Technical Report

Assessing the Effect of Hydrating Snake Warrior's Island Natural Area with Urban Storm Water

Technical Report 06-02

Broward County Environmental Protection Department
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EXECUTIVE SUMMARY

Snake Warrior's Island Natural Area (SWI) is a 53-acre park located in Miramar Florida. This multi-use system was developed by Broward County's Department of Community Services' Parks and Recreation Division (PRD) in partnership with Broward County Water and Wastewater Services. The primary management concern is the preservation and protection of the archeological and cultural resources of SWI. Secondary management considerations include the use of the site as a passive recreational and educational facility, restoration and maintenance of historic wetlands and use as a storm water management area. Storm water is used to hydrate the wetlands cells during the rainy season. Concerns over the quality of storm water entering the SWI system led to a request from PRD to Broward County's Environmental Protection Department to assess surface water quality in the wetlands of SWI.

This report details a seven month water quality study of the reconstructed wetlands in the Snake Warrior's Island Natural Area, and its primary surface water inputs. This study was conducted by Broward County's Environmental Protection Department (BCEPD)'s Environmental Monitoring Division (EMD) to determine if local drainage systems were providing adequate pre-treatment of storm water, and to assess the benefits and concerns of rewatering/rehydrating natural systems with urban storm water. The water quality assessment results and associated management applications will be the primary topic covered in this document. Specific activities included; characterizing the composition of the water masses entering the SWI system and determining the distribution of nutrients, metals, and organic compounds in the water, sediment and plants in the three major wetland cells.

The C-9 canal via the US 441 storm water system and ground water are the two primary sources of water to the wetlands of Snake Warrior's Island. Rain and storm water provide some additional water to the wetlands. Hydraulic gradients in the storm water system along US 441 allow water to flow north from the C-9 canal into SWI as long as water is not being released to tide through the S29 salinity control structure on the C-9 canal. The S29 structure is located approximately 5 miles south east of SWI on the C-9 canal. Water management practices at S29 strongly influences water levels at SWI. If gates are open at S29 during and after rain events, the hydraulic gradients along US 441 are reversed and storm water bypasses SWI and flows south to the C-9 canal. The only time this connection is severed is during very heavy or protracted rain events when the storm water system is overloaded and excess water is then diverted into SWI.

YSI sondes were deployed in the retention pond and wetland 3 within the Snake Warrior's Island Natural Area. Sondes were programmed to log water quality parameters every 15 minutes and were deployed for a week at a time. Parameters measured included: water elevation, specific conductance, dissolved oxygen, pH, chlorophyll, and turbidity. Monthly water column samples and YSI readings were collected June through December 2003 from 6 sites within SWI and the C-9 canal – the main source of water to SWI. Samples were analyzed for inorganic nutrients, metals, organic compounds, turbidity and total organic carbon. Nutrient and metal concentrations were determined in plant and sediment samples collected in August and December 2003. In addition to water column sampling, storm water samples were collected at two sites – a storm water grate just inside SWI and at Ronald St. in Miami Gardens. A multi-

million dollar retrofit of the storm water system in the Miami Gardens neighborhood was completed in spring 2003. One of the goals of the retrofit was to improved drainage in this neighborhood so the system was designed such that excess storm water from Miami Gardens would be diverted into the wetlands cells of SWI during the rainy season. Storm water samples were analyzed for the same parameters as monthly samples.

Results of this study suggest biogeochemical processes internal to the wetlands of SWI rather than external inputs from the C-9 canal and storm water govern the distribution of nutrients, metals and organic compounds in the surface waters and sediments of the Snake Warrior's Island Natural Area. Water column process (photosynthesis/respiration) and benthic flux are probably the primary drivers influencing the distribution of materials in this system. Nutrient concentrations were typically lower in the retention pond which receives direct inputs of C-9 water and storm water, relative to wetland 5A, the wetland furthest from source waters.

No consistent trends in metals concentrations were observed in surface waters in SWI or storm waters with the exception of vanadium. Vanadium concentrations in surface waters decreased with distance from the C-9 canal. The lowest levels were measured in wetland 5A, the last wetland along the gradient at SWI. The concentrations of most other metals were below Broward County's surface water standards for fresh water and often close to minimum detection limits. Selenium, zinc and copper were the three exceptions. Elevated water column selenium levels were found on one date at all sites within SWI but not at the C-9 canal, suggesting localized source within SWI. Elevated zinc levels were measured at all sites including the C-9 on two consecutive dates. The broad geographic distribution of zinc hits, suggests an atmospheric source.

Elevated copper concentrations were measured at some of the sites in SWI but no consistent trend was observed. Copper was also the only metal detected in sediment samples from the wetlands at SWI. Aquatic weed management practices within the boundaries of SWI may account for the spikes of copper in the water column and its persistence in sediments. A copper based herbicide was used regularly in the wetlands to control for the exotic aquatic plant *Hydrilla verticilatta* at SWI. The repeated application of this product may also explain why copper is accumulating in sediments from the wetlands. Switching to an alternative non-copper based herbicide should prevent the further accumulation of copper in the wetlands of SWI. Polycyclic aromatic hydrocarbon concentrations in surface waters as well as storm water from both Miami Gardens and Snake Warrior's Island were all below minimum detection limits. The data suggest pretreatment of storm water is effective.

Overall, the results of this study, suggest that composition of external inputs such as C-9 water and storm water to Snake Warrior's Island, have a minimal effect on the distribution and cycling on materials in the wetlands of SWI. Biological, physical and chemical processes internal to the wetlands appear to drive the absolute concentrations and distribution of dissolved nutrients and many of metals.

Diverting water from the C-9 canal has been shown to be both an effective and innovative means of hydrating the wetlands of Snake Warrior's Island Natural Area. Regional water management activities, however, will determine the sustainability of this strategy. The results of this study also pointed to the complex hydrology of this system. Diversion of storm water into SWI was only partially successful as water management activities at the S29 structure on the C-9 canal altered hydraulic gradients in unanticipated ways. Releasing water to tide through S29, shifted hydraulic gradients such that storm water bypassed SWI and flowed directly south to the C-9 during most rainfall events. Construction of any additional storm water/wetland projects may need to consider the regional hydrology during the planning process. The newly constructed drainage system in Miami Gardens appears to be functioning as designed and is providing adequate pretreatment of storm water while minimizing flooding.

The Snake Warrior Island project should be considered one of the success stories of the Integrated Water Resource Plan of Broward County and is a good example of several government organizations working together to meet the ecological, recreational and archaeological goals of a project.

The following recommendations were made at the conclusion of this project.

1. Based on monthly water quality sampling results, the C-9 Canal should continue to be used as the main surface water source for SWI. Regional water management activities will ultimately determine the sustainability of this localized wetland hydration strategy.

2. The utilization of a pre-existing storm water treatment pond with a wetlands system appears to have at least some 'pretreatment' advantages (e.g., herbicides) and should be considered in future projects. However, storm events do not always guarantee movement of pollutants in a specified direction, (i.e. into a reconstructed wetland). Changes in hydraulic gradients on a broad geographic scale can redirect flow in the opposite direction. Thus, future storm water/wetland projects should consider the complexity of the overall hydrologic system before including a pond.

3. The retention areas within Miami Gardens appear to be functioning as designed. The performance of this system should be a goal for future storm water management projects countywide for the Broward County Water and Wastewater Services.

4. The Broward County Parks and Recreation Division may consider the use of non-copper based herbicide treatments in order to reduce external copper loadings to the SWI. In addition, the consistent decay of exotic vegetation is likely enhancing the internal cycling of nutrients. Ultimately, the aquatic plant management decisions will have to balance the constant challenge of controlling aggressive, opportunistic exotic species such as *Hydrilla* and impacts of those controls on the ecosystem.

5. This project should be considered one of the success stories of the Integrated Water Resources Plan and is an example of several governmental entities coming together to meet ecological, hydrological, recreational, and archeological goals of this project.

I. Introduction

Snake Warrior's Island Natural Area (SWI) is a 53-acre Broward County park located in the City of Miramar, FL (USA) (Fig. 1). The SWI site was once a part of the historic Snake Creek tributary system and surrounding Everglades (Fig 2a). The site includes one of the oldest documented Seminole settlements in the eastern Everglades (~1828). Subsequent to that (~1890s), the land was claimed by settlers, drained and used for pastureland and supported citrus groves. SWI is one of the few remaining underdeveloped areas in Broward County's urban core (Fig. 2b). The site was purchased in 1992 using monies from the State of Florida Emergency Archeological Property Acquisition Fund. The present day SWI site contains a dredged lake, a retention pond, eight reconstructed wetland cells connected by a series of culverts, and two archeological sites containing prehistoric and Seminole artifacts (Broward County Parks and Recreation Division (PRD) 2003).

SWI was designed as a multi-use system. Broward County Water and Wastewater Services in partnership with Broward County's Department of Community Services' Parks and Recreation Division (PRD) funded the construction of SWI. The overall project included a multi-million dollar retrofit of the storm water system in the adjacent Miami Gardens community which allows excess storm water from Miami Gardens to flow into the wetlands cells of SWI during the rainy season. PRD developed and maintains SWI as an archaeological preserve as well as a passive recreational and educational area. In addition, the PRD operates SWI as a natural area and as such had concerns over the water quality of storm water entering the system. This report details a seven month water quality assessment of the reconstructed wetlands in the Snake Warrior's Island Natural Area, and its primary surface water inputs.

Changes in land use practices over the last fifty years have significantly altered the local and regional hydrology of South Florida (Fig. 2a & 2b). In an effort to effectively manage this system, Broward County's Environmental Protection Department (BCEPD) with numerous partners, has developed the Integrated Water Resource Plan (IWRP) which includes wetland hydration as a priority for the county's eastern, urban core (Broward's County-Wide Integrated Water Resource Plan DRAFT February 2005). One of the key components of the IWRP is utilizing storm water as a renewable resource for wetland (created and remnant) hydration within urban Broward County. Since storm water reflects a major hydration mechanism for the park during the rainy season, SWI represents one the first implementation projects of the IWRP planning process.

The major objective of this study was to determine the surface water quality characteristics of the Snake Warrior's Island Natural Area (SWI) and of its major source water inputs – the C-9 also known as Snake Creek Canal, ground water and storm water. Additional objectives include; determining if the South County Improvement Project in Miami Gardens, is providing adequate pre-treatment of storm water from the Miami Gardens neighborhood, and investigate any potential impacts of management practices related to the control of the aquatic exotic plant *Hydrilla verticillata* in the wetlands of Snake Warrior's Island. The information gathered will be used to assess the benefits and concerns of rewatering/rehydrating systems with urban storm water.

Figure. 1. Map of Snake Warrior's Island Natural Area and the Surrounding City of Miramar, Broward County, FL USA.

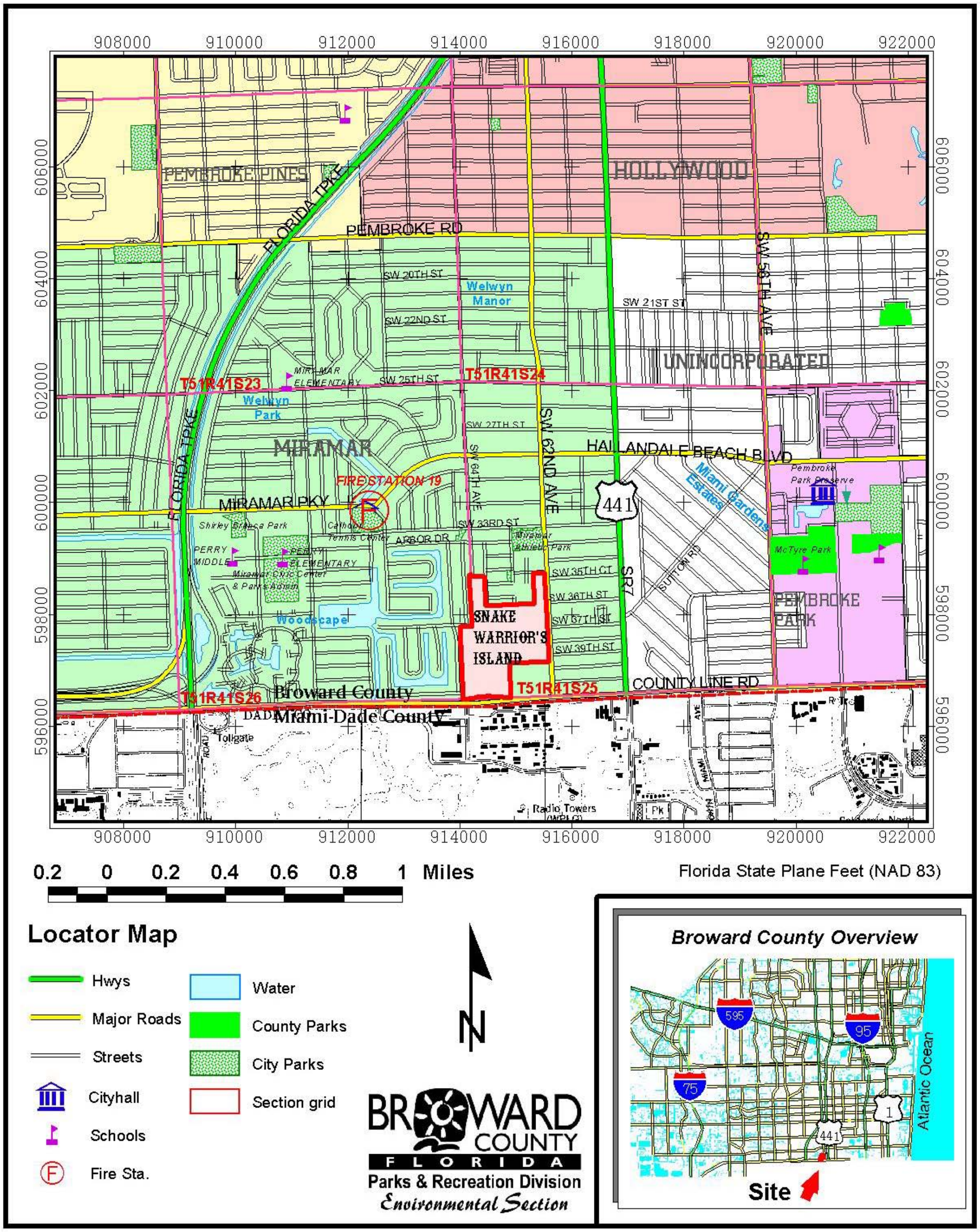


Figure 2a. 1947 Aerial Photograph of Snake Warrior's Island Natural Area. The yellow arrows indicate the direction of historical surface water flows.

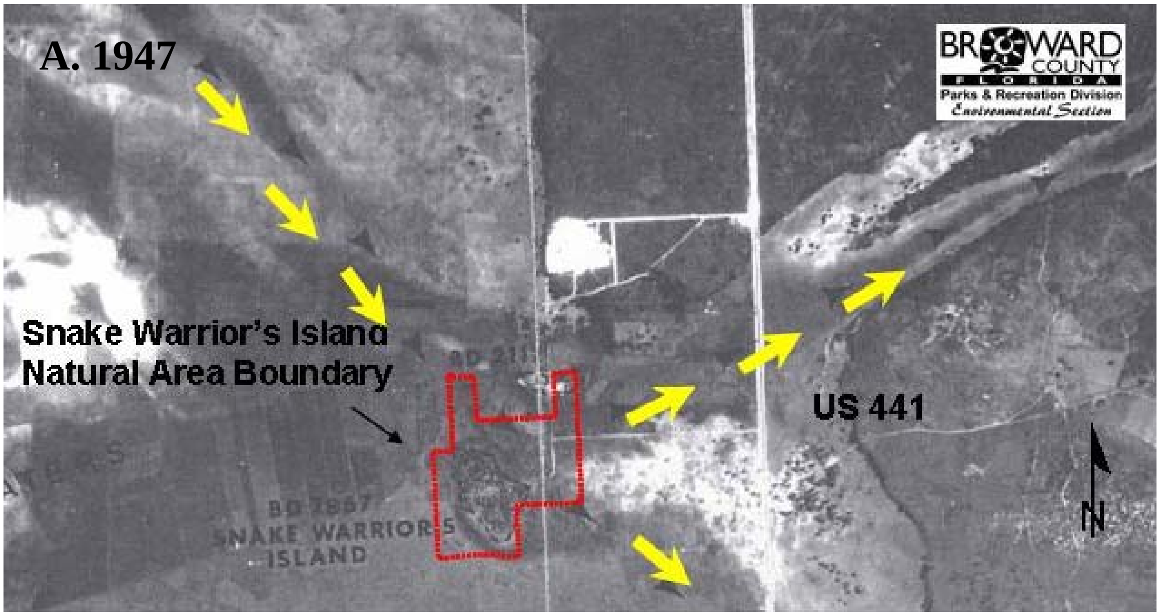


Figure 2b. 2003 Aerial Photograph of Snake Warrior's Island Natural Area.

II. Materials and Methods

A. Site Hydrology

The C-9 canal via the US 441 storm water system and ground water are the two primary sources of water to Snake Warrior's Island Natural Area (SWI) (Fig. 3). Secondary and somewhat sporadic sources of water to SWI include rain and storm water. The C-9 canal provides approximately 1 to 3 million gallons of water per day to SWI during non-rainy periods. Hydraulic gradients in the storm water system connecting the C-9 canal to SWI allow water to flow north from the C-9 canal as long as water is not being released to tide through the S29 salinity structure on the C-9 canal. The S29 control structure is located approximately 5 south east of SWI on the C-9 canal in Miami-Dade County. If water is being released to tide through S29, storm water bypasses SWI and flows south into the C-9 canal. During heavy and/or prolonged rain events storm water from the area immediately adjacent to SWI and the nearby community of Miami Gardens is diverted into SWI. Water enters the park through a six foot diameter storm water culvert connected to the retention pond. A broad crested weir with two 24 inch diameter flap gates connects the retention pond to wetland 3 (Fig. 4a & b). Movement of water through the flap gates is controlled by hydraulic gradients between the retention pond and wetland 3. If water levels are higher in the retention pond than in the wetland, water flows into the wetland. However, if water levels are higher in the wetlands, the flap gates are forced closed and the water is retained in the wetlands. Once water enters the wetlands, it moves from wetland 3 into adjacent wetlands (Fig. 5).

B. Monitoring Program

Water quality was monitored from June 2003 thru December 2003. The purpose of this project was to characterize the composition of C-9 water, ground water and storm water entering SWI. Specific goals include; determining the relative contribution of C-9 water, ground water and storm water, if any to the composition of surface waters in the wetlands at SWI, and assess the benefits and concerns of rehydrating systems such as SWI with urban storm water. Rain is an additional source of water to SWI, and while there is no question rain inputs can influence the composition of surface waters at SWI on the short term, it was beyond the scope of this study to assess the effects atmospheric inputs have on surface waters in the wetlands.

1. *In situ* Unattended Monitoring

Two YSI series 6600 multi-parameter water quality monitoring instruments were placed at SWI. One instrument or sonde was located in the retention pond and the other in wetland 3, the wetland adjacent to the retention pond (Fig. 5). Sondes were housed in perforated PVC casings attached to poles in the retention pond and wetland 3, and were accessible by boat (Fig. 6 a and 6b). Sondes were exchanged on a weekly basis in order to download data, conduct maintenance and verify sensors remained within the accepted calibration ranges for each parameter. Measurements were collected every 15 minutes, 24 hours a day, providing a record of fine scale temporal variability for the following parameters; water level, dissolved oxygen (D.O.), temperature, specific conductance, chlorophyll by fluorescence, pH, and turbidity. In conjunction with the weekly exchanges of sondes, water column samples for chlorophyll-a (Chl_a)

Figure 3. Map of the Drainage and Storm Water System Flowing into Snake Warrior's Island Natural Area (SWI). Water flows north from the C-9 canal under U.S. 441 and then west into Snake Warrior's Island during non rainy periods. During rainy periods, water in the canal is released to tide through the S29 salinity structure on the C-9 canal. Releasing water to tide creates hydraulic gradients such that the direction of flow is reversed along U.S. 441 and the storm water flows south to the C-9 canal. Water enters the C-9 canal and flows south/southeast eventually passing through the S29 salinity structure. The S29 structure on the C-9 canal is located approximately 5 miles southeast of SWI in Miami-Dade County.

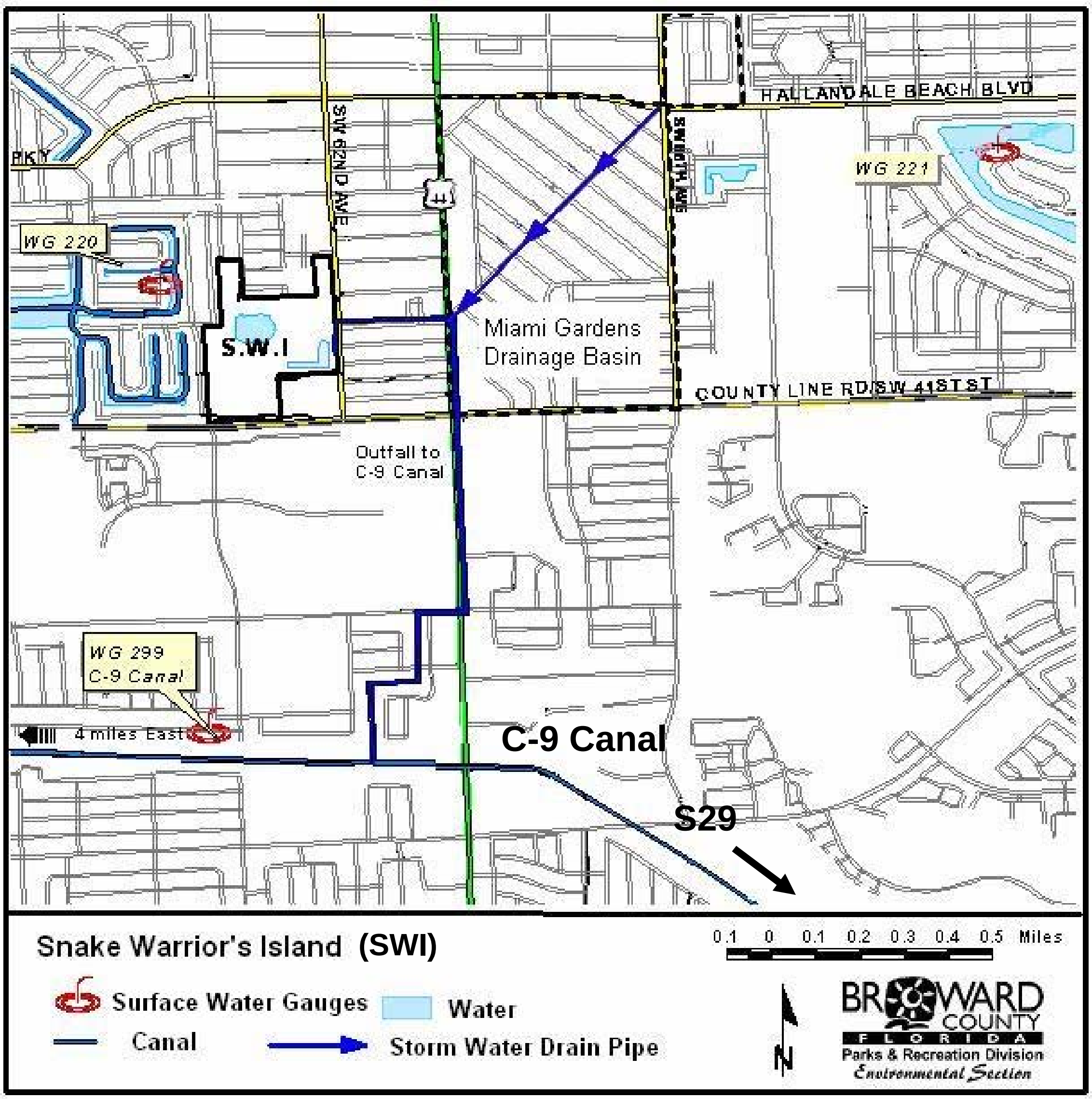


Figure 4a. The Broad Crested Weir between the Retention Pond and Wetland 3 at Snake Warrior's Island Natural Area. The aquatic exotic weed *Hydrilla verticillata* can be seen in the retention pond and was introduced to Snake Warrior's Island via the C-9 canal.

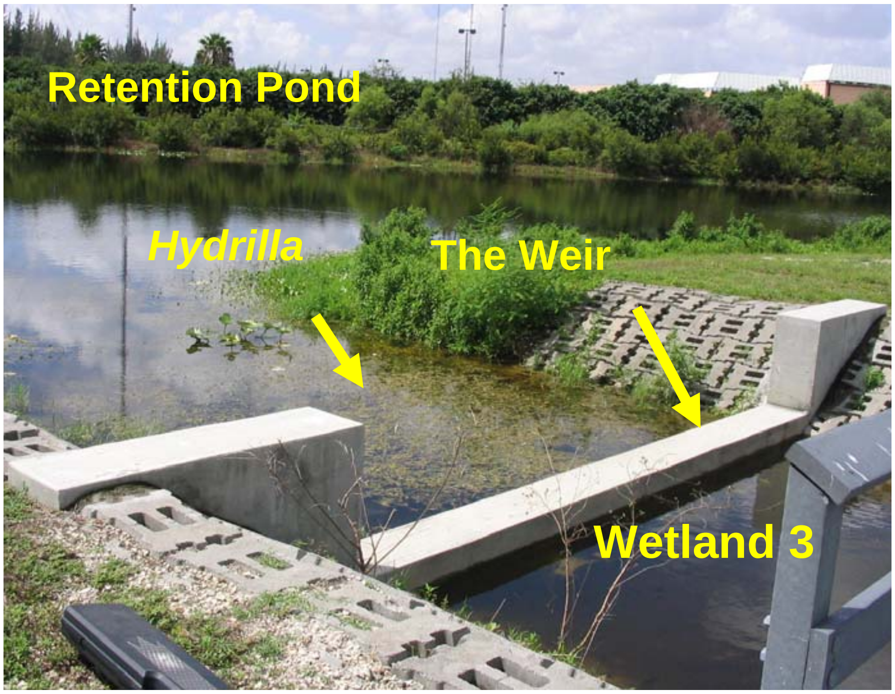


Figure 4b. A Close-Up View of One of Two Flap Gates in the Weir at Snake Warrior's Island. The gates allow water to flow from the retention pond into wetland 3.

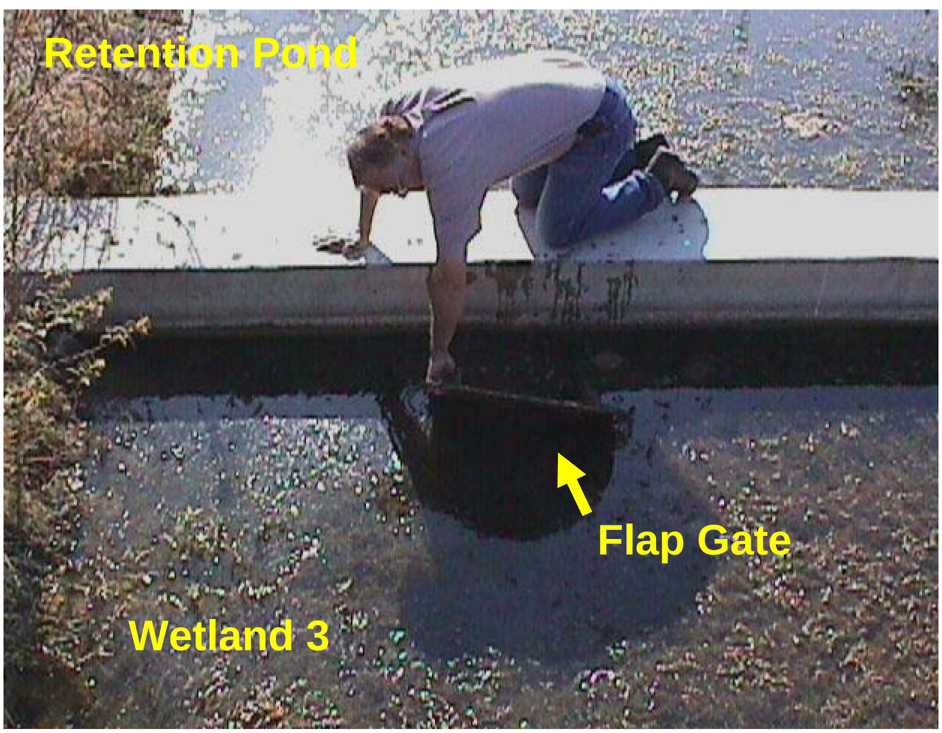


Figure 5. 2003 Aerial Photograph of Snake Warrior's Island Natural Area. X's indicate the location of the two YSI data sondes. Bullets (●)'s indicate the locations of the monthly sample sites at Snake Warrior's Island Natural Area. The blue arrows show where surface water and storm water enter SWI.

Figure 6a. YSI Data Sondes Similar to the Ones Deployed at Snake Warrior's Island Natural Area. The sondes measure temperature, pH, water elevation, dissolved oxygen, chlorophyll and turbidity. The sondes were programmed to log readings every 15 minutes. Sondes were deployed inside PVC housings for a week at a time in wetland 3 and the retention pond at Snake Warrior's Island Natural Area.

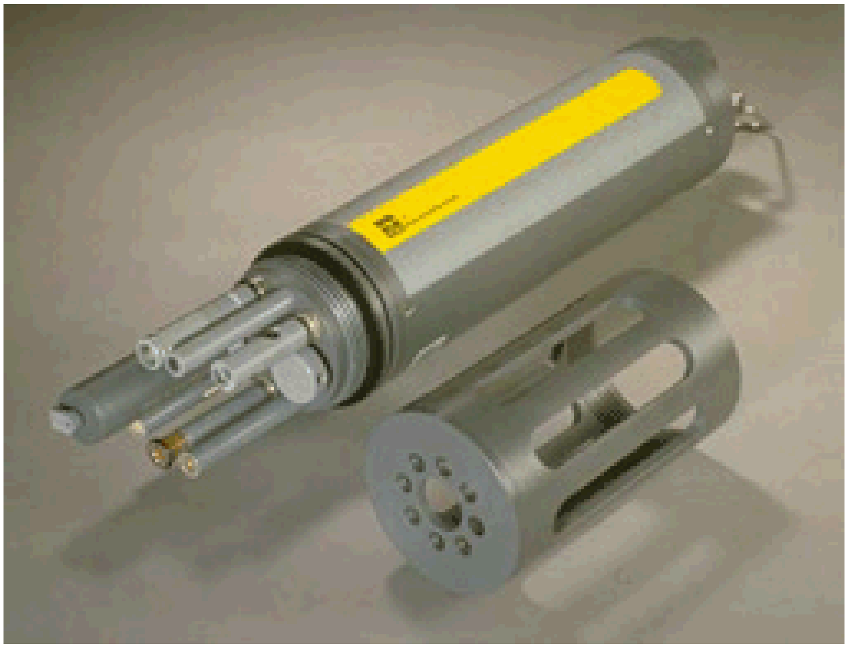


Figure 6b. PVC Housing Containing One of the Sondes Deployed at Snake Warrior's Island Natural Area. This sonde is located in wetland 3.

analysis were also collected and water clarity as indicated by secchi depth was noted at the two YSI sites. Note: In order to compare YSI parameters across all seven sites, discrete YSI readings were also collected during the monthly water column sampling events in addition to the data collected by the YSI sondes deployed wetland 3 and the retention pond. These discrete monthly values represent a snapshot of the day and not the diel variation recorded by the YSI sondes left in place at the two sites. The sonde used during monthly water column sampling, was submerged 0.5 m below the surface of the water and allowed to log readings for several minutes.

2. Monthly Water Column Sampling – SWI Natural Area

Monthly water column samples were collected from six sites within SWI and at a site along the C-9 canal, the primary source of water for rehydrating the wetlands at SWI. Sites internal to SWI include; the grate where water first enters the SWI property, the retention pond, wetland 3, wetland 2, wetland 5a, and the lake (Fig. 5). Monthly samples were analyzed for the following parameters: total organic carbon (TOC), total phosphorus and ortho – phosphate (TP & OPO_4), nitrate + nitrite (NO_x), ammonia (NH_3), total Kjeldahl nitrogen (TKN), total and dissolved metals (aluminum, arsenic, cadmium, copper, chromium, nickel, lead, zinc, beryllium, selenium, vanadium, iron, manganese, and barium), Chl_a, total suspended solids (TSS), turbidity and alkalinity. Samples for polycyclic aromatic hydrocarbons (PAHs) and herbicides samples were collected bimonthly. Water samples were collected using a variety of techniques including; a horizontal Niskin bottle, by hand or peristaltic pump as necessitated by sampling location. Samples were collected from the same depth at all sites regardless of method of collection. Nutrients were preserved using 1:1 sulfuric acid (H_2SO_4) to a pH < 2. Chl_a samples were filtered in the field onto a 47 mm (0.45 micron) nitrocellulose filters and stored on ice in darkened test tubes. Dissolved metal samples were filtered through a high capacity in-line ground water sampling capsule (0.45 micron) using a peristaltic pump. Total and dissolved metals were preserved with 1:1 nitric acid (HNO_3) to a pH < 2. Secchi depth, a measure of water clarity, was also noted when possible. The size of the wetlands sampled in this study ranged from 0.74 to 2.46 acres and 1.0 to 4.5 ft deep (Table 1).

BCEPD's Environmental Monitoring Division is certified under the National Environmental Laboratory Accreditation Conference (NELAC) and follows a comprehensive quality assurance/control plan. Samples were preserved and analyzed according to the U.S. Environmental Protection Agency (EPA) and Standard Methods protocols (Table 2). Samples were stored on ice during transit to the laboratory and placed in a walk-in cooler once they arrived with the exception of Chl_a samples which were placed in a freezer.

3. Storm Event Sampling at SWI Natural Area and Miami Gardens

A Sigma 900 Max autosampler and rain gauge was deployed in August 2004 at the storm grate where water first enters SWI (Fig. 5). This site also one of the sites within SWI, sampled on a monthly basis. The rain gauge was set to trigger the autosampler to fill 4 two liter glass jars if 0.2 inches of rain fell into the rain gauge within a 30 minute period. These samples were considered first flush samples. A second set of samples, second flush samples, were collected two hours after the first set of samples. Water samples were also collected at the storm water grate in front of 36 Ronald St. in Miami Gardens (Fig. 3). The Miami Gardens system was

Table 1. Acreage and Depth of the Water Column in the Wetlands, Retention Pond and Lake at the Snake Warrior's Island Natural Area. Please note the retention pond, wetlands and lake are artificial features.

Site	**Acreage**	**Maximum Depth (ft)**
Retention Pond	2.62	16
Wetland 3	1.66	4.1
Wetland 2	2.46	4.5
Wetland 5A	0.74	1
Lake	3.29	22

Table 2. Broward County Environmental Protection Department's Laboratory Methodologies for Water Quality Parameters. Total nitrogen was determined by adding nitrate + nitrite nitrogen to the total Kjeldahl nitrogen.

Parameter	**Technique**	**Method**
Temperature	Thermistor	EPA 170.1
Specific Conductance	Wheatstone bridge or equivalent	EPA 120.1
pH	Glass electrode	EPA 150.1
Depth	Pressure transducer	
Dissolved Oxygen	Membrane electrode	EPA 360.1
Turbidity	Nephelometric	EPA 180.1
Total Suspended Solids	Gravimetric	SM2540D
Total Organic Carbon	Persulfate digestion	EPA 415.1
Total Phosphorus	Acid block digestion, automated, ascorbic acid	EPA 365.4
Nitrate + Nitrite - Nitrogen	Cadmium reduction, automated	EPA 353.2
Ammonia - Nitrogen	Automated, phenate	EPA 350.1
Total Kjeldahl Nitrogen	Acid block digestion, automated phenate	EPA 351.2
Chlorophyll/Pheophytin	Acetone (95%) extraction, 47 mm (0.45µm) nitrocellulose filter, fluorometric	SM 10200HNC
Metals	Acid digestion	EPA 200.7 EPA 206.2 SM846 7060
PAHs	Soxhlet & continuous liquid extraction	SM 846 8270
Pesticides	Soxhlet & continuous liquid extraction	SM 846 8141

EPA = United States Environmental Protection Agency Methods for Chemical Analysis of Water and Wastes., EPA-600/4-79-020, March 1983.
SM = Standard Methods for Water and Waste Water, 18^{th} ed., American Public Health Association, 1992.

designed with the intention that the bulk of local storm water would be retained in swales and exfiltration trenches within the Miami Gardens subdivision. However, if rainfall exceeds 3.5 inches in a 24 hour period in Miami Gardens' subdivision, storm water would be discharged over the control weirs at the end of the exfiltration trenches on each street and flow into Snake Warrior's Island Natural Area (Broward County Office of Environmental Services 1997). Storm water samples were only collected when there was sufficient water in the system to over flow the weir located at the end of Ronald St. Storm water samples were collected twice from Miami Gardens Storm (May and November 2003). Samples were analyzed for total organic carbon, total Kjeldahl nitrogen, nitrate + nitrite, ammonia, total phosphorus, ortho-phosphate and total metals, PAHs and herbicides (Table 2).

4. Plant and Sediment Sampling

Plant samples and sediment cores were collected in August and December 2003. The top 5 cm of sediment were collected using 7.6 cm diameter cores. Plant samples consisted of leaves from the common wetland plant *Pontederia cordata* also know as Pickerel Weed. Plants samples were analyzed for nitrogen, phosphorus, carbon and metals (aluminum, arsenic, cadmium, copper, chromium, nickel, lead, zinc, beryllium, selenium, vanadium, iron, manganese, and barium). Sediment samples were analyzed for as the above parameters as well as for PAHs, and herbicides.

C. Ancillary Data

1. Stage Elevation Data

Hourly stage elevation of the headwaters at the S29 salinity structure on the C-9 canal was obtained from the South Florida Water Management District.

2. Rainfall Data

Daily rainfall data was obtained from the Miramar West Water Treatment Facility located near the Snake Warrior Island Natural Area.

