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Water Quality Characterization in the Northern Florida Everglades

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Abstract The Loxahatchee National Wildlife Refuge (Refuge) developed as a system with waters low in nutrients. Today, the Refuge wetlands are impacted by inflows containing elevated nutrient concentrations originating from agricultural sources flowing into canals surrounding the west side and from urban and horticultural areas flowing into canals surrounding the eastern side of the Refuge. We analyzed water quality sampled at 40 sites divided into eastern and western areas and four zones in the Refuge. We defined four zones as the canals surrounding the Refuge marsh, the perimeter zone, the transition zone, and the interior zone. The canal receiving agricultural inflows had greater alkalinity and conductivity (SpC), Si and SO_4 but lower turbidity and total suspended solids than the canal receiving urban and horticultural inflows. Alkalinity, total dissolved solids (TDS), SpC, Ca, Cl, and SO_4 concentrations were greater in the perimeter than in transition and interior zones. Alkalinity and SpC values and SO_4 concentrations were greater in the transition than in interior zone. Alkalinity, SpC, and TDS values and Ca, SO_4, and Cl concentrations correlated in negative curvilinear relationships with distance from the canal (r^2=0.78, 0.70, 0.61, 0.78, 0.64, 0.57, respectively). Analysis of multiple water quality parameters may reveal the complexity of interactions that might be overlooked in a simple single parameter analysis. These data show an impact of canal water containing high nutrient concentrations on water quality flowing from the canal towards the Refuge interior.

Keywords Stormwater treatment areas · Long term monitoring · Enhanced monitoring · Depth of the clear water column · Depth to consolidated substrate

1 Introduction

The Northern Everglades was developed as a rainfall-driven system with surface waters low in nutrients and inorganic ions and is characterized as an oligotrophic ecosystem with low dissolved mineral concentration and low conductivity (Davis 1994). The Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge) contains the last major remnant of the Northern Everglades ecosystem that continues to be characterized by relatively low conductivity and mineral content. Predevelopment Everglade's fauna and flora are adapted to extremely low phosphorus (P) concentrations. Therefore ecosystem function changes with very small increases in this nutrient. Refuge surface water is classified by

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the State of Florida as class III freshwater with corresponding water quality standards established to protect recreation, propagation, and maintenance of a healthy, well-balanced population of fish and wildlife (Section 62-302.400, Florida Administrative Code (F.A.C.). The Refuge is also classified as an Outstanding Florida Waters (Section 62-302.700, F.A.C.) which, beyond the class III water quality standards, requires no degradation of water quality other than that allowed in Rule 62-4.242(2) and (3), F.A.C.

Prior to discharge into the Refuge, most pumped inflows are first treated in large constructed wetlands called stormwater treatment areas (STAs) adjacent to the Refuge northern boundary. Untreated water has also been discharged to the northern Refuge, but at a much lower frequency, rate, and volume (USFWS 2007a, b). Stormwater originating from urban, agricultural, and horticultural is treated in STA1-East while stormwater treated in STA1-West originates primarily in the 280,000 ha Everglades Agricultural Area (EAA) located northwest of the Refuge. STA-1 West receives water draining primarily from sugarcane (*Saccharum* spp.) and vegetable production. Approximately 80% of the EAA is planted with sugarcane with the remaining land used for vegetable production (Izuno and Capone 1995). Drainage and exposure of anaerobic histosols to aerobic conditions required for agriculture results in nutrient mineralization associated with the organic matter decomposition (Morris et al. 2004). Microbial oxidation of organic soils in the EAA makes excessive N available to sugarcane (Glaz and Gilbert 2006). Sugarcane and vegetable fertilizer application rates are often greater than recommended rates to ensure productivity despite high nutrient losses. Heavy rains are common in Florida and nutrients often leach out of the root zone into a network of ditches and canals (Zhang et al. 2004; Rehage and Trexler 2006) that convey the water to large pumping stations, which move it into the STAs. STA-1 East receives inflow from mainly urban and horticulture sources. Horticultural crops include woody ornamental landscape plants and various genera of palm trees. Sources of urban runoff or leaching are primarily from turfgrass and runoff from roads and construction.

