harbor was one of 19 Puget Sound areas judged to be relatively sensitive to anthropogenic nutrient inputs (Rensel Associates and PTI 1991). Nitrogen and phosphorus are essential nutrients for marine plants and phytoplankton, however, excess nutrients (nitrogen compounds in particular) can lead to excessive phytoplankton and algae growth. Excessive growth can deplete oxygen concentrations when the algae die and are decomposed by bacteria in the water column and sediments (Figure 1-1). Although phosphorus compounds are important for phytoplankton growth, nitrogen is generally considered to be the limiting nutrient in marine waters of Puget Sound (Rensel Associates and PTI 1991).

Nitrate, algal biomass, and DO are interconnected variables. Algal biomass generally peaks during spring and summer, which coincides with a reduction of nitrate concentrations often to below detectable limits as a result of algal uptake and growth. The low oxygen concentrations observed in late summer and fall are associated with the final decline in the summer peaks in algal biomass.

The purpose of the Quartermaster Harbor Nitrogen Management Study is to determine how nitrogen from a variety of sources affects DO levels in Quartermaster Harbor. The expected long-term outcomes are improved policies in the King County Comprehensive Plan and the implementation of land use management best management practices (BMPs) to reduce nitrogen loading to Quartermaster Harbor in an effort to prevent lethal low oxygen events.

Marine monitoring data collected in Quartermaster Harbor assisted achievement of the project goals and outcomes by:

- characterizing existing water quality in Quartermaster Harbor;
- linking water properties and environmental conditions with nutrient patterns that influence water quality, in particular the relationship between nutrients and phytoplankton abundance;
- assessing water quality variability on various temporal scales (e.g., daily and seasonally); and
- assessing water quality throughout Quartermaster Harbor to identify areas of highest concern.

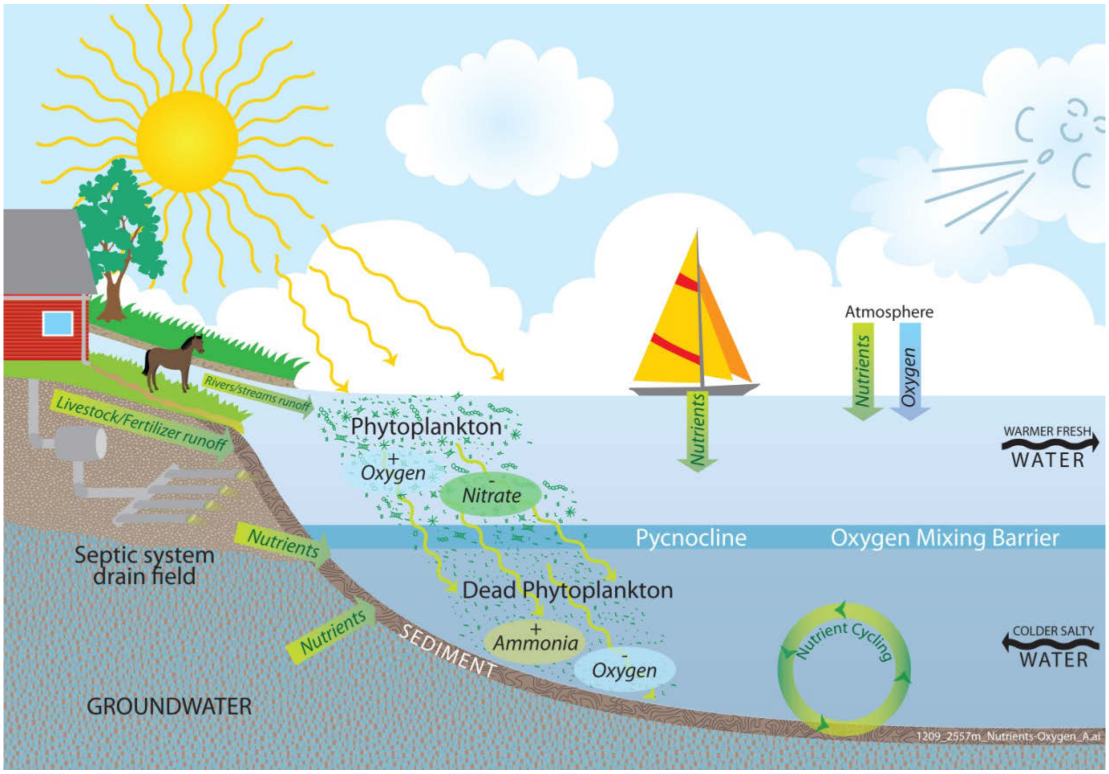


Figure 1-1. Conceptual diagram of marine nutrient-oxygen dynamics

1.2 Study Area

The overall general flow pattern in Puget Sound is driven by estuarine circulation (Figure 1-2) with freshwater outflow at the surface and oceanic inflow over sills at the bottom (Ebbsmeyer and Cannon, 2001). Riverine and overland freshwater outflows are balanced by saltwater intrusions from the coast through the Strait of Juan de Fuca that are in turn tied to coastal upwelling and downwelling conditions (Cannon et al. 1990; Moore et al., 2008). The largest freshwater influx to Puget Sound tends to be associated with winter storms and freshwater runoff from the mountains during the late spring snow melt. Saltwater intrusions occur intermittently year round in the Main Basin modulated by the fortnightly tidal pattern, wind direction, and the volume of freshwater outflow (Geyer and Cannon, 1982; Leonov and Kawase, 2009). The most intense intrusions occur in late summer/early fall associated with the summer upwelling season off the coast (Lavelle et al., 1991).

Superimposed on this general estuarine circulation pattern are wind-driven flows and strong tidal currents that travel over complex topography and bathymetry. The Puget Sound lowlands are bounded to the west by the Olympic Mountains and to the east by the north-sound trending Cascade Range. Winds are topographically steered and on average flow from the northwest through the Strait of Juan de Fuca southward into Puget Sound in the summer and around the southern end of the Olympics northward through Puget Sound

in the winter (Lilly, 1983). Winds affect surface mixing and local circulation (Matsuura and Cannon, 1997), but Puget Sound currents are primarily tidally driven (Mofjeld and Larsen, 1984, Lavelle et al., 1988). The tidal range varies from 2.4 meters at the northern entrance to Puget Sound to 4.6 meters in the South Basin, with strong tidal currents at constrictions and sills, such as the Tacoma Narrows. Intense mixing at the Tacoma Narrows sill, in conjunction with lower freshwater input in the South Basin, result in less stratification in this basin compared with other parts of Puget Sound (Moore et al., 2008).

Quartermaster Harbor is a shallow, southward facing bay flanked by Vashon-Maury Island that connects to the Puget Sound Main Basin. This protected embayment, sheltered from wind and waves, comprises approximately 12.1 km^2 (3,000 acres) of water surface area which receives runoff from about 40 percent of the island (Figure 1-). It has a shallow inner bay (average depth of 6 m) and a deeper outer bay (average depth of 12 m with a range from about 11 to 46m) connected by a channel on the eastern side. The harbor entrance has a small sill followed by a steep drop off (180 m) into Commencement Bay to the south. Tidal currents at the harbor entrance rarely exceed 50 cm/second, but outflow is constrained during an ebb tide by strong northward currents across the mouth.

Quartermaster Harbor subtidal sediments are generally dominated by silt and clay, although some shallow areas, especially in the outer harbor near the mouth, are dominated by sand (University of Washington 1976, Long et al. 2002, King County 2009b, Schatz et al. 2009).

Inner Quartermaster Harbor is especially sheltered and Judd Creek, located in the northwestern portion of the inner harbor, is the largest freshwater input to Quartermaster Harbor. Transition zones between freshwater surface flows and the marine water within the bay include the subestuaries at the mouth of Judd Creek, Fisher Creek, Mileta Creek, and Raab's Lagoon along with numerous smaller streams. Dependent upon the time of year, flushing times in the inner harbor can vary from 20 to over 100 days (Albertson 2013). Outer Quartermaster Harbor has more rapid flushing varying from 10 to 40 days (Albertson 2013).

Sampling sites included in this data report are located throughout Quartermaster Harbor, both in the inner and outer harbors. In addition, two sites are located outside of Quartermaster Harbor and data from these sites are included for comparative purposes. UWT and King County water monitoring sites are shown in Figure 1-4. A detailed description of the sampling locations, monitoring frequency, and parameters measured is provided in Section 2.0.

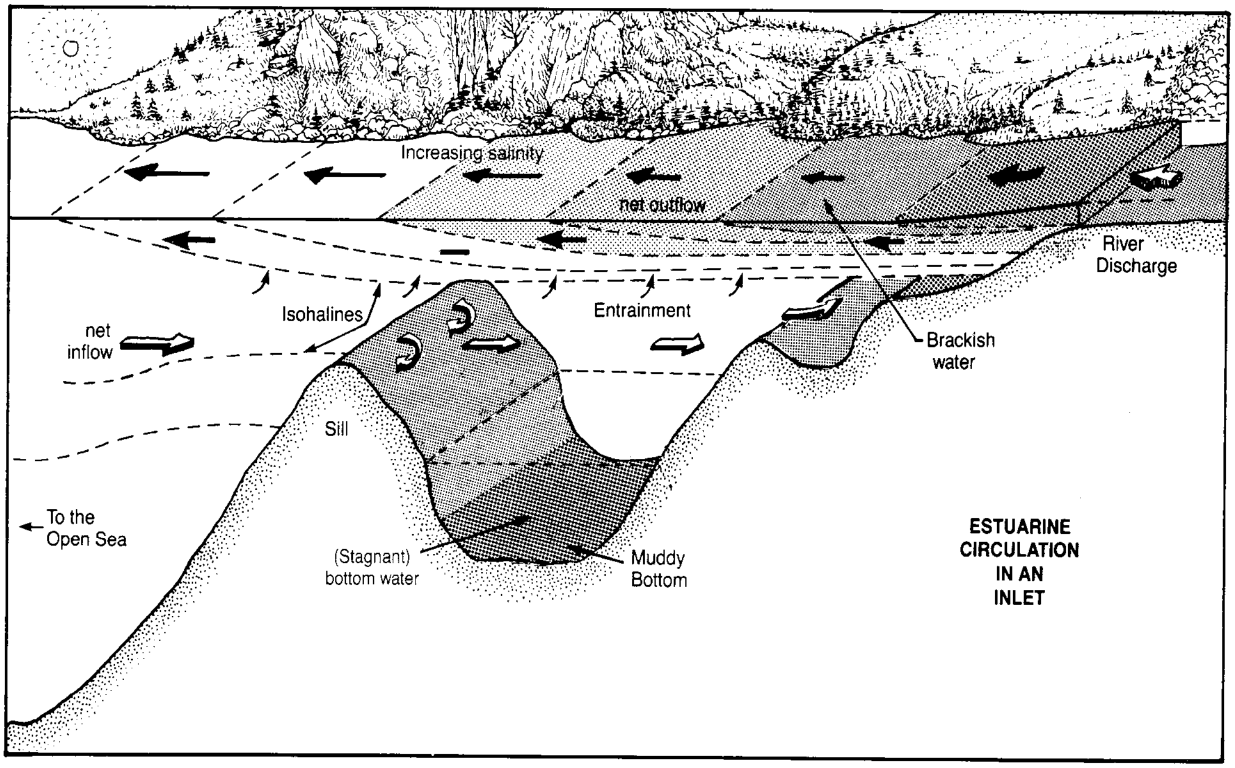


Figure 1-2. Conceptual diagram of estuarine circulation in an inlet (Thomson 1981).

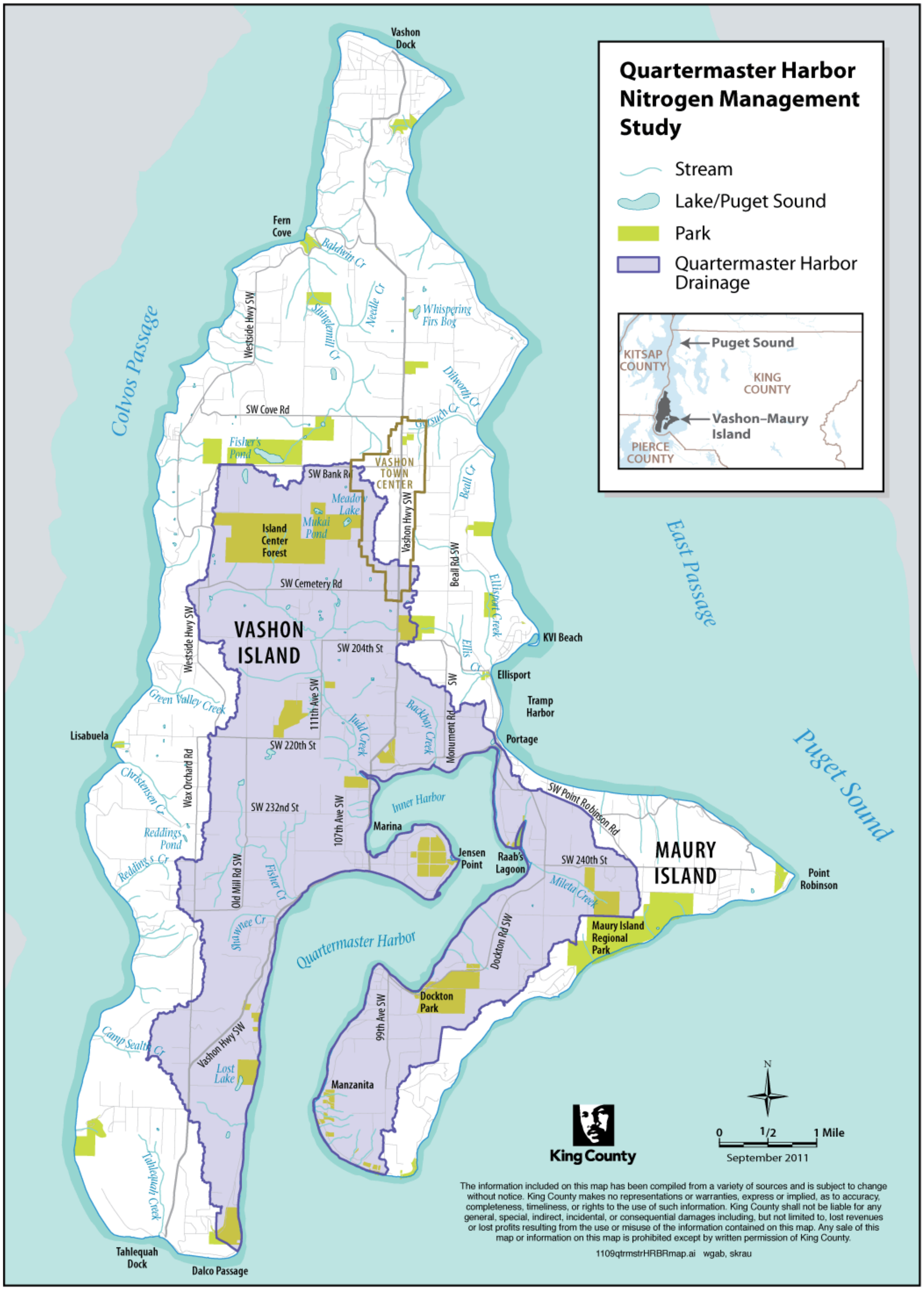


Figure 1-3. Quartermaster Harbor location

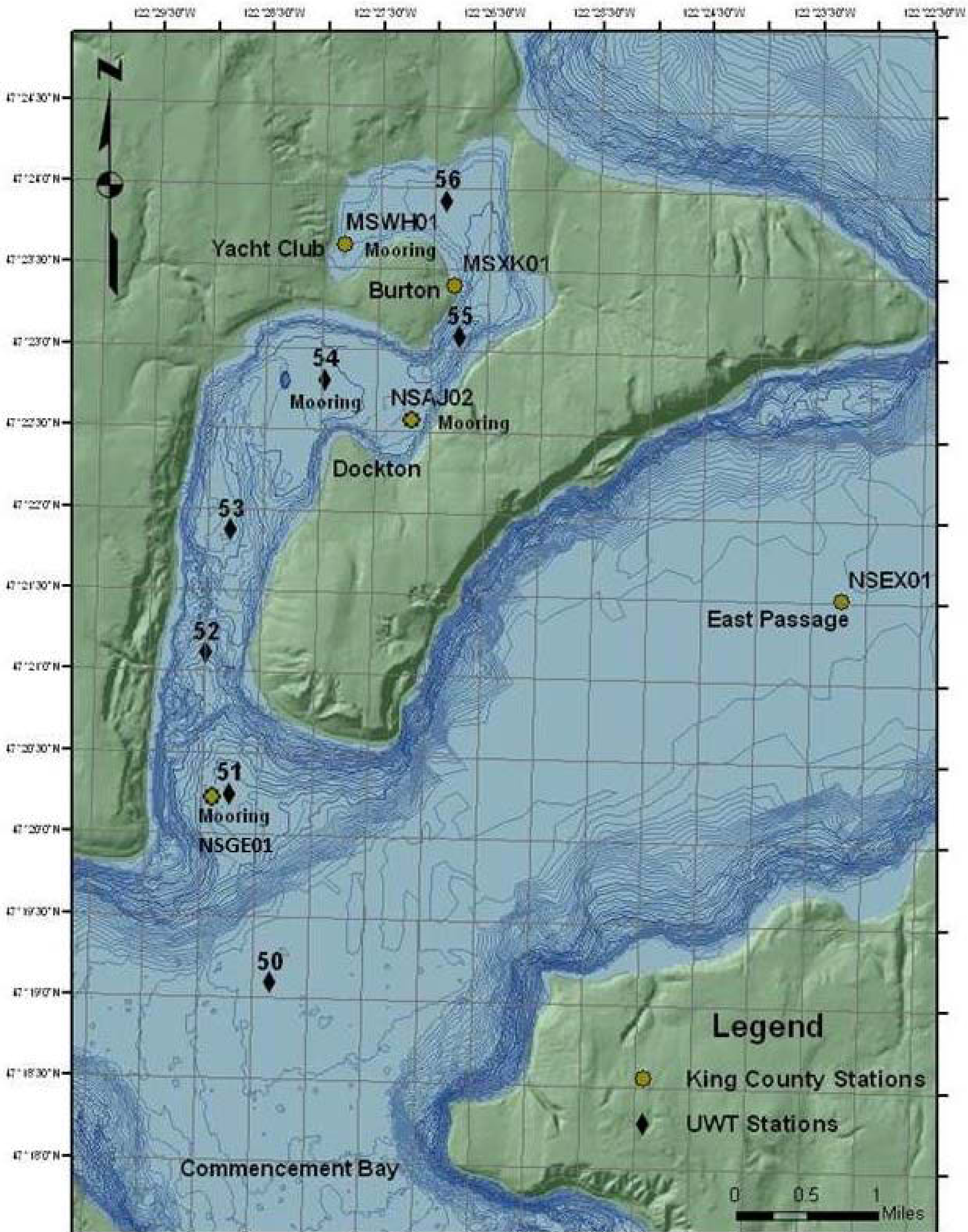


Figure 1-4. Quartermaster Harbor marine sampling sites.

1.3 Previous Studies

Quartermaster Harbor and the upland areas draining to the harbor have been the subject of water quality and quantity investigations beginning as far back as the early 1970s. These studies are summarized below. The summaries are not intended to be exhaustive and the reader is referred to the original sources for more detailed information.

Marine Park Study (University of Washington 1976).

Perhaps the most comprehensive study of QMH was conducted in the early 1970s by the University of Washington for the King County Division of Parks and Recreation (University of Washington, 1976). The study was conducted in response to public concerns over the expansion of overnight recreational boat moorage facilities at Dockton Park in QMH. The study included investigation of historical recreation patterns, land use, and environmental impacts; surficial soils and geology, landslide hazards, drain field performance, and beach forming processes; marine circulation, flushing rates, and water temperatures; marine biological conditions; magnitude and spatial extent of marine fecal contamination; and terrestrial vegetation and wildlife primarily in relation to recreational activities and values.

The University of Washington harbor circulation study was also published as a graduate study thesis by Turnbeaugh (1976). Based on a combination of physical observations – including drift drogues, velocity, direction, temperature, and salinity measurements – it appeared that the inner harbor had poorer circulation than the outer harbor with poorest circulation observed around the Burton dock and the mouth of Judd Creek.

The terrestrial vegetation studies determined that the vegetation structure of the island changed from primarily coniferous to deciduous hardwoods as the result of logging without active replanting. This shift to deciduous vegetation increased the annual discharge of leaves from canopy and undergrowth. The researchers concluded that this vegetation shift, along with contributions from other sources (e.g., agricultural and residential fertilizers, livestock manure, on-site septic systems, and vessel sewage discharges) has resulted in an increase in nutrient discharges into the harbor, potentially overloading the water's nutrient assimilation capacity.

Primarily based on measurements of fecal indicator bacteria, the University of Washington researchers concluded that water quality was degraded most significantly in the inner harbor between the mouth of Judd Creek and the Burton marina and suspected nearshore septic systems as the primary source. Judd Creek was also found to be degraded by fecal pollution and suggested stream-side homes, livestock, poultry, wildlife, and the King County landfill at the headwaters of the creek as potential sources. The researchers suggested that water quality of the inner harbor could be maintained or possibly improved by removing septic tank effluent near water areas of high soil permeability by installation of sewer systems. A number of recommendations were made to improve the quality of Judd Creek, but ultimately the UW suggested further study might be necessary to quantify the contributions of various sources and determine the most feasible means of control.

Less attention was given to evaluating the dissolved oxygen condition of the harbor. Five stations were sampled along the harbor axis at three depths (surface, mid-depth, and near bottom) on October 12, 1974. The lowest DO level was found at the inner most station near the bottom (3.8 mg/L).

Paralytic Shellfish Poison Study (Nishitani *et al.* 1988)

Nishitani *et al*. (1988) reported on a study of paralytic shellfish poisoning (PSP) toxins conducted in Quartermaster Harbor. The focus of the study was on the environmental controls of the growth and accumulation of the toxin producing dinoflagellate *Gonyaulax catenella* and the effects of the dinoflagellate toxins on Puget Sound finfish. The study included measurements of temperature, salinity, Secchi depth, and nutrient concentrations in Quartermaster Harbor. Blooms of *G. catenella* dinoflagellate were observed in the inner harbor in late June of two years under stratified conditions when marine surface water temperatures increased above 13 ^{o}C. Nutrient limitation of *G. catenella* blooms was suspected. Low concentrations of either nitrogen or phosphorus appeared to be a causal factor in bloom decline and suppression of bloom formation. Nishitani *et al*. (1988) speculated that this algal species might have higher relative phosphorus vs. nitrogen requirement than other typical phytoplankton, which would have implications for management of anthropogenic nutrient sources. Recommendations for future monitoring included a suggestion that because of the migratory behavior of these (and other) dinoflagellates, standard water quality sampling techniques (typically grab samples at a few discrete depths) might often miss the greatest density of dinoflagellates. In their study, the highest densities of *G. catenella* were found between 4 and 7 m.

Ulvoid monitoring (Frankenstein 2000)

Frankenstein (2000) identified sites in Puget Sound where ulvoid (a type of marine macroalgae) blooms were occurring and might be considered a growing or ongoing ecological concern. Concerns associated with ulvoid blooms included objectionable odors, detrimental effects on seagrass and macrofauna, and potential for enhancing sediment nutrient recycling into the water column. Quartermaster Harbor was identified as a location where ulvoid blooms might be occurring. Shoreline alteration, failing onsite septic systems, and tributary streams were suggested as potential nutrient sources that could provide fuel for these blooms. Frankenstein (2000) proposed a study to quantify the accumulation of ulvoids and associated environmental conditions at a range of Puget Sound locations to better establish where blooms are occurring and why.

Washington State Department of Ecology Monitoring in Quartermaster Harbor

The Washington Dept. of Ecology conducts monthly marine water quality monitoring at some stations every year while others are monitored on a rotating schedule. Rotating schedule stations have been located in outer Quartermaster Harbor (QMH001-Burton (near this study's station 54) sampled Oct 1991-Sep 1992 and Oct 1994- Sep 1995) and in the inner harbor (QMH002-Quartermaster Harbor (near this study's station 56) sampled Nov 1997-Sep 1998, 2001, and 2004). Profiles of temperature, salinity, density, dissolved oxygen, light transmission, and pH are measured at 0.5 m intervals at each station. Discrete samples are also collected at various depths for laboratory analysis of chlorophyll-a,

nitrate, nitrite, ammonium, orthophosphate, and silica. Generally, discrete samples are taken at 0, 10, and 30 m depths depending on the total depth at a particular station. Secchi disk depth is also recorded at each station.

Ecology found that DO near bottom concentrations less than 7.0 mg/L at the outer (QMH001) and inner (QMH002) stations have occurred on a regular basis – particularly in the late summer and early fall. Seasonal patterns of nitrate and phytoplankton biomass showed the highest nitrate values in winter followed by an initially large spring bloom and subsequent decline in nitrate due to phytoplankton growth.

King County Marine Monitoring in Quartermaster Harbor

King County has monitored water quality in Quartermaster Harbor on a monthly basis since 2006 as part of a larger long-term marine monitoring program that assesses water quality in the Central Puget Sound Basin. King County has been conducting sampling at four stations relevant to this study (see Figure1-4). Discrete water column samples have been taken from docks and public beaches in Quartermaster Harbor – outer harbor at Dockton (Station NSAJ02), the inner harbor at the Quartermaster Yacht Club (Station MSWH01), and an intertidal station at Burton Acres Park in the inner harbor (MSXK01) . From December 2007 through December 2008, continuous data collection via a mooring was conducted at Station MSWH01. In January 2008, the mooring was moved to Station NSAJ02 in order to collect data in deeper water than at Station MSWH01. Continuous data collection was re-established at MSWH01 as part of this study in early 2011. Semi-monthly phytoplankton samples (March through October) have been collected and analyzed starting in 2008 at station MSWH01 and 2009 at station NSAJ02. Details of this sampling are provided in section 2.0.

University of Washington-Tacoma

Work within Quartermaster Harbor grew out of a larger National Oceanic and Atmospheric Administration (NOAA)/Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) study (2004-2008) with researchers from University of Washington-Seattle (UWS) and University of Washington-Tacoma (UWT) investigating the distribution of the phytoplankton species *Alexandrium catenella* (PSP causing dinoflagellate) cysts in the sediments of Puget Sound. This study found two orders of magnitude higher concentration of *Alexandrium catenella* cysts in the sediments of Quartermaster Harbor (QMH) than anywhere else in Puget Sound (Horner et al., 2011). Continuing NOAA/ECOHAB (2010-2014) and Sea Grant (2012-2014) studies of *A. catenella* cyst distributions in Puget Sound show that Quartermaster Harbor remains a “hotspot” for high concentrations of these cysts (Greengrove et al. 2012). Prior to the this study, funding was provided by the Russell Family Foundation for UWT to begin monitoring water properties in Quartermaster Harbor with monthly CTD transects and a continuous sampling mooring starting in October of 2006. These data have been incorporated in this report and sampling details are included in section 2.0.

2.0 METHODS

The following section provides a summary of the sampling locations where data were collected during the course of this study. A summary of field and laboratory methods and parameters measured is also included.

2.1 Sampling Locations and Parameters Measured

2.1.1 King County

King County collected water samples monthly at Dockton Park (station NSAJ02) and at the Yacht Club (station MSWH01) in the inner harbor for the following parameters: temperature, salinity, dissolved oxygen (DO), nutrients (ammonia, nitrate+nitrite, total phosphorus, and silica), chlorophyll-*a*, pheophytin-*a*, total suspended solids, and fecal indicator bacteria (fecal coliforms and enterococci). Semi-monthly phytoplankton samples were collected April through October for semi-quantitative analysis at the Yacht Club in 2008 and at Dockton from 2009 through 2011. Total phosphorus was analyzed through June 2010, at which time the method changed to orthophosphate phosphorus (orthophosphorus). Secchi disk water clarity data were collected at Dockton Park from April 2009 through November 2011 but due to the shallow depth at the Yacht Club, data were not collected at this location.

Beach water at Burton Acres (station MSXK01) was analyzed monthly for fecal indicator bacteria, temperature, salinity, and nutrients (ammonia, nitrate+nitrite, and total phosphorus). Beginning in mid-2010, orthophosphorus was measured rather than total phosphorus.

An in situ monitoring system was installed on the Yacht Club dock throughout 2008. This system was then moved to the dock at Dockton Park in 2009, where it currently remains. An additional system was re-installed at the Yacht Club in March 2011. These systems collect depth, temperature, salinity, dissolved oxygen, turbidity, fluorescence (an indicator of chlorophyll concentration/phytoplankton biomass), and pH data at 15-minute intervals. The water quality sensors at the Yacht Club are at approximately 1 m below the water surface and the sensor depths at Dockton vary between about 4 to 8 m, depending upon the tidal stage.

An in situ monitoring system was deployed at the outer entrance to Quartermaster Harbor (station NSGE01; see Figure 1-3) specifically to support data collection efforts for the Quartermaster Harbor Nitrogen Management Study. Both surface (~1 m) and bottom sensors (~51 m) were deployed from late February 2009 until the first week in December 2010. The sensor setup was the same as mentioned above with the following two exceptions: a nitrate sensor was installed at the surface and fluorescence data were not collected at the bottom depth.

Monthly water column profiles outside of Quartermaster Harbor were collected in East Passage (station NSEX01) for the following parameters: temperature, salinity, density (calculated parameter), transmissivity, DO, fluorescence, Secchi disk water clarity, and photosynthetically active radiation (PAR). Monthly grab samples from seven depths were collected for: nutrients (ammonia, nitrate+nitrite, total phosphorus, and silica), chlorophyll-*a*, pheophytin-*a,* total suspended solids, and fecal indicator bacteria (fecal coliforms and enterococci). Data from this open Central Puget Sound station were used to compare with Quartermaster Harbor results.

Enterococci and pH data are not discussed in this report. The Washington State marine surface water quality standard for primary contact recreation is based upon fecal coliform bacteria, which are provided in this report. Due to pH sensor inconsistencies, the majority of the pH data were deemed unusable. These data, however, are available upon request, as are all monitoring data. In situ data are available at the following website: http://green.kingcounty.gov/marine/HiFrequency.htm. Table 2-1 provides an inventory of all the marine data collected in Quartermaster Harbor from 2006 through 2012.

2.1.2 University of Washington-Tacoma (UWT)

UWT collected monthly water column profile data at six stations within QMH and at one location in outer Commencement Bay (see Figure 1-3) for comparative purposes for the following parameters: temperature, salinity, density, DO, fluorescence, transmissivity, and Secchi disk water clarity. Monthly grab samples at all seven locations were collected at a minimum of two depths for the following parameters: DO, nutrients (ammonia, nitrate, nitrite, orthophosphorus, and silica), and chlorophyll-*a*. The sampling depths are near-surface, near-bottom and seasonally at the pycnocline when present. Monthly phytoplankton samples were collected for quantitative analysis at all seven stations. Live samples were collected from a surface tow using a 20 µm mesh net and qualitatively analyzed for species composition and abundance. Phytoplankton samples for quantitative laboratory analysis (using a compound microscope and a Palmer-Maloney counting chamber) were collected at the surface and seasonally at the pycnocline using a Niskin bottle and preserved with a formalin solution.

An in situ monitoring system was deployed in mid Quartermaster Harbor (station 54) in October 2006 and remained through February 2013 (see Figure 1-3). Temperature and salinity sensors were deployed 1 m below the surface and 1 m above the seafloor (~14 m). A DO sensor was added to the bottom array from August 2009 through March 2011. Sensors on this mooring collected measurements at 15-minute intervals. See Table 1 for a summary of UWT data collected in Quartermaster Harbor from 2006 through 2012.

Table 2-1. Inventory of marine data collected in Quartermaster Harbor, outer Commencement Bay, and East Passage

	Station											
	56	**55**	**54**	**53**	**52**	**51**	**50**	**MSWH01**	**NSAJ02**	**NSEX01**	**NSGE01**	**MSXK01**
Station Depth (m)	6	16	14	20	18	54	170	4.6	7.4	178	48	<1
# of Depths Sampled [1]	wc, 2	wc, 2	wc, 2	wc, 2	wc, 2	wc, 2	wc, 2	2	2	wc, 7	2	1
Sampling frequency	monthly	monthly	monthly, continuous	monthly	monthly	monthly	monthly	monthly[2], continuous	monthly[2], continuous	monthly[2]	continuous	monthly
Date sampled	2006-2012	2006-2012	2006-2012[3]	2006-2012	2006-2012	2006-2012	2006-2012	2006-present[3]	2006-present[3]	2003-present	2009-2010	2007-present
Laboratory analyses												
Ammonia nitrogen (NH_3)	●	●	●	●	●	●	●	●	●	●		●
Nitrate nitrogen (NO_3)	●	●	●	●	●	●	●					
Nitrite nitrogen (NO_2)	●	●	●	●	●	●	●				●	
NO_3+NO_2nitrogen								●	●	●		●
Silica (SiO_2)	●	●	●	●	●	●	●	●	●	●		
Orthophosphorus (PO_4) [4]	●	●	●	●	●	●	●	●	●	●		●
Chlorophyll-*a*	●	●	●	●	●	●	●	●	●	●		
Pheophytin								●	●	●		
Phytoplankton	●	●	●	●	●	●	●		●[5]			
Fecal indicator bacteria								●	●	●		●
Total suspended solids								●	●	●		
Salinity								●	●			●
Field analyses												
Temperature	●	●	●	●	●	●	●	●	●	●	●	●
Dissolved oxygen	●	●	●	●	●	●	●	●	●	●	●	
Light intensity (PAR)										●		
Transmissivity	●	●	●	●	●	●	●			●		
Salinity	●	●	●	●	●	●	●	●	●	●	●	
Chlorophyll-*a*	●	●	●	●	●	●	●	●	●	●	●	
Turbidity								●	●		●	
pH								●	●		●	
Secchi water clarity	●	●	●	●	●	●	●		●	●		
Meteorological									●			

[1] wc = entire water column
[2] semi-monthly sampling from March-October
[3] DO sensor added to bottom mooring at station 54 from 2009-2011;MSWH01 mooring in 2008 & 2011-present; NSAJ02 mooring from 2009-present
[4] Total phosphorus analyzed at MSWH01,NSAJ02, NSEX01, and MSXK01 through June 2010. Orthophosphorus analyzed June 2010 to present.
[5] Phytoplankton analysis from 2009-present; 2008 phytoplankton collected at station MSWH01
● indicates continuous parameter

2.2 Field Methods

The following section provides a summary of field methods. A description of both field and laboratory methods, as well as data quality objectives, can be found in the *Quality Assurance Project Plan for Quartermaster Harbor Nitrogen Management Study* (King County 2009) available at http://www.kingcounty.gov/environment/watersheds/central-puget-sound/vashon-maury-island/quartermaster-nitrogen-study/QMH-documents.aspx.

2.2.1 King County

Water samples were collected by the King County Environmental Laboratory Field Science Unit in accordance with the *Recommended Guidelines for Sampling Marine Sediment, Water Column, and Tissues in Puget Sound* (PSEP, 1997). The Field Science Unit also has a specific Standard Operating Procedure (SOP) for each type of field sample and data collection process.

Samples at Dockton and the Yacht Club were collected from docks rather than by boat. Dissolved oxygen and temperature at these two sites were sampled in the field using a Hydrolab®. Water samples for laboratory analysis (salinity, nutrients, fecal indicator bacteria, chlorophyll-*a*, and total suspended solids) were collected using a five-liter Niskin bottle lowered by hand to the selected depth. Two depths (1 m and near bottom) were sampled at each location.

Beach (intertidal) water samples at Burton Acres were collected by wading knee-deep in the water and inverting sample containers just above the water surface, then sinking the bottle down to approximately three to six inches below the water surface. The bottles were not filled completely in order to allow room for mixing. Field methods and detection limits are provided in Table 2-2.

The East Passage samples were collected from the *R/V Liberty*, a 42-ft research vessel. Water column profiles were collected using a Sea-Bird Electronics SBE 25 SEALOGGER conductivity-temperature-depth (CTD) profiler. Parameters measured by the CTD included temperature, salinity, light transmission, DO, PAR, and fluorescence (an indicator of chlorophyll abundance). Density is a calculated parameter using temperature and salinity measurements.

The CTD was lowered into the water using a hydraulic boom and allowed to equilibrate for five minutes at the surface before being lowered to a few meters above the seabed. Measurements were collected on the downcast at 1 m intervals. Multiple five-liter Niskin bottles were mounted onto the rosette containing the CTD profiler for collecting discrete water samples on the upcast at seven pre-determined depths for analysis of nutrients, total suspended solids, and bacteria. The rosette was electronically programmed to close individual bottles at specific depths as the system ascended through the water column. The rosette was then brought on deck and water samples were immediately drawn from the Niskin bottles and placed into appropriate sample containers. Sample containers were stored on ice until delivered to the King County Environmental Laboratory.

Water clarity measurements were collected using a 12-inch diameter black and white Secchi disk. Secchi depths were recorded to the nearest 0.1 meter. As readings may vary depending upon environmental conditions (e.g., waves and glare), readings were taken on the shaded and downwind side of the boat to standardize results among individual field personnel and atmospheric conditions as much as possible.

The in situ systems consisted of YSI 6600 EDS multiparameter sondes. For each system, an anti-fouling sonde guard and copper tape (wrapped around each sensor) were utilized. A Satlantic SUNA (nitrate) sensor was added to the system at the entrance to Quartermaster Harbor. Sondes were calibrated monthly and freshly calibrated sondes were installed approximately every 4 weeks. Post-deployment calibration and end checks were conducted and evaluated against the initial calibrations. In situ sensor specifications are provided in Table 2-3.

Table 2-2. Field Methods and Detection Limits for King County Samples

Parameter	Units	MDL	Method
Salinity	PSU	na	SOP 220v3
Dissolved Oxygen: CTD	mg/L	0.5	SOP 220v3
Dissolved Oxygen: Hydrolab	mg/L	0.5	SOP 205v4
Temperature: CTD	^{o}C	na	SOP 220v3
Temperature: Hydrolab	^{o}C	na	SOP 205v4
Photosynthetically active radiation (PAR)	µmol/sm^2	na	SOP 220v3
Light Transmission	% light	0.01	SOP 220v3
Chlorophyll-*a*	µg/L	0.06	SOP 220v3
Secchi water clarity	m	na	SOP 212v2

PSU = practical salinity unit
mg/L = milligram per liter
µg/L = microgram per liter
MDL = method detection limit
sm^2 = second per square meter
na = not applicable
µmol = micromole
m = meter

Table 2-3. King County in situ sensor specifications

Parameter	Units	Resolution	Accuracy	Method
Salinity	PSU	0.01	0.1	SOP 208v2
Dissolved Oxygen	mg/L	0.01	+/-0.1	SOP 208v2
Temperature	^{o}C	0.01	+/-0.15	SOP 208v2
Turbidity	NTU	0.1	0.3	SOP 208v2
Chlorophyll	µg/L	0.1	0.1	SOP 208v2
pH	--	0.01	+/-0.2	SOP 208v2
Nitrate	mg/L	0.028	0.028	SOP 208v2

PSU = practical salinity unit
mg/L = milligram per liter
µg/L = microgram per liter
NTU = nephelometric turbidity unit

2.2.2 UWT

All water samples were collected from a small boat, the *R/V Weelander*, by UWT researchers and students in accordance with the *Recommended Guidelines for Sampling Marine Sediment, Water Column, and Tissues in Puget Sound* (PSEP, 1997).

Secchi disk readings were made at each station using a 12-inch Secchi disk attached to a rope marked with 0.5 m increments. The disk was lowered vertically in the water until it could no longer be seen with the naked eye. The maximum depth where it could still be seen was then recorded in meters.

Water samples for laboratory analyses were obtained by lowering a 2.5 liter Niskin bottle to specific depths at each station. A messenger (copper weight) was sent from the surface

along the deployment line that triggered the bottle to close at the desired depths. Samples were immediately drawn from the Niskin bottles and placed into appropriate sample containers. All samples were stored on ice and DO and chlorophyll-*a* were processed immediately at the UWT lab and nutrients were frozen and delivered to the University of Washington Technical Services Marine Chemistry Laboratory for analysis.

Water column profiles at each station were collected using a Sea-Bird Electronics SBE 19 SeaCAT CTD profiler. At each station, the device was lowered from the surface at a rate of approximately one meter per second to just above the seabed. The CTD profiler collected data on the downcast at two samples per second every 0.5 m. The data were later averaged into one meter bins. Parameters measured by the CTD included depth, temperature, salinity, density (calculated), DO, fluorescence, and transmissivity. Field methods and detection limits are provided in Table 2-4.

Phytoplankton tow samples were collected using a 20 µm mesh, 0.25 m diameter net. The net was lowered from the *R/V Weelander* and horizontally towed along the surface. Samples collected by this method were used to qualitatively examine live phytoplankton within about 8 hours of collection. Additional phytoplankton samples were collected at the surface and pycnocline if present using the Niskin bottle described above, then fixed with formalin and enumerated at the UWT lab.

The in situ system consisted of a Sea-Bird SBE 19 SeaCAT with temperature and salinity sensors. Copper tape was wrapped around each sensor to prevent biofouling. The sensors were removed, cleaned, and replaced at varying intervals--approximately every four to eight weeks. Measurements were taken at the in situ system with the CTD profiler to verify sensor performance. In situ sensor specifications are provided in Table 2-4.

Table 2-4. Field Methods and Detection Limits for UWT Samples

Parameter	Units	MDL	Method
Salinity	PSU	na	CTD
Dissolved Oxygen	mg/L	0.5	CTD
Temperature	^oC	na	CTD
Photosynthetically active radiation (PAR)	µmol/sm^2	na	CTD
Light Transmission	% light	0.01	CTD
Chlorophyll	µg/L	0.06	CTD
Secchi water clarity	m	na	--

PSU = practical salinity unit
mg/L = milligram per liter
µg/L = microgram per liter
MDL = method detection limit
sm^2 = second per square meter
na = not applicable
µmol = micromole
m = meter

2.3 Laboratory Methods

2.3.1 King County

Laboratory methods and detection limits are provided in Table 2-5. Quality assurance/quality control procedures included the use of blanks, duplicates, matrix spikes, and laboratory control samples when appropriate. All data were reviewed prior to entry into the County's Laboratory Information Management System (LIMS) database.

Table 2-5. Laboratory methods and detection limits for King County samples

Parameter	Units	MDL	Method
Salinity	PSU	2.0	SM2520-B
Dissolved oxygen	mg/L	0.1	SM4500-O-C
Chlorophyll-*a*	ug/L	0.05	EPA 445.0
Pheophytin-*a*	ug/L	0.1	EPA 445.0
Ammonia-Nitrogen	mg/L	0.005	SM4500-NH3-H
Nitrate+Nitrite (NO_3+NO_2)	mg/L	0.01	SM4500-NO3-F
Total phosphorous	mg/L	0.005	SM4500-P-B,E
Orthophosphorus	mg/L	0.005	SM4500-P-F,S
Silica	mg/L	0.05	SM4500-SI-D
Total suspended solids	mg/L	0.5	SM2540-D
Fecal coliform bacteria	cfu/100 ml	1	SM 9222-D
Phytoplankton abundance	cells	--	Horner 2002

PSU = practical salinity unit
mg/L = milligram per liter
ug/L = microgram per liter
MDL = method detection limit
cfu = colony forming units

2.3.2 UWT

Laboratory methods and detection limits are provided in Table 2-6. Quality assurance/quality control procedures included the use of method blanks and duplicates when appropriate. All data were reviewed prior to use.

Table 2-6. Laboratory methods and detection limits for UWT samples

Parameter	Units	MDL	Method
Salinity	PSU	2.0	SM2520-B
Dissolved Oxygen	mg/L	0.01	Carpenter, 1966
Chlorophyll-*a*	ug/L	0.01	EPA, 1977
Ammonia-Nitrogen	mg/L	0.01	Slawyk & MacIsaac, 1972
Nitrate	mg/L	0.002	Armstrong et al., 1967
Nitrite	mg/L	0.0001	Armstrong et al., 1967
Orthophosphorus	mg/L	0.001	Bernhardt & Wilhelms, 1967
Silica	mg/L	0.001	Armstrong et al., 1967
Phytoplankton abundance	cells/L	--	Horner 2002

PSU = practical salinity unit
mg/L = milligram per liter
MDL = method detection limit

3.0 FRESHWATER INPUT AND METEOROLOGICAL DATA

3.1 Freshwater Input

Freshwater input into marine waters from rivers and streams is important as it affects both physical and biological processes. Freshwater flow influences Puget Sound water circulation as the amount of freshwater input varies seasonally and affects density and stratification of the water column. Water column stratification can affect biological populations by trapping nutrients in the deeper layer and reducing vertical migration. Freshwater flow can also increase the amount of nutrients transported into marine waters. Freshwater input to rivers is primarily through rainfall, however, snowmelt also contributes a large source in late spring and early summer dependent upon location and hydrology of the drainage basin.

The main freshwater input into Central Basin marine waters are the Green/Duwamish River system, the Lake Washington Drainage system, and the Skagit, Stillaguamish, Snohomish, and Puyallup Rivers. The Puyallup River empties into Commencement Bay, which is southeast of the entrance to Quartermaster Harbor. Figure 3-1 shows the mean daily discharge for the Skagit and Puyallup Rivers between 2007 and 2011. Although the Skagit River has the highest flow, the seasonal pattern of increased flow due to snowmelt in May and June is similar to the other rivers mentioned above. The Puyallup River plume is visible at the entrance to Quartermaster Harbor and in the outer harbor during high flow periods, however, the plume was not observed to penetrate into the inner harbor based upon images from Ecology's Eyes Over Puget Sound (http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html). Figure 3-2 shows the Puyallup River plume at the Quartermaster Harbor outer entrance.

The highest river flows are in the winter months (rainfall) and May/June (snowmelt) and the lowest flows are in August and September. Figure 3-3 shows the monthly means for daily discharge from the Puyallup River. The monthly means were calculated using data between 1990 and 2011.

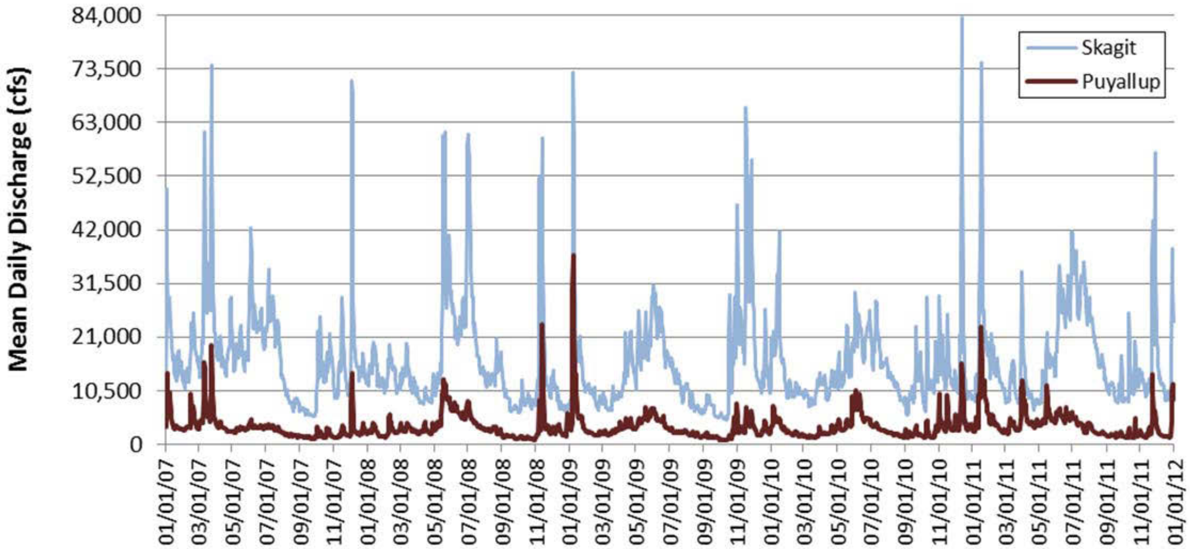


Figure 3-1. Skagit River (USGS station 12200500) and Puyallup River (USGS station 12101500) mean daily discharge between 2007 and 2011.

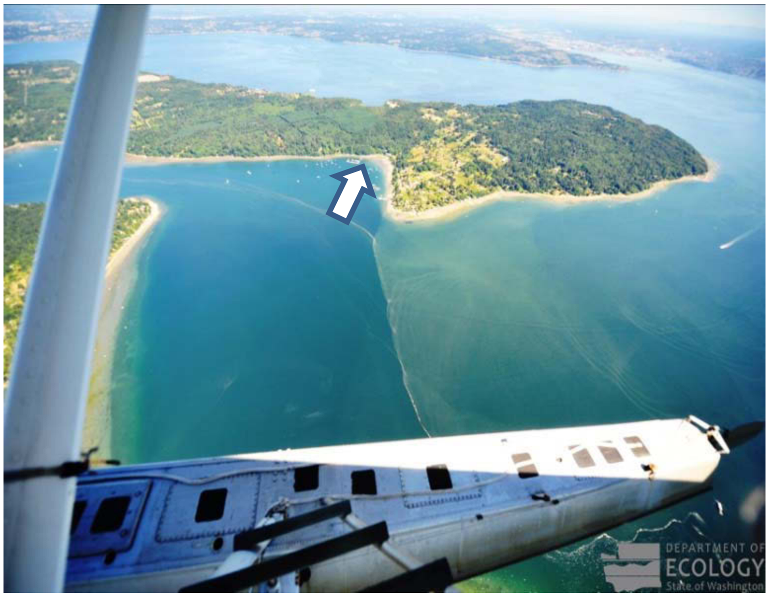


Figure 3-2. Puyallup River plume visible in Quartermaster Harbor near outer entrance on July 6, 2011. Photo from Ecology's Eyes Over Puget Sound looking toward Dockton area (indicated by white arrow) of Maury Island (Ecology, 2011; http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html)

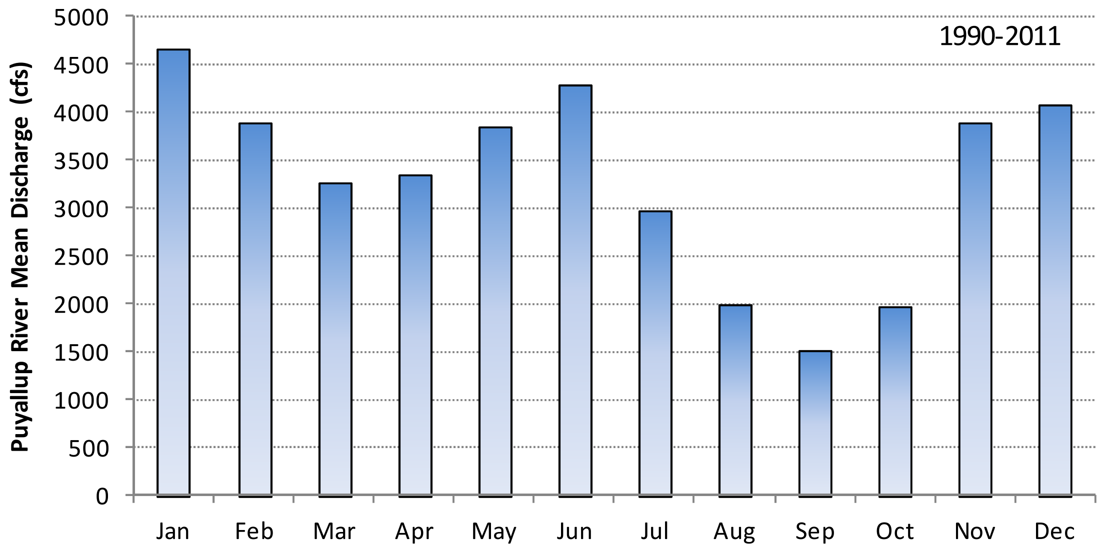
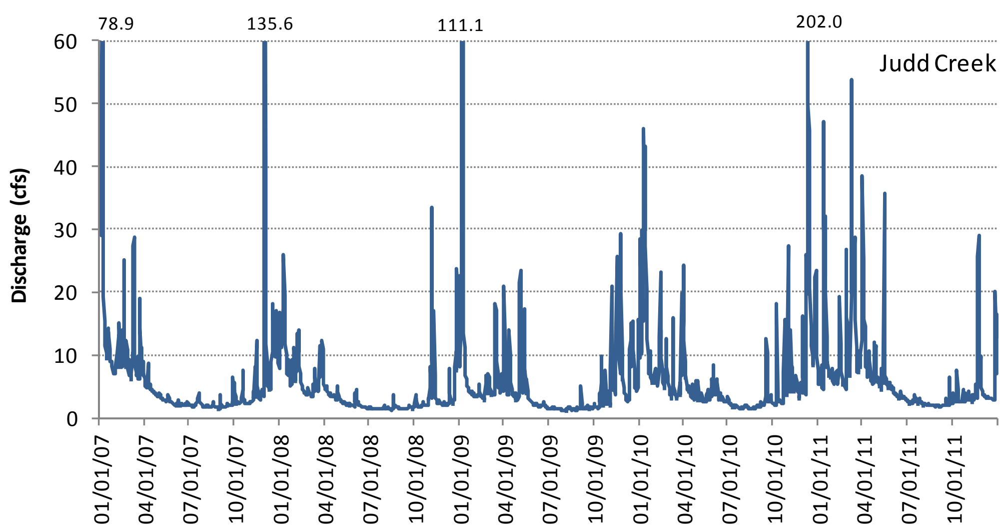


Figure 3-3. Puyallup River daily discharge monthly means from 1990-2011 (station 12101500)

The two main freshwater inputs into Quartermaster Harbor are Judd Creek in the inner harbor and Fisher Creek in the outer harbor. Mileta Creek in the mid-harbor is one of the largest freshwater inputs from Maury Island (see Figure 1-2). Judd Creek has the highest flows of the three freshwater inputs as shown in Figure 3-4. A detailed description of freshwater flows to the harbor is provided in Quartermaster Harbor Nearshore Freshwater Inflows Assessment (King County, 2012).



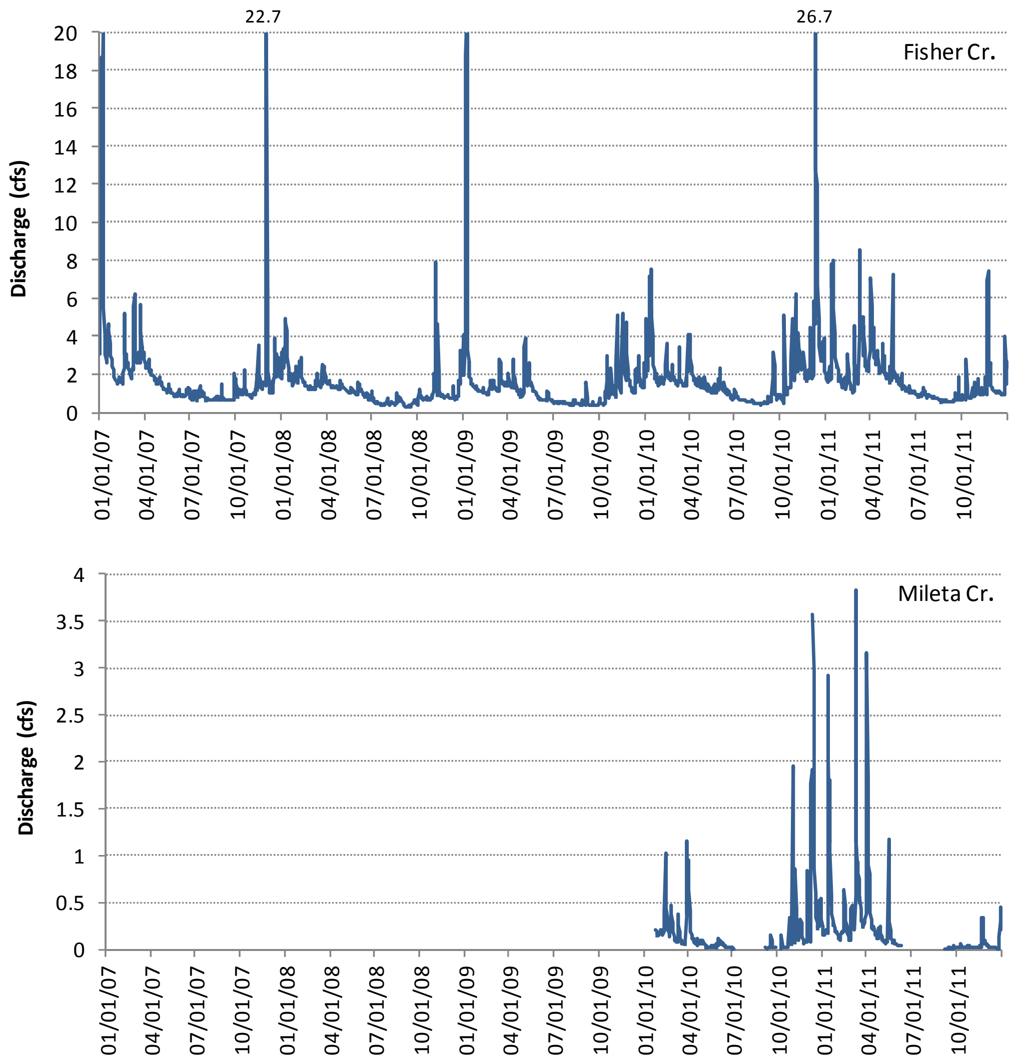


Figure 3-4. Average daily discharge for three Quartermaster Harbor freshwater inputs (note the different scales on the y-axis).

3.2 Meteorological Data

Weather and climate in general are determined by latitude, altitude, land/sea distribution, ocean currents, local topography and global atmospheric circulation patterns. Puget Sound is located in the westerly wind belt with most of our weather patterns arriving from over the Pacific Ocean. These westerly winds are then topographically steered by the local Olympic and Cascade mountain ranges. Winds tend to be funneled through the Strait of Juan de Fuca and then southward down through the Puget Sound Main Basin in the summer and travel around the Olympics from the south heading northward through the Main Basin in the winter (Lilly 1983). Pacific Northwest weather and climate are characterized by wet winters and dry summers with relatively mild temperatures year round due to the moderating influence of Puget Sound waters. Water has a high heat

capacity, heating and cooling more slowly than land, thus moderating the local climate. Average annual rainfall in the Puget lowlands is around 100 cm/year (40 inches/year) and average temperatures are around 20°C (high 60's°F) in the summer and 5°C (low 40's °F) in the winter (www.wrcc.dri.edu).

Precipitation (VMI)

Although Vashon Island, particularly the northern end, tends to receive more rainfall than Seattle (measured at Sea-Tac airport) and other areas along the western portion of King County, rainfall patterns between Vashon-Maury Island and Seatac airport are similar. Figure 3-5 shows precipitation patterns for calendar years 2007 through 2011 from the North Vashon (43u) rain gauge located close to the northern tip of Vashon-Maury Island. The highest amount of rain typically falls in the winter months between November and January, which results in high streamflows and freshwater input into the harbor. The lowest amounts of rain occur in the summer months, typically between June and August, which results in low streamflows and less freshwater input. Rainfall data from the North Vashon site, as well as other locations, can be accessed at http://green.kingcounty.gov/WLR/Waterres/hydrology/GaugeMap.aspx?TabDefault=Map.

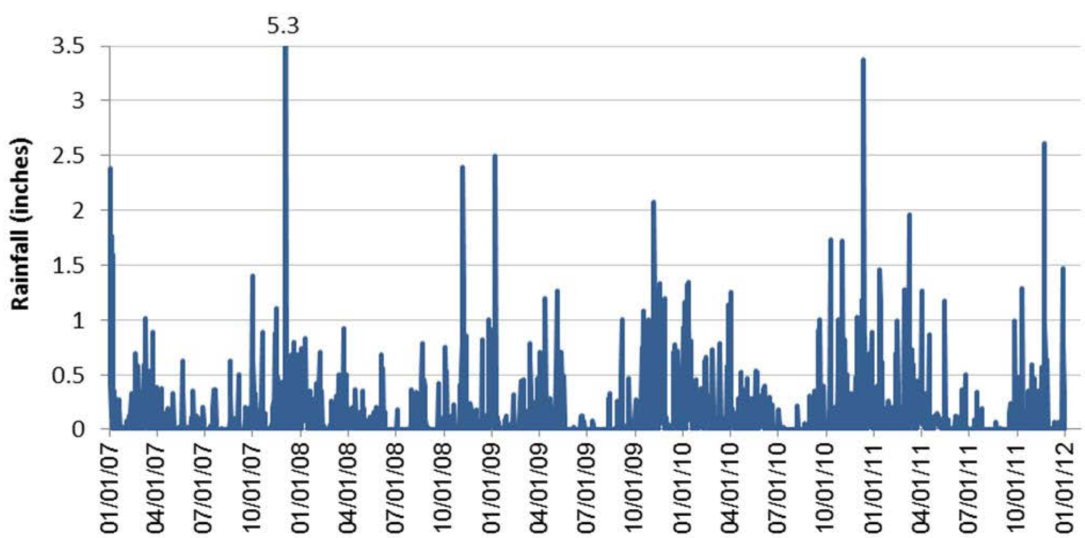


Figure 3-5. Daily rainfall total at the North Vashon (gauge 43u) site.

Precipitation (Sea-Tac airport)

In terms of annual rainfall amounts, both 2007 and 2009 had typical amounts of rainfall, whereas 2008 was a drier than normal year when compared to the 30-year average (Figure 3-6). In 2008, most months were drier than normal but August and December were wet and cold with record amounts of snowfall in December. With the exception of 2006, the highest total amount of rainfall in 16 years was recorded in 2010. The 2010 fall and winter months (September, October, and December) were particularly wetter than normal. Overall, 2011 was slightly drier than normal, particularly December. December

2011 had the lowest recorded total rainfall for the month (2.24 inches) since 1985. However, March through May 2011 were wetter than normal.

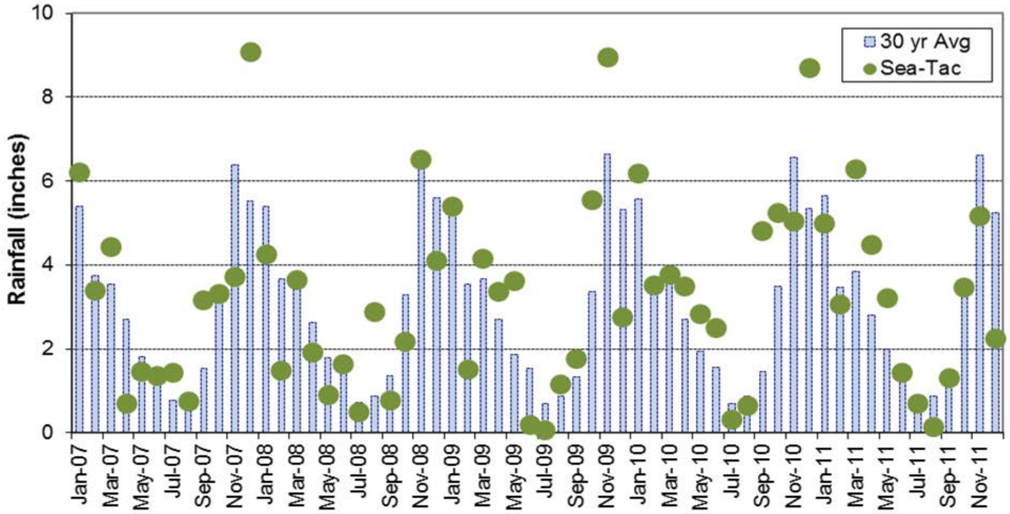


Figure 3-6. Monthly rainfall totals compared to the 30-yr average at Sea-Tac airport.

Air Temperature (Sea-Tac airport)

January 2007 had cooler than normal air temperatures as did the latter part of the year from September through December. There was only one day (in July) with an air temperature above 32°C . In 2008, average monthly air temperatures were fairly typical, with slightly colder spring and early summer temperatures. June 2008 was colder than normal, with the first 11 days the coldest in Seattle history at an average daily temperature of 11.1 °C. The last four days in June had above-normal temperatures, with two days between 32.7-33.3 °C . Record-setting low temperatures were also recorded the last two weeks in December.

In 2009, air temperatures were colder than normal the first three months of the year with March being a particularly cold month. Maximum mean temperatures indicate that air temperature in March was over five degrees below normal when compared to the 30-year average. May, June, and July had above average maximum mean temperatures with July having five days of 32°C and above temperatures including a record setting 39.4 °C day. The El Niño event observed in early summer was a likely causal factor for the warm air temperatures in July and overall generally mild winter temperatures (http://www.esrl.noaa.gov/psd/enso/mei/).

For 2010, January and February were unseasonably warm, January in particular, with above average monthly temperatures. The average monthly temperature for January was 8.3 °C, the highest on record. The El Niño observed in 2009 was a likely causal factor for the warm temperatures in early 2010. July and August each had three days of 32 °C or above temperatures but overall, temperatures were slightly cooler than normal. Although November had cooler than normal temperatures, a record high temperature of 23.3 °C occurred on November 3rd.

Ten out of the 12 months in 2011 were colder than normal. February through July were all colder than normal, particularly April, and there were no days with temperatures above 32 °C. Figure 3-7 shows air temperature anomalies (departure from 30-yr average) from 2007 through 2011 measured at Sea-Tac Airport.

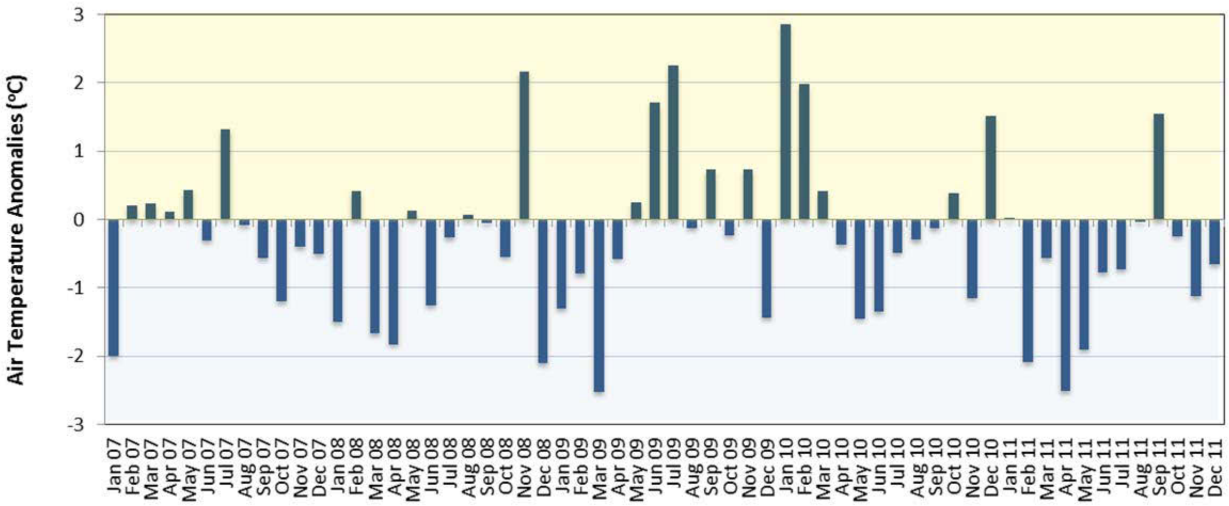


Figure3- 7. Sea-Tac air temperature anomalies (departure from the 30-yr average) from 2007 through 2011. The yellow area indicates warmer than normal and the blue area colder than normal temperatures.

Air Temperature (VMI)

Air temperatures measured at Dockton Park every 15-minutes from January 2009 through December 2011 are shown in Figure 3-8. The seasonal pattern and temperature range are evident, with the highest temperatures in July and August and the lowest typically in December and January. Air temperatures measured hourly near west Judd Creek (north and west of Quartermaster Harbor) from April 2007 through December 2011 are shown in Figure 3-9. Air temperature patterns near west Judd Creek were similar to Dockton, although slightly cooler temperatures were observed near the western portion of Vashon Island likely due to a higher elevation.

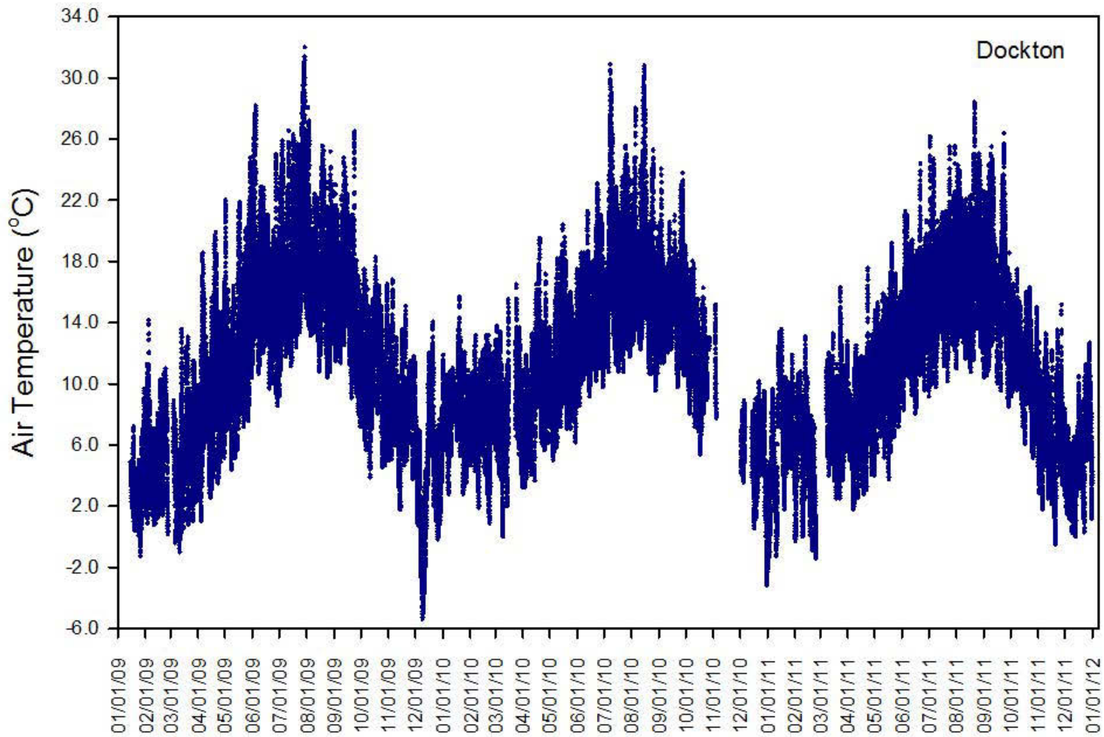


Figure 3-8. Air temperature seasonal patterns at Dockton from 2009 through 2011 (15-minute interval data).

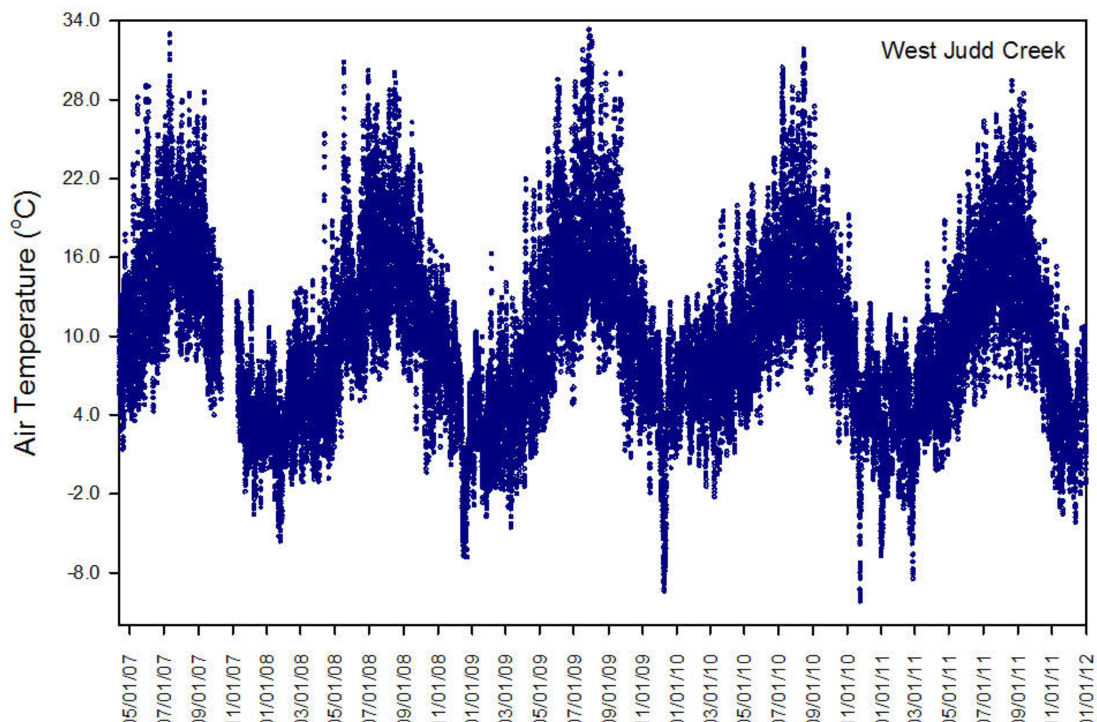


Figure 3-9. Air temperature seasonal patterns at west Judd Creek from April 2007 through 2011 (hourly data).

Wind

Winds can cause significant variation in water circulation and phytoplankton distribution, particularly as Quartermaster Harbor has a south-facing entrance. Winds from the north may augment the surface outflowing water and winds from the south may impede surface outflow. The winds in Quartermaster Harbor are primarily from the south and south-southwest, particularly in the spring and summer months. Besides winds from the south-southwest, winter winds are often from the east to east-southeast. For the months of April and December, Figure 3-10 shows the amount of time winds were blowing from a specific direction between January 2009 and December 2011 to represent spring and winter winds. Figure 3-11 shows the predominant wind direction as well as wind speeds for all months combined.

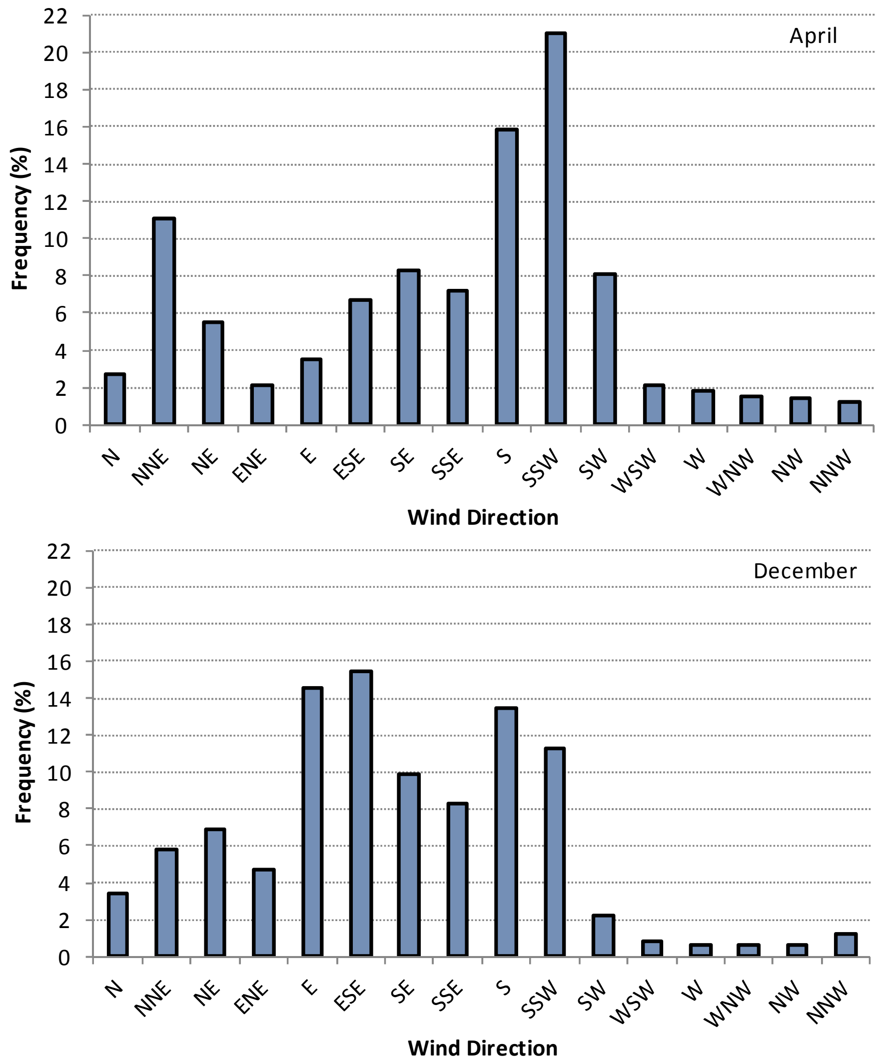


Figure 3-10. Predominant wind direction at Dockton between January 2009 and December 2011 for April and December.

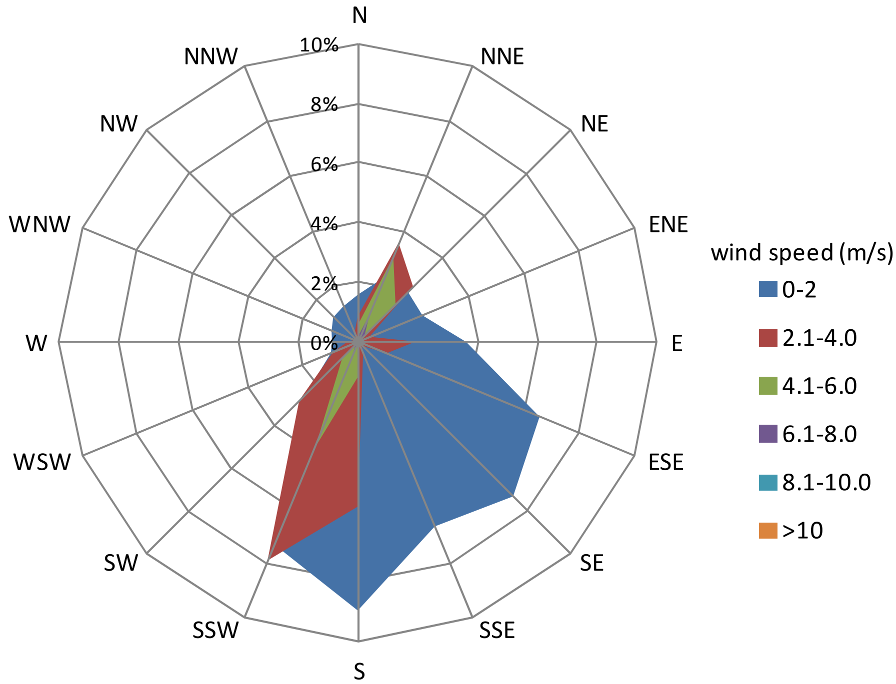


Figure 3-11. Diagram shows the predominant wind direction and frequency of various wind speeds at Dockton between 2009 and 2011.

3.3 Tides

Tides have daily, monthly, and yearly cycles. Puget Sound has mixed semi-diurnal tides which means there are two highs and two lows each day, but the range between the two highs and lows can be very different. The height and timing of the tides varies from day to day as a reflection of the monthly lunar cycles. When the moon is new and when the moon is full, the tides (spring tides) are higher and lower. When the moon is in its quarter phase, the tides (neap tides) are less extreme. The lowest and highest tides of the year occur near the summer and winter solstices in June and December, respectively.

The maximum tidal range in Quartermaster Harbor (Burton) is around 17 feet, with the largest ranges typically occurring in December/January and June/July (from http://tidesandcurrents.noaa.gov). The mean tidal range is 8 ft, the mean higher high water (the highest of the two high tides) is 12 ft and the mean tide is 7ft. These are estimated values as the nearest actual tide gauge to Quartermaster Harbor is at Tacoma in Commencement Bay (Station 9446484). Tidal currents at the mouth of Quartermaster Harbor rarely exceed 50 cm/sec and average around 20 cm/sec along channel in a north-south direction. These tidal currents are consistent with the velocities measured by the current meters used in the hydrodynamic study part of this project (Albertson 2013).

4.0 MARINE WATER QUALITY MONITORING RESULTS

The results section of this report provides data observations between 2007 and 2011 in Quartermaster Harbor and compares the results to data from nearby stations outside of the harbor. Additional data plots are provided in Appendices A through D of this report. A brief synthesis of these data are provided in the discussion (Section 5.0).

4.1 Water Temperature, Salinity, and Density

Water temperature is an important physical characteristic. When temperature increases, biological and chemical activity usually increases while the capacity of water to hold dissolved oxygen decreases. Water temperature is dependent upon factors such as depth, season, amount of tidal mixing, wind, storms, amount of freshwater input, and the amount of vertical stratification.

Salinity fluctuates as the amount of freshwater input increases or decreases, particularly in surface waters. Other factors influencing salinity include tides, input of high-salinity ocean water, precipitation, and the amount of water column mixing from winds.

Although water density is a function of both temperature and salinity, with density increasing with higher salinity and lower temperature, salinity tends to have a stronger influence on density. Density stratification within the water column impedes vertical mixing and can affect the concentration of substances, such as nutrients, at different depths in the water column. Density stratification is usually the strongest in the late spring/early summer due to increased solar heating and freshwater surface runoff from snow melt. Stratification usually weakens in the winter due to reduced solar influence and increased mixing in the water column from wind and storms.

Factors that affect temperature and salinity, and in turn determine density distribution, are: 1) local and regional atmospheric forcing conditions, such as solar radiation, air temperature, wind and rainfall (including the resulting freshwater input from terrestrial sources such as rivers, snowmelt, run-off and groundwater); 2) exchange of water with the ocean, including the impacts of coastal upwelling on exchange water properties; 3) tides; and 4) the physical configuration of the basin; geographic shape, size, orientation, bathymetry and surrounding land surface topography. Warmer and fresher water is less dense and therefore tends to be found in the surface layer, while colder and saltier water is more dense, which sinks to the bottom layer.

4.1.1 Water Temperature

Water temperatures in both inner and outer Quartermaster Harbor exhibited a seasonal pattern, with the shallow inner harbor having a larger range as solar radiation heavily influences surface water temperatures. Figures 4-1 and 4-2 show monthly results for both surface (1 m) and bottom waters from 2007 through 2011 for both King County and UWT stations. Surface water temperatures generally peaked in July with bottom temperatures peaking later in August and September. The coldest water temperatures were usually measured in December and January and corresponded with lower amounts of solar radiation, and consequently low air temperatures. The inner harbor had both the warmest and coldest temperatures as this part of the harbor is very shallow and most affected by solar radiation.

Figure 4-3 shows annual and water column variation at station 54 in the outer harbor and NSEX01 (East Passage). The warmer surface waters, particularly less than 3 m, in Quartermaster Harbor compared to open waters are evident in the summer to early fall months. In summer, the thermocline forms at about 4 m throughout Quartermaster Harbor compared to about 10 m in open waters. The relatively well-mixed water column with uniform temperatures in the winter and early spring months (December to early April) is also seen in Figure 4-3 and in the water property contoured sections in Appendix A. For most years sampled, less than 1 ^{o}C was observed between surface and bottom waters for all stations sampled during the winter and early spring months. The contoured sections also show that more variation between surface and bottom waters occurs earlier in the year in the inner harbor than the stations in the outer harbor and Commencement Bay.

Water temperatures in the inner harbor ranged from 2.5 to 21.2 ^{o}C during 2007 through 2011 whereas the temperature range in the outer harbor at Dockton (NSAJ02) was 6.7 to 17.9 ^{o}C. The temperature range at stations 51 through 54 in the outer harbor was 6.9 to 16.7 ^{o}C. Surface temperatures at the outer entrance to the harbor (NSGE01) between 2009 and 2010 ranged from 6.6 to 19.3 ^{o}C and bottom temperatures showed less variation, ranging from 7.4 to 12.6 ^{o}C. The 2.5 ^{o}C water temperature was measured in the inner harbor at MSWH01 in December 2008. Figures 4-4 through 4-6 show average monthly mean, minimum, and maximum temperatures between 2007 and 2011 and the differences between the inner and outer harbors.

Daily and monthly water temperature variations recorded throughout the year by the moorings are shown in Figures 4-7 through 4-11. For the UWT mooring in the outer harbor (Station 54), additional annual temperature plots are provided in Appendix B. Record setting low air temperatures were observed in 2008 between December 13 and 26 and affected water temperatures, particularly in the inner harbor. Figure 4-7 shows these low water temperatures at station MSWH01 in the inner harbor. Low water temperatures (< 5.0 ^{o}C) were also seen in January 2007. The warmest water temperatures in the inner harbor were observed in August 2008 following three days of 32 ^{o}C and above air temperatures (see Figure 4-7).

From 2009 through 2011 at Dockton (NSAJ02), the coldest water temperatures were observed in January and December 2009 (Figure 4-8). The warmest temperatures usually occurred in July and August following successive days with air temperatures above 32 ^{o}C. The July 2010 peak shown in Figures 4-8 and 4-9 followed this pattern and was seen subsequent to 3 consecutive days of 32 ^{o}C air temperatures, including one day at 35 ^{o}C. It should be noted that the Dockton sensor is in a fixed position on a piling and, therefore, the water depth above the sensor changes with tidal elevation. This affects water temperature data as the sensor is closer to the water surface during low tides, which results in higher observed temperatures (see Figure 4-9).

Surface water temperatures measured at the outer entrance to Quartermaster Harbor mooring followed a similar seasonal pattern to that at Dockton and the timing of the high and low temperatures was also similar. However, the magnitude of both high and low short-term spikes at the outer entrance mooring were more pronounced (Figure 4-11) at this site than in the inner harbor. Bottom water temperatures at the outer entrance mooring also showed a seasonal pattern but had less variation than surface waters. A time lag when seasonal high and low temperatures occurred was observed between bottom and surface waters, with bottom water highs and lows occurring around four to six weeks later. This time lag was also observed at the mooring at Station 54 (see Figure 4-10). Of note is that the water column becomes isothermal in winter and for a time, the deep water is warmer than the surface water at both the entrance and outer bay moorings. A semi-diurnal tidal signal was observed in bottom waters at the outer Quartermaster Harbor entrance mooring (Figure 4-12) where sensors were fixed at a constant depth above the seafloor. As there was less variation in bottom waters, the tidal signal was more pronounced than surface waters as the amount of variation seen in surface waters masks the tidal signal.

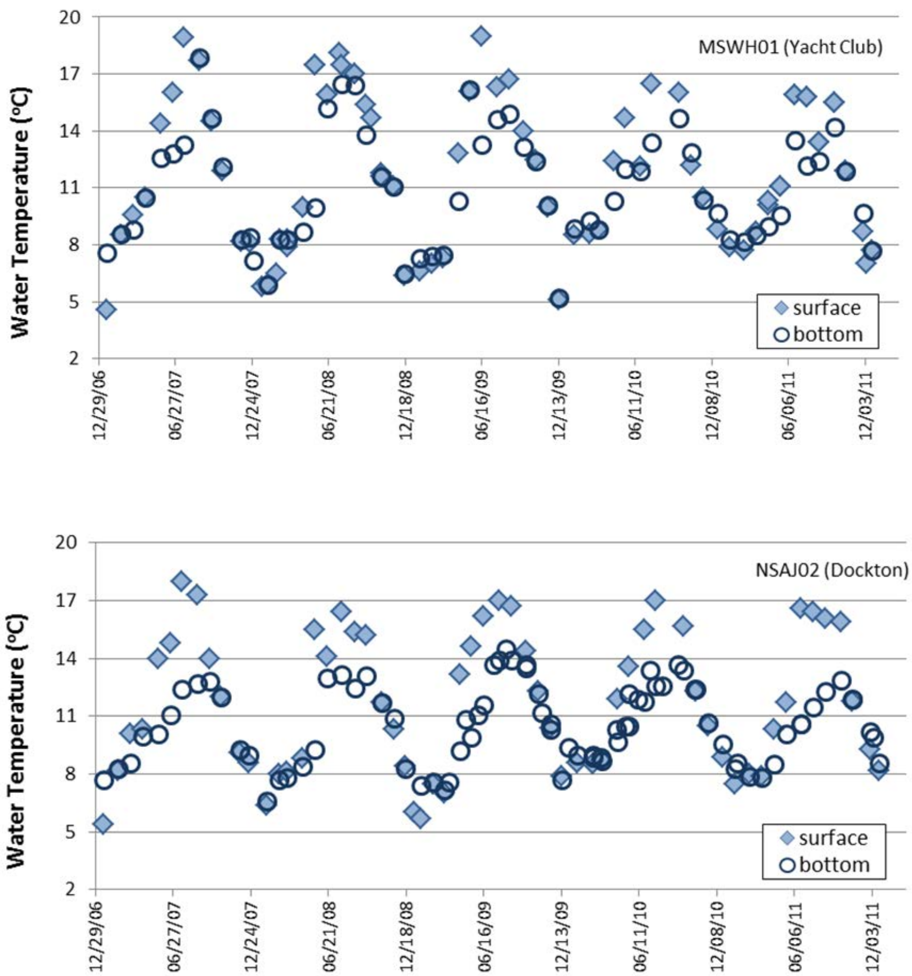


Figure 4-1. Seasonal water temperature patterns for surface and bottom waters from 2007 to 2011 (KC monthly data).