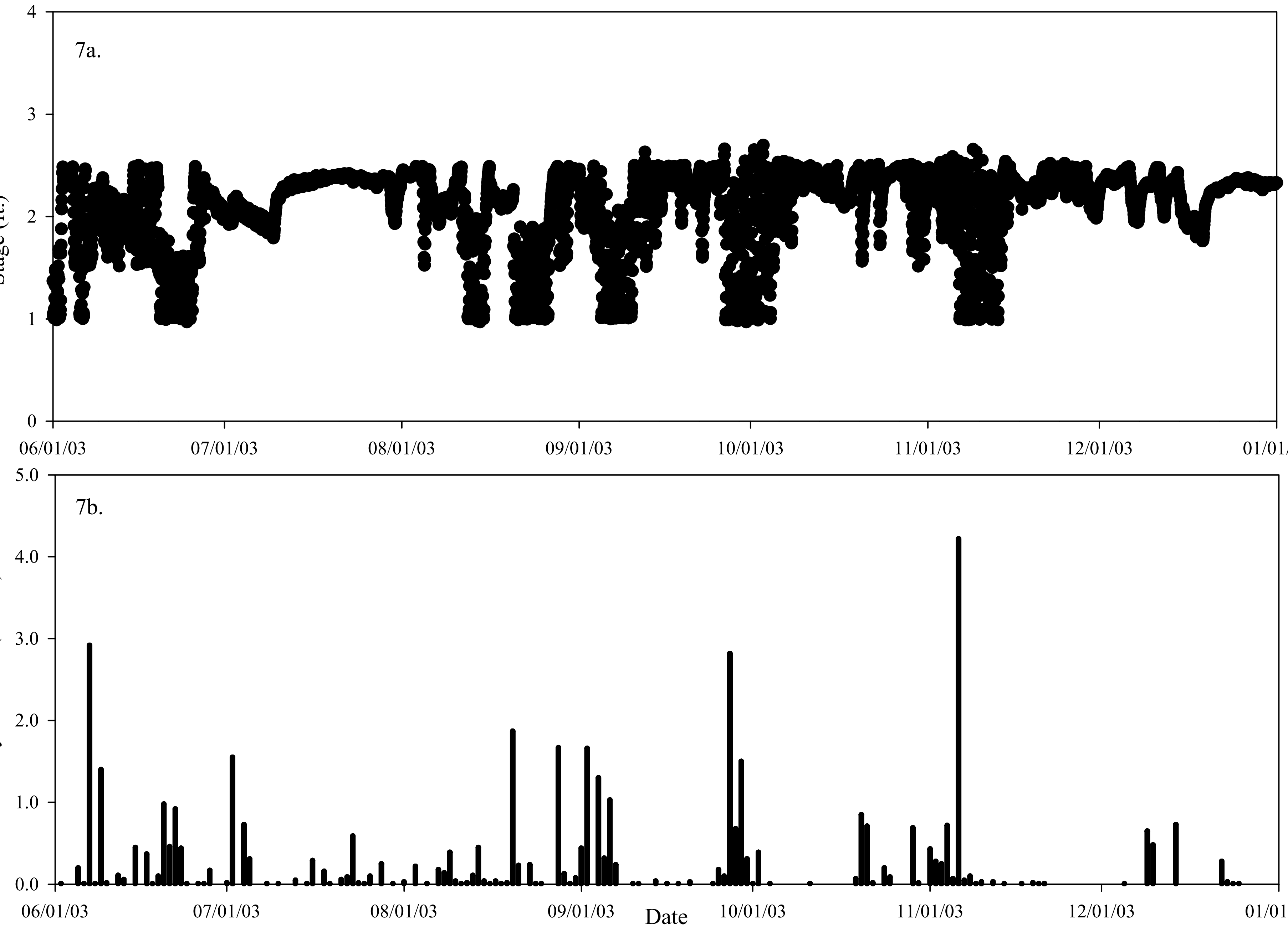
III. Results

A. Hydrological and Meteorological Monitoring

1. Stage Elevation at Salinity Structure (S29) on the C-9 Canal

Water elevations at S29 (headwaters) on the C-9 Canal ranged from a low of 0.97 ft to a high of 2.7 ft. NGVD over the course of the SWI study (June- December 2003) (Fig. 7a) (Data provided by the South Florida Management District). Large scale excursions (several inches) in water levels were typically associated with rain events (Fig. 7b) and reflect the dynamic nature of the system as well as regional water management practices. The number of gates opened at S29 depended on the magnitude and duration of the rain event. During heavy rain events, additional gates can be opened at S29 so more water is released to tide allowing water levels to decline and reduce the risk of flooding.

Figure 7a. Stage Data (ft.) from the S29 Salinity Structure on the C-9 Canal, June - December 2003. Data was obtained from the South Florida Water Management District. Figure 7b. Daily Rainfall Data (inches) from the Miramar West Water Treatment Plant, near Snake Warrior's Island Natural Area, June - December 2003. Changes in stage height at S29 are associated with rain events. Water is released to tide through S29 during rain events as a part of a flood prevention strategy.



B. YSI Unattended Weekly Sampling

1. Water Elevation

Water levels in the retention pond and wetland 3 mimicked each other and were strongly influenced by changes in water levels in the C-9 canal (Fig. 8a & b, 9a - f). In general, the retention pond and wetland 3 tracked changes in water levels at the S29 structure of the C-9 canal (Fig. 8a & b). The only time the C-9 signal was overridden at SWI was during prolonged and heavy rain events (i.e. November 2003, see Fig. 8a & 9e) when water levels in the retention pond and wetland 3 at SWI increased even though water levels at S29 of the C-9 canal dropped. The volume of storm water in the storm water system along US 441 exceeded the system's capacity so excess storm water was diverted into SWI causing water elevations in the retention pond and wetland 3 increased. Changes in water levels at S29 were related to regional water management activities for flood prevention.

Secondary influences on water elevations at SWI were also detected by examining the data on a finer time scale (monthly) (Fig. 9a –f). These finer scale oscillations in water levels occurred approximately every 6 hours for several days at a time throughout the study. The signal was more pronounced in the retention pond than wetland 3 and may be related to changes in the height of the water table in the area surrounding SWI. In general, the data suggest the retention pond is more sensitive to changes in water levels (surface and ground water) than wetland 3.

2. Specific Conductance

The specific conductance of surface waters in the retention pond and wetland 3 were similar, ranging from ~ 300 and 600 μhmos/cm (Fig. 10a & 10b). Declines in specific conductance were associated with rain events reflecting both direct inputs from rain as well as storm water. Changes in specific conductivity associated with direct input of rain water were more pronounced in wetland 3 compared to the retention pond and can probably be attributed to wetland 3's smaller size and shallower depth (Table 1). Wetland 3 had a slightly lower average specific conductance of 445 $\pm$ 56 μhmos/cm (mean $\pm$ SD) compared to the retention pond with a value of 473 $\pm$ 44 μhmos/cm. The specific conductance of waters at both sites tended to increase towards the end of the study with the onset of the dry season (Fig. 11a-f).

3. Temperature

Temperature values ranged from 17.7 to 33.5 °C in the retention pond and 15.6 to 32 °C in wetland 3 (Fig. 12). The average temperature in the retention pond was 27.3 $\pm$ 3.7 °C (mean $\pm$ SD) and 26.4 $\pm$ 3.7 in Wetland 3. Water temperatures remained in the high twenties at both sites through October 2003 (Fig. 13a – d). Temperatures began to slowly decline at beginning of November followed by a sharp drop in temperature at the end of November 2003 (Fig.13a-f). Temperature data exhibited diurnal oscillations as expected.

4. pH

The pH in the retention pond typically exceeded pH values in wetland 3, ranging from 7.2 to a high of 8.8 with an average value of 7.9 $\pm$ 0.3 (mean $\pm$ SD). Wetland 3 pH ranged from 6.9 to

Figure 8a. Stage data (ft.) from the S29 Salinity Structure on the C-9 Canal and Water Elevation Data from the YSI Sondes in the Retention Pond and Wetland 3 at the Snake Warrior's Island Natural Area, June - December 2003. Figure 8b. Daily Rainfall Data from the Miramar West Water Treatment Plant Located near Snake Warrior's Island Natural Area, June - December 2003.

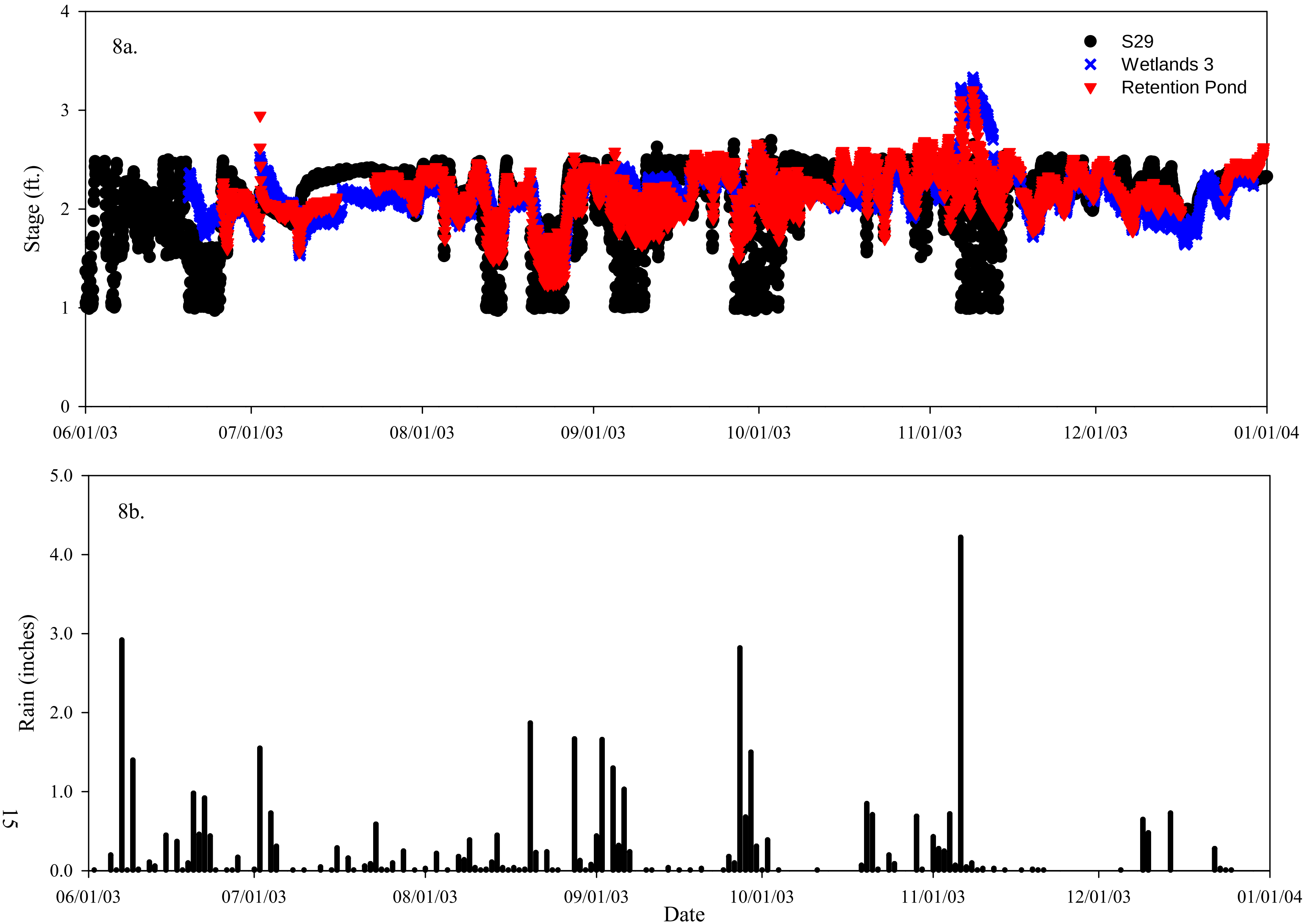
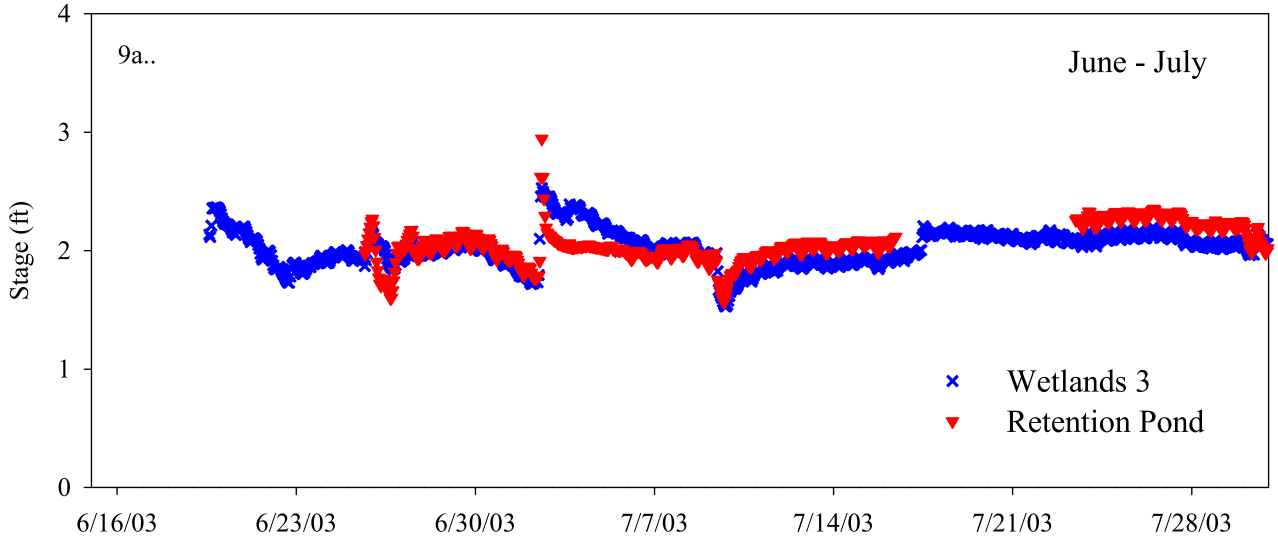
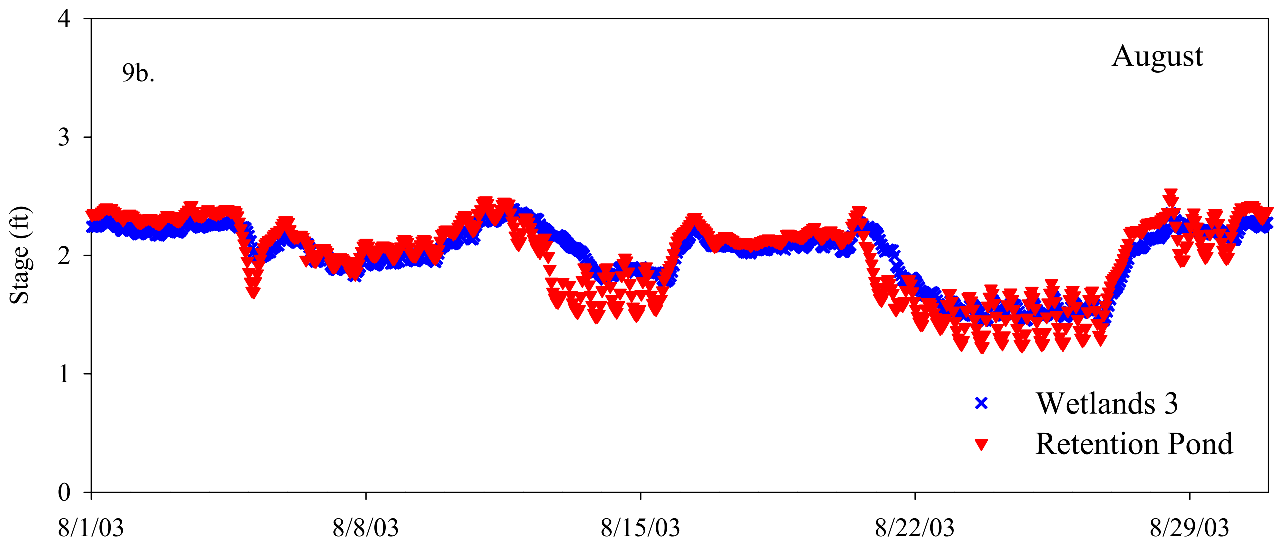


Figure 9a - c. Hourly Averages of Water Elevation (ft.), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island Natural Area, June through September 2003. Data was collected at 15 minute intervals by a YSI data sonde located at each site.





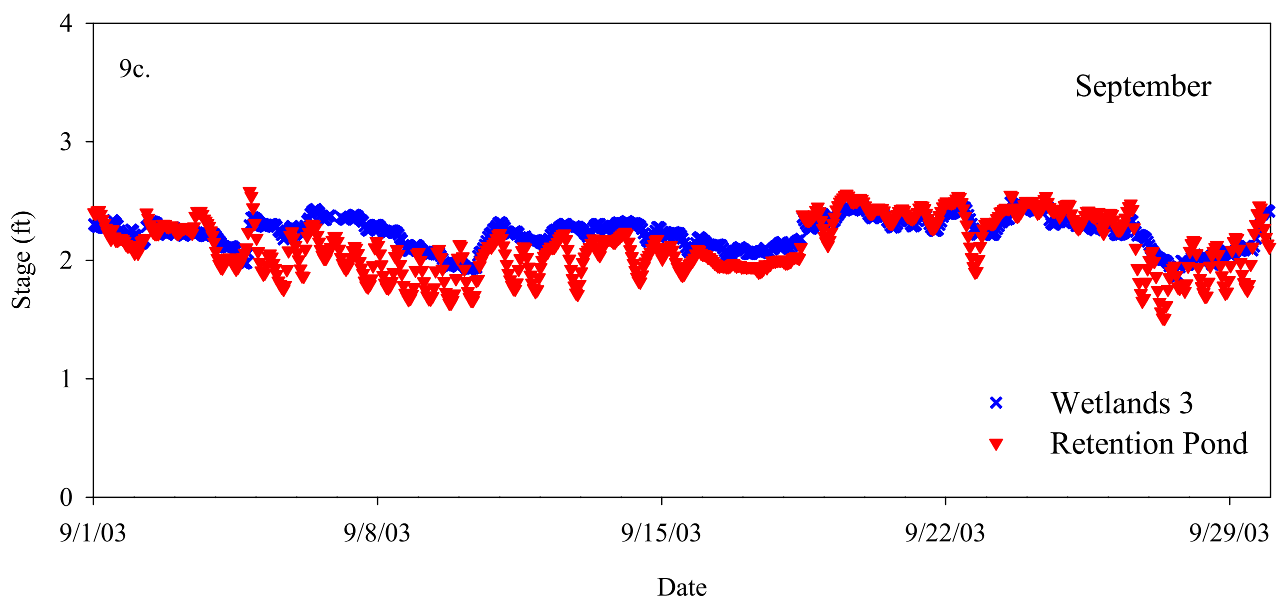
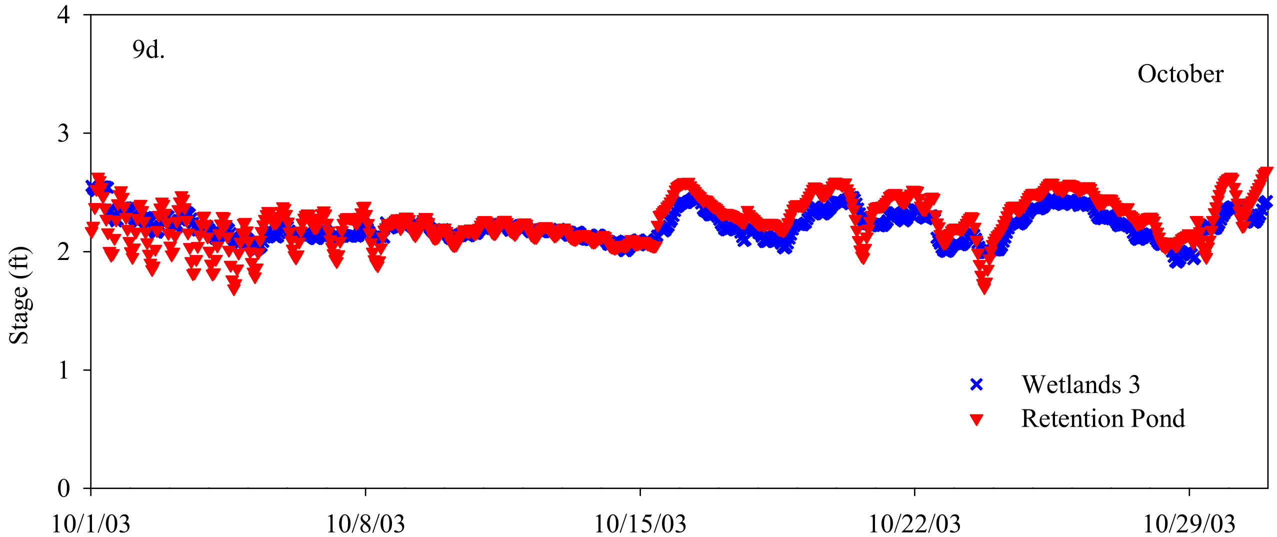
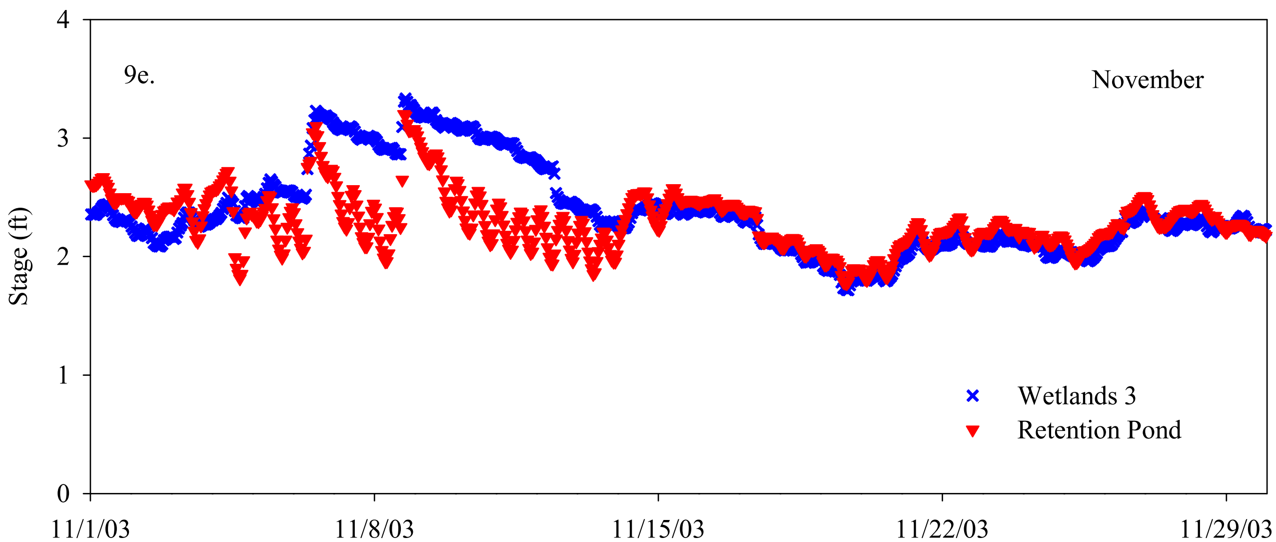


Figure 9d - f. Hourly averages of Water Elevation (ft.), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, October through December 2003. Data was collected at 15 minute intervals by a YSI data sonde located at each site.





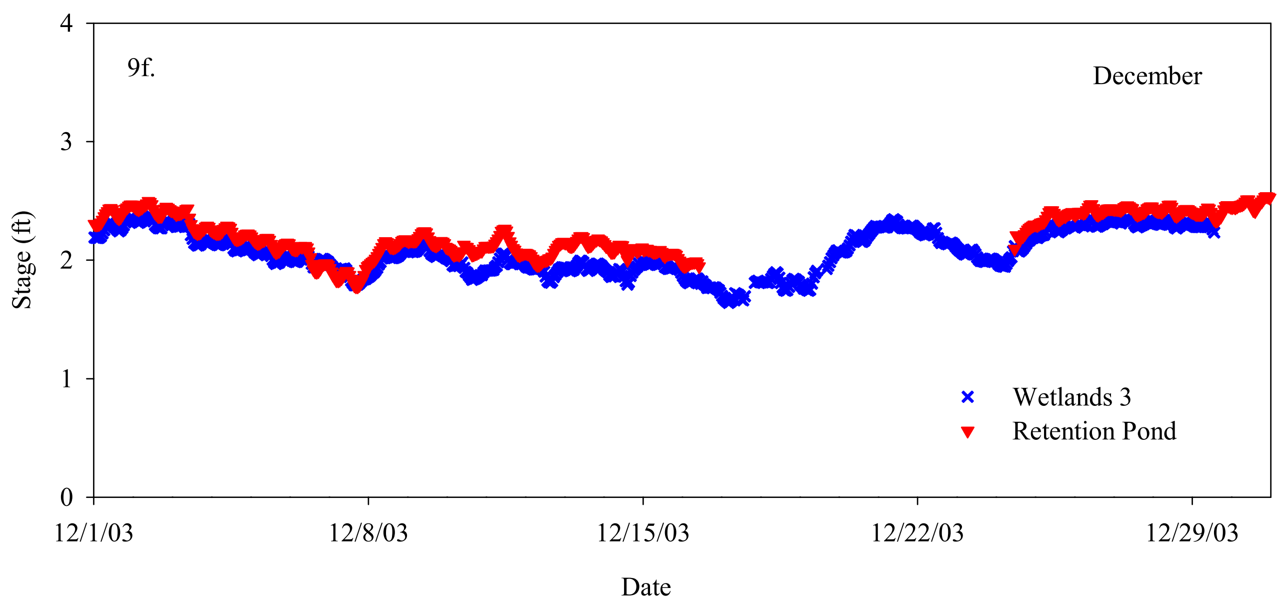


Figure 10a. Hourly Averages of Specific Conductivity (µS/cm) in the Retention Pond and Wetland 3 at Snake Warrior's Island Natural Area, June - December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site. Figure 10b. Daily Rainfall Data Measured at the Miramar West Water Treatment Plant near Snake Warrior's Island, June - December 2003. Rapid declines in specific conductivity at SWI coincided with rain events due to the direct inputs of rain and possibly storm water.

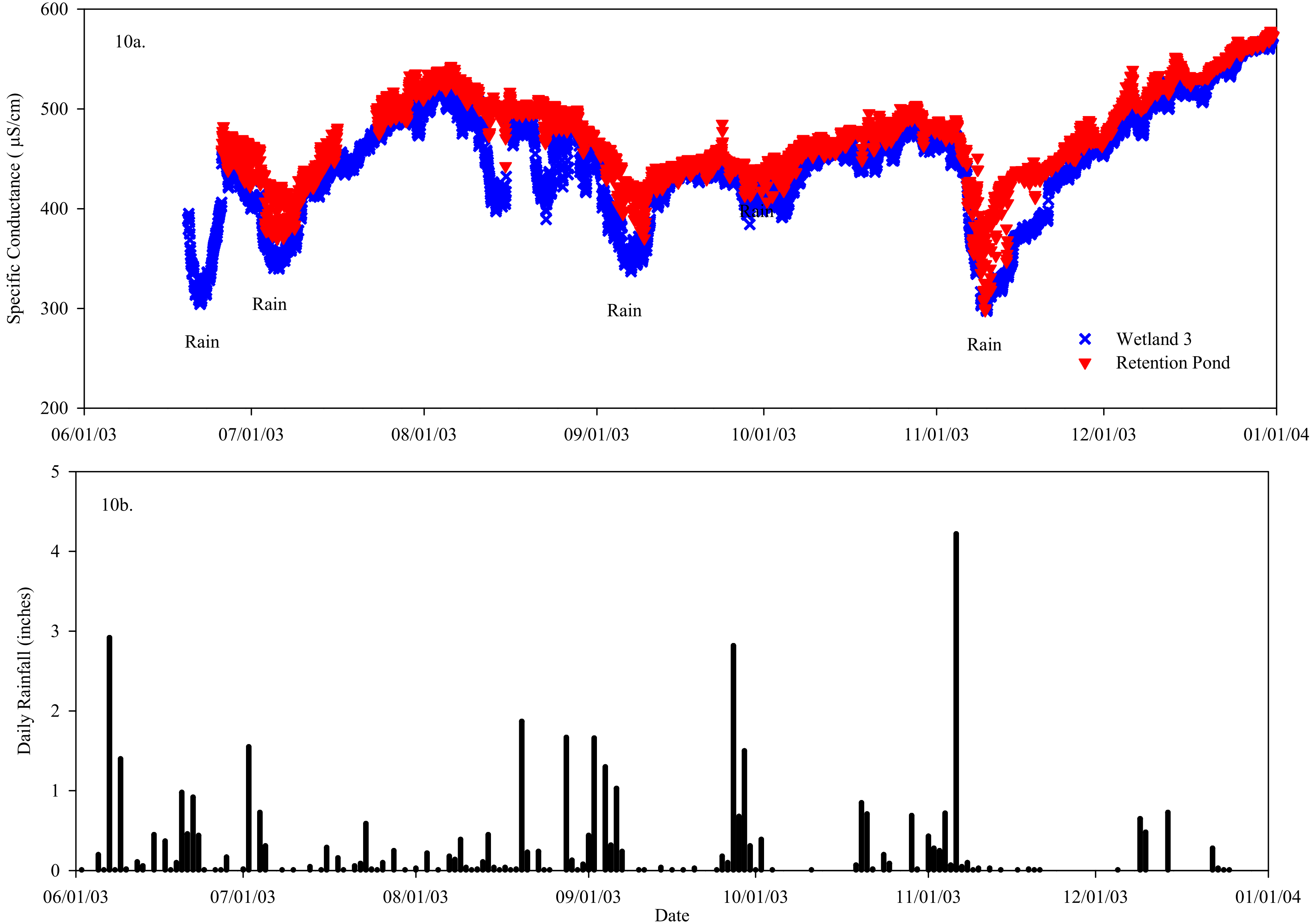
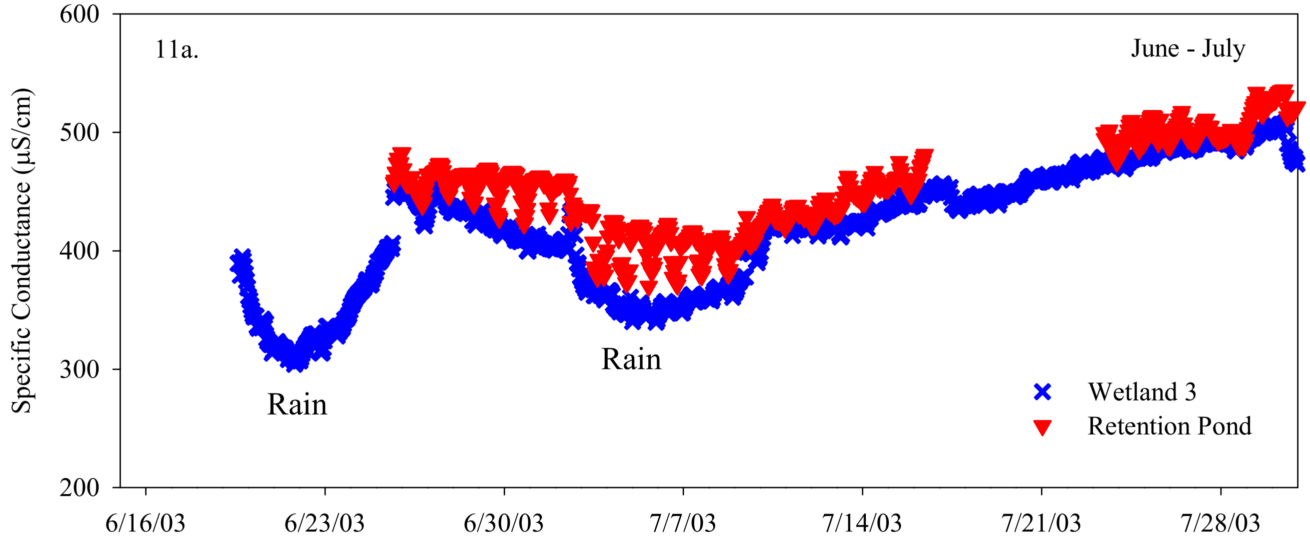
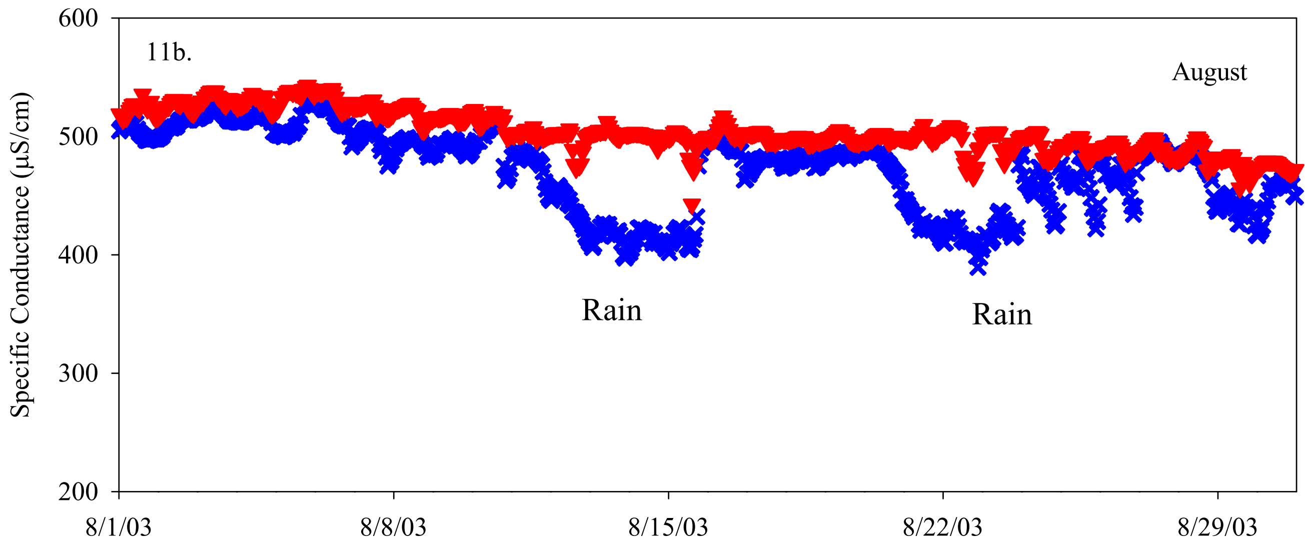


Figure 11a - c. Hourly Averages of Specific Conductivity (μS/cm), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - September 2003. Data was collected every 15 minute by a YSI data sonde located at each site.





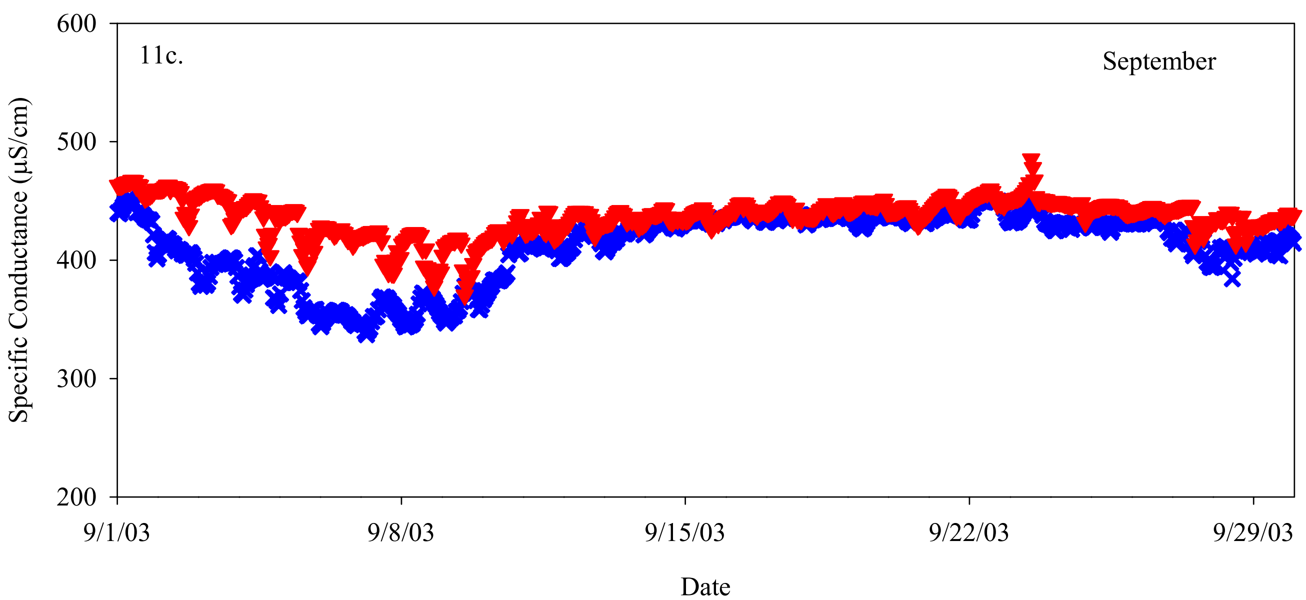


Figure 11d - f. Hourly Averages of Specific Conductivity (µS/cm), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, October through December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

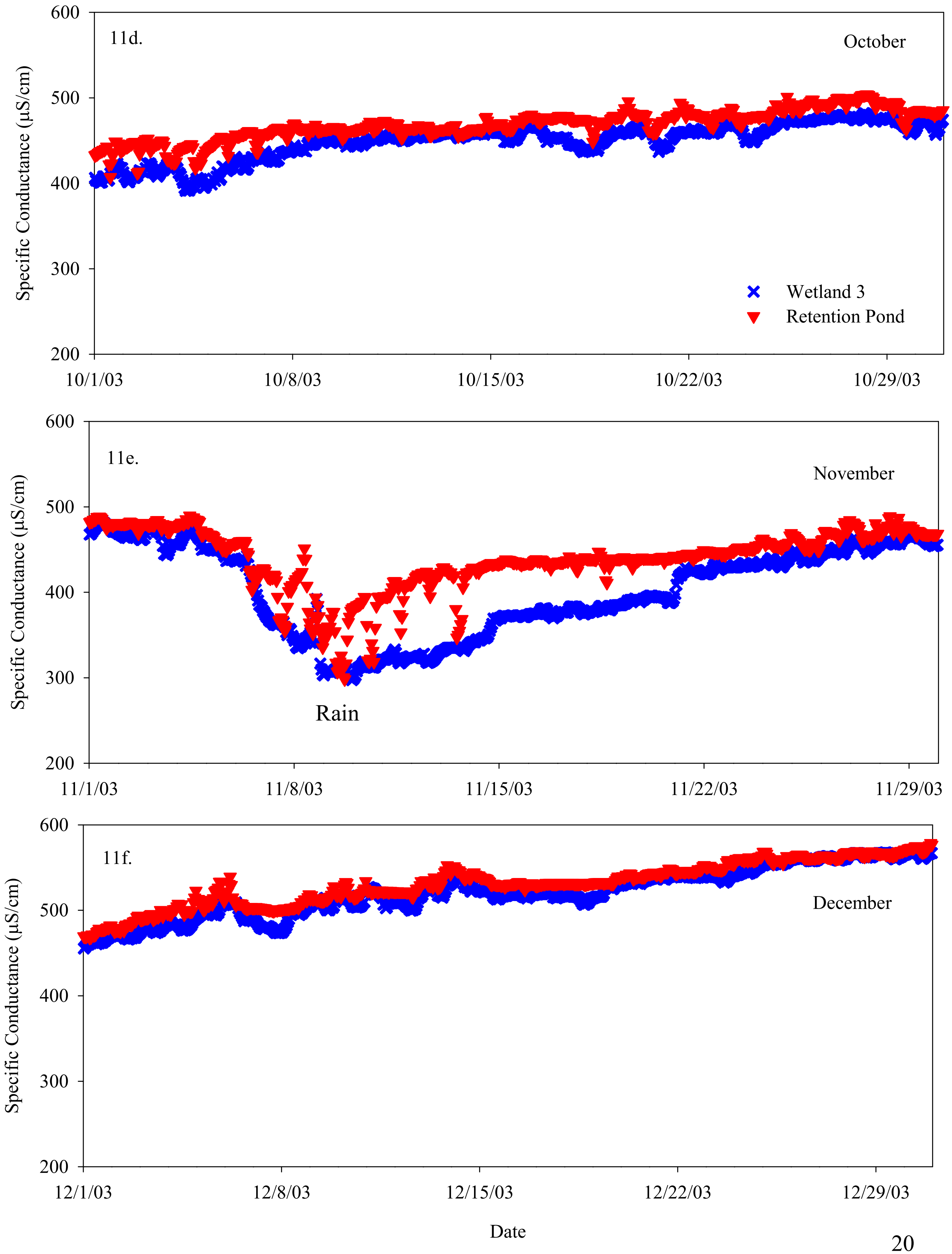


Figure 12. Hourly Averages of Temperature (^{o}C) in the Retention Pond and Wetland 3 at Snake Warrior's Island, June - December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