Horticultural crops and turfgrass are intensively managed, especially on golf courses, where excessive amounts of N can be applied for esthetic reasons and to reduce weed invasion (Busey 2003). Excess N has been shown to alter nutrient dynamics and macrophyte growth in the Everglades ecosystem. Relationships between δ15N signatures and changes in water chemistry caused by canal water intrusion into the Refuge were evident although less pronounced than the latitudinal gradient. Detritus, floc, metaphyton, and cattail δ15N values were significantly correlated with specific conductance (Chang et al. 2009). Rooted macrophyte δ15N, by contrast, appeared more responsive to soil nutrient pools. Cattail (8.9% to +7.7%) was restricted to the wetland perimeter and had the widest δ15N range, which was positively correlated with soil P. Sawgrass (5.3% to +7.7%) occurred across most of the wetland, but its δ15N was not strongly correlated to any gradient (Chang et al. 2009). Interspecific variation in N isotopic composition in submerged aquatic vegetation suggest greater N demand by submerged species, followed by emergent and floating-leaved species. However, N content was similar between *Nymphaea odorata* and *Utricularia foliosa*, *N. odorata*, as well as *U. foliosa*'s congener (Troxler and Richards 2009). In contrast to *U. foliosa*, *Utricularia purpurea* have a low P content, although the two species are more similar in N content and δ15N, resulting in a much higher N:P and thus potentially greater P limitation in *U. purpurea* (Troxler and Richards 2009). Sulfur fertilization as gypsum (168 kg Sha^{-1} year^{-1}) greatly reduces weed growth in many turfgrass species (Goss 1974). Methylmercury (MeHg) is a neurotoxin that will bioaccumulate in the muscle tissues of organisms causing harm to fish, wildlife, and human health (Selin 2009; Zhang and Hsu-Kim 2010). Concentrations of MeHg in organisms increase up the food chain, with very high concentrations in animals such as large fish and predatory birds (Corrales et al. 2010; Ye et al. 2010). Effects of MeHg exposure are most severe in fetuses, causing damage to the developing brain and nervous system (Crump et al. 1998). Sulfate contamination has a significant environmental implication through the stimulation of toxic hydrogen sulfide and MeHg production. The production of MeHg methylation process is carried out by sulfate-reducing bacteria in presence of mercury (Hg (II)) and sulfate labile organic material under anaerobic conditions (King et al. 2000; Harmon et al. 2007). Agricultural fertilizer has been identified as a major contributor to sulfate concentrations in the Everglades canals (Bates et al. 2002; Orem et al. 2011).

Water flows downstream from agricultural and urban areas and is diverted to one or more of the STAs to reduce nutrient loads and then conveyed to one of the water conservation areas (WCAs) through a series of canals. The STAs are designed to remove nutrients by cycling stormwater first through cells containing emergent vegetation and then through cells containing submerged aquatic vegetation. Emergent vegetation, usually cattail, removes nutrients, especially P from stormwater by uptake; nutrients are then cycled through the system and eventually deposited into the soil via litterfall. Since water levels are high enough to keep the emergent vegetation soil anaerobic, organic matter decomposition and nutrient mineralization is minimized and resuspension into the water column is limited. Water is then conveyed to a submerged aquatic vegetation (SAV) cell where additional nutrients are removed. SAV plants are *Hydrilla verticillata* (L.F.) Royle, *Najas guadalupensis* Morong and *Chara* spp. or a combination of these three species. After nutrients have been removed, stormwater is pumped into a canal and then pumped into a WCA. The efficacy of nutrient removal from stormwater varies temporally and among STAs and depends on several factors including: (1) antecedent land use, (2) nutrient and hydraulic loading, (3) vegetation condition, (4) soil type, (5) cell topography, (6) cell size and shape, and (7) construction activities to improve P removal (Ivanoff and Chen 2012). Both STA1-East and STA1-West have received stormwater in excess of their design capacity for several years, and STA-1 East has design and construction flaws resulting in increased mineral and nutrient inflow into the Refuge.

Water containing elevated nutrients flowing into the Everglades ecosystems have been associated with altered ecosystem structure and function (DeBusk et al. 1994, 2001; Davis et al. 2003; Noe et al. 2003; Childers et al. 2003; King et al. 2004; Liston and Trexler 2005; Hagerthey et al. 2008) including conversion of sawgrass (*Cladium jamaicense* Crantz) stands to cattail (*Typha domingensis* Pers.) (Debusk et al. 1994, 2001; Doren et al. 1997; Stewart et al. 1997; Lorenzen et al. 2000; Miao et al 2001; 2000; McCormick et al. 2009).

The objective of this research was to determine if: (1) the water quality in the Refuge marsh is reflected by STA-1 West relative to STA-1 East discharge, (2) if water quality parameters differ among zones, and (3) the efficacy of relying solely on total phosphorus (TP) compared with using TP in combination with other water quality parameters to develop understanding the effect of canal water diffusion and intrusion on Refuge water quality.