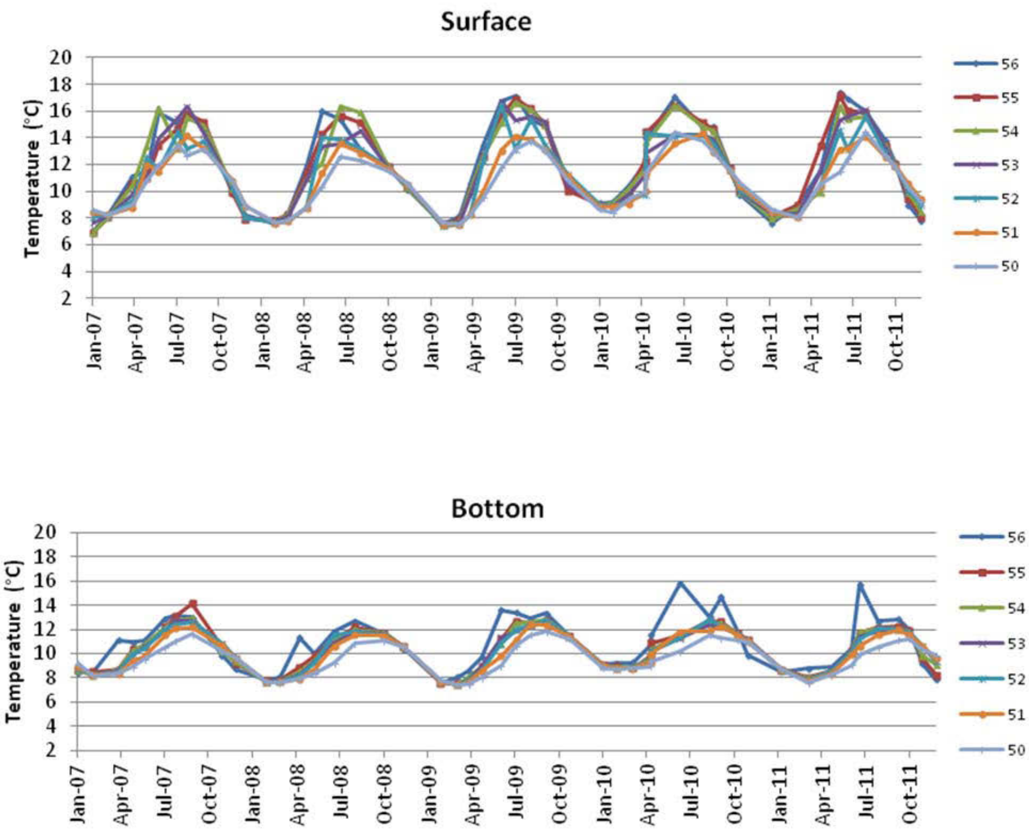


Figure 4-2. Monthly seasonal water temperature patterns for surface and bottom waters from 2007 through 2011 (UWT stations).

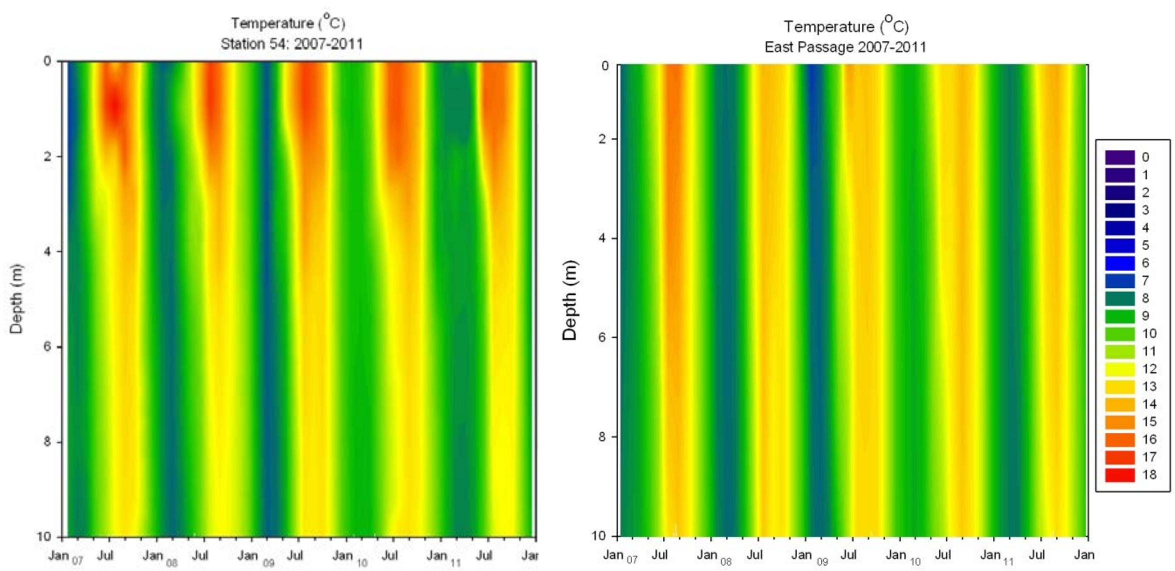


Figure 4-3. Water temperature variation at Stations 54 and NSEX01 (only top 10m shown) from 2007 through 2011.

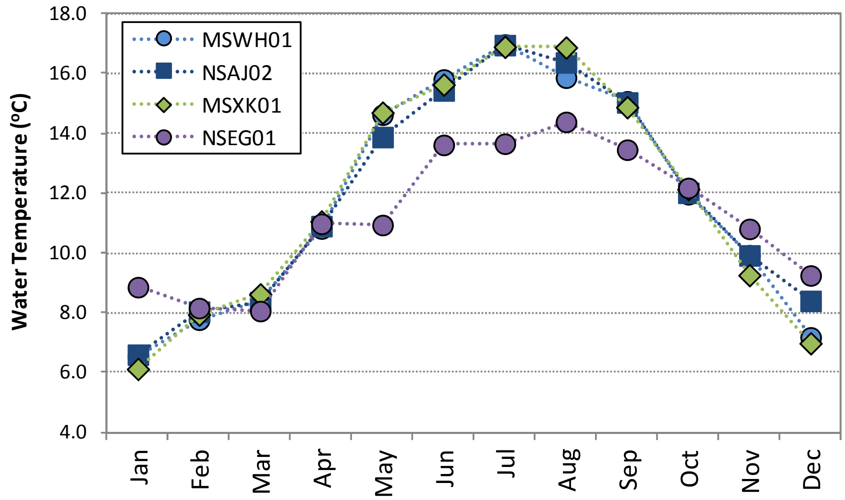


Figure 4-4. Monthly mean water temperature for surface waters (1 m) from 2007 through 2011.

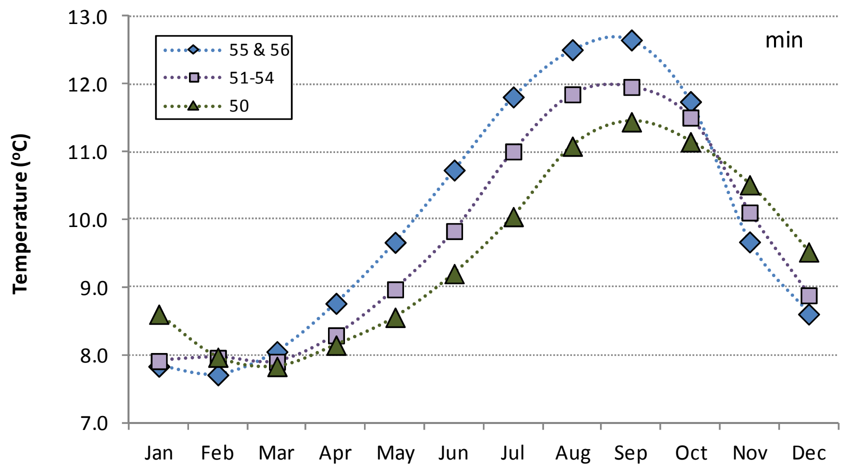


Figure 4-5. Average monthly minimum water temperature from 2007 through 2011 for all depths

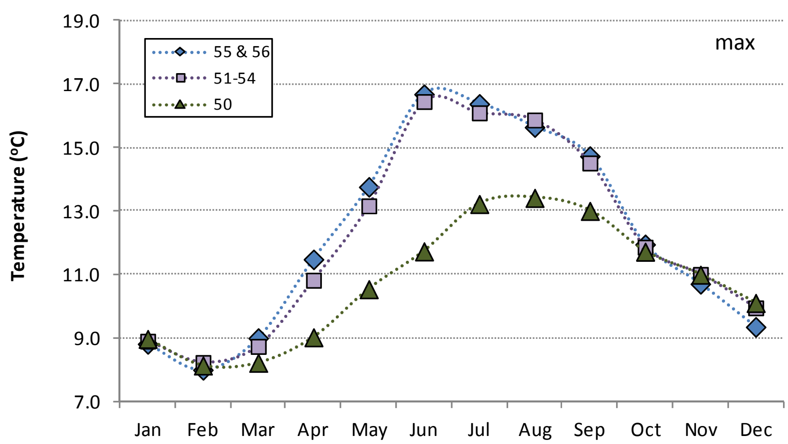


Figure 4-6. Average monthly maximum water temperature from 2007 through 2011 for all depths

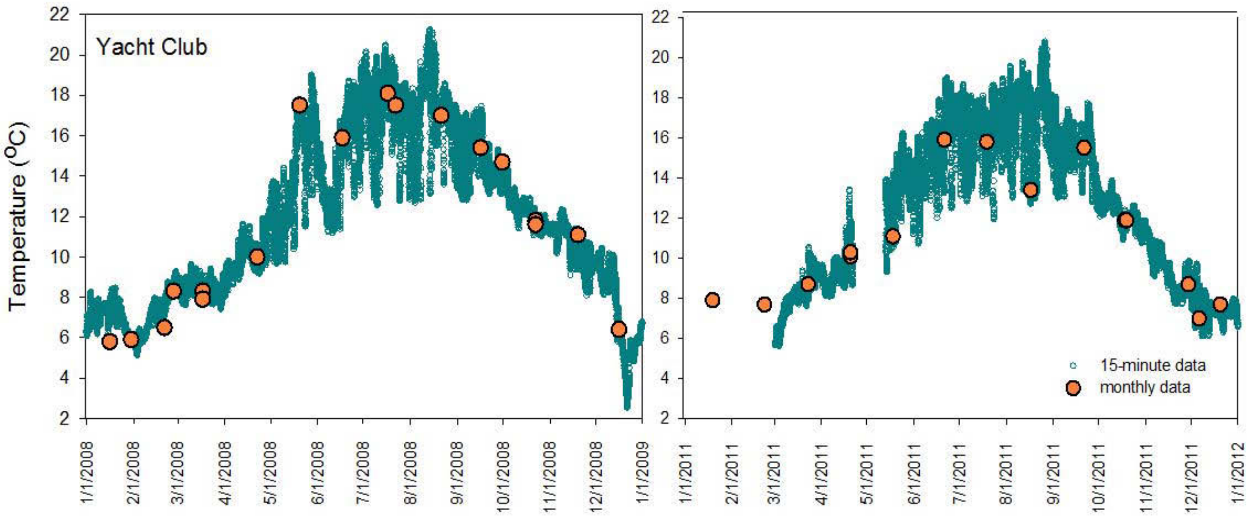


Figure 4-7. 15-minute interval water temperatures at the Yacht Club (MSWH01) during 2008 (left) and 2011 (right). Orange circles indicate monthly data.

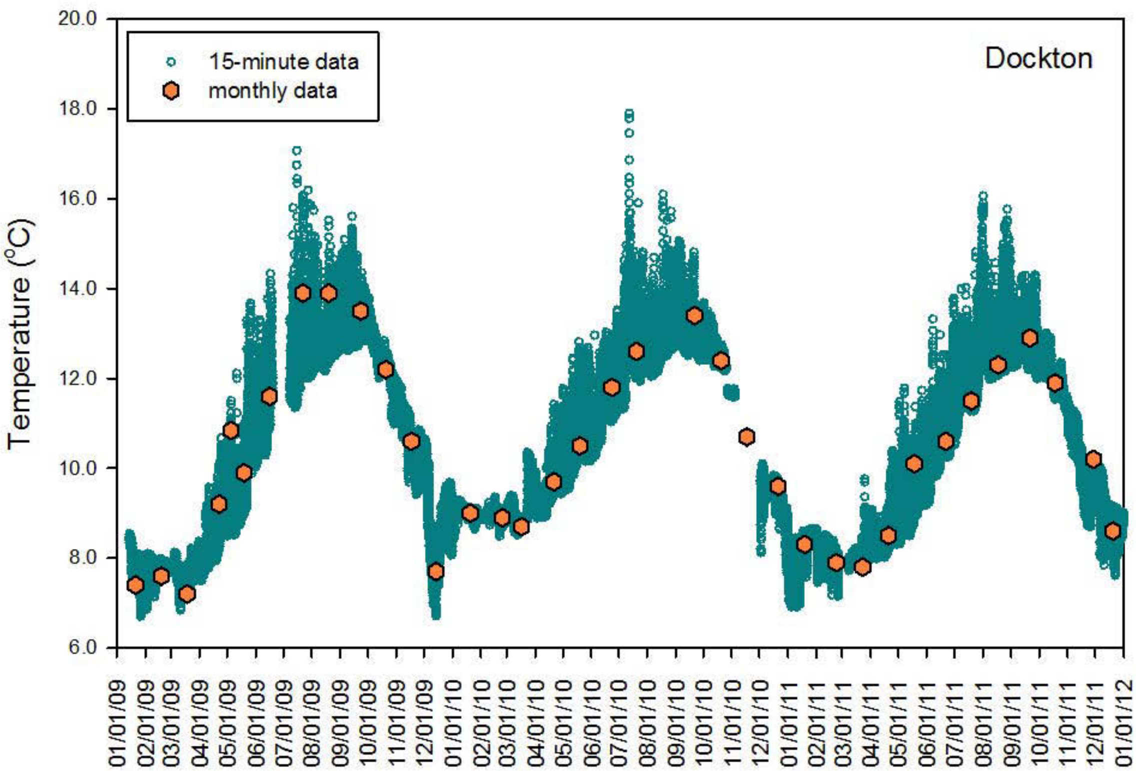


Figure 4-8. 15-minute interval water temperatures at Dockton from 2009 through 2011.

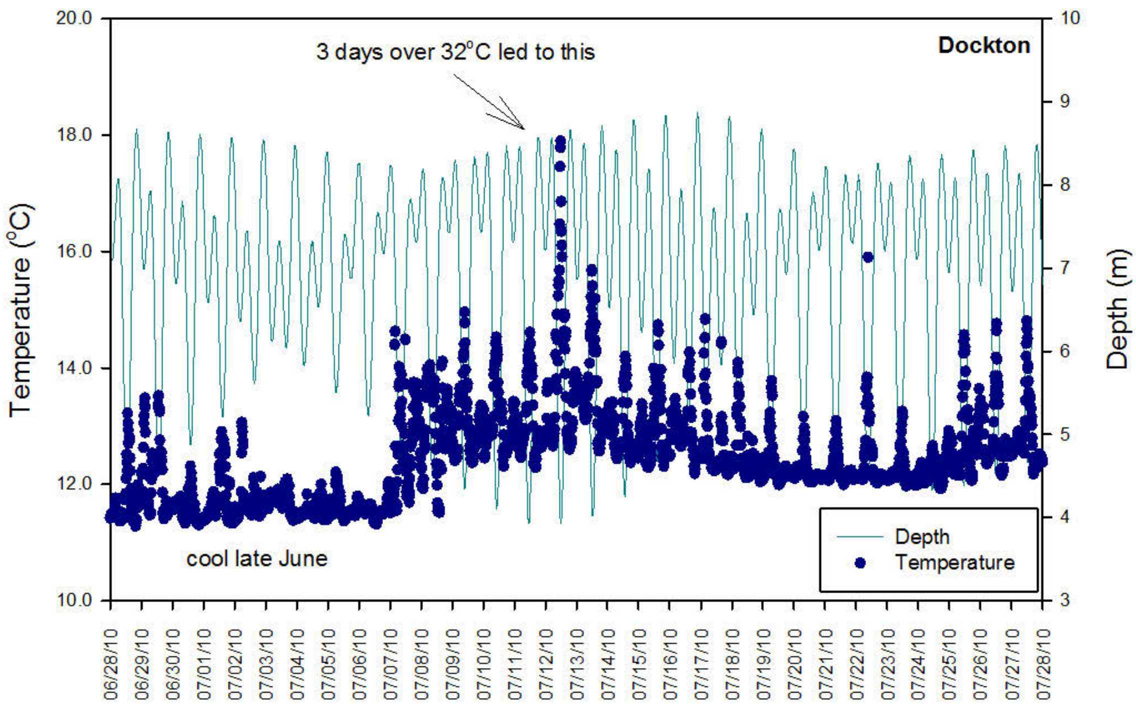


Figure 4-9. Daily water temperature variation during a 1-month period in 2010 at Dockton (NSAJ02).

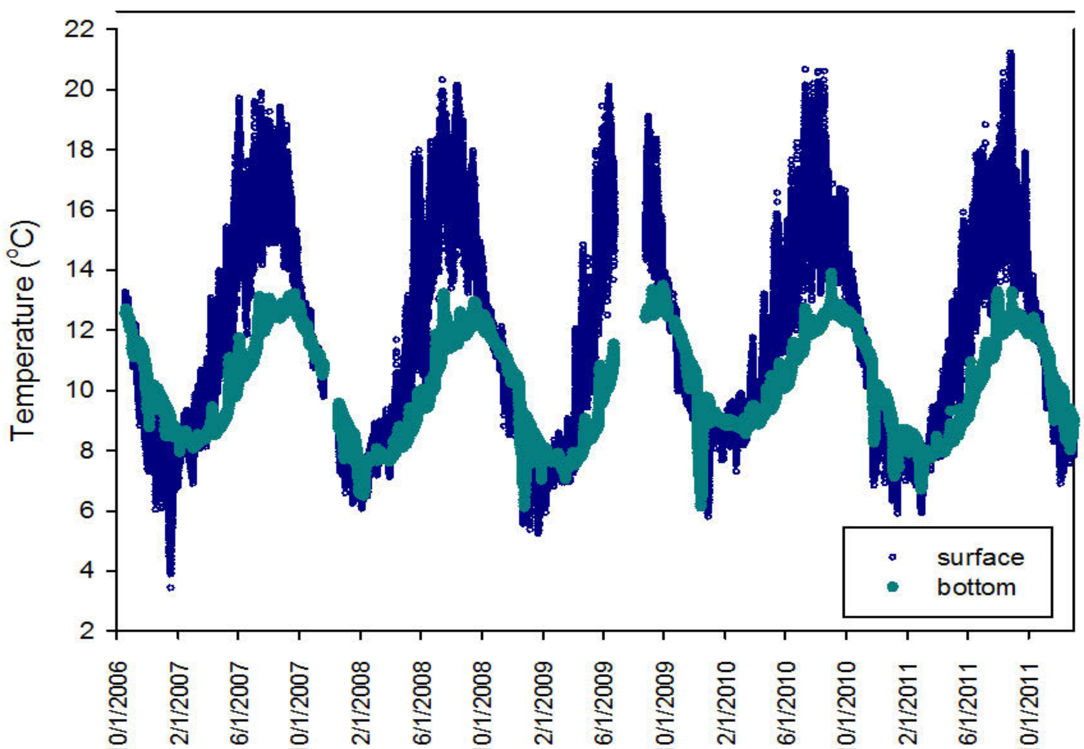


Figure 4-10. 15-minute interval surface and bottom water temperatures in the outer harbor (Station 54) showing seasonal and annual variation.

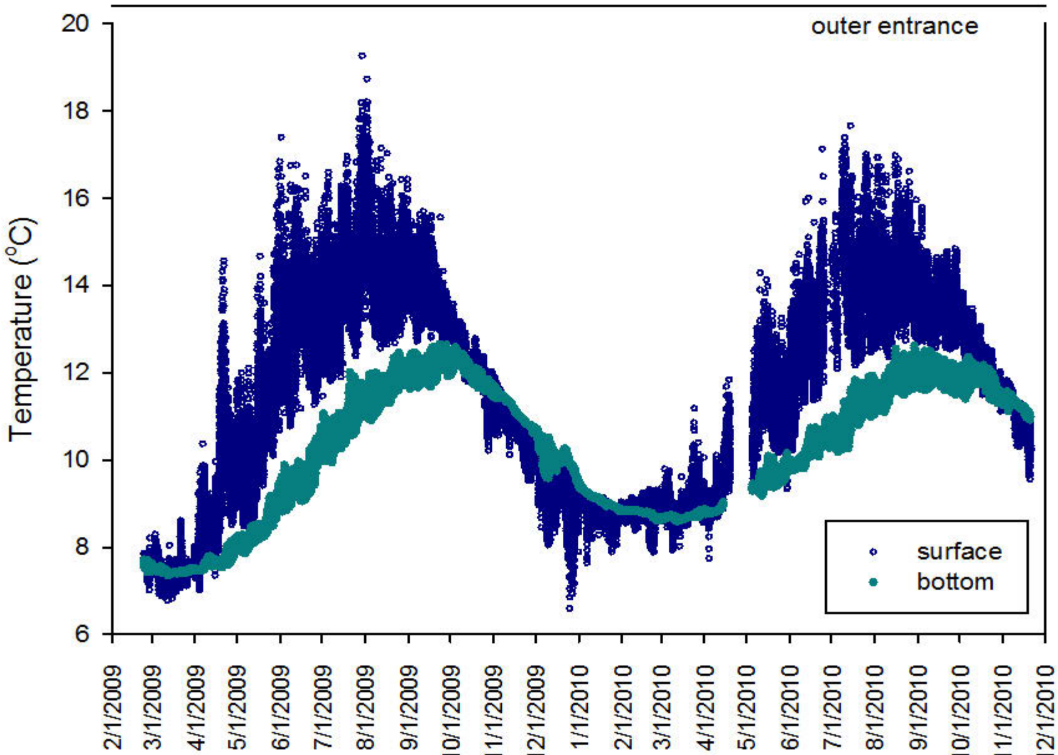


Figure 4-11. 15-minute interval water temperatures at the entrance to Quartermaster Harbor (NSGE01) in 2009 and 2010

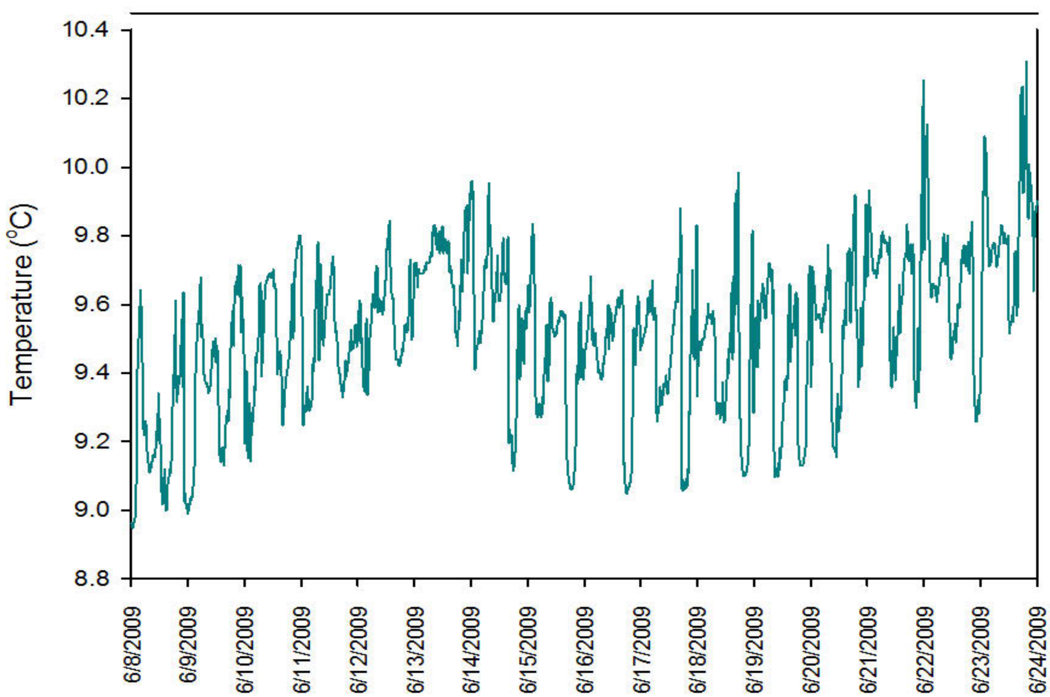


Figure 4-12. 15-minute interval water temperatures in bottom waters (50m) at the entrance to Quartermaster Harbor (NSGE01) for just over a 2-week period.

4.1.2 Salinity

Salinities in both the inner and outer harbors varied seasonally due to freshwater in the surface layer and oceanic water inputs in the lower layer, with surface salinities showing the greatest variability. During 2007 through 2011, salinities throughout the entire water column in the inner harbor ranged between 20.68 and 30.48 PSU while salinities in the outer harbor ranged from 17.31 to 31.82 PSU. Surface salinities at the outer entrance to the harbor showed the greatest variation (17.31 to 30.96 PSU) due to riverine freshwater input, particularly from large rainfall events and snowmelt runoff. Bottom salinities at the outer entrance and outer harbor varied the least.

Figures 4-13 and 4-14 show monthly results for both surface (1 m) and bottom waters from 2007 through 2011. Both surface and bottom salinities were highest in the late summer and fall months, August through October, generally peaking in October. August is typically the driest month of the year and salinities reflect the lack of freshwater input. The higher salinities in September and October are due to the input of higher salinity upwelled oceanic waters in the deeper waters. Figure 4-15 shows the average monthly mean salinities for surface waters at King County sites and as would be expected, salinities at the intertidal location (MSXK01) were lowest throughout the year. The site at the outer entrance to the harbor (NSGE01) generally had the highest salinities throughout the year, with the exception of April. Figure 4-16 shows the average monthly mean and minimum surface salinities for all depths combined from 2007 through 2011 at UWT sites. Figures 4-15 and 4-16 indicate that on average, surface water is freshest during the spring between April and June, with minimums occurring in May. The inner harbor had the lowest average salinities throughout the year and lowest mean minimum salinities from November through March compared to the other sites. Seasonal salinity patterns for all UWT sites are shown in the contoured section plots in Appendix A. Seasonal and annual variation throughout the water column at Station 54 compared to the East Passage site (NSEX01) is shown in Figure 4-17. A halocline (a strong vertical salinity gradient) typically occurs between 2-4 m in Quartermaster Harbor, whereas this occurs at about 10 m in Commencement Bay and East Passage. The overall lower salinities in Quartermaster Harbor compared to the open water site can be seen in Figure 4-17, as well as the effect of increased freshwater input on surface salinities at both sites.

Although the lowest salinities varied by year and location and were affected by large rain events and snowmelt runoff, the lowest surface salinities most often occurred in May and June and lowest bottom salinities January through April. Figures 4-18 through 4-22 show the short-term effects (generally less than three days duration) of rain events captured by 15-minute interval mooring data and also seasonal patterns at each of the four locations. The large amount of surface variation at the outer entrance to the harbor (NSGE01) and in the outer harbor (Station 54) are shown in Figures 4-20 and 4-21; both moorings indicated a similar pattern. Figure 4-22 shows surface salinities at the outer harbor mooring (Station 54) in relation to freshwater input, as indicated by the Puyallup River discharge volume. Additional annual salinity plots for the UWT mooring (Station 54) are provided in Appendix B.

Of the five years sampled, bottom salinities were highest in 2009 and from mid-summer through December in 2008. Surface salinities were also higher from mid-summer through December in both 2008 and 2009. Although both surface and bottom salinities were generally the lowest in 2011 compared to the other years monitored, spring salinities in 2008 were also low.

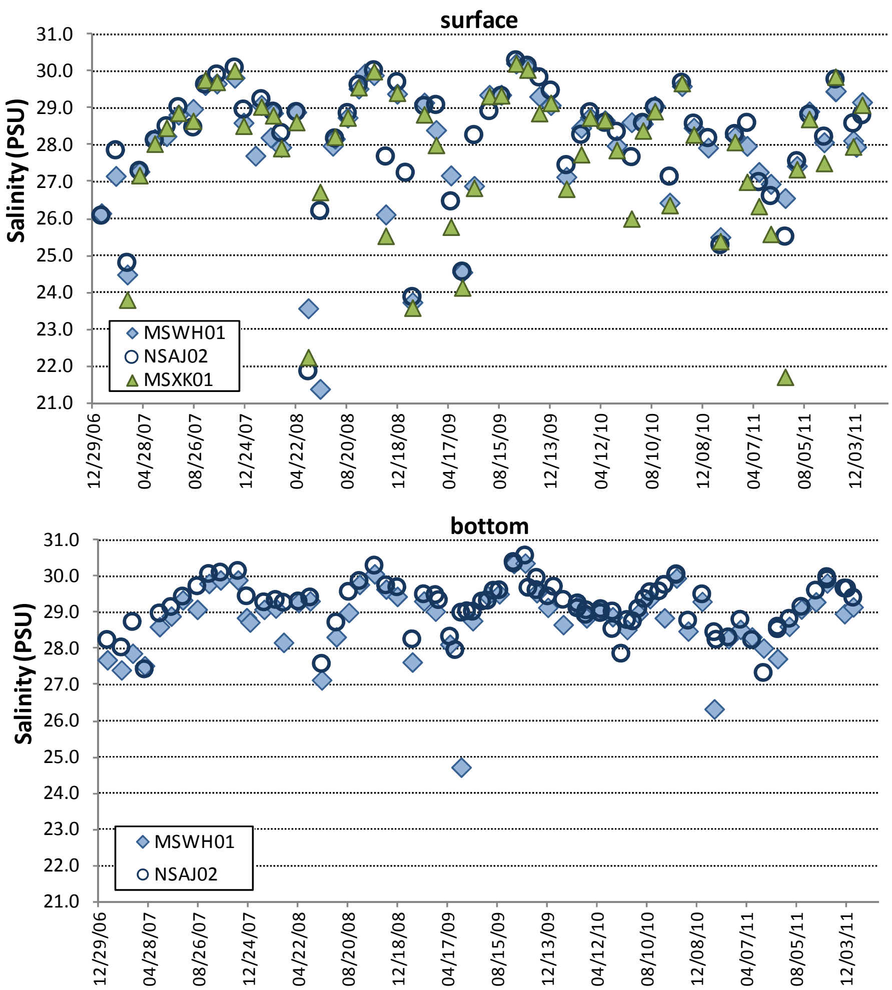


Figure 4-13. Seasonal salinity patterns for surface and bottom waters from 2007 through 2011 (KC monthly data).

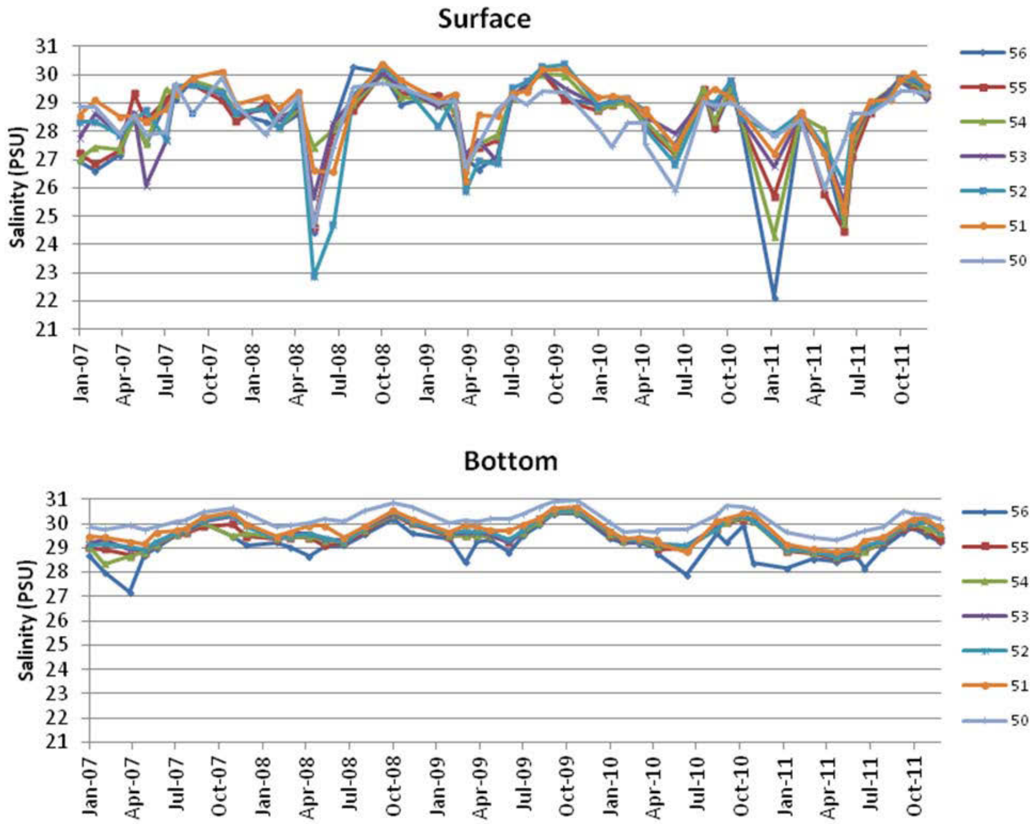


Figure 4-14. Seasonal salinity patterns for surface and bottom waters from 2007 through 2011 (UWT monthly data).

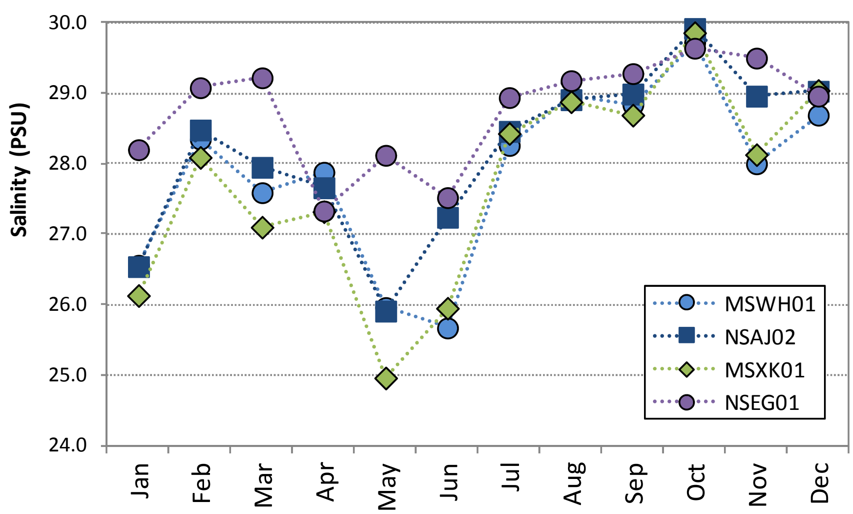


Figure 4-15. Monthly mean salinity for surface waters (1 m) from 2007 through 2011 (King County monthly data).

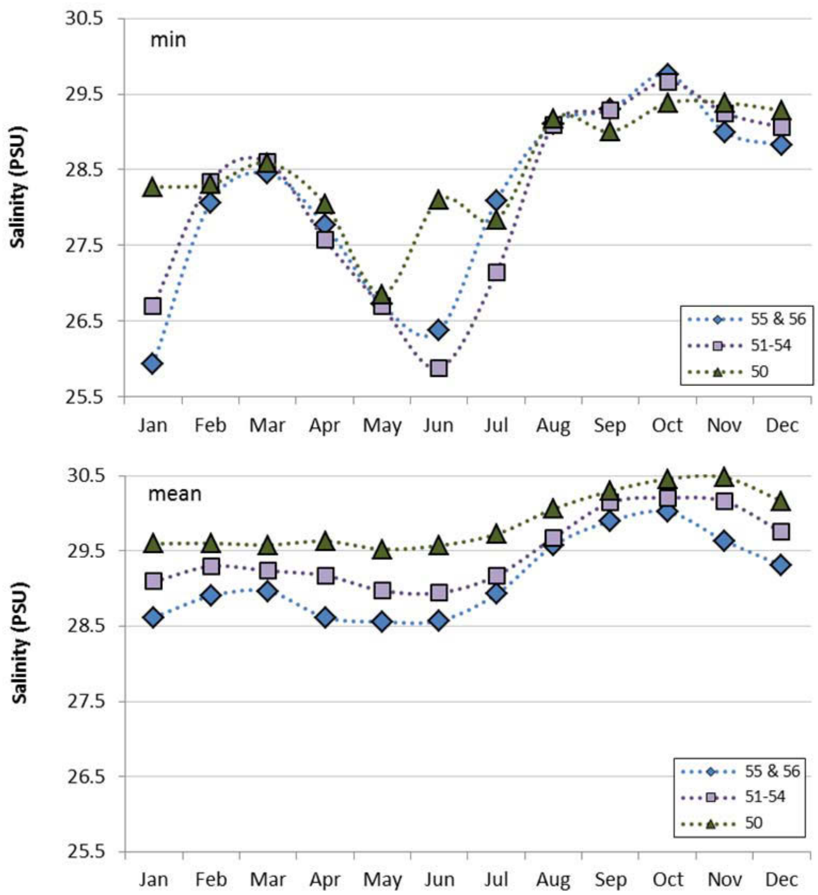


Figure 4-16. Average monthly minimum and mean salinities from 2007 through 2011 for all depths (UWT monthly data)

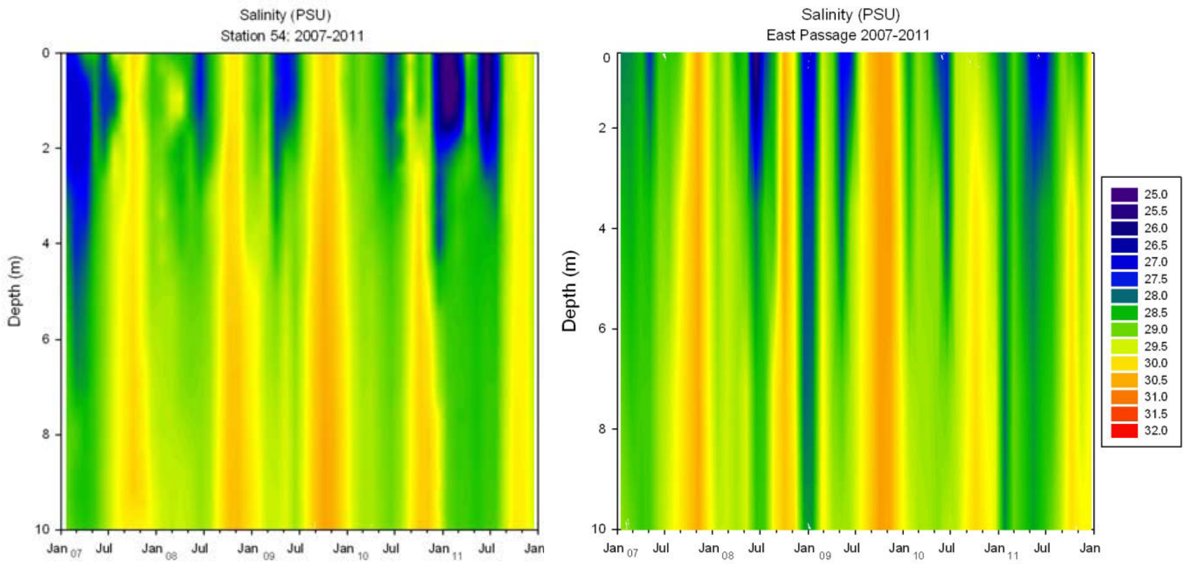


Figure 4-17. Salinity variation at Stations 54 and NSEX01 (only top 10 m shown) from 2007 through 2011

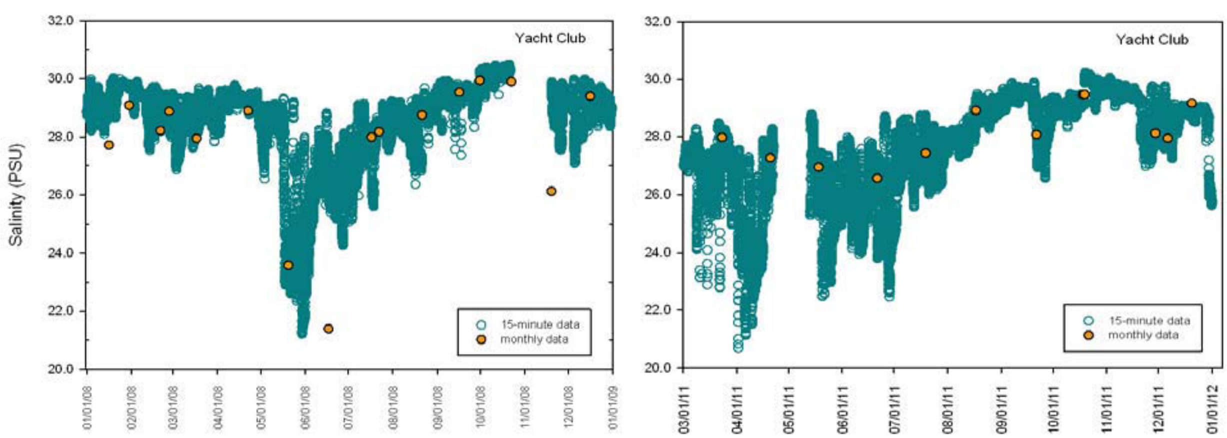


Figure 4-18. 15-minute interval surface salinities at the Yacht Club (MSWH01) during 2008 (left) and 2011 (right)

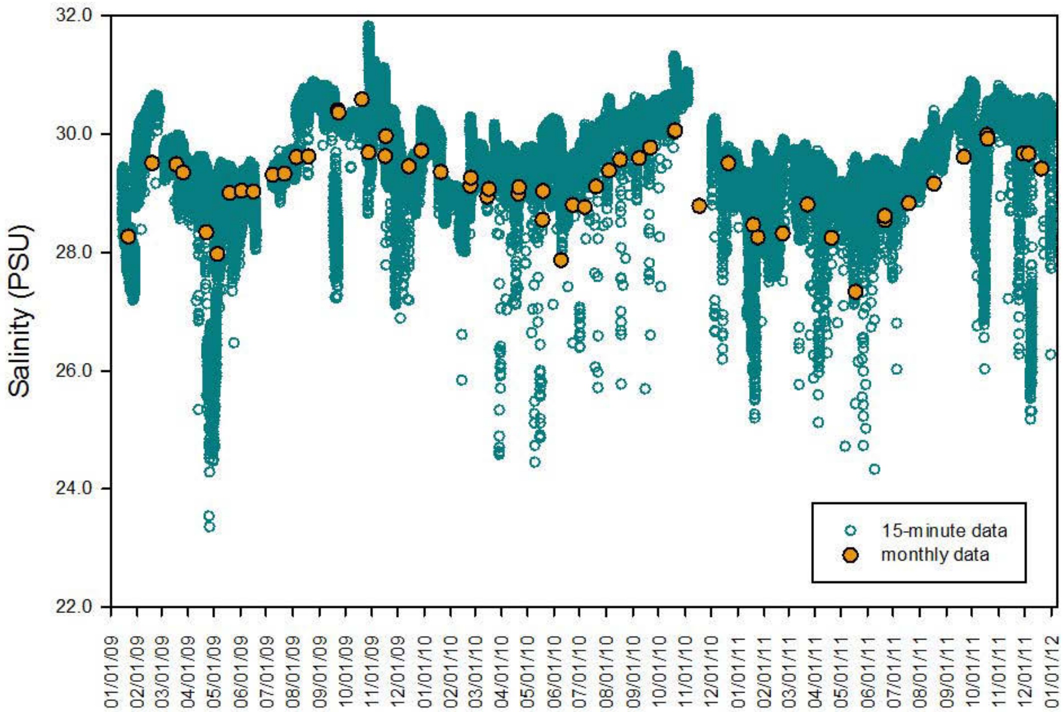


Figure 4-19. 15-minute interval salinities at Dockton from 2009 through 2011

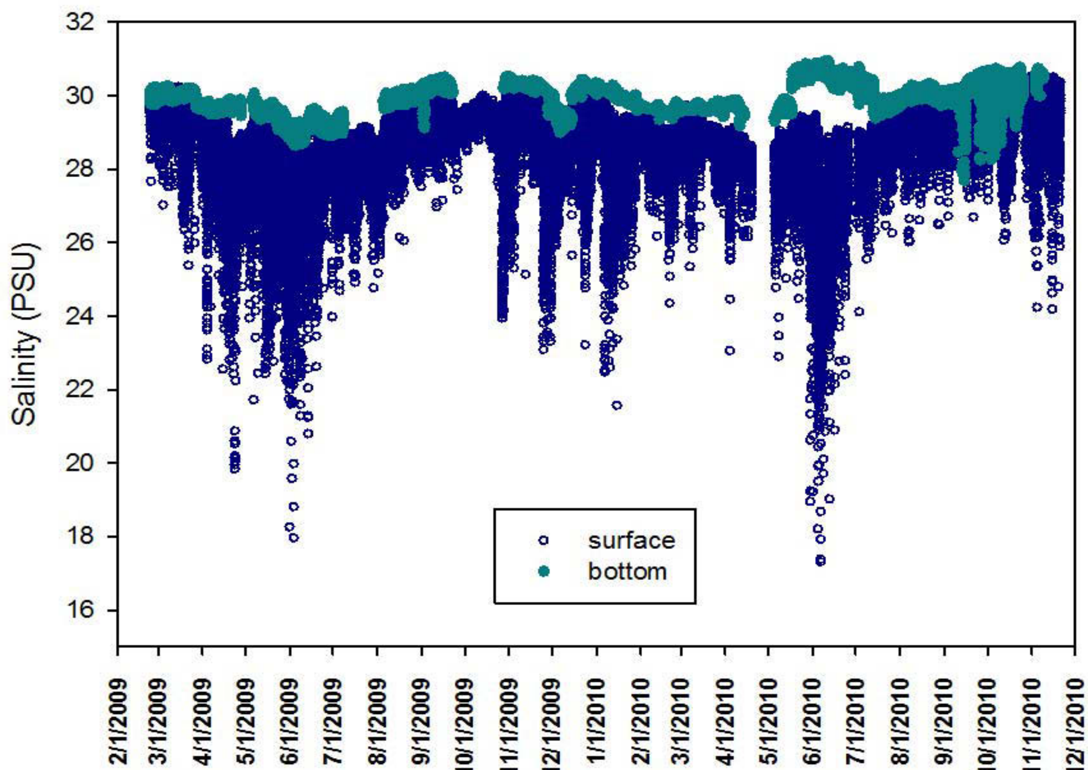


Figure 4-20. 15-minute interval salinities at the entrance to Quartermaster Harbor (NSGE01) in 2009 and 2010

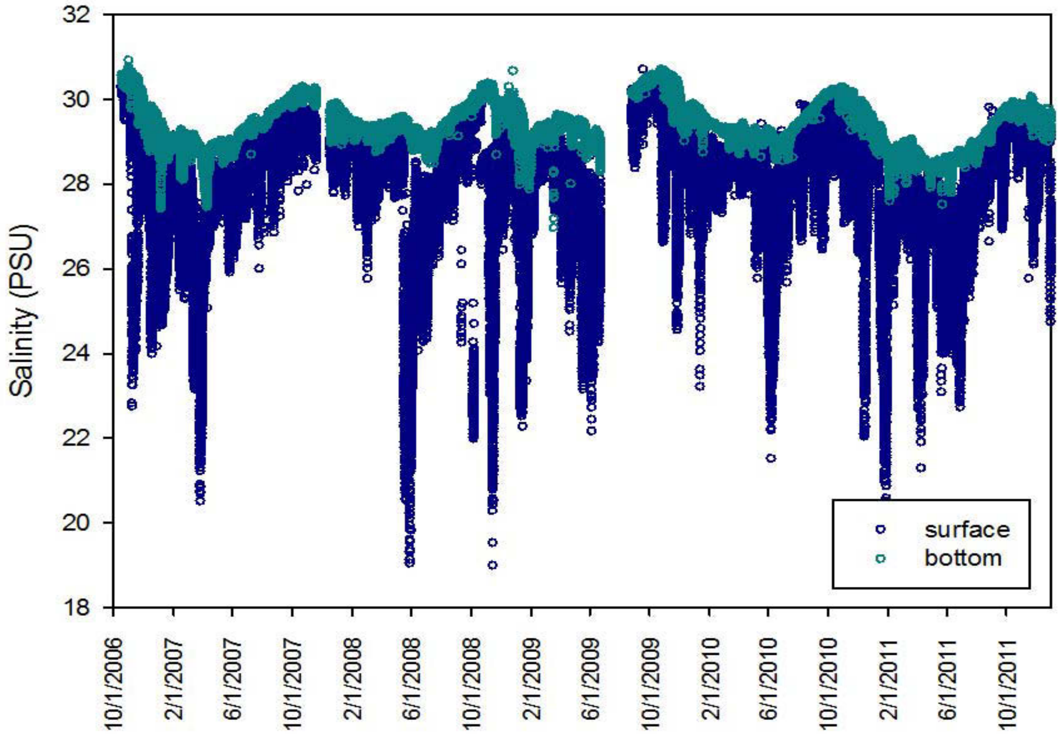


Figure 4-21. 15-minute interval salinities in the outer harbor (Station 54) from late 2006 through 2011

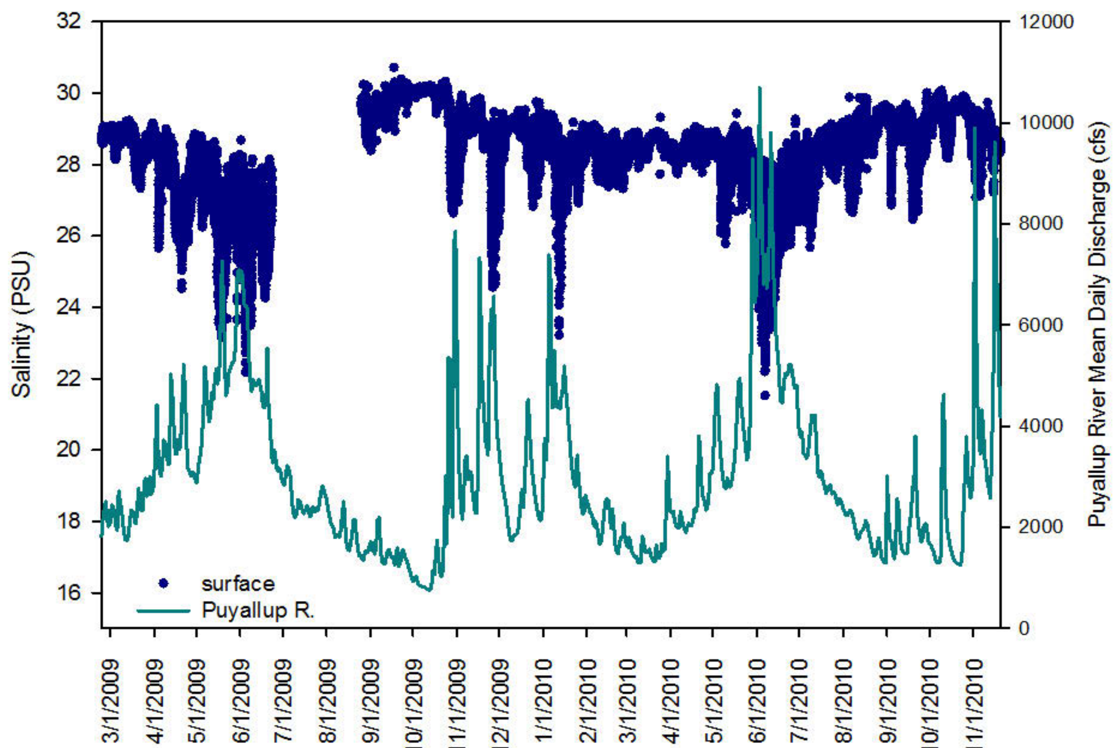
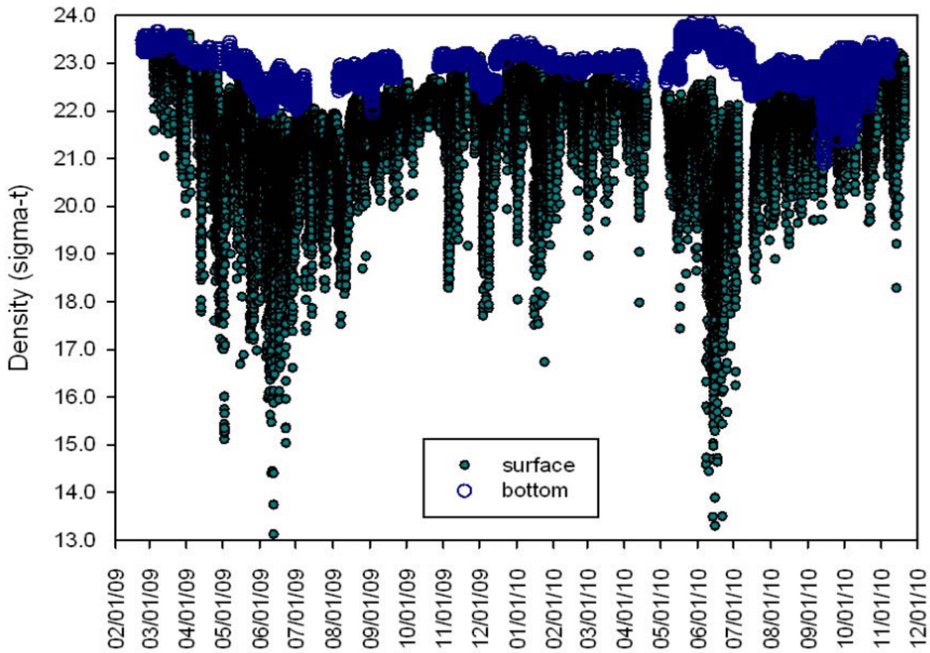


Figure 4-22. 15-minute interval surface salinities in the outer harbor (Station 54) mooring and Puyallup River discharge.

4.1.3 Density

Density in the surface layer of Quartermaster Harbor is highly variable compared to bottom density due to surface atmospheric forcing conditions such as freshwater influxes, seasonal heating and cooling, and storms (Figure 4-23). Stratification is primarily driven by surface salinity and the water column tends to be the most strongly stratifiied in the late spring/early summer (May through July) (see salinity section & CTD density sections in Appendix A). This is due to high seasonal run-off associated with storms and spring snowmelt which may be periodically transported via the Puyallup River plume into Commencement Bay and outer Quartermaster Harbor (see meteorology section). There is also the occasional winter storm where high surface water run-off creates a highly stratified freshwater layer (such as in January 2011- see salinity section), but these stratification events are more short-lived due to more intense wind mixing in the winter (Figures 4-24 and 4-25). The pycnocline in East Passage during the more prolonged spring stratification period is typically around 10 m depth, while the Quartermaster Harbor pycnocline is almost always near 4 m depth (Figure 4-25). On average, East Passage is less stratified than either Station 50 in Commencement Bay or outer Quartermaster harbor at Station 54, which tends to be the most stratified of these three sites consistent with its more sheltered configuration (Figure 4-24).

Although both temperature and salinity determine density, it can be seen in Figure 4-26 that salinity differences dominate the density signal, and to a large extent, determine stratification in Quartermaster Harbor.



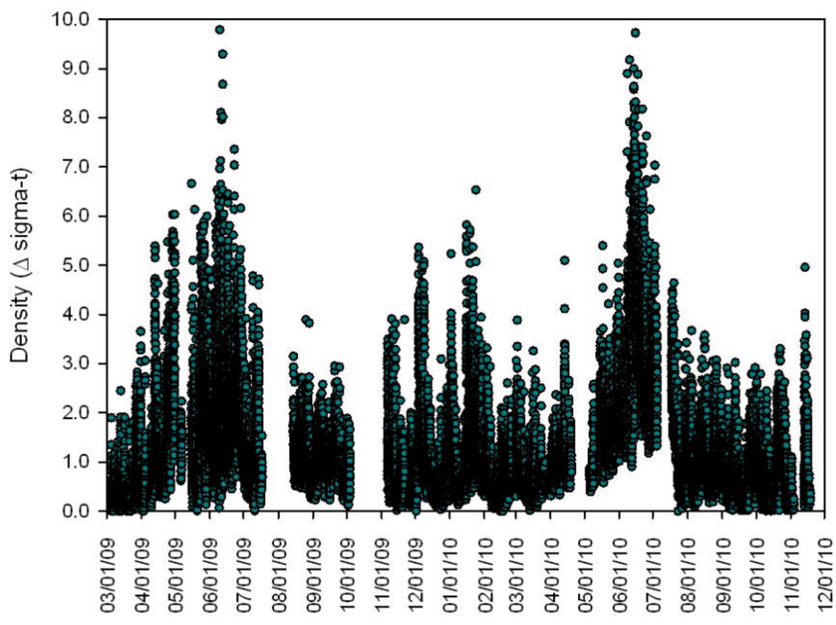


Figure 4-23. Surface and bottom density (sigma-t) at site NSGE01 at the mouth of Quartermaster Harbor (top graph) and difference between suface and bottom densities (Δ sigma-t), an indication of stratification strength (bottom graph). Mooring data were collected at 15-minute intervals.

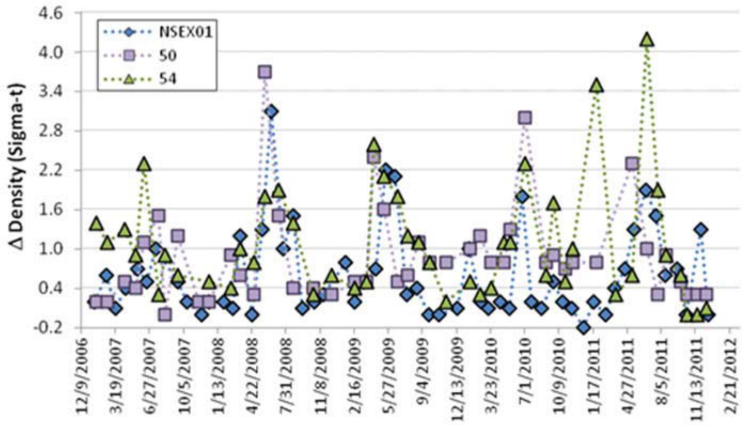


Figure 4-24. Density (sigma-t) differences indicating stratification strength between 1-10 m at East Passage (NSEX01), Commencement Bay (Station 50), Quartermaster Harbor (Station 54).

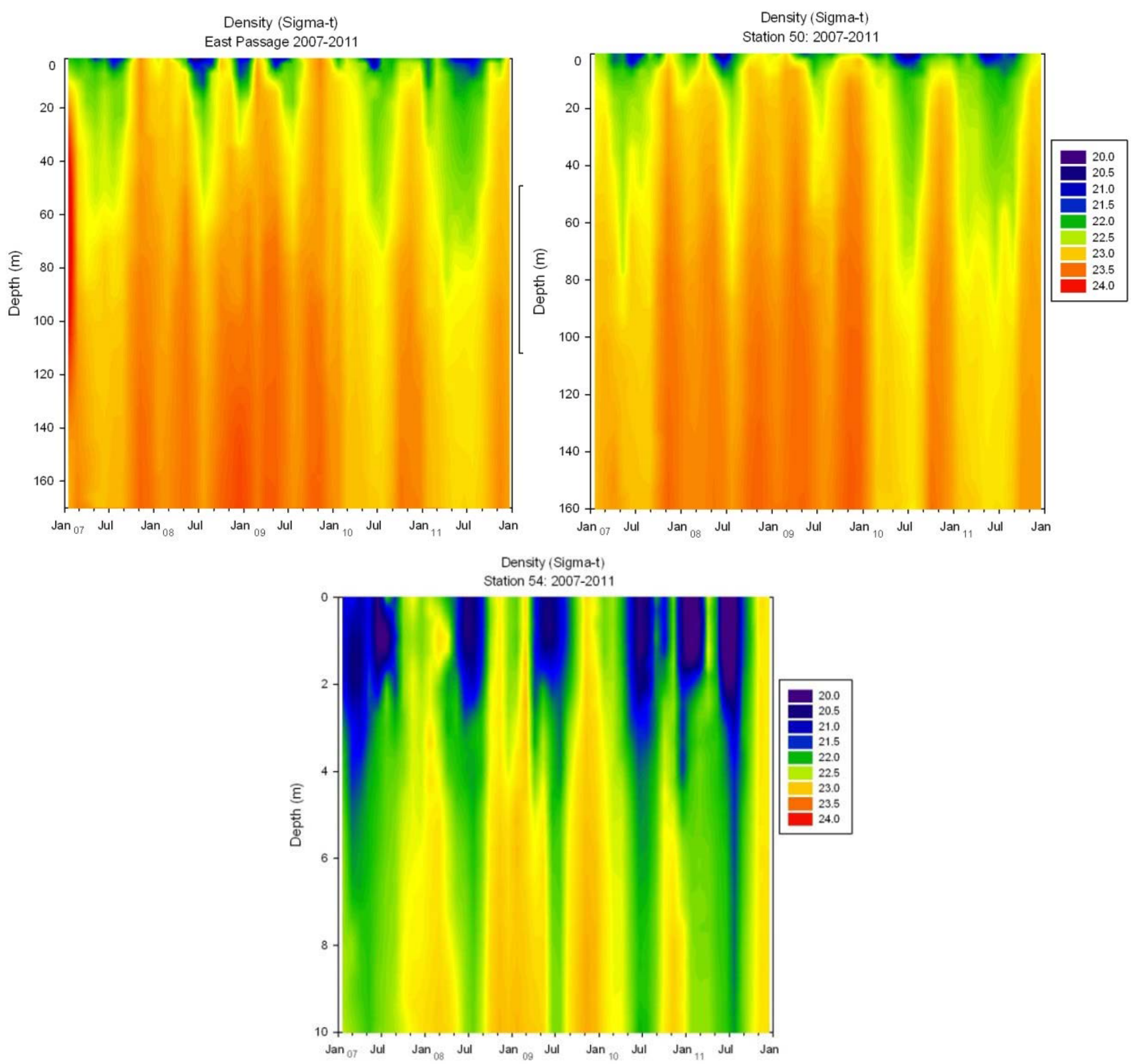


Figure 4-25. Density (sigma-t) time series plots (2007-2011) for NSEX01, Station 50, and Station 54.

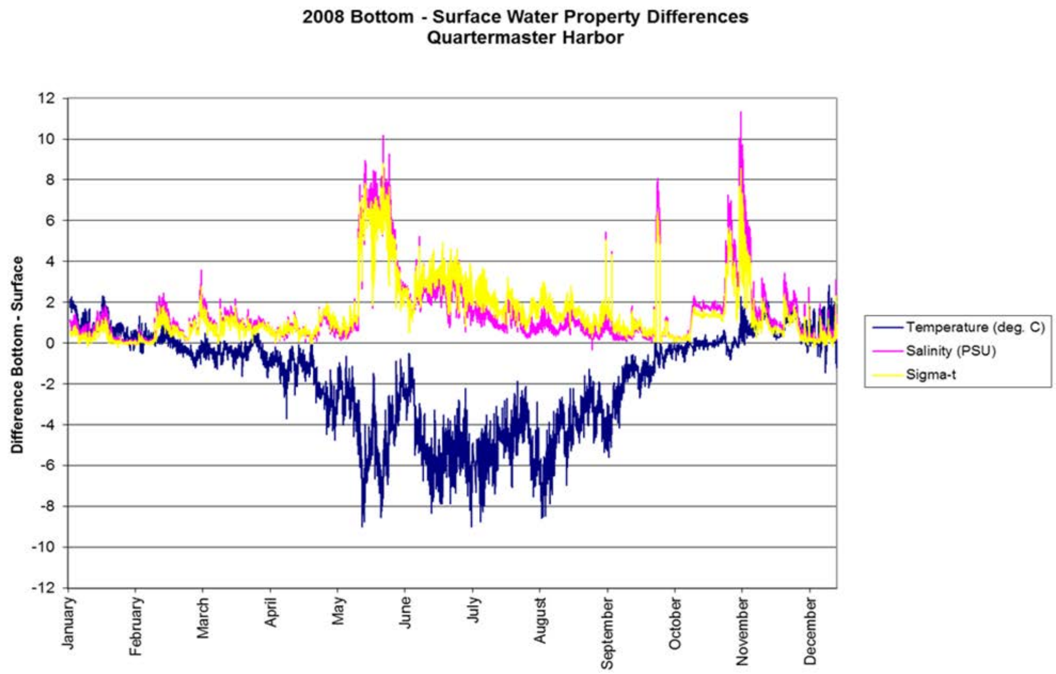


Figure 4-26. Difference between suface and bottom temperature, salinity, and density (sigma-t) in 2008 from the Station 54 (outer Quartermaster Harbor) mooring. Data were collected at 15-minute intervals.

4.2 Dissolved Oxygen

As mentioned previously, the input of fresh and oceanic water, circulation patterns, stratification, amount of mixing within the water column, biological activity (e.g., photosynthesis and respiration), and chemical oxidation all affect dissolved oxygen (DO) levels. Low DO levels can occur when organic matter decomposes in waters that do not mix with the surface layer where aeration with atmospheric oxygen can occur. In addition, upwelled oceanic waters with naturally occurring low DO enter inland Puget Sound waters, including Quartermaster Harbor, seasonally in the fall.

DO was measured monthly throughout the water column at six locations (stations 51 through 56) within Quartermaster Harbor and two sites outside the harbor for comparative purposes (stations 50 and NSEX01). DO was also measured at 15-minute intervals at four mooring locations (stations 54, MSWH01, NSAJ02, and NSGE01). For stations 50 through 56, contoured water column sections are provided in Appendix A.

Table 4-1 provides a summary of DO results obtained from monthly sampling from 2007 through 2011. Overall, results show that DO levels were lowest in bottom waters in late summer and fall between August and October and highest in the upper layer in spring between April and May (Figure 4-27). The highest values corresponded with high chlorophyll levels during the spring phytoplankton bloom which are associated with an increase in photosynthesis and oxygen production. High DO values during the summer

months also correspond with high chlorophyll levels and increased phytoplankton abundance.

A decrease in DO occurs annually throughout Puget Sound, including Quartermaster Harbor, in the late summer/fall due to the input of oceanic upwelled water with lower oxygen levels (Ebbsmeyer and Cannon 2001). However, these low DO levels are exacerbated in Quartermaster Harbor by the decomposition of large amounts of phytoplankton detritus using up oxygen, strong stratification, and low flushing rates limiting influxes of oxygenated waters. Deep water oxygen in Quartermaster Harbor decreases from May until late summer/early fall and then steadily increases again over the winter. Mooring data collected every 15-minutes indicated that DO values have dropped below 1.0 mg/L in the inner harbor and that values below 3.0 mg/L have frequently occurred in both the inner and outer harbors during the late summer/fall (Figures 4-28 and 4-30). The monthly variation throughout the year from factors described above is also shown in Figures 4-28 through 4-31. Bottom waters in the outer harbor at Station 54 showed a similar seasonal pattern to Dockton for the time period measured and DO values were also low during September 2009 (see Figure 4-30). Mooring data from the entrance to Quartermaster Harbor (station NSGE01) also showed a seasonal pattern similar to the other sites. However, the minimum values in bottom waters in late summer and fall were higher and always above 5.0 mg/L during the two-year monitoring period (Figure 4-31).

Figures 4-32 and 4-33 show the minimum and maximum values observed for each month during the five-year monitoring period for sites sampled monthly. Median values obtained by averaging stations and years are also shown.

Table 4-1. DO summary from 2007 through 2011 (monthly data)

	2007--2011			
	1m		above bottom	
Dissolved oxygen (mg/L)	MSWH01	NSAJ02	MSWH01	NSAJ02
minimum	4.10	5.90	2.10	3.60
maximum	17.80	16.00	16.10	12.20
mean	9.10	9.38	8.18	7.63
median	8.90	8.80	8.00	7.05

	2007--2011											
	1m						above bottom					
Dissolved Oxygen (mg/L)	51	52	53	54	55	56	51	52	53	54	55	56
minimum	5.26	4.68	5.44	5.58	5.75	5.39	4.60	4.55	4.47	4.83	4.70	3.34
maximum	15.39	14.29	15.50	15.65	16.31	14.83	9.59	10.06	9.82	9.34	11.15	13.30
mean	8.51	9.06	9.88	9.83	10.05	10.12	7.11	7.48	7.37	7.28	7.25	8.12
median	7.71	8.42	8.67	9.26	9.27	9.93	7.15	7.63	7.63	7.26	7.29	7.97

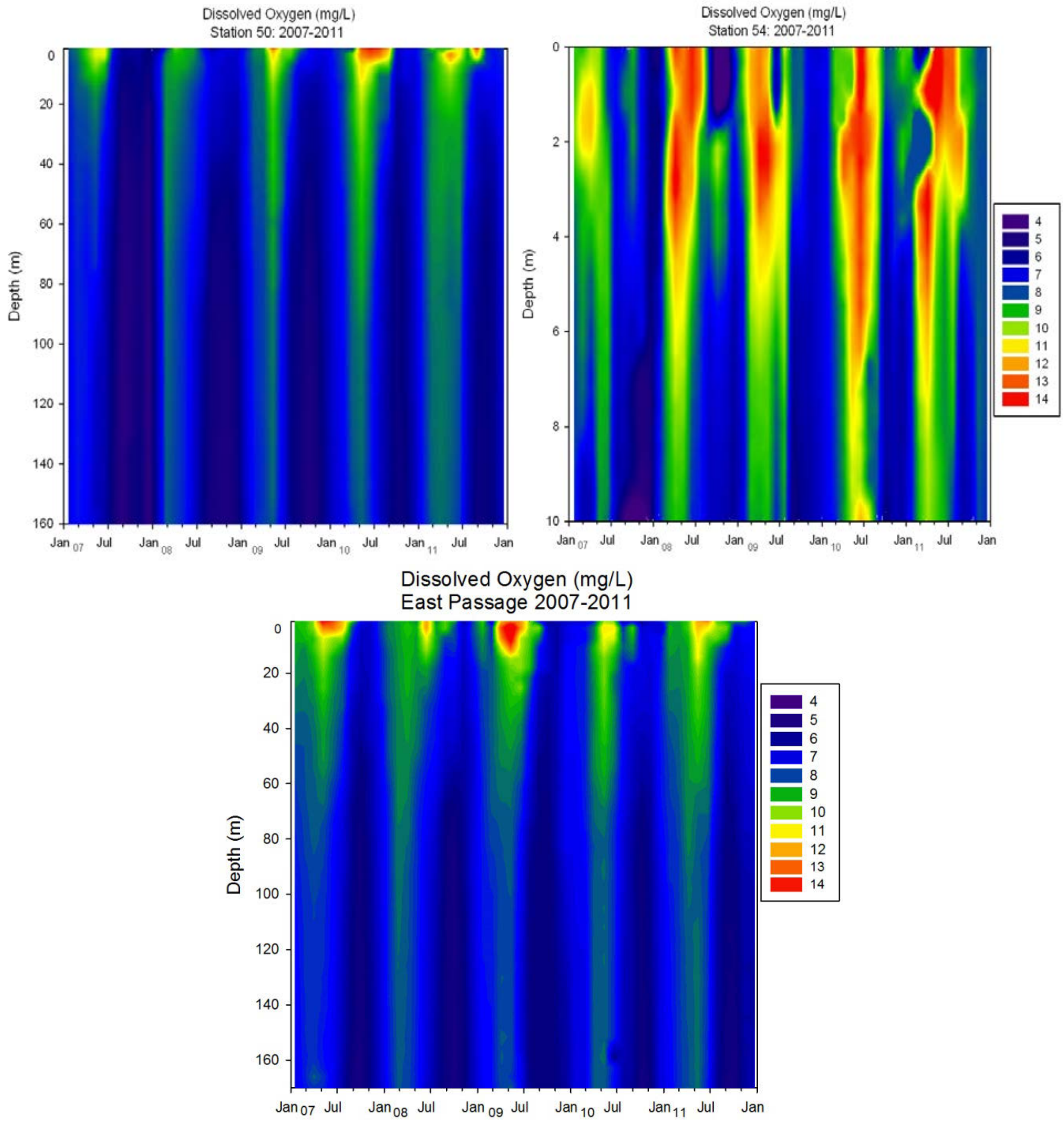


Figure 4-27. Monthly water column profile data at stations 50, 54, and East Passage (NSEX01). Note the shallow depth for station 54.

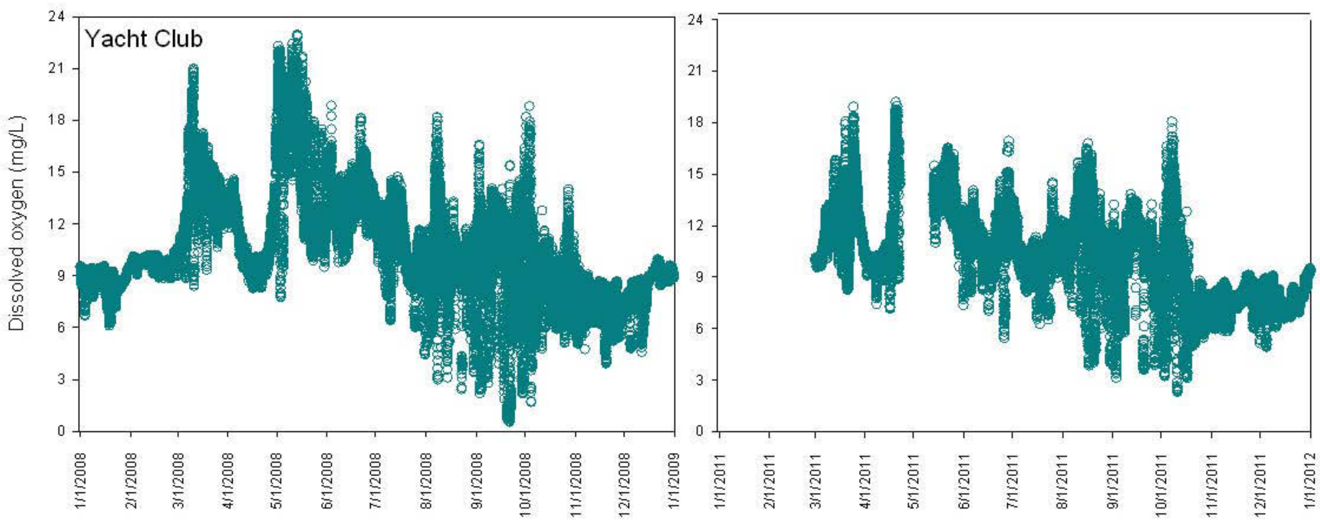


Figure 4-28. DO 15-minute interval data from the Yacht Club (MSWH01) in the inner harbor in 2008 and 2011

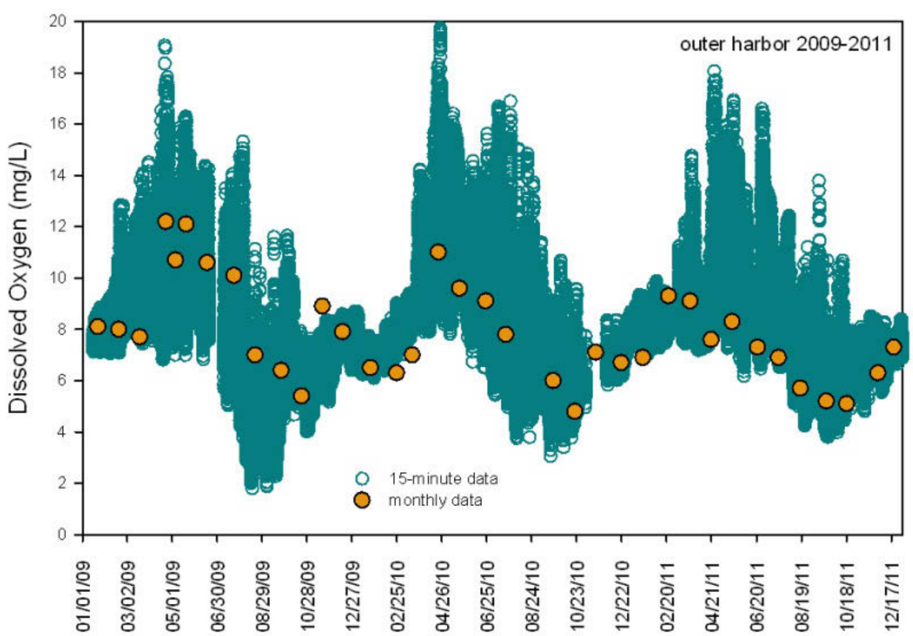


Figure 4-29. 15-minute interval DO data from Dockton (NSAJ02) in the outer harbor from 2009 through 2011

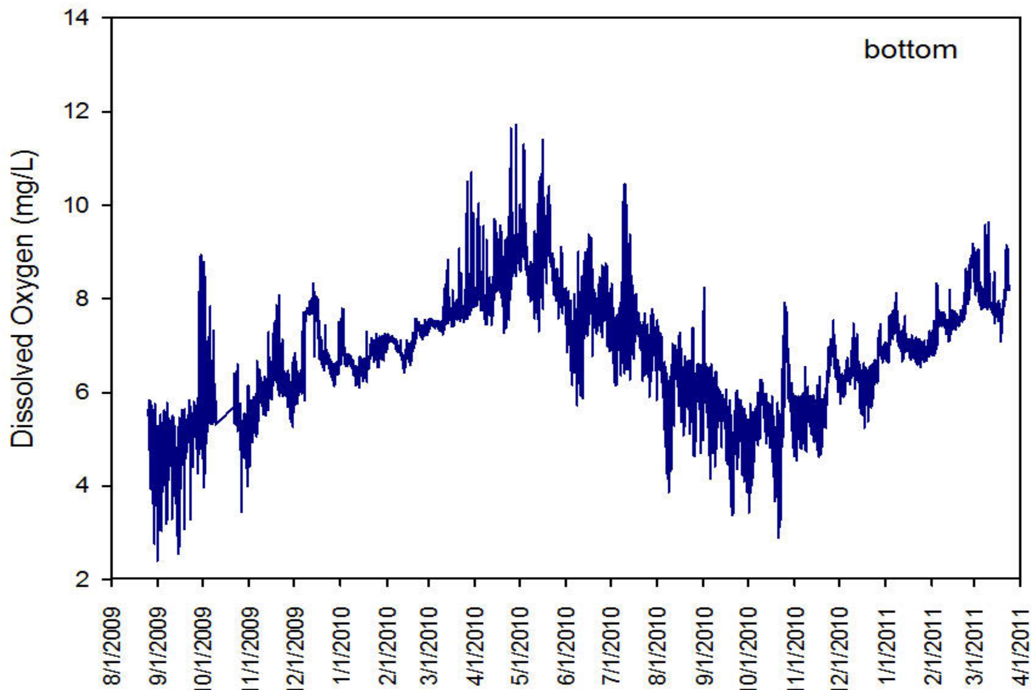


Figure 4-30. Outer Quartermaster Harbor (Station 54) 15-minute interval bottom water DO

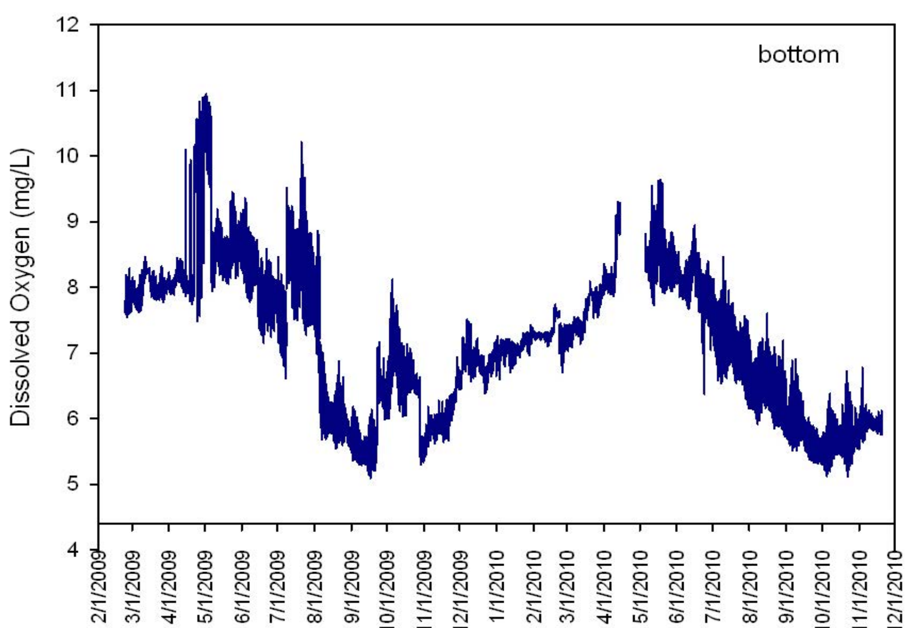


Figure 4-31. Quartermaster Harbor entrance station (NSGE01) 15-minute interval bottom water DO: 2009 and 2010

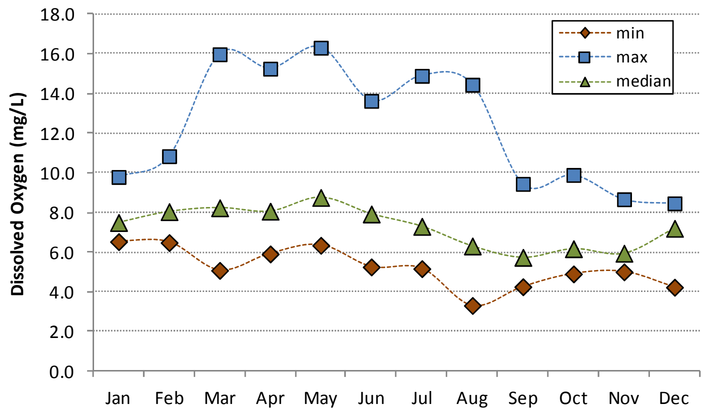


Figure 4-32. Monthly minimum, maximum, and medians from 2007 through 2011 for all UWT stations (50-56)

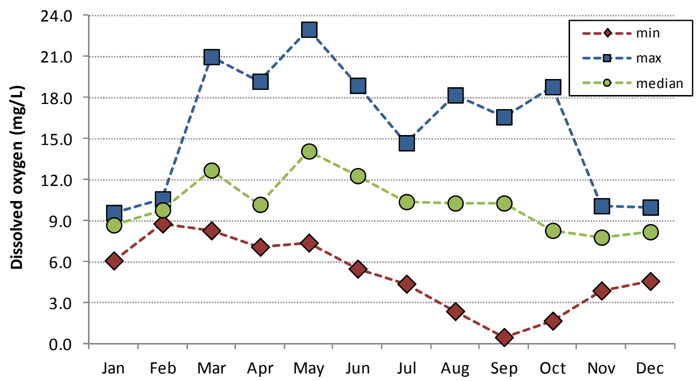


Figure 4-33. Monthly minimum, maximum, and medians from 2008 through 2011 for station MSWH01

In addition to seasonal differences, the mooring data showed some degree of diurnal variation. During phytoplankton blooms, DO concentrations increased during daylight hours due to primary production and photosynthesis and decreased at night from respiration and lack of photosynthesis. Diurnal variability in land/sea breezes during this time of year reinforce this pattern, with light southerly winds during the night resulting in less vertical mixing and slightly stronger northerly winds during the day with more mixing. Tidal phases affected DO concentrations, particularly low tides in the fall months. DO decreased to low levels during the lower of the two daily low tides and increased during a flood tidal cycle. Figure 4-34 shows this tidal cycle effect at the inner Quartermaster Harbor station over a week-long period in September. The tidal effect was more pronounced at the inner Quartermaster Harbor site due to the shallowness of this area during low tides, particularly tides that are 0 ft mean lower low water (MLLW) or lower. The DO sensor at this site always remained about 1-m below the surface, however, the water depth decreased as the tide receded and during the very low tides, the sensor was not far off the seafloor. The amount of oxygen in the water above the seafloor was low during the fall months, September in particular, likely due to increased sediment oxygen demand from organic matter decay as well as water column stratification which prevents mixing.

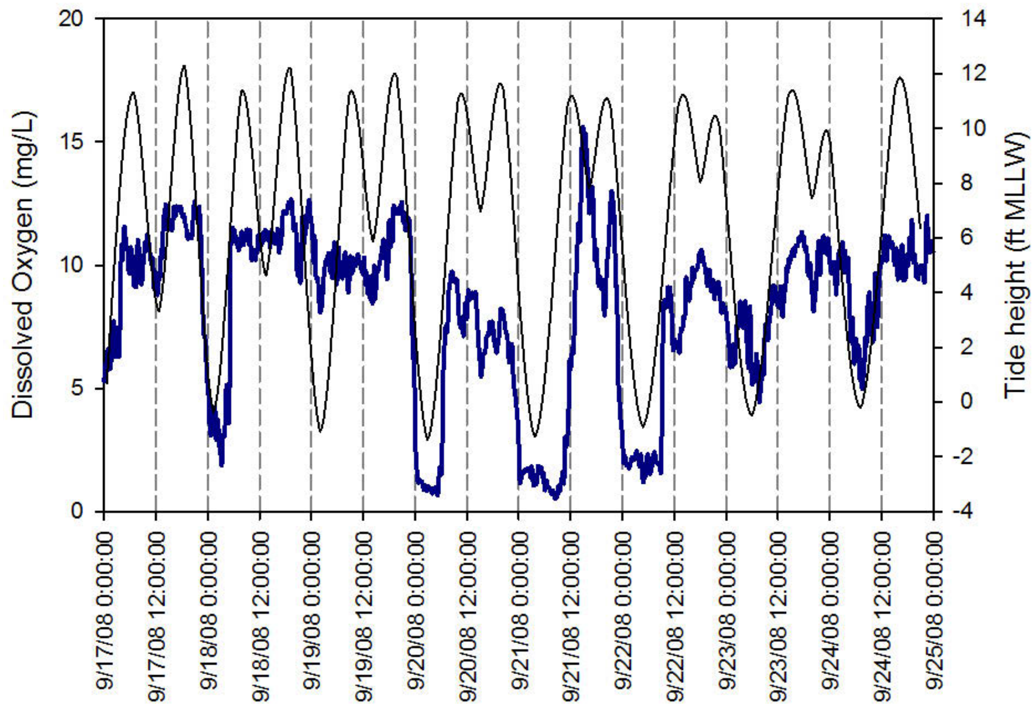


Figure 4-34. Tidal phase effect on DO in inner Quartermaster Harbor (MSWH01) during a 1-week period (blue line= DO; black line=tidal height)

From 2007 through 2011, both the lowest and highest DO values were observed in the inner harbor (see Figures 4-27 and 4-28). During large phytoplankton blooms, DO concentrations often reached over 200% saturation (18.0 mg/L) in the inner harbor and values of 250% saturation (22.0 mg/L) were recorded during spring blooms. Figure 4-35 shows monthly minimum and maximum values for stations 50 through 56. For comparative purposes, the inner harbor stations (55 and 56) were combined as were the outer harbor sites (51 through 54). In addition to low values in the inner harbor, concentrations of less than 6.0 mg/L were seen in bottom waters in the outer harbor near the entrance during the fall months when upwelled oceanic water was evident in the Sound (see salinity profile plots in Appendix A).

Of the five years sampled, the overall lowest DO concentrations were seen between 2007 and 2009, with 2008 having both the lowest and highest values observed of all the years sampled.

