Water Quality Trends at Inflows to Everglades National Park, 1977–2005

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Restoration of the Florida Everglades is important for the health of the natural system, including both the "River of Grass" and its downstream estuaries. Water quality improvement is one indicator of successful restoration in this complex ecosystem. Using the period of record of 1977 through 2005, we evaluated data from seven inflow sites to the Everglades National Park (ENP) for temporal trends of various forms of phosphorus (P) and nitrogen (N) and analyzed them using principal component analysis and factor analysis without flow adjustments. Locally estimated scatter plot smoothing (LOESS) trend lines identified two inflection points (three time periods) of changing trend in total P (TP) concentration at the seven sites. Results indicated that overall water quality in ENP inflow improved from 1977 to 2005, with significant downward trends in TP concentration. The overall trend of TP is probably mediated by hydrology, which is evident by a negative relationship between flow and annual average TP concentration at the majority of stations within the available data, although additional changes in vegetation due to hydroperiod may have some effects. Total N (TN), total Kjeldahl N, and total organic N concentrations also generally decreased at inflow sites. Water quality standards for TP, TN, and NH_4^+–N were exceeded at selected sites during the study period. Principle component analysis and factor analysis detected a grouping of sampling sites related to the water delivery system that could be used as indicators to better manage monitoring resources. Study results suggest that water quality data analyses could provide additional insight into the success of a restoration management plan and on how monitoring may be modified for more efficient use of resources.

Human activities have become synonymous with changes in surface water quality from many contributing sources (Simeonov et al., 2003). These changes are particularly important with respect to the Florida Everglades. The Everglades, a vast subtropical wetland, dominates the landscape of south Florida and is widely recognized as an ecosystem of great ecological importance (Chimney and Gorforth, 2001; Sklar et al., 2005). The Everglades is a wide, flat expanse of peatlands and tree islands that historically served as the primary drainage path from water overflowing the southern bank of Lake Okeechobee, as well as from direct rainfall. Physical alterations of the landscape and associated water-management practices, including canal and levee construction, agriculture and residential development, and the operation of pumps and flood gates beginning in the 1900s, have altered the volume, timing, distribution, and quality of surface water in this system (McPherson et al., 2001). Efforts to mitigate water quality and quantity problems have been ongoing. Canalization of the Kissimmee River, which drains a large part of the peninsula from Orlando, FL, into Lake Okeechobee and urbanization of that part of the watershed have greatly increased drainage volume with reduced water quality. Management of Lake Okeechobee is complex due to the dike finished in 1937. However, this modification greatly reduced hurricane damage to surrounding towns and agricultural lands. Lastly, discharge of water compared to the natural flows in the past from the Lake have all been canalized and greatly reduced. This system was designed to protect humans, drain lands that were too wet for urbanization and agriculture, and support the economy of southern Florida. Environmental concerns, starting in the 1960s, introduced considerable additional changes to this complex water management system with the goal of repairing current environmental imbalances, including nutrients, water volume, and timing issues.

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Abbreviations: BMP, best management practice; EAA, Everglades Agricultural Area; ENP, Everglades National Park; ENR, Everglades nutrient removal project; ESTREND, Estimate TREND; FA, factor analysis; FAC, flow-adjusted concentration; LOESS, locally estimated scatter plot smoothing; PCA, principle component analysis; SFWMD, South Florida Water Management District; SK, Seasonal Kendall; STA, Stormwater Treatment Area; TKN, total Kjeldahl N; TN, total nitrogen; TON, total organic nitrogen; TP, total phosphorus; WCA, Water Conservation Area.

The Everglades National Park (ENP) was created by Congress in 1947 to preserve and protect portions of the south Florida ecosystem that have remained relatively intact and free of human development (Fig. 1). Because the ENP is located in the downstream region of the Everglades, the area is subject to upstream water-management practices. Waters in the ENP are currently designated as both Outstanding Florida Waters and Outstanding Natural Resource Waters and therefore must be monitored and protected (McPherson et al., 2001). To that end, a complex system of Water Conservation Areas (WCAs) and Stormwater Treatment Areas (STAs) were constructed to the north of the ENP to improve water quality. Waters from Lake Okeechobee, the Everglades Agricultural Area (EAA), and urban areas are directed to one or more of these structures that use constructed wetlands and other approaches to remove sediments and reduce nutrients, primarily phosphorus and to a lesser extent nitrogen. Water from these large structures is then conveyed to the ENP by canals. The largest WCA (WCA-3) lies along the northern boundary of the ENP (WCA-3) and covers approximately 2800 km^2 (SFWMD, 2001). Extensive monitoring of inflows to the ENP was an assessment part of this strategy to document improvements in water quality, quantity, and timing issues.

The effectiveness of management decisions during restoration can be assessed by evaluating changes to water quality with time. Because the Everglades historically was a highly oligotrophic system, the sensitivity to minor nutrient changes demands a high level of monitoring to detect subtle changes in measured data. The goal of the ENP restoration efforts is to modify flows into the park to more closely mimic historical hydrology. At the same time, water managers must consider the dangers due to flooding and work within the current water control system. The question is how these modifications change water quality, including the sources and processes that affect nutrients and their availability. Previously, Walker (1991) evaluated water quality data collected at seven ENP inflow points between 1977 and 1989. Walker's results indicated a pattern of increasing P concentrations and decreasing N/P ratios at ENP inflow points during this time period.

To document and assess water quality changes, long-term monitoring programs have been established. The collected data are then evaluated using different statistical techniques. The most commonly used method for evaluating long-term water quality is trend analysis. Trend analysis is performed by comparing changes in either the mean or the median of the water quality parameters of interest with time (Helsel and Hirsch, 1992). Selected methods include Sen's T, Spearman's Rho, the Mann–Kendall test, the seasonal Kendall test, and the Tobit test (Hirsch et al., 1991; Schertz et al., 1991). Parsing datasets to explore temporal or seasonal effects may prove useful given south Florida's climate, weather patterns, and drainage characteristics. The seasonal Kendall test, a modification of the Mann–Kendall test, allows for the testing of seasonality and has been applied frequently to water quality time-series datasets (Hirsch et al., 1982; Walker, 1991; Qian et al., 2007; Miller and McPherson, 2008). Improvements to this statistical method have included serial correlation, spatial variation across sites, and accountability for anomalies within the dataset (Hirsch et al., 1982; Hirsch and Slack, 1984; Hirsch et al., 1991; Helsel and Hirsch, 1992). Walker (1991) used the seasonal Kendall test to analyze water quality trends at inflows to ENP and found identical significant ($P < 0.10$) increasing trends in TP concentration at eight out of the nine stations included in the trend analysis. Although the seasonal Kendall test is generally preferred, it is recommended for use with datasets with fewer than 5% censored values. The presence of datasets with greater than 5% censored values requires the use of an alternative test, such as the Tobit test (Schertz et al., 1991).