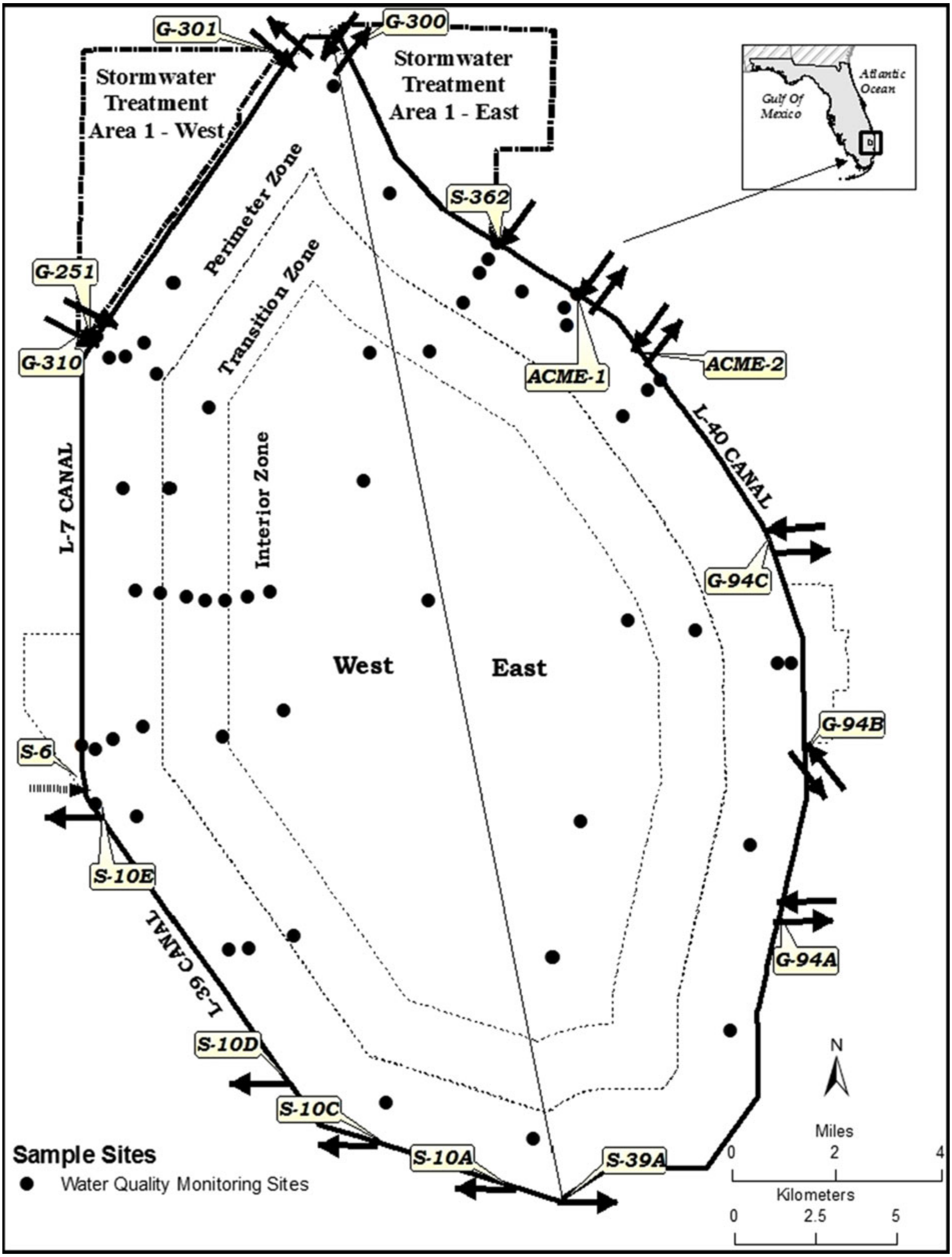
2 Materials and Methods

2.1 The Site

Since completion of construction in the early 1960s, the Refuge wetland has been surrounded by perimeter levees and associated canals encircling the wetland on the interior side of the levees (Fig. 1). Inflows into this impounded system are controlled by the South Florida Water Management District (SFWMD) and outflows controlled by the US Army Corps of Engineers, the SFWMD, and local drainage districts. Areas of pristine Refuge wetlands have been impacted by canal water intrusion containing elevated concentrations of nutrients and minerals (Childers et al. 2003; Harwell et al. 2008; Surratt et al. 2008; Wang et al. 2009; Chang et al. 2009). Treated water is pumped into the Refuge from STA-1 East into the eastern L-40 canal and from STA-1 West into the western L-7 canal forming a perimeter around the Refuge. Once discharged to the canals surrounding the Refuge wetland, these waters mix and tend to move into the marsh when water levels are high (>4.57 m NGVD 1929) and inflow rates are moderate to high (>14.18 $m^3 s^{-1}$) (Harwell et al. 2008; Surratt et al. 2008). Harwell et al. (2008) classified the Refuge into four separate zones based on surface water conductivity. Specific conductivity (SpC), a tracer of canal water movement, declined across each zone from the canal toward the Refuge interior. The perimeter zone was from the canal to 2.5 km into the marsh, the transition zone was from 2.5 to 4.5 km into the marsh, and the interior zone was comprised of sites located greater than 4.5 km into the marsh.

2.2 Marsh Zones and Delineations

Water quality in the Refuge has historically been monitored by the SFWMD at 14 interior sites. In 2004, 39 additional sampling sites, mostly located in areas not previously monitored, were established to examine water quality from the perimeter canals into the marsh interior (Surratt et al. 2008; Harwell et al. 2008). The Refuge was divided into east and west areas, and four zones from the canal to the marsh interior to characterize different Refuge water quality. The Refuge was divided into eastern and western areas reflecting sites that receive water primarily from STA1-East and STA1-West, and four zones delineated as the canal surrounding the Refuge marsh, the perimeter zone (0


G-301
G-300
Stormwater Treatment Area 1 - West
Stormwater Treatment Area 1 - East
Atlantic Ocean
Gulf Of Mexico
Perimeter Zone
Transition Zone
Interior Zone
S-362
G-251
G-310
ACME-1
ACME-2
L-40 CANAL
L-7 CANAL
G-94C
West
East
G-94B
S-6
S-10E
L-39 CANAL
G-94A
S-10D
S-10C
S-10A
S-39A
N
Miles
0
2
4
Kilometers
0
2.5
5
Sample Sites
● Water Quality Monitoring Sites