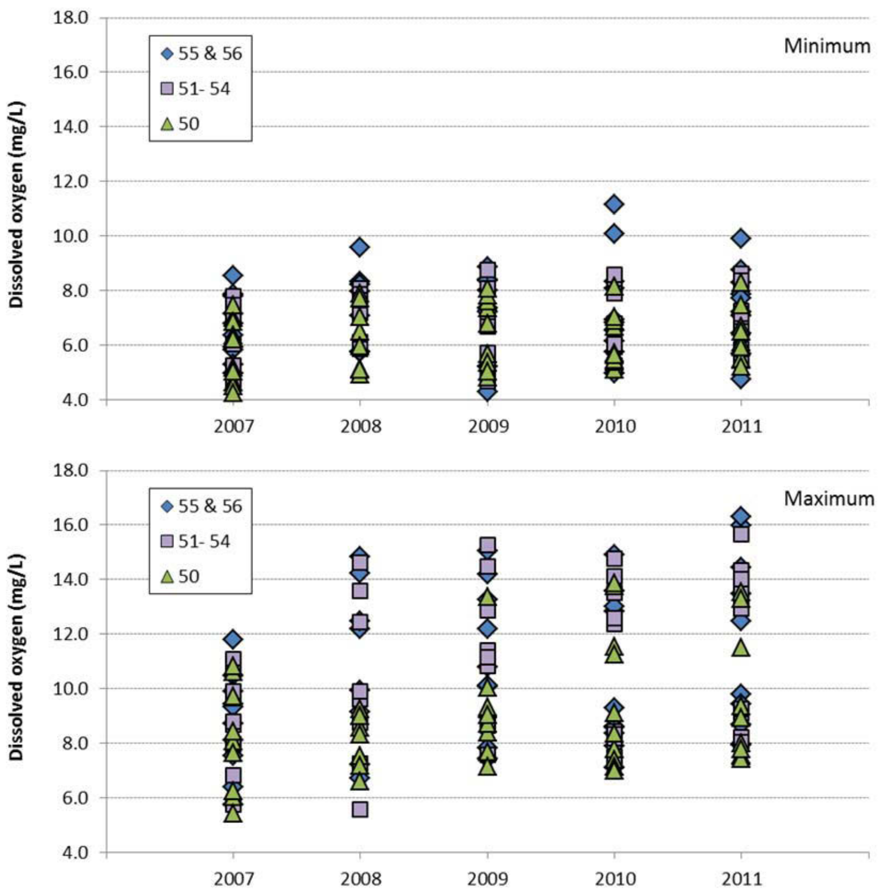


Figure 4-35. Minimum and maximum values for monthly profile stations, all depths combined

4.3 Chlorophyll and Pheophytin

Chlorophyll-*a* is a green pigment produced by algae and other green plants that is used during photosynthesis to convert light, carbon dioxide, and water to sugar and oxygen. Chlorophyll-*a* levels are an indicator of phytoplankton biomass but are not an exact measurement of phytoplankton abundance as the ratio of biomass to chlorophyll varies with species and environmental conditions. Pheopigments, such as pheophytin-*a*, are degradation products of chlorophyll and are primarily produced in the water column when phytoplankton cells are grazed upon by herbivorous zooplankton. High concentrations of pheopigments relative to chlorophyll-*a* indicate a large amount of grazing. This section provides results from 2007 through 2011 for chlorophyll-*a* and pheopigment levels determined by fluorescence (both laboratory and in situ). For stations 50 through 56, phytoplankton species and abundance data are provided in Section 9.0 and all fluorescence water column contour sections are provided in Appendix A.

In general, the annual spring phytoplankton bloom in Quartermaster Harbor began in March and chlorophyll-*a* levels remained elevated throughout the spring and early summer until they decreased in June and July. A fall bloom typically occurred in August and chlorophyll levels remained elevated through October, particularly in the inner harbor.

Table 4-2 provides chlorophyll-*a* summary statistics and Figures 4-36 and 4-37 show monthly means for two sites; one located in the inner harbor (Yacht Club: MSWH01) and one in the outer harbor (Dockton: NSAJ02). Figure 4-38 shows monthly results at those two stations. Figure 4-39 shows monthly water column profile results from 2007 through 2011 at station 54 in the outer harbor and at East Passage (NSEX01) for comparison. The blooms at station 54 were more frequent, longer in duration, and more intense than in East Passage, which was also the pattern seen in inner Quartermaster Harbor. The chlorophyll-*a* maximum typically occurred just below the pycnocline in both the inner and outer harbors between 4-6 m (also see fluorescence water column sections in Appendix A) and between 4-10 m in East passage.

Overall throughout the year, chlorophyll-*a* levels were highest in the inner harbor and decreased in the direction of the outer harbor. This pattern was particularly pronounced during the spring bloom, which was seen in the inner harbor earlier than the outer harbor. The spring bloom chlorophyll-*a* values (March and April) were typically the highest observed during the year followed by levels in August. Of the five years monitored, chlorophyll-*a* values were lowest in 2007 and 2010. In 2009, the spring bloom occurred in February (values over 15 ug/L) at multiple locations throughout the harbor. The northern Central Basin (near Pt. Wells and Pt. Jefferson) was the only other area observed with elevated chlorophyll levels in February 2009.

Table 4-2. Data summary for two sites.

	1m: 2007-2011		above bottom: 2007-2011	
	MSWH01	**NSAJ02**	**MSWH01**	**NSAJ02**
Chlorophyll-a (µg/L)				
minimum	0.59	0.47	0.34	0.25
maximum	32.80	79.50	56.60	94.40
mean	7.18	9.34	9.90	10.01
median	4.81	5.41	4.80	4.71

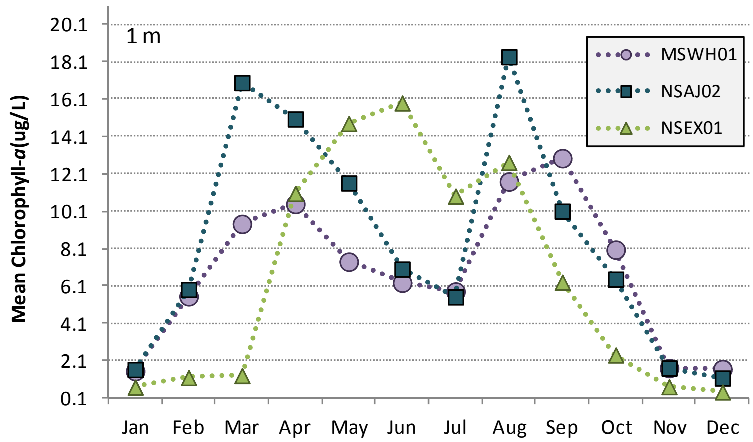


Figure 4-36. Monthly chlorophyll-*a* means from 2007 through 2011 for surface samples at two Quartermaster Harbor sites. East Passage (NSEX01) is shown for comparison.

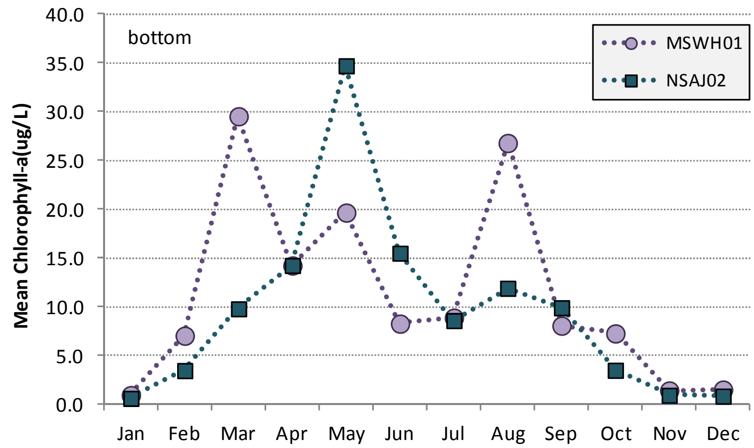


Figure 4-37. Monthly chlorophyll-*a* means from 2007 through 2011 for bottom samples at two Quartermaster Harbor sites.

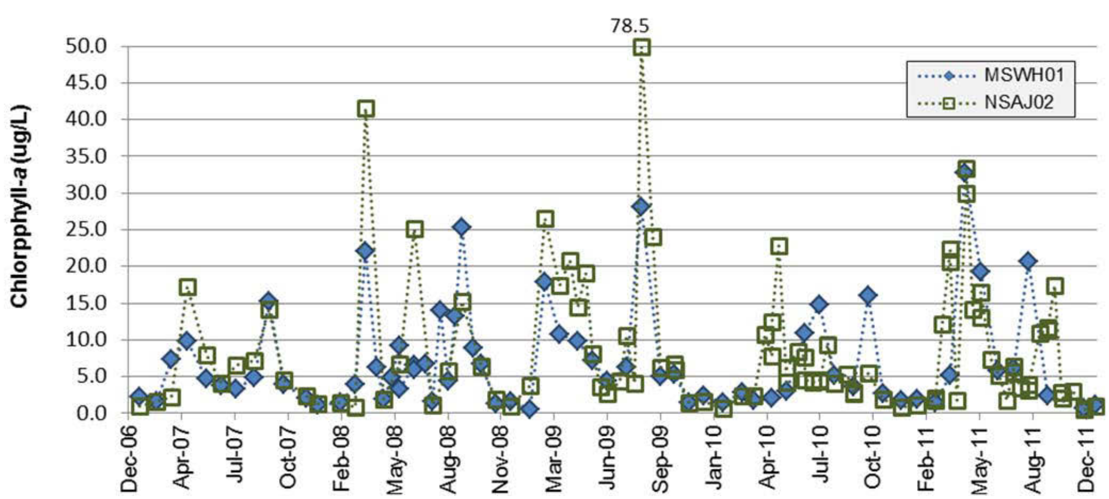


Figure 4-38. Monthly chlorophyll-*a* data from 2007 through 2011 for surface samples at two Quartermaster Harbor sites

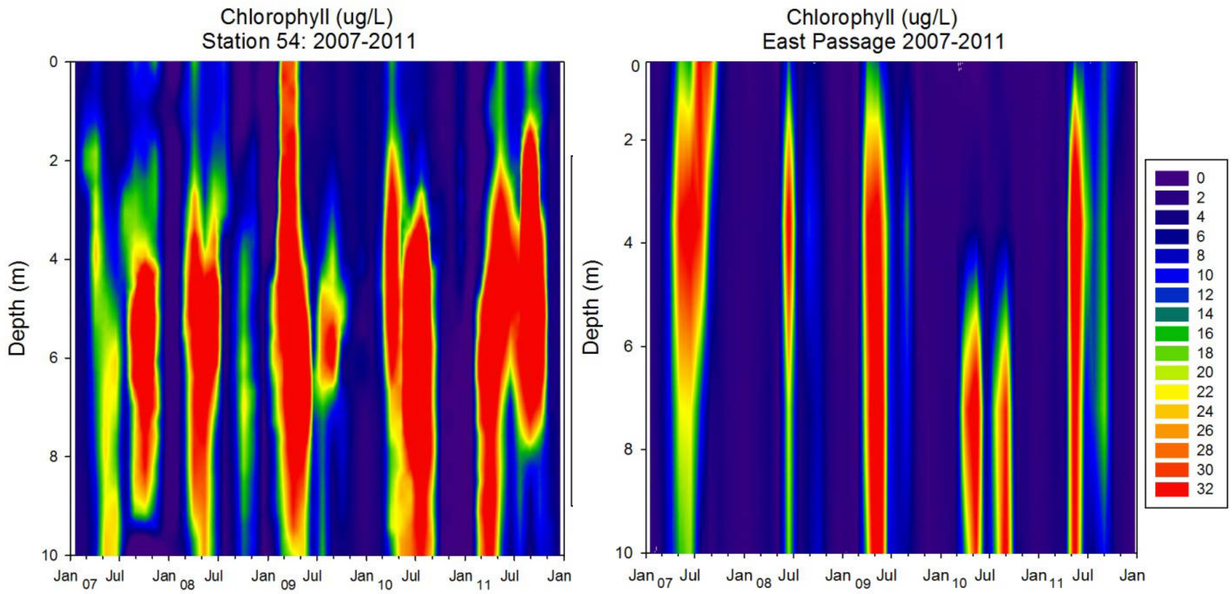


Figure 4-39. Monthly water column chlorophyll profile data at stations 54 and NSEX01 (only top 10 m shown) from 2007 through 2011

Figures 4-40 through 4-41 show chlorophyll patterns determined by high temporal resolution (15-minute intervals) fluorescence mooring data. Figure 4-40 shows the spring blooms in 2008 and 2011 at the inner harbor station and a decrease in chlorophyll levels in November for both years. Variability and short term chlorophyll increases, lasting a week or less, are also shown. Figure 4-41 shows the initiation of the spring bloom in 2011 at Dockton and chlorophyll levels throughout the year. Figure 4-42 shows an increase in spring chlorophyll levels on a finer temporal scale at the outer entrance to Quartermaster Harbor mooring, over a 30 day period in 2009, and daily fluctuations.

Transmissivity and Secchi disk data corroborate the chlorophyll patterns seen in the upper water column. Low transmissivity or shallow Secchi depths are indicative of more material in the water, which means more light attenuation in surface waters. Low transmissivity and shallow Secchi depths are often associated with phytoplankton blooms or more suspended sediments in the water column brought in by run-off or re-suspended from storms or other forms of turbulence (Figure 4-43 & transmissivity sections in Appendix A). The shallowest Secchi depths occurred between April and August during bloom season, with greater water clarity September through March. February Secchi depths were also somewhat shallower, which may be due to additional suspended sediments associated with winter storms and run-off. Both transmissivity and Secchi depths tended to decrease heading into the harbor from station 51 to 56, which is consistent with relative phytoplankton abundances (see phytoplankton section). However, station 50 in Commencement Bay often had shallower Secchi depths associated with an observed muddy Puyallup River plume. Transmissivity sections in Appendix A also show periodic evidence of a Puyallup River plume in Commencement Bay at the surface.

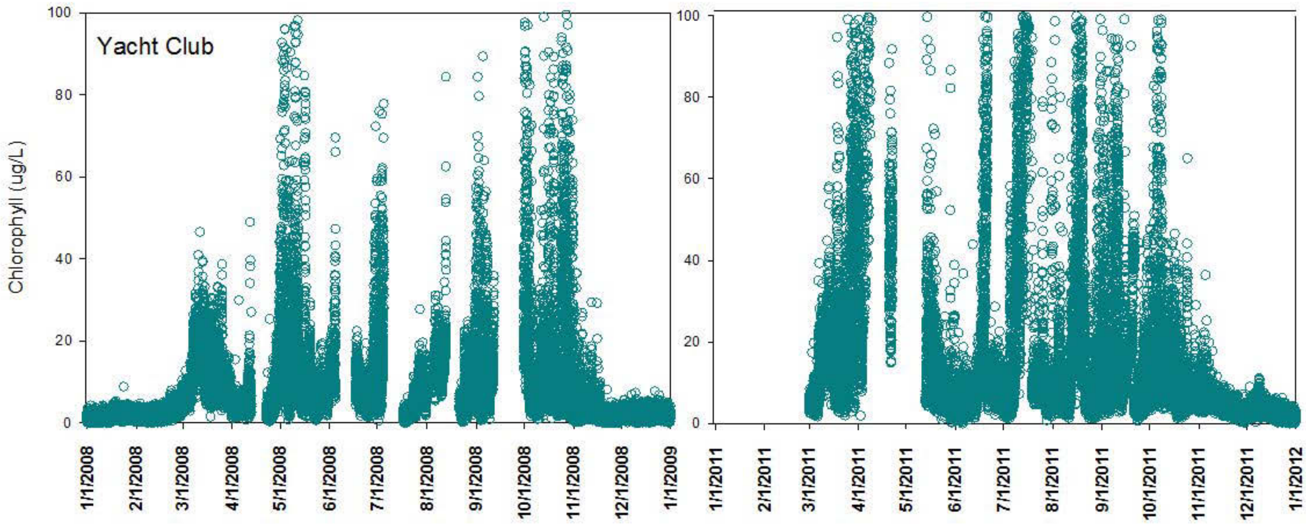


Figure 4-40. Inner harbor (MSWH01) chlorophyll mooring data from 2008 and 2011

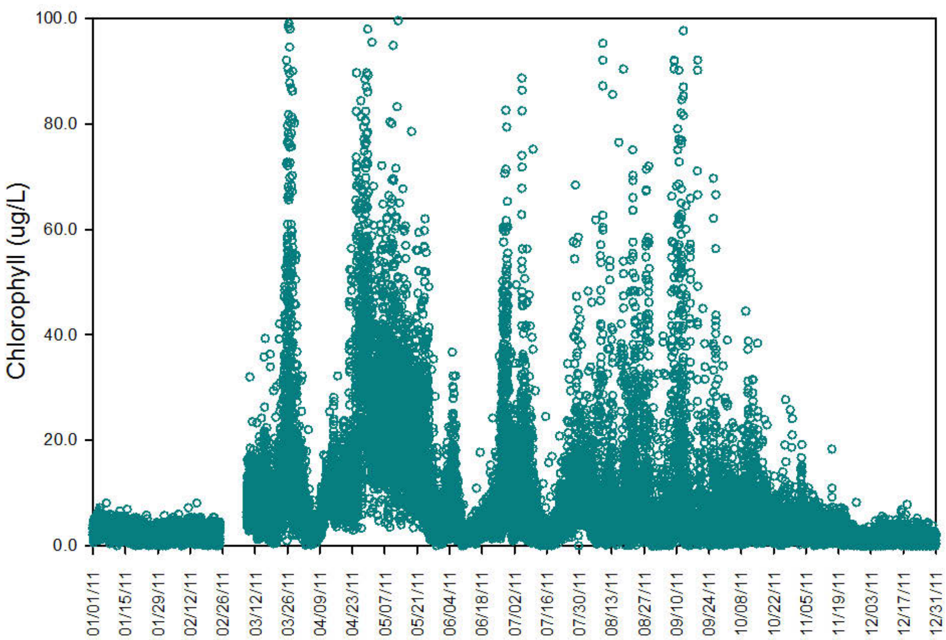


Figure 4-41. Chlorophyll mooring data from the outer harbor at Dockton (NSAJ02) in 2011

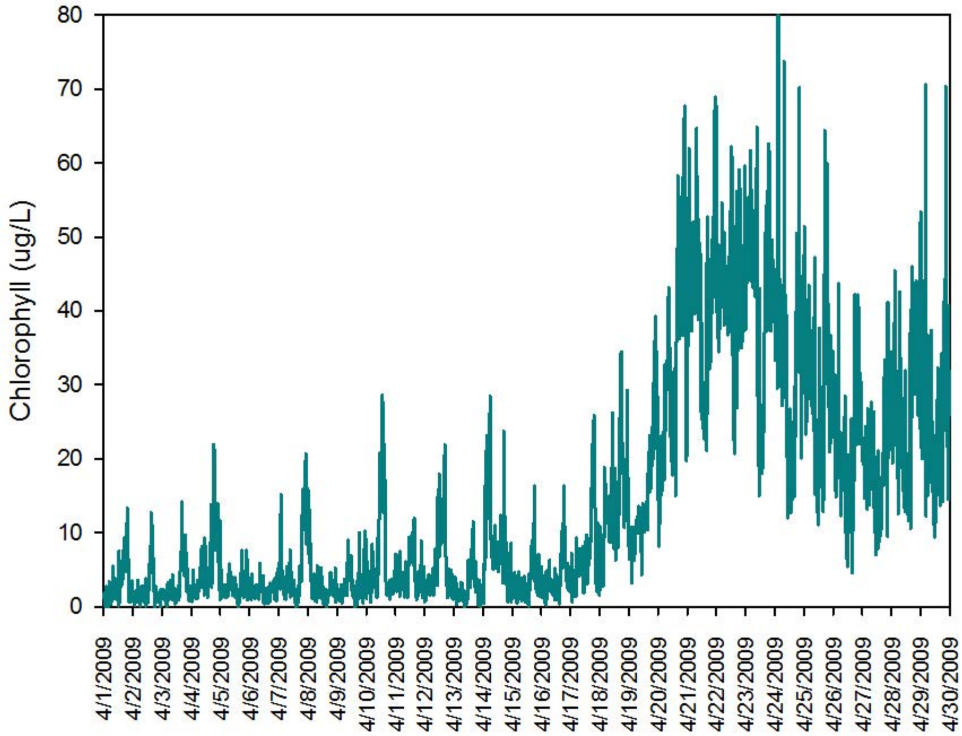


Figure 4-42. Outer Quartermaster Harbor entrance (NSGE01) chlorophyll mooring data over a 30-day period in April 2009

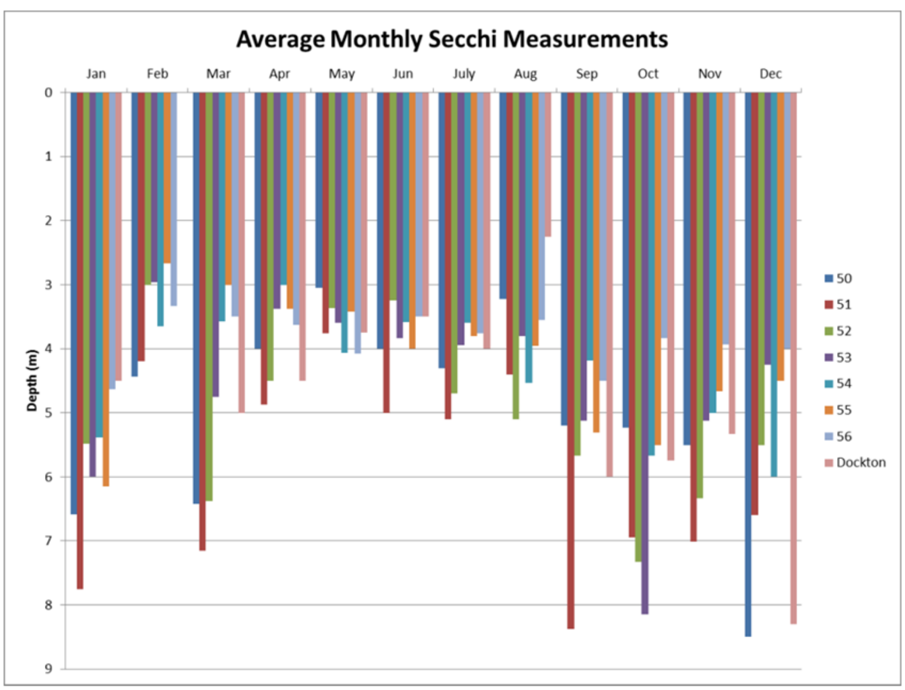


Figure 4-43. Secchi depth data averaged by month between 2007 through 2011 for UWT stations.

Figure 4-44 shows pheophytin levels relative to chlorophyll-*a* levels. Overall, increases in chlorophyll-*a* corresponded to increases in pheophytin levels, however, higher pheophytin levels relative to chlorophyll-*a* values were noted at various times and indicate a large amount of grazing. The higher pheophytin to chlorophyll-*a* values were often seen in November for all years monitored. Pheophytin levels throughout much of 2010 were higher than in other years sampled.

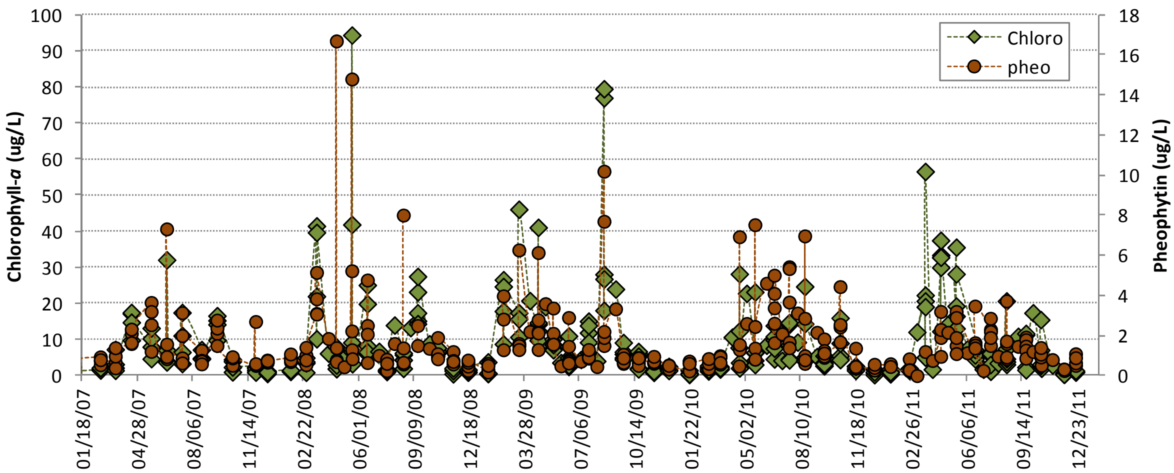


Figure 4-44. Pheophytin and chlorophyll levels at Dockton and the Yacht Club (MSWH01 and NSAJ02).

4.4 Nutrients

The addition of nutrients can have a considerable effect on water quality, particularly in the nearshore environment where nutrient input typically occurs. Nutrients, such as nitrogen and phosphorus compounds, may enter marine waters from wastewater discharges, nonpoint source runoff, and riverine and oceanic sources. The greatest impact these nutrients may have, nitrogen in particular (as it is the primary limiting nutrient in marine waters), is a sudden increase in aquatic plant growth when other conditions are favorable, such as light and temperature. Eutrophication occurs when a waterbody receives a high concentration of nutrients, especially nitrogen and phosphorus compounds that cause excess algal growth. The water column can be depleted of oxygen during the decay process as the algae die and decompose. This process can lead to the death of many marine organisms if oxygen levels are depleted to a level too low to sustain life. Figure 4-45 shows a conceptual diagram for nutrient cycling.

Nitrate, nitrite, ammonia, orthophosphorus, and silica were measured monthly at two depths (1 m and near-bottom) at six locations (Stations 51 through 56) within Quartermaster Harbor and at Station 50 located outside the harbor for comparative

purposes. Nitrate+nitrite, ammonia, orthophosphorus, and silica, were also measured monthly at two depths at MSWH01 and NSAJ02, as well as bi-weekly from April through October. These same nutrients were measured monthly at a single depth at the intertidal site MSXK01 (with the exception silica was not measured) and at seven depths for NSEX01, located in East Passage. In situ nitrate was also measured at 15-minute intervals at one location (NSGE01) at a 1 m depth in 2009 and 2010, although the sensor was not functioning properly for much of the time. Time series plots for all nutrients are provided in Appendix C.

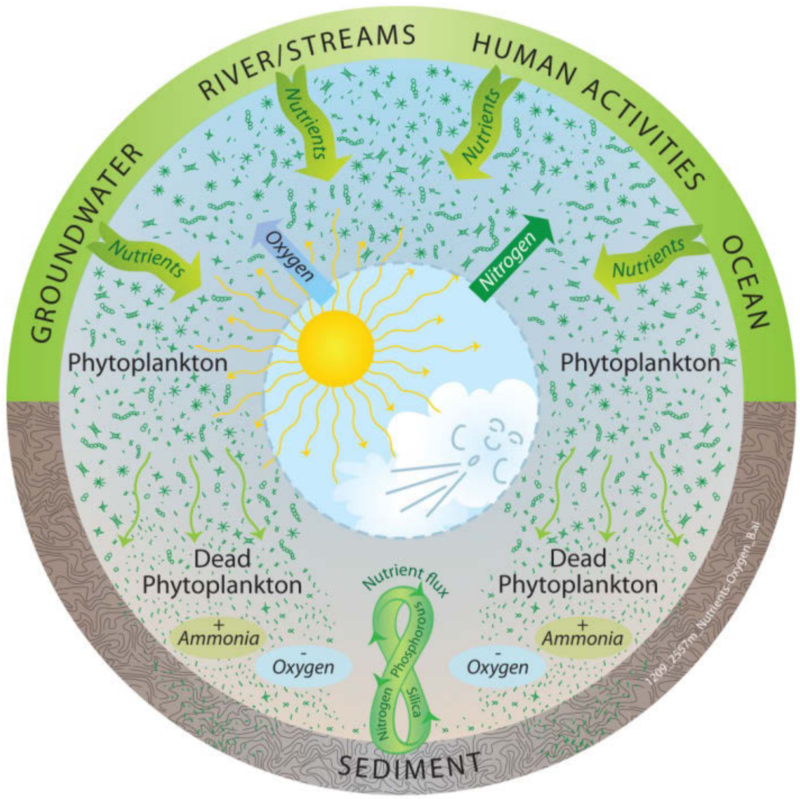


Figure 4-45. Nutrient cycling conceptual diagram

4.4.1 Nitrate and nitrite

Overall, results show that nitrate+nitrite (nitrate) levels were lowest between May and July when phytoplankton abundance was high. The lowest values corresponded with high chlorophyll levels during the spring phytoplankton bloom. The highest values occurred in the late fall/winter months from November through February when nutrient uptake by phytoplankton was at a minimum and freshwater and ocean input was high.

Figure 4-46 shows monthly nitrate values from 2007 through 2011 for all sites, including the two sites outside of Quartermaster Harbor (Station 50 in Commencement Bay and NSEX01 in East Passage) for comparative purposes. The prolonged reduction in nitrate concentrations from spring through summer, particularly in the inner harbor, is evident. Also shown are the anomalously high values seen only at stations 54 and 56 in August of 2009. Figure 4-47 shows nitrate values collected at 15-minute intervals in the outer harbor (Station NSGE01) at the entrance near station 51. The same seasonal pattern is noted at this site in terms of higher winter concentrations and reduced levels from spring through summer. Short duration high nitrate events are also seen in Figure 4-47. Figure 4-48 shows the same dataset, along with tidal stage and height, but on a finer temporal scale from May 15 to June 2, 2010. Daily fluctuations frequently correlated with tidal stage; nitrate concentrations increased on a flood tide and decreased on an ebb tide.

Figure 4-49 shows both the surface and bottom monthly means (2007-2011) for each station and Figure 4-50 shows the monthly means for this same time period for the two inner harbor (56 and MSWH01) and outer harbor (stations 51 through 54) sites grouped together. The lower values in the inner harbor starting in March and April compared to the outer harbor are shown in Figure 4-50, as well as the lower values in surface waters during the phytoplankton growing season.

Figure 4-51 shows surface water monthly nitrate means for the two inner (Station 56 and MSWH01) and five outer harbor (Stations 51-54) sites by year. Interannual variation is less pronounced in the months without phytoplankton uptake (November through February) but shows considerable variation during the spring bloom months. This is particularly apparent for the inner harbor.

Table 4-3 gives an overall summary for all the sites from 2007 through 2011 for both surface and bottom waters. Median values in both surface and bottom waters at the inner harbor sites are lower than the outer harbor sites.

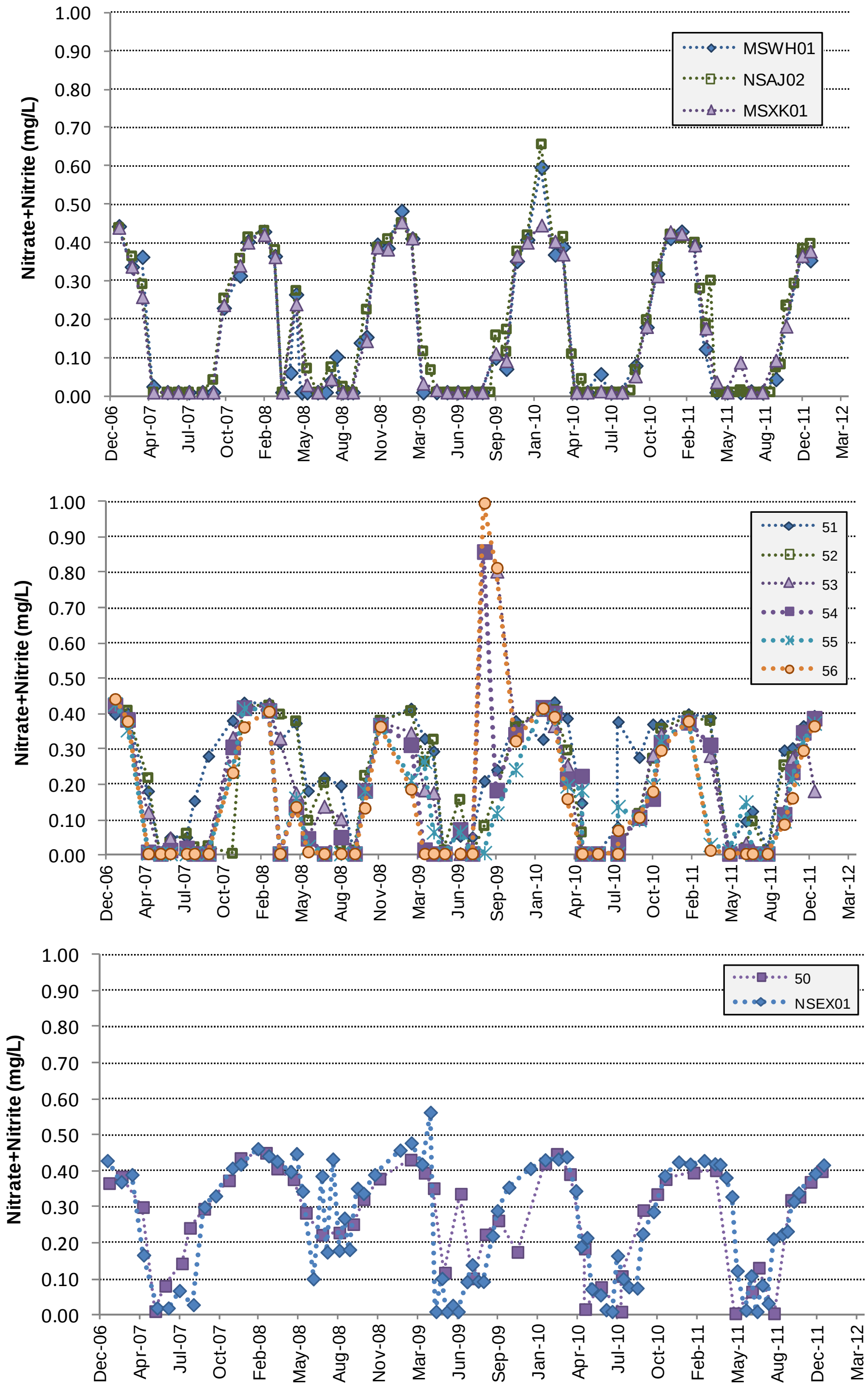


Figure 4-46. Monthly nitrate+nitrite surface (1 m) values for all Quartermaster Harbor sampling sites.

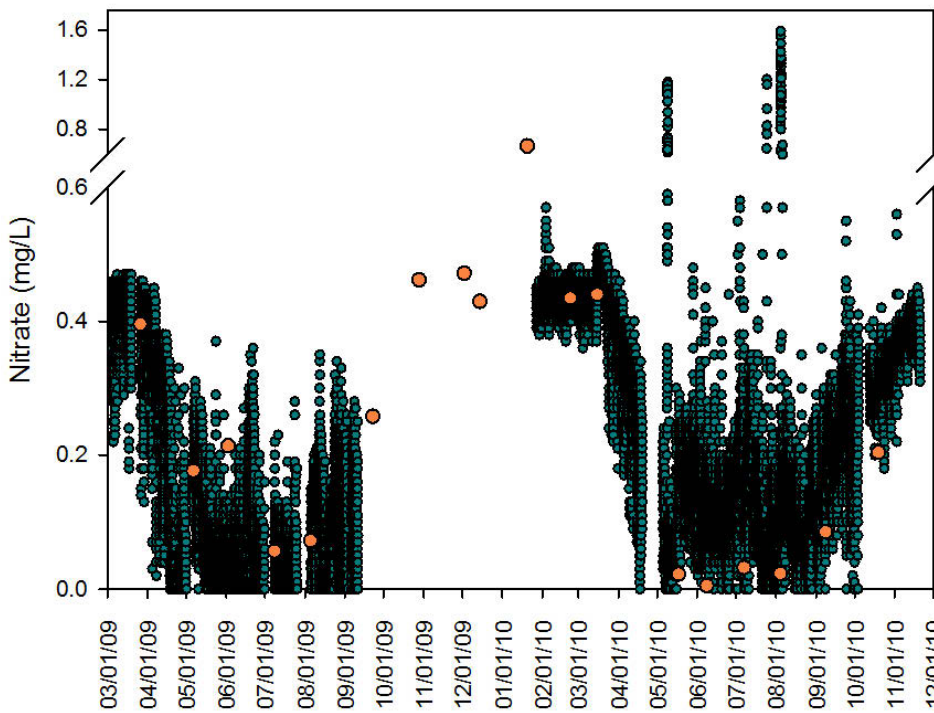


Figure 4-47. Nitrate in surface water (1m) measured at 15-minute intervals at station NSGE01 in 2009 and 2010 (blue circles). Orange circles indicate samples taken to confirm sensor values. Although nitrite is negligible, verification results include both and nitrate+nitrite.

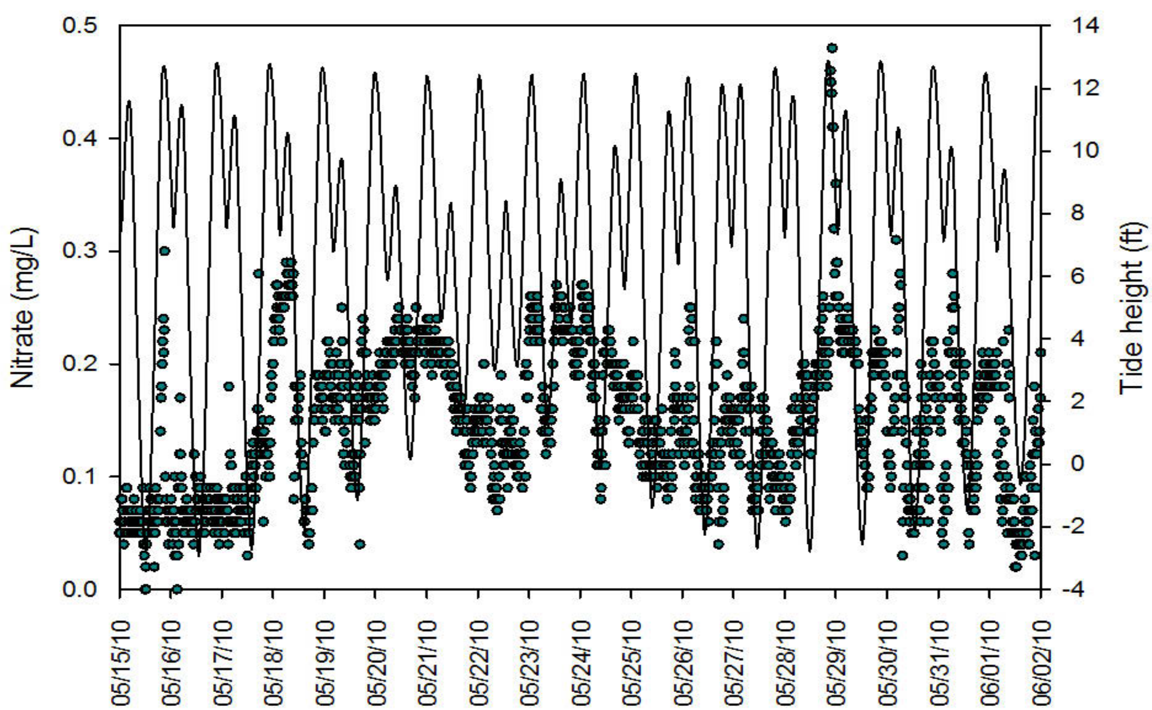


Figure 4-48. Nitrate in surface water (1m) measured at 15-minute intervals at station NSGE01 in May 2010 (blue circles). Lines indicate tidal stage and height.

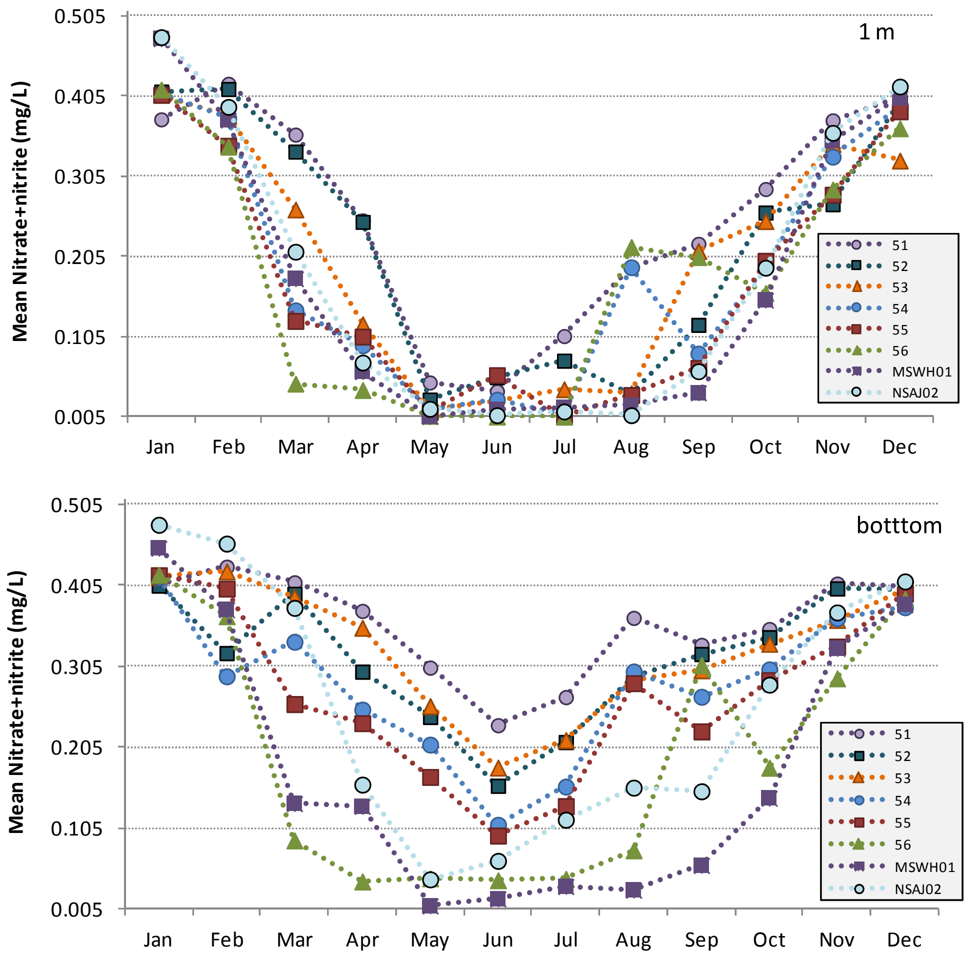
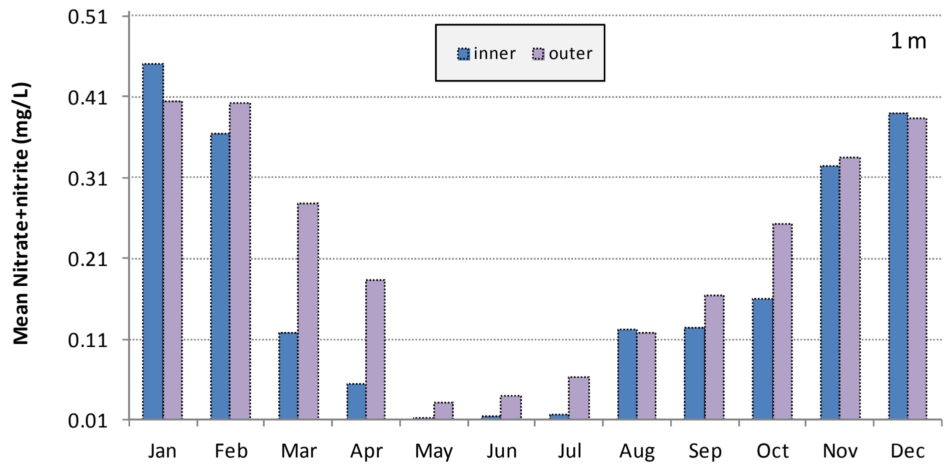


Figure 4-49. Monthly nitrate+nitrite means from 2007 through 2011 for both surface and bottom values at each site.



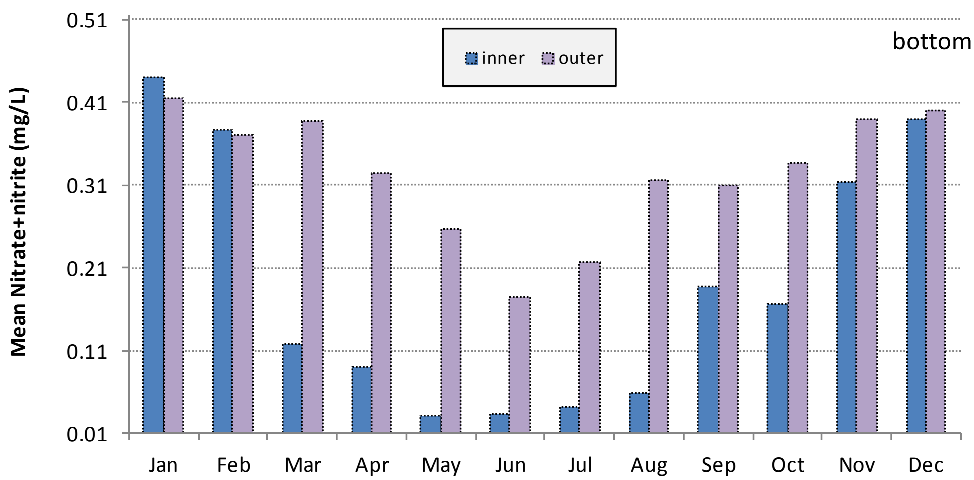


Figure 4-50. Monthly nitrate+nitrite means for both surface and bottom values for inner (56 and MSWH01) and outer (51-54) harbor stations.

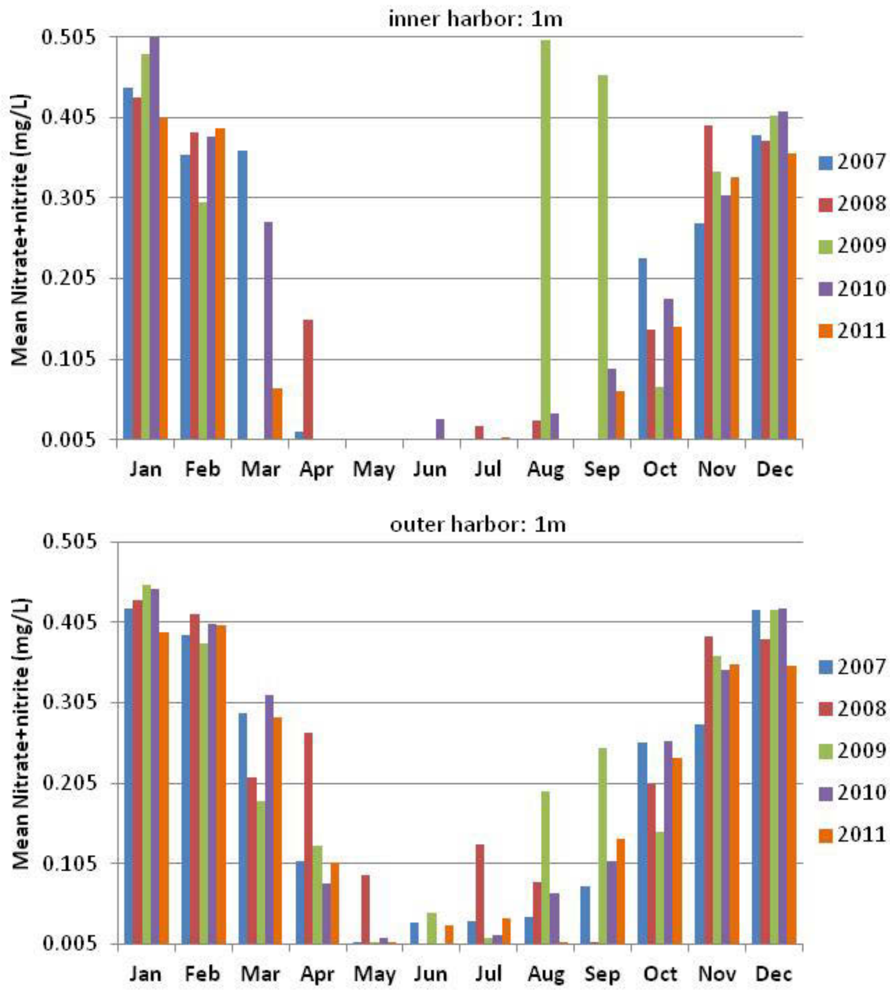


Figure 4-51. Surface water monthly nitrate+nitrite means for the two inner (Station 56 and MSWH01) and five outer harbor (Stations 51-54) sites by year (note that the number of samples varied from year to year).

Table 4-3. Nitrate+nitrite summary from 2007 through 2011. Mean and median values were calculated using the full MDL for values less than the minimum value shown.

	1m: 2007-2011								
Nitrate+nitrite (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**	**MSXK01**
minimum	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.010	<0.010	<0.010
maximum	0.434	0.424	1.408	0.859	0.428	0.997	0.597	0.657	0.454
mean	0.242	0.203	0.211	0.173	0.147	0.160	0.154	0.137	0.171
median	0.281	0.212	0.176	0.112	0.101	0.014	0.043	0.016	0.092

	bottom: 2007-2011							
Nitrate+nitrite (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**
minimum	0.202	0.052	0.155	<0.005	<0.005	<0.005	<0.010	<0.010
maximum	0.599	0.494	0.432	0.527	0.646	1.075	0.539	0.677
mean	0.351	0.313	0.317	0.272	0.258	0.176	0.176	0.256
median	0.348	0.338	0.327	0.295	0.257	0.130	0.109	0.283

4.4.2 Ammonia Nitrogen

Results from 2007 through 2011 showed that ammonia nitrogen (ammonia) values ranged from less than 0.005 (the MDL) to 0.569 mg/L and were lowest between February and April and the highest values most often occurred in September and October following large phytoplankton blooms. Table 4-4 gives an overall summary for all sites from 2007 through 2011 for both surface and bottom waters. Figure 4-52 shows monthly surface values from 2007 through 2011 for all sites, including the two sites outside of Quartermaster Harbor for comparative purposes. The figure shows ammonia values were higher in Quartermaster Harbor than in waters outside the harbor and values in the inner harbor were typically higher than the outer harbor.

Figure 4-53 shows monthly bottom values from 2007 through 2011 for all the Quartermaster Harbor sites. Bottom values are distinctly higher than surface values, particularly in the inner harbor. Ammonia levels in bottom waters show a higher association with seasonal phytoplankton patterns than surface values due to ammonia production from bacterial decay of phytoplankton . Overall for the five years sampled, ammonia levels were often below 0.005 mg/L in surface waters between April and September during the phytoplankton growing season. In contrast, ammonia concentrations were rarely below 0.005 mg/L in October (one sample) or January (two samples) (Figure 4-54). The opposite pattern was seen in bottom waters, with more samples below 0.005 mg/L in the winter months and the fewest samples during the phytoplankton growing season.

Figure 4-55 shows both the surface and bottom ammonia monthly means (2007-2011) for each station and Figure 4-57 shows the monthly means for this same time period for the

two inner harbor (56 and MSWH01) and outer harbor (stations 51 through 54 and NSAJ02) sites grouped together. Both figures show an increase in ammonia concentrations in surface waters in October and November, particularly in the inner harbor. As stated above, ammonia values are higher in bottom waters in both the inner and outer harbors in the late spring to summer months and Figure 4-56 shows the higher mean values in the inner harbor from October to December.

Figure 4-57 shows surface water monthly ammonia means for the two inner (56 and MSWH01) and five outer harbor (stations 51 to 54) sites by year. As ammonia values are higher in the inner harbor, more interannual variation is evident compared to the outer harbor. The interannual variation in the inner harbor is most noticeable from April through September and in June and July in the outer harbor. Ammonia values in the outer harbor in 2007 and 2009 were higher from May to October than other years while 2011 had some of the lowest values throughout the year.

Table 4-4. Ammonia summary from 2007 through 2011. Mean and median values were calculated using the full MDL value for results reported as less than the MDL; therefore, these values have a high bias.

	1m: 2007-2011								
Ammonia (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**	**MSXK01**
minimum	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
maximum	0.212	0.078	0.089	0.174	0.569	0.118	0.280	0.084	0.127
mean	0.013	0.015	0.014	0.026	0.042	0.025	0.042	0.019	0.036
median	0.007	0.008	0.006	0.011	0.014	0.011	0.024	0.011	0.027

	bottom: 2007-2011							
Ammonia (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**
minimum	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
maximum	0.208	0.101	0.262	0.212	0.167	0.202	0.316	0.172
mean	0.022	0.019	0.031	0.039	0.054	0.039	0.066	0.044
median	0.005	0.008	0.012	0.022	0.049	0.019	0.040	0.028

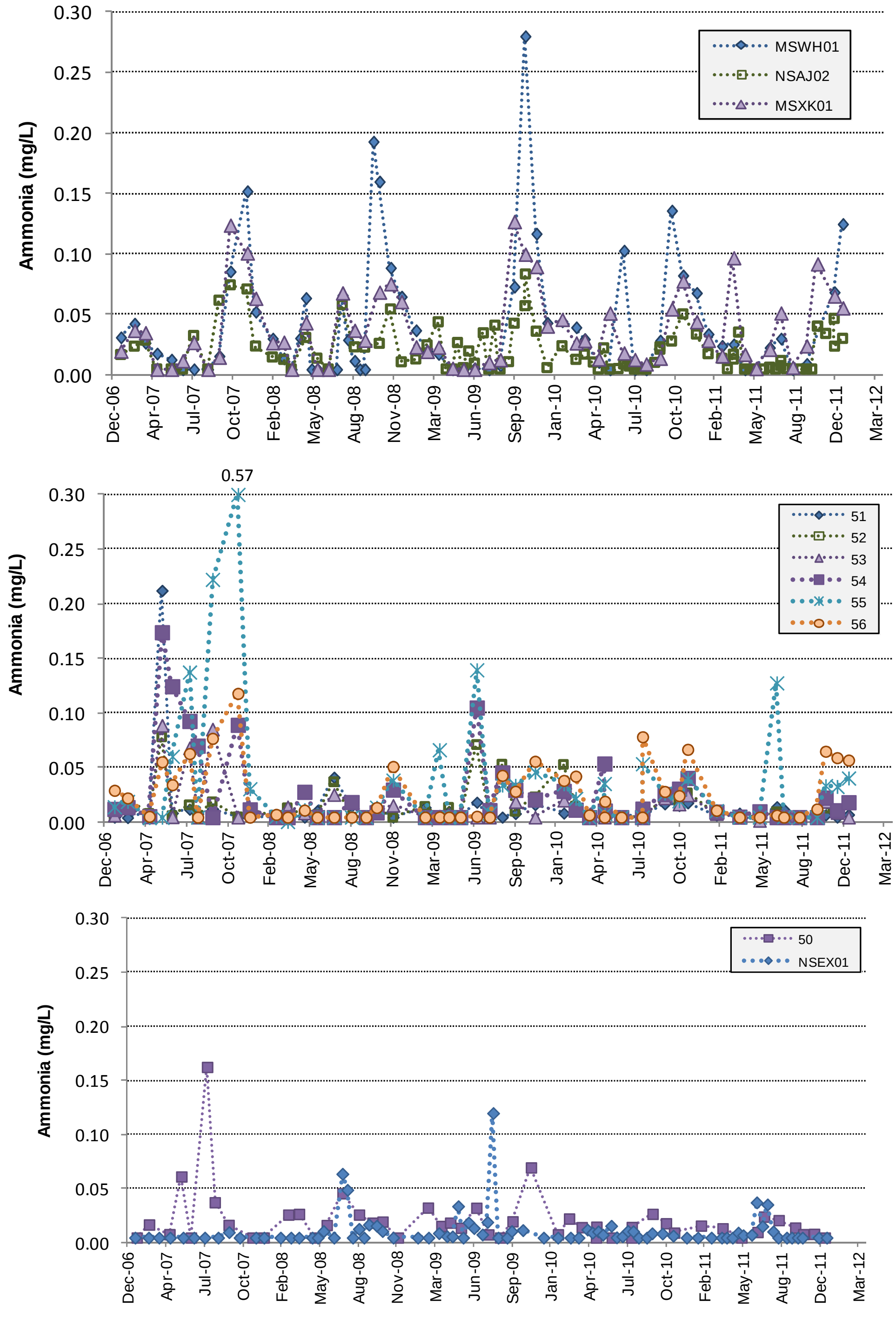


Figure 4-52. Monthly surface (1 m) ammonia values for all Quartermaster Harbor sampling sites.

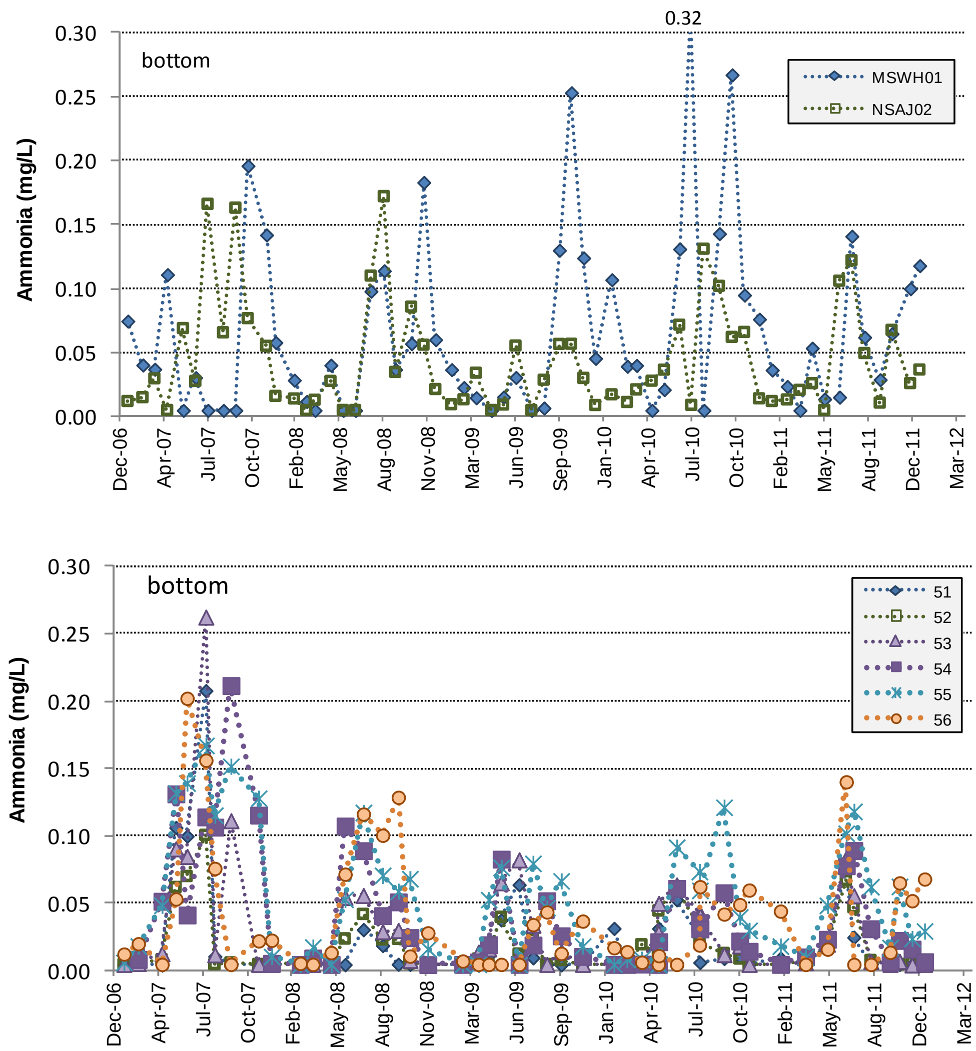


Figure 4-53. Monthly bottom ammonia values for all Quartermaster Harbor sampling sites.

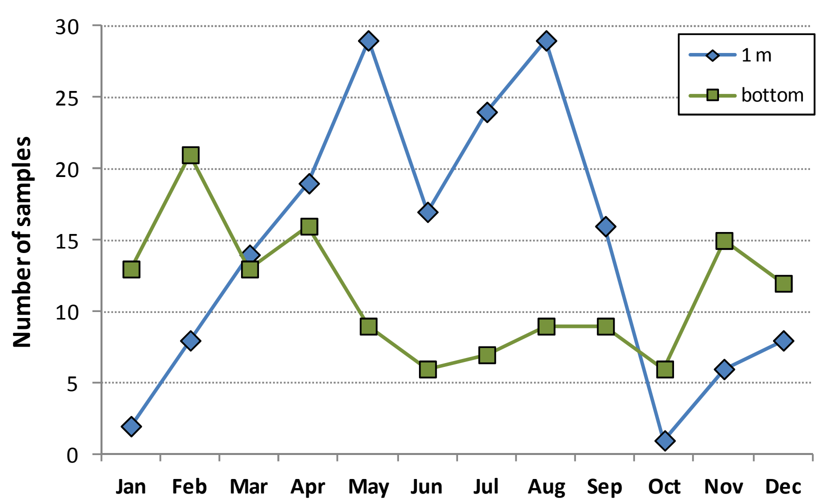


Figure 4-54. Number of samples (8 sites combined) from 2007 through 2011 with values less than 0.005 mg/L

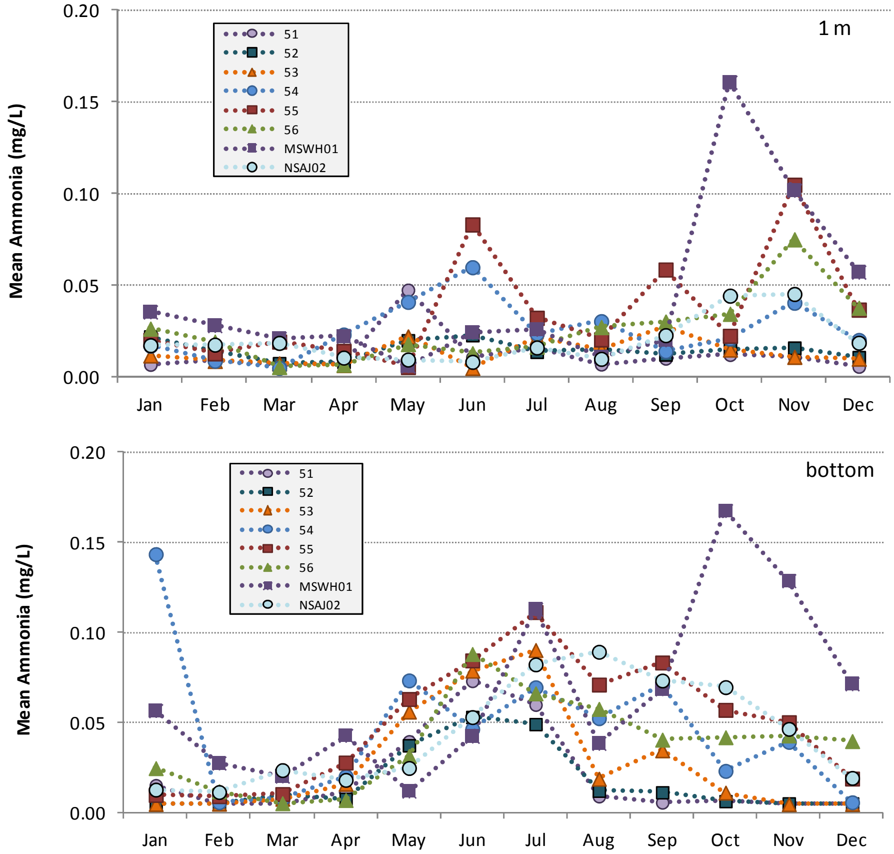


Figure 4-55. Monthly ammonia means from 2007 through 2011 for both surface and bottom values for eight sites

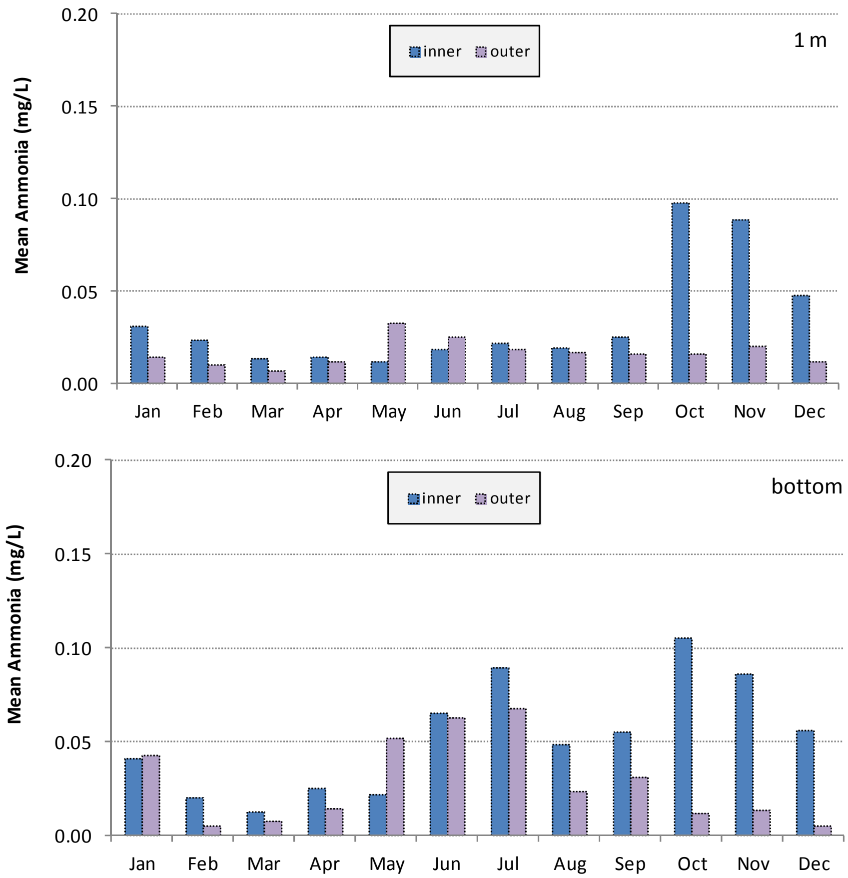


Figure 4-56. Ammonia monthly means for both surface and bottom values for inner (56 and MSWH01) and outer (51-54 and NSAJ02) harbor stations.

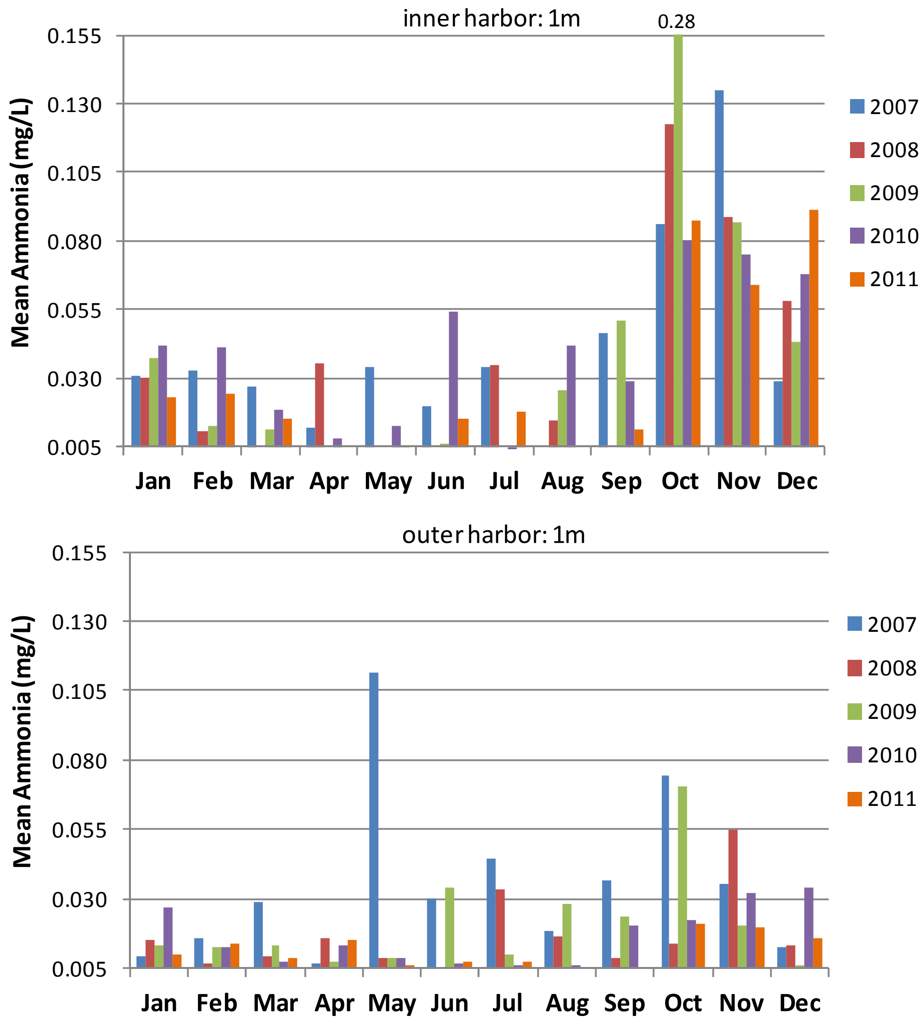


Figure 4-57. Surface water monthly ammonia means for the two inner (Station 56 and MSWH01) and five outer harbor (Stations 51-54 and NSAJ02) sites by year (note that the number of samples varied from year to year).

4.4.3 Silica

Table 4-5 gives an overall summary for silica concentrations at all the sites from 2007 through 2011 for both surface and bottom waters. Silica values ranged from less than 0.05 (the MDL) to 6.57 mg/L and were lowest May through July and highest in the winter months. Figure 4-58 shows monthly surface values from 2007 through 2011 for all sites, including the two sites outside of Quartermaster Harbor for comparative purposes. The figure shows silica values were low from April through July due to phytoplankton uptake, primarily by diatoms, and followed a seasonal pattern similar to that of chlorophyll. Values were lowest in the inner harbor in the spring months, particularly in May following the spring diatom bloom. Surface water silica values were lower in both the inner and outer harbors compared to the two sites outside the harbor in outer Commencement Bay

(Station 50) and East Passage (NSEX01). Station 50 surface waters generally had higher silica values than East Passage, particularly in late January and February. Although the Puyallup River surface plume moves primarily to the north/northwest via Dalco and Colvos Passages, the higher silica values in outer Commencement Bay do not appear correlated with increased flows from the Puyallup River.

Figure 4-59 shows both the surface and bottom monthly silica means (2007-2011) for each station and Figure 4-60 shows the monthly means for this same time period for the two inner harbor (56 and MSWH01) and outer harbor (stations 51 through 54 and NSAJ02) sites grouped together. Both figures show a seasonal cycle with a large decrease in silica concentrations starting in March that continue to decrease through June. Silica values begin increasing in July and continue to increase through January. Both surface and bottom values exhibit a similar pattern, although silica values are higher in bottom waters. Inner harbor monthly means are lower in the spring months than outer harbor means and higher during the late summer months through winter.

Figure 4-61 shows surface water monthly silica means for the two inner (56 and MSWH01) and five outer harbor (stations 51 to 54 and NSAJ02) sites by year. Interannual variation between the inner and outer harbors is most noticeable in April likely due to timing of the spring phytoplankton bloom. Silica values during May 2008 were higher in both the inner and outer harbors than in other years, most likely due to freshwater input from snowmelt. Unusually warm air temperatures occurred in mid-May of 2008 (including a 90^{o}F day), resulting in early snowmelt and an influx of riverine silica.

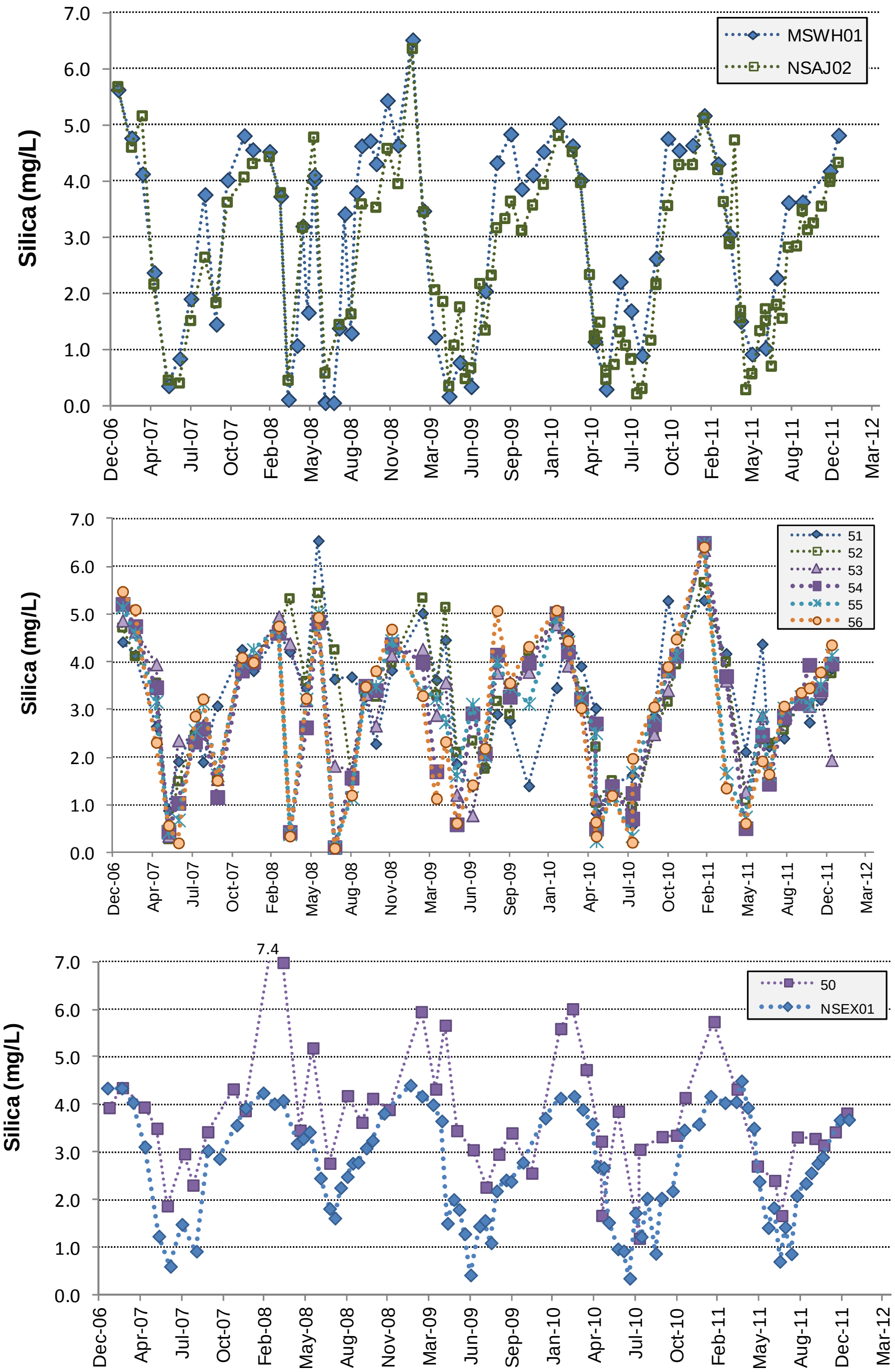


Figure 4-58. Monthly surface (1 m) silica values for all sampling sites.

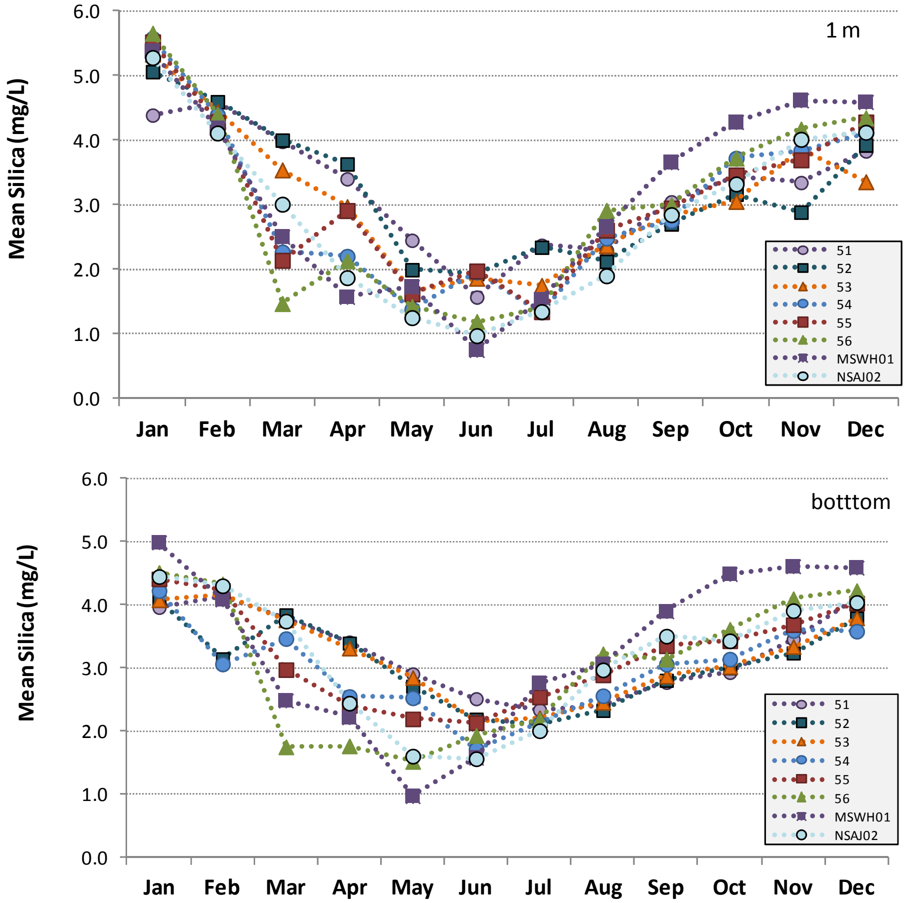


Figure 4-59. Monthly silica means from 2007 through2011 for both surface and bottom values at eight sites

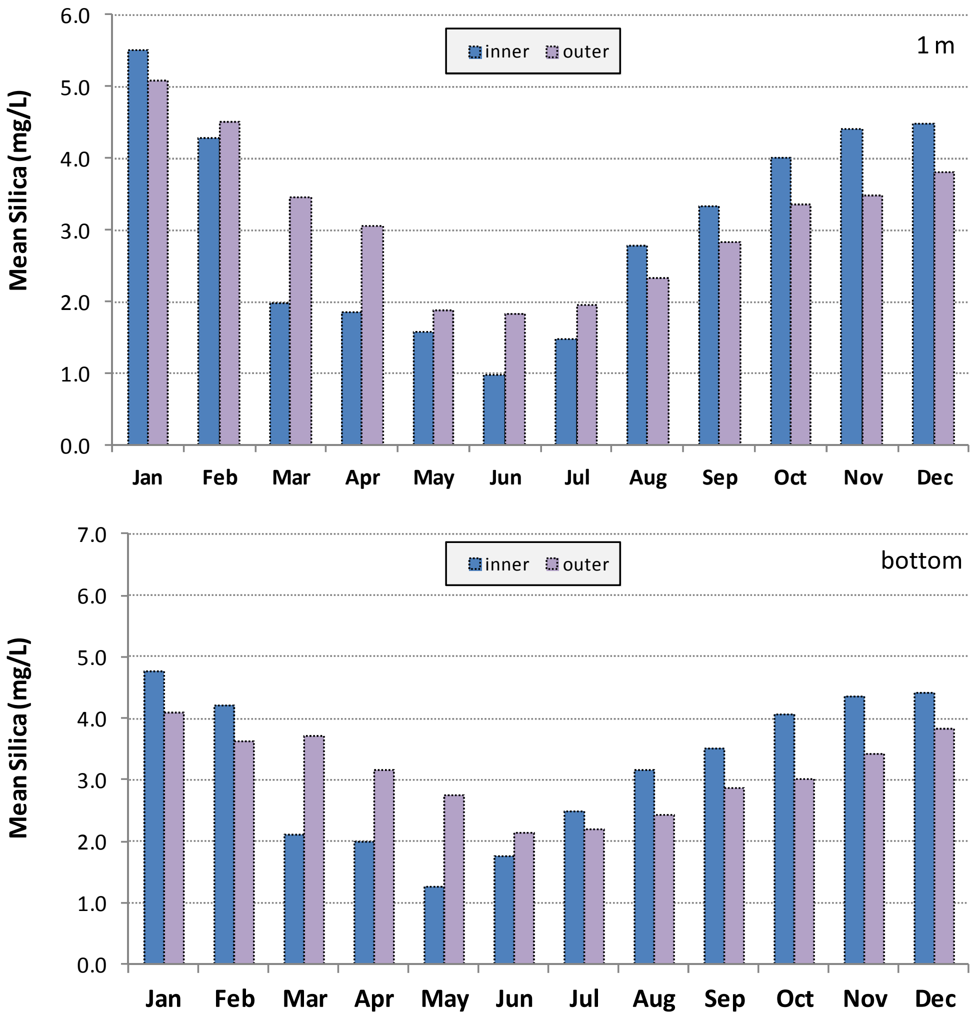


Figure 4-60. Silica monthly means for both surface and bottom values for inner (56 and MSWH01) and outer (51-54 and NSAJ02) harbor stations.

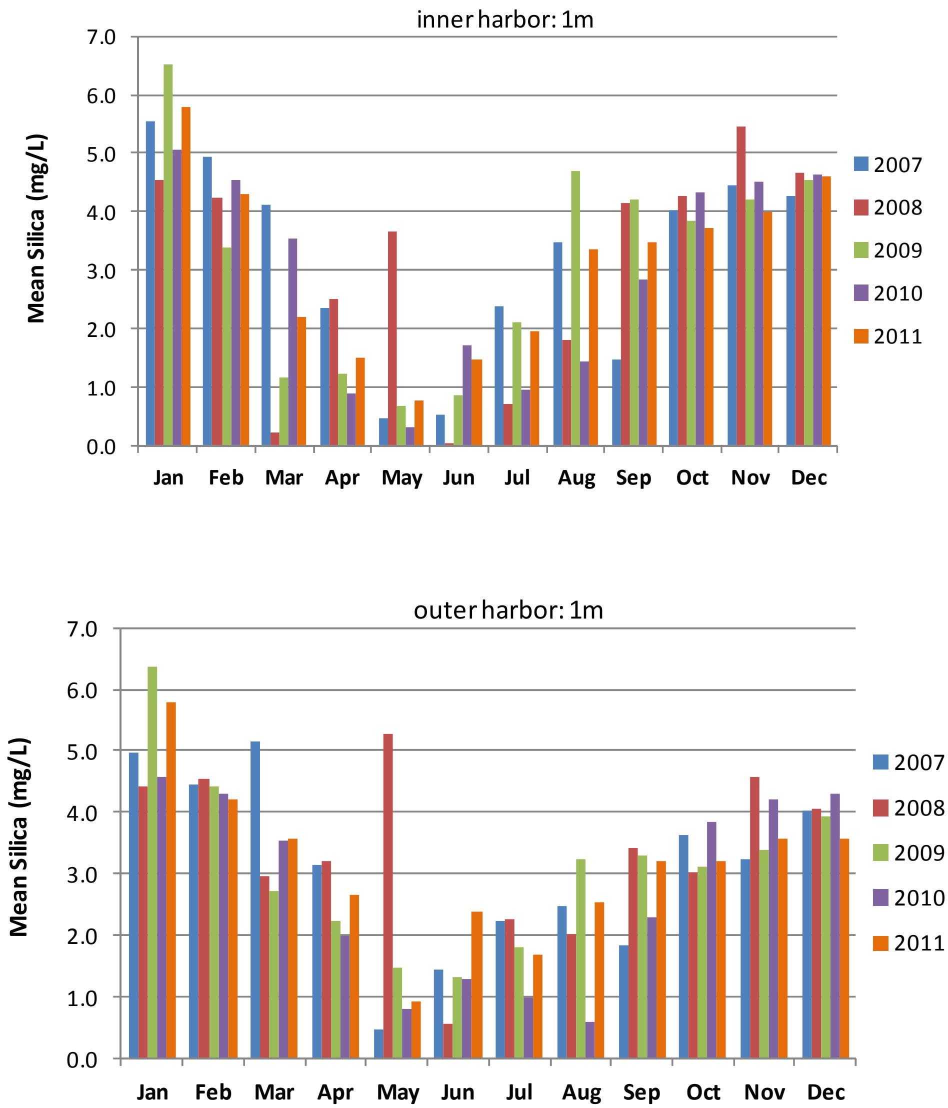


Figure 4-61. Surface water silica monthly means for the two inner (Station 56 and MSWH01) and five outer harbor (Stations 51-54 and NSAJ02) sites by year (note that the number of samples varied from year to year).

Table 4-5. Silica summary from 2007 through 2011. Mean and median values were calculated using the full MDL for values less than the minimum value shown.

	1m: 2007-2011							
Silica (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**
minimum	0.58	0.29	0.36	0.12	0.11	0.10	<0.05	0.20
maximum	6.54	5.67	6.35	6.49	6.48	6.41	6.52	6.36
mean	3.19	3.13	2.96	2.89	2.91	2.82	2.99	2.48
median	3.22	3.22	3.20	3.18	3.14	3.07	3.63	2.32

	bottom: 2007-2011							
Silica (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**
minimum	2.18	1.88	1.78	0.78	0.66	0.51	0.09	0.37
maximum	4.87	4.41	4.38	4.37	4.55	4.97	6.57	4.71
mean	3.15	3.04	3.09	2.95	3.17	2.92	3.31	3.16
median	3.09	3.02	3.09	3.11	3.30	3.24	3.70	3.49

4.4.4 Orthophosphate phosphorus

In aquatic systems, phosphorus occurs in both organic (associated with plant and organism tissues) and inorganic forms. While organisms can use either form, plants require the dissolved inorganic form of orthophosphate phosphorus (orthophosphorus). Orthophosphorus values from 2007 through 2011 ranged from less than 0.005 (the MDL) to 0.138 mg/L and were lowest in May and highest in the winter months. Figure 4-62 shows monthly surface values from 2007 through 2011 for all sites, including the two sites outside of Quartermaster Harbor for comparative purposes. The figure shows orthophosphorus values were lowest from March to August due to phytoplankton uptake and followed a seasonal pattern similar to that of chlorophyll. Of all the nutrients measured, orthophosphorus concentrations were the least variable and were similar between the inner and outer harbor sites, as well as at the two sites located in outer Commencement Bay and East Passage.

Table 4-6 gives an overall summary for all the sites from 2007 through 2011 for both surface and bottom waters. Note that King County had an analytical method change from measuring total phosphorus to orthophosphorus in June 2010, therefore, limited data are available for stations MSWH01, NSAJ02, and NSEX01. There is no consistent correlation between total phosphorus and orthophosphorus in surface waters; therefore a conversion factor cannot be applied to the total phosphorus data.

Figure 4-63 shows both the surface and bottom monthly means (2007-2011) for each station and Figure 4-64 shows the monthly means for this same time period for the two inner harbor (56 and MSWH01) and outer harbor (stations 51 through 54 and NSAJ02) sites grouped together. Both figures show a seasonal cycle with a decrease in orthophosphorus concentrations starting in March and continuing to decrease through May. Orthophosphorus values in the outer harbor begin increasing in June and continue to increase through November, when values remain relatively constant until the spring phytoplankton bloom begins the following March. Inner harbor values follow the same pattern, however, the drawdown during the spring bloom is more evident in the inner harbor in March and April. Bottom values in the outer harbor exhibit a similar pattern, although orthophosphorus values are higher in bottom waters. Inner harbor monthly means in bottom waters are lowest in March then increase until values peak in July.

Figures 4-65 and 4-66 show surface and bottom water monthly means for the two inner (56 and MSWH01) and five outer harbor (stations 51 to 54) sites by year, respectively. Interannual variation between the inner and outer harbors is most noticeable during the spring due to timing of the spring phytoplankton bloom. Interannual variation was more pronounced in bottom waters in the inner harbor than for the outer harbor.

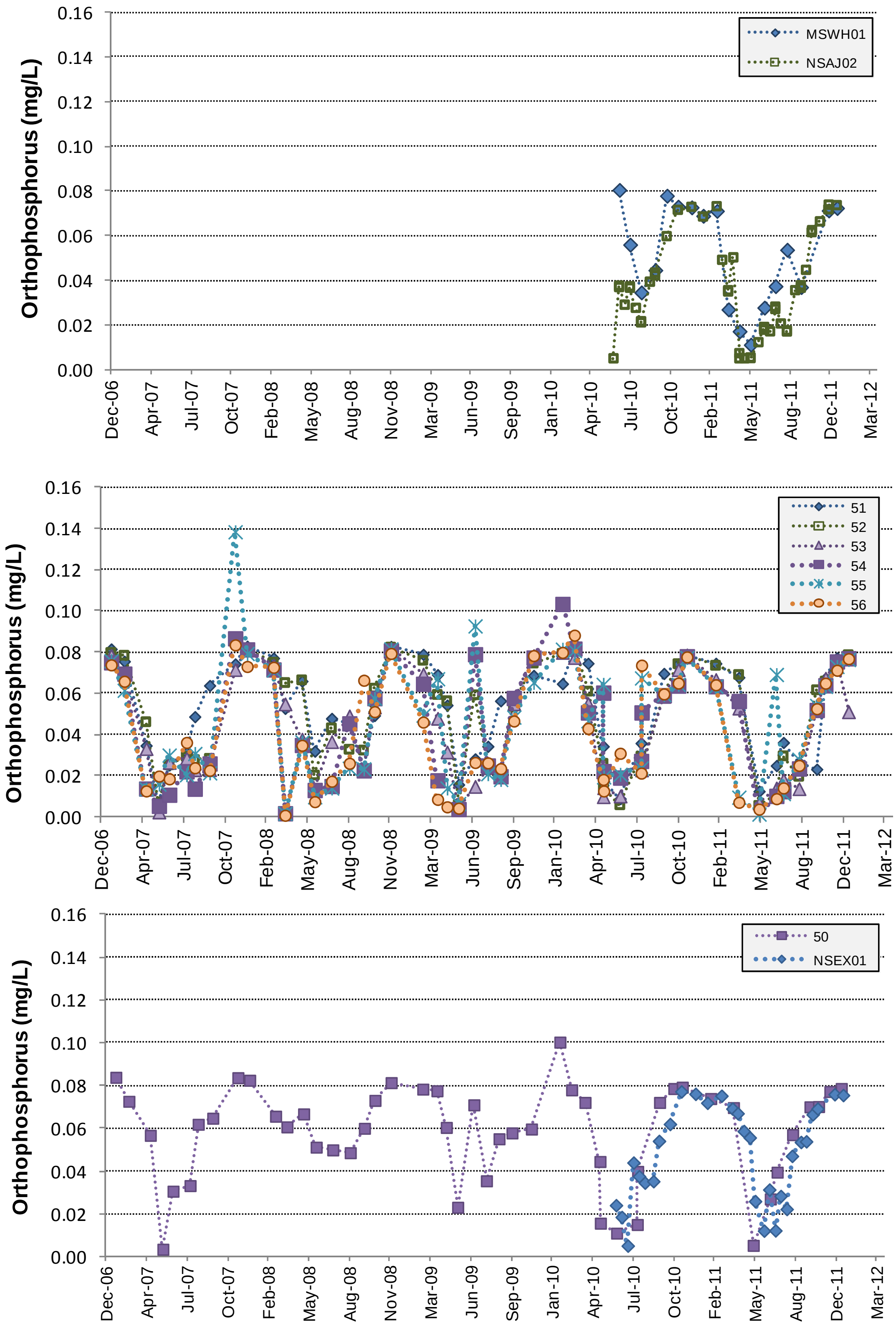


Figure 4-62. Monthly surface (1 m) orthophosphorus values for all sampling sites.

