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Spatial and temporal phosphorus distribution changes in a large wetland ecosystem

Xavier Zapata-Rios,[1,2] Rosanna G. Rivero,[1,3] Ghinwa M. Naja,[1] and Pierre Goovaerts[4]

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[1] Long- and short-term changes in the spatial distribution of surface water phosphorus concentrations were assessed for the Everglades wetland (USA) from 12 years of monitoring data. Changes in phosphorus spatial distributions, before and after implementation of measures to reduce phosphorus, including stormwater treatment areas (STAs) and best management practices (BMPs), were used to evaluate the effect of the remediation strategies in the naturally oligotrophic wetland. Results showed a clear spatial and temporal gradient in phosphorus concentrations, with highest total phosphorus (TP) reaching 200 μg/L in the northern Water Conservation Areas (WCAs) because of canal inflow from the Everglades Agricultural Area (EAA). Long-term records of TP concentrations from 1995 to 2007 showed declines in Water Conservation Area WCA1 during the dry season (-5.1%). Short-term changes (2003–2007) showed increasing trends in TP concentrations elsewhere in the Everglades, mainly in the southern areas: WCA3 and Everglades National Park (ENP). From 2003 to 2007, phosphorus increased by 7.4% per year in the ENP during the dry season. The area of the Everglades that exceeded the 10 μg/L surface water TP concentration ecological threshold was quantified and showed a long-term overall decline. However, except for the ENP, more than 65% of the Everglades surface area exceeded the 10 μg/L water quality threshold in 2007. During recent years, ENP and WCA3 surface areas that exceeded the alternative 15 μg/L annual geometric mean slightly increased, confirming the need to closely monitor these two regions.

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1. Introduction

[2] During the last decades, nutrient loading to surface waters has increased dramatically because of agricultural intensification and urban development [*Lemly et al.*, 2000; *Blann et al.*, 2009]. Freshwater natural wetlands that generally function as filters and retain nutrients, are increasingly threatened by high-nutrient fluxes [*Brinson and Malvarez*, 2002; *Gibbs*, 2001; *Reddy and Delaune*, 2008]. Algal and plant communities in nutrient-enriched wetlands shift in species composition, thus altering the food web dynamics [*Engelhardt and Ritchie*, 2001; *Craft et al.*, 2007].

[3] One example of these threatened ecosystems is the Everglades, a major freshwater wetland located in south Florida, and a historically phosphorus (P) limited system characterized by a limited microbial and plant productivity and decomposition. The 12,000 km^2 of Everglades marshes south of Lake Okeechobee were drained and developed and only 6,000 km^2 remain in the natural state [*Lodge*, 2010]. Eutrophication from anthropogenic nutrient enrichment is a primary threat to the oligotrophic Everglades [*Noe et al.*, 2001]. High P levels originating from the Everglades Agricultural Area (EAA; Figure 1) cause imbalances in the flora and fauna natural populations [*Richardson et al.*, 2007]. Periphyton mats loss and plant community have shifted from sawgrass to cattails due to elevated P levels [*Childers et al.*, 2003; *Gaiser et al.*, 2006]. In 1992, significant efforts were made to manage nutrient runoffs and loads from the EAA down gradient into the larger Everglades area. Six stormwater treatment areas (STAs) were built (with a total effective treatment surface area of 167 km^2) to remove P from EAA runoff water before it flowed into the four major compartments of the greater Everglades (Water Conservation Areas (WCAs) 1, 2, and 3 and the Everglades National Park (ENP)) [*Walker*, 1995; *Juston and DeBusk*, 2006]. The overall objective has been to reach a long-term regulatory geometric mean of 10 μg/L of P in surface waters in WCAs and the ENP [*National Research Council* (*NRC*), 2010].

[4] Several authors mapped the historical and spatial changes of P in Everglades soils but very few attempted to map phosphorus changes in surface water because of the higher variability [*Bruland et al.*, 2007]. For example, *DeBusk et al.* [2001] used a geotemporal analysis to evaluate temporal changes in the spatial extent and patterns of soil P enrichment in WCA-2A showing that 73% of the total land area of WCA-2A could be considered P enriched in 1998, compared with

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[1] Science Department, Everglades Foundation, Palmetto Bay, Florida, USA.

[2] Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA.

[3] College of Environment and Design, University of Georgia, Athens, Georgia, USA.

[4] BioMedware, Inc., Ann Arbor, Michigan, USA.

Corresponding author: R. G. Rivero, College of Environment and Design, University of Georgia, 206 Tanner Bldg., Athens, GA 30603, USA. (rrivero@uga.edu)

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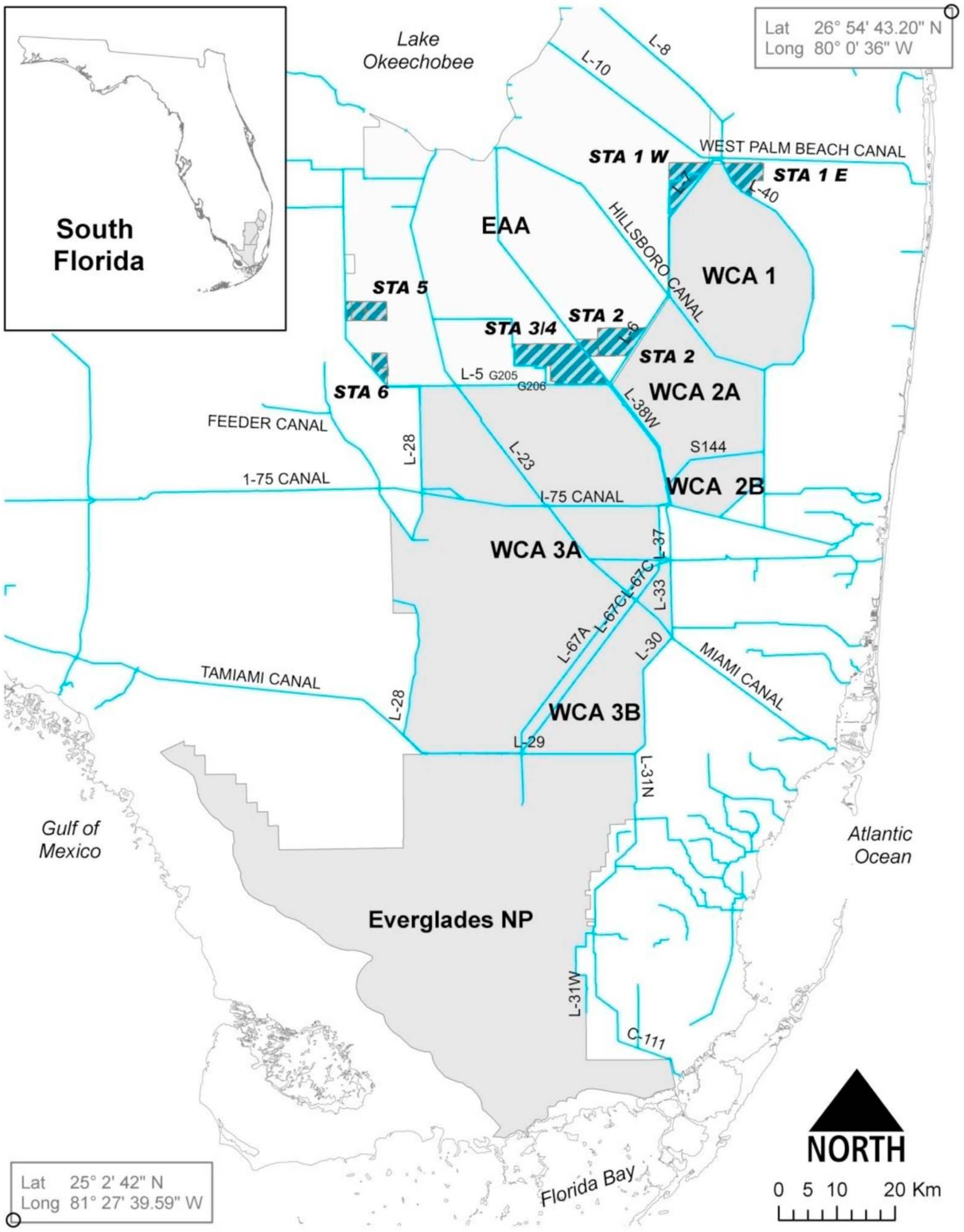

Figure 1. Study area location. EAA, Everglades Agricultural Area; WCA, Water Conservation Areas; STA, stormwater treatment areas; L, levees; C, canals.

only 48% of the land area in 1990. *Grunwald et al.* [2008] used a fuzzy temporal trajectory analysis to map floc and soil P as well as the pedopatterns within WCA-2A. *Scheidt and Kalla* [2007] showed that 27.2 ± 7.5% of the Everglades surface area had a Total Phosphorus (TP) concentration in waters exceeding the 10 μg/L level during the 2005 dry season, decreasing from 57.8 ± 7.8% value observed during the 1995 dry season.

