WATER RESOURCES BULLETIN
VOL. 27, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 1991

WATER QUALITY TRENDS AT INFLOWS TO EVERGLADES NATIONAL PARK[1]

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ABSTRACT: Water quality data collected at inflows to Everglades National Park (ENP) are analyzed for trends using the seasonal Kendall test (Hirsch *et al.*, 1982; Hirsch and Slack, 1984). The period of record is 1977-1989 for inflows to Shark River Slough and 1983-1989 for inflows to Taylor Slough and ENP's Coastal Basin. The analysis considers 20 water quality components, including nutrients, field measurements, inorganic species, and optical properties.

Significant ($p<0.10$) increasing trends in total phosphorus concentration are indicated at eight out of nine stations examined. When the data are adjusted to account for variations in antecedent rainfall and water surface elevation, increasing trends are indicated at seven out of nine stations. Phosphorus trend magnitudes range from 4 percent/year to 21 percent/year. Decreasing trends in the Total N/P ratio are detected at seven out of nine stations. N/P trend magnitudes range from –7 percent/year to –15 percent/year. Trends in water quality components other than nutrients are observed less frequently and are of less importance from a water-quality-management perspective. The apparent nutrient trends are not explained by variations in marsh water elevation, antecedent rainfall, flow, or season.

(KEY TERMS: Everglades; seasonal Kendall test; water quality; statistics; eutrophication; trend analysis; phosphorus; nitrogen; nutrients; wetlands; Florida.)

INTRODUCTION

Maintenance of the unique ecology of Everglades National park (ENP) in south Florida relies on the supply of high-quality water in the forms of direct rainfall and flow releases from the Everglades Water Conservation Areas (WCAs). Five WCAs function as shallow wetland reservoirs in meeting the flood-control, water-supply, and wetland-preservation needs of south Florida (Figure 1). Sources of flow to the WCAs include runoff from adjacent agricultural, urban, and undeveloped watersheds, releases from Lake Okeechobee, and direct rainfall. In retaining 94 percent of the total phosphorus load discharged from these sources between 1979 and 1988 (South Florida Water Management District, 1990), the WCAs have been utilized as water quality buffers. Given the existence of potent nutrient sources in WCA watersheds, maintenance of high water quality at ENP inflow points relies heavily on WCA nutrient trap efficiency, the longevity of which is unknown. Under a plan adopted in 1979 to abate eutrophication problems in Lake Okeechobee, additional nutrient loadings from the Everglades Agricultural Area have been intentionally diverted into the WCAs. Increases in phosphorus concentration have been associated with changes in plant communities and with declining water quality in portions of the WCAs (Belanger *et al.*, 1989); Lake Okeechobee Technical Advisory Council, 1990). This has raised concerns over possible deterioration of water quality at ENP inflow points and subsequent impacts on water quality and ecology within the Park.

Water quality data collected at seven ENP inflow points between 1977 and 1989 are analyzed for trends using the seasonal Kendall test (Hirsch *et al.*, 1982; Hirsch and Slack, 1984). Sensitivities of the results to hydrologic factors and to various aspects of the statistical methodology are explored. Detailed results are described in a separate report (Walker, 1990).

DATA SET

The water quality data analyzed below are derived from a monitoring program conducted by South Florida Water Management District (SFWMD) since December 1977 (Germain and Shaw, 1988). The program involves biweekly sampling at seven locations where flow is discharged from the Central and Southern Florida Flood Control Project into ENP (Figure 1). Stations are distributed among three ENP

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[1] Paper No. 90144 of the *Water Resources Bulletin*. **Discussions are open until October 1, 1991.**