◀ **Fig. 1** Water quality sites in the A.R.M. Loxahatachee National Wildlife Refuge classified by zones (canal, perimeter, transition, and interior) and East and West areas. Inflow sites are indicated by *arrows pointing into the Refuge*. Outflow sites are indicated by *arrows pointing out of the Refuge*

to 2.5 km into the Refuge marsh), the transition zone (2.5 to 4.5 km into the marsh), and the interior zone (>4.5 km into the marsh) (Harwell et al. 2008).

2.3 Sample Collection

Surface water samples were collected monthly at 48 marsh and 5 canal sites from November 2004 through August 2007. Marsh sites were accessed by float helicopter and sampled by wading out into the marsh to collect 3.0 L of undisturbed water and to make field measurements of SpC, dissolved oxygen (DO), and pH using Hydrolab multiprobe datasondes, (Hydrolab, Mini Sonde 4a; Loveland, CO, USA); depth of the clear water column (CWdepth); and CSdepth (SFWMD 2006). Depths were measured within a 10-m radius of each sampling point. At water levels greater than 20 cm, 3 L of water was collected for analysis. Samples were stored on ice at 4°C, filtered, and preserved within 4 h of collection.

2.4 Laboratory Analysis

All samples collected from January 2005 through May 2006 were analyzed by the SFWMD chemistry laboratory in West Palm Beach, Florida. Samples collected from the Consent Decree Network (SFWMD 2006) from January 2005 through December 2006 were analyzed by the SFWMD chemistry laboratory in West Palm Beach, Florida. Samples from the Refuge's enhanced network collected from June 2006 to December 2006 were analyzed by Columbia Analytical Services (Jacksonville, FL, USA). Alkalinity, as $CaCO_3$, was measured by titration with 0.02 N H_2SO_4 using the EPA 310.1 method described in APHA (1998). Total organic carbon (TOC) was determined by thermal combustion as described in the EPA 415.1. Dissolved organic carbon (DOC) and total dissolved solids (TDS) were measured in water passed through a 0.45-μm filter. TDS was measured using the EPA 160.1 method (APHA 2005). Turbidity (TB) was measured following the EPA 160.2 method (APHA 2005) and is expressed as a formazin turbidity unit. Total suspended solids (TSS) was measured after the sample was dried at 103°C and weighed as described in the EPA 160.2 method (APHA 2005). TDS was measured by weighing filters which were dried at 90°C and fixed at 180°C (APHA 2005). Sulfate was determined by the EPA 300.1 method (APHA 2005). After water samples were filtered through a 0.45-μm filter, a 2.0-ml subsample was analyzed for Ca, Cl, and inductively coupled plasma emission spectrometer (SM 3120.B method; APHA 2005). TP was determined by digesting water aliquots in an autoclave at 103.5 kPa and 121°C for 60 min with 4.0 mL acidified ammonium persulfate (APHA 2005).