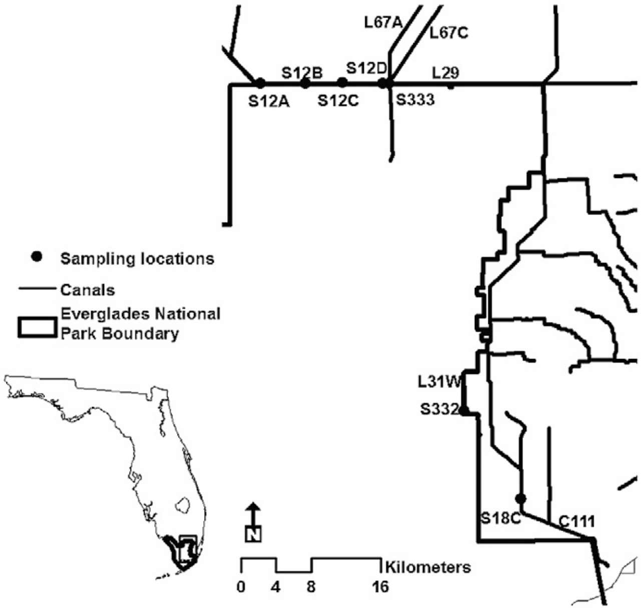

Fig. 1. Location of inflow water quality monitoring stations to the Everglades National Park.

Due to the number of variables, samples, and stations, locations, and sites included in most water quality datasets, trend analysis may be complemented by a more global statistical evaluation such as principal component analysis (PCA) and factor analysis (FA) (Singh et al., 2004; Ouyang, 2005). Principal component analysis and FA are used in water quality evaluations to identify latent variables that cannot be directly or easily measured. Results from PCA and FA applications to water quality datasets have been used in various ways, such as to identify noncritical water quality monitoring sites to reduce monitoring costs (Ouyang, 2005), to collapse the number of stations into fewer groups to evaluate results (Caccia and Boyer, 2005), and to examine the importance of different water quality variables (Qian et al., 2007).

The objectives of this study were (i) to evaluate the trends of phosphorus (P) and nitrogen (N) species concentrations at seven inflow stations to the ENP and (ii) to establish a statistical basis for comparing changes to the complex Everglades system and resulting water quality responses.

Materials and Methods

Site Description

Water quality data were collected from multiple sites in the ENP (Fig. 1; Table 1). The most northern sites were located on the L29 canal, which is situated east–west and forms a divide between WCA-3A and the northernmost part of the ENP. The purpose of the L29 canal is to collect water from lands to

Table 1. Sampling sites from which 1977 through 2005 data were collected for trend analyses.

Sample site	Site location	Contributing water source	Receiving water source	Period of record
S12A	Spillway on levee L-29	Water Conservation Area 3A	Shark River Slough	Dec. 1977–Dec. 2005
S12B	Spillway on levee L-29	Water Conservation Area 3A	Shark River Slough	Dec. 1977–Dec. 2005
S12C	Spillway on levee L-29	Water Conservation Area 3A	Shark River Slough	Dec. 1977–Dec. 2005
S12D	Spillway on levee L-29	Water Conservation Area 3A	Shark River Slough	Dec. 1977–Dec. 2005
S333	Tamiami Canal below S-333	L-76 and L-29 levees	Shark River Slough	Dec. 1977–Dec. 2005
S332	Pump Station	L-31W Borrow Canal	Taylor Slough	Oct. 1983–Dec. 2005
S18C	Canal 111	South Dade Conveyance System	Coastal	Oct. 1983–Dec. 2005

the west, north, and east of the ENP. A number of structures (S12A, S12B, S12C, and S12D) along the L29 canal introduce and distribute water into the northern part of the ENP. Located in the same area, the S333 structure receives water from the L67 and L67A canals, introducing water directly into the ENP. Additional data included in the evaluation were collected at structures S18C and S332, which are located on the eastern side of the ENP, approximately 32 km south and east of the structures located along the L29 canal. Because of their location, these structures received water that had traveled considerable distance through unlined canals, compared with those along the L29 canal.

Data Sources

Water quality data and hydrogeologic parameters collected from the structures described above (Table 1; Fig. 1) were retrieved primarily from the DBHYDRO database managed by the South Florida Water Management District (SFWMD; http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_era/pg_sfwmd_era_dbhydrobrowser). Retrieved data include the period between 1977 and 2005. The monitoring sites are identified by their structure name and include S12A, S12B, S12C, S12D, S333, S332, and S18C. The period of data record for each monitoring site is listed in Table 1. Chemical analyses and sample handling were conducted according to published protocols (APHA, 1998). All data were inspected for errors. Measurements of ammonia nitrogen (NH_4^+–N), total nitrate plus nitrite (NO_X–N), total Kjeldahl nitrogen (TKN), total organic nitrogen [(TON, calculated as TKN – (NH_4^+–N)], total nitrogen (TN as TKN + NO_X–N), ortho phosphorus (PO_4–P), and total phosphorus (TP) were used in the statistical evaluations.

Data Evaluation

All data were statistically reviewed for normality, as water quality data are often characterized by non-normal skewed distributions (Hirsch et al., 1991). If a dataset was found to have a non-normal distribution, the data were transformed using natural logarithms and retested to ensure normality. Data were tested for normality using the Jarque–Bera (Skewness–Kurtosis) test (Jarque and Bera, 1980).

All analyses are based on nonflow adjusted trend analysis. An exploratory evaluation of the data was conducted to see if trend analysis with flow adjustment would influence trend results. Results with flow adjustments were similar to those reported for nonflow adjustment and therefore are not included. No hysteresis effects were found during this evaluation.

Time series data were also evaluated using graphical techniques. Due to the changes in management that occurred within the contributing drainage area during the period of record, changes in water quality trends within the period of record were expected for some species. Traditional trend analysis, such as the seasonal Kendall test and the Tobit test, evaluates the overall direction (increase or decrease) of the trend considering the complete dataset analyzed by section. The LOESS line fits simple models to localized subsets of the data, while sectioning was based on obvious changes in the LOESS smooth line and on changes in external features, such as adoption of a new water management strategy that resulted in changes to waters at the selected inflows. Whisker box plots were created showing median, geometric mean, selected quartiles, and outliers.

Trend Analysis

A trend test was applied to the seven selected water quality measurements for each station. Trends were evaluated considering complete datasets and subsets of the data depending on LOESS results. Measured concentration data were analyzed without flow adjustments since the water-control structures were subject to human influences that modified the probability distribution of the flow measurement over the time period of interest (Lietz, 2000; Helsel and Hirsch, 2002).

The USGS computerized statistical program Estimate Trend (ESTREND) (Schertz et al., 1991) was used with SPLUS software (TIBCO Software Inc. Palo Alto, CA). ESTREND includes different parametric (Tobit) and nonparametric (seasonal Kendall) statistical trend tests. Data points reported at or less than the method detection limit were censored by assigning a value of one half that of the minimum detection limit (Schertz et al., 1991). Trends in nutrient concentrations were evaluated as follows: nutrient species with <5% censored data were evaluated using the uncensored seasonal Kendall procedure ($P < 0.1$); nutrient species with ≥5% censored data and a single reporting limit were evaluated using censored seasonal Kendall procedure ($P < 0.1$); and nutrient species with ≥5% censored data and multiple reporting limits were evaluated using the Tobit parametric test ($P < 0.1$). A probability value of 0.1 was selected on the basis of the sensitivity of the ENP system to small changes in water nutrient concentrations.