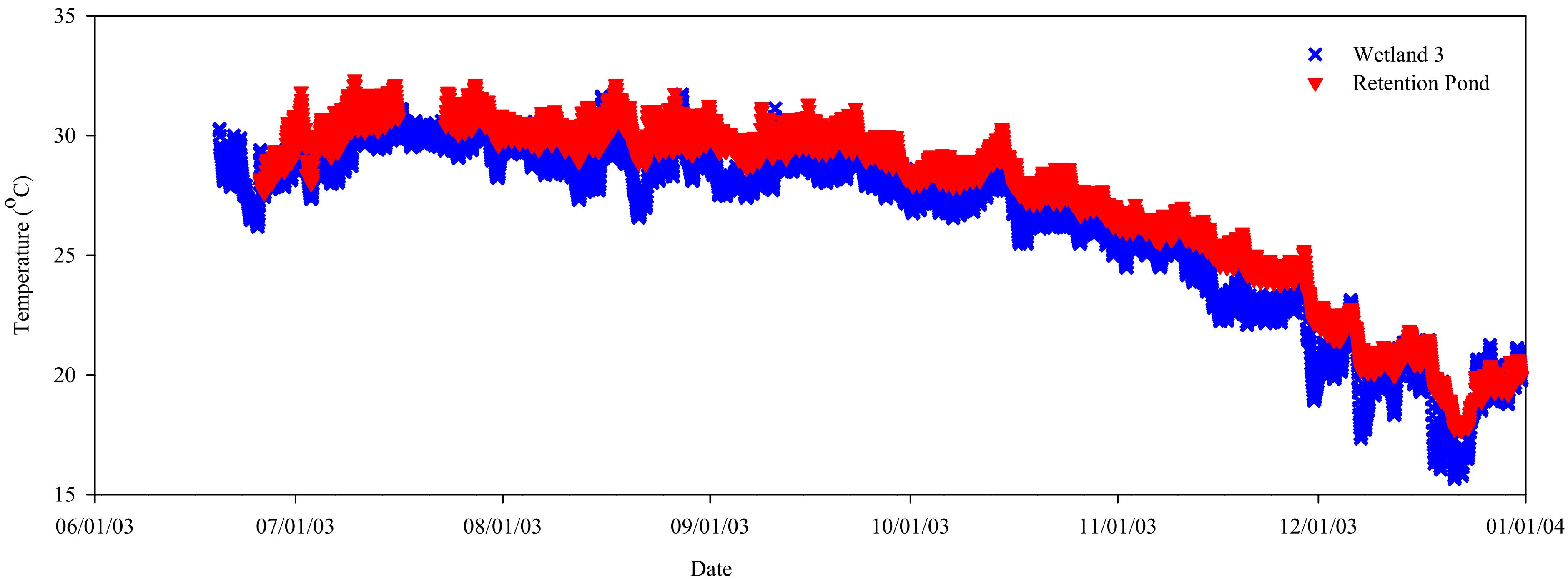


Figure 13a - c. Hourly Averages of Water Temperature (^{o}C), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - September 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

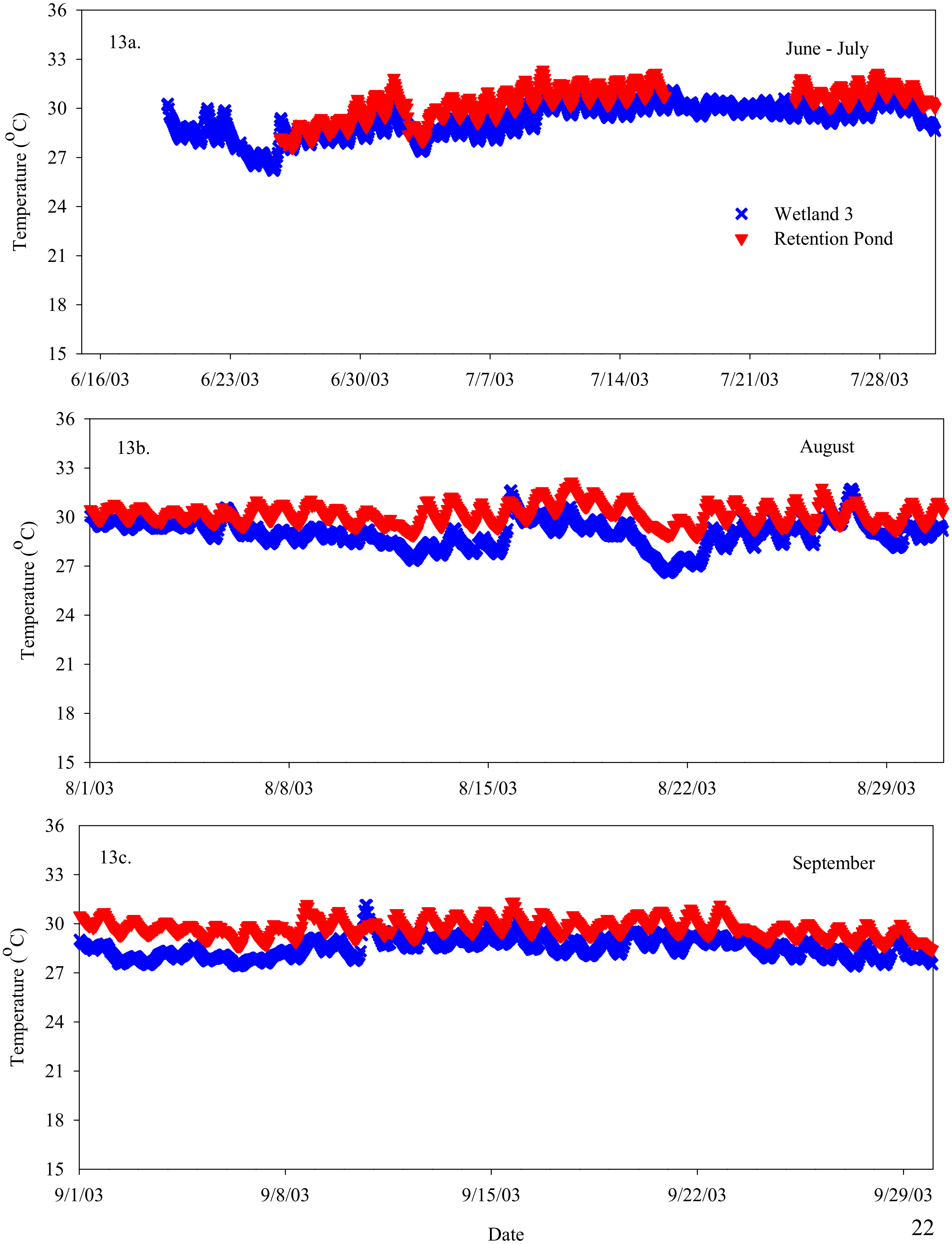
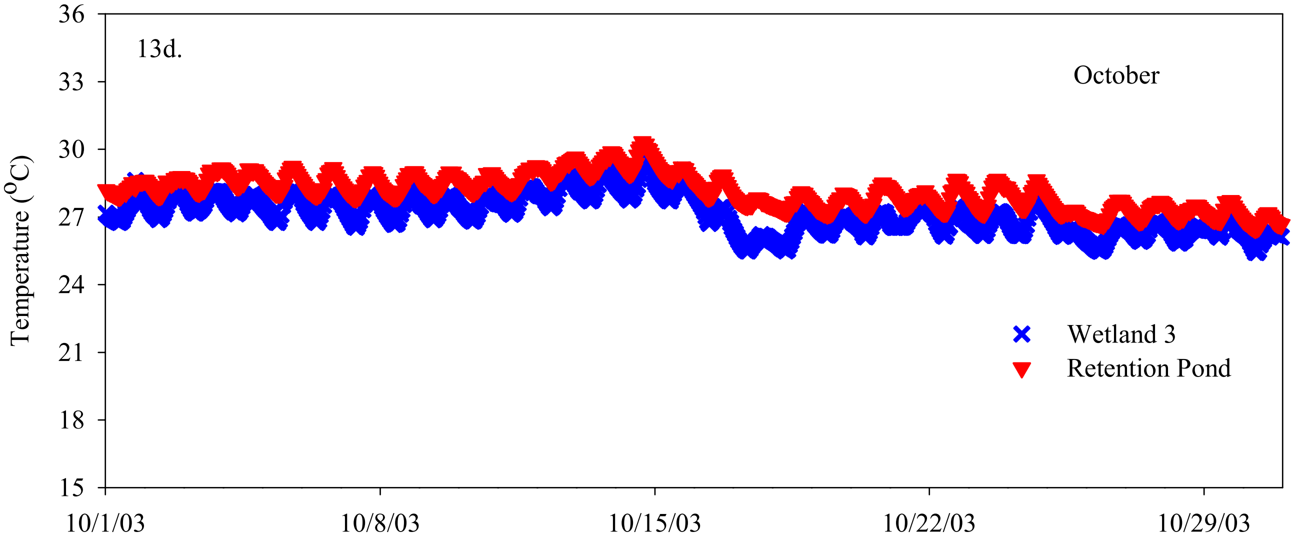
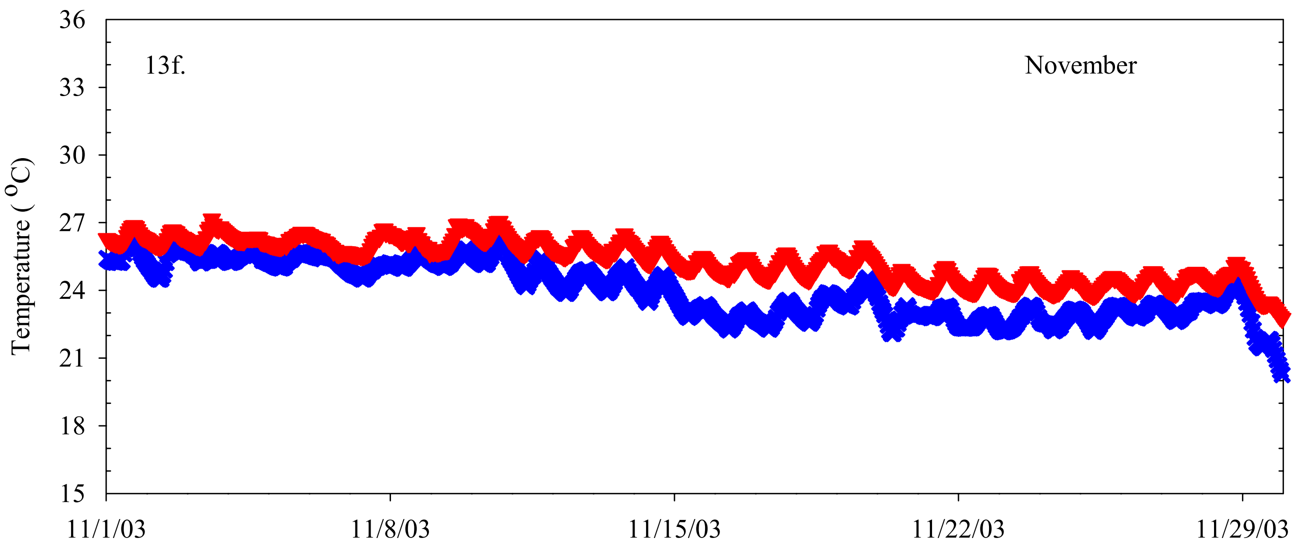
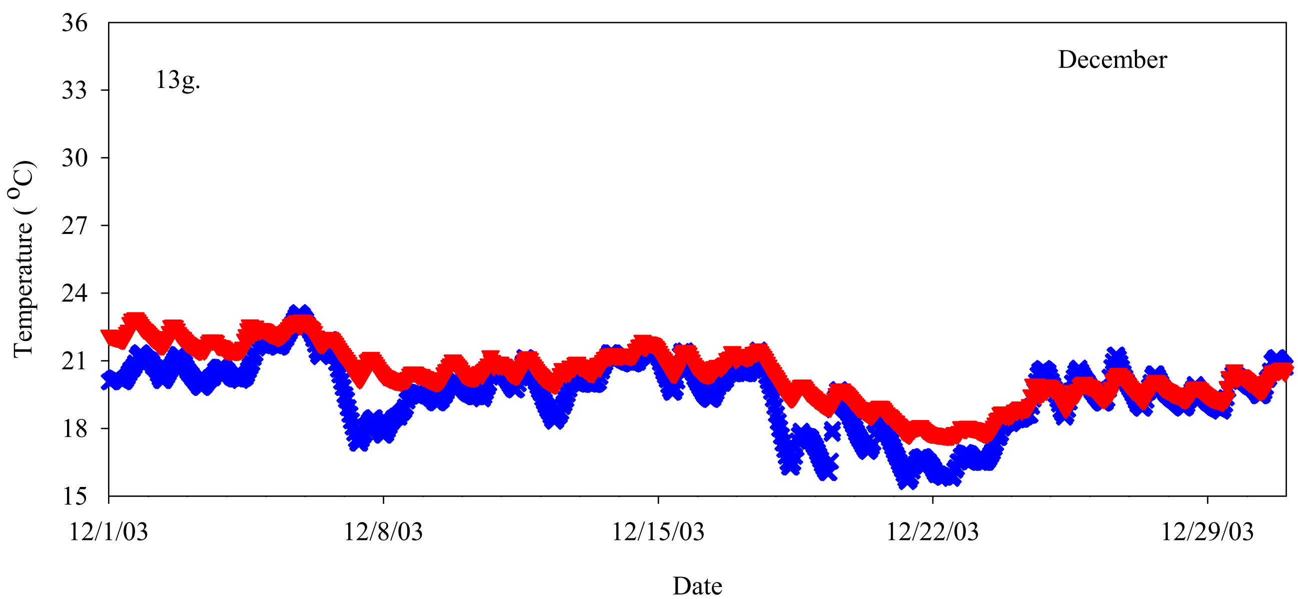


Figure 13d - f. Hourly averages of Temperature (^{O}C), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, October - December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.







8.5 with an average value of 7.5 ± 0.2 (Fig. 14). The diel variation of pH at both sites reflects the balance between respiration and photosynthesis during the daytime and respiration alone during the night (Fig. 15a – f). The difference between day time pH vs. nighttime pH also varied over time. Daily excursions in pH were larger June through September compared to October through December (Fig. 15a-f).

5. Dissolved Oxygen (D.O.)

Dissolved oxygen concentrations in the retention pond ranged from 2.03 mg/l to 13.01 mg/l with an average value of 6.27 ± 2.38 mg/l (mean ± SD). Wetland 3 values ranged from 0.03 mg/l to a high of 11.74 mg/l with an average concentration of 3.25 ± 2.24 mg/l (Fig. 16). Both the retention pond and wetland 3 experienced large diel variations in dissolved oxygen (D.O.) though the magnitude of these daily excursions seemed to diminish in latter part of the study (November and December, Fig. 17a-f). Shorter days, cooler temperatures and the die off *Hydrilla* in late October 2003 probably all influenced dissolved oxygen concentrations in the retention pond and wetland 3.

Following each deployment of a YSI data sonde, all parameters were checked to make sure they were meeting quality assurance requirements and the continuing calibration verification (CCV). The criteria for dissolved oxygen are ± 0.2 mg/l of the water saturated air value. YSI data sondes were deployed at total of 55 times with one failure (battery casing flooded). Based on the ± 0.2 mg/l criteria, the dissolved oxygen probes was out of range 12/55 deployments or 21.8%. Subsequent to the completion of the SWI project in December 2003, the CCV was increased to ± 0.3 mg/l (Fall 2004). Using newer criteria, D.O. exceeded the CCV four out of 55 times (7.3%). It was determined that the D.O. probe on one specific YSI accounted for 7 of the 12 failures, highlighting the need to evaluate CCVs on a real time basis.

6. Chlorophyll

The YSI sondes measure fluorescence optically and chlorophyll values were calculated using an algorithm (YSI Incorporated 1999). In the retention pond, YSI chlorophyll values varied from 5.1 to 61.3 μg/l with a mean of 12.2 ± 5.7 μg/l. Wetland 3 YSI values ranged from 4.9 to 25.1 μg/l with a mean of 8.5 ± 1.9 μg/l. The YSI chlorophyll data suggests the retention pond had higher and more variable chlorophyll concentrations than wetland 3 through out most of the study (Fig. 18a & b). Absolute concentrations and diel variability in chlorophyll-a (Chl_a) concentrations declined in November in both the retention pond and wetland 3, following the addition of Sonar ® to the retention pond (Fig. 18a & b). Sonar is an aquatic herbicide that is used to control *Hydrilla verticillata*, an exotic, invasive plant.

Extracted chlorophyll-a (Chl_a) was also measured from weekly water column grab samples collected at the retention pond and wetland 3. There was poor agreement between the Chl_a values measured *in situ* by the YSI sonde and those determined from grab samples during the first 4½ months of the study (June – October 2003, Fig. 19a & b). Chlorophyll as measured optically by the YSI sondes was substantially lower than the extracted Chl_a values determined from the weekly grab samples. Better agreement between the two methods was observed November – December and may be related to the addition of Sonar to the system. Grab sample

Figure 14. Hourly Averages of pH (units) in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

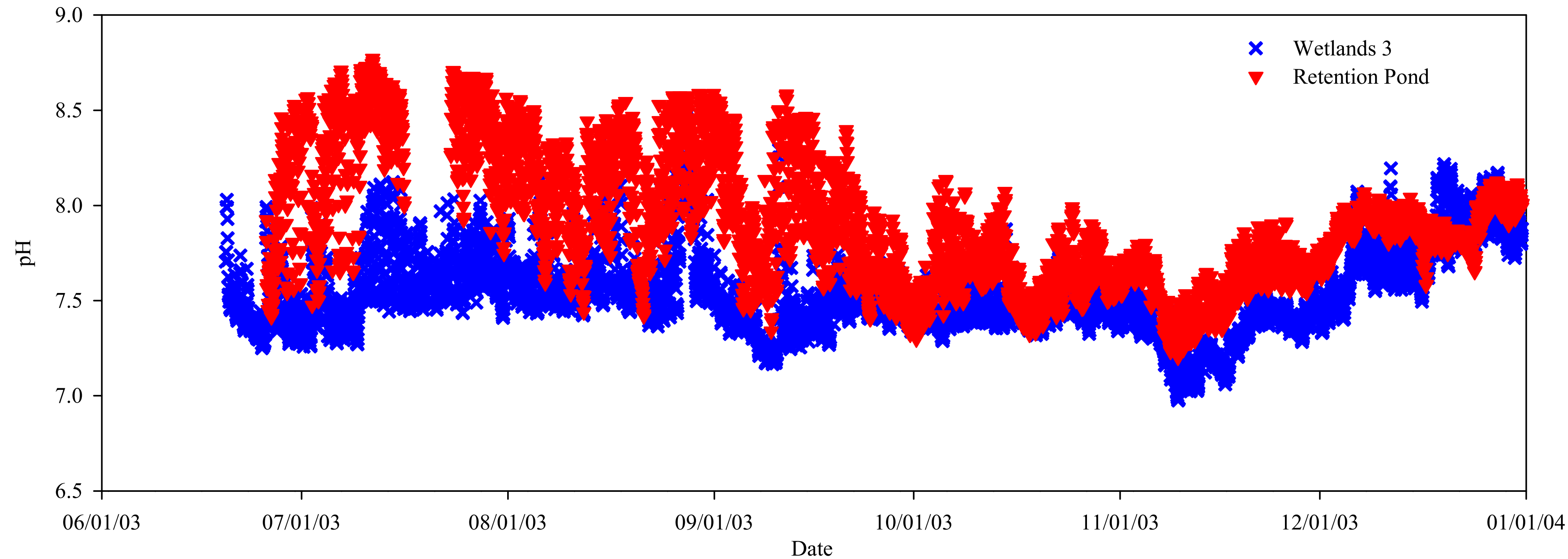


Figure 15a - c. Hourly Averages of pH (units), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - September 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

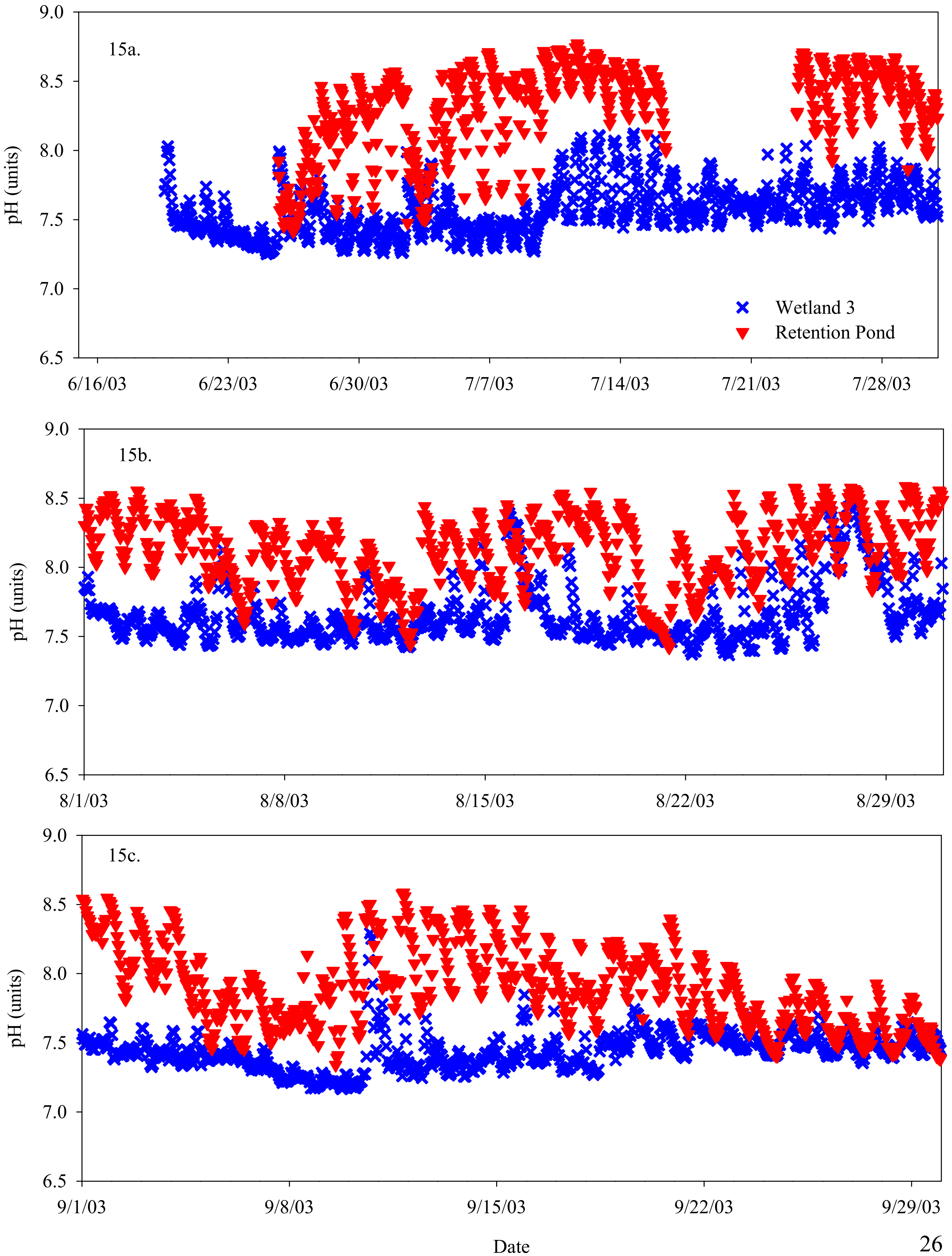


Figure 15d - f. Hourly Averages of pH (units), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, October - December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

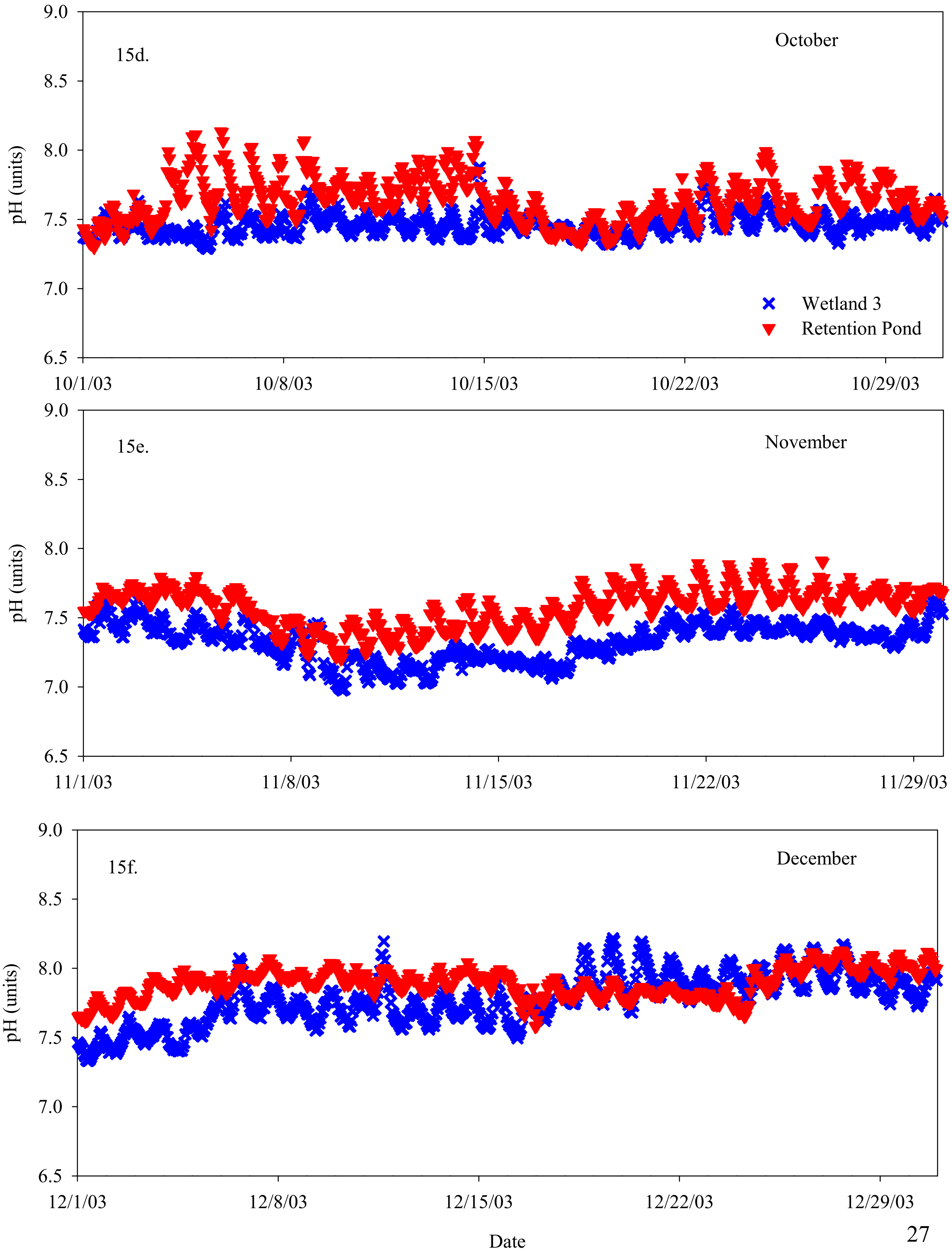


Figure 16. Hourly Averages of Dissolved Oxygen (D.O.) (mg/l) in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - December 2003. Data was collected ievery 15 minutes by YSI sondes located at each site.

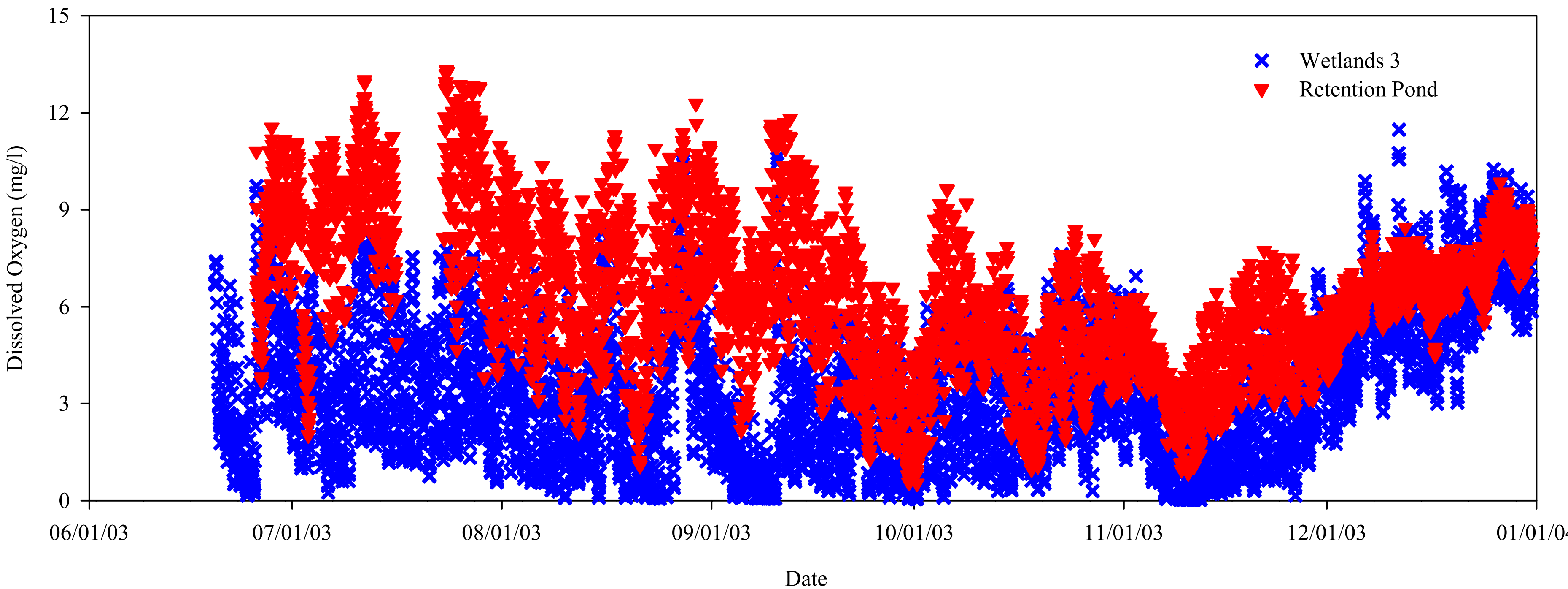


Figure 17a - c. Hourly Averages of Dissolved Oxygen (D.O) (mg/l), by Month, in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - September 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

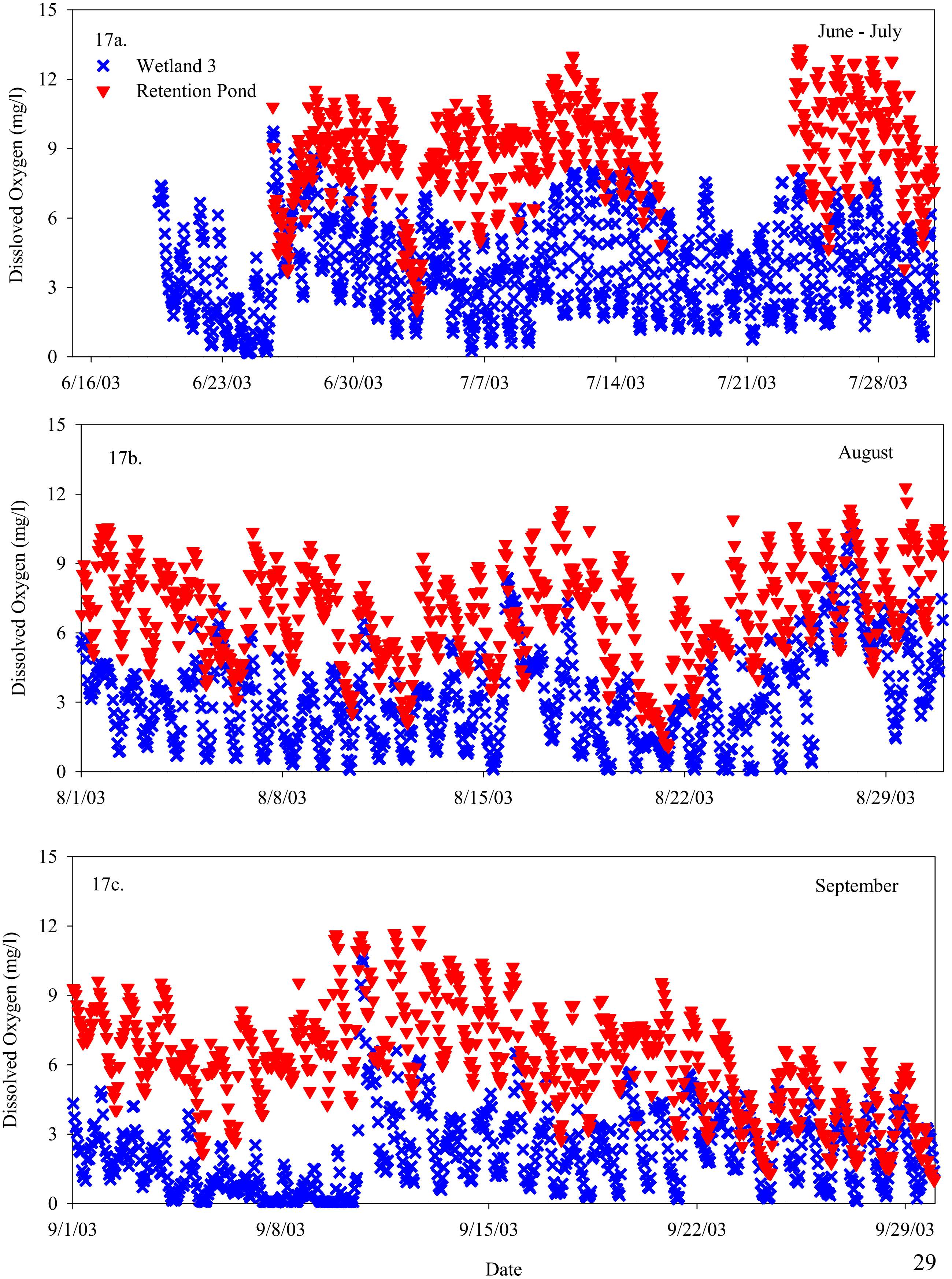


Figure 17d - f. Hourly Averages of Dissolved Oxygen (D.O.) (mg/l), by Month in the Retention Pond and Wetland 3 in Snake Warrior's Island, October - December 2003. Data was collected every 15 minutes by a YSI data sonde located at each site.

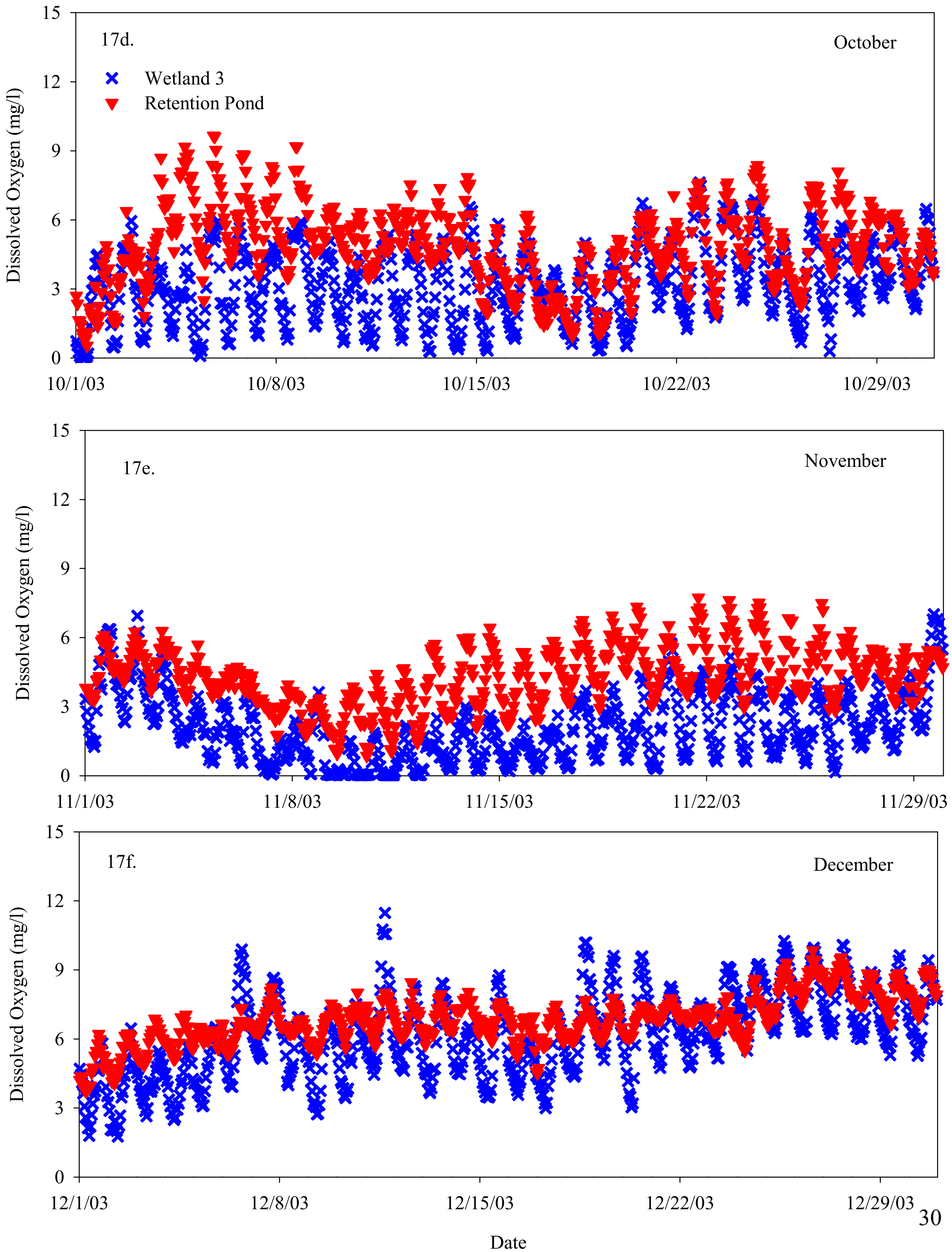


Figure 18a - b. Hourly Averages of Chlorophyll (Chl) (µg/l) Determined by a Fluorescence Probe on the YSI Sondes in the Retention Pond and Wetland 3 in Snake Warrior's Island, June - December 2003. Data was collected every 15 minutes by a YSI sonde located at each site. Sonar is an aquatic herbicide that was applied to the retention pond in October 2003 as part of an effort to eliminate the aquatic weed *Hydrilla*.

