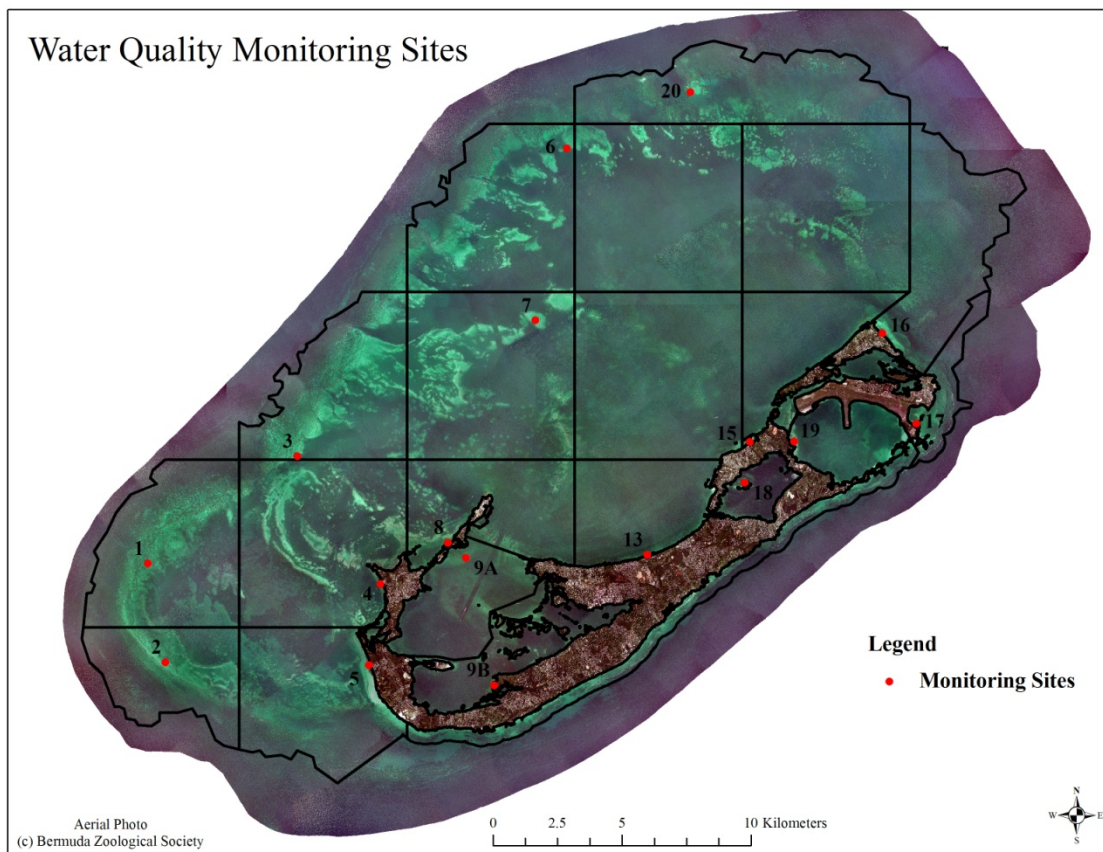


Water Quality Monitoring Program for Bermuda's Coastal Resources



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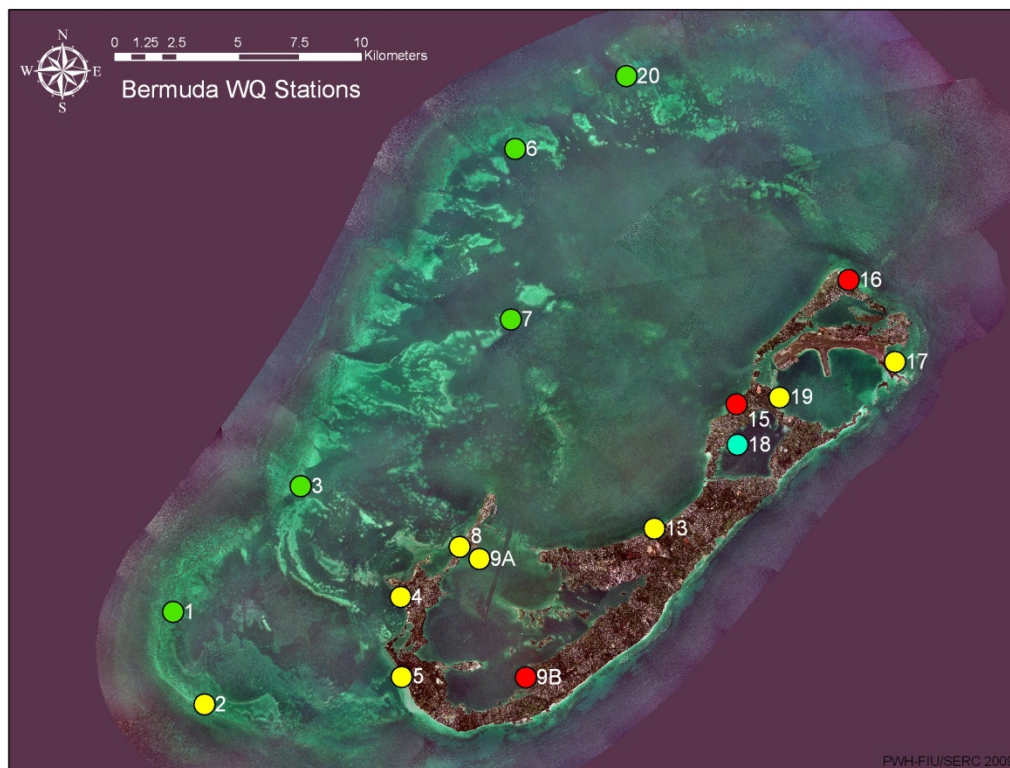
WATER QUALITY MONITORING PROGRAM FOR BERMUDA'S COASTAL RESOURCES

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Funded by the Bermuda Department of Conservation Services

EXECUTIVE SUMMARY

This report serves as a summary of our efforts to date in the execution of the Water Quality Monitoring Program for the Bermuda Department of Conservation Services (BDCS). The Bermuda Government initiated a water quality monitoring program in September, 2007 at 17 sites with seagrass, which are spread across the Bermuda Platform. At each of these sites chemical and physical water quality characteristics are monitored monthly and a continuous temperature data logger is deployed. At least one species of seagrass is present at each site.



The period of record for this report spans the 19 months from Sept. 2007 up to and including March 2009. Physical, chemical, and biological parameters were collected by BDCS personnel and water samples shipped to the Southeast Environmental Research Center at Florida International University for nutrient analysis. Field parameters measured at each station include salinity (practical salinity scale), temperature ($^{\circ}\text{C}$), dissolved oxygen (DO , mg l^{-1}), turbidity (NTU), pH, and Secchi depth (m). Water quality variables include the dissolved nutrients nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN), and soluble reactive

phosphate (SRP). Total unfiltered concentrations include those of nitrogen (TN), organic nitrogen (TON), organic carbon (TOC), phosphorus (TP), silicate (SiO_2) and chlorophyll *a* (CHLA, $\mu\text{g l}^{-1}$).

Cluster analysis of water quality variables by site resulted in 4 groups which had distinct differences in water quality. **Cluster 1** (in red) was composed of stations 9B, 15, and 16, which are those sites most strongly affected by anthropogenic nutrient inputs as indicated by their high levels of NO_3^- , TP, TOC, and turbidity. Interestingly, this cluster also showed high DO but did not have elevated CHLA. **Cluster 2** (in yellow) included a mix of stations on the SW and NE part of the platform (#2, 4, 5, 8, 9A, 13, 17, & 19). These sites exhibited lower NO_3^- , TP, TOC, CHLA, and turbidity than Cluster 1. **Cluster 3** (in green) was composed of far offshore sites along the northwestern part of the platform (#1, 3, 6, 7, & 20). These stations had the lowest NO_3^- , TP, TOC, SiO_2 , CHLA, DO, and turbidity. Interestingly, these sites also had lowest light penetration, not because of optical clarity but because of greater water column depth. Salinity was also the most invariable at these sites. **Cluster 4** (in blue) consisted of only one site, station #18 off Trunk Island, but it was so different than any of the other sites that it had to be treated separately. It had the highest NO_3^- , NH_4^+ , SRP, SiO_2 , CHLA, and the lowest salinity of any other sites in the monitoring network. These all may be due to the location of this site in an enclosed bay. The low salinity reflects a source of terrestrial freshwater from either runoff or outfall and the enclosed nature of the bay (Harrington Sound) means that water residence time is probably higher than other areas. Longer water residence time allows more nutrients to be incorporated into phytoplankton biomass, hence the high CHLA levels at this site.

We developed and maintain a website (serc.fiu.edu/wqmnetwork/BERMUDA/) where anyone can download 1) all data from the program, 2) the interpretive reports, and 3) Google maps of all measured variables, by month, in classified post style.

INTRODUCTION

The Bermuda Government initiated a water quality monitoring program in September, 2007 at 17 sites with seagrass, which are spread across the Bermuda Platform (Fig. 1). At each of these sites chemical and physical water quality characteristics are monitored monthly and a continuous temperature data logger is deployed. At least one species of seagrass is present at each site.

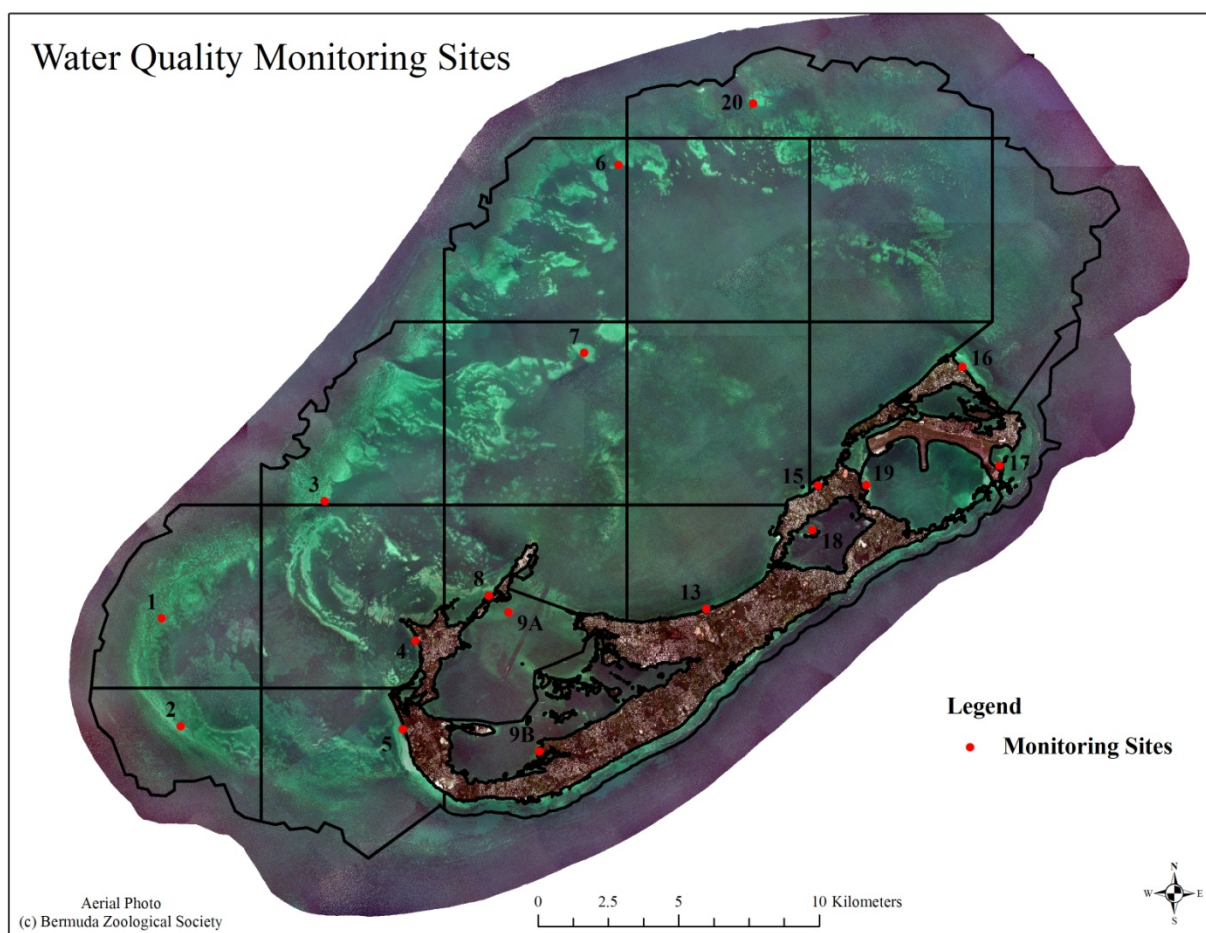


Figure 1. Location of water quality sampling sites which coincide with existing seagrass sites.

It has long been acknowledged that moorings, anchoring, dredging, and dock construction have impacted Bermuda's inshore seagrass beds but recently it has been recognized that the extensive offshore beds are also in decline. In 2004, intensive site surveys and mapping of Bermuda seagrass meadows, by the Bermuda Reef Ecosystem Assessment and Mapping Programme (of the Bermuda Biodiversity Project), documented a loss of about one-quarter of the total area estimated from aerial images taken in 1997. Other studies indicate a significant loss of seagrass area began about 1995 and was precipitous between then and 1997; however, the recent studies (2006-2010) do not indicate that loss is ongoing at this level, but also do not indicate significant recovery of the impacted beds. This decline did not occur uniformly across the Bermuda platform - and massive loss of area was only apparent in meadows far from shore, which we think are removed from local anthropogenic impacts.

There are no comprehensive data or information we can use to explain this decline, in particular there are no applicable data on nutrients, temperature, and light penetration for any of the beds for periods relevant to the onset of seagrass decline.

Water quality and physical characteristics of the water column are among the ultimate limiting conditions for the presence of seagrass. Transmission of light, temperature and the presence of adequate nutrients can all determine survival of a seagrass bed. Mean salinity, salinity variability, light transmission, and mean nutrient concentrations are important predictor variables to models of landscape-scale changes of marine benthic habitats (Fourqurean et al. 2003). Nutrient levels in the seagrass habitat, which includes both pore water and water column, are the primary driving factors to degradation of seagrass beds in the conceptual model of seagrass community dynamics, which underlies this program.

It has been clearly outlined in the Bermuda Seagrass Conservation and Management Plan that comprehensive water quality monitoring is an essential component of overall management of seagrass habitats in Bermuda. Such a program did not exist in Bermuda until the Government initiated their seagrass habitat studies. The water quality monitoring program also can provide useful data to other management and monitoring issues in the marine environment, including tracking terrestrial runoff and ground water and their significance to nutrient loading.

We monitor water quality at 17 sites spread across the Bermuda platform in locations at which seagrass occurs or where there are historical records of dense seagrass beds. We do not monitor any sites on or adjacent to the south shore of the islands, such as Hungry Bay. There are records of seagrass beds in Hungry Bay, but the condition of these beds has not been checked recently and, anecdotally, it is reported that this bed was lost during Hurricane Fabian (2003).

Seagrass beds in Bermuda occur from the shallow subtidal, with a very few beds that are exposed at extreme low tides, to maximum depths of just over 20 meters. These beds occur along the shoreline of the islands, both in bays and along exposed lengths of the shoreline, and around reef patches and barriers as far out as the rim of the shallow platform. The sites we monitor range from about 1 meter depth at extreme low tide to about 13 meters depth.

Four seagrass species are found in the Bermuda seagrass beds, *Thalassia testudinum*, *Syringodium filiforme*, *Halodule* sp. and *Halophila decipiens*. *Syringodium filiforme* is the most widespread and prevalent; the other three species are encountered about equally frequently, with *H. decipiens* occurring at the deepest and lowest light sites. Generally, the presence of a particular species at any site is determined by the combination of light transmission and depth at the site. Sediment characteristics may also be significant, but that has not been investigated to date. Sediments at the water quality monitoring sites range only from fine to medium sands, and do not cover the complete range of sediment types inhabited by seagrass in Bermuda (SAM and KAC, pers. obs.).

SITE DESCRIPTIONS

The 17 water quality monitoring sites in Bermuda can be roughly grouped based on some of the environmental and seagrass characteristics we have assessed over the past three years. Seagrass and other habitat characteristics have been measured on a quarterly basis since March 2007; water quality sampling at these sites has been done on a monthly basis since

September 2007. Seagrass density, canopy height, blade nutrient ratios, and other habitat characteristics (e.g., sediment type and water depth) are measured along a 50 m X 0.50 m transect that originates at the “center” of the water quality monitoring site. The following summary of site groupings is based on a visual assessment of these characteristics.

Group I - offshore (Primarily water quality **Cluster 3** (green) sites)

1. low seagrass density, east 6, 7, 20
2. high seagrass density, west 1, 2
3. moderate seagrass density, west 3

Group II – nearshore (**Cluster 1** (red), **Cluster 2** (yellow) and **Cluster 4** (blue) sites)

1. high likelihood anthropogenic nutrients
 - a. moderate to dense grass
 - i. phosphorus limited 4, 5, 15
 - ii. light or slightly phosphorus limited 8, 9B, 16
 - b. lower density grass
 - i. phosphorous limited 13
 - ii. light or slightly phosphorous limited 18
2. other impacts (**Cluster 2** (yellow) sites only)
 - a. moderate density *Syringodium* beds 9A
 - b. high density beds, low light 17, 19

Group I

Offshore sites either near the rim reefs or in the outer part of the lagoon, associated with patch reefs (mini-atoll like formations). These sites have high light quality (low k values) and are in moderately deep to deep water and are predicted to be subject to very low anthropogenic impacts of any kind.

1. Sites with low density seagrass in the eastern part of the platform.

Sites PS07 and PS20 are reported to have had much higher seagrass cover in (at least) the early to mid 1990's.

PS06 is just inside the rim reef to the west of the popular dive site North Rock. It has a resident population of large, very old, queen conch. It is our deepest site at an average of about 13 meters. The sandy bottom is highly bioturbated, with deep pits and corresponding conical mounds. Water clarity is high year round probably due to the regular intrusion of deep ocean water from outside the rim reef. Of the three sites included in this grouping, PS06 has the most dense seagrass cover, due largely to the regular presence of *Halophila decipiens*. *S. filiforme* and *Halodule* sp are also found here.

PS07 is located among a group of patch reefs collectively called “The Crescent” and is approximately 1700 m southwest of the original Bermuda CARICOMP sites. The decline of the CARICOMP seagrass beds in the mid 1990's was documented by the CARICOMP program. No anthropogenic influences have been identified that are likely to have contributed to the specific decline of this seagrass bed. We have considered this a lagoonal rather than a rim reef associated site, however, few of our measures distinguish it from PS20 and PS06, although it is somewhat shallower. Very sparse *T. testudinum* and *S. filiforme* are found at this site.

PS20 is the closest to PS06, located to the east of North Rock. It is somewhat shallower, about 10 m, and the sandy bottom is riffled and not highly bioturbated. There

is also a resident queen conch population at this site. *T. testudinum* and *S. filiforme* are regularly found here, *Halodule* is sometimes found.

2. Sites with high density grass in the western part of the platform.

PS01 is located to the north and east of the Chub Head beacon, among reefs that coalesce further west to form a rim on the platform. There is a regular onshore flow of deep clear water, as at the previous locations, and water clarity is on average among the highest of all the monitoring sites. *T. testudinum*, *S. filiforme* and *Halodule* sp. form quite dense and extensive beds in this area.

PS02 is south of the Chub Head beacon and slightly further east than PS01. Of the offshore sites, this has the highest density grass beds. Water clarity is on average lower than at the other sites but this is also the shallowest of the offshore beds. The dense bed is bordered by a permanently grazed area of dense but very short *T. testudinum*. *T. testudinum*, *S. filiforme* and *Halodule* sp. form dense beds in this area. (Note: this site is grouped in a different cluster based on water quality characteristics, of which water clarity is probably of prime significance.)

3. Sites with low to moderate density grass in the western part of the platform

PS03 runs down a slope from about 3 meters to just over 10 meters depth. The shallow area is usually populated by *Halodule* sp; *Halodule* and sparse *Syringodium* are found along the slope and *H. decipiens* is found at the deep end of the slope. Water clarity at this site is quite good, similar to PS02, but the greater depth along the site transect probably limits seagrass density. There is no *Thalassia* at this site.

Group II

These are the nearshore sites and due to the various coastal influences this is a complex and diverse group of sites.

1. Higher probability of anthropogenic influences due to industry or medium to high residential coastlines

a. *With moderately dense to dense seagrass, with medium to very poor water quality, shallow to very shallow depths*

i. *strongly P limited - with seagrass N:P ratios greater than 40*

PS04 has moderately poor water clarity and fairly high seagrass cover, only *T. testudinum* occurs at this site. The ratio of N:P for *T. testudinum* is in the low 60's so that P is extremely limited relative to N; which could indicate an unusually high N availability. This site is located to the south of an abattoir and grazing area for a variety of domestic animals. Immediately adjacent to the abattoir is an ecotourism resort.

PS05 has poor water clarity characteristics. Nutrient impacts due to residences and development may in fact be low (possibly misclassified in this group) although the median N:P for *T. testudinum* is about 45. P availability is limiting; this could be due to very limited available P (related possibly to sediment type) or to relatively high levels of available N. Impacts in this grass bed are/have been physical – strong wave action. Exposure at these beds to wind driven waves from the southeast is quite high. *T. testudinum*, *S. filiforme* and *Halodule* sp. are all present in these moderately dense beds.

PS15 is also very shallow with very low water clarity and with high density grass beds. Only *T. testudinum* is found along the site transect line. The coastline around the bay is heavily developed with residential properties and there are many moorings in the bay, but there is no industrial development. N:P ratios for *T. testudinum* (median about 52.7) indicate significant P limitation.

ii. *slightly P limited (potentially light limited) – with seagrass N:P ratios in the mid 30's*

PS08 has relatively poor water clarity and is moderately deep, about 3 m. Although residential density appears to be low in the immediate area of the site, there is a major road along the adjacent coastline and an open water way to the Great Sound. N:P ratios for *T. testudinum* (median about 35) indicate that P availability is slightly limiting to growth and density but that light may also be a limiting factor. Cover of calcareous green algae is the highest for all the monitoring sites, which might suggest high nutrient (both N and P) availability. *T. testudinum* and *S. filiforme* are both present forming moderately dense beds.

PS09B is a very shallow site with very low water clarity and very high grass cover. *T. testudinum* and *S. filiforme* occur at this site, and there is a relatively dense population (for Bermuda) of the purple sea urchin, *Lytechinus purpuratus*. The small bay where the site is located is surrounded by a regularly watered and fertilized golf course. N:P ratios for *T. testudinum* (median about 34) indicate a fairly balanced supply of these nutrients, P is only slightly limiting. There is regular evidence of cool water seeping up from the bottom into the surface seawater but we have not measured consistently lower salinities at this site.

PS16 is moderately shallow, with moderate water clarity and medium dense seagrass beds. The bottom sediments are quite compact and both wave surge and tidal currents can be moderately strong in this area. *T. testudinum*, *S. filiforme* and *Halodule* sp all occur at this site. A dairy farm is located along the coast immediately west of the site. There is some P limitation, with a median N:P ratio for *T. testudinum* about 36.8.

b. *With lower density seagrass*

i. *strongly P limited - with seagrass N:P ratios greater than 40*

PS13 is located in a long semi-continuous bed running along the southern boundary of the North Lagoon. It is offshore of the site of the domestic garbage incinerator, which has a warm water outfall. These beds were studied during an impact assessment program before and after the installation of the outfall. Our permanent site is very near what was identified as the East Impact study in studies done in the mid 1990's. More recently, a reverse osmosis outflow has been installed adjacent to the site. *T. testudinum*, *S. filiforme* and *Halodule* sp are all found at this site. The N:P ratio for *T. testudinum* (median about 50) indicates P limitation at the site, even though water clarity is also moderately low and the site is of a moderate depth light is not the primary limit to the density of this seagrass.

ii. *slightly P limited (potentially light limited) – with seagrass N:P ratios in the mid 30's*

PS18 is at a small seagrass bed at an occasionally occupied island near the northwest shore of Harrington Sound. The apparent low cover of the seagrass at this site is due to the small size of the bed consisting of *T. testudinum* and *S. filiforme*. Water clarity is

moderately low and seagrass is only found here at depths shallower than about 1.3 meters. Near the shoreline there is considerable shading by coastal “cliffs” and this is where the *S. filiforme* is found. The N:P ratio for *T. testudinum* indicates minor P limitation (median about 33); generally nutrients may be highly available in this location although the northwest shore of Harrington Sound has overall much lower density residential development than other parts of the Sound.

2. Anthropogenic impacts, for example nutrient input, not expected to be significant, other impacts such as physical disturbance may be significant either directly or through creating, for example, low light conditions

a. *with low to moderate density seagrass beds, dominated by S. filiforme, moderate water clarity*

PS09A is located near the mouth of Great Sound, off to the northwest. As a whole, this part of the Sound does not appear to be nutrient enriched, but direct experience at the site indicate that physical disturbance at depth may be common, passing boats and ferries create strong surges at depth. The median water clarity is fairly high and the site is of a moderate depth, just under 6 m. Only *S. filiforme* and *Halodule* sp are present at this site, and it is one of the most sexually active/productive *S. filiforme* beds we have found in Bermuda. The lower density of this healthy bed is a reflection of the absence of *T. testudinum*. The N:P ratio for *S. filiforme* (about 38), if assessed the same as has been done for *T. testudinum*, suggests some P limitation for this grass. The absence of *T. testudinum* may be indicative of low light levels at the bottom.

b. *with high density seagrass beds, poor light, very shallow*

PS17 is located in the shallow bay offshore of the southern beach at Clearwater Park. This is a well-used public swimming beach on the recovered lands of the former US Naval Air Base. There are no residences or industries along the immediate coastline and up until the past 20 years access to the area was highly controlled. This site is subjected to strong surge action when the winds are blowing from an easterly direction and the nearshore waters can become very turbid. The physical structure of the seagrass bed, with eroded terraces is related to the shallow depth of the beds and translation of wave energy to the sea bottom. *T. testudinum*, *S. filiforme* and *Halodule* sp are all present at this site; overall these beds have the second highest grass cover of the 17 monitoring sites. N:P ratios (median about 34) for *T. testudinum* suggest minor P limitation.

PS19 is located in the west side of Castle Harbour in the Walsingham National Marine Park. The Walsingham Tract, which is a nature reserve, is riddled with caves and low salinity ponds, some of which drain into Castle Harbour. Residential development is low density. Similar to **PS17**, this site can be affected by easterly winds and can be very turbid; water clarity is on average quite low. *T. testudinum*, *S. filiforme* and *Halodule* sp. are present in the dense beds at this site. N:P ratios for *T. testudinum* (median about 32) suggest minor limitation to growth due to P availability.

METHODS

Field protocols for water quality sampling

Water quality samples were collected by staff of the Bermuda Department of Conservation Services on a monthly basis, over a period of 1-3 days, from 17 permanent monitoring stations as described above (Fig. 1). The period of record of this report was from Sept. 2007 to Mar. 2009 which included 19 monthly sampling events.

From September 2007 to present, salinity (practical scale salinity) was measured using a YSI 30 handheld salinity, temperature and conductivity instrument. Dissolved oxygen (DO) was measured using a YSI 550A handheld instrument. Exceptions are dates during which an instrument had been sent away for maintenance. DO (mg l^{-1}) was automatically corrected for temperature (value measured by the instrument), ambient salinity (value manually entered into the instrument) and altitude (value manually entered into the instrument). The YSI salinity instrument was calibrated quarterly (or more frequently), single point, using YSI 3169 conductivity calibrator solution, 50,000 μS . The YSI 550A DO instrument was calibrated in % saturation mode (1 point) each day it was used. These were all surface readings (probe suspended at about 20-30 cm below the water surface).

From June 2008, salinity (practical salinity scale), temperature ($^{\circ}\text{C}$) (YSI 6560 conductivity/temperature probe), and dissolved oxygen (mg l^{-1}) (YSI 6150 ROX optical dissolved oxygen sensor) were also measured using a YSI 650 MDS with YSI 600 XL sonde. DO was automatically corrected for salinity, temperature and barometric pressure (value in mm manually entered into the instrument daily). The salinity probe was calibrated at least quarterly, single point, using YSI 3169 conductivity calibrator solution, 50,000 μS . Additional calibrations were done when a notable difference between the YSI 550A and the sonde probe was apparent. The DO sensor was calibrated in % saturation mode (1 point) each day of use. From February 2009, pH (YSI 6561 pH probe) was also measured using the YSI sonde system. Two point calibrations, YSI pH 7.00 and 10.00 standards, were done approximately quarterly. Field readings using the sonde system were done at approximately 1 m and at the bottom. Only the 1 m readings are included in this report. Secchi depth (m) was measured as well as water column depth (m) and % Secchi depth relative to water depth was calculated.

Water was collected directly into pre-acidified 250 ml HDPE sample bottles. For chlorophyll *a* (CHLA), 140 ml of water was collected via syringe and filtered by hand through 25 mm Whatman GF/F glass fiber filters. The filters were then placed in 1.8 ml plastic centrifuge tubes, capped, and kept frozen in a dark Nalgene bottle until analysis. Turbidity was measured using a Hach portable turbidimeter model 2100P and reported in NTU.

Laboratory Analysis

Unfiltered water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), silicate (SiO_2), and turbidity. TOC was measured by direct injection onto hot platinum catalyst in a Shimadzu TOC-5000 after first acidifying to $\text{pH} < 2$ and purging with CO_2 -free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O_2 as carrier gas to promote complete recovery of the nitrogen in the water samples (Frankovich and Jones 1998). TP was determined using a dry ashing, acid hydrolysis technique (Solórzano and Sharp 1980). SiO_2 was measured using the molybdosilicate method (Strickland and Parsons 1972). Filtrates were analyzed for nitrate+nitrite (NO_x^-), nitrite (NO_2^-), ammonium (NH_4^+), and soluble reactive phosphorus (SRP) by flow injection analysis (Alpkem model RFA 300, APHA 1999).

Filters for CHLA ($\mu\text{g l}^{-1}$) to which 1.5 ml of 90% acetone/water were added (Strickland and Parsons 1972) were allowed to extract for a minimum of 2 days at -20°C before analysis. Extracts were analyzed using a Gilford Fluoro IV Spectrofluorometer (excitation = 435 nm, emission = 667 nm). All analyses were completed within 28 days after receipt in accordance to SERC laboratory QA/QC guidelines. Turbidity measurements were completed within 12 hours of sample collection.

Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3^-) was calculated as $\text{NO}_x^- - \text{NO}_2^-$, dissolved inorganic nitrogen (DIN) as $\text{NO}_x^- + \text{NH}_4^+$, and total organic nitrogen (TON) defined as $\text{TN} - \text{DIN}$. All concentrations are reported as μM unless noted. All elemental ratios discussed were calculated on a molar basis. Percent DO saturation in the water column (DO_{sat}) was calculated using the equations of Garcia and Gordon (1992).

Cluster Analysis

Stations were stratified according to water quality characteristics (i.e. physical, chemical, and biological variables) using a multivariate statistical approach. Multivariate statistical techniques have been shown to be useful in reducing large data sets into a smaller set of independent, synthetic variables that capture much of the original variance. Briefly, data were first standardized as Z-scores prior to analysis to reduce artifacts of differences in magnitude among variables. Both the mean and SD of the data for each station over the entire period of record were then used as independent variables in a hierarchical cluster analysis (Ward method) in order to aggregate stations into groups of similar water quality.

Box and Whisker Plots

Typically, water quality data are skewed to the left (predominance of low concentrations and below detects) resulting in non-normal distributions. Therefore it is more appropriate to use the median as the measure of central tendency because the mean is inflated by high outliers (Christian et al. 1991). Data distributions of water quality variables are reported as box-and-whiskers plots. The box-and-whisker plot is a powerful statistic as it shows the median, range, the data distribution as well as serving as a graphical, nonparametric ANOVA. The center horizontal line of the box is the median of the data, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch in the box is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are considered significantly different. Outliers (<5th and >95th percentiles) were excluded from the graphs to reduce visual compression. Differences in variables were also tested between groups using the Wilcoxon Ranked Sign test (comparable to a *t*-test) and among groups by the Kruskal-Wallis test (ANOVA) with significance set at $P < 0.05$.

Time Series Analysis

Individual site data for the complete period of record were plotted as time series graphs to illustrate any temporal trends that might have occurred over the period of record. As this was only a 19 month record, temporal trends were not calculated but will be done with future data collection

Web Site Development

We developed and maintain a website (serc.fiu.edu/wqmnetwork/BERMUDA/) where anyone can download 1) all data from the program, 2) the interpretive reports, and 3) Google maps of all measured variables, by month, in classified post style. The site and graphics are still under development but we expect it to be fully functional soon.

RESULTS & DISCUSSION

Overall Conditions

Summary statistics for all water quality variables from all 19 sampling events are shown as median, minimum, maximum, and number of samples (Table 1). Overall, the region was warm and euhaline with a median temperature of 21.3 °C and salinity of 36.6; dissolved oxygen in the water column (DO) was high at 7.4 mg l⁻¹. On this coarse scale, the Bermuda coastal waters exhibited good water quality with median NO₃⁻, NH₄⁺, and TP concentrations of 0.36, 1.15, and 0.14 μM, respectively. NH₄⁺ was the dominant DIN species in almost all of the samples (64%). However, DIN comprised a small fraction (15%) of the TN pool with TON making up the bulk (median 9.98 μM or 83% of TN). SRP concentrations were low (median 0.05 μM) and comprised 34% of the TP pool. CHLA concentrations were also very low overall, 0.19 μg l⁻¹, but ranged from 0.02 to 2.79 μg l⁻¹. TOC was 98.3 with DOC making up 95% of the pool. These values are slightly higher than open ocean levels but consistent with coastal areas. Median turbidity was low (0.48 NTU) as reflected in a high Secchi:water column depth (99%). Molar ratios of N to P suggested a strong P limitation of the water column (median TN:TP = 87.6) but this must be tempered by the fact that much of the TN may not be bioavailable.

Spatial Clustering

Cluster analysis of water quality variables by site resulted in 4 groups which had distinct differences in water quality (Fig. 2). **Cluster 1** (in red) was composed of stations 9B, 15, and 16, which are those sites most strongly affected by anthropogenic nutrient inputs as indicated by their high levels of NO₃⁻, TP, TOC, and turbidity (Fig. 3-15). Interestingly, this cluster also showed high DO but did not have elevated CHLA. **Cluster 2** (in yellow) included a mix of stations on the SW and NE part of the platform (#2, 4, 5, 8, 9A, 17, & 19). These sites exhibited lower NO₃⁻, TP, TOC, CHLA, and turbidity than Cluster 1. **Cluster 3** (in green) was composed of far offshore sites out on the western platform (#1, 3, 6, 7, & 20). These stations had the lowest NO₃⁻, TP, TOC, SiO₂, CHLA, DO, and turbidity. Interestingly, these sites also had lowest light penetration, not because of optical clarity but because of greater water column depth. Salinity was also the most invariable at these sites. **Cluster 4** (in blue) consisted of only one site, station #18 off Trunk Island, but it was so different than any of the other sites that it had to be treated separately. It had the highest NO₃⁻, NH₄⁺, SRP, SiO₂, CHLA, and the lowest salinity than any other sites in the monitoring network which may be due to its location within an enclosed bay. The low salinity reflects a source of terrestrial freshwater from either runoff or outfall and the enclosed nature of the bay means that water residence time is probably higher than other areas. Longer water residence time allows more nutrients to be incorporated into phytoplankton biomass, hence the high CHLA levels at this site.

Time Series Plots

Measured water quality variables were plotted with time to observe any seasonal differences or episodic effects (Fig. 16-66). As this was only a 19 month record, temporal trends were not calculated but will be performed with future data collection.

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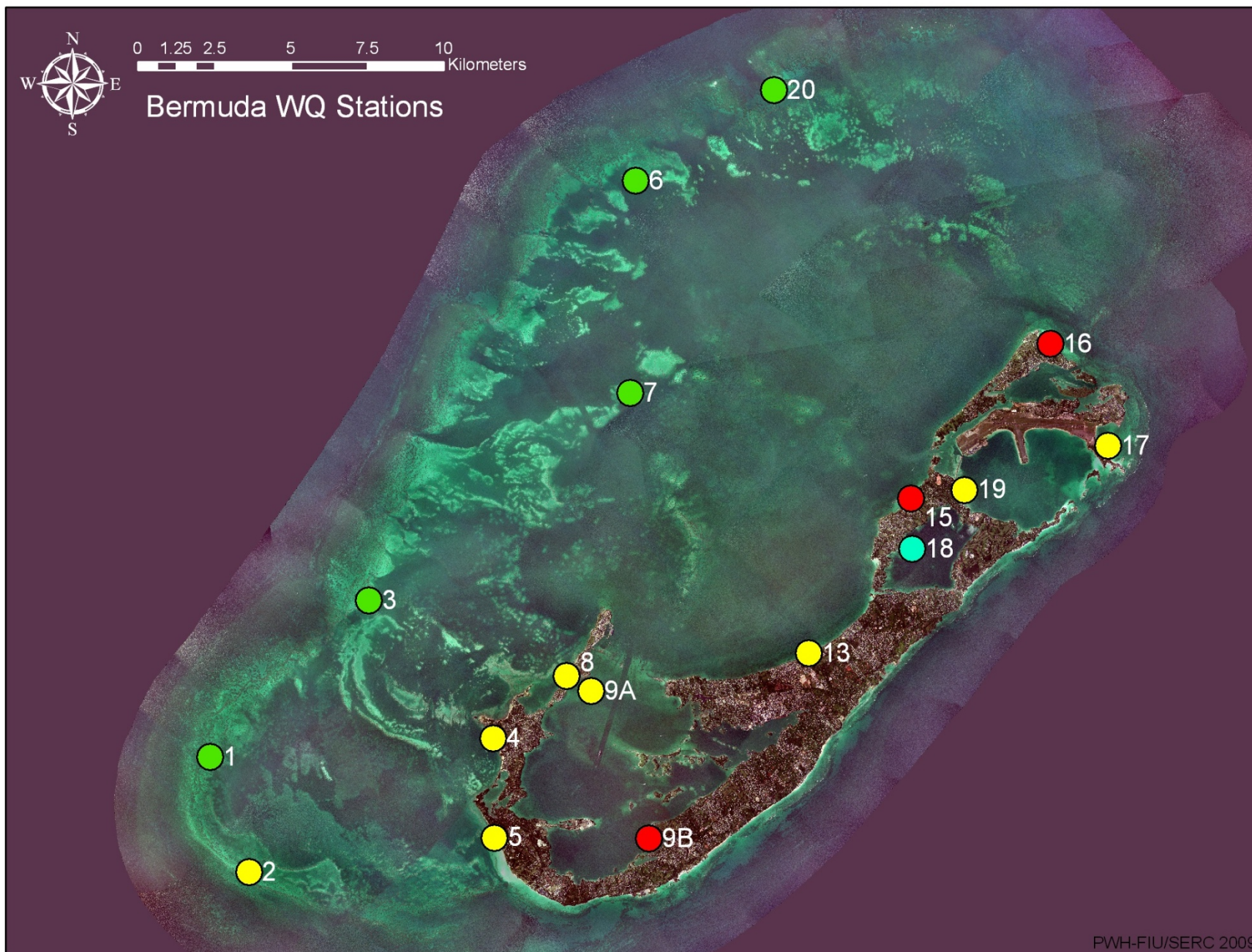


Figure 2. Map showing stations as clustered by water quality conditions.

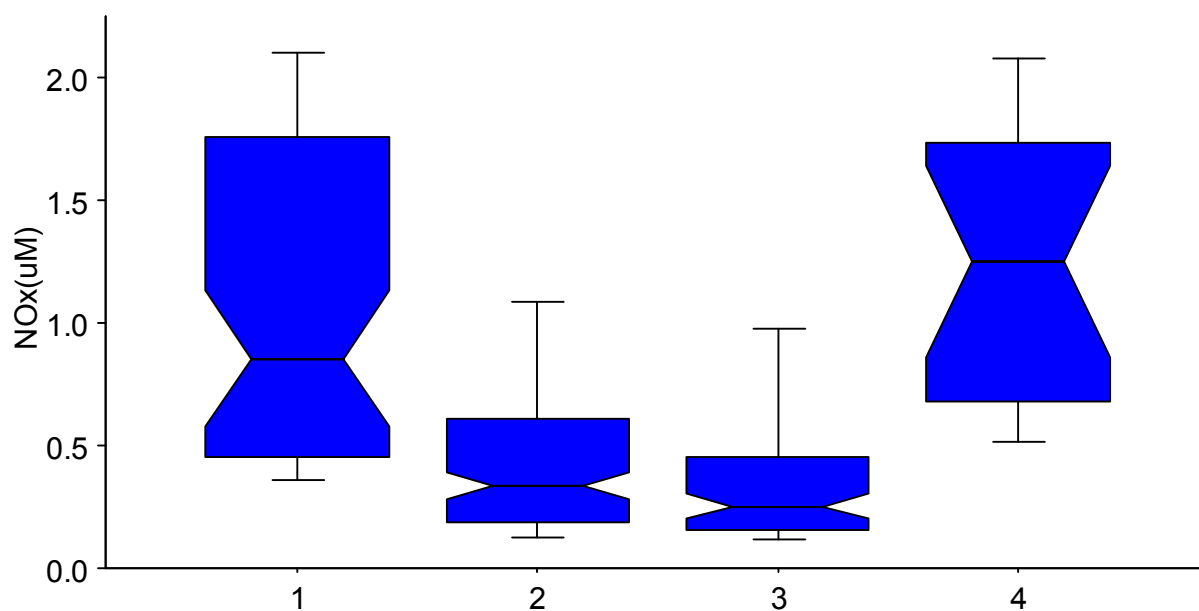


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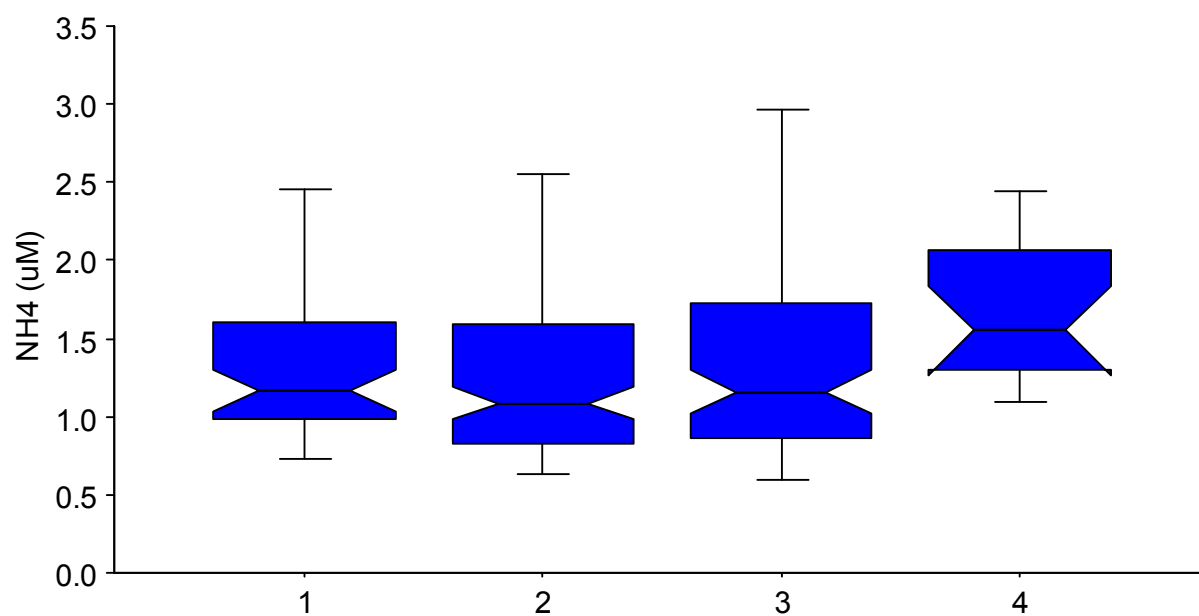


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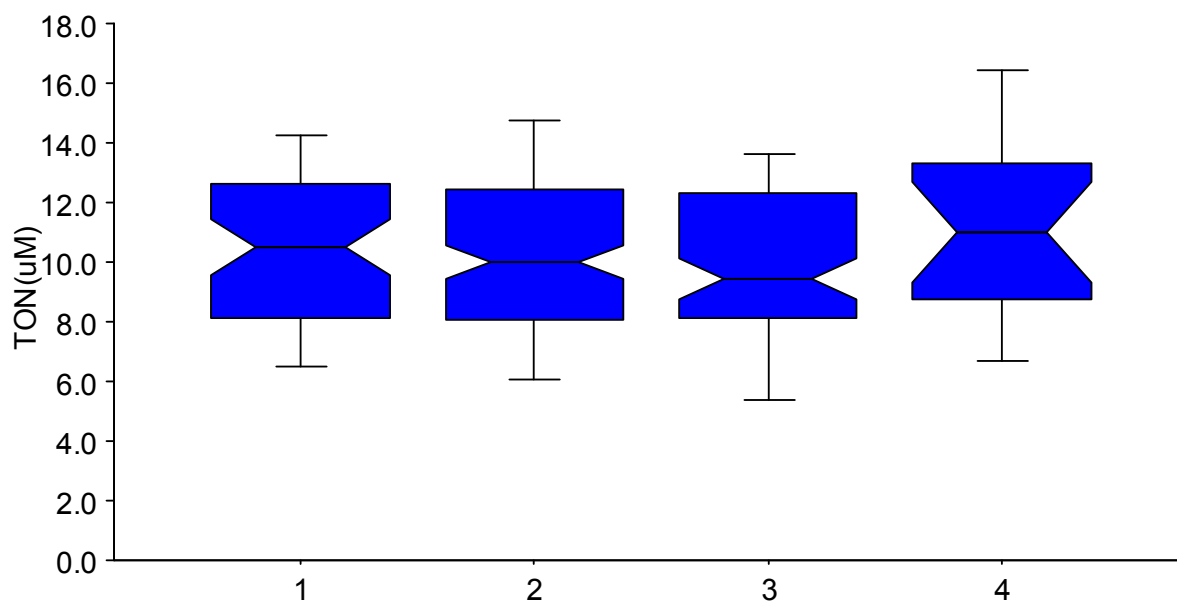


