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The Efficacy of the Four-Part Test Network to Monitor Water Quality in the Loxahatchee National Wildlife Refuge

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Abstract The Loxahatchee National Wildlife Refuge (Refuge) is impacted by inflows containing elevated contaminant concentrations originating from agricultural and urban areas. Water quality was analyzed using the Enhanced Refuge (ERN), the four-part test (FPTN), and the Consent Decree (CDN) monitoring networks within four zones in the Refuge. The zones were defined as the canal surrounding the marsh, the perimeter, the transition, and the interior zones. Although regression coefficients for ALK and SpC, and Ca, Cl, and SO_4 concentrations with distance from the canal were lower using the FPTN than when using the ERN, using the FPTN to measure water quality parameters in the Refuge would give similar results as the ERN. Most of the ERN and FPTN sites are located in the northern and central areas of the Refuge. Water is deeper in the southern Refuge, and on an area basis contains a greater volume of water than the northern and central Refuge and therefore, water flow from the canal into the marsh in the northern and southern Refuge may differ. Numerous water quality monitoring sites must be added to the ERN and FPTN in the southern area to characterize water quality in the southern Refuge with confidence.

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1 Introduction

The Loxahatchee National Wildlife Refuge (Refuge) developed as a rainfall-driven system with surface waters low in nutrients and inorganic ions and therefore is low in conductivity. The Refuge, a 58,320 ha^{-1} remnant of the northern Everglades ecosystem is the last remaining soft-water wetland in the Everglades ecosystem (USFWS, 2000). The Refuge has been designated as an Outstanding Florida Waterbody (Florida Statute 403.061). Historically, rainfall and sheet flow were the primary source of water to the Refuge. The Refuge was part of the predrainage Everglades hydrology pattern which was a wide expanse of relatively shallow water moving downstream through a low-gradient wetland landscape (Harvey et al. 2005). Water flow was regionally uniform across a broad expanse with the absence of drainage channels. The flow discharged south and west and ultimately through the mangrove estuaries into the Gulf of Mexico (Harvey et al. 2005).

Areas of pristine marsh throughout the Everglades have been impacted to various degrees by intrusion of water with elevated nutrient and cation concentrations. Changes in total phosphorus (TP) and cations can cause undesirable ecological changes in the Everglades ecosystems (Childers et al. 2003; Davis et al. 2003; King et al. 2004). Nutrient- and ion-enriched waters intrude into the interior Refuge marsh (Surratt et al. 2008) and may cause ecosystem alterations such as sawgrass (*Cladium jamaicense* Crantz.) stands converted to cattail (*Typha domingensis* Pers.) (Debusk et al. 2001; Doren et al. 1997; Newman et al. 1997; Corstanje et al. 2006). In addition to elevated TP concentrations, canal water has high conductivity compared to the naturally low conductance marsh (Surratt et al. 2008). Canal water has intruded up to 5 km into the Refuge marsh as measured by conductivity (Harwell et al. 2008; Surratt et al. 2008; Entry 2012a).

There are presently three networks used to monitor water quality in the Refuge: the Consent Decree Network (CDN), the four-part test network (FPTN), and the Refuge's enhanced network (Enhanced Refuge Network, ERN). The14 Consent Decree monitoring sites, located in the Refuge, monitored monthly since 1978, were adopted as monitoring sites for the geometric mean of 10 mg TP L^{-1} water as stipulated in the 1992 Consent Decree ruling (Case No. 88-1886-CIV-HOEVELER; Case No. 88-1886-CIV-MORENO). The CDN consists of only 14 sampling sites to estimate water quality in the 58,320 ha Refuge marsh. At least half of the CDN sites are located towards the interior of the Refuge. The nearest CDN site is located 2.3 km from the STA1-East at the S362 outflow pump and 4.9 km from the STA1-West at the G-310 and G251 outflow pumps. In the northern Refuge, where stormwater is pumped into the Refuge, there are only three CDN sites within 2 km of the canal.

The State of Florida's Department of Environmental Protection (FDEP) implemented the four-part test in 2006 to comply with the Everglades Forever Act (EFA). The EFA [Section 373.4592, Florida Statutes (FS)] specifically states that waters flowing into a part of the remnant Everglades, which includes the Refuge, contain excessive phosphorus (P), and a reduction in TP concentrations will benefit the ecology of the Everglades. The EFA further directs the FDEP to develop a numeric TP criterion by numerically interpreting the existing Class III narrative criterion. The assessment methodology specified in the rule consists of the maintenance of a 5-year geometric mean TP concentration across a network of marsh sites and a series of three components intended to protect against localized or shorter-term imbalances in the natural flora and fauna, while allowing for natural temporal and spatial variability.

The State of Florida's four-part test as stated in (62-302.540 FAC, paragraph 4 b) divides the Refuge into impacted and unimpacted areas and specifies that water quality criterion be assessed separately in both portions of each area. The unimpacted sites are those with sediment TP concentrations less than 500 mg kg^{-1} and impacted sites with concentrations greater than 500 mg kg^{-1}. Unimpacted sites are also designated as those with a 5-year TP geometric mean, less than or equal to 10 μg TP L^{-1} and an annual geometric TP mean less than or equal to15 μg TP L^{-1}. The unimpacted sampling sites are the same 14 sampling sites used in the CDN, with an additional 20 sampling sites located in impacted areas (Payne et al. 2011). The following four components of the assessment test must be achieved for a water body to be considered to comply with the TP criterion (Fig. 1). To be in compliance with the four-part test, unimpacted sites must meet the following criteria: (1) water must meet an annual geometric TP mean of 10 μg L^{-1} or less when averaged across the monitoring network, (2) water must meet an annual geometric TP mean of 10 μg TP L^{-1} or less in 3 of 5 years when averaged across all stations, (3) water must meet an annual geometric TP mean of 11 ppb or less averaged across all stations, and (4) water measured at individual stations must meet an annual geometric TP mean of 15 μg TP L^{-1} or less (Payne et al. 2007).

In June 2004, the Refuge established the Enhanced Refuge Network (ERN), which consists of the 14 CDN sampling sites and 40 additional sites. Water collected using all three networks at all sites follow the exact same sampling protocols used for Consent Decree compliance. The 40 additional sites are mostly located along transects near STA discharges and other areas not monitored by the CDN to examine water quality gradients from the perimeter canals into the marsh interior. Entry (2012b) compared water quality using the Northern Refuge (NRN), the Southern Refuge (SRN), and the Northern Consent Decree (NCDN)