2.5 Statistical Analysis

Only data with complete records for all parameters measured were analyzed. Data were subjected to a two-way general linear model (GLM) analysis (Snedecor and Cochran 1994; Kirk 1995) using Statistical Analysis Software programs version 8.01(SAS Institute Inc. 1999). Significance of treatment means was determined at $p \leq 0.05$ with the least square means test. After values were lognormal transformed, residuals were normally distributed with constant variance. Statistical comparisons in the GLM showed that all parameters, except turbidity and pH, in the zone by STA by CWdepth, zone by CWdepth, and STA by CWdepth interactions were not significant at $p \leq 0.05$. Therefore, results are discussed with respect to zone (canal, perimeter, transition, and interior) by STA differences (Snedecor and Cochran 1994; Kirk 1995).

3 Results

The canal receiving STA-1 West discharge had greater alkalinity (ALK) and SpC values and Si and SO_4 concentrations but lower TB and TSS values than the canal receiving STA-1 East discharge. Alkalinity, TDS, TB, pH, SpC, and T values and Ca, Cl, SO_4, and TP concentrations were higher in the canal than in the perimeter, transition, or interior zones (Table 1). Alkalinity, DOC, TDS, and SpC values and Ca, Cl, and SO_4 concentrations were greater in the perimeter than in transition or interior zones. ALK and SpC values and SO_4 concentrations were greater in the transition than in interior zone. DO was greater than in the interior zone than all other zones. Except for the

Table 1 Mean alkalinity (ALK), pH, dissolved organic carbon (DOC), dissolved oxygen (DO), total organic carbon (TOC), total dissolved solids (TDS), total suspended solids (TSS), turbidity (TB), conductivity (SpC), and temperature (T) in four zones in the A.R.M. Loxahatchee National Wildlife Refuge, Boynton Beach, Florida from 2004 through 2007

Zone	Side of Refuge	ALK	DOC	DO	TOC	TDS	TSS	TB	pH	SpC	T	Ca	Cl	Si	SO_4	TP
		mg L^{-1}						FTU L^{-1}		μS/cm^{-3}	°C	mg L^{-1} water				
Canal	West	204a	30.4a	4.31b	30.0a	540a	4.48b	5.19b	7.61a	832a	25.6a	63a	110a	16a	49.7a	0.087a
	East	175b	24.9a	3.52b	25.9a	444a	8.04a	6.39a	7.42a	702b	25.4a	68a	92a	10b	32.5b	0.090a
Perimeter	West	103c	25.7a	2.40c	23.8a	287b	3.39c	1.19c	6.80b	417c	22.9b	32b	56b	14a	15.6c	0.020b
	East	88c	22.4a	3.42b	23.0ab	248b	2.39c	0.86c	6.89b	362c	23.4b	29b	50b	9b	9.5c	0.019b
Transition	West	39d	17.8c	4.00b	18.0b	130c	3.20b	1.09c	6.70b	164d	24.8b	11c	24c	8b	1.2d	0.011b
	East	24d	21.7c	3.68b	22.0b	125c	2.69c	0.80c	6.57c	142d	24.3b	9c	26c	7b	1.2d	0.014b
Interior	None	15e	20.5c	5.16a	20.7b	112c	4.04b	1.07c	6.41c	113e	23.1b	6c	22c	4c	0.1e	0.010b

In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$; $n \geq 58$). Statistical comparisons of parameters in water are presented with regard to zone × STA because interactions of zone × STA × sampling time were not significant in the GLM model ($p \leq 0.05$; $n \geq 23$)