[5] The objective of our paper is to explore temporal and spatial phosphorus changes in surface water in the greater Everglades. To do this, we compiled a database to create maps and assess spatial and temporal distribution changes of surface water TP in the Everglades. Geostatistics, Geographic Information System (GIS) map algebra techniques, and interpolated raster maps were used to quantify the spatial distribution changes (1985–2007) of surface water TP. The main goal was to determine whether the surface water quality has improved since 1985. The work amounted to (1) creating a database compiling the scattered phosphorus data collected by various agencies (state, federal, universities, etc.) involved in the Everglades and (2) mapping the obtained data through time and across the greater Everglades.

2. Methods

2.1. Study Area

[6] We assembled water quality data in the Water Conservation Areas (WCA1, 2 and 3) and in the Everglades National

Park (ENP) from 1985 to 2007 during the wet and dry seasons. Figure 1 indicates the location of these four compartments in south Florida as well as the location of the stormwater treatment areas (STAs) and the main canals and levees. Because of P enrichment impacting the Everglades and the water degradation implications, STAs were built north of the WCAs to improve the water quality and fix phosphorus before flowing into the Everglades. The construction of these STAs was completed in 2004 for STA1E, 1999 for STA1W, 2000 for STA2, 2004 for STA3/4, 1999 for STA5 and 1998 for STA6. The water flowing into WCA1 (590 km^2) is mainly from rain and from the P enriched surrounding canals. WCA2 (547 km^2) is receiving water discharged from WCA1 and from the EAA runoff. WCA3 (2,330 km^2) is receiving water from WCA2, EAA runoff and through the L-28 canal. The Everglades National Park (5,929 km^2) receives its majority of water from WCA3. Depending on the selected year, water flowing into the WCAs could have been filtered and partially treated for phosphorus removal through the STAs.

2.2. Database Compilation

[7] A data mining outreach was first done to identify agencies and researchers working on water sampling and phosphorus analysis in the Everglades. The received databases were sorted for site, date and sample type before compiling an overall database containing water quality and other important parameters (location, matrix, units) assembled from different agencies and projects, namely the Florida Coastal Everglades Long Term Ecological Research Project (FCE-LTER), the Regional Environmental Monitoring and Assessment Project (REMAP) phases I, II and III, the U.S. Geological Survey (USGS), the DBHYDRO database from the South Florida Water Management District (SFWMD), the STORET database from the Florida Department of Environmental Protection (FDEP) and the Arthur R. Marshall Loxahatchee National Wildlife Refuge Enhanced Water Quality Monitoring and Modeling project. The data from all these different sources were merged, column headings standardized and data converted in a single format for comparison purposes. The merged database was then checked for some common problems such as incompatible units for TP concentrations and lack of spatial coordinates or inconsistencies in locations for some samples. The compiled database contained both continuous and discontinuous data since some stations had a time series of monthly TP concentrations, other stations presented data with a discontinuous sampling scheme and others were collected only once.

[8] Microsoft Excel and Microsoft Access were used to merge the databases and to average yearly TP concentrations for the dry (November through April) and wet (May to October) seasons from 1985 to 2007. Based on the samples spatial distribution, the years selected for the geostatistical analysis were 1995, 1999, 2003 and 2007.

2.3. Spatial and Temporal Phosphorus Distribution Analysis

[9] A sub–data set summary was created for TP in surface water by averaging the values per season, year and location. Observations were then imported into ArcGIS 9.0 for an exploratory data analysis that included testing for normality and skewness. If necessary a log transformation was applied to symmetrize the sample histograms. The Kolmogorov-Smirnov (KS) test was employed to assess the distributions normality before and after the log transformation using EasyFit Professional Version 5.5 (MathWave Technologies). This non parametric test is generally used to evaluate the differences between two data sets and is based on the largest vertical difference between the theoretical and the empirical cumulative distribution functions. The hypothesis regarding the distributional form is rejected at a chosen significance level (in this case, 0.05) if KS is greater than the critical value obtained from a table (MathWave Technologies).

[10] A geostatistical analysis was conducted using SpaceStat version 2.0 [*BioMedware, Inc.*, 2011]. Omnidirectional semivariograms were first computed to describe the spatial distribution of TP in water. These semivariograms measure the dissimilarity between data separated by a distance h (lag size) following

$$\gamma(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(\mathbf{h})} [z(u_\alpha) - z(u_\alpha + h)]^2 \qquad (1)$$

where N(h) is the number of pairs of observations ($z(u_\alpha)$, $z(u_\alpha + h)$), collected at locations u_α and $u_\alpha + h$ separated by vector h.

[11] The semivariogram construction and modeling followed standard procedures extensively described by *Isaaks and Srivastava* [1989] and *Goovaerts* [1997]. Different lag sizes were tried and the semivariograms were modeled using an interactive weighted least squares fitting procedure implemented in SpaceStat 2.0.

[12] Semivariogram models were used with ordinary kriging to map the spatial distribution of TP concentrations in surface water. This interpolation technique has been widely applied for modeling landscape features in south Florida wetlands [*Corstanje et al.*, 2006; *Grunwald et al.*, 2006; *Rivero et al.*, 2007]. Ordinary kriging estimates the attribute of interest (e.g., TP concentration) at unsampled locations u using a linear combination of neighboring observations following

$$z^*_{OK}(u) = \sum_{\alpha=1}^{n(\mathbf{u})} \lambda_\alpha^{OK}(u) z(u_\alpha) \qquad (2)$$

[13] The locations u were here identified with the nodes of a 100 m spacing grid. The weight $\lambda_\alpha^{OK}(u)$ assigned to each observation $z(u_\alpha)$ takes into account the proximity of these observations to the grid node u, the spatial arrangement of these observations (data configuration) and the spatial structure of the phenomenon as modeled by the semivariogram. The kriging weights $\lambda_\alpha^{OK}(u)$ are the solution of a system of linear equations that ensures that the kriging estimator is unbiased and the variance of prediction errors is minimal. A complete explanation of the kriging approach can be found in textbooks, such as *Isaaks and Srivastava* [1989] or *Goovaerts* [1997].

[14] A cross validation analysis was performed to assess the accuracy and bias of the predictions. Each observation was removed at a time and reestimated using the remaining observations. Observed and predicted values were then compared and the errors were calculated following equations (3) and (4). The prediction accuracy increases as the mean absolute error (MAE) and the root-mean-square error (RMSE) decreases. Additional indicators of the robustness of the

predictions were established by estimating the mean standardized prediction error (MSE) and the root-mean standardized prediction error (RMSSE), following equations (5) and (6). Kriging errors were normalized at the cross validation points by subtracting the kriged estimate from the measurement and dividing the result by the kriging standard deviation. The obtained normalized residuals would have a mean around zero (if the kriging estimate is truly unbiased) and a standard deviation of 1 (if the sill and correlation parameters estimated for the experimental semivariograms are valid).

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left[z(u_i) - z^*(u_i)\right] \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[z(u_i) - z^*(u_i)\right]^2} \tag{4}$$

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n}\left[z(u_i) - z^*(u_i)\right]/\hat{\sigma}(u_i)}{n} \tag{5}$$

$$\mathrm{RMSSE} = \frac{\sqrt{\sum_{i=1}^{n}\left[\left[z(u_i) - z^*(u_i)\right]/\hat{\sigma}(u_i)\right]^2}}{n} \tag{6}$$

[15] The log predicted values were back transformed using the empirical procedure described in *Goovaerts et al.* [2005] for normal scores and implemented in SpaceStat2.0. The final surface water TP concentration maps were drawn using a color legend with nine categories of TP concentrations: 0–10, 10–20, 20–30, 30–40, 40–50, 50–100, 100–150, 150–200, and >200 μg/L. Changes in surface water TP concentration during the four selected years (1995, 1999, 2003 and 2007) were estimated using map algebra in ArcGIS. The same software was used for the model output visualization. Surface areas corresponding to TP concentrations higher than 10 μg/L and 15 μg/L were also estimated.

[16] Density of measurements, particularly with respect to the size of the 100 m estimation grid and the estimated range, were computed based on the total area and number of samples in each area. Moreover the Point Distance Analysis in ArcGIS was used to quantitatively assess the Euclidean distance between all sampled points in each area.