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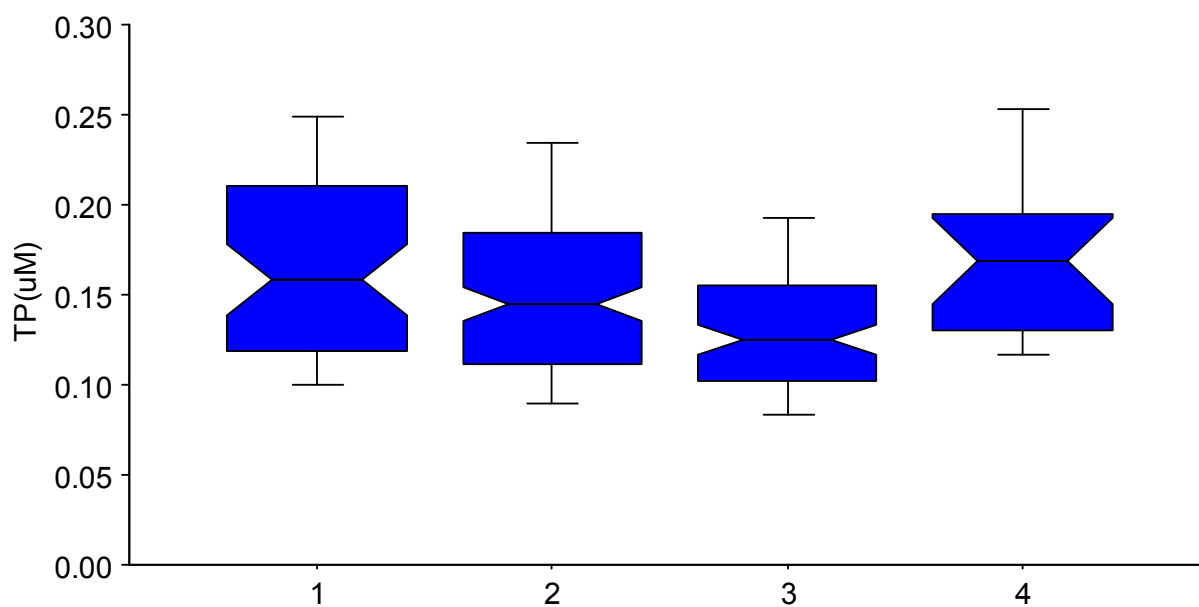


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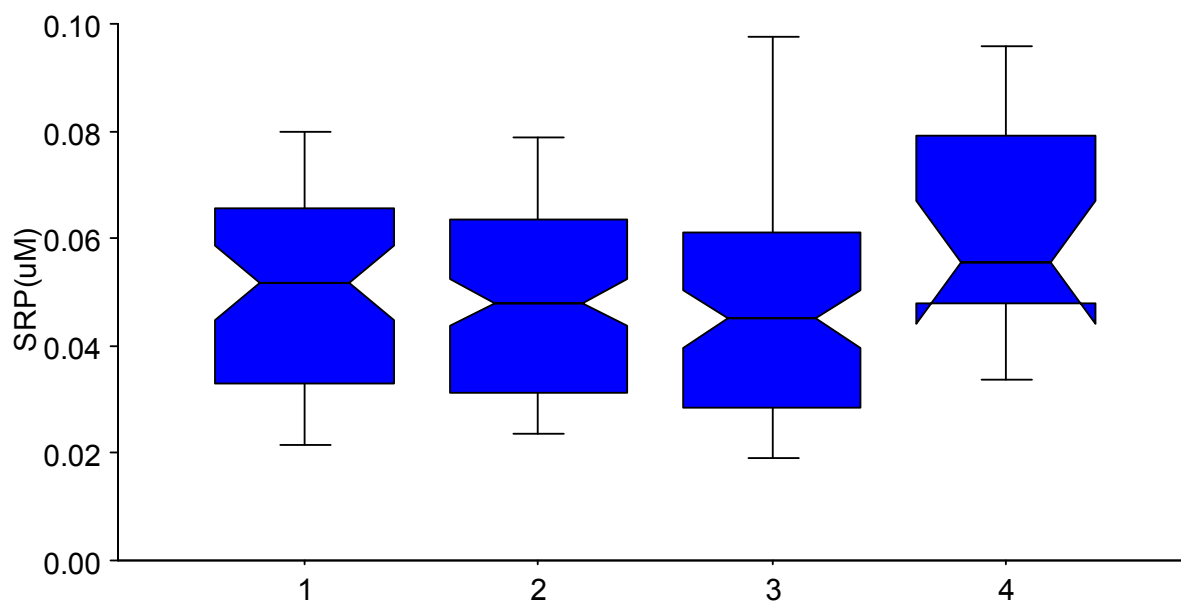


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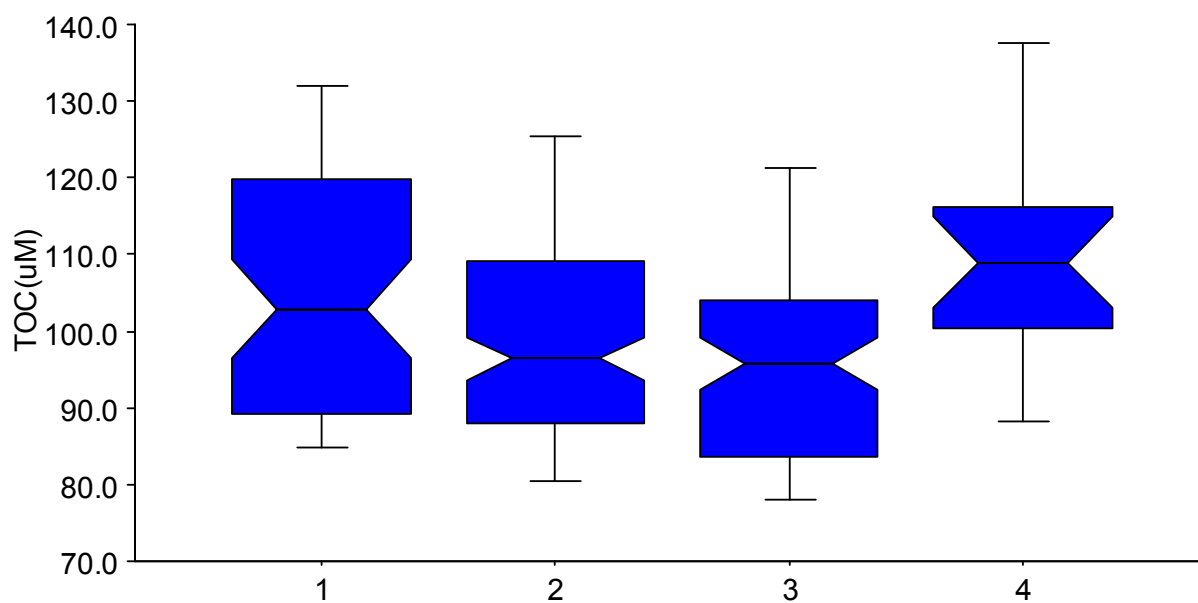


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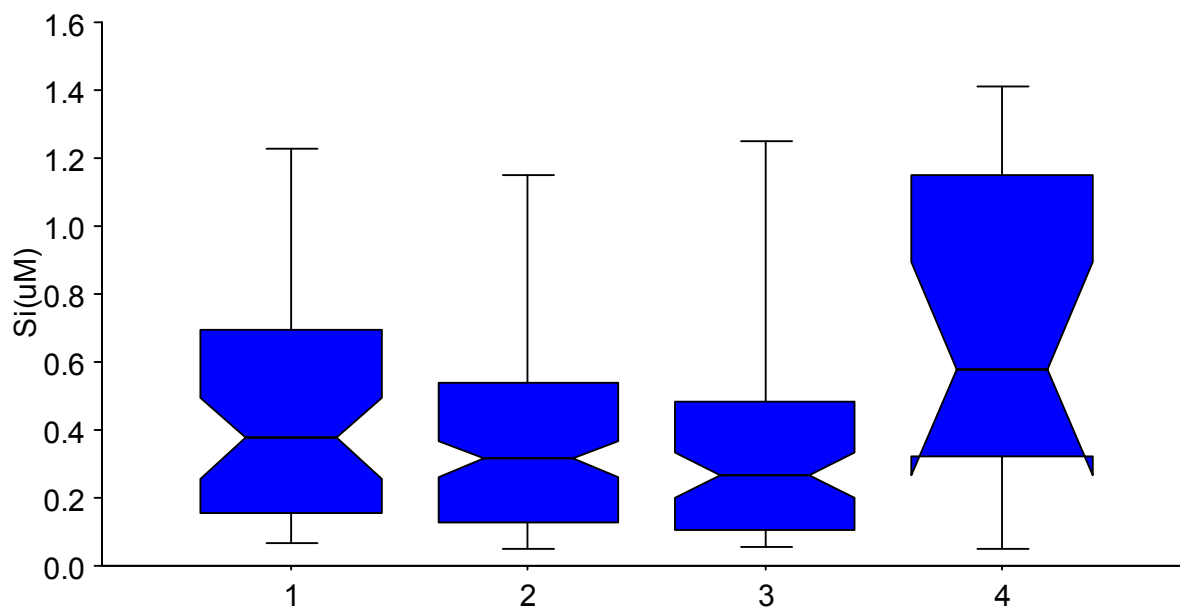


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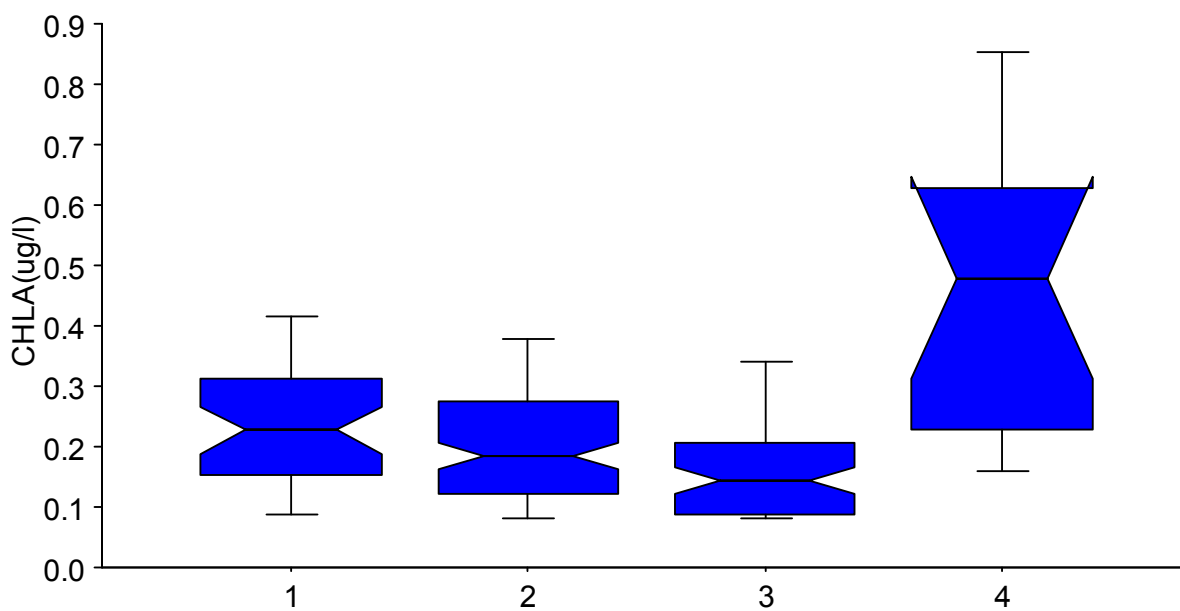


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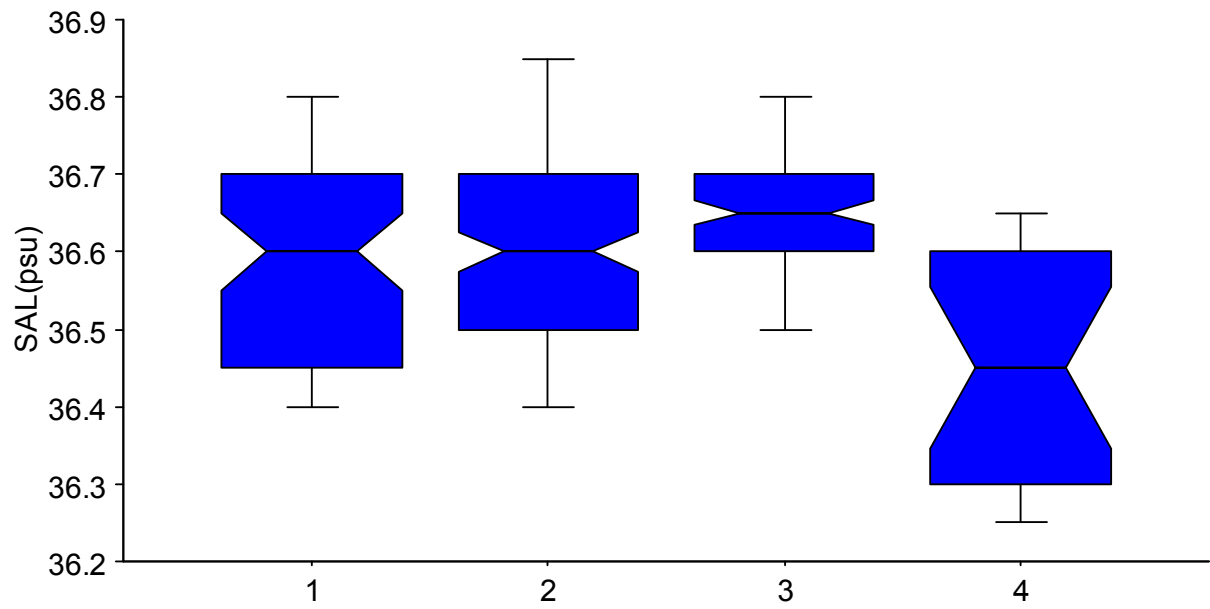


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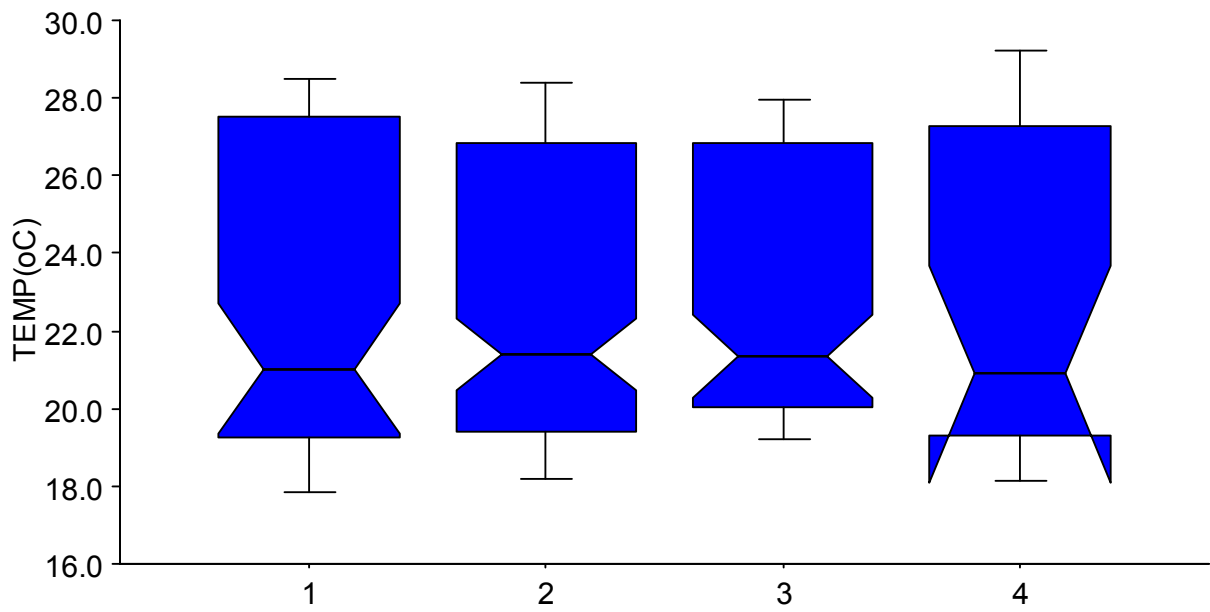


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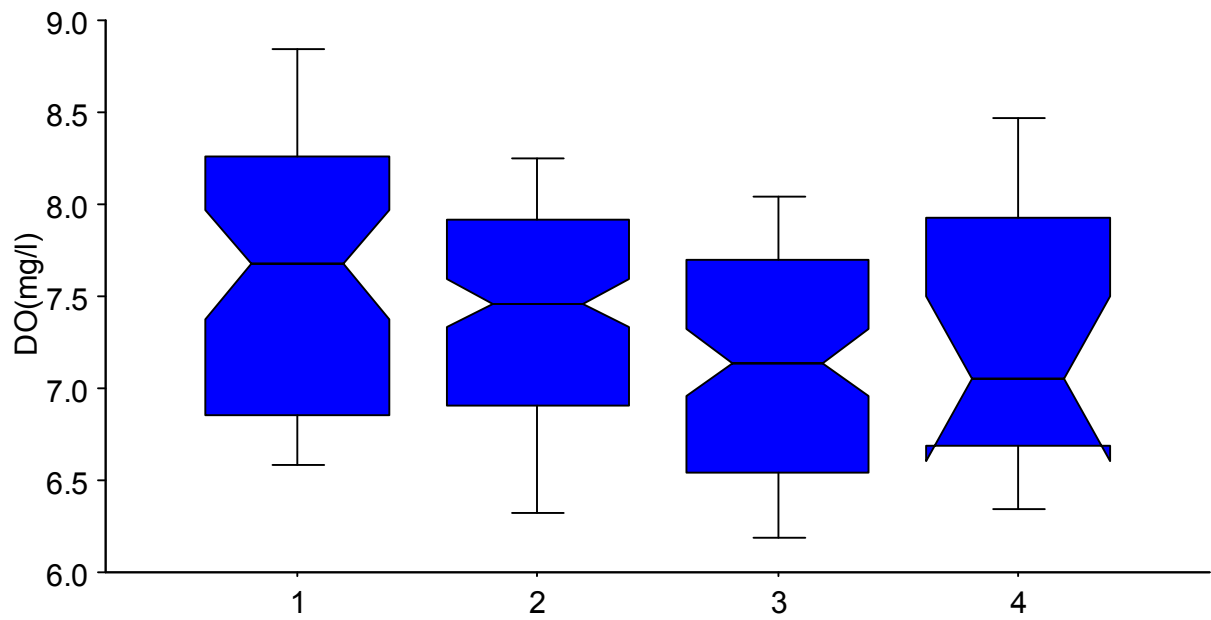


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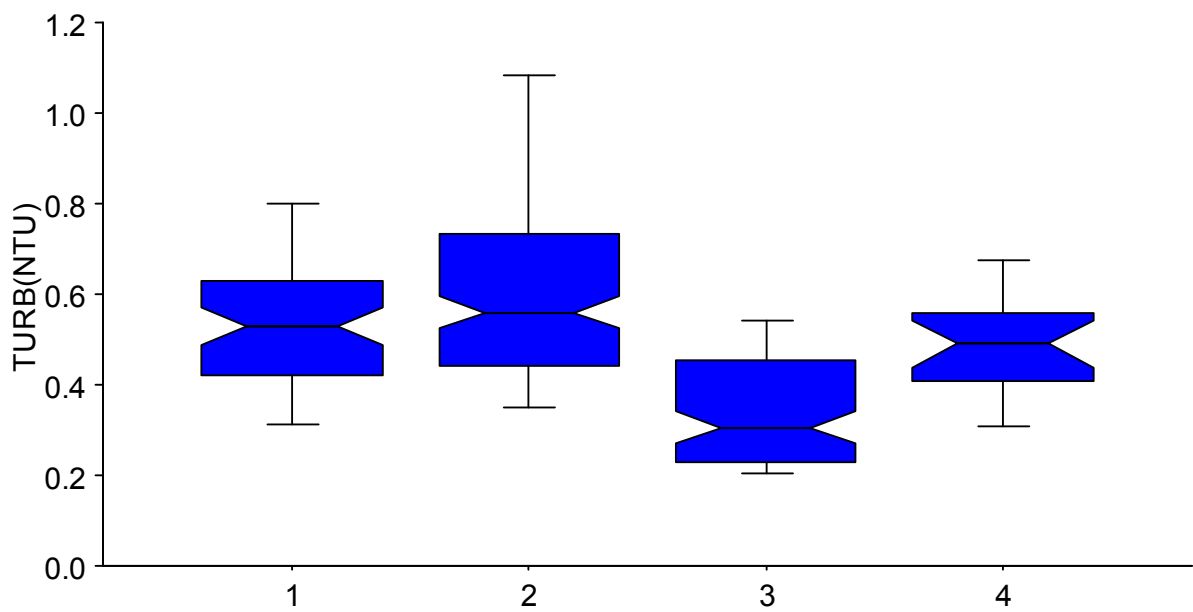


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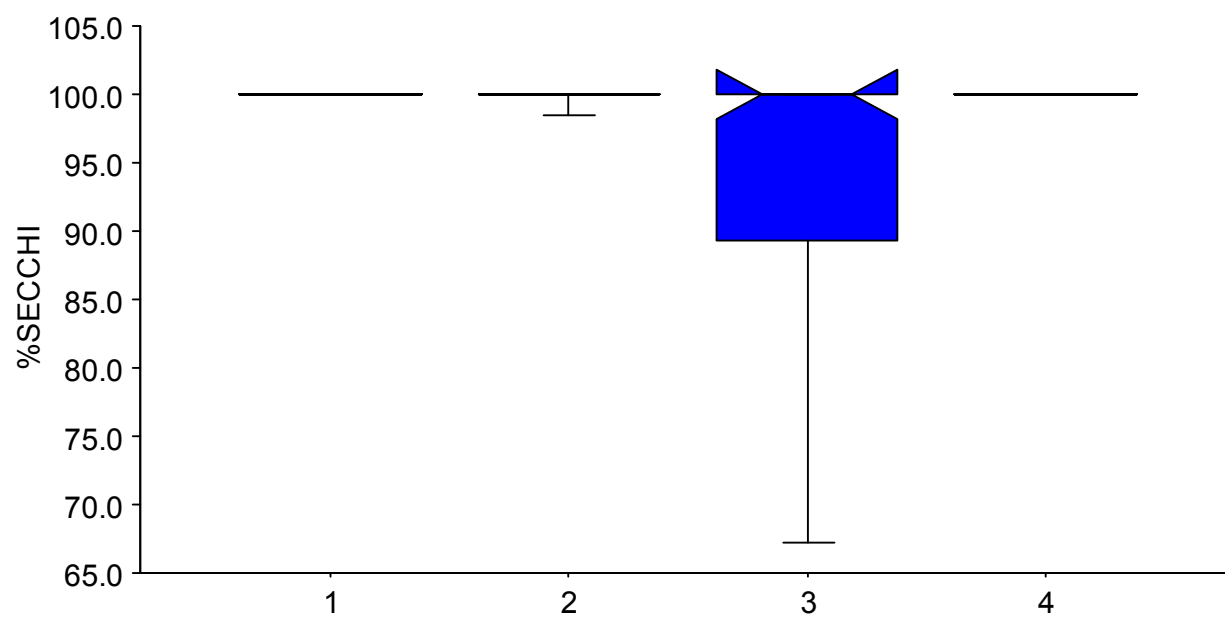
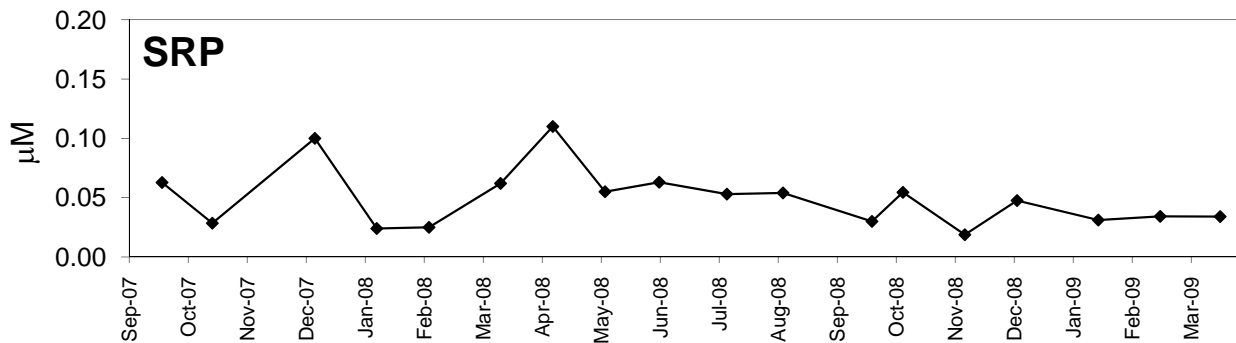
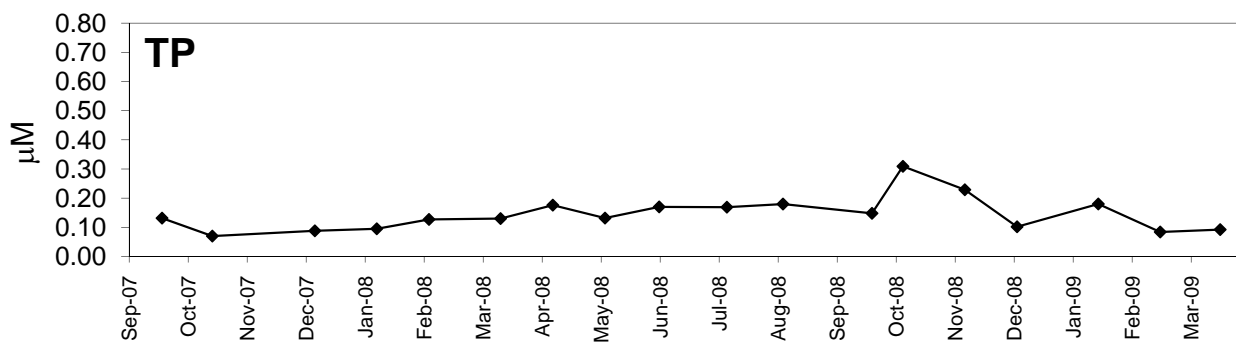
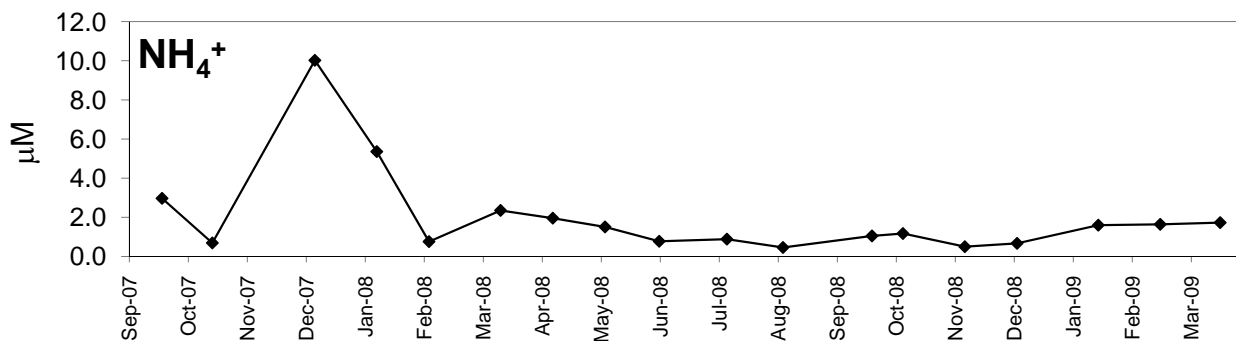
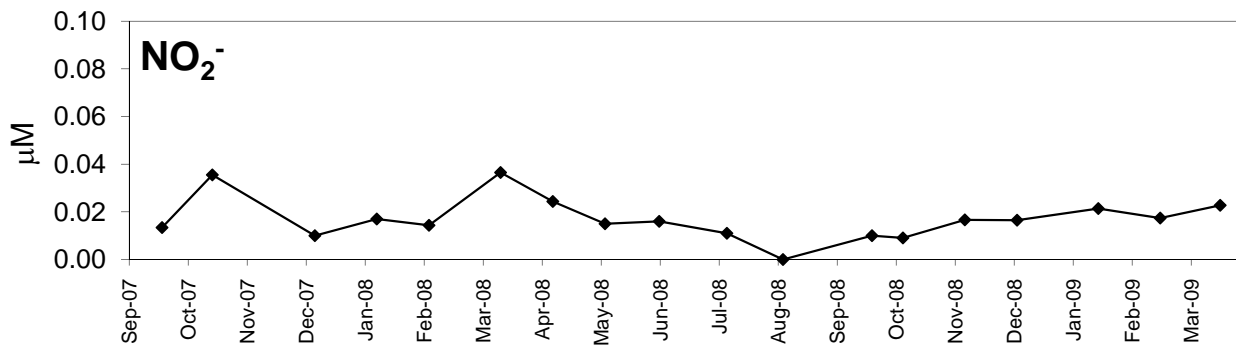
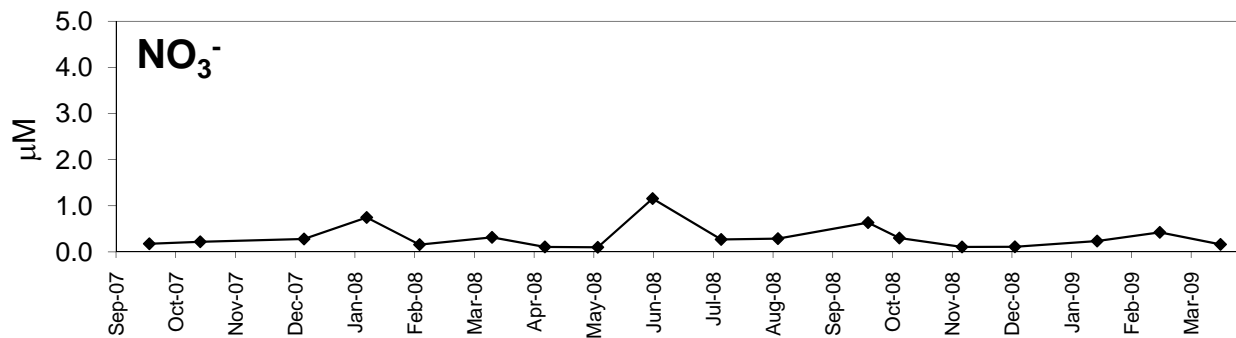
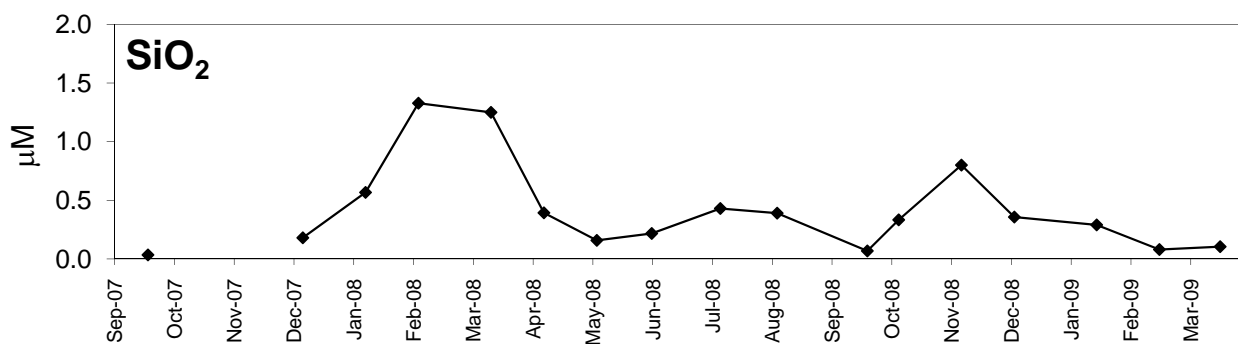
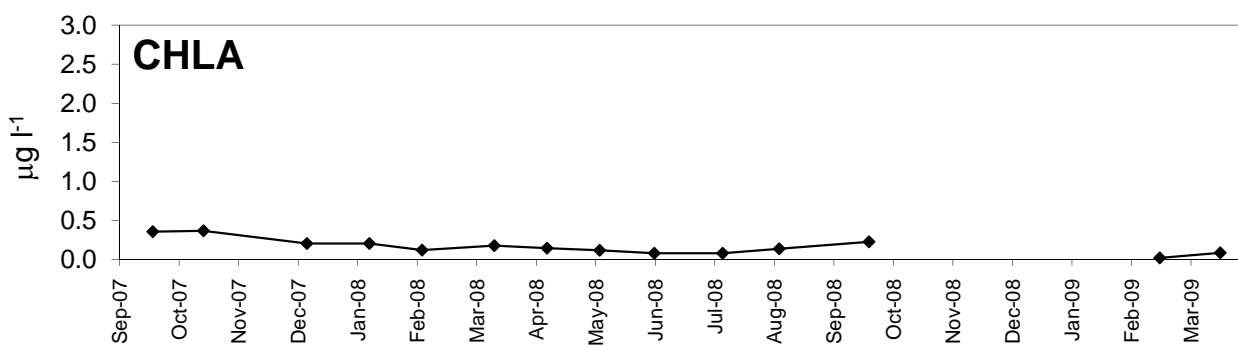
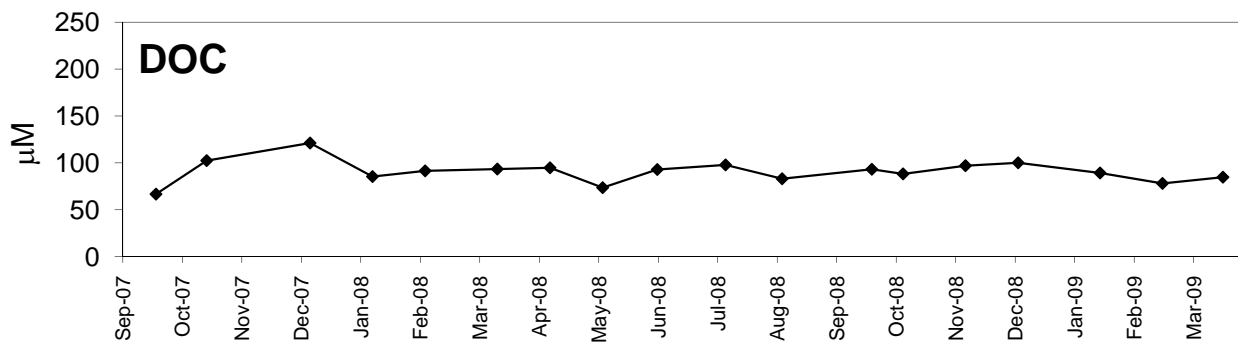
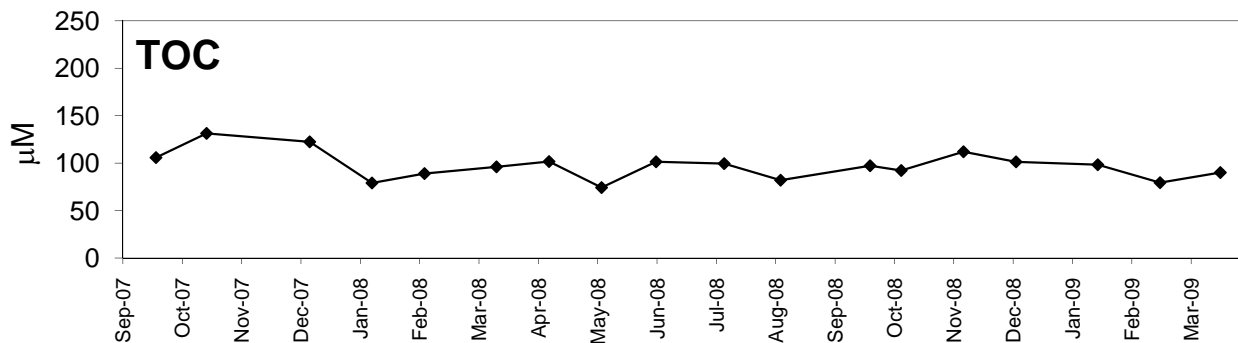
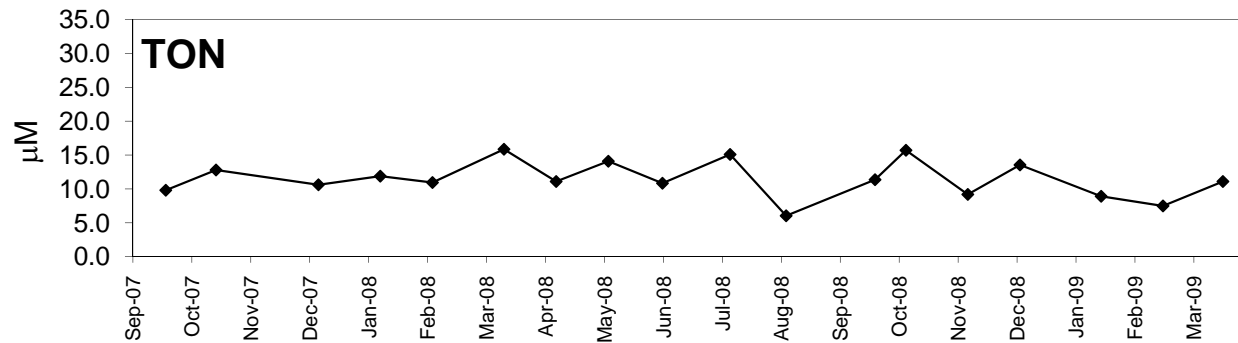