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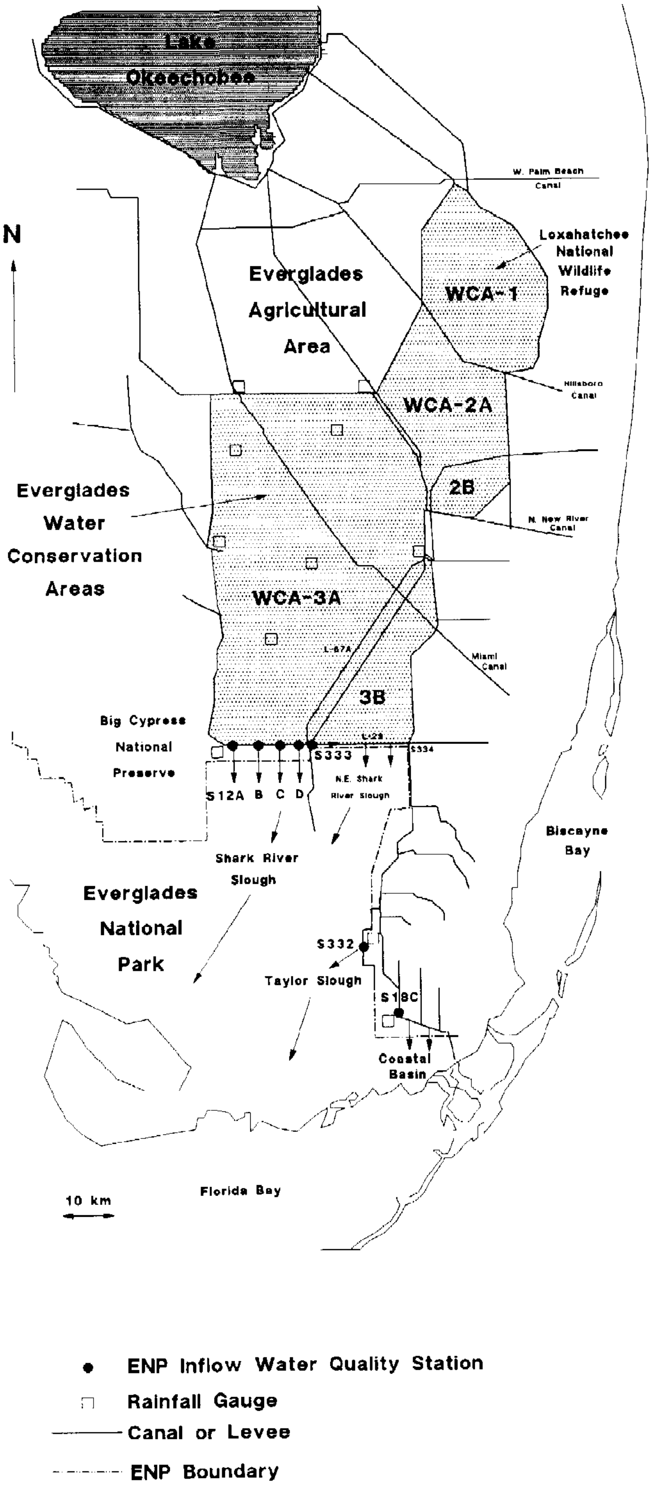

Figure 1. Station Map.

watersheds: Shark River Slough (S12A, S12B, S12C, S12D, and S333), Taylor Slough (S332), and Coastal (S18C). The period of record is December 1977-September 1989 for Shark River Slough and October 1983-September 1989 for Taylor Slough and Coastal stations.

Two composite time series (S12T and S12.334) have been constructed by calculating flow-weighted-mean concentrations across structures in Shark River Slough on each sampling date. Station S12T reflects total discharge Shark River Slough west of L67 (= S12A + S12B + S12C + S12D). Station S12.334 reflects total discharge to Shark River Slough, including the Northeast portion. These composite series have been constructed to reflect total releases to Shark River Slough and to minimize effects of shifts in flow distribution across the individual outlet structures during the monitoring period (SFWMD, 1990; Walker, 1990).