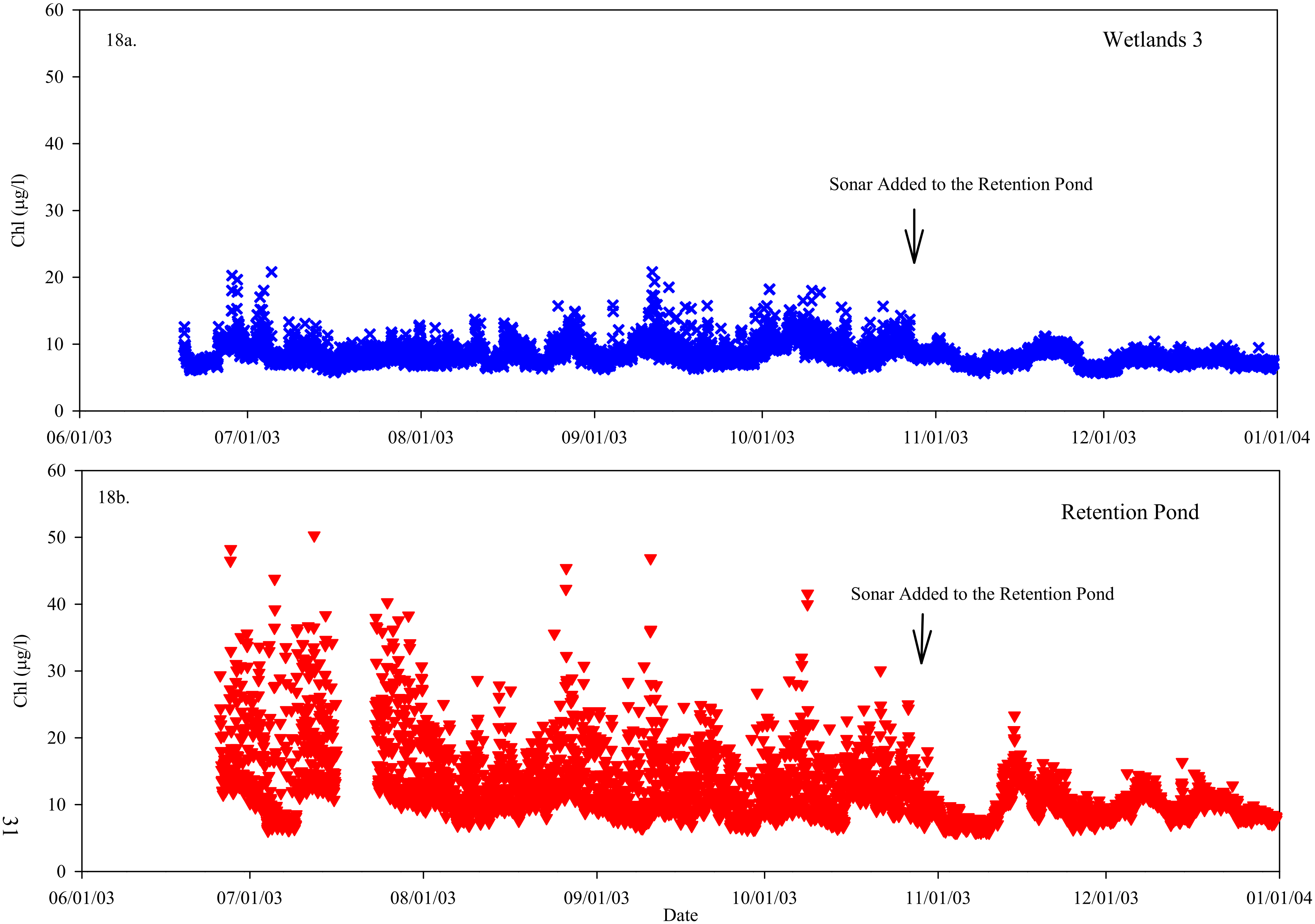
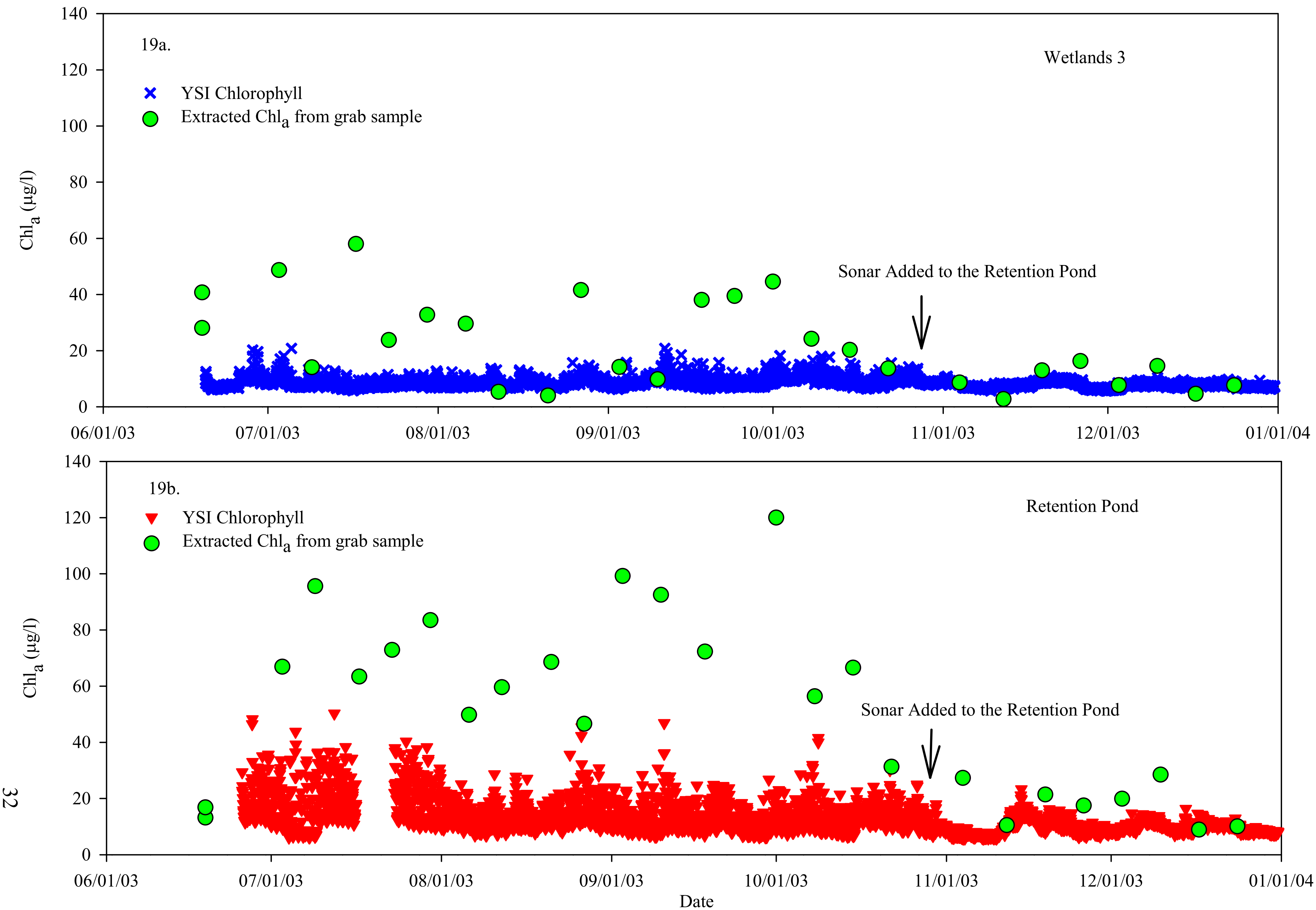


Figure 19a - b. Hourly Averages of Chlorophyll (Chl) (µg/l) Determined by a Fluorescence Probe on the YSI Sonde Compared to Extracted Chlorophyll-a (Chla) (µg/l) Measured in Weekly Grab Samples from the Retention Pond and Wetland 3, June - December 2003. Sonar is an aquatic herbicide that was applied to the retention pond in October 2003, as part of an effort to eliminate the aquatic weed *Hydrilla*. Hydraulic gradients cause the treated water to flow from retention pond into wetland 3.



Chl_a values for the retention pond ranged from 8.9 to 120 µg/l with a mean of 52.2 ± 32.0 µg/l. Wetland 3 grab sample Chl_a values ranged from 2.7 to 48.7 µg/l with a mean value of 22.0 ± 15.7 µg/l.

7. Turbidity

Turbidity levels were similar between the retention pond and wetland 3 and generally less that 5 nephelometric turbidity units (NTUs) over the course of this study (Fig. 20a & b). Turbidity in wetland 3 ranged from 0 to 5.10 NTUs with a mean of 0.79 ± 0.65 NTUs (mean ± STD). Turbidity values in the retention pond varied from 0.0 to 7.83 NTUs with a mean value of 1.85 ± 1.23 NTUs. YSI turbidity measurements were in good agreement with turbidity measurements taken from the monthly water column grab samples (Fig. 20 a & b).

C. Monthly Grab Sampling

1. Physical Characteristics - Chlorides, Total Alkalinity, TSS, Turbidity and Secchi Depth

The surface waters of the C-9 canal had the highest average chloride values (53.8 + 6.2 mg/l) while the lake had the lowest values, averaging 13.8 + 0.6 mg/l (Fig. 21a). A similar pattern was observed for total alkalinity (Fig. 21b). There were no consistent trends in total suspended solids (TSS) or turbidity as determined by laboratory analysis (Fig. 21 c & d). Secchi depth was also measured in the retention pond, wetlands 2, 3 and the lake (Fig. 21e). The retention pond had an average secchi depth of 4.0 ± 0.8 ft. Wetlands 2 and 3 had similar secchi depths averaging 4.0 ± 0.6 and 4.0 ± 0.6 ft respectively but that was due to hitting bottom rather than an accurate measure light attenuation in the wetlands (Fig. 21e, Craig per. observ.). The secchi disk hit bottom 69% (18/26 – weekly sampling) of the time in wetland 3 and 43% (3/7 - monthly sampling) in wetland 2. The lake had the deepest and most variable secchi depths, averaging 7.67 ± 2.18 ft for the study. Secchi depth was not measured in the C-9 canal, the grate or in wetland 5A due to logistical considerations.

2. YSI Discrete Monthly Measurements

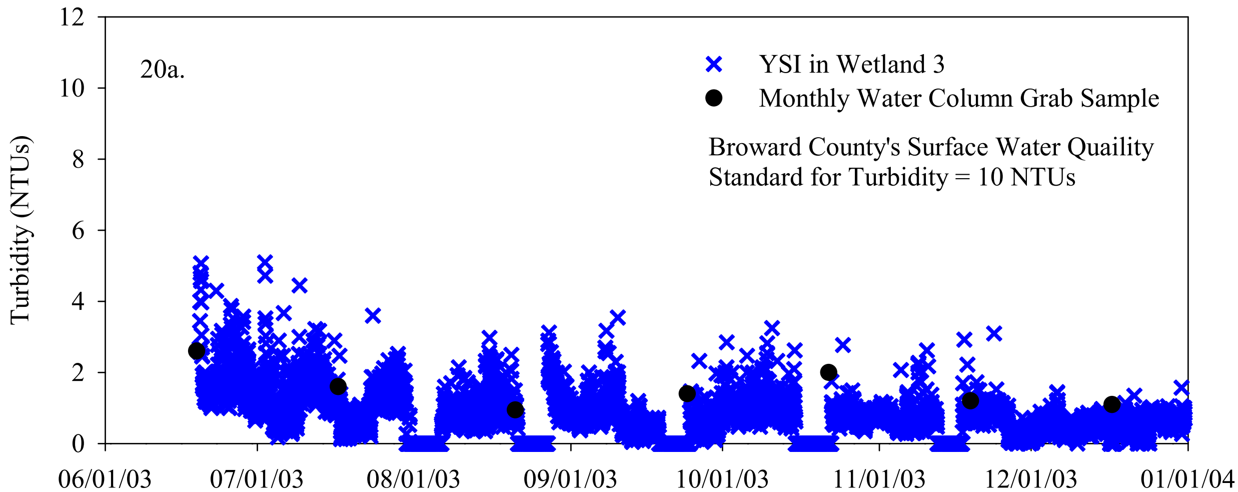
a. Specific Conductance

C-9 surface waters had the highest specific conductance of all the sites with a mean value of 571 ± 18 µmhos/cm (mean ± SD). Specific conductivity declined as C-9 surface water was mixed into surface waters of the wetlands at SWI (Table 3). The lake, which is geographically isolated from the wetlands and retention pond, had the lowest specific conductance, 232 ± 5 µmhos/cm, reflecting groundwater and rain inputs.

b. Temperature

No unexpected trends in temperature observed within SWI or at the C-9 canal. Temperatures remained in the mid to high twenties until the beginning of November after which they declined (Table 3). The lowest temperatures were observed in Wetland 5A with a recorded temperature of 14 °C at the time of the December 2003 sampling.

Figure 20a - b. Hourly Averages of Turbidity (NTUs) Compared to Turbidity Values from Monthly Water Column Grab Samples from the Retention Pond and Wetland 3 in Snake Warrior's Island, June - December 2003. Data was collected every 15 minutes by a YSI sonde located at each site. Broward County's Surface Water Quality Standard for Turbidity = 10 NTUs.



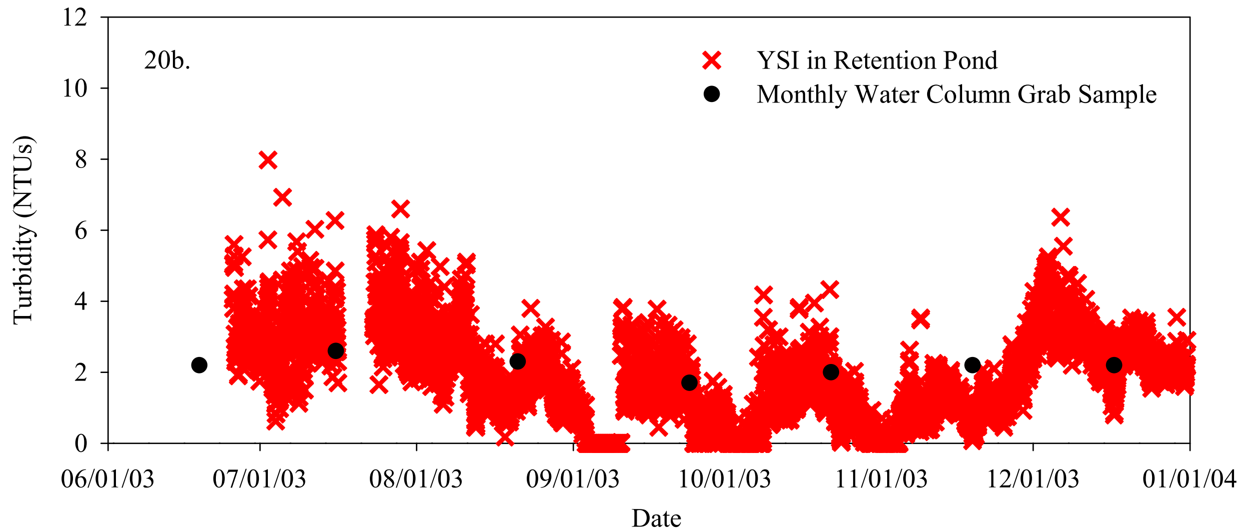


Figure 21a - e. Site Averaged Chlorides (mg/l), Total Alkalinity (mg/l), Total Suspended Solids (TSS) (mg/l), Turbidity (NTUs) and Secchi Depth (ft.) as a Measure of Water Clarity, from the Seven Sampling Events, June - December 2003. Please note that the secchi disk hit bottom 69% (18/26 - weekly sampling) of the time in wetland 3 and 43% (3/7 - monthly sampling) in wetland 2. Secchi depth was not recorded in wetland 5A (W 5A) because of a persistent macrophyte bloom on the surface of the water.

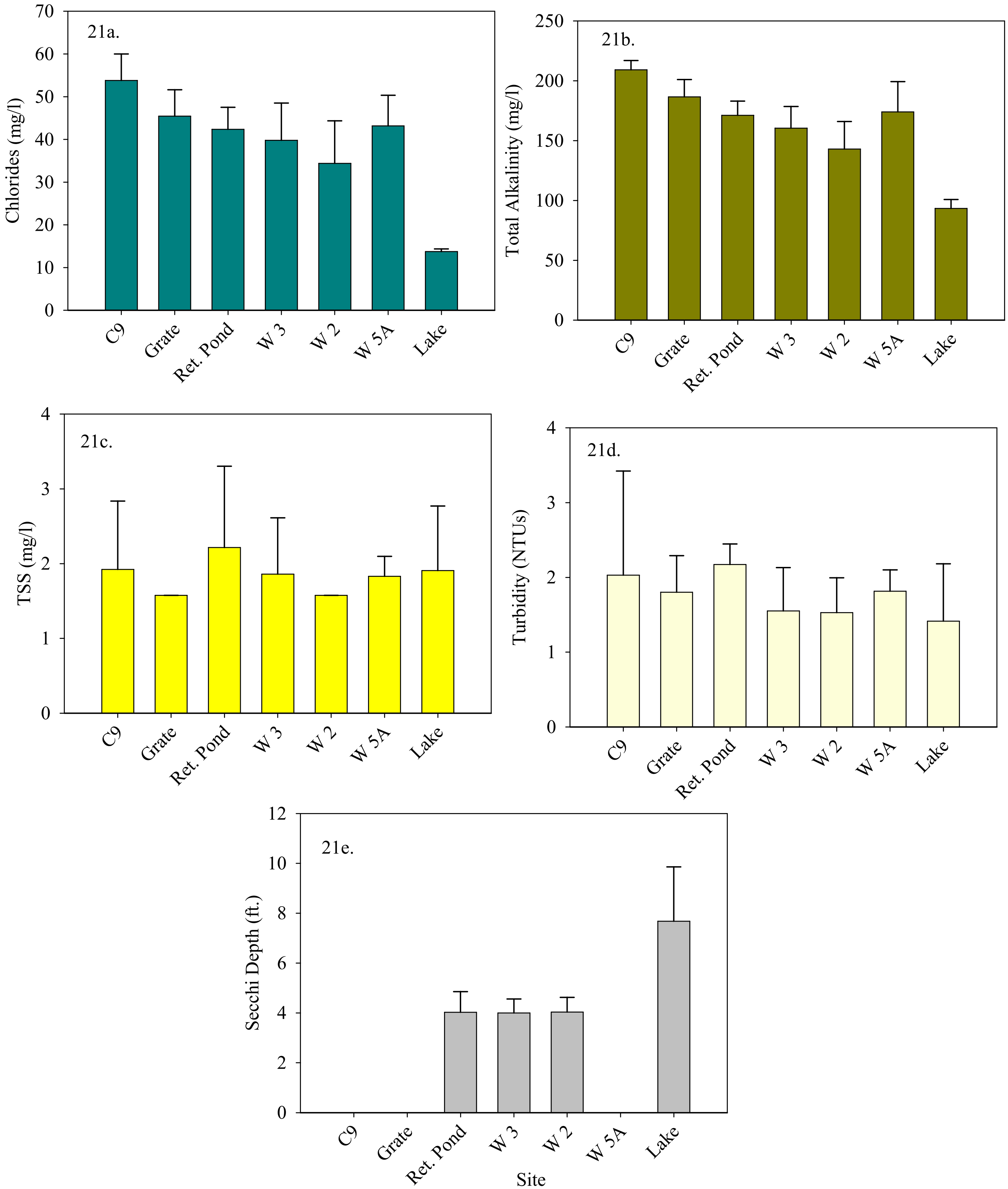


Table 3. Physical Parameters Measured During Monthly Water Column Sampling at Snake Warrior's Island and the C-9 Canal (Avg. ± SD) June through December 2003.

Site	YSI -Specific Conductance (μmhos/cm)	YSI Temperature °C	YSI - pH	YSI - Dissolved Oxygen (mg/l)	YSI - Chl (μg/l)	YSI -Turbidity (NTUs)
C9 Canal	571 ± 18	24.0 ±2.6	7.44 ± 0.20	3.90 ± 1.09	9.02 + 2.20	2.03 ± 1.39
Grate	476 ± 10	27.8 ± 2.6	7.66 ± 0.26	4.68 ± 2.11	7.59 + 3.16	1.80 ± 0.49
Retention Pond	465 ± 34	28.1 ± 3.2	7.95 ± 0.39	7.86 ± 2.72	18.97 + 8.06	2.17 ± 0.28
Wetland 3	436 ± 42	26.9 ± 3.1	7.51 ± 0.18	4.44 ± 1.98	13.82 + 3.52	1.55 ± 0.58
Wetland 2	393 ± 49	26.9 ± 2.8	7.44 ± 0.08	3.51 ± 1.69	11.09 + 2.52	1.53 ± 0.46
Wetland 5A	431 ± 43	23.7 ±4.5	6.99 ±0.16	1.74 ± 0.81	17.30 + 8.00	2.40 ± 0.94
Lake	232 ± 5	28.1 ± 4.0	8.01 ± 0.18	6.87 ± 0.91	2.97 + 0.90	1.41 ± 0.77

c. pH

pH ranged from a low of 6.80 in wetland 5A to a high of 8.70 in the retention pond. Wetland 5A had the lowest average pH with a value of 6.99 $\pm$ 0.16 (mean $\pm$ SD). Waters from the lake and the retention pond had the highest pH with average values of 8.01 $\pm$ 0.18 (mean $\pm$ SD) and 7.95 $\pm$ 0.31 respectively (Table 3). The retention pond was also the most variable with a range in pH values of 7.59 to 8.65. All the other sites fell in between those values.

d. Dissolved Oxygen

The retention pond had the highest average concentration of dissolved oxygen (D.O.) of all the sites with a value 7.78 $\pm$ 2.72 mg/l, followed by the lake, 6.87 $\pm$ 0.91(mean $\pm$ SD). The retention pond also had the greatest variability in dissolved oxygen. The C-9 canal, grate and wetlands 3, and 2 had similar D.O. concentrations ranging from 3.50 to 4.68 mg/l well within expected values (Table 3). Wetland 5A had much lower dissolved oxygen concentrations averaging only 1.74 $\pm$ 0.91 mg/l.

e. Turbidity

Turbidity as measured by the YSI sonde averaged less than 5 NTUs at all sites (Table 3). There was generally good agreement between turbidity as measured by the YSI sonde and turbidity determined from the monthly water column grab samples with the exception of wetland 5a which had a persistent bloom of a small macrophyte (Fig. 22). Wetland 5A was the only site that exceeded the Broward County standard of 10 NTUs (Broward County 2001).

f. Chlorophyll

The retention pond and wetlands 5A had the highest averaged chlorophyll concentrations, 18.97 $\pm$ 8.06 μg/l and 17.30 $\pm$ 8.00 μg/l respectively, of all sites based on fluorescence as measured by the YSI sonde (Table 3). The lake had the lowest chlorophyll values averaging of 2.97 $\pm$ 0.90 μg/l. Chlorophyll-a (Chl_a) was also determined from the monthly water column grab samples collected from all the sites (Fig. 23a-g). Extracted chlorophyll values tended to be higher and more variable than values obtained from the YSI sonde for most sites (Fig. 23a-g). This was similar to what was seen previously with in the longer term YSI and extracted chlorophyll record for wetland 3 and the retention pond (Fig. 19).

3. Nutrients

a. Ammonia (NH_3)

Ammonia concentrations at the C-9 canal, the major source of surface water to SWI, were consistently higher than ammonia concentrations at any of the other monthly sites. The C-9 canal had an average concentration of 0.366 $\pm$ 0.218 mg/l with values ranging from 0.092 to 0.70 mg/l (Fig. 24a-g). Ammonia concentrations at the sites within SWI were substantially lower than concentrations in the C-9. Half (21 /42) of the monthly samples collected within the SWI Natural Area were below minimum detection limits (MDL = 0.024 mg/l). The retention pond had the lowest average concentration, 0.017 $\pm$ 0.014 mg/l, while the two end member sites within

Figure 22. The Average Turbidity from the Seven Monthly Grab Samples Compared to Turbidity Values Measured by the YSI Sonde During Monthly Sampling. There is reasonable agreement between the two methods of determining turbidity with the exception of wetland 5A. One possible explanation is that wetland 5A had persistent bloom of a small macrophyte that was not present at the other sites.

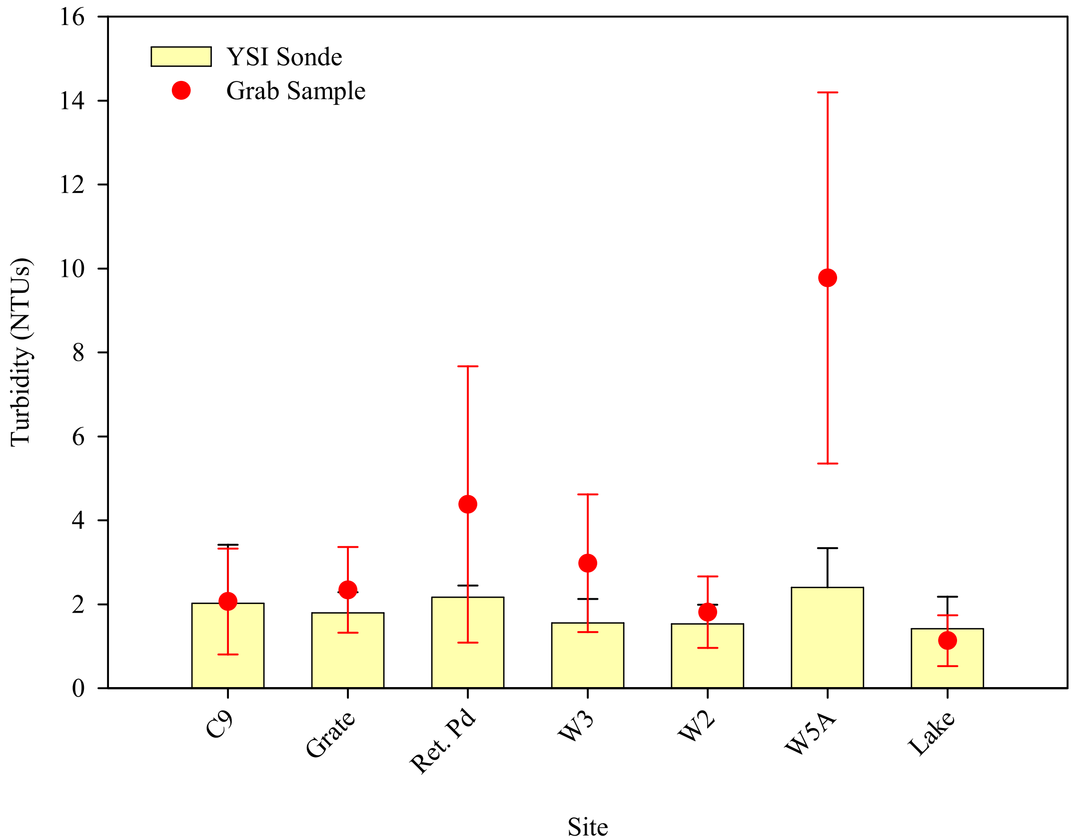


Figure 23a - g. Monthly Extracted Chlorophyll a (µg/l) by Site Compared to YSI Chlorophyll measured by the Florescence Probe on the YSI Sonde, June - December 2003.

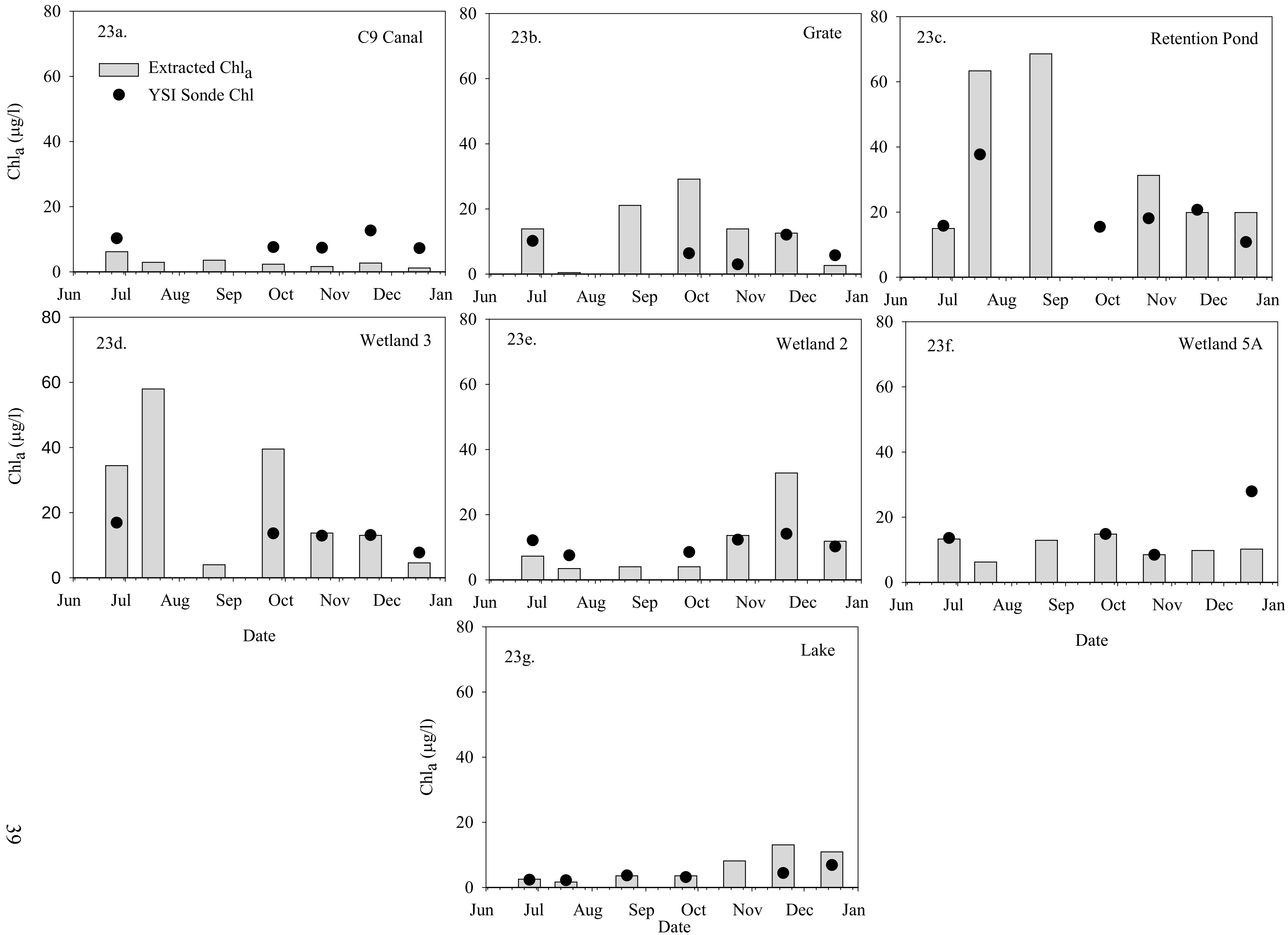
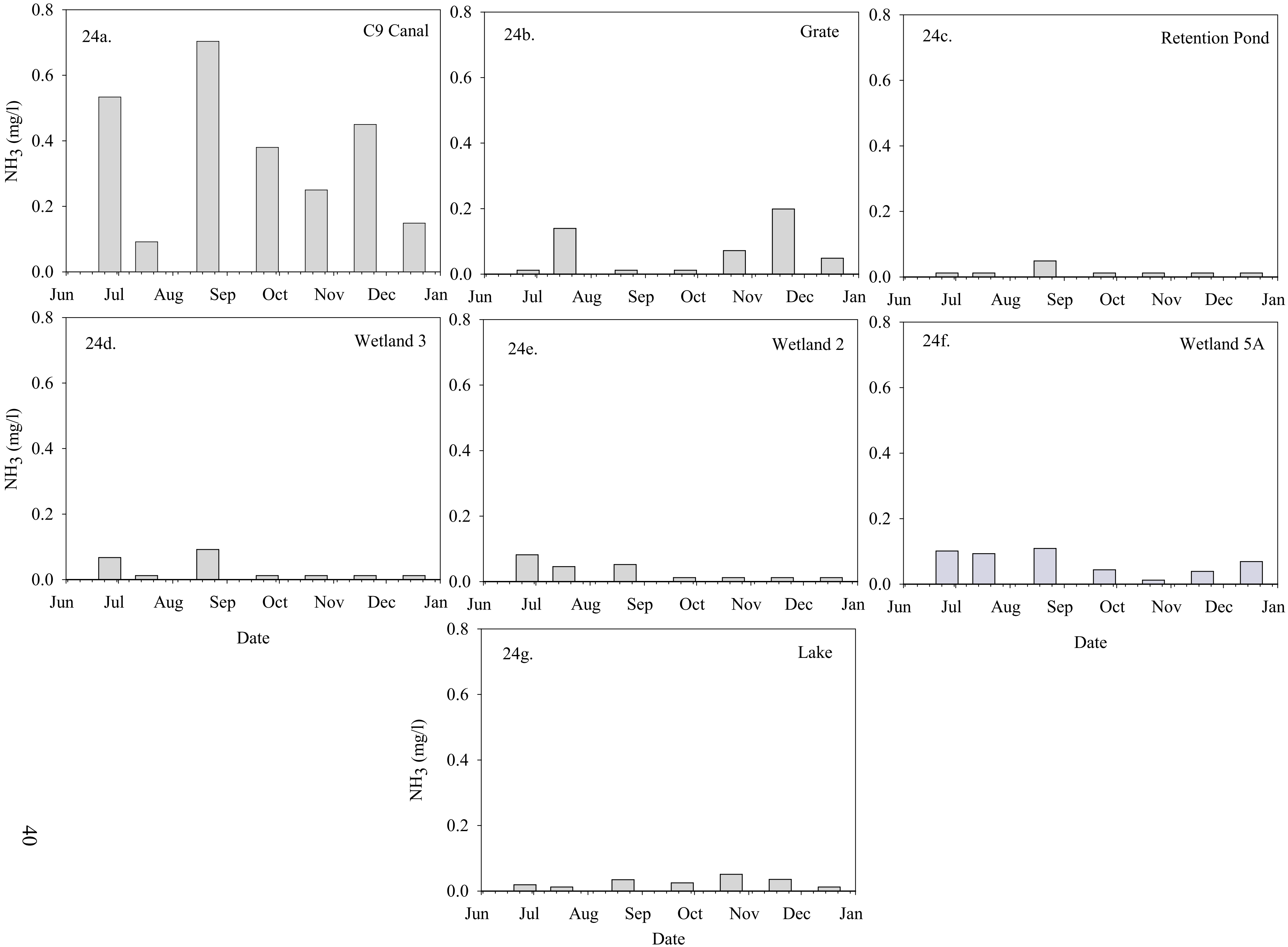


Figure 24 a - g. Monthly Ammonia (NH_3) Concentrations (mg/l) at the Six Sites within Snake Warrior's Island and at C-9 Canal, June - December 2003.



SWI, wetland 5A and the grate had the highest average ammonia concentrations, 0.067 $\pm$ 0.036 mg/l and 0.071 + 0.073 mg/l respectively.

b. Nitrate + Nitrate (NOx)

Nitrate +Nitrite concentrations were five to six times higher at the grate and C-9 canal compared to the other 5 sites within SWI (Fig. 25a-g). The grate site had the highest and most variable concentrations of NO_x. The average concentration at the grate was 0.174 $\pm$ 0.109 mg/l but values ranged from below the MDL (0.007 mg/l) to 0.306 mg/l. The C-9 had an average NOx concentration of 0.127 $\pm$ 0.067 mg/l for the 7 month study. NO_x concentrations were substantially lower at the remaining sites. The retention pond had an average concentration of 0.031 $\pm$ 0.045 mg/l, followed by the lake with a value of 0.015 $\pm$ 0.021 mg/l. The three wetlands had the lowest concentrations of NO_x, with values ranging from below the MDL (0.007 mg/l) to 0.014 mg/l (Fig. 25a-g).

c. Total Nitrogen (TN)

Total nitrogen values ranged from a low of 0.77 $\pm$ 0.39 mg/l at the lake to a high of 1.39 $\pm$ 0.18 mg/l at the C-9 canal (Fig. 26 a-g). TN concentrations were below Broward County's surface water quality standard of 1.5 mg/l at most sites. The C-9 canal, grate and wetland 5A exceeded the 1.5 mg/l standard during the first three months of the study. Wetland 5A was anomalous in that it had the highest concentrations of TN of all the wetlands even though it was the farthest away from C-9 and storm water inputs. The average TN concentration in wetland 5A was 1.36 $\pm$ 0.22 mg/l.

d. Ortho-Phosphate (OPO_4)

All the sites with the exception of wetland 5A had similar and low concentrations of ortho-phosphate ($O\text{-}PO_4$) (Fig. 27a-g). Excluding wetland 5A, mean concentrations of $O\text{-}PO_4$ ranged from low of 0.003 $\pm$ 0.001 mg/l at the C-9 to a high of 0.016 $\pm$ 0.012 mg/l at the grate. Wetland 5A had substantially higher OPO4 concentrations, averaging 0.063 $\pm$ 0.025 mg/l over the course of the study.

e. Total Phosphorus (TP)

Total phosphorus (TP) concentrations in the wetlands and retention pond at SWI were close to or exceeded Broward County's surface water criteria of 0.02 mg/l on almost all sampling dates. The retention pond, grate, and wetlands 2 and 3 had similar values ranging from a low of 0.011 mg/l in wetland 3 to high of 0.079 mg/ in wetland 2a (Fig. 28a-g). TP values in the lake and C-9 canal were generally below the 0.02 mg/l standard though on occasion TP values did exceed the 0.02 mg/l standard (Fig. 28a-g). Elevated TP values were observed at all sites in November and may be related protracted rain events prior to sampling (Fig. 10b). Wetland 5A was again anomalous with TP concentrations substantially higher there than at any of the other sites. TP concentrations in wetlands 5A ranged from 0.081 to 0.196 mg/l with an average value of 0.136 $\pm$ 0.045 mg/l (Fig. 28a–g). Wetland 5A's small size and shallow depth coupled with being at the

Figure 25a - g. Monthly Nitrate + Nitrite (NOx) Concentrations (mg/l) at the Six Sites within Snake Warrior's Island and the C-9 Canal, June - December 2003.

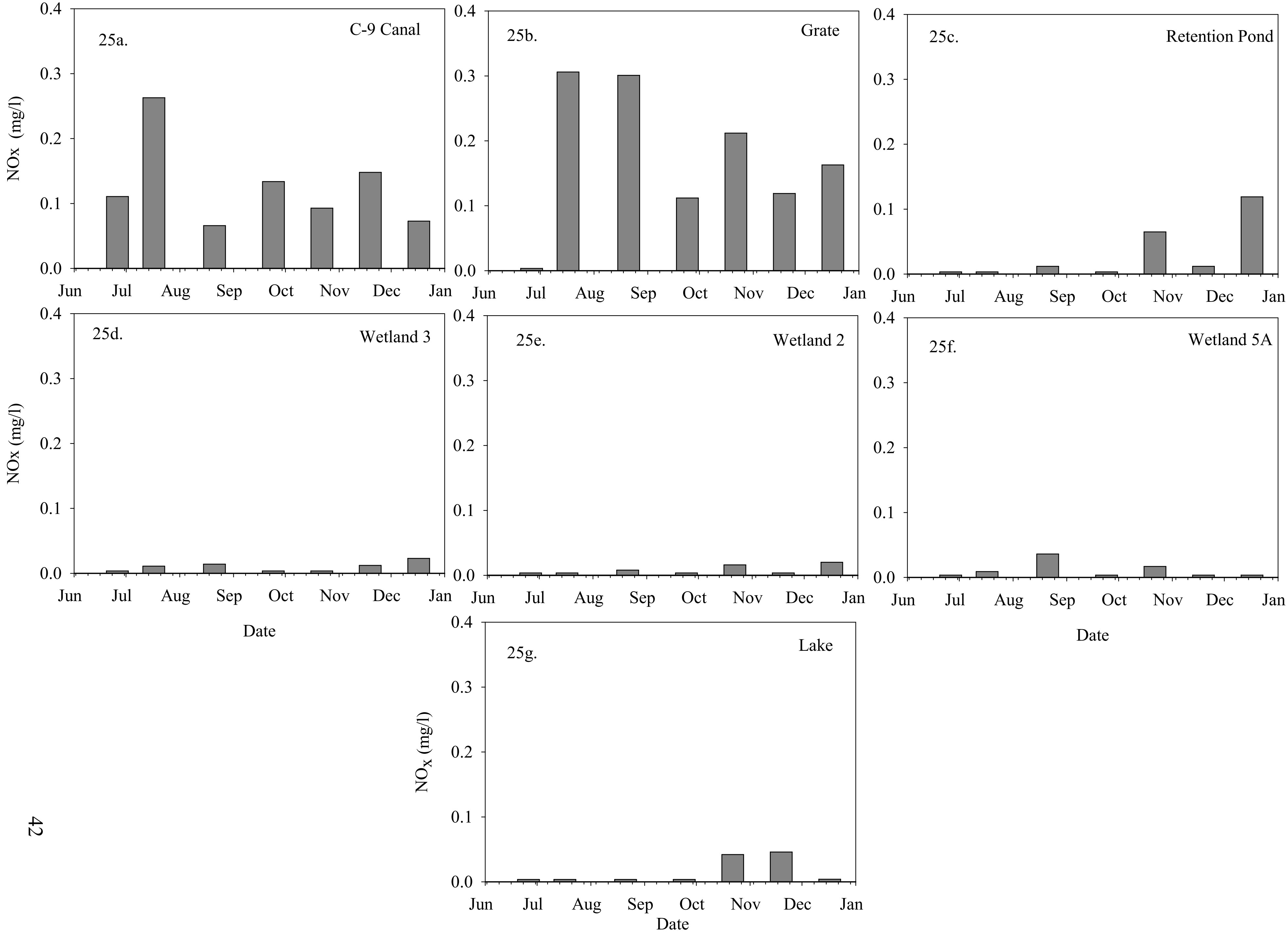


Figure 26a - g. Monthly Total Nitrogen (TN) Concentrations (mg/l) at Snake Warrior's Island and at the C-9 Canal. The black solid line indicates Broward County's surface water quality standard = 1.50 mg/l. Samples were collected June through December 2003.