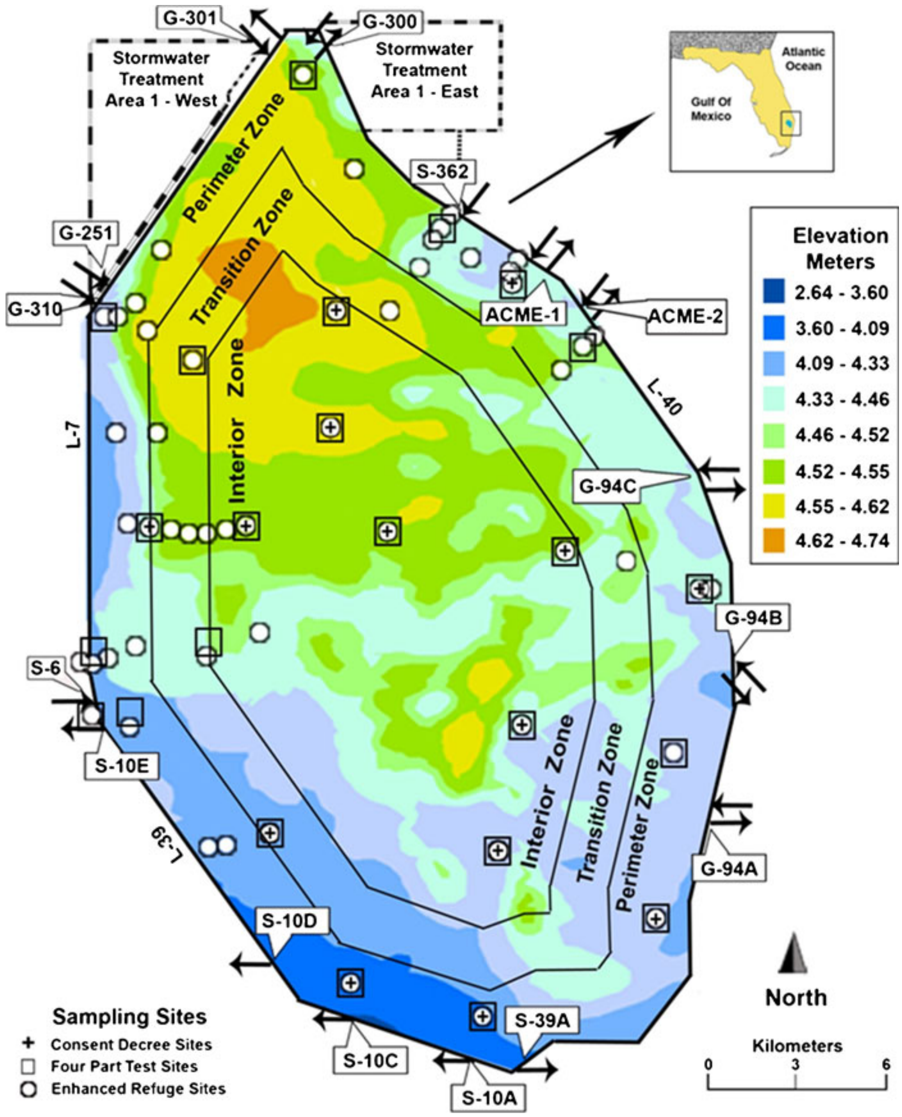

Fig. 1 Enhanced Refuge, Consent Decree, and four-part test water quality monitoring sites in the ARM Loxahatchee National Wildlife Refuge classified by zones (canal, perimeter, transition, and interior). Inflow sites are indicated by *arrows* pointing into the Refuge. Outflow sites are indicated by *arrows* pointing out of the Refuge. Elevation provided by USGS (2005)

monitoring networks using four zones in the Refuge as (1) the canal surrounding the marsh, (2) the perimeter zone (0 to 2.5 km into the marsh), the (3) transition zone (2.5 to 4.5 km into the marsh), and (4) the interior zone (>4.5 km into the marsh). In the NRN, ALK values and DO, DOC, TOC, TDS Ca, Cl, Si, SO_4, and TP concentrations were higher in the perimeter zone than when measured using the ERN than the CDN Entry (2012b). When measured using NRN, ALK and SpC values, and DO, DOC, TOC, TDS Ca, Cl, Si, SO_4, and TP concentrations measured in the interior zone did not differ than when these parameters were measured using the NCDN. There were insufficient sampling sites in the southern Refuge to compare water quality-monitored samples with the enhanced network to that sampled with the NCDN. The objectives of this research were: 1) to determine if water quality parameters as sampled by each network change over the sampling period, 2) to determine if water quality parameters differ among zones, and 3) determine the efficacy of ERN, FPTN, and CDN to assess water quality in the Refuge.

2 Material and Methods

2.1 The Site

Since the early 1960s, the Refuge marsh has been surrounded by constructed perimeter levees and associated canals encircling the Refuge on the interior side of the levees. Inflows are controlled by the South Florida Water Management District (SFWMD) and outflows by the US Army Corps of Engineers, the SFWMD, and local drainage districts (USFWS 2000). Prior to discharge into the canals surrounding the Refuge, most, but not all, inflows are first treated in large constructed wetlands termed stormwater treatment areas (STAs) (Fig. 1). Untreated water has been discharged to the northern Refuge but at a much lower rate and volume (USFWS 2007a; USFWS 2007b). STA-treated water is pumped into the L-40 canal on the eastern edge of the Refuge from STA-1 East and into the western L-7 from STA-1 West canal. These two canals are continuous with the L-39 canal forming a perimeter around Refuge marsh (Entry 2012a). Once in the canal, water generally flows southward and can be discharged downstream through the S-10A, S10-C, S-10-D, S10-E, and S-39 gates or G94A, G94B, and G94C gates. While flowing southward, canal water also can move into the marsh when water levels are high (>4.57 m) and inflow rates are moderate to high (>14.18 $m^3\ s^{-1}$) (Harwell et al. 2008; Surratt et al. 2008). Canal water containing elevated nutrient and mineral concentrations has intruded into pristine areas of the Refuge (Harwell et al. 2008; Surratt et al. 2008; Wang et al. 2009; Chang et al. 2009).

2.2 Marsh Zones and Delineations

Harwell et al. (2008) classified the Refuge into four separate zones based on surface water specific conductivity (SpC). 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 km to 4.5 km into the marsh, and the interior zone was comprised of sites located greater than 4.5 km into the marsh. Water quality in the Refuge was monitored using the ERN and FTPN (Payne et al. 2007) to more accurately measure water quality in the four zones than the CDN. In most months, the FTPN network is only sampled for TP; therefore, in order for the same parameters to be measured, several ERN sites were substituted for nearby FTPN sites.

2.3 Sample Collection

Surface water samples were collected monthly at 48 marsh and five canal sites from January 2005 through December 2009. Marsh sites were accessed by float helicopter and sampled by wading out into the marsh to collect 0.5 to 3 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); depth of clear water column (CWdepth); and depth to consolidated substrate (CSdepth) using a graduated meter stick (SFWMD 2006). All samples were taken, and all 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 allowing a full suite of chemical analyses to be performed. Samples were stored on ice at 4 °C, filtered, and preserved within 4 h of collection.

2.4 Laboratory Analysis

All samples collected for all three networks from January 2005 through May 2006 were analyzed by the SFWMD chemistry laboratory in West Palm Beach, Florida. Samples collected from January 2005 through December 2009 for the 14 CD network sites and the 14 CD network sites used in the FPTN were analyzed by SFWMD chemistry laboratory in West Palm Beach, Florida. Samples collected from June 2006 to December 2009 for the ERN were analyzed by Columbia Analytical Services (Jacksonville, FL). Alkalinity, as $CaCO_3$, was measured by titration with 0.02 N H_2SO_4 using the EPA 310.1 method described in APHA (2005). Total organic carbon (TOC) was determined by thermal combustion as described in the EPA 415.1 method. Dissolved organic carbon (DOC) and total dissolved solids (TDS) were measured in water passed through a 0.45-µm filter (APHA 2005). TDS was measured using thermal combustion. Turbidity was measured following the EPA 160.2 method (APHA 2005). 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). 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).

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 Si using an 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).

3 Statistical Analysis

3.1 Individual Networks

Only months with complete records for all parameters measured were analyzed. Data collected from each network was first analyzed separately. All data were subjected to a two-way general linear model (GLM) analysis (Snedecor and Cochran 1994; Kirk 1995) using Statistical Analysis Software programs (SAS Institute Inc 2008). Significance of treatment means was determined at $p \leq 0.05$ with the Least-Square Means test. After values were log-normal transformed, residuals were normally distributed with constant variance. In each network, treatments were zone, year, and month. In each network, statistical comparisons in the GLM showed that all parameters zone × year × month interactions were not significant at $p \leq 0.05$. Statistical comparisons in the GLM showed that all parameters zone × year were significant at $p \leq 0.05$. Therefore, in each network, results are discussed with respect to zone (canal, perimeter, transition, and interior) × year (2005 through 2009) (Snedecor and Cochran 1994; Kirk 1995). In the ERN, SRN, and CDNs, regressions were determined with distance from canal (Table 1) as independent (x) variables and relative to the natural log of all analyzed parameters as dependent (y) variables.