[17] A wilcoxon signed rank test was conducted to quantitatively assess the long- and short-term TP level changes at specific sampling locations (ENP and WCAs, during the wet and dry seasons) and on the average values reported in Table 1. The wilcoxon nonparametric test (no particular data distribution assumptions are made) is generally used to compare samples and measurements before and after an operational change and employed to detect trends for water quality time series data. In the present work, this test was used to verify the statistical significance of the long-term and short-term trends in the time series of TP during the wet and dry seasons at the ENP and WCAs. Short-term (2003–2007) and long-term (1995–2007) trends were analyzed to distinguish temporal changes that occurred recently (mostly after STAs construction and operation) or over longer periods (pre- and post-STAs operation). Additional to the average values reported in Table 1, specific sampling locations where continuous monitoring was conducted since 1995 were selected for this analysis. The number of these sampling locations (n) was 13, 15, 6 and 15 for the short-term analysis and 9, 15, 6, 12 for the long-term analysis, for the ENP, WCA1, WCA2 and WCA3, respectively (including the average values presented in Table 1). The trend percentage was also calculated following equation (7).

[18] For example, the short-term wet season trend in WCA1 was calculated using the 2003 and 2007 (wet season) TP data series (TP_{2003}i and TP'_{2007}i) as follows:

$$\frac{\sum_{i=1}^{n}\frac{TP'_{2007i} - TP_{2003i}}{TP'_{2007i}}}{n} \tag{7}$$

where TP_{2003}i and TP'_{2007}i are the TP levels in WCA1 during 2003 and 2007 wet seasons at the specific location (i) and n-1 is the total number of continuous sampling locations (WCA1, short-term analysis, n = 15). One additional data point representing the average value reported in Table 1 was added to the analysis. The wilcoxon statistical test was then applied to the two data series (TP_{2003} and TP'_{2007}) to calculate the p value. The same methodology was then used to calculate the trend and p values during the dry seasons of 2003 and 2007.

2.4. Water Levels and Ground Elevation Data

[19] Water level data were collected from 226 stage gages within WCAs and ENP. The daily mean water level data collected for the years 1995, 1999, 2003 and 2007 were obtained from DBHYDRO (http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu) and EDEN databases (http://sofia.usgs.gov/eden/stationlist.php). Water level data were converted from feet to meters, tabulated in Excel and the seasonal (wet and dry seasons) means calculated for each station for the above years. Geographical coordinates available in National Geodetic Vertical Datum of 1929 (NGVD 29) were converted to the North American Vertical Datum of 1988 (NAVD 88). Ground elevation data were downloaded from the U.S. Geological Survey (USGS) Everglades Depth Estimation Network (EDEN) digital elevation model (DEM) (http://sofia.usgs.gov/eden/models/groundelevmod.php). The original 400 m spacing grid was later interpolated to a 100 m spacing grid using ArcGIS.

2.4.1. Spatial Distribution of Water Level

[20] Seasonal water level means for each station with NAVD 88 geographical coordinates were imported into ArcGIS 10. WCAs and ENP were divided into seven sections bounded by L29, L35B, L38W, and L39 canals. Grids (100 m spacing) were overlaid on each section and the water level was interpolated to each grid node using the radial basis function (RBF) of the multiquadratic methodology implemented in the ArcGIS geostatistical analyst. The RBF exact interpolation technique used a multiquadratic parameter (kernel function) of 16.77, a shape type of 8 sectors and an angle of 350 [*Pearlstine et al.*, 2007]. The water depth was then obtained by subtracting the water surface elevation

Table 1. Summary Statistics for the Surface Water Total Phosphorus (TP) Concentration (μg/L) Measured During the Dry and Wet Seasons of 1995, 1999, 2003, and 2007 for the Everglades National Park (ENP) and the Water Conservation Areas (WCAs)[a]

	1995		1999		2003		2007	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
ENP								
N samples	98	107	62	89	52	56	67	49
Mean	17.6	10.46	18.64	12.55	8.54	8.57	17.89	11.65
Standard deviation	22.67	6.88	27.47	4.55	4.18	4.9	29.91	11.58
Minimum	1.7	1	2.97	2.2	1.21	1.02	3	1.6
Median	8	8.7	10.87	13.54	8.39	6.75	10	7.33
Maximum	139.1	35.4	191.48	25.05	19	25.44	182	56.4
Skewness	3.45	1.77	4.45	−0.11	0.22	0.94	4.03	2.41
Kurtosis	14.77	3.57	23.81	−0.21	−0.63	0.93	17.05	5.87
KS normality value BT	0.4382	0.1487	0.43321	0.09781	0.4382	0.1487	0.42795	0.24537
KS normality value AT	0.5249	0.09991	0.52988	0.1712	0.53439	0.09069	0.52895	0.10045
CV at 0.05	0.13469	0.13128	0.16823	0.14195	0.13469	0.13128	0.16204	0.19028
Test rejected BT	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Test rejected AT	Yes	No	Yes	No	Yes	No	Yes	No
WCA3								
N samples	153	137	87	113	61	66	109	69
Mean	25.79	18.7	32.47	26.03	20.1	21.04	22.81	19.41
Standard deviation	20.95	28.41	40.78	34.45	14.24	24.97	24.39	13.16
Minimum	2.9	2.5	1.26	5.2	3.5	3.55	4	5
Median	23.9	9.78	17.57	17.4	14.58	13.89	15	15.94
Maximum	144.5	250.2	266.08	270.43	75.67	181	182	74.49
Skewness	2.65	5.54	3.47	5.41	1.42	4.27	4.1	2.04
Kurtosis	11.69	36.85	14.19	32.6	2.4	23.74	21.2	4.64
KS normality value BT	0.28424	0.28428	0.2363	0.31214	0.18617	0.26057	0.22345	0.17977
KS normality value AT	0.10702	0.10808	0.07662	0.15183	0.12305	0.10967	0.09381	0.09224
CV at 0.05	0.10979	0.11602	0.14355	0.12775	0.17091	0.16443	0.13007	0.16088
Test rejected BT	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Test rejected AT	No	No	No	No	No	No	No	No
WCA2								
N samples	75	71	75	72	30	30	40	41
Mean	34.62	29.25	33.98	28.96	28.3	25.94	16.74	17.36
Standard deviation	23.9	28.01	23.28	27.91	13.97	18.7	12.19	9.84
Minimum	5.3	2.3	5	2.3	4.97	3.82	6	5
Median	30.5	14.1	28.7	14.1	26.2	21.48	14.34	17.5
Maximum	101.67	93.63	94.71	93.63	60	81.2	62.3	43.25
Skewness	0.82	1.11	0.69	1.13	0.2	1.48	1.93	0.6
Kurtosis	0.09	−0.11	−0.32	−0.06	−0.46	1.88	4.06	−0.16
KS normality value BT	0.14849	0.23688	0.13933	0.23862	0.10398	0.1881	0.18894	0.13088
KS normality value AT	0.09514	0.13691	0.10633	0.14181	0.18599	0.13591	0.12959	0.13454
CV at 0.05	0.15442	0.15864	0.15442	0.15755	0.2417	0.2417	0.21012	0.2076
Test rejected BT	No	Yes	No	Yes	No	No	No	No
Test rejected AT	No	No	No	No	No	No	No	No
WCA1								
N samples	80	77	47	44	42	36	109	78
Mean	43.08	32.25	62.78	71.35	60.39	50.02	21.38	29.64
Standard deviation	51.57	38.76	55.23	88.89	76.8	44.87	23.4	36.51
Minimum	4.79	4.6	9.4	6.17	4.93	5.3	1.87	2.2
Median	24.25	7.5	29.15	57.49	34.19	38.5	8.4	10.78
Maximum	281	136.48	201.5	419.25	436	144.73	121	170.8
Skewness	2.7	1.21	0.75	2.7	2.93	0.61	1.59	1.7
Kurtosis	9.14	0.02	−0.75	7.8	11.57	−0.95	2.23	2.17
KS normality value BT	0.26749	0.26749	0.23936	0.1216	0.23511	0.2012	0.26365	0.29683
KS normality value AT	0.09345	0.15244	0.14883	0.17446	0.14834	0.18822	0.16989	0.16989
CV at 0.05	0.1496	0.1829	0.1942	0.20056	0.20517	0.22119	0.13007	0.15147
Test rejected BT	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Test rejected AT	No	No	No	No	No	No	Yes	Yes

[a] KS, Kolgomorov-Smirnov; BT, before transformation; AT, after log transformation; CV at 0.05, critical value at a confidence level of 0.05.

grid, interpolated per season and per year, from the DEM grid using the ArcGIS raster calculator tool.

2.4.2. Water Depth and Total Phosphorus Correlation

[21] A total of 16 rasters (eight for TP and eight for water depth, per season and per year) were consolidated and the correlation matrices were calculated for the 16 data sets, using the Band Collection Statistic and the principal component analysis (PCA) of ArcGIS multivariate tools. This calculation was conducted considering the entire ecosystem

and for each individual compartment (WCAs and ENP) to account for potential variations.