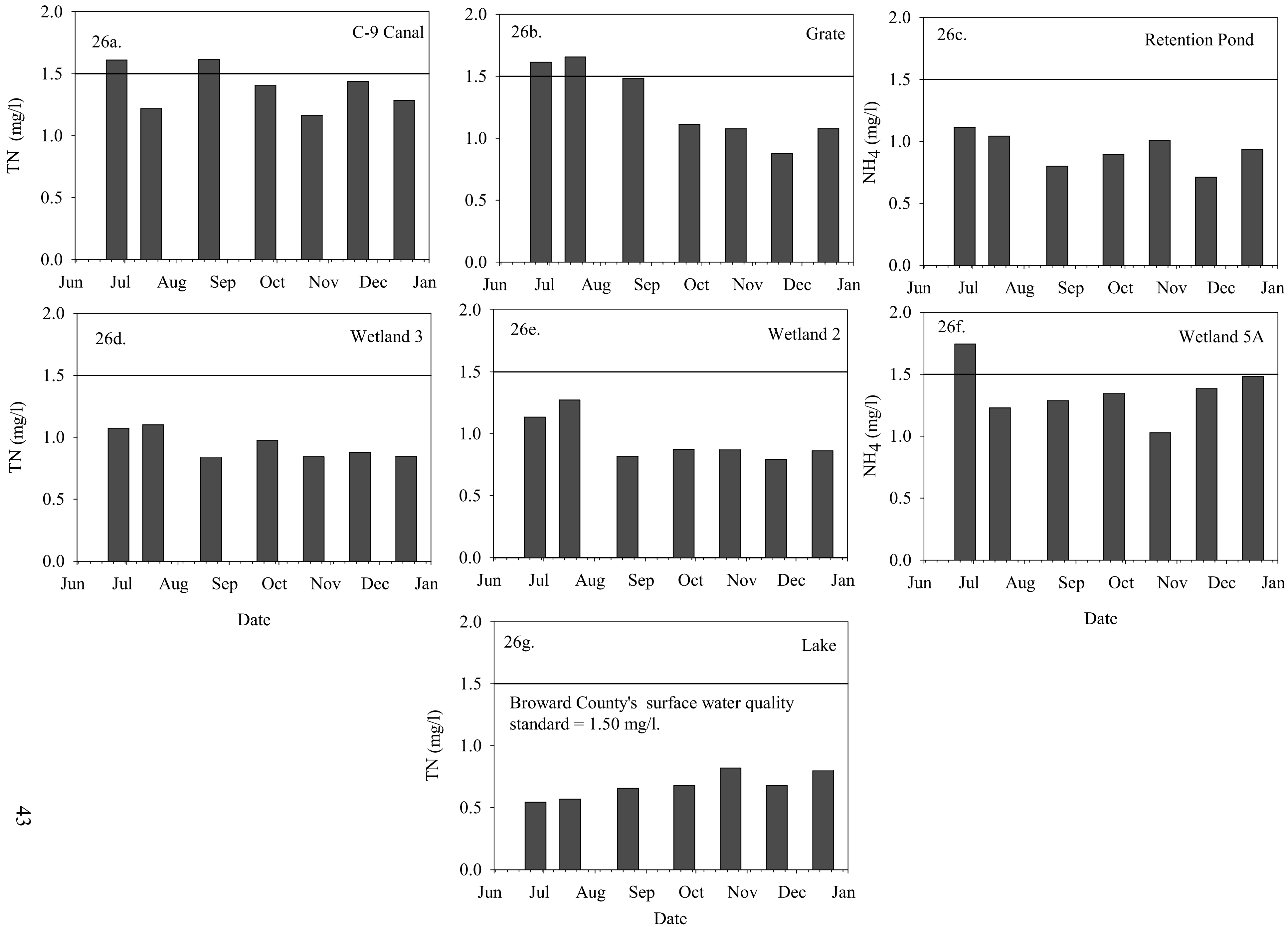


Figure 27a - g. Monthly Ortho-phosphate (OPO_4) Concentrations (mg/l) at Snake Warrior's Island and at the C-9 Canal. Samples were collected June through December 2003.

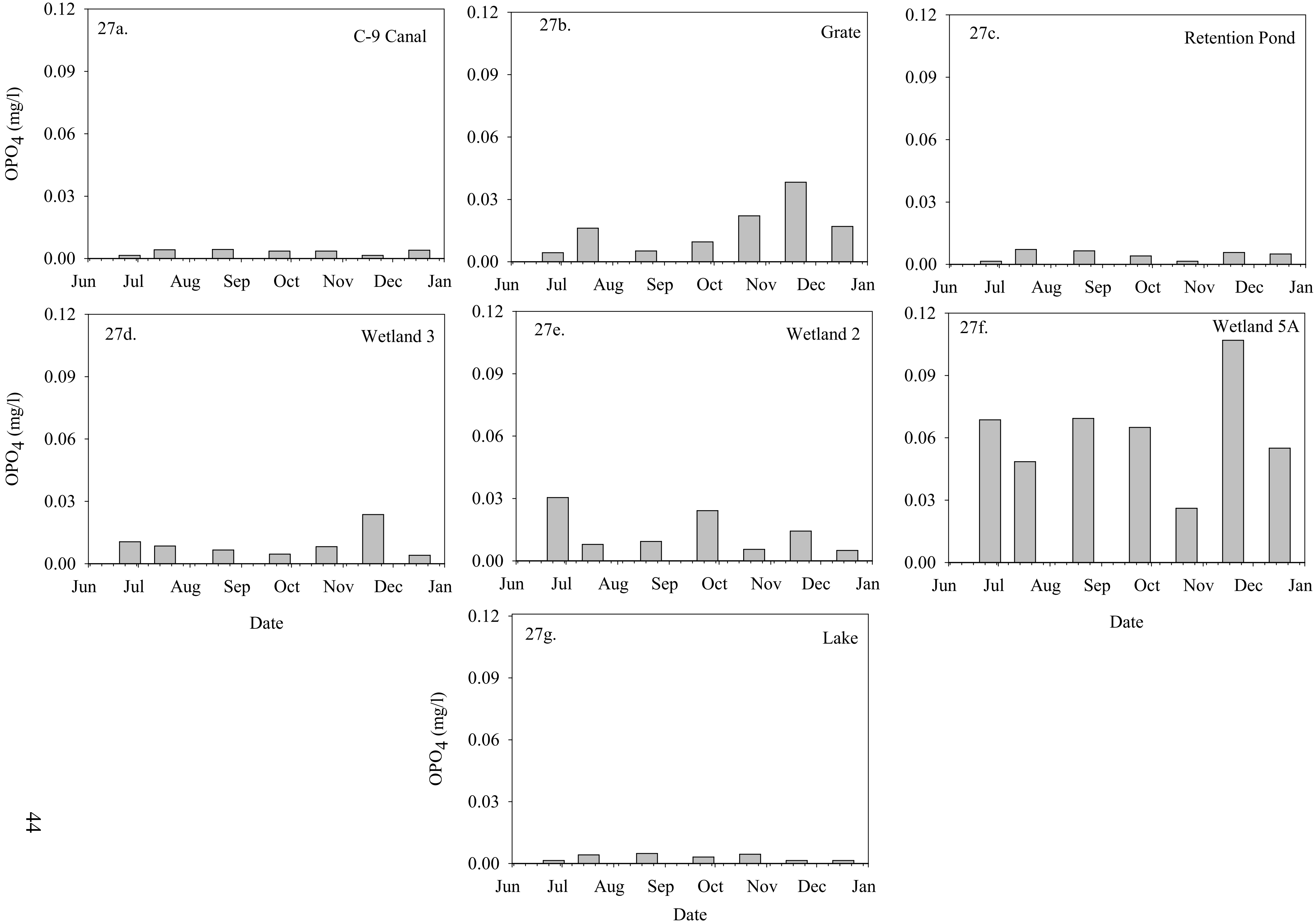


Figure 28a - g. Monthly Total Phosphate (TP) Concentrations (mg/l) at Snake Warrior's Island and at the C-9 Canal. The solid black line indicates Broward County's surface water quality standard = 0.02 mg/l. Samples were collected June through December 2003.

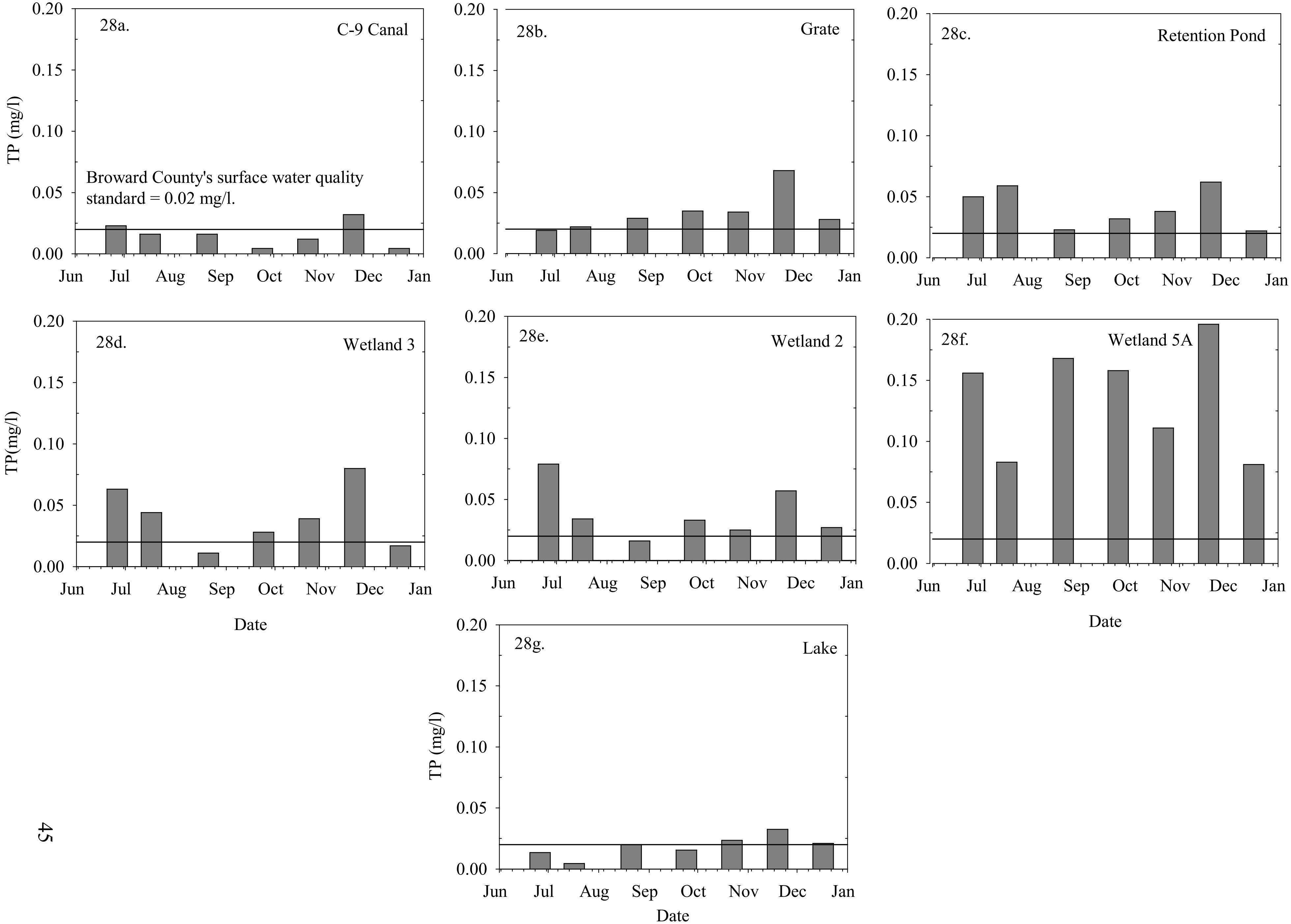


Table 4. Percentage of Total Metal Samples from Surface Waters at Snake Warrior's Island and the -9 Canal above Minimum Detection Limits (MDL) and the Percentage of Samples that Exceeded Surface Water Quality Criteria for Fresh Water Based on Broward County's Chapter 27 Surface Water Standards (Broward County 2001). MCL = maximum contaminant level. N.S. = no standard.

Metal	MDL (µg/l)	MCL (µg/l)	>MDL	>MCL	Sites
Arsenic	1.47	50	57% (32/56)	0%	Variable with date and site
Barium	2.08	N.S.	45% (25/56)		Variable with date and site
Beryllium	1.75	0.13	0%	0%	< MDLs on all dates and for all sites-
Cadmium	0.999	1	0%	0%	< MDLs on all dates and for all sites
Chromium	1.37	50	0%	0%	< MDLs on all dates and for all sites
Copper	3.9	3	7% (4/56)	7% (4/56)	> MDL on 7/17/03 – W5A > MCL on 8/21/03 – RP, W3, W5A
Nickel	2.94	100	9% (5/56)	0%	> MDL on 6/26/03 – C-9, Grate, W5A, Lake
Lead	9.13	30	2% (1/56)	0%	> MDL on 11/19/03 – C-9 Canal
Selenium	14	5	11% (6/56)	11% (6/56)	> MCL on 10/22/03 - all sites except C-9
Vanadium	2.59	N.S.	88% (49/56)		< MDL on 9/25/03 - W5A < MDL on 10/22/03 -RP, W3, W2, W5A < MDL on 12/18/03 - Lake
Zinc	3.65	86	36% (20/56)	2% (1/56)	> MDL on 6/26/03 – W5A > MDL on 8/21/03 – W3, Lake > MDL on 9/24/03 – all sites > MDL on 10/22/03 – all site

end member wetland at SWI, may in part explain the relatively high TP concentrations compared to the other sites (Table 1).

f. Total Organic Carbon

Total organic carbon concentrations were similar between the adjoining sites (C-9 canal, grate, retention pond and the wetlands). Values ranged from 9.0 to 15.0 mg/l. The lake had lower TOC values compared to the other sites, ranging from 6.0 to 6.7 mg/l (Fig. 29a-g).

4. Metal and Ion Concentrations

The total and dissolved metal concentrations of arsenic, barium, beryllium, copper, cadmium, chromium, iron, nickel, lead, selenium, vanadium and zinc, were determined in surface waters at SWI and at the C-9 canal. No consistent temporal trends were observed for most of the metals at any of the sites (e.g. Fig. 30a-g – vanadium, Fig. 31a-g – arsenic, Fig. 32a-g – selenium). With a few exceptions, the concentrations of most metals were low with a large percentage of the samples falling near or below minimum detection limit (MDLs) (Table 4). On those occasions when metal concentrations exceeded MDLs, the hits generally occurred on the same date at several sites (Fig. 32a-g - selenium and 33a-g - zinc). Selenium concentrations exceeded MDLs and Broward County's water quality standard of 5 µg/l in October for all the SWI sites. Selenium concentration at the C-9 canal was below the MDL for that date, suggesting a localized source of selenium around SWI (Fig. 32a–g). Zinc concentrations followed a similar pattern though on a broader geographic scale which included the C-9 canal (Fig. 33a- g). Zinc concentrations exceeded detection limits at every site including the lake and the C-9 canal in October and November 2003 again suggesting an atmospheric source but one that dispersed the zinc over a larger geographic range compared to selenium. Zinc distribution may be related to rain events that occurred in that area.

Some metals like vanadium proved to be useful tracers of water mass movement (Fig. 34a-g). Vanadium concentrations were typically highest at the C-9 canal and declined with distance through the wetlands. The lake which is hydrologically isolated from C-9 had the lowest vanadium concentrations. Another interesting observation becomes apparent when looking at the time series at each site (Fig. 30a-g). Va concentrations at all sites were substantially lower during the October and November sampling events, and may reflect dilution due to direct rain inputs or storm water.

Ion ratios were also examined to get an idea of the extent of water mass mixing at SWI. The ionic composition of lake water is distinct from all other sites (Fig. 35a-c). If lake samples are excluded, some additional trends emerge with respect to distance from the C-9 canal and sites within SWI. The ratio of Ca/K while variable had a trend similar to vanadium. The ratio decreased with increasing distance from the C-9 canal (Fig. 36). The plot of Ca versus K indicates the ionic composition of C-9 water is somewhat distinct from the wetlands at SWI and that the grate and retention pond fall in between the two (Fig. 36).

Figure 29a - g. Monthly Total Organic Carbon (TOC) Concentrations (mg/l) at Snake Warrior Island and at the C-9 Canal. Samples were collected June through December 2003.

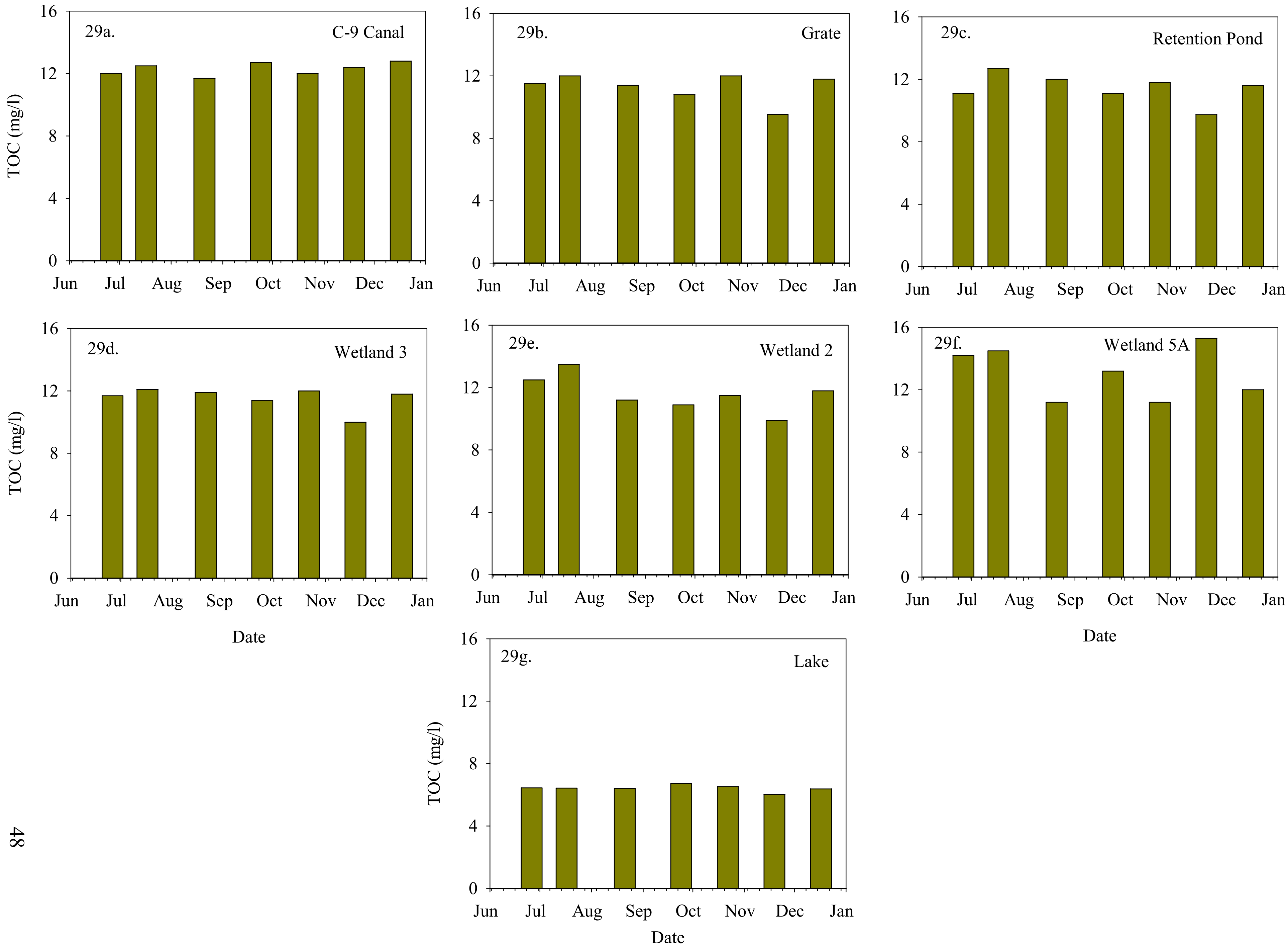


Figure. 30a - g. Vanadium (Va) Concentrations (µg/l) in Monthly Water Column Samples Collected at Snake Warrior's Island and the C-9 Canal. Samples were collected June through December 2003.

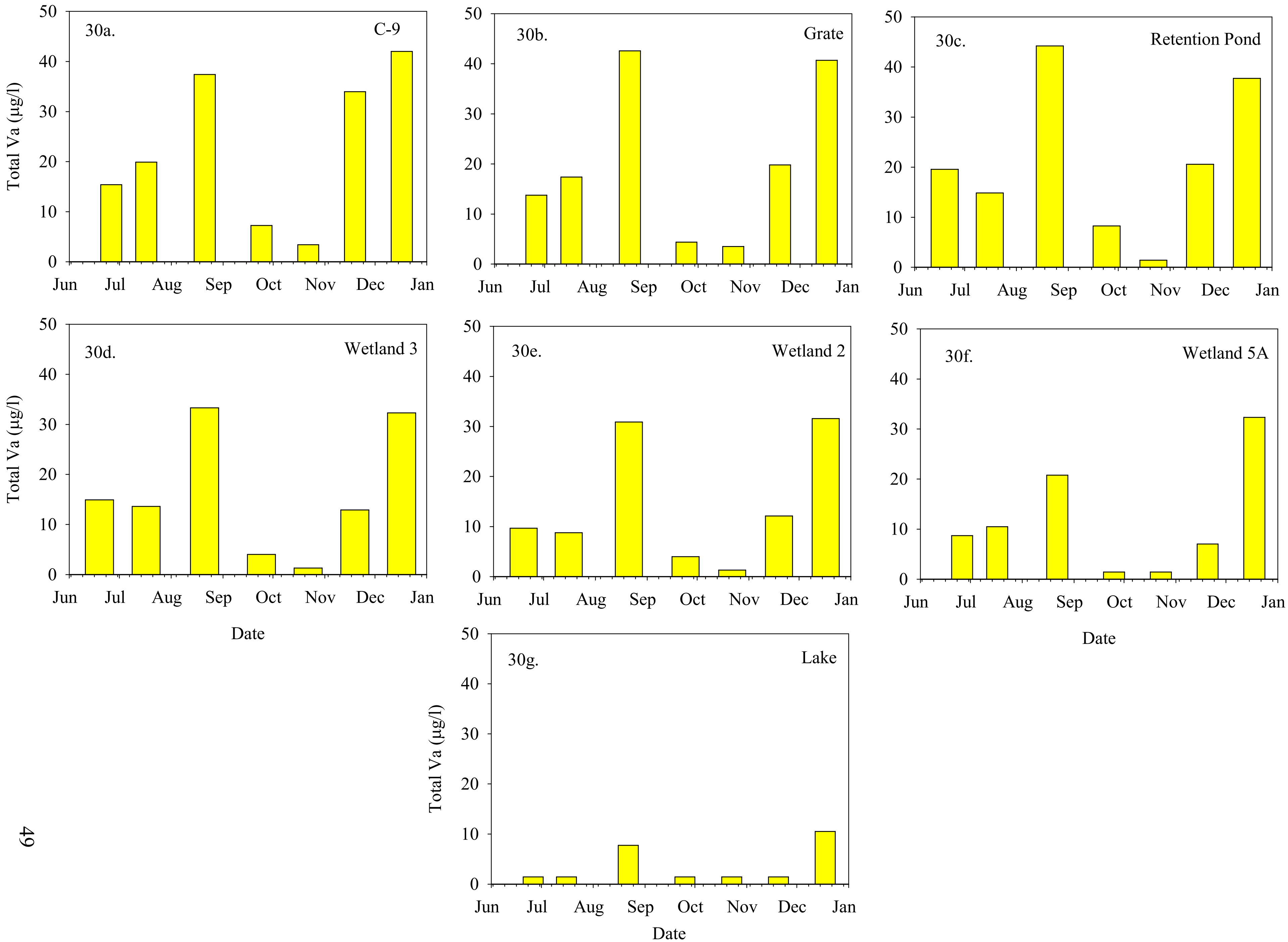


Figure 31a - g. Arsenic (As) Concentrations (µg/l) in Monthly Water Samples by Site. Samples were collected June through December 2003. Broward County's water quality standard is 50 µg/l.

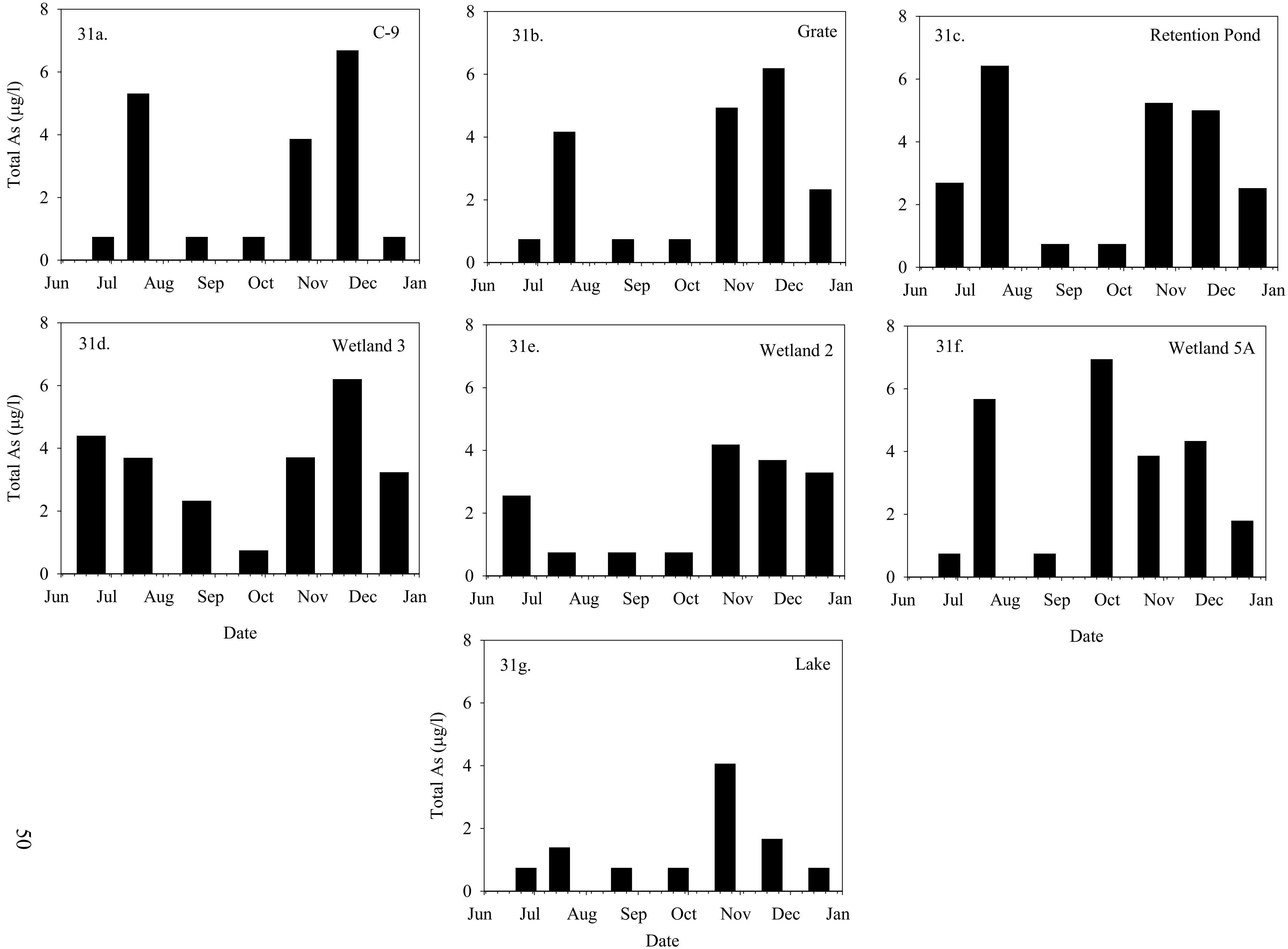


Figure 32a - g. Selenium (Se) Concentrations (µg/l) in Monthly Water Column Samples Collected at Snake Warrior's Island and the C-9 Canal. Samples were collected June trhough December 2003. Broward County's water quality standard is 5 µg/l and is indicated by the solid black line.

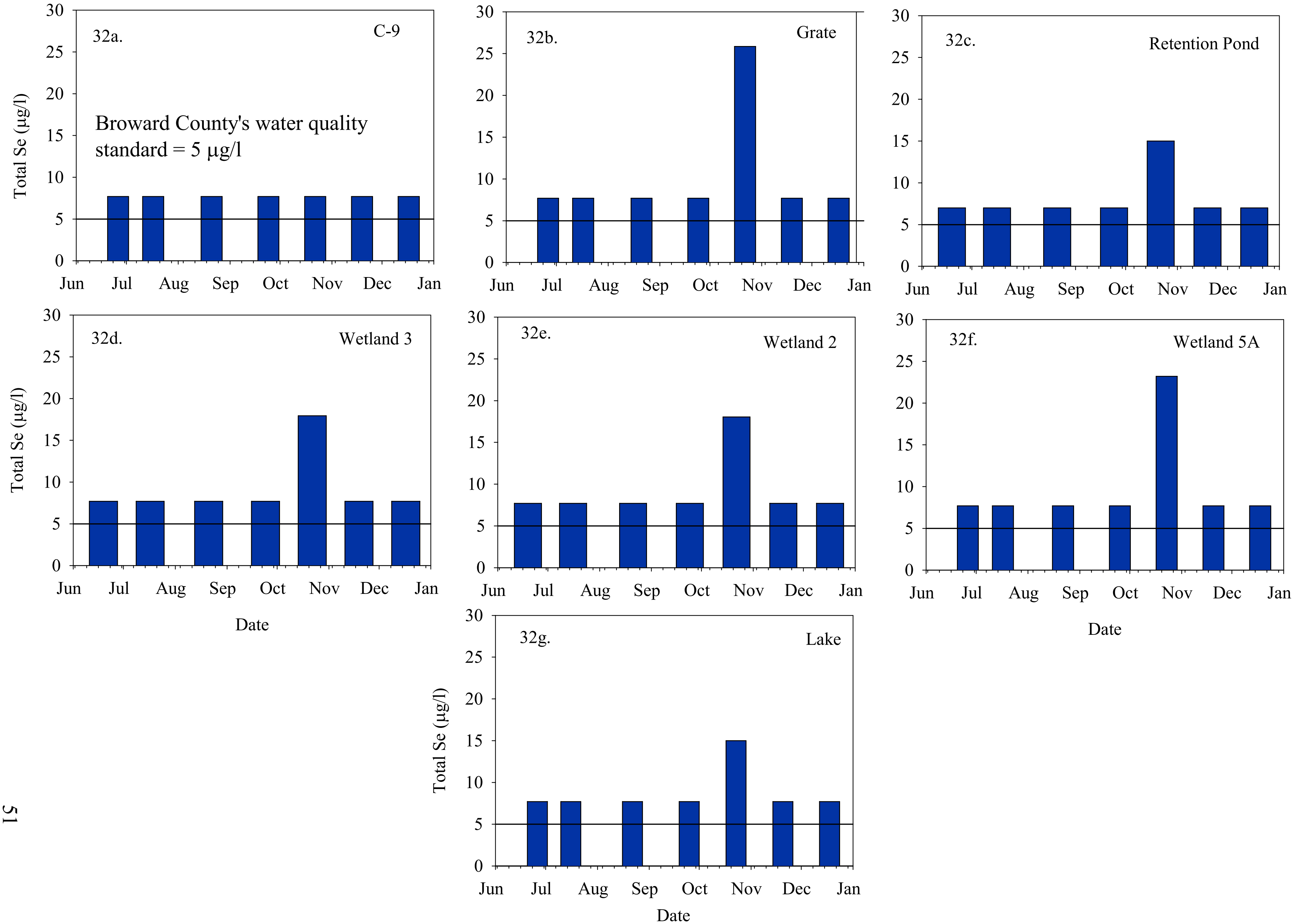


Figure 33a - g. Zinc (Zn) Concentrations (µg/l) in Monthly Water Column Samples Collected at Snake Warrior's Island and the C-9 Canal. Samples were collected June through December 2003. Broward County's surface water quality standard for zinc is 86 µg/l and is indicated by the solid black line (Broward County 2001).

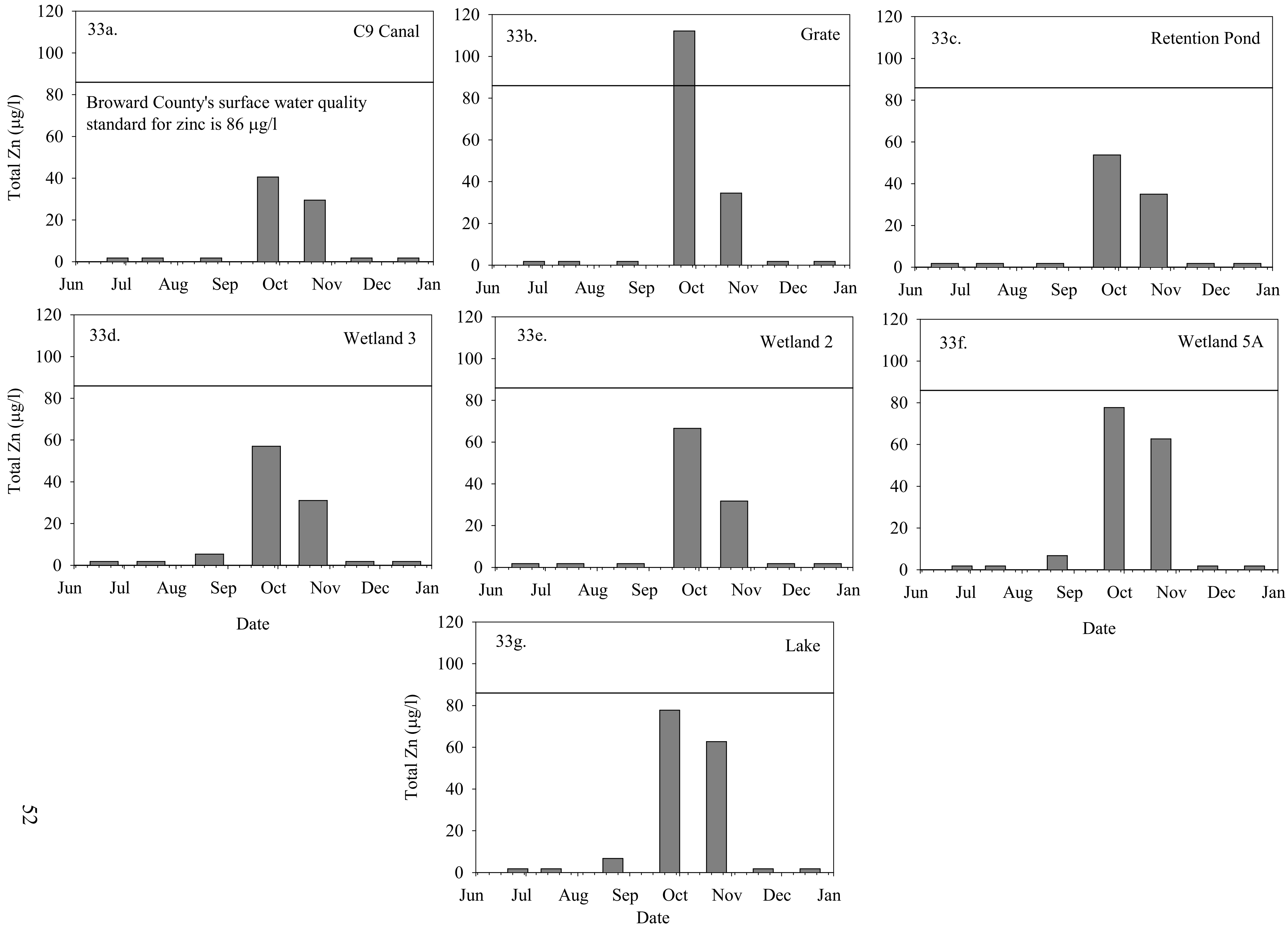


Figure. 34a - g. Vanadium (Va) Concentrations (µg/l) in Monthly Water Column Samples Collected at Snake Warrior's Island and the C-9 Canal, June - December 2003. Va concentrations decreased with increasing distance from the C-9 Canal. Water flow from the C-9 > Grate > Retention Pond >Wetland 3 > Wetland 2 > Wetland 5a. The lake is geographically isolated from the other water bodies.