3.1.1 Comparison of Networks

Results obtained from the ERN, the FPTN, and the CDN were analyzed to compare water quality in each network with the four zones. In the northern Refuge, the efficacy of each network to characterize water quality could be compared because each network covers the exact same area of the Refuge. The ERN, FPTN, and CDN data were subjected to a two-way GLM analysis (Snedecor and Cochran 1994; Kirk 1995) using Statistical Analysis Software programs (SAS Institute Inc. 2008). Significance of treatment means was determined at $p \leq 0.05$ with the Least-Square Means test. After values were log-normal transformed, residuals were normally distributed with constant variance. Statistical comparisons in the GLM showed that all parameters' network by network × zone × year × month and network × zone × year interactions were not significant at $p \leq 0.05$. Statistical comparisons in the GLM showed that all parameters network × zone interactions were significant at $p \leq 0.05$. Therefore, results are discussed with respect to network (ERN, FPTN, and CDN) × zone differences (Snedecor and Cochran 1994; Kirk 1995).

4 Results

4.1 Individual Networks

4.1.1 Enhanced Refuge Network

Alkalinity, pH, SpC, and TB, and DOC, TDS, Ca, Cl, SO_4, and TP concentrations were higher in the canal than in the perimeter, transition, or interior zones (Table 1). Alkalinity and SpC, and DOC, TOC, TDS, Ca, Cl, and SO_4 concentrations were greater in the perimeter than in transition or interior zones. Alkalinity concentrations were greater in the transition than in interior zone. DO was greater than in the interior zone than in the perimeter or the transition zones. Alkalinity, TB, and SpC and Ca and SO_4 concentrations decreased in the canal and perimeter zones from 2005 through 2009. Only SpC and SO_4 concentrations decreased in the transition zone during the same period. Alkalinity, SpC, and pH had negative curvilinear relationships with distance from the canal (r^2=0.78, 0.67, and 0.45, respectively) (Figs. 2–7). Concentrations of Ca, SO_4, Cl, and TDS correlated in curvilinear relationships with distance from the canal (r^2=0.77, 0.64, 0.57, and 0.61, respectively). There is an exponential decrease in ALK, SpC, and pH, and TDS, Ca, Cl, and SO_4 concentrations from the canal to the perimeter zone resulting in a 60–80 % lower alkalinity, pH, TB, and SpC, and DOC, TOC, TDS, Ca, Cl, SO_4, and TP concentrations. Alkalinity, SpC, Ca, and SO_4 concentrations were lower in the interior than to the transition zone. Using the ERN, ALK, DOC, TDS, TSS, TB, and SpC, and Ca, Cl, Si,

Table 1 Mean annual alkalinity (ALK), pH, dissolved organic carbon (DOC), dissolved oxygen (DO), total organic carbon (TOC), total dissolved solids (TDS), suspended solids (TSS), turbidity (TB), and conductivity (SpC) in four zones in the Enhanced Refuge Network (ERN) in the Loxahatchee National Wildlife Refuge from 2005 through 2009

Zone	Year	ALK (mg L^{-1})	DOC (mg L^{-1})	DO (mg L^{-1})	TOC (mg L^{-1})	TDS (mg L^{-1})	TSS (mg L^{-1})	TB (FTU L^{-1})	pH	SpC (μS/cm^{-3})	Ca (mg L^{-1})	Cl (mg L^{-1})	Si (mg L^{-1})	SO_4 (mg L^{-1})	TP (mg L^{-1})
Canal	2005	212 a	29.6 a	3.75 b	30.1 a	540 a	7.02 a	7.27 a	7.50 a	847 a	75 a	108 a	17 a	46.25 a	0.150 a
	2006	227 a	30.6 a	4.23b	30.7 a	586 a	6.18 a	5.92 a	7.52 a	921 a	76 a	126 a	14 a	49.43 a	0.076 b
	2007	138 b	21.7 a	4.07 b	22.0 b	345 c	6.37 a	4.76 b	7.48 a	543 c	48 b	72 b	8 bc	23.77 b	0.057 b
	2008	142 b	23.7 a	4.20 b	23.8 b	354 c	4.22 b	2.50 c	7.46 a	570 c	47 b	76 b	10 b	24.19 b	0.032 b
	2009	167 b	28.1 a	5.00 a	28.5 a	458 b	6.75 a	3.60 c	7.55 a	737b	54 b	111a	12bc	32.86 b	0.034 c
Perimeter	2005	97 c	24.2 b	3.15 c	24.4 b	271 d	3.08 c	1.02 d	6.84 b	403 c	31 c	57 c	10 b	10.90 c	0.018 d
	2006	99 c	23.0 b	3.18 c	22.8 b	282 d	2.12 c	0.81 de	6.89 b	397 c	31 c	57 c	12 ab	12.22 c	0.011 e
	2007	72 d	22.2 b	3.15 c	22.5 b	216 e	3.08 c	1.07 d	6.83 b	295 d	23 d	41 d	11 b	5.02 cd	0.018 d
	2008	76 d	21.5 b	3.65 b	21.9 b	209 e	2.51 c	0.74 e	6.92 b	305 d	24 d	42 d	10 b	9.87 c	0.011 e
	2009	71 d	21.8 b	3.45 b	22.2 b	193 e	1.83 c	0.63 e	6.82 b	281 d	22 d	40 d	9 b	5.66 d	0.011 e
Transition	2005	31 e	17.8 c	3.91 b	18.2 c	114 f	7.62 a	1.03 d	6.65 b	140 e	10 e	22 e	5 c	1.02 e	0.014 e
	2006	30 e	18.5 c	4.05 b	18.5 c	121 f	2.56 c	0.71 e	6.47 b	144 e	11 e	26 e	8 bc	1.02 e	0.020 d
	2007	26 e	20.8 bc	4.30 b	20.8 c	111 f	2.06 c	0.67 e	6.84 b	122 f	8 e	19 e	10 a	0.35 f	0.014 e
	2008	22 e	18.8 c	4.47 b	19.4 bc	87 g	1.94 c	0.62 e	6.89 b	120 f	7 e	16 e	6 c	0.39 f	0.006 e
	2009	24 e	18.0 b	4.46 b	18.3 a	91 g	2.00 c	0.60 e	6.90 b	108 f	7 e	17 e	7 bc	0.19 f	0.007 e
Interior	2005	13 f	19.5 bc	5.19 a	19.8 bc	113f	8.99 a	1.59 d	6.30 c	111 f	6 e	22 e	5 c	0.21 f	0.010 e
	2006	15 f	25.0 a	5.19 a	25.0 a	129 e	1.60 c	0.80 e	6.36 c	135 f	7 e	28 e	5 c	0.18 f	0.009 e
	2007	11 f	21.1 b	4.93 a	21.0 b	105 e	1.76 c	0.75 e	6.19 c	101 f	5 e	20 e	4 c	0.09 g	0.010 e
	2008	15 f	18.9 b	5.03 a	19. 5 bc	99 g	2.14 c	0.88 e	6.43 c	125 f	5 e	20 e	4 c	0.05 g	0.008 e
	2009	19 f	21.7 b	4.80 a	21.4 b	98 g	2.06 c	0.86 e	6.44 c	116 f	6 e	20 e	5 c	0.02 g	0.010 e

In each column, values followed by the same letter are not significantly different as determined by the least-square means test ($p \leq 0.05$; $n \geq 58$)