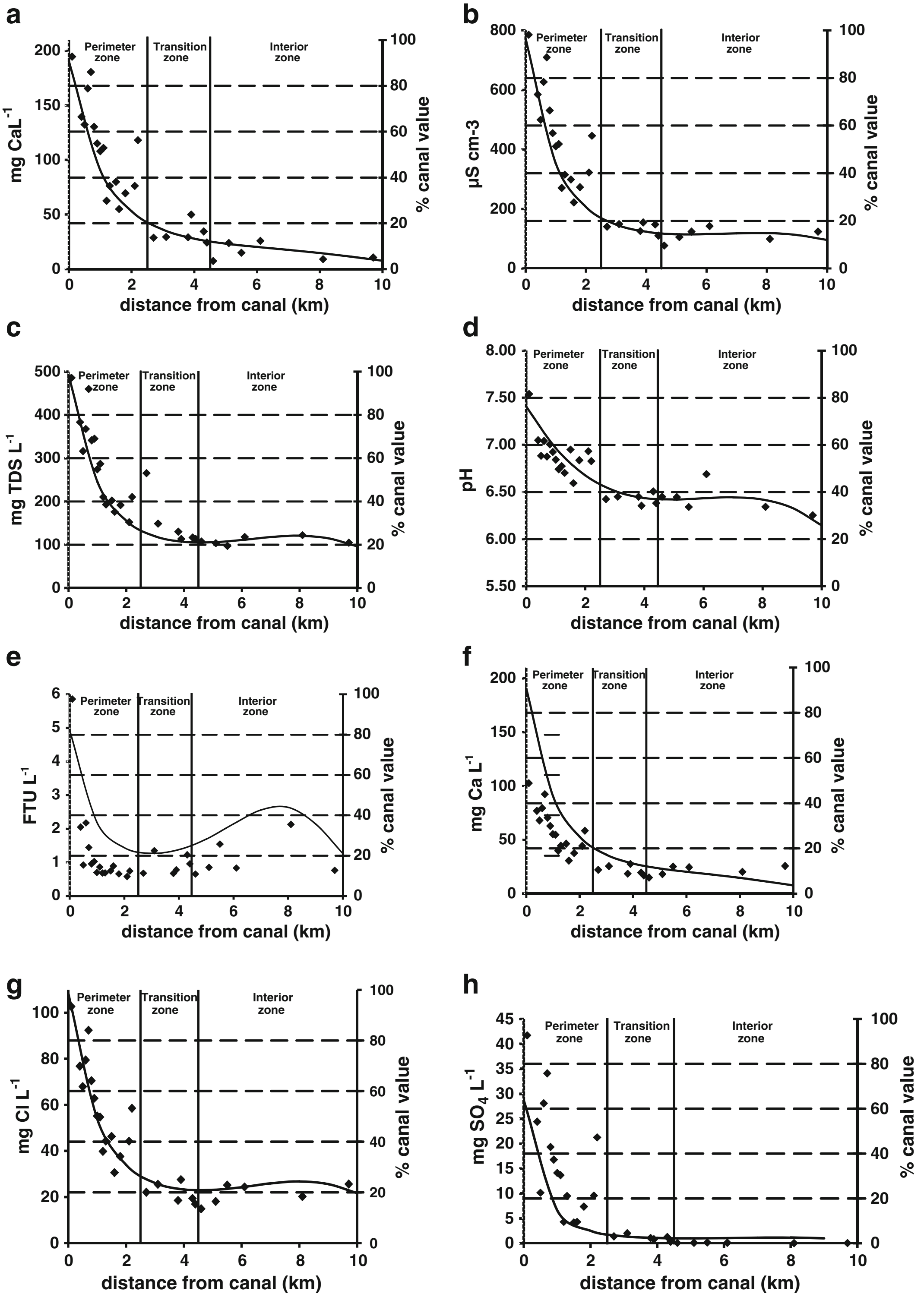
FTU formazin turbidity unit

DO and Si concentrations, water quality parameters did not differ between east and west sites in the perimeter zone. In the transition zone, TSS, and pH were greater the western than the eastern side of the Refuge. The interior zone had lower ALK and SpC values and SO_4 concentrations than all other zones. Alkalinity, SpC, TDS, pH, and TB values correlated in negative curvilinear relationships with distance from the canal (r^2=0.78, 0.70, 0.61, 0.49, and 0.46, respectively) (Fig. 2a–e). Calcium, Cl, and SO_4 concentrations correlated in negative curvilinear relationships with distance from the canal (r^2=0.78, 0.57, and 0.64, respectively) (Fig. 2f–h). Dissolved organic carbon, DO, TOC, TSS, T, SI, and TP did not correlate with distance from the canal (r^2=0.24, 0.11, 0.20, 0.20, 0.09, 0.19, and 0.25, respectively) (data not shown). Alkalinity, pH, SpC, TB, and TDS values and Ca, and Cl, and SO_4 concentrations were 60–90% lower in the perimeter zone than in the canal zone. Alkalinity, SpC, and Ca and SO_4 concentrations were 5% to 7% higher in the perimeter than in the transition zone. Turbidity correlated with CSdepth (r^2=0.57) (data not shown).