Principle component analysis and FA were applied to the dataset to determine latent variables and to identify possible modifications to the sampling protocol to increase monitoring efficiency. Additionally, both PCA and FA were also applied to the seven inflow sites to test if sites receiving similar water source(s) were clustered. Both PCA and FA were conducted using SPLUS software program. Data were input into the program as multivariate, and principal component methods using a covariance matrix were adopted. Varimax rotation was used in factor analysis.

Results and Discussion

The statistical tests for normality showed that all data for the individual species were not normally distributed, as is common with nutrient water quality data (e.g., Singh et al., 2004; White et al., 2004; Ouyang, 2005). All data were transformed using natural logarithms.

PCA and FA Analyses

The results of PCA followed by FA produced a clustering of sites (Fig. 2). The sites located on the northern boundary of the ENP were expected to be related, and the statistical results confirmed that this link exists. The sites located on the eastern boarder of the ENP (S332 and S18C) receive waters from canals bordering and in proximity to the eastern ENP boundary. Again, the PCA and FA analyses demonstrated a relationship between these two sampling sites. These findings can be used in designing management practice strategies for targeted water quality improvements and can also be used in designing water quality monitoring programs to maximize the amount of variability captured in as few stations as possible.

Factor analyses (Fig. 3) showed that there was little correlation among the chemical forms and that TKN and TP were the main factors. This outcome was predictable as NO_X–N, NH_4–N, and PO_4–P concentrations were quite low in comparison. The calculated TON was not used in further analyses because of the findings regarding TKN and inorganic N form. Both TKN and TP were dominant loadings for Factor1 and Factor2, respectively, (Fig. 3), indicating that the controlling mechanisms (or latent variables) for each is different (Ouyang, 2005).

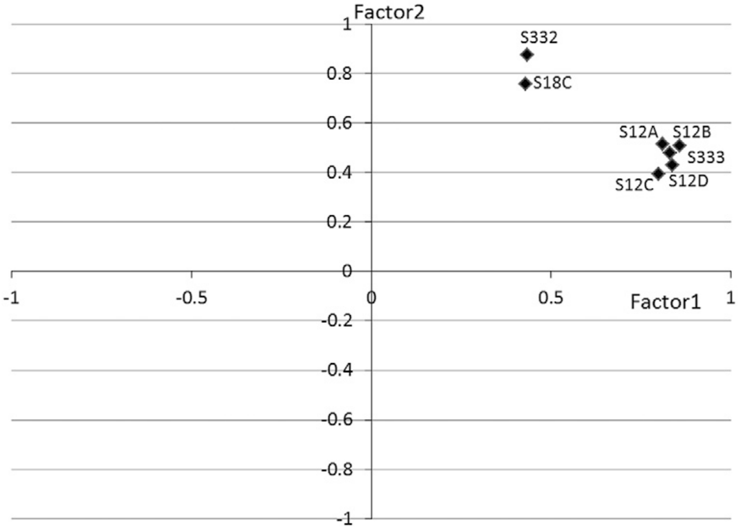

Fig. 2. Factor analyses of all species data by inflow site using only P and N. Water quality trends are responding similarly at sites within clusters.

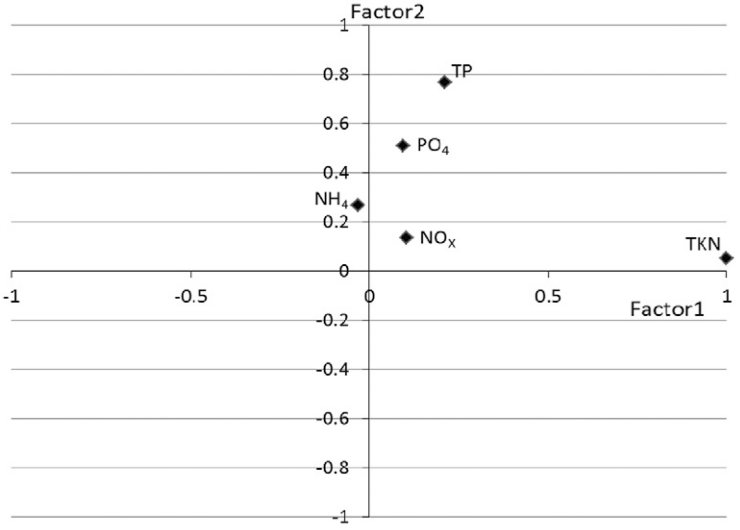

Fig. 3. Factor loadings for the first factor (Factor 1) and the second factor (Factor 2) (only N and P parameters obtained from each station were used for the analysis). TKN, total Kjeldahl N; TP, total P.

Trend Analyses

LOESS trend lines (Fig. 4) identified two inflection points (or three time periods) of changing trends in TP concentration during the monitoring period at the seven sites. Total P concentrations at S12A, S12B, S12C, S12D, and S333 increased during 1977 to 1989, decreased from 1990 to 1995, and increased from 1996 to 2005. Total P concentrations at S18C and S332 rose during 1983 to 1989, declined during 1990 to 1997, and increased from 1998 to 2005. Because the trend lines are statistically generated at the indicated confidence interval, we should use these trends as indicators of performance but also verify these findings using the PCA, FA, and traditional statistical evidence.

Total Phosphorus and PO_4–P

Long-term trends in TP concentrations for the period of record (1977–2005) were downward at three stations (S12C, S12D, and S333) with slopes of −0.21, −0.61, and −1.19% per year, respectively (Table 2), with only S12D and S333 indicating statistically significant decreasing trends ($P < 0.1$). Conversely, upward trends were observed at four stations (S12A, S12B, S332, and S18C) by 1.16, 0.74, 1.57, and 0.62% per year, respectively, with only S12A and S332 showing significant increasing trends ($P < 0.1$) (Table 2). The median concentrations of TP at the seven stations were 0.006 to 0.012 mg L^{-1} between 1977 and 2005 (Fig. 5) with the median concentration of TP at S333 (0.012 mg L^{-1}) being double of that at S18C (0.006 mg L^{-1}). There was an increasing gradient in P concentration from west to east (S12A to S333) with the greatest values measured at S333. Walker (2002) indicated that this phenomenon reflected a decreasing influence of overland sheet flow from the WCA-3A marsh and an increasing influence of channelizing flows that transport flow and P along the L29 and L67 levees. The median concentrations of TP at all S12 structures and S333 were higher than those at S18C and S332. Water flowing through S333 directly contributes to the S12 structures and then into the ENP from the S12 structures. Water entering the L29 originates from WCA-3. There are natural variations in geology, hydrology, and vegetation and differences in water management and land uses for the two different regions that explain the differences in observed values between the northern group and the eastern structure group. For example, water flowing into WCA-3 has passed through