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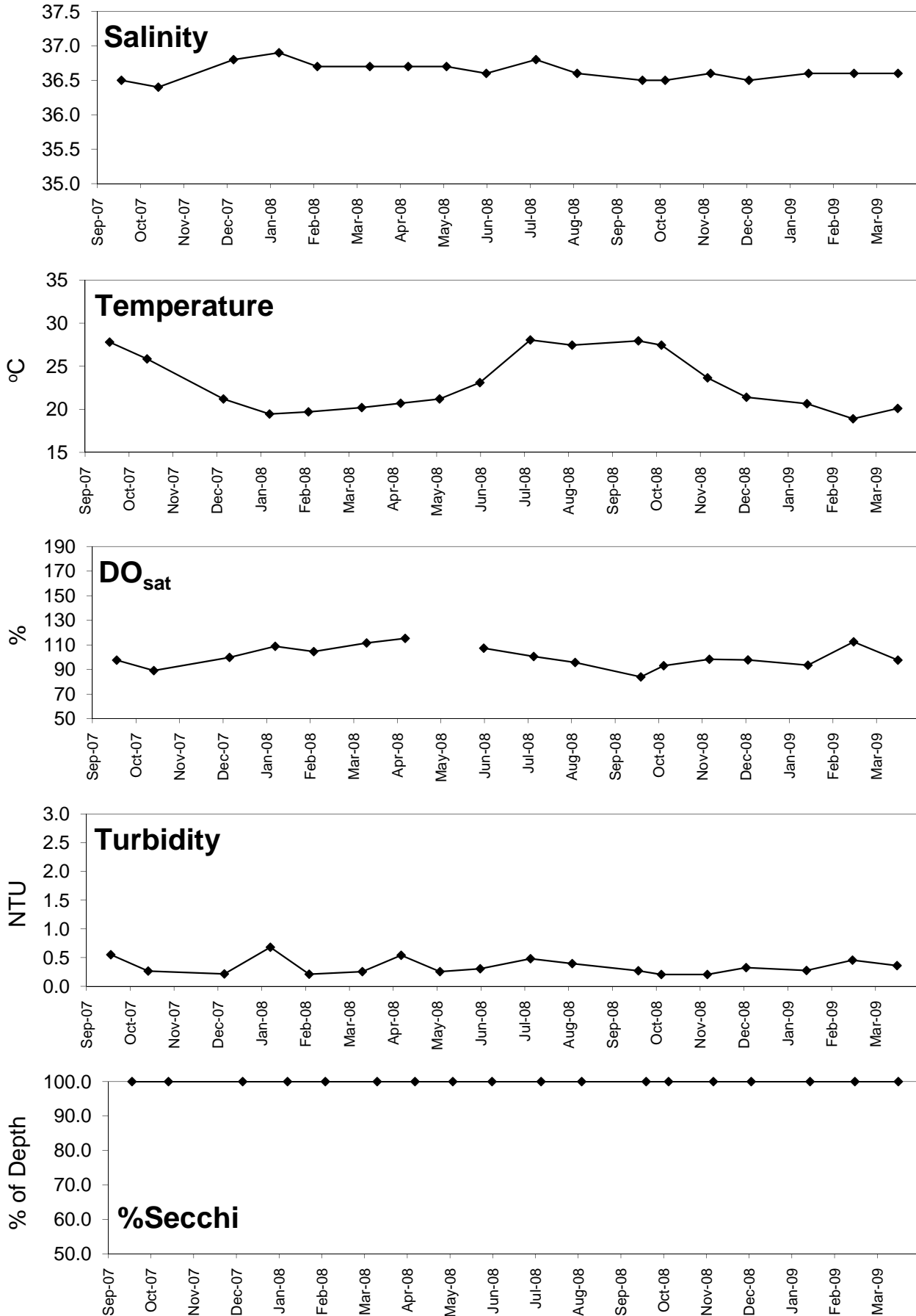
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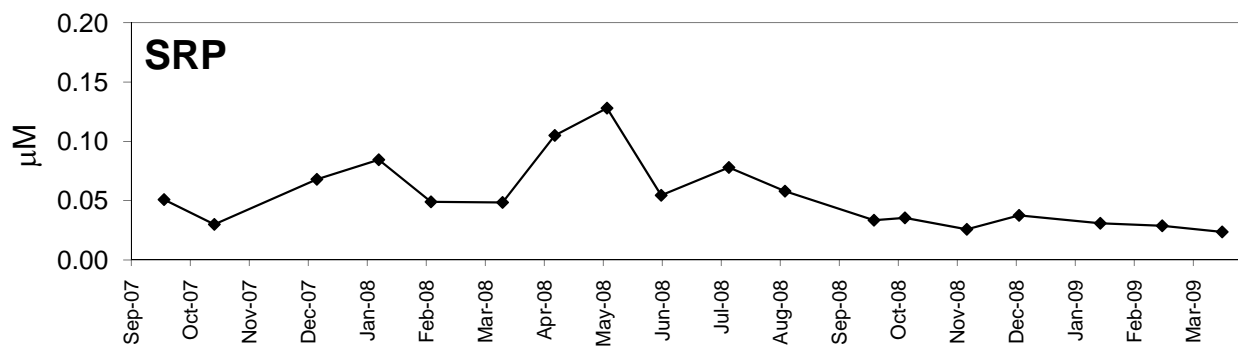
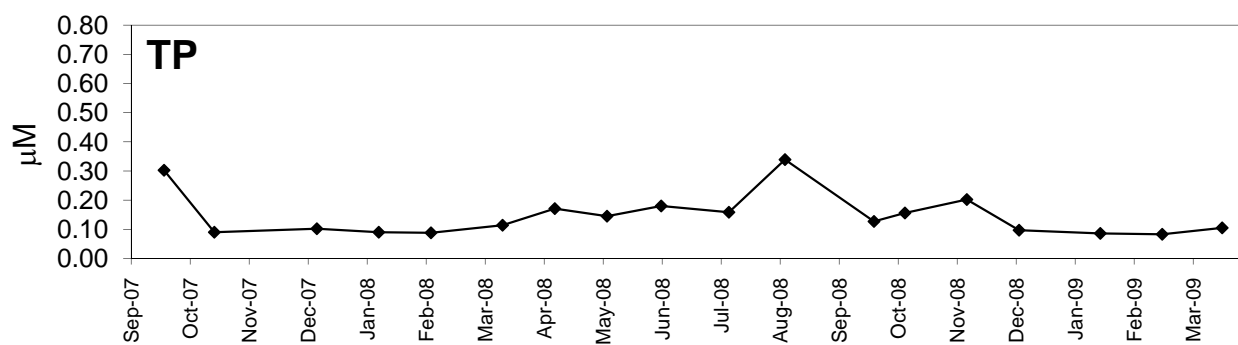
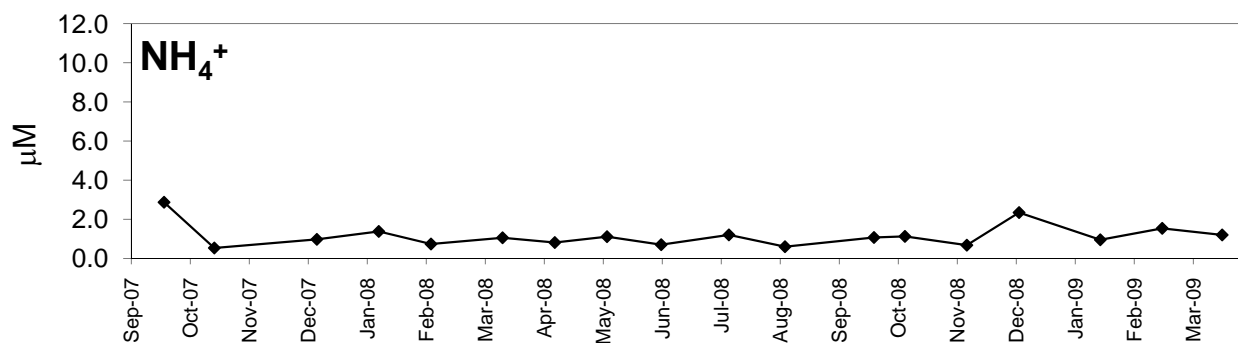
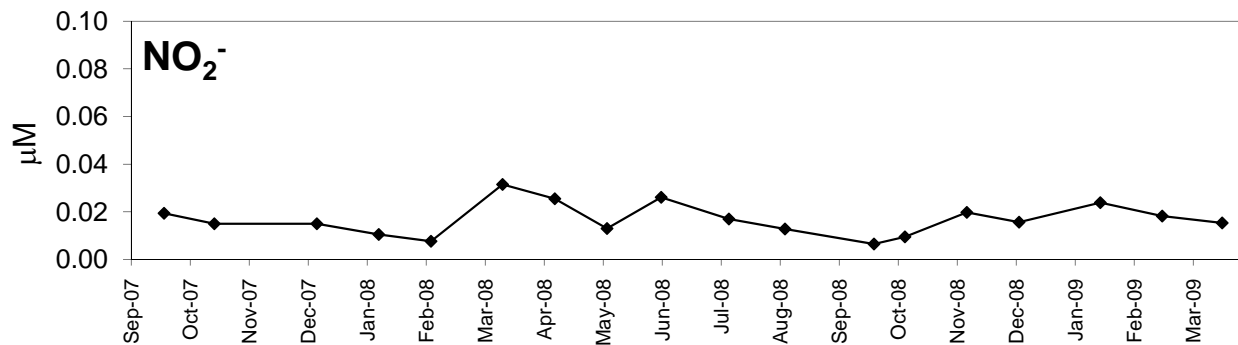
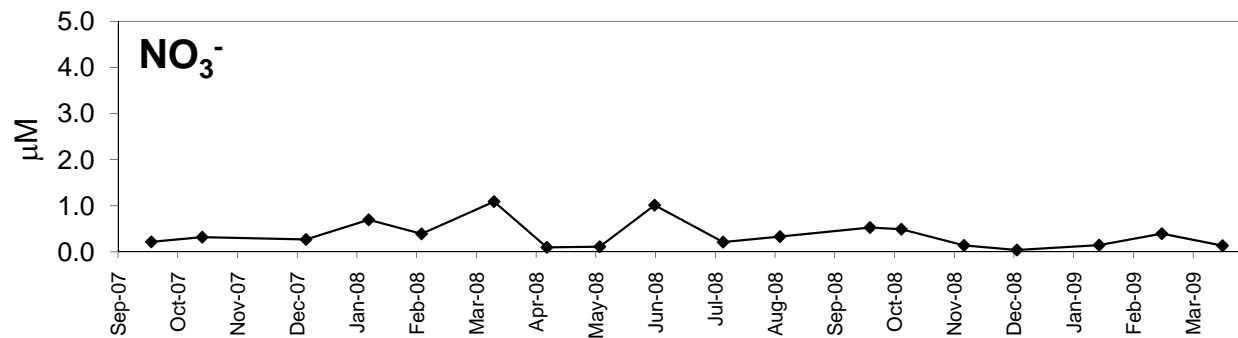
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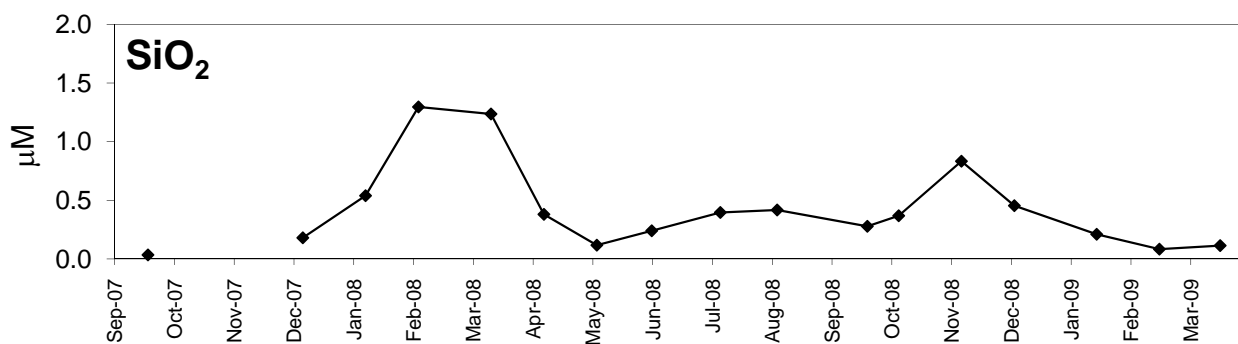
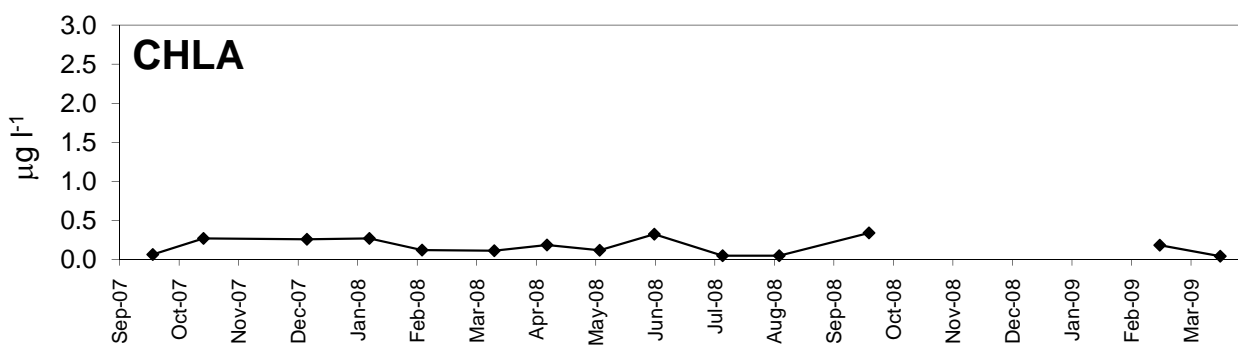
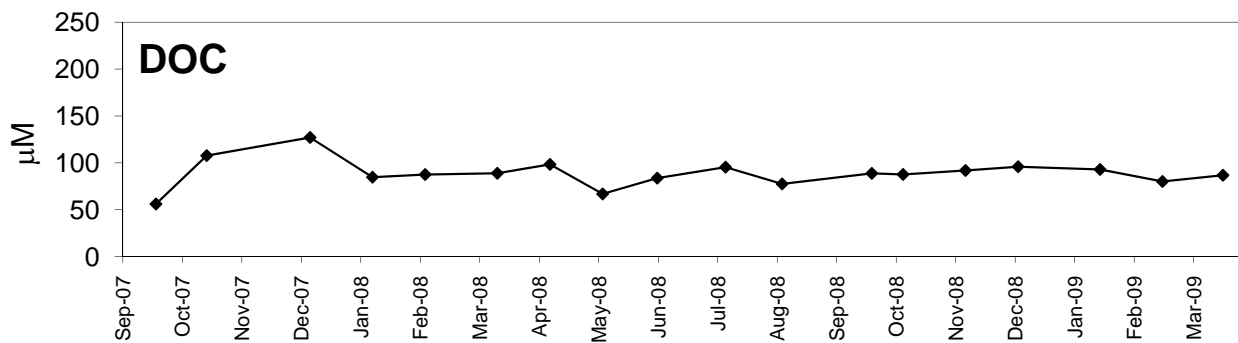
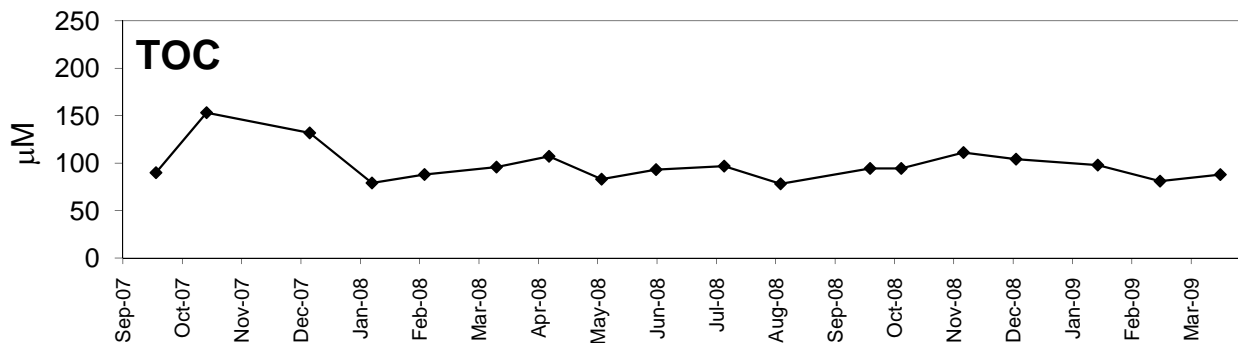
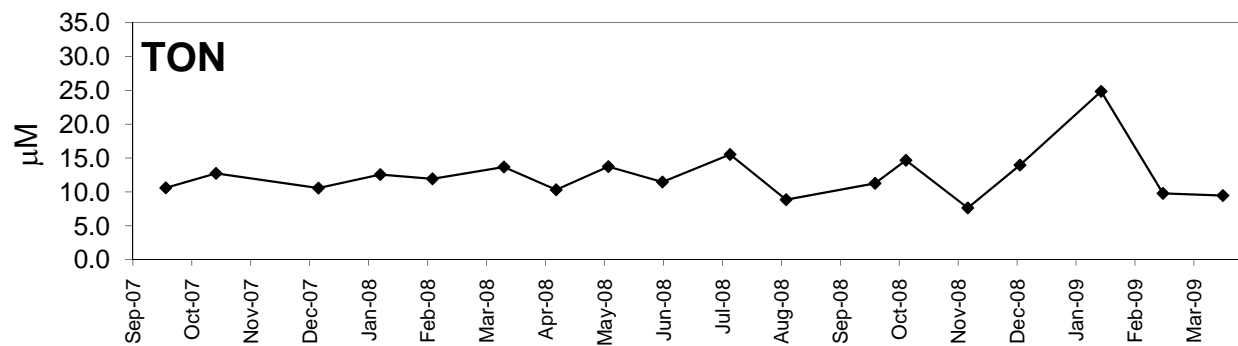
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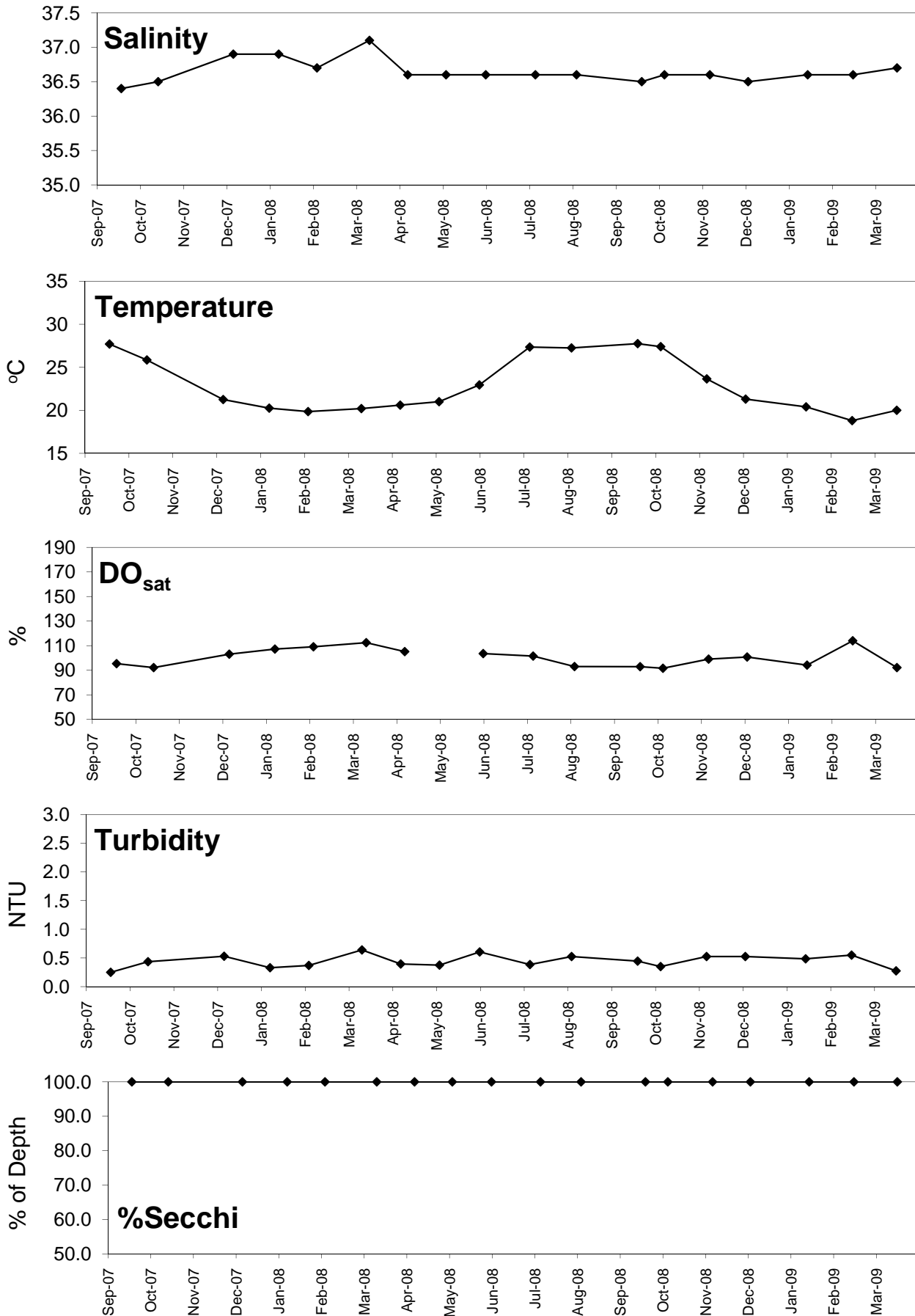
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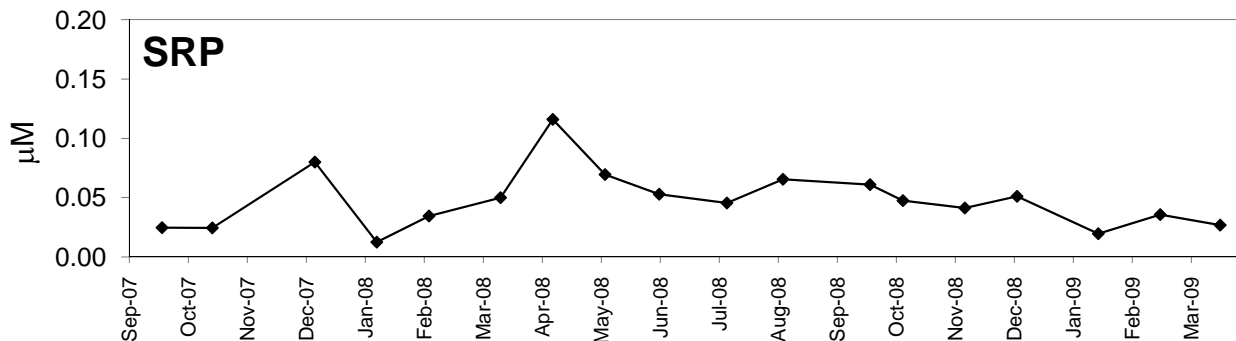
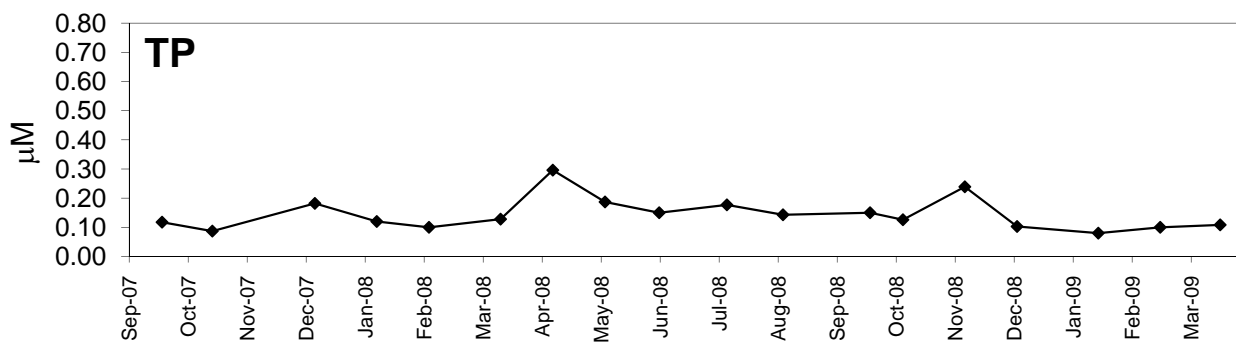
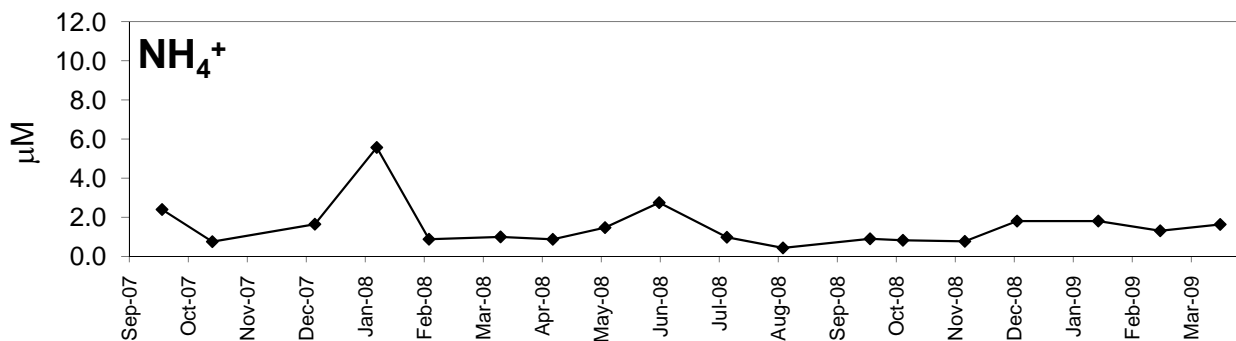
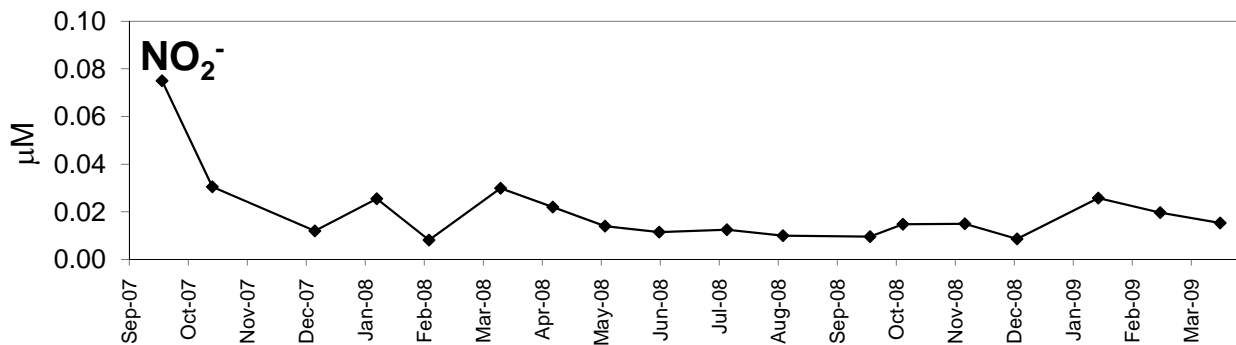
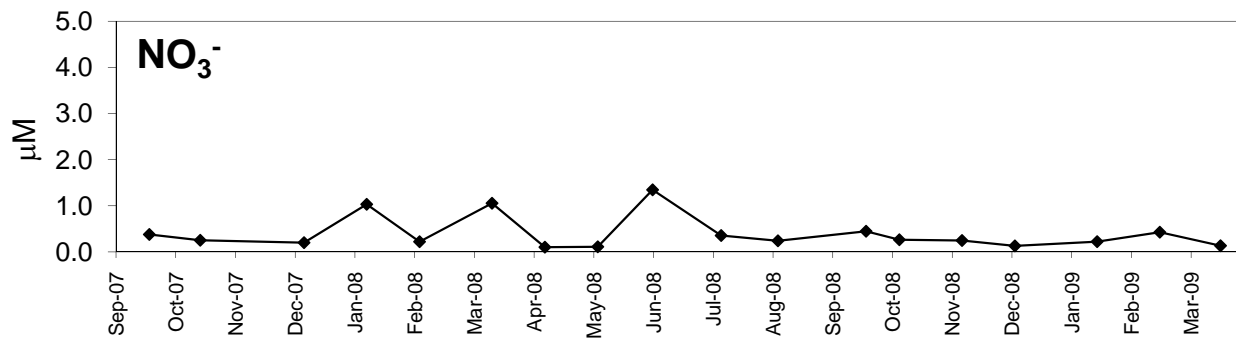
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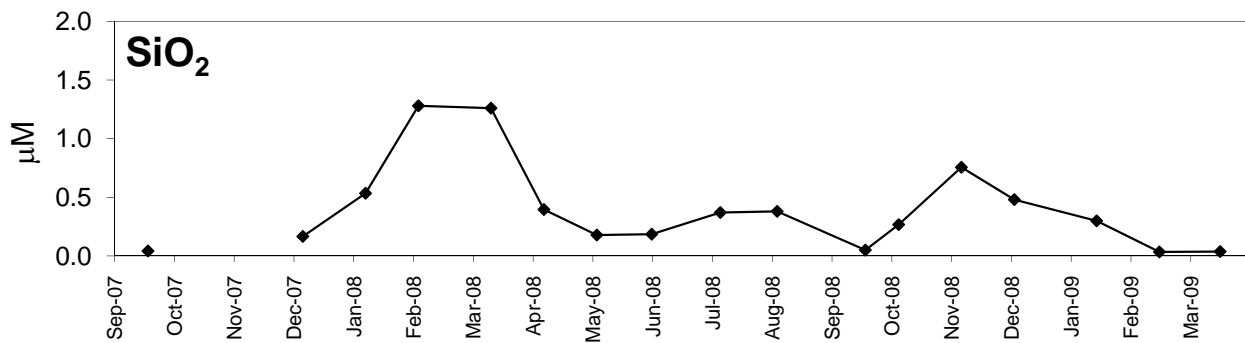
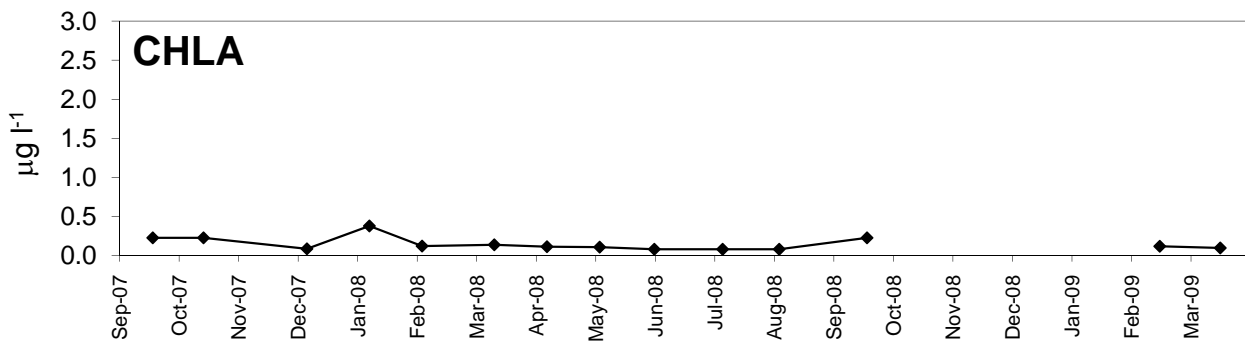
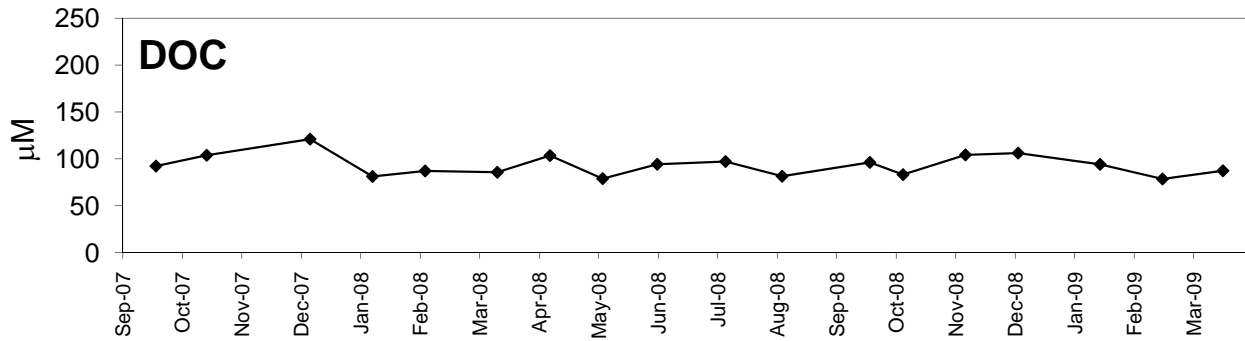
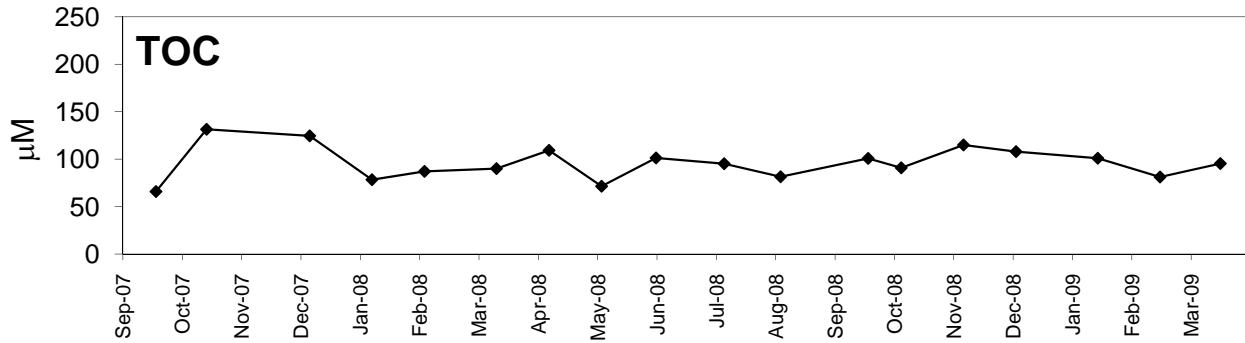
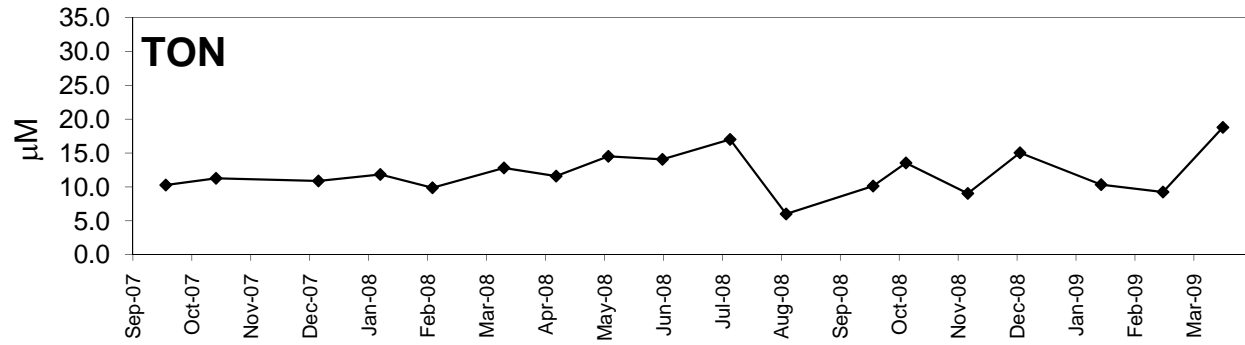
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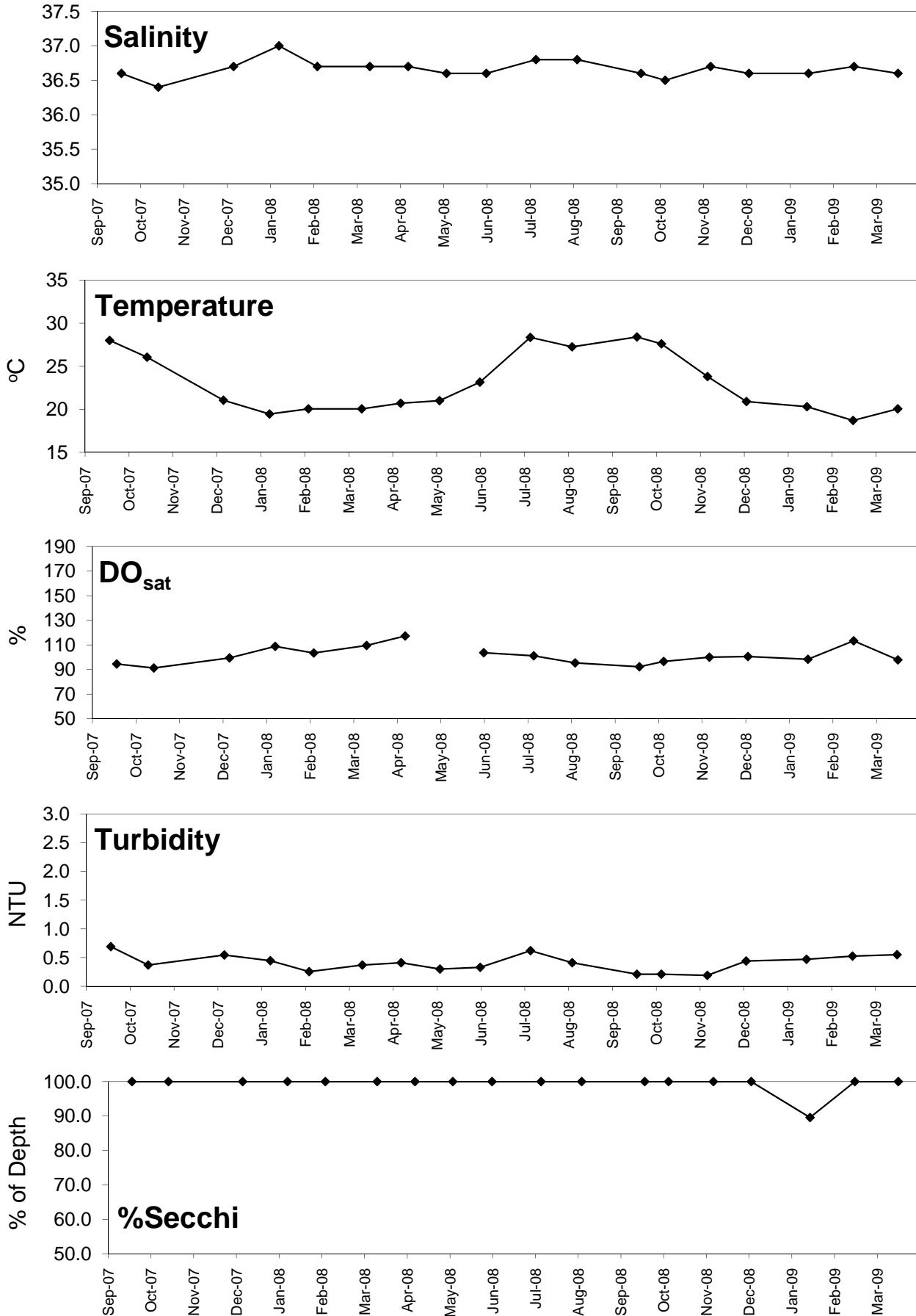
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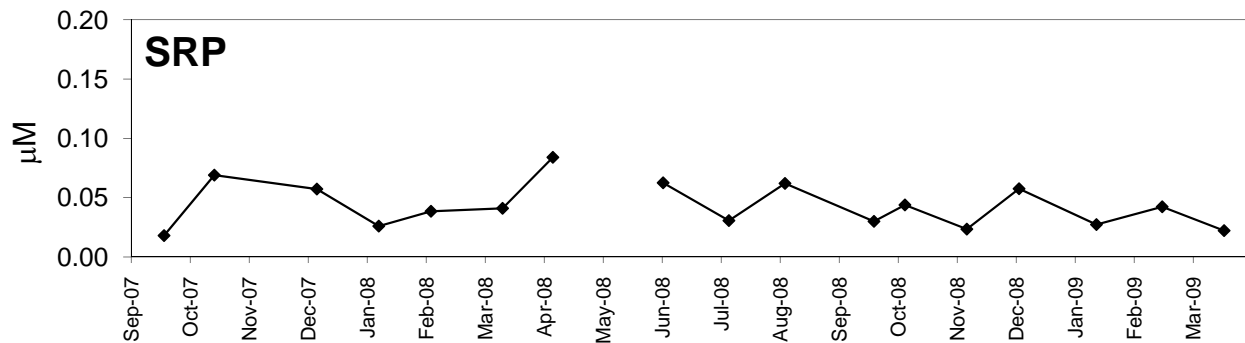
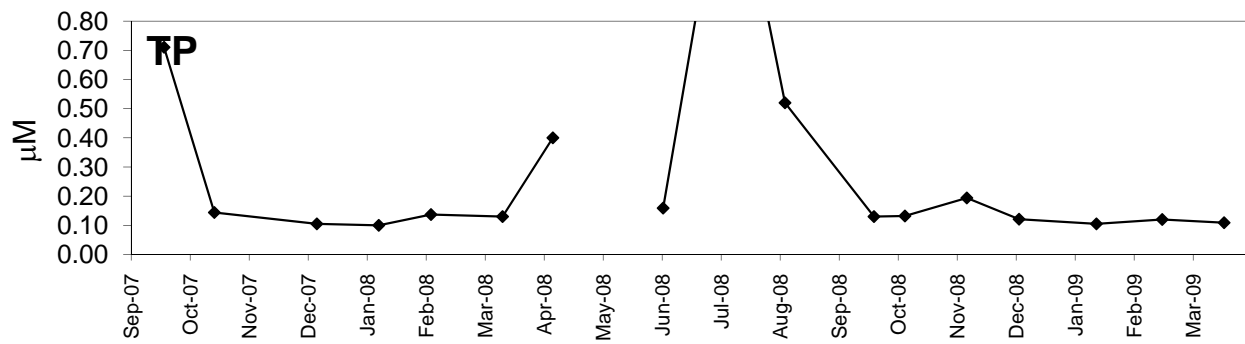
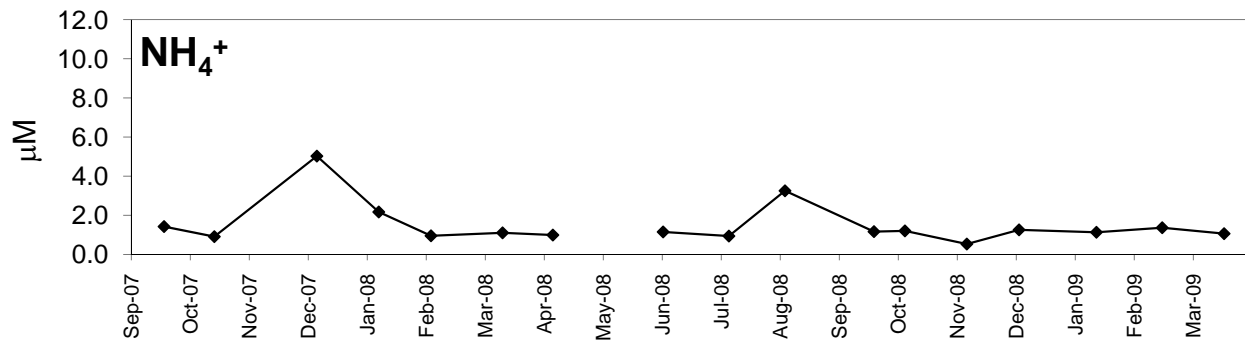
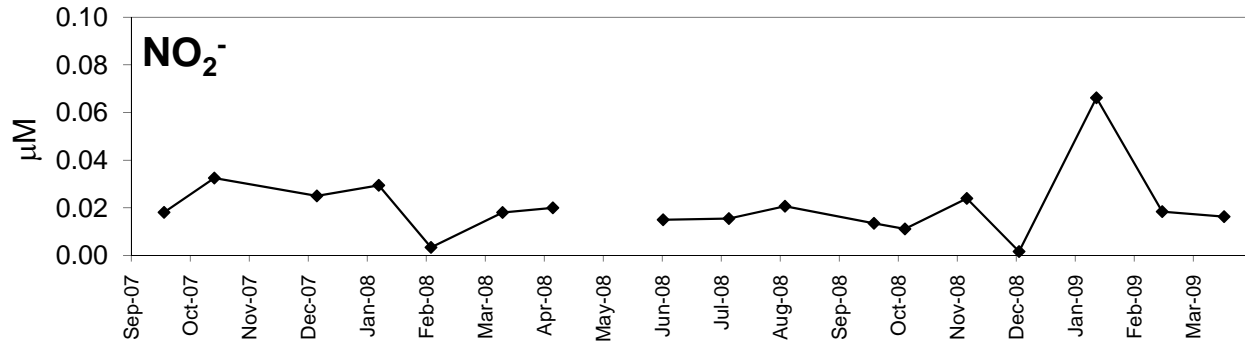
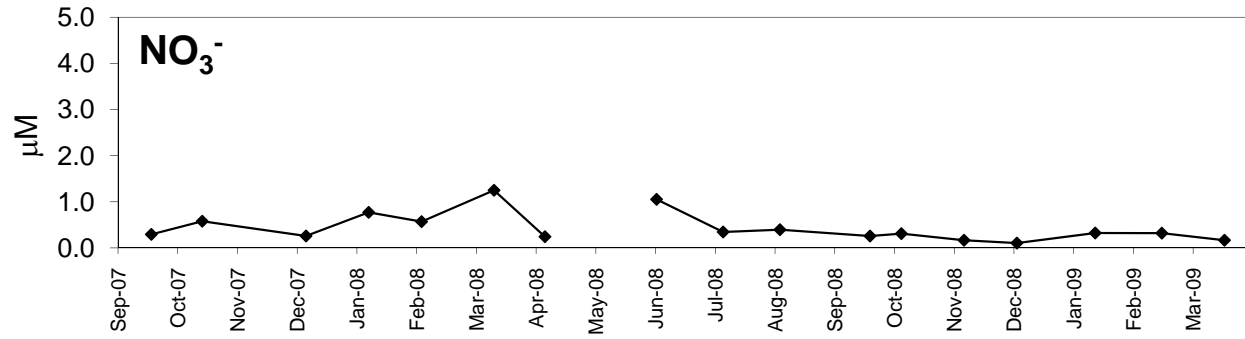
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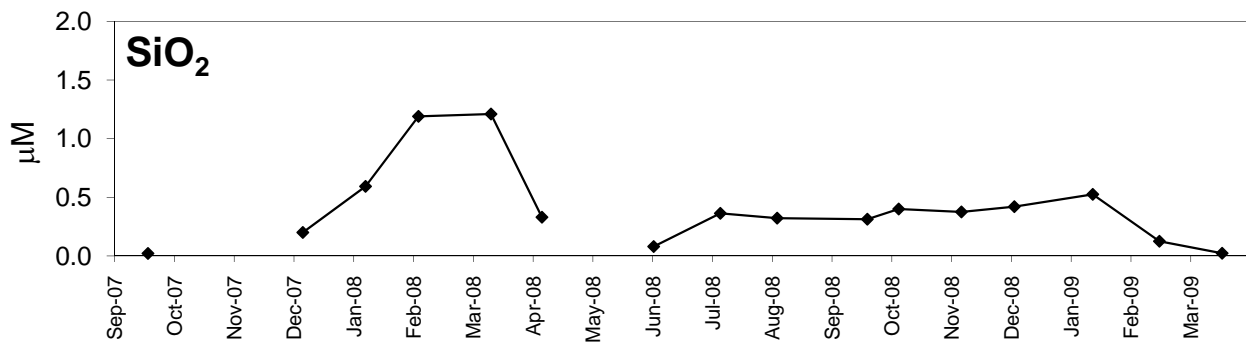
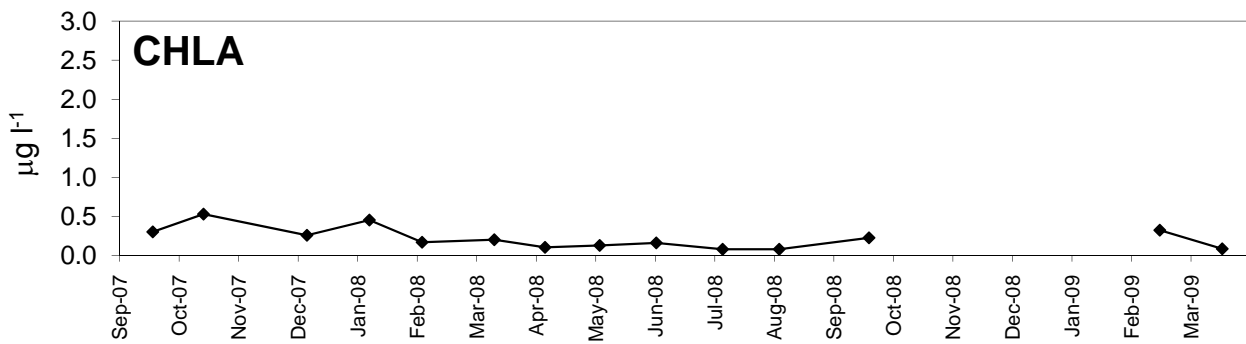
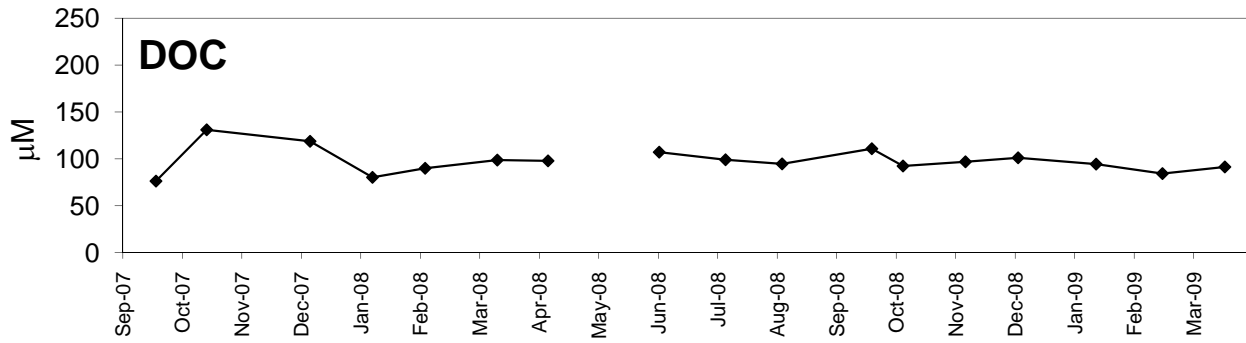
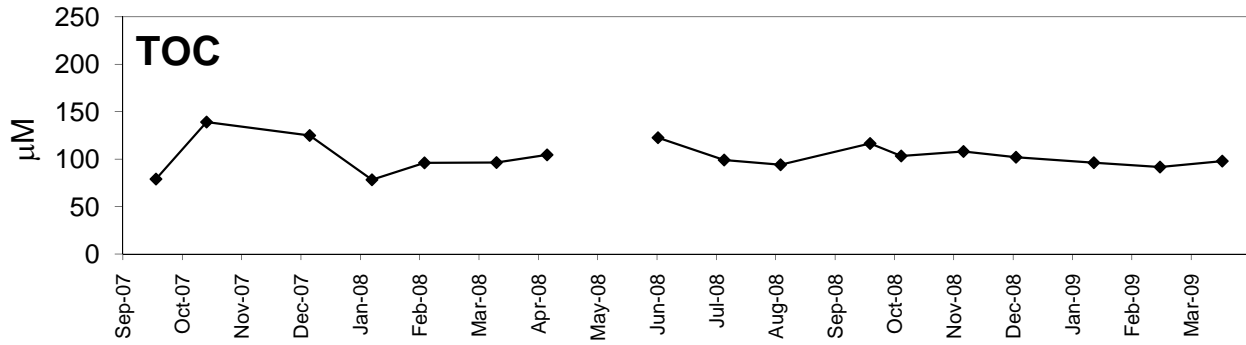
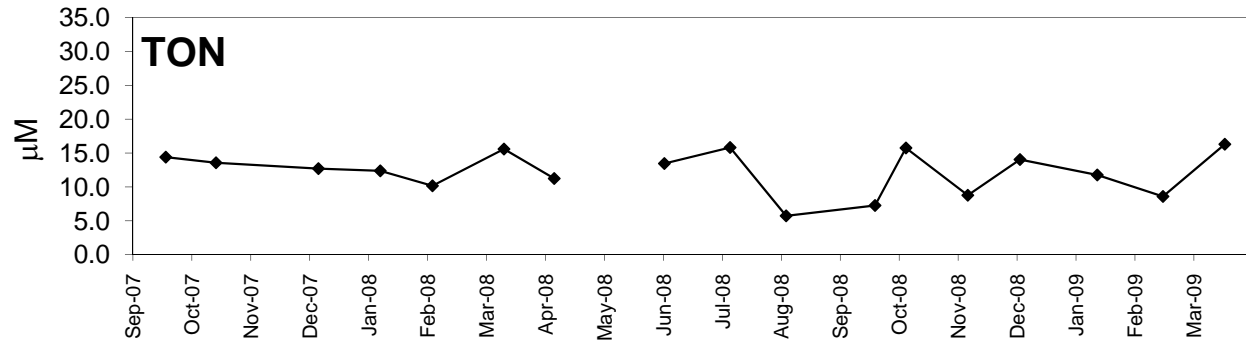
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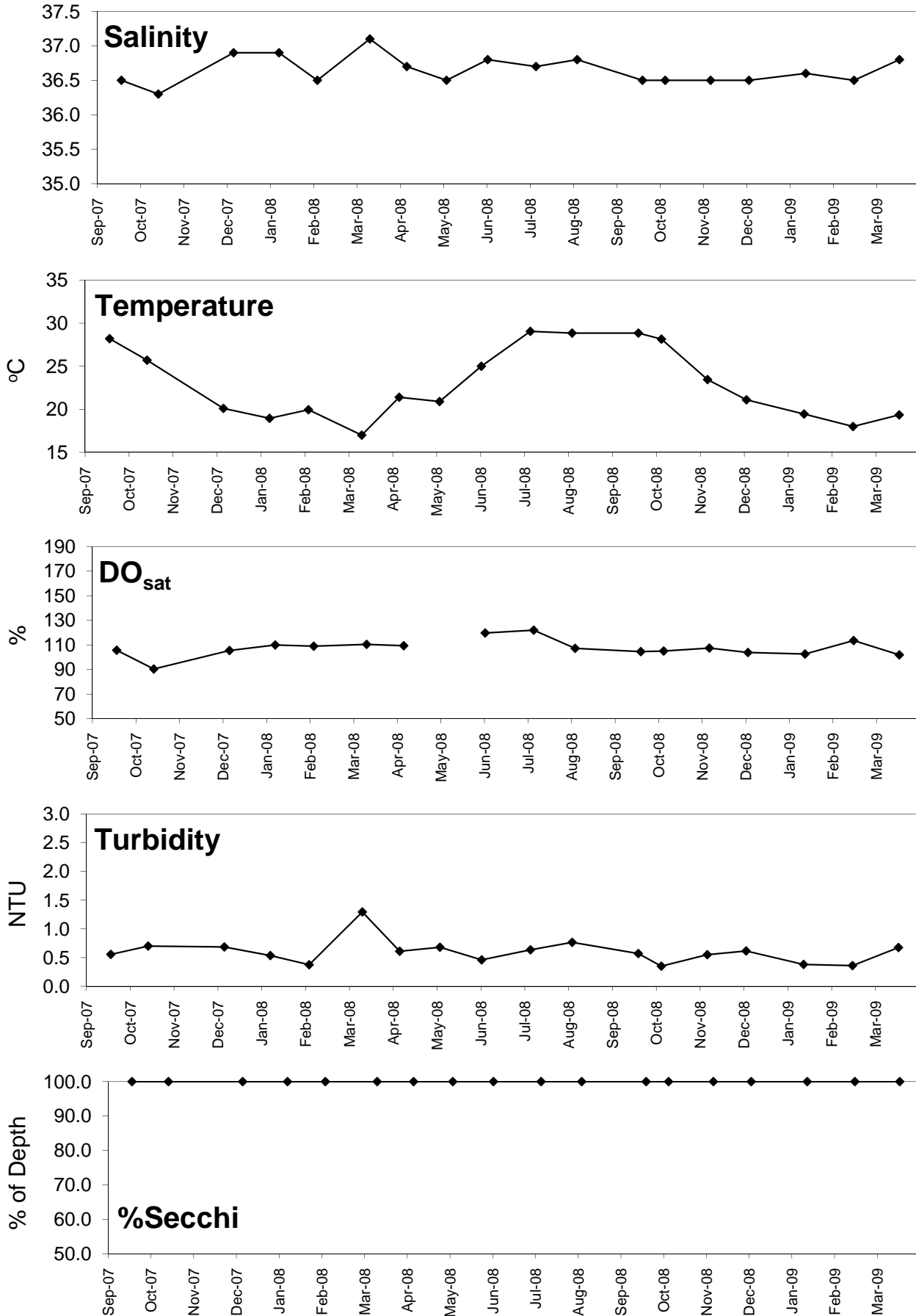
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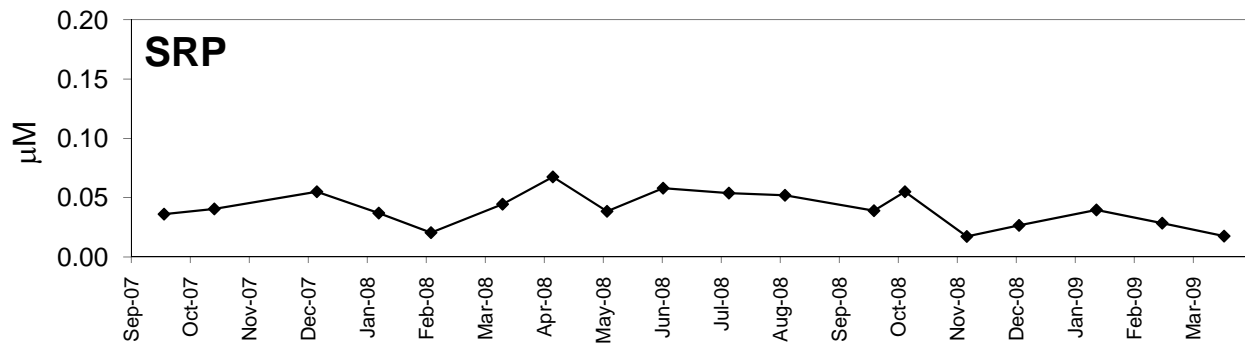
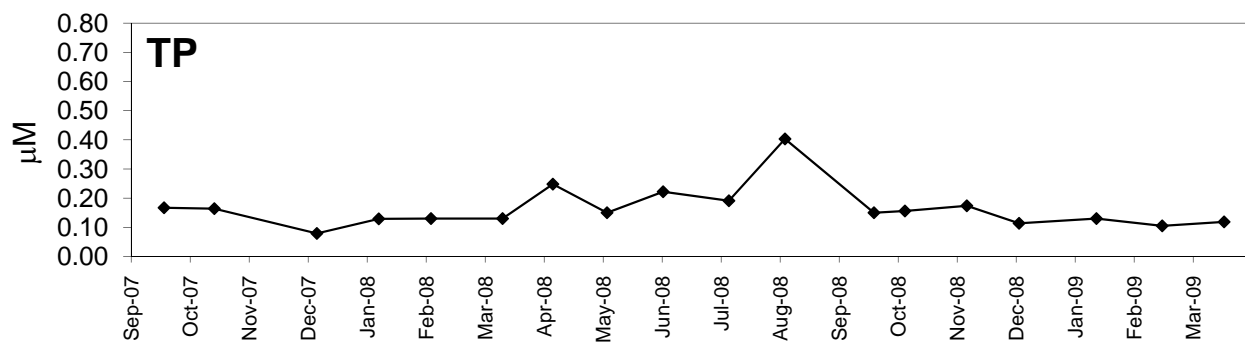
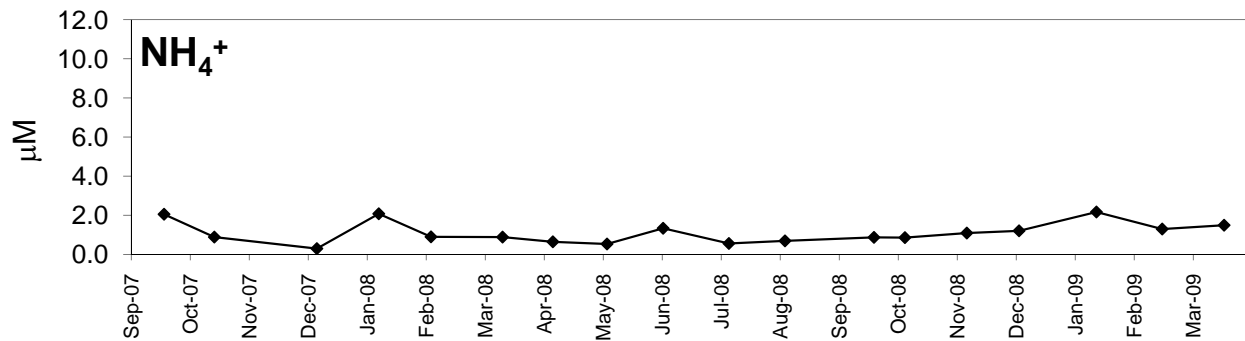
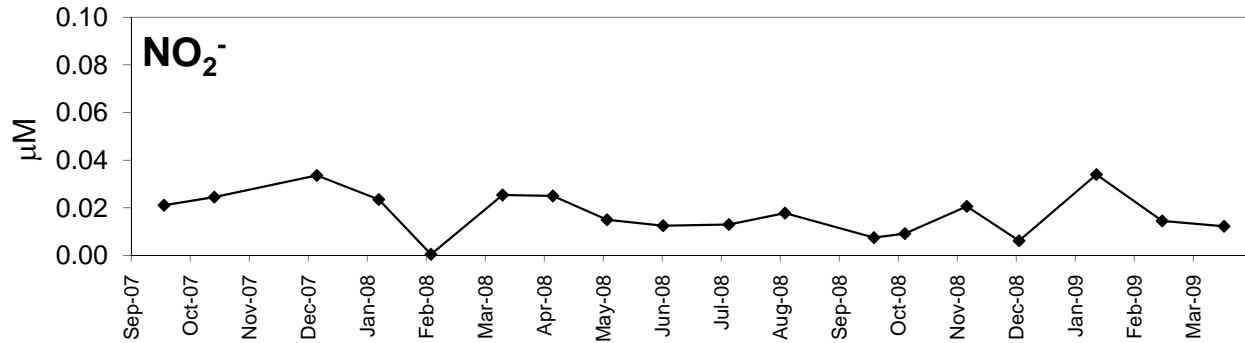
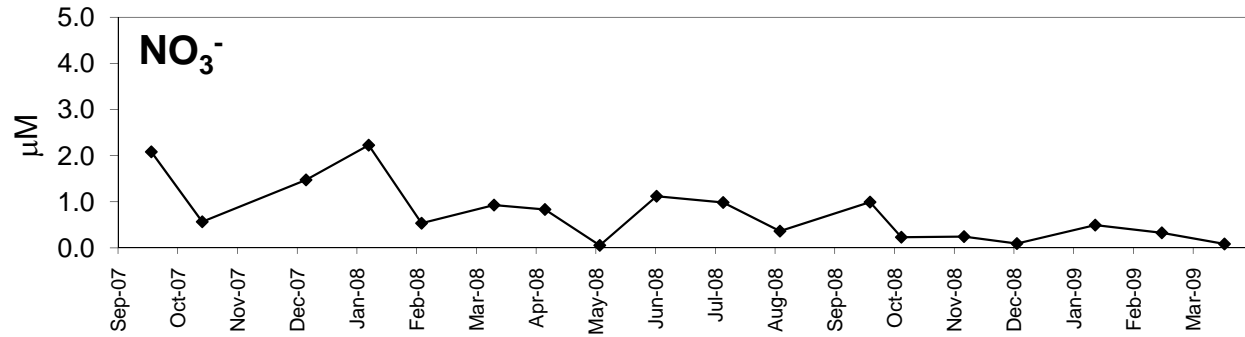
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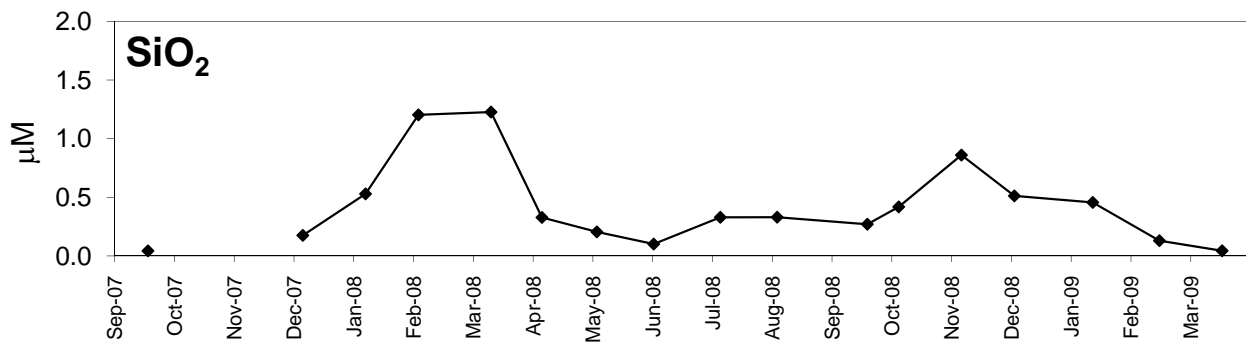
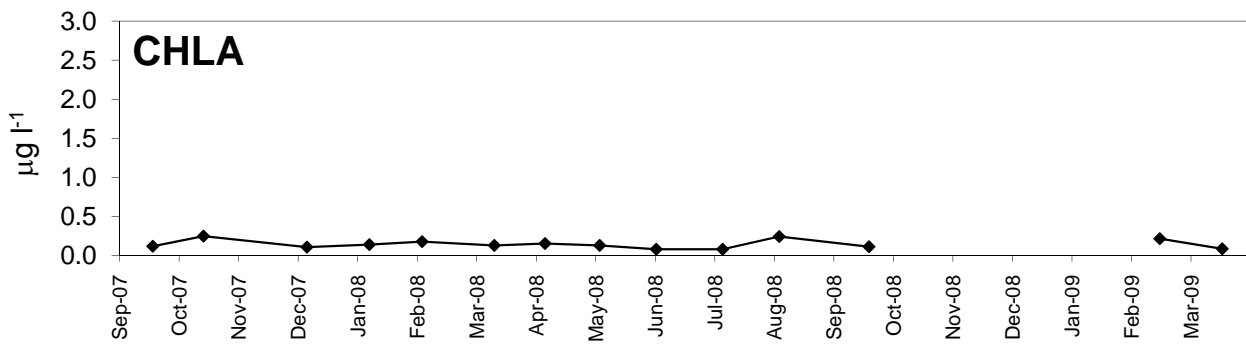
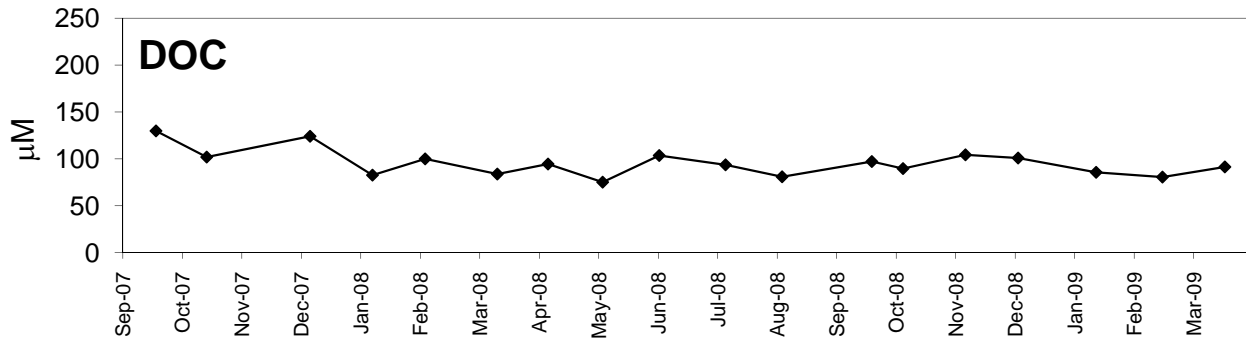
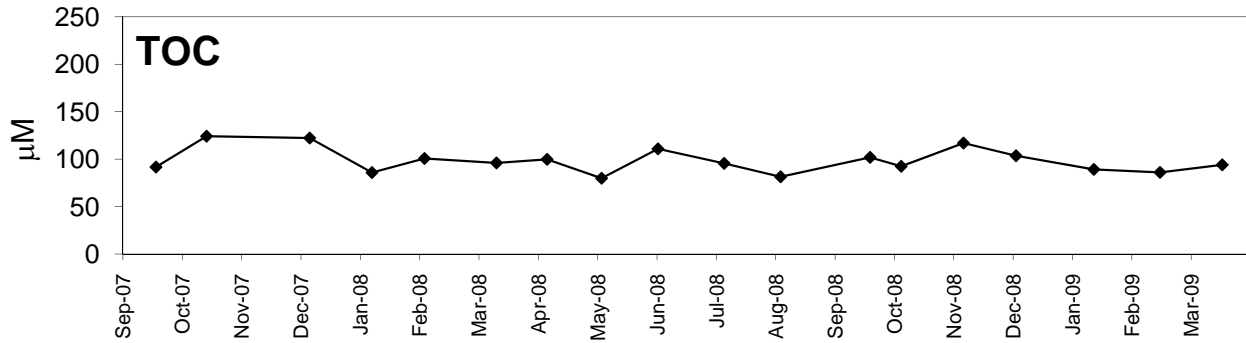
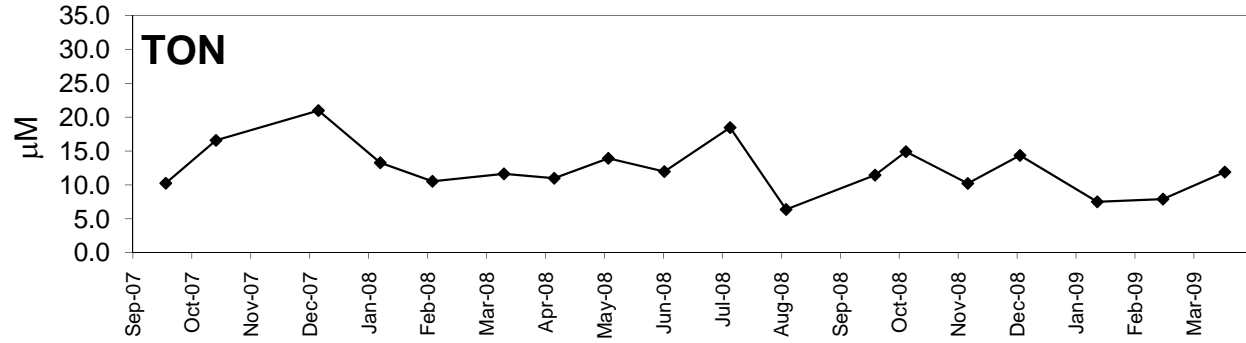
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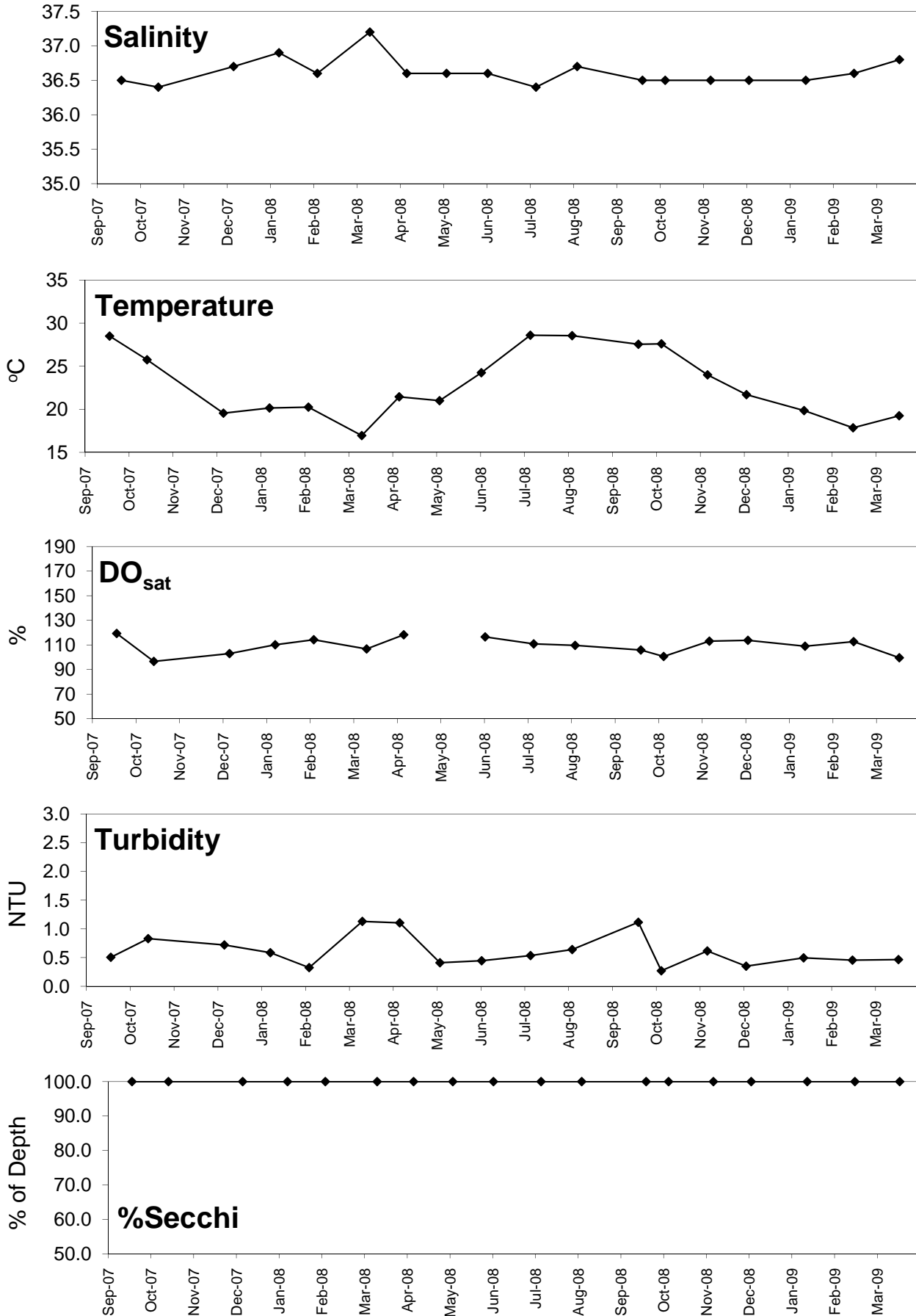
Station 5, Hog Bay Park