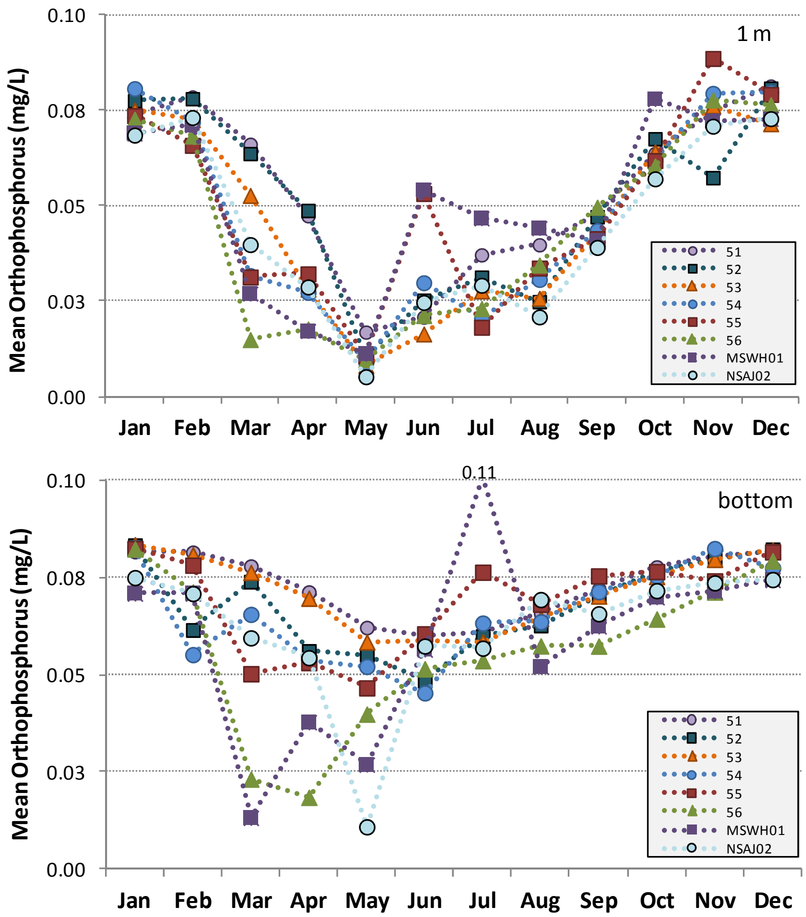


Figure 4-63. Monthly orthophosphorus means from 2007 through 2011 for both surface and bottom values

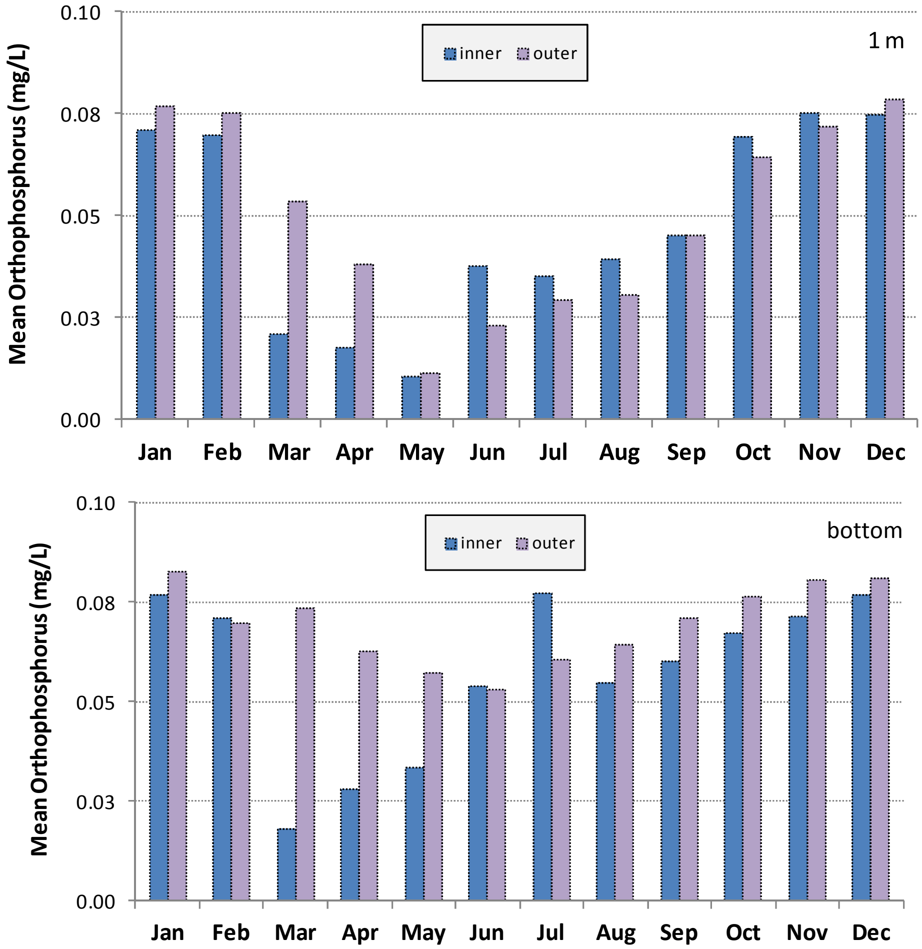


Figure 4-64. Orthophosphorus monthly means for both surface and bottom values for inner (56 and MSWH01) and outer (51-54 and NSAJ02) harbor stations.

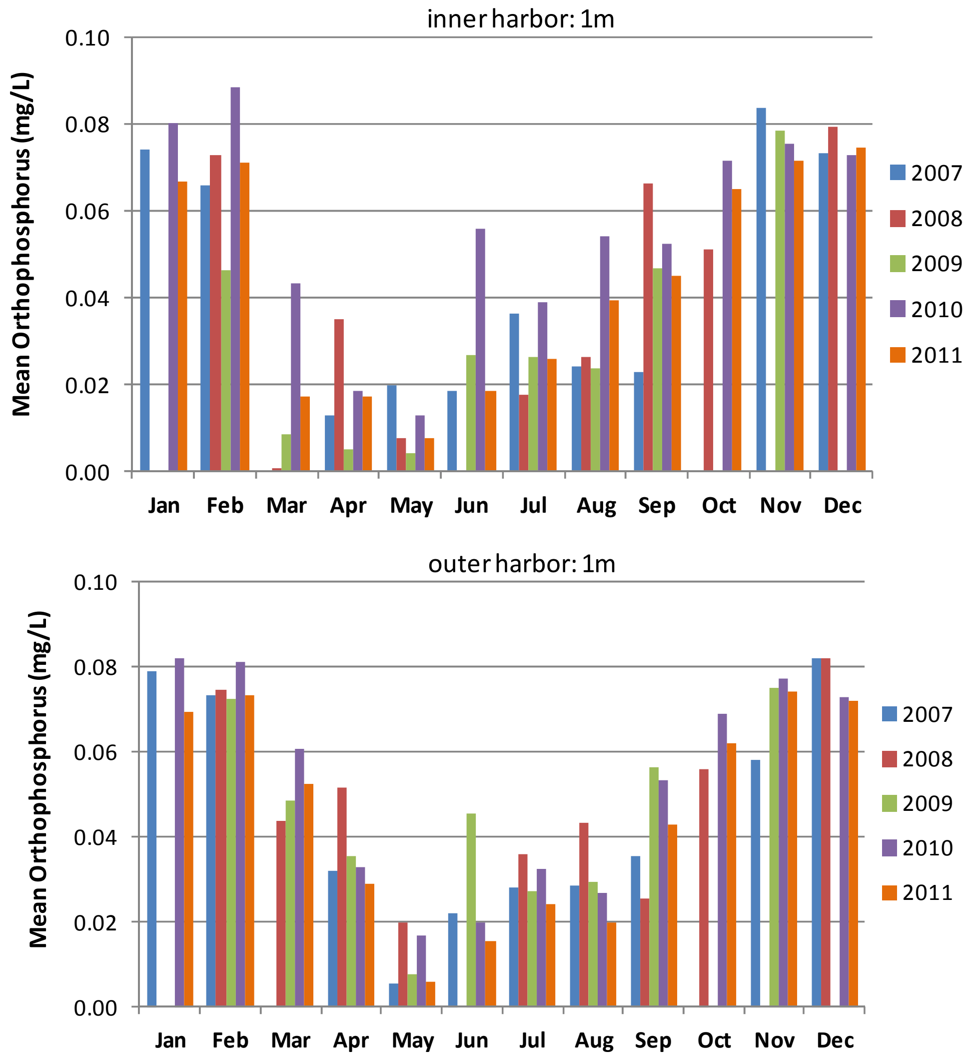


Figure 4-65. Surface water orthophosphorus monthly means for the two inner (Station 56 and MSWH01) and five outer harbor (Stations 51-54 and NSAJ02) sites by year (note that the number of samples varied from year to year).

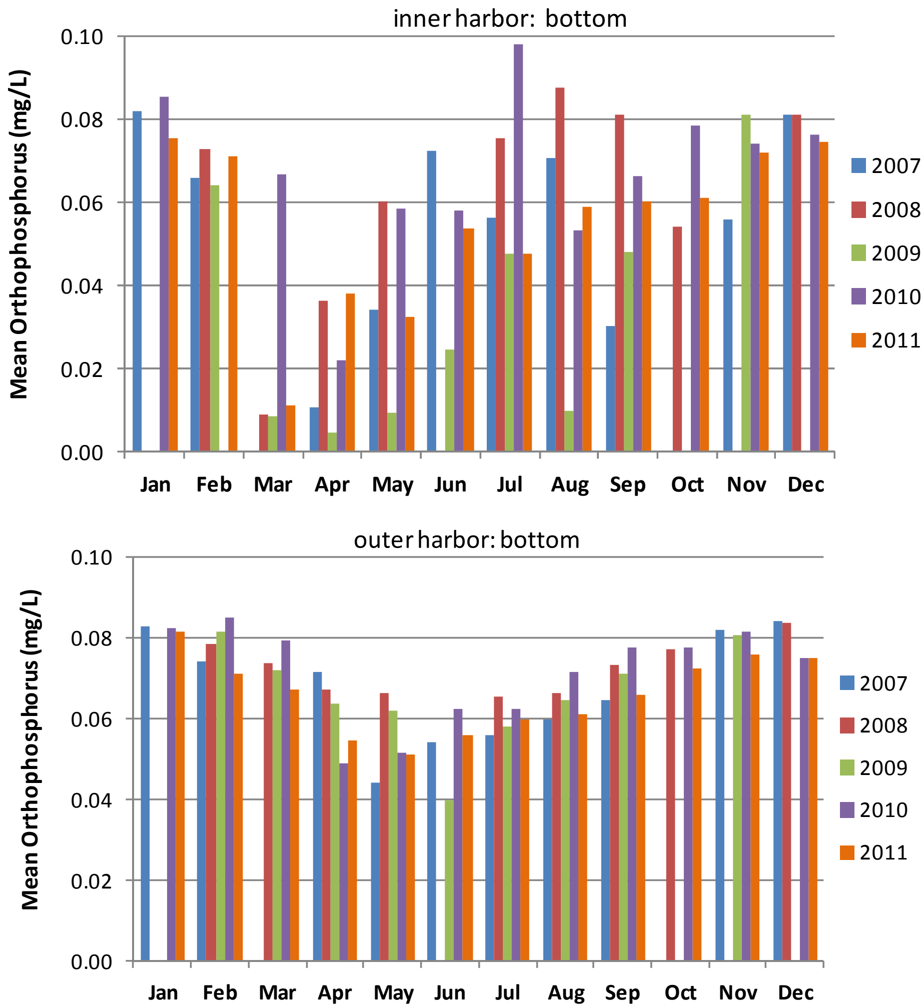


Figure 4-66. Bottom water orthophosphorus monthly means for the two inner (Station 56 and MSWH01) and five outer harbor (Stations 51-54 and NSAJ02) sites by year (note that the number of samples varied from year to year).

Table 4-6. Orthophosphorus summary between 2007 and 2011. Mean and median values were calculated using the full MDL for values less than the minimum value shown. Note: for stations MSWH01 and NSAJ02, values shown are for data collected between June 2010 and December 2011.

	1m: 2007-2011							
Orthophosphorus (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**
minimum	0.007	0.006	0.002	0.003	0.003	0.003	0.011	<0.005
maximum	0.083	0.083	0.082	0.103	0.138	0.088	0.081	0.074
mean	0.051	0.049	0.044	0.045	0.046	0.041	0.052	0.039
median	0.054	0.058	0.048	0.051	0.049	0.035	0.055	0.037
	bottom: 2007-2011							
Orthophosphorus (mg/L)	**51**	**52**	**53**	**54**	**55**	**56**	**MSWH01**	**NSAJ02**
minimum	0.050	0.023	0.042	0.013	0.012	0.005	0.013	0.011
maximum	0.085	0.085	0.085	0.090	0.099	0.087	0.133	0.082
mean	0.072	0.068	0.070	0.066	0.069	0.054	0.063	0.064
median	0.073	0.069	0.072	0.067	0.074	0.063	0.070	0.068

4.5 Phytoplankton

During the course of the Quartermaster Harbor nitrogen management study, King County collected phytoplankton samples from the surface and chlorophyll maximum layer semi-monthly March through October at three stations in the Puget Sound Central Basin. UWT collected surface and thermocline (when one existed) phytoplankton samples as part of the monthly seven-station longitudinal transect in Quartermaster Harbor and outer Commencement Bay (see Figure 1-3). The results from the three King County sampling locations, Point Jefferson in the northern Main Basin (KSBP01), East Passage just north of Commencement Bay (NSEX01), and within Quartermaster Harbor at either the Yacht Club (MSWH01) or Dockton (NSAJ02) are reported here to provide spatial and temporal context to observed phytoplankton patterns in Quartermaster Harbor as reported by the UWT monthly samples. Given that the sampling and analytical methods (see methods section) for King County (semi-quantitative) and UWT (quantitative) are different and that sampling was done on either a semi-monthly or monthly basis, comparisons are limited to broader qualitative results. Due to temporal sampling limitations, more rapid changes (i.e., on the order of days or weeks) in phytoplankton communities may not have been captured. These results still provide a useful overview of the changing patterns of phytoplankton communities over space and time in Quartermaster Harbor and central Puget Sound.

Phytoplankton blooms typically occur in early spring (April) and again in late summer/early fall (August/September) in open Puget Sound waters (Figure 4-69). Note that Figure 4-67 provides chlorophyll-*a* concentrations as an indicator of phytoplankton biomass but that chlorophyll-*a* is not an exact measurement of phytoplankton abundance. In Quartermaster Harbor, the spring bloom occurs earlier and was evident in March in

most sampling years. In 2009, the Quartermaster Harbor spring bloom was observed even earlier in the year, in February. The fall bloom season is also extended in Quartermaster Harbor compared to open waters and was often observed through mid-October. A reduction in surface water nutrients associated with the spring bloom are often observed (see nutrient section) as the spring bloom is typically a large bloom event. Diatoms dominate the phytoplankton community in the spring and dinoflagellates are more common in late summer/early fall which is similar to many estuarine systems (Table 4-7).

Phytoplankton species diversity in Quartermaster Harbor was less than that observed at the more open sampling sites, although phytoplankton biomass was generally greater in Quartermaster Harbor (see Table 4-7). The dominant genus in almost all samples throughout the Sound was the diatom *Chaetoceros* spp. (Table 4-8). One of the exceptions to this was that Quartermaster Harbor tended to have more *Pseudo-nitzschia* spp. and *Alexandrium* spp. in early fall. *Alexandrium catenella* is frequently found in Quartermaster Harbor starting in late spring and is often one of the dominant species in late summer/early fall (Tables 4-9a though 4-9). *Alexandrium catenella* is the main causative agent of Paralytic Shellfish Poisoning (PSP) in Puget Sound. *Alexandrium catenella* can produce a suite of neurotoxins, called saxitoxin, which concentrates in the tissues of filter-feeding shellfish and can be lethal in small doses to humans and other mammals if the contaminated shellfish are consumed. Washington State Department of Health monitors toxin levels in shellfish throughout Puget Sound and closes shellfish beds to harvesting when toxin levels exceed safe limits for human consumption. Quartermaster Harbor is an initiation site for these toxic blooms and is frequently closed due to PSP (Horner et al. 2011).

There is a seasonal pattern to frequently occurring phytoplankton genera in Quartermaster Harbor, as well as Puget Sound. In Quartermaster Harbor, dominant genera in February include the diatoms *Thalassiosira* spp. and *Thalassionema* spp., but by April the dominant diatom species are *Chaetoceros* spp., *Pseudo-nitzschia* spp. and *Skeletonema* spp.. In July and August, *Prorocentrum* spp. is common, September is often dominated by *Ceratium* spp., October by *Pseudo-nitzschia* spp., and December *Navicula* spp. and *Pseudo-nitzschia* spp. are in abundance. Unlike open Puget Sound waters, *Alexandrium* spp. is often one of the dominant species in Quartermaster Harbor August through November. The top twenty phytoplankton genera in terms of abundance and frequency of occurrence in Quartermaster Harbor and Commencement Bay for comparison are given in Tables 4-10 and 4-11, respectively.

In terms of interannual variability in Quartermaster Harbor, blooms regularly occur in the April and September time frames with higher abundances associated with the September blooms. Particularly low abundances were observed in 2009 compared with the other years of the study and it is hypothesized that this may be associated with an El Niño that year (Figure 4-68) (Gierach et al. 2012). There was a huge bloom of *Heterosigma* spp., three times larger than any other phytoplankton bloom in Quartermaster Harbor, in September 2011 (see Appendix D). Spatially, phytoplankton abundances are often highest in outer Quartermaster Harbor around station 53 (see Figure 4-68 and Appendix D). Figure 4-69 provides photographs of common phytoplankton species in Quartermaster Harbor.

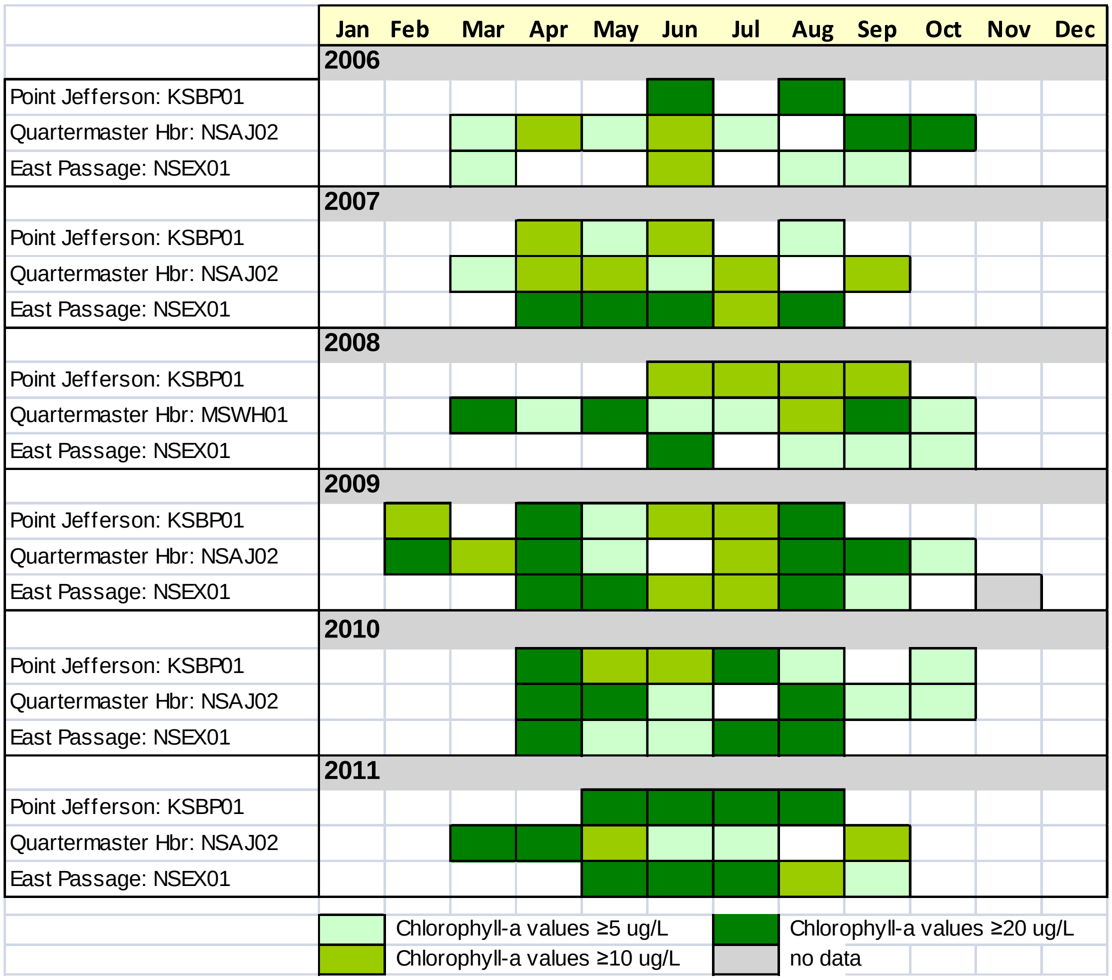


Figure 4-67. Monthly chlorophyll-a values at three locations. Note that 2008-2011 results are based upon semi-monthly data.

Table 4-7. Number of total species and percent diatom genera for two open waters sites and QMH.

Total # of Species		2008			2009			2010			2011		
	week	KSBP01	NSEX01	MSWH01	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02
April	1	--	--	15	20	25	26	32	36	22	12	7	18
	3	3	7	--	28	24	14	34	34	27	13	23	18
May	1	9	29	8	35	26	25	25	34	31	31	29	14
	3	18	12	11	31	18	14	42	42	21	31	26	19
June	1	--	--	--	36	39	22	39	32	20	23	24	19
	3	24	22	13	32	34	17	28	27	17	8	14	16
July	1	23	12	15	27	14	10	30	23	17	25	22	16
	3	17	17	13	23	17	20	26	23	12	14	24	12
August	1	24	25	22	33	17	9	23	21	17	33	35	23
	3	41	21	20	19	24	11	32	35	20	10	14	6
September	1	15	22	17	--	29	20	34	37	26	9	12	18
	3	35	27	10	18	30	17	27	29	18	19	17	11
October *	1	23	30	18	30	30	20	--	--	--	22	27	24

≤ 15	16 - 29	≥ 30

% Diatom Genera		2008			2009			2010			2011		
	week	KSBP01	NSEX01	MSWH01	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02
March	1	--	--	--	--	--	--	--	--	--	--	--	100
	3	--	--	--	--	--	--	--	--	--	90.9	100	75.0
April	1	--	--	50.0	64.3	75.0	76.2	85.0	78.9	78.6	88.9	83.3	69.2
	3	100.0	85.7	--	83.3	87.5	90.9	66.7	75.0	77.8	58.3	68.4	75.0
May	1	87.5	65.2	85.7	74.1	71.4	64.7	89.5	85.0	84.2	68.8	71.4	100
	3	50.0	60.0	33.3	68.2	76.9	80.0	76.0	84.0	83.3	80.0	91.7	66.7
June	1	--	--	--	78.3	65.2	58.3	65.2	82.4	70.0	61.5	71.4	63.6
	3	73.3	66.7	72.7	70.0	55.6	46.7	59.1	64.7	57.1	37.5	55.6	80.0
July	1	68.8	50.0	75.0	42.8	58.3	22.2	63.2	46.7	66.7	61.9	53.8	71.4
	3	53.8	57.1	50.0	83.3	57.1	47.4	57.1	85.7	62.5	45.4	31.2	30.0
August	1	55.0	61.9	50.0	56.5	57.1	55.6	71.4	85.7	66.7	60.0	50.0	47.0
	3	60.7	64.7	46.7	50.0	60.0	27.3	75.0	81.8	78.6	50.0	30.0	16.7
September	1	57.1	66.7	33.3	--	61.9	50.0	59.1	62.5	65.0	12.5	36.4	50.0
	3	66.7	75.0	37.5	52.9	57.1	60.0	71.4	77.3	53.3	50.0	45.4	22.2
October	1	68.4	76.2	66.7	--	--	--	--	--	--	60.0	57.1	55.6
	3	--	--	--	72.7	60.0	40.0	--	--	--	61.5	75.0	70.0

≤ 50	51 - 74	≥ 75

Table 4-8. Dominant and subdominant species and genera identified from 2008 through 2011 by month

	Dominant and subdominant species, 2008-2011		
	Point Jefferson	**East Passage**	**Quartermaster Harbor**
April	*Chaetoceros* (Hyalochaete) spp. *Thalassiosira* spp.	*Chaetoceros* (Hyalochaete) spp.	*Chaetoceros* (Hyalochaete) spp. *Coscinodiscus spp.* *Skeletonema costatum*
May	*Chaetoceros* (Hyalochaete) spp. *Detonula pumila* *Thalassiosira nordenskioeldii* *Thalassiosira sp.*	*Chaetoceros* (Hyalochaete) spp. *Thalassiosira nordenskioeldii* *Thalassiosira sp.*	*Chaetoceros* (Hyalochaete) spp. *Detonula pumila* *Thalassiosira nordenskioeldii* *Thalassiosira sp.*
June	*Chaetoceros* (Hyalochaete) spp. *Eucampia zodiacus* *Pseudo-nitzschia spp.* *Rhizosolenia setigera* *Thalassiosira nordenskioeldii* *Skeletonema costatum*	*Chaetoceros* (Hyalochaete) spp. *Thalassiosira* spp. *Thalassiosira nordenskioeldii* *Chaetoceros debilis*	*Chaetoceros* (Hyalochaete) spp. *Rhizosolenia setigera* *Thalassionema nitzschioides* *Thalassiosira nordenskioeldii*
July	*Cylindrotheca closterium* *Pseudo-nitzschia* spp. *Skeletonema costatum* *Prorocentrum gracile* *Chaetoceros debilis*	*Chaetoceros* (Hyalochaete) spp. *Chaetoceros convolutus* *Coscinodiscus wailesii* *Eucampia zodiacus* *Rhizosolenia setigera* *Ceratium fusus* *Chaetoceros debilis*	*Chaetoceros* (Hyalochaete) spp. *Chaetoceros convolutus* *Rhizosolenia setigera* *Prorocentrum gracile* *Chaetoceros debilis*
August	*Chaetoceros* (Hyalochaete) spp. *Detonula pumila* *Thalassiosira rotula* *Pseudo-nitzschia* spp. *Heterosigma akashiwo*	*Chaetoceros* (Hyalochaete) spp. *Skeletonema costatum* *Ceratium fusus* *Pseudo-nitzschia* spp. *Heterosigma akashiwo*	*Chaetoceros* (Hyalochaete) spp. *Leptocylindrus danicus* *Prorocentrum gracile* *Pseudo-nitzschia* spp. *Heterosigma akashiwo*
September	*Chaetoceros* (Hyalochaete) spp. *Ceratium fusus* *Akashiwo sanguinea*	*Chaetoceros* (Hyalochaete) spp. *Thalassiosira* spp. *Pseudo-nitzschia* spp. *Akashiwo sanguinea* *Ceratium fusus* *Heterosigma akashiwo*	*Chaetoceros* (Hyalochaete) spp. *Alexandrium catenella* *Prorocentrum gracile* *Heterosigma akashiwo* *Ceratium fusus*
October	*Chaetoceros* (Hyalochaete) spp. *Pseudo-nitzschia* spp.	*Chaetoceros* (Hyalochaete) spp. *Leptocylindrus minimus* *Thalassiosira* spp.	*Pseudo-nitzschia* spp. *Alexandrium* sp. *Ceratium fusus*

Table 4-9a. Dominant genera identified by month in Station 51 through 54 samples from outer Quartermaster Harbor between 2007 and 2011.

	Stations 51--54 Dominant Genera									
	2007		2008		2009		2010		2011	
	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L
January	*Asteromphalus spp.*	3,639	no data	n/a	no data	n/a	*Pseudo-nitzschia spp.*	28,539	*Actinoptychus spp.*	2,186
	Chaetoceros spp.	1,337					*Navicula spp.*	10,220	*Skeletonema spp.*	1,649
	Thalassiosira spp.	1,169					*Prorocentrum spp.*	2,761	*Phaeocystis spp.*	1,355
	Leptocylindrus spp.	999					*Thalassionema spp.*	2,747	*Pseudo-nitzschia spp.*	1,075
February	*Chaetoceros spp.*	4,120	*Thalassiosira spp.*	1,388	*Thalassiosira spp.*	39,731	*Cylindrotheca spp.*	7,250	no data	n/a
	Thalassionema spp.	2,924	*Coscinodiscus spp.*	1,367	*Chaetoceros spp.*	15,986	*Navicula spp.*	3,322		
	Thalassiosira spp.	2,036	*Thalassionema spp.*	1,171	*Skeletonema spp.*	6,845	*Thalassionema spp.*	3,248		
	Prorocentrum spp.	1,685	*Navicula spp.*	773	*Leptocylindrus spp.*	3,295	*Actinoptychus spp.*	2,290		
March	no data	n/a	*Thalassiosira spp.*	128,128	*Thalassiosira spp.*	63,451	*Skeletonema spp.*	65,996	*Thalassiosira spp.*	7,437
			Thalassionema spp.	24,789	*Chaetoceros spp.*	26,866	*Chaetoceros spp.*	65,679	*Chaetoceros spp.*	4,345
			Pleurosigma spp.	5,561	*Pseudo-nitzschia spp.*	5,219	*Pseudo-nitzschia spp.*	21,848	*Navicula spp.*	4,188
			Navicula spp.	5,537	*Alexandrium spp.*	3,544	*Thalassiosira spp.*	12,167	*Cylindrotheca spp.*	3,553
April	*Chaetoceros spp.*	164,706	*Thalassiosira spp.*	88,691	*Pseudo-nitzschia spp.*	58,178	*Chaetoceros spp.*	897,873	no data	n/a
	Pseudo-nitzschia spp.	17,018	*Thalassionema spp.*	13,900	*Skeletonema spp.*	53,775	*Skeletonema spp.*	67,451		
	Skeletonema spp.	14,132	*Cerataulina spp.*	11,542	*Chaetoceros spp.*	33,176	*Cylindrotheca spp.*	62,546		
	Thalassiosira spp.	8,535	*Navicula spp.*	10,395	*Thalassionema spp.*	4,507	*Pseudo-nitzschia spp.*	47,733		
May	no data	n/a	*Thalassiosira spp.*	138,286	*Chaetoceros spp.*	35,249	*Chaetoceros spp.*	82,702	*Chaetoceros spp.*	105,679
			Thalassionema spp.	17,255	*Thalassionema spp.*	17,812	*Pseudo-nitzschia spp.*	24,522	*Pseudo-nitzschia spp.*	23,145
			Chaetoceros spp.	5,871	*Pseudo-nitzschia spp.*	7,366	*Cylindrotheca spp.*	18,414	*Thalassiosira spp.*	17,849
			Navicula spp.	5,388	*Thalassiosira spp.*	6,816	*Heterosigma spp.*	4,861	*Skeletonema spp.*	14,933
June	no data	n/a	no data	n/a	*Pseudo-nitzschia spp.*	157,172	*Chaetoceros spp.*	57,101	*Chaetoceros spp.*	534,401
					Rhizosolenia spp.	54,389	*Cylindrotheca spp.*	27,188	*Cylindrotheca spp.*	135,795
					Prorocentrum spp.	12,050	*Leptocylindrus spp.*	11,381	*Skeletonema spp.*	87,925
					Ceratium spp.	2,324	*Rhizosolenia spp.*	10,842	*Pseudo-nitzschia spp.*	64,040
July	unknown unicellular	96,529	*Rhizosolenia spp.*	130,230	*Prorocentrum spp.*	26,252	*Chaetoceros spp.*	214,149	*Chaetoceros spp.*	191,230
	Prorocentrum spp.	18,919	*Chaetoceros spp.*	60,391	*Dinophysis spp.*	19,542	*Eucampia spp.*	53,160	*Pyrophacus spp.*	8,335
	Scrippsiella spp.	10,428	*Pseudo-nitzschia spp.*	7,449	*Skeletonema spp.*	18,059	*Ditylum spp.*	18,197	*Alexandrium spp.*	6,612
	Ceratium spp.	5,001	*Skeletonema spp.*	5,212	*Ceratium spp.*	9,597	*Alexandrium spp.*	17,459	*Scrippsiella spp.*	6,567
August	*Leptocylindrus spp.*	77,873	*Alexandrium spp.*	14,414	*Prorocentrum spp.*	25,776	*Chaetoceros spp.*	205,214	*Heterosigma spp.*	1,359,466
	unknown unicellular	74,045	*Leptocylindrus spp.*	9,292	*Alexandrium spp.*	3,651	*Eucampia spp.*	8,126	*Prorocentrum spp.*	813,791
	Prorocentrum spp.	23,145	*Chaetoceros spp.*	5,362	*Scrippsiella spp.*	1,830	*Thalassionema spp.*	6,941	*Pseudo-nitzschia spp.*	118,903
	Pseudo-nitzschia spp.	22,850	*Rhizosolenia spp.*	3,445	*Ceratium spp.*	1,317	*Thalassiosira spp.*	3,613	*Pyrophacus spp.*	47,065
September	*Thalassionema spp.*	676,261	*Thalassiosira spp.*	785,011	*Pseudo-nitzschia spp.*	3,492	*Pyrophacus spp.*	3,708	*Heterosigma spp.*	196,495
	Chaetoceros spp.	673,549	*Chaetoceros spp.*	233,735	*Cylindrotheca spp.*	677	*Actinoptychus spp.*	2,702	*Ceratium spp.*	28,504
	Pseudo-nitzschia spp.	98,928	*Alexandrium spp.*	71,254	*Coscinodiscus spp.*	382	*Thalassiosira spp.*	1,774	*Prorocentrum spp.*	11,402
	Rhizosolenia spp.	24,686	*Ceratium spp.*	56,448	*Skeletonema spp.*	294	*Scrippsiella spp.*	1,292	*Dactyliosolen spp.*	5,430
October	no data	n/a	*Chaetoceros spp.*	65,562	no data	n/a	*Pseudo-nitzschia spp.*	5,489	*Heterosigma spp.*	29,477
			Ceratium spp.	12,435			*Pyrophacus spp.*	1,762	*Chaetoceros spp.*	27,871
			Thalassiosira spp.	9,573			*Alexandrium spp.*	978	*Pseudo-nitzschia spp.*	23,730
			Pseudo-nitzschia spp.	9,288			*Heterosigma spp.*	784	*Ceratium spp.*	8,649
November	*Chaetoceros spp.*	12,281	no data	n/a	*Skeletonema spp.*	546	*Chaetoceros spp.*	6,877	*Melosira spp.*	17,468
	Unknown red-ciliated	9,620			*Pseudo-nitzschia spp.*	424	*Pyrophacus spp.*	5,372	*Heterosigma spp.*	14,373
	Asteromphalus spp.	6,433			*Pyrophacus spp.*	403	*Navicula spp.*	4,943	*Chaetoceros spp.*	12,674
	Thalassiosira spp.	4,976			*Thalassiosira spp.*	382	*Alexandrium spp.*	3,984	*Meringosphaera spp.*	3,787
December	*Navicula spp.*	6,400	*Chaetoceros spp.*	2,136	no data	n/a	no data	n/a	*Navicula spp.*	973
	Thalassionema spp.	1,457	*Thalassiosira spp.*	1,687					*Pseudo-nitzschia spp.*	620
	Cylindrotheca spp.	1,254	*Pseudo-nitzschia spp.*	1,304					*Cerataulina spp.*	600
	Dinophysis spp.	1,030	*Cylindrotheca spp.*	652					*Chaetoceros spp.*	400

One of the top 4 genera in at least 3 of the 5 years sampled for that month. (shaded cells)

Table 4-9b. Dominant genera identified by month in Station 55 and 56 samples from mid and inner Quartermaster Harbor between 2007 and 2011.

	Stations 55--56 Dominant Genera									
	2007		2008		2009		2010		2011	
	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L
January	*Asteromphalus spp.*	4,430	no data	n/a	no data	n/a	*Actinoptychus spp.*	26,672	Unknown star-shap	18,333
	Dictyocha spp.	2,683					*Pseudo-nitzschia spp.*	5,328	*Pyrophacus spp.*	4,850
	Leptocylindrus spp.	1,747					*Navicula spp.*	2,622	*Actinoptychus spp.*	2,833
	Chaetoceros spp.	1,393					*Pyrophacus spp.*	820	*Chaetoceros spp.*	1,617
February	*Dictyocha spp.*	7,415	*Thalassionema spp.*	5,801	*Thalassiosira spp.*	91,936	*Cylindrotheca spp.*	10,084	no data	n/a
	Thalassiosira spp.	1,938	*Navicula spp.*	2,778	*Coscinodiscus spp.*	55,450	*Pyrophacus spp.*	3,771		
	Chaetoceros spp.	785	*Coscinodiscus spp.*	2,717	*Thalassionema spp.*	43,161	*Pseudo-nitzschia spp.*	2,934		
	Ebria spp.	785	*Skeletonema spp.*	1,542	*Actinoptychus spp.*	37,789	*Navicula spp.*	2,931		
March	no data	n/a	*Thalassiosira spp.*	261,671	*Thalassiosira spp.*	62,000	*Skeletonema spp.*	269,348	*Thalassionema spp.*	43,040
			Thalassionema spp.	61,713	*Actinoptychus spp.*	14,000	*Chaetoceros spp.*	194,820	*Thalassiosira spp.*	14,583
			Navicula spp.	6,413	*Skeletonema spp.*	13,200	*Pseudo-nitzschia spp.*	50,280	*Chaetoceros spp.*	6,810
			Pleurosigma spp.	5,210	*Detonula spp.*	4,400	*Thalassiosira spp.*	30,837	*Cylindrotheca spp.*	4,113
April	*Chaetoceros spp.*	284,421	*Thalassiosira spp.*	142,687	*Skeletonema spp.*	93,625	*Chaetoceros spp.*	347,400	no data	n/a
	Pseudo-nitzschia spp.	37,189	*Thalassionema spp.*	24,152	*Chaetoceros spp.*	57,313	*Leptocylindrus spp.*	39,186		
	Thalassiosira spp.	16,945	*Scrippsiella spp.*	4,435	*Pseudo-nitzschia spp.*	41,835	*Cylindrotheca spp.*	32,749		
	Skeletonema spp.	5,121	*Chaetoceros spp.*	3,223	*Dinophysis spp.*	3,089	*Pseudo-nitzschia spp.*	22,848		
May	no data	n/a	*Thalassiosira spp.*	203,911	*Chaetoceros spp.*	10,270	*Chaetoceros spp.*	80,813	*Chaetoceros spp.*	106,635
			Thalassionema spp.	25,649	*Thalassionema spp.*	8,485	*Rhizosolenia spp.*	57,957	*Thalassiosira spp.*	10,758
			Coscinodiscus spp.	14,436	*Thalassiosira spp.*	7,873	*Cylindrotheca spp.*	54,553	*Skeletonema spp.*	5,658
			Cerataulina spp.	8,582	*Pseudo-nitzschia spp.*	5,741	*Pseudo-nitzschia spp.*	23,332	*spp.*	4,256
June	no data	n/a	no data	n/a	*Pseudo-nitzschia spp.*	128,460	*Dactyliosolen spp.*	60,984	*Chaetoceros spp.*	1,057,869
					Gonyaulax spp.	1,699	*Rhizosolenia spp.*	39,424	*Cylindrotheca spp.*	282,381
					Ceratium spp.	1,182	*Chaetoceros spp.*	34,274	*spp.*	102,913
					Rhizosolenia spp.	954	*Leptocylindrus spp.*	12,568	*Skeletonema spp.*	63,957
July	unknown unicellular plank	199,212	*Rhizosolenia spp.*	521,721	*Prorocentrum spp.*	49,865	*Chaetoceros spp.*	238,583	*Chaetoceros spp.*	131,784
	Prorocentrum spp.	194,988	*Chaetoceros spp.*	452,731	*Dinophysis spp.*	8,594	*Prorocentrum spp.*	55,836	*Prorocentrum spp.*	68,051
	Heterocapsa spp.	31,811	*Pseudo-nitzschia spp.*	129,435	*Skeletonema spp.*	4,597	*Eucampia spp.*	26,557	*Pyrophacus spp.*	29,400
	Pyrophacus spp.	14,815	*Cylindrotheca spp.*	18,229	*Rhizosolenia spp.*	3,445	*Hemiaulus spp.*	4,270	*Pseudo-nitzschia spp.*	12,088
August	unknown unicellular plank	146,693	*Leptocylindrus spp.*	6,380	*Alexandrium spp.*	58,214	*Chaetoceros spp.*	22,849	*Prorocentrum spp.*	3,464,682
	Leptocylindrus spp.	133,567	*Pseudo-nitzschia spp.*	5,922	*Prorocentrum spp.*	27,736	*Cylindrotheca spp.*	7,329	*Heterosigma spp.*	2,874,078
	Prorocentrum spp.	51,304	*Chaetoceros spp.*	5,528	*Actinoptychus spp.*	1,291	*Pyrophacus spp.*	2,117	*Scrippsiella spp.*	52,585
	Pseudo-nitzschia spp.	39,569	*Ceratium spp.*	5,247	*Chaetoceros spp.*	1,072	*Thalassionema spp.*	2,092	*Heterocapsa spp.*	39,408
September	*Thalassionema spp.*	935,262	*Thalassiosira spp.*	682,286	*Ceratium spp.*	1,010	*Pyrophacus spp.*	5,945	*Heterosigma spp.*	142,727
	Chaetoceros spp.	867,016	*Chaetoceros spp.*	86,648	*Oxyphysis spp.*	764	*Thalassiosira spp.*	4,502	*Dactyliosolen spp.*	16,706
	Pseudo-nitzschia spp.	131,316	*Skeletonema spp.*	30,985	*Coscinodiscus spp.*	752	*Actinoptychus spp.*	2,667	*Scrippsiella spp.*	11,708
	Ceratium spp.	71,797	*Ceratium spp.*	26,545	*Eucampia spp.*	505	*Alexandrium spp.*	1,145	*Protoperidinium sp*	7,173
October	no data	n/a	*Ceratium spp.*	41,284	no data	n/a	*Pyrophacus spp.*	2,983	*Heterosigma spp.*	18,803
			Chaetoceros spp.	12,657			*Scrippsiella spp.*	2,813	*Ceratium spp.*	12,821
			Thalassiosira spp.	7,978			*Alexandrium spp.*	1,802	*spp.*	11,538
			Cylindrotheca spp.	5,026			*Chaetoceros spp.*	1,632	*Actinoptychus spp.*	5,983
November	Unknown red-ciliated plar	126,233	no data	n/a	*Actinoptychus spp.*	769	*Alexandrium spp.*	15,326	*Chaetoceros spp.*	88,178
	Chaetoceros spp.	9,851			*Coscinodiscus spp.*	394	*Chaetoceros spp.*	11,818	*Melosira spp.*	30,446
	Asteromphalus spp.	5,138			*Skeletonema spp.*	394	*Actinoptychus spp.*	6,876	*Actinoptychus spp.*	11,482
	Cylindrotheca spp.	4,301			*Pyrophacus spp.*	394	*Heterosigma spp.*	5,746	*Navicula spp.*	11,311
December	*Navicula spp.*	11,364	*Thalassiosira spp.*	4,174	no data	n/a	no data	n/a	*Navicula spp.*	1,818
	Pseudo-nitzschia spp.	3,938	*Navicula spp.*	2,500					*Chaetoceros spp.*	1,802
	Thalassiosira spp.	2,763	*Thalassionema spp.*	2,087					Unidentified	1,364
	Thalassionema spp.	1,600	*Chaetoceros spp.*	1,677					*Cylindrotheca spp.*	1,266

One of the top 4 genera in at least 3 of the 5 years sampled for that month.

Table 4-9c. Dominant genera identified by month in Station 50 samples from outer Commencement Bay between 2007 and 2011.

	Station 50 Dominant Genera									
	2007		2008		2009		2010		2011	
	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L	Genera	Average cells/L
January	*Skeletonema spp.*	1,481	no data	n/a	no data	n/a	*Skeletonema spp.*	851	*Actinoptychus spp.*	813
	Cylindrotheca spp.	1,481							*Skeletonema spp.*	813
	Thalassiosira spp.	741							Unknown 3 cell chai	813
	Asteromphalus spp.	741							*Navicula spp.*	813
February	*Thalassiosira spp.*	2,500	*Navicula spp.*	2,362	*Thalassiosira spp.*	3,030	*Thalassionema spp.*	6,557	no data	n/a
	Dictyocha spp.	1,667	*Skeletonema spp.*	787	*Skeletonema spp.*	3,030	*Chaetoceros spp.*	2,459		
	Chaetoceros spp.	1,667	*Asteromphalus spp.*	787	*Chaetoceros spp.*	758	*Pyrophacus spp.*	1,639		
			Chaetoceros spp.	787	*Pseudo-nitzschia spp.*	758	*Actinoptychus spp.*	820		
March	no data	n/a	*Navicula spp.*	13,740	*Thalassiosira spp.*	2,439	*Skeletonema spp.*	23,333	*Cylindrotheca spp.*	18,584
			Thalassiosira spp.	6,870	*Cylindrotheca spp.*	1,626	*Cylindrotheca spp.*	16,667	*Skeletonema spp.*	7,965
			Chaetoceros spp.	3,817	*Chaetoceros spp.*	813	*Thalassiosira spp.*	14,167	*Chaetoceros spp.*	5,310
			Pseudo-nitzschia spp.	3,817	*Prorocentrum spp.*	813	*Thalassionema spp.*	9,167	*Navicula spp.*	4,425
April	*Chaetoceros spp.*	62,992	*Thalassiosira spp.*	6,316	*Pseudo-nitzschia spp.*	8,203	*Chaetoceros spp.*	1,040,945	no data	n/a
	Skeletonema spp.	10,236	*Cylindrotheca spp.*	4,211	*Chaetoceros spp.*	6,850	*Skeletonema spp.*	201,575		
	Pseudo-nitzschia spp.	9,449	*Chaetoceros spp.*	3,158	*Thalassionema spp.*	5,385	*Pseudo-nitzschia spp.*	58,268		
	Thalassiosira spp.	8,661	*Navicula spp.*	2,105	*Skeletonema spp.*	2,818	*Cylindrotheca spp.*	48,819		
May	no data	n/a	*Thalassiosira spp.*	7,537	*Coscinodiscus spp.*	27,409	*Chaetoceros spp.*	100,321	*Chaetoceros spp.*	147,794
			Cylindrotheca spp.	4,724	*Pseudo-nitzschia spp.*	17,729	*Pseudo-nitzschia spp.*	100,107	*Skeletonema spp.*	42,968
			Chaetoceros spp.	2,362	*Chaetoceros spp.*	13,266	*Thalassiosira spp.*	22,756	*Thalassiosira spp.*	37,280
			Thalassionema spp.	2,362	*Cylindrotheca spp.*	4,499	*Ditylum spp.*	9,004	*spp.*	15,418
June	no data	n/a	no data	n/a	*Proboscia spp.*	5,725	*Chaetoceros spp.*	49,800	*Chaetoceros spp.*	148,851
					Pseudo-nitzschia spp.	4,563	*Cylindrotheca spp.*	27,755	*Skeletonema spp.*	74,529
					Ceratium spp.	1,515	*Heterosigma spp.*	14,852	*Cylindrotheca spp.*	11,871
					Actinoptychus spp.	1,139	*Pseudo-nitzschia spp.*	12,077	*spp.*	4,848
July	*Chaetoceros spp.*	4,615	*Skeletonema spp.*	11,538	*Skeletonema spp.*	11,250	*Chaetoceros spp.*	250,933	*Chaetoceros spp.*	168,752
	Pseudo-nitzschia spp.	3,077	*Rhizosolenia spp.*	1,923	*Coscinodiscus spp.*	2,084	*Eucampia spp.*	42,988	*Heterosigma spp.*	3,297
	Cylindrotheca spp.	769	*Protoperidinium spp.*	1,538	*Dinophysis spp.*	1,250	*Ditylum spp.*	34,440	*Detonula spp.*	3,132
	Leptocylindrus spp.	769	*Cylindrotheca spp.*	1,154	*Ceratium spp.*	1,186	*Cylindrotheca spp.*	14,854	*Alexandrium spp.*	2,665
August	*Pseudo-nitzschia spp.*	2,526	*Alexandrium spp.*	8,170	*Actinoptychus spp.*	10,836	*Chaetoceros spp.*	158,946	*Heterosigma spp.*	5,984,395
	Chaetoceros spp.	2,187	*Skeletonema spp.*	7,317	*Alexandrium spp.*	775	*Eucampia spp.*	12,026	*Ceratium spp.*	321,115
	Thalassiosira spp.	1,302	*Ceratium spp.*	4,092	*Coscinodiscus spp.*	388	*Ditylum spp.*	10,478	*Skeletonema spp.*	122,689
	Prorocentrum spp.	1,276	*Thalassiosira spp.*	2,869			*Coscinodiscus spp.*	8,130	*Scrippsiella spp.*	38,936
September	*Thalassionema spp.*	29,949	*Chaetoceros spp.*	85,907	*Skeletonema spp.*	1,498	*Actinoptychus spp.*	2,019	*Heterosigma spp.*	264,248
	Chaetoceros spp.	15,141	*Thalassiosira spp.*	71,121	*Actinoptychus spp.*	1,111	*Detonula spp.*	813	*Scrippsiella spp.*	1,230
	Pseudo-nitzschia spp.	10,502	*Skeletonema spp.*	25,094	*Coscinodiscus spp.*	1,111	*Eucampia spp.*	407	*Prorocentrum spp.*	1,664
	Rhizosolenia spp.	2,713	*Ceratium spp.*	12,166	*Prorocentrum spp.*	750	*Heterosigma spp.*	407	*Coscinodiscus spp.*	820
October	no data	n/a	*Chaetoceros spp.*	12,128	no data	n/a	*Actinoptychus spp.*	1,538	*Akashiwo spp.*	4,167
			Cerataulina spp.	3,137			*Chaetoceros spp.*	769	*Ceratium spp.*	3,333
			Ditylum spp.	1,569			*Pyrophacus spp.*	769	*Scrippsiella spp.*	3,333
			Thalassionema spp.	1,563			*Ceratium spp.*	769	*Ditylum spp.*	2,500
November	*Asteromphalus spp.*	4,032	no data	n/a	*Skeletonema spp.*	2,256	*Thalassionema spp.*	2,419	*Navicula spp.*	6,412
	Chaetoceros spp.	2,419					*Navicula spp.*	1,613	*Chaetoceros spp.*	5,344
	Pseudo-nitzschia spp.	2,419					Unknown - green nucle	1,613	*Protoperidinium sp*	1,069
	Leptocylindrus spp.	1,613					*Actinoptychus spp.*	806	*Pyrophacus spp.*	1,069
December	Unknown red-ciliated plar	2,326	*Thalassiosira spp.*	1,724	no data	n/a	no data	n/a	*Pyrophacus spp.*	1,739
	Navicula spp.	775	*Ceratium spp.*	862					*Navicula spp.*	870
	Skeletonema spp.	775							*Protoperidinium sp*	870
	Scrippsiella spp.	775							*Actinoptychus spp.*	870

One of the top 4 genera in at least 3 of the 5 years sampled for that month.

Table 4-10. Top 20 genera by abundance present in Quartermaster Harbor from 2007 through 2011

Stations 51-54				Stations 55-56			
Genera	Total cells	Avg cells/L *	Frequency of Occurrence (%)	Genera	Total cells	Avg cells/L *	Frequency of Occurrence (%)
Chaetoceros spp.	26,802,904	95,046	78	*Chaetoceros spp.*	26,837,291	100,261	81
Heterosigma spp.	12,851,260	45,572	23	*Prorocentrum spp.*	12,854,190	100,251	45
Thalassiosira spp.	9,377,048	33,252	68	*Heterosigma spp.*	9,380,970	78,761	25
Prorocentrum spp.	7,674,464	27,214	33	*Thalassiosira spp.*	7,675,464	34,829	62
Thalassionema spp.	6,184,667	21,931	36	*Thalassionema spp.*	6,189,644	28,533	38
Pseudo-nitzschia spp.	5,610,661	19,896	59	*Rhizosolenia spp.*	5,618,483	18,899	38
Skeletonema spp.	2,667,084	9,458	48	*Pseudo-nitzschia spp.*	2,672,967	18,768	53
Cylindrotheca spp.	2,388,275	8,469	57	*Cylindrotheca spp.*	2,400,081	11,548	50
Rhizosolenia spp.	1,958,254	6,944	27	*Skeletonema spp.*	1,958,254	9,658	41
unknown unicellular	1,366,169	4,845	5	Unknown unicellular	1,366,169	8,842	7
Ceratium spp.	1,348,224	4,781	32	*Leptocylindrus spp.*	1,349,224	5,421	20
Alexandrium spp.	1,044,793	3,705	27	*Ceratium spp.*	1,064,715	5,289	29
Leptocylindrus spp.	955,934	3,390	20	*Actinoptychus spp.*	955,934	3,268	45
Pyrophacus spp.	789,366	2,799	41	*Scrippsiella spp.*	816,226	3,043	43
Scrippsiella spp.	642,571	2,279	32	*Alexandrium spp.*	646,540	2,920	31
Eucampia spp.	562,764	1,996	20	*Pyrophacus spp.*	562,764	2,854	52
Navicula spp.	455,527	1,615	50	Unknown red-ciliated	480,240	2,140	3
Actinoptychus spp.	414,695	1,471	38	*Dactyliosolen spp.*	417,640	2,042	9
Protoperidinium spp.	313,689	1,112	33	*Navicula spp.*	313,689	2,011	47
Dinophysis spp.	308,611	1,094	24	*Heterocapsa spp.*	308,611	2,005	13
* Avg cells/L based upon 286 samples				* Avg cells/L based upon 118 samples			

Table 4-11. Top 20 genera by abundance present in Commencement Bay from 2007 through 2011

Station 50			
Genera	Total cells	Avg cells/L *	Frequency of Occurrence (%)
Heterosigma spp.	12,538,378	179,120	16
Chaetoceros spp.	3,511,129	50,159	67
Skeletonema spp.	891,644	12,738	57
Ceratium spp.	729,025	10,415	36
Pseudo-nitzschia spp.	476,299	6,804	53
Thalassiosira spp.	375,461	5,364	53
Cylindrotheca spp.	270,204	3,860	49
Thalassionema spp.	140,508	2,007	24
Ditylum spp.	127,098	1,816	19
Eucampia spp.	125,931	1,799	24
Scrippsiella spp.	104,467	1,492	21
Coscinodiscus spp.	95,215	1,360	23
Prorocentrum spp.	94,012	1,343	31
Actinoptychus spp.	93,691	1,338	40
Navicula spp.	84,564	1,208	41
Heterocapsa spp.	72,846	1,041	7
Alexandrium spp.	66,822	955	26
Pyrophacus spp.	58,108	830	26
Protoperidinium spp.	40,559	579	29
Hemiaulus spp.	38,522	550	10
* Avg cells/L based upon 70 samples			

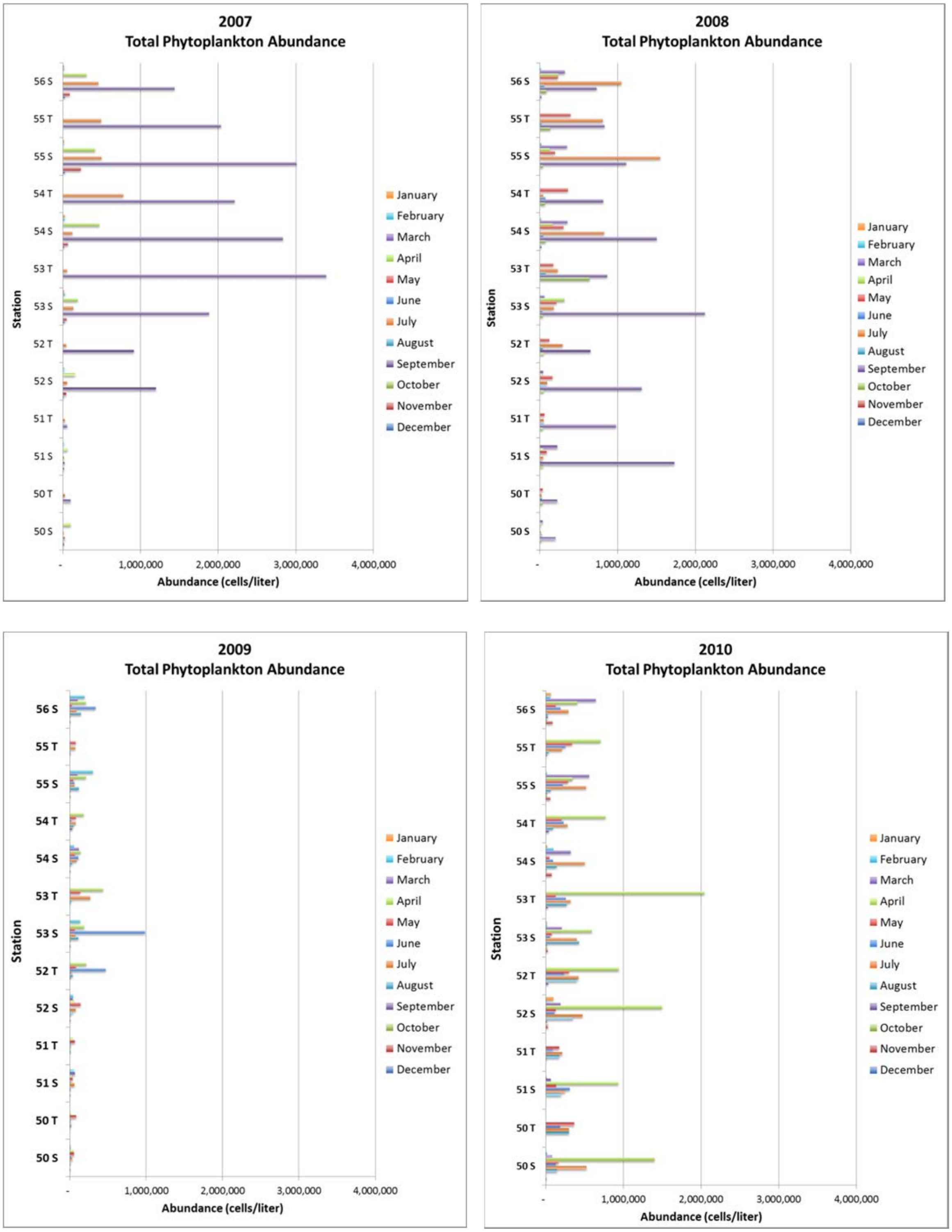


Figure 4-68. Total phytoplankton abundance by year and by station. The 'S' and 'T' next to the station name refer to surface and thermocline. Note the scale is different for 2011.

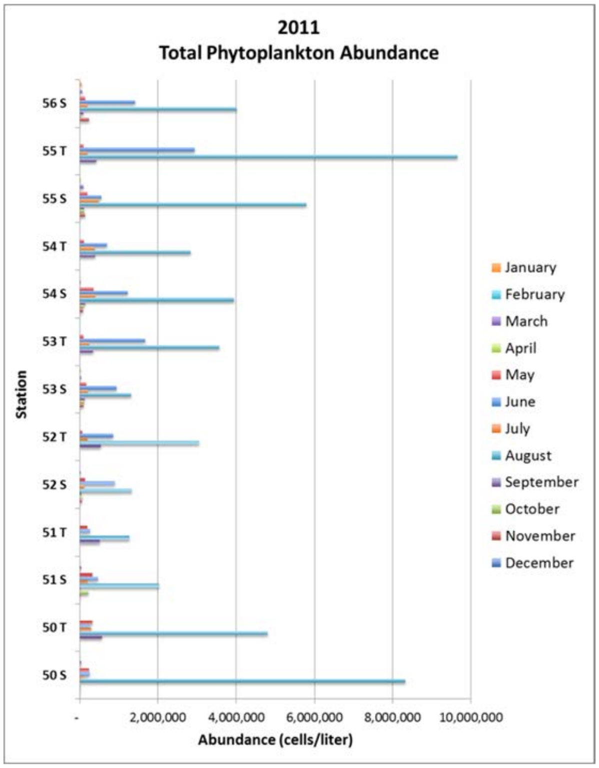


Figure 4-68 (cont.)Total phytoplankton abundance by year and by station. The 'S' and 'T' next to the station name refer to surface and thermocline. Note the scale is different for 2011.

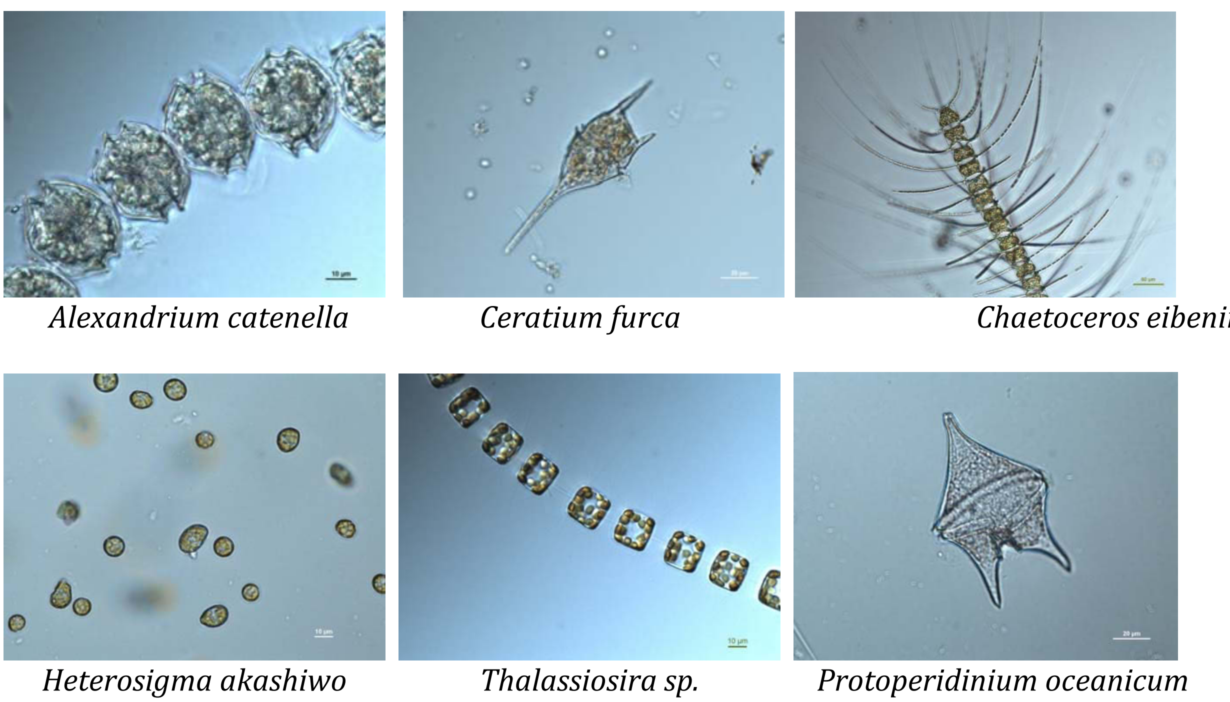


Figure 4-69. Phytoplankton species commonly seen in Quartermaster Harbor, Photographs by Gabriela Hannach

4.6 Fecal Coliform Bacteria

Fecal coliform bacteria results from 2007 through 2011 for the three Quartermaster Harbor stations monitored by King County are summarized below. Only surface water (1 m depth) results are summarized as values tend to be the highest in the surface layer. Fecal coliform results are provided as they are found in the intestinal tract and feces of humans and other warm-blooded animals and can be an indicator of potential wastewater input, including failing septic systems.

Monthly fecal coliform results indicate little to no bacteria are present in marine waters throughout the year at the sites sampled. The running geometric means, calculated using the 12 most recent samples, for all three sites were either at or below 3 colony forming units (cfu)/100 ml between 2007 and 2011. The majority of values were 0 cfu/100 ml for the Dockton Park (NSAJ02) and Yacht Club (MSWH01) sites. Although the beach site at Burton Acres (MSXK01) had generally higher fecal coliform counts, which is typical for a beach site compared to an offshore site, the values were still low and the highest geometric mean was just above 3 cfu/100 ml. Figure 4-70 shows monthly results for all three sites and Figure 4-71 shows the geometric means in relation to the Washington state fecal coliform water quality standard of 14 cfu/100ml.

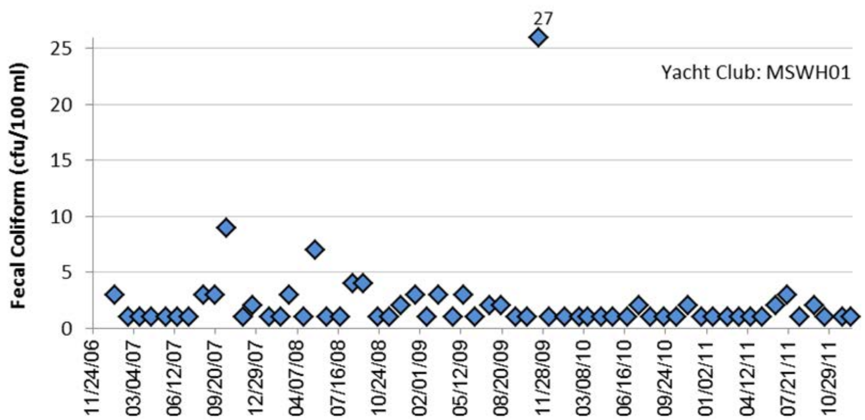


Figure 4-70. Monthly Quartermaster Harbor fecal coliform sampling results.

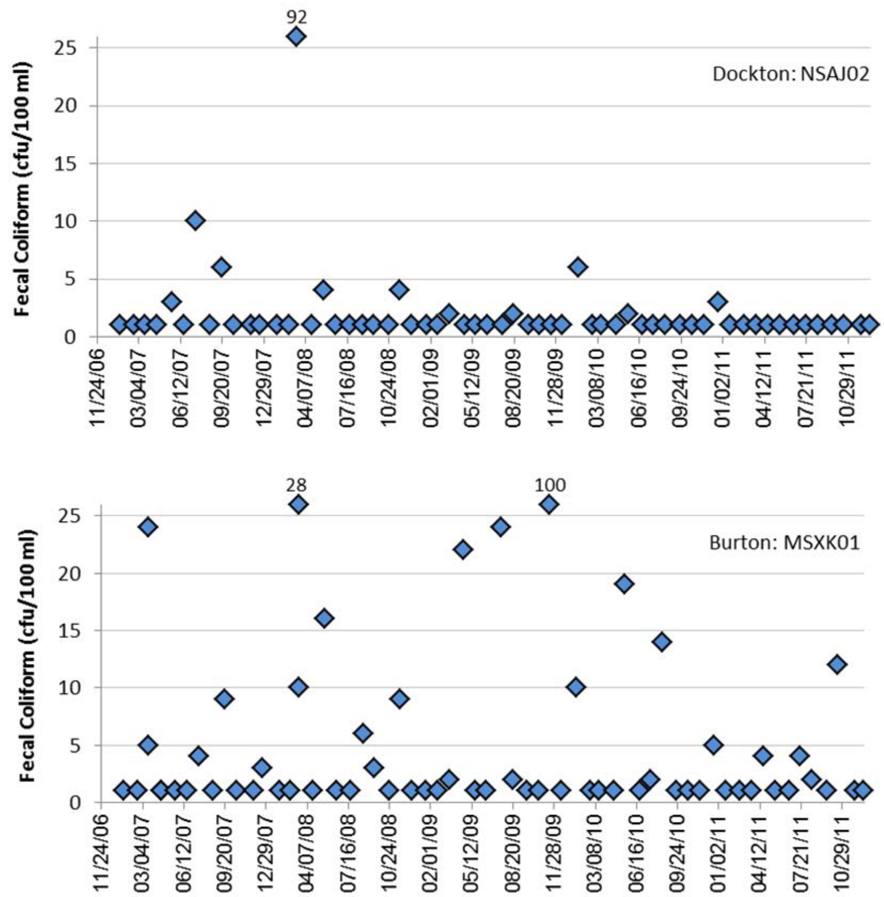


Figure 4-70 (cont.). Monthly Quartermaster Harbor fecal coliform sampling results.

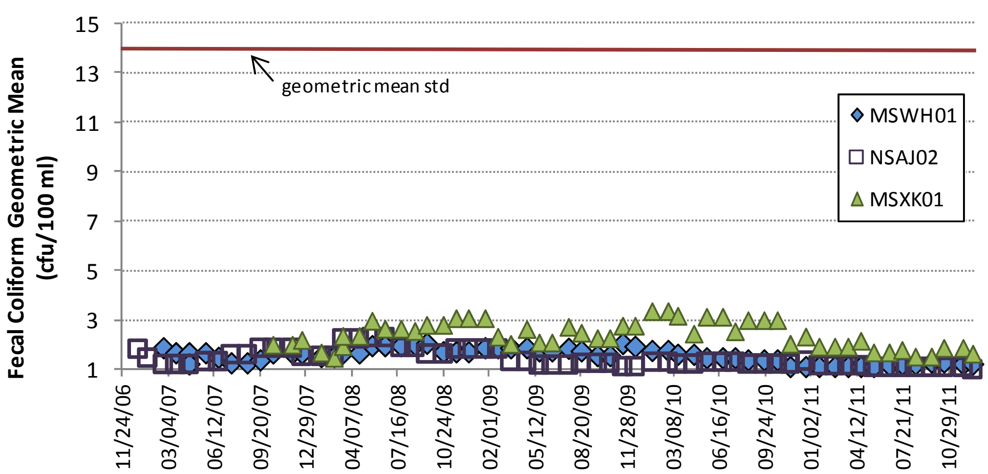


Figure 4-71. Running geometric means for fecal coliform bacteria

5.0 DISCUSSION

The information provided in this report allows for a characterization of the complex water quality conditions and processes in Quartermaster Harbor. As stated previously, Quartermaster Harbor is a small, shallow, southward facing embayment with only one outlet connecting to the Puget Sound Main Basin. Given the shallow depth of this bay, when density stratification is weak, wind energy can mix water from top to bottom in the bay (unlike a large portion of Puget Sound where it is too deep for this to occur). These conditions often occur during winter when stratification is weak and winds are strong and storms are frequent. In the summer, the water column becomes more stratified and winds are weaker, so there tends to be less vertical mixing. Stratification in Quartermaster Harbor, like the rest of Puget Sound, is dominated by salinity influenced by freshwater input at the surface, which is often highest in the spring due to river runoff and snowmelt inputs into the Main Basin. These physical mechanisms also affect biological processes in Quartermaster Harbor. Temperature increases often lead to increased biological and chemical activity which decreases the capacity of water to hold DO.

Quartermaster Harbor exhibits a seasonal cycle typical for a shallow embayment. Winter winds and surface cooling lead to a well-mixed, homogeneous water column from top to bottom with no stratification. DO and nutrients are also available throughout the water column due to mixing and lack of phytoplankton growth. Water temperature, solar radiation, and freshwater input increase in the spring which increases water column stratification and allows for a spring phytoplankton bloom. The spring bloom typically leads to an increase in DO in the upper water column. In summer, the upper layer warms and remains stratified, limiting nutrient and oxygen exchange between these two layers. During this time, nutrients are depleted and oxygen begins to decline in the lower layer as it becomes isolated from the atmosphere. In addition, as the phytoplankton die or are eaten by zooplankton and then eliminated as waste, this organic material sinks to the seafloor where it is decomposed by bacteria and the nutrients are recycled back into a form that can be used by phytoplankton if transported back to the surface. Bacteria use up oxygen as part of the decomposition process. As a result, late summer/fall is typically when the lowest levels of DO are observed in Quartermaster Harbor. The low oxygen concentrations can be exacerbated by low flushing rates that restrict water exchange between the bay and rest of Puget Sound. This is particularly true for the inner harbor where the flushing rates in October are on the order of up to 100 days (Albertson 2013). In early fall, as winds start to increase and stratification starts to decrease, some of these nutrients make it back to the surface through vertical mixing and a fall phytoplankton bloom occurs. The cycle then repeats itself.

Water circulation in Quartermaster Harbor is heavily influenced by tides, winds, strong seasonal stratification, and freshwater influx (including the occasional intrusion of the Puyallup River plume into the outer harbor). Figures 4-22 and 5-1 show the influence of freshwater input, represented by discharge flows from the Puyallup River, on surface salinities in the outer harbor (Station 54) and at the entrance to Quartermaster Harbor (Station NSGE01). The geographic configuration of Quartermaster Harbor and the

combined influence of these physical forcing conditions have an impact on the flushing rate. Residence times for water parcels in the inner harbor tend to be high, on the order of two months, due to the limited flow through the one outlet (Albertson 2013). This flow is primarily limited by tidal currents across the mouth of the harbor and the occasional influx of the Puyallup River plume that acts as a low density barrier to estuarine outflow of surface water from the harbor. Restricted water flow, when combined with the shallow, protected physical configuration of the harbor, leads to strong seasonal stratification and a relatively shallow pycnocline as compared to areas outside the harbor.

During late-fall to mid-winter months, from November through February, nutrient levels within and outside of Quartermaster Harbor are comparable and tend to be high due to low levels of phytoplankton and photosynthetic biological activity associated with lower winter light levels and temperatures. Figure 5-2 shows solar radiation at Dockton recorded at 15-minute intervals throughout the year from 2009 through 2011. Overall, light levels increase in early spring until late June, corresponding to the seasonal increase in available daylight hours. In early spring, phytoplankton abundance increases with increased daylight and, at the same time, surface stratification increases due to increased spring freshwater runoff. These conditions lead to a system which is both vertically and horizontally constrained and this is the time of the spring phytoplankton bloom in Quartermaster Harbor, typically in early March. The spring bloom in Quartermaster Harbor occurs earlier than in open waters of the Main Basin.

The spring bloom is dominated by diatoms as they are efficient at nutrient uptake and have a fast growth rate. During the spring bloom, nutrients in both the upper and lower water column in Quartermaster Harbor are taken up until nitrate/nitrite, and occasionally silica, are depleted below detectable levels. This depletion typically occurs between April and August until nutrients are replenished by freshwater input and biogeochemical pathways. Of the external nutrient sources evaluated in the *Initial Assessment of Nutrient Loading to Quartermaster Harbor* report, tributary streams were identified as the most significant source of nitrogen and silica (KC 2010). Nutrient depletion occurs earlier in the inner harbor (March) and can persist through September. A benthic nutrient flux study conducted in September 2010 indicated that sediments may be a significant source of nutrients during the late summer/early fall period when DO values are low. The largest nutrient flux was seen in the inner harbor (KC 2011). Figure 5-3 shows the seasonal relationship between nitrate+nitrite and chlorophyll-*a* for both the outer (Dockton) and inner (Yacht Club) harbors from 2007 through 2011. Following large blooms, silica can be depleted below detectable levels during the initial spring bloom but levels are replenished by freshwater input subsequent to the bloom and/or remineralization from the sediments. Nutrients are also drawn down to nearly undetectable levels in the surface waters of Commencement Bay and below detectable levels in East Passage, although nutrients in deep waters in both these areas remain high due to the lack of photosynthetic activity.

The phytoplankton community in Quartermaster Harbor differs from that observed in Commencement Bay and East Passage in that phytoplankton abundances generally appear to be higher, but diversity is lower. This may be indicative of a eutrophic system as well as a dinoflagellate-based (microbial) food web as dinoflagellates have lower species diversity

than diatoms. During late summer when the water column is highly stratified causing low surface nutrients, dinoflagellates take over as the dominant phytoplankton group in the water column. Dinoflagellates are adapted to be able to swim which allows them to migrate vertically to take advantage of nutrients that may be available below the pycnocline. QMH is a documented hotspot for the occurrence of the dinoflagellate, *Alexandrium catenella,* which causes paralytic shellfish poisoning (Horner et al. 2011).

Once phytoplankton deplete nutrients, they die and sink to the seafloor where they are decomposed by bacteria. This decay process uses up oxygen leading to low bottom oxygen levels as well as causing high ammonia values as a byproduct of decomposition. DO levels typically drop following the spring bloom, recover to high levels, then continue to drop throughout the summer until annual lows are reached in the fall months, typically late August through September (Figure 5-4). This is also the time when flushing rates in Quartermaster Harbor, in particular the inner harbor where the lowest DO levels occur, are the lowest of the year.

Low oxygen levels typically observed during the day do not represent the lowest oxygen levels in Quartermaster Harbor. There are diurnal variations of the oxygen levels in Quartermaster Harbor, with nighttime levels being the lowest due to lack of oxygen production from photosynthesis and uptake from respiration. As most sampling throughout Puget Sound occurs during daylight hours, the diurnal signal and the lowest levels of DO are only captured by continuous sampling techniques, emphasizing the importance of these sampling systems.

During large phytoplankton blooms, DO levels in the surface layer increase dramatically due to the increased oxygen production through photosynthesis. Both continuous monitoring and monthly sampling indicate that oxygen levels in the surface layer of inner Quartermaster Harbor are often supersaturated (>200%) during this time. It is recommended that more continuous time series data are needed as a way to more accurately reflect daily variability and to evaluate the health of Puget Sound marine ecosystems, particularly in sensitive areas.

Quartermaster Harbor is a biologically-driven system with phytoplankton dynamics having a considerable influence on nutrient and DO levels. The physical configuration of Quartermaster Harbor and, consequently poor flushing rate, exacerbates this influence. Unlike in open waters, phytoplankton are present at substantial levels throughout much of the year in Quartermaster Harbor, particularly in early spring and in the fall months. The sinking and decay of phytoplankton plays a critical role in the biogeochemical nutrient cycle and sediments in the shallow inner harbor, in particular, are likely an important source of nutrients to the water column. Both high and low DO levels observed at various times throughout the year are connected with phytoplankton productivity. Thus, understanding nutrient availability during the summer and fall months and the associated effects on and phytoplankton and DO levels is crucial. Key findings from this study are as follows:

- the sediment biogeochemical cycle likely plays a large role in nutrient cycling, but the role sediments play in replenishing and adding nutrients to the water column needs further study;
- the shallow inner harbor is the area of most concern based upon DO and nutrient data;
- the lowest DO values occur in the inner harbor usually in late August through September, occasionally in October;
- the inner harbor exhibits diurnal and tidal cycle DO variations with nighttime levels sometimes falling below 1.0 mg/L;
- nitrate/nitrite is depleted below detectable levels in the water column for extended periods, up to five consecutive months, and the addition of more nutrients during this time could lead to even lower DO levels;
- diatoms dominate during the spring months and dinoflagellates during the late summer and early fall months; and
- bacteria levels do not indicate a sustained wastewater source but does not exclude drain fields as a nutrient source.

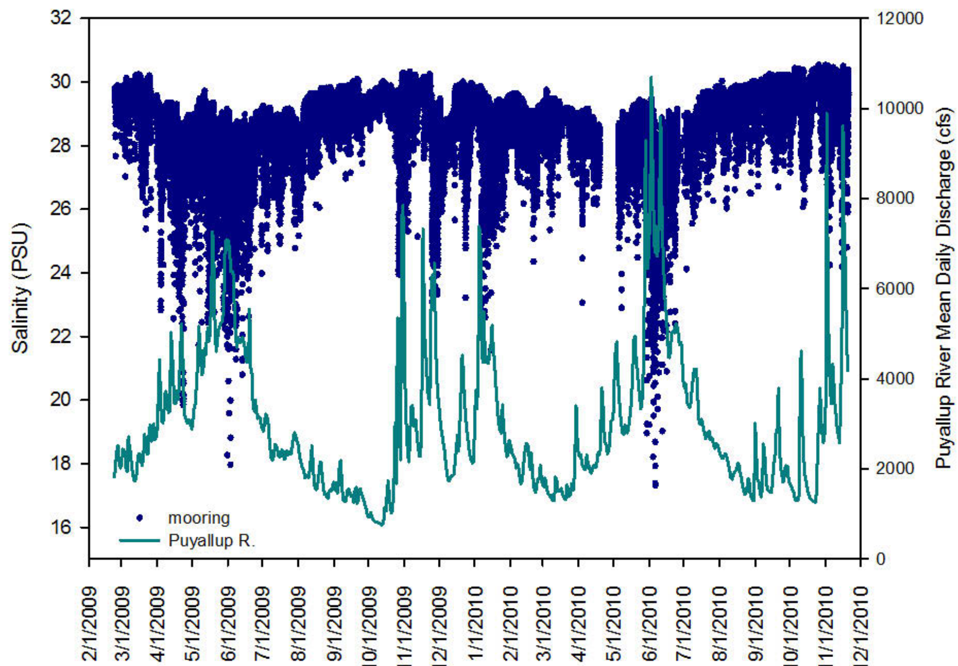


Figure 5-1. Surface salinities at the entrance to QMH (NSGE01) and the influence of freshwater input. Salinity data were recorded at 15-minute intervals.

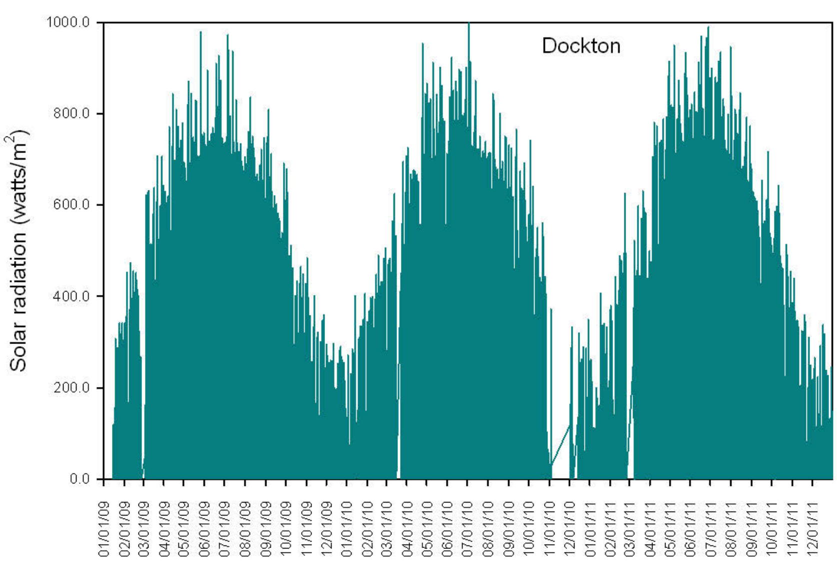


Figure 5-2. Solar radiation seasonal cycle at Dockton recorded at 15-minute intervals between 2009 and 2011.