3. Results and Discussions

3.1. Database Compilation

[22] The compiled phosphorus database contains 361,000 records distributed geographically (WCAs and ENP) and temporally (year and season). Table 1 presents the 1995, 1999, 2003, and 2007 seasonal statistical summary of surface water TP concentrations in WCAs and ENP. The mean TP values were generally higher during the dry season and decreased from north (WCA1) to south (ENP). A general decrease of the mean TP values in WCA2 during the dry and wet seasons was observed. In the case of WCA1 and WCA3, the mean TP values increased between 1995 and 1999 and slightly decreased from 1999 onward. For the ENP, an increase in TP concentrations was observed between 1995 and 1999, followed by a decrease in TP levels until 2003 and then followed by an increase in TP levels from 2003 onward. From 1995 to 2007, the ENP, WCA3, WCA2 and WCA1 registered minimum and maximum TP values of 1.02–191.48, 1.26–270.43, 2.30–101.67, and 1.87–436 μg/L, respectively.

[23] The TP spatial variability, quantified using the standard deviation, was the lowest in the ENP followed by WCA3 and WCA2. TP levels in WCA1 presented the highest TP variability. Most data sets in Table 1 had a positively skewed histogram and thus underwent a logarithmic transformation. Additional results from the Kilmogorov-Smirnof (KS) normality test are also shown in Table 1.

[24] When comparing KS normality values with critical values (CV) at a confidence level of 0.05 the hypothesis of normality was not rejected, confirming the need for a logarithmic transformation. Exceptions were the ENP 1999 wet, ENP 2003 dry and WCA2 2003 dry seasons where a transformation was not considered necessary. Table 1 indicates that normality was not achieved for WCA1 (2007) and ENP dry seasons, the latter due to the presence of areas of higher concentrations (>10 μg/L) along Tamiami Trail (coming from northern canals), even more accentuated during the first 2 years of the analysis (1995 and 1999), in contrast with the southern part of the system. These results indicate the need of the area stratification for future analyses in the ENP.

3.2. Geostatistical Analysis

[25] Table 2 lists the experimental semivariogram and fitted model parameters for WCAs and ENP, displaying a similar pattern of spatial variability. Figure S1 (in the auxiliary material), showing the experimental semivariograms and fitted models for WCAs and ENP, provides additional graphical information.[1] The high nugget effect for WCA3 can be explained by the high TP concentration variability within distances smaller than the shortest sampling interval, the existence of measurement errors or an effect of the ridge and slough distribution as reported by *Watts et al.* [2010]. In contrast, the relative nugget effects in WCA2 and WCA1 were low, indicating that the spatial variability is relatively continuous. The range, measuring the distance in meters beyond which observations become uncorrelated, varied between 7,500 and 18,000 (ENP), 8,000 to 21,000 (WCA3), 10,000 to 14,000 (WCA2) and 8,000 to 11,500 m (WCA1). Similar range values have been reported for interpolation of soil parameters in WCA1 [*Corstanje et al.*, 2006], WCA2 [*DeBusk et al.*, 2001], and WCA3 [*Bruland et al.*, 2006].

[26] Table 2 lists the results of the cross validation analysis. In general, the interpolation errors were smaller than the standard deviation values reported in Table 1, thus the semivariograms and fitted models were deemed acceptable. For ENP the mean absolute error (MAE) was less than 4 μg/L with the exception of the 1999 and 2007 dry seasons with higher MAE values of 12.4 μg/L and 10.6 μg/L, respectively. Interpolation in WCA3 resulted in MAE less than 12.5 μg/L with the exception of the 1995 wet season and the 1999 dry season, with 60.7 μg/L and 23.3 μg/L, respectively. In the case of WCA2, MAE did not exceed 8 μg/L during all years and seasons. WCA1 showed higher MAE values during the 1999 and 2003 dry and wet seasons and lower MAE values during the 1995 and 2007 dry and wet seasons.

[27] The RMSE of the semivariograms were lower than the standard deviations reported in Table 1, except for the ENP (wet season of 1999) and the WCA3 (dry season of 1999). For both of those cases, the RMSE exceeded the corresponding standard deviation only by 13% and 6%, respectively. Values of standardized errors (MSE and RMSSE) shown in Table 2 confirmed the robustness of the analysis for the majority of the areas and seasons. Areas of higher variability (RMSSE values exceeding 1) such as in the ENP and WCA3 indicated kriging limitations and the underestimation of the variability of the predictions. The density of the sampling locations in these areas (less than 0.07 sample/km^2) in contrast with WCA1 and WCA2 (smaller areas, with sampling densities in some cases above 0.1 sample/km^2) are one of many factors accounting for these underestimations. However, the distribution and spacing of sampling locations (shown in Table 3) indicated a good representation of short- and long-range distances for the purpose of the kriging semivariogram fitting.

[28] Density of measurements and point distance assessment (Table 3) indicated that some areas (WCA1 and WCA2) showed a better spatial distribution of sampling points than others, with distances below the grid spacing (100 m). Ranges in WCA1 extended from 8,000 to 11,500 m, with a maximum distance in this area of 37,113 m. Almost 30% of the points (22 out of 80) were within the 100 m grid size and the percentage of sampling pairs within the estimated range was above 20%, except for the 2007 wet period. WCA2 contained between 20% and 50% of the samples within the 100 m size grid. This area showed higher relative ranges and percentage of sampling pairs within the estimated range (between 25.5% and 45%). WCA3 contained only 5.8% of sampling locations within the 100 m grid size, but the estimated range and percentage of sampling pairs within this range size reached very low values (6.19% and 9.5%) during the 1995 dry and 2007 wet seasons. The ENP showed the lowest sampling densities with very low percentages of sampling pairs within this range, between 6.5% and 26%, indicating a limitation in capturing the variability of the southern part of the ecosystem.

3.3. Surface Water Total Phosphorus Concentration Maps

[29] Kriged TP maps in Figure 2 showed a spatial gradient from north to south with lower TP concentrations in the southern region (ENP) and higher concentrations in the

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011WR011421.

Table 2. Semivariogram Model Parameters and Cross-Validation Statistics for the Interpolation of Surface Water Total Phosphorus (TP) Concentrations (μg/L) in the Everglades National Park and Water Conservation Areas (WCAs) During the Dry and Wet Seasons of 1995, 1999, 2003, and 2007[a]

	1995		1999		2003		2007	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
				ENP				
Model	Spherical	Spherical	Exponential	Spherical	Spherical	Spherical	Spherical	Spherical
Nugget	0.007	0	0.2	5	4	0.05	0.24	0.15
Sill	0.85	0.45	0.67	23	18	0.39	0.69	0.5
Range (m)	12000	7500	12000	7500	18000	18000	12000	12000
MAE	1.188	1.238	12.42	3.83	2.83	2.767	10.56	3.102
RMSE	3.495	2.768	25.631	5.148	3.843	4.009	24.913	3.96
MSE	−0.084	−0.242	−0.169	−0.027	−0.041	−0.211	−0.131	−0.217
RMSSE	1.616	1.521	1.545	1.317	1.324	1.693	1.03	1.651
				WCA3				
Model	Exponential	Spherical	Spherical	Exponential	Exponential	Exponential	Spherical	Spherical
Nugget	0.15	0.22	0.29	0.1	0.06	0.15	0.2	0.02
Sill	0.53	0.68	1.02	0.37	0.6	0.69	0.49	0.335
Range (m)	8000	13000	18300	21000	18000	18000	10300	9000
MAE	6.743	60.703	23.269	10.678	9.699	12.456	10.614	7.691
RMSE	12.209	24.705	43.154	28.196	14.399	25.002	21.525	11.955
MSE	0.095	0.001	−0.182	−0.002	−0.253	−0.224	−0.059	−0.199
RMSSE	0.572	1.468	1.469	1.094	1.568	1.591	1.309	1.844
				WCA2				
Model	Exponential	Spherical	Exponential	Spherical	Exponential	Spherical	Exponential	Spherical
Nugget	0.07	0.01	0.1	0.05	10	0.03	0	0.01
Sill	0.67	0.96	0.73	0.9	220	0.61	0.5	0.51
Range (m)	12000	13000	14000	12000	12000	11000	10500	10000
MAE	6.737	1.929	6.81	2.826	7.983	7.855	7.183	5.3956
RMSE	11.21	3.565	11.114	4.774	10.886	10.551	10.7766	7.4092
MSE	0.046	0.017	0.067	0.087	−0.001	0.038	−0.235	−0.071
RMSSE	0.725	0.878	0.705	0.506	0.917	1.082	2.304	1.385
				WCA1				
Model	Spherical	Exponential	Exponential	Exponential	Exponential	Spherical	Exponential	Exponential
Nugget	0.18	0.05	0.15	0.2	0	0.1	0.23	0.25
Sill	0.99	1.35	1.05	1.9	1.7	1.6	1.13	1.23
Range (m)	11000	11500	10200	9000	8000	10000	9000	8000
MAE	14.8989	7.005	37.6552	69.3743	34.8352	24.7311	7.8334	14.2608
RMSE	26.25532	16.29	46.699	111.4406	74.27045	33.1149	13.40759	24.31723
MSE	−0.017	0.159	−0.228	−1.121	−0.318	−0.034	0.084	0.043
RMSSE	1.262	0.496	1.219	4.341	2.128	0.719	0.683	0.716