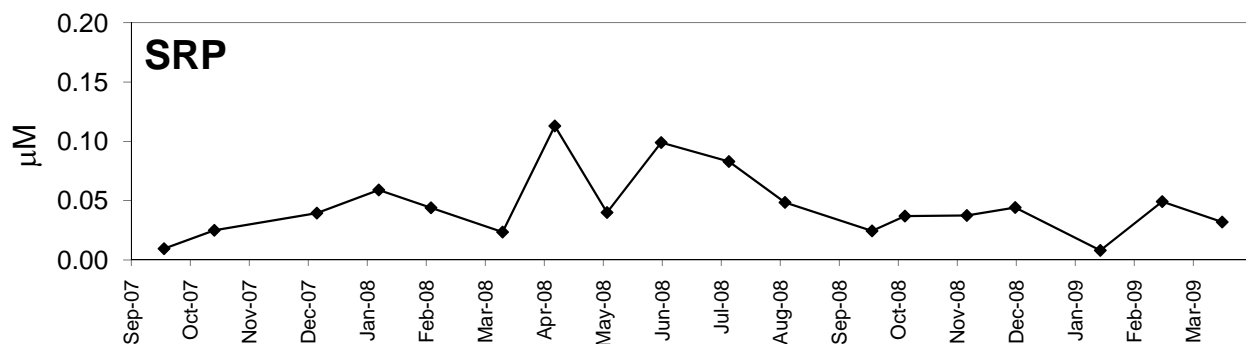
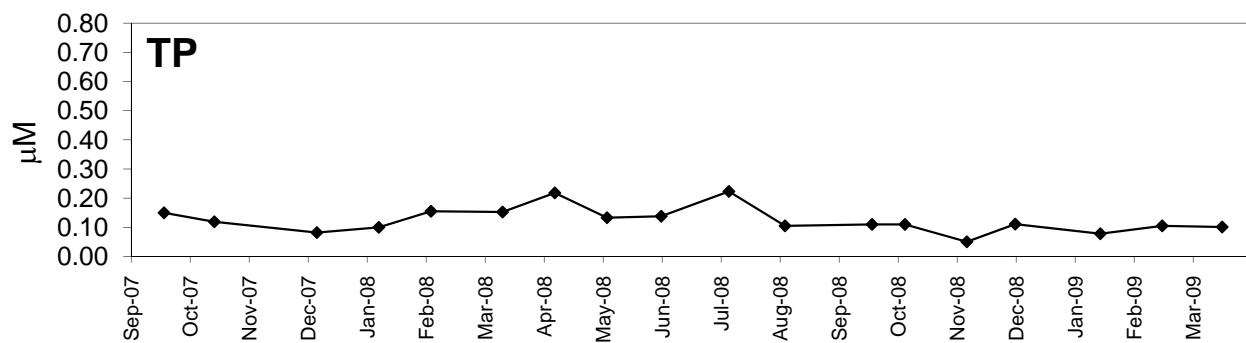
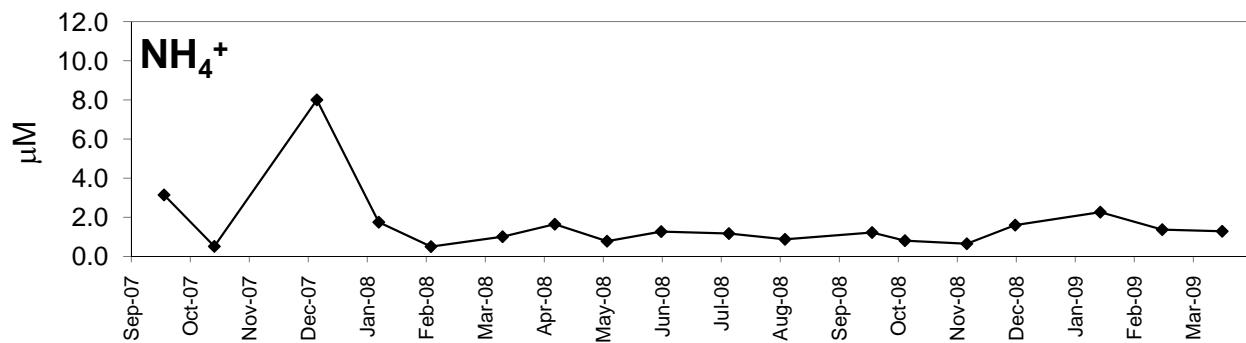
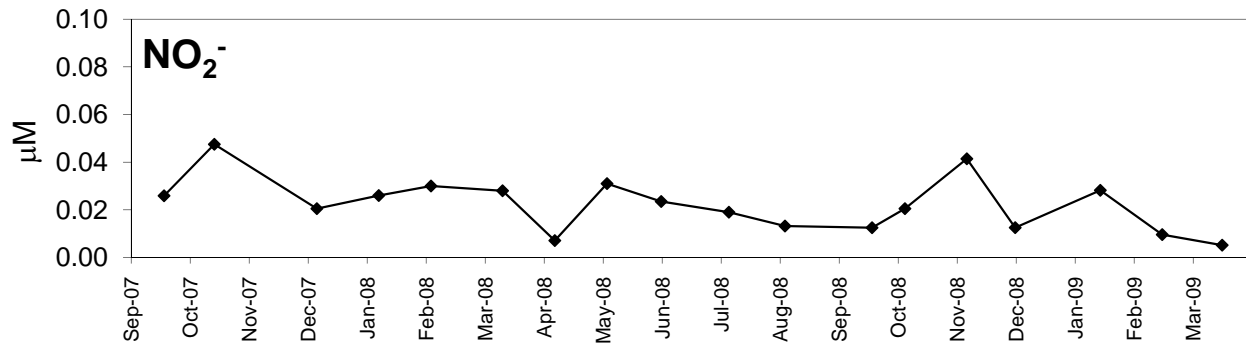
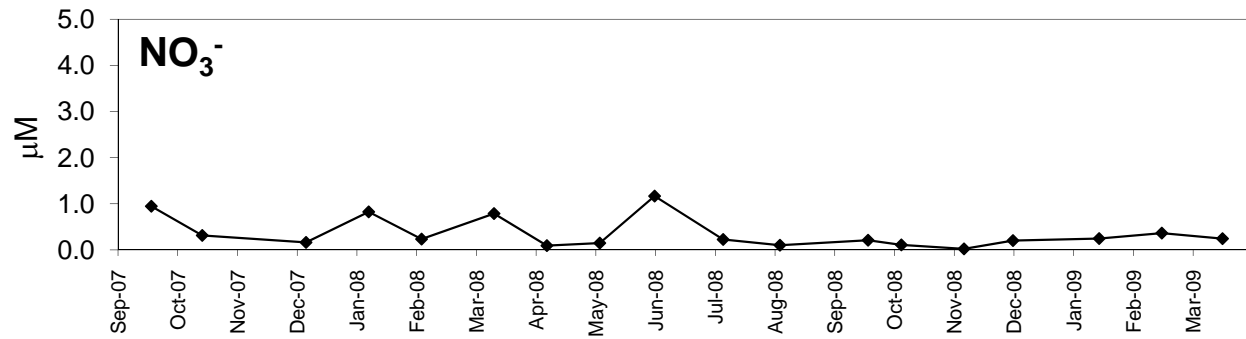
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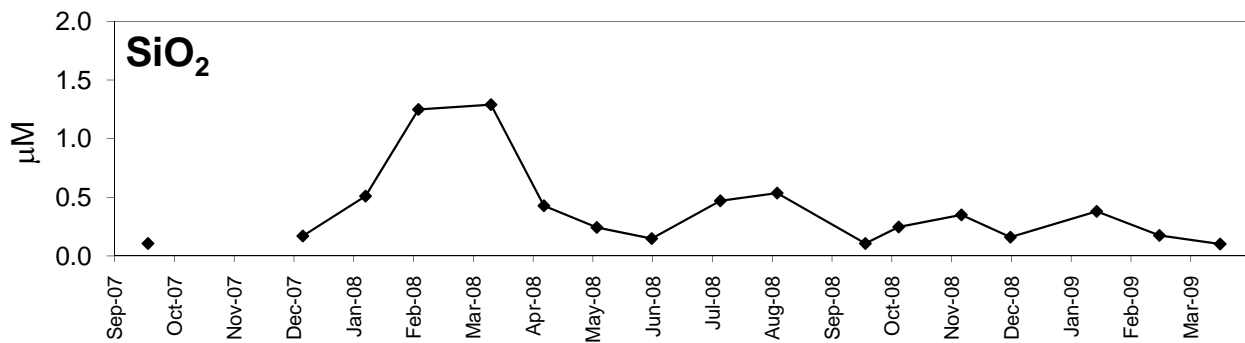
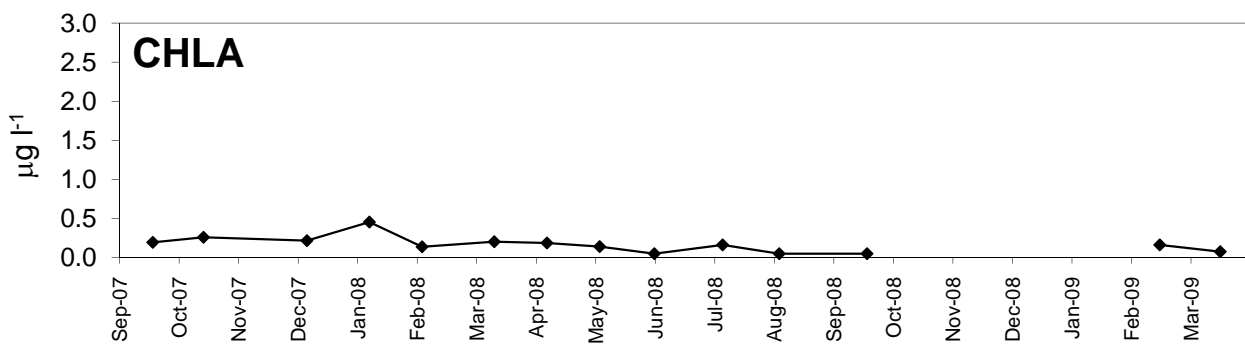
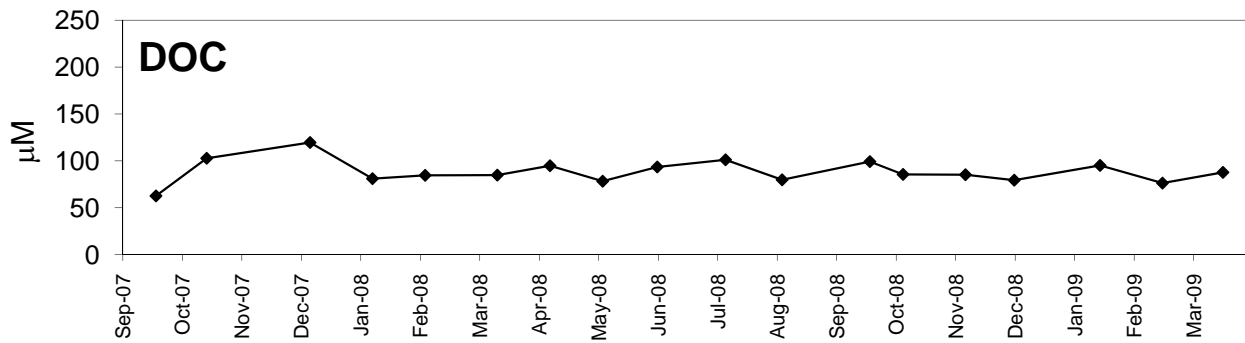
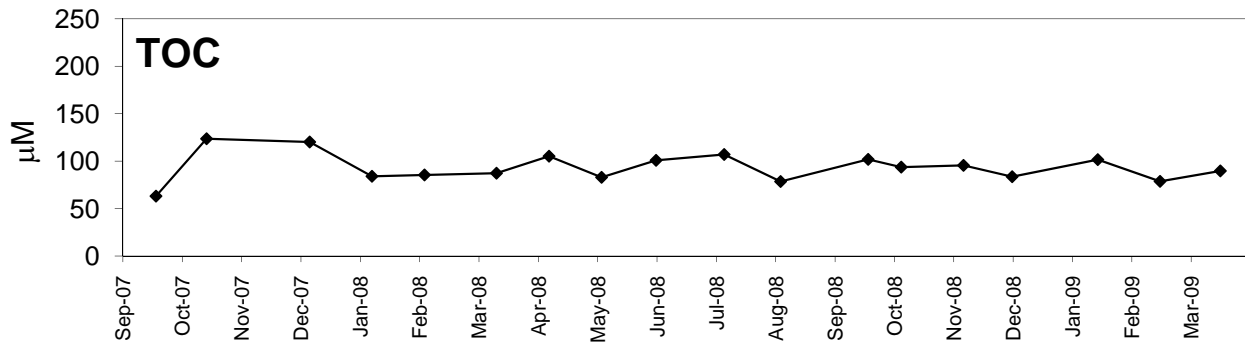
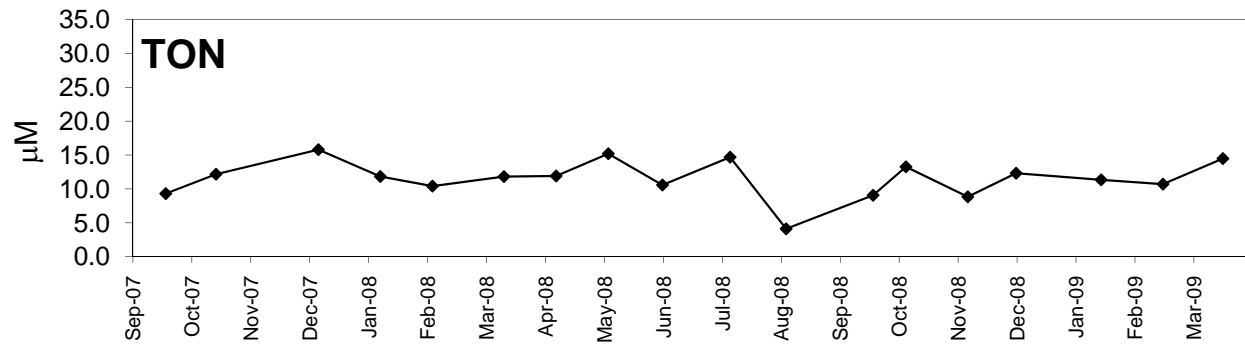
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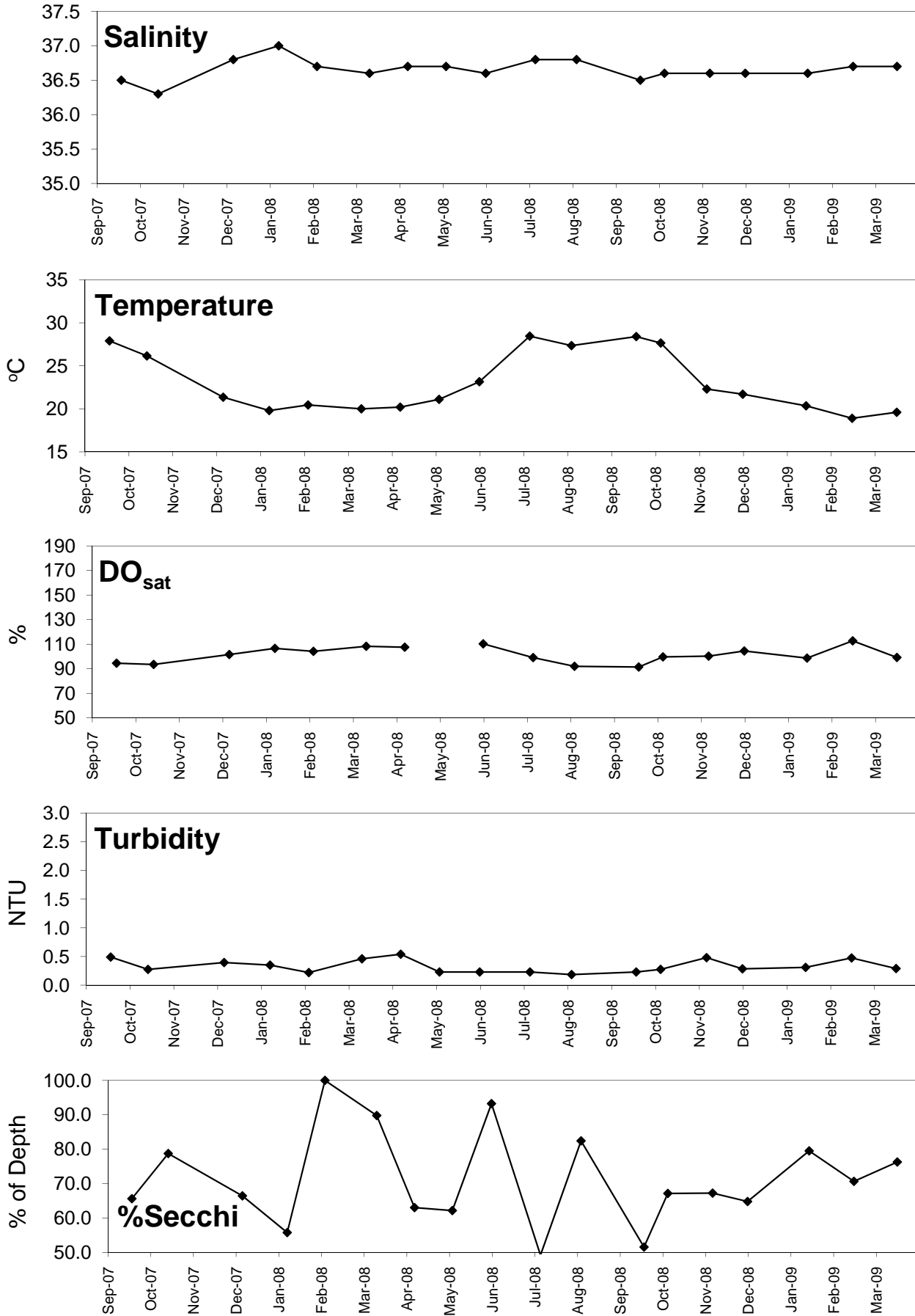
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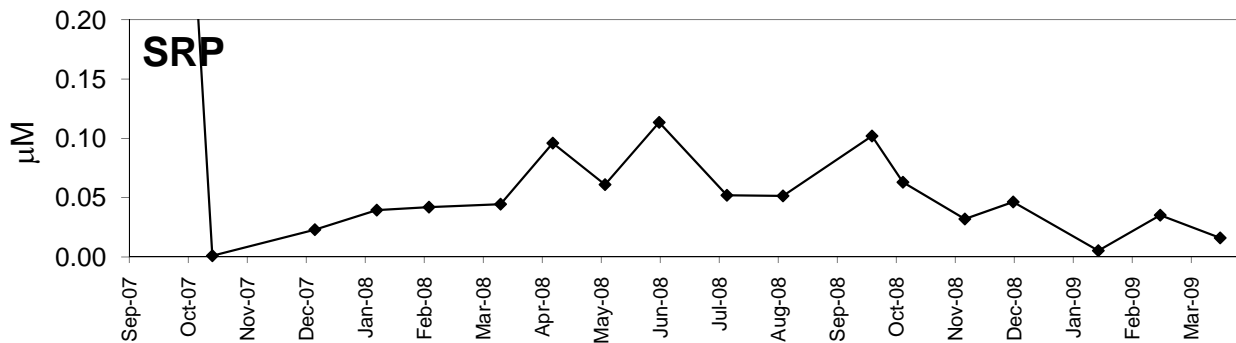
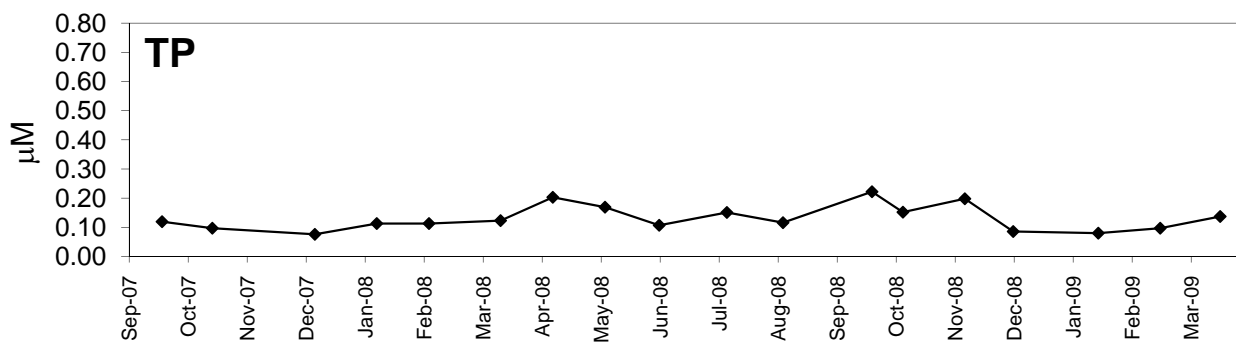
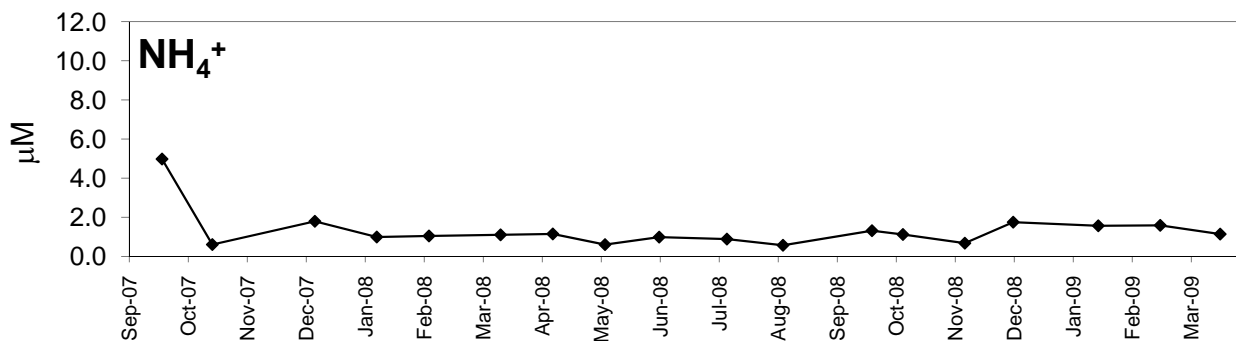
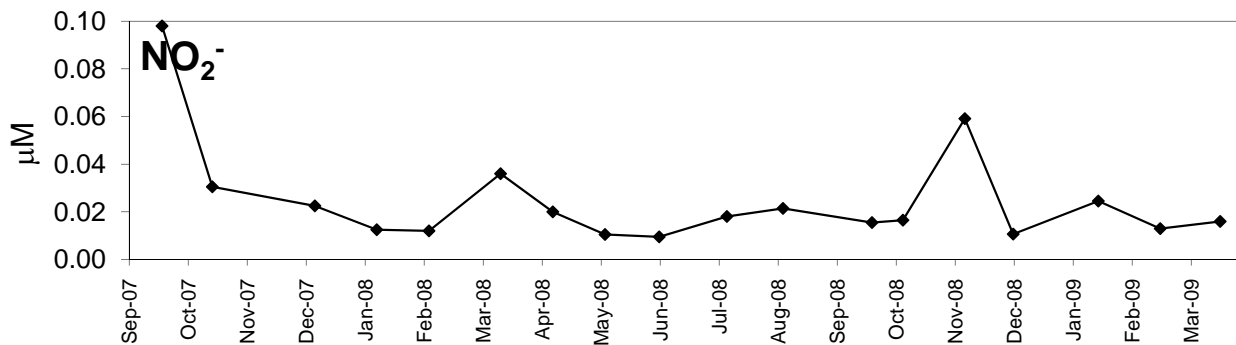
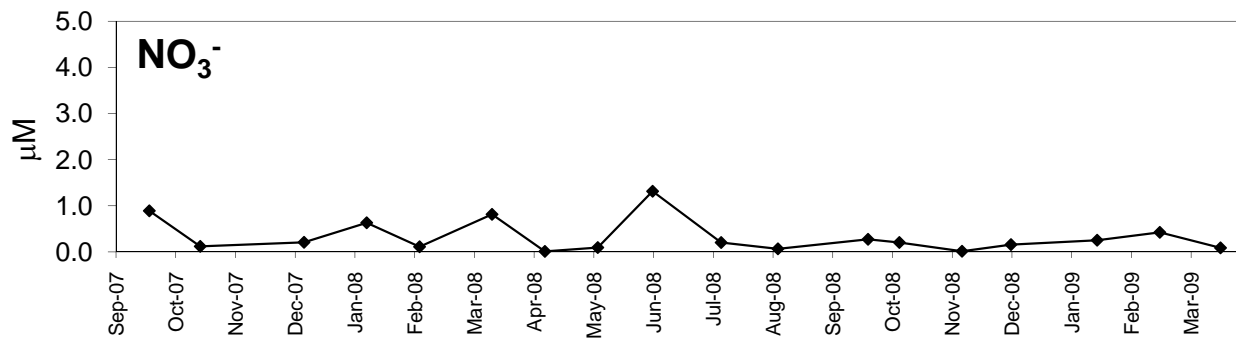
Station 6, North Rock West



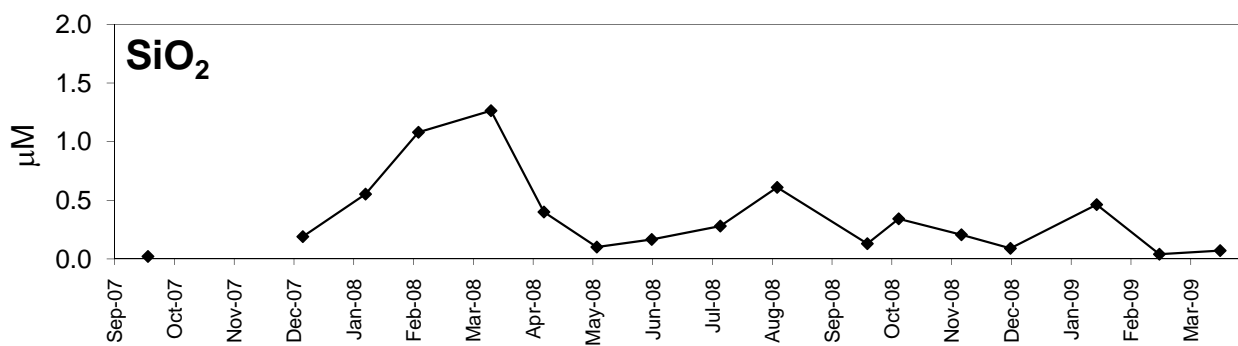
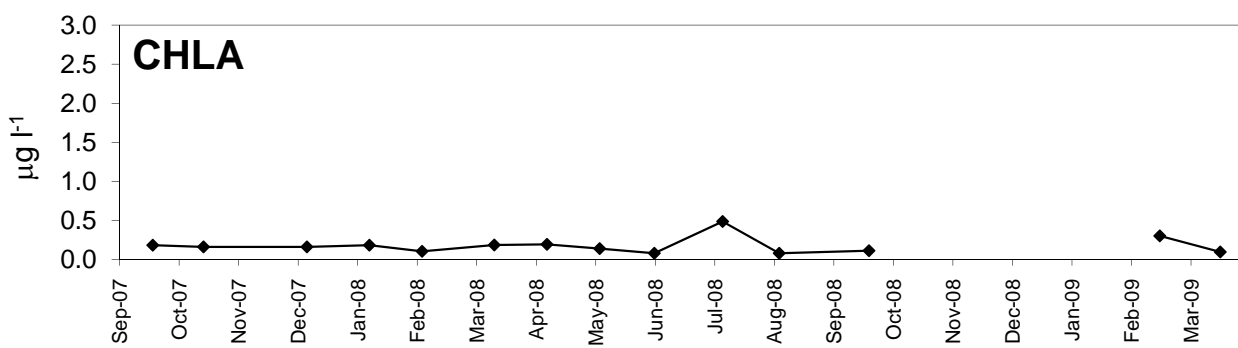
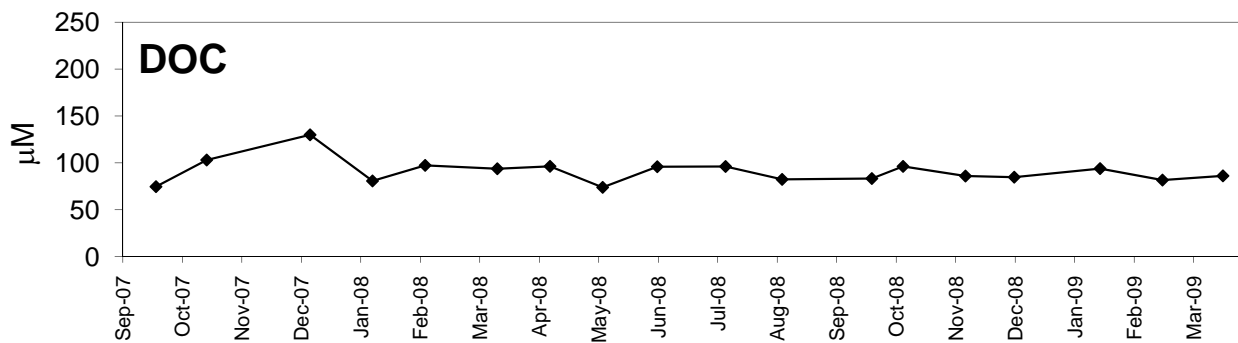
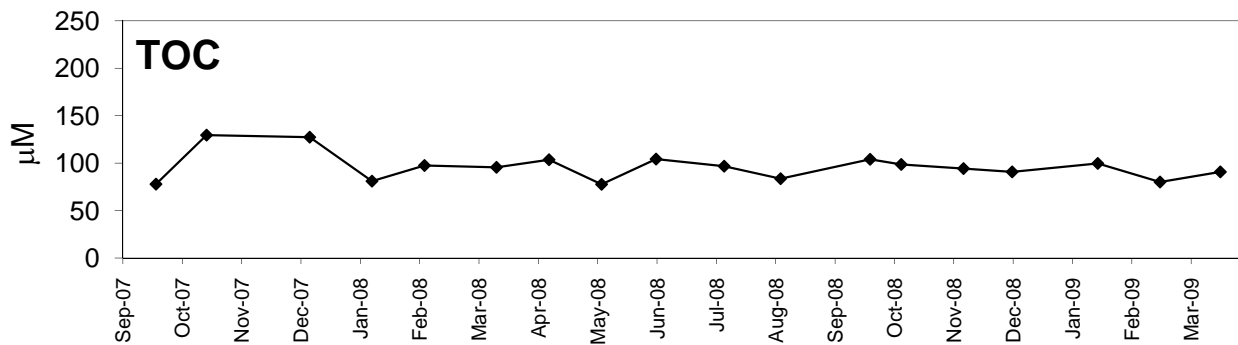
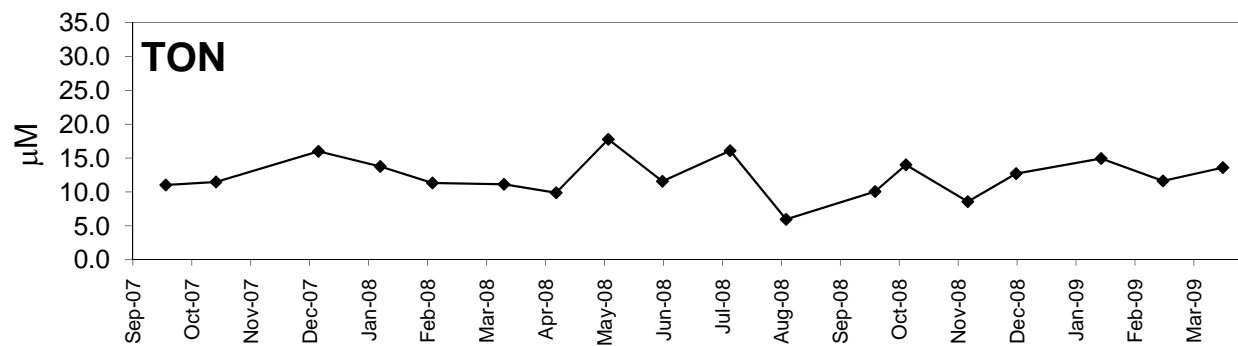
Station 6, North Rock West