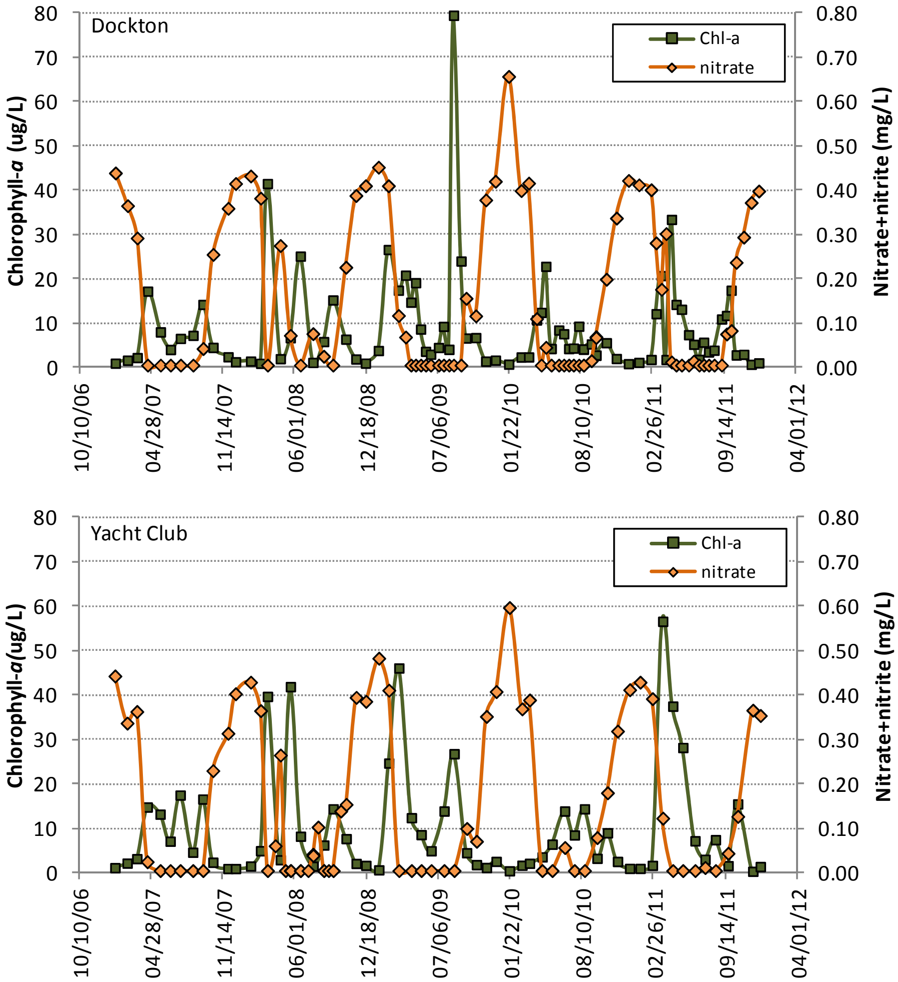
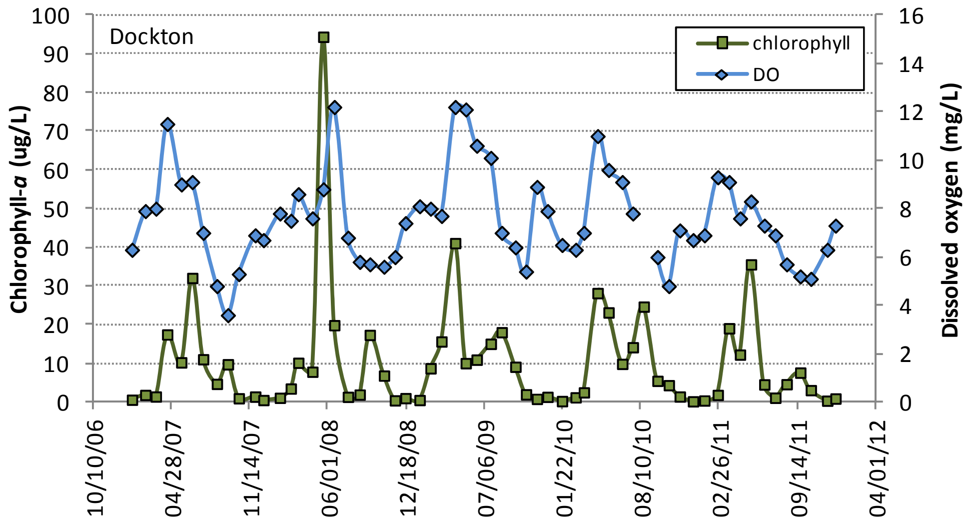


Figure 5-3. Seasonal nitrate/nitrite and chlorophyll pattern in surface waters (1 m)



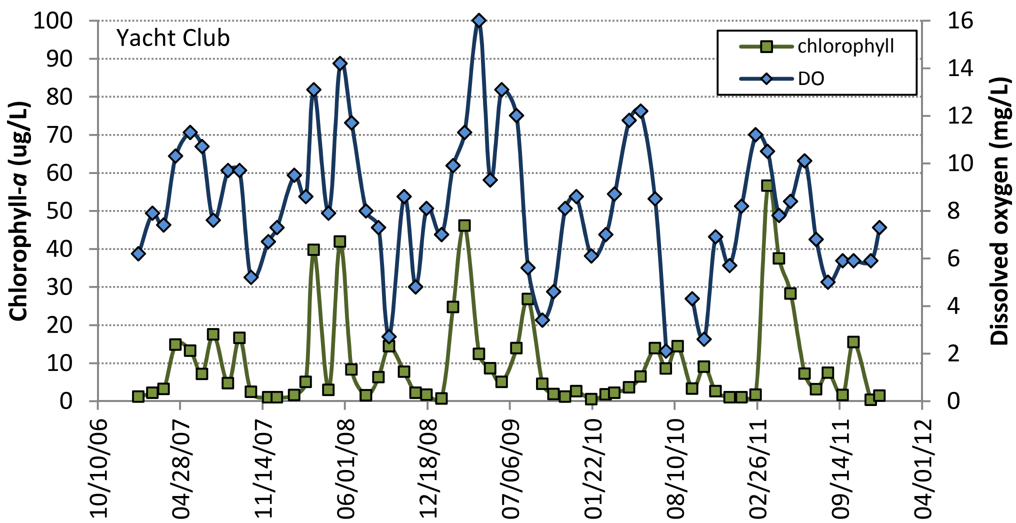


Figure 5-4. Chlorophyll and DO relationship in bottom waters in both the inner and outer harbors

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APPENDICES

Appendix A UWT water column profile plots 2007-2011

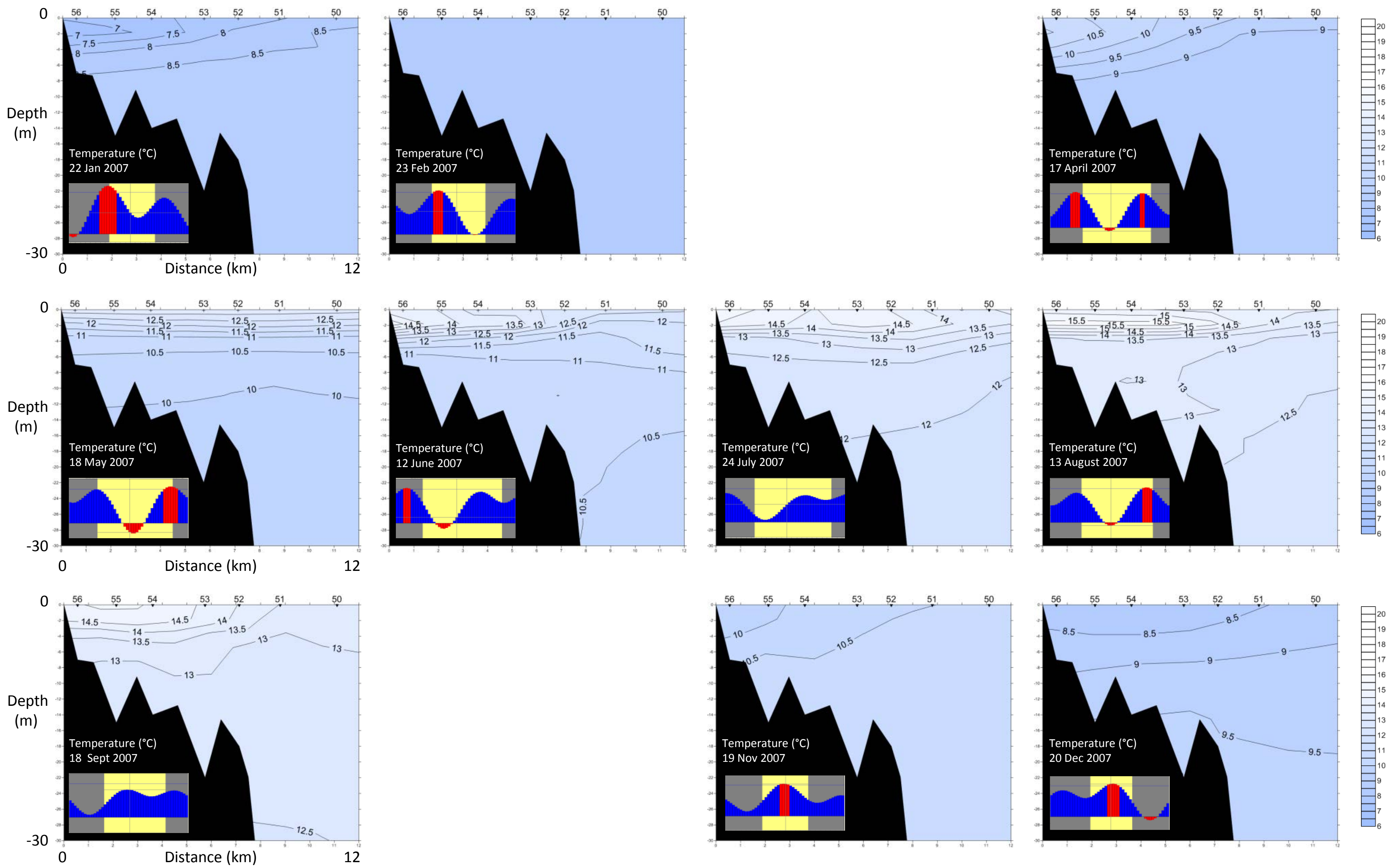
Appendix B UWT Mooring data (station 54)

Appendix C UWT Time series & property-property plots

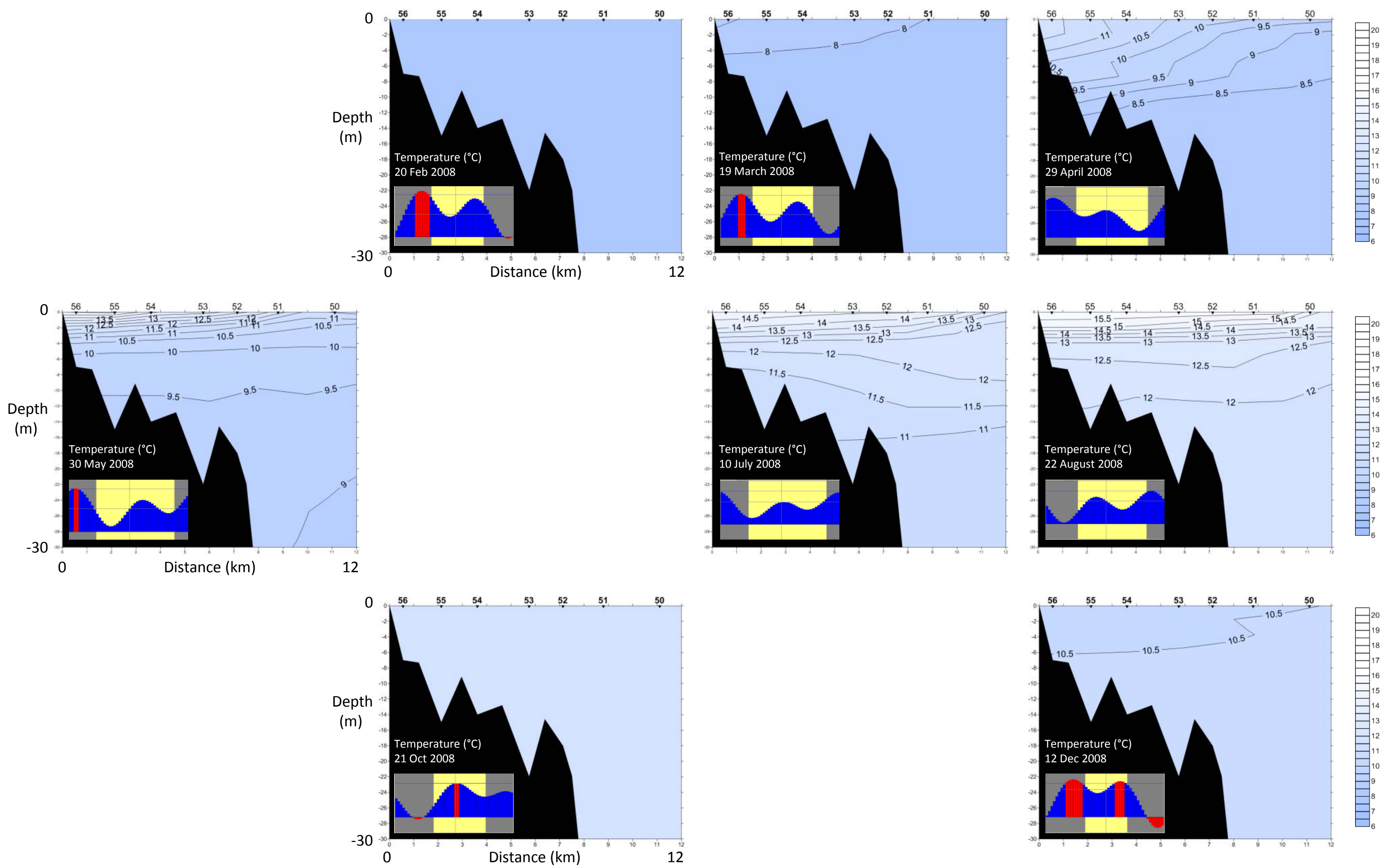
Appendix D Marine phytoplankton

Appendix A: UWT Water Column Profile Plots 2007--2011

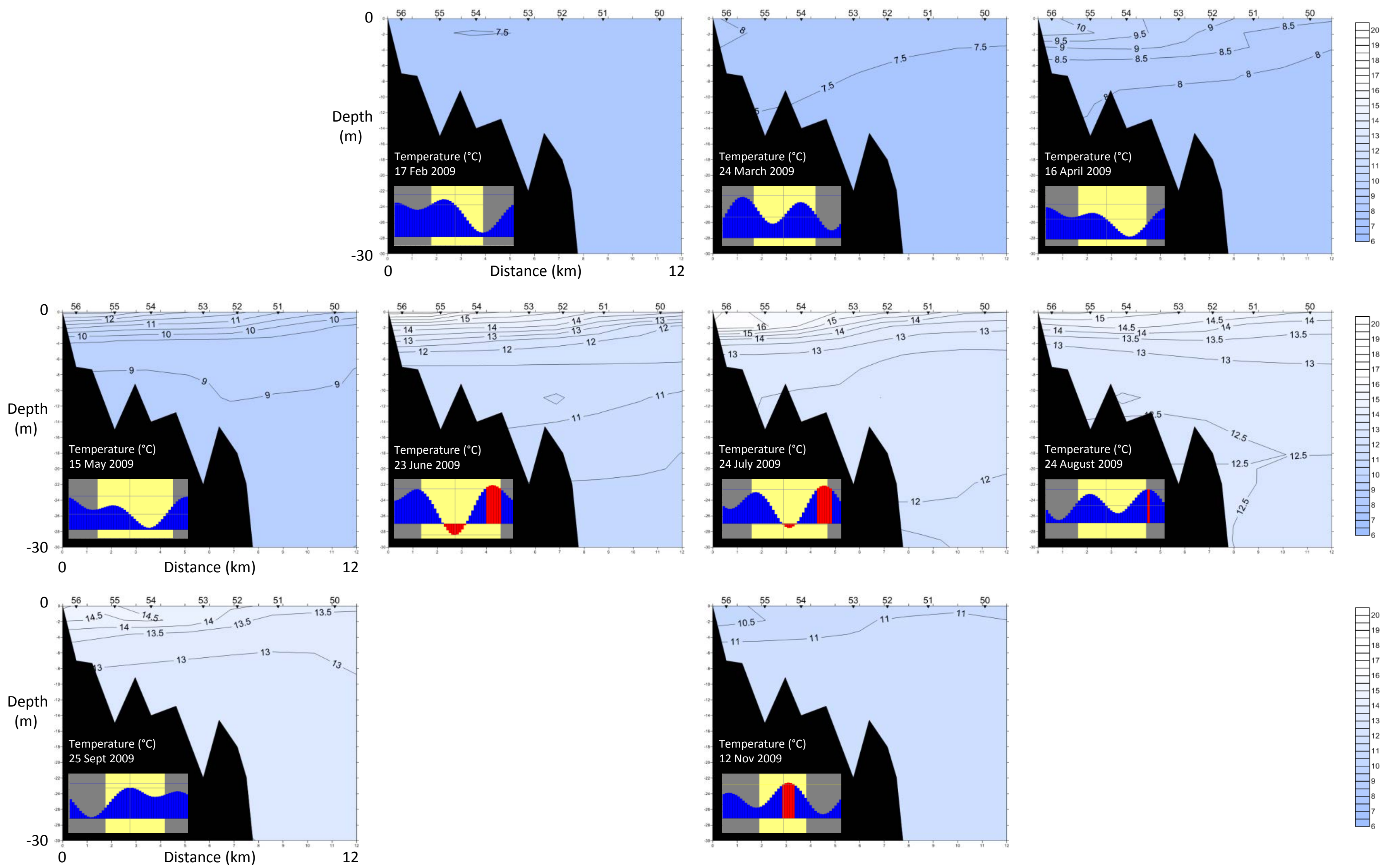
2007 Temperature (°C)



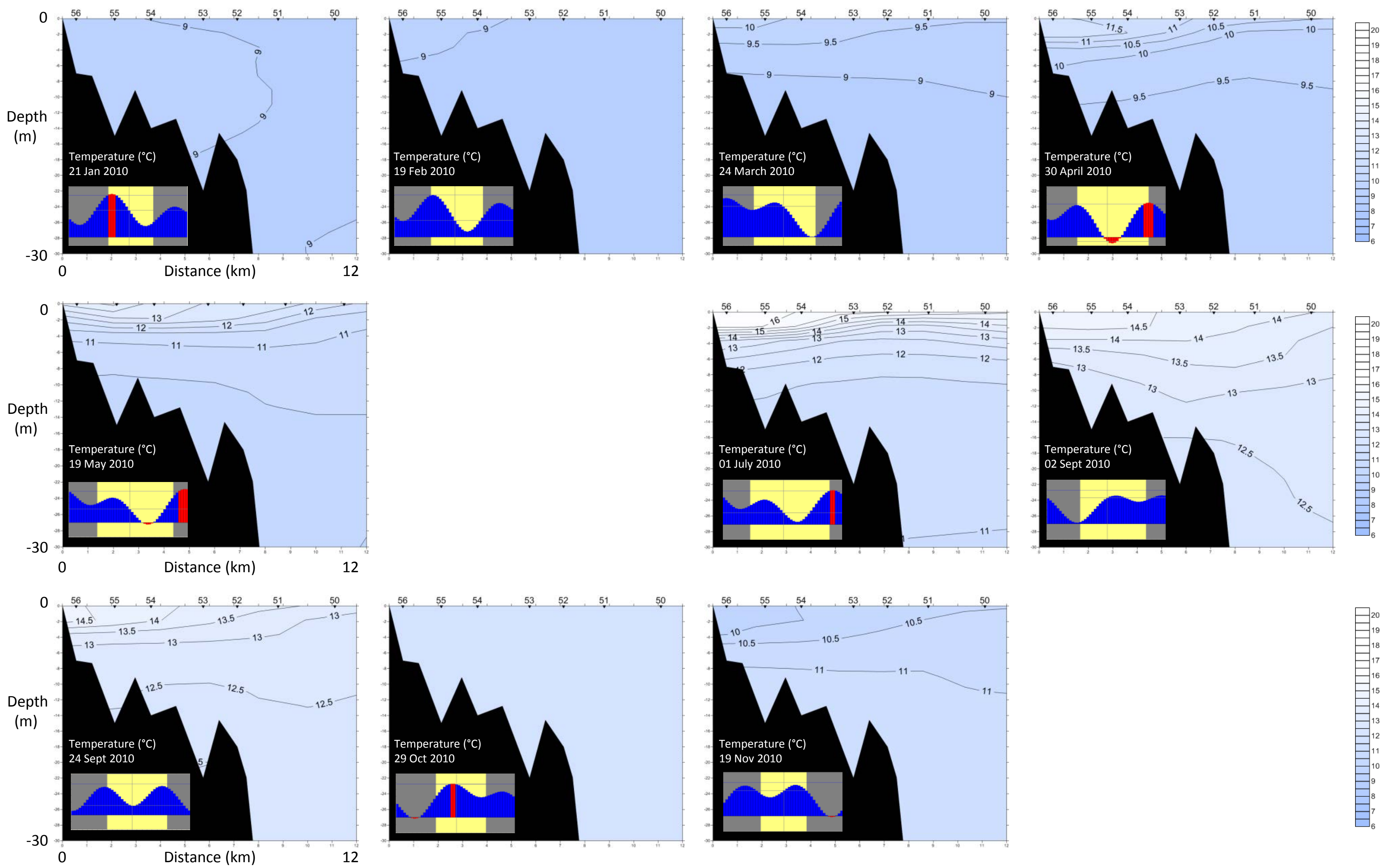
2008 Temperature (°C)



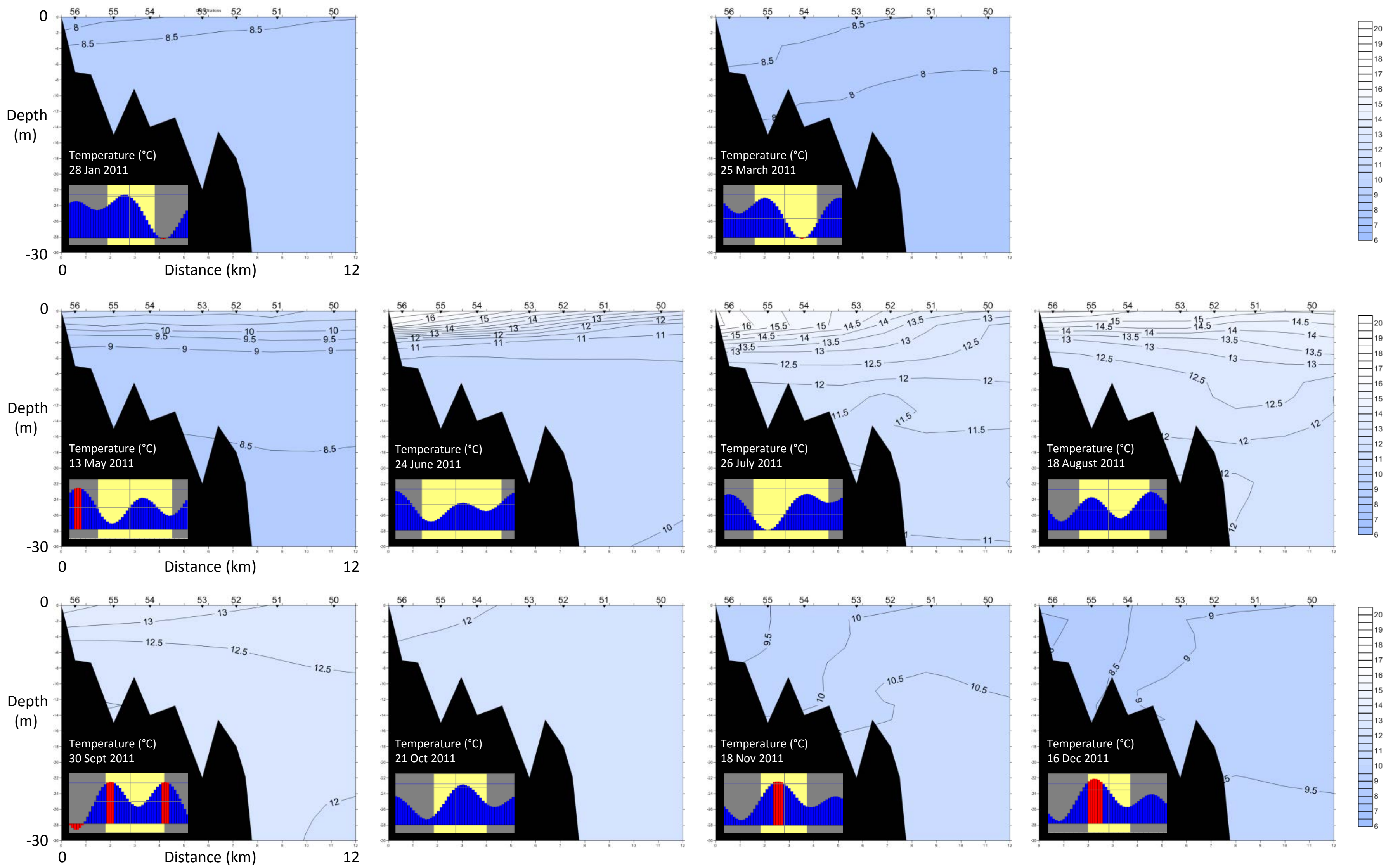
2009 Temperature (°C)



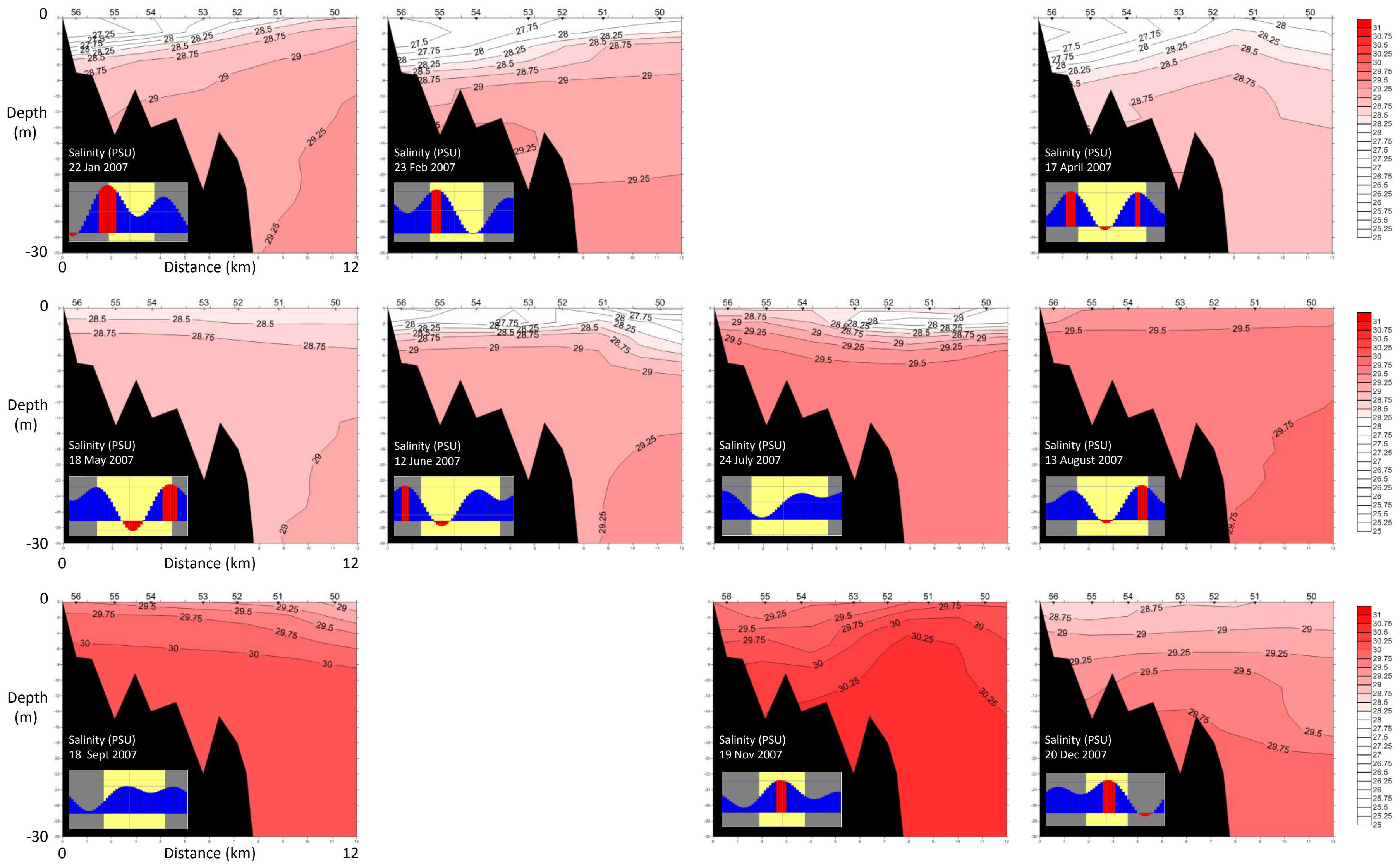
2010 Temperature (°C)



2011 Temperature (°C)



2007 Salinity (PSU)



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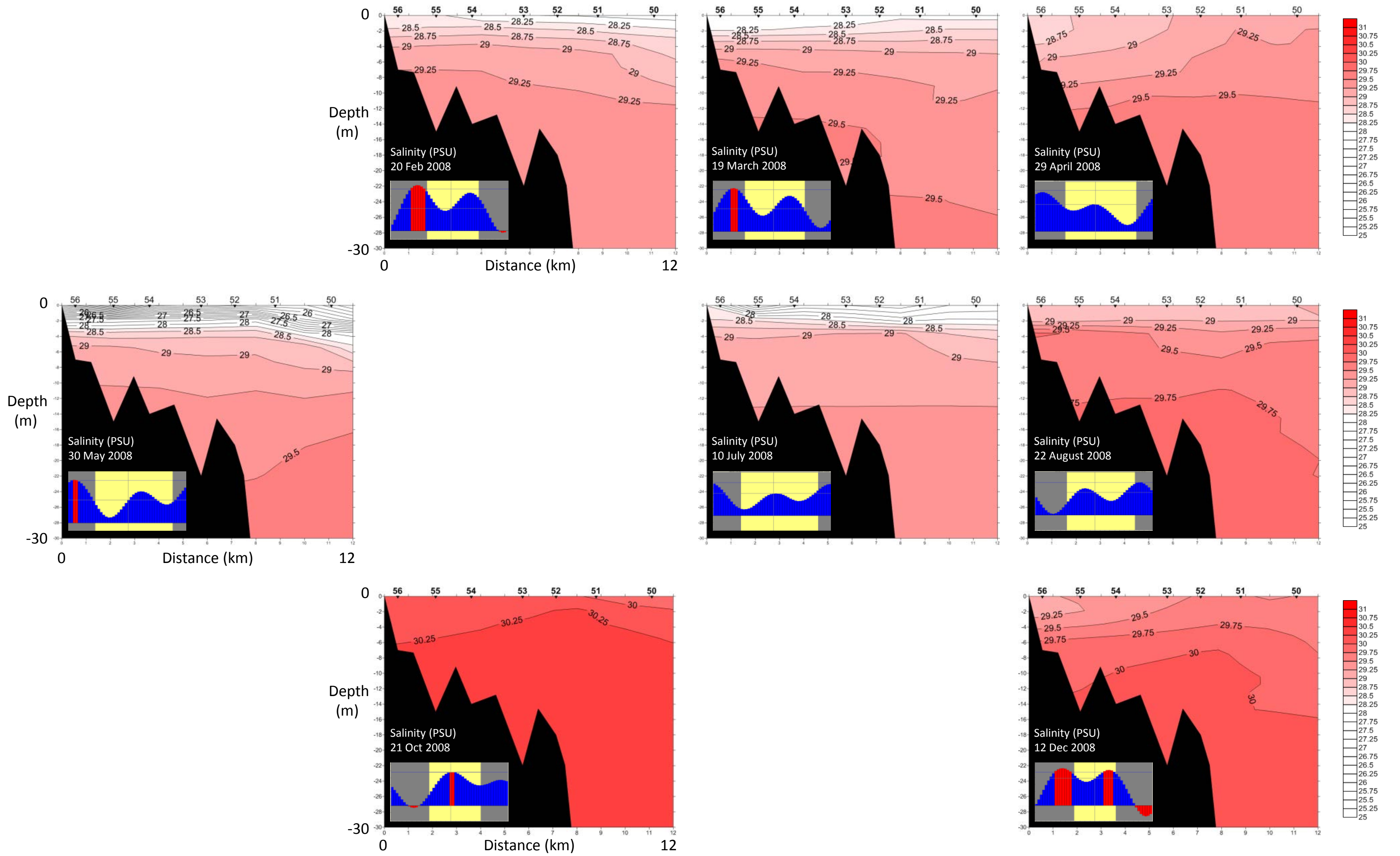

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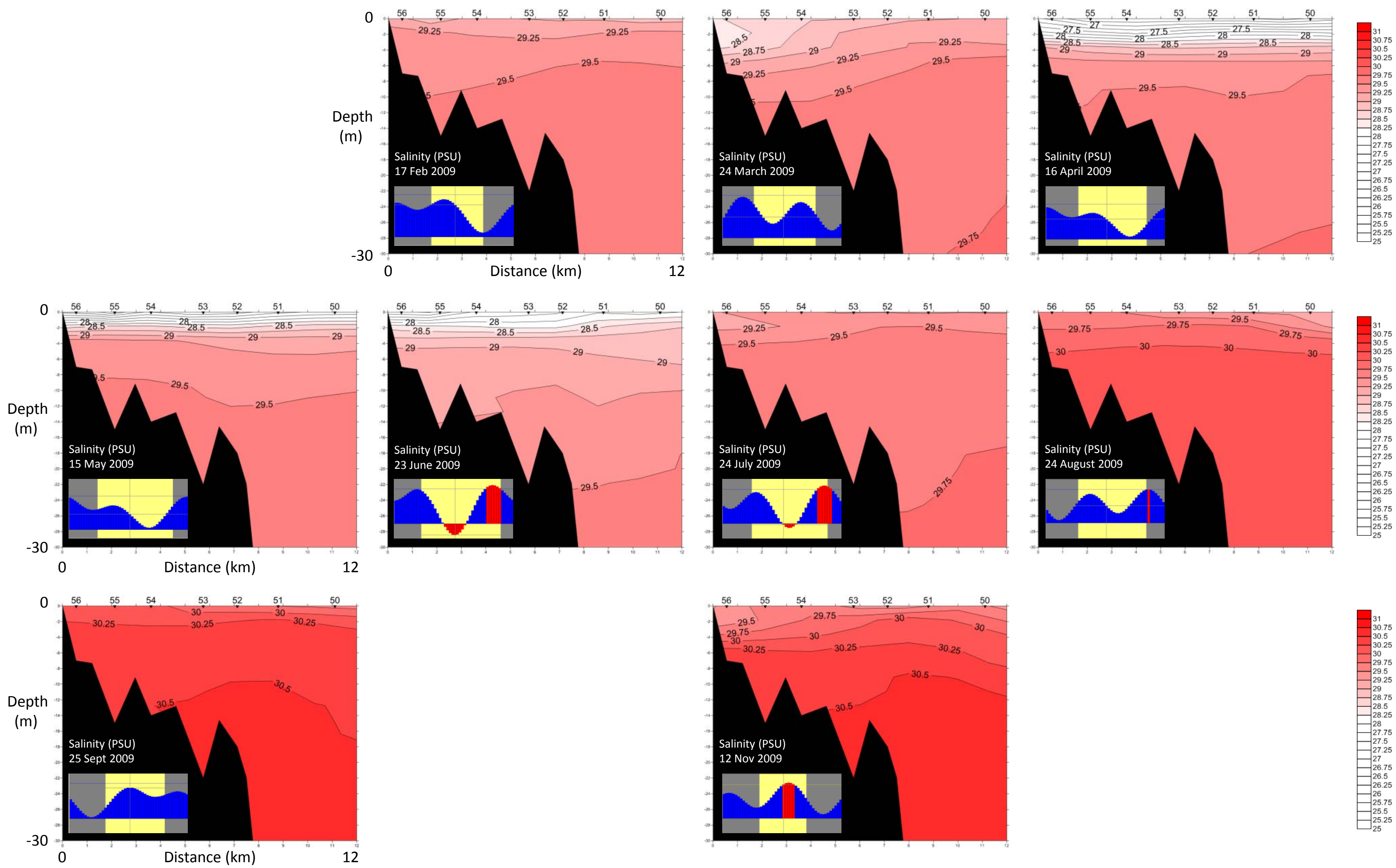

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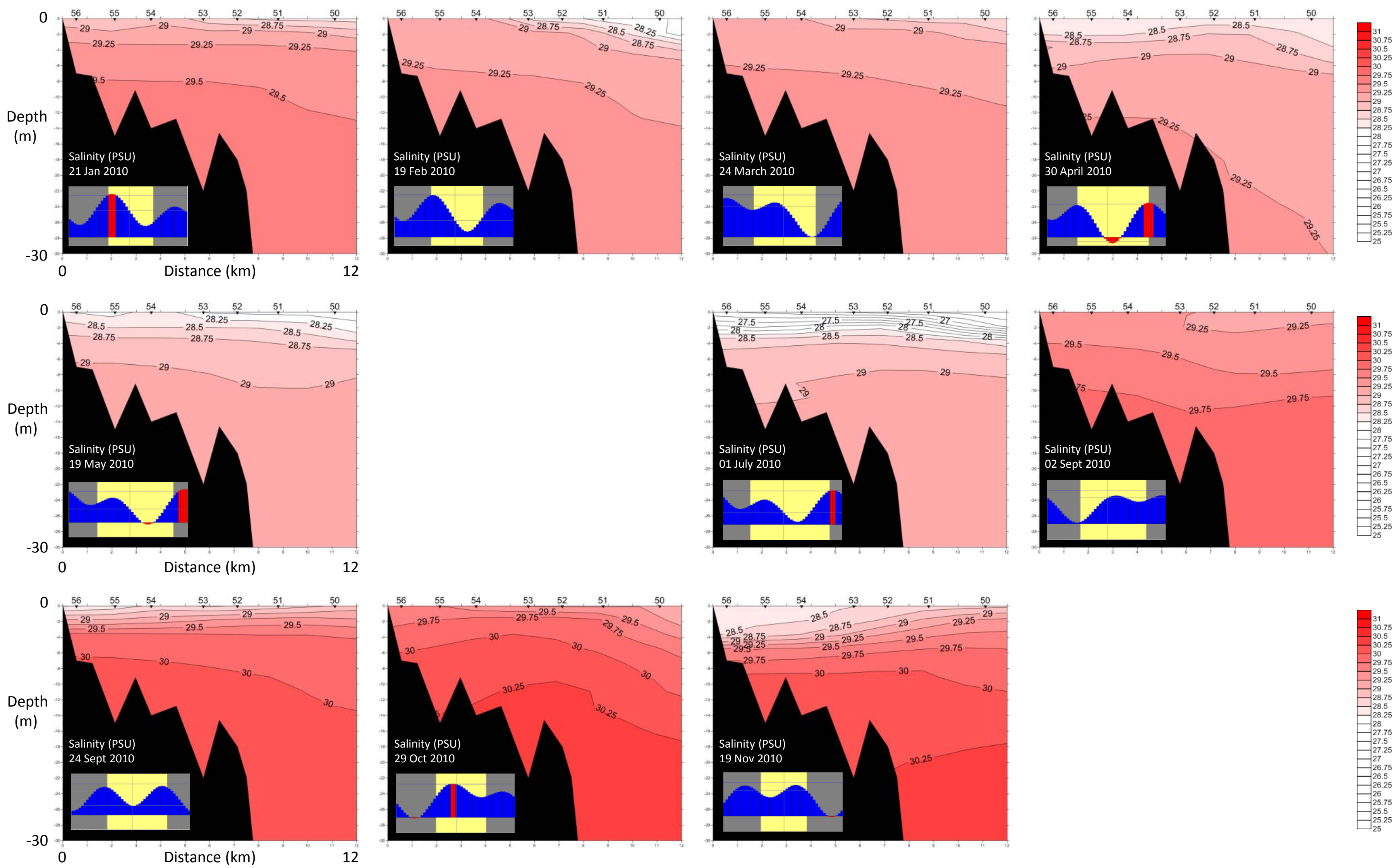
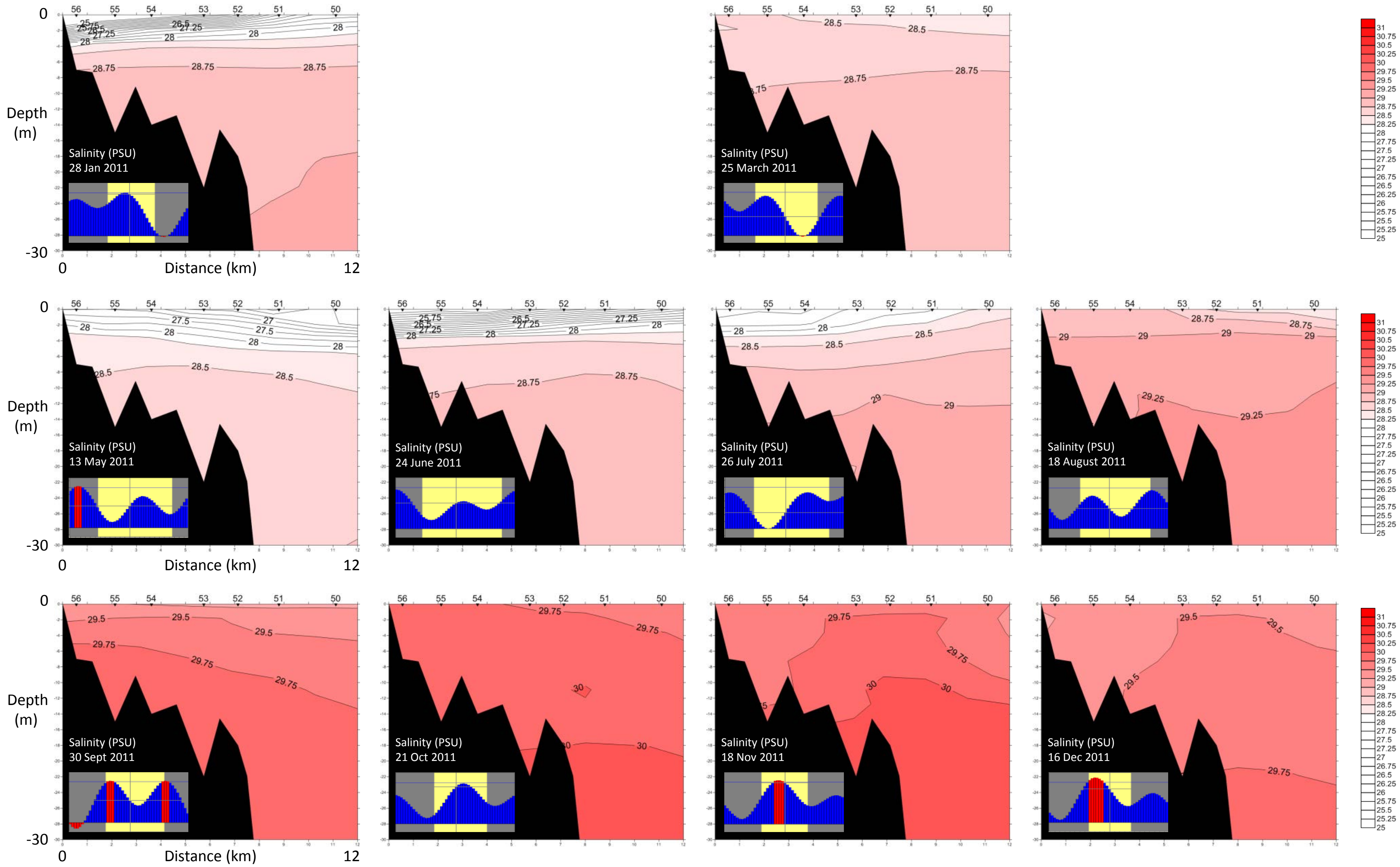
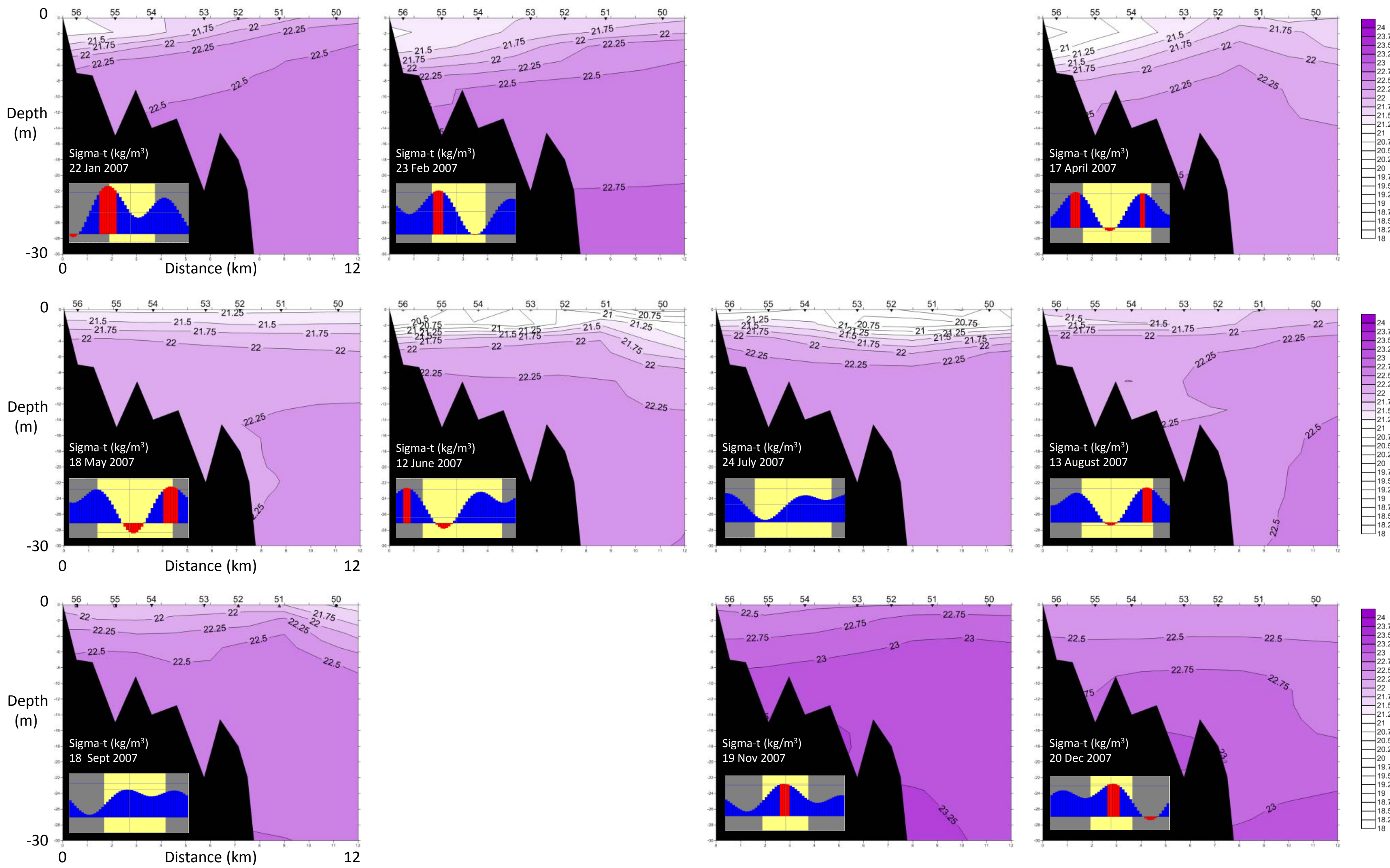


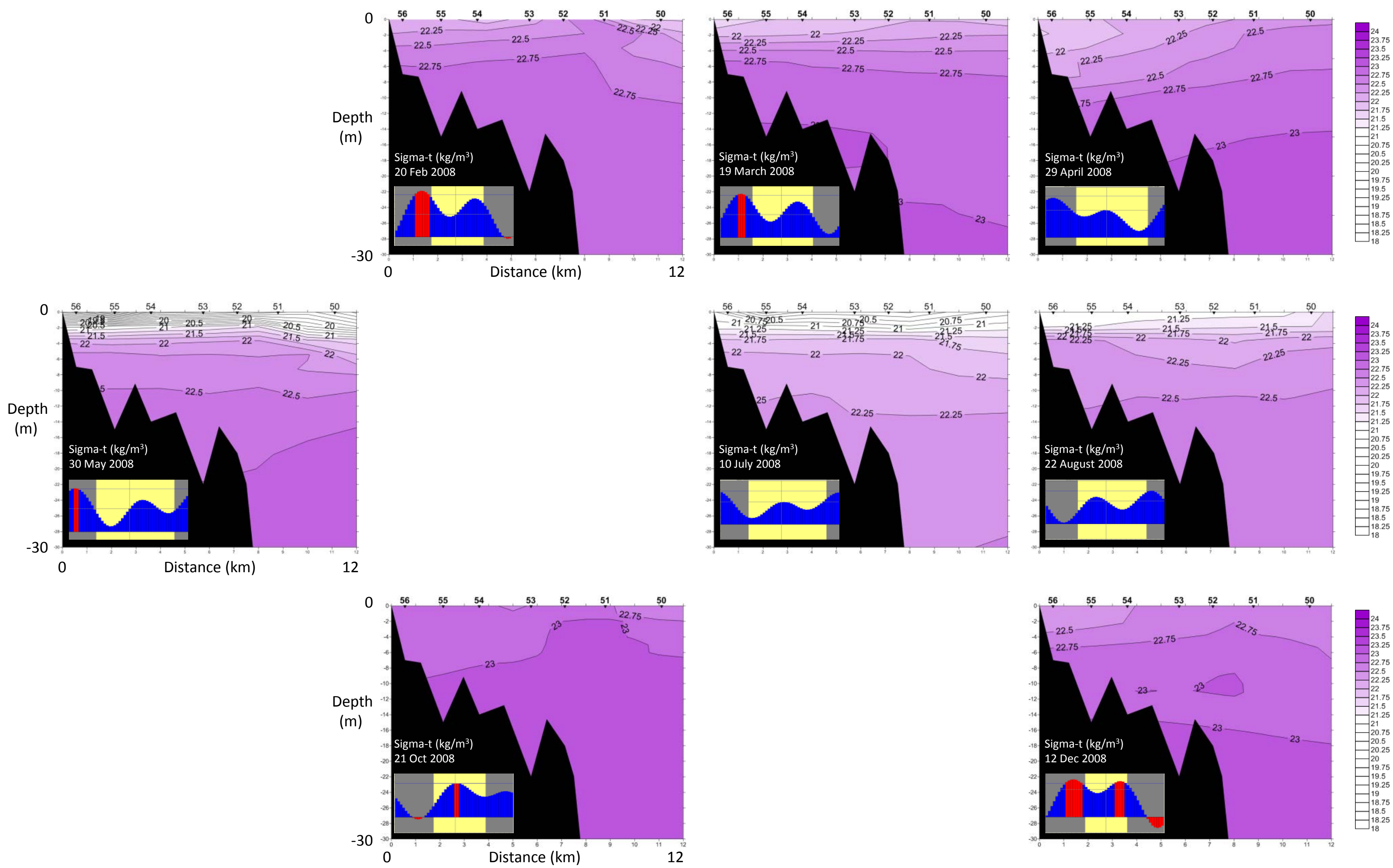
2011 Salinity (PSU)



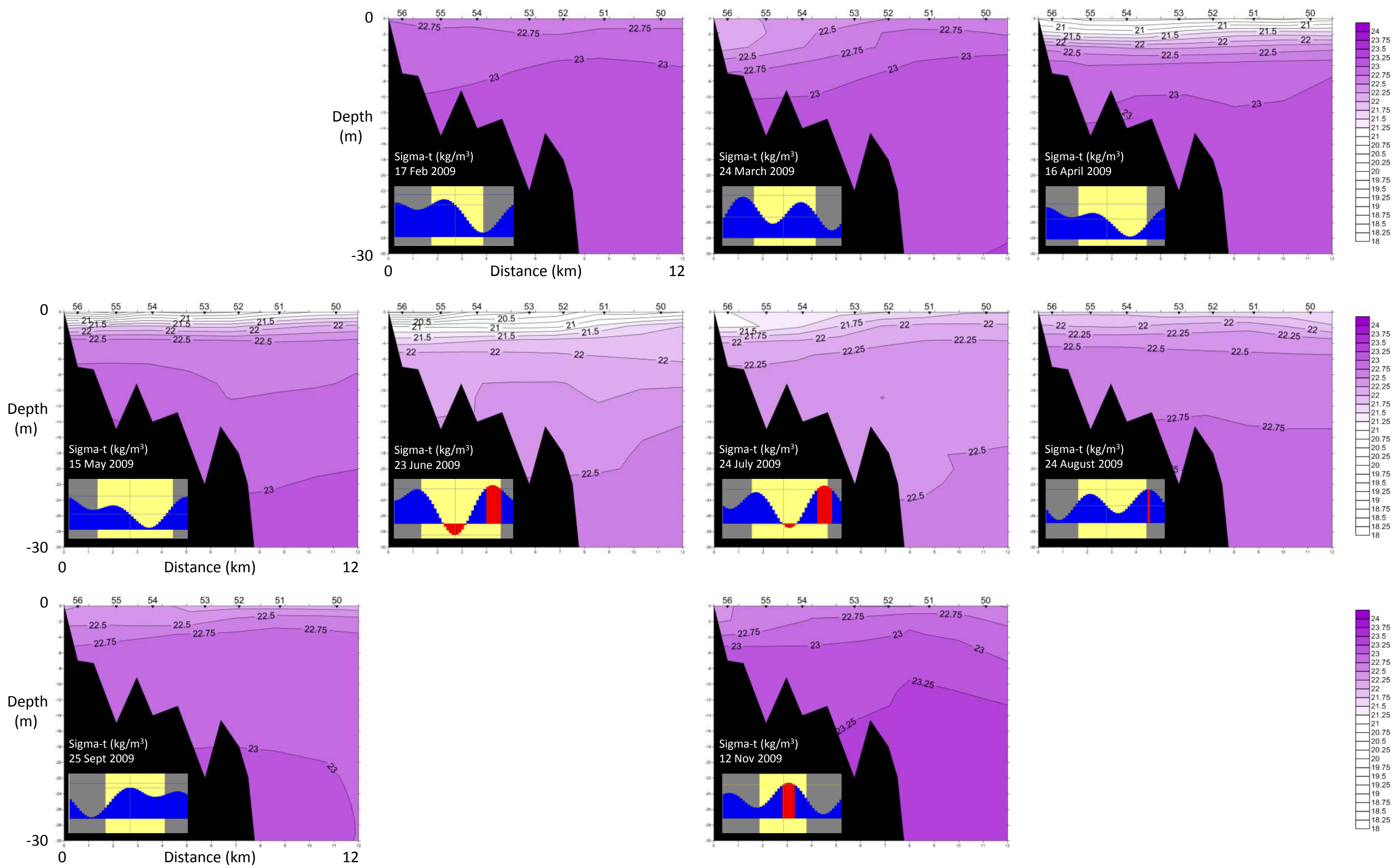
2007 Density (sigma-t) (kg/m^3)



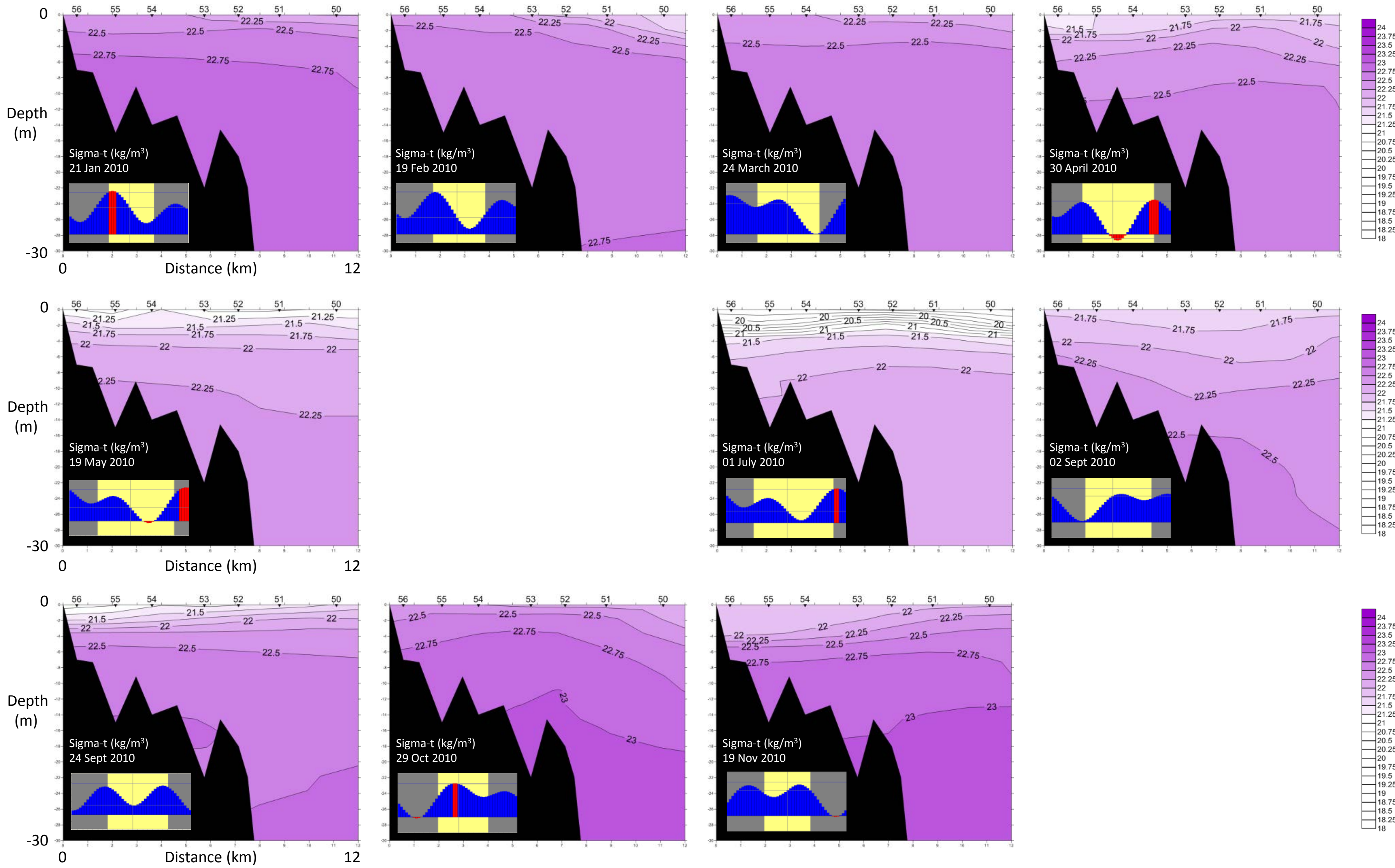
2008 Density (sigma-t) (kg/m^3)



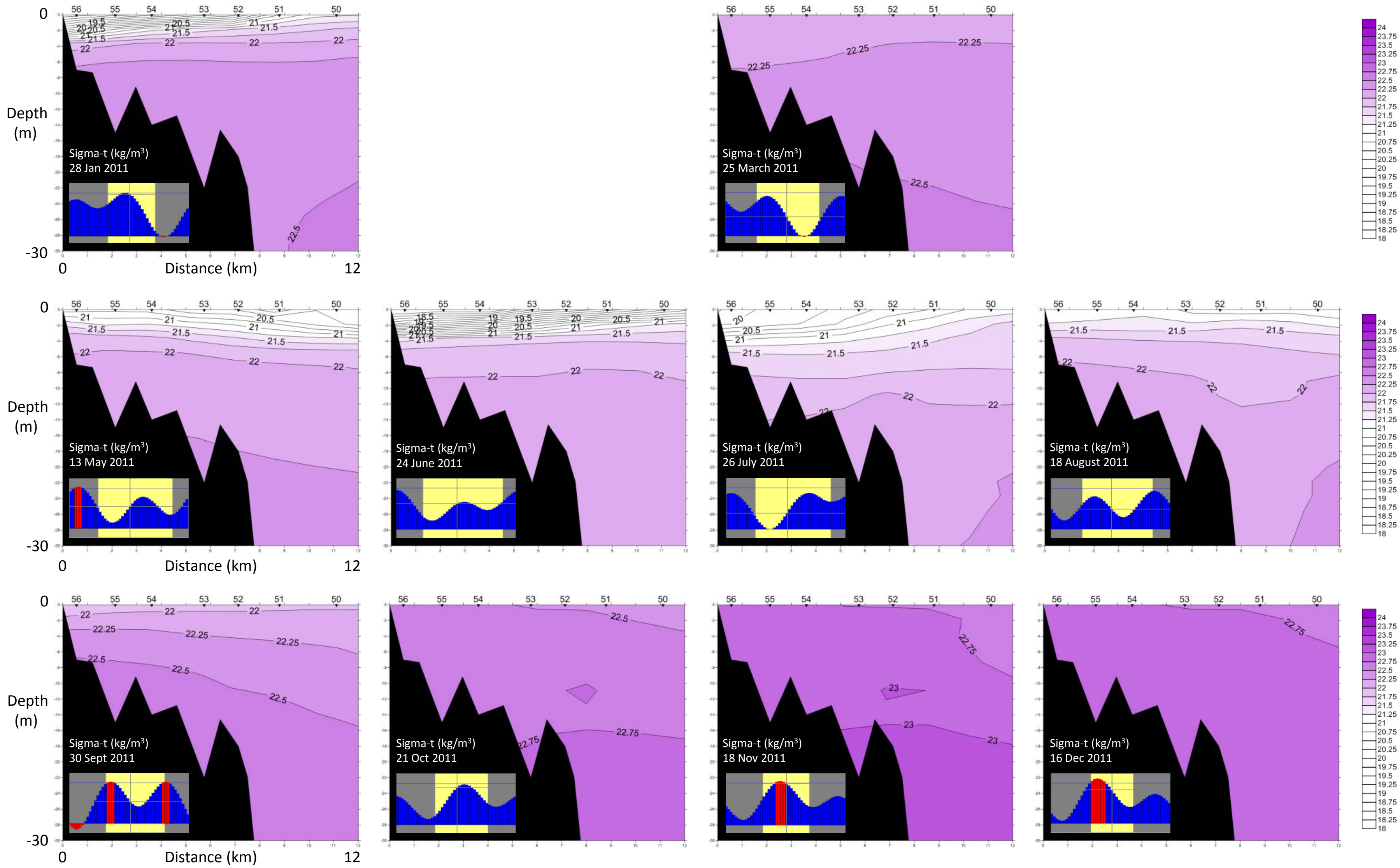
2009 Density (sigma-t) (kg/m³)



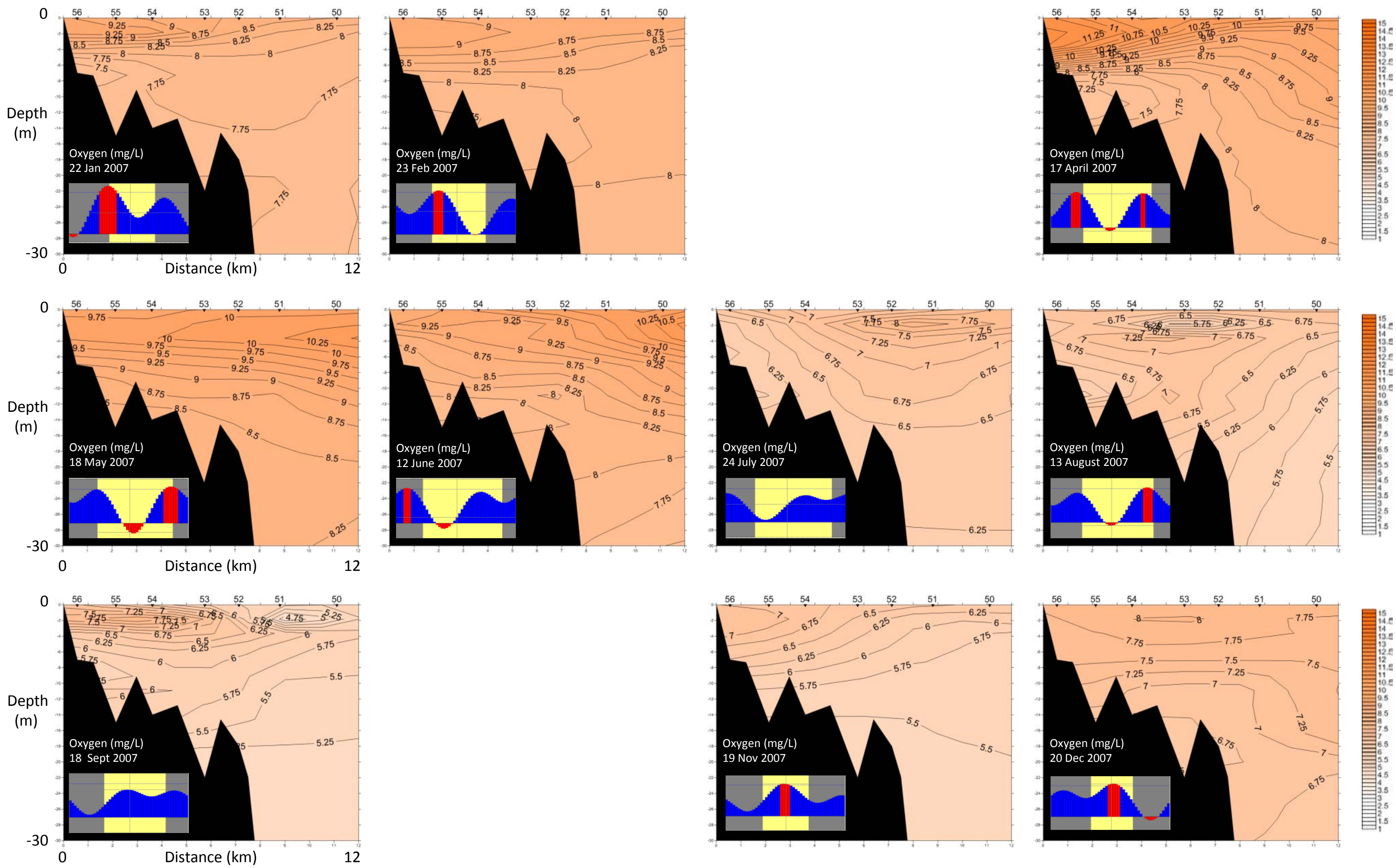
2010 Density (sigma-t) (kg/m^3)



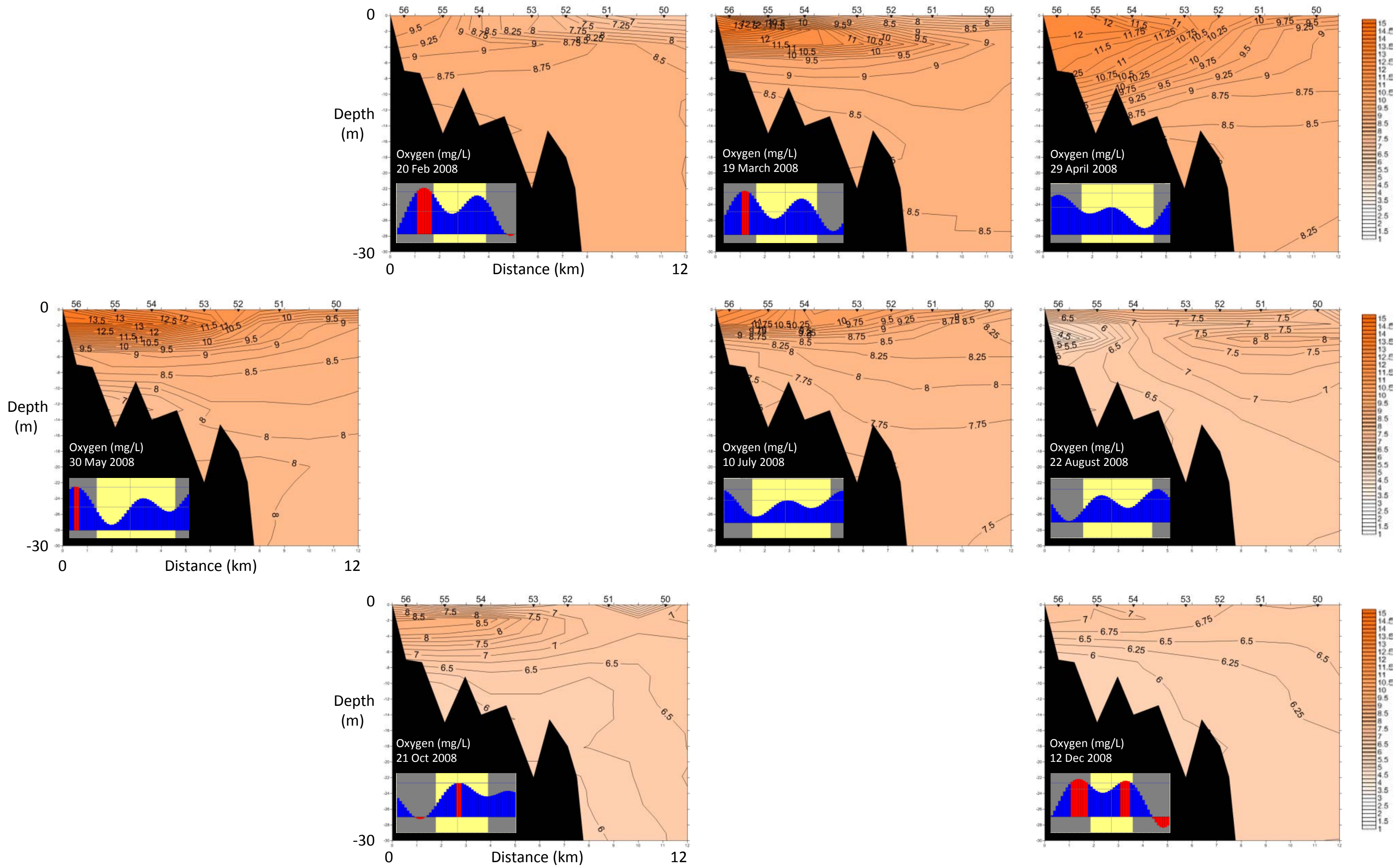
2011 Density (sigma-t) (kg/m^3)



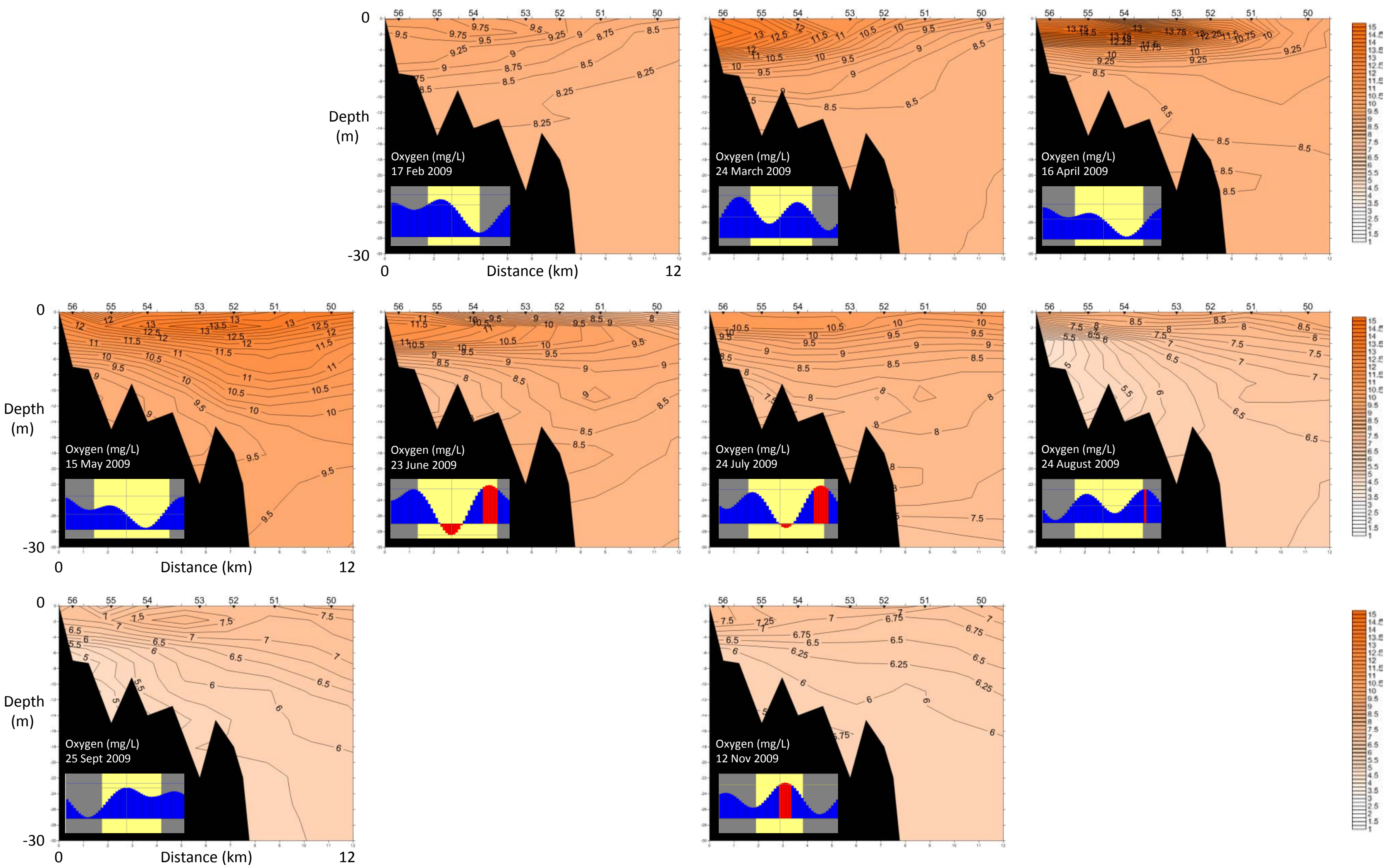
2007 Dissolved Oxygen (mg/L)



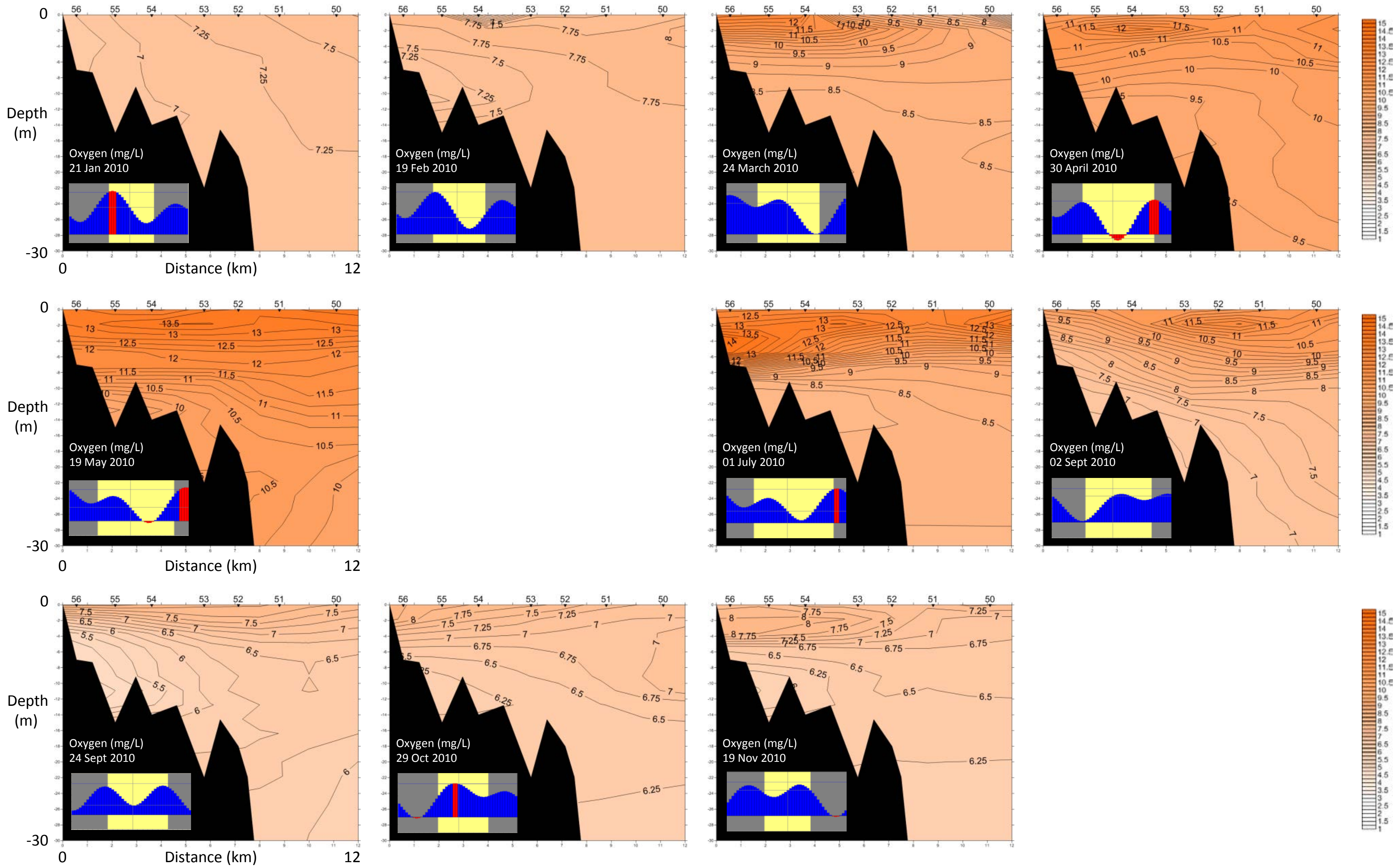
2008 Dissolved Oxygen (mg/L)



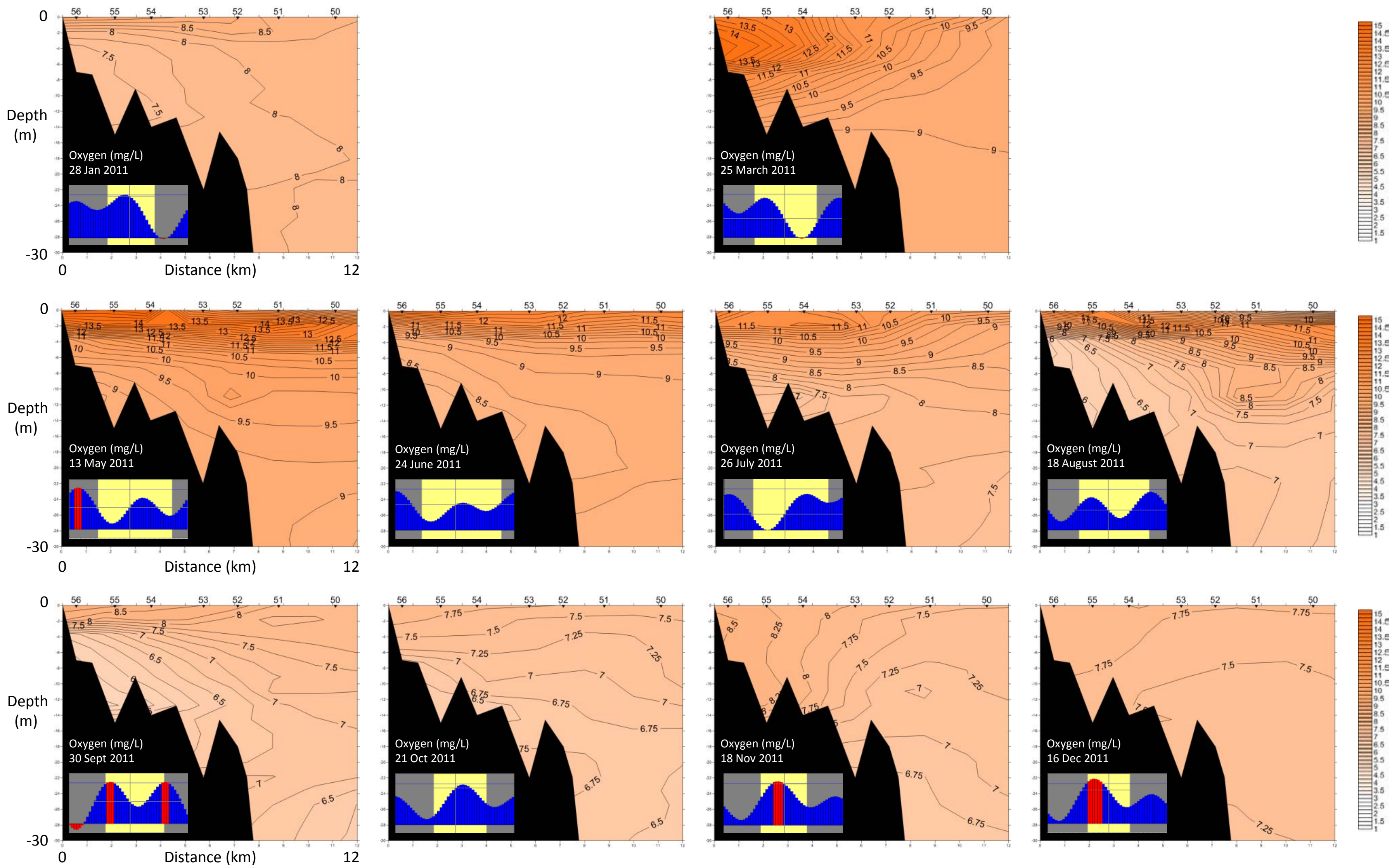
2009 Dissolved Oxygen (mg/L)



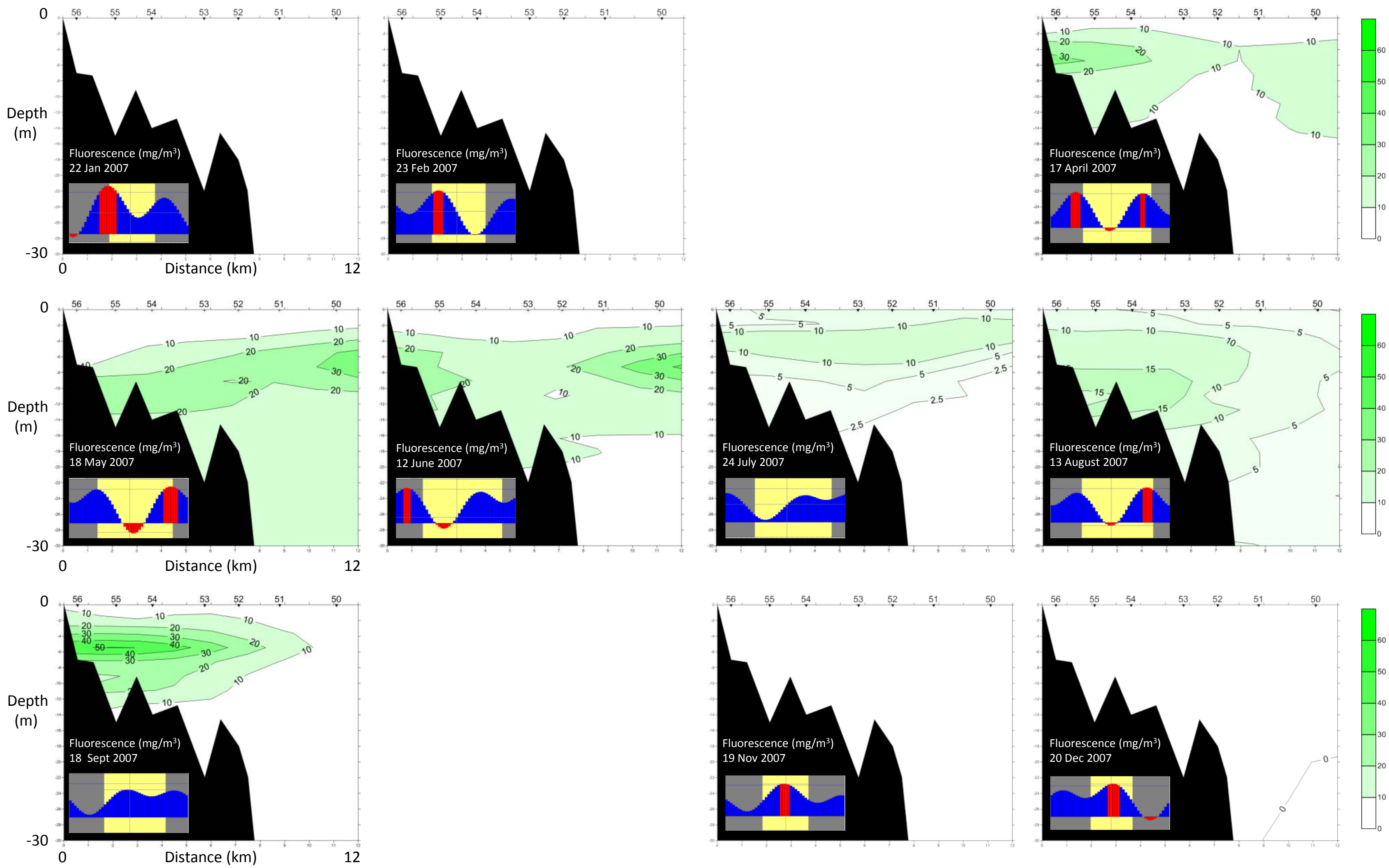
2010 Dissolved Oxygen (mg/L)



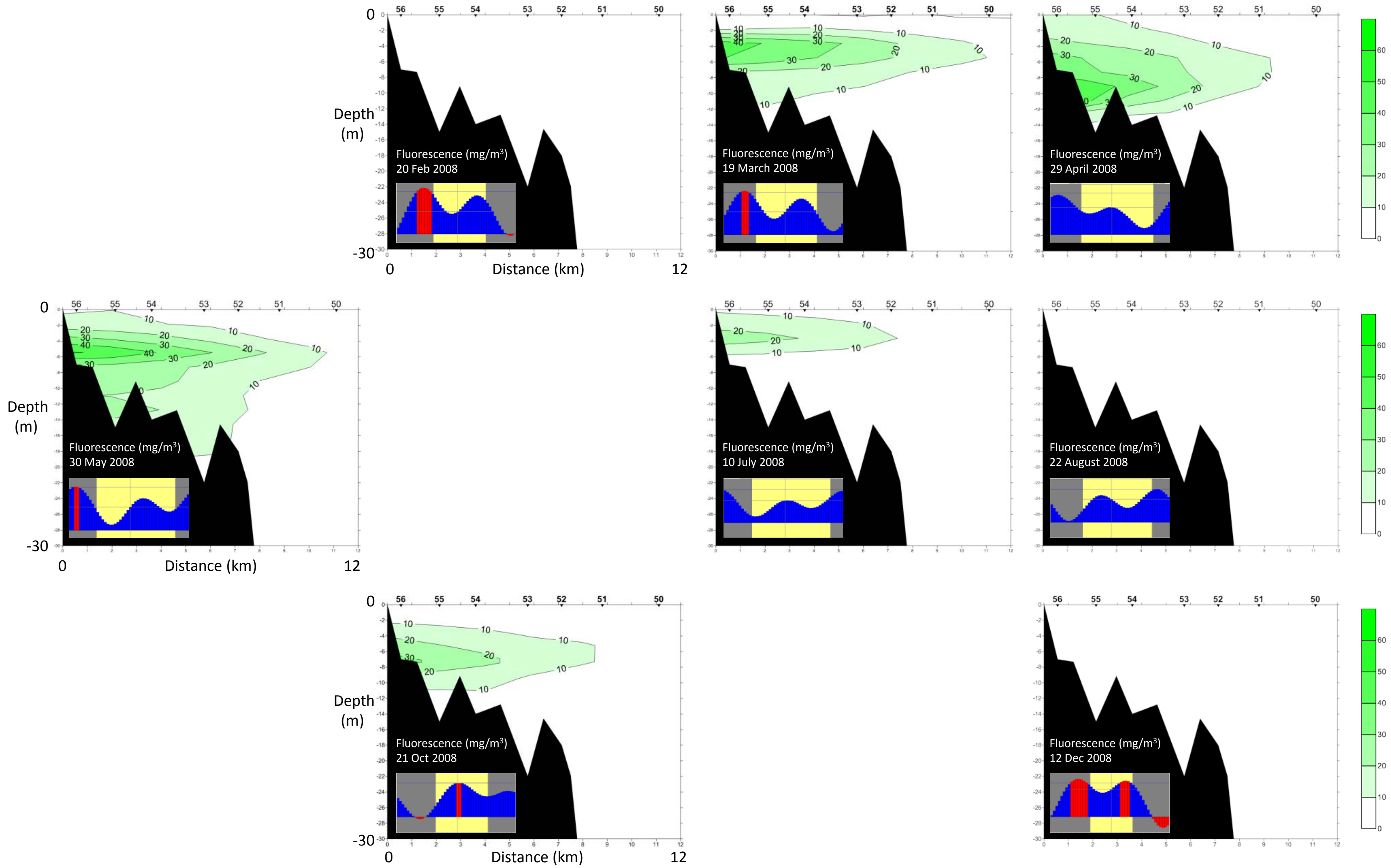
2011 Dissolved Oxygen (mg/L)



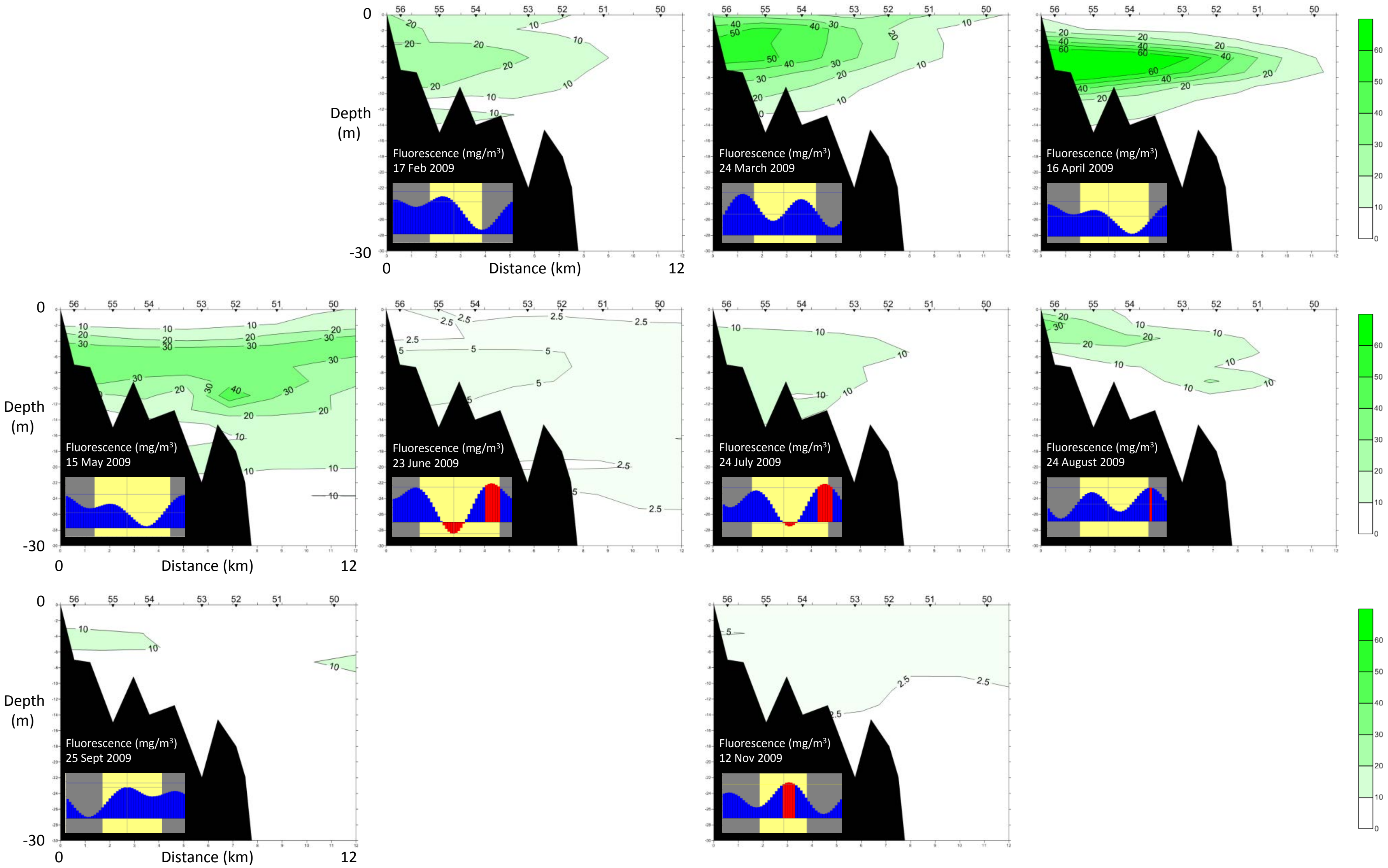
2007 Fluorescence (mg/m^3)