[a] MAE, mean absolute error of the predicted values; RMSE, root mean square error of the predicted values; MSE, mean standardized prediction error; RMSSE, root mean square standardized prediction error.

northern compartments (WCA1 and 2), close to the STAs and EAA. Except during the 1999 and 2007 (Figure 2a) dry seasons in WCA1, results showed that the dry season is the period of the year with higher TP concentrations. The highest TP concentrations were found in WCA1 surface waters during the dry and the wet seasons of 1999 and 2003 (Table 1). In 2003 and 2007, the average TP concentrations during the dry and wet seasons slightly decreased for WCA2 and WCA1, whereas the average TP concentrations in ENP and WCA3 surface waters slightly increased. A Wilcoxon signed statistical analysis was used to assess the statistical significance of those trends. The TP surface water concentration decrease could be associated with the TP loading reduction due to implementation of best management practices (BMPs) in the EAA and the construction of STAs to remove phosphorus by physical, biological and chemical processes [*Hanlon et al.*, 2010; *SFWMD*, 2010]. Because of these measures and since 1994, 3,200 metric tons of TP have been prevented to enter the Everglades [*SFWMD*, 2010].

[30] In general, the highest surface water TP values were located close to canals and inflow structures, a common result that was already observed in soil and floc [*DeBusk et al.*, 2001; *Grunwald et al.*, 2004; *Rivero et al.*, 2007]. This result is also consistent with other water quality reports indicating that water TP concentrations in interior marshes (i.e., at interior sites away from the influence of point source canal inflows) are generally below 10 μg/L, but concentrations near point source inflows are still elevated compared with interior marshes concentrations [*Scheidt and Kalla*, 2007].

[31] High TP concentrations were observed in the northern part of ENP near the Tamiami canal with values of 100 μg/L in 1995 and decreasing to around 50 μg/L in 1999 and 2007 (Figure 2a). The year with the highest TP concentration was 1999 (Figures 2a and 2b), where almost the entire ENP showed a TP concentration higher than 10 μg/L (during the wet and dry seasons). A significant decline in TP concentrations in the ENP was observed in 2003 followed by an increase in 2007 (Figures 2a and 2b). In 2007, surface water TP concentration in the northern ENP was higher than 10 μg/L reaching 50 μg/L in some spots near the Tamiami Canal (Figures 2a and 2b).

Table 3. Sampling Density and Sampling Distance Distribution Within Estimated Range for Water Conservation Areas and the Everglades National Park During the Dry and Wet Seasons

	1995		1999		2003		2007	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
			ENP					
N samples	98	107	62	89	52	56	67	49
Sampling density[a]	0.041	0.044	0.026	0.037	0.022	0.023	0.028	0.02
Kriging range (m)	12000	7500	12000	7500	18000	18000	12000	12000
Sampling pairs within range (%)	15.53%	7.76%	16.82%	6.51%	26.02%	22.08%	22.03%	18.28%
			WCA3					
N samples	153	137	87	113	61	66	109	69
Sampling density[a]	0.064	0.057	0.036	0.047	0.025	0.028	0.046	0.029
Kriging range (m)	8000	13000	18300	21000	18000	18000	10300	9000
Sampling pairs within range (%)	6.19%	14.15%	26.76%	32.85%	25.25%	24.52%	12.10%	9.55%
			WCA2					
N samples	75	71	75	72	30	30	40	41
Sampling density[a]	0.141	0.133	0.141	0.135	0.056	0.056	0.075	0.077
Kriging range (m)	12000	13000	14000	12000	12000	11000	10500	10000
Sampling pairs within range (%)	34.88%	41.37%	45.33%	37.01%	28.05%	25.52%	33.33%	32.07%
			WCA1					
N samples	80	77	47	44	42	36	109	78
Sampling density[a]	0.143	0.138	0.084	0.079	0.075	0.064	0.195	0.139
Kriging range (m)	11000	11500	10200	9000	8000	10000	9000	8000
Sampling pairs within range (%)	29.97%	34.04%	24.24%	20.30%	15.91%	23.49%	23.05%	18.85%

[a] Number of samples per km^2.

[32] During the four dry seasons under study, the southern part of WCA3 showed high interannual temporal variability with values around 50 and 100 μg/L in 1999 to values around 20–30 μg/L in 2003 and 2007 (Figure 2a). On the contrary and during the four wet seasons, the northern part of WCA3 presented high interannual variability with concentrations varying between 50 and 100 μg/L in 1999 to values around 20–30 μg/L in 2003 and 2007 (Figure 2b). In WCA2, a general decrease in TP surface water concentrations was observed during the wet and dry seasons since 1995, from values around 50–100 μg/L (1995) to below 30 μg/L (2007). The higher TP values are located in the northern part of WCA2 indicating high TP loading from WCA1, STA1 and STA2.

[33] Finally, the highest TP concentrations in this entire ecosystem were located in WCA1 where TP concentrations exceeded 200 μg/L (interior marsh, wet season of 1999, Figure 2b). Even though a general long-term decline in TP concentrations could be observed in WCA1 (during the dry season), Figure 2b indicated that water from the surrounding canals was intruding in the marsh of WCA1 at some specific locations during those years. Approximate locations where the canal water is intruding could be determined from Figures 2a and 2b.

3.4. Long- and Short-Term Changes in Total Phosphorus Spatial Distribution

[34] Change maps are displayed using a color gradation for positive and negative changes: light to dark green indicates a decline in surface water TP concentration whereas light orange to red indicates an increase (Figure 3). Short-term (4 year period, 2003–2007) and long-term (12 year period, 1995–2007) trends were analyzed to distinguish temporal changes that occurred recently (mostly after STAs construction and operation) or over longer periods (pre and post STAs operation).

[35] A broad regional assessment shows a long-term TP concentration decrease but a short-term increase of TP concentrations in the Everglades. Indeed, during the dry season, the long-term TP reduction (Figure 3a) occurred in northern WCA1 and northern WCA2 in proximity to inflows from canals, in WCA-3B and northern ENP. During the dry season, long-term TP concentration increases occurred in southern ENP, southern WCA3 and WCA-2B (Figure 3a). During the wet season (Figure 3b), long-term TP concentration increases occurred in WCA1, southern WCA-2A, WCA-2B, western WCA-3A (south of I-75) and north east of WCA-3A (north of I-75). Figure 3b indicate that short-term TP increases (0–25 μg/L range) showed similar widespread distribution in ENP and WCA3 for the dry and wet seasons, with TP increases also occurring during the wet season across the southern part of WCA1 and WCA-2A, and WCA-2B.

[36] These changes may be a response to a combination of several factors: (1) operation of STAs, built between 1998 and 2004, with outflow long-term TP levels exceeding 10 μg/L, (2) the type of BMP program (reduction required at a basin scale) implemented in the EAA since 1995 [*Daroub et al.*, 2009], (3) additional effects from comparison between wetter and drier years, (4) internal phosphorus fluxes from soils to the water column due to legacy phosphorus (estimated at 6 mt/km^2 in the ENP) [*Reddy et al.*, 2011], and (5) loss of tree islands in some locations reducing the effectiveness of an important internal P sink in this region, which may result in increasing nutrient levels in the rest of the Everglades [*Wetzel et al.*, 2005].