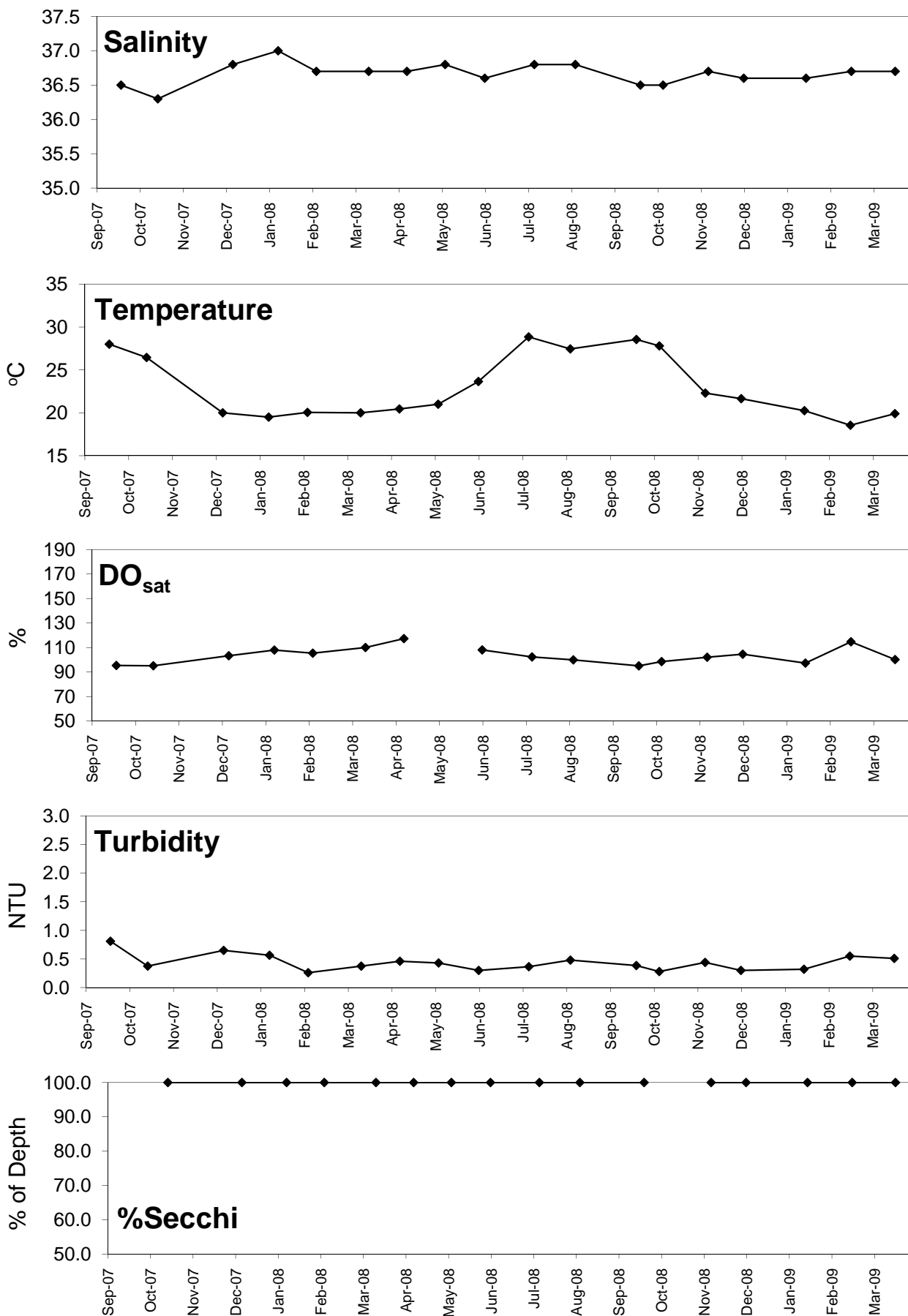
Station 7, Crescent West



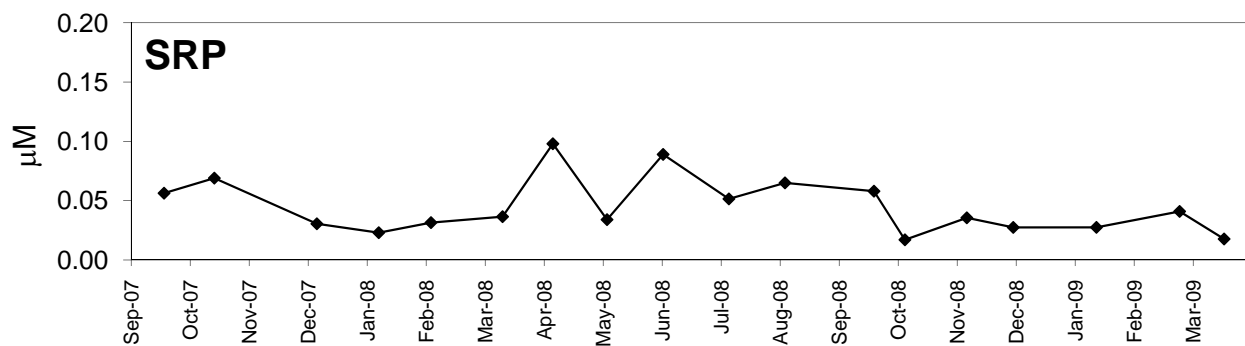
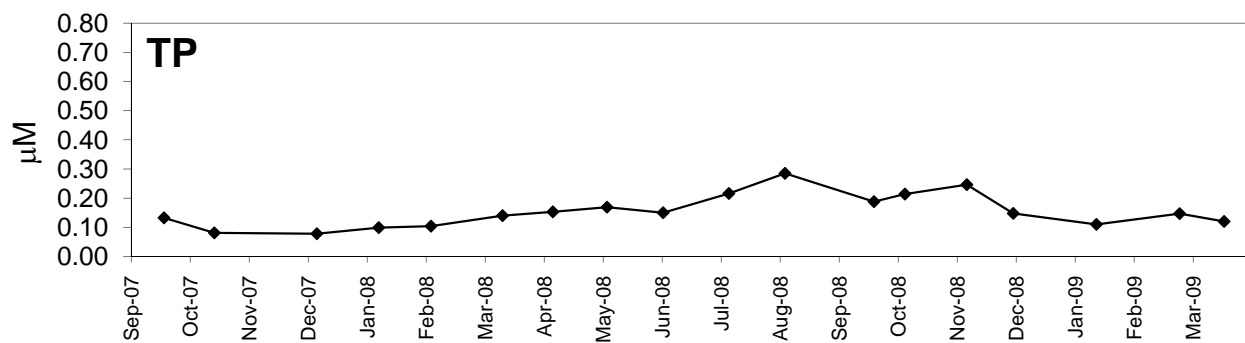
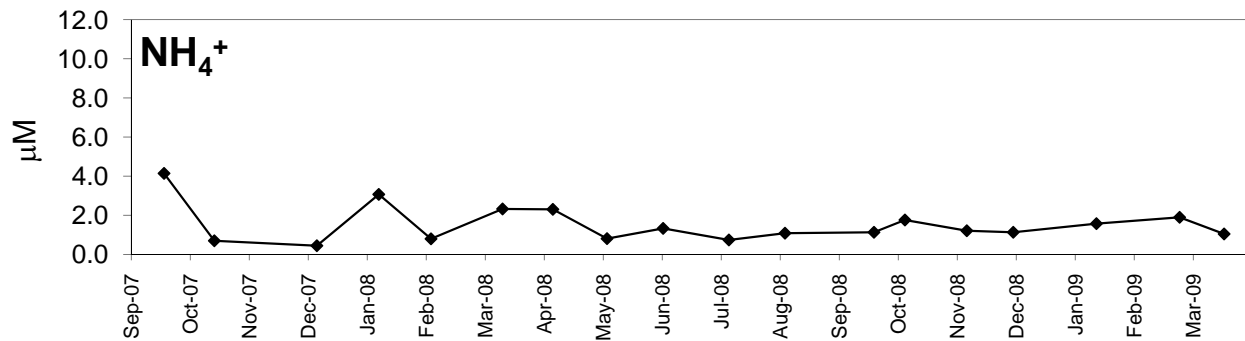
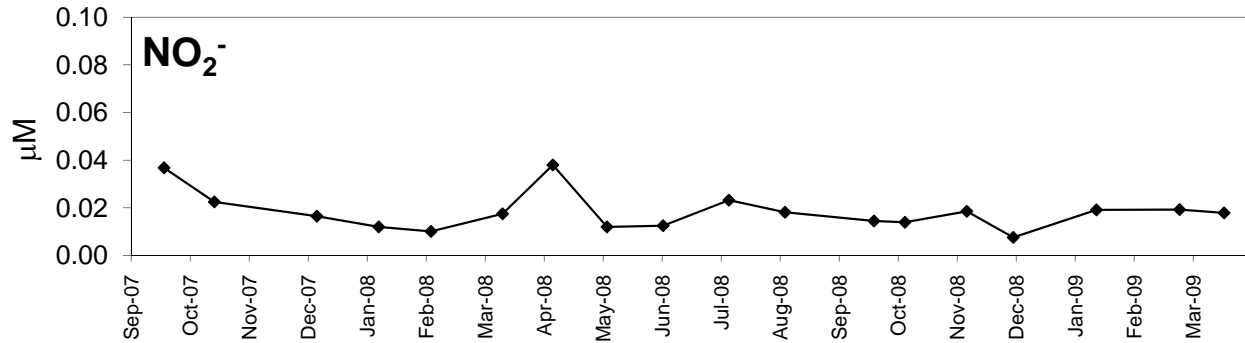
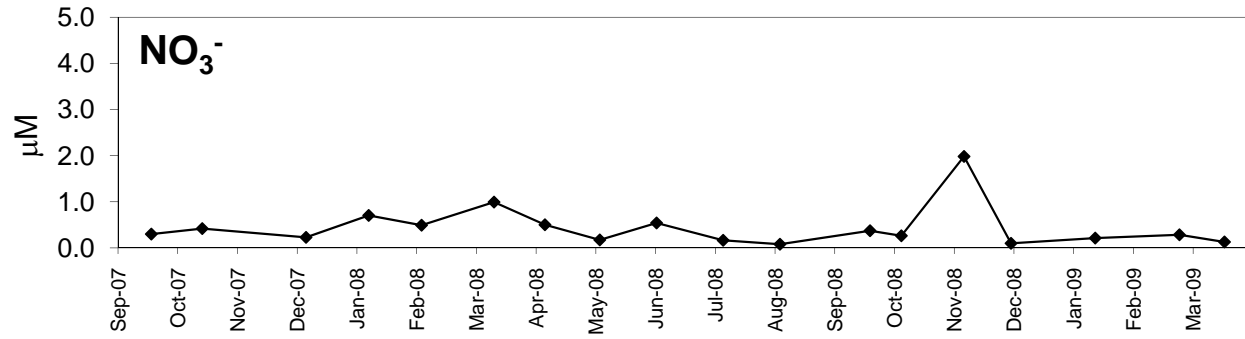
Station 7, Crescent West



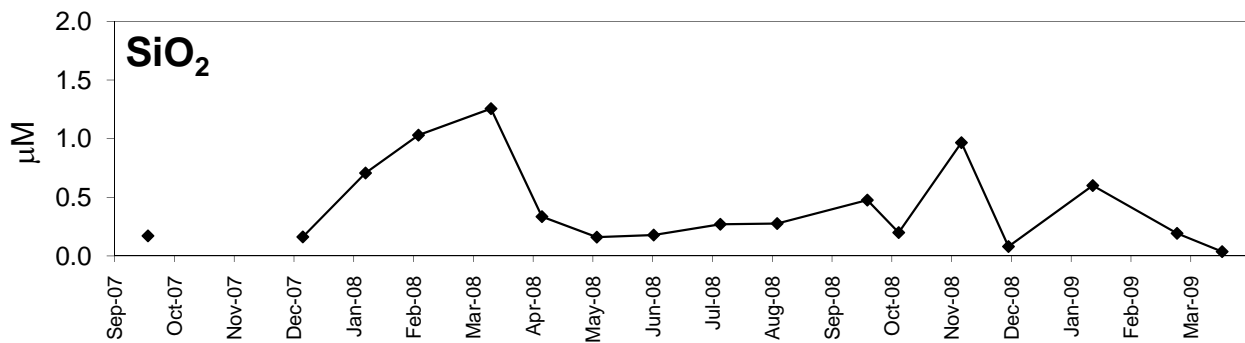
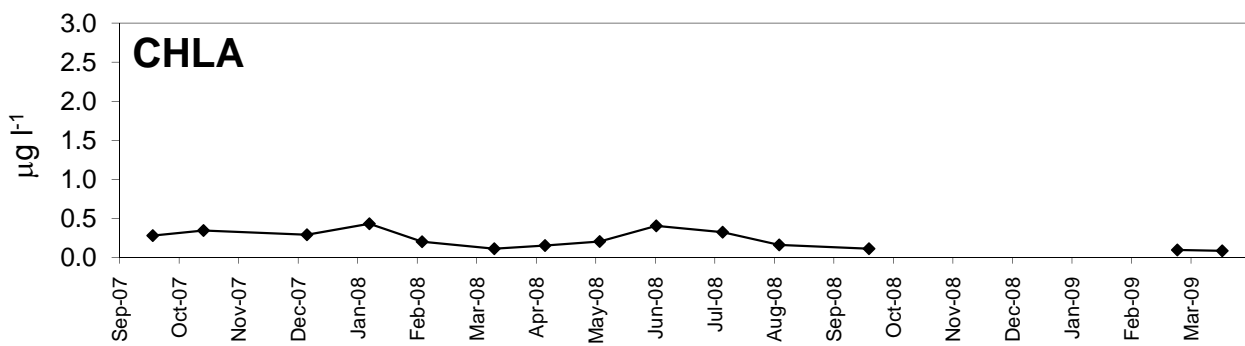
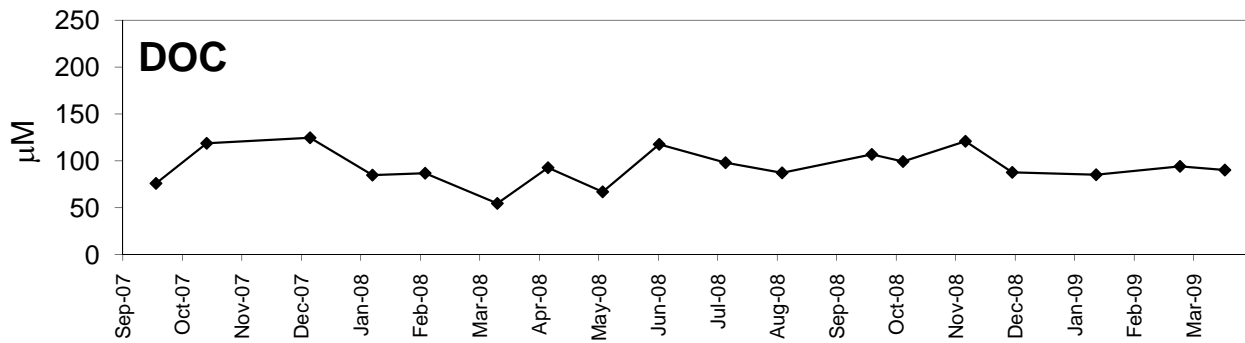
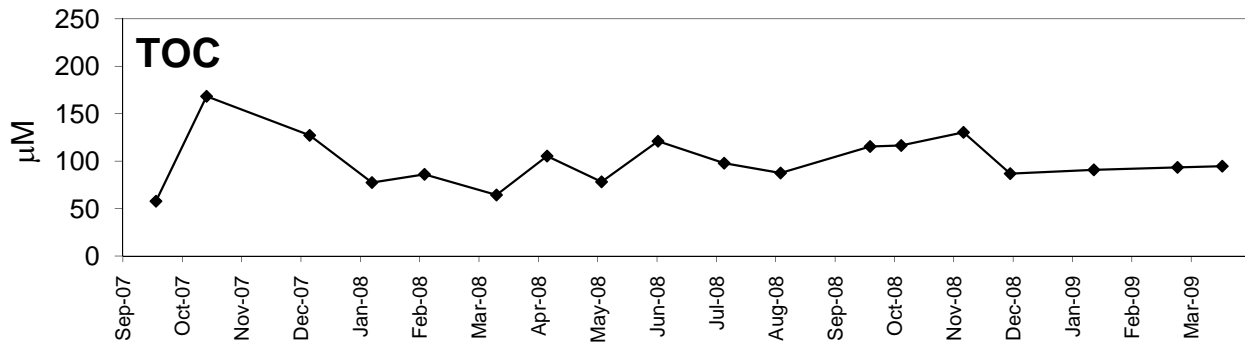
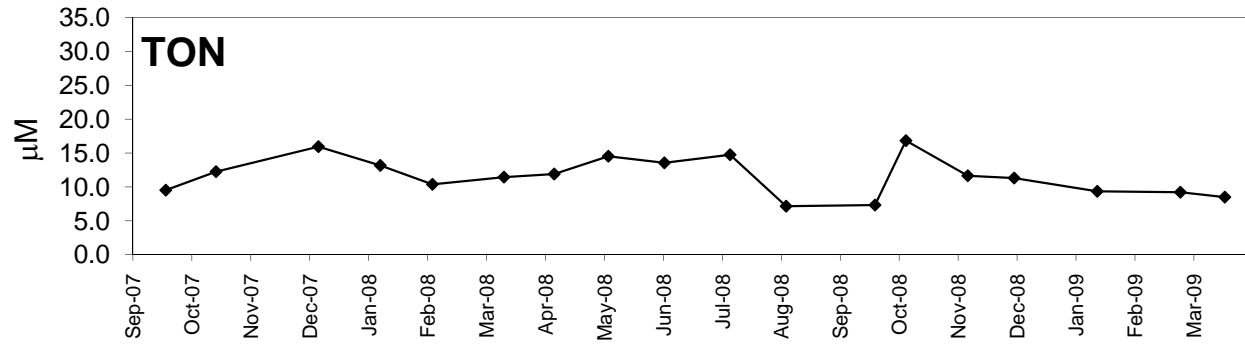
Station 7, Crescent West



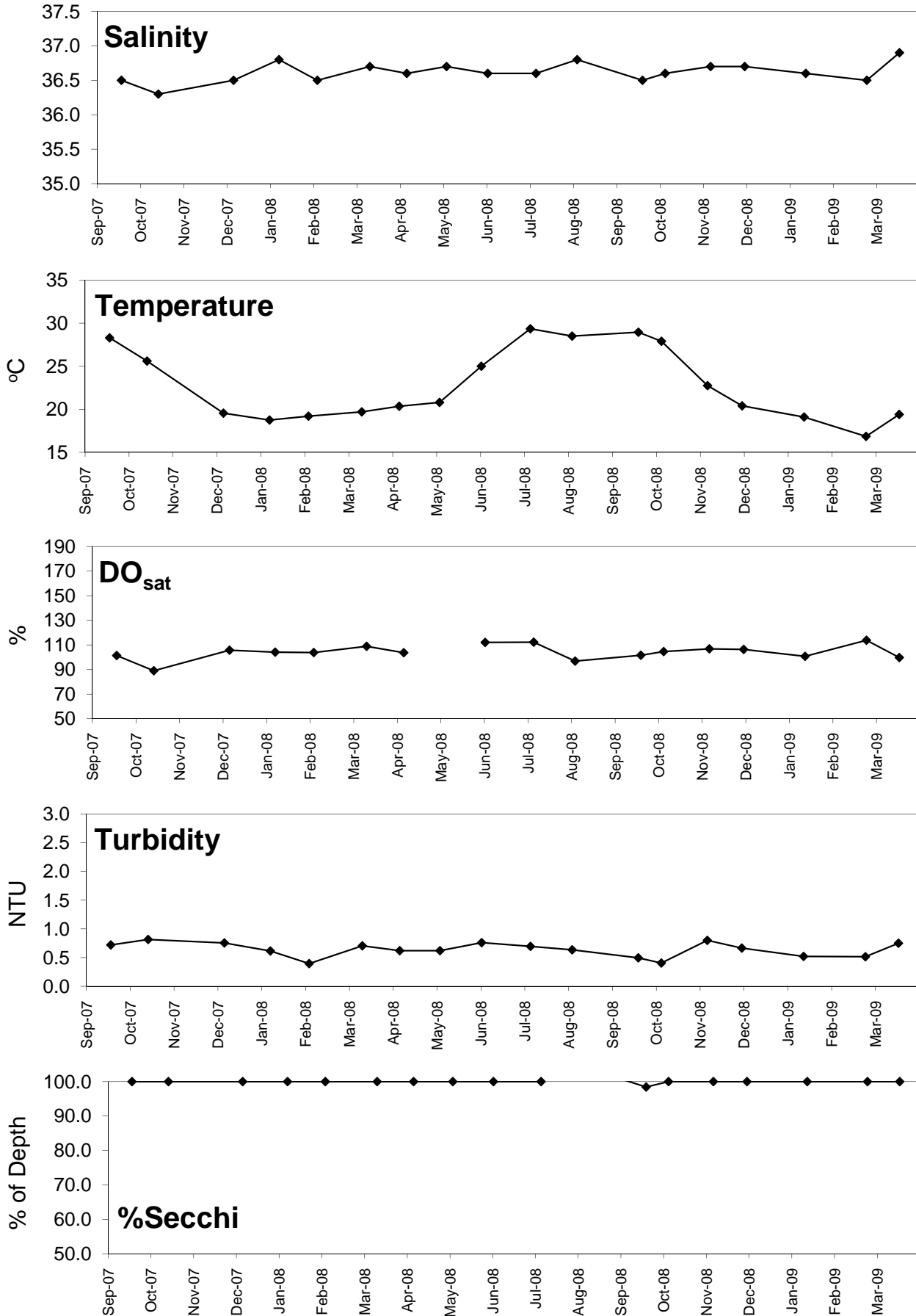
Station 8, Grey's Bridge



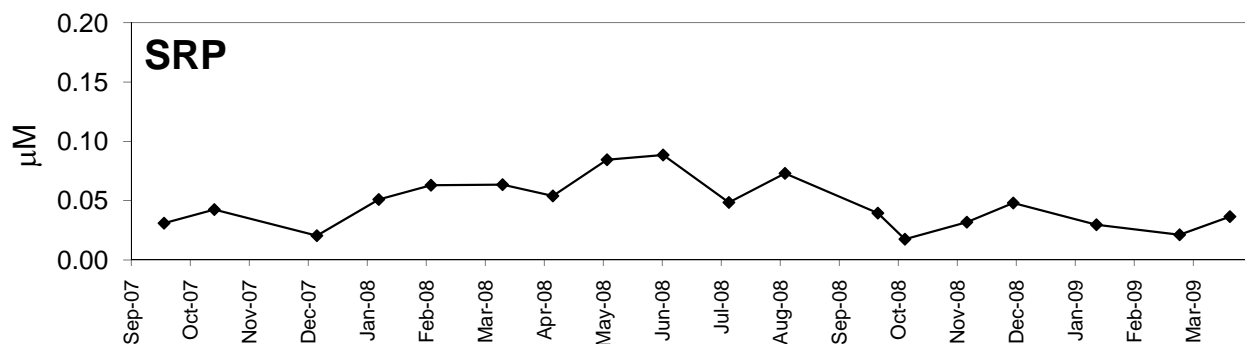
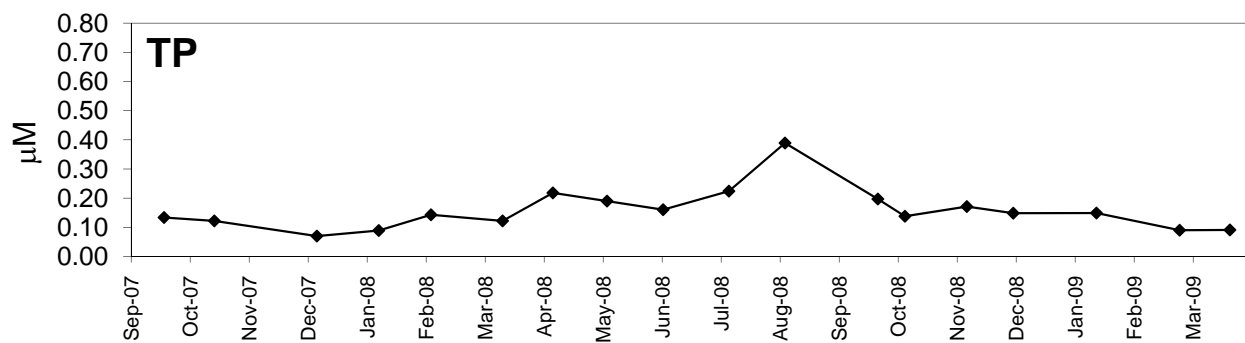
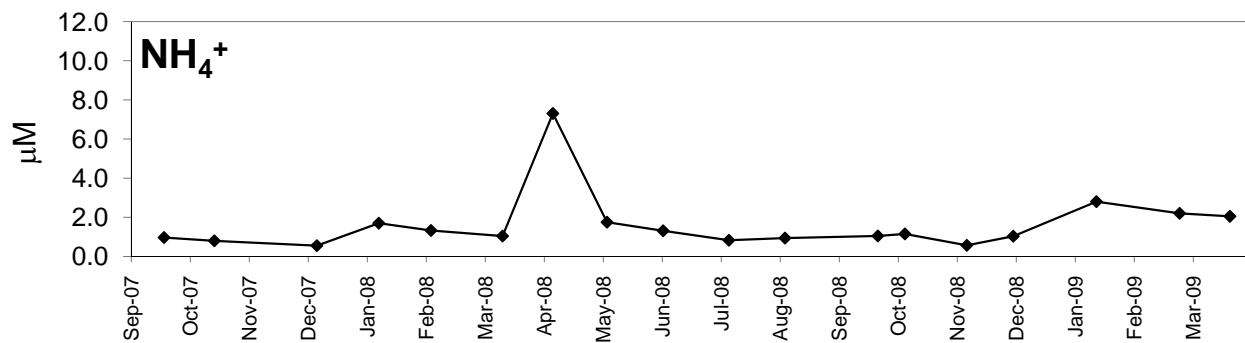
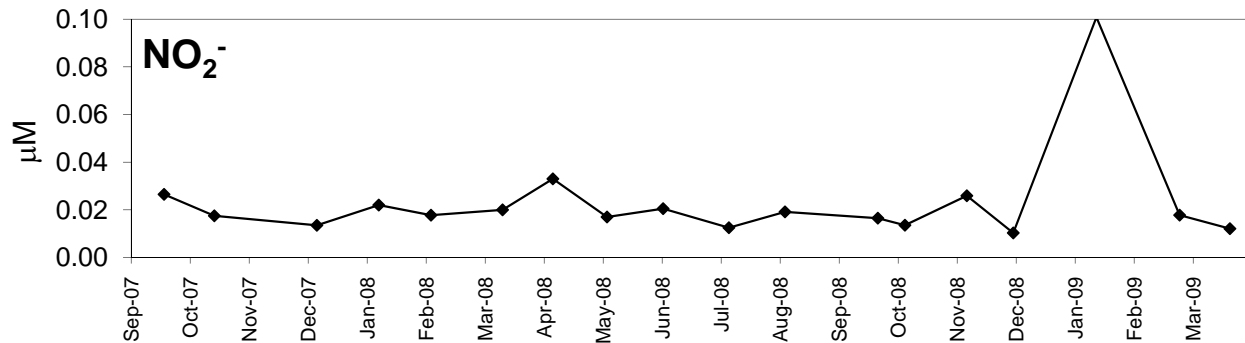
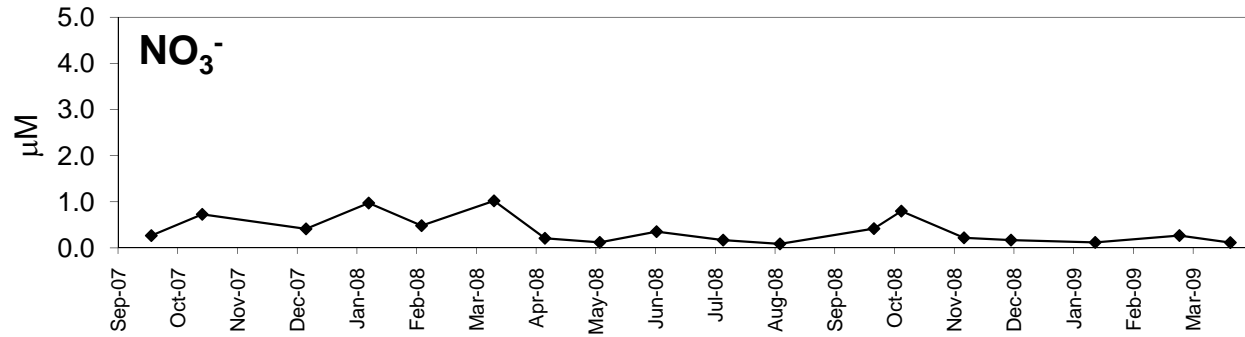
Station 8, Grey's Bridge



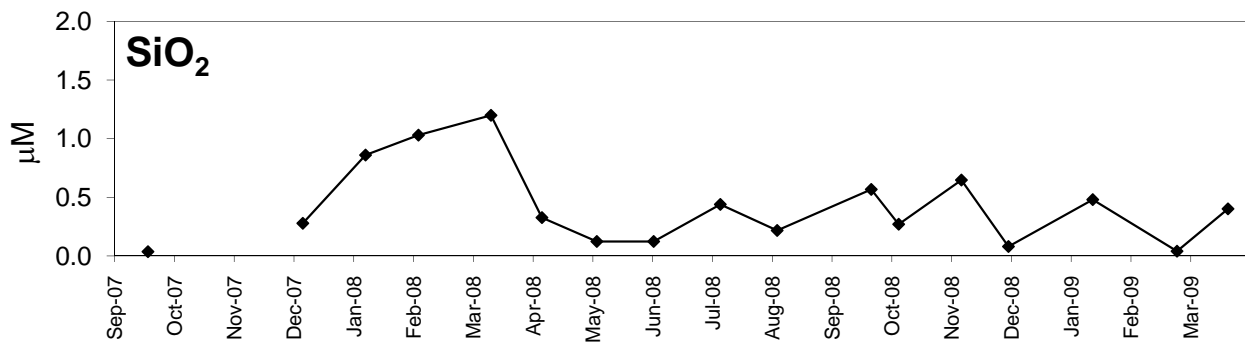
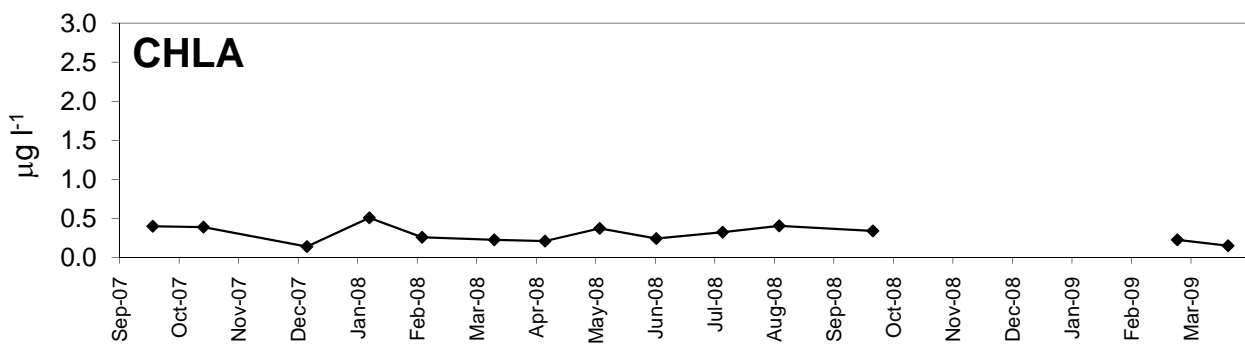
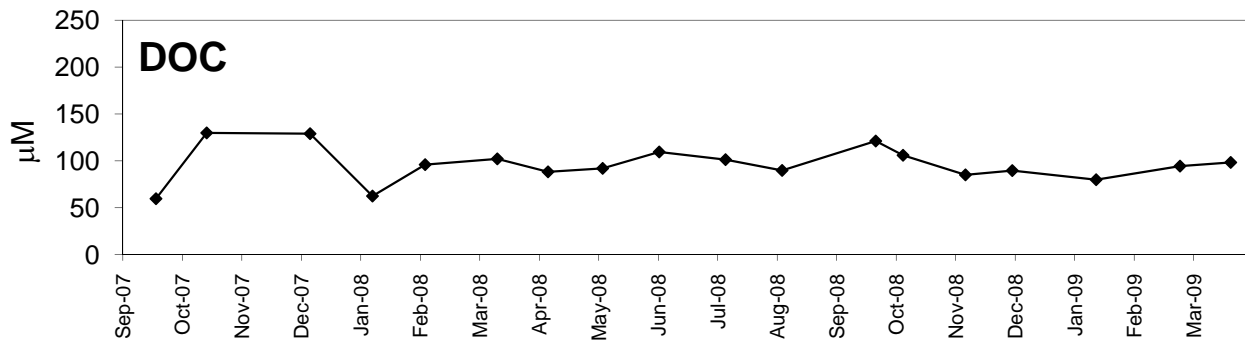
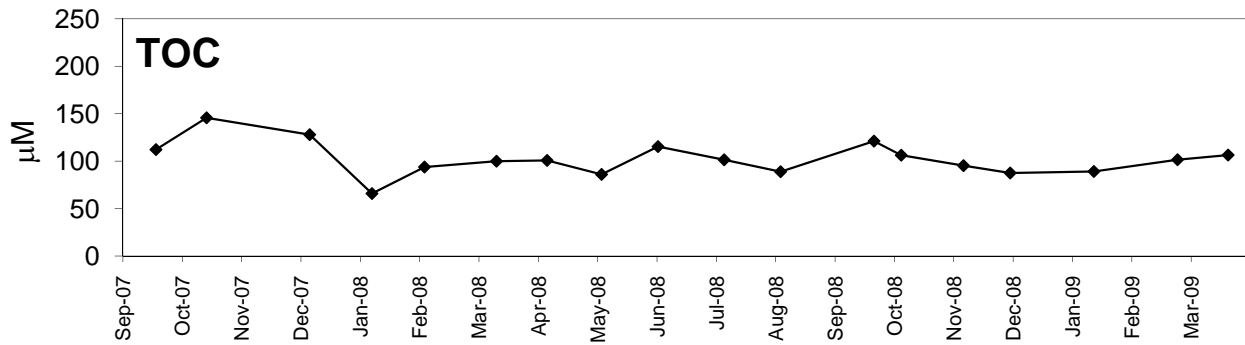
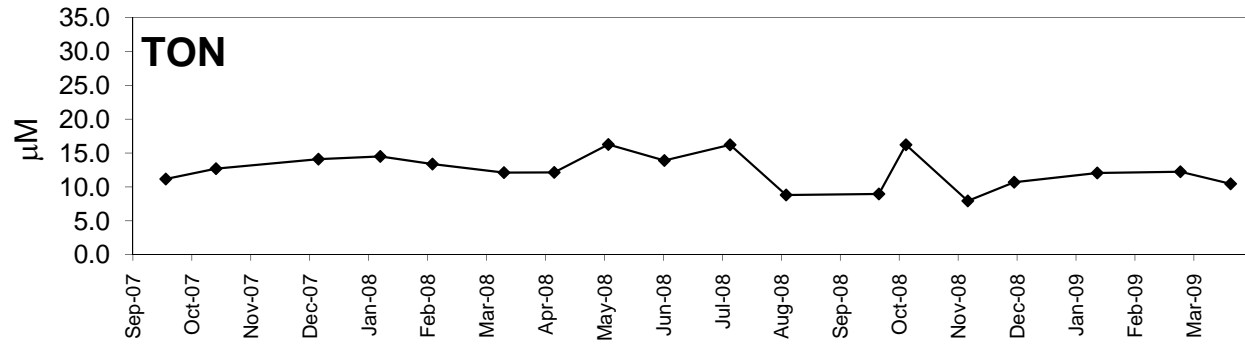
Station 8, Grey's Bridge



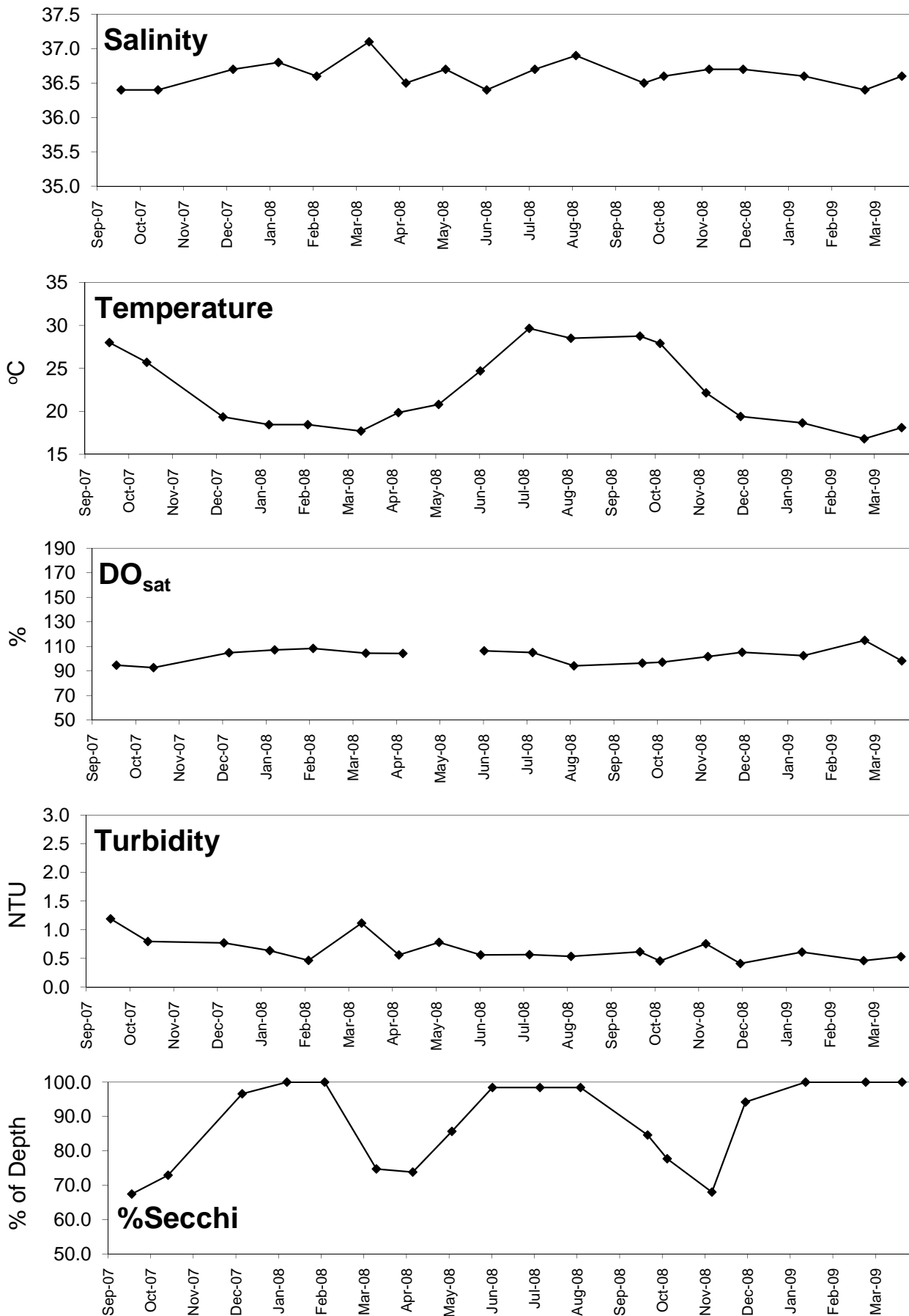
Station 9A, Regatta Island



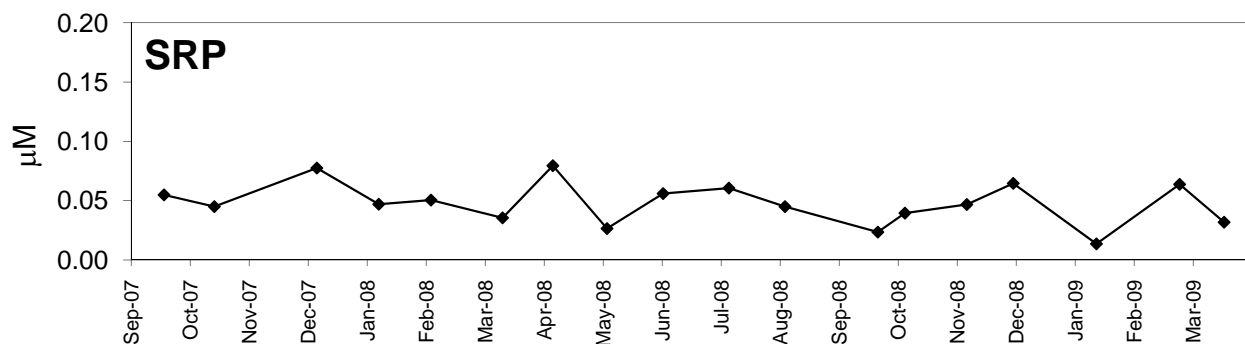
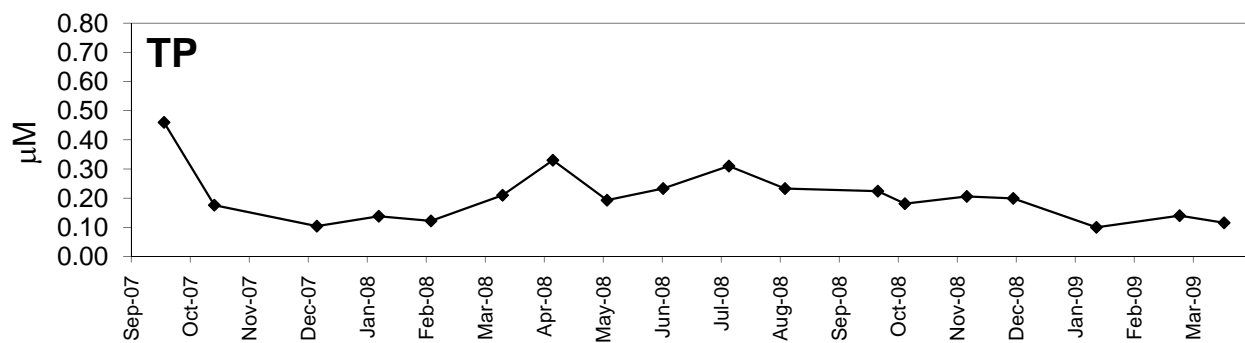
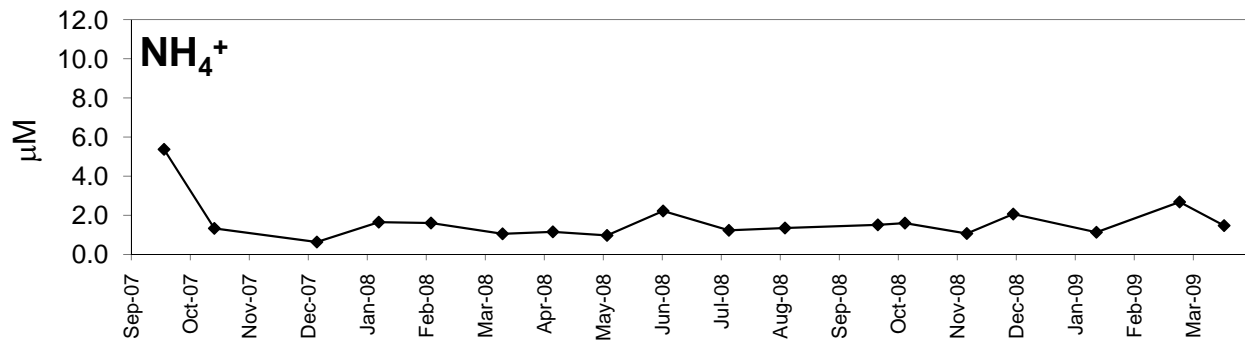
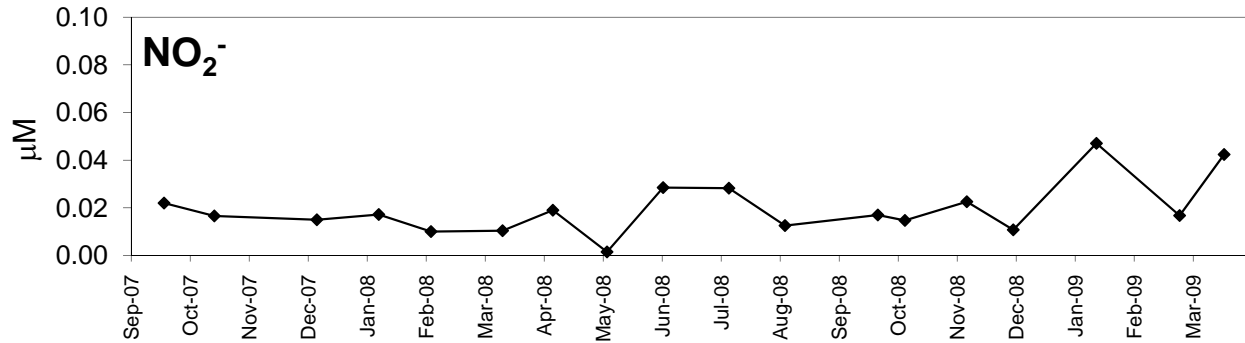
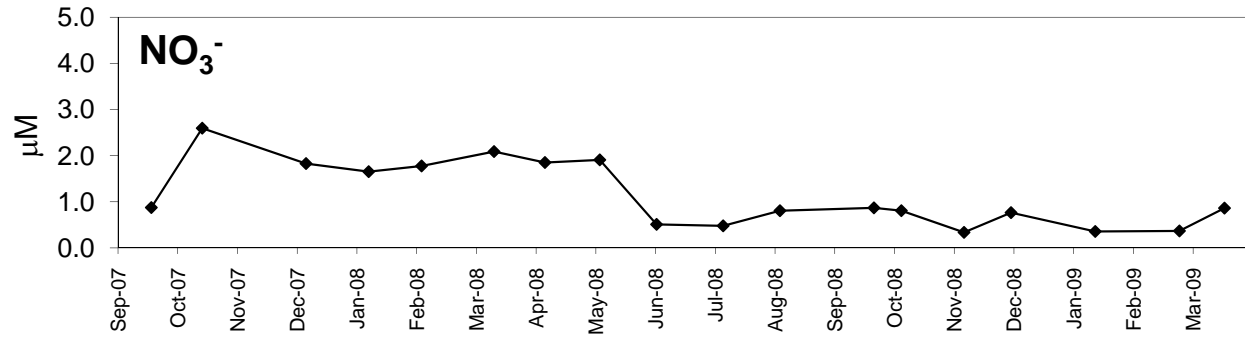
Station 9A, Regatta Island