4 Discussion

The difference in water quality between the eastern and western perimeter zones were not as apparent as between the east and west canals, suggesting that nutrient-limited vegetation is assimilating nutrients from canal water flowing into the Refuge marsh. The differences in vegetation density, shape of tree islands, and topography create different flow patterns in the east and

Fig. 2 **a**, **b** Plots of alkalinity (ALK) and conductivity (SpC) ▶ values in Refuge water with distance from the canal (in kilometers) and percent of the canal values with distance (*d*) from the canal (in kilometer) of the Loxahatachee National Wildlife Refuge, Boynton Beach, Florida. **a** r^2=0.78; ALK=5.250−0.8546×d+0.1024×d^2−0.0047d^3; n=947 taken at 40 sampling locations. **b**.r^2=0.70; SpC=6.649−0.9177×d+0.1439×d^2−0.0073×d^3; n=947 taken at 40 sampling locations. **c**, **d** Plots of the total dissolved solids (TDS) and hydrogen ion (pH) concentrations in Refuge water with distance from the canal (in kilometers) and percent of the canal values with distance (*d*) from the canal (in kilometers) of the Loxahatachee National Wildlife Refuge, Boynton Beach, Florida. **c** r^2=0.61; TDS=6.1981−0.8314×d+0.1428×d^2−0.0076×d^3; n=947 taken at 40 sampling locations. **d** r^2=0.49; pH=7.407−0.5285×d+0.09224×d^2−0.0052×d^3; n=947 taken at 40 sampling locations. **e**, **f** Plots of turbidity (TB) and (Ca) concentrations in Refuge water with distance from the canal (in kilometer) and percent of the canal values with distance (*d*) from the canal (in kilometer) of the Loxahatachee National Wildlife Refuge, Boynton Beach, Florida. **e** r^2=0.46; TB=1.5941−1.0324×d+0.0238×d^2−0.0148×d^3; n=947 taken at 40 sampling locations. **f** r^2=0.78; Ca=4.2250−1.0178×d+0.1594×d^2−0.0083×d^3; n=947 taken at 40 sampling locations. **e**, **f** Plots of chloride (Cl) and sulfate (SO_4) concentrations in Refuge water with distance from the canal (in kilometer) and percent of the canal values with distance (*d*) from the canal (in kilometer) of the Loxahatachee National Wildlife Refuge, Boynton Beach, Florida. **g** r^2=0.57; Cl=4.5937−0.8384×d+0.1437×d^2−0.0076×d^3; n=947 taken at 40 sampling locations. **h** r^2=0.64; SO_4=3.5264−1.7329×d+0.2895×d^2−0.0154×d^3; n=947 taken at 40 sampling locations



west sides of the Refuge. The western side of the Refuge was a part of the great sawgrass plain that covered the Everglades Agricultural Area, while the central and western Refuge had a tree island-dominated landscape.

Historically, the Refuge was oligotrophic and the vegetation was adapted to the low nutrient condition (Richardson et al. 1990; Miller and McPherson 2008). Along the western border of the Refuge marsh, expanding cattail vegetation, which can outcompete sawgrass under elevated nutrient conditions, may be responsible for the higher nutrient uptake capacity observed in these analyses. Cattails are known to thrive in nutrient-rich conditions (Miao et al 2000, 2001; Hagerthey et al. 2008; McCormick et al. 2009).

Distance from the canal towards the Refuge interior is the dominant factor explaining water quality in the Refuge marsh. The perimeter zone has been highly impacted with higher ALK, TDS, pH, and SpC values and Ca, Cl, Si, and SO_4 concentrations relative to the interior zone. The transition zone was moderately impacted by higher ALK and SpC values and Si and SO_4 concentrations relative to the interior zone. Calcium, SO_4, and Cl concentrations correlated in negative curvilinear relationships with distance from the canal towards the Refuge interior while TP concentrations in the Refuge did not, suggesting that excess inorganic P is quickly assimilated by nutrient-limited periphyton and plants. The Refuge has an exponential decrease in ALK, pH, SpC, TB, and TDS values and Ca, Cl, and SO_4 concentrations from the canal through the perimeter zone resulting in an approximately 60–90% reduction of the values found in the canal. The exponential decrease of these parameters and elements with distance from canal suggest that these relationships may be a result of canal water intrusion towards the Refuge interior with inorganic P being quickly assimilated by plants and algae in the northern Everglades system. Therefore, multiple water quality parameters are expected to provide increased clarity when assessing processes affecting the Refuge marsh. Patterns of ALK, TDS, SpC, and Cl reveal canal water intrusion into the Refuge interior which would be masked when monitoring only TP concentration in marsh water because macrophytes rapidly remove TP from the water column as to Ca, Cl, and Si which are much more slowly taken up than TP or N.