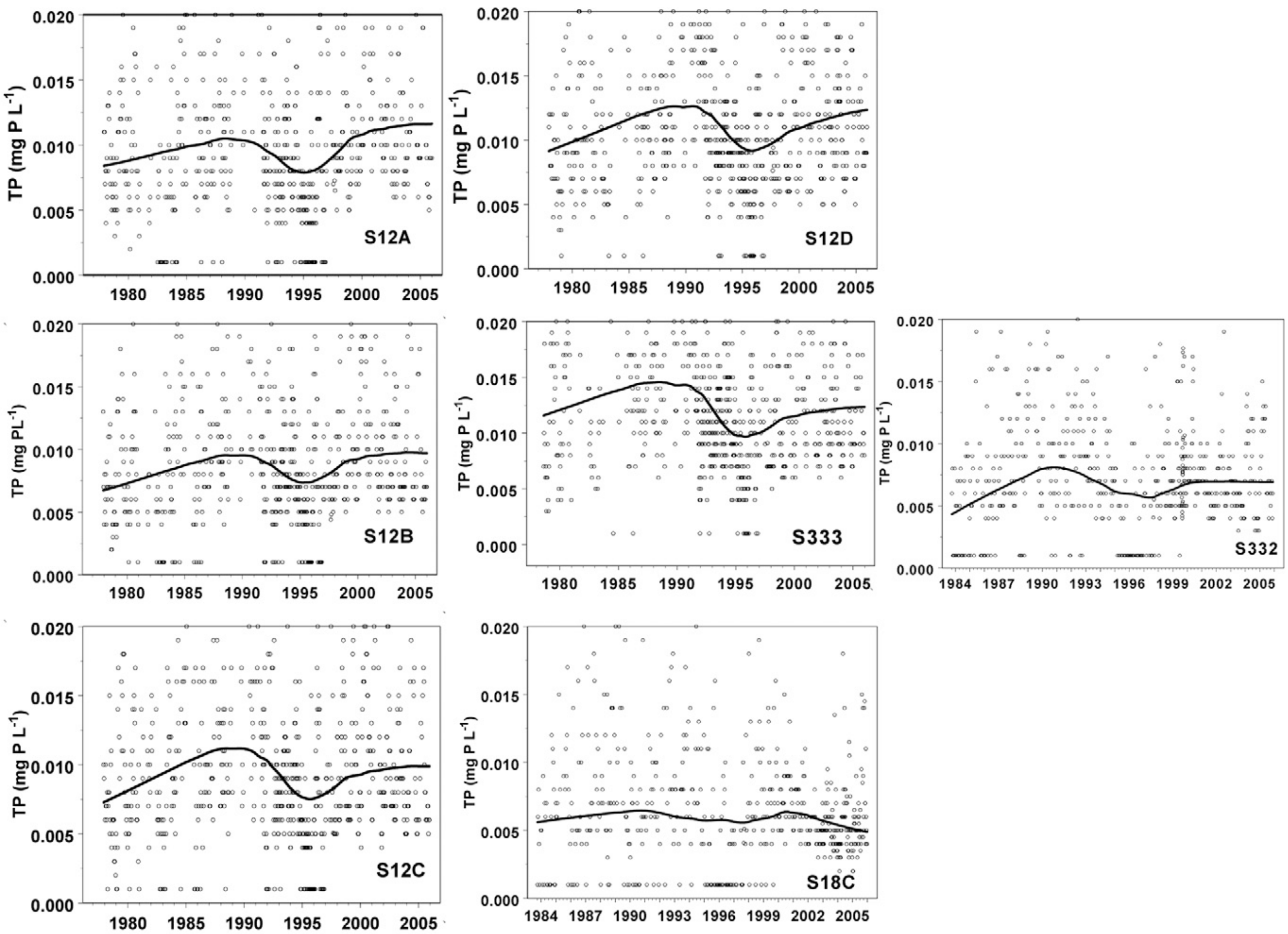

Fig. 4. Time series plot of total P (TP) at S12A, S12B, S12C, S12D, S333, S18C, and S332 with LOESS smoothing.

Table 2. Statistical summary and trends of selected water-quality constituents for all data from 1977 to 2005 without flow adjustment.†

Constituent‡	Type	S12A		S12B		S12C		S12D		S333		S332		S18C	
		Trend%	*P* value	Trend%	*P* value	Trend%	*P* value	Trend%	*P* value	Trend%	*P* value	Trend%	*P* value	Trend%	*P* value
TP	Tobit	1.16	0.02	0.74	0.12	−0.21	0.64	−0.61	0.07	−1.19	0.00	1.57	0.01	0.62	0.29
PO_4– P	Tobit	3.17	0.07	1.61	0.39	2.33	0.17	4.68	0.00	3.74	0.01	4.09	0.10	−4.08	0.11
TN	uncensored	−2.53	0.00	−2.61	0.00	−3.11	0.00	−2.88	0.00	−2.27	0.00	−1.67	0.12	−3.29	0.03
TKN	uncensored	−2.41	0.00	−2.57	0.00	−3.00	0.00	−2.55	0.00	−1.94	0.00	−2.12	0.03	−1.79	0.06
TON	uncensored	−2.45	0.00	−2.56	0.00	−2.87	0.00	−2.73	0.00	−2.36	0.00	−2.32	0.05	−3.25	0.02
NH_4–N	Tobit	1.52	0.06	0.63	0.40	1.90	0.01	4.30	0.00	5.19	0.00	0.29	0.76	−1.45	0.23
NO_X–N	Tobit	3.00	0.00	0.23	0.76	−0.49	0.51	−0.46	0.45	−0.98	0.09	1.49	0.09	3.75	0.00

† Table lists trend magnitudes (percent/year) with two-tailed significance levels < 0.10.

‡ TP, total P; TN, total N; TKN, total Kjeldahl N; TON, total organic N.

the STA system with resulting water quality improvement. The water inflowing from the eastern structures have a considerable residence time in canals before entering the ENP, and land uses adjacent to these canals include agricultural and urban uses, both of which have implemented best management practices (BMPs).

Results of the Tobit regression analysis in TP concentrations for the subset time periods (as identified by LOESS smoothing) are presented in Table 3. For S12A, S12B, S12C, S12D, and S333, significant upward trends in TP concentration were identified from 1977 to 1989 by 4.3 to 8.5% per year and by 3.8 to 6.0% per year from 1996 to 2005. Significant downward trend occurred from 1990 to 1995 by −32.3 to −14.0% per year. S18C and S332 showed a significant upward trend by 22.98 and 43.92% per year during 1983 to 1989 and a significant downtrend by −14.0 and −22.6% per year during 1990 to 1997. A significant decreasing trend at S18C and no significant trend at S332 were found from 1998 to 2005. Median TP concentration varied with the three periods from 0.007 to 0.015 mg L^{-1} for 1977 or 1983 to 1989, 0.06 to 0.011 mg L^{-1} from 1990 to 1995 or 1990 to 1997, and 0.06 to 0.011 mg L^{-1} from 1996 or 1998 to 2005 (Fig. 6).