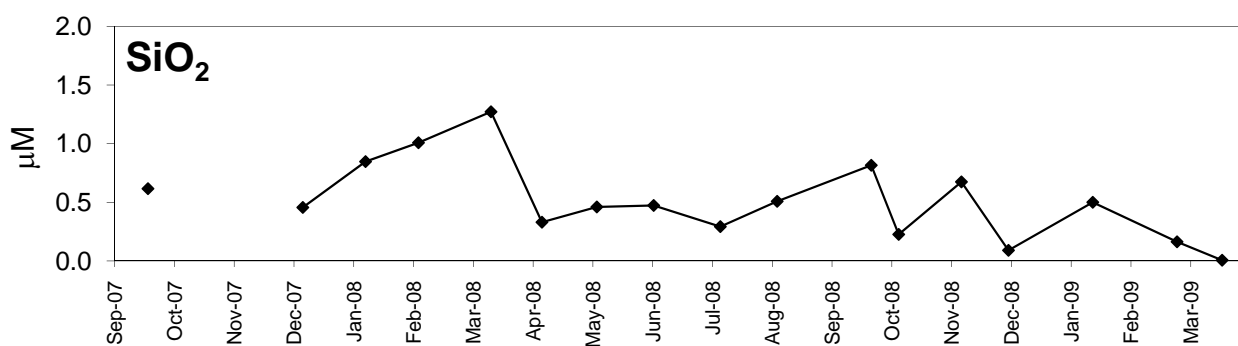
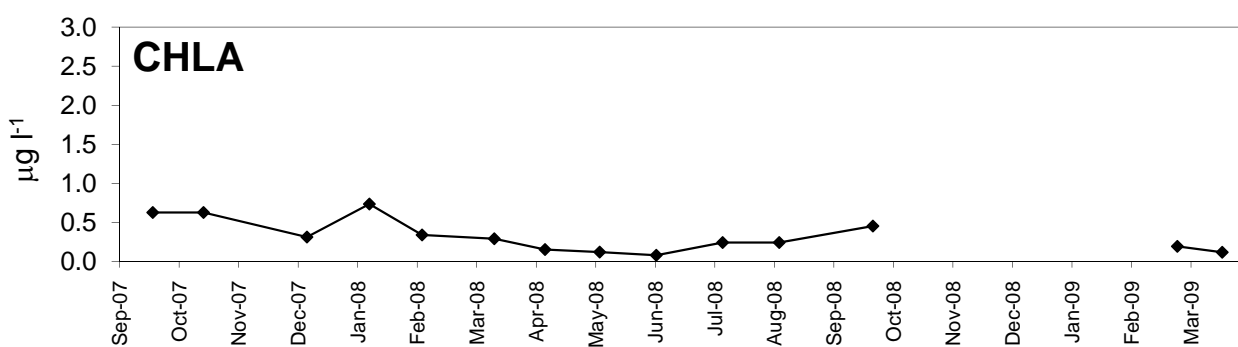
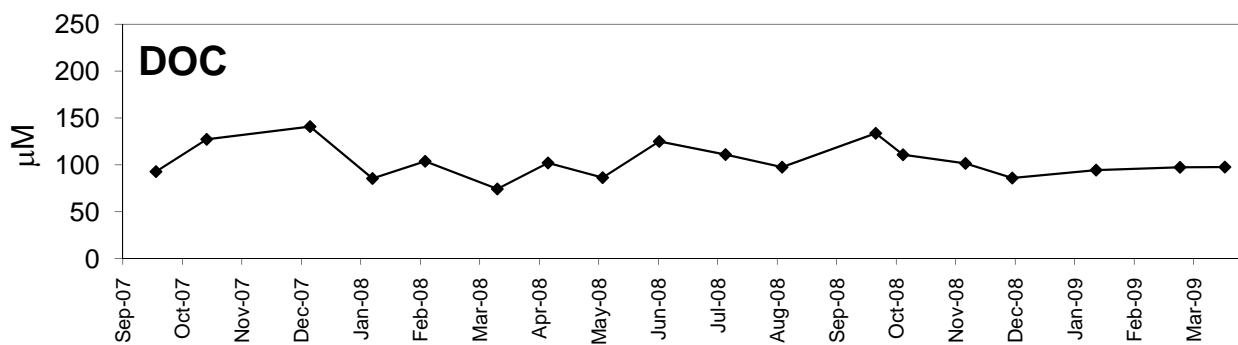
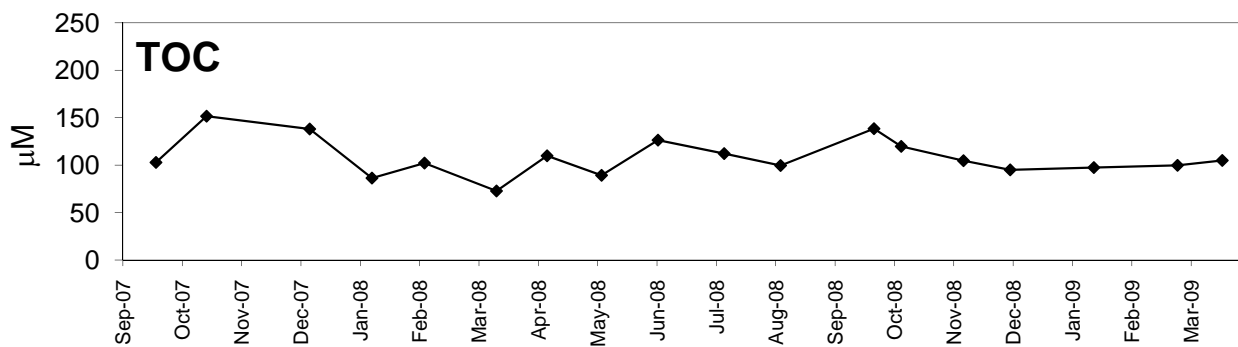
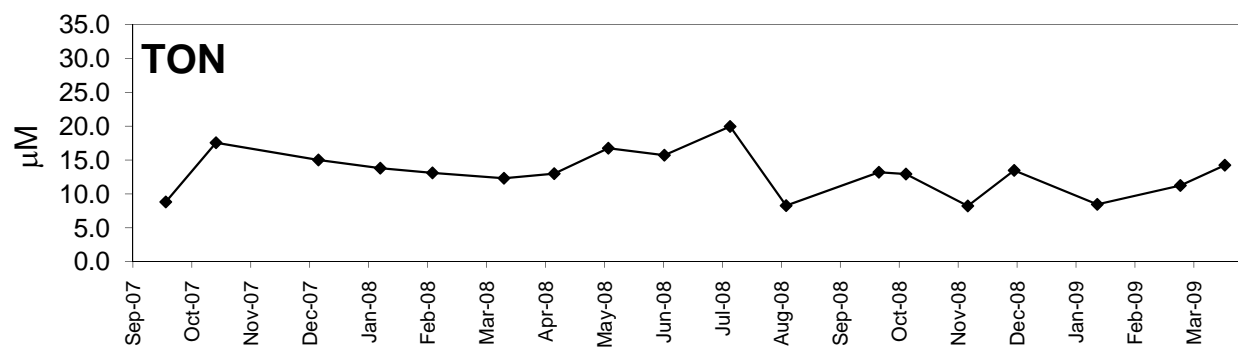
Station 9A, Regatta Island



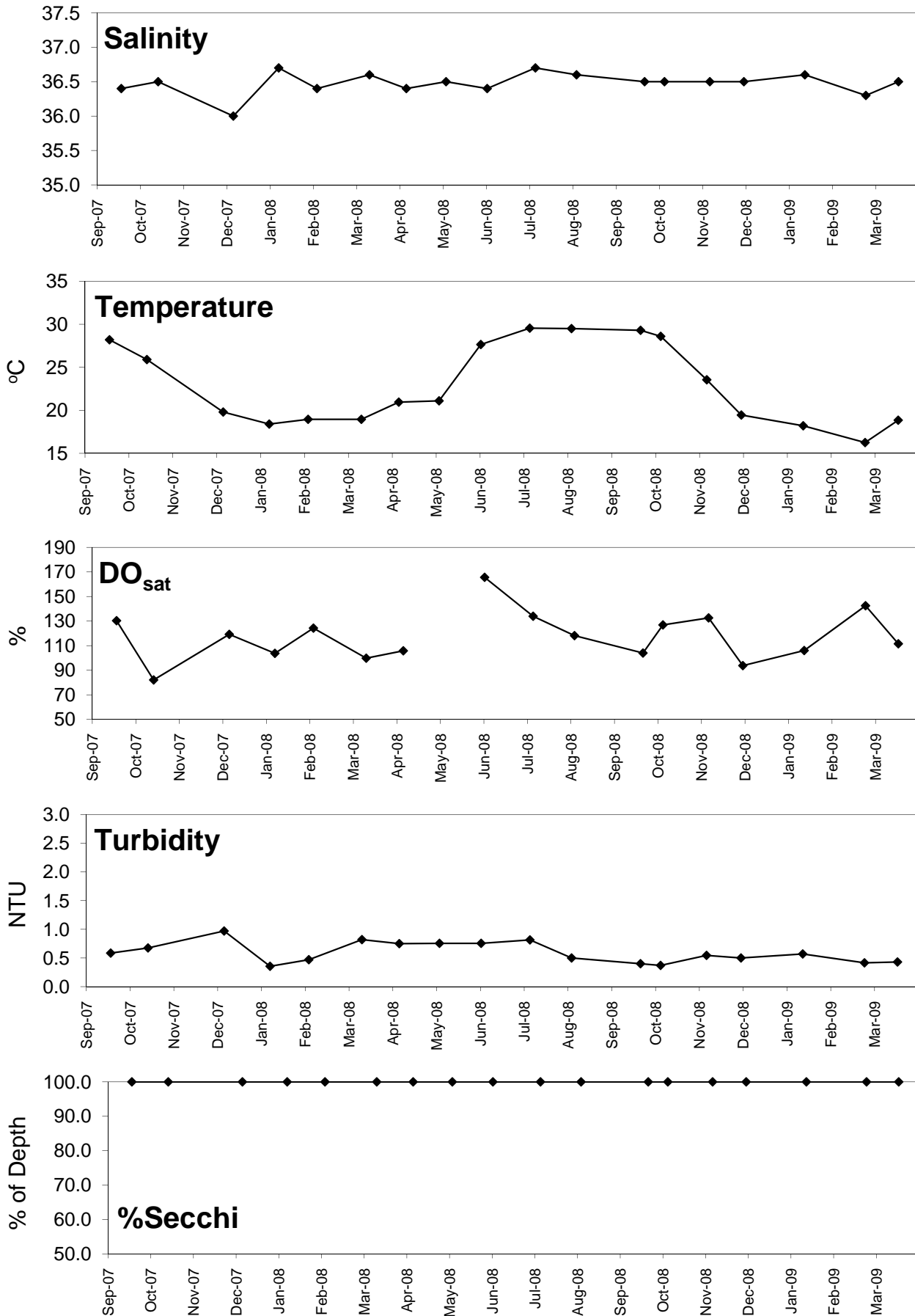
Station 9B, Riddell's Bay Golf Course



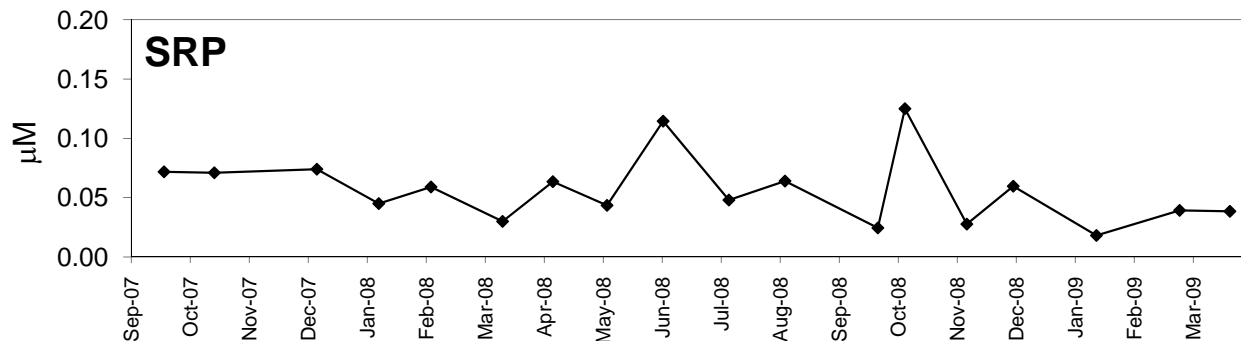
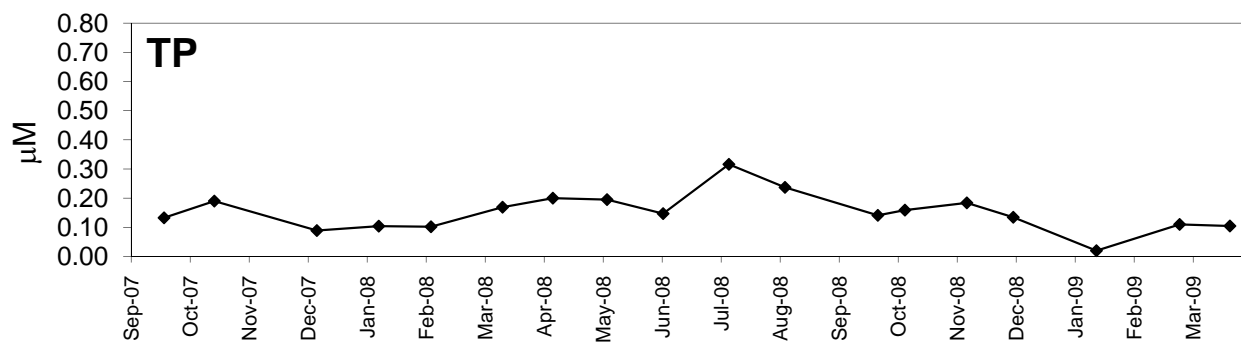
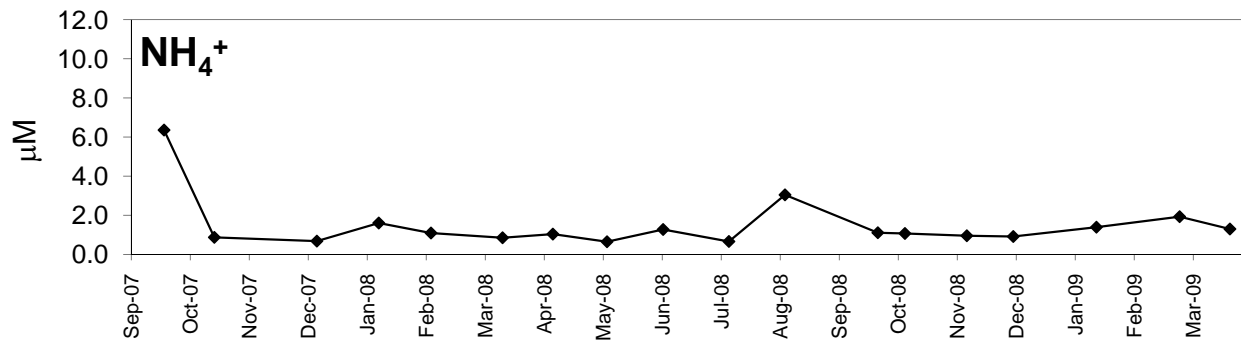
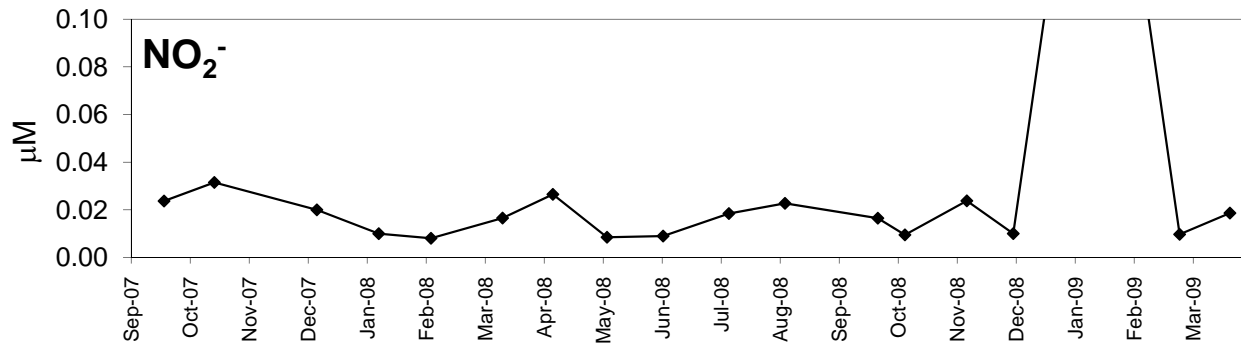
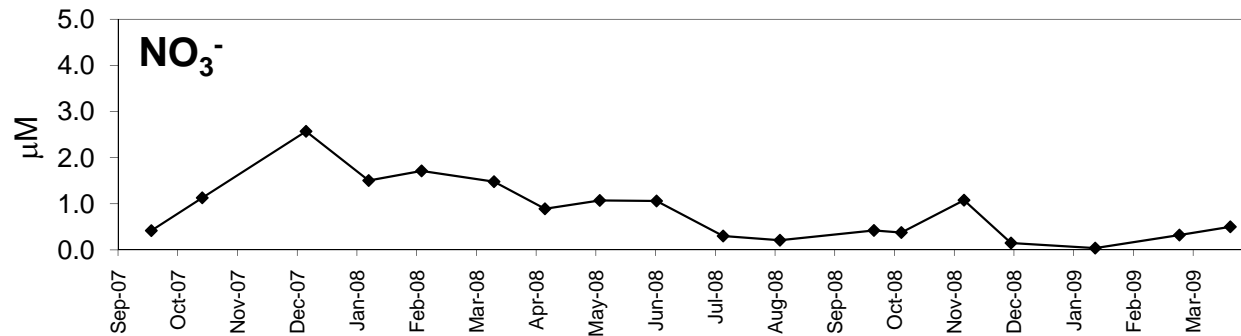
Station 9B, Riddell's Bay Golf Course



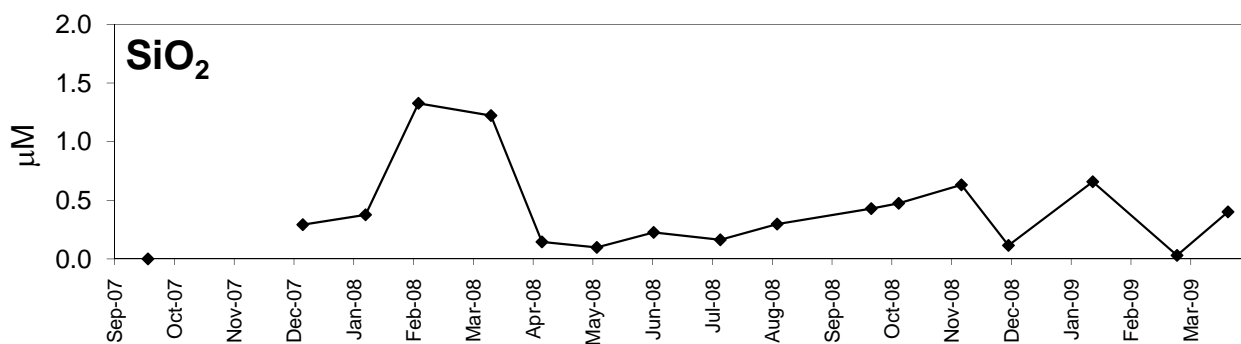
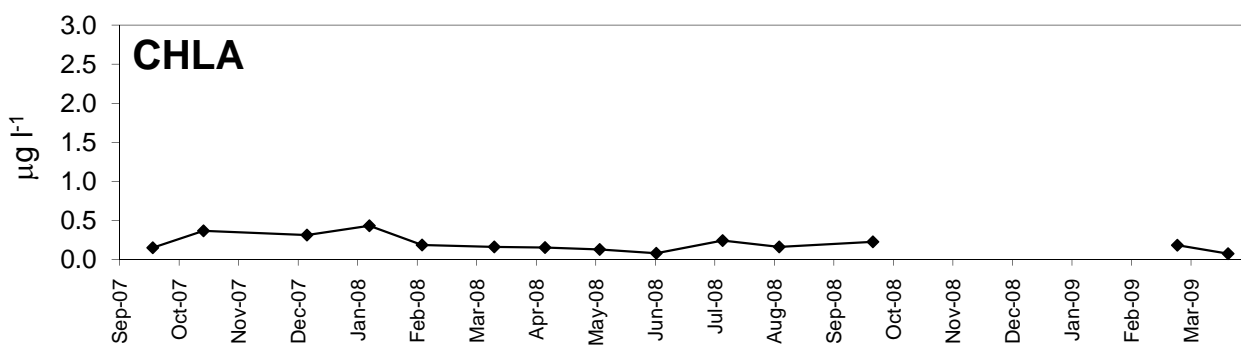
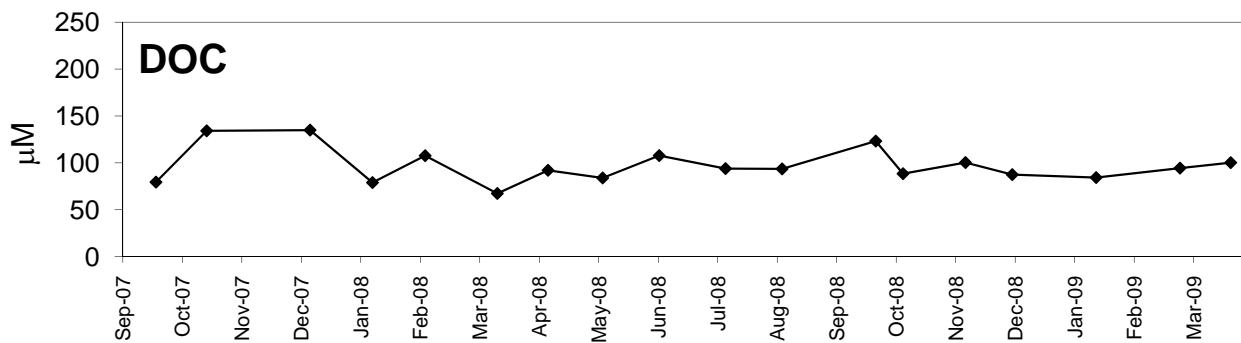
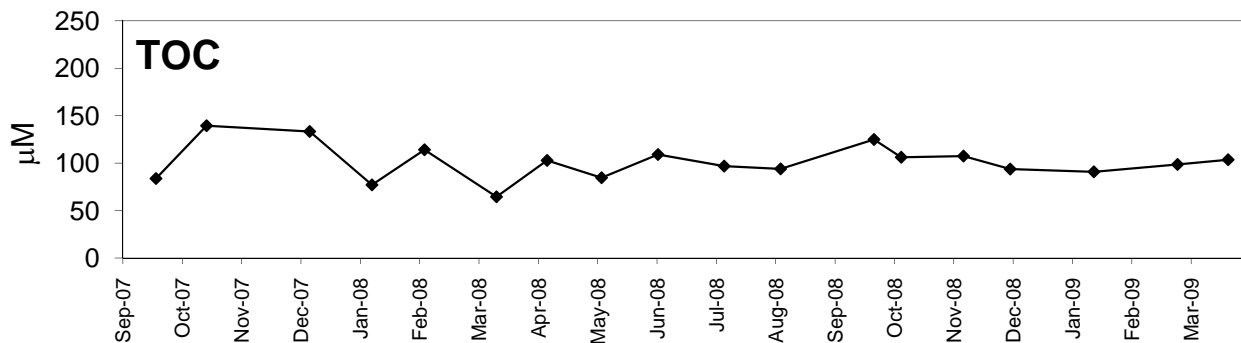
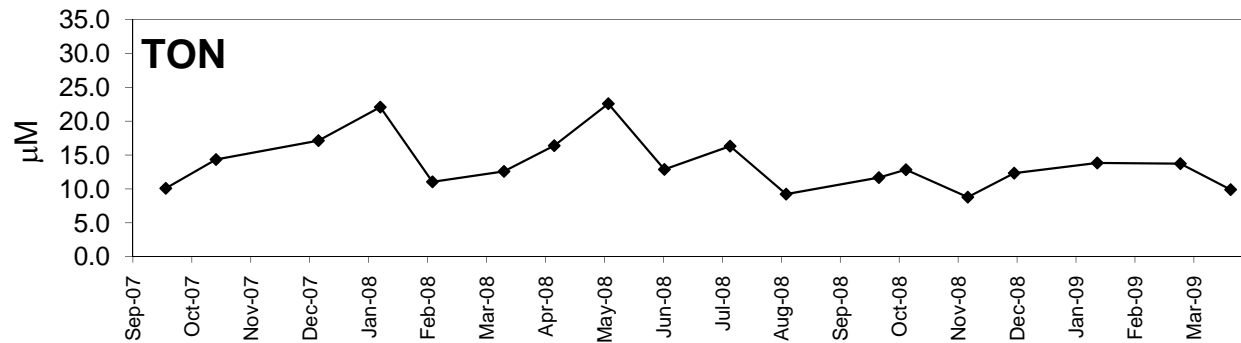
Station 9B, Riddell's Bay Golf Course



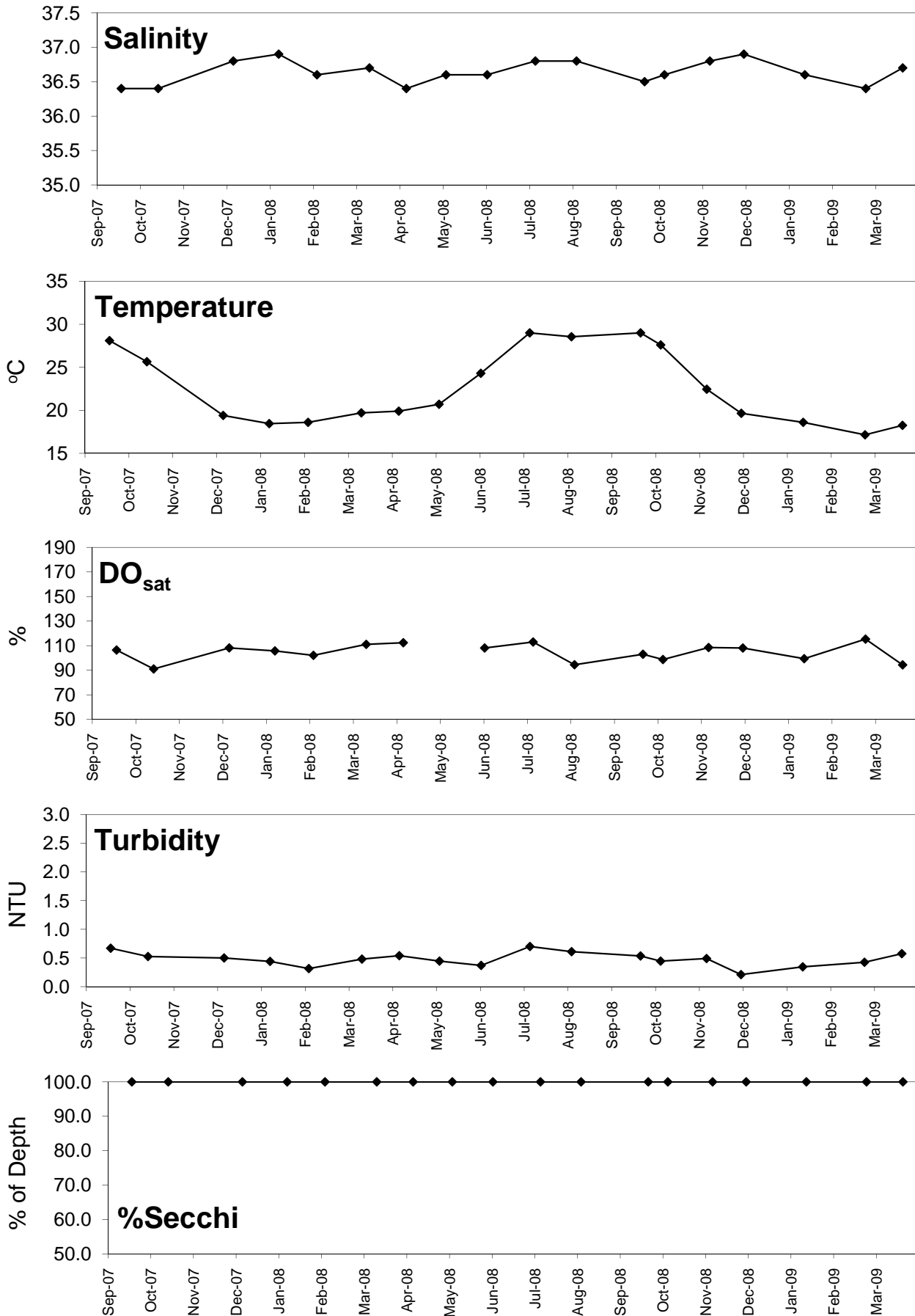
Station 13, Tynes Bay



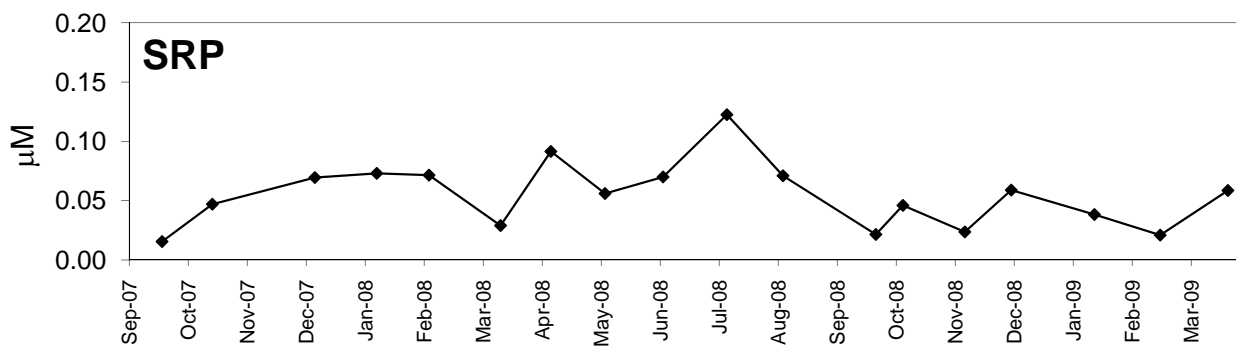
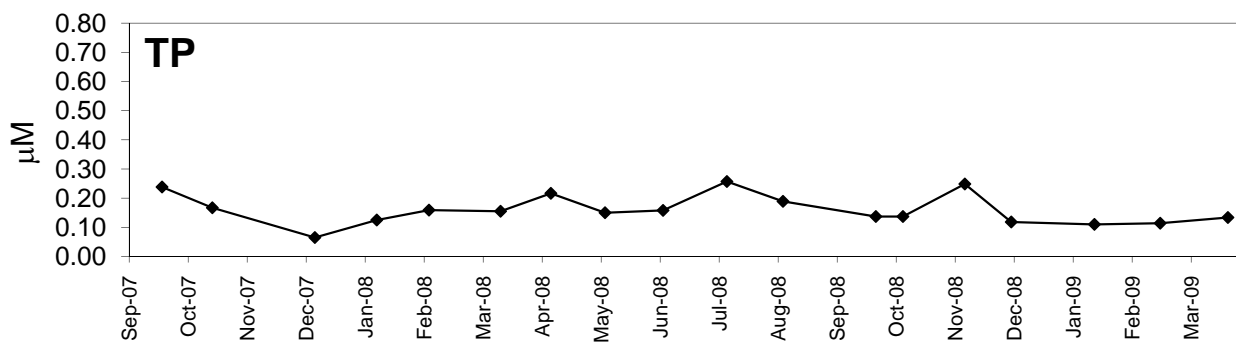
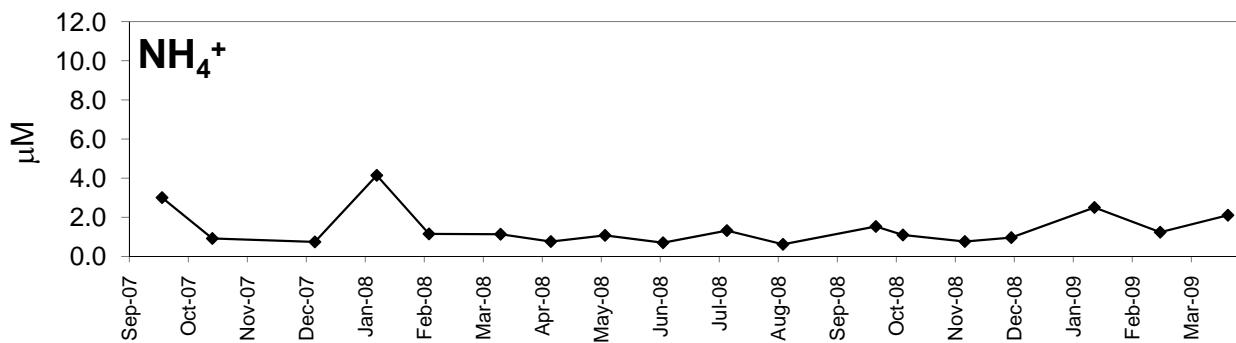
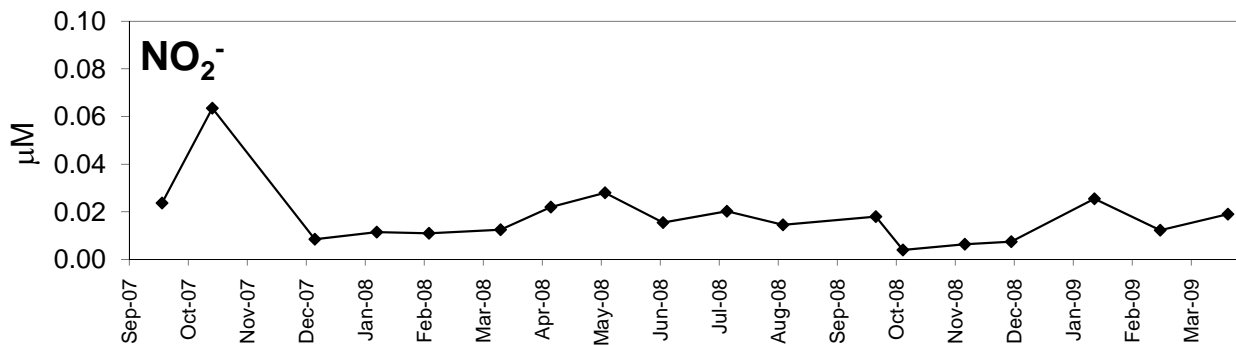
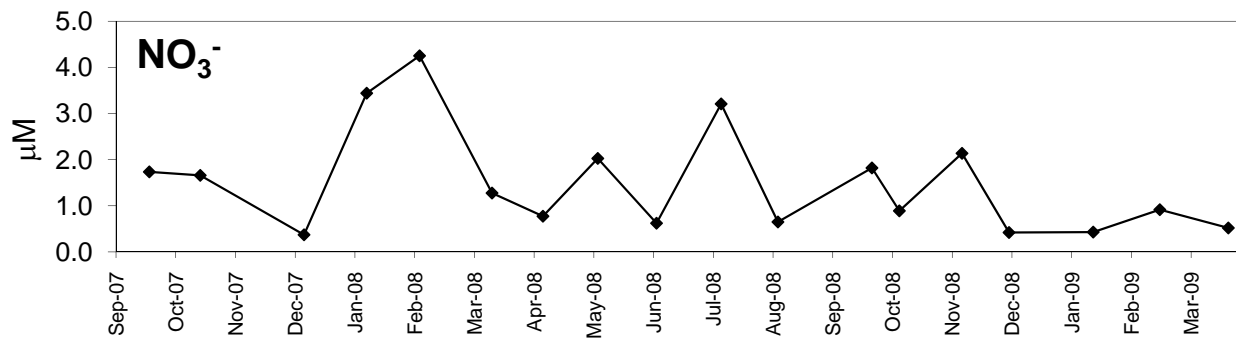
Station 13, Tynes Bay



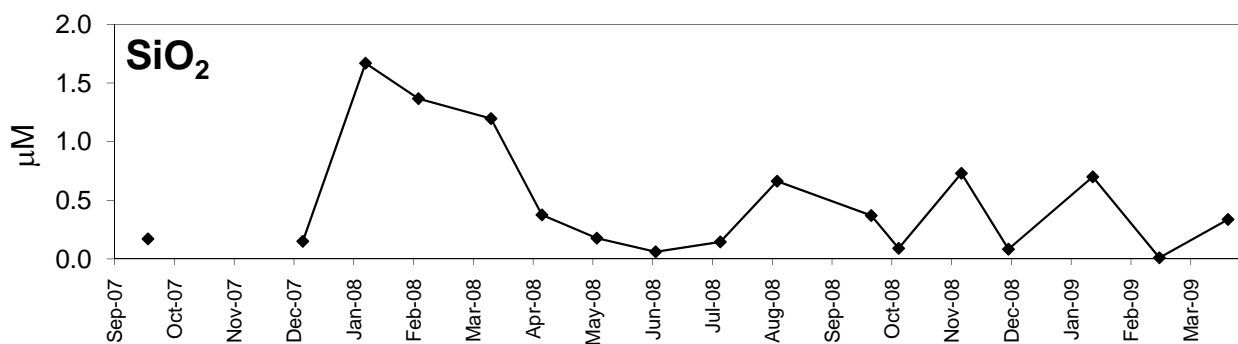
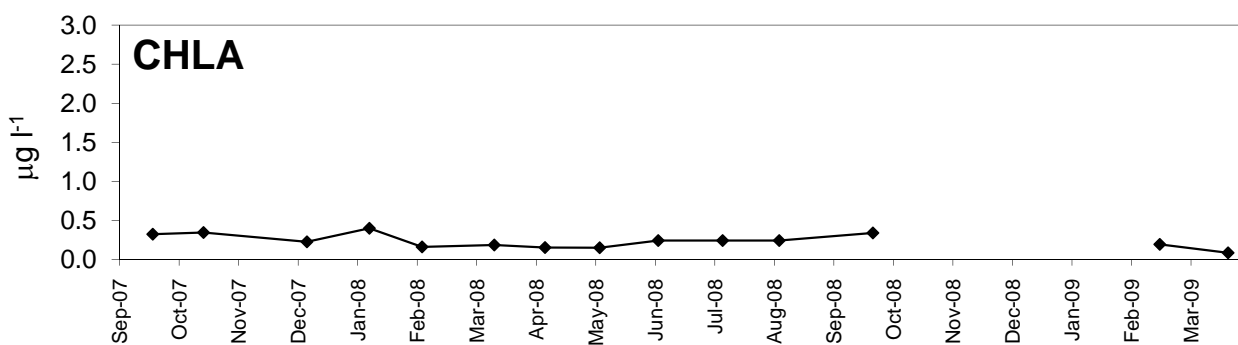
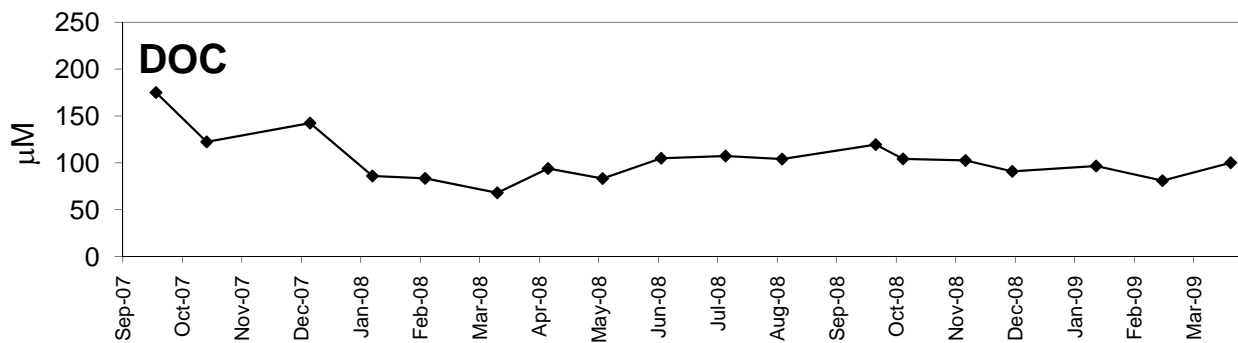
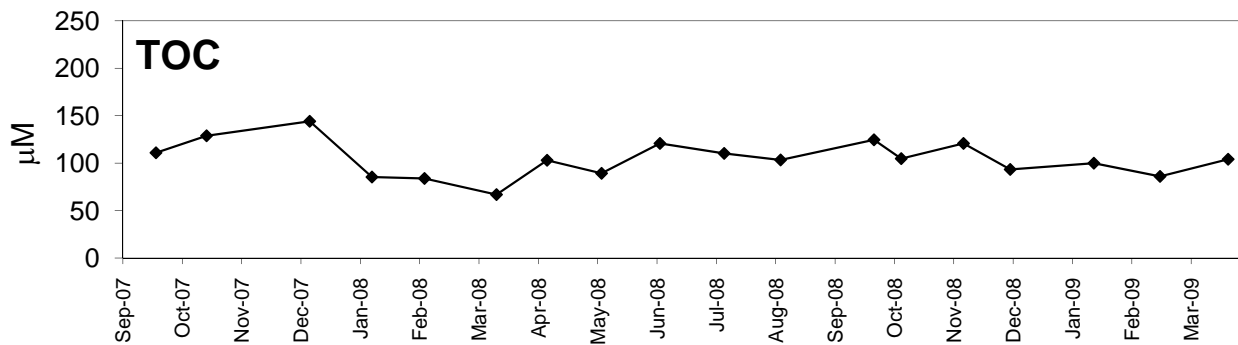
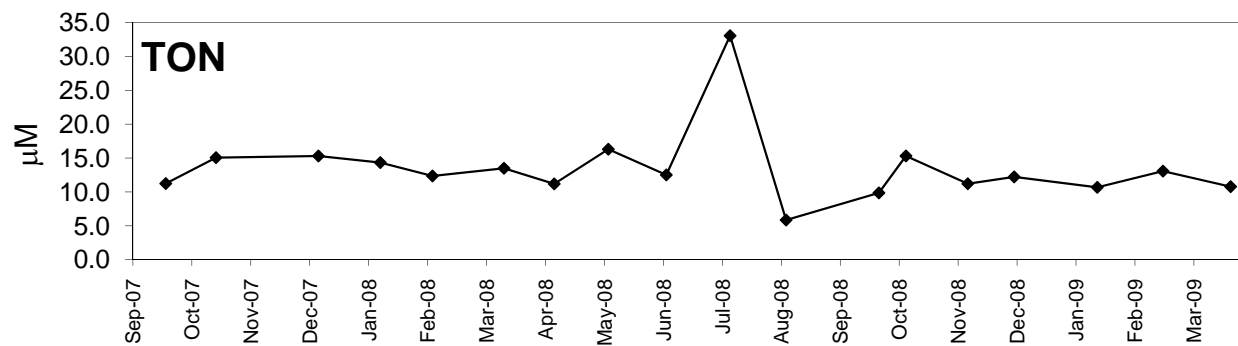
Station 13, Tynes Bay