Detection of water quality trends is often complicated by hydrologic variations (Smith *et al.,* 1982). Daily flow, water elevation, and rainfall measurements have been compiled for studying correlations between hydrology and water quality (SFWMD, 1988; USGS, 1989). A spatially-averaged rainfall time series for WCA-3A has been constructed by averaging data from nine gauges in and around the reservoir (Figure 1). Mean daily water surface elevation measured by the U.S. Geological Survey upstream of S12C in WCA-3A provides an additional hydrologic variable for use in analyzing concentration data at inflows to Shark River Slough.

The analysis considers 20 water quality components, including nutrients, field measurements (dissolved oxygen, temperature, pH, conductivity), inorganic species, and optical properties (color, turbidity). Table 1 summarizes the number of observations and median concentration for each station and water quality variable. Values reported below the detection limit have been set equal to the detection limit minus a small concentration increment (0.0001 mg/liter). In this way, such values can be distinguished from values equal to the detection limit (Hirsch *et al.,* 1982). Since the trend test is based upon ranks, the precise magnitude of the concentration increment does not influence computed significance levels. The percentage of total phosphorus values reported below detection limits ranges from 1 percent to 20 percent for the individual sampling stations.

STATISTICAL METHODS

The trend analysis methodology (Figure 2) employs the seasonal Kendall test (Hirsch *et al.,* 1982; Hirsch

TABLE 1. Data Summary by Station and Water Quality Component.

	ENP Inflow Station								
Station	**S12A**	**S12B**	**S12C**	**S12D**	**S12T**	**S333**	**S12,334**	**S332**	**S18C**
ENP Basin	**◄------ Shark River Slough ------►**							**Taylor Slough**	**Coastal**
Number of Observations									
Total Phosphorus	241	246	255	249	281	196	281	143	118
Ortho Phosphorus	239	245	253	247	278	195	278	141	117
Total Nitrogen	244	249	257	250	282	194	282	146	122
Total N/P Ratio	241	246	254	247	281	194	281	143	118
Total Kjeldahl N	244	249	258	251	282	196	282	146	122
Organic Nitrogen	243	248	256	249	281	196	281	145	121
Ammonia Nitrogen	243	247	256	250	281	196	281	145	121
Nitrate+Nitrite N	244	248	256	251	281	194	281	146	122
Turbidity (NTU)	220	226	233	229	259	190	259	142	119
Color (Pt-Co Units)	209	214	222	217	246	179	246	139	114
Temperature (deg-C)	240	244	254	248	278	193	278	144	119
Dissolved Oxygen	237	242	252	246	276	191	276	141	116
pH	233	238	248	242	272	188	272	140	116
Conductivity (umhos)	237	241	251	245	275	190	275	142	118
Alkalinity	223	227	234	231	260	192	260	146	122
Chlorides	244	249	257	252	282	196	282	146	122
Calcium	81	156	93	194	200	166	201	145	122
Magnesium	80	155	92	193	199	165	200	145	122
Potassium	50	125	51	141	145	134	145	132	111
Sodium	50	125	51	143	147	136	148	145	121
Median Concentrations (mg/liter)									
Total Phosphorus	*0.010*	*0.010*	*0.010*	*0.012*	*0.011*	*0.014*	*0.013*	*0.007*	*0.007*
Ortho Phosphorus	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Total Nitrogen	1.49	1.57	1.65	1.78	1.72	1.70	1.74	0.98	1.03
Total N/P Ratio	144	154	157	138	146	112	144	123	127
Total Kjeldahl N	1.46	1.55	1.62	1.70	1.63	1.67	1.64	0.95	0.98
Organic Nitrogen	1.40	1.48	1.59	1.65	1.59	1.64	1.60	0.76	0.87
Ammonia Nitrogen	0.020	0.022	0.020	0.020	0.025	0.020	0.024	0.151	0.069
Nitrate+Nitrite N	0.010	0.016	0.022	0.036	0.030	0.051	0.035	0.028	0.031
Turbidity (NTU)	0.9	0.9	1.0	1.0	1.0	1.1	1.1	2.5	1.9
Color (Pt-Co Units)	28.0	38.0	51.2	58.3	48.2	63.7	54.2	26.2	26.4
Temperature (deg-C)	25.7	25.8	25.2	25.6	25.7	26.1	25.6	25.5	25.5
Dissolved Oxygen	4.7	4.0	3.8	3.9	3.9	3.6	3.8	4.1	5.4
pH	7.21	7.11	7.10	7.24	7.18	7.19	7.18	7.19	7.35
Conductivity (umhos)	308	361	485	617	512	658	547	495	568
Alkalinity	120	133	161	191	167	201	177	198	203
Chlorides	22.6	30.6	50.2	68.9	50.5	82.0	58.5	36.5	53.7
Calcium	40.1	46.8	53.5	62.5	57.7	63.5	60.1	72.8	75.3
Magnesium	3.0	4.1	8.3	12.8	9.0	14.9	11.1	5.1	6.9
Potassium	0.93	1.34	2.36	2.86	2.28	3.24	2.85	1.12	2.78
Sodium	13.2	21.3	35.9	44.8	35.4	52.6	42.3	22.7	33.3