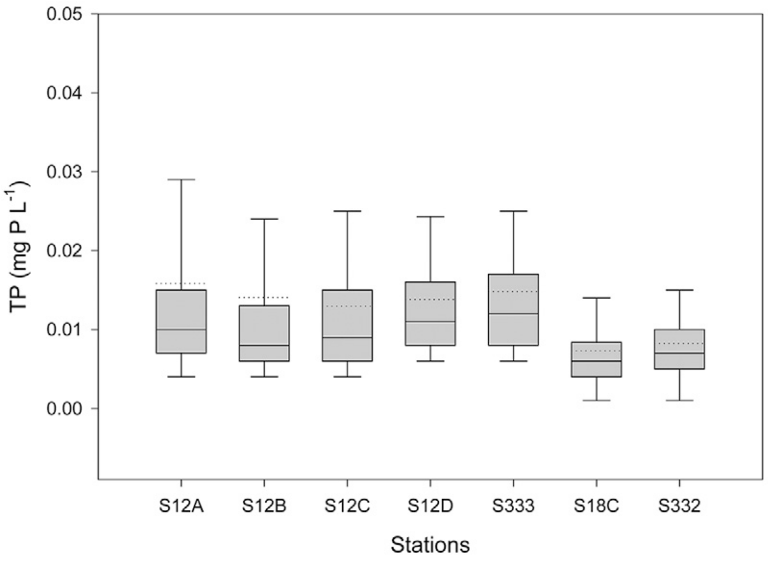

Fig. 5. Total P (TP) concentrations among the stations during the period 1977 to 2005 (S12A, S12B, S12C, S12D, and S333) and 1983 to 2005 (S18C and S332).The boundary of the box closest to zero indicates the 25th percentile; a line within the box marks the median; a dotted line marks mean; and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles.

The Everglades water quality standard is 0.01 mg L^{-1} for TP (Florida Administrative Code, FAC 62-302.540). Median TP concentrations at S12D and S333 exceeded this P standard. Total P concentrations during 1990 to 1996 decreased at each station as compared to 1977 to 1989 TP concentration. This changing pattern is consistent with beneficial impacts of control measures that included BMP implementation in the EAA and shifts in agricultural crops (away from vegetables). For example, the requirement for low P fertilizers to avoid decreasing sugar production from sugarcane (*Saccharum officinarum* L.) is well known within the EAA. For that reason, Daroub et al. (2009) reported that farms producing solely sugarcane have significantly less P loading that those farms with vegetables. In particular, high flows and stage heights in the WCAs may have also contributed to the apparent water quality improvements (Walker, 1997, 2002).

The trend of annual precipitation recorded at one weather station north of ENP by LOESS smoothing indicated that annual precipitation increased from 1990 to 1995 and decreased from 1996 to 2005, which was an opposite trend to TP concentration trend at the inflow sites (e.g., S333) (Fig. 7). A significant negative correlation was observed between annual water flow into ENP from 1977 to 2005 and average annual total P concentration at three out of four stations (Fig. 8).

Management changes during the early 1990s may not have been the only factor influence TP concentrations. Because the entire system is dynamic, several management changes were made during this time. For example, the Army Corps of Engineers and the SFWMD made selected operational changes to Lake Okeechobee water control, the EAA implemented BMPs, which became mandatory for all EAA farms in 1995, and both STA and WCA management, including construction projects, were implemented. One of the most effective BMPs in the EAA has been control of water movement, specifically discharge of drainage due to rainfall from the farm (Daroub et al., 2008). To facilitate water movement in ditches and canals, control of plant materials in and around these conveyances is a BMP since vegetative recycling of nutrients is one means of releasing N and P directly into the water column. Weather patterns may have also contributed to nutrient trends. The previously noted increase in

Table 3. Trends of total P concentrations at 7 stations during three different periods.

Stations	Test type	Time period	Slope (%)†	*P* value	Sig. trend†
S12A	Tobit	1977–1989	7.61	<0.001	up
S12B	Tobit	1977–1989	8.52	<0.001	up
S12C	Tobit	1977–1989	7.66	<0.001	up
S12D	Tobit	1977–1989	4.27	0.001	up
S333	Tobit	1978–1989	5.12	0.001	up
S18C	Tobit	1983–1989	22.98	<0.001	up
S332	Tobit	1983–1989	43.92	<0.001	up
S12A	Tobit	1990–1995	−31.01	<0.001	down
S12B	Tobit	1990–1995	−27.63	<0.001	down
S12C	Tobit	1990–1995	−32.28	<0.001	down
S12D	Tobit	1990–1995	−24.99	<0.001	down
S333	Tobit	1990–1995	−19.91	<0.001	down
S18C	Tobit	1990–1997	−13.95	0.001	down
S332	Tobit	1990–1997	−22.61	<0.001	down
S12A	Tobit	1996–2005	6.00	0.001	up
S12B	Tobit	1996–2005	5.55	0.000	up
S12C	Tobit	1996–2005	4.46	0.002	up
S12D	Tobit	1996–2005	3.89	0.000	up
S333	Tobit	1996–2005	3.77	0.001	up
S18C	Tobit	1998–2005	−3.07	0.022	down
S332	Tobit	1998–2005	−1.54	0.211	none

† Slope (%) = trend slope, percentage per year; Sig. trend = significant trend, $p < 0.1$.

yearly precipitation at ENP increased flows and subsequently diluted TP concentration (Fig. 8). Alternately, decreased flow in the canals during 1996 to 2005 resulting from decreased upstream annual rainfall may have contributed to increasing TP concentrations at all S12 structures and S333. Longer residence time of waters within the canals could also result in P release from nutrient-enriched soils in canals and impacted marsh areas within WCA-3A (Walker, 2002).

Water releases from WCA-3 flow directly to the L-29 canal. Thus, water quality in the southern part of the WCA-3 along the canal can have a substantial effect on water quality inflows to the ENP. Slow increasing or decreasing trends for the studied inflows are most readily influenced by nearby sources, such as the WCA-3. Due to seepage issues (USGS, 2000) in the northeast of the L-29, stage height of water at S333 has been limited to a maximum value (2.07 m National Geodetic Vertical Datum, SFWMD DBHYDRO database). Thus, water has been directed to the western portion of WCA-3, making that area considerably wetter than would be the case if sheet flow existed (SFWMD, 2001). In turn, higher water tables in WCA-3 have caused changes in the plant communities, releasing nutrients as these vegetative changes occur. This change is readily observed in plant community changes throughout WCA-3 but most dramatically in the western portion (SFWMD, 2001), just to the north of the S12 structures.