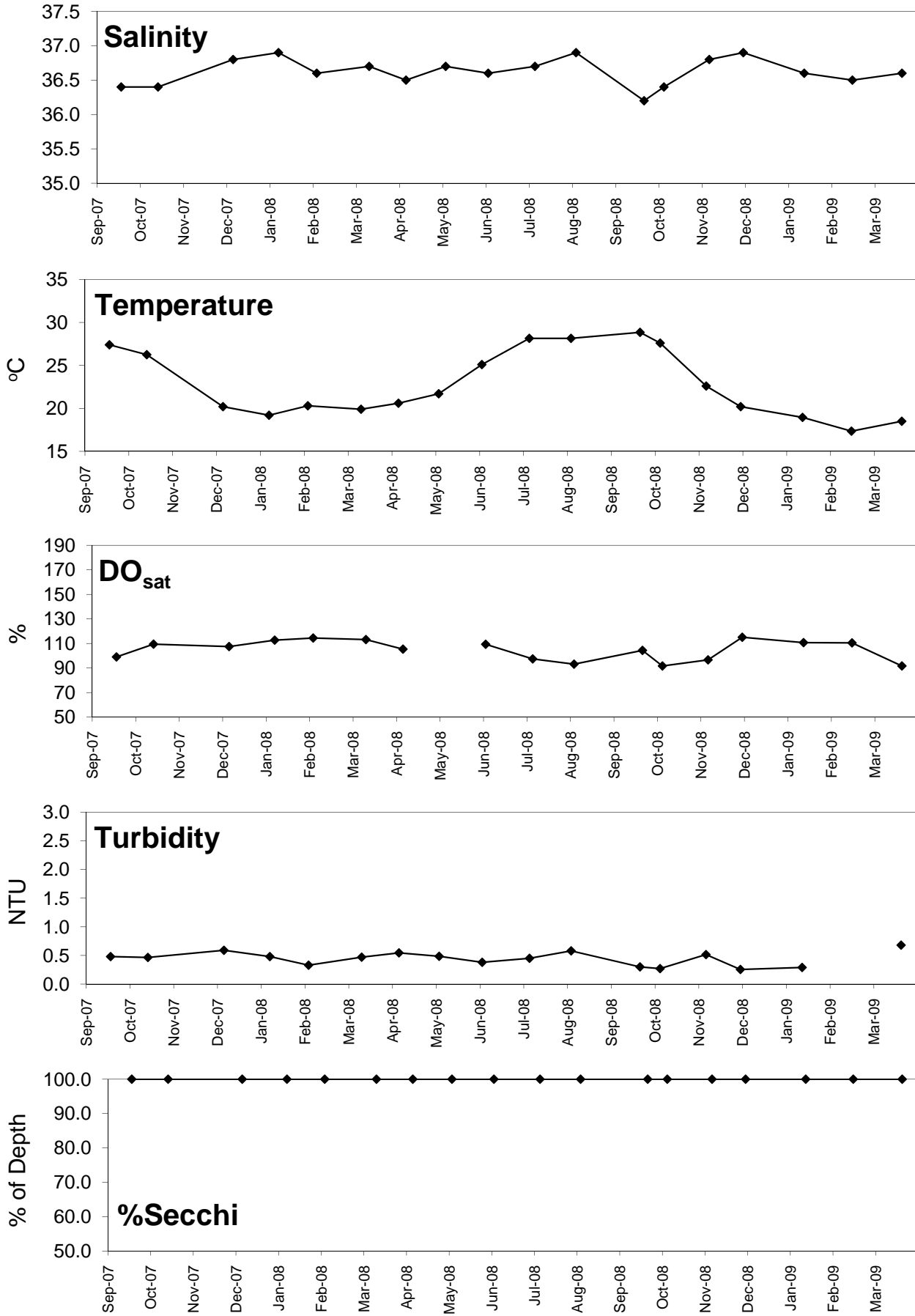
Station 15, Bailey's Bay



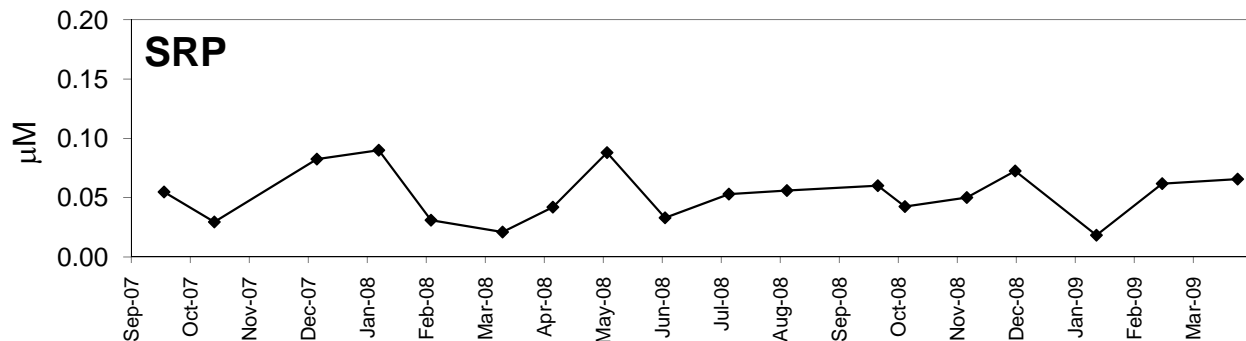
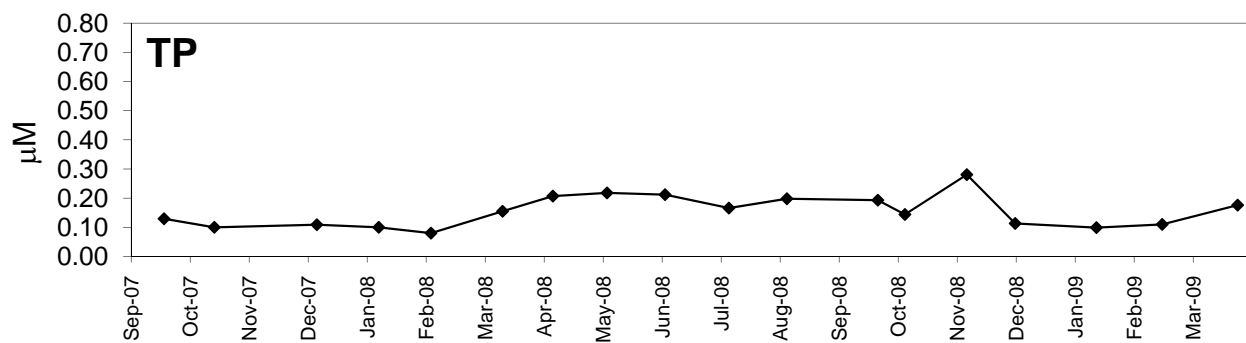
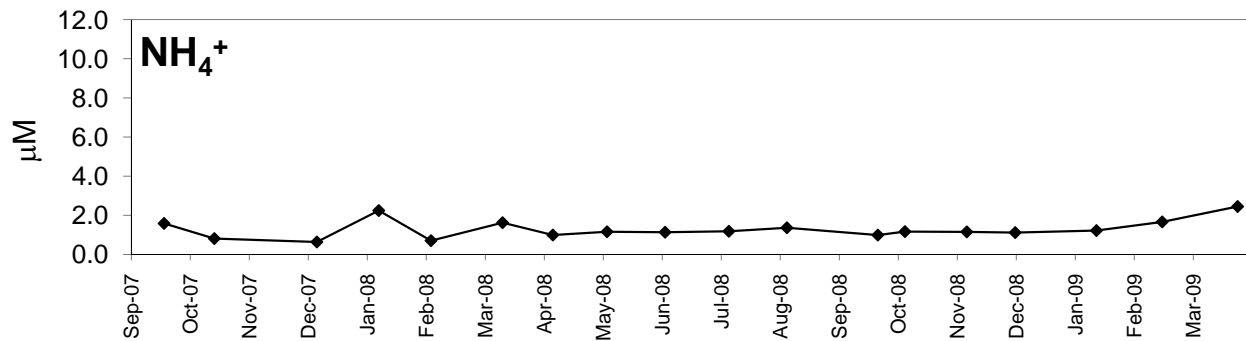
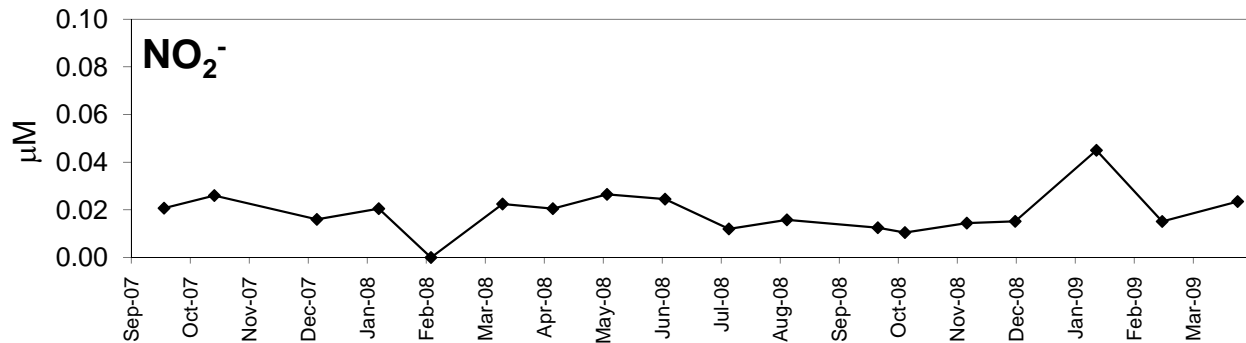
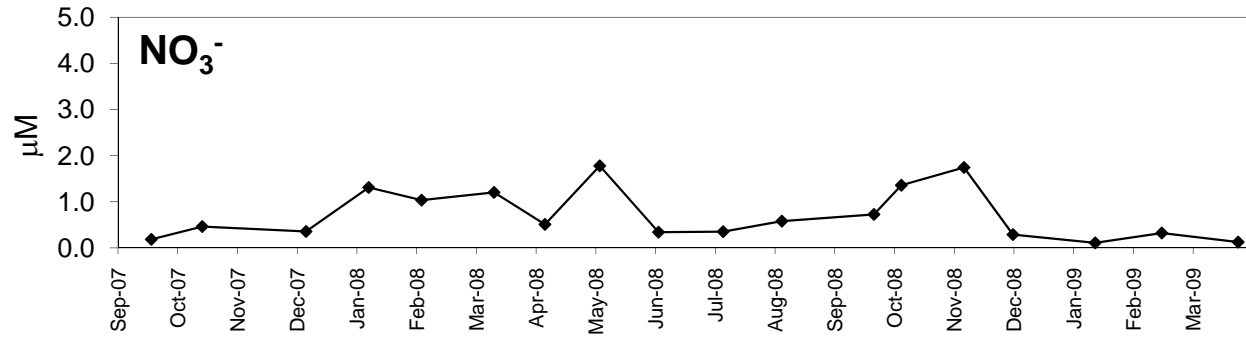
Station 15, Bailey's Bay



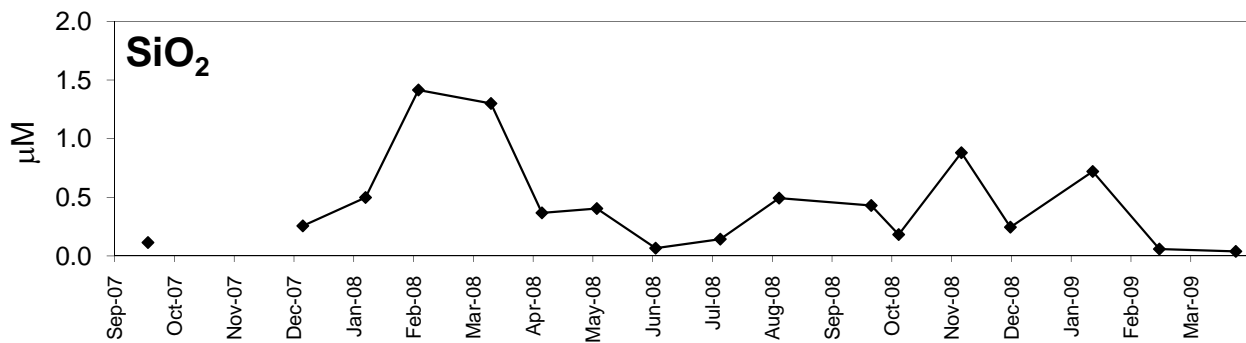
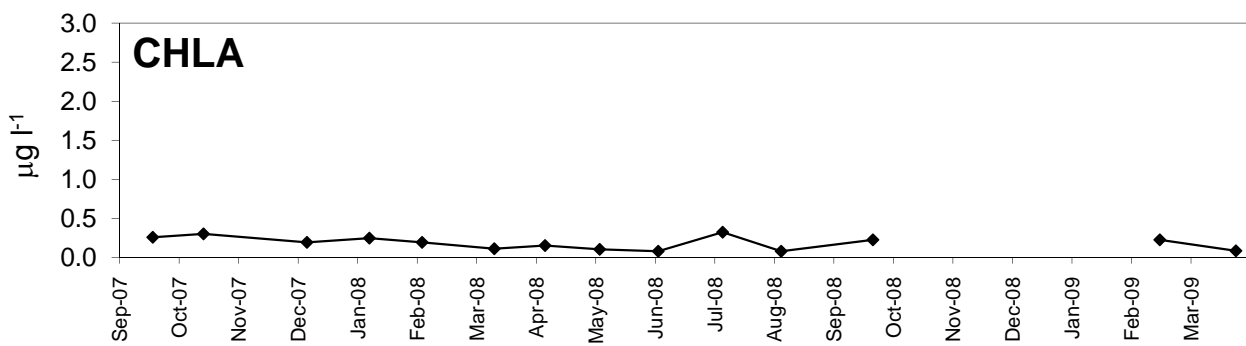
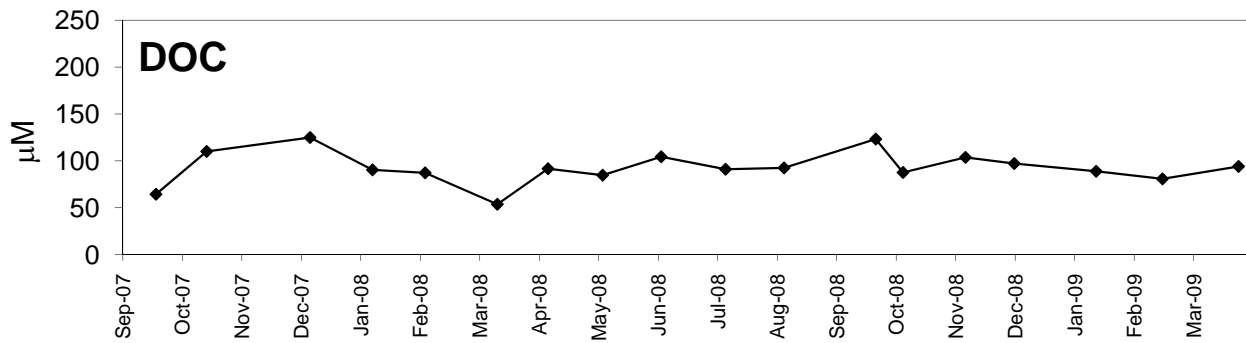
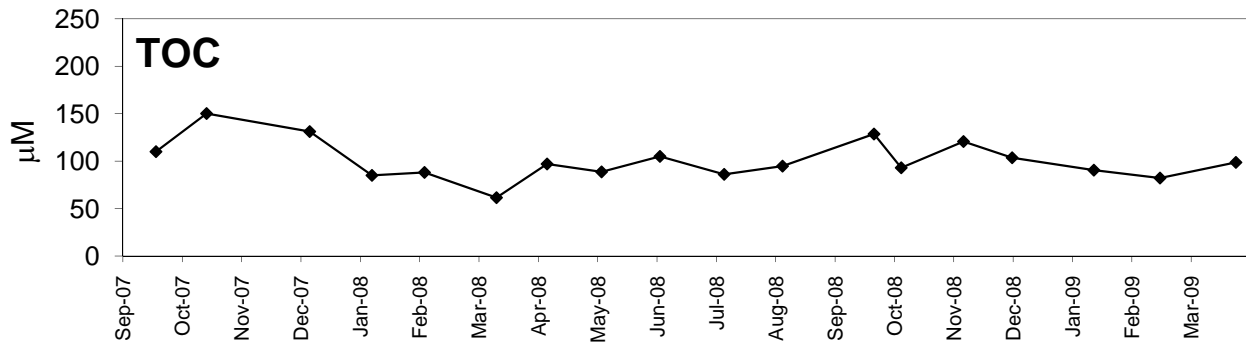
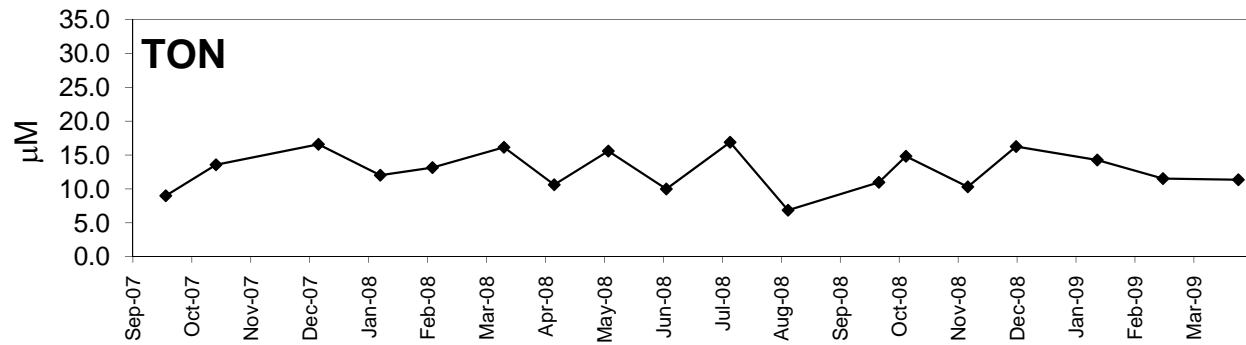
Station 15, Bailey's Bay



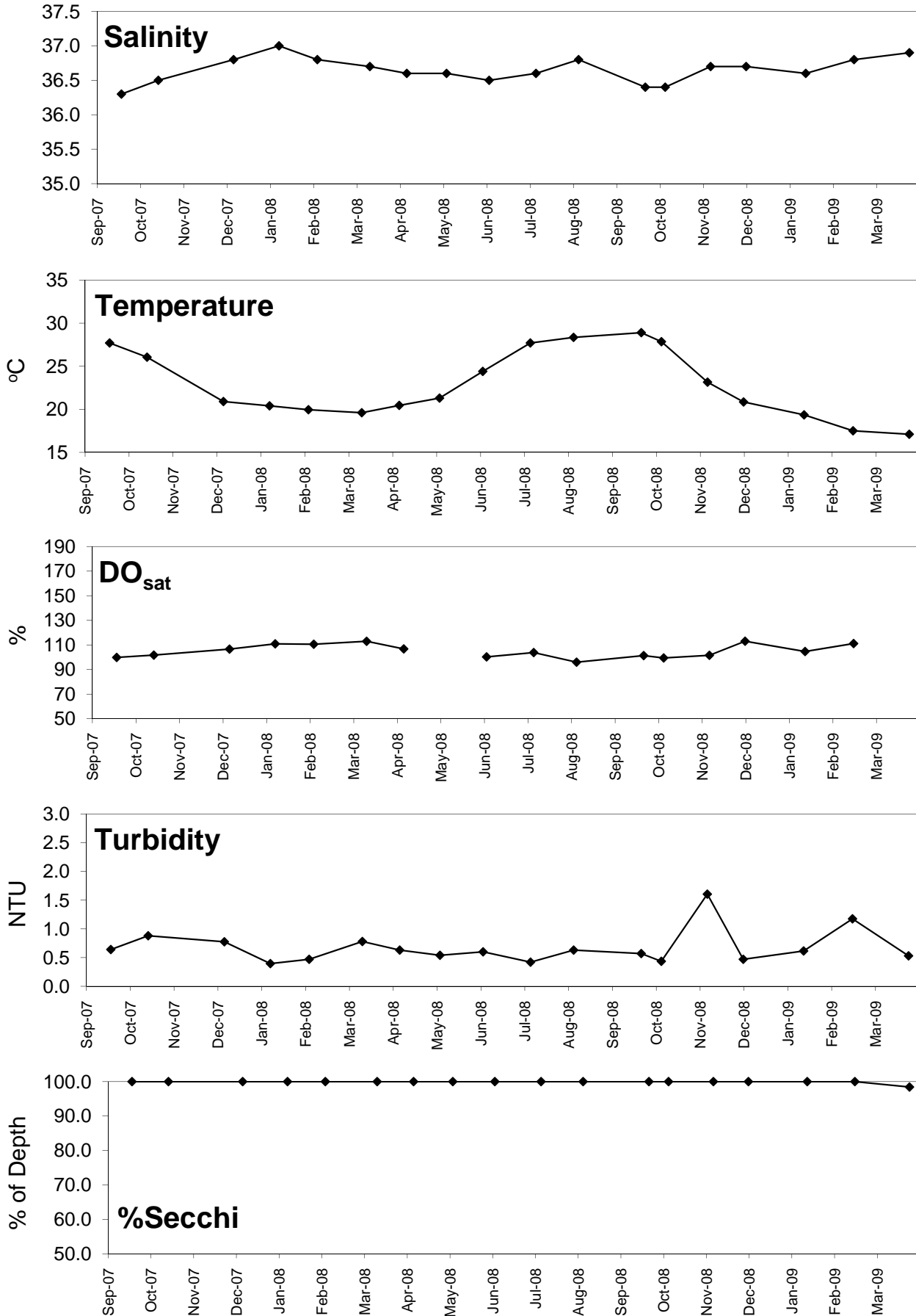
Station 16, Fort St. Catherine's



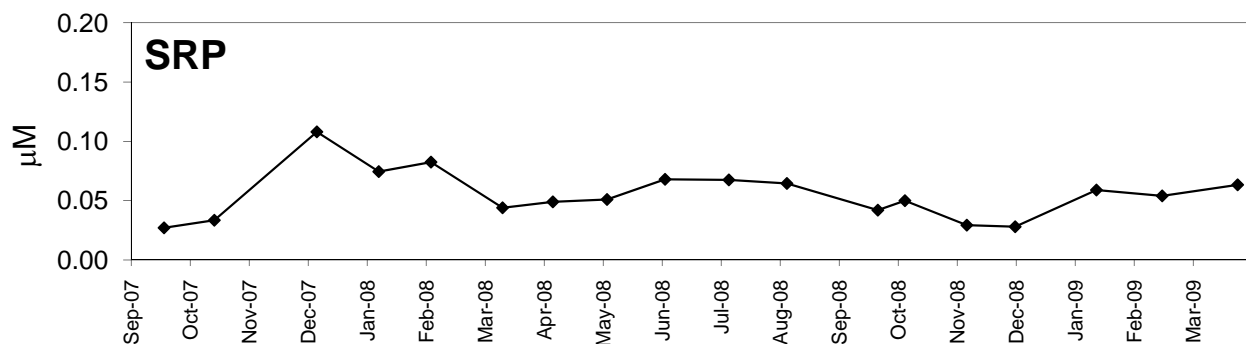
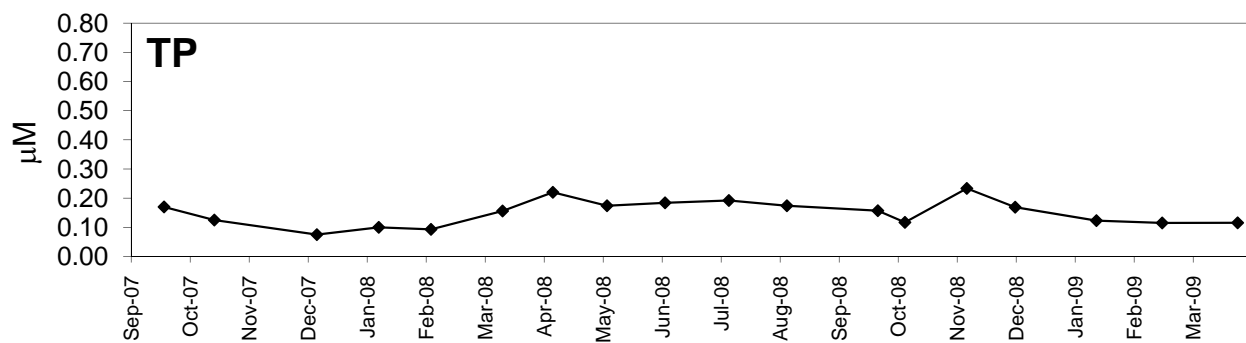
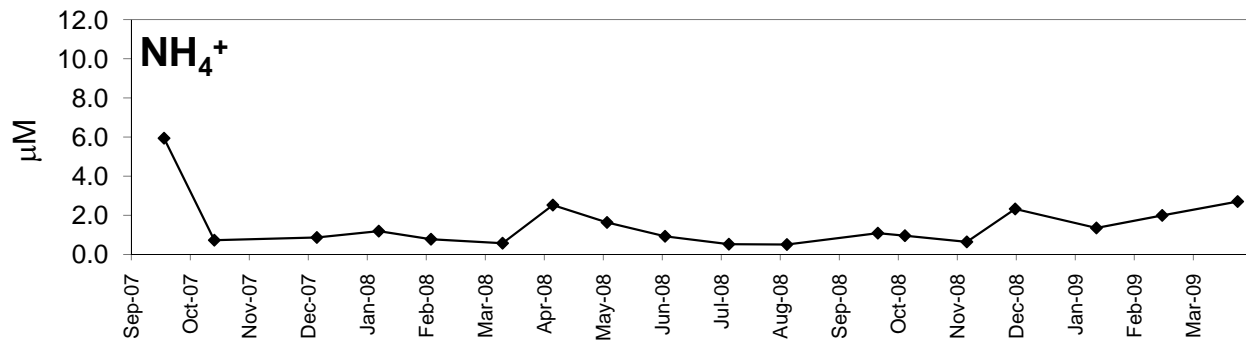
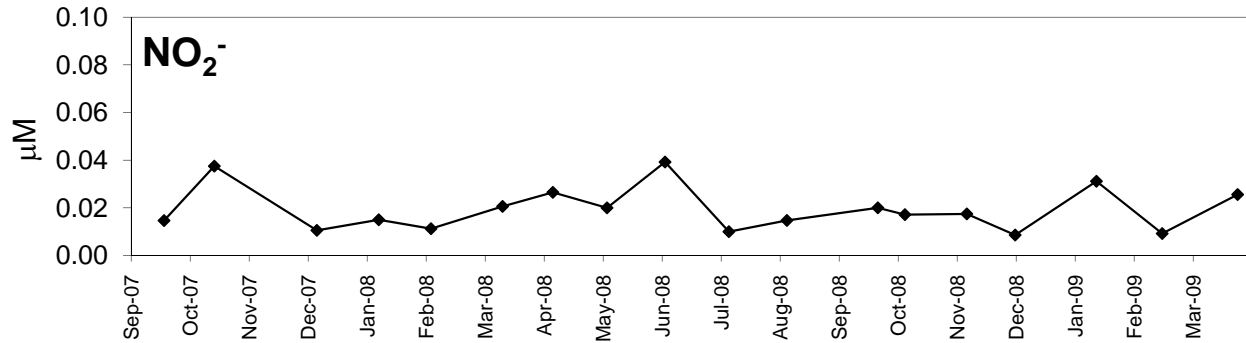
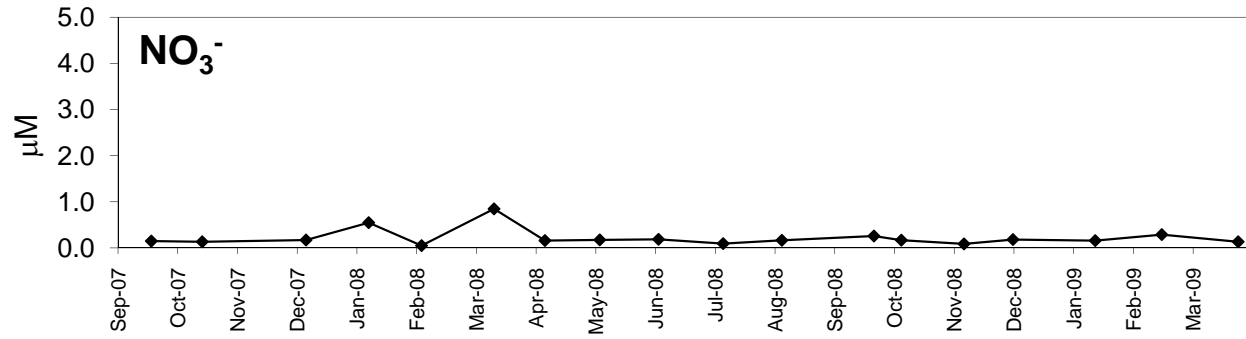
Station 16, Fort St. Catherine's



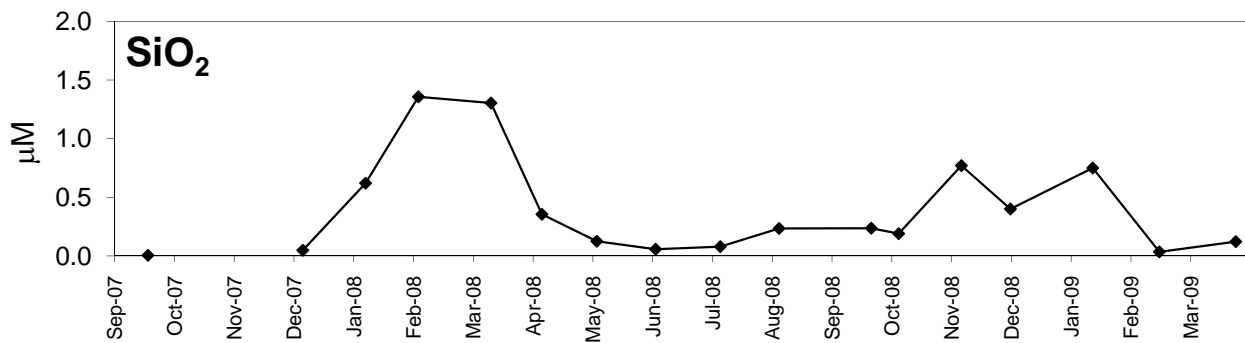
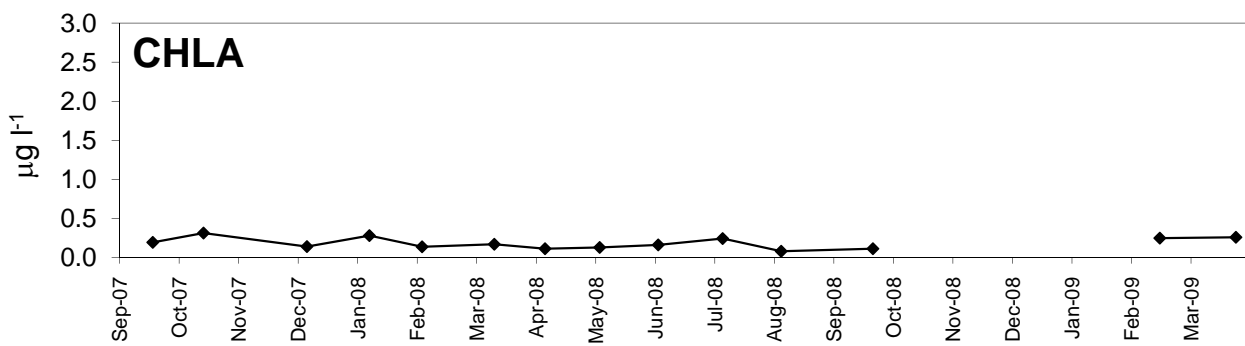
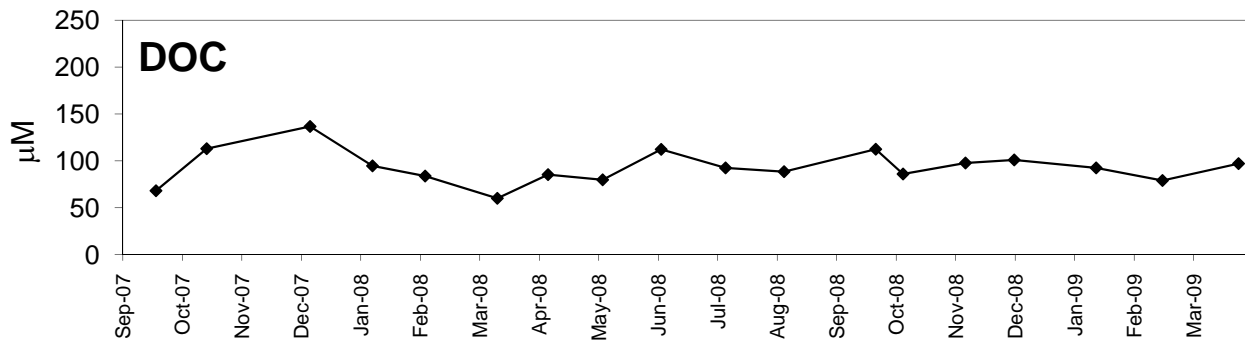
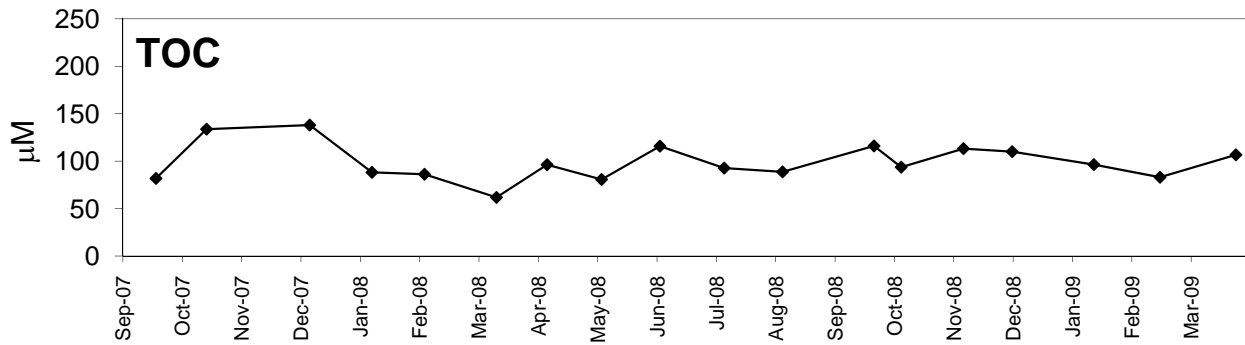
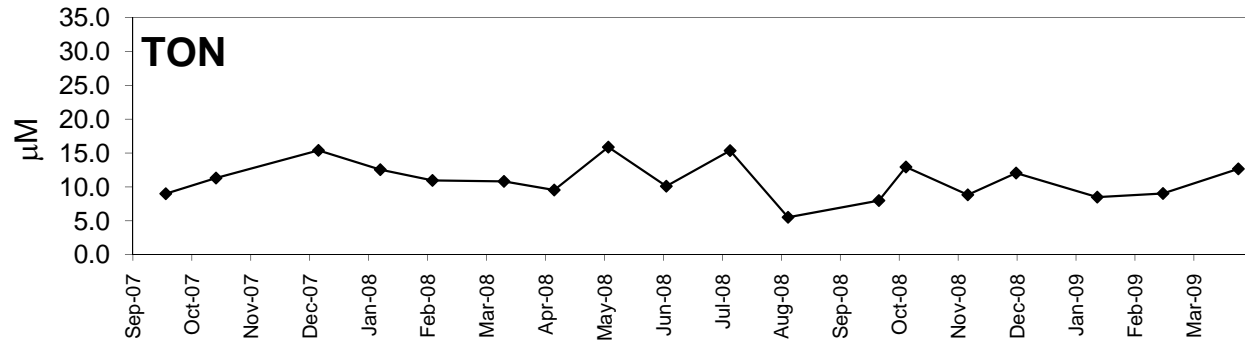
Station 16, Fort St. Catherine's



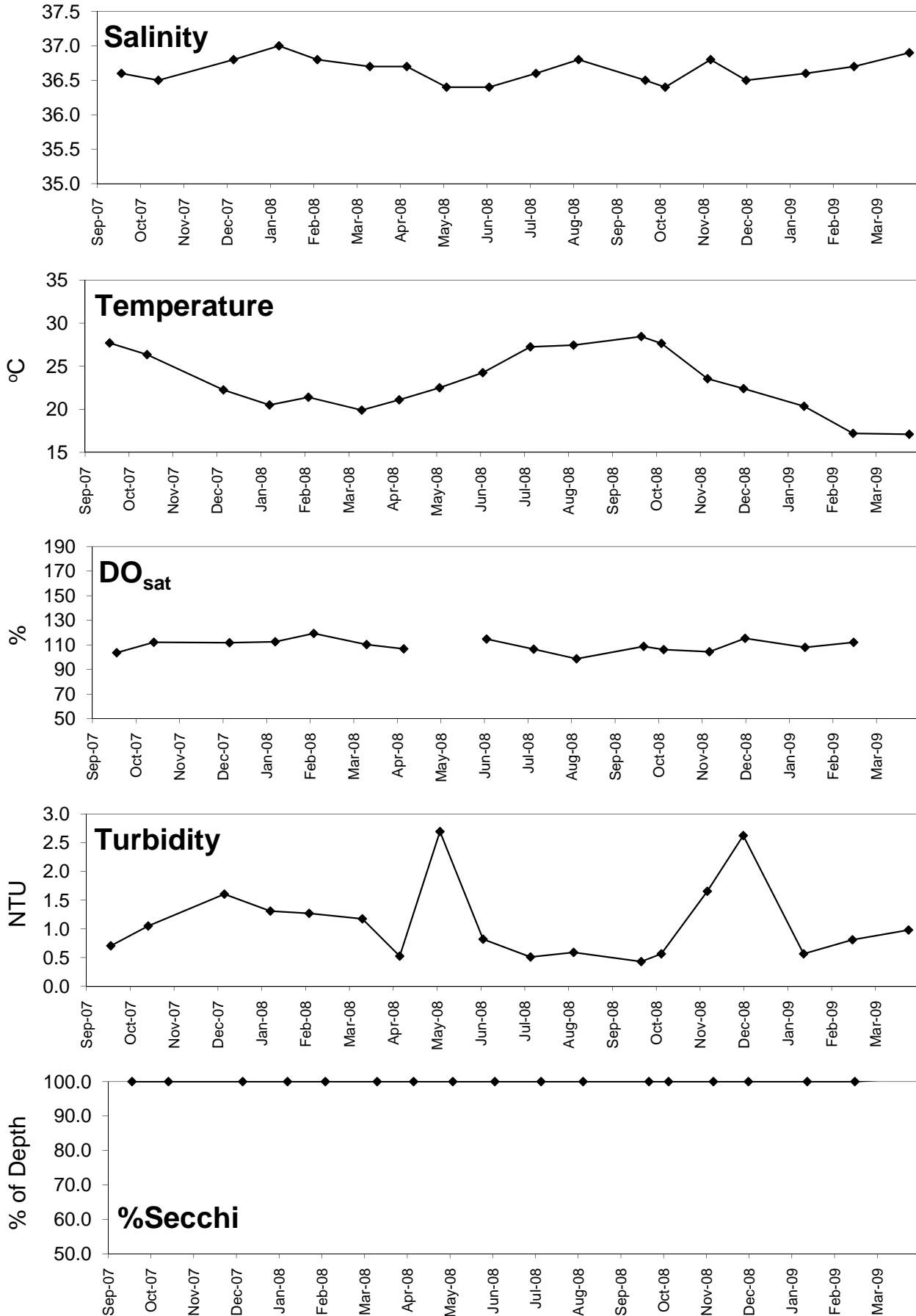
Station 17, Annie's Bay



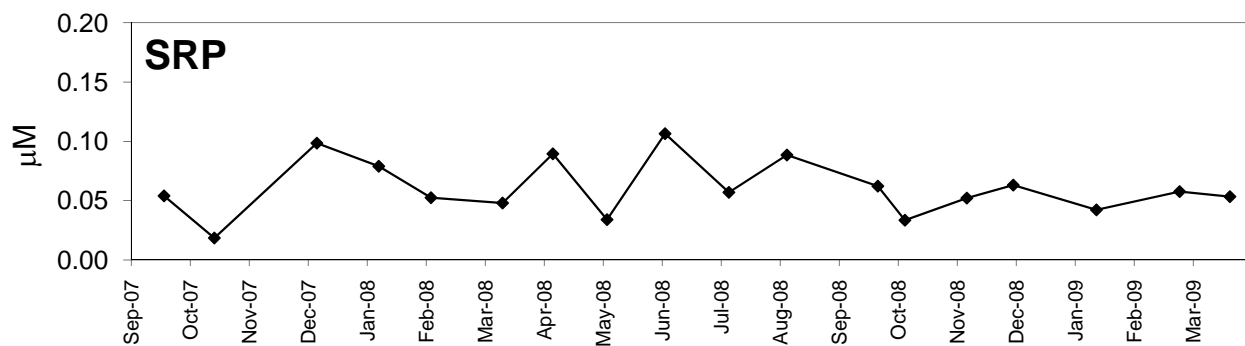
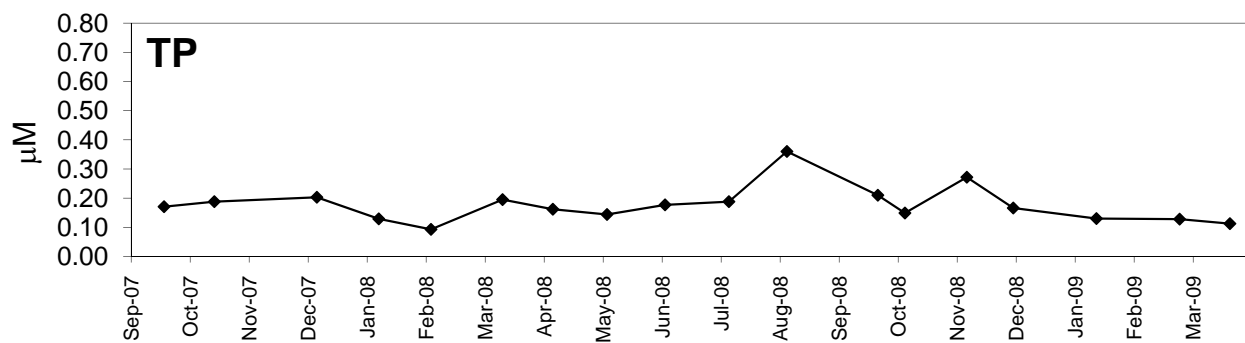
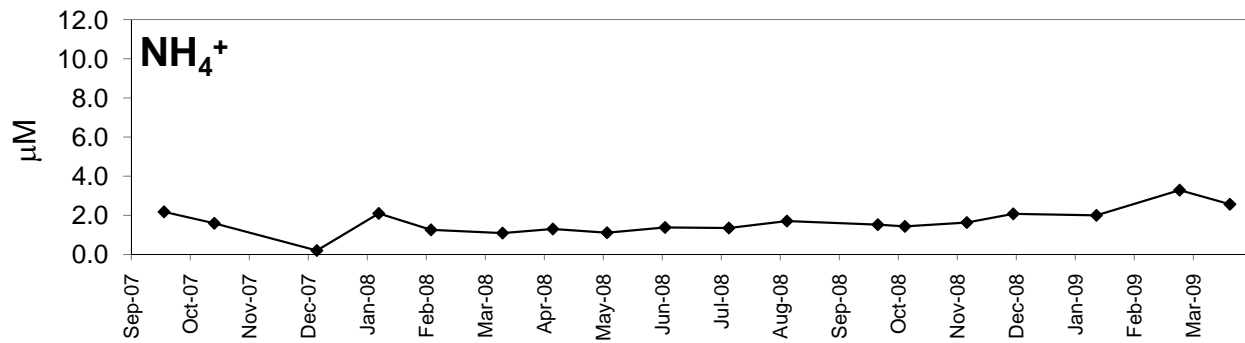
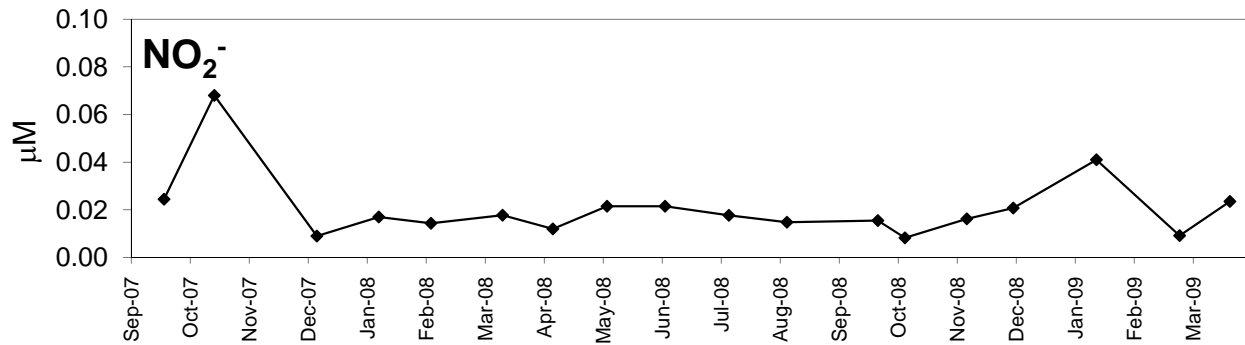
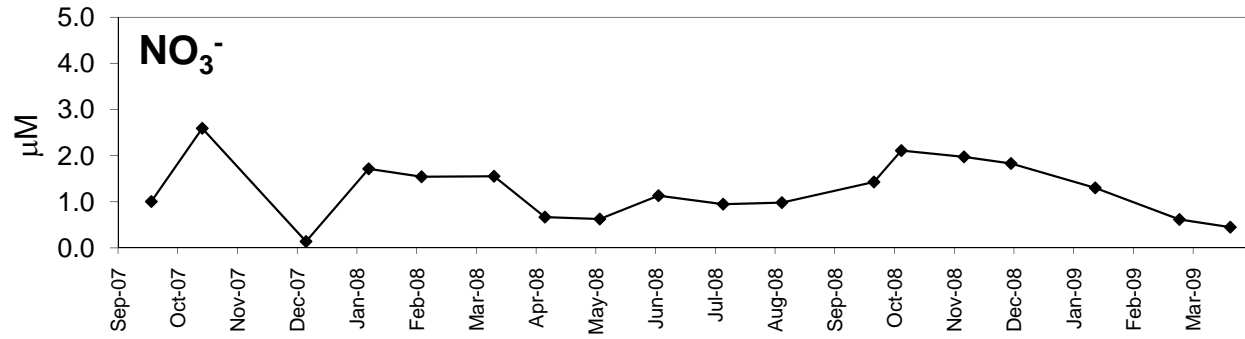
Station 17, Annie's Bay



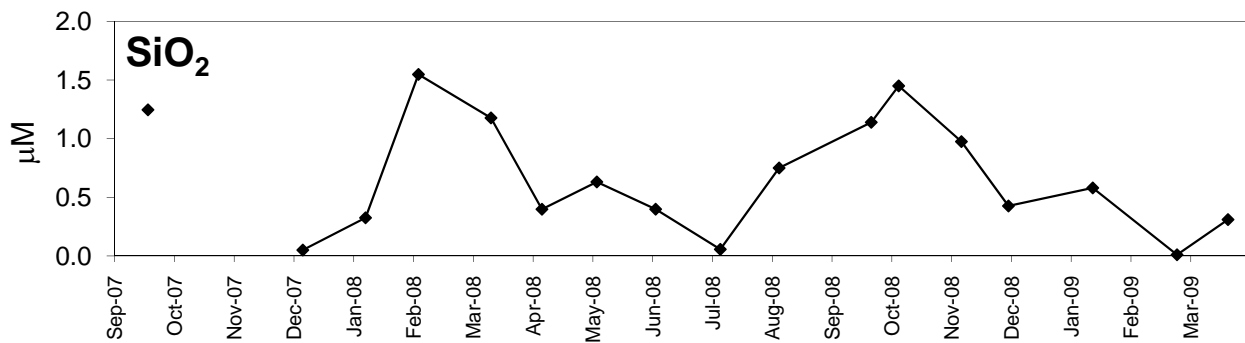
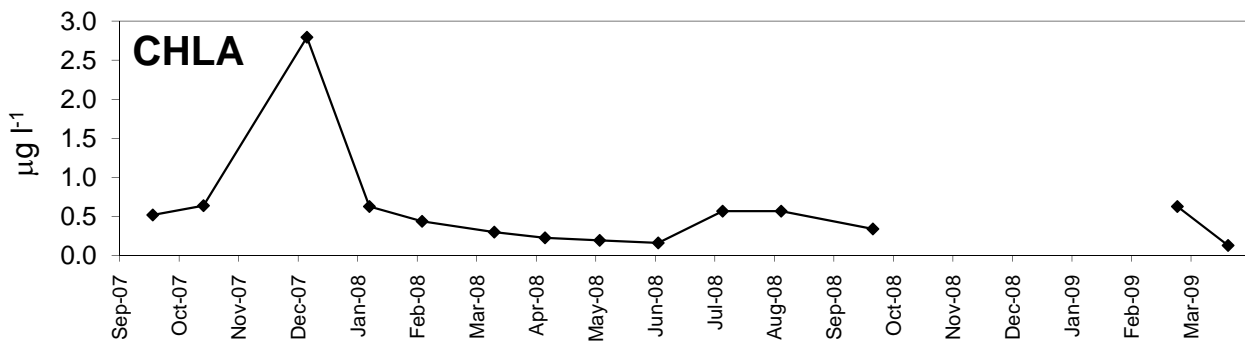
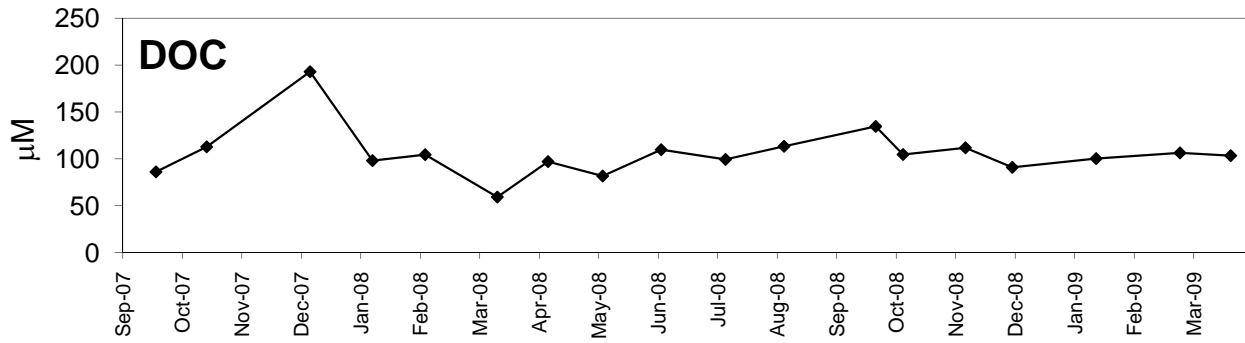
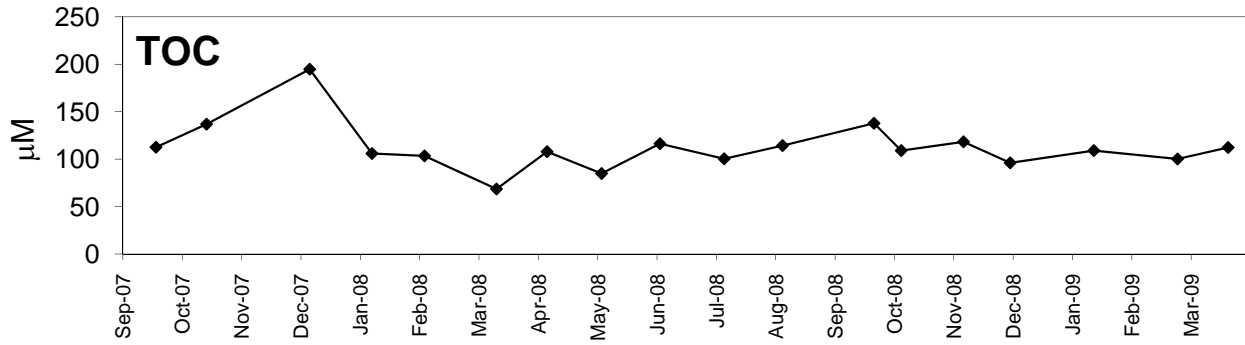
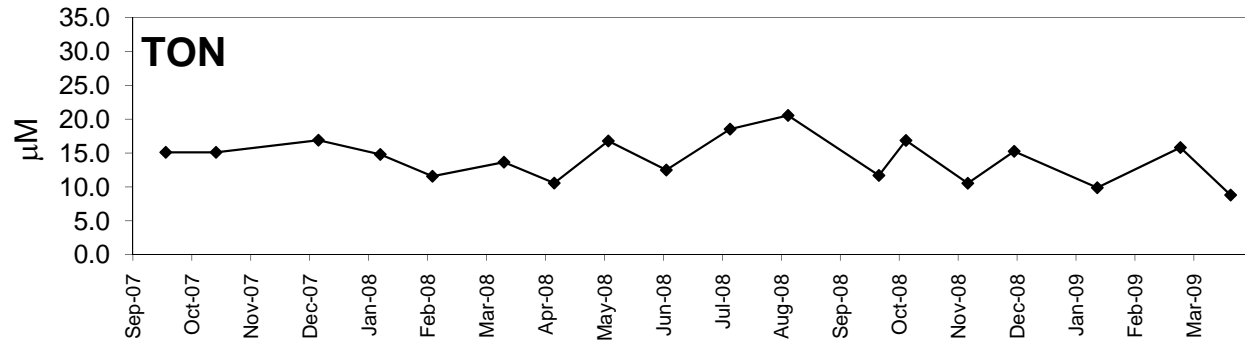
Station 17, Annie's Bay