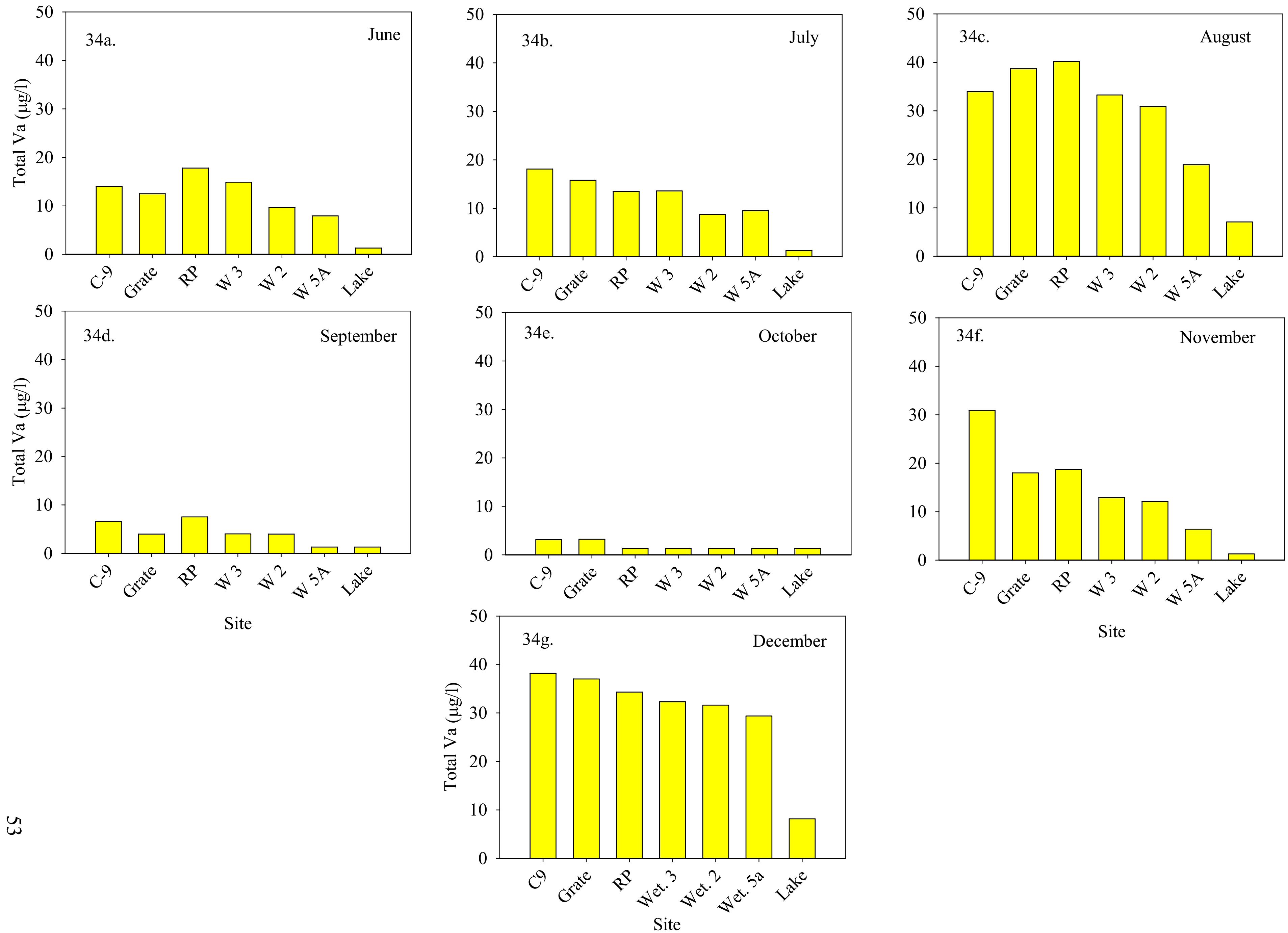


Figure 35a - c. Ion Ratios in Surface Waters from Snake Warrior's Island and the C-9 Canal, June - December 2003. The lake has a distinct ion ratio compared to the C-9 canal and the wetlands of Snake Warrior's Island.

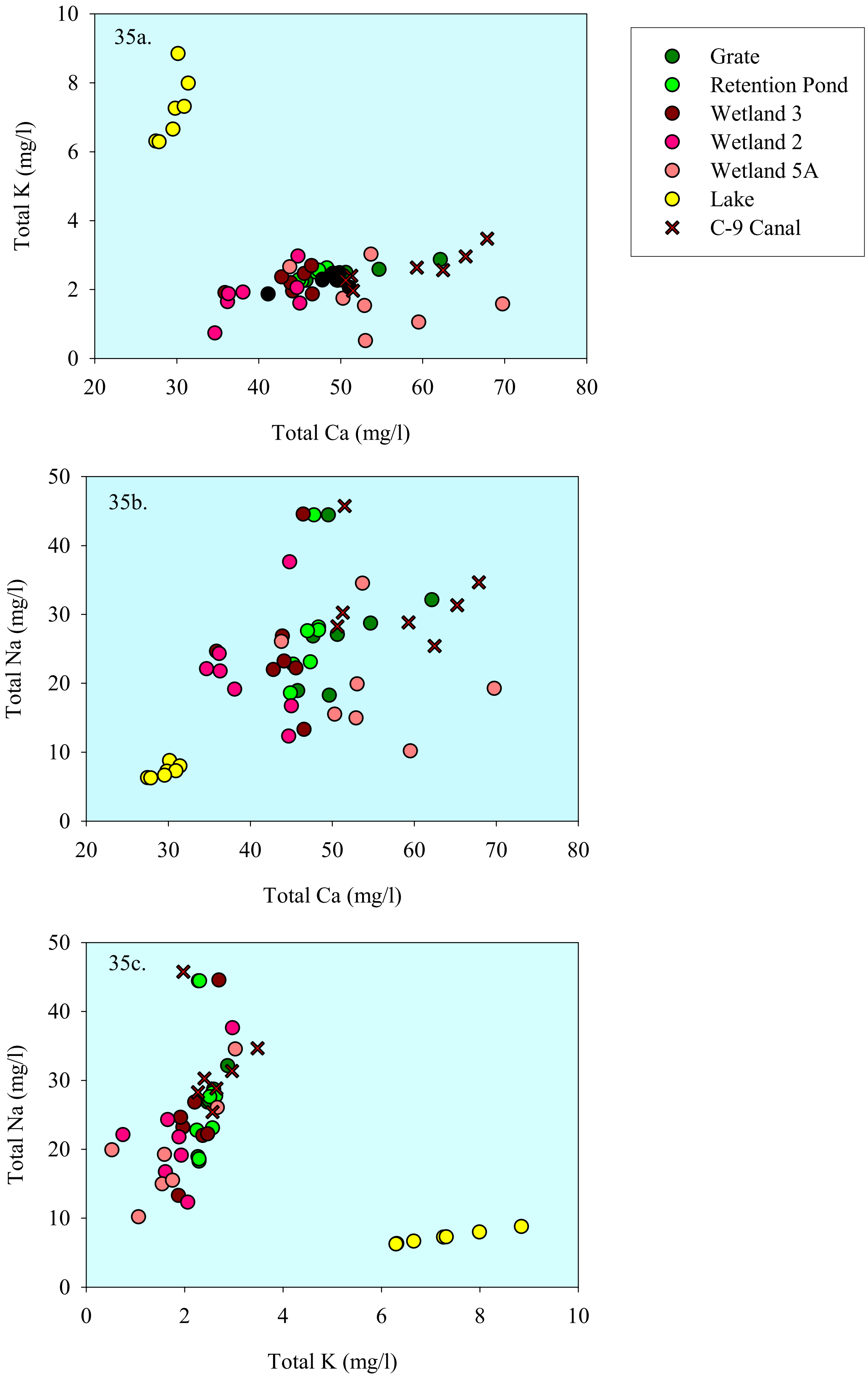
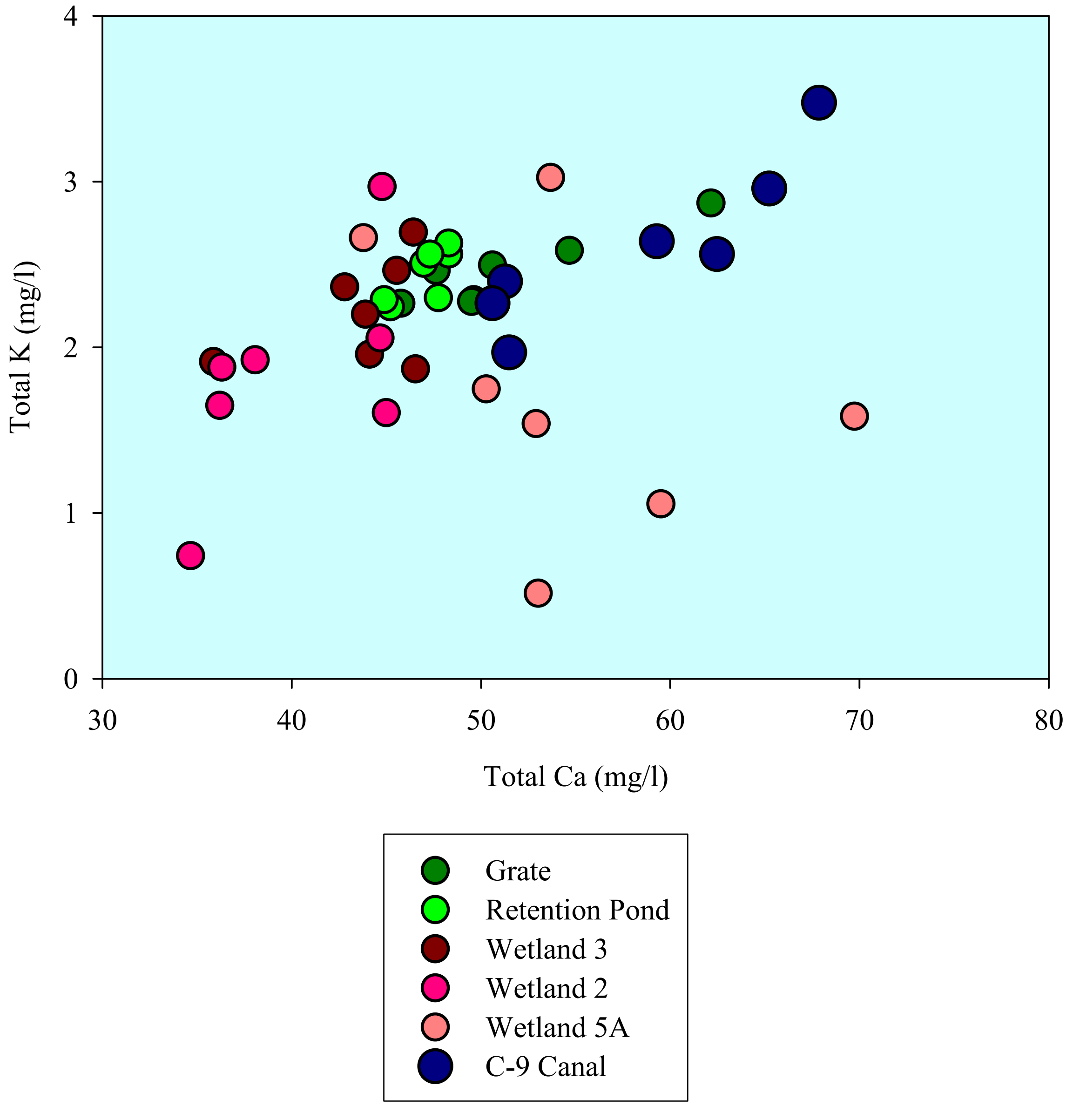


Figure 36. Ratio of Calcium (Ca) to Potassium (K) in Surfaces Waters from Snake Warrior's Island and the C-9 Canal. Lake data has been excluded. The ratio of calcium to potassium decreases with increasing distance from the C-9 canal.



5. Polycyclic Aromatic Hydrocarbons (PAHs) and Pesticides/Herbicides

Water column samples collected at SWI and the C-9 canal were below the minimum detection limits for PAHs and most of the herbicides tested for. Three sites, the grate, retention pond, wetland 3 had detectable but low concentrations of the herbicide Atrazine in July 2003 (Table 5).

C. Storm Event Samples

1. Nutrients

a. Ammonia (NH_3)

Ammonia concentrations in storm water samples collected at SWI and from Miami Gardens were variable, ranging from 0.03 to 0.26 mg/l (Fig. 37a-c). No distinct trends were observed between first and second flush samples collected at SWI. Ammonia concentration in the two storm water samples collected from Miami Gardens bracketed the SWI storm water samples. Miami Gardens samples had both the lowest and highest ammonia concentrations.

b. Nitrate + Nitrite (NOx)

No clear trends in nitrate + nitrite concentrations were noted in storm water collected at either Miami Gardens or SWI (Fig. 38a-c). Concentrations were variable at both sites. Second flush samples collected at SWI tended to have higher NOx concentrations compared to first flush samples but both were lower than Miami Gardens' values. First flush samples averaged 0.36 $\pm$ 0.30 mg/l of NOx, while second flush samples averaged 0.55 $\pm$ 0.45 mg/l. NOx concentrations in Miami Gardens samples were 0.84 and 1.20 mg/l (May and November 2003 respectively) and exceeded all of the SWI values with the exception of one second flush sample collected in December 2003.

c. Total Nitrogen (TN)

Storm water total nitrogen values were similar at the grate at SWI and Ronald St. in Miami Gardens. No clear trends were apparent (Fig. 39a-c). Approximately half of the samples were above Broward County's surface water quality standard of 1.5 mg/l (Fig. 39a-c). Storm water values ranged from 1.09 to 2.45 mg/l for all sites. TN concentrations exceeded Broward County's water quality standard of 1.5 mg/l for TN in 50% (8/16) of the time.

d. Ortho-Phosphate (O-PO_4)

Miami Gardens' storm water had higher O-PO_4 concentrations than storm water collected at SWI (Fig. 40a-c). Values ranged from 0.06 to 0.072 mg/l at Miami Gardens and between 0.0017 and 0.0274 mg/l at SWI. First flush samples, collected at the storm grate at SWI, tended to have higher orthophosphate concentrations than second flush samples (Fig. 40a-c).

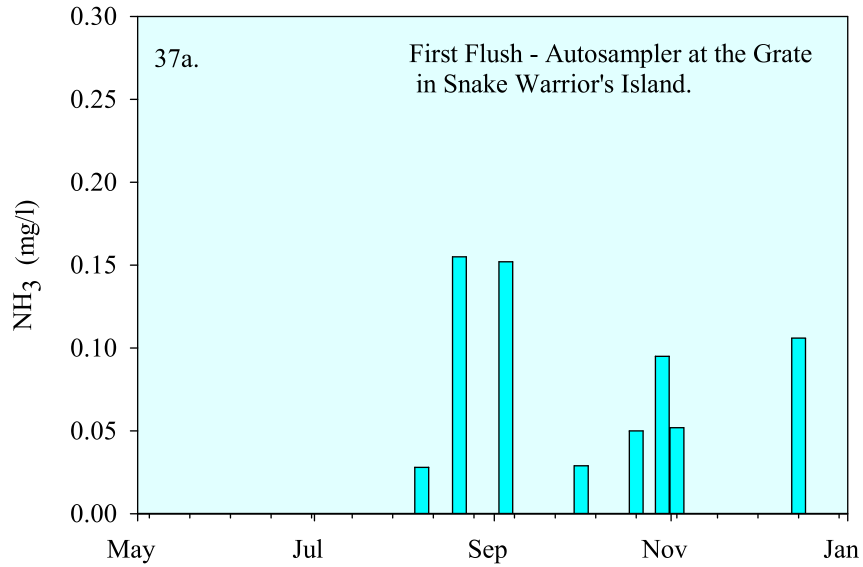
e. Total Phosphorus (TP)

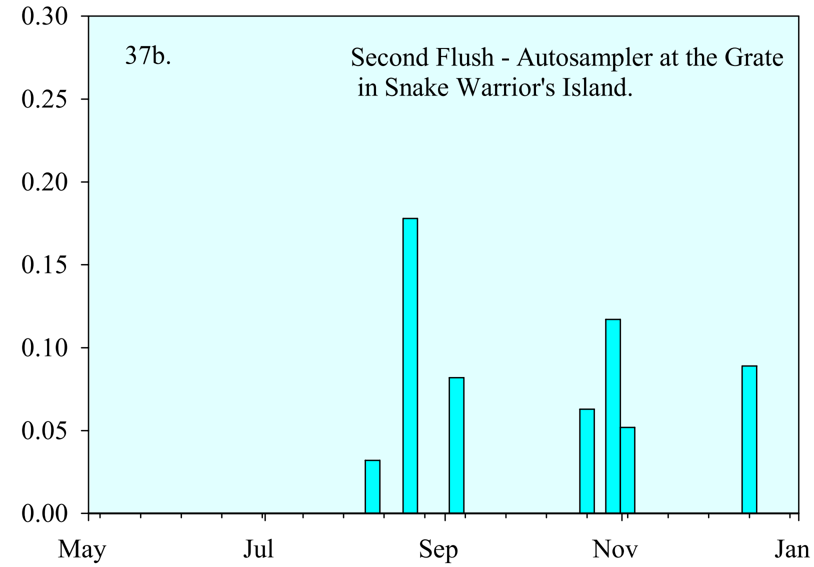
The total phosphorus concentration of storm water from Miami Gardens and SWI were variable, ranging from 0.017 to 0.102 mg/l (Fig. 41a-c). Levels of total phosphorus were generally higher

Table 5. Number of Times Samples Exceeded Water Quality Standards Acceptable for Surface Waters Based on Broward County's Chapter 27 Surface Water Criteria for Herbicides and Polycyclic Aromatic Hydrocarbons (PAHs) (Broward County 2001). MCL = Maximum Contaminant Level. The MCL for PAHs = 0.031 μg/l. There is no standard (NS) for atrazine for Broward County at this point in time. The minimum detection limit (MDL) for atrazine = 0.046 μg/l. "<MDL" means samples were below minimum detection limits for all parameters tested.

Site	Herbicides	PAHs	Comments
C9 Canal	0	0	All samples were below minimum detection limits for parameters tested.
Grate	0	0	1 hit of Atrazine (0.1 μg/l) on 7/17/03
Retention Pond	0	0	1 hit of Atrazine (0.08 μg/l) on 7/17/03
Wetland 3	0	0	1 hit of Atrazine (0.086 μg/l) on 7/17/03
Wetland 2	0	0	All samples were below minimum detection limits for parameters tested.
Wetland 5A	0	0	All samples were below minimum detection limits for parameters tested.
Autosampler - SWI	1	0	1 hit of Simazine – 2nd Flush 11/03/03
Miami Gardens	1	0	1 hit of Atrazine (0.307 μg/l) on 5/28/03 1 hit of Atrazine (5.85 μg/l) on 11/04/03

Figure 37a - c. Ammonia (NH_3) Concentrations (mg/l) in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. The autosampler at SWI was programmed to collect storm water samples if more than 0.2 inches of rain fell within a 30 minute period. Second flush samples were collected 2 hours after first flush samples. Samples were collected from Miami Gardens when storm water over flowed the weir at the end of Ronald St. in Miami Gardens.





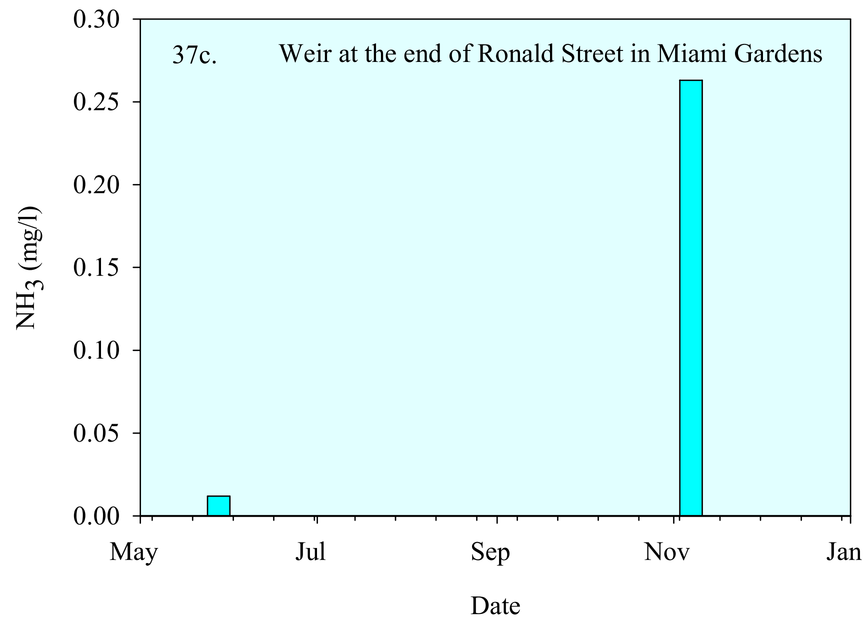


Figure 38a - c. Nitrate + Nitrite (NOx) Concentrations (mg/l) in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. The autosampler at SWI was programmed to collect storm water samples if more than 0.2 inches of rain fell within a 30 minute period. Second flush samples were collected 2 hours after first flush samples. Samples were collected from Miami Gardens when storm water over flowed the weir at the end of Ronald St. in Miami Gardens.

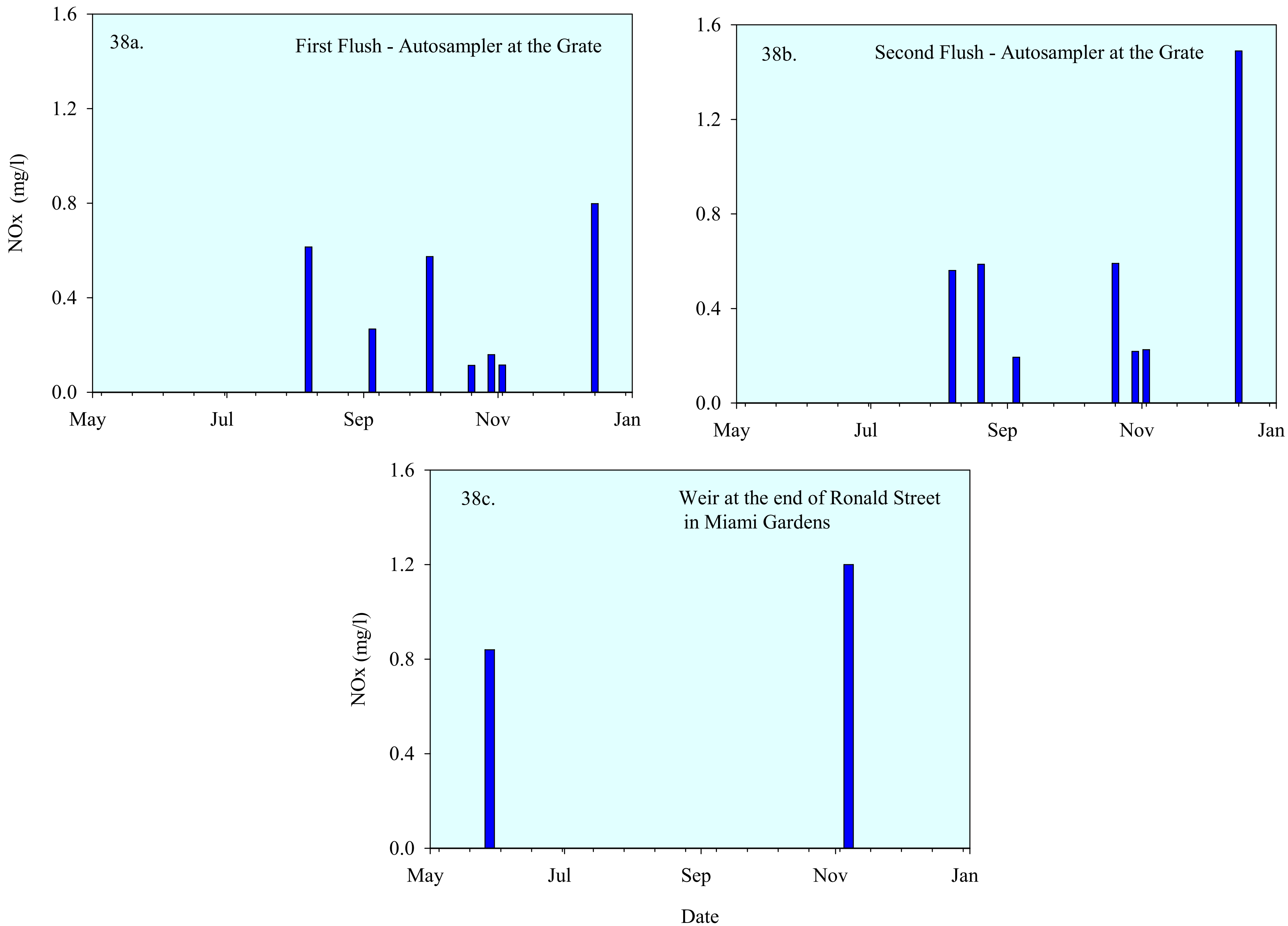


Figure 39a - c. Total Nitrogen (TN) Concentrations (mg/l) in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. The autosampler at SWI was programmed to collect storm water samples if more than 0.2 inches of rain fell within a 30 minute period. Second flush samples were collected 2 hours after first flush samples. Storm water was collected from Miami Gardens when storm water over flowed the weir at the end of Ronald St. in Miami Gardens.
Broward County's surface water criteria for TN = 1.5 mg/l as indicated by the red line.

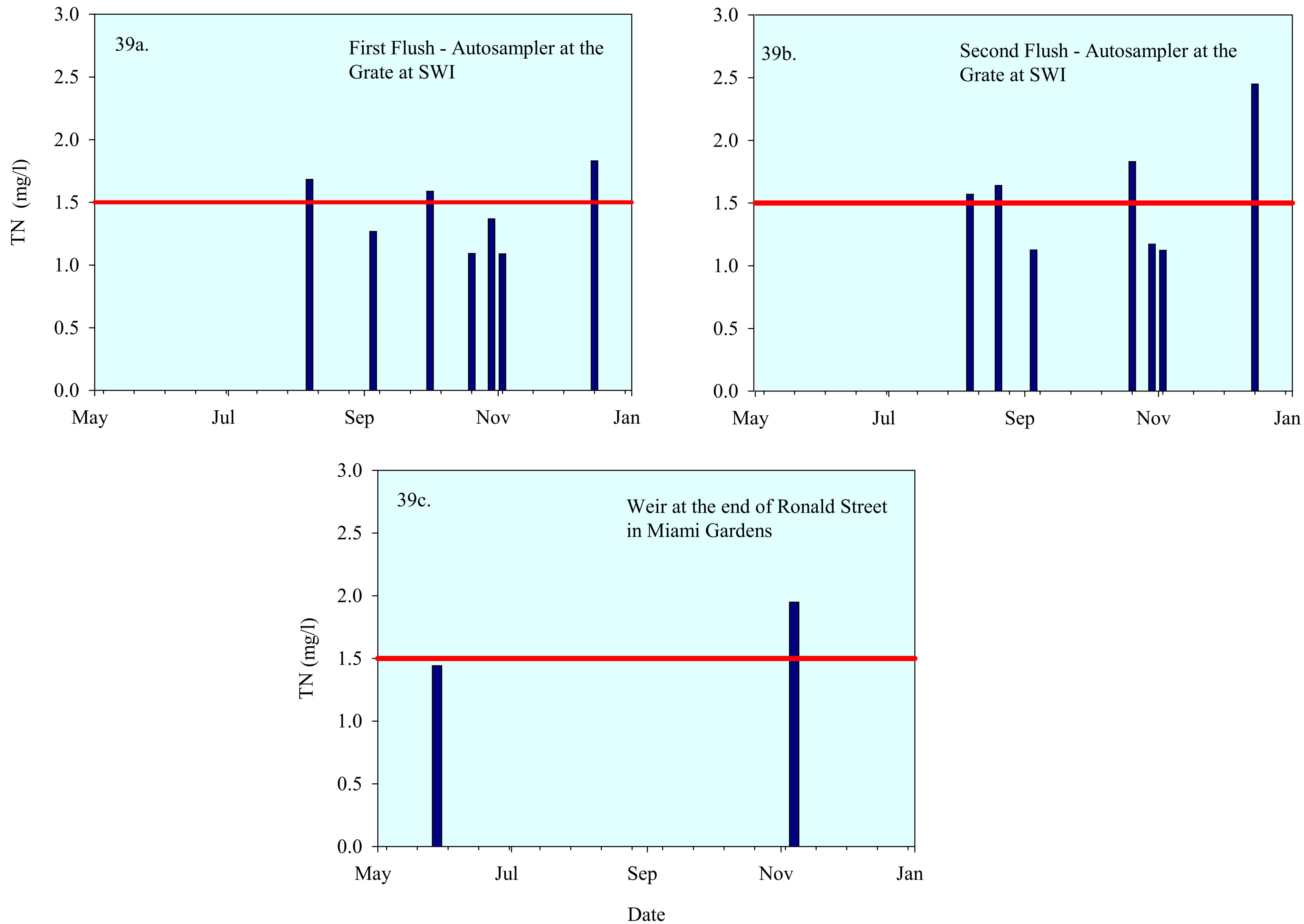


Figure 40a - c. Ortho-Phosphate (OPO_4) Concentrations (mg/l) in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. The autosampler at SWI was programmed to collect storm water samples if more than 0.2 inches of rain fell within a 30 minute period. Second flush samples were collected 2 hours after first flush samples. Samples were collected from Miami Gardens when storm water over flowed the weir at the end of Ronald St. in Miami Gardens.

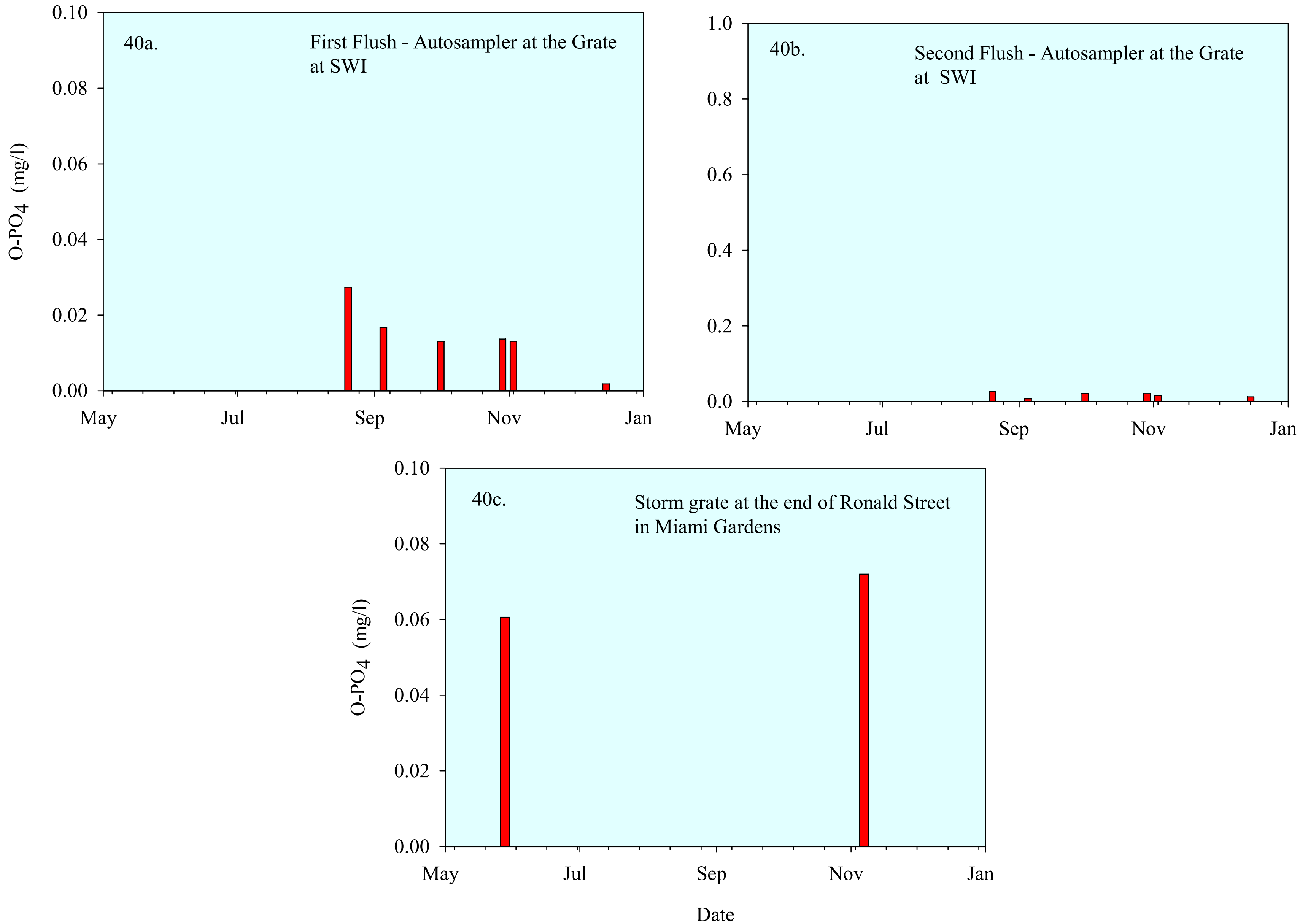
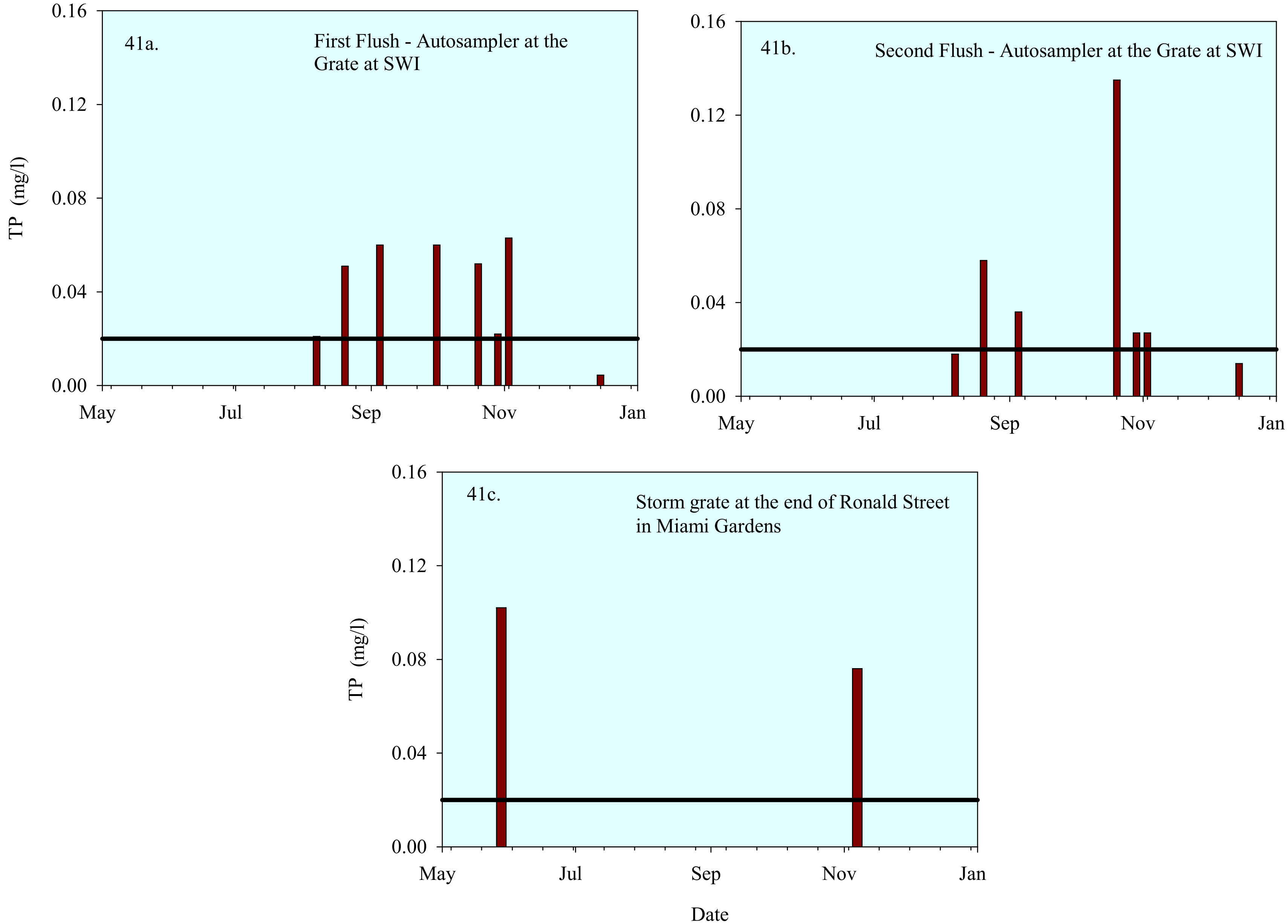


Figure 41a - c. Total Phosphorus (TP) Concentrations (mg/l) in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. The autosampler at SWI was programmed to collect storm water samples if more than 0.2 inches of rain fell within a 30 minute period. Second flush samples were collected 2 hours after first flush samples. Samples were collected from Miami Gardens when storm water over flowed the weir at the end of Ronald St. in Miami Gardens.
Broward County's surface water criteria for TP = 0.2 mg/l as indicated by the red line.



storm water exiting Miami Gardens compared to TP concentrations in storm water entering SWI. Storm water TP values generally exceeded Broward County's surface water criteria of 0.02 mg/l on nearly all occasions at both sites (14/16 samples).

f. Total Carbon (TOC)

Total carbon levels were similar in the first and second flush samples collected at SWI but higher than TOC values at Miami Gardens (Fig. 42a-c). Concentrations ranged from 10 to 36 mg/l TOC in the first and second flush samples collected at SWI. TOC values were less than 10 mg/l in the two Miami Gardens storm water samples.

2. Metals and Ion Concentrations

The total metal concentrations of arsenic, barium, beryllium, copper, cadmium, chromium, iron, nickel, lead, selenium, vanadium and zinc were determined in storm water collected at SWI and Miami Garden. No apparent trends were observed for any of the metals measured in storm water. Typically, values were below Broward County's Surface Water Quality Standards and near or below minimum detection limit (Table 6). None of the samples collected at Miami Gardens were above the accepted maximum criteria for metal based on Broward County's Chapter 27. One storm water sample from SWI exceeded the Broward County's criteria for selenium and two exceeded it for copper **(**Fig. 43a-f**)**.

Attempts to use metals such as vanadium as a tracer for storm water from Miami Gardens met with little success (Fig. 44). Miami Gardens' vanadium concentrations were variable and fell within the range of values observed in the surfaces of SWI and the C-9 canal. Storm water samples collected at SWI had concentrations similar to the C-9 canal, the grate, and retention pond at SWI. The limited number of samples collected from Miami Gardens (n=2), makes it difficult to formulate any firm statements regarding the relative of the impact of Miami Gardens storm water on SWI.

Ions ratios in storm water from Miami Gardens (MG) were distinct from storm water collected at SWI (Fig. 45a-c). Ion ratios in storm water samples from SWI fell along a gradient between surface water values in SWI and the C-9. Ion ratios can not be used as tracer of storm water mixing into the wetlands at SWI. One possible explanation for the loss of the Miami Gardens signal is that the signal is diluted out as water masses mix with water in the US 441drainage system and with SWI surface waters.

3. Polycyclic Aromatic Hydrocarbons (PAHs) and Herbicides

None of the eight storm water samples collected at SWI nor the two collected at Miami Gardens exceeded Broward County's Surface Water Criteria for total PAHs. All samples were below minimum detection limits for each of the parameters that comprise total PAHs. A few storm water samples did exceed minimum detection limits for two herbicides. There was one hit for the herbicide Simazine in a 2nd flush collected on 11/3/05 (Table 5). Most of the storm water samples collected at SWI were near or below minimum detection limits for the herbicides tested

Figure 42a - c. Total Organic Carbon (TOC) Concentrations (mg/l) in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. The autosampler at SWI was programmed to collect storm water samples if more than 0.2 inches of rain fell within a 30 minute period. Second flush samples were collected 2 hours after first flush samples. Samples were collected from Miami Gardens when storm water over flowed the weir at the end of Ronald St. in Miami Gardens.