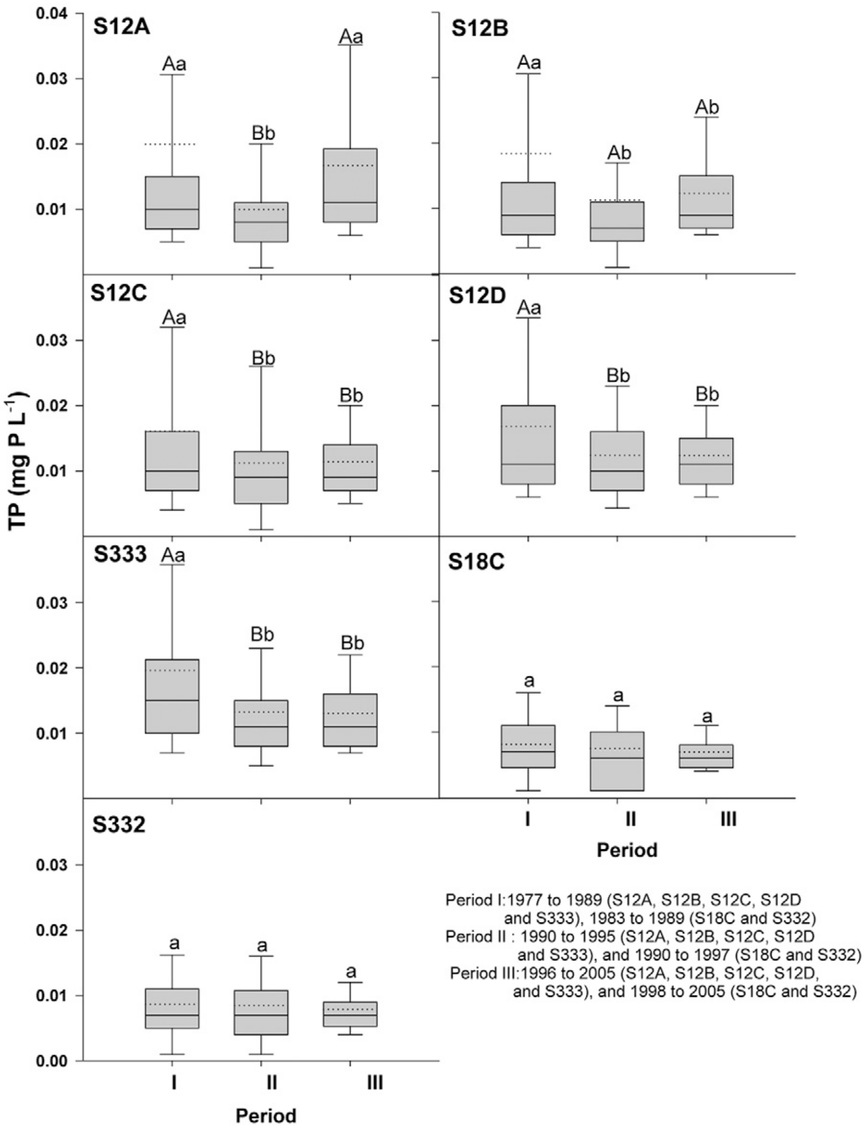

Fig. 6. Box plots of total P (TP) concentrations for the three time periods at the seven inflow stations of the Everglades National Park. Box boundaries indicate the 25th and 75th percentiles; whiskers indicate the 10th and 90th percentiles; the inner solid horizontal line is the median; and the dash horizontal line is mean. Boxes marked with the same lowercase letters are not significantly different at $P \leq 0.05$. Boxes marked with the same capital letters are not significantly different at $P \leq 0.01$.

Similar TP trend analyses were reported for Stormwater Treatment Area-5 (STA-5), located to the north and east of WCA-3, which receives water from Lake Okeechobee and the EAA (Daroub et al., 2009). The STA-5 flows discharge to the south and contribute to WCA-3. Thus, small amounts of nutrients, such as TP, are available for transport to ENP inflows. With additional small amounts of nutrients entering the ENP, flows through the S12 structures should change as nutrients create vegetation changes within the park zone receiving these waters. Indeed, a single stage height at the S12D structure only created half the inflow into the ENP in 2001 when compared with flow data from 1997 (SFWMD DBHYDRO database, data not shown). This reduced flow is suggestive of vegetation changes within the ENP and reported in WCA-3 (SFWMD, 2001). There are probably other unknown factors in this complex system that need to be investigated.

Total P concentrations at both south sites, S332 and S18C, were much lower than at the other five north inflow sites (Fig. 6). Both south sites had almost identical median TP concentrations from 1977 to 1989 (Fig. 6). Muñoz-Carpena et al. (2005) indicated that concentrations of TP from canal L-31W were consistently higher than those obtained from canal C-111 and implied that farming practices in the Frog Pond area may have affected water quality in L31W.

Significant upward trends in PO_4–P were observed at three (S12A, S12D, and S333) of the seven stations (Table 2). Because of the high percentage of PO_4–P measurements at or less than the minimum detection limit (0.004 mg L^{-1}) (Fig. 9), this trend test may overestimate the true trend of PO_4–P concentration change.

Total Nitrogen, Total Kjeldahl Nitrogen, Total Organic Nitrogen, NO_X–N, NH_4–N

Statistically significant decreasing trends in TN are evident at six of seven stations (except for S332) with the trend slope range from −3.3 to −2.3% per year (Table 2). This trend reduction is a positive contribution from improved management of TN, as described above for changes of TP, such as agricultural

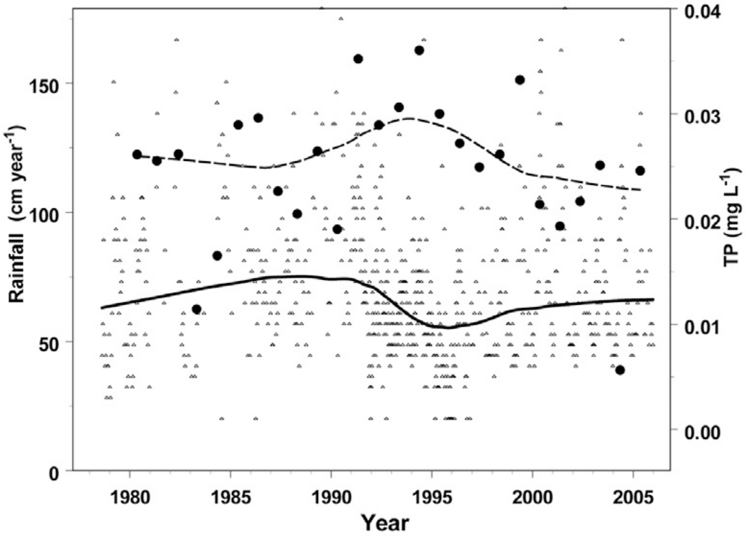

Fig. 7. Time series of yearly precipitation at one weather station (SR8, north of Everglades National Park) and monthly total P (TP) concentration at S333 with LOESS smoothing. Point (circle, solid): rainfall; point (triangle, up, empty): TP concentration; straight smoothing line: TP trend; break smooth line: rainfall trend.