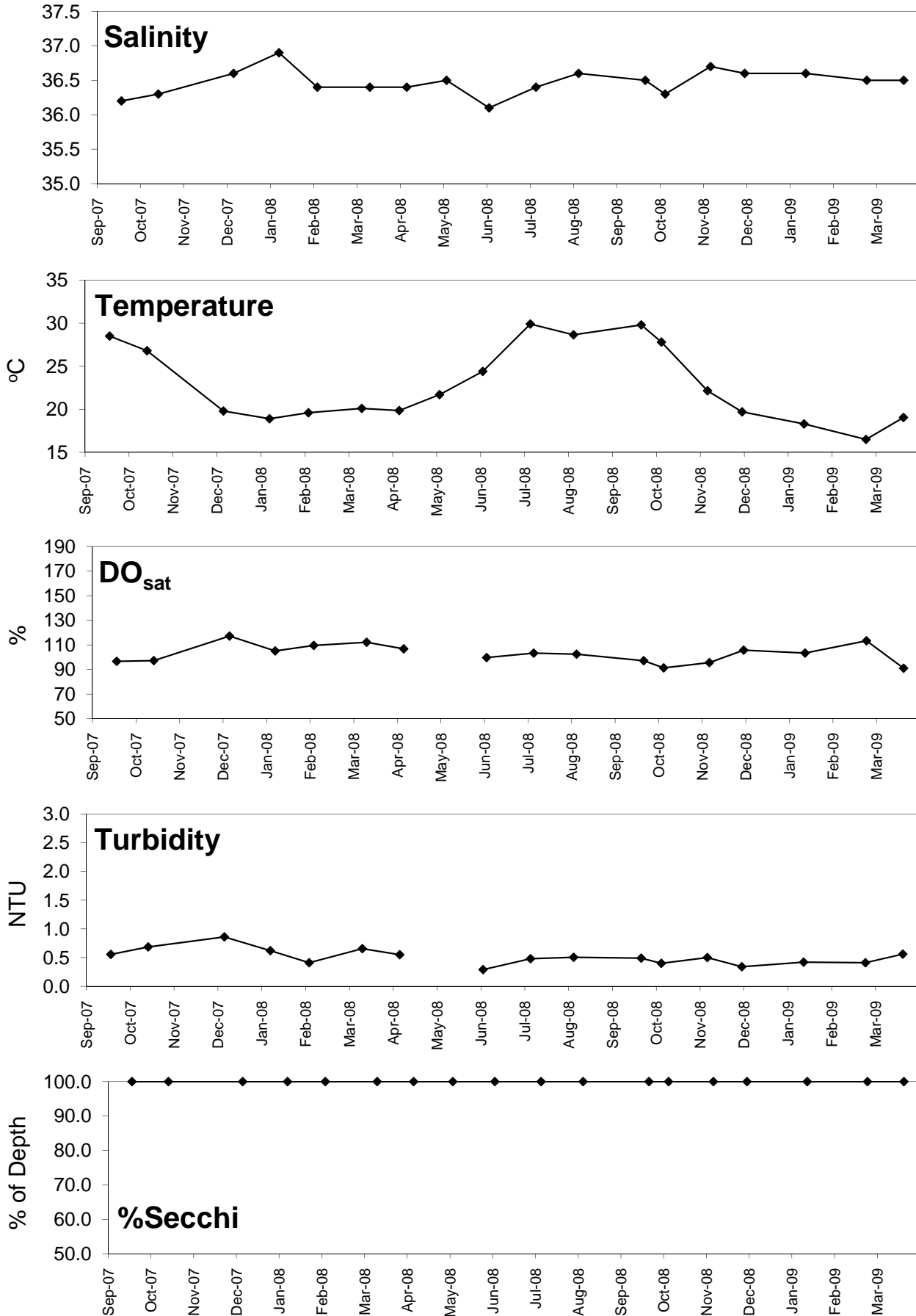
Station 18, Trunk Island



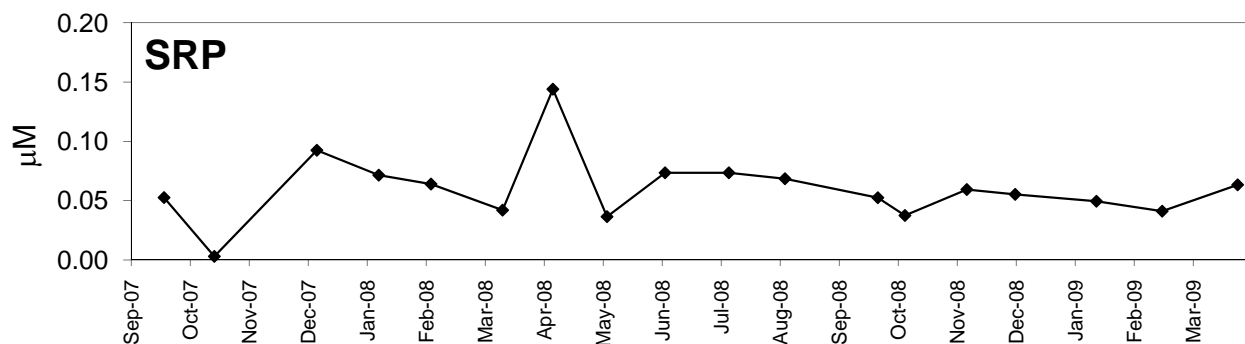
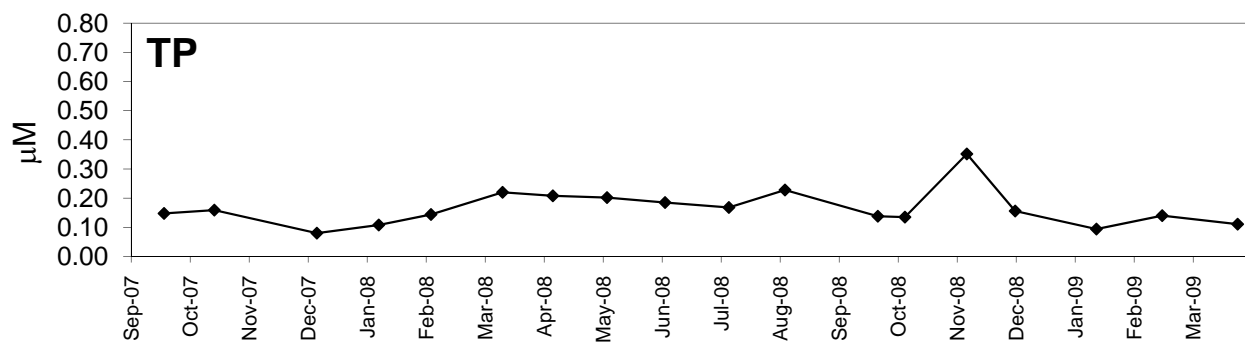
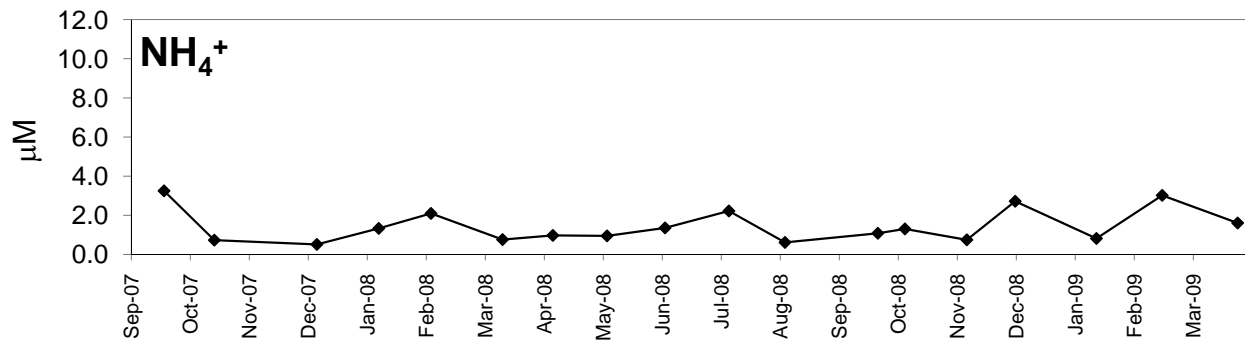
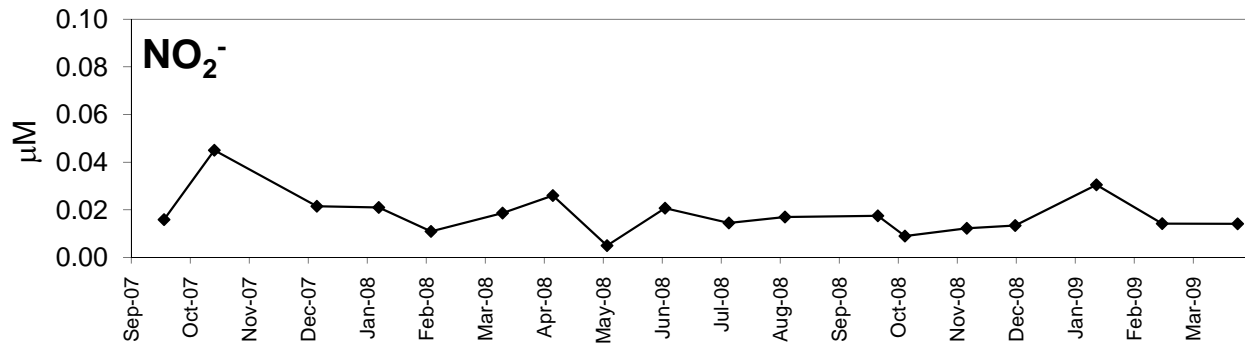
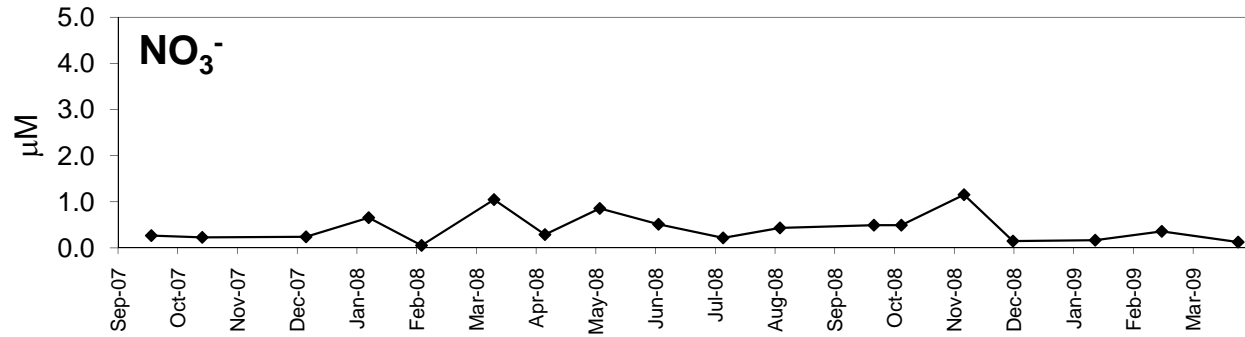
Station 18, Trunk Island



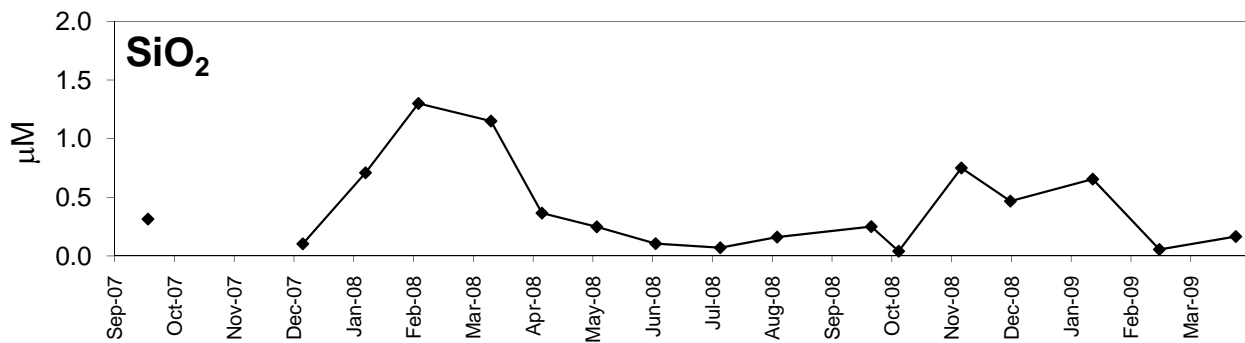
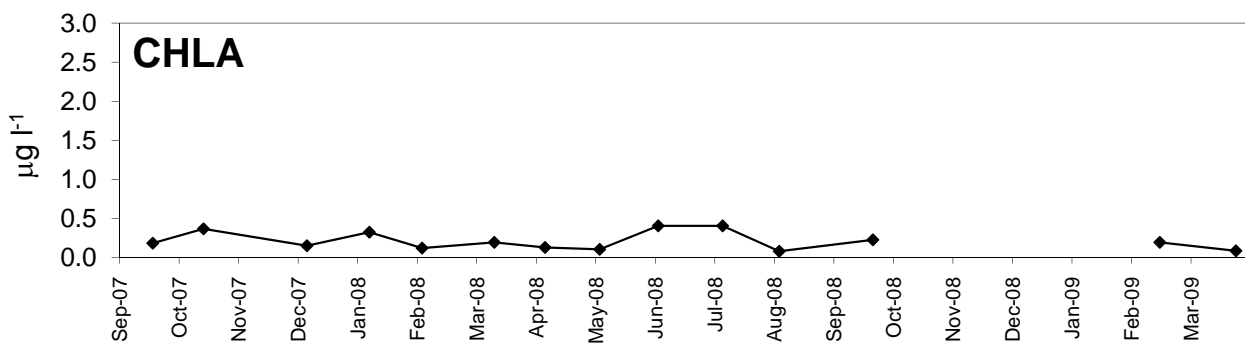
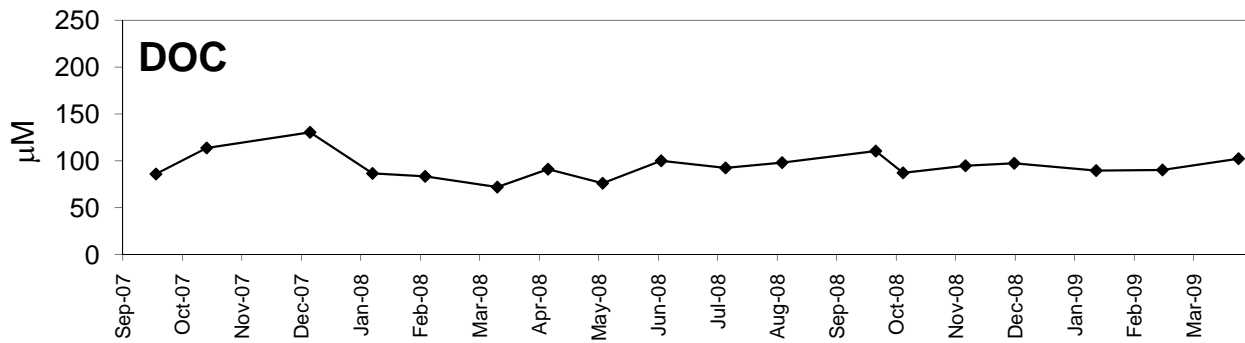
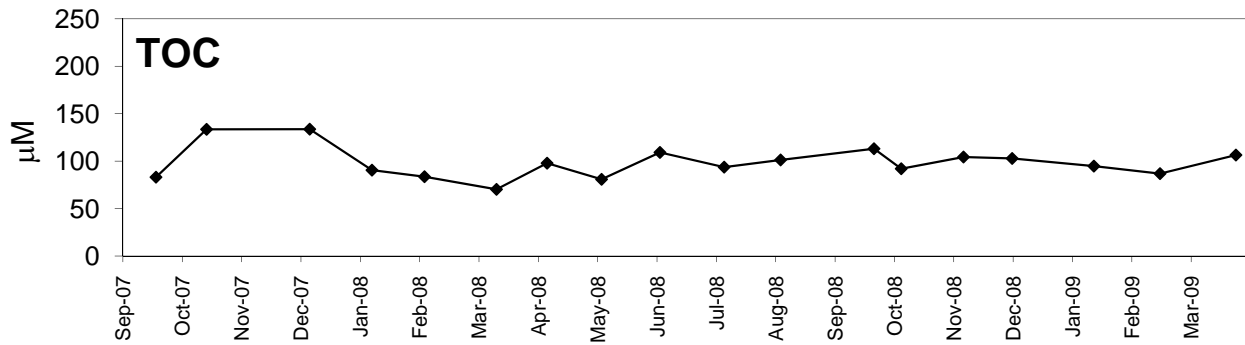
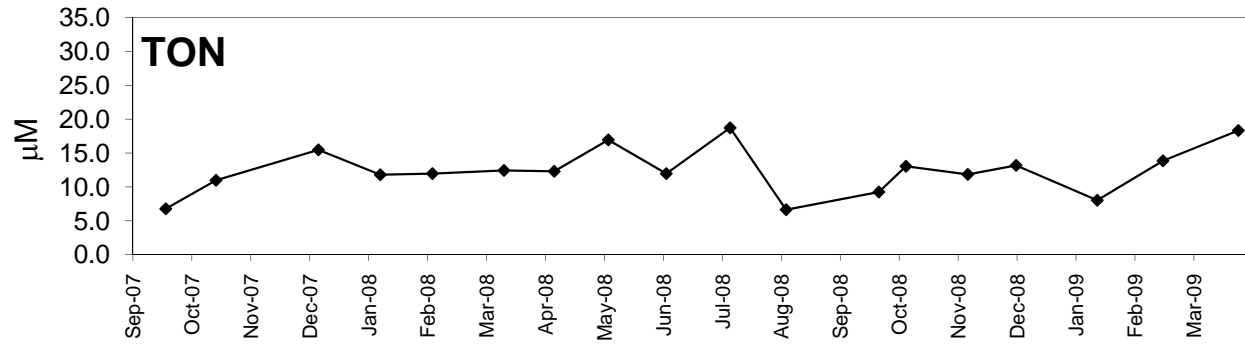
Station 18, Trunk Island



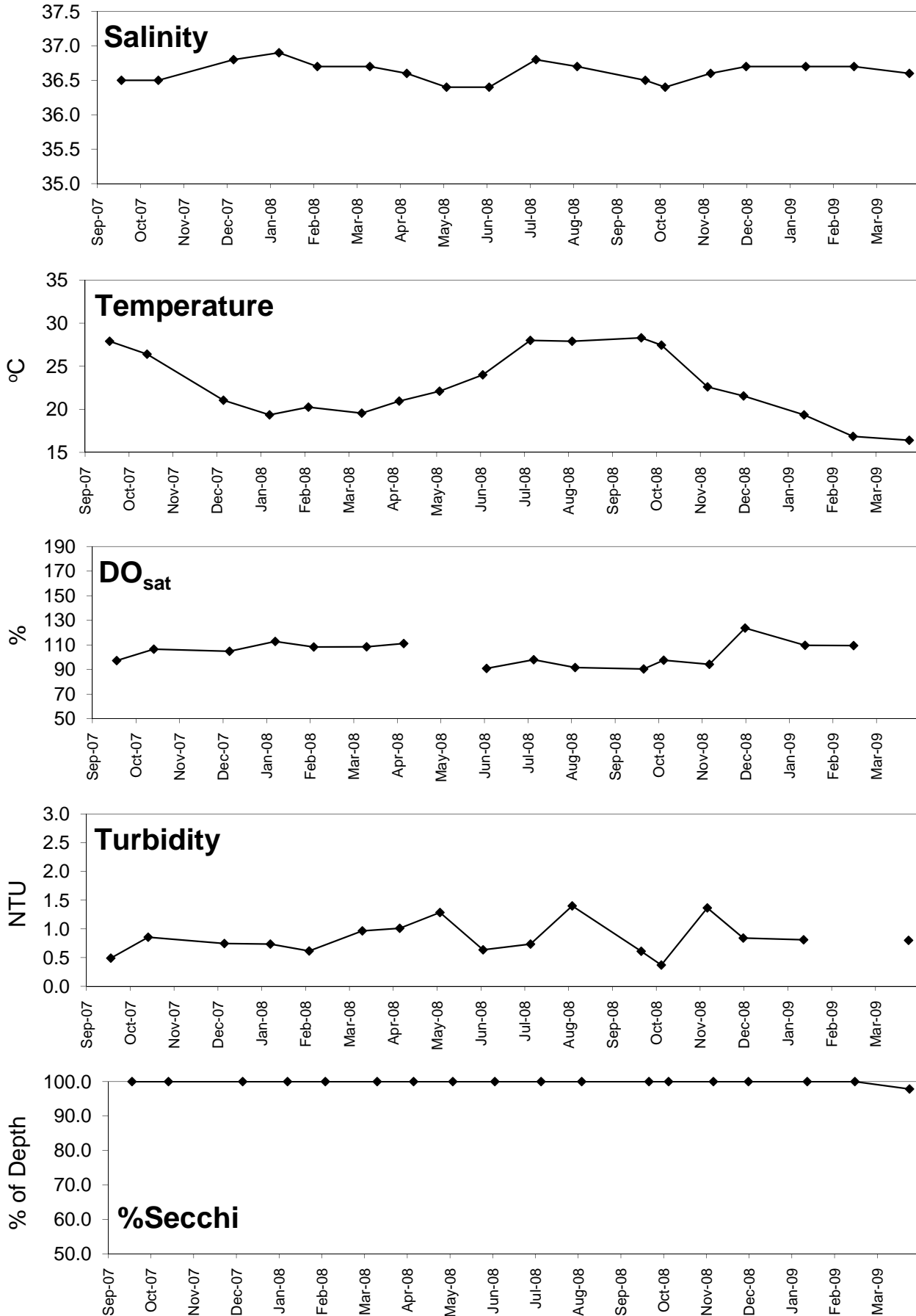
Station 19, Walsingham Park



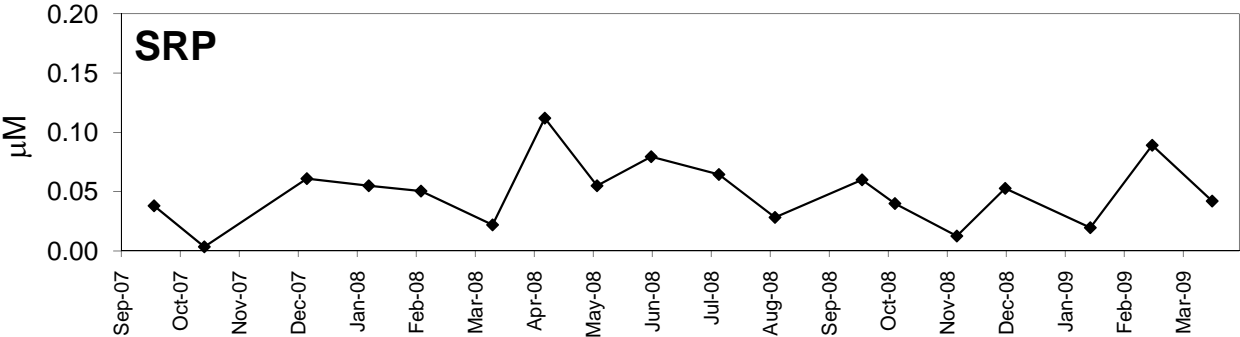
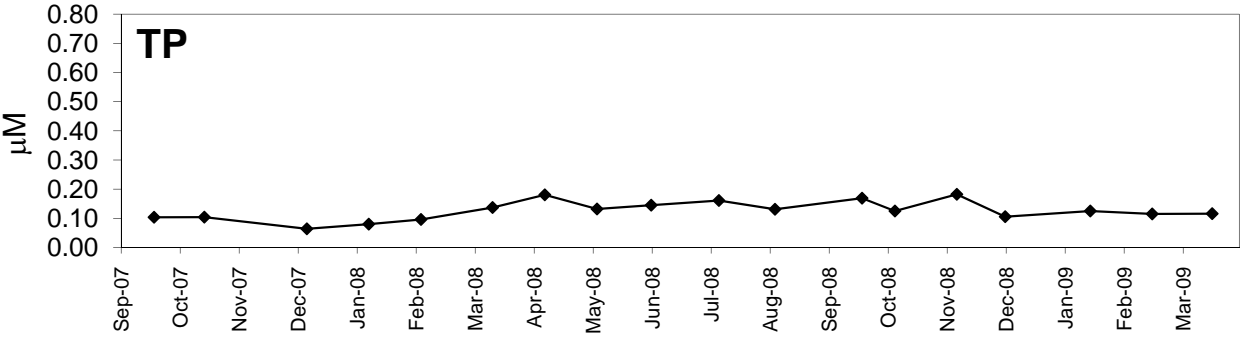
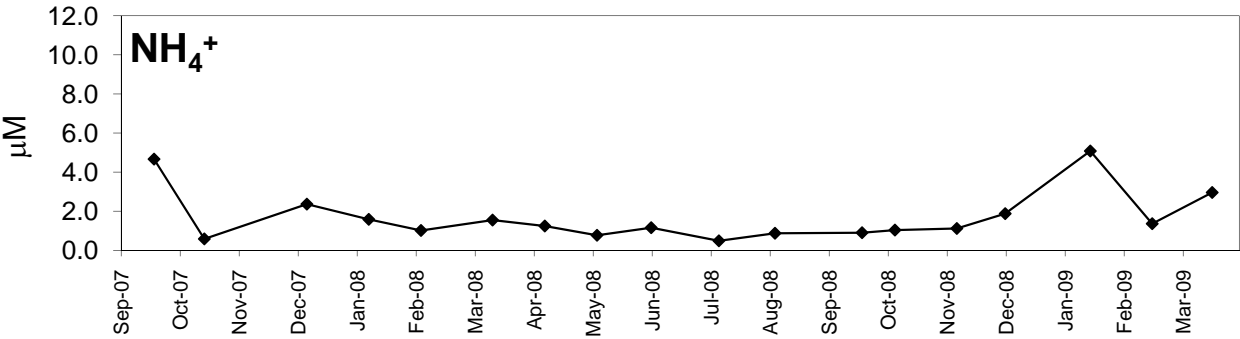
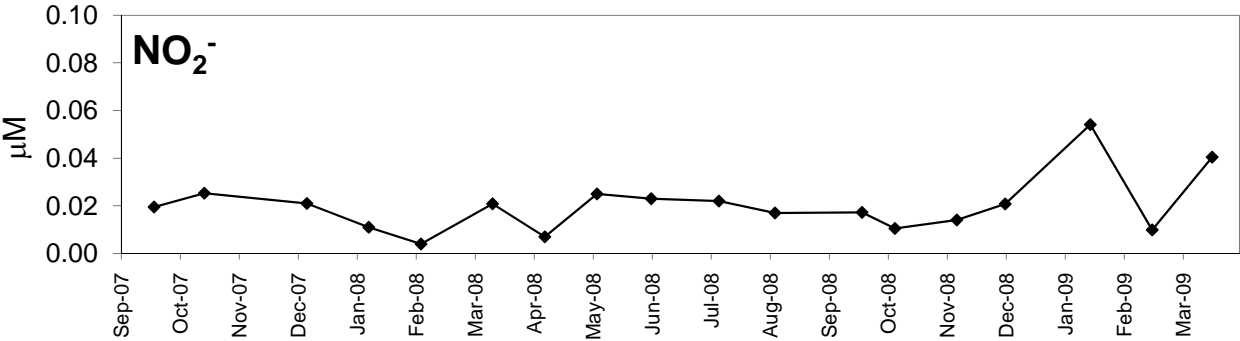
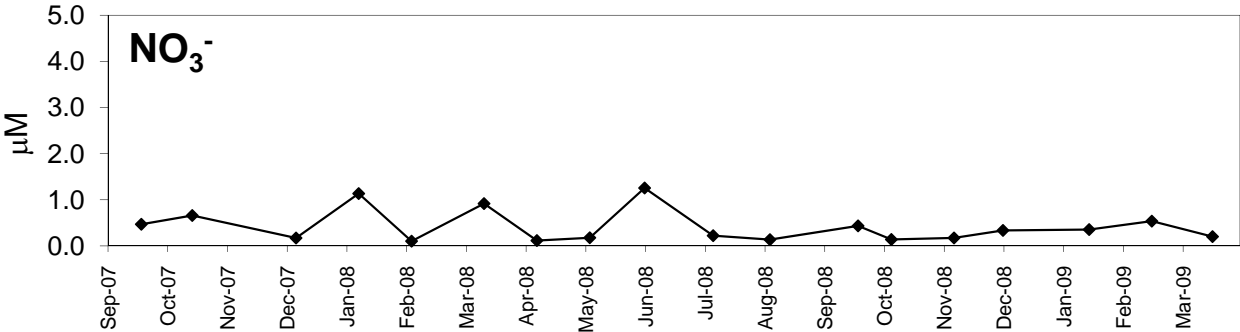
Station 19, Walsingham Park



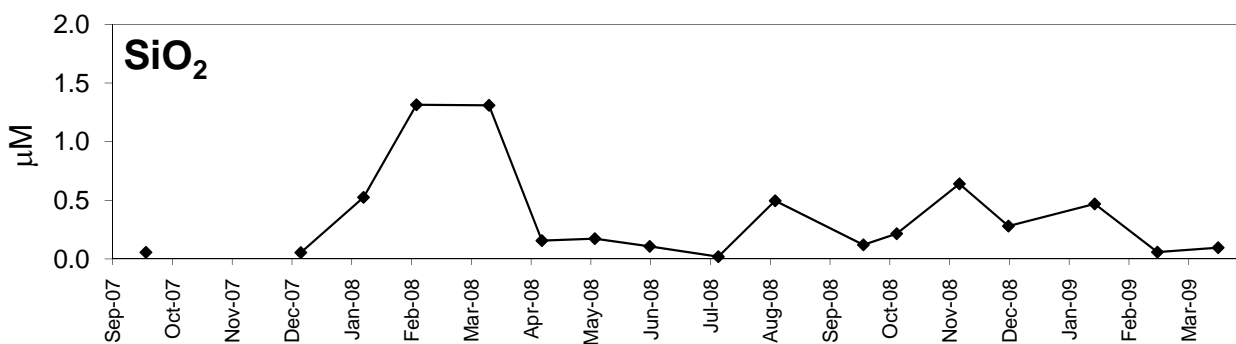
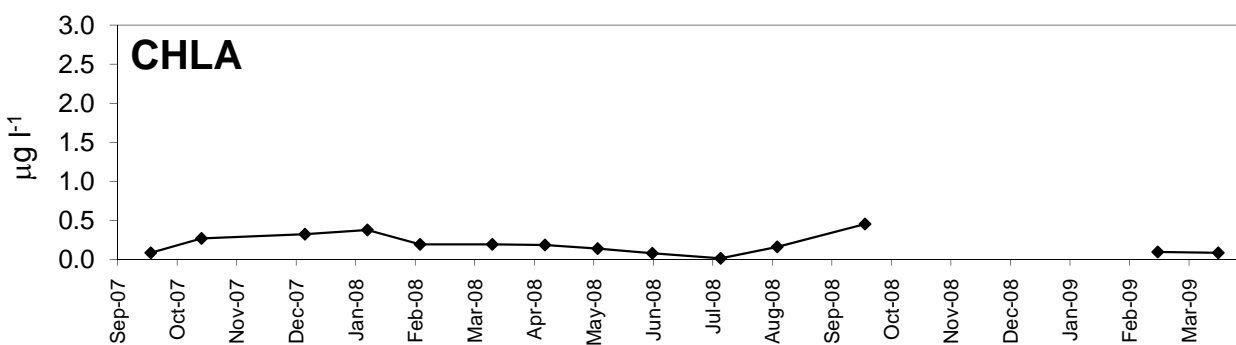
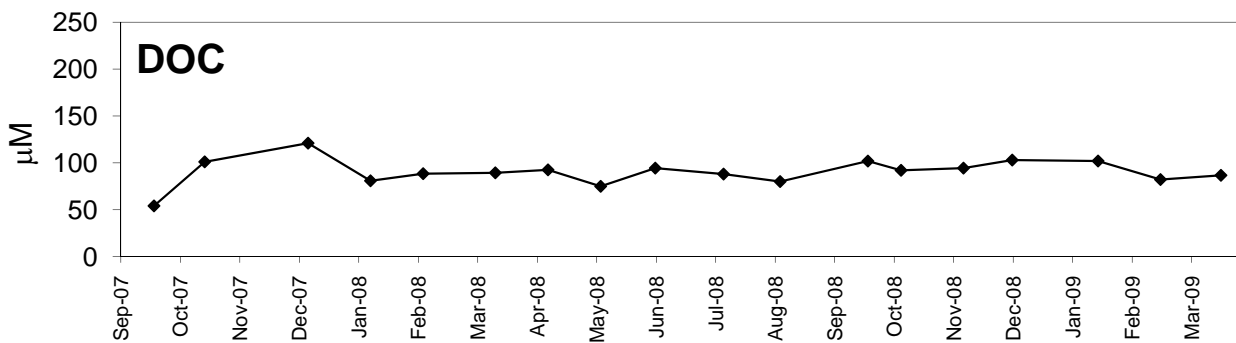
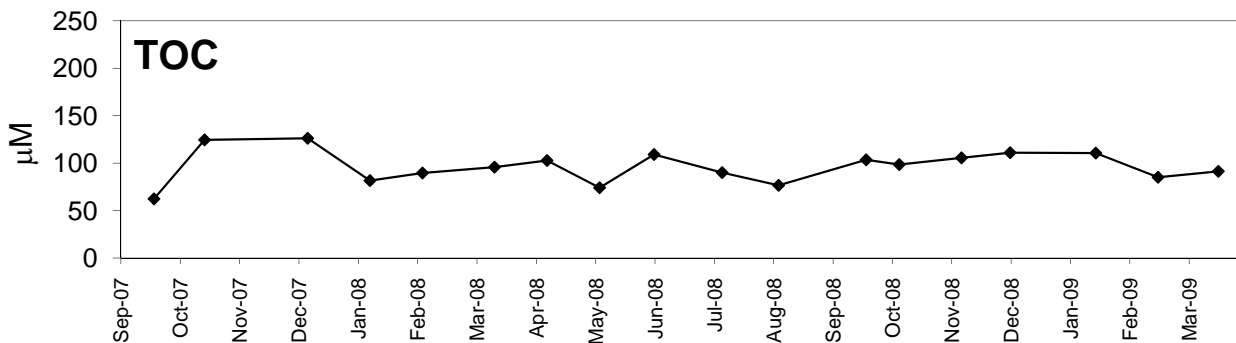
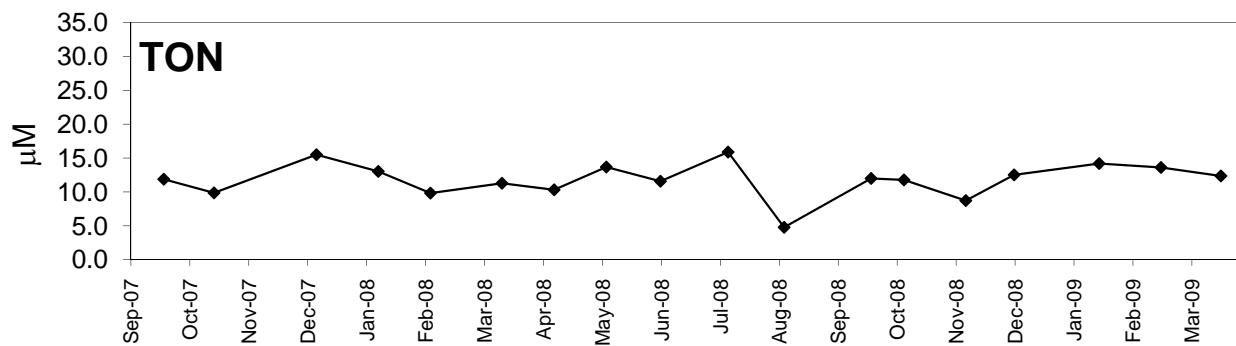
Station 19, Walsingham Park



Station 20, North Rock Conch Bed



Station 20, North Rock Conch Bed



Station 20, North Rock Conch Bed

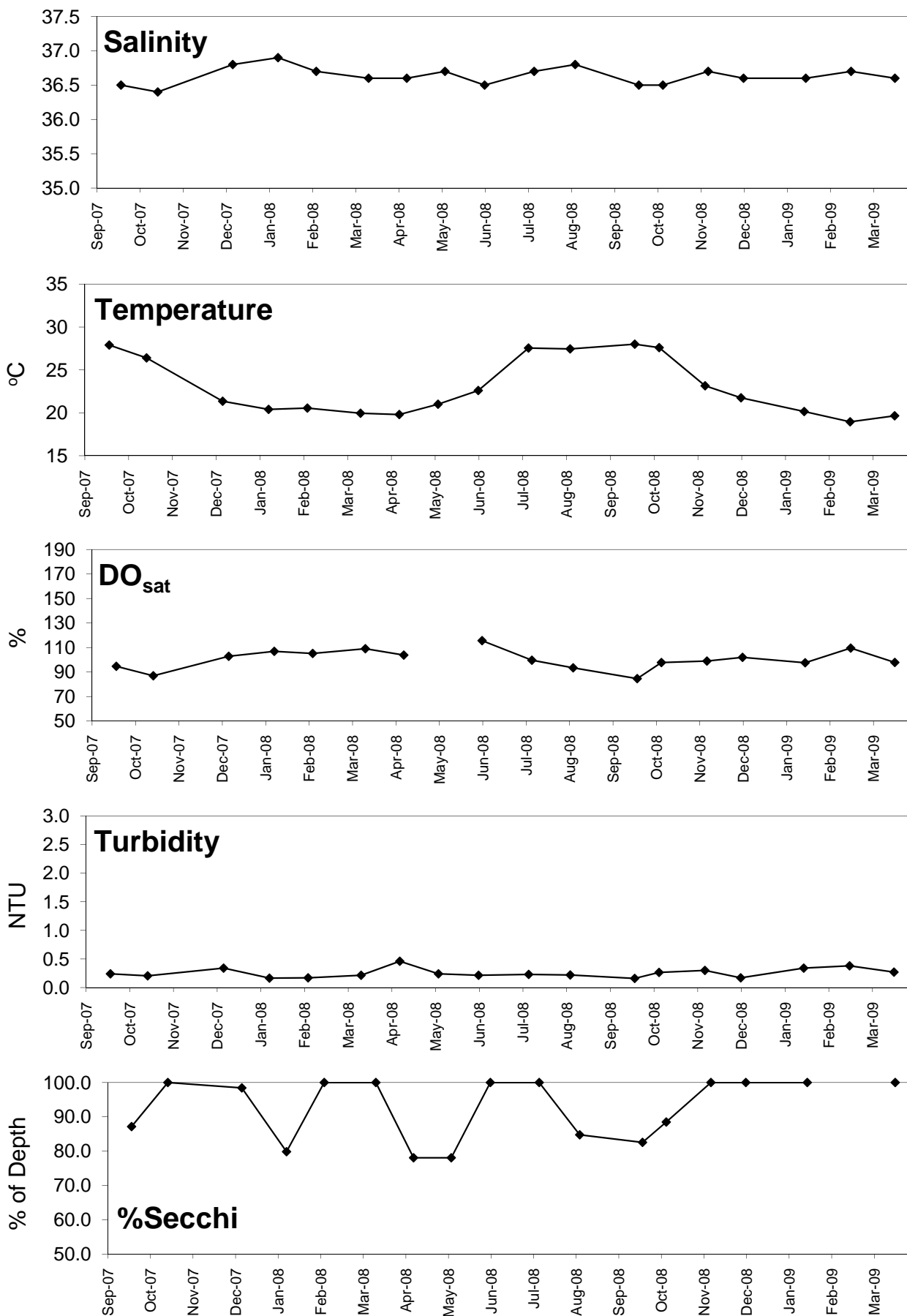


Table 1.

Variable	Cluster	Median	Min.	Max.	<i>n</i>
Surface	Total	0.356	0.010	4.250	305
NO ₃ (μM)	1	0.834	0.109	4.250	54
	2	0.319	0.038	2.570	143
	3	0.235	0.010	1.345	90
	4	1.217	0.139	2.592	18
Surface	Total	0.017	0.000	0.253	305
NO ₂ (μM)	1	0.017	0.000	0.064	54
	2	0.018	0.001	0.253	143
	3	0.017	0.000	0.098	90
	4	0.017	0.008	0.068	18
Surface	Total	1.149	0.193	10.026	305
NH ₄ (μM)	1	1.168	0.612	5.368	54
	2	1.087	0.290	7.308	143
	3	1.159	0.427	10.026	90
	4	1.550	0.193	3.281	18
Surface	Total	12.05	4.11	33.05	305
TN (μM)	1	13.03	5.85	33.05	54
	2	12.05	5.52	24.83	143
	3	11.61	4.11	18.78	90
	4	14.95	8.80	20.55	18
Surface	Total	9.98	0.30	28.50	305
TON (μM)	1	10.50	2.55	28.50	54
	2	9.99	2.07	23.72	143
	3	9.44	0.30	17.06	90
	4	10.98	5.77	17.85	18
Surface	Total	0.141	0.020	1.474	305
TP (μM)	1	0.158	0.065	0.460	54
	2	0.145	0.020	1.474	143
	3	0.125	0.050	0.309	90
	4	0.168	0.093	0.360	18
Surface	Total	0.048	0.001	0.715	305
SRP (μM)	1	0.052	0.014	0.123	54
	2	0.048	0.003	0.144	143
	3	0.045	0.001	0.715	90
	4	0.056	0.019	0.107	18

Variable	Cluster	Median	Min.	Max.	<i>n</i>
Surface	Total	98.333	57.750	194.750	305
TOC	1	102.917	61.500	151.583	54
(μM)	2	96.417	57.750	168.333	143
	3	95.667	62.333	131.417	90
	4	109.000	68.500	194.750	18
Surface	Total	93.6	53.8	192.9	305
DOC	1	97.3	53.8	175.0	54
(μM)	2	92.8	54.7	136.7	143
	3	90.5	54.2	129.9	90
	4	104.0	59.3	192.9	18
Surface	Total	0.33	0.00	1.67	288
SiO ₂	1	0.38	0.01	1.67	51
(μM)	2	0.31	0.00	1.36	135
	3	0.27	0.02	1.33	85
	4	0.58	0.01	1.55	17
Surface	Total	0.19	0.02	2.79	238
CHLA	1	0.23	0.08	0.74	42
($\mu\text{g l}^{-1}$)	2	0.18	0.04	0.53	112
	3	0.14	0.02	0.49	70
	4	0.48	0.13	2.79	14
Surface	Total	36.60	36.00	37.20	340
Salinity	1	36.60	36.00	37.00	60
	2	36.60	36.30	37.20	160
	3	36.65	36.30	37.00	100
	4	36.45	36.10	36.90	20
Surface	Total	21.33	16.25	29.90	340
Temp.	1	21.03	16.25	29.55	60
($^{\circ}\text{C}$)	2	21.40	16.40	29.65	160
	3	21.35	17.50	28.85	100
	4	20.90	16.50	29.90	20
Surface	Total	7.40	5.53	10.98	320
DO	1	7.68	5.53	10.98	56
(mg l^{-1})	2	7.46	5.96	8.97	150
	3	7.14	5.55	8.47	95
	4	7.05	6.05	8.67	19
Surface	Total	0.48	0.16	2.70	336
Turbidity	1	0.53	0.24	1.61	59
(NTU)	2	0.56	0.19	2.70	159
	3	0.31	0.16	0.81	99
	4	0.49	0.28	0.86	19

Variable	Cluster	Median	Min.	Max.	<i>n</i>
% Secchi	Total	100.0	49.2	106.9	305
	1	100.0	98.4	100.0	54
	2	100.0	67.4	104.4	144
	3	100.0	49.2	106.9	89
	4	100.0	100.0	100.0	18
Surface TN:TP	Total	87.6	10.7	691.6	305
	1	82.6	19.2	235.4	54
	2	84.5	10.7	691.6	143
	3	98.6	33.6	242.1	90
	4	81.8	38.8	124.4	18
Surface DO _{sat} (%)	Total	104.9	82.1	165.6	320
	1	108.1	82.1	165.6	56
	2	106.0	89.0	123.7	150
	3	101.2	84.0	117.3	95
	4	103.4	91.0	117.2	19