FTU formazin turbidity unit

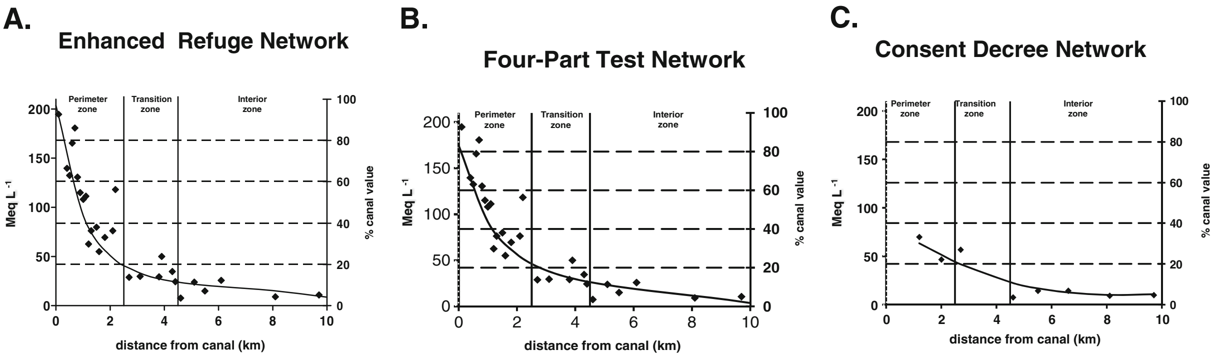

Fig. 2 Plots of alkalinity (ALK) measurements in Refuge water with distance from the canal (kilometer) and percentage of the canal values with distance (d) from the canal (kilometer) as determined at the Enhanced Refuge Network. **b** Four-Part Test Network and **c** Consent Decree Network in the Loxahatchee National Wildlife Refuge. **a** Enhanced Refuge Network $r^2=0.78$, $ALK=5.204-0.939\times d+0.126\times d^2-0.006d^3$ n=1,195 taken at 40 sampling locations; **b** Four-Part Test Network $r^2=0.72$, $ALK=5.193-0.939\times d+0.121\times d^2-0.006d^3$; $p\leq0.05$; n=814 samples taken at 24 sampling locations; **c** Consent Decree Network $r^2=0.72$, $ALK=4.516-0.348\times d-0.008\times d^2+0.003d^3$; $p\leq0.05$; n=499; samples taken at 14 sampling locations

SO_4, and TP concentrations decreased and DO increased from 2005 through 2009 in the canal (Table 1). The ALK, TDS, TB, and SpC, and Ca, Cl, Si, SO_4, and TP concentrations decreased from 2005 through 2009 in the perimeter zone; TDS, TSS, TB, and SpC and SO_4 and TP concentrations decreased in the transition zone; TDS, TSS, and TB, and SO_4 concentrations decreased from 2005 through 2009 in the interior zone.

4.1.2 Four-Part Test Network

Alkalinity, TDS, and SpC, and Ca, Cl, and SO_4 concentrations were higher in the perimeter than in the transition or interior zones (Table 2). Alkalinity and the SO_4 concentration were greater in the transition than in the interior zone. DO was greater than in the interior and transition zones than the perimeter zone. Alkalinity, TDS, and SpC, and Ca, Cl, SO_4, and TP concentrations decreased in the perimeter zone from 2005 through 2009. Alkalinity, TDS, and SpC, and Ca and SO_4 concentrations decreased in the transition zone during the same period. Alkalinity and SpC had negative curvilinear relationships with distance from the canal (r^2=0.72, 0.54, respectively) (Figs. 2–5). Calcium, Cl, and SO_4 concentrations

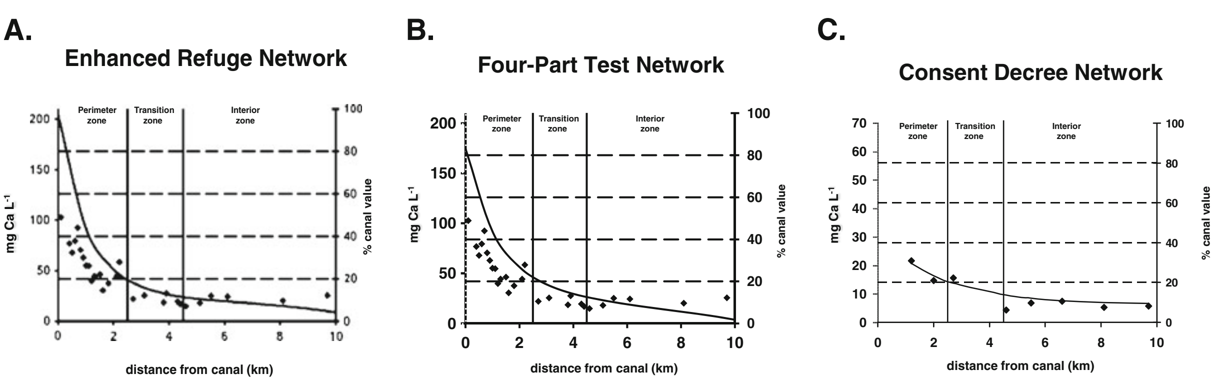

Fig. 3 Plots of calcium (Ca) concentrations in Refuge water with distance from the canal (kilometer) and percentage of the canal values with distance (d) from the canal (kilometer) determined at the **a** Enhanced Refuge Network, **b** Four-Part Test Network, and **c** Consent Decree Network in the Loxahatchee National Wildlife Refuge. **a** Enhanced Refuge Network $r^2=0.77$, $Ca=4.139-1.037\times d+0.162\times d^2-0.008\times d^3$; $p\leq0.05$; n=1,195, samples taken at 40 locations; **b** Four-Part Test Network $r^2=0.68$, $Ca=4.188-1.094\times d+0.178\times d^2-0.009\times d^3$; $p\leq0.05$; n=814; samples taken at 24 locations; **c** Consent Decree Network $r^2=0.63$, $Ca=3.585-0.564\times d+0.064\times d^2-0.002\times d^3$; $p\leq0.05$; n=499; samples taken at 14 locations

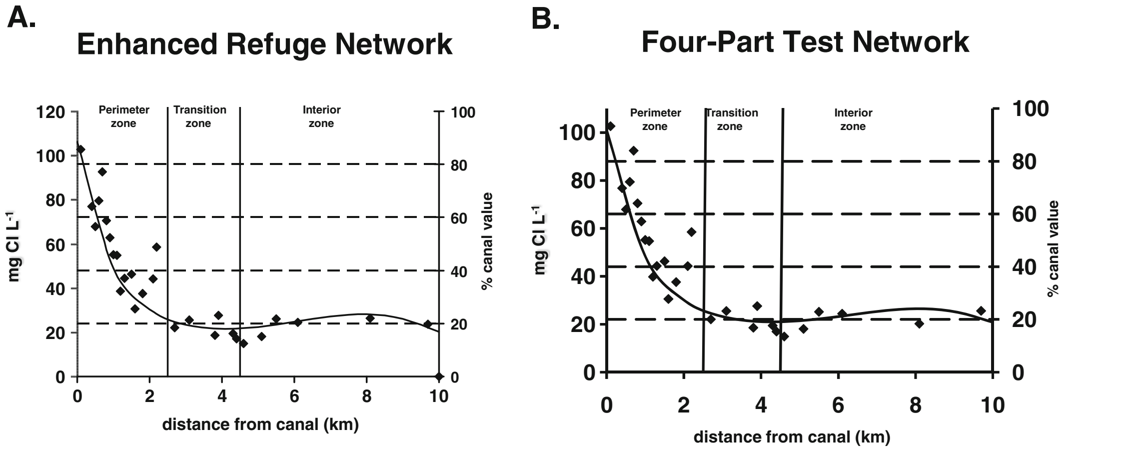

Fig. 4 Plots of (Cl),chloride concentration in Refuge water with distance (d) from the canal (kilometer) and percentage of the canal values with distance from the canal (kilometer) in the **a** Enhanced Refuge Network in the Loxahatchee National Wildlife Refuge. **a** Chloride r^2=0.57, Cl=4.585−0.994×d+0.185×d^2−0.010×d^3; $p \leq 0.05$; n=1,195, samples taken at 40 locations; **b** Four-Part Test Network r^2=0.40, Cl=4.519−0.888×d+0.158×d^2−0.009×d^3; $p \leq 0.05$; n=814; samples taken at 24 locations

correlated in curvilinear relationships with distance from the canal (r^2=0.68, 0.40, and 0.50, respectively) (Figs. 3, 4 and 6). There is an exponential decrease in ALK and SpC, and Ca, Cl, and SO_4 concentrations near canal to 2.5 km into the Refuge marsh resulting in a 60–80 % lower ALK and SpC, and Ca, Cl, and SO_4 and concentrations. Alkalinity, SpC, and Ca, and SO_4 concentrations were lower in the interior than in the transition zone.

4.1.3 Consent Decree Network

Alkalinity and SpC, and TDS and SO_4 concentrations were higher in the perimeter than the transition zones (Table 3). Alkalinity and SO_4 concentrations were higher in the transition zone than the interior zone. Alkalinity, TDS, SpC, and SO_4 concentrations decreased in the perimeter and transition zones from 2005 through 2009. Only ALK and SO_4 concentrations decreased in the interior zone during the same period.