Stations	**Period of Record**	**Number of Water Years/Variable**
Shark River Slough	**Dec. 1977-Sept. 1989**	**11-12**
S332, S18C	**Oct. 1983-Sept. 1989**	**6**

and Slack, 1984). This test has been recommended frequently for application to water quality time series (Smith *et al.*, 1982; Van Belle and Hughes, 1984; Gilbert, 1987; Hipel *et al.*, 1988; Mattraw *et al.*, 1987; Berryman *et al.*, 1988; Loftis *et al.*, 1989; Reckhow and Stow, 1990). Desirable properties of the test include that it is nonparametric and that it is applicable to time series containing values which are missing, below detection limits, and/or influenced by seasonal factors. A robust estimate of trend magnitude, the seasonal Kendall slope (Hirsch *et al.*, 1982), is also computed for each station and water quality component.

Two versions of the seasonal Kendall test are used in screening ENP inflow data for trends. One version (Hirsch *et al.*, 1982) assumes that there is no

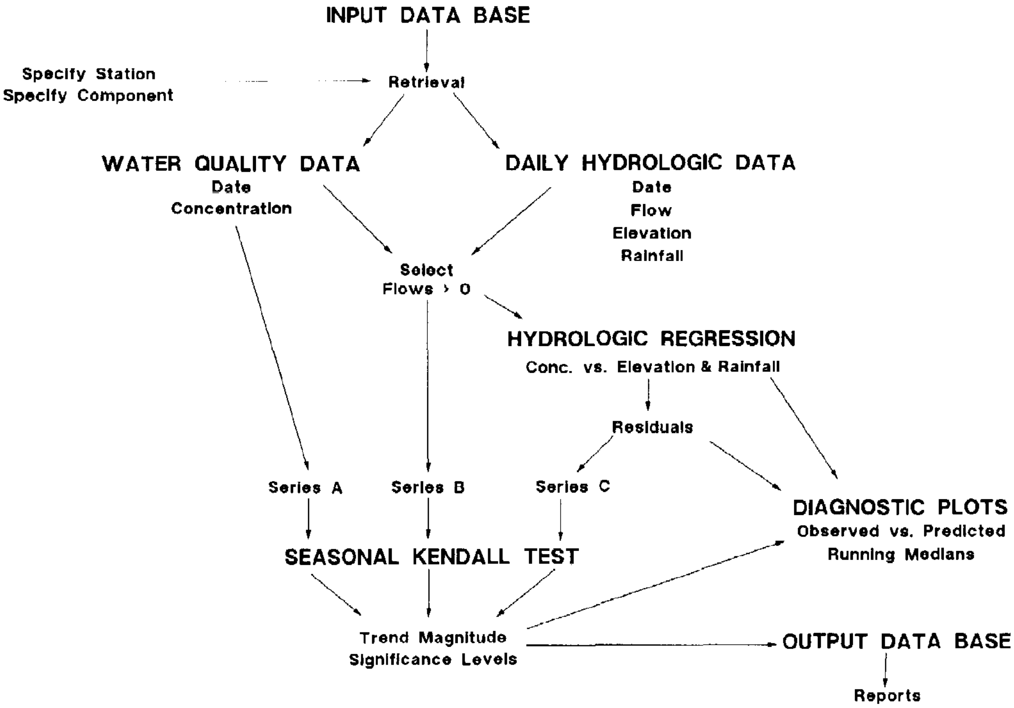

Figure 2. Trend Analysis Methodology.

covariance among seasons. The predicted significance levels for this test trend to be too low for serially correlated time series (Hirsch *et al.*, 1982). This causes rejection of the null hypothesis at too high a frequency or "false trends." A second version of the test (Hirsch and Slack, 1984) accounts for serial correlation. Simulation studies indicate that the test overestimates significance levels (causing rejection of the null hypothesis at too low a frequency or failure to detect trends) for time series less than about 10 years in length (Hirsch and Slack, 1984). Both significance levels have been computed for each test, along with estimates of trend magnitude and serial correlation. Because serial correlation is present in most of the time series, results of the second significance test are emphasized. Because of the relatively short period of record for stations S18C and S332 (six years), this test may overestimate significance levels and thereby fail to detect trends at these stations.

As illustrated in Figure 2, trend tests are applied to three time series for each station and water quality component:

Series A – all concentration data, $\log_{10}$ transformed;

Series B – concentrations measured on days when positive flow was reported at the sampled structure, $\log_{10}$ transformed;