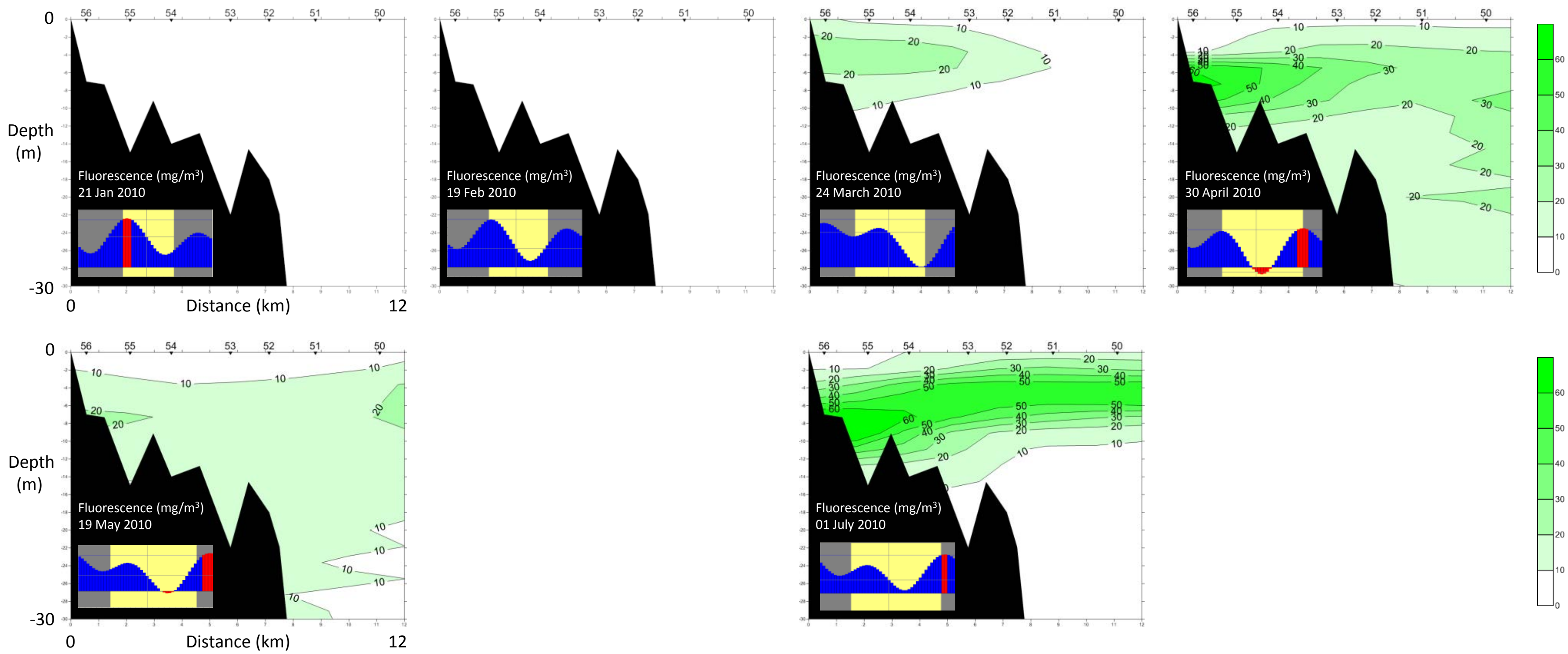
2008 Fluorescence (mg/m^3)



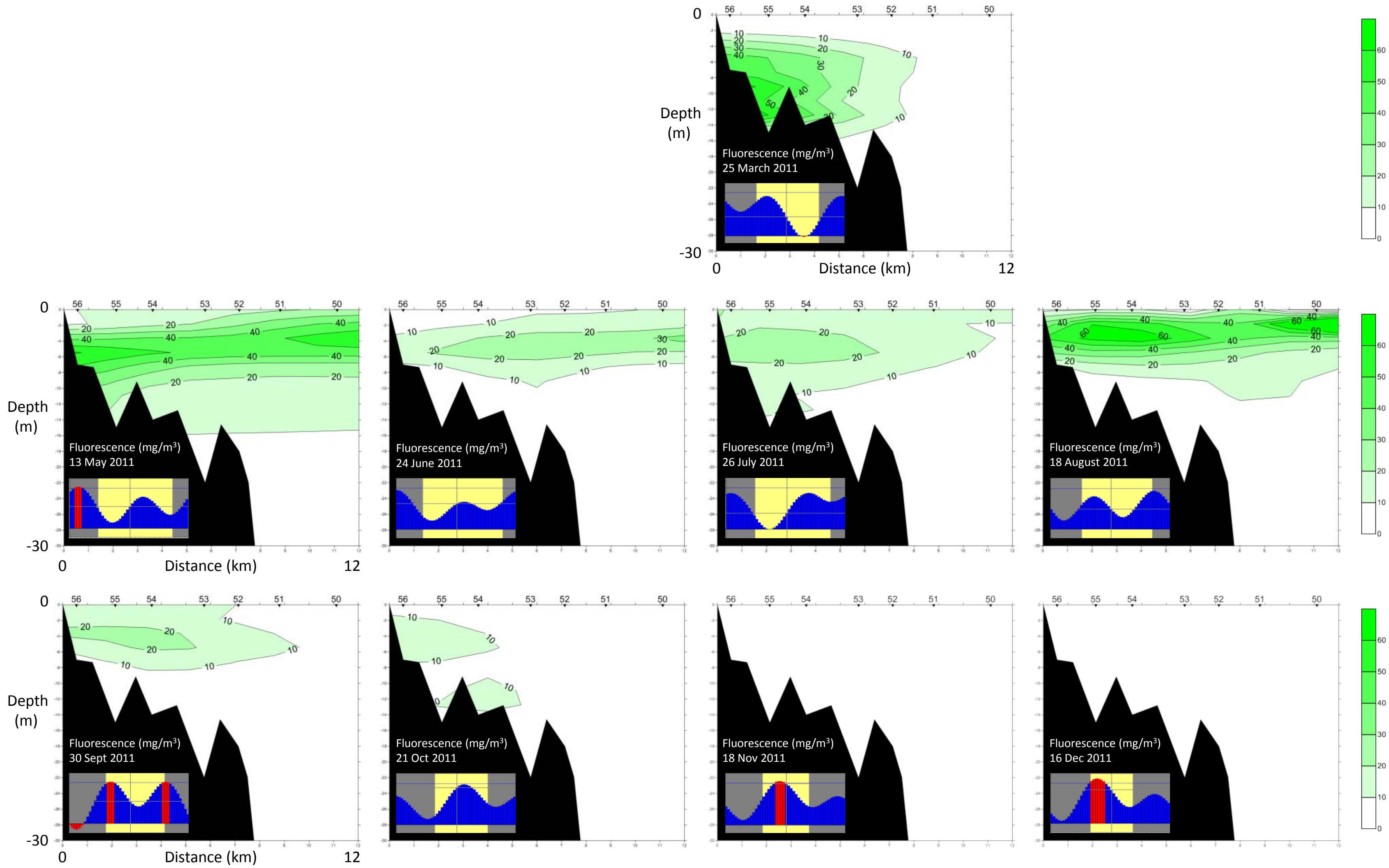
2009 Fluorescence (mg/m^3)



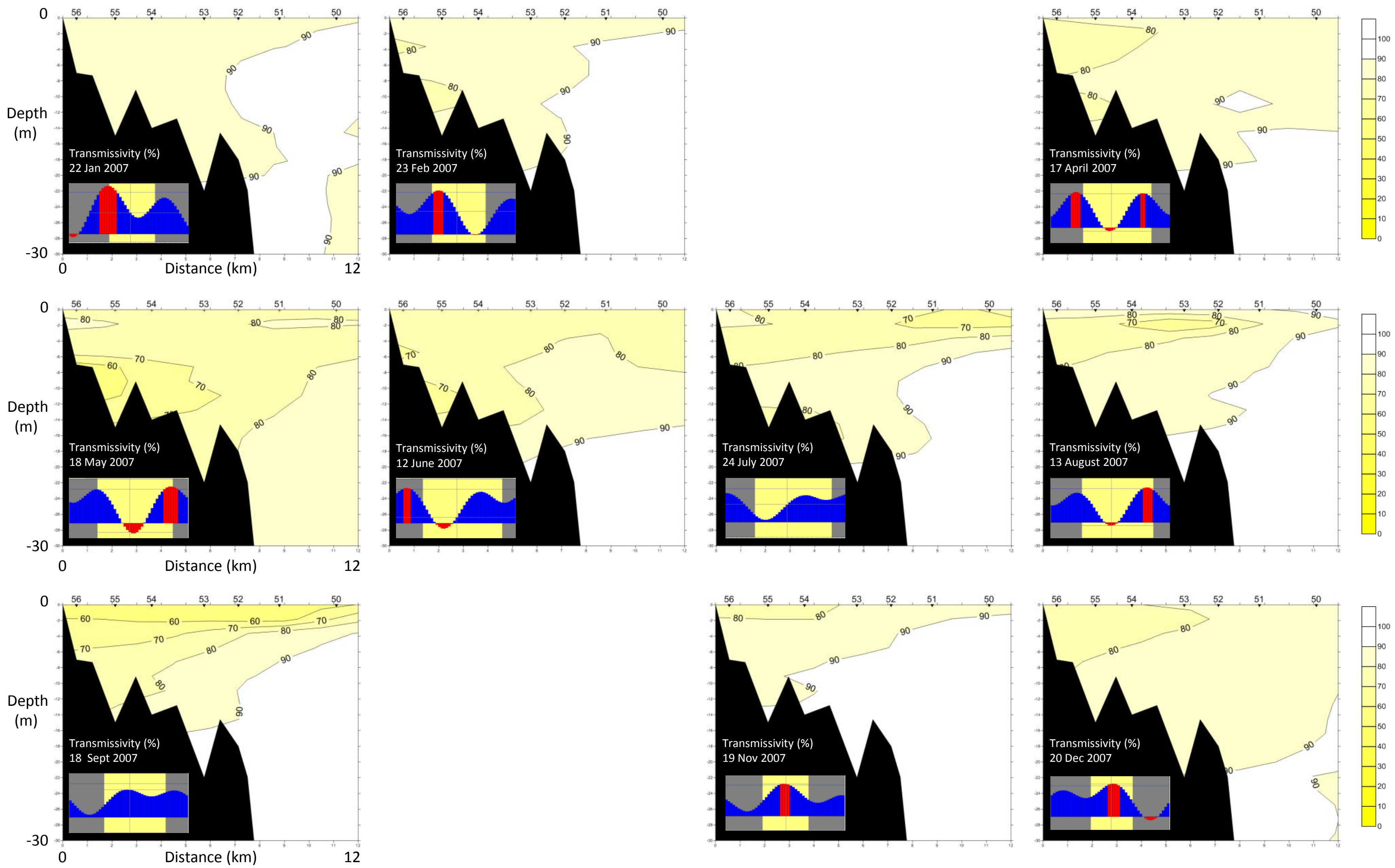
2010 Fluorescence (mg/m^3)



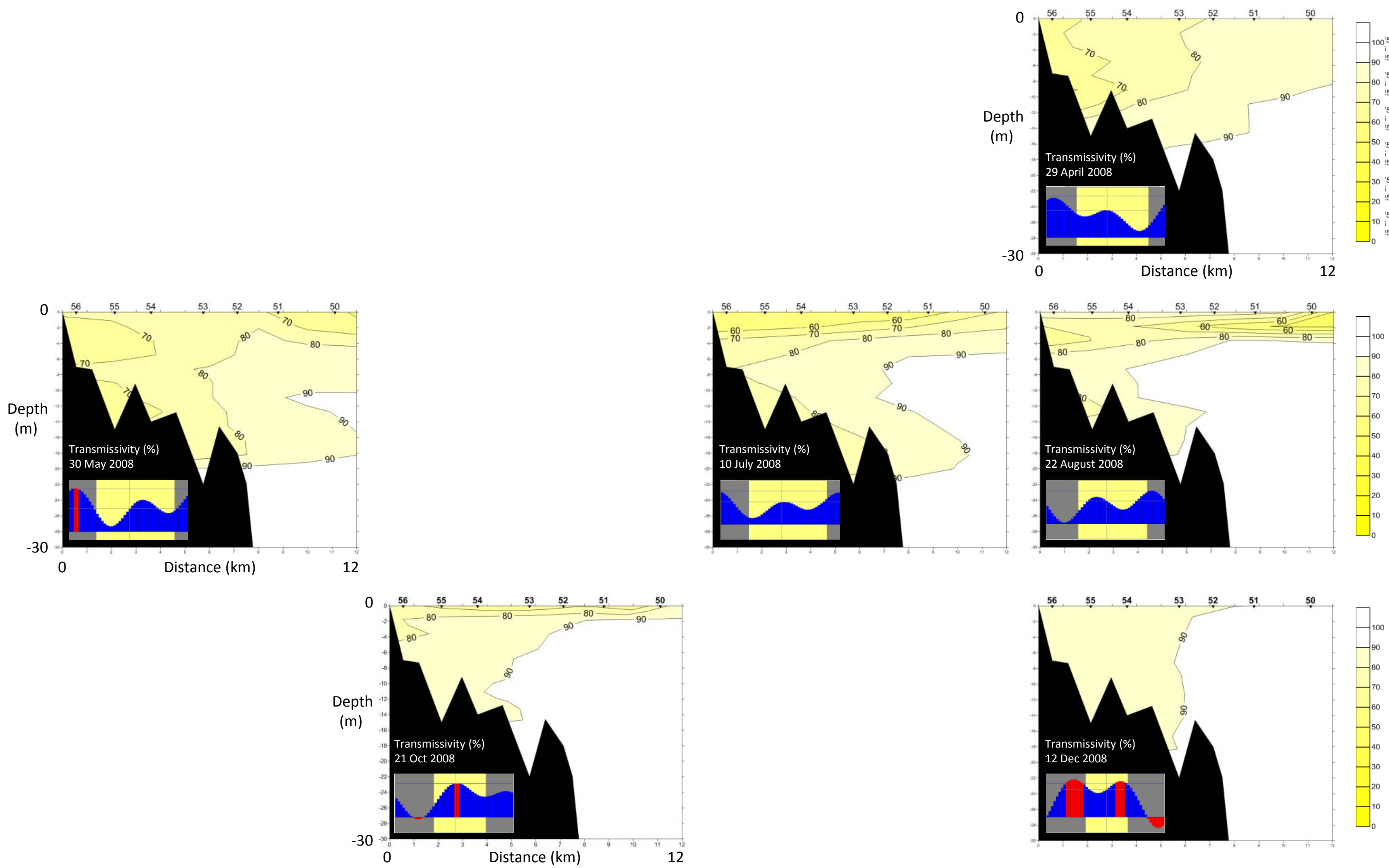
2011 Fluorescence (mg/m^3)



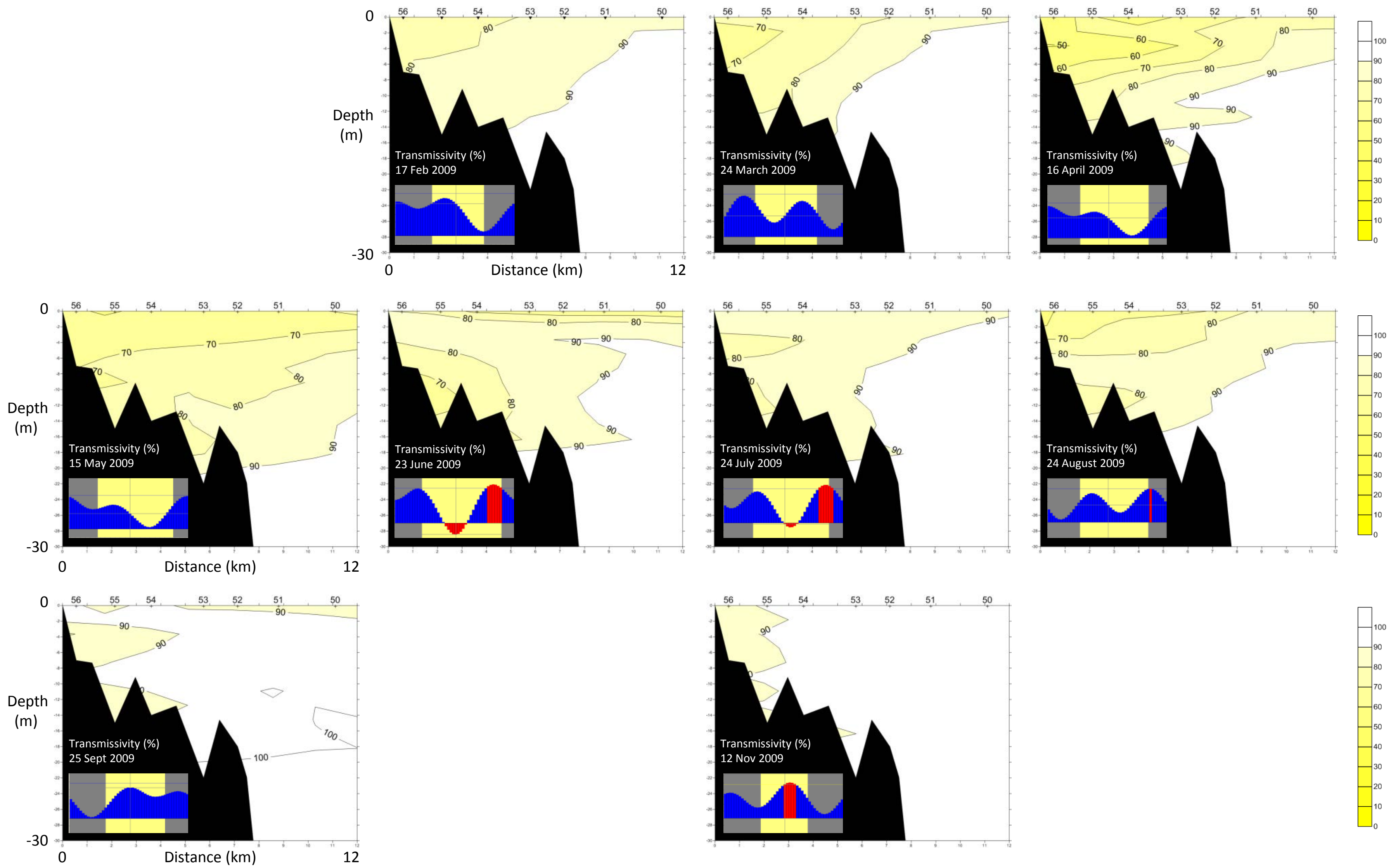
2007 Transmissivity (%)



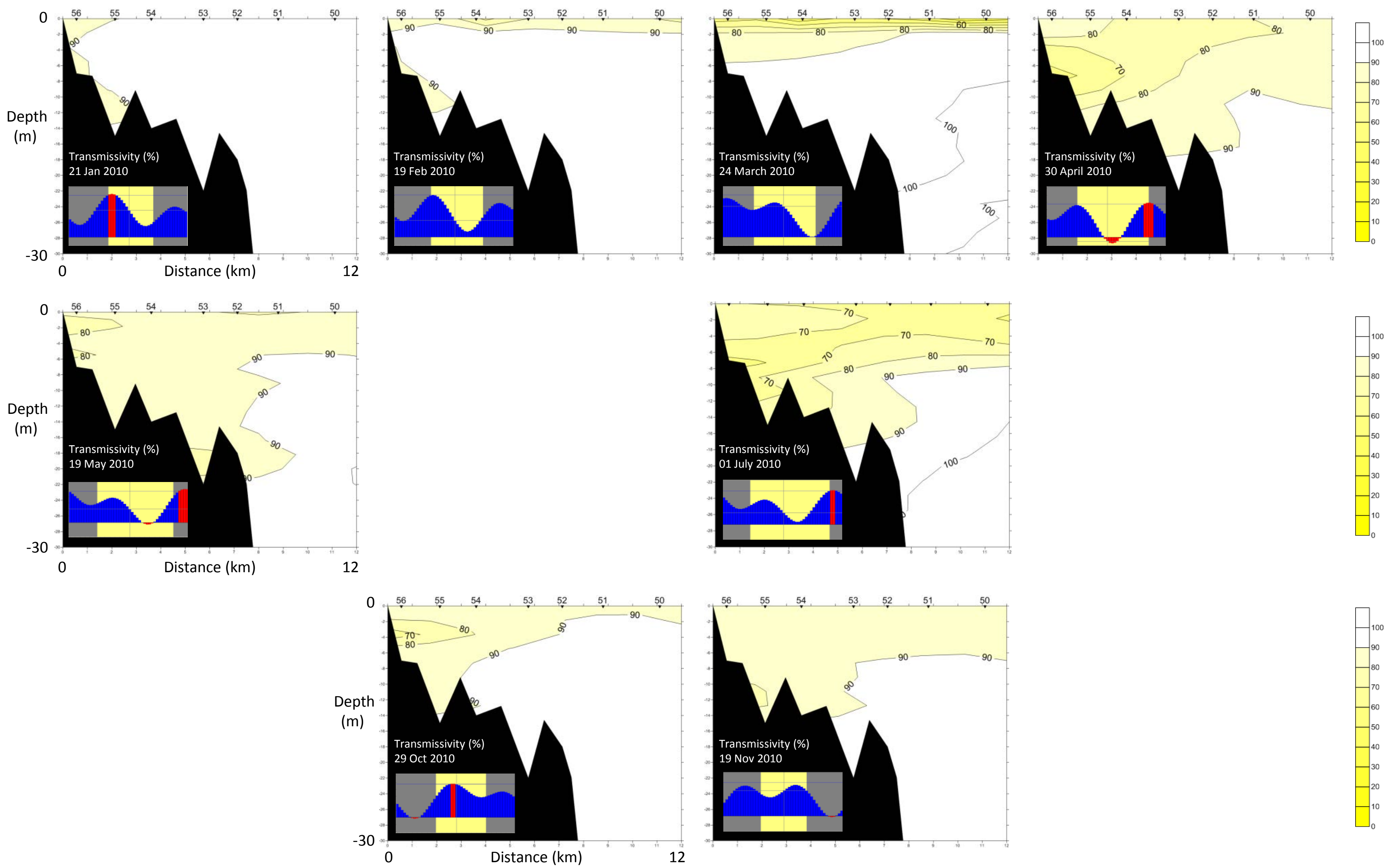
2008 Transmissivity (%)



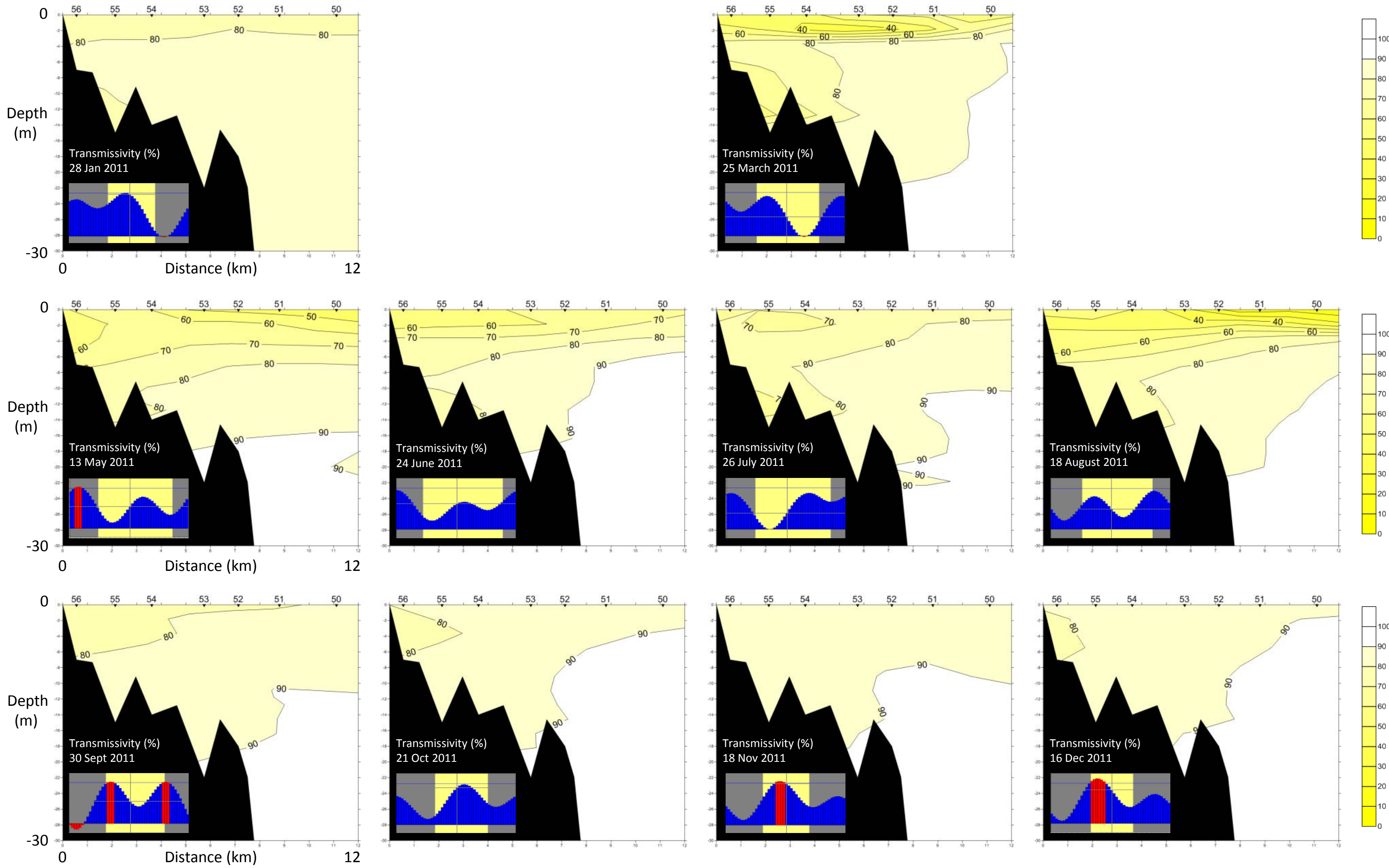
2009 Transmissivity (%)



2010 Transmissivity (%)

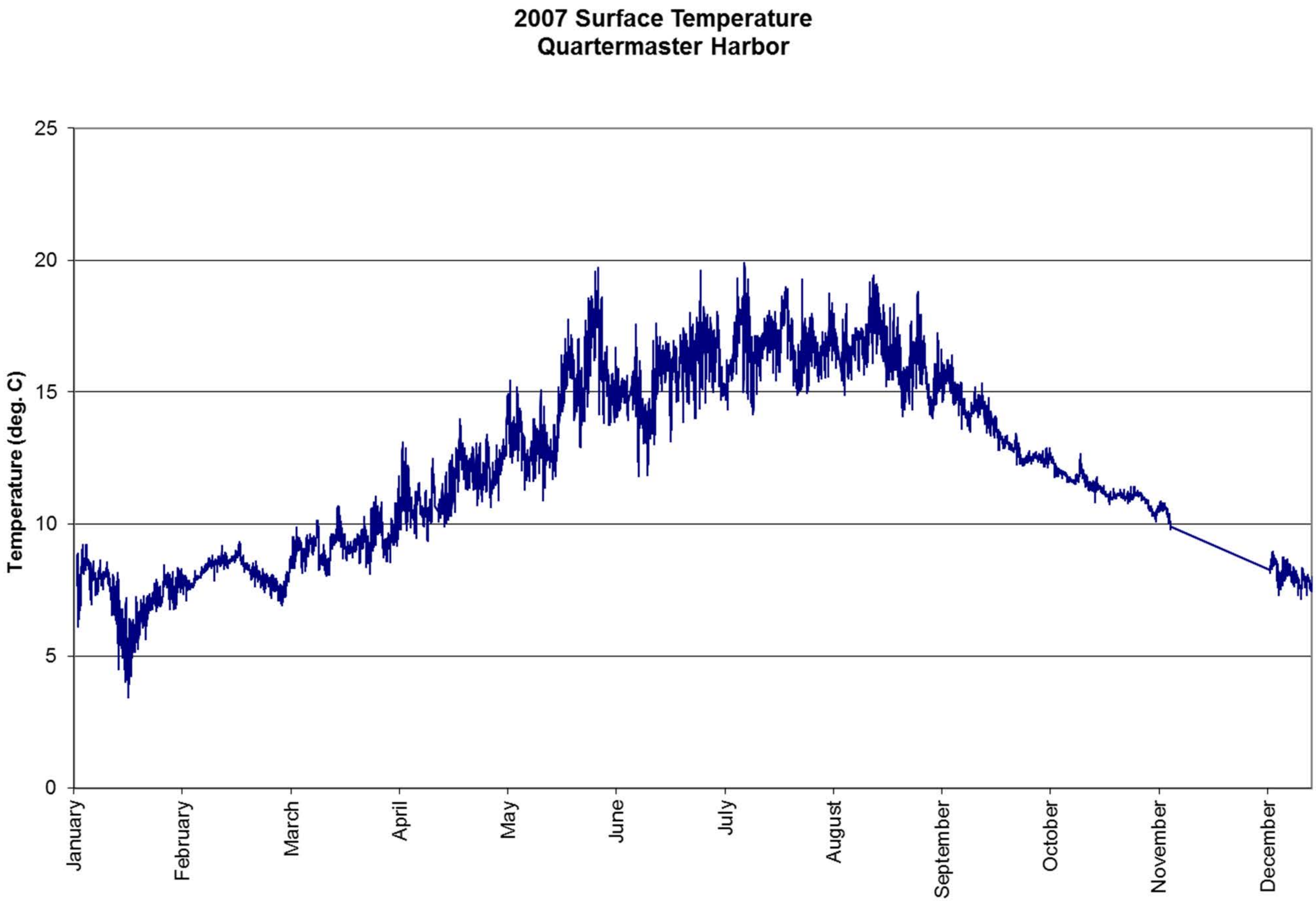


2011 Transmissivity (%)

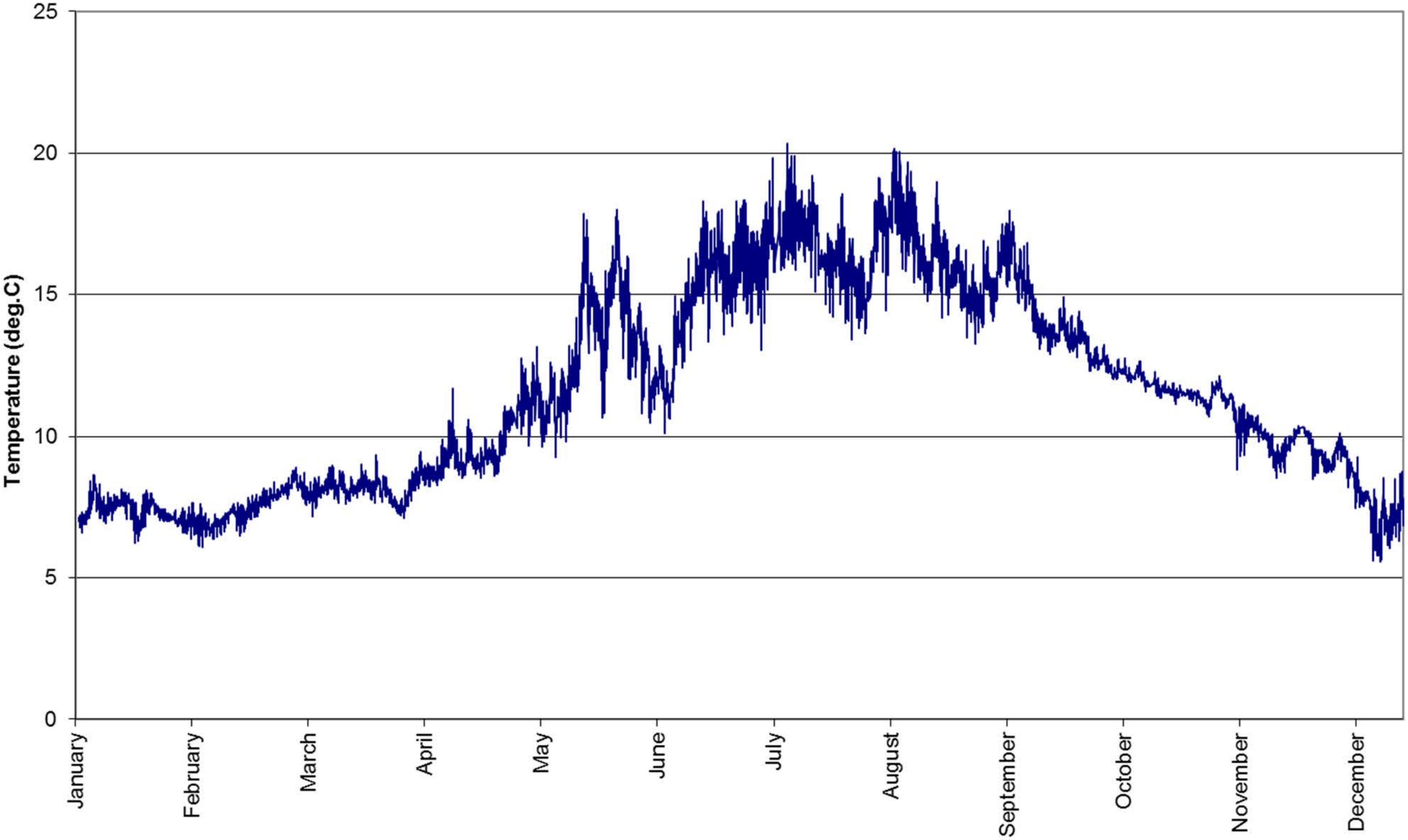


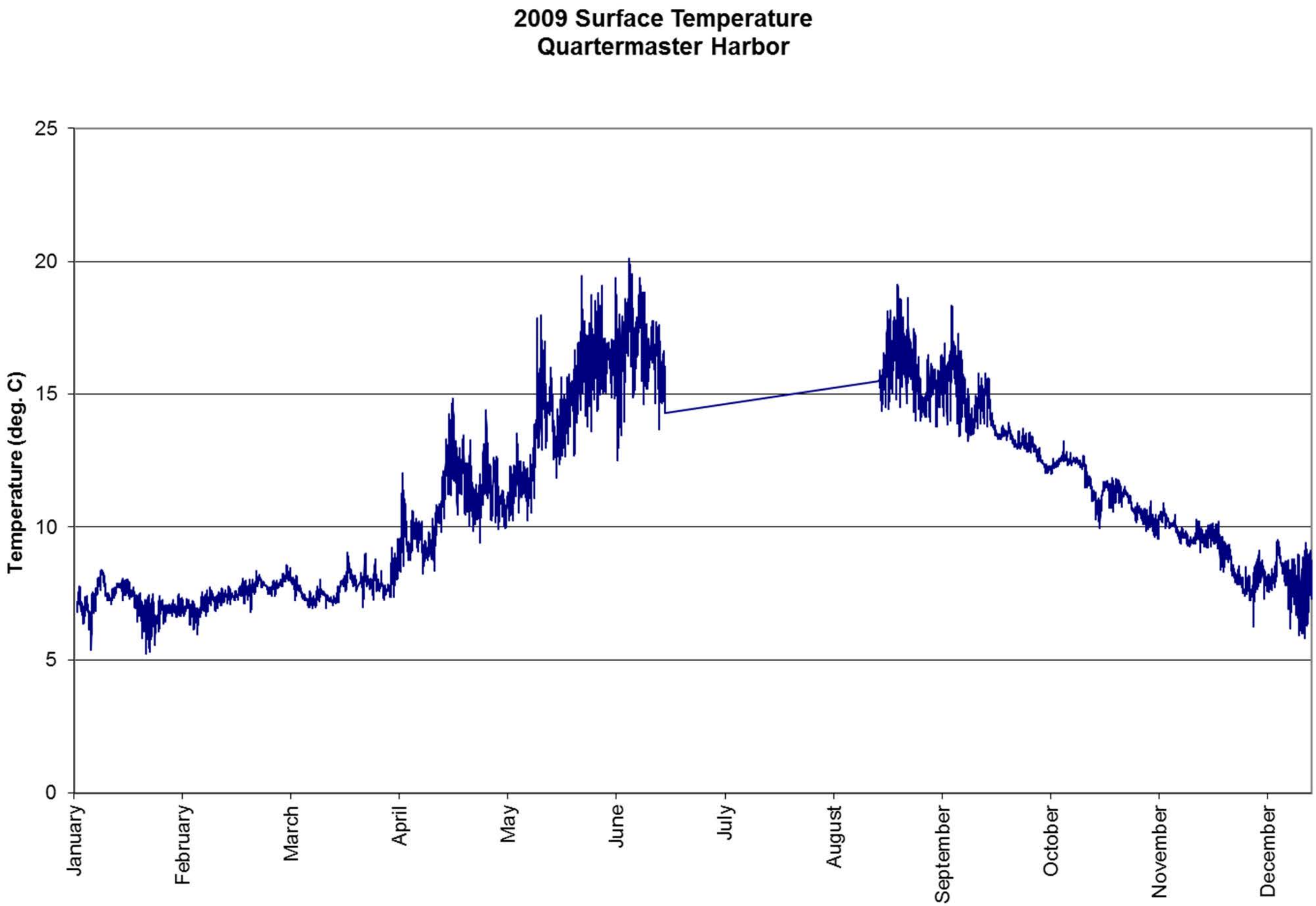
Appendix B: UWT Mooring

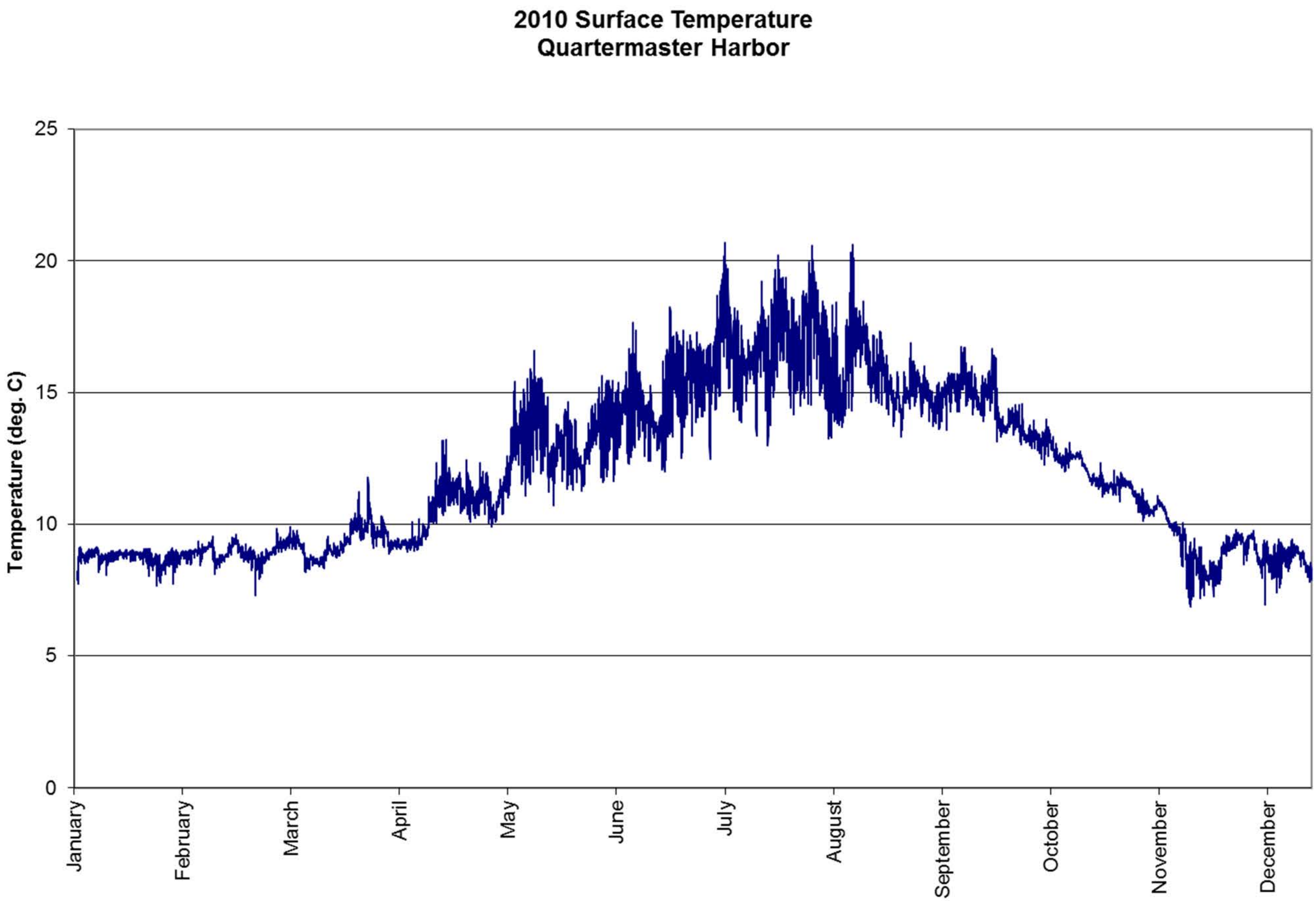
(Station 54, 15-minute interval data)

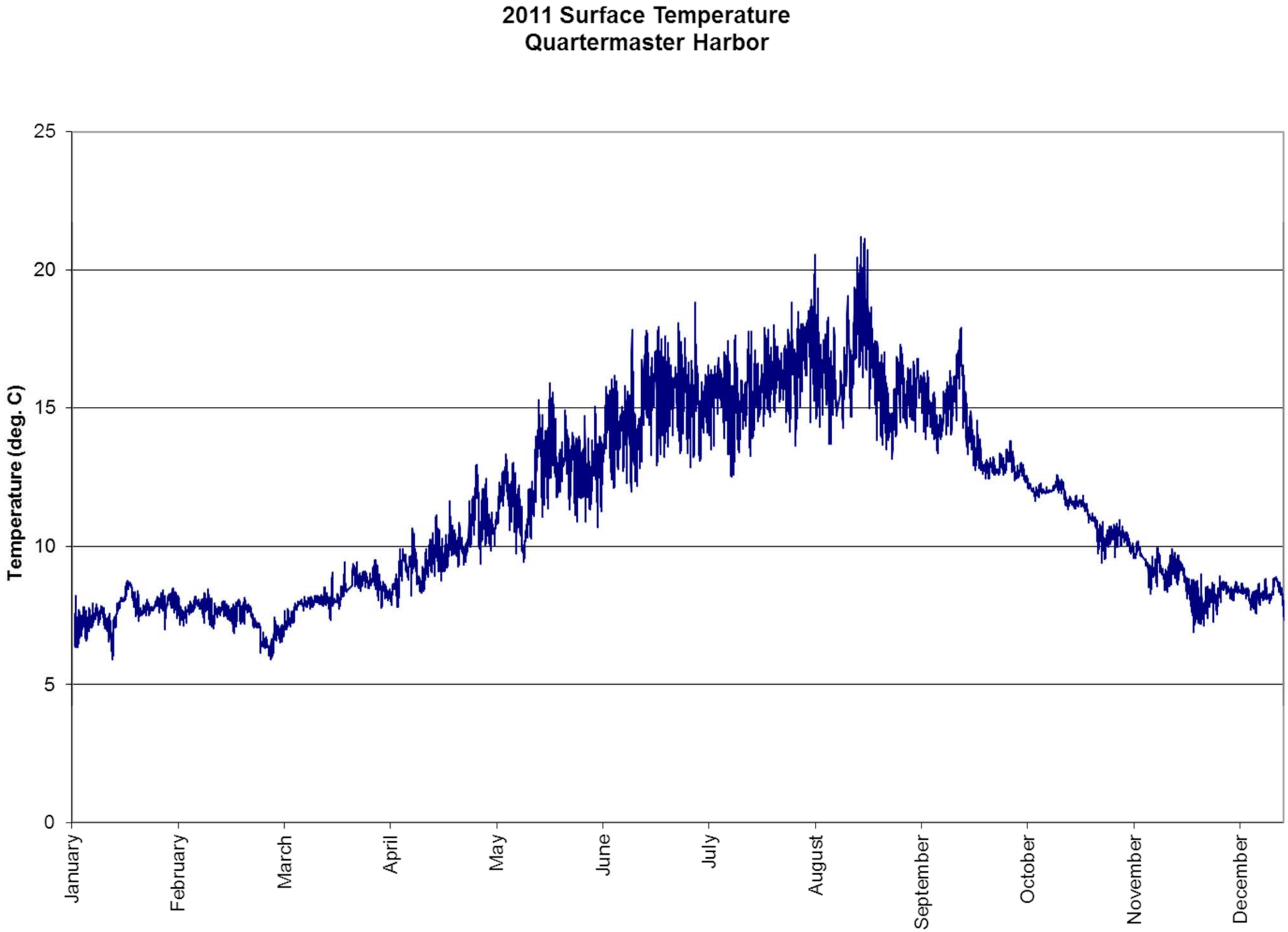

2007 Surface Temperature
Quartermaster Harbor
Temperature (deg. C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December

2008 Surface Temperature
Quartermaster Harbor



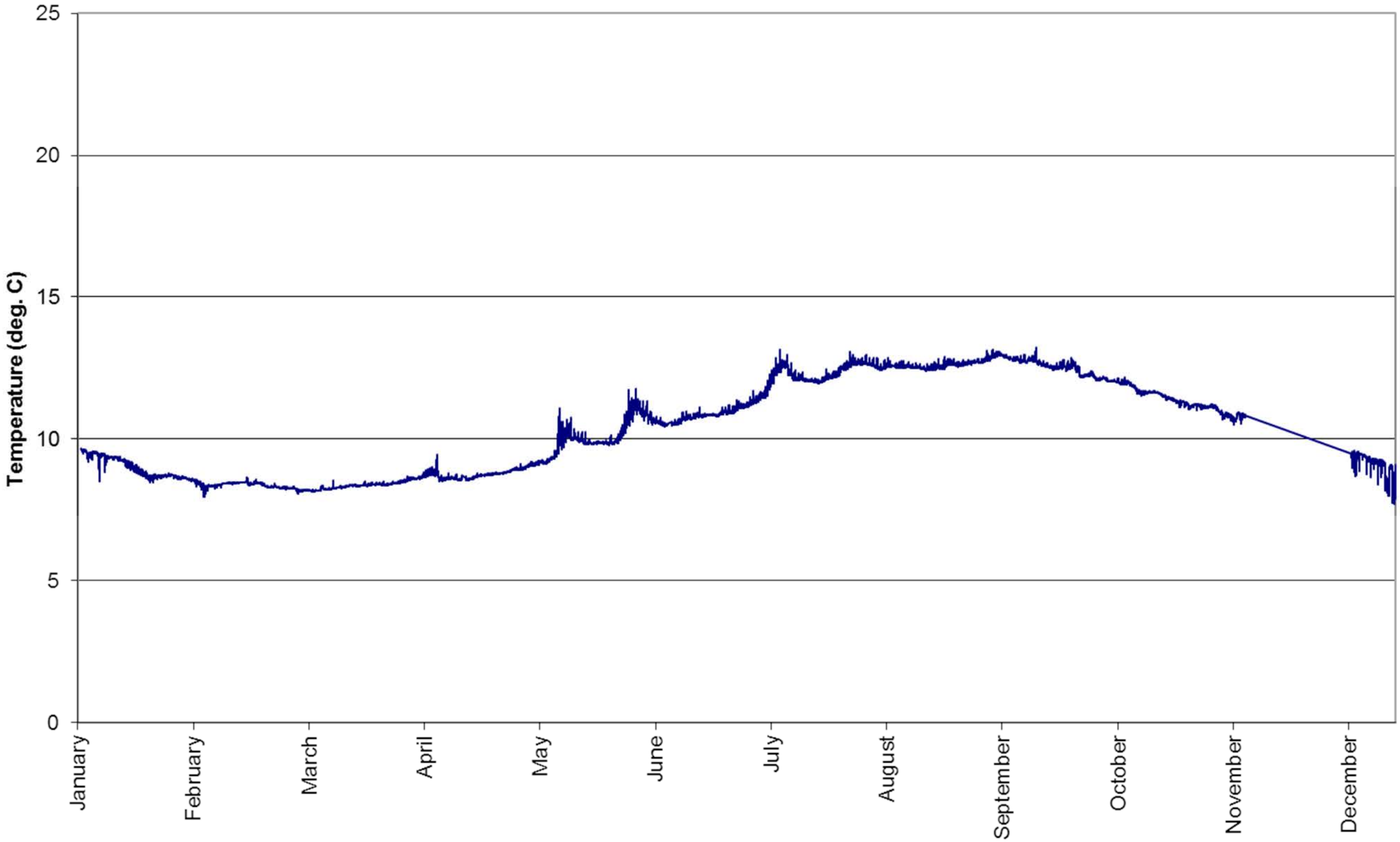

2009 Surface Temperature
Quartermaster Harbor
Temperature (deg. C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December

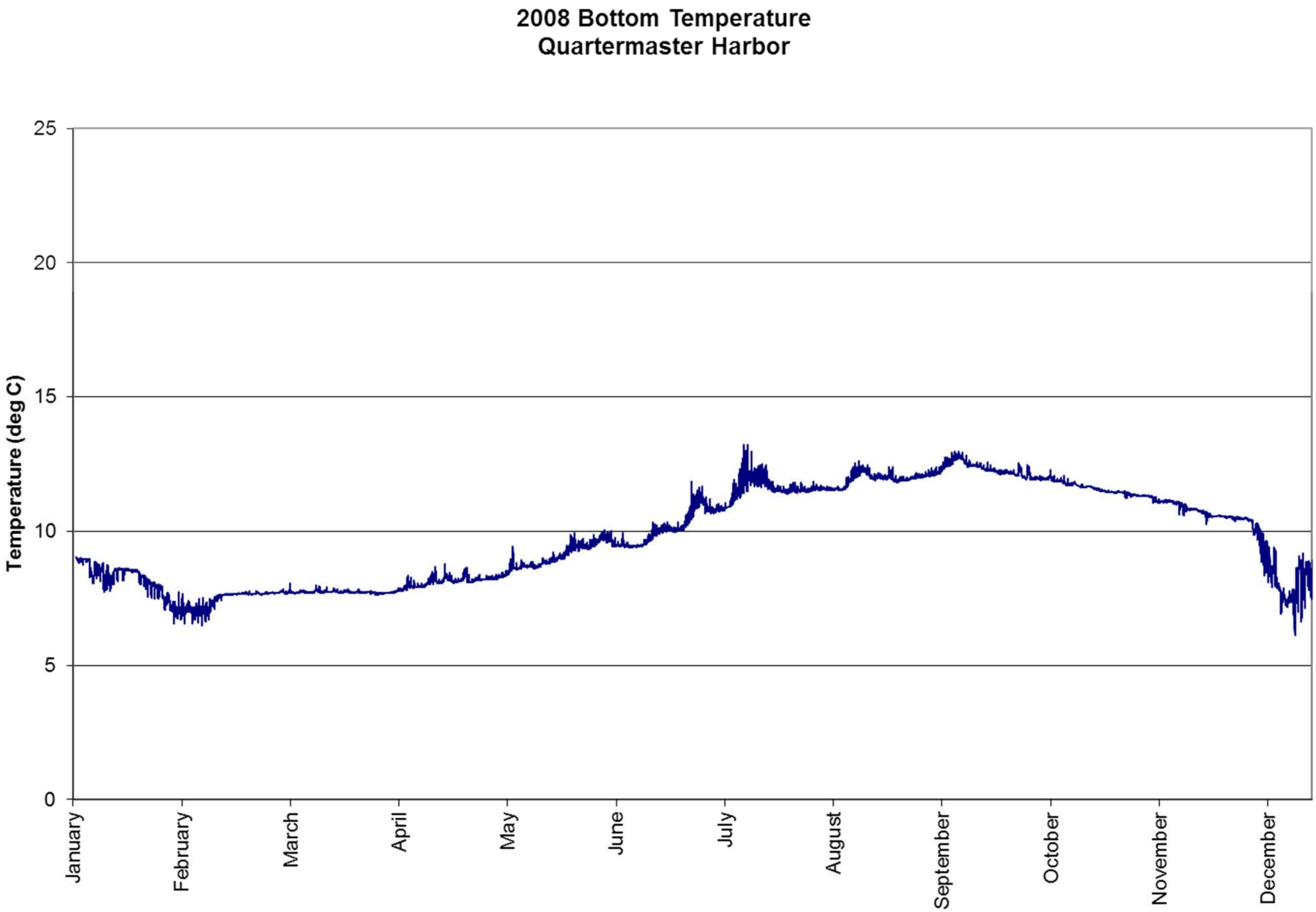

2010 Surface Temperature
Quartermaster Harbor
Temperature (deg. C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December



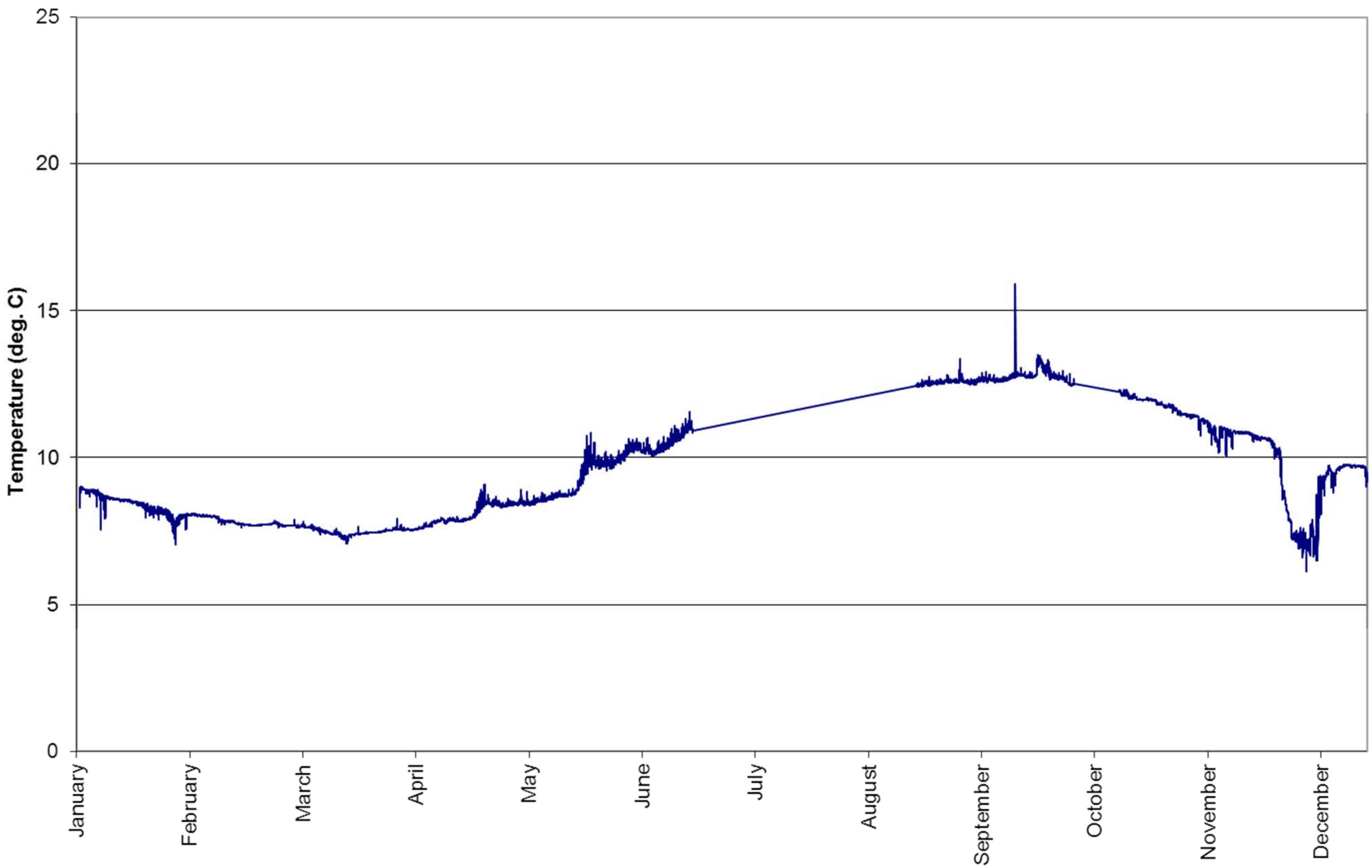
2011 Surface Temperature
Quartermaster Harbor
Temperature (deg. C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December

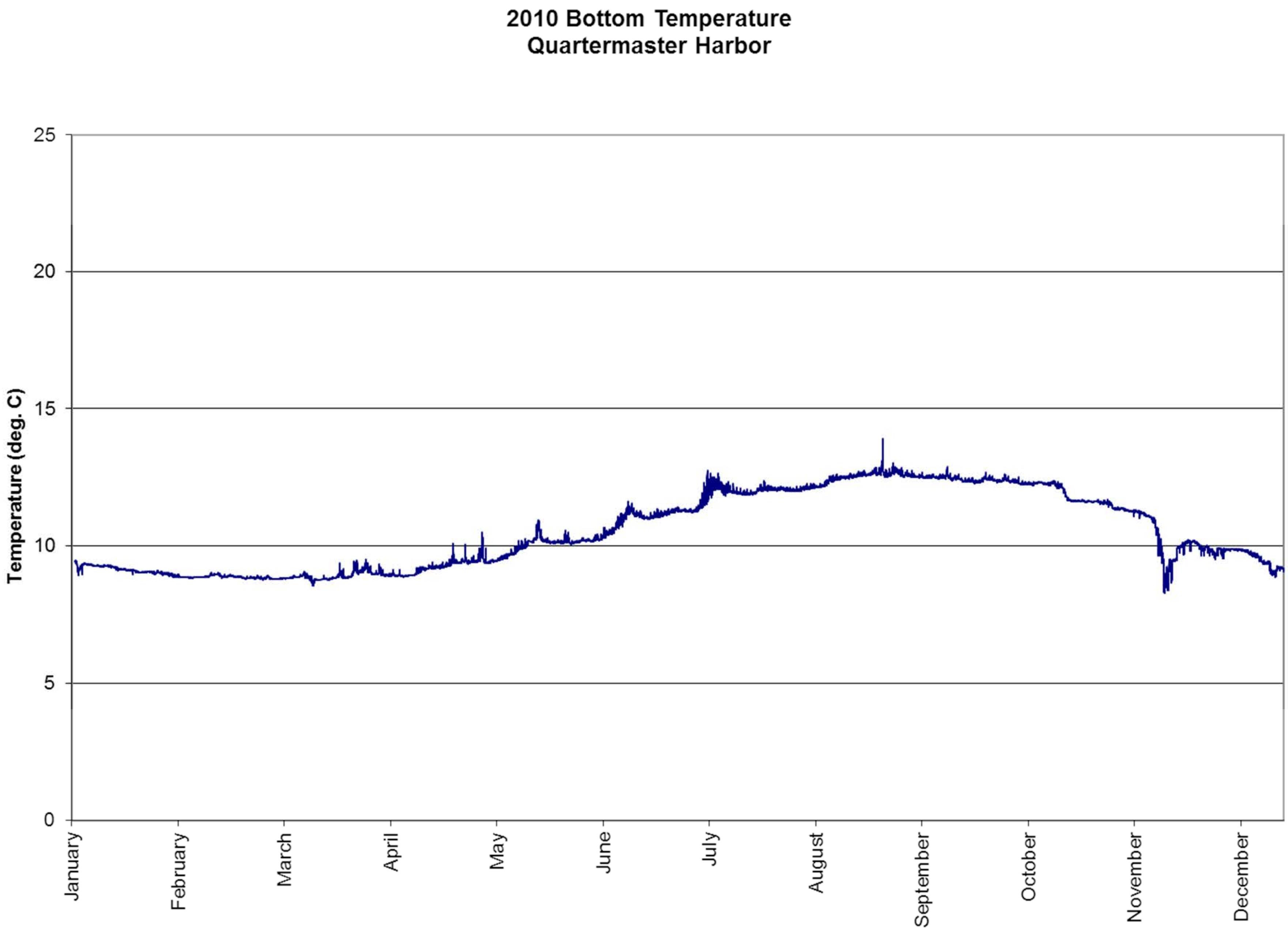
2007 Bottom Temperature
Quartermaster Harbor

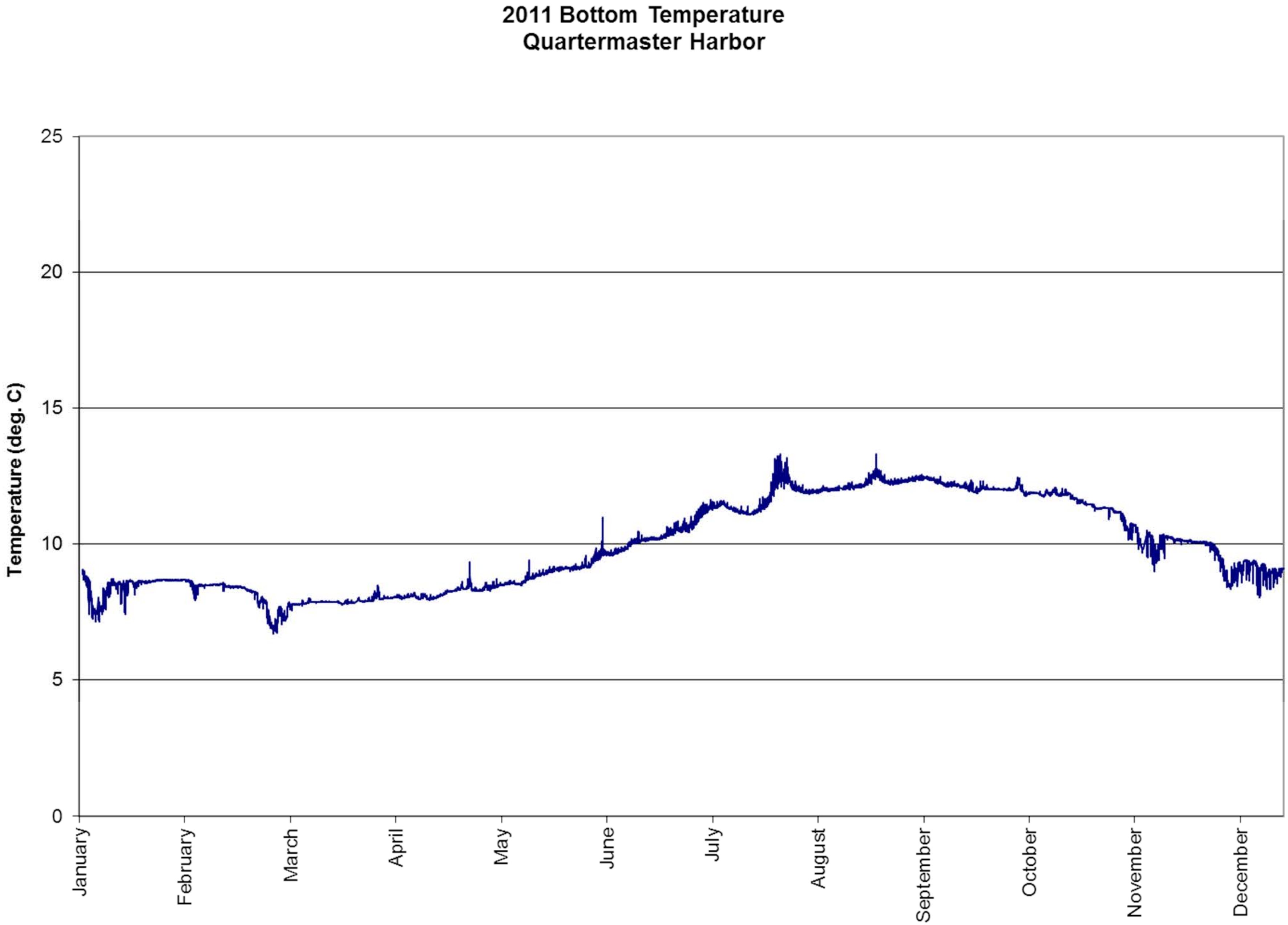


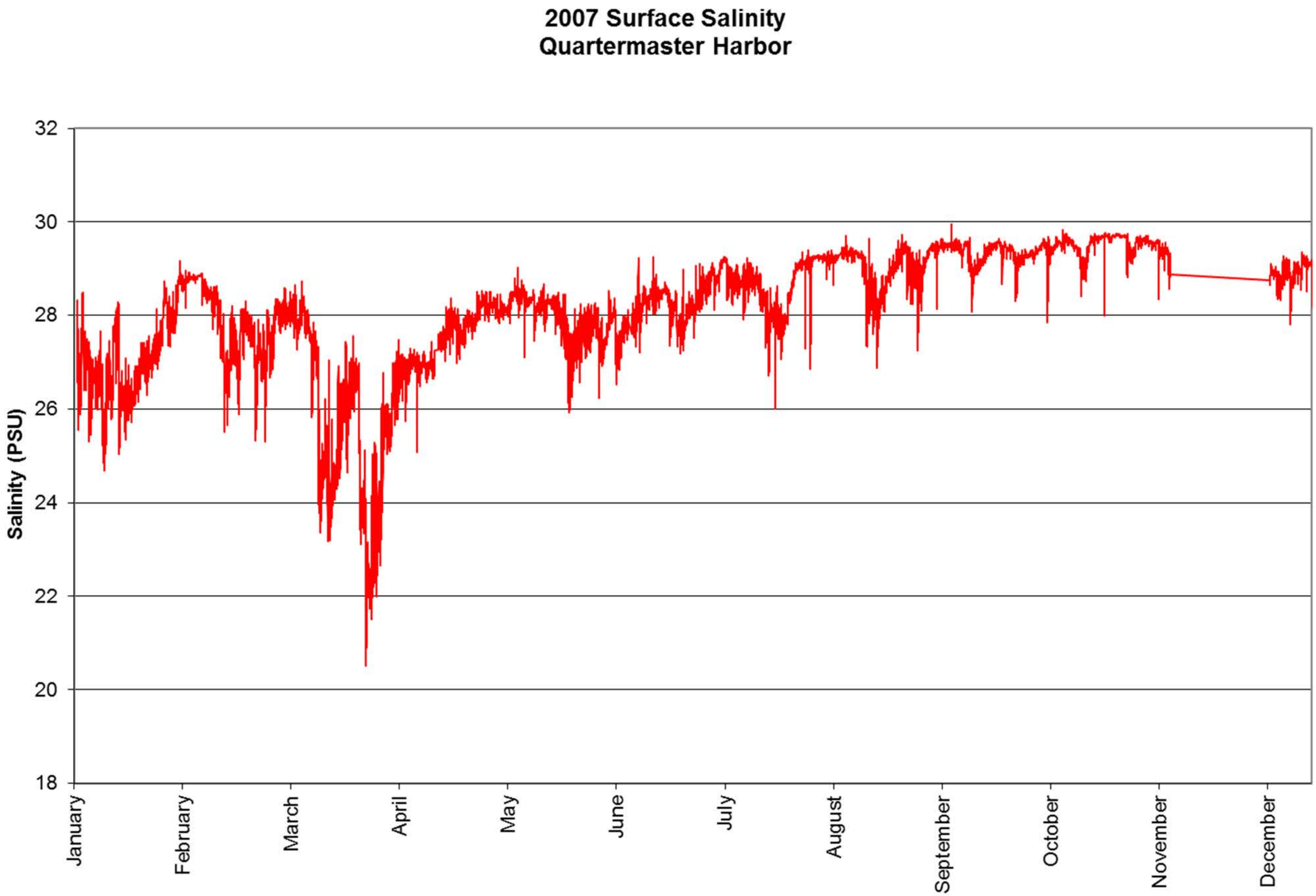

2008 Bottom Temperature
Quartermaster Harbor
Temperature (deg C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December

2009 Bottom Temperature
Quartermaster Harbor

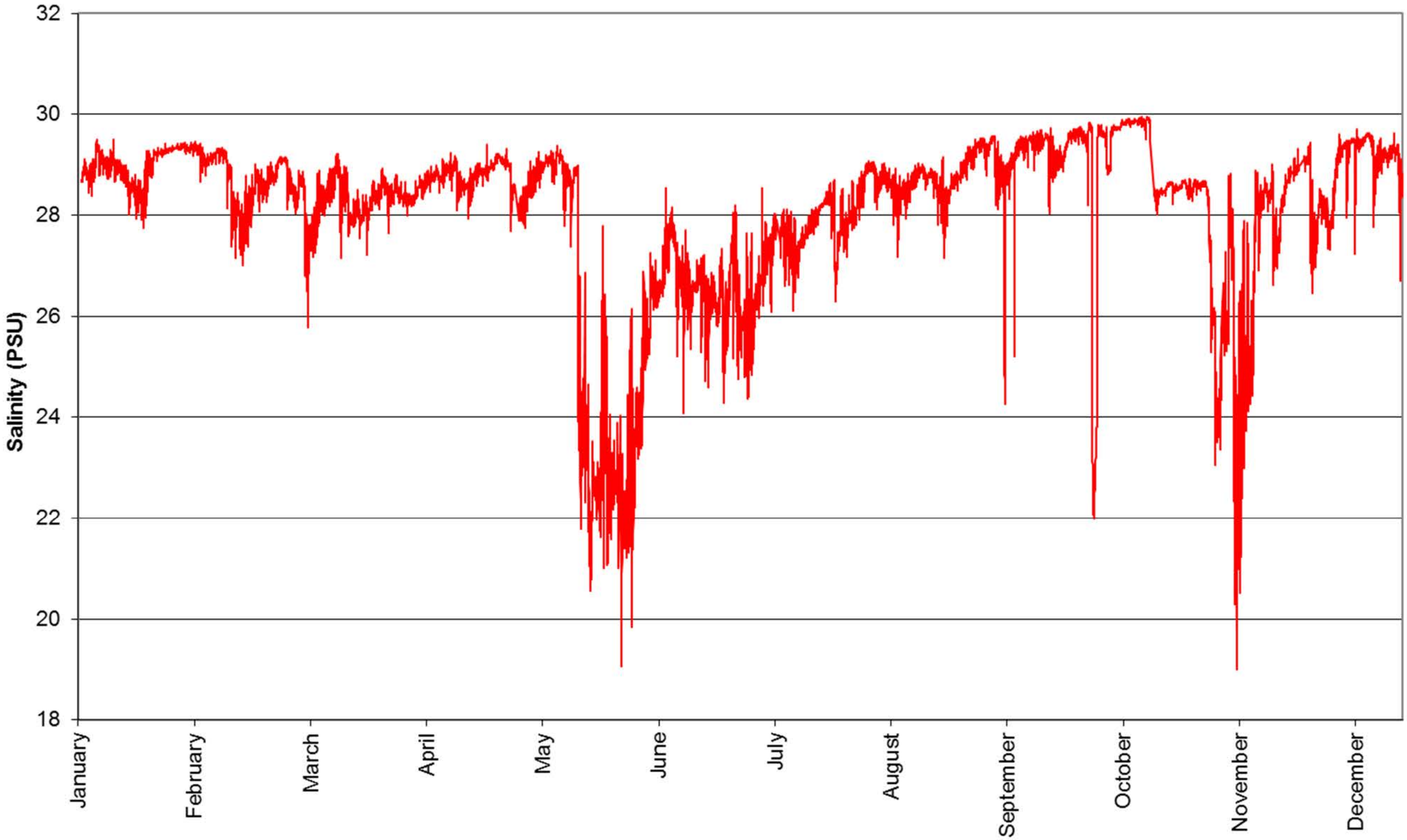


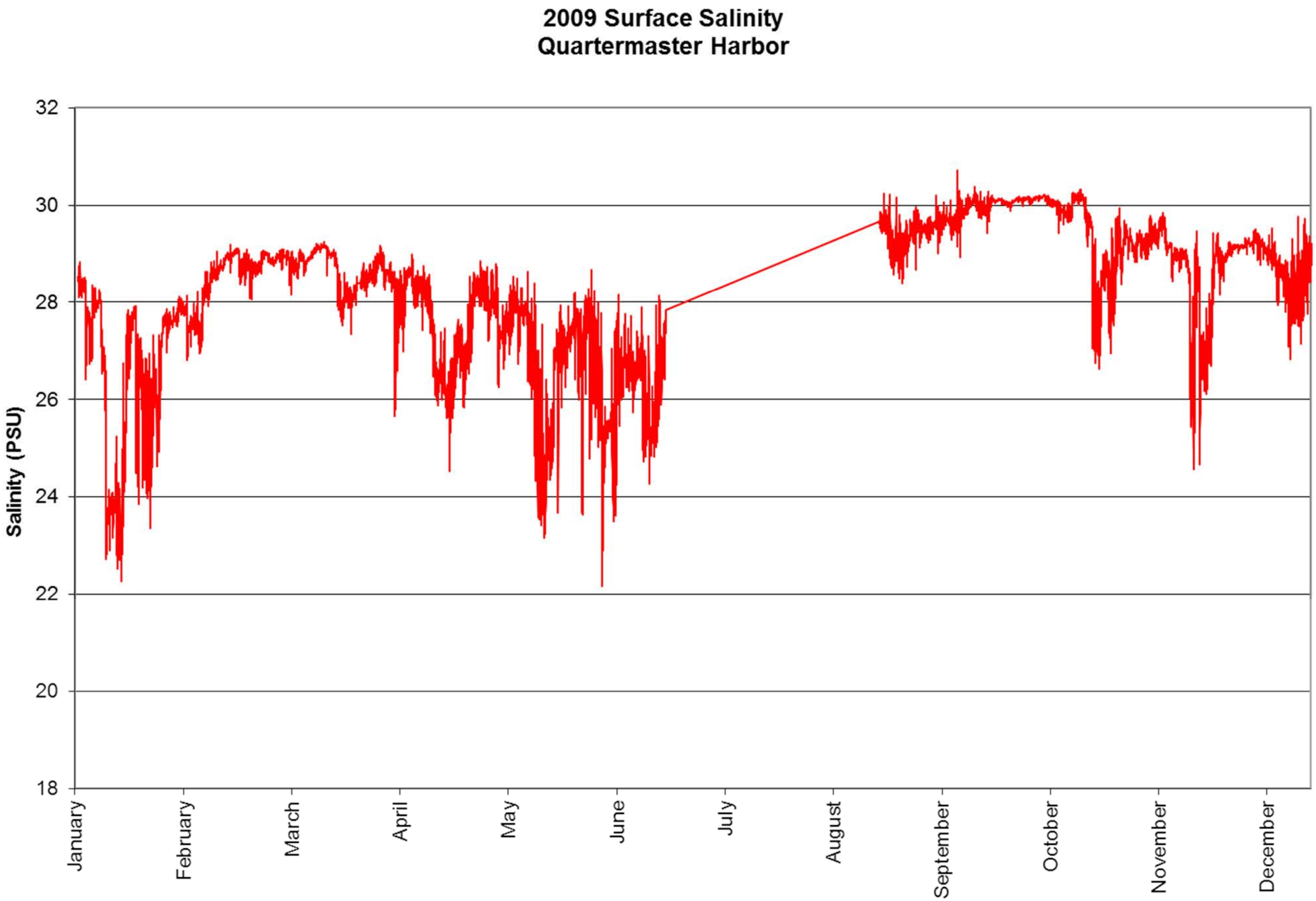

2010 Bottom Temperature
Quartermaster Harbor
Temperature (deg. C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December

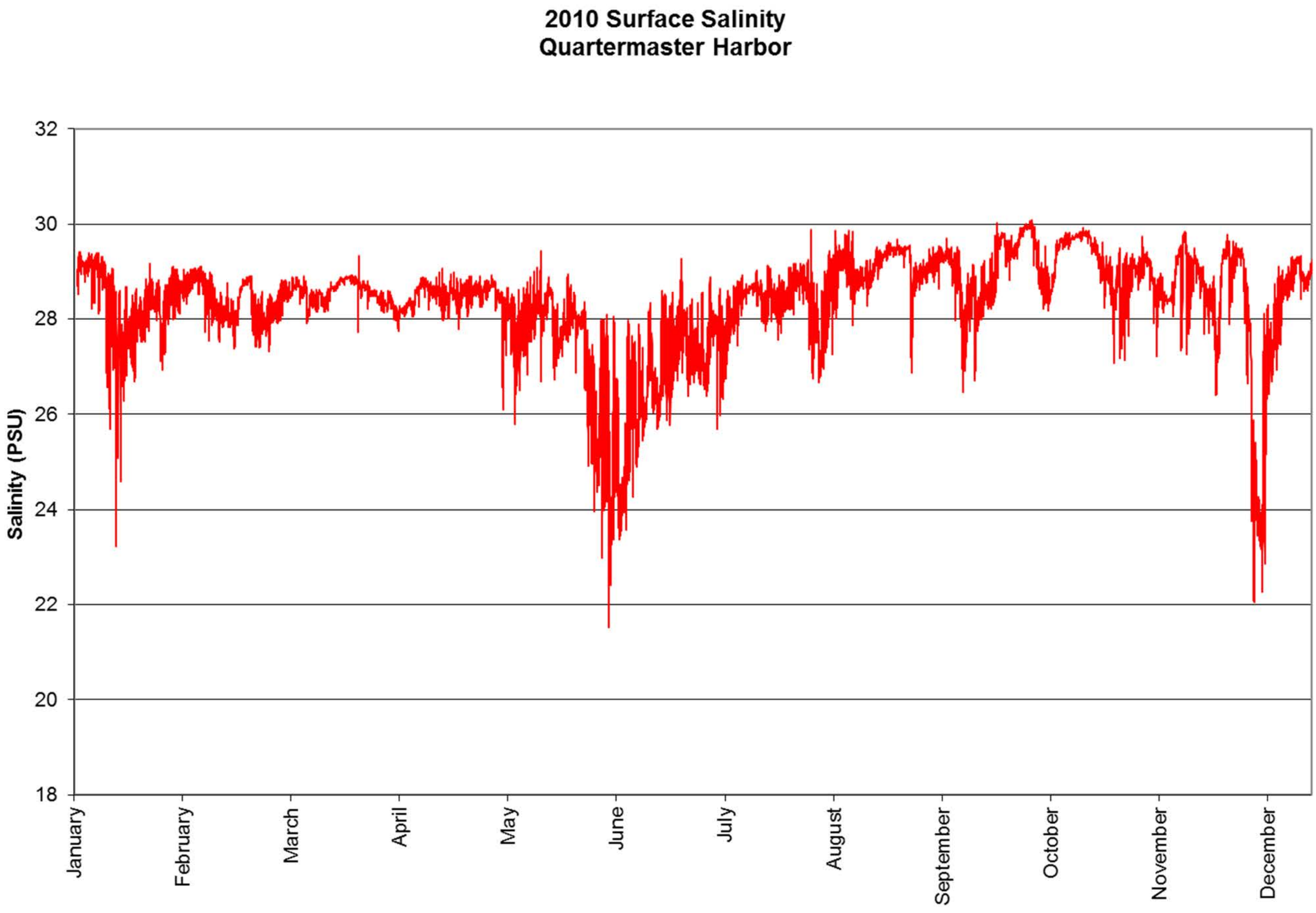

2011 Bottom Temperature
Quartermaster Harbor
Temperature (deg. C)
25
20
15
10
5
0
January
February
March
April
May
June
July
August
September
October
November
December

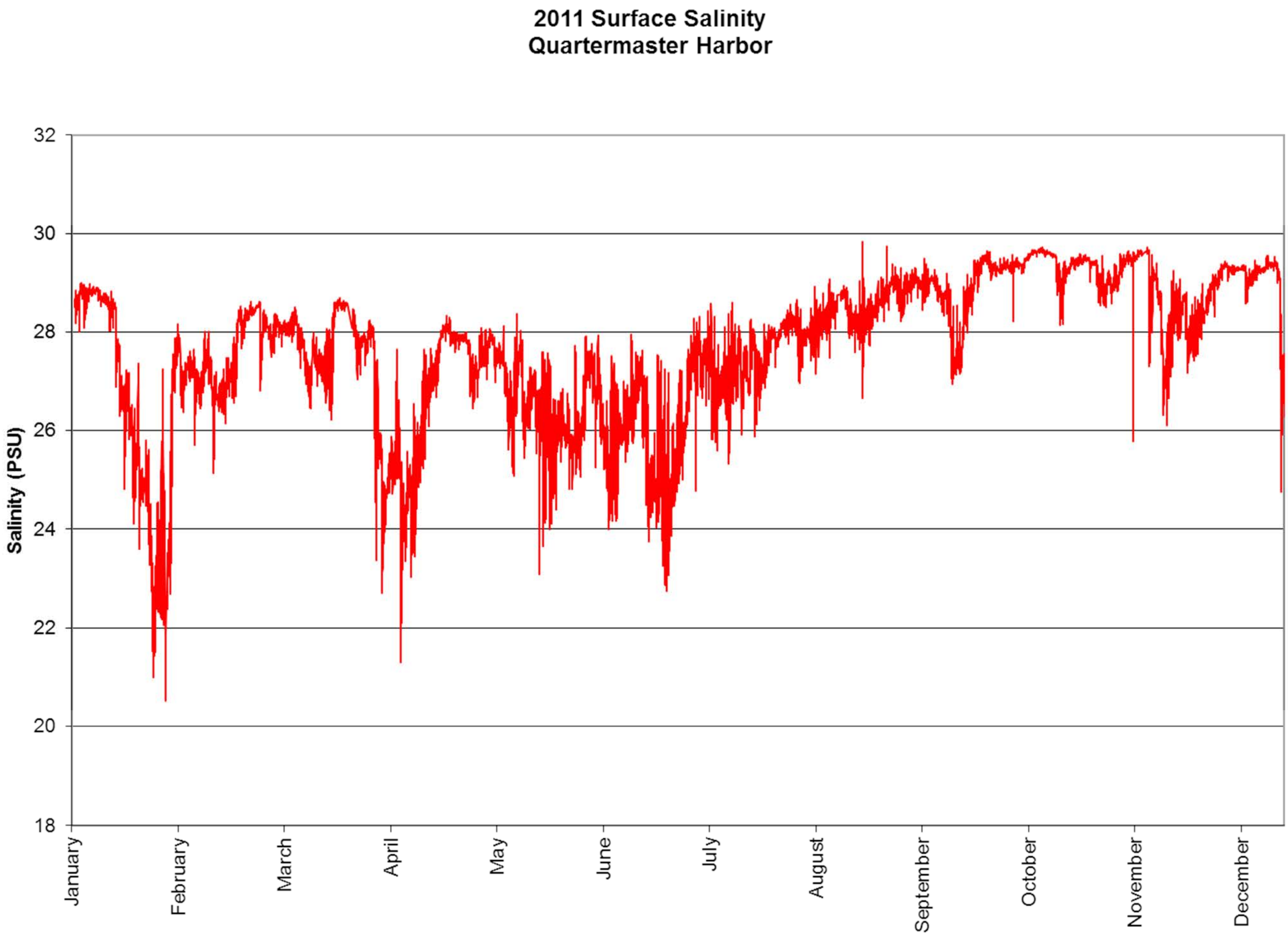

2007 Surface Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

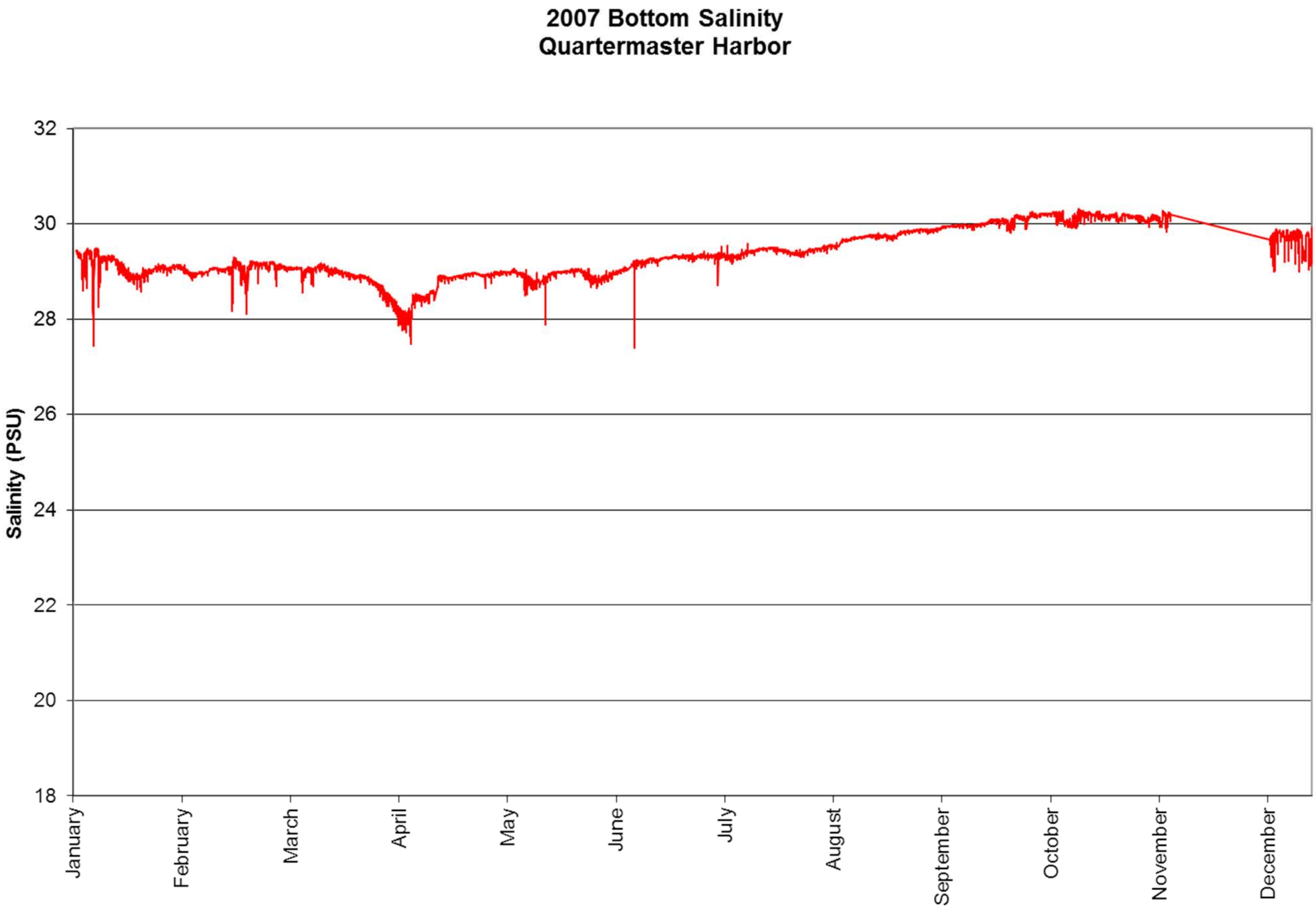
2008 Surface Salinity
Quartermaster Harbor