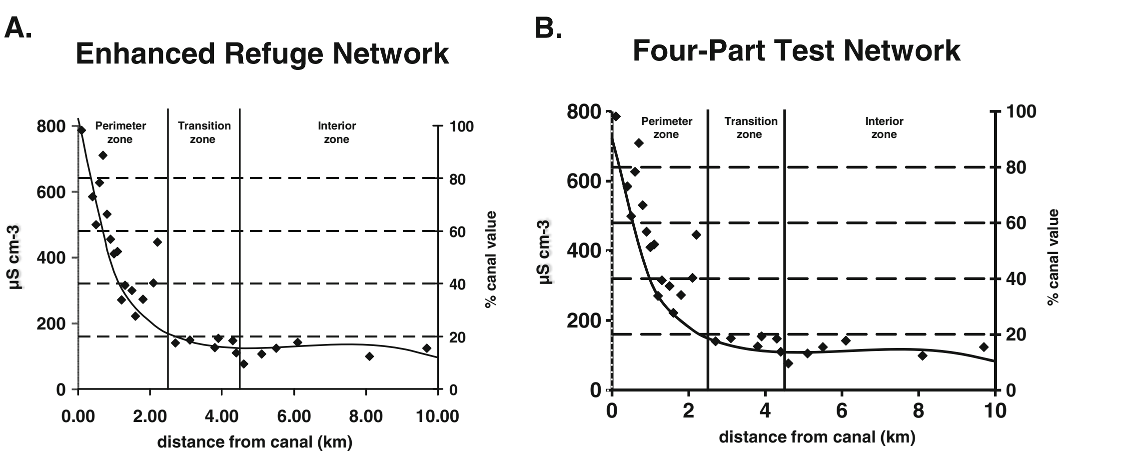

Fig. 5 Plots of conductivity (SpC) in Refuge water with distance (d) from the canal (kilometer) and percentage of the canal values with distance from the canal (kilometer) in the **a** Enhanced Refuge Network in the Loxahatchee National Wildlife Refuge. Conductivity **a** r^2=0.67, SpC=6.606−1.038×d+0.182×d^2−0.010×d^3; $p \leq 0.05$; n=1,195, samples taken at 40 locations; **b** Four-Part Test Network r^2=0.54, SpC=6,582−0.989×d+0.167×d^2−0.009×d^3; $p \leq 0.05$; n=814, samples taken at 24 locations

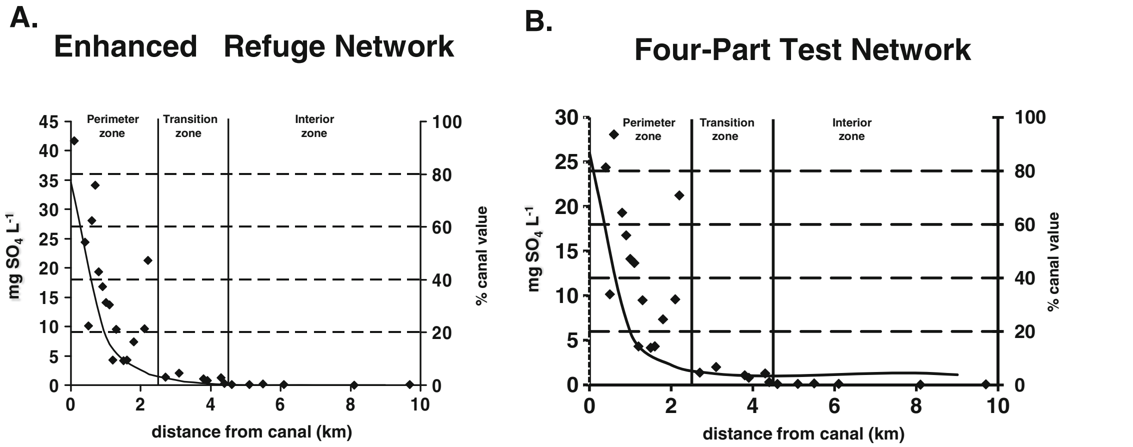

Fig. 6 Plots of the sulfate (SO_4) concentration in Refuge water with distance from the canal (kilometer) and percentage of the canal values with distance (d) from the canal (kilometer) in the **a** Enhanced Refuge Network r^2=0.61, $SO_4=3.3716-1.8288\times d+0.3261\times d^2-0.0182\times d^3$; $p\leq0.05$; n=814; samples taken at 54 locations. **b** Four-Part Test r^2=0.50, $SO_4=3.259-1.780\times d+0.312\times d^2-0.0170\times d^3$; $p\leq0.05$; n=814; samples taken at 24 locations

Samples from the CDN show that only ALK and Ca correlated with distance from the canal (r^2=0.72 and 0.63, respectively). Distance from canal accounted for less of the variability for all parameters using the CDN. In the CDN, SpC and SO_4 concentrations decreased from 2005 through 2009 in the perimeter and transition zones but not the interior zone. Alkalinity, TDS, and TSS decreased from 2005 through 2009 in the transition but not the perimeter and interior zones. Alkalinity, TDS, and SpC, and Ca, Cl, and SO_4 concentrations decreased from 2005 through 2009 in the perimeter zone. Alkalinity, TDS, SpC and Ca, and SO_4 concentrations decreased from 2005 through 2009 in the transition zone; the SO_4 concentration decreased from 2005 through 2009 in the interior zone.

4.2 Comparison of the Enhanced, Four-Part Test, and Consent Decree Networks

In the perimeter zone, there were no significant differences in any water quality parameter measures when using the ERN as compared to the FPTN. In the

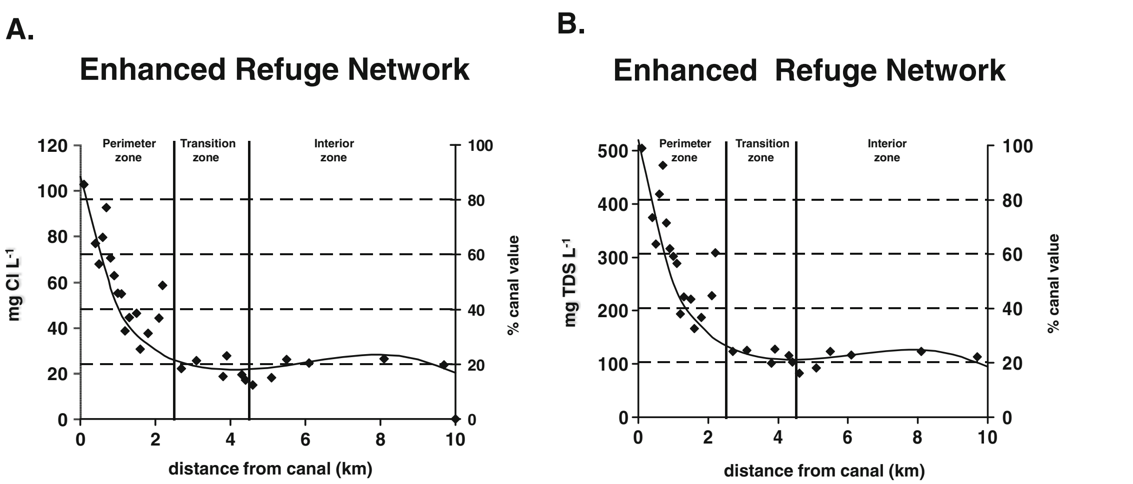

Fig. 7 Plots of **a** pH and **b** total dissolved solids (TDS) in Refuge water with distance (d) from the canal (kilometer) and percentage of the canal values with distance from the canal (kilometer) in the Enhanced Refuge Network in the Loxahatchee National Wildlife Refuge. **a** pH r^2=0.45, pH=$7.429-0.562\times d+0.109\times d^2-0.007\times d^3$; $p\leq0.05$; n=1,195; samples taken at 54 locations; **b** total dissolved solids r^2=0.61, TDS=$6.133-0.880\times d+0.157\times d^2-0.008\times d^3$; $p\leq0.05$; n=1,195; samples taken at 54 locations