[37] A Wilcoxon signed statistical analysis was also done to assess the long-term and short-term TP concentration trends at specific sampling locations in WCAs and ENP. A probability value of 0.05 was selected to evaluate the statistical significance of the test. Results are summarized in Table 4 presenting the long- and short-term trends expressed

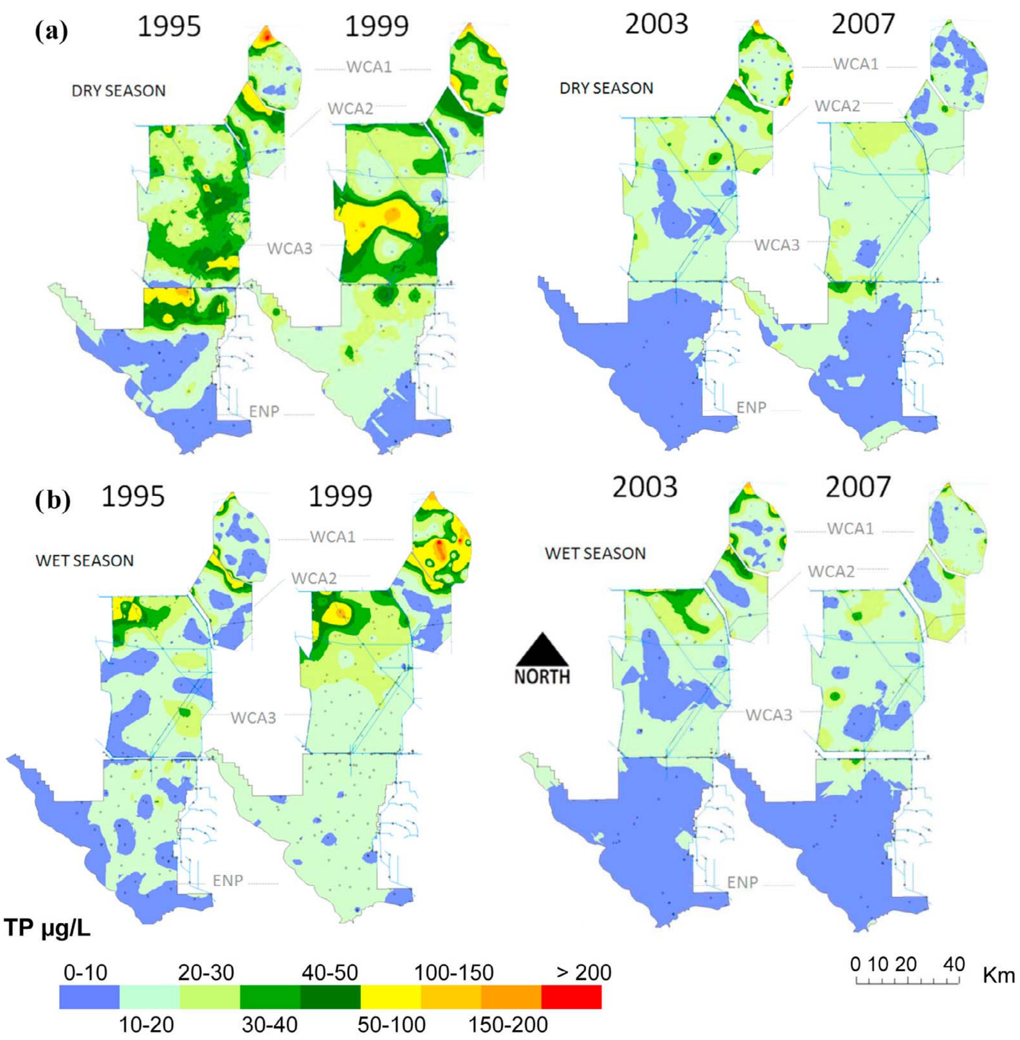

Figure 2. Maps for the surface water total phosphorus (TP) concentration (μg/L) for each season and year: (a) dry season in 1995, 1999, 2003, and 2007 and (b) wet season in 1995, 1999, 2003, and 2007.

in percentage per year, per compartment and per season. Results indicated that, except for the wet season in WCA2, a significant upward trend in TP concentrations was identified from 2003 to 2007 (short term), confirming the results obtained in Figure 3. Moreover and except for WCA1, the long-term (generally decreasing) trend was not statistically significant. The long-term increase during the wet season and decrease during the dry season in WCA1 confirmed the results from Figures 3a and 3b.

3.4.1. WCA1

[38] Unlike other areas of the Everglades where distinct point source inputs exist, WCA1 receives the majority of its water from rainfall and from the surface water that generally moves around the marsh edges via the perimeter canals. Many scientists have monitored surface water in WCA1 marsh and perimeter canals. *Surratt et al.* [2008] reported nutrient and mineral gradients from the canals to the interior of the marsh, produced by canal water inflow. It was only until recently that the canal water was filtered through an STA (STA1W and E) [*Corstanje et al.*, 2006]. Figure 3 indicates that water quality near canals and structures in WCA1 improved during the dry and wet seasons for the long- and short-term periods considered. However, it is noteworthy that these areas adjacent to the surrounding canals showing a slight TP concentration decrease (Figure 3) were also characterized with high TP values (Figure 2). Short-term trends during the dry and wet seasons indicated that WCA1 interior marshes did not improve and in some locations (during the wet season) the TP concentrations slightly increased (as also indicated in the trend analysis presented in Table 4).

3.4.2. WCA2

[39] WCA2 was impounded with canals and levees in the early 1950s and the increase in TP loading started in the 1970s when excess water from the EAA was pumped to the south [*Surratt et al.*, 2008]. An extensive line of research focused on documenting TP gradients along the impacted and nonimpacted areas in soil, water and vegetation [*Noe et al.*, 2001; *Newman et al.*, 2004; *Rivero et al.*, 2007]. However, very few of these studies had comprehensive sampling schemes or aimed to assess changes in the water TP concentration [*Hanlon et al.*, 2010; *Noe et al.*, 2001; *Scheidt and Kalla*, 2007].

[40] Long- and short-term changes in this area showed a very distinctive gradient with improvement in TP concentrations in WCA-2A from an average of 50 μg/L (near

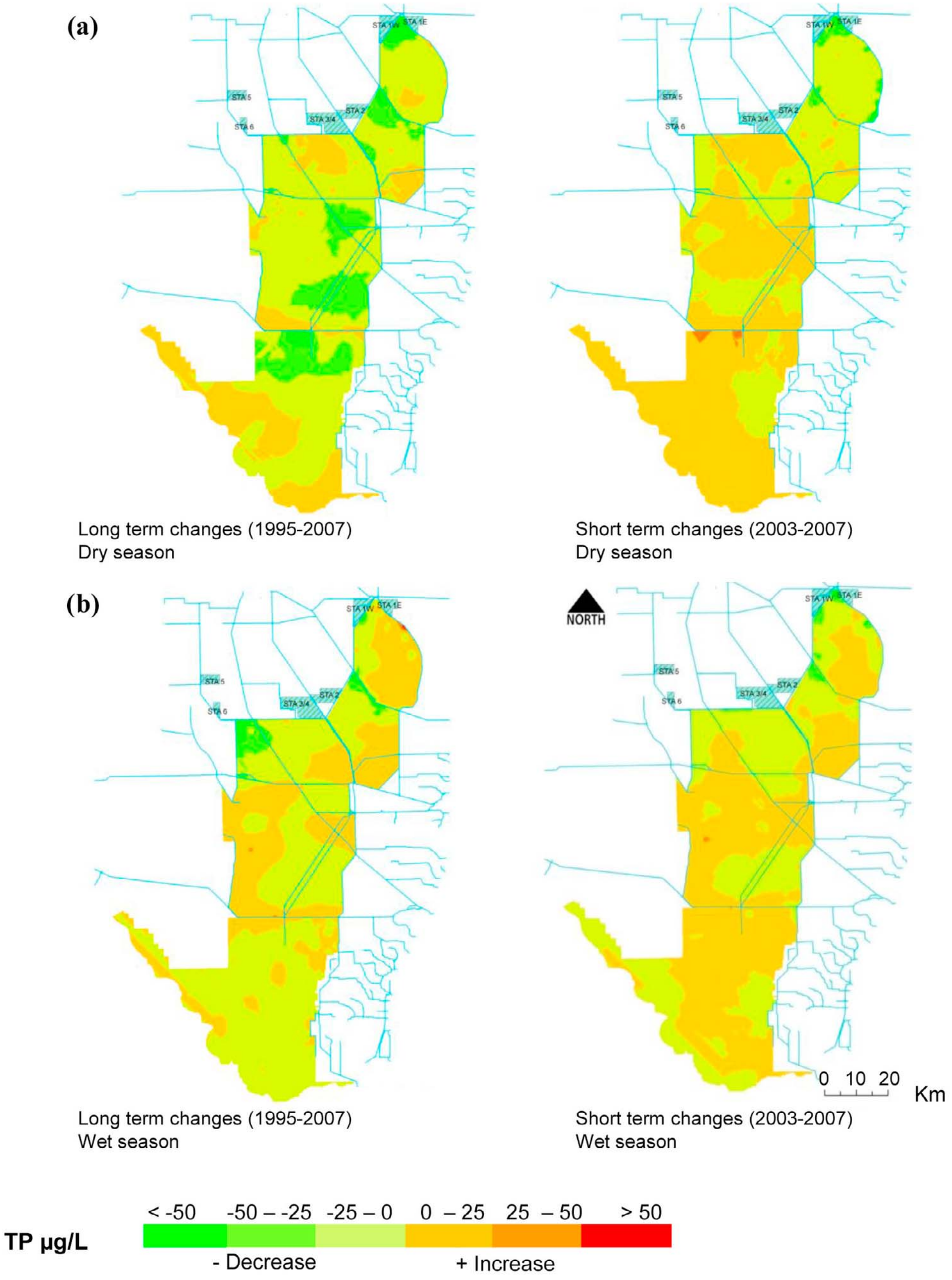

Figure 3. Long-term (1995–2007) and short-term (2003–2007) changes in the surface water total phosphorus (TP) concentration (μg/L): (a) dry season changes and (b) wet season changes.

the canals) to around 25 μg/L (interior marshes). The TP reduction trend could be explained by the constructed STA1 and 2 to deliver cleaner water to WCA1 and to WCA2 [*SFWMD*, 2004]. Opposite trends were observed in WCA-2B where an increase in TP concentration was observed during short- and long-term periods.