BMPs addressing nutrients and water management, among other actions. The median concentration of TN ranged from 1.232 to 1.477 mg L^{-1} at all S12 structures and S333 and was 0.678 and 0.842 mg L^{-1} at S18C and S332 (Fig. 10). The USEPA ambient water quality criteria recommendation is 1.27 mg L^{-1} for TN (USEPA, 2000), and median TN concentrations at S12C, S12D, and S333 exceeded this criterion. All seven stations also showed significant downward slope trends in TKN by −3.0 to −1.8% per year (Table 2), and in TON by −3.3 to −2.3% per year (Table 2).

Median NO_X–N concentrations at S333 and S18C were four- and fivefold more, respectively, than that at S12A (Fig. 11). NO_X–N showed a statistically significant increase at S332, S18C, and S12A by 11.5, 3.8, and 3.0% per year, respectively, and significant decrease at S333 by −0.98% per year (Table 2). NH_4^+-N increased significantly at four (S12A, S12C, S12D, and S333) of seven sites by 1.5 to 5.2% per year (Table 2). Median NH_4–N concentration at S332 (0.15 mg L^{-1}) was six- and sevenfold of that at all S12 structures and S333; the next higher median concentration of NH_4–N was 0.064 mg L^{-1} at S18C (Fig. 11). Canal L31W is located in close proximity to agricultural production, which may contribute to the greater NH_4–N concentrations at S332. S18C and S332 had very high concentrations of NH_4–N, which may be related

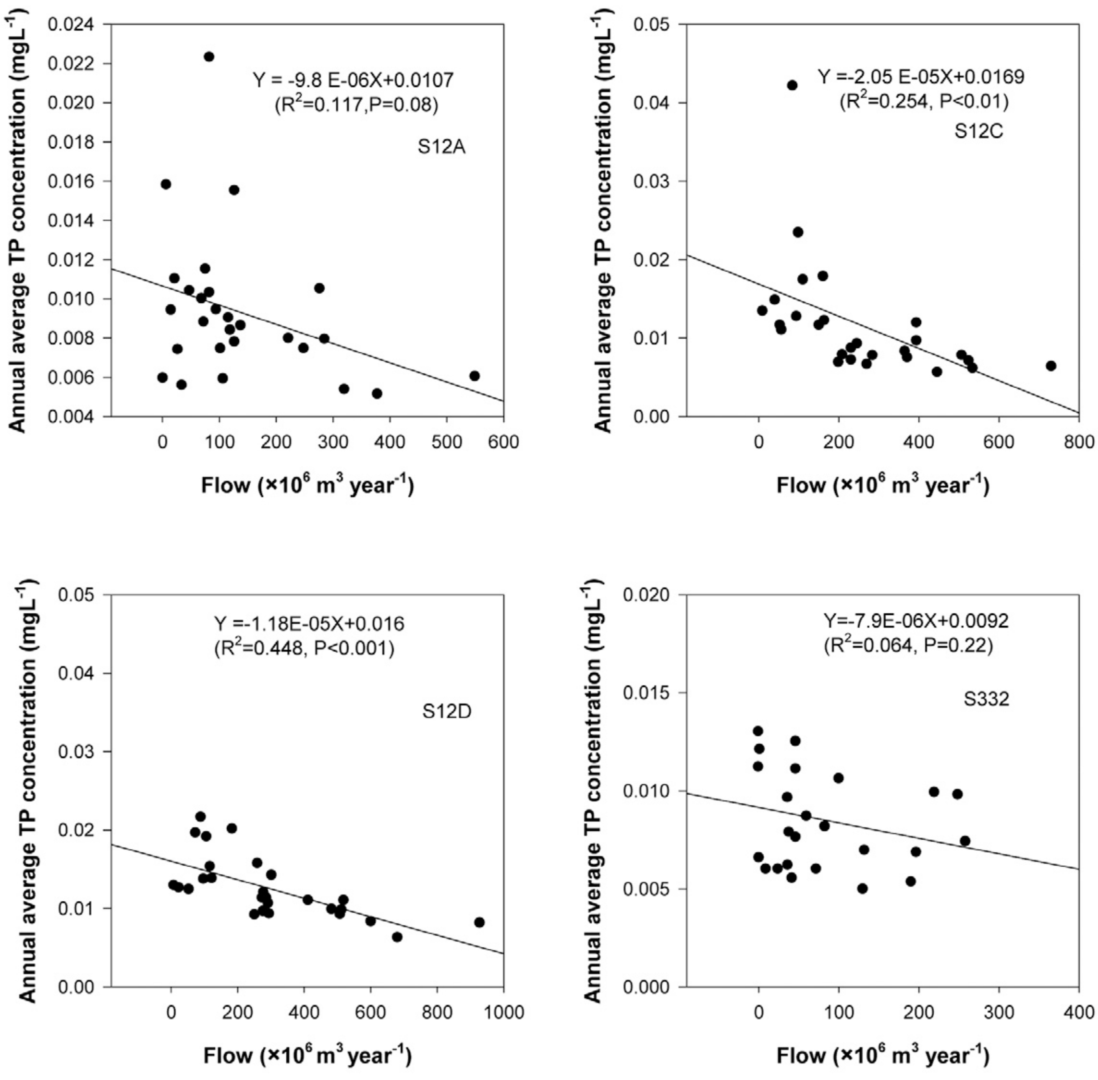

Fig. 8. Liner regression between average annual total P (TP) concentration and annual flow at S12A, S12C, S12D, and S332 from 1977 to 2005.

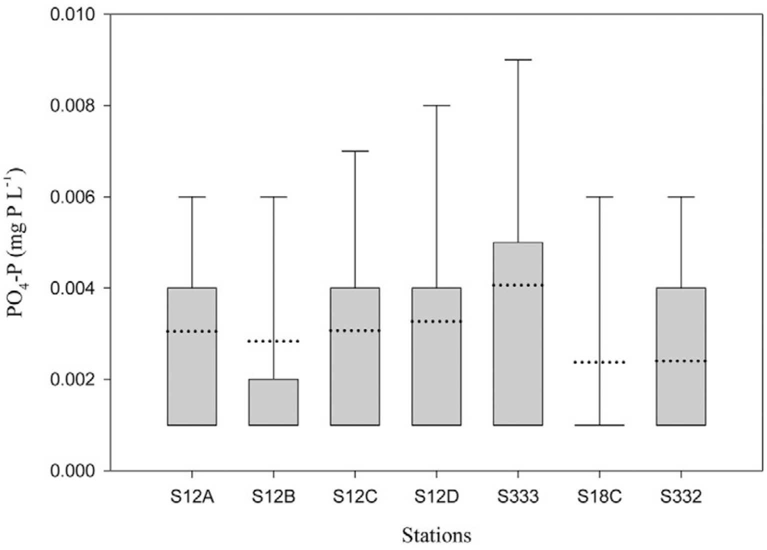

Fig. 9. PO_4–P concentrations among the stations during the period 1977 to 2005 (S12A, S12B, S12C, S12D, and S333) and 1983 to 2005 (S18C and S332).

to fertilizers applied in agricultural lands (Muñoz-Carpena et al., 2005). The state of Florida has specified an upper limit for NH_4–N of 0.02 mg L^{-1} as the surface water quality criterion of a class III freshwater body. The median concentrations of NH_4–N in the seven monitor stations were from 0.02 to 0.15 mg L^{-1}, which exceeded Class III water quality criteria (Fig. 11). Nitrogen and P are the most important water parameters in controlling eutrophication. The fact that median N concentration exceeds water quality criteria should be of concern in planning future water quality strategies.