Table 2 Mean annual alkalinity (ALK), pH, dissolved organic carbon (DOC), dissolved oxygen (DO), total organic carbon (TOC), total dissolved solids (TDS), suspended solids (TSS), turbidity (TB), and conductivity (SpC) in four zones determined using the four-part test Network (FTPN) in the Loxahatchee National Wildlife Refuge from 2005 through 2009

Zone	Year	ALK (mg L^{-1})	DOC (mg L^{-1})	DO (mg L^{-1})	TOC (mg L^{-1})	TDS (mg L^{-1})	TSS (mg L^{-1})	TB (FTU L^{-1})	pH	SpC (μS/cm^{-3})	Ca (mg L^{-1})	Cl (mg L^{-1})	Si (mg L^{-1})	SO_4 (mg L^{-1})	TP (mg L^{-1})
Perimeter	2005	103 a	23.5 a	3.14 c	23.9 a	274 a	2.59 a	0.94 a	6.85 a	414 a	33 a	57 a	10 a	11.71 a	0.018 a
	2006	106 a	23.1 a	3.67 c	23.2 a	295 a	2.03 a	0.76 a	6.94 a	437 a	34 a	62 a	10 a	13.89 a	0.016 a
	2007	74 b	21.3 a	3.42 c	21.6 a	218 b	3.26 a	1.08 a	6.84 a	298 b	24 b	42 b	9 a	5.14 b	0.012 b
	2008	76 b	20.7 ab	3.06 c	21.1 a	209 b	2.80 a	0.74 a	6.86 a	301 b	24 b	42 b	9 a	7.01 b	0.012 b
	2009	70 b	21.1 a	3.36 c	22.1 a	197 b	1.96 a	0.66 a	6.73 a	296 b	23 b	42 b	9 a	6.70 b	0.011 b
Transition	2005	44 c	17.3 b	5.05 a	17.5 a	122 c	2.75 a	1.16 a	6.79 a	173 c	13 c	25 c	6 a	1.13 c	0.014 ab
	2006	43 c	17.9 b	4.35 b	18.0 a	137 c	2.41 a	0.65 a	6.61 a	180 c	12 c	28 c	10 a	0.90 c	0.020 a
	2007	30 d	20.2 ab	4.56 b	20.4 a	121 c	2.04a	0.73 a	6.76 a	135 d	9 d	21 c	8 a	0.59 d	0.009 b
	2008	25 d	17.4 b	4.57 b	18.5 a	94 d	2.16 a	0.62 a	6.70 a	138 d	7 d	17 c	7 a	0.31 d	0.007 b
	2009	31 d	17.6 b	4.07 b	17.6 a	99 d	2.09 a	0.72 a	6.83 a	131 d	9 d	19 c	8 a	0.20 de	0.008 b
Interior	2005	11 e	19.4 ab	5.01 a	19.8 a	110 d	1.78 a	0.92 a	6.22 a	105 e	6 d	21 c	4 b	0.16 e	0.008 b
	2006	15 e	23.4 a	5.02 a	23.4 a	121 c	1.60 a	0.79 a	6.30 a	127 d	8 d	26 c	4 b	0.12 e	0.009 b
	2007	11 e	19.6 b	5.09 a	19.7 a	105 d	1.65 a	0.74 a	6.19 a	98 e	6 d	19 c	3 b	0.06 f	0.008 b
	2008	13 e	18.3 b	4.59 b	18.6 a	98 d	2.19 a	0.89 a	6.39 a	190 c	5 d	20 c	4 b	0.04 f	0.008 b
	2009	15 e	22.2 ab	3.94 b	22.0 a	101 d	2.06 a	0.87 a	6.27 a	119 e	6 d	20 c	5 b	0.01 f	0.008 b

In each column, values followed by the same letter are not significantly different as determined by the least-square means test ($p \leq 0.05$; $n \geq 12$)

FTU formazin turbidity unit

Table 3 Mean annual alkalinity (ALK), pH, dissolved organic carbon (DOC), dissolved oxygen (DO), total organic carbon (TOC), total dissolved solids (TDS), suspended solids (TSS), turbidity (TB), and conductivity (SpC) in four zones determined at the Consent Decree Network (CDN) in the Loxahatchee National Wildlife Refuge from 2005 through 2009

Zone	Year	ALK (mg L^{-1})	DOC (mg L^{-1})	DO (mg L^{-1})	TOC (mg L^{-1})	TDS (mg L^{-1})	TSS (mg L^{-1})	TB (FTU L^{-1})	pH	SpC (μS/cm^{-3})	Ca (mg L^{-1})	Cl (mg L^{-1})	Si (mg L^{-1})	SO_4 (mg L^{-1})	TP (mg L^{-1})
Perimeter	2005	65 a	19.1 a	4.33 a	19.4 a	184 a	1.87 a	0.62 a	6.83 a	271 a	20 a	39 a	6 a	3.93 a	0.008 a
	2006	74 a	19.8 a	4.55 a	19.7 a	210 a	1.64 a	0.58 a	6.90 a	300 a	22 a	44 a	6 a	5.59 a	0.008 a
	2007	59 b	18.0 a	4.29 a	18.5 a	189 a	1.64 a	0.61 a	6.82 a	243 b	19 a	36 a	7 a	3.54 a	0.008 a
	2008	49 b	17.3 a	3.96 a	17.3 a	158 b	2.27 a	0.67 a	6.76 a	215 b	16 b	29 b	6 a	3.47 a	0.008 a
	2009	57 b	19.8 a	3.50 a	17.6 a	171 b	2.04 a	0.64 a	6.62 a	258 b	19 b	36 a	8 a	5.82 a	0.008 a
Transition	2005	53 b	16.4 a	5.63 a	16.5 a	135 b	1.60 a	0.60 a	6.95 a	201 b	14 b	28 b	7 a	1.24 b	0.008 a
	2006	56 b	17.2 a	4.70 b	17.2 a	147 b	1.60 a	0.58 a	6.89 a	209 b	15 b	30 b	9 a	1.00 b	0.007 a
	2007	43 b	17.6 a	4.81 b	17.6 a	149 b	1.60 a	0.73 a	6.77 a	174 bc	13 b	26 b	6 a	0.77 c	0.008 a
	2008	31 c	14.1 a	4.48 b	14.0 a	100 c	2.24 a	0.62 a	6.75 a	126 c	9 c	22 b	5 a	0.28 d	0.007 a
	2009	34 c	16.1 a	4.04 a	16.0 a	99 c	2.06 a	0.78 a	6.70 a	149 c	10 c	20 b	6 a	0.20 d	0.010 a
Interior	2005	11 d	19.4 a	5.01 a	19.8 a	110 c	1.78 a	0.92 a	6.22 b	105 c	6 c	21 b	4 a	0.16 e	0.008 a
	2006	15 d	23.4 a	5.02 a	23.4 a	121 c	1.60 a	0.79 a	6.30 b	127 c	8 c	26 b	4 a	0.12 e	0.009 a
	2007	12 d	19.6 a	5.09 a	19.7 a	105 c	1.64 a	0.74 a	6.19 b	98 c	6 c	19 b	3 a	0.06 f	0.008 a
	2008	13 d	18.3 a	4.59 a	18.6 a	98 c	2.19 a	0.87 a	6.39 b	90 c	5 c	20 b	4 a	0.04 f	0.008 a
	2009	15 d	22.1 a	3.95 a	21.9 a	101 c	2.06 a	0.87 a	6.27 b	119 c	6 c	20 b	5 a	0.01 f	0.008 a

In each column, values followed by the same letter are not significantly different as determined by the least-square means test ($p \leq 0.05$; $n \geq 23$)

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interior zone, TSS and SpC were greater when using the ERN as compared to the FPTN (Table 4). In the perimeter zone, ALK, SpC, and TB, and DOC, TSS, TDS Ca, Cl, Si, SO_4, and TP concentrations were higher and the DO value was lower when using the ERN and FPTN as compared to the CDN. In the interior zone, TSS and SpC values were higher when using the ERN and FPTN as compared to the CDN.