When combined with our understanding of the influence of the canal water intrusion into the marsh (Surratt et al. 2008; Harwell et al. 2008), these data show an impact of canal water containing high nutrient and cation concentrations on water quality flowing from the canal towards the Refuge interior. While rainfall and canal water movement influence the perimeter zone water chemistry, fluctuating exposure to nutrient and ion-enriched canal water conditions may be sufficient to alter the ecology of the marsh transition and interior zones (Childers et al. 2003; McCormick and Laing 2003; Gaiser et al. 2006). The perimeter zone, which is 20,932 ha^{-1}, comprises 37% of the Refuge, is highly impacted. The transition zone, which is an additional 13,314 ha^{-1} and comprises 24% of the Refuge, is moderately impacted. Thus, approximately 61% of the water in the Refuge is at least moderately impacted relative to the interior marsh. The interior zone may also be affected to an undefined lesser degree by loading from pumped inflows.

Total P in this oligotrophic ecosystem is quickly assimilated by primary producers (Noe et al. 2001; 2003; Childers et al. 2003; Gaiser 2009). One of the early physiological effects of P deficiency is a rerouting of primary metabolism and the accumulation of sugars in leaves. This rerouting increases the transport of sugars to the roots, which serves to increase the root to shoot biomass ratio and, with changes in hormone concentrations, modifies root morphology. These changes enable Everglade's plants to respond to P deficiencies by optimizing root morphology and increasing the assimilative capacity for minerals with low availability in the rhizosphere (Jayachandran and Shetty 2003). Alternatively, these changes in sugar routing mechanisms can offset the competitive advantage of plants adapted to soil P deficiency. This is evident in the transition of sawgrass communities to cattail communities that are adapted to higher soil P concentrations (Davis 1994; Miao et al 2000, 2001; Debusk et al. 2001; Asaeda and Hung 2007; Hagerthey et al. 2008; McCormick et al. 2009). Such a transition was the case for the western border of the Refuge marsh. Further, substantial ecological changes have been reported downstream of P sources in the Everglades ecosystem (McCormick et al. 1996; Cooper et al. 1999; Pan et al. 2000; Noe et al. 2001; Gaiser et al. 2005). Periphyton mats are a unique feature of the Everglades ecosystem contributing to a large portion of net primary production (Noe et al. 2003; Gaiser et al. 2004, 2006). In the Everglades ecosystem, increasing P and ion concentrations can ultimately decrease periphyton biomass (Davis 1994; McCormick and Stevenson 1998) and dramatically shift the periphyton community structure (Sklar et al. 2005; McCormick et al. 2009) ultimately impacting higher levels of flora and fauna.

All parameters except TB did not correlate with CWdepth or CSdepth, suggesting that water samples were collected in a manner that did not introduce sediment or plant-associated particles into the water column. Samples were not collected when water levels dropped below 20 cm. The relationship of TB with CSdepth may be a function of vertical mixing due to outgassing from peat decomposition (Kadlec and Knight 1996), thermal overturn occurring during diurnal heating and cooling, wind-induced turbulence causing vertical mixing (Schaffeanek and Jenter 2001), and/or vertical mixing caused by high energy rainfall (Kang and Trefry 2003). If these factors were exerting a substantial influence on the water column prior to sampling, they would most likely cause mixing visible detrital particles in the water column. A more thorough sampling of Refuge water with regard to zones and depth, both in the clear water column and in the floc layer, may be necessary to determine the influence of depth on elemental and particle concentrations in the water column.

5 Conclusions

- The canal receiving STA-1 West discharge had greater ALK and SpC values and Cl and SO_4 concentrations but lower TB and TSS values than the canal receiving STA-1 East discharge. However, only ALK differed between east and west sites in the perimeter zone.
- Continual canal water intrusion into the Refuge marsh has resulted in a highly impacted perimeter zone and a moderately impacted transition zone relative to the interior zone.
- The Refuge has an exponential decrease in ALK, pH, TDS, TB, and SpC values and Ca, Cl, and SO_4 concentrations from the canal through the interior zone.
- Distance from the canal towards the Refuge interior is the dominant factor explaining water quality in the Refuge marsh.
- Analysis of multiple water quality parameters provides advantages in assessing processes affecting wetlands. Patterns of ALK, TDS, SpC, and Cl may reveal the complexity of interactions that might be overlooked in a simple single parameter analysis. It is likely true in other wetland systems, monitoring networks that collect a suite of water quality parameters exhibit improved power to identify unknown or unexpected processes that are fundamental to the understanding of the ecosystem.

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