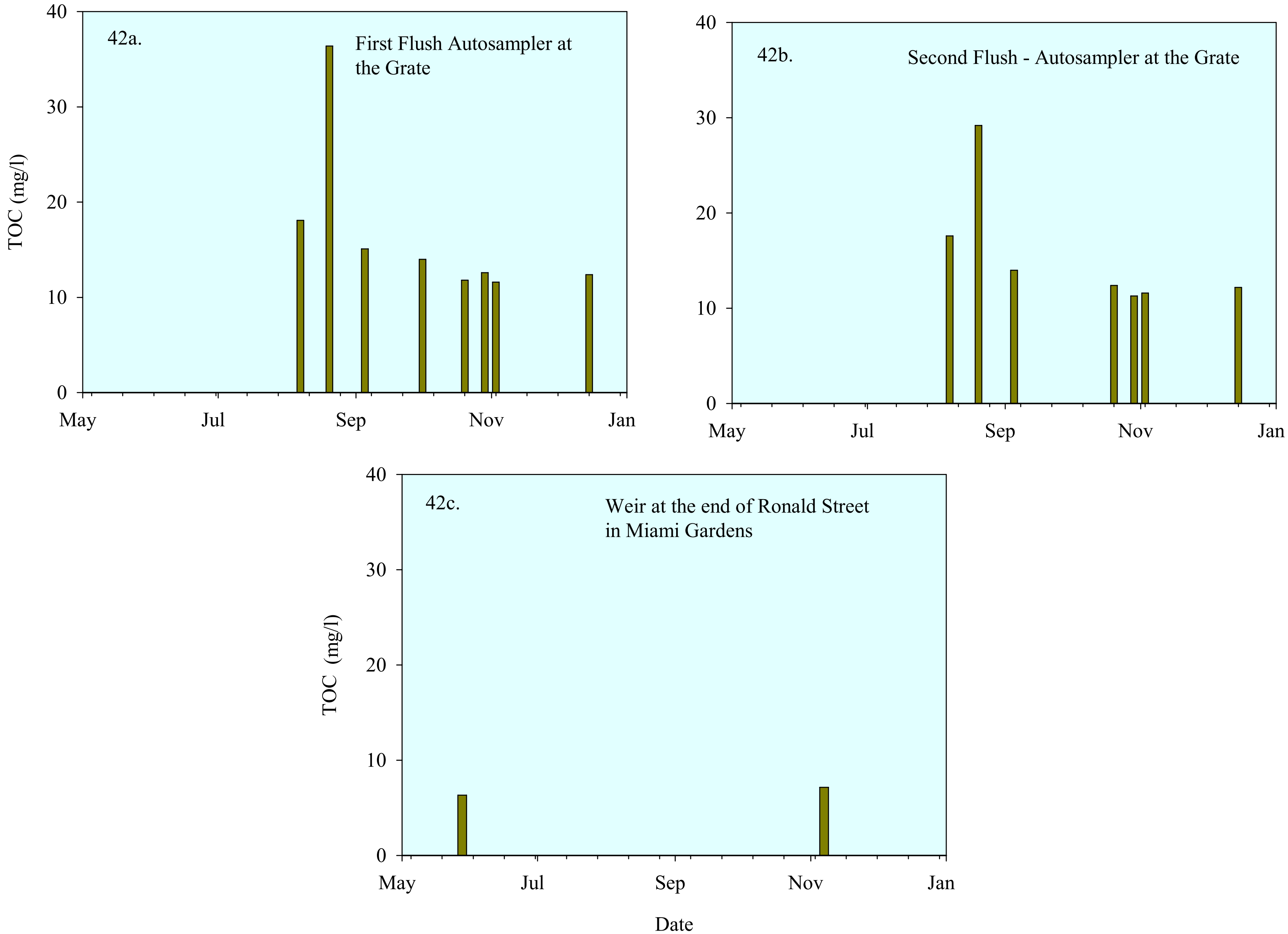


Table 6. Percentage of Total Metal Samples from the Storm Waters at Snake Warrior's Island and Miami Gardens (MG) above Minimum Detection Limits (MDL), and the Percentage of Samples Exceeding the Water Quality Standard (WQS) Acceptable for Surface Waters Based on Broward County's Chapter 27 Surface Water Criteria (Broward County 2001). MCL = Maximum contaminant level. N.S. = no standard.

Metal	**MDL (µg/l)**	**MCL (µg/l)**	**> MDL**	**> BC WQS**	**Site**
Arsenic	1.47	50	55% (10/18)	0%	Values low at both SWI and MG
Barium	2.08	N.S.	50% (9/18)	N.S.	Values low at both SWI and MG
Beryllium	1.75	0.13	0%	0%	Values low at both SWI and MG
Cadmium	0.999	1	0%	0%	All sample for all sites were below the MDL
Chromium	1.37	N.S.	0%	N.S.	All sample for all sites were below the MDL
Copper	3.9	3	11% (2/18)	11% (2/18))	> MCL on 8/17/03 and 12/15/03 – First Flush SWI
Nickel	2.94	100	6% (1/18)	0%	Low and variable at SWI and MG
Lead	9.13	30	0%	0%	All sample for all sites were below the MDL
Selenium	14	5	6% (1/18)	6% (1/18)	> MCL on 10/29/03 – First Flush SWI
Vanadium	2.59	N.S.	61% (11/18)	N.S.	Values variable at both SWI and MG
Zinc	3.65	86	22% (4/18)	0%	Values low at both SWI and MG

Figure 43a - f. Total Metal Concentrations in Storm Water Collected from the Grate at Snake Warrior's Island and Miami Gardens. Broward County's surface water criteria are indicated by a solid black line for the individual metals. As = Arsenic, Se = Selenium, Cu = Copper, Ni = Nickel, Pb = Lead, Zn = Zinc.

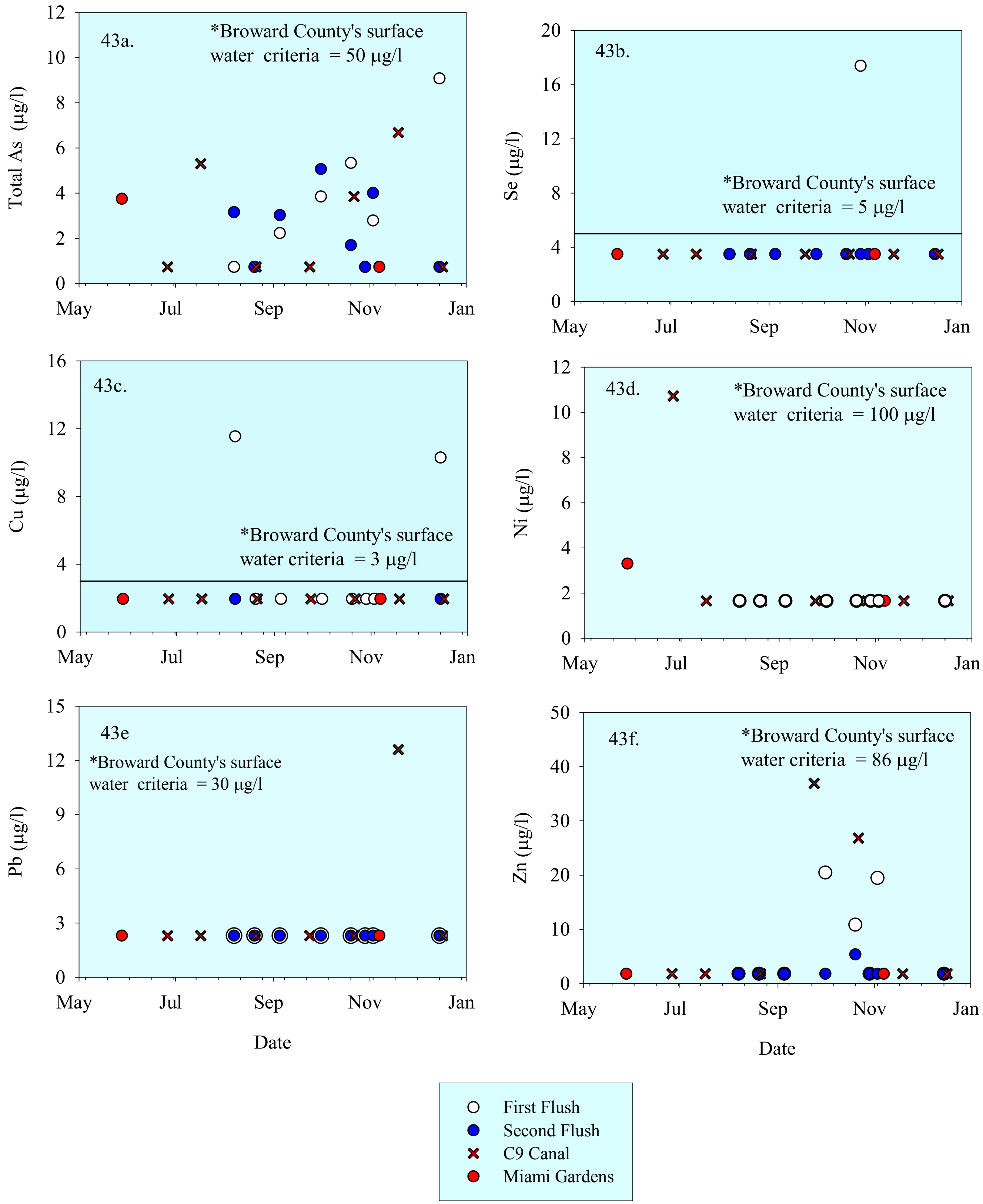


Figure 44. The Average Concentration of Total Vanadium (Va) (mg/l) in Surface Water Samples from Snake Warrior's Island and the C-9 Canal, and Average Storm Water values from the 1st and 2nd Flush at SWI, and Miami Gardens. Samples were averaged for the entire seven months of the study. Vanadium concentrations in the wetlands decreased with distance from C-9. Vanadium concentration in storm water were variable and not useful as an indicator of storm water mixing into the wetlands at SWI.

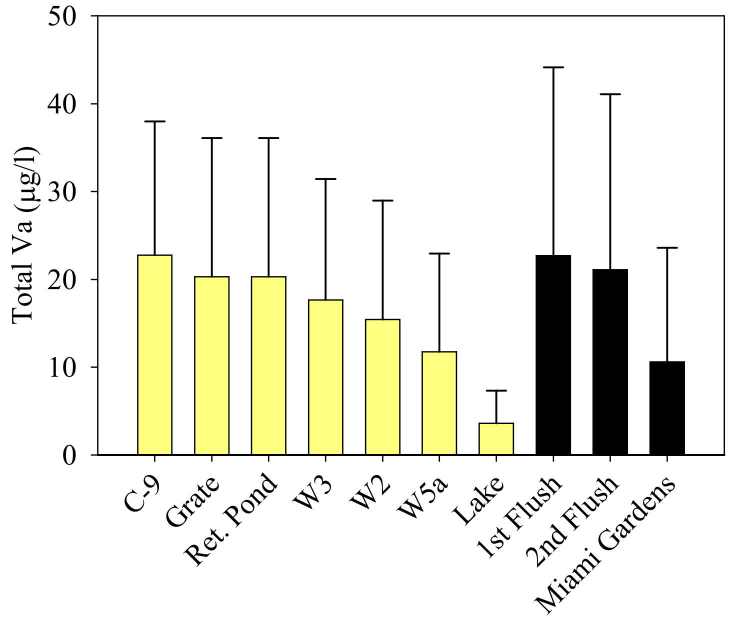
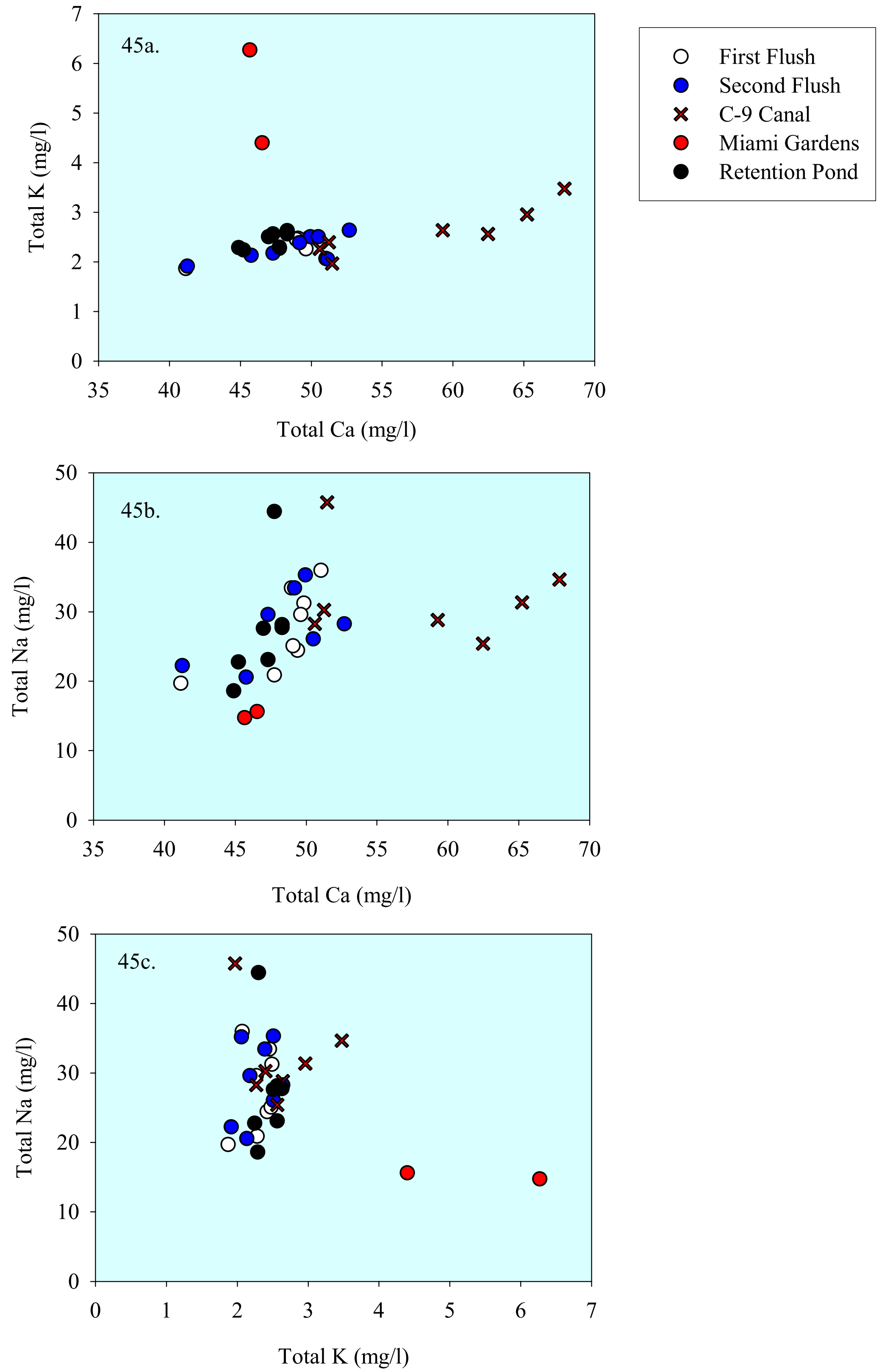


Figure 45 a - c. Ion Ratios from Storm Water Collected at Miami Gardens and the Grate at Snake Warrior's Island (SWI) Compared to Ion Ratios in Surface Waters from the C-9 Canal, the Retention Pond and Lake at SWI. The C-9 canal and the lake, as a proxy for ground water, are the two largest sources of water to SWI.



for. However, both storm water samples from Miami Gardens (5/28/03 and 11/7/05) did contain detectable amounts of the herbicide Atrazine, 0.31 and 5.85 μg/l respectively (Table 5).

D. Plants and Sediments

Plant and sediment samples were collected in August and December 2003 from wetland 3, 2 and 5A. Sediment samples were analyzed for carbon, nitrogen, phosphorus content, metals, polycyclic aromatic hydrocarbons and the presence of herbicides. Sediment porosity was also determined for each site. Carbon, nitrogen and phosphorus content as well as metal concentrations were measured in the leaves of Pickerel weeds.

1. C, N and P in Plants and Sediments

The carbon, nitrogen and phosphorus content of sediments at SWI varied over time and space (Table 7). The only consistent trend was that wetland 2 sediments had the highest C, N and P values and the lowest % solids of the three wetlands for both sample dates. Differences in the % solid values and sediment porosity suggest that wetland 2 sediments were composed of finer grained material compared to wetland 3 and 5A. There was no difference in the carbon content of pickerel weed leaves from the three wetlands (Table 7). The %N and %P content in the leaves from the three wetlands were also similar though the data suggest pickerel weed from wetlands 2 and 5A had a higher % P compared to wetland 3 in the December sampling.

2. Metals

Metal concentrations were variable in the sediments at Snake Warrior's Island (Table 8). Beryllium, cadmium, nickel and selenium concentrations in sediments were at or near detection limits in both August and December 2003. All other metals tested were generally low, with the exception of copper. Copper was detected in the sediments from all three wetlands though copper concentrations wetland 2 sediment was substantially higher than wetlands 3 and 5A (Fig. 46). The elevated levels of copper in wetland 2 may be a function of several things including grain size. Wetland 2 had the highest porosity, (indicating smaller particles), of the three wetlands (Table 7). Smaller particles allow for a great adsorption of particle reactive compounds onto their surface (Berner 1980). Sediment metal concentrations were compared to the Florida Department of Environmental Protection's (FDEP) Sediment Quality Assessment Guidelines (SQUAGs) (MacDonald et al. 2003). Copper was the only metal that exceeded the probable effect concentration (PECs).

No clear pattern of metal accumulation in leaf material was observed. Leaf metal concentrations were generally at or near detections limits for most metals in both the August and December samples (Table 9).

3. Polycyclic Aromatic Hydrocarbons (PAHs) and Herbicides

Low levels of PAHs were detected in all wetland sediment during the August sampling (Fig. 47). Wetland 3 had the lowest total PAH concentration, averaging 0.155 $\pm$ 0.186 mg/kg dry weight (DW), followed by wetland 5A with a concentration of 1.059 $\pm$ 0.749 mg/kg. Wetland 2 had the

Table 7. Carbon, Nitrogen and Phosphorus Content in Sediment and Pickerel Weed Leaves Collected at Snake Warrior's Island in August and December 2003. The molar ratio of N/P is also listed. Sediment nutrient data are composite samples from three cores.

Site	Date	% Solids	Porosity	%C	%N	%P	N/P
Sediment							
Wetland 3	8/03	29.60 + 8.00	71.6 ± 11.8	16. 71	0.84	0.05	34.3
Wetland 2	8/03	16.77 + 3.62	86.1 ± 3.9	25.41	1.66	0.14	26.9
Wetland 5A	8/03	52.75 ± 13.11	48.3 ± 14.2	6.46	0.37	0.03	31.4
Wetland 3	12/03	52.20 + 10.82	55.5 ± 11.6	8.53	0.36	0.03	26.4
Wetland 2	12/03	11.60 + 2.75	89.3 ± 1.9	24.32	1.55	0.12	28.2
Wetland 5A	12/03	21.13 + 2.40	76.7 ± 4. 8	12.36	0.64	0.09	21.5
Pickerel Weed							
Wetland 3	8/03	NA	NA	43.24 ± 1.39	2.37 ± 0.20	0.17 ± 0.003	32.4 ± 3.6
Wetland 2	8/03	NA	NA	43.22 ± 0.45	3.12 ± 0.14	0.21 ± 0.020	33.3 ± 3.3
Wetland 5A	8/03	NA	NA	42.33 ± 0.65	2.25 ± 0.30	0.21 ± 0.039	23.9 ± 3.5
Wetland 3	12/03	NA	NA	42.50 ± 0.21	2.83 ± 0.23	0.17 ± 0.021	36.6 + 3.6
Wetland 2	12/03	NA	NA	42.05 ± 0.14	2.91 ± 0.32	0.31 ±0.061	21.1 + 2.5
Wetland 5A	12/03	NA	NA	42.05 ± 1.62	2.77 ± 0.16	0.25 ±0.047	25.1 + 5.9

Table 8. Metal Concentrations (Mean ± Std. Dev.) in Sediments Collected in August and December 2003 from the Three Wetlands in Snake Warrior's Island (n=3 cores per wetland). Florida sediment quality guidelines for inland waters (SQAGs) are also listed. "<" indicates metals concentrations were below the minimum detection limit (MDL). Threshold Effect Concentration (TEC) is the concentration of chemicals of potential concern that are unlikely to cause or substantially contribute to sediment toxicity. Probable Effect Concentration (PEC) is the concentration of chemicals of potential concern that are sufficient to cause or substantially contribute to sediment toxicity. (MacDonald et al. 2003).

METAL (mg/kg DW)	Wetland 3 August	Wetland 2 August	Wetland 5A August		Wetland 3 December	Wetland 2 December	Wetland 5A December	TEC	PEC
Arsenic	2.9± 1.1	3.6 ± 0.9	30.3		1.6 ± 0.7	7.0 + 2.2	2.8 + 0.3	9.8	33
Barium	23.9 ± 4.1	24.7 ± 2.3	1.2 ± 2.2		9.5 ± 4.7	22.3 + 4.7	12.2 + 1.5	20	60
Beryllium	< 0.0110	< 0.0110	< 0.0110		< 0.0110	< 0.0110	< 0.0110	NG	NG
Cadmium	< 0.341	< 0.341	< 0.341		< 0.341	< 0.341	< 0.341	1.0	5.0
Chromium	4.58 ± 5.9	6.23 ± 4.1	< 0.287		4.1 ± 3.2	15.1 + 4.3	10.1 + 2.1	43	110
Copper	30.9 ± 34.3	319.3 ± 85.45	10.4 ± 17.3		20.9 ± 22.8	439 + 109.4	107.8 + 38.5	32	150
Lead	12.5 ± 5.9	22.1 ± 1.6	6.4 ± 4.5		4.7 ± 3.2	18.8 + 4.9	20.9 + 2.1	36	130
Nickel	< 1.31	< 1.31	< 1.31		< 1.31	< 1.31	1.7 + 0.9	23	49
Selenium	2.56 + 3.11	<1.52	1.52		1.52	1.52	1.52	NA	NA
Zinc	3.4 ± 3.3	10.8 ± 5.3	< 1.96		4.23 ± 3.1	< 1.96	8 + 6.3	120	460

Figure 46. Copper Concentrations (mg/kg Dry Weight (DW)) in Sediment Collected from Wetlands 3, 2 and 5A in August and December 2003. The dashed line is the threshold effect concentration (TEC - the concentration of chemicals of potential concernthat are unlikely to cause or substantially contribute to sediment toxicity). The solid line is the probable effect concentration (PEC - the concentration of chemicals of potential concern that are sufficient to cause or substantially contribute to sediment toxicity) (MacDonald et al. 2003).

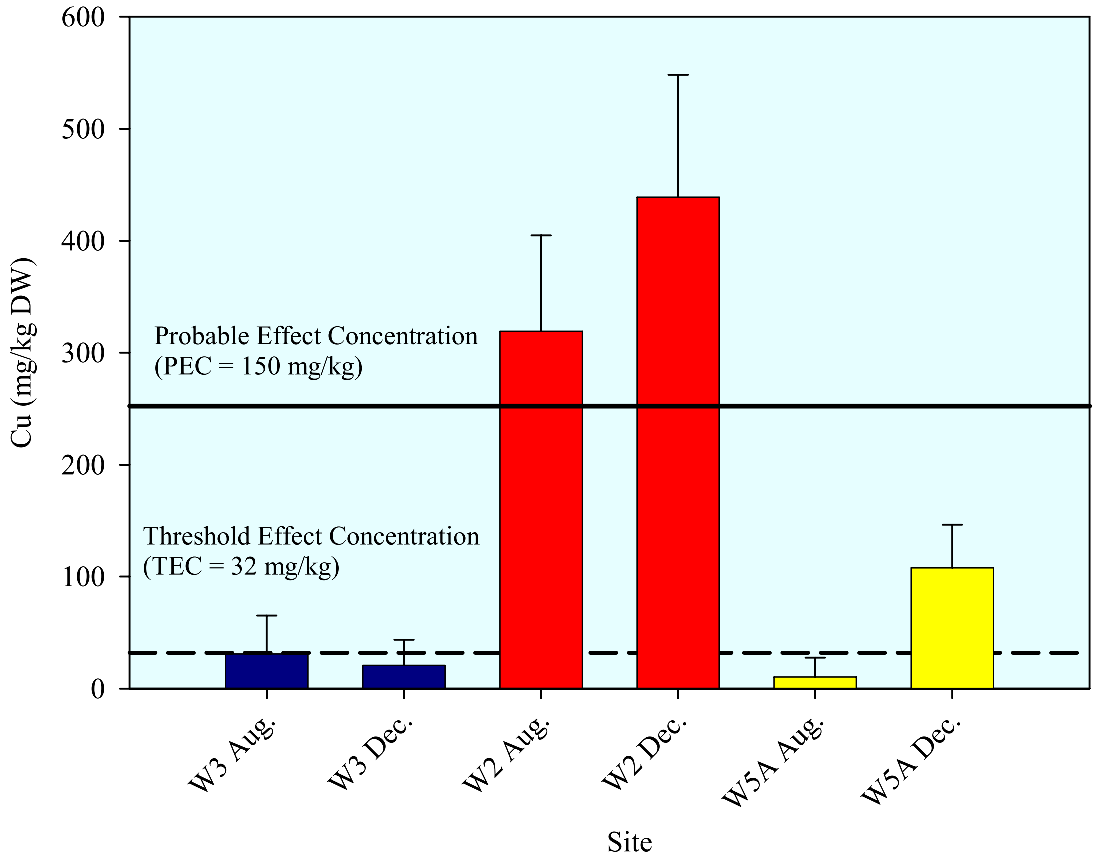
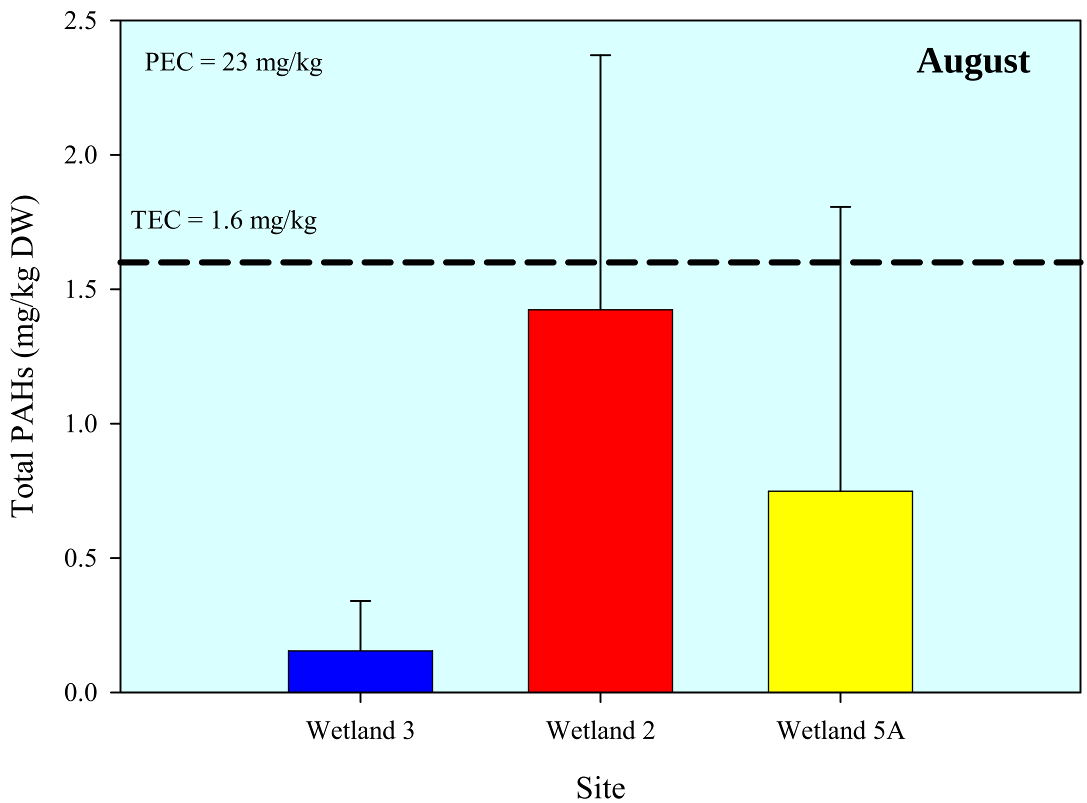


Table 9. Metal Concentrations in Composite Samples in Pickerel Weed Leafs collected in August and December 2003 from the Three Wetlands at Snake Warrior’s Island. Each value a composite of three leafs (1 leaf per plant, 3 plants per wetland). “<” indicates metals concentrations were below the minimum detection limit (MDL).

METAL (mg/kg DW)	Wetland 3 August	Wetland 2 August	Wetland 5A August		Wetland 3 December	Wetland 2 December	Wetland 5A December
Arsenic	<0.556	<0.556	<0.556		<0.556	<0.556	<0.556
Barium	<0.825	<0.825	<0.825		3.73	6.11	4.35
Beryllium	<0.0110	<0.0110	<0.0110		<0.0110	<0.0110	<0.0110
Cadmium	<0.341	<0.341	<0.341		<0.341	<0.341	<0.341
Chromium	<0.287	<0.287	<0.287		<0.287	<0.287	<0.287
Copper	<0.810	<0.810	<0.810		<0.810	2.02	0.912
Lead	<1.06	<1.06	<1.06		<1.06	<1.06	<1.06
Nickel	<1.31	<1.31	<1.31		<1.31	<1.31	<1.31
Selenium	<1.52	<1.52	<1.52		<1.52	<1.52	<1.52
Zinc	24	4.25	31		<1.96	11.2	7.13

Figure 47. The Average Concentration (mg/kg Dry Weight (DW)) of Polycyclic Aromatic Hydrocarbons (PAHs) in Sediment from Wetlands 3, 2, and 5A Compared to the FDEP's Sediment Quality Assessment Guidelines (SQAGs) for Florida Inland Waters. TEC = threshold effect concentration - the concentraion below which harmful effects are unlikely to be observed. PEC = probable effect concentration - the concentration above which harmful effects are likely to be observed (MacDonald et al. 2003).



highest total PAH concentration, 1.424 ± 0.947 mg/kg. As with copper, the consistently higher values of PAHs in wetland 2 sediment may in part be a function of grain size. PAH concentrations in sediments collected in December 2003 were below minimum detection limits (MDLs) for all the wetlands. None of the sediment samples from SWI contained any detectable amounts of herbicides. Leaf material was not tested for PAHs and herbicides.

IV. Discussion

Snake Warrior's Island Natural Area is a reconstructed freshwater wetland located in suburban South Florida. Eight linked wetland cells were constructed within the park. The two major sources of water to the wetlands are supplied by the C-9 canal and ground water. Intermittent sources of water include rain and storm water which is routed into the system during and after rain events. A seven month water quality monitoring program was implemented in June 2003 to characterize the composition of the water entering the wetlands through the storm water system and to assess the benefits and concerns of rehydrating SWI with urban storm water.

Primary Sources of Water Influencing the Hydrology of Snake Warrior's Island Natural Area

Water is introduced into the Snake Warrior's Island (SWI) Natural Area three ways; through the US 441 drainage system (C-9 water and storm water), subsurface inputs from ground water and atmospheric deposition (rain). The C-9 canal is the biggest single source of water to SWI. Snake Warrior's Island and the surrounding storm water drainage system was engineered and built such that approximately 1 to 3 million gallons of water a day is gravity fed from the C-9 canal into SWI during non-rainy periods to keep the wetlands hydrated (per. comm. David Markward, Broward County's Office of Water and Wastewater Services). During rain events, hydraulic gradients in the local drainage system were designed so that storm water from the local area around SWI and Miami Gardens neighborhood would be diverted into SWI given sufficient volume.

Water levels in the C-9 canal strongly influence water levels at Snake Warrior's Island Natural Area. A comparison of water levels at the S29 structure at the eastern end of the C-9 canal, and at SWI, indicates a tight coupling between the two systems. Water elevation data collected by the YSI sondes in the retention pond and wetland 3 showed that SWI usually mimicked S29 water levels (Fig. 8a). Decreases in water levels at S29 associated with rain events and flood management practices typically resulted in similar declines in water levels at SWI. Releasing water to tide through the S29 salinity structure on the C-9 canal reversed the hydraulic gradients between SWI and the C-9 canal, i.e. water levels at S29 dropped below water levels at SWI, so water flowed out of SWI south to the C-9 canal rather than north to SWI. Once water levels returned to management elevations at S29, similar rebounds in water level occurred in the retention pond and wetland 3 at SWI. Hydraulic gradients were reestablished and gravity feed of C-9 water into SWI was restored. However, the strong connection between the C-9 and SWI can be severed at least on the short term by intense and/or protracted rain events. The capacity of the storm water system can be exceeded which causes water to backs up into SWI temporarily regardless of management activities at S29.

SWI was built with the idea that it would be a multi-purpose system. One of the objectives was to provide an area where storm water could be routed as a part of a flood prevention management strategy. In November 2003, water levels at SWI increased even though significant declines in water level were noted at S29 (Fig. 8a). This event was associated with a protracted and heavy rain fall of several inches in less than 24 hours (Fig. 8b). It is clear from the data that water was not draining from SWI even though the gates at S29 were open and water was being released to tide. It is likely that the storm water system around SWI was at its maximum capacity. Water was entering the system faster than it could exit it so excess water backed up into SWI. The differences in water elevation at S29 and SWI, suggest that storm water was diverted into Snake Warrior's Island causing an increase in water elevations in the retention pond and wetland 3 and reducing the likelihood of flooding in the local area. Water levels at SWI returned to pre-event levels and once again mimicked S29 levels within a few days indicating the dynamic nature of the system.

Ground water is another likely source of water to Snake Warrior's Island Natural Area. While it was beyond the scope of this study to quantify the amount of ground water entering the SWI system. However, short term changes, (on the order of hours) in water elevations in wetland 3 and the retention pond do suggest ground water can influence the volume of surface waters at SWI. Repeated measures of water height, (every 15 minutes) by the unattended YSI sondes in the retention pond and wetland 3 revealed a smaller, secondary oscillation in water levels that would have otherwise remained undetected even with daily monitoring (Fig. 9a-g). Water levels would decline several inches and then rebound every 6 to 8 hours in both the retention pond and wetland 3. This signal was more apparent in the retention pond but still observed to a lesser extent in wetland 3. While the data suggests tidal influences, it is unlikely since SWI is several miles inland from the coast and west of S29, the salinity structure on the C-9 canal. It seems more likely that the short term changes in surface water levels were related to localized fluctuations in ground water levels. The more pronounced signal in the retention pond compared to wetland 3, suggested a tighter coupling between the deeper retention (~22ft) and the top of the water table compared to the shallower wetland (~ 4 ft deep). The reoccurring nature of the events may have been the result of ground water pumping activities at a nearby water treatment plant although this cannot be confirmed since the facility does not maintain a permanent record of daily pumping activities. Similar oscillations were also observed with specific conductivity data again suggesting a fresh water input into the system (Fig. 11a-f).

Identifying Major Sources of Water to Snake Warrior's Island Natural Area

Metal concentrations and ion ratios were used to trace parcels of water as they mixed into the Snake Warrior's Island Natural Area system. Total vanadium (Va) concentrations proved to be a useful tracer of C-9 water. Vanadium concentrations were higher at the C-9 and decreased as water moved from the C-9 canal, past the grate into the retention pond and through the wetlands at SWI (Fig. 30 a-g). Lake water, which had neither surface water connection to C-9 nor the wetlands, had consistently lower Va concentrations, suggesting that ground water; the other major source of water to SWI, contained relatively low levels of Va. The gradient in vanadium did not persist in either sediments or plants collected along the gradient from wetland 3 to 5A (Table 10).

Table 10. Vanadium (Va) Concentrations in Sediments and Pickerel Weed (mg/kg Dry Weight) Collected in August and December 2003 from Wetlands 3, 2, and 5A at Snake Warrior's Island. Unlike water column samples, no consistent trends were noted for Va concentrations sediment and plant samples over time or place. Va concentrations decreased in sediments from wetlands 3 and 2 but increased in wetland 5A over time. Va concentrations appeared to increase in plant tissue over time but no apparent gradient between wetlands was observed. Minimum detection limit for Va = <1.60 mg/kg. Sediment values are an average of 3 cores. Pickerell Weed values are composite values of 3 leaves from 3 separate plants collected from each of the wetlands.

Site	**August**		**December**
Sediment	(mg/kg DW)		(mg/kg DW)
Wetland 3	11.28 ± 2.43		4.23 ± 3.05
Wetland 2	10.72 ± 1.06		4.35 ± 3.09
Wetland 5A	< 1.60		6.32 ± 1.02
Pickerell Weed			
Wetland 3	< 1.60		6.56
Wetland 2	< 1.60		5.83
Wetland 5A	< 1.60		8.93

Ion ratios also provided some information on the influence of ground water, C-9 water and storm water on the composition of water in the wetlands. The lake, used as a proxy for ground water, had Ca/K, Na/Ca, and Na/K ratios that differed substantially from C-9 and wetland waters (Fig. 35a-c). The absence of the lake ion signature in wetland surface waters suggests the contribution of ground water was minor compared to C-9 water. If lake data is excluded, trends in ion ratios, in particular, K/Ca ratios, are similar to the one observed with total Va (Fig. 34a-g). C-9 water had the highest K/Ca ratio and ratios decreased with distance from C-9 (Fig. 36). The wetland 5a signal was anomalous compared to the other SWI sites. The relatively small size and shallow depth of this wetland may account for the observed differences (Table 1). Using vanadium concentration and ion ratios as conservative tracers along with the physical data (water elevation data) from the YSI sondes supports idea that C-9 water does make up the bulk of the water in the wetlands of SWI. YSI water elevation data did suggest a secondary ground water effect in the retention pond and to a lesser extent wetland but it does not appear to strongly influence surface water composition, in the wetlands. Tracer data, (vanadium concentrations and ion ratio data) does not suggest a strong influence of ground water on the wetlands (Fig. 34a-g & 35).

No clear trend in vanadium (Va) concentration were observed in storm water collected at SWI and Miami Gardens (MG), other than they were similar magnitude Va concentrations measured at the C-9, grate and retention pond (Figs. 44). Miami Gardens' storm water did have a distinct Ca/K ratio (Fig. 45a-c). The loss of the Miami Gardens signal as indicated by the difference in ionic composition of the storm water collected at SWI and MG may be explained a few different ways. MG storm water is only a periodic component of the storm water entering SWI. Local runoff constitutes a much larger percentage of storm water to SWI and could override any potential Miami Gardens signal (Fig. 45a-c). The ionic compositions of storm water from first and second flushes at SWI were very similar to each other and to the ionic composition of monthly surface water samples (C-9 and retention pond). During smaller rain events water may actually be flowing out of rather than into SWI as hydraulic gradients shift between SWI and the C-9 canal. The YSI water elevation data typically showed a tight coupling between flood management activities at the S29 structure on the C-9 and SWI. Water levels dropped at both SWI and S29 when water was being released to tide through S29. During small rain events, storm water from the area surrounding SWI may never make it into SWI but rather flows directly into the C-9 canal and is released to tide. However, a large, sustained rain event in November 2003 appeared to decoupled SWI water levels from the C-9. Water level in the retention pond and wetland 3 at SWI remained high even though water levels at S29 were substantially lower suggesting the system was overloaded and excess storm water was being pushed into SWI.

Influences on the Composition of Surface Waters in Snake Warrior's Island

The above discussion suggests that C-9, groundwater and even episodic rain events influence physical parameters such as water level and specific conductivity and were useful in identifying the major sources of water (C-9, ground water), to SWI. However, does not show if the composition of these inputs influences the biogeochemical cycles within SWI. Surface water at SWI and the C-9 canal were sampled on a monthly basis in order to provide information about the transport and fate of the less conservative parameters such as nutrients, metals and organic compounds once they enter the SWI system.

YSI Parameters

Water quality parameters recorded by the YSI sondes in the retention pond and wetland 3 suggest internal processes within SWI were very dynamic in nature especially during the first four months of the study (Fig. 15 a-g, 17 a-g). Diel variations in dissolved oxygen (D.O.) concentrations and pH as a result of the balance between primary production and respiration were observed throughout the seven month study. However, the magnitude of these excursions diminished during the last three months of the study (Fig. 15e-g, & 17e-g). pH and D.O. oscillations in both the retention pond and wetland 3 were smaller in magnitude and overlapped more with each other during the last three months suggesting biological activities in both systems were slowing down most likely as a consequence of declining temperatures (Fig. 12).