5 Discussion

5.1 Enhanced Refuge Network

The data suggest that the perimeter zone has been highly impacted with substantially elevated ALK, pH, and SpC, and DOC, TOC, TDS, Ca, Cl, Si, and SO_4 concentrations relative to the interior zone. The transition zone is moderately impacted by higher ALK and SpC values and Si and SO_4 concentrations relative to the interior zone. Alkalinity, SpC, TDS, Ca, Cl, and SO_4 concentrations all decreased in negative curvilinear relationships with distance from the canal toward the Refuge interior, while TP concentrations in the Refuge did not, suggesting that excess inorganic N and P are quickly assimilated by nutrient-limited periphyton and plants. The Refuge has an exponential decrease in ALK, SpC, and TDS, and Ca, Cl, and SO_4 concentrations from the canal through the perimeter zone resulting in an approximately 80 % reduction of these relative to the values found in the canal. The exponential decrease in ALK, SpC, TDS, Ca, Cl, and SO_4 with distance from canal suggests that these relationships may be a result of canal water intrusion towards the Refuge interior with inorganic N and P being quickly assimilated by plants and algae in the northern Everglades system. TP in this oligotrophic ecosystem is quickly assimilated by primary producers (Noe et al. 2001; 2003; Childers et al. 2003). Sawgrass communities will transition to cattail communities, which are adapted to higher soil P concentrations (Miao et al, 2000; 2001; Debusk et al. 2001; Asaeda and Hung 2007; Hagerthey et al. 2008; McCormick et al. 2009). 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

Table 4 Mean alkalinity (ALK), pH, dissolved organic carbon (DOC), dissolved oxygen (DO), total organic carbon (TOC), total dissolved solids (TDS), suspended solids (TSS), turbidity (TB), conductivity (SpC) and temperature (T) in two zones among the Enhanced Refuge Network, (ERN), four-part test network (FPTN) and Consent Decree Network (CDN) in the Loxahatchee National Wildlife Refuge from 2005 through 2009

Network	Zone	ALK b (mg L^{-1})	DOC (mg L^{-1})	DO (mg L^{-1})	TOC (mg L^{-1})	TDS (mg L^{-1})	TSS (FTU L^{-1})	TB (FTU L^{-1})	pH	SpC (µS/cm^{-1})	Ca (mg L^{-1})	Cl (mg L^{-1})	Si (mg L^{-1})	SO_4 (mg L^{-1})	TP (mg L^{-1})
ERN	Perimeter	90 a	23.2 a	3.06 c	23.6 a	252 a	2.68 a	0.94 a	6.87 a	366 a	29 a	50 a	11 a	11.01 a	0.018 a
FPTN	Perimeter	89 a	22.3 a	3.13 c	22.7 ab	247 a	2.64 a	0.91 a	6.84 a	362 a	29a	50 a	10 a	10.55 a	0.016 a
CDN	Perimeter	61 b	18.9 b	4.04 b	19.1 b	186 b	2.05 b	0.67 b	6.78 a	263 b	20 b	37 b	7 b	5.33 b	0.007 b
ERN	Interior	16 c	20.7 b	5.10 a	20.9 b	108 c	3.83 a	1.06 a	6.38 b	120 c	6 c	22 c	4 c	0.12 c	0.010 b
FPTN	Interior	13 c	20.5 b	4.84 a	20.7 b	107 c	2.17 b	0.89 a	6.31 b	197 b	6 c	21 c	4 c	0.82 c	0.009 b
CDN	Interior	11 c	20.5 b	4.84 a	20.7 b	107 c	2.17 b	0.89 a	6.31 b	196 b	6 c	21 c	4 c	0.11 c	0.008 b

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 are presented with regard to network×zone ($p \geq 0.05$; $n \geq 202$)

There are no sampling sites in the canal or transition zones in the Consent Decree Network (CDN); there are no sampling sites in the canal zone in the four-part test network (FPTN)

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to a large portion of net primary production (Noe et al. 2003; Gaiser et al. 2004; Gaiser et al. 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 (McCormick et al. 2009; Sklar et al. 2005), ultimately impacting higher levels of flora and fauna.

5.2 Four-Part Test Network

The FPTN showed similar, but not as thorough, water quality patterns as the ERN. The FPTN showed that the perimeter zone has been highly impacted with substantially elevated ALK, SpC and DOC, TDS, Ca, Cl, Si, and SO_4 concentrations relative to the interior zone. As with the ERN, the FPTN data indicate that the transition zone is moderately impacted by higher ALK and SpC values and Si and SO_4 concentrations relative to the interior zone. As with the ERN, the FPTN shows that the Refuge has an exponential decrease in ALK and SpC, and Ca, Cl, and SO_4 concentrations from the canal through the perimeter zone resulting in an approximately 80 % reduction of these relative to the values found in the canal. Unlike the ERN, the FPTN did not show that TDS values correlated with distance from the canal. The regression coefficients showing the exponential decrease in ALK and SpC, and Ca, Cl, and SO_4 concentrations with distance from the canal were lower using the FPTN than when using the ERN. The FPTN also showed that ALK, TDS and SpC, and Ca, Cl and SO_4 concentrations decreased from 2005 through 2009 in the perimeter zone. Unlike the ERN, the FTPN showed that the TP concentration decreased from 2005 through 2009 in the perimeter zone. As with the ERN, the FTPN showed that ALK, TDS, and SpC, and Ca and SO_4 concentrations decreased from 2005 through 2009 in the transition zone and SO_4 concentration decreased from 2005 through 2009 in the interior zone. In the perimeter zone, there was no statistical difference in any water quality parameter measured when using the FPTN than when using the ERN. In the transition zone, TSS values were lower and SpC values were higher when using the FPTN than when using the ERN. Entry (2012c) found similar results using trend analysis. Although the trends were not significant in every analysis, nutrient and inorganic ion, SpC, and ALK trends were negative in all zones on an annual basis and both the wet and dry seasons indicating that the concentration of these nutrients and inorganic ions in Refuge water has generally decreased over the past 7 years. Inorganic ion slopes were more negative in the more nutrient-enriched canal and perimeter zones than the less nutrient-enriched transition and interior zones. These results indicate that nutrient and ion concentrations in Refuge water have decreased more rapidly in the more nutrient-enriched zones near the canal than the less nutrient-enriched zones and that nutrients have been cycling more rapidly in the more enriched zones than in the less enriched zones (Entry 2012c).

Although regression coefficients for ALK and SpC, and Ca, Cl, and SO_4 concentrations with distance from the canal were lower using the FPTN than when using the ERN, and using the FPTN to measure water quality parameters in the Refuge would give similar results as the ERN. However, the southern Refuge has only 11 water quality sites, which provides insufficient data to characterize Refuge water quality with any confidence (Entry 2012b). In addition, most of the ERN and FTPN sites are located in the northern and central areas of the Refuge. Water is deeper in the southern Refuge and, on an area basis, contains a greater volume of water than the southern and central Refuge and therefore, water flow from the canal into the marsh in the northern and southern Refuge may differ (Entry 2012b). Canal water should become diluted and dispersed more rapidly when intruding into the southern Refuge because it is intruding into a greater volume of nutrient-poor water than when intruding into the northern Refuge (Entry, 2012b). Numerous water quality monitoring sites must be added to the ERN and FPTN in the southern area to characterize water quality in the southern Refuge with confidence.

5.3 Consent Decree Monitoring Network

I found a greater number of water quality parameters were statistically different using the ERN and SRN as compared to the same parameters analyzed using the CDN. Samples from the CD network show that only ALK and Ca correlate with distance from the canal (r^2=0.72 and 0.63, respectively). Distance from canal accounted for less of the variability for all parameters measured as part of the 14-site CD network. The Consent Decree authors adopted the 14-site network for compliance because these sites had a long-term sampling history. However, scientists established these sites to measure water quality in the Refuge marsh; the sites were not intended to be used for water quality compliance with a legal decision. The location and sparseness of CDN water quality monitoring sites suggests the network is inadequate to accurately characterize water quality in the Refuge and should be improved.