3.4.3. WCA3

[41] WCA3 had wider spatial and temporal changes than other regions, pointing to several factors that may influence these trends. Historically, the highest TP levels in water and soil, have been caused by water inputs from canals, as well as in areas adjacent to the southern structures along the Tamiami Canal and along the L-5 canal in the northern boundary [*Bruland et al.*, 2007]. Long-term dry season changes (Figure 3a) indicate an improvement in TP concentrations in WCA-3B and southern WCA-3A (close to L-67 canal). However, a general TP increasing trend of about 25 μg/L was observed in the area close to the L-28 extension canal (west of WCA3) impacting WCA3 surface water quality. It is noteworthy that since WY 2004, almost 38% of the total TP load to WCA3 was originating from the L28 and the feeder canals [*SFWMD*, 2011]. When comparing 1995 to 2003 (dry and wet seasons) water quality data, results show a water quality improvement along the L-28 and L-23 canals, confirming soil results published by *Bruland et al.* [2007] where a decline in soil TP was also observed along those canals.

Table 4. Statistical Long-Term (1995–2007) and Short-Term (2003–2007) Trend Analysis of Surface Water Total Phosphorus (TP) Concentrations (μg/L) in the Water Conservation Areas and the Everglades National Park During the Dry and Wet Seasons[a]

	ENP				WCA3			
	Short Term		Long Term		Short Term		Long Term	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Trend	7.4	4.3	−2.1	−2.4	5.6	3.1	−2.3	−1.9
p value	0	0.02	0.42	0.47	0.02	0.03	0.48	0.59
Significant trend	up	up	none	none	up	up	none	none

	WCA2				WCA1			
	Short Term		Long Term		Short Term		Long Term	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Trend	5.4	2.5	0.9	−1.5	1.8	6.4	−5.1	3.4
p value	0.03	0.31	0.41	0.22	0.03	0	0	0
Significant trend	up	none	none	none	up	up	down	up

[a] The trend magnitude is listed as a percentage per year with significant levels at p value <0.05.

3.4.4. Everglades National Park

[42] Short-term TP trends (Figures 3a and 3b) revealed a general increase in TP concentrations of about 25 μg/L. Hotspots of larger TP increase (>50 μg/L) are located near the Tamiami canal. Long-term changes (Figures 3a and 3b) showed a general TP decrease during the dry and wet seasons except at some specific locations (adjacent to the Tamiami canal during the wet season and in the southern part of the system, in Taylor Slough and parts of Shark River slough during the dry season). *Hanlon et al.* [2010] conducted a trend analysis at sites along Tamiami Trail and on the eastern side of the ENP reporting an increase in TP concentration from 1996 to 2005. Our results showed a general long-term (1995–2007) decrease (around 25–50 μg/L) and a short-term (2003–2007) increase (around 25–50 μg/L) in surface water TP concentrations for the areas adjacent to the Tamiami Canal.

[43] Differences in water management, soil type and hydrology as well as other water quality drivers explain the different water quality trends in WCA3 and ENP. An elaborate discussion regarding the water quality drivers in the

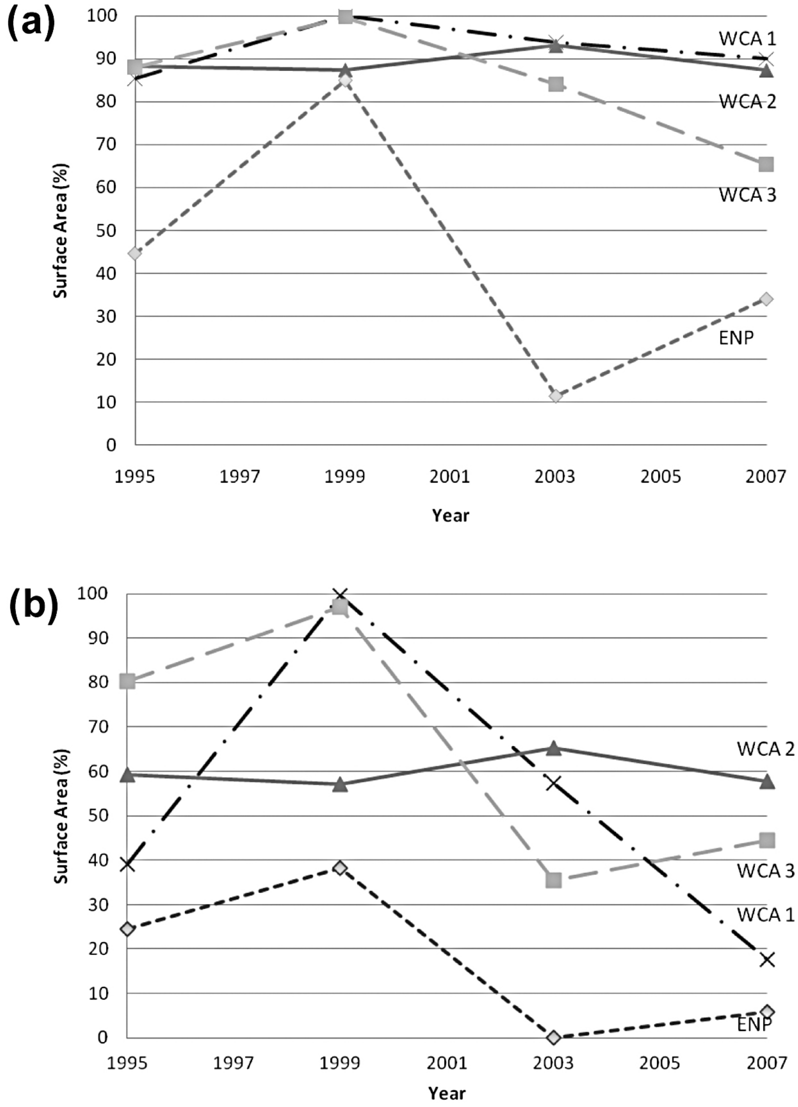

Figure 4. Percentage of each of the four compartments that exceeds surface water total phosphorus (TP) concentrations of (a) 10 μg/L and (b) 15 μg/L for different years.

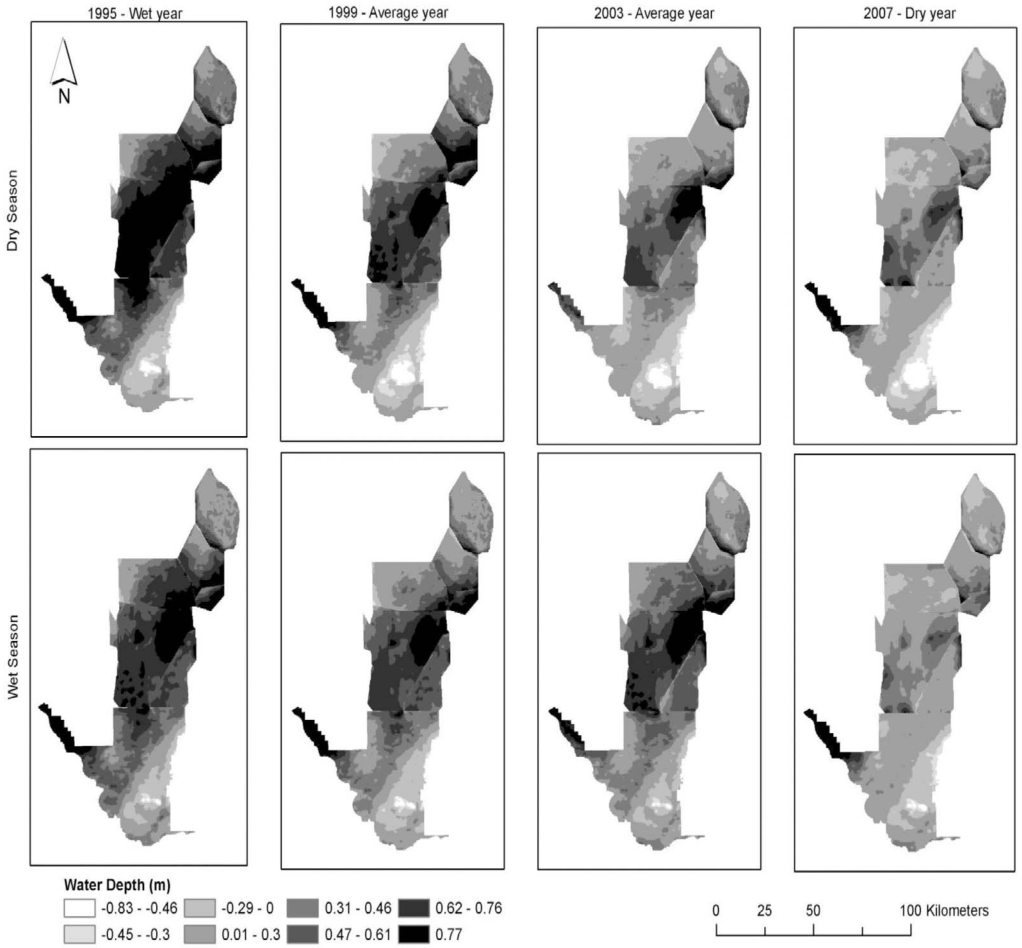

Figure 5. Maps of water depth (m) in the Everglades created for each season (dry and wet) and year (1995, 1999, 2003, and 2007).