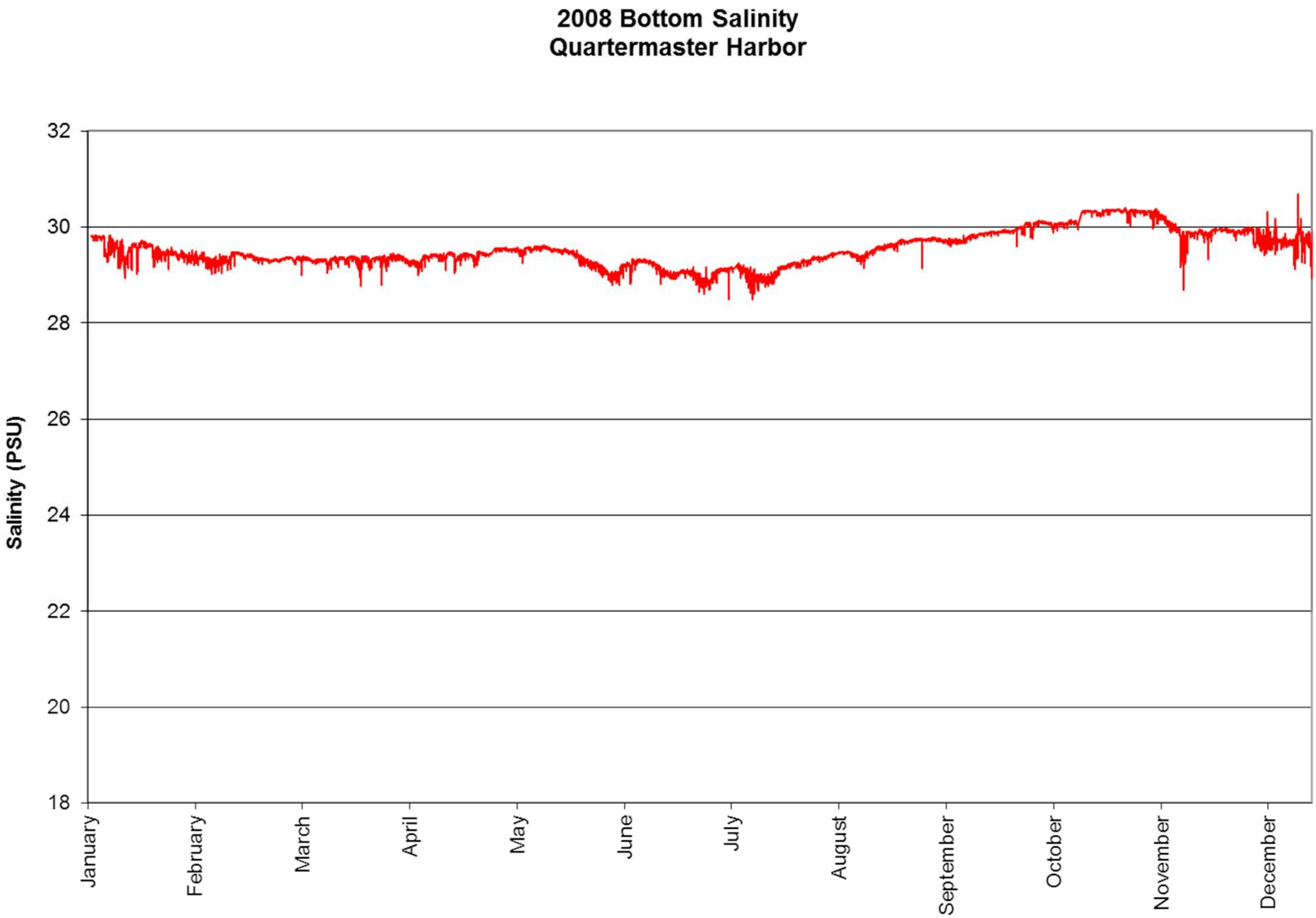


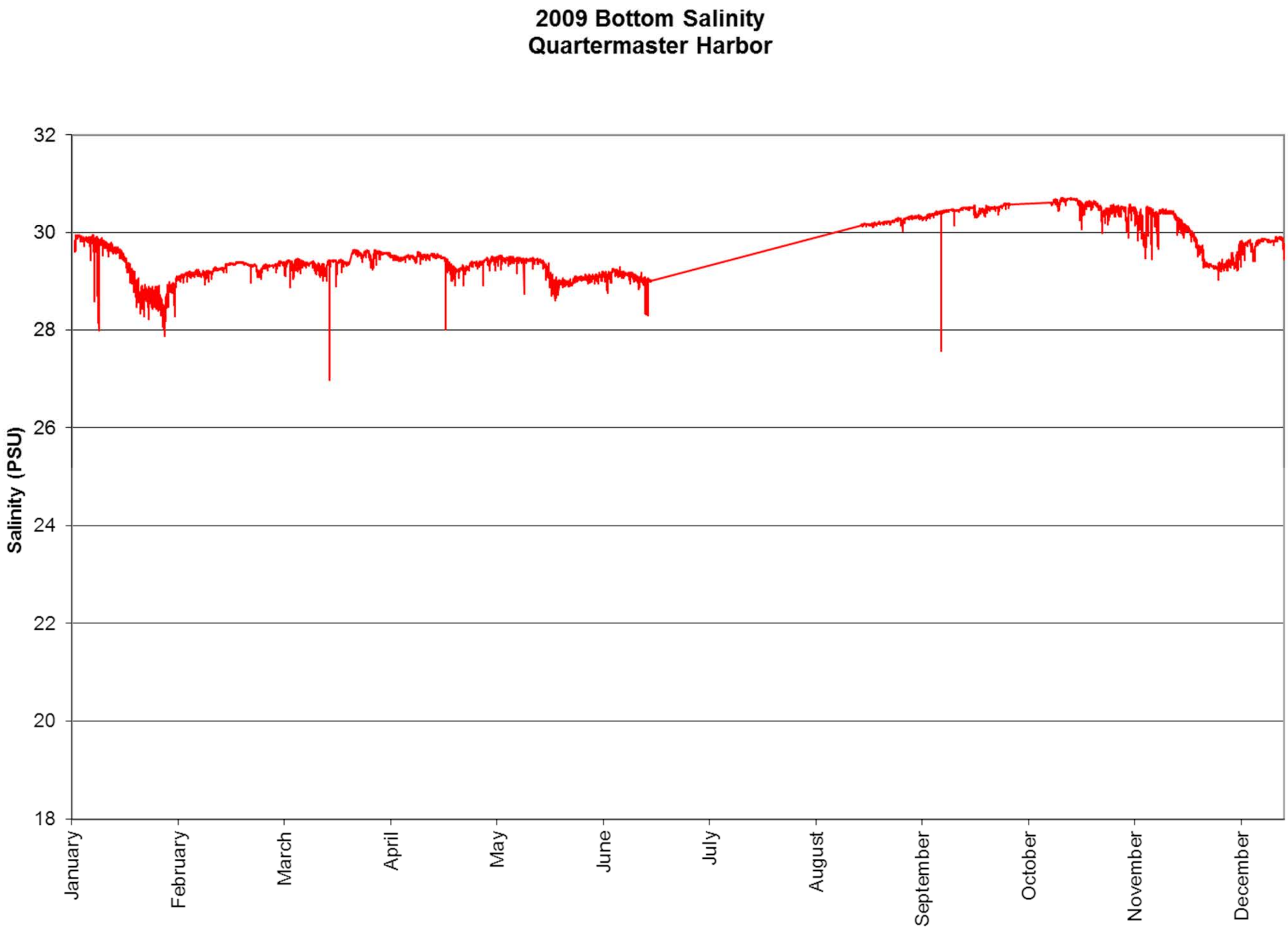

2009 Surface Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December


2010 Surface Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

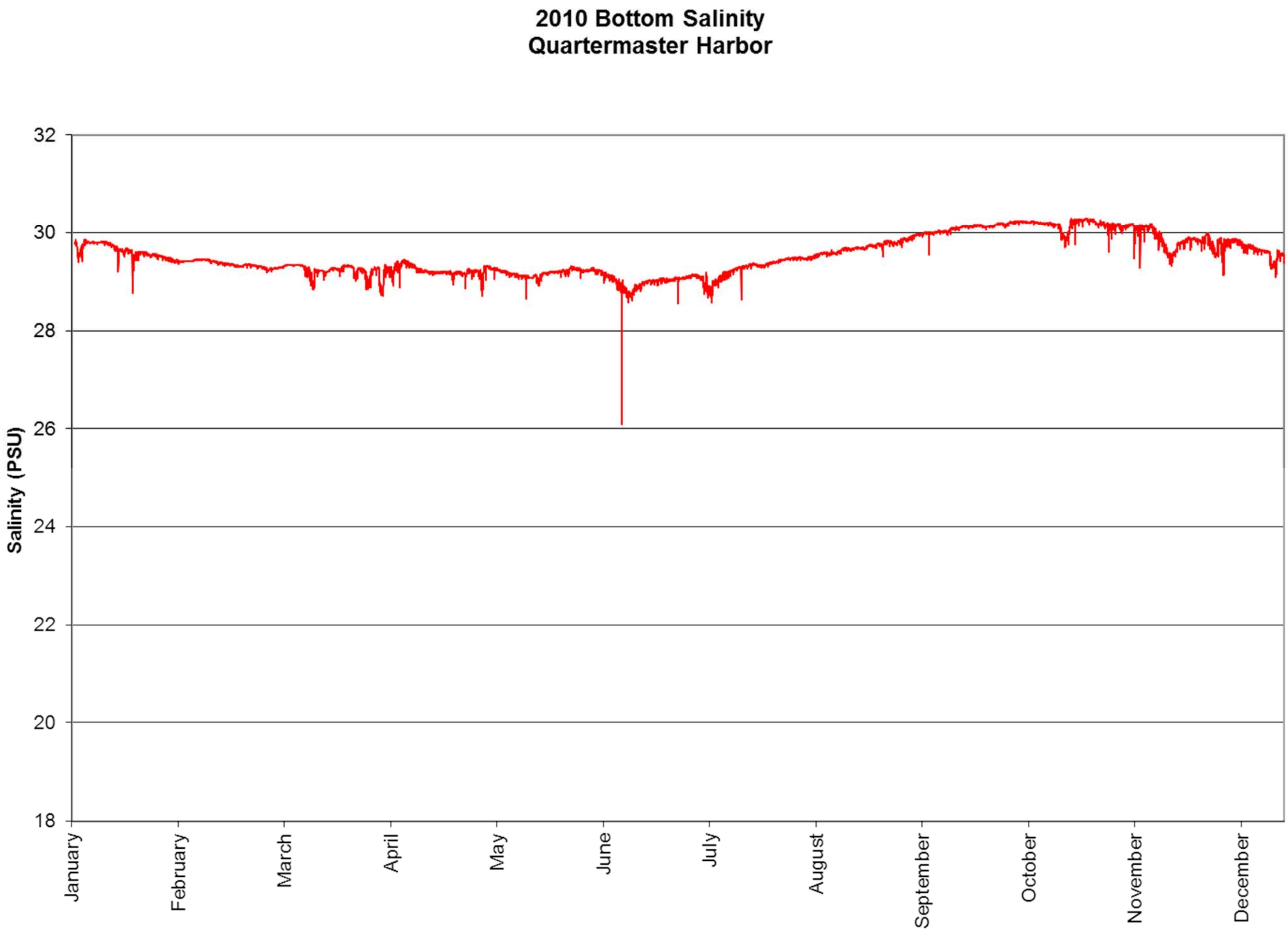

2011 Surface Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

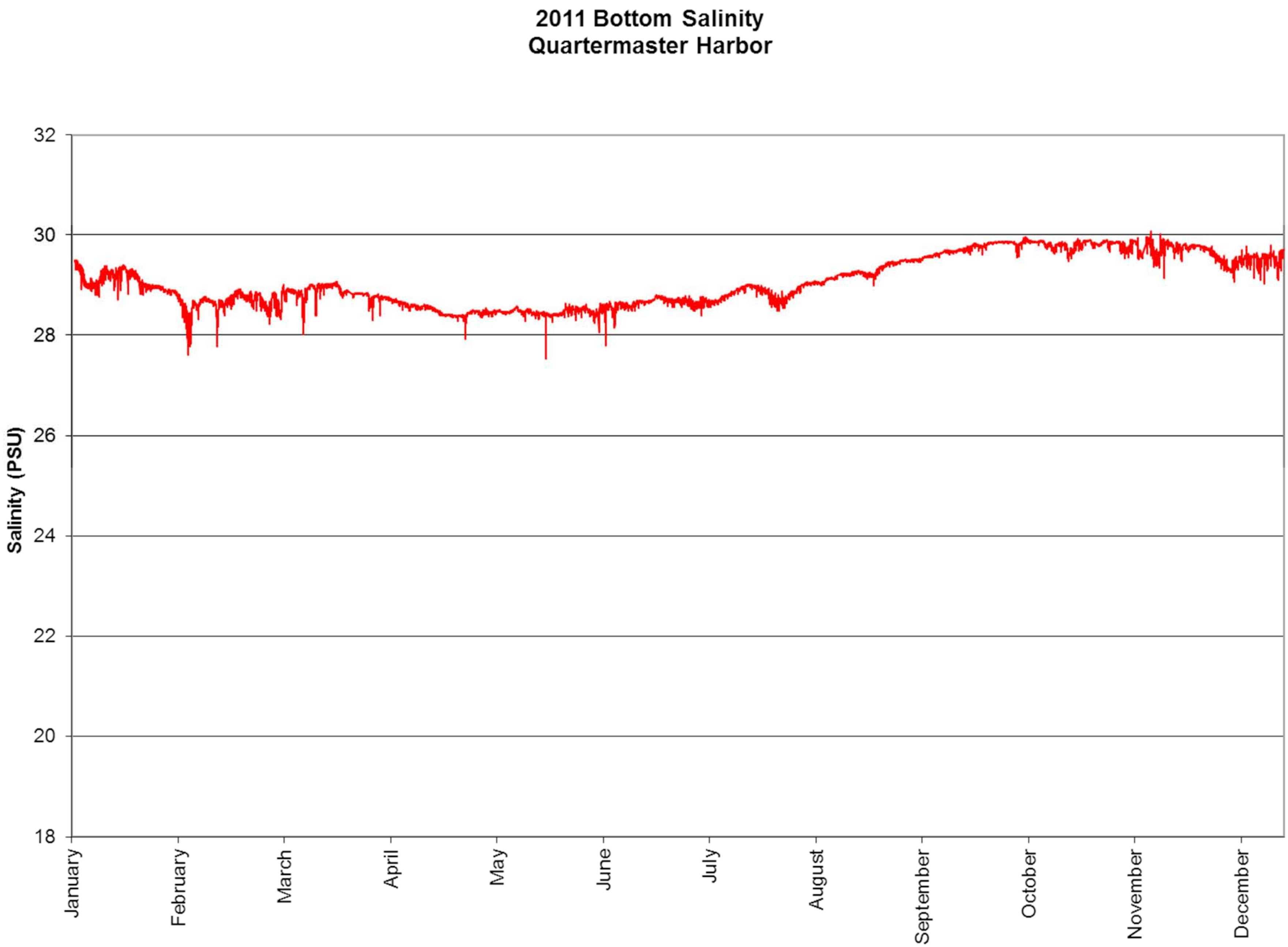

2007 Bottom Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

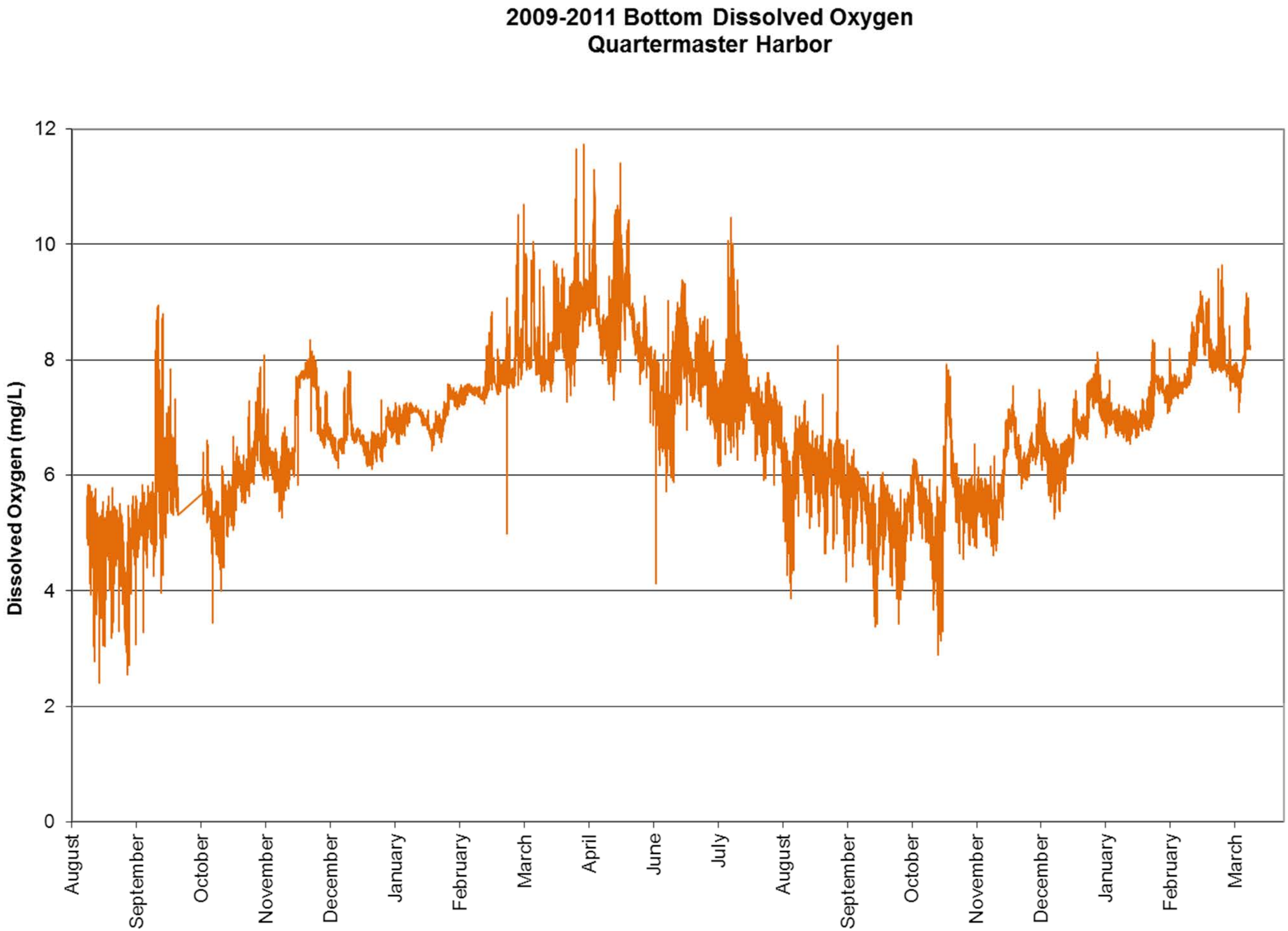

2008 Bottom Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

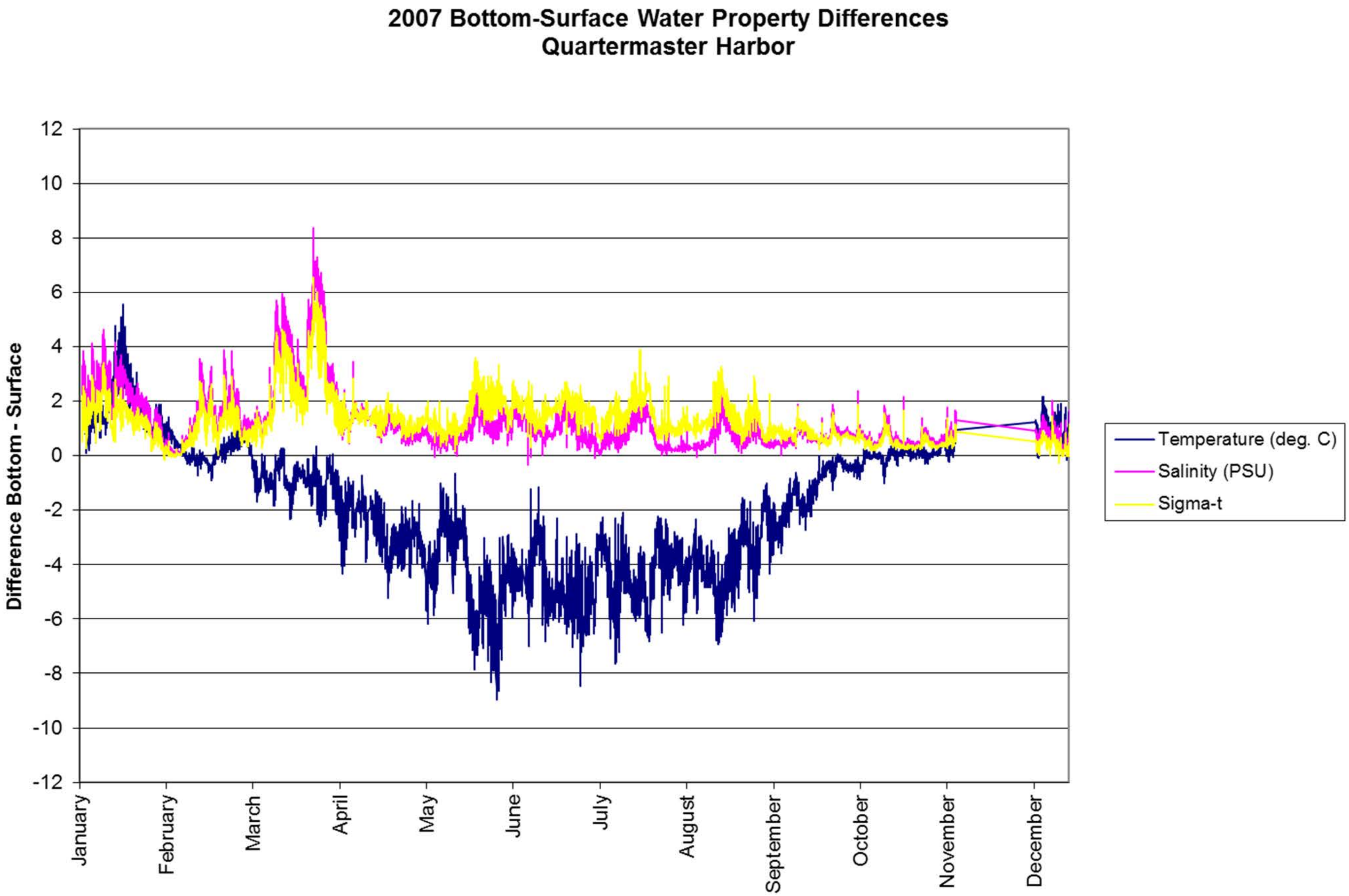


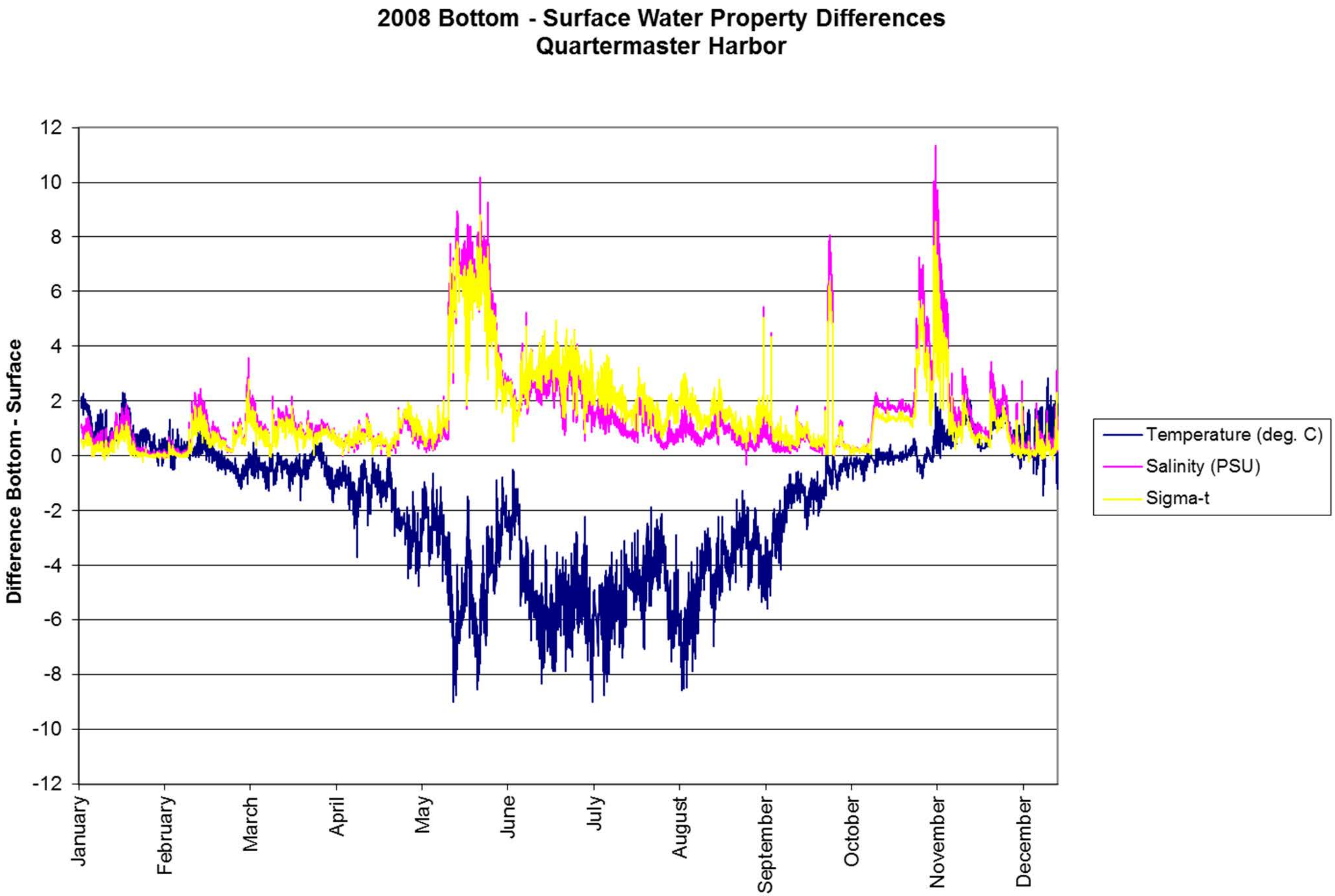
2009 Bottom Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

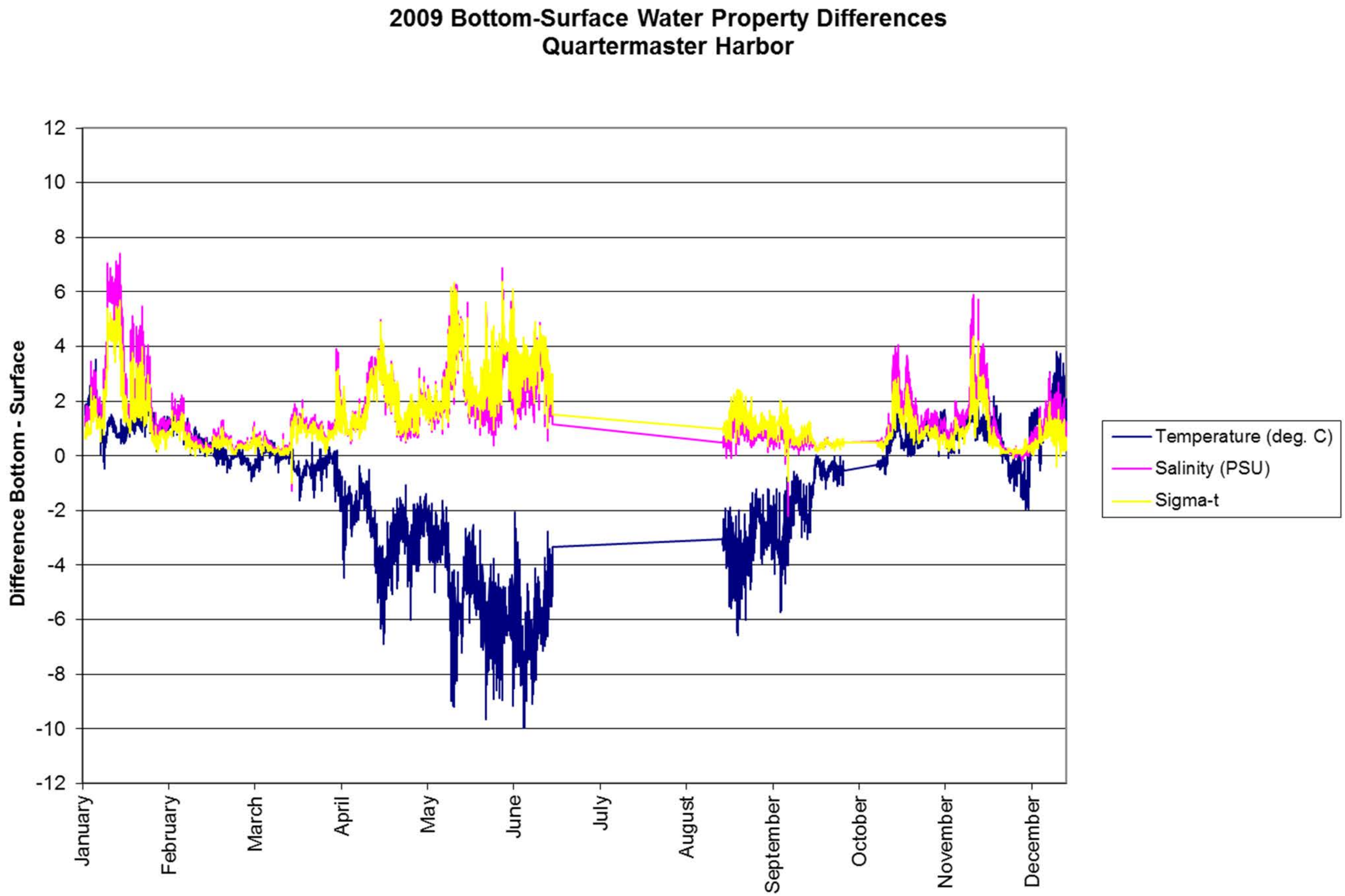

2010 Bottom Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December


2011 Bottom Salinity
Quartermaster Harbor
Salinity (PSU)
32
30
28
26
24
22
20
18
January
February
March
April
May
June
July
August
September
October
November
December

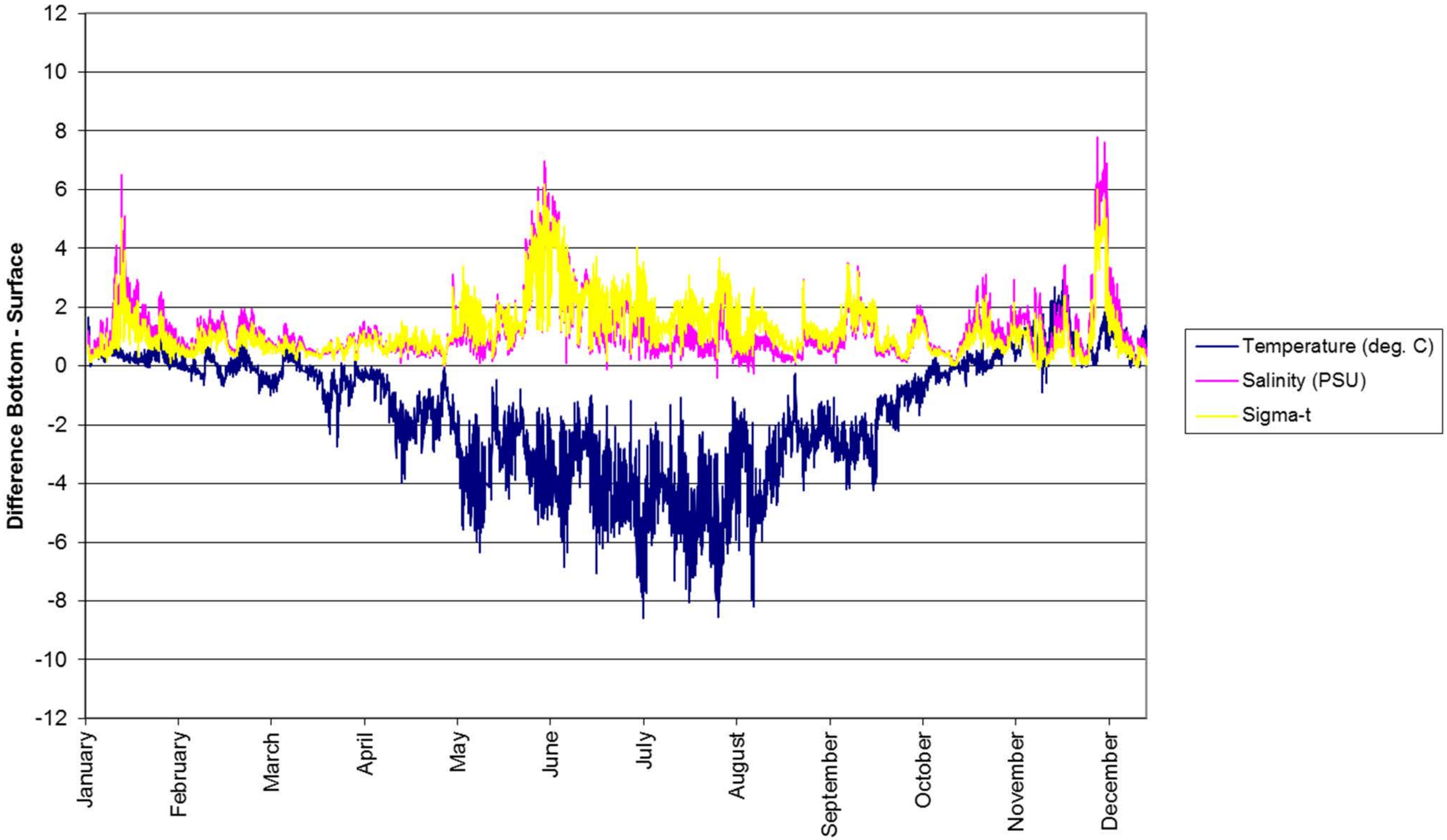

2009-2011 Bottom Dissolved Oxygen
Quartermaster Harbor
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
August
September
October
November
December
January
February
March
April
June
July
August
September
October
November
December
January
February
March

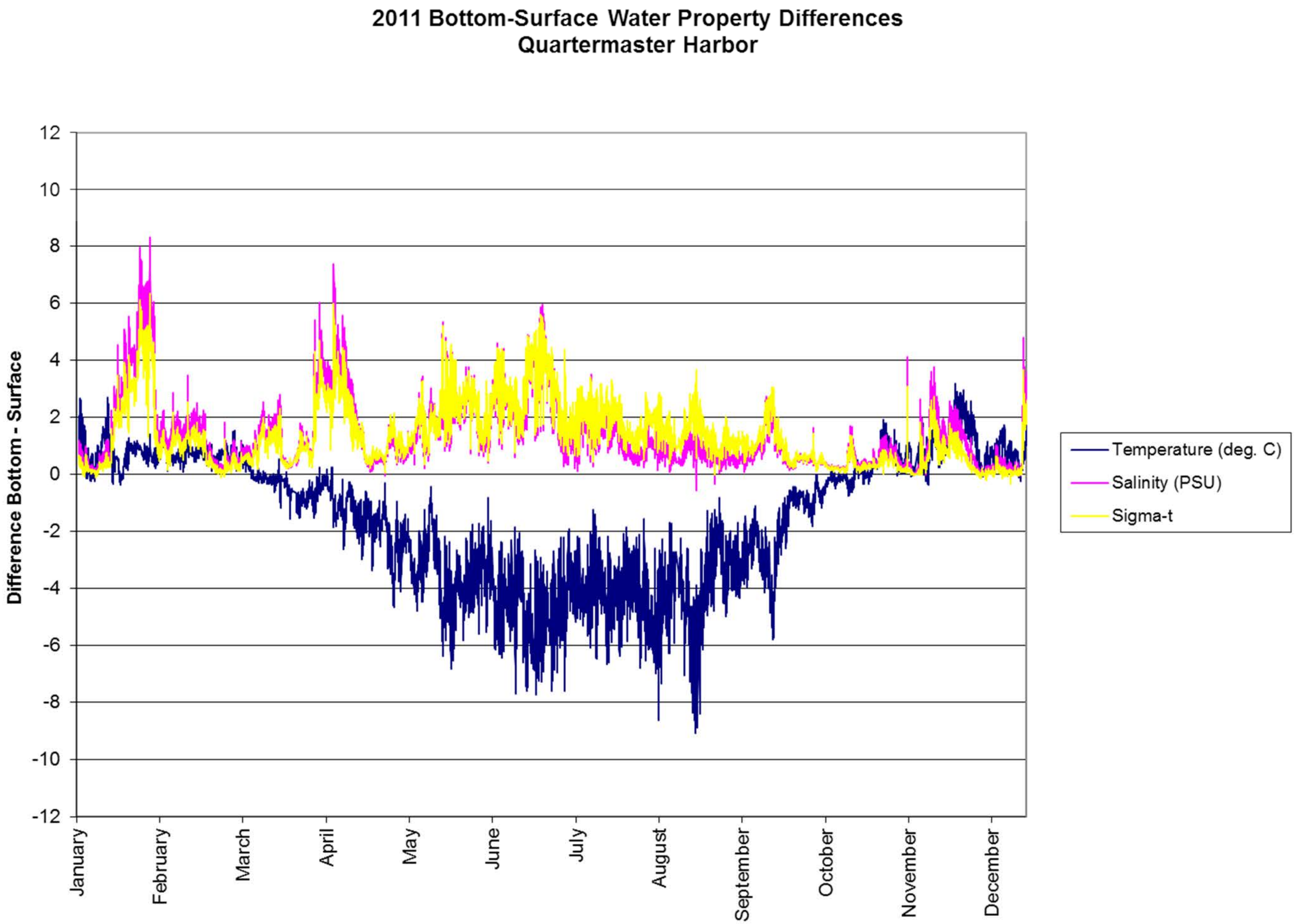

2007 Bottom-Surface Water Property Differences
Quartermaster Harbor
Difference Bottom - Surface
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
January
February
March
April
May
June
July
August
September
October
November
December
Temperature (deg. C)
Salinity (PSU)
Sigma-t


2008 Bottom - Surface Water Property Differences
Quartermaster Harbor
Difference Bottom - Surface
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
January
February
March
April
May
June
July
August
September
October
November
December
Temperature (deg. C)
Salinity (PSU)
Sigma-t


2009 Bottom-Surface Water Property Differences
Quartermaster Harbor
Difference Bottom - Surface
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
January
February
March
April
May
June
July
August
September
October
November
December
Temperature (deg. C)
Salinity (PSU)
Sigma-t

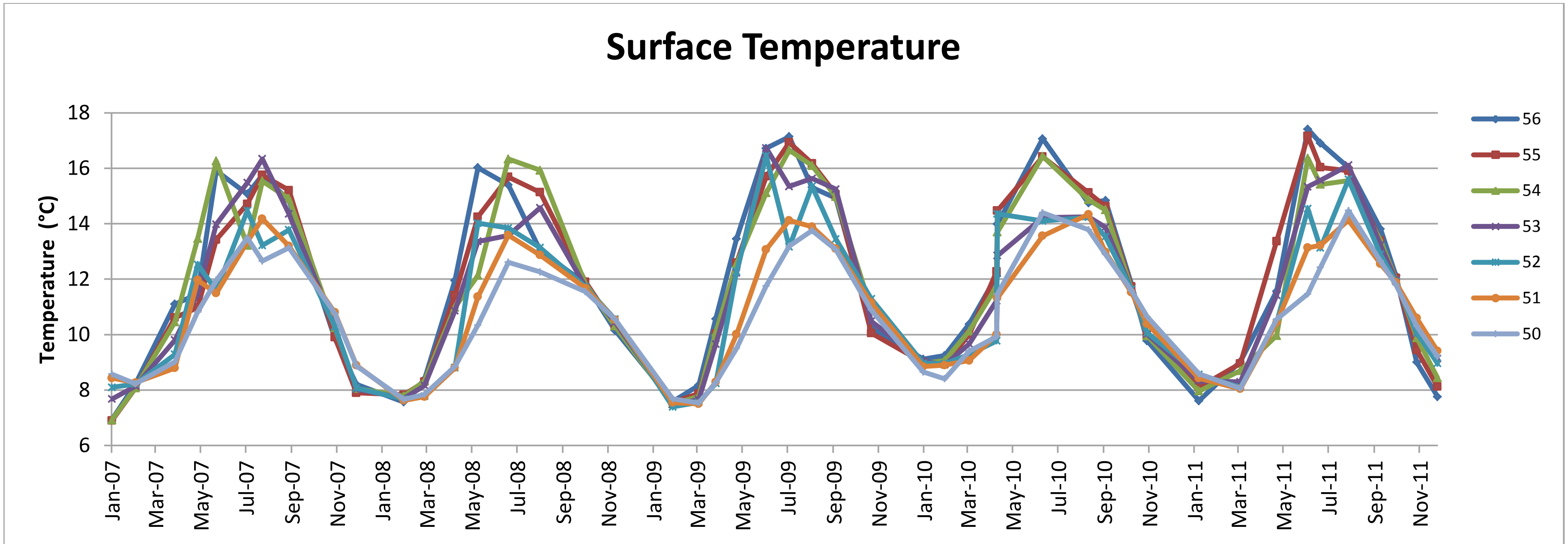
2010 Bottom-Surface Water Property Differences
Quartermaster Harbor



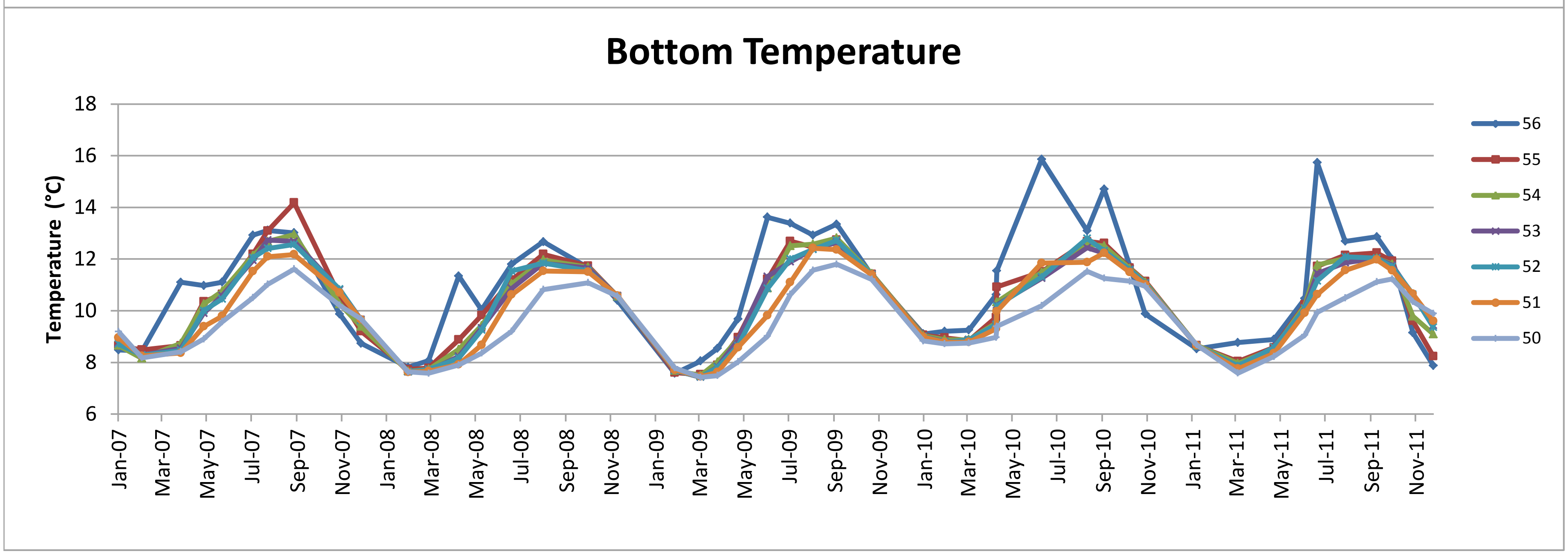


2011 Bottom-Surface Water Property Differences
Quartermaster Harbor
Difference Bottom - Surface
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
January
February
March
April
May
June
July
August
September
October
November
December
Temperature (deg. C)
Salinity (PSU)
Sigma-t

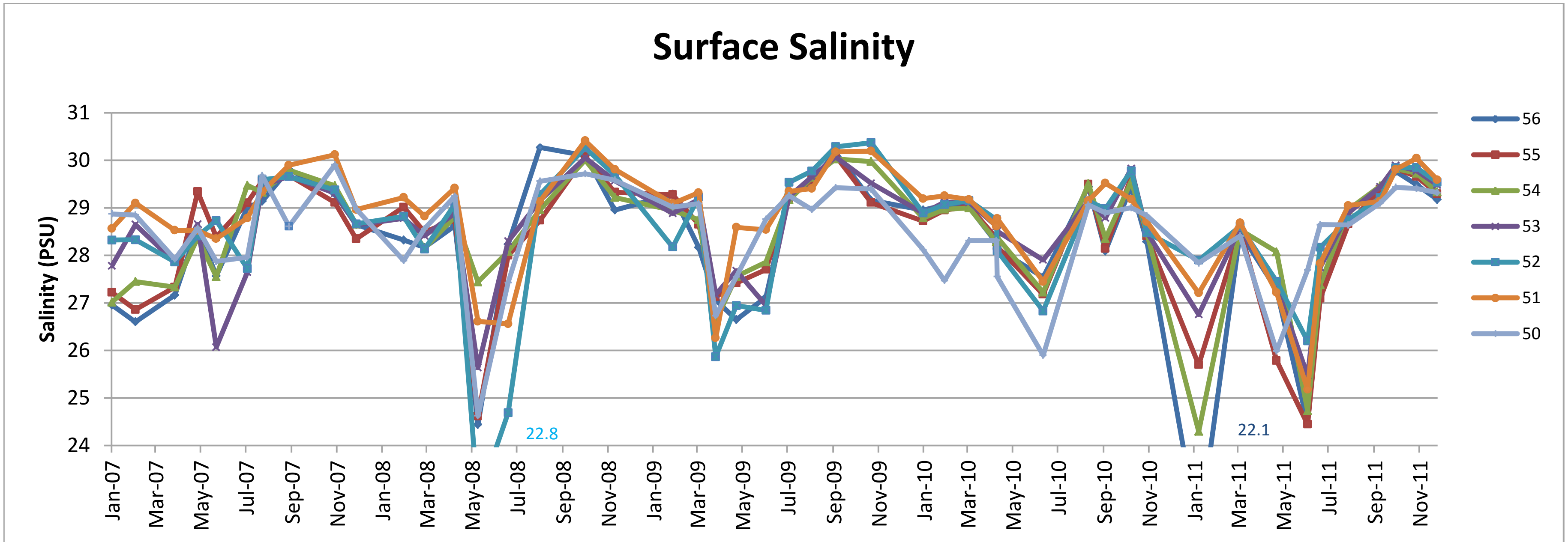
Appendix C: UWT Time Series and Property-Property Plots

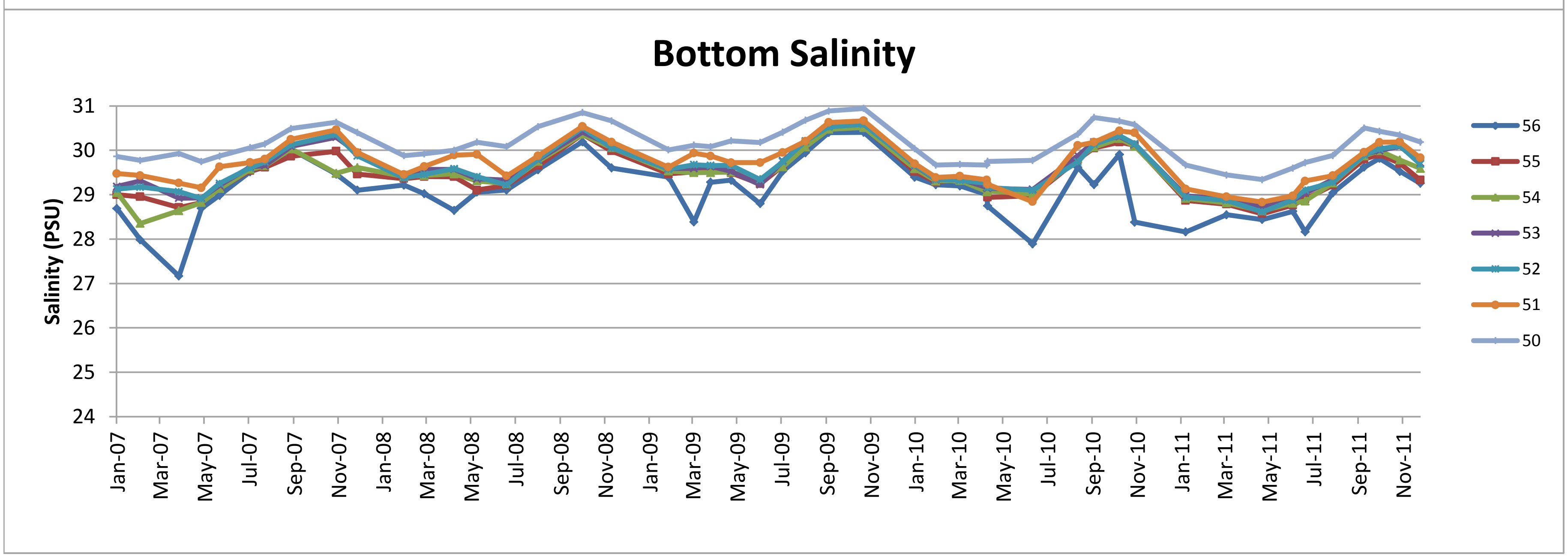


Surface Temperature
Temperature (°C)
18
16
14
12
10
8
6
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50



Bottom Temperature
Temperature (°C)
18
16
14
12
10
8
6
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50


Surface Salinity
Salinity (PSU)
31
30
29
28
27
26
25
24
22.8
22.1
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50


Bottom Salinity
Salinity (PSU)
31
30
29
28
27
26
25
24
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
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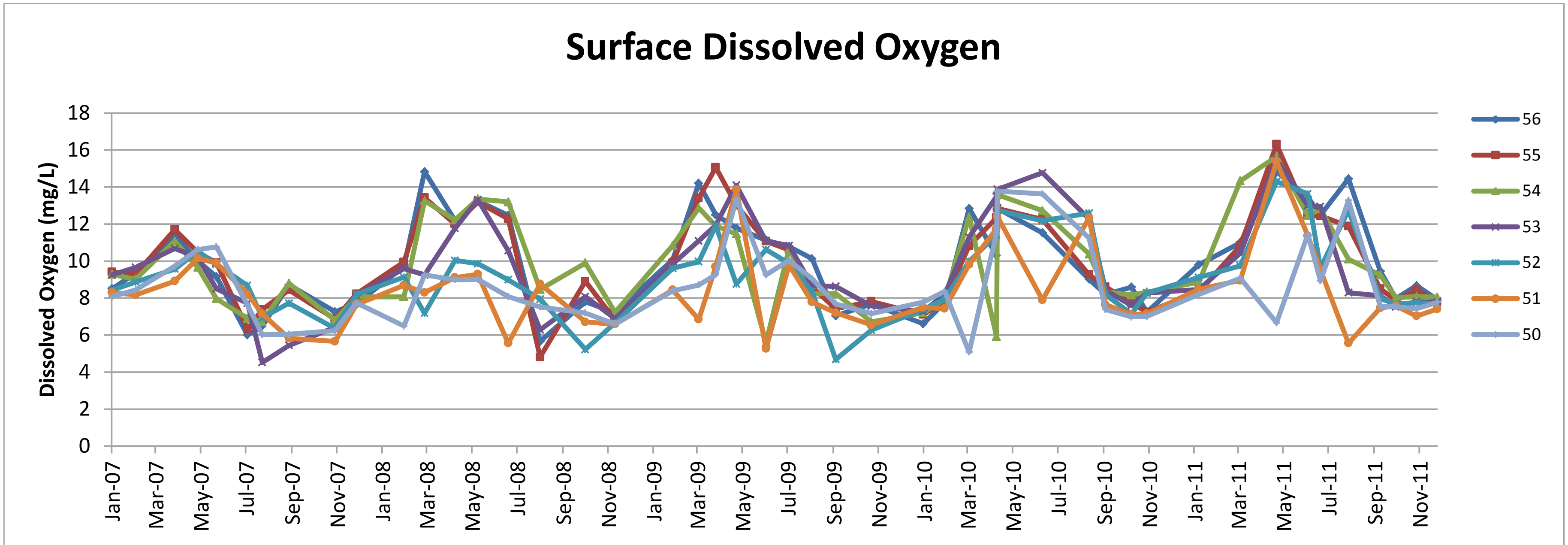
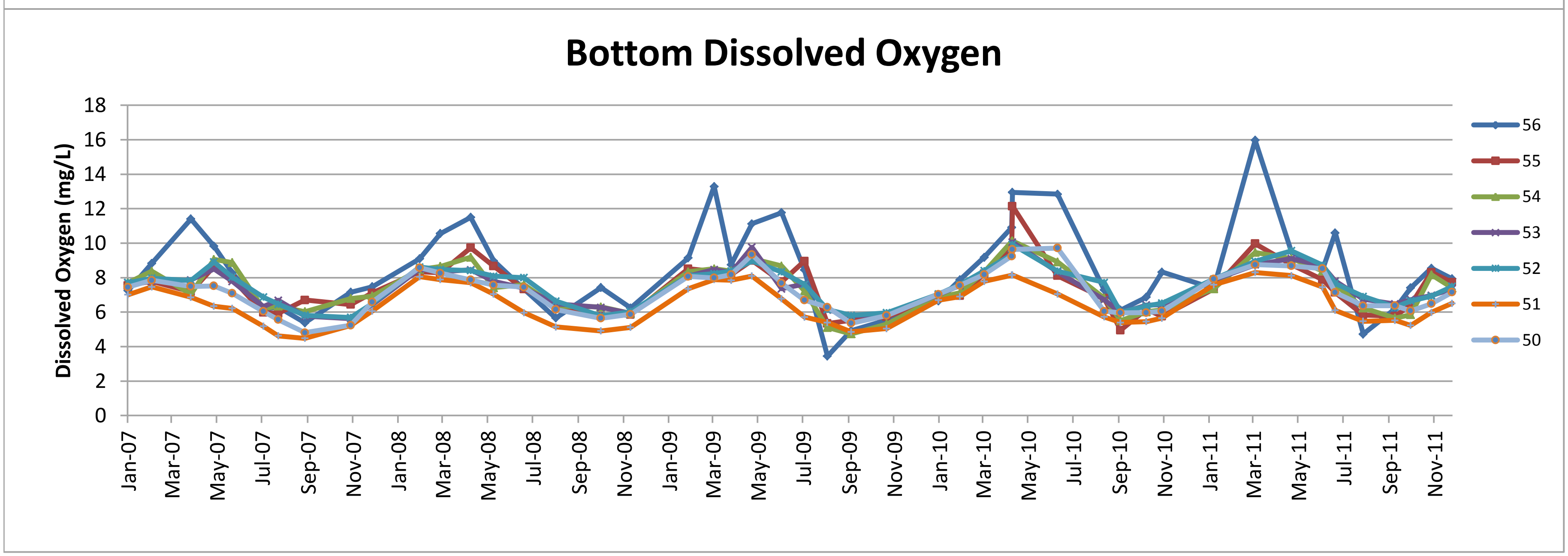
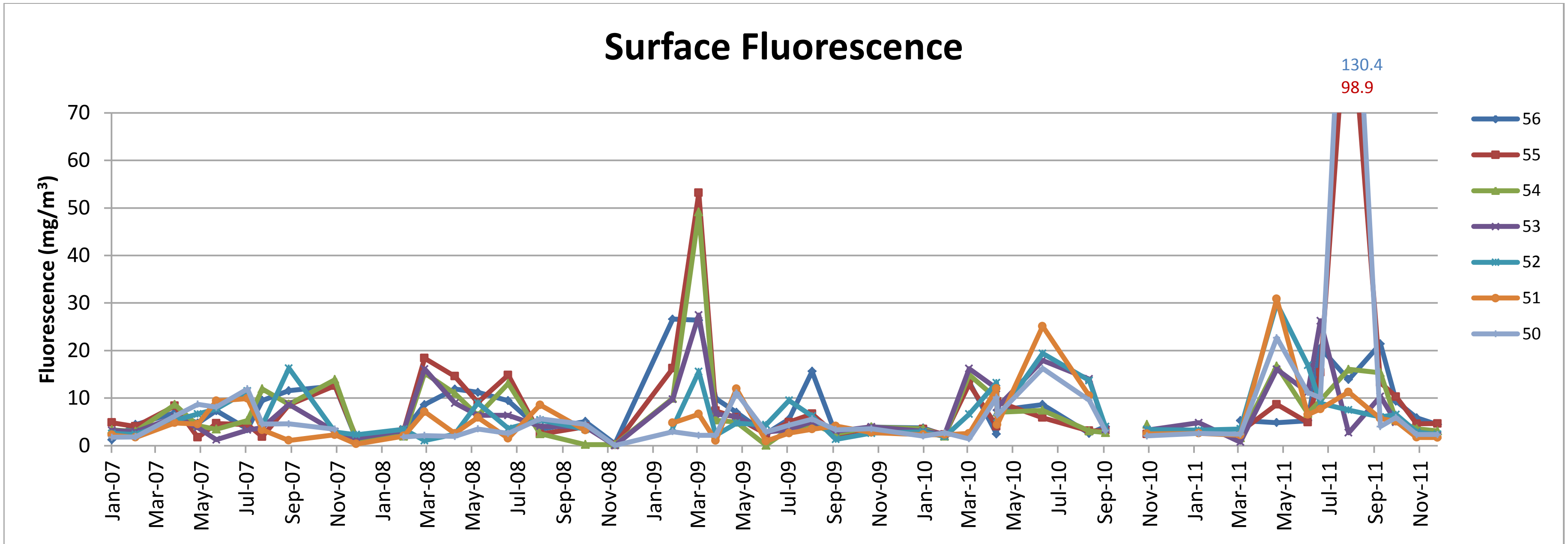
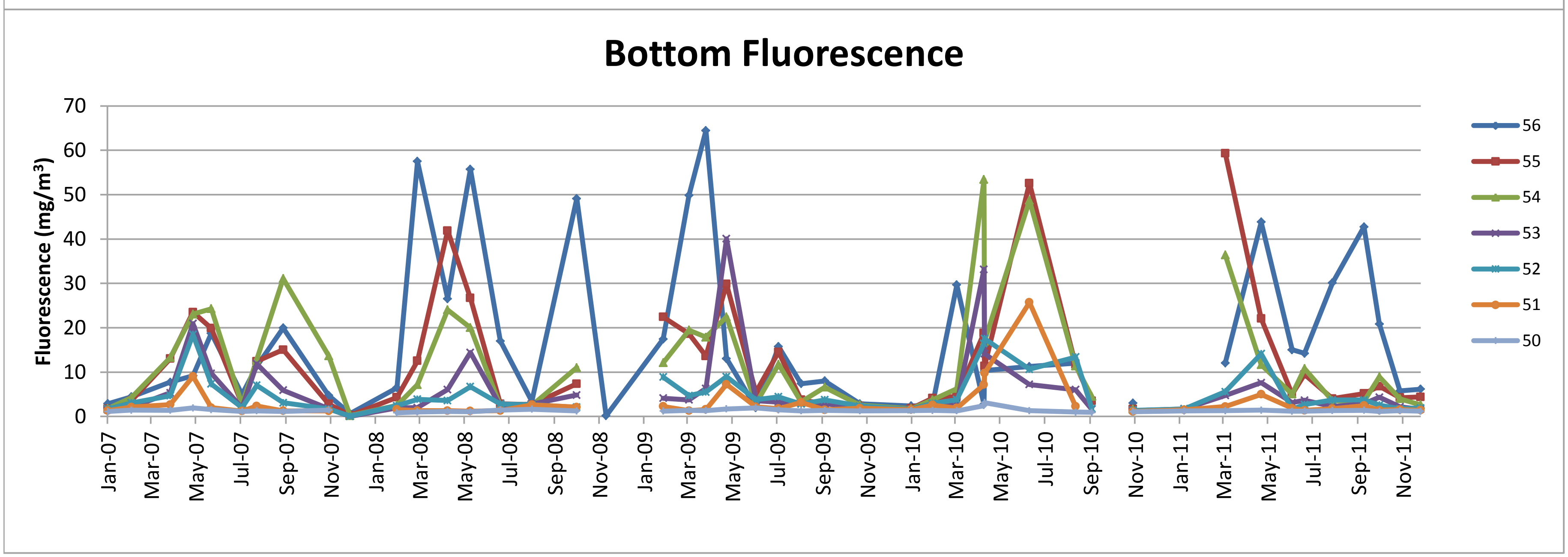
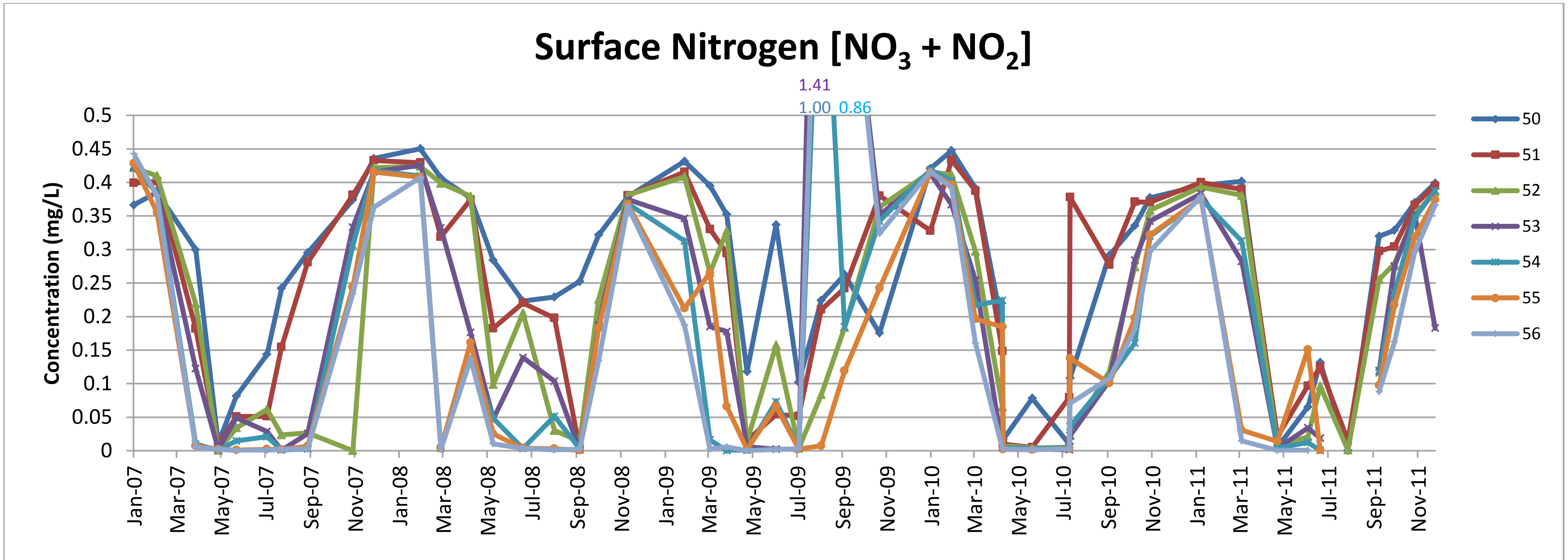
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50


Surface Dissolved Oxygen
Dissolved Oxygen (mg/L)
18
16
14
12
10
8
6
4
2
0
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50

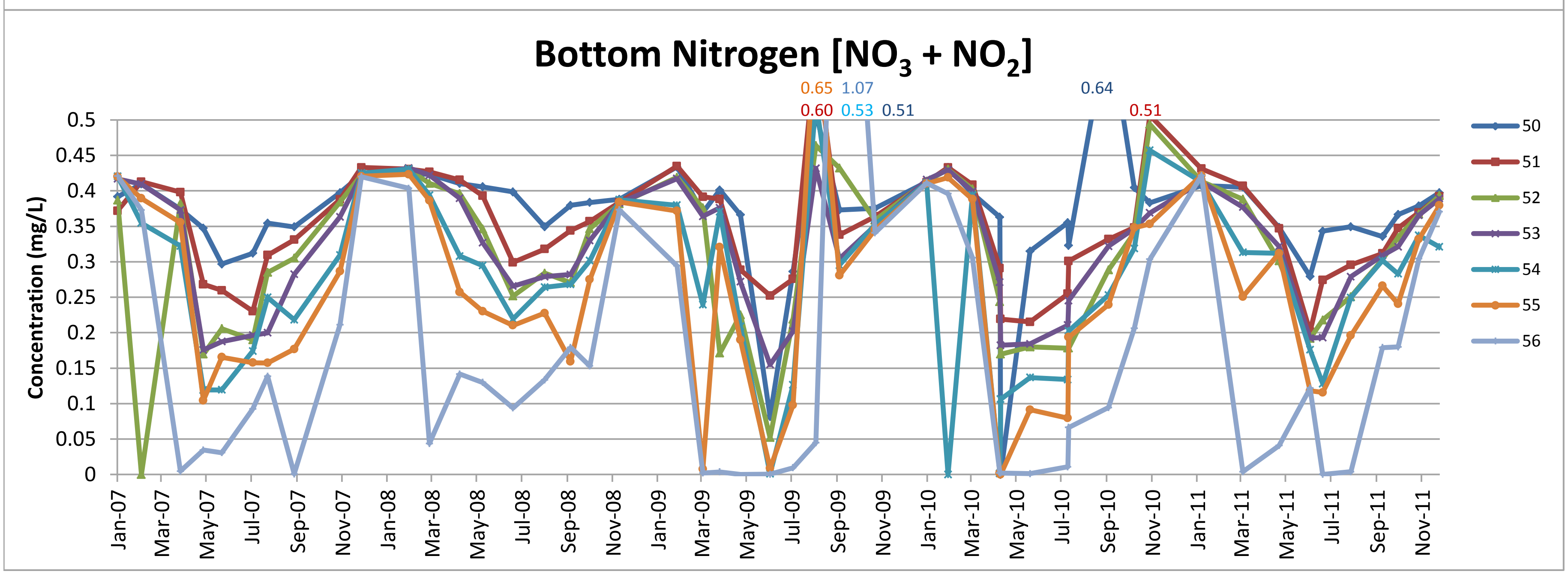

Bottom Dissolved Oxygen
Dissolved Oxygen (mg/L)
18
16
14
12
10
8
6
4
2
0
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50


Surface Fluorescence
130.4
98.9
Fluorescence (mg/m³)
70
60
50
40
30
20
10
0
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50

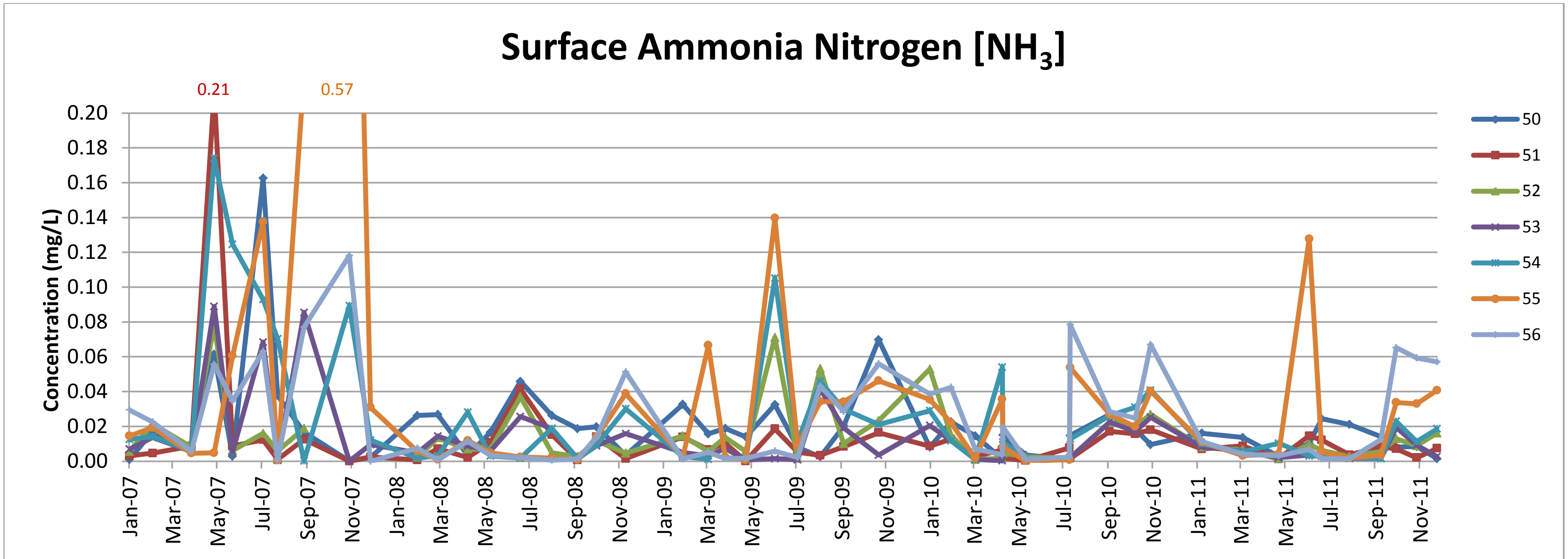

Bottom Fluorescence
Fluorescence (mg/m³)
70
60
50
40
30
20
10
0
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
56
55
54
53
52
51
50

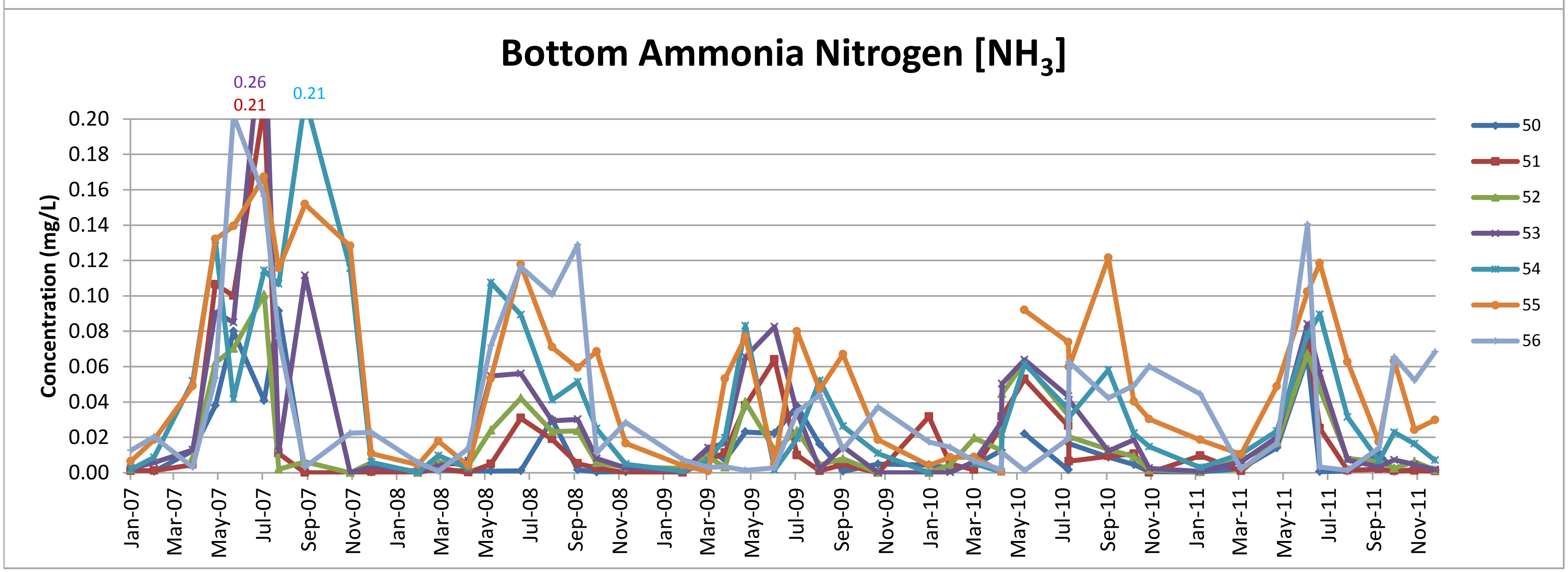


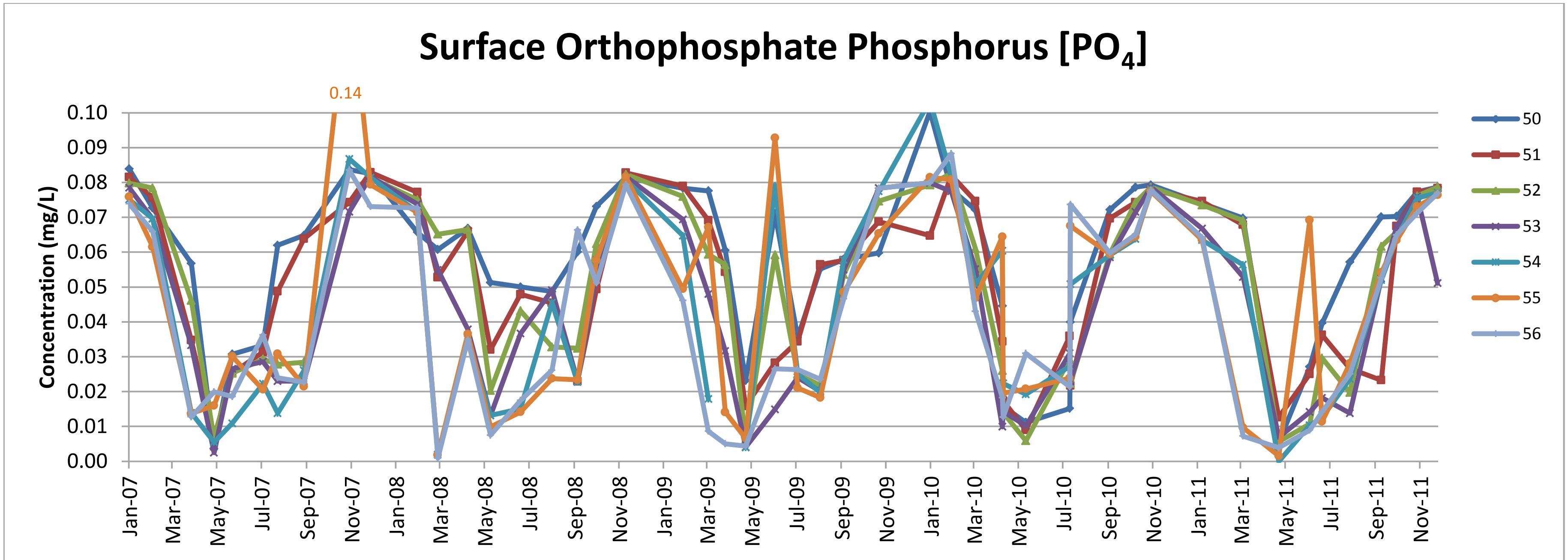
Surface Nitrogen [NO_3 + NO_2]
1.41
1.00 0.86
Concentration (mg/L)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

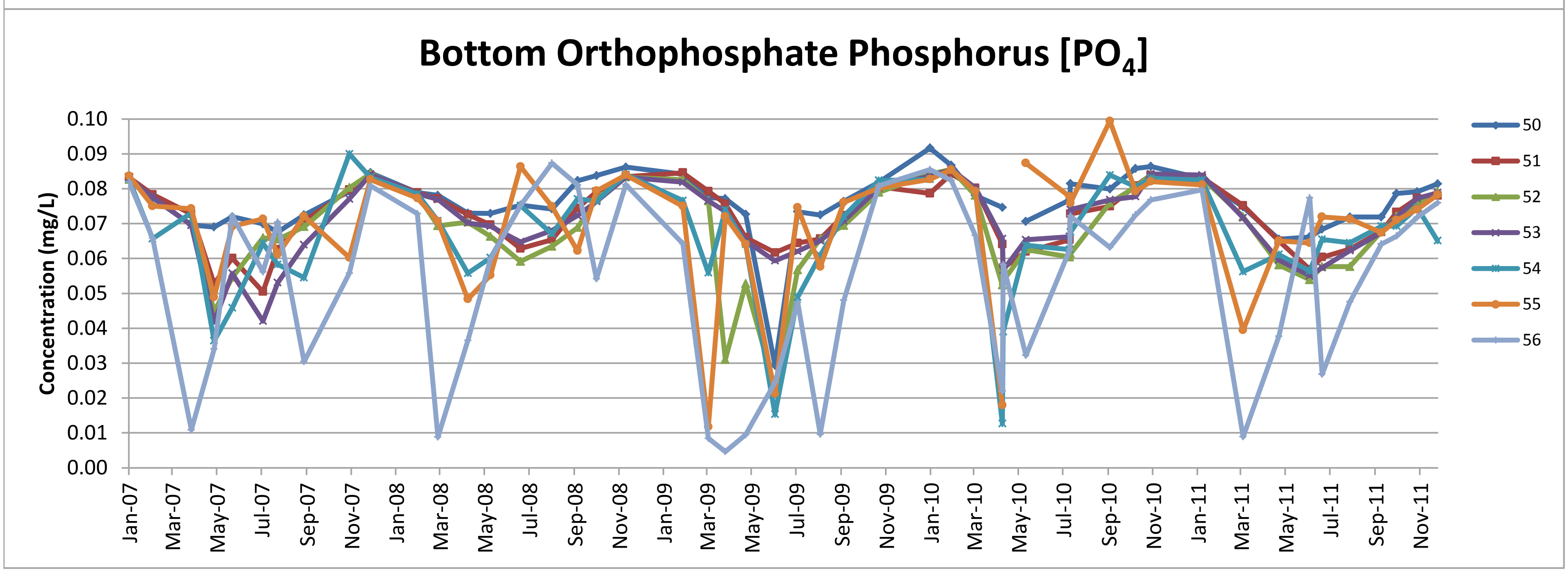


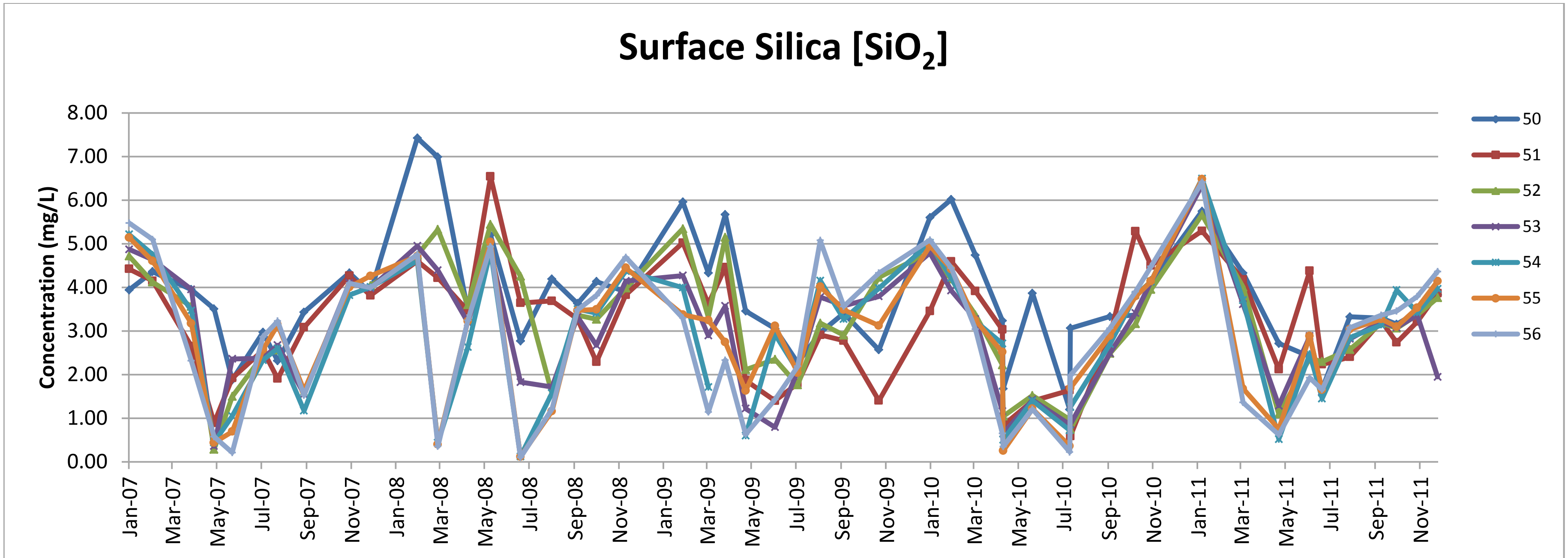
Bottom Nitrogen [NO_3 + NO_2]
0.65 1.07
0.64
0.60 0.53 0.51
0.51
Concentration (mg/L)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

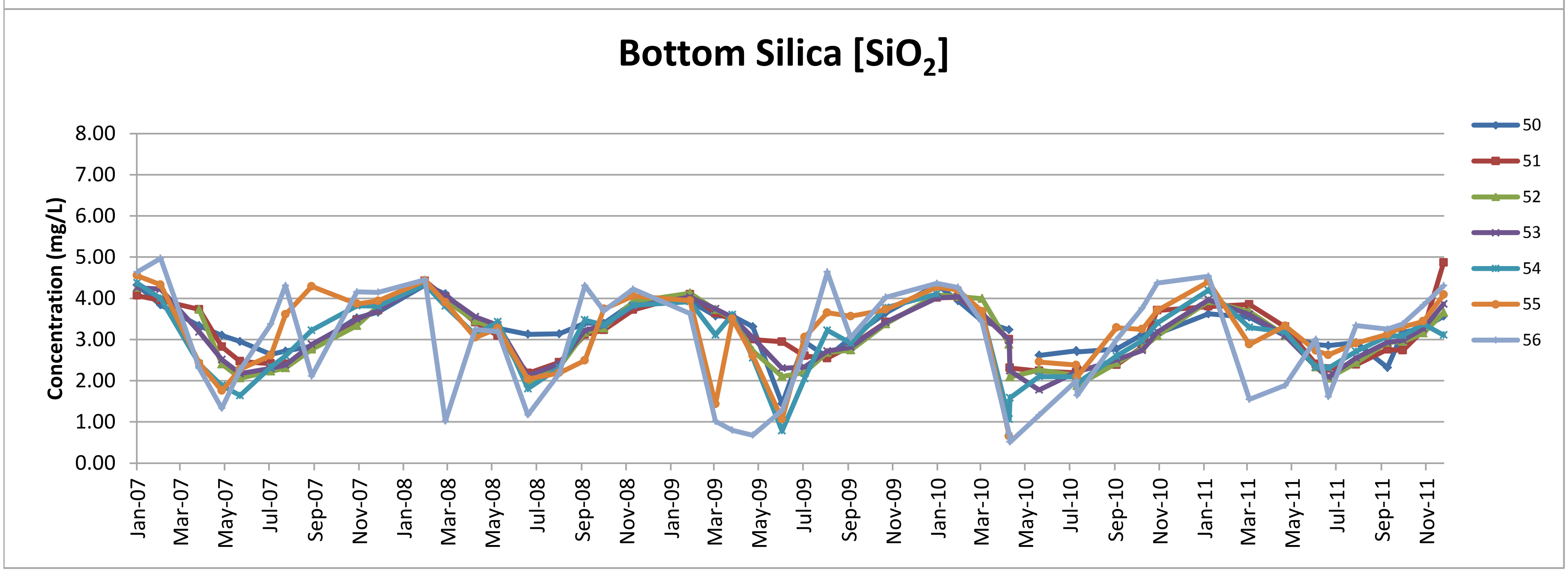

Surface Ammonia Nitrogen [NH3]
0.21
0.57
Concentration (mg/L)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

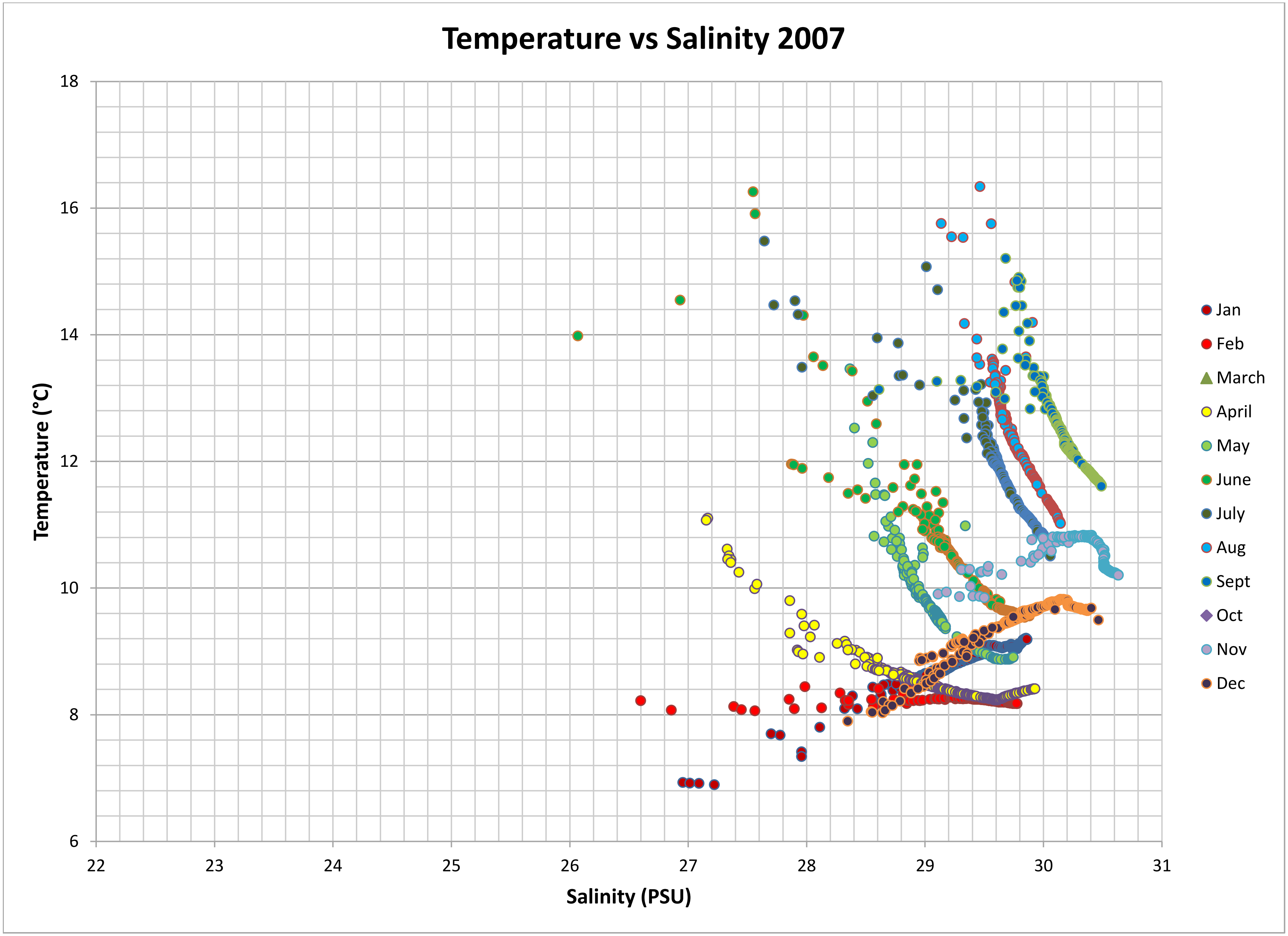

Bottom Ammonia Nitrogen [NH3]
0.26
0.21
0.21
Concentration (mg/L)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56


Surface Orthophosphate Phosphorus [PO4]
0.14
Concentration (mg/L)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

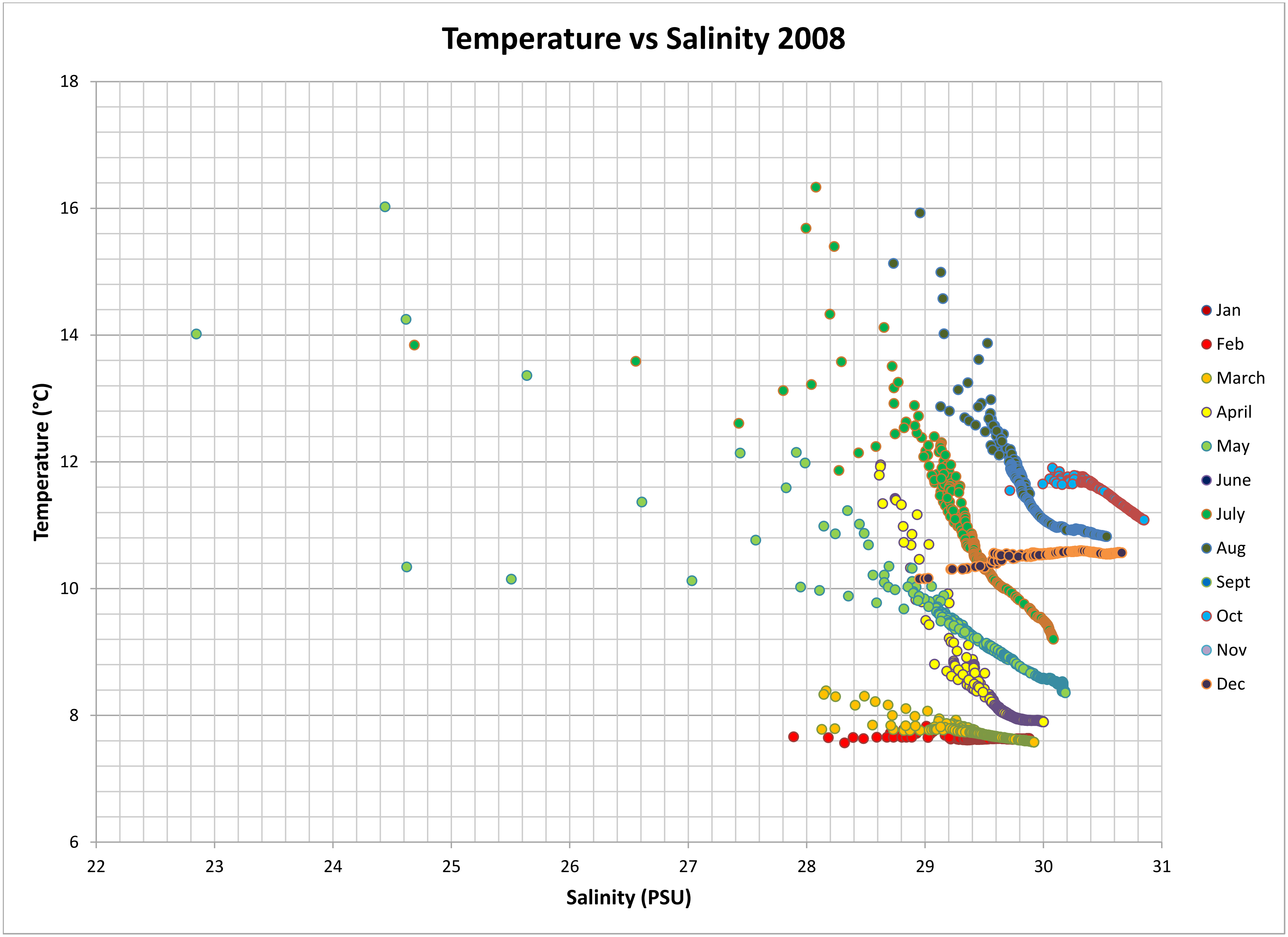

Bottom Orthophosphate Phosphorus [PO4]
Concentration (mg/L)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