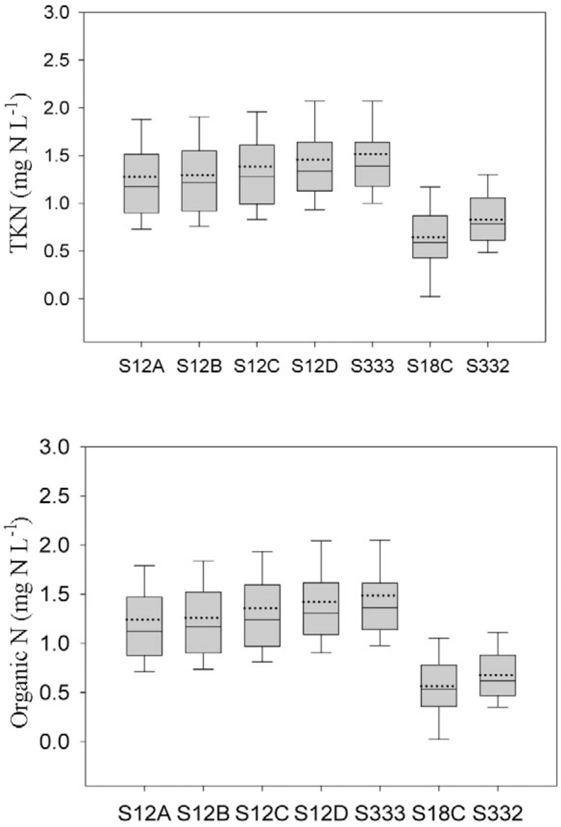

Fig. 10. Total Kjeldahl N (TKN) and organic N concentrations among the stations during the period of 1977 to 2005 (S12A, S12B, S12C, S12D, and S333) and 1983 to 2005 (S18C and S332).

Annual rainfall (Fig. 7) is probably the primary agent affecting N concentrations entering the ENP. As noted above, changes in vegetation, discussed above regarding TP, may also be contributing to N in inflow waters to the ENP. If appropriate, harvesting or other vegetation removal methods both within WCA-3 and along L-29 will probably remove a considerable amount of N from the system directly adjacent to the ENP inflows along the northern ENP boundary. However, the seepage issue, which is a result of protecting urban land uses to the east of the ENP from flooding, appears to be the causative factor in increasing water residence time in WCA-3. These aspects, including the WCA-3 water levels and seepage flows, are part of a much larger and complex system that cannot be viewed simplistically.

Conclusions

Water quality trend analysis from the seven monitoring stations at inflows to the ENP indicated that water quality improved from 1977 to 2005. Significant downward trends in TP were detected at stations S12D and S333. Subsets of the overall period showed TP concentration decreased during 1990 to 1996 at the seven inflows, consistent with the beneficial impacts: the implementation of agricultural BMPs and the construction of STAs to reduce P loads from the EAA. Other mechanisms, particularly high annual precipitation, high flows, and stage heights in the WCAs, probably also contributed to lower concentrations. The increases in TP concentration from 1995 to 2005 may be attributed to the sharp decline in precipitation. The hydrology-mediated trend of TP is supported by a negative relationship between flow and annual average TP concentration at the majority of stations. Total N, TKN, and TON also showed a significant downward trend at all seven inflows. Ammonium N, TN, and TP water quality standards were exceeded at some of the sites during the study period. Results indicate that water quality at inflow sites to the ENP has changed during the period of interest such that a statistical evaluation of the time-series data provided a better description of the current water quality status than an evaluation that only included the entire period of interest. Other issues, such as the required stage height within the western portion of the WCA-3 in an effort to control seepage in the northeastern section of the ENP, will probably persist. In turn, vegetation changes will continue to release low concentrations into the ENP through the S12 structures. Vegetation changes within the northern boundary of the ENP can be predicted to continue in response to nutrients, further restricting inflows through the S12 structures from WCA-3. Principle component analysis and FA results suggested that monitoring sites could be categorized into two groups. These findings can be used in designing water quality monitoring programs to maximize the amount of variability captured in as few stations as possible. The statistical evaluation of the data provided insight into the water quality impacts of management changes since 1977.

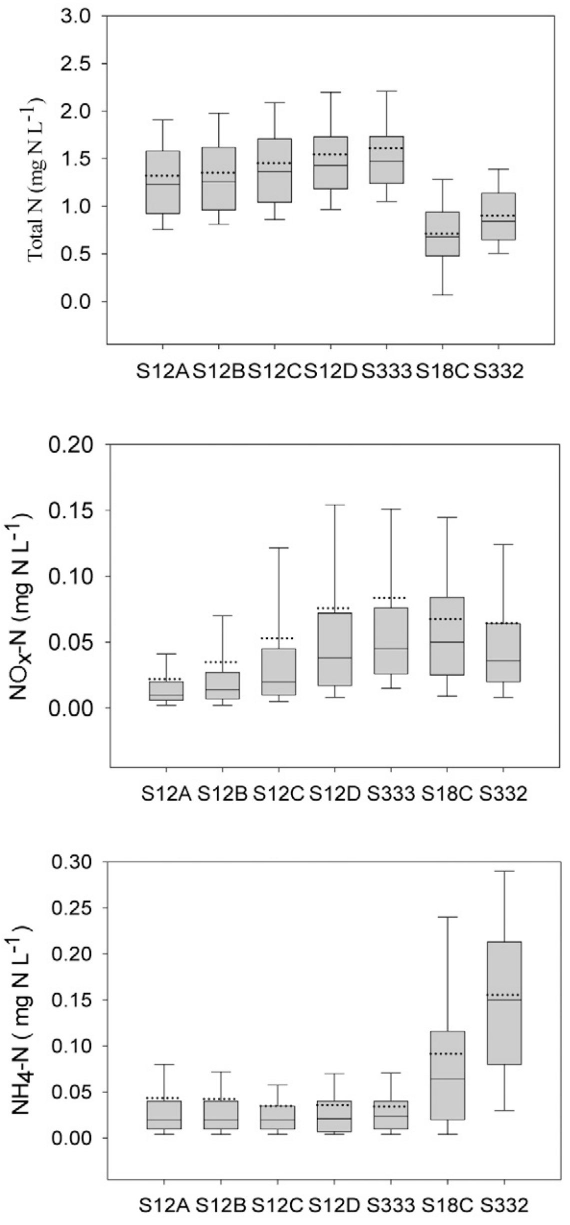

Fig. 11. Total N, NO_x–N, and NH_4–N concentrations among the stations during the period 1977 to 2005 (S12A, S12B, S12C, S12D and S333) and 1983 to 2005 (S18C and S332).

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