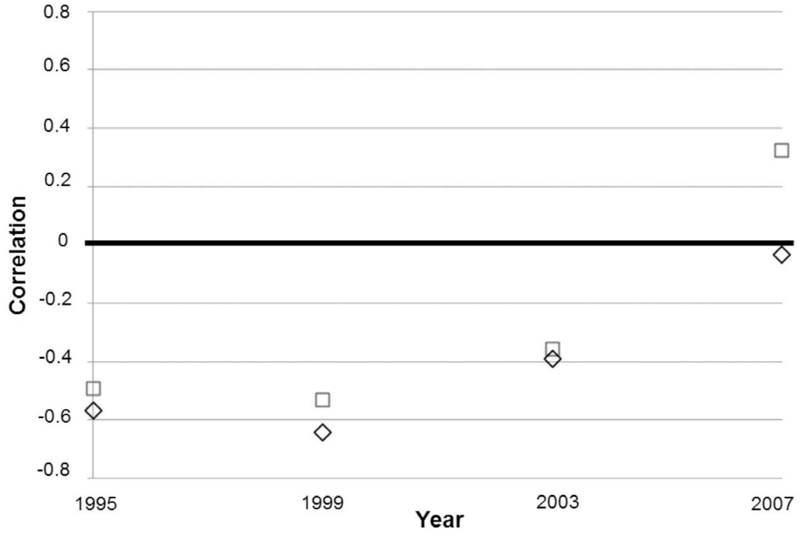

Figure 6. Correlation coefficients between surface water TP concentrations (μg/L) and water depth (m) derived from the principal component analysis for WCA2 (squares) and WCA3 (diamonds) during the wet season.

ENP can be found in *Hanlon et al.* [2010]. A special area of interest is along L-31W canal (Figure 1; southeast of the ENP) where Figure 3 indicates long- and short-term wet and dry season increases in TP levels in surface water. This area is currently of a great concern due to recent findings of cattail expansion as well as high TP levels in soil [*Osborne et al.*, 2011a].

3.5. Ecological Threshold Exceedance

[44] The TP level of 10 μg/L was established as an ecological threshold – exceeding this value in the water column would cause an ecological imbalance impacting the algal and plant communities and altering the indigenous system [*Gaiser et al.*, 2006]. This threshold was translated into a Class III Numerical Phosphorus Water Quality Criterion for the Everglades [*U.S. Environmental Protection Agency*, 2010].

[45] Figure 4a illustrates the percentage of the surface area in the Everglades Ecosystem exceeding the 10 μg/L ecological threshold (yearly average). In 1995 and 1999, almost 80% of the Everglades surface area exceeded this threshold (except for the ENP in 1995). A decline in the ENP surface area above 10 μg/L was observed from 85% in 1999 to 32% in 2007. WCA3 showed a slight decrease in its surface area above 10 μg/L threshold reaching 65% in 2007. WCA2 and WCA1 remained steady over time, with 86% and 92% of the area exceeding the threshold, respectively.

[46] Another threshold directly obtained from the Class III Numerical Phosphorus Water Quality Criterion for the Everglades [*U.S. Environmental Protection Agency*, 2010] is 15 μg/L that cannot be exceeded by the annual geometric mean TP at all individual monitoring stations. Extending this alternative annual threshold to all the Everglades ecosystem would lead to results in Figure 4b. With the exception of WCA2 with a steady 60% of its surface above 15 μg/L, WCA1, WCA3 and ENP showed a long-term reduction since 1999. In recent years (2003 and 2007), results from the ENP and WCA3 showed a slight increase by 6% and 9%, respectively.

3.6. Water Depths and TP Correlations

[47] Mean water depths were mapped per year and per season for the four compartments in Figure 5, reflecting the combined effect of the annual rainfall variability and the changes in water management operations between 1995 and 2007. According to the average annual rainfall trend for those years, 1995 was a wet year; 1999 and 2003 were average years and 2007 was a dry year.

[48] Historically, the central Everglades (currently WCA-3A and Shark River Slough in the central ENP) was a deeper path of uninterrupted water flow. Figure 5 indicates that the water flow was altered after the implementation of the Central and Southern Florida Project that compartmentalized the system in the late 1960s in order to provide urban and agricultural areas with flood protection during wet years, as well as water supply during the dry season [*Light and Dineen*, 1994].

[49] Figure 5 indicates that the distribution of dry and wet areas in WCA3 has changed noticeably during the last 10 years. Drier areas have expanded from the northwest corner of WCA3 to the northern southeast quadrant (north of I-75). The southern area of WCA3, adjacent to the northern boundary of ENP, is impacted by the effect of the artificial boundary created by the L-67 levees dividing WCA-3A and WCA-3B, augmented by the impoundment of water north of Tamiami Trail in WCA-3A (southwestern portion of the WCA3). As a result, water depths are high in southern WCA-3A (west of L-67) and low in WCA-3B (Figure 5). Other impacts of the operational changes are drying trends in north central areas of WCA1, reduced water levels in northern WCA-3A and the impoundment noticeable in WCA-2B.

[50] These results agree with those reported by *Watts et al.* [2010] demonstrating that the present-day water management favors the conservation of landscape patterning in central WCA-3A, but not in northern WCA-3A where drainage has made conditions too dry or in southern WCA-3A where levee impoundment has made conditions too wet. It has been suggested that soil oxidation in northern WCA3 due to drought, subsidence and possibly fire contributed internal loading of TP [*Osborne et al.*, 2011b].

[51] Figure 6 displays the correlation coefficient between seasonal water depth and TP concentrations during the wet seasons in WCA2 and WCA3. These correlations could help analyze the spatial and temporal distribution patterns of water TP as related to changes in water depth. Correlations were negative during the wet season of the average years (1995, 1999, and 2003) in WCA2 and WCA3. These results indicate that water depth and TP levels were more significantly correlated in the central WCAs. Results obtained for the other remaining Everglades areas during the wet and dry seasons showed important spatial and temporal variability and the correlation results indicated a relatively low and erratic correlation through time in these compartments.

4. Conclusions

[52] A database was assembled containing 361,000 records of water quality and other important parameters from more than 10 years of monitoring data in the Everglades region. A most valuable assessment tool was then developed to evaluate the effects of operational changes and other environmental factors while mapping the temporal and spatial TP distribution changes.

[53] The spatial gradient indicated that the TP values decreased from north to south. The temporal gradient indicated that the dry season is the period of the year with higher TP concentrations. The highest TP concentrations were found in WCA1 surface waters during the dry and wet seasons of 1999 and 2003 with values reaching 200 μg/L at some locations. Even though a general decline in TP concentrations could be observed in WCA1 (long term significant decrease of -5.1% per year during the dry season), water from the surrounding canals was intruding and impacting the perimeter marshes. A decline in ENP TP concentrations was observed in 2003 followed by a significant increase in 2007 (+7.4% and +4.3%, short-term dry and wet season increases, respectively). In 2007, surface water TP concentration in the northern ENP reached 50 μg/L in some spots near the Tamiami Canal.

[54] A broad regional assessment of temporal changes showed a long-term TP concentration decrease but a short-term significant increase in the Everglades, as also confirmed by the trend statistical analysis. The general short-term increase was the highest in the ENP reaching 7.4% per

year in some locations. This was confirmed when calculating the Everglades surface area above the 10 μg/L and 15 μg/L thresholds. This indicates that the current measures implemented to reduce phosphorus are not sufficient to reach the ecological threshold. These results agree with the *NRC* [2010] assessment related to water quality whereby (1) the current acreage of STAs is not sufficient to treat existing water flows and loads into the Everglades Protection Area and (2) there is a need to develop and implement improved best management practices in the EAA.

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