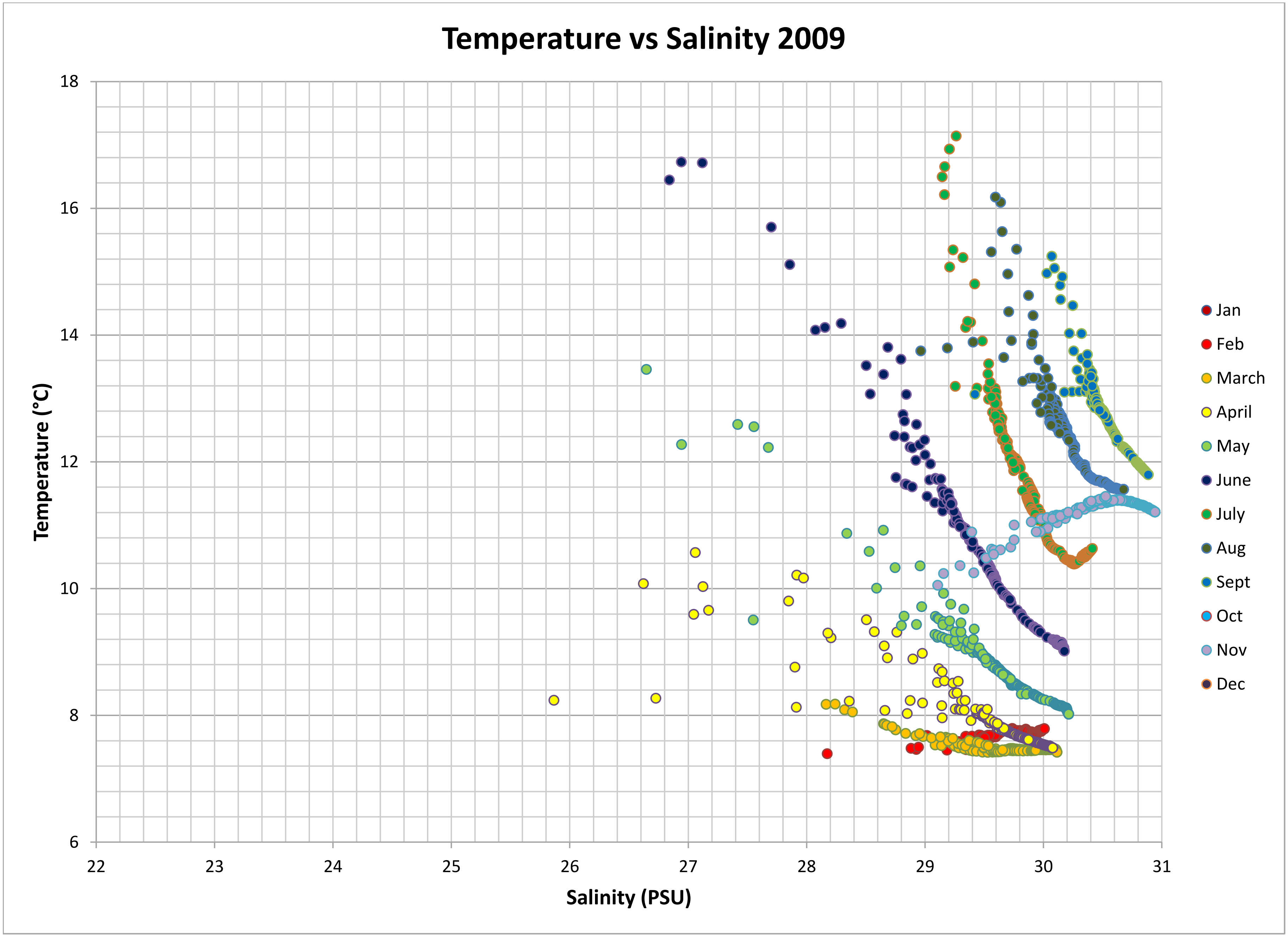

Surface Silica [SiO_2]
Concentration (mg/L)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

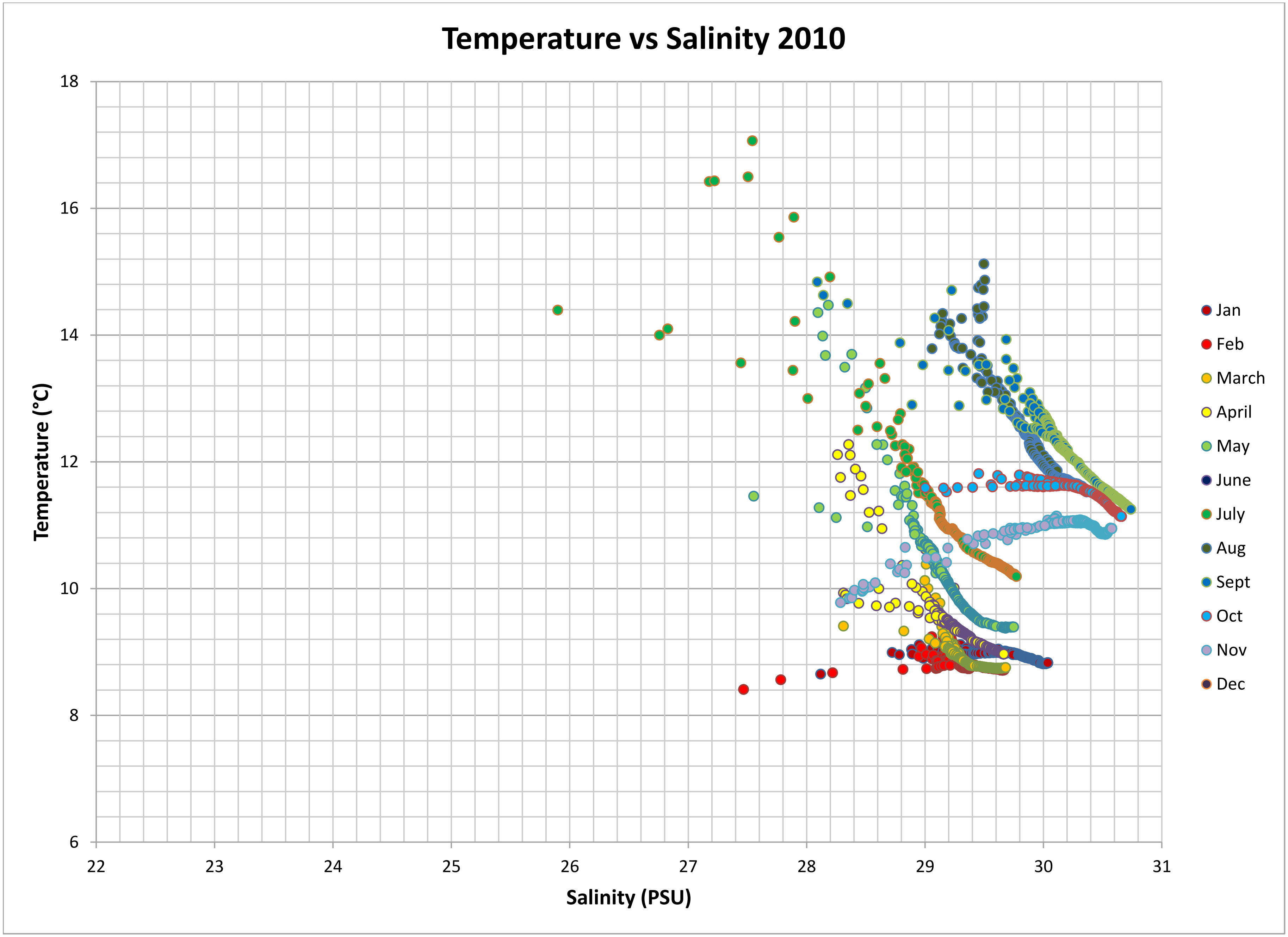

Bottom Silica [SiO_2]
Concentration (mg/L)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
50
51
52
53
54
55
56

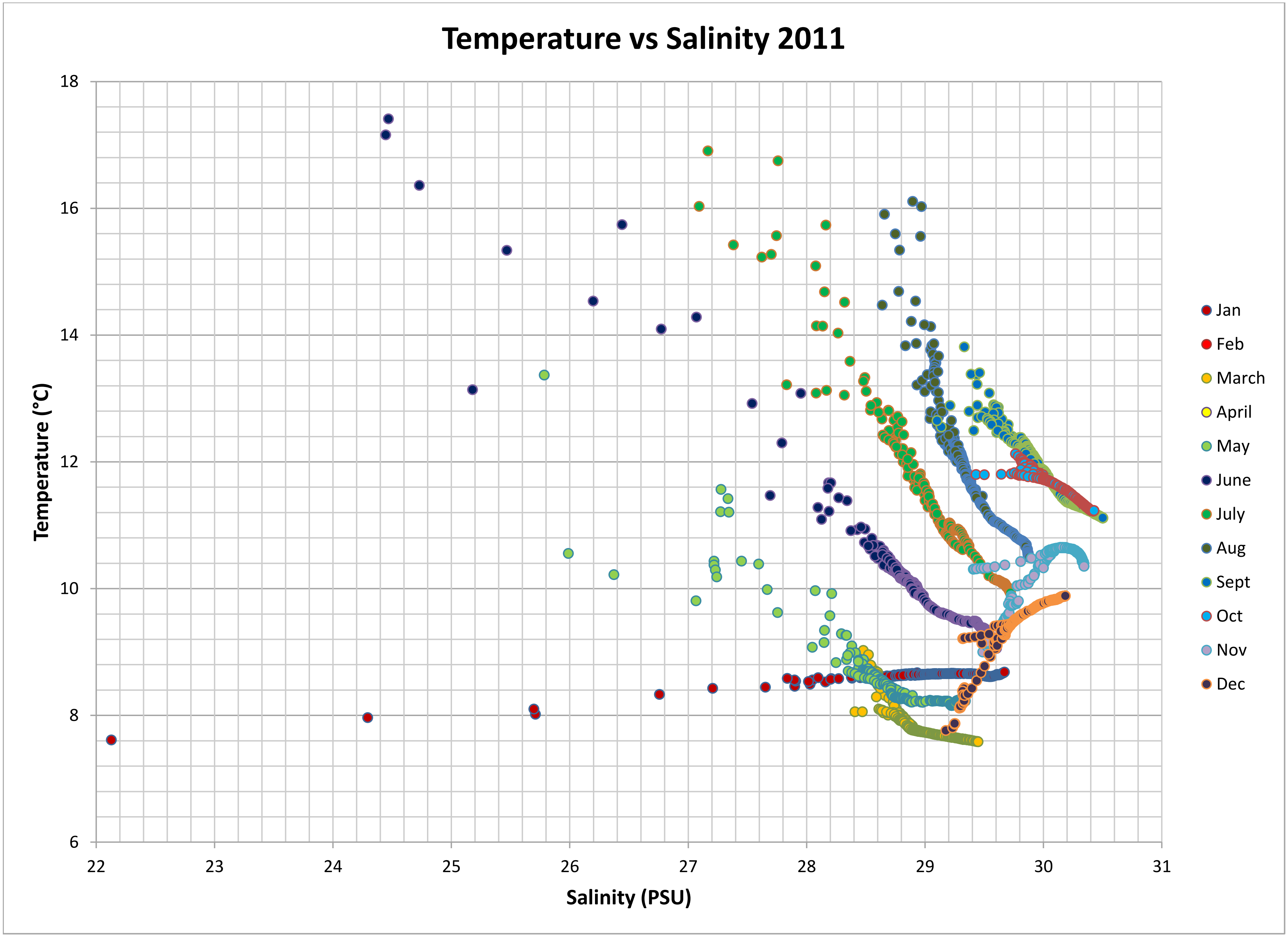

Temperature vs Salinity 2007
Temperature (°C)
18
16
14
12
10
8
6
22
23
24
25
26
27
28
29
30
31
Salinity (PSU)
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

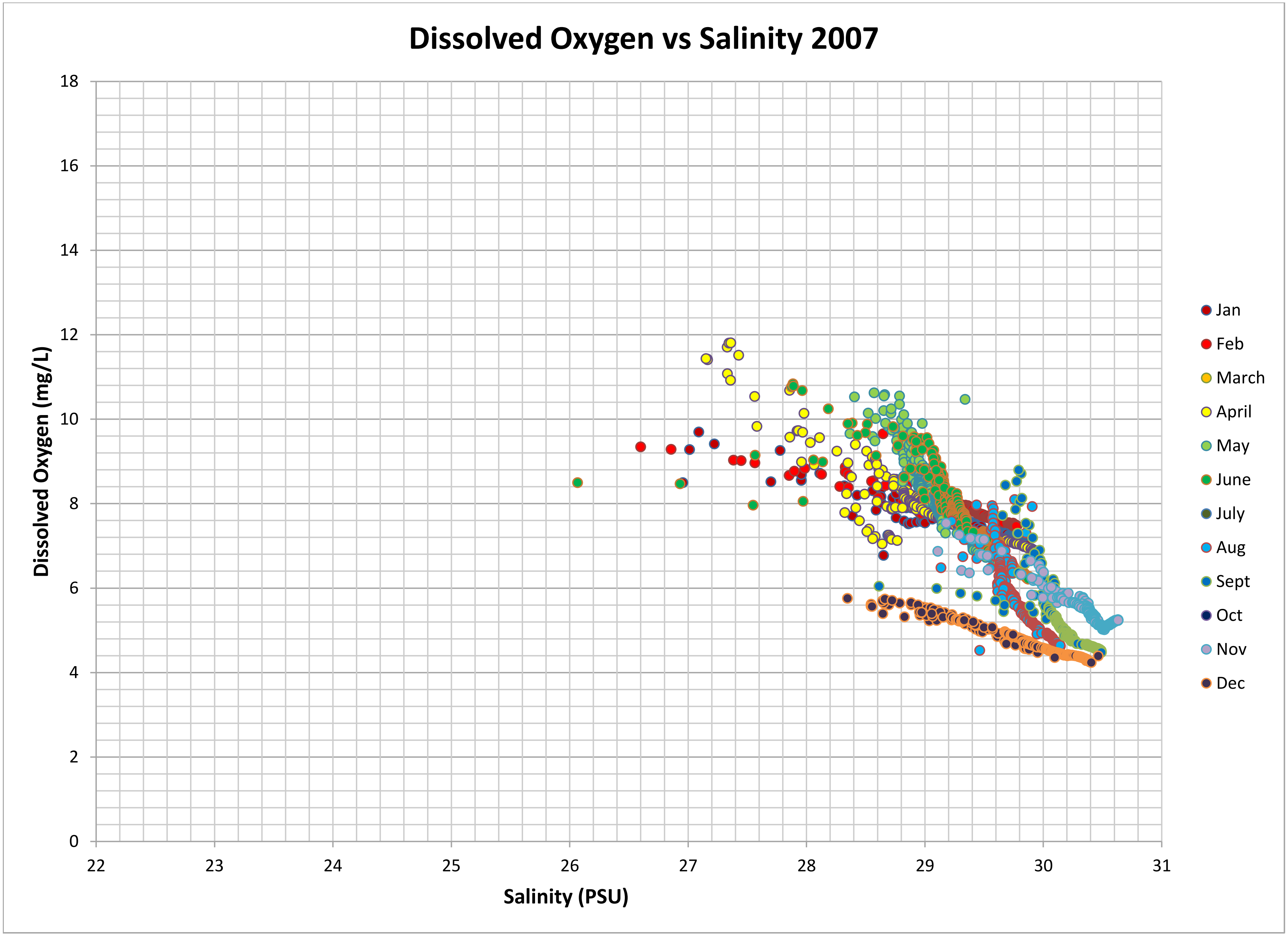
Appendix C


Temperature vs Salinity 2008
Temperature (°C)
Salinity (PSU)
18
16
14
12
10
8
6
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

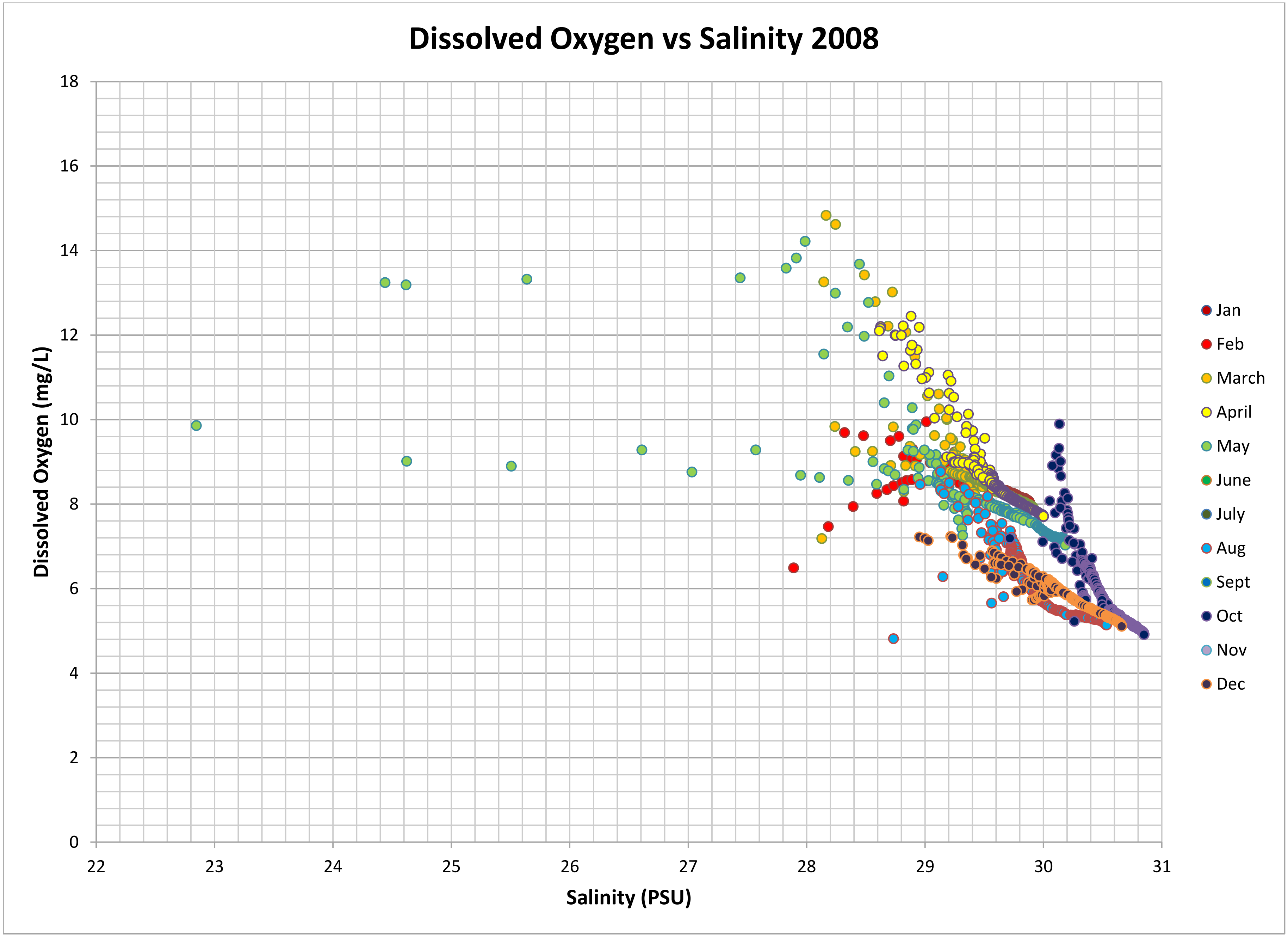

Temperature vs Salinity 2009
Temperature (°C)
18
16
14
12
10
8
6
22
23
24
25
26
27
28
29
30
31
Salinity (PSU)
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

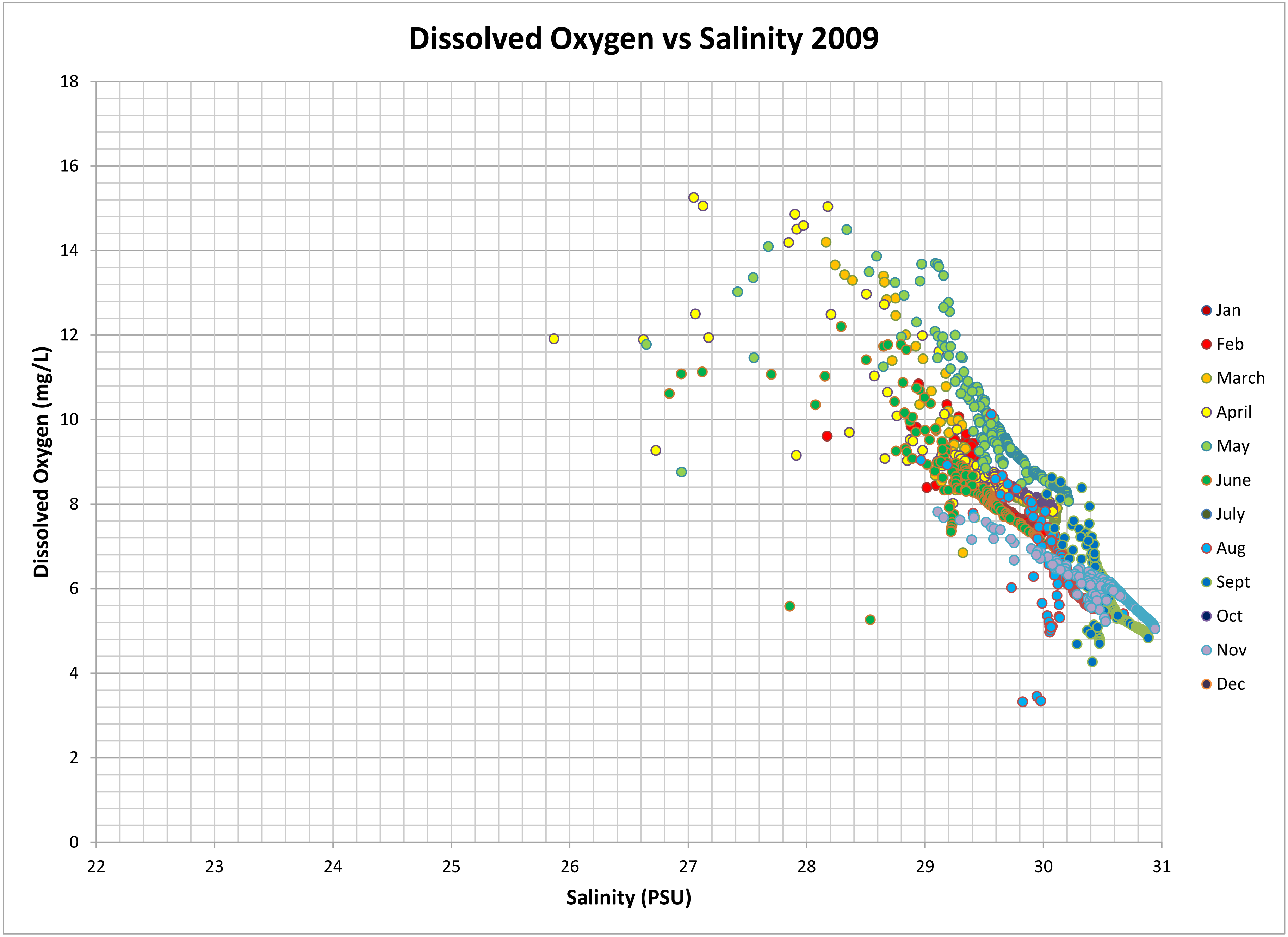

Temperature vs Salinity 2010
Temperature (°C)
18
16
14
12
10
8
6
22
23
24
25
26
27
28
29
30
31
Salinity (PSU)
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

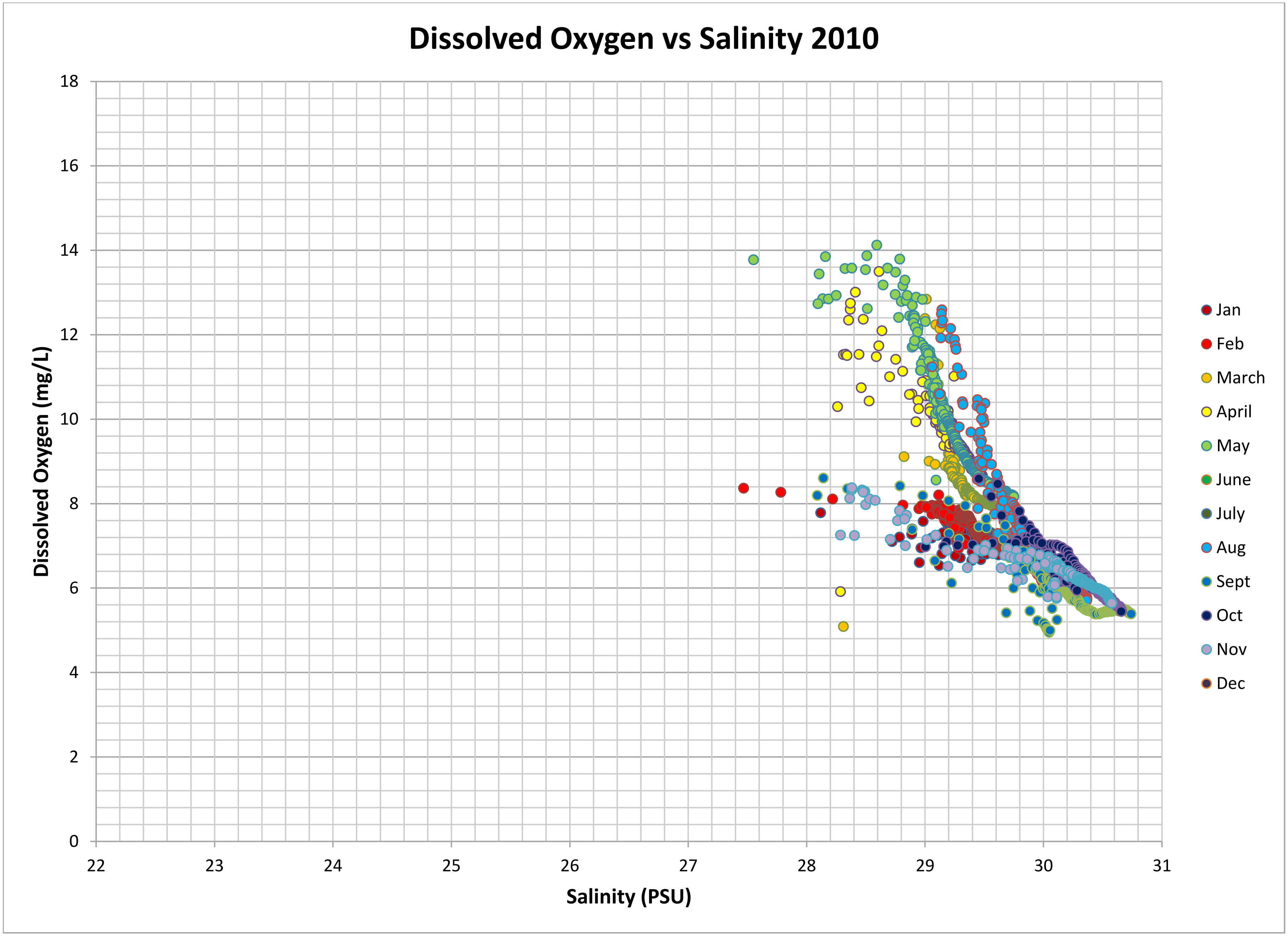

Temperature vs Salinity 2011
Temperature (°C)
Salinity (PSU)
18
16
14
12
10
8
6
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

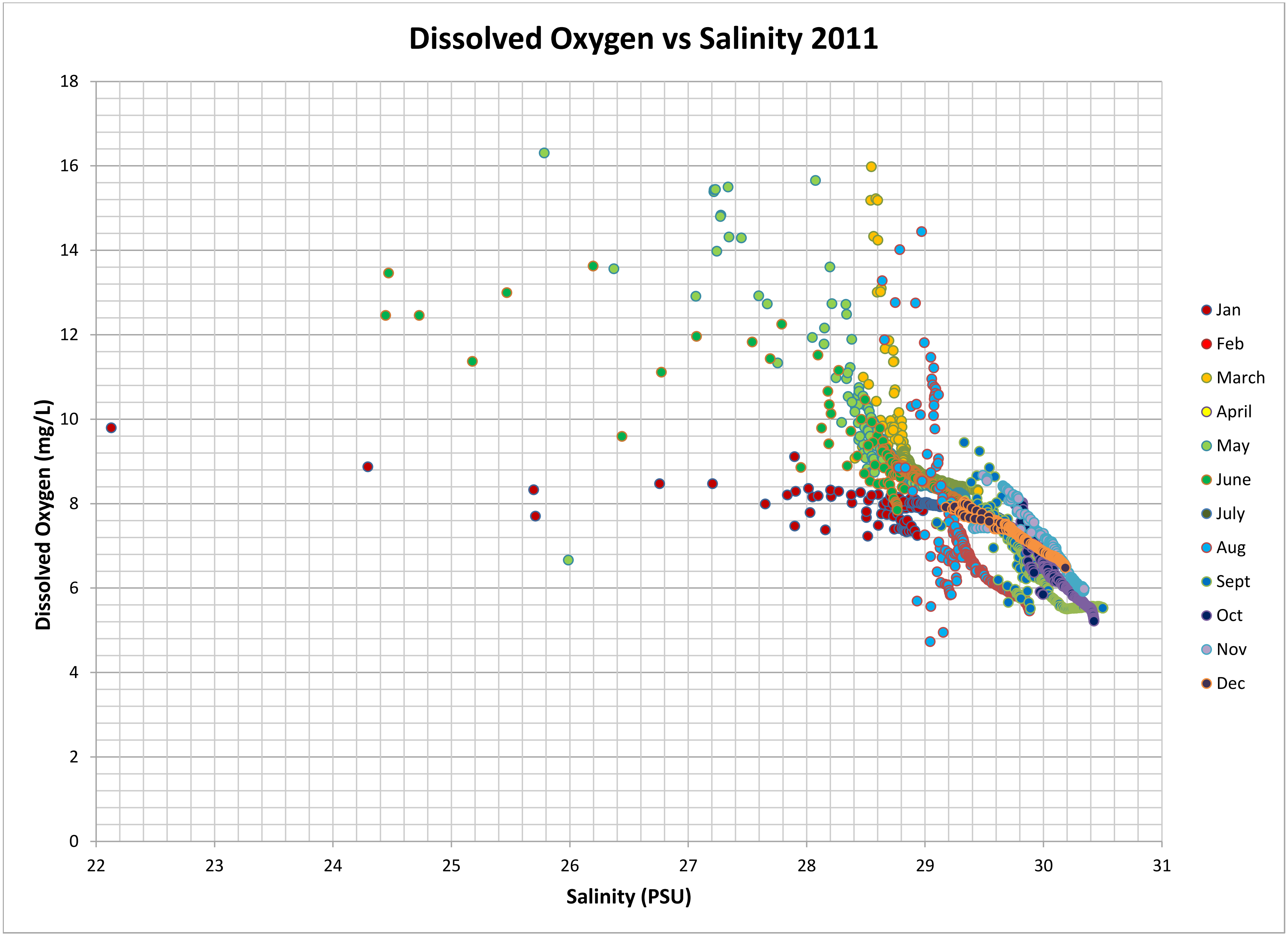


Dissolved Oxygen vs Salinity 2007
Dissolved Oxygen (mg/L)
0
2
4
6
8
10
12
14
16
18
Salinity (PSU)
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

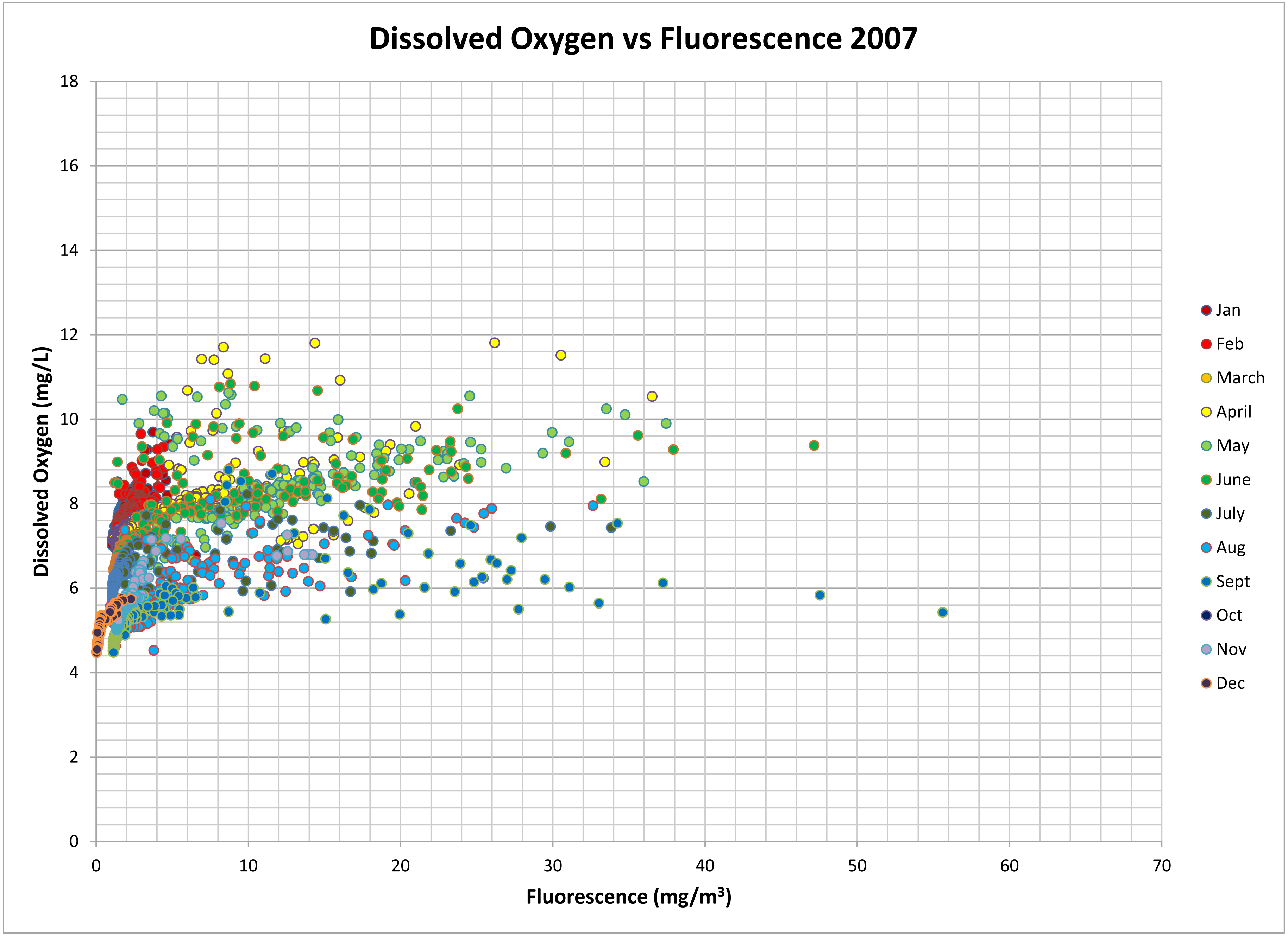

Dissolved Oxygen vs Salinity 2008
Dissolved Oxygen (mg/L)
0
2
4
6
8
10
12
14
16
18
Salinity (PSU)
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

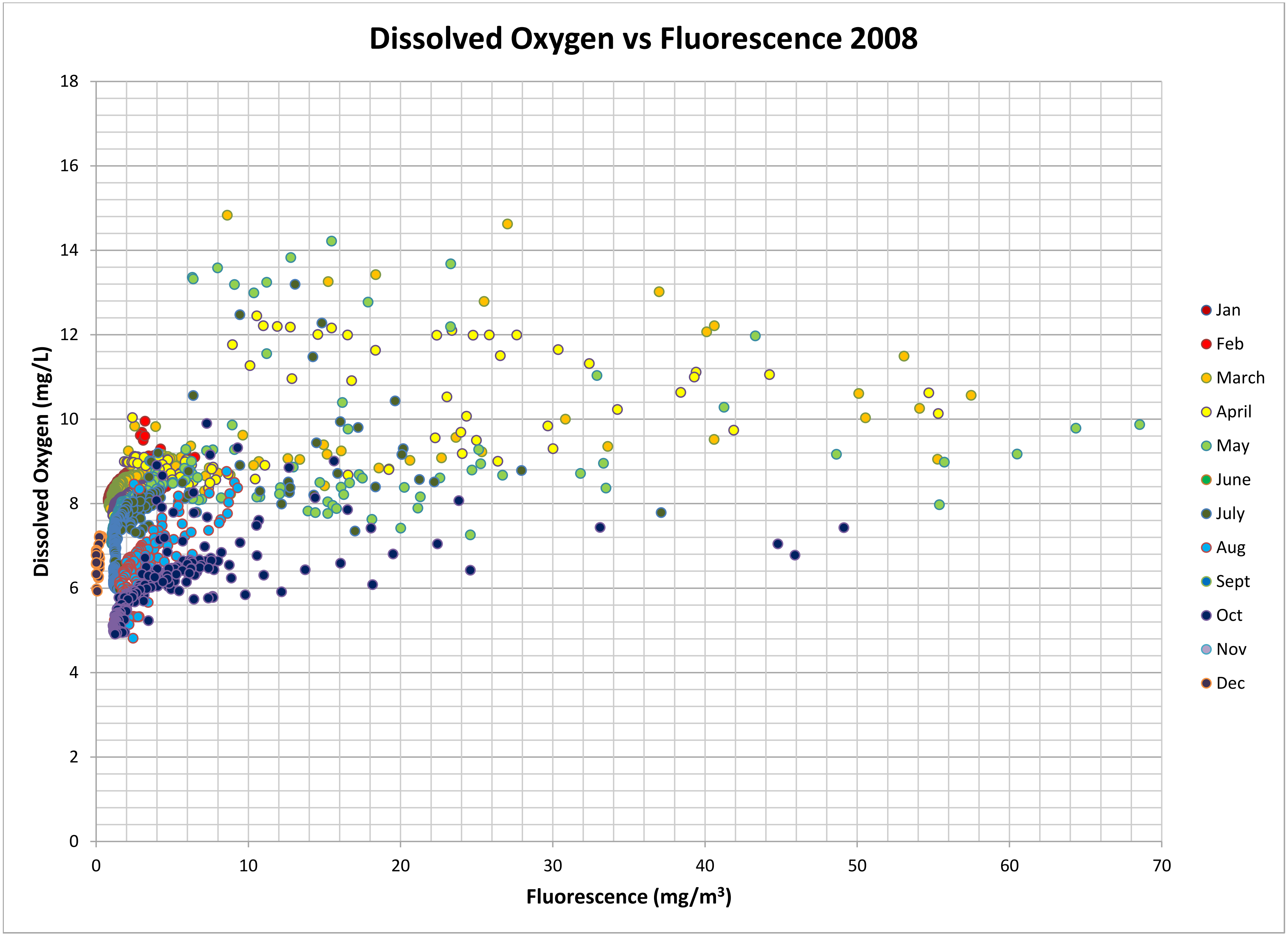

Dissolved Oxygen vs Salinity 2009
Dissolved Oxygen (mg/L)
Salinity (PSU)
0
2
4
6
8
10
12
14
16
18
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec


Dissolved Oxygen vs Salinity 2010
Dissolved Oxygen (mg/L)
0
2
4
6
8
10
12
14
16
18
Salinity (PSU)
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

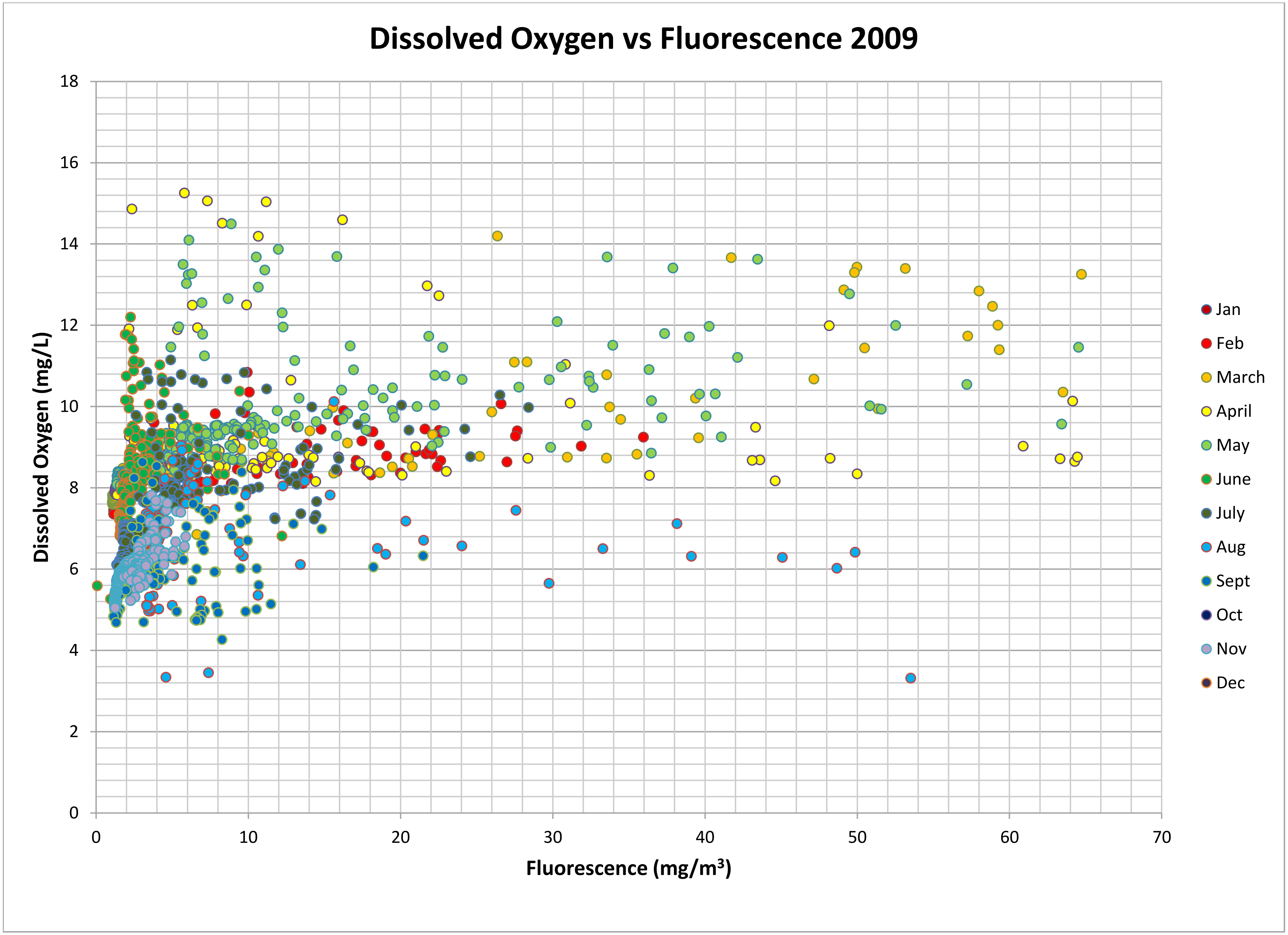


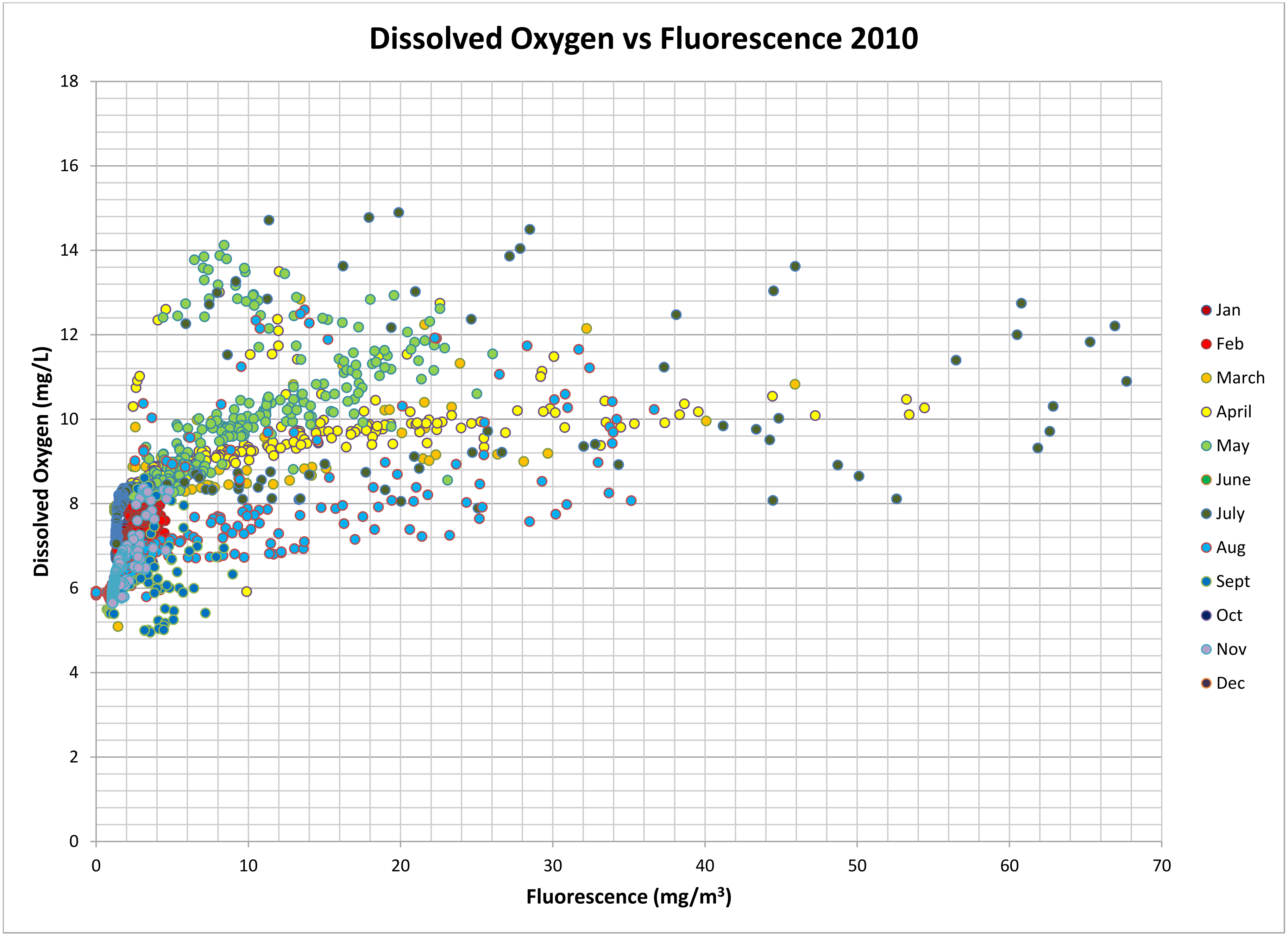
Dissolved Oxygen vs Salinity 2011
Dissolved Oxygen (mg/L)
Salinity (PSU)
0
2
4
6
8
10
12
14
16
18
22
23
24
25
26
27
28
29
30
31
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec


Dissolved Oxygen vs Fluorescence 2007
Dissolved Oxygen (mg/L)
Fluorescence (mg/m³)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

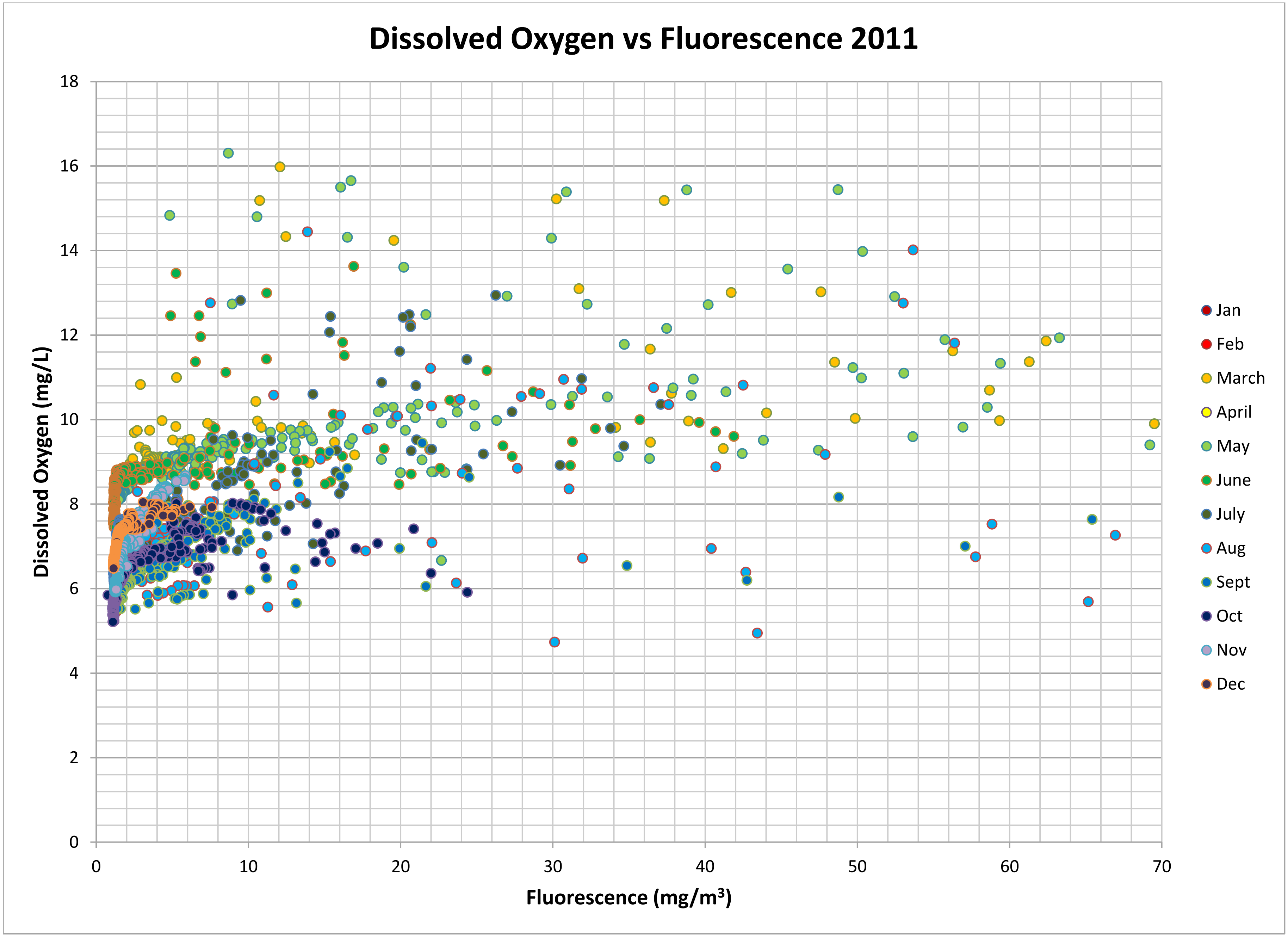


Dissolved Oxygen vs Fluorescence 2008
Dissolved Oxygen (mg/L)
Fluorescence (mg/m³)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec


Dissolved Oxygen vs Fluorescence 2009
Dissolved Oxygen (mg/L)
0
2
4
6
8
10
12
14
16
18
Fluorescence (mg/m³)
0
10
20
30
40
50
60
70
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec



Dissolved Oxygen vs Fluorescence 2010
Dissolved Oxygen (mg/L)
Fluorescence (mg/m³)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec



Dissolved Oxygen vs Fluorescence 2011
Dissolved Oxygen (mg/L)
Fluorescence (mg/m³)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

Appendix D:

Marine Phytoplankton

Table D-1. Phytoplankton species present in King County samples between 2008 and 2011

	2008			2009			2010			2011		
	KSBP01	NSEX01	MSWH01	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02
Actinoptychus senarius	●	●	●	●	●	●	●	●	●	●	●	●
Akashiwo sanguinea	●	●		●	●	●	●	●	●	●	●	
Alexandrium spp.	●	●	●			●	●		●	●	●	●
Alexandrium catenella			●					●	●		●	●
Amylax triacantha			●		●	●						
Asterionellopsis glacialis				●		●	●	●	●	●		●
Asteromphalus heptactis	●	●	●	●	●		●	●	●	●	●	●
Cerataulina pelagica				●	●	●	●	●	●	●	●	●
Ceratium spp.	●				●		●					
Ceratium furca				●								
Ceratium fusus	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros (Hyalochaete) spp.	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros (Phaeoceros) spp.	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros concavicornis	●											
Chaetoceros contortus							●	●	●	●	●	●
Chaetoceros convolutus		●								●	●	
Chaetoceros danicus	●			●	●	●						
Chaetoceros debilis	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros decipiens	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros diadema				●				●				
Chaetoceros didymus				●		●	●	●	●	●	●	●
Chaetoceros eibenii							●	●	●	●	●	●
Chaetoceros laciniosus				●	●	●	●	●	●	●	●	●
Chaetoceros lorenzianus						●		●	●			
Chaetoceros radicans	●			●	●	●	●	●	●	●	●	●
Chaetoceros similis	●			●	●	●	●				●	●
Chaetoceros socialis	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros teres				●	●			●		●	●	●
Chaetoceros vanheurckii				●	●	●	●	●	●	●	●	●
Corethron hystrix							●			●	●	●
Coscinodiscus spp.	●	●	●	●	●	●	●	●	●	●	●	●
Coscinodiscus centralis	●	●								●	●	●
Coscinodiscus concinnus		●										
Coscinodiscus curvatulus	●	●								●	●	●
Coscinodiscus granii									●		●	●
Coscinodiscus oculus-iridis	●											
Coscinodiscus wailesii	●	●		●	●	●	●		●	●	●	●
Cylindrotheca closterium	●	●	●	●	●	●	●	●	●	●	●	●
Dactyliosolen fragilissimus			●	●	●	●		●	●	●	●	●
Detonula pumila	●	●	●	●		●	●	●	●	●	●	●
Dictyocha fibula	●	●	●	●	●	●					●	
Dictyocha speculum	●	●	●	●	●	●	●	●	●	●	●	●
Dinophysis spp.	●	●	●	●	●	●	●	●		●	●	

Table D-1 (cont.). Phytoplankton species present in King County samples between 2008 and 2011

	2008			2009			2010			2011		
	KSBP01	NSEX01	MSWH01	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02
Dinophysis acuminata				●	●	●	●	●	●	●	●	●
Dinophysis acuta/norvegica				●	●	●	●			●	●	●
Dinophysis fortii				●	●	●	●		●	●	●	●
Dinophysis parva				●	●		●	●	●	●	●	
Dinophysis rotundata					●		●		●		●	●
Diplopsalid dinoflagellate				●	●	●	●		●	●	●	
Dissodinium pseudolunula							●				●	●
Ditylum brightwellii	●	●	●	●	●	●	●	●	●	●	●	●
Ebria tripartita	●	●	●							●	●	
Eucampia zodiacus	●	●	●	●	●	●	●	●	●	●	●	●
Gonyaulax spp.		●		●	●		●			●		
Gonyaulax digitale							●	●	●	●	●	●
Guinardia delicatula		●		●	●	●	●		●	●	●	
gymnodinioid dinoflagellate				●	●	●	●	●	●	●	●	●
Gymnodinium spp.	●	●	●	●	●	●	●		●			●
Gymnodinium gracile							●			●	●	
Gyrodinium spp.	●			●	●	●	●	●	●	●	●	
Gyrodinium spirale	●	●		●	●	●	●	●	●	●	●	●
Hemiaulus hauckii	●	●					●	●	●	●		
Heterocapsa triquetra	●		●	●	●	●	●			●	●	●
Heterosigma akashiwo	●	●	●	●	●	●				●	●	●
Lauderia annulata			●	●	●	●	●	●	●	●	●	●
Leptocylindrus danicus	●	●	●	●	●	●	●	●	●	●	●	
Leptocylindrus minimus				●	●	●				●	●	●
Melosira moniliformis					●		●	●				
Meringosphaera mediterranea			●		●	●		●	●	●	●	
Nitzschia acicularis	●	●	●	●	●	●	●	●	●	●	●	●
Noctiluca scintillans	●	●	●	●	●	●	●	●	●	●	●	●
Odontella longicruris	●	●		●	●	●	●	●	●		●	●
Oxyphysis oxytoxoides	●	●	●	●	●	●	●				●	●
Oxytoxum spp.				●		●			●			
Paralia sulcata		●		●	●		●	●	●	●	●	●
Phaeocystis spp.	●			●			●		●			●
Pleurosigma spp.	●	●	●	●	●	●	●	●	●	●	●	●
Polykrikos schwartzii								●				
Prorocentrum gracile	●	●	●	●	●	●	●	●	●	●	●	●
Prorocentrum micans	●											
Protoceratium reticulatum				●	●	●	●			●	●	●
Protoperidinium spp.	●	●	●	●	●	●	●	●	●	●	●	●
Protoperidinium brevipes		●	●		●	●						
Protoperidinium conicum	●	●	●	●	●	●	●	●	●	●	●	●
Protoperidinium depressum	●	●	●	●	●	●	●	●	●	●	●	●
Protoperidinium excentricum	●											
Protoperidinium leonis		●		●				●				

Table D-1 (cont.). Phytoplankton species present in King County samples between 2008 and 2011

	2008			2009			2010			2011		
	KSBP01	NSEX01	MSWH01	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02	KSBP01	NSEX01	NSAJ02
Protoperidinium oblongum								●	●		●	●
Protoperidinium oceanicum		●		●	●	●						
Protoperidinium steinii	●	●	●	●	●	●	●	●	●	●	●	●
Pseudo-nitzschia spp. (large)	●	●	●	●	●	●	●	●	●	●	●	●
Pseudo-nitzschia spp. (small)	●	●		●	●	●	●	●		●	●	●
Pseudo-nitzschia americana				●	●	●	●	●	●	●	●	●
Pyrophacus horologium	●	●	●									
Rhizosolenia setigera	●	●	●	●	●	●	●	●	●	●	●	●
Scrippsiella trochoidea	●	●	●	●	●	●	●	●	●	●	●	●
Skeletonema costatum	●	●	●	●	●	●	●	●	●	●	●	●
Stephanopyxis nipponica	●	●		●	●	●	●					●
Stephanopyxis palmeriana	●	●		●	●	●	●	●	●	●	●	
Thalassionema nitzschioides	●	●	●	●	●	●	●	●	●	●	●	●
Thalassiosira spp.	●	●	●	●	●	●	●	●	●	●	●	●
Thalassiosira anguste-lineata	●	●	●	●	●	●	●	●	●	●	●	●
Thalassiosira eccentrica			●									
Thalassiosira nordenskioeldii	●			●	●	●	●	●	●	●	●	●
Thalassiosira pacifica/aestivalis							●	●	●	●	●	●
Thalassiosira punctigera	●	●		●	●	●	●	●	●	●	●	●
Thalassiosira rotula	●	●	●	●	●	●	●	●	●	●	●	●
Tropidoneis antarctica	●	●		●	●	●	●	●	●			●
unidentified centric diatom	●	●	●	●	●	●		●		●	●	●
unidentified dinoflagellate (<25 um)	●	●	●	●	●	●	●	●	●	●	●	●
unidentified dinoflagellate (>25 um)	●	●	●	●	●	●	●	●	●	●	●	●
unidentified nanoflagellates	●	●	●	●	●	●	●	●	●	●	●	●
unidentified pennate diatom	●	●	●	●	●	●	●	●	●	●	●	●

Notes: The resolution of microscopic observation may at times be adequate for genus-level but not species-level identification.
Generic categories like “unidentified centric” contain a mix of cells that could not be further identified.
Chaetoceros affinis and *C. crucifer* tentatively identified in 2011.

Table D-2. Phytoplankton species present in Univeristy of Washington-Tacoma samples between 2007 and 2011

	2007			2008			2009			2010			2011		
	50	51-54	55-60	50	51-54	55-56	50	51-54	55-56	50	51-54	55-56	50	51-54	55-56
Actinoptychus senarius		●					●	●	●	●	●	●	●	●	●
Akashiwo sanguinea					●						●	●	●	●	
Alexandrium spp.							●	●	●	●	●	●			●
Alexandrium catenella	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Alexandrium fundyense											●	●			
Alexandrium ostenfeldii										●	●	●	●	●	●
Alexandrium tamarense											●	●			
Amylax spp.															●
Amylax triacantha		●			●	●									
Asterionellopsis spp.									●					●	
Asterionellopsis glacialis										●	●			●	●
Asterionellopsis socialis		●													
Asterolampra spp.					●										
Asteromphalus spp.							●	●	●						
Asteromphalus heptactis		●			●	●		●		●	●	●		●	●
Asteromphalus sarcophagus	●	●	●	●	●										
Attheya aumatus									●						
Attheya decora		●													
Aulacodiscus spp.								●	●						
Bacillaria paxillifera														●	●
Cerataulina bergonii														●	
Cerataulina pelagica		●	●	●	●	●		●		●	●	●	●	●	●
Ceratium spp.											●				
Ceratium fusus	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Ceratium lineatum												●			
Chaetoceros spp.	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Chaetoceros affinis										●	●	●	●	●	●
Chaetoceros anastomosans													●	●	
Chaetoceros armatus											●				
chaetoceros concavicornis											●		●	●	
Chaetoceros contortus											●	●			
Chaetoceros convolutus										●	●			●	
Chaetoceros danicus				●	●	●				●	●	●	●	●	●
Chaetoceros debilis										●	●	●	●	●	●
Chaetoceros decipiens				●	●	●				●	●	●	●	●	●
Chaetoceros diadema											●				
Chaetoceros laciniosus										●			●	●	●
Chaetoceros lorenzianus					●										
Chaetoceros radicans										●	●	●	●	●	●
Chaetoceros socialis										●	●		●	●	●
Chaetoceros teres										●	●		●	●	●
Chaetoceros vanheurckii														●	
Corethron spp.													●		
Corethron hystrix						●					●	●	●	●	●
Coscinodiscus spp.	●	●	●		●	●	●	●	●	●	●	●	●	●	
Coscinodiscus centralis					●	●					●		●	●	●
Coscinodiscus eccentricus				●	●	●					●				
Coscinodiscus granii											●		●	●	
Coscinodiscus marginata															●
Cylindrotheca closterium	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

Table D-2 (cont.). Phytoplankton species present in Univeristy of Washington-Tacoma samples between 2007 and 2011

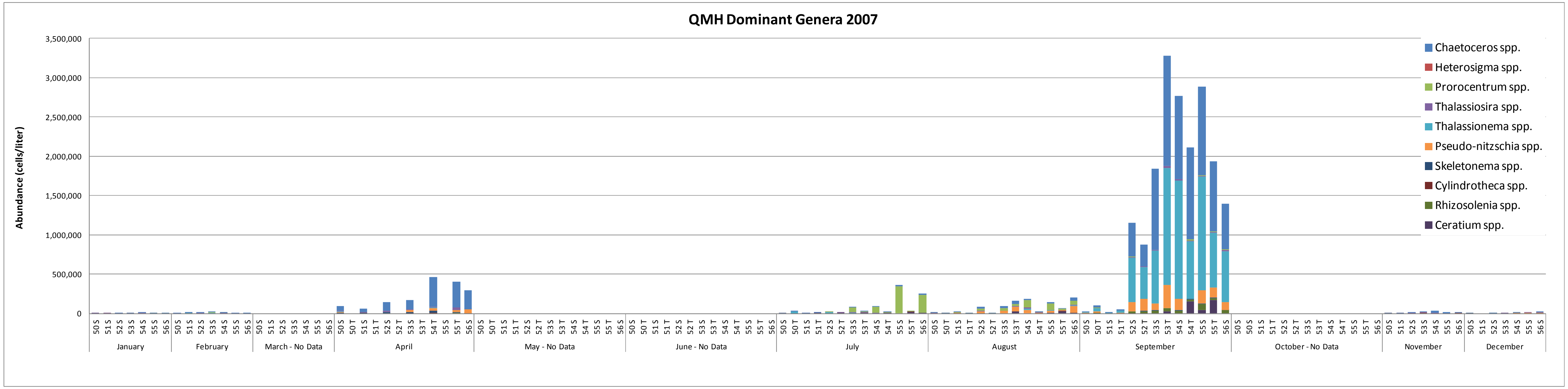
	2007			2008			2009			2010			2011		
	50	51-54	55-60	50	51-54	55-56	50	51-54	55-56	50	51-54	55-56	50	51-54	55-56
Cylindrotheca giant					●	●									
Dactyliosolen blavyanus														●	●
Dactyliosolen fragilissimus										●	●	●		●	●
Detonula spp.								●	●						
Detonula pumila										●	●	●	●	●	●
Dictyocha spp.											●				
Dictyocha fibula		●	●		●	●				●	●		●		
Dictyocha speculum	●	●	●	●	●	●	●				●	●	●	●	●
Dinophysis spp.		●	●	●	●	●	●	●	●		●	●	●	●	●
Dinophysis acuminata				●	●	●				●	●	●		●	●
Dinophysis acuta					●	●									
Dinophysis fortii														●	●
Dinophysis norvegica					●										
Dinophysis odiosa				●	●										
Dinophysis parva												●		●	
Dinophysis rotundata											●				
Dissodinium pseudolunula											●				
Ditylum brightwellii	●	●		●	●	●		●	●	●	●	●	●	●	●
Ebria spp.									●						
Ebria Tripartita		●	●	●	●	●									
Eucampia zodiacus	●	●	●	●	●			●	●	●	●	●	●	●	●
Gonyaulax spp.								●	●		●	●			
Gonyaulax digitale										●					●
Gonyaulax polyedia											●				
Gonyaulax verior					●	●									
Guinardia spp.			●												●
Guinardia delicatula											●	●			
Guinardia striata										●	●	●			
Gymnodinium spp.	●	●	●				●	●							
Gymnodinium gracile				●	●										
Gymnodinium rubrum															●
Gyrodinium spp.									●						
Hemiaulus spp.								●							
Hemiaulus hauckii		●	●	●	●					●	●	●		●	●
Heterocapsa spp.							●						●	●	●
Heterocapsa triquetra	●	●	●		●						●	●		●	●
Heterosigma spp.													●	●	●
Heterosigma akashiwo										●	●	●	●	●	●
Lauderia spp.									●						
Lauderia annulata														●	●
Leptocylindrus spp.							●	●				●			
Leptocylindrus danicus		●	●		●	●				●	●	●			
Leptocylindrus minimus	●	●	●	●	●	●								●	●
Manginea fusiformis					●										
Melosira spp.														●	●
Melosira moniliformis		●	●								●				
Meringosphaera mediterranea		●	●								●	●	●	●	●
Minuscula bipes					●						●				●
Navicula spp.	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Nematodinium armatum		●									●				

Table D-2 (cont.). Phytoplankton species present in Univeriesty of Washington-Tacoma samples between 2007 and 2011

	2007			2008			2009			2010			2011		
	50	51-54	55-60	50	51-54	55-56	50	51-54	55-56	50	51-54	55-56	50	51-54	55-56
Noctiluca spp.														●	
Noctiluca scintillans		●	●		●	●					●	●			●
Odontella spp.				●		●		●	●	●	●				●
Odontella auriata											●	●			
Odontella longicruris										●	●	●	●	●	
Oxyphysis spp.								●	●					●	
Oxyphysis Oxytoxoides		●	●		●						●	●		●	●
Paralia sulcata					●										
Peridinium spp.		●	●												
Phaecystis pouchetti								●							
phaeocystis spp.			●										●	●	
Plagiogrammopsis spp.													●		●
Pleurosigma spp.	●	●	●		●	●		●		●	●	●	●	●	●
Pleurosigma normanii					●	●									
Polykrikos spp.					●			●	●						
Proboscia spp.							●	●							
Prorocentrum spp.							●	●	●		●	●			
Prorocentrum gracile	●	●	●	●	●	●				●	●	●	●	●	●
Prorocentrum micans	●	●	●								●	●		●	
Protoceratium reticulatum		●	●		●	●					●		●		
Protoperidinium spp.	●	●	●	●	●	●		●	●	●	●	●	●	●	●
Protoperidinium brevipes					●						●	●		●	●
Protoperidinium conicum										●	●				
Protoperidinium depressum					●	●					●	●	●	●	●
Protoperidinium leonis											●				
Protoperidinium oceanicum											●			●	●
Protoperidinium steinii				●	●	●	●	●	●	●	●	●	●	●	●
Pseudo-nitzschia spp.	●	●	●	●	●	●	●	●	●		●	●	●	●	
Pseudo-nitzschia spp. (large)				●	●	●				●	●	●	●	●	●
Pseudo-nitzschia spp. (small)					●	●				●	●	●	●	●	●
Pyrophacus horologium		●	●		●	●	●	●	●	●	●	●	●	●	●
Pyrophacus steinii					●										
Rhizosolenia spp.	●	●	●	●	●	●		●	●						
Rhizosolenia setigera										●	●	●	●	●	●
Rhizosolenia styliformis															●
Scrippsiella spp.	●	●	●	●											
Scrippsiella trochoidea				●	●	●	●	●	●	●	●	●	●	●	●
Skeletonema spp.														●	
Skeletonema costatum	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Stephanopyxis spp.				●			●	●	●	●	●				
Stephanopyxis nipponica										●	●	●	●	●	
Stephanopyxis palmeriana											●	●			
Thalassionema spp.	●	●	●	●	●	●	●	●	●		●				
Thalassionema nitzschoides				●	●	●				●	●	●	●	●	●
Thalassiosira spp.	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Thalassiosira anguste-lineata											●	●			
Thalassiosira condensata				●	●	●									
Thalassiosira eccentrica					●										
Thalassiosira pacifica													●	●	●
Triceratium americanium		●													
Tropidoneis spp.									●						
Tropidoneis antarctica		●								●	●				
Unknown	●	●	●					●		●	●	●	●	●	●

Notes: The resolution of microscopic observation may at times be adequate for genus-level but not species-level identification. The generic category of "unknown" contains a mix of cells that could not be further identified.

Table D-3. Dominant genera by year: University of Washington-Tacoma samples



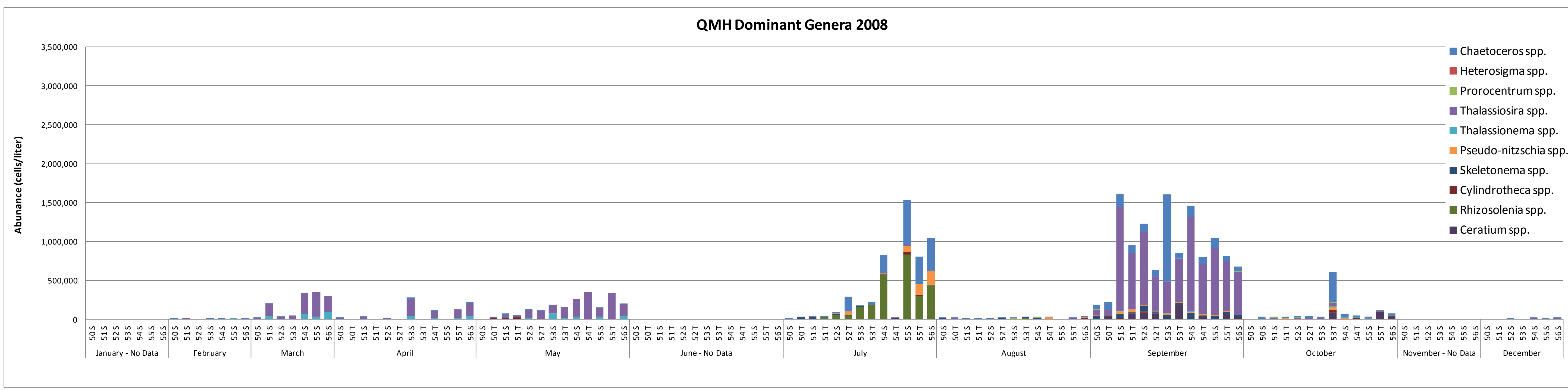
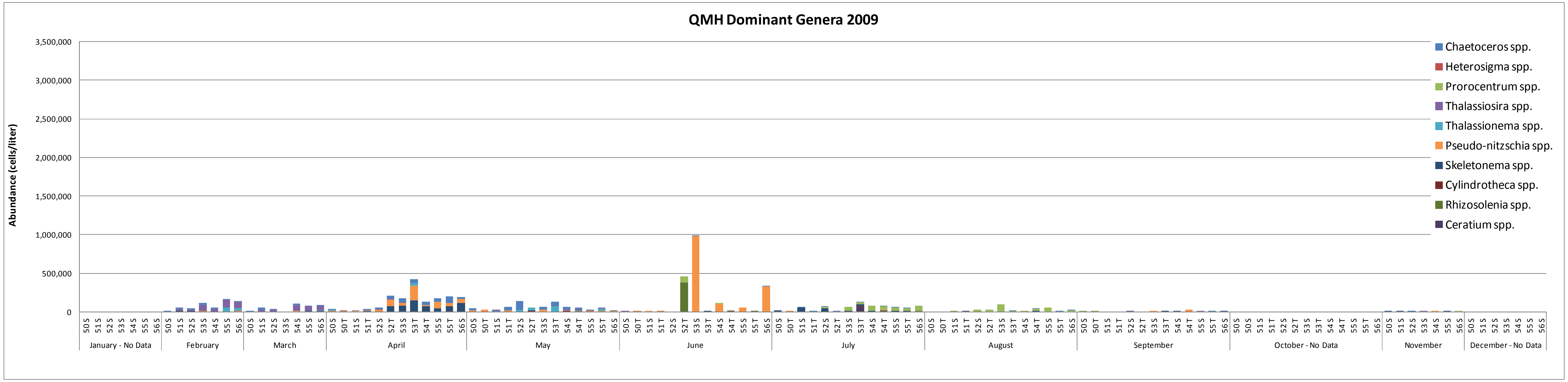


Table D-3 (cont.). Dominant genera by year in University of Washington-Tacoma samples



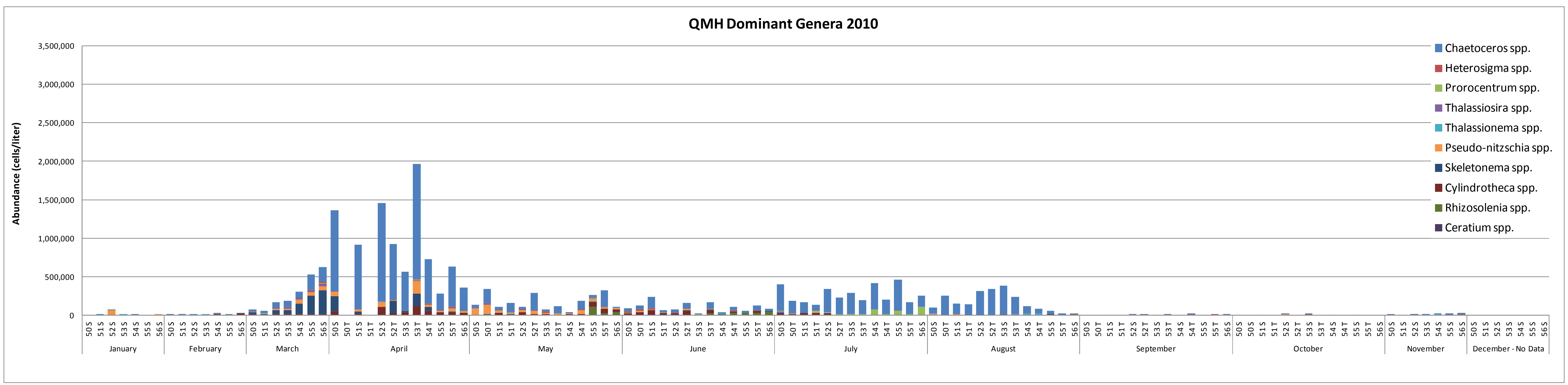


Table D-3 (cont.). Dominant genera by year in University of Washington-Tacoma samples

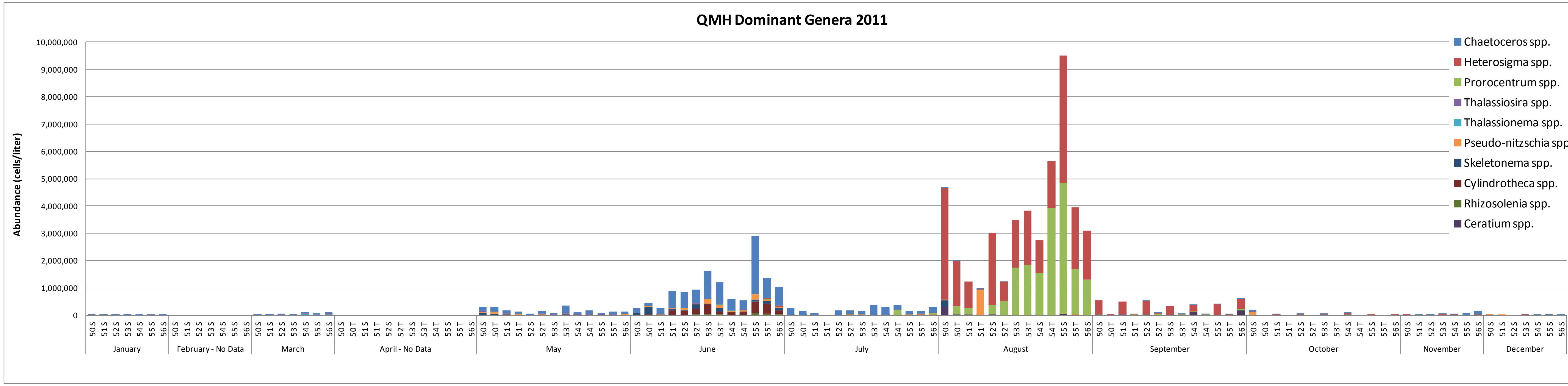


Table D-4. Proportion of major taxa: University of Washington-Tacoma samples.

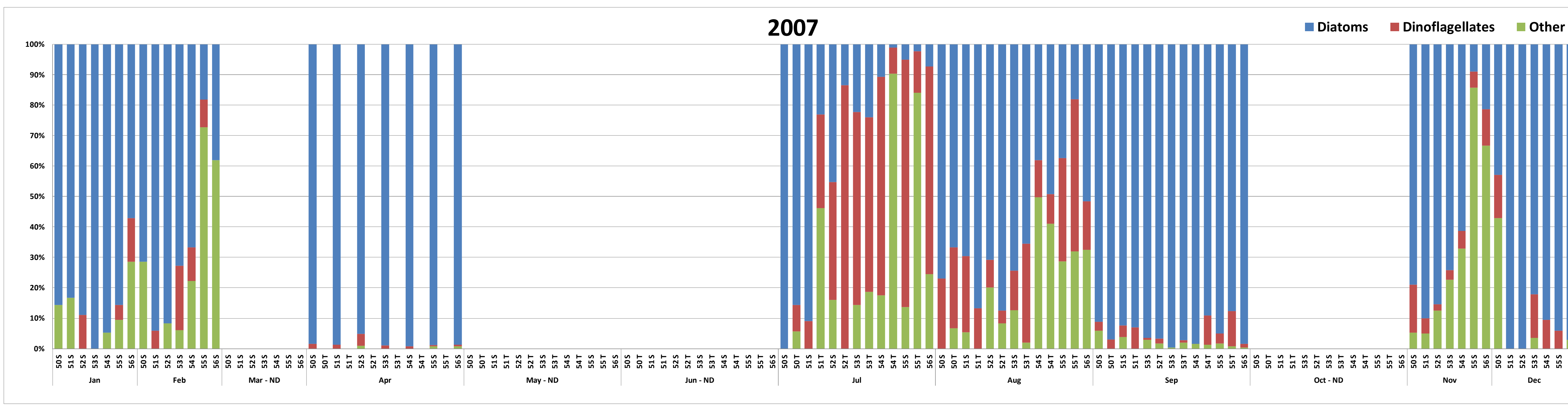
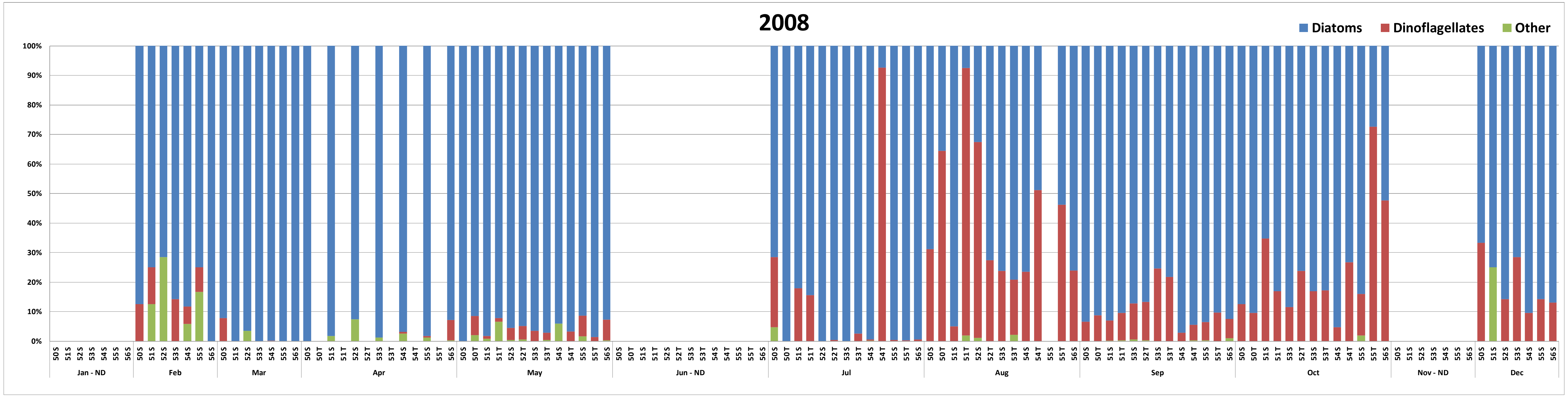
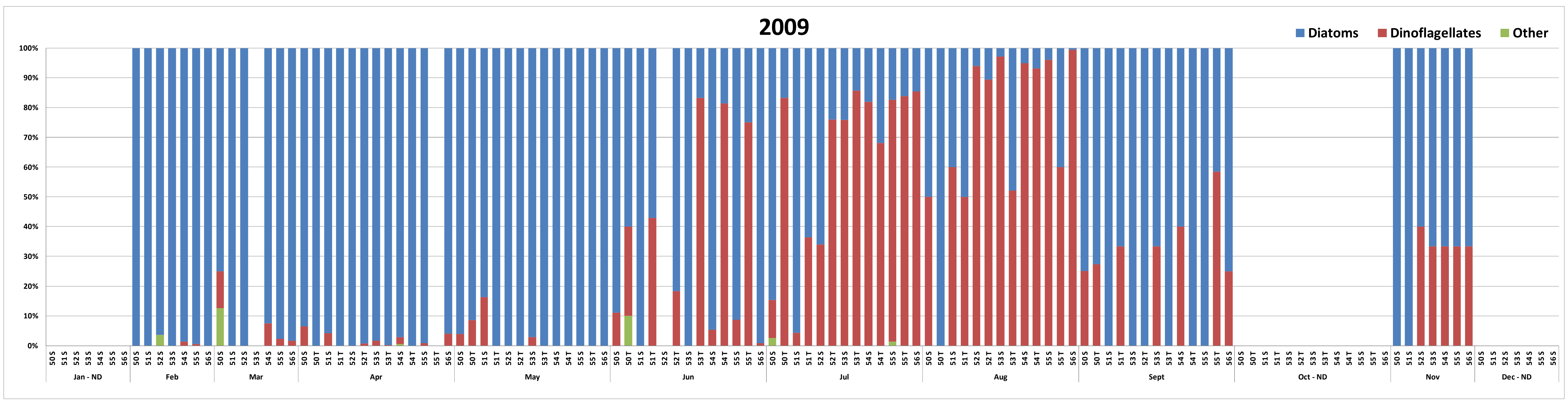


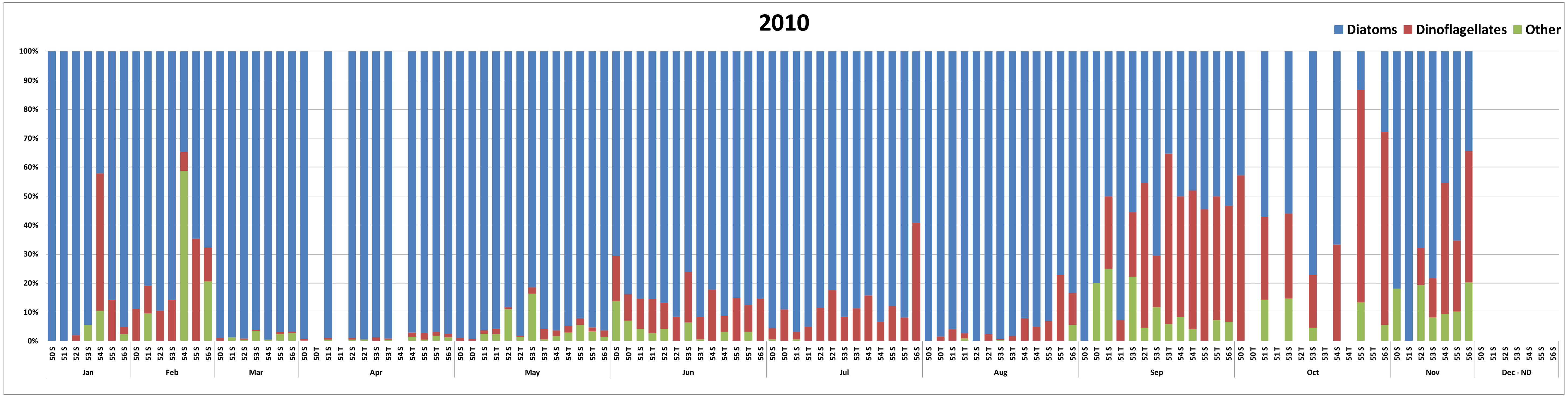
Table D-4. Proportion of major taxa: University of Washington-Tacoma samples.

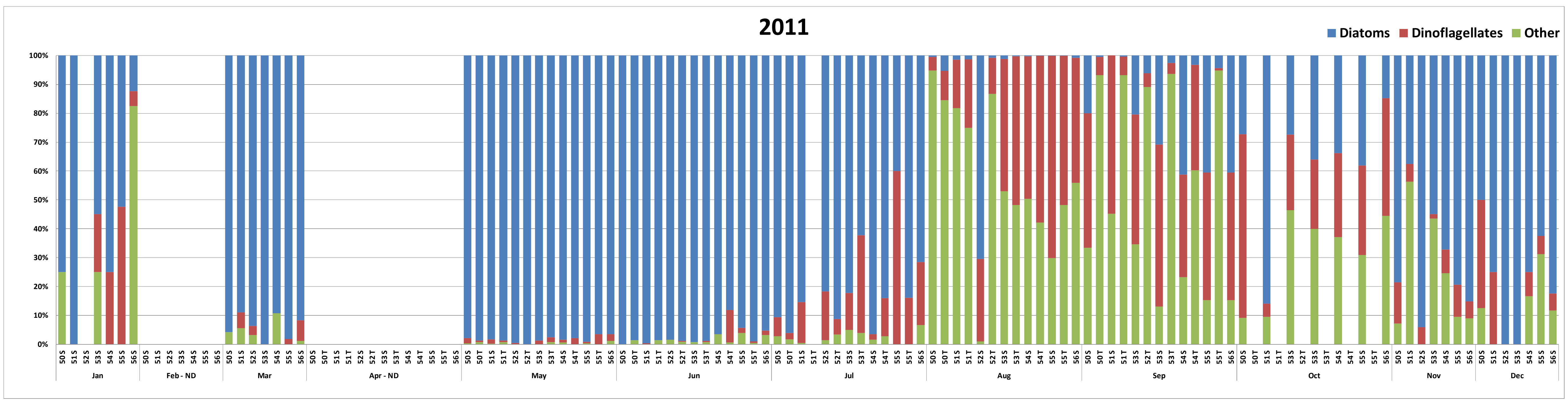




Note: No data is indicted by 'ND'

Table D-4 (cont.). Proportion of major taxa: University of Washington-Tacoma samples





Note: No data is indicted by ‘ND’