Nutrients

Nitrogen - Ammonia (NH_3), Nitrate + Nitrite (NOx), Total Nitrogen (TN)

Analysis of nutrient data produced some intriguing results. The highest ammonia concentrations were found in the C-9 canal, the main source of water to Snake Warrior's Island (Fig. 48a). However, ammonia levels were approximately five times lower by the time water had reached the grate at the entrance of SWI. The specific mechanisms resulting in the loss of ammonia between the C-9 canal and the grate but they may include: volatilization, adsorption onto particles, and microbial transformations (Dillon and Chanton 2005, Berner 1980). The retention pond, the next site along the gradient after the grate at SWI, had the lowest ammonia levels of all the SWI sites, averaging only 0.017 $\pm$ 0.014 mg/l (Table 11). The data suggest that what little ammonia is entering SWI via the C-9 canal is being utilized in the retention pond and is not making its way into the wetlands of SWI (Fig.48a). However, ammonia levels increased once again in the wetlands. Wetland 5A, the wetland furthest from any point source inputs, had the highest ammonia value, averaging 0.067 $\pm$ 0.036 mg/l (Table 11). The data suggest that physical or biogeochemical processes in the US 441 drainage system and in the retention pond are removing the C-9 ammonia. Internal cycling rather than external inputs appears to be influencing ammonia concentrations in the wetlands. Lake ammonia values were generally less than wetland concentrations suggesting that groundwater was not a significant source of ammonia to the system (Table 11).

Storm water samples collected from the grate and Miami Gardens were episodic in nature and did not coincide with monthly sampling for most dates. For ease of comparison, monthly samples and storm water values were averaged for the entire seven months of the study. Storm water generally had higher concentrations of NH_3 than what was measured in SWI (Fig. 48a). Storm water collected at the grate in SWI averaged 0.083 $\pm$ 0.052 mg/l and 0.088 $\pm$ 0.048 mg/l, first and second flush respectively. Two Miami Gardens samples were collected over the study period and values ranged from a low of 0.012 to a high of 0.263 mg/l. Storm water may introduce ammonia into the retention pond but the retention pond is mitigating any potential impacts of the storm water through dilution and/or biogeochemical processes. Another likely possibility is storm water in the drainage system is not even making it into SWI. The tight coupling between the C-9 and SWI water levels lends support to this possibility. As water is released to tide through the S29 structure on the C-9 canal, hydraulic gradients reverse and water

Figure 48a - c. Average Concentrations (Mean + Std. Dev.) of Nitrogen Species in Surface Waters and Storm Water Samples Collected in and near Snake Warrior's Island Natural Area. The solid black line indicates the water quality standard acceptable for surface waters based on Broward County's Chapter 27 Surface Water Criteria. RP = the retention pond.

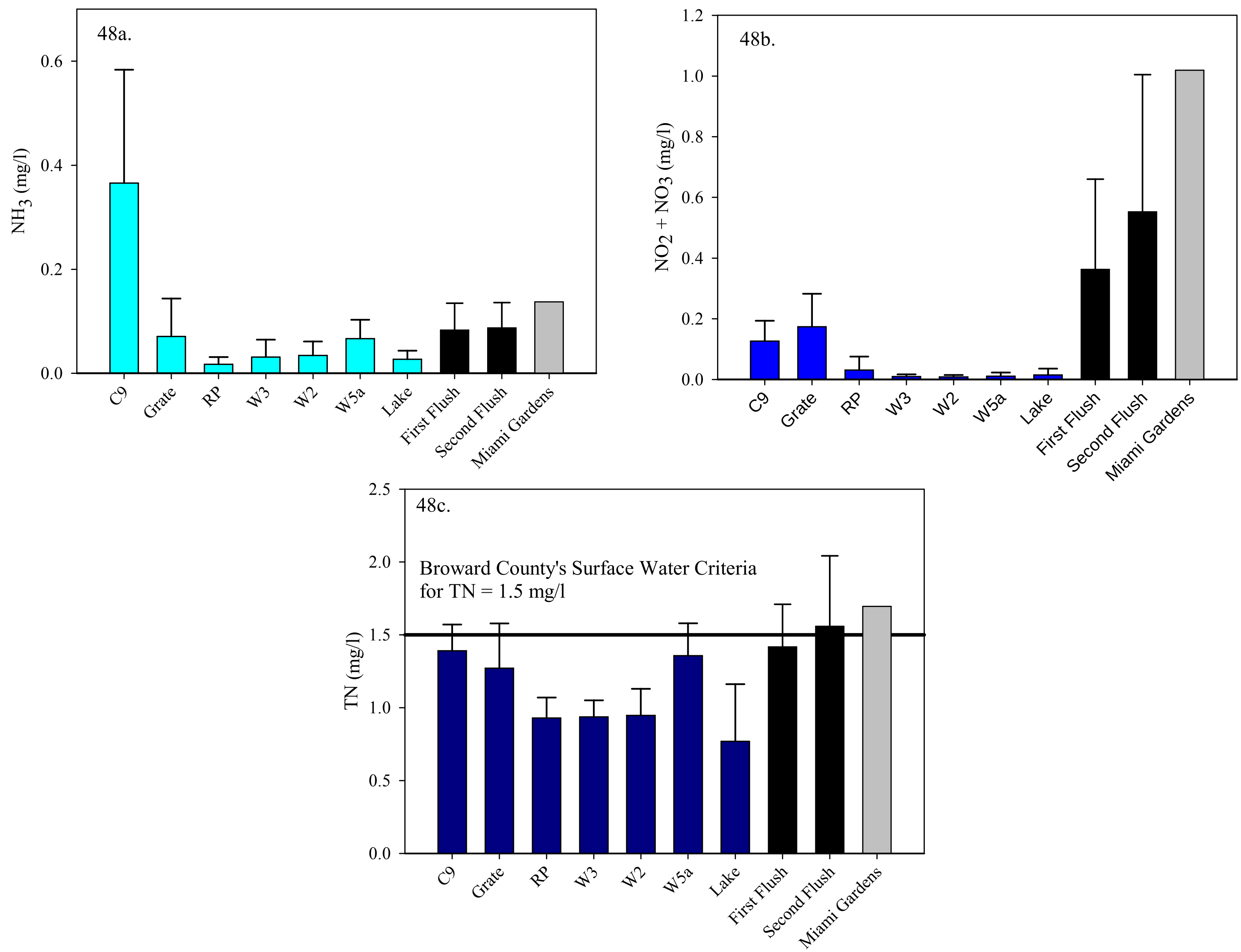


Table 11. Average Concentrations (Mean ± Std. Dev) of Water Column Ammonia (NH_3), Nitrate + Nitrite (NOx), Ortho-Phosphate (OPO_4), Total Nitrogen (TN), Total Phosphorus (TP) and Total Organic Carbon (TOC) for the C-9 Canal, the 6 Monthly Sites Within Snake Warrior's Island Natural Area (SWI) and Storm Water from Miami Gardens and SWI, June through December 2003.

Site	**NH_3 ± SD (mg/l)**	**NO_x ± SD (mg/l)**	**O-PO_4 ± SD (mg/l)**	**Total N ± SD (mg/l)**	**Total P ± SD (mg/l)**	**TN/TP ratio mg/l**	**TOC ± SD (mg/l)**
C-9	0.336 ± 0.218	0.127 ± 0.067	0.003 ± 0.001	1.390 ± 0.180	0.015 ± 0.010	77.8 + 22.6	12.300 ± 0.408
Grate	0.071 ± 0.073	0.174 ± 0.109	0.016 ± 0.012	1.270 ± 0.307	0.034 ± 0.016	46.6 + 25.7	11.291 ± 0.878
Retention Pond	0.017 ± 0.014	0.031 ±0.045	0.005 ± 0.002	0.929 ± 0.140	0.041 ± 0.016	26.2 + 10.4	11.434 ± 0.929
Wetland 3	0.031 ± 0.034	0.010 ± 0.007	0.009 ± 0.007	0.936 ± 0.114	0.030 ± 0.025	33.6 + 22.6	11.557 ± 0.723
Wetland 2	0.034 ± 0.027	0.008 ± 0.007	0.014 ± 0.010	0.946 ± 0.183	0.040 ± 0.022	30.0 + 13.2	11.613 ± 1.158
Wetland 5a	0.067 ± 0.036	0.011 ± 0.012	0.063 ± 0.025	1.357 ± 0.222	0.136 ± 0.045	11.0 + 4.2	13.086 ± 1.656
Lake	0.027 ± 0.017	0.015 ± 0.021	0.003 ± 0.002	0.768 ± 0.394	0.019 ± 0.009	36.3 + 12.4	6.240 ±0.230
First Flush SWI	0.083 ± 0.052	0.710 ± 1.019	0.014 ± 0.008	1.780 ± 1.054	0.042 ± 0.022	38.1 + 26.5	16.500 ± 8.323
Second Flush SWI	0.088 ± 0.048	0.553 ± 0.452	0.017 ± 0.007	1.559 ±0.483	0.045 ±00.042	49.9 + 23.0	15.471 ± 6.425
Miami Gardens	0.138 ± .177	1.020 ± 0.255	0.066 ±0.008	1.696 ± 0.359	0.089 ± 0.018	19.9 + 8.1	6.745 ± 0.587

flows out of SWI and south through the US 441 drainage system to the C-9 canal, instead of north (Fig. 8a & 8b).

Trends with NOx and total nitrogen (TN) were similar to NH_3 (Fig. 48a-c). C-9 water and storm water contained higher concentrations of NOx and TN compared to the wetlands (Fig. 25a-g and 26a-g, and 48a-c). The overall quality of source water (C-9 and storm water) was assessed using Broward County Chapter 27 surface water criteria. Broward County has a surface water criteria of 1.5 mg/l for TN (Broward County 2001). Both storm water and C-9 concentrations exceeded the 1.5 mg/l standard but retention pond, and wetlands were well below the 1.5 mg/l criteria suggesting that the retention pond may be acting a sink for any nutrients that maybe entering the system (Fig. 48c). The data suggests internal processes rather than external sources are strongly influencing nitrogen cycling in the wetlands (Fig. 48a-c). The only wetland to show an increase in nitrogen and actually exceed the Broward County 1.5 mg/l criteria was wetlands 5A – the wetland furthest away from C-9 and storm water inputs (Figs. 26 g and 48c).

Phosphate – Orthophosphate (OPO_4) and Total Phosphate (TP)

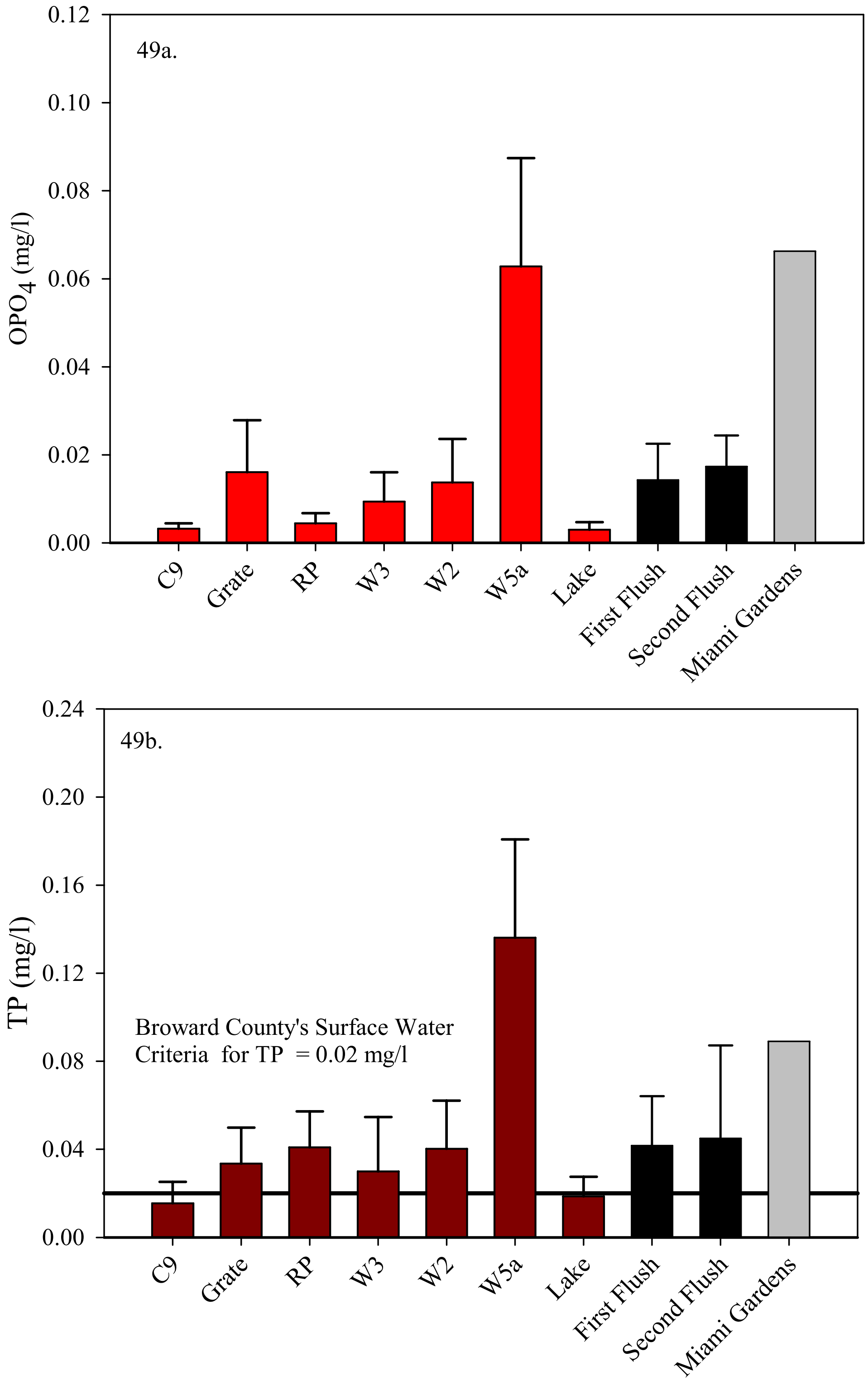
C-9 and ground water, (as indicated by the lake), provided very little phosphorus to the wetlands of Snake Warrior's Island (Fig. 27 a-g). The highest average phosphorus concentrations were once again measured in wetland 5A (Fig. 49a). This result is consistent with the idea that internal cycling rather than source inputs are influencing nutrient concentrations at SWI. Internal cycling is defined as any fluxes or biogeochemical transformations that occur once materials enter the wetlands. The average concentration of ortho-phosphate in wetland 5A was over an order of magnitude higher than the average concentration of ortho-phosphate in C-9 water, 0.0628 ± 0.0247 mg/l vs. 0.0033 ± 0.0012 mg/l (Fig. 49a). Total phosphorus levels also increased with distance from C-9 (Fig. 49b). Wetland 5a again, had the highest TP concentration, averaging 0.136 ± 0.045 mg/l compared to 0.015 ± 0.010 mg/l for C-9 water. The inorganic form of phosphorus, OPO_4, comprised approximately half of the TP (Fig. 49a & b). Storm water phosphate concentrations were higher than the C-9 but similar to OPO_4 levels measured at the all sites with SWI with the exception of wetland 5A. so it is not clear what impacts if any storm water P would have on the wetlands.

Wetland 5A is anomalously high compared to all other sites (Fig. 49a & b). Internal cycling appears to be strongest in this wetland possibly because it is the smallest and shallowest of the wetlands monitored in this study. All sites and storm water samples were close to or exceeded Broward County's surface water criteria of 0.02 mg/l for total phosphorus (Broward County Chapter 27) on at least one occasion, most on several occasions (Fig. 28a-g, 49b). There is a suggestion of a seasonal trend in TP, with values increasing in the November and December 2003 samples at many of the sites (Fig. 28a-g)

Water Column Metals

Surface water and storm water samples were analyzed for arsenic, barium, beryllium, cadmium, chromium, copper, nickel, lead, selenium, vanadium, and zinc, (As, Ba, Be, Cd, Cr, Cu, Fe, Ni, Pb, Se, Va, and Zn), respectively. No consistent trends where observed in surface water or storm water samples collected at Snake Warrior's Island and Miami Gardens and most samples had

Figure 49a - b. Average Concentrations (Mean $\pm$ Std. Dev.) of Ortho-Phosphate and Total Phosphate (TP) in Surface Waters and Storm Water Samples Collected in and near Snake Warrior's Island Natural Area. Solid black line indicates the water quality standard allowable acceptable for surface waters based on Broward County's Chapter 27 Surface Water Criteria.



metal concentrations well below Broward County's accepted water quality criteria with two exceptions, copper and selenium (Fig. 50a-f). Elevated copper concentrations were measured surface water samples collected from wetlands 3 and 5A and the retention pond during the July and August sampling (Fig. 50c). C-9 canal and lake concentrations were below minimum detections limits on all data so C-9 water and ground water are not a likely source of copper to the wetlands at SWI. One potential source of copper to the wetlands at SWI may be the result of management strategies implemented to combat the invasive aquatic exotic *Hydrilla verticillata* at SWI (Fig. 51a - b).

Hydrilla is commonly found in Florida's freshwater canals and lakes. This submerged macrophyte was originally native to parts of Asia. Since its discovery in the United States in 1960, is has since rapidly spread throughout freshwater bodies in the southern U. S. (University of Florida, Center for Aquatic and Invasive Plants 2005 http://aquat1.ifas.ufl.edu/hyvepic.html). *Hydrilla* was introduced into Snake Warriors Island via the C-9 canal. A variety of different management strategies were employed to control the spread of this exotic macrophyte at SWI including the use of an herbicide "Komeen" which contains copper (Gretel McCausland BCPRD per. comm.). The wetlands of SWI were treated with "Komeen" on a quarterly basis to try to reduce/eliminate the occurrence of *Hydrilla* in the retention pond and wetlands. Unfortunately, it proved difficult to eliminate the *Hydrilla* because the C-9 water contains the macrophyte and continually reseeded the population at SWI. The use of a copper-based herbicide at SWI may also account for the presence of elevated copper concentrations in two first flush storm water samples (Aug. 8 and Dec. 12, 2003) (Fig. 31c). As mentioned in the hydrology section, operations at the S29 structure of the C-9 canal strongly influence water levels in the retention pond and wetlands of SWI (Fig. 8a). During small scale rain events, hydraulic gradients shift and water may be flowing out of SWI south to the C-9 canal. Storm water samples collected by the autosampler at the grate at SWI would actually be surface water from SWI and not storm water from the surrounding area which could explain the occasional elevated copper concentrations.

Copper was also the only metal in sediment samples that exceeded Florida's DEP probable effect concentration (PEC) in both the August and December samples from wetlands 2 (Fig. 46) (MacDonald et al. 2003). Exposure to values above the PEC would likely have harmful effects on sediment organisms (MacDonald et al. 2003). Elevated copper levels were measured in sediments, at all sites sampled (wetland 3, 2 and 5A). Wetland 2 had the highest concentrations of copper which is probably a function of both proximity to source as well as particle size. Smaller particles size would allow for greater adsorption of copper onto the particles. Wetlands 2 had the highest porosity indicating a smaller grain size and higher carbon content compared to the other wetlands (Table 7). Copper concentrations in wetlands 3 hovered around the threshold effect concentration (TEC) which is the concentration below which harmful effects are unlikely to be observed (MacDonald 2003). Copper concentrations in wetland 5A were also below the TEC in August but by December, copper levels had exceeded the TEC and were close to the probable effect concentration (PEC) (Fig. 46). The observed increase in copper between the August and December samples may indicate transport of fine grained, copper laden particles from wetland 2 to wetland 5A. The wetlands at SWI were constructed so that water would flow from the retention pond to wetland 3 to wetland 2 and finally dead ending in wetland 5A (Broward County Office of Environmental Services 1997). Increases in porosity in wetland 5A

Figure 50a - f. Average Concentrations (Mean ± Std. Dev.) of Total Metals in Surface Waters from Snake Warrior's Island (SWI), the C-9 Canal and Storm Water from SWI and Miami Gardens (MG). Storm water sites are indicated by the vertical black bars. The solid black horizontal line indicates the water quality standard acceptable for surface waters based on Broward County's Chapter 27 Surface Water Criteria. As = Arsenic, Se = Selenium, Cu = Copper, Ni = Nickel, Pb = Lead, and Zn = Zinc.

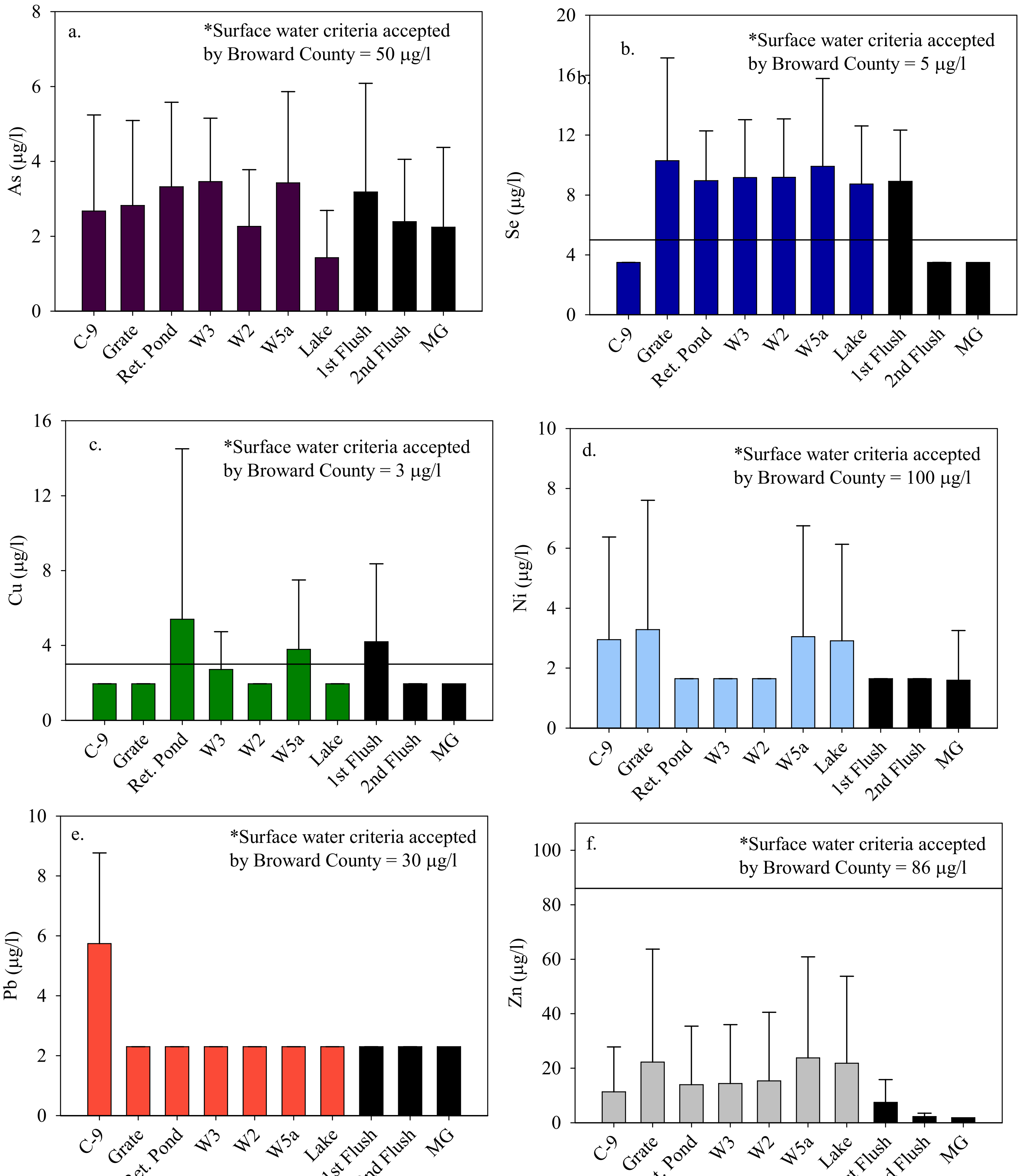
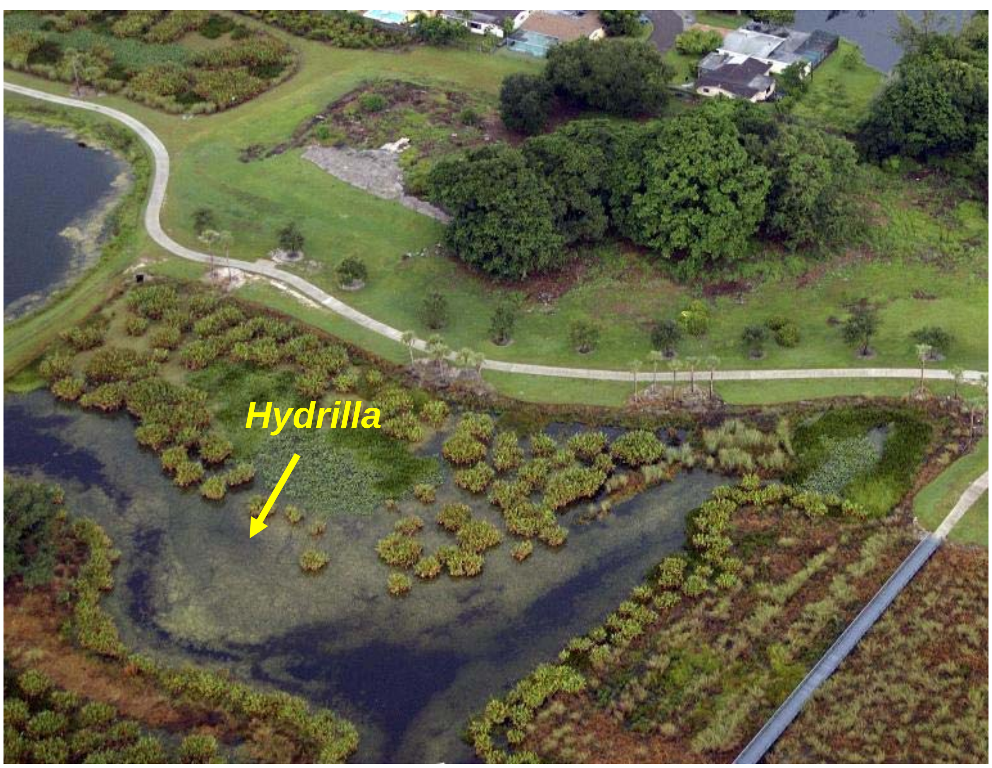


Figure 51a. *Hydrilla verticillata* in the Wetlands of Snake Warrior's Island.

Figure 51b. 2003 Aerial Photo of Wetlands 3 and 2 Containing *Hydrilla*.



between the August and December sampling events also suggest finer grained sediments are accumulating in wetland 5A (Table 7). Workers preparing to spray for *Hydrilla* frequently set up their equipment on and around the culvert in the northwest corner of wetland 2 (Fig. 5). Sediment cores were collected in this area and coincidently had the highest copper concentrations on both sample dates. This culvert also connects wetland 2 to wetland 5A (Fig. 5). Copper is likely to continue to accumulate in sediments as long as copper based herbicides are in use to manage *Hydrilla verticillata* in SWI.

Selenium was a "one hit wonder" metal. The only time surface water concentrations exceeded the minimum detection limit and Broward County's surface water criteria (5 mg/l), was during the October sampling at all the sites in the Snake Warrior's Island Natural Area, including the lake. However, it was not detected in water samples from the C-9 collected at the same time (Fig. 32 a-g). The presence of a spike of selenium in all sites except C-9 suggests there is a localized source of selenium within SWI. Selenium was measured in the lake but it seems unlikely that ground water is the source since it was detected in only one of seven monthly samples. Selenium concentrations in sediments samples were at or below minimum detection limits (16/17 cores) indicating the sediments around SWI were not a source of selenium to overlying waters (Table 8). Atmospheric deposition of selenium may explain its distribution at SWI but no clear sources have been identified**.**

Potential sources of selenium to the environment include: production of pigments, rubber, steel and phosphate fertilizers, and discharge of municipal wastewaters (Minnesota Pollution Control Agency – http://www.pca.state.mn.us/water/groundwater/gwmap/index.html , Government of Alberta 2006 - http://www3.gov.ab.ca/env/water/SWQ/faqs04.cfm). However, these activities did not occur around the SWI Natural Area, so it seems unlikely they would be responsible the one time event at SWI. One possible explanation for the elevated October values may be related to construction activities occurring within the park. Beginning in late September and lasting through part of November, concrete walkways were being laid all around the park (Fig. 52, McCausland BCPRD per. comm. Craig per. obser.). The elevated selenium levels at the sites in SWI may have been a consequence of these activities. Fly ash produced by coal-fueled power plants is a coal combustion product (CCP) and a common constituent in construction and industrial materials such as concrete and cement. We are unable to determine the specific composition of the material used to lay the walkways and concrete pads around SWI, but the correlation between the construction of the pathways coincides with the elevated levels of selenium at all sites at SWI suggests the events may be related.

Elevated selenium concentrations were also found in the first flush storm water sample collected approximately one week after the October sampling at SWI (Table 4, & Fig. 43b). Given the very dynamic nature of water movement into and out of the SWI Natural Area, surface waters may have been flowing out of SWI through the storm water system rather than storm water flowing into SWI so the "storm water" sample was actually SWI surface water. The system was designed to divert storm water into SWI only after the US 441 storm water drainage system reached capacity. Until that happens, water management activities at the S29 structure on the C-9 strongly influence whether water is flowing into or out of SWI (Fig. 8a). During this rain event water, water released to tide through the S29 altered hydraulic gradients along the US 441 storm water drainage system and caused water to flow out of SWI which would account for the

Figure 52. 2003 Aerial Photograph of the Lake and the Western Portions of the Retention Pond and Wetland 2 in the Snake Warrior's Island Natural Area.

elevated selenium concentrations in the storm water sample collected at the grate at SWI. Selenium concentrations were below detection limits for SWI second flush samples and storm water samples collected in Miami Gardens.

Spikes in zinc (Zn) were also observed during the September and October monthly sampling events as well as in storm water collected at Snake Warrior's Island but were below the water quality standard of 86 µg/l accepted by Broward County (Fig. 33a-g and 43f). Unlike selenium (Se), Zn was detected not only in SWI surface waters but also the in water samples from the C-9 canal (Fig. 33 a-g). The spike of Zn at the C-9 site suggests that whatever was responsible for the spike was affecting a broader geographic area than just the area around SWI. Zn is a naturally occurring metal but elevated levels of Zn are usually related to human activities. Zn can be released into the environment through commercial activities such as mining, steel production, smelting metals, and the burning of waste (ASTDR 2005 http://www.atsdr.cdc.gov/tfacts60.html). Zn is usually particle reactive and can attach to soil, sediment, and dust particles in the air. The specific source of Zn to SWI and the surrounding area during the September and October sampling events remains unknown. None of the typical activities that would produce Zn as a by-product occur in or around SWI. The broad geographic distribution (C-9 and SWI) suggest that atmospheric deposition may play a role in the distribution of Zn during September and October 2003.

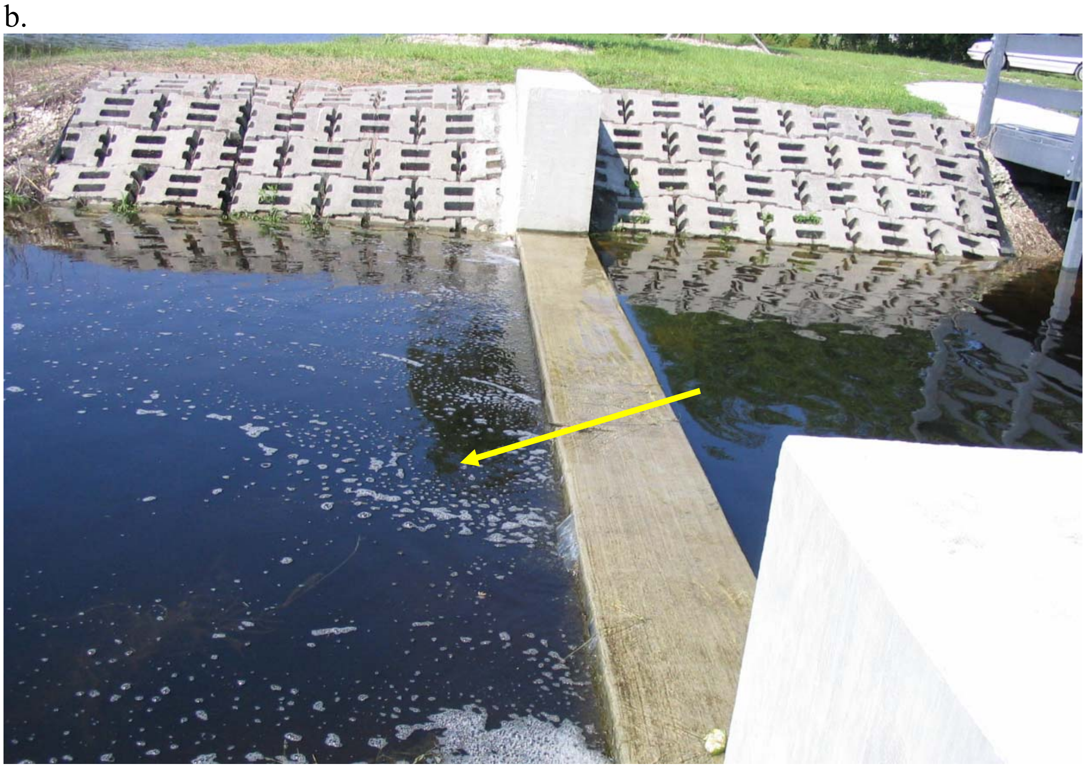
Other Potential Pollutants - Polycyclic Aromatic Hydrocarbons (PAHs) and Pesticides/Herbicides

Polycyclic aromatic hydrocarbons (PAHs) were not found in any of the water column or storm water samples collected during this 7 month study (Table 5). The absence of PAHs in storm water from sampled at Ronald St. in Miami Gardens and at Snake Warrior's Island suggests pretreatment of storm water is working. Low levels of PAHs were found in wetland sediments during the August sampling (Fig. 47) but average values were all below the threshold effect concentration designated by the Florida DEP's sediment quality assessment guidelines for inland waters (MaDonald et al. 2003). None of the sediment samples collected in December 2003 contained detectable concentrations of PAHs suggesting PAHs are not accumulating in the sediments of SWI. Wetland 2 had the highest concentration of PAH and is probably a consequence grain size. Wetlands 2 sediment was finer grained than either wetland 3 or 5A as indicated by the % solid values and sediment porosity (Table 7). PAHs are more readily adsorbed onto finer grained, organic rich particles (U.S. EPA 2000 http://www.epa.gov/glnpo/lakemich/).

Detectable levels of the triazine herbicide atrazine were measured in surface waters from the grate, retention pond and wetland 3 SWI during the July 2003 sampling event. Atrazine and simazine were also detected in 3 storm water samples, two of which were from Miami Gardens (Table 5). Atrazine is one of the most common herbicides used in landscaping in North America and is used to control for broadleaf and grass weeds and can be found in surface and ground waters all over North America (http://www.epa.gov/glnpo/lakemich/). Atrazine and simazine are probably entering the system as runoff from the surrounding residential areas and reflect local landscaping practices. Sediment samples were all below minimum detection limits for the

Figure 53a. Water Flows from the Retention Pond over the Top of the Weir into Wetlands 3 During a Protracted Rain Event. Figure 53b. Following the Rain Event, Water Flows out of Wetland 3 Over the Top of the Weir into the Retention Pond. Water is released to tide through the S29 structure on C-9 during and following rain events. This shifts hydraulic gradients such that water will flow out of the retention pond at Snake Warrior's Island into the C-9. Once the gates are closed at S29, hydraulic gradients are restored, and water flows from C-9 into SWI.

b.



herbicides/pesticides tested for suggesting they are degraded in the water column and never reach the sediment.

V. Conclusions

Hydraulic gradients coupled with water management activities at the S29 on the C-9 determine if water is flowing into or out of SWI. During non rainy periods, water flows north from the C-9 canal into SWI hydrating the wetlands. However, both physical and chemical data suggests that during small or short term rain events, the direction of water movement is out of the SWI system. Releasing water to tide through the S29 structure on the C-9 alters hydraulic gradients and cause water to flow south to the C-9 as long when the gates are open.

Storm water does briefly flow into SWI during major or prolonged rain events. The flow of storm water into SWI occurs when the US 441 storm water drainage system is at capacity and excess water is funneled into SWI to prevent flooding in Miami Gardens. However, as water continues to be released to tide through the S29 structure, the load in the storm water system is reduced, and water once again flows out of SWI (Fig. 53a & b).

Conservative and non conservative parameters were measured to assess what if any impacts the composition of source waters (C-9, ground water and storm water), had on surface water quality in the wetlands of SWI. Conservative tracers such as vanadium indicated C-9 water was mixed into the wetlands. However, non conservative tracers such as nutrients and metals indicate source inputs did not strongly influence surface waters in the wetlands. Internal processes rather than external inputs appear to be governing the transformation and flux of materials and nutrients in the wetlands of Snake Warrior's Island Natural Area. Wetland 5A consistently had the highest nutrient concentrations of all the wetlands even though it was the furthest from source inputs.

In addition to processes occurring internal to the wetlands, source waters are probably being diluted and/or undergoing biogeochemical transformations in the retention pond prior to entering the wetlands. Given the above considerations, some parameters may be elevated in storm water collected from grate at SWI and Miami Gardens, but their impact on water quality in the wetlands of SWI is minimal.

The one potential negative impact on the wetlands of Snake Warrior's Island Natural Area is a consequence of aquatic weed management activities occurring within SWI. The use of a copper based herbicide to control for the exotic aquatic *Hydrilla verticilatta* is probably responsible for the persistent and elevated levels of copper found in the sediments of the wetlands of SWI. Switching to a non-copper based herbicide would prevent additional accumulation of copper in the sediments of SWI. However, repeated additions of any herbicide may also be stimulating internal nutrient cycles in the wetlands. Pulses of detrital material will be added to the system every time an herbicide in applied to kill off the *Hydrilla*.

VI. Recommendations

1. Based on monthly water quality sampling results, the C-9 Canal should continue to be used as the main surface water source for SWI. Regional water management activities will ultimately determine the sustainability of this localized wetland hydration strategy.

2. The utilization of a pre-existing storm water treatment pond with a wetlands system appears to have at least some 'pretreatment' advantages (e.g., herbicides) and should be considered in future projects. However, storm events do not always guarantee movement of pollutants in a specified direction, (i.e. into a reconstructed wetland). Changes in hydraulic gradients on a broad geographic scale can redirect flow in the opposite direction. Thus, future storm water/wetland projects should consider the complexity of the overall hydrologic system before including a pond.

3. The retention areas within Miami Gardens appear to be functioning as designed. The performance of this system should be a goal for future storm water management projects countywide for the Broward County Water and Wastewater Services.

4. The Broward County Parks and Recreation Division may consider the use of non-copper based herbicide treatments in order to reduce external copper loadings to the SWI. In addition, the consistent decay of exotic vegetation is likely enhancing the internal cycling of nutrients. Ultimately, the aquatic plant management decisions will have to balance the constant challenge of controlling aggressive, opportunistic exotic species such as *Hydrilla* and impacts of those controls on the ecosystem.

5. This project should be considered one of the success stories of the Integrated Water Resources Plan and is an example of several governmental entities coming together to meet ecological, hydrological, recreational, and archeological goals of this project.

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