5.4 Comparison of Water Quality Monitoring Networks

The average area and volume of water at the sites were calculated in the ERN, and FPTN and CDN were used to estimate water quality. The average area characterized per site in each network area was determined by dividing the area in each network by the number of sampling sites. The average water volume characterized per site in each network was estimated by multiplying the average depth at the time of sampling by the average area in each sampling network.

In the ERN, there are 54 sampling sites used to determine water quality for an average area of 56,079 ha. When these sites were sampled, the average depth to consolidated substrate was 0.62 m; therefore, each sampling site estimates water quality for an average water volume of 6,439 ML. In the FPTN, there are 24 sampling sites used to determine water quality for an average area of 56,079 ha. The average water depth was 0.59 m when these sites were sampled. Therefore, each sampling site estimates water quality for an average water volume of 13,693 ML. In the CDN, there are 14 sites used to estimate water quality for the entire Refuge with an average area of 56,079 ha. The average water depth when these sites were sampled was 0.59 m; therefore, each sampling site estimates an average of 24,543 ML Refuge water. The average volume of water represented by each site in the CDN is nearly four times greater than the average volume of water represented by each site in the ERN and is nearly double the average volume of water represented by each site in the FTPN. Since 2006, at least ten additional sites have been added to the FTPN (Payne et al. 2011); therefore, the FTPN analyzed in 2011 have results more similar to the ERN.

In the Everglades ecosystem, the inadequate number and location of site monitoring in the CDN and FTPN have been unnecessarily complicated due to excess on legal negotiations (Case No. 88-1886-CIV-Hoeveler; Case No. 88-1886-CIV-MORENO). Sampling locations of a water quality monitoring network should be based on the objectives of the network, water flow pattern, and speed, water quality parameters necessary to make the desired ecological decisions (Strobl et al. 2006a; 2006b; Park et al. 2006; Strobl and Robillard 2008). Monitoring the Refuge with the ERN and FPTN has shown that the perimeter zone is highly impacted and the transition zone moderately impacted by apparent canal water intrusion. The ERN and FPTN networks showed that the ALK and SpC values, and Ca, Cl, and SO_4 concentrations decreased in the canal, perimeter, transition, and interior zones. One cannot make many of the necessary monitoring water quality assessments using the CDN because of the sparseness and location of these sites, which is at least 2.3 km from the contaminant source (canals). The 14 sampling sites used for Consent Decree compliance were adopted because TP was historically sampled at these sites. The Consent Decree, Appendix B, # 3 states that “Monitoring shall be implemented to identify the variation (temporal and spatial) in biological and water quality parameters along transects in the WCAs, Park and Refuge originating at the major surface water inflow points and continuing along flow gradients” (Case No. 88-1886-CIV-HOEVELER; Case No. 88-1886-CIV-MORENO). While water quality parameters are more accurately characterized using the ERN, it is not used to determine compliance. The Everglades is an ologotrphic ecosystem and phosphorus is rapidly removed from marsh water by periphyton and macrophytes. When the water level in the canal is higher than the water level in the Refuge marsh, canal water containing elevated concentrations of nutrients will move toward the Refuge interior (Surratt et al. 2008). Nutrients, especially TP, are rapidly removed by periphyton and higher vegetation, effectively filtering them out of the intruding canal water creating the highly impacted perimeter and moderately impacted transition zones (Entry 2012a). TP concentration did not correlate with distance from the canal toward the Refuge interior; however, it was approximately 80 % less in the perimeter zone than the canal and from 26 to 45 % less in the transition zone than the perimeter zone (Entry 2012a; 2012b). The CDN sites are an average of 4.1 km from the canal. Results show that 60–80 % of the ALK, SpC, TB, TDS, Ca, Cl, Si, SO_4, and TP are removed in the first 2.6 km from the canal (Entry 2012a). This may be the reason why, using the CDN, there have only been four instances since 2004 when the monthly network average geometric mean of TP measured at 14 Consent Decree sites (CDN) has exceeded 10 μg L^{-1}. As much 37 % of the Refuge may be highly impacted and an additional 24 % of the Refuge may be moderately impacted due to excessive TP loading from STA inflow (Entry 2012a; 2012b).

To improve compliance with the Consent Decree, the number and placement of sampling sites in marsh monitoring network in the Refuge, and possibly the entire Everglades ecosystem, may require optimization based on flow pattern and distance from the contaminant source. Comparison of the ERN and FPTN with the CDN shows that in the Refuge, the CDN lacks a sufficient number of sites to characterize the Refuge's perimeter and possibly the transition zones. Although the FTPN characterizes water quality nearly as well as the ERN, further study of the efficacy of the number and placement of FPTN monitoring sites is necessary before the network can be shown to characterize Refuge water quality for four-part test compliance. These results show that the number and placement of CDN, and possibly the FPTN monitoring sites, are inadequate to characterize water quality in the Refuge. It is imperative that the number and placement of sampling sites in the Refuge should be based on flow pattern, distance from canal, and volume rather than professional judgment and legal negotiation.

Water Conservation Area 2 (WCA-2) marsh is 54,027 ha and is sampled at 21 monitoring sites resulting in each site characterizing water quality for 2,573 ha. Water Conservation Area 3 (WCA-3) marsh is 237,152 ha^{-2} and is sampled at 23 sites resulting in each site characterizing water quality for 10,311 ha. Everglades National Park is 557,280 ha and is sampled at ten inflow and 11 marsh monitoring sites resulting in each marsh monitoring site to characterize water quality for 55,728 ha. Ecosystem structure and function in WCA-2 (DeBusk et al. 2001; Noe et al. 2001; 2003; Hagerthey et al. 2008; Rutchey et al. 2008; McCormick et al. 2009), in WCA-3 (Noe et al. 2001; 2003; Bruland et al. 2006; 2007) and in small, but important, areas of Everglades National Park (Gaiser 2009; Gaiser et al. 2006; 2004; Childers et al. 2003) has been altered due to excessive hydrologic manipulation and nutrient loading. There are large areas in the entire Everglades ecosystem that lack sampling sites to adequately assess water quality. It is especially important to sample areas where urban or agricultural water pumped in to the Everglades ecosystem has created steep water quality and nutrient gradients.

Managers are currently using adaptive resource management to restore Everglades ecosystem and monitoring water quality is crucial to this process. Adaptive resource management requires an objective for evaluating alternative management strategies, predictive models of system dynamics, a finite set of alternative management actions, and a rigorous monitoring program to follow the system's response to management (Dorazio and Johnson 2003). Uncertainty in adaptive management can arise from errors in measurement and sampling of ecological systems, environmental variability, or incomplete knowledge of system behavior (Williams 1996). Managers will be unable to adapt their management strategy if they are unable to detect changes in ecosystem response. By implementing an inadequate monitoring system, Everglades managers are inviting, at the least, reduced management performance and, at the worst, catastrophic environmental damage (Entry 2012b). Hydrologic manipulation and nutrient loading have dramatically altered the ecosystem structure and function throughout large areas of the Everglades. It is necessary to reexamine the Consent Decree and the four-part test monitoring networks in the entire Everglades ecosystem.

6 Conclusions

Using the FPTN to measure water quality parameters in the Refuge would give similar results as the ERN. Most of the ERN and FPTN sites are located in the northern and central areas of the Refuge. Water is deeper in the southern Refuge and on an area basis, contains a greater volume of water than the northern and central Refuge; therefore, water flow from the canal into the marsh in the northern and southern Refuge may differ. Numerous water quality monitoring sites must be added to the ERN and FPTN in the southern area to characterize water quality in the southern Refuge with confidence. Managers are currently using adaptive resource management to restore Everglades ecosystem and monitoring water quality is crucial to this process. By implementing an inadequate monitoring system, managers are inviting, at the least, reduced management performance and, at the worst, catastrophic environmental damage. It is necessary to reexamine the Consent Decree and the four-part test monitoring network in the entire Everglades ecosystem.

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