Series C – residuals (observed-predicted) from regression models relating concentration to antecedent rainfall and upstream water elevation, for samples collected on days with positive flow.

Most of the variables have positively skewed distributions. Use of the logarithmic transformation reduces skewness and facilitates expression of trend magnitudes in consistent units (percent per year), as described below. Because the tests are nonparametric and based upon ranks, significance levels calculated for the seasonal Kendall tests are independent of the logarithmic transformation.

The objective of Series C is to adjust concentration time series for variations in hydrologic conditions. Regression-based adjustment procedures have been used in testing water quality time series for trend (Hirsch *et al.*, 1982; Smith *et al.*, 1982; Montgomery and Reckhow, 1984; Reckhow and Stow, 1990). This adjustment provides two basic advantages over testing raw data time series:

(1) It can reduce variability and serial correlation in the time series and thereby increase power for detecting trends (Lettenmaier, 1976).

(2) It can reduce the probability of "false trends," or rejections of the null hypothesis which reflect variations in rainfall and/or elevation, rather than true long-term trends.

The extent of these advantages depends upon the particular time series and upon the performance of the regression model, as measured by reductions in variance and serial correlation.

In the Series C tests, concentrations are regressed against antecedent rainfall and upstream water elevation using a model of the following form:

$$\log_{10}(C) = A_0 + A_1 \log_{10}\left(P_i + 0.01\right) + A_2 \; E_j \tag{1}$$

where,

C = sample concentration (mg/liter);

P_i = total precipitation for i antecedent days, where i=1 on the date of the sample (inches);

E_j = average water elevation upstream of S12C for j antecedent days (feet); and

A_0, A_1, A_2 = regression coefficients.

It is impossible to select *a-priori* the appropriate time scales (i,j) for relating hydrologic factors to concentration. Time scales would depend upon the rates of physical, chemical, and biological processes influencing concentration levels at each station. Stepwise multiple regression (Snedecor and Cochran, 1989) is performed to select optimal values of i and j for each station and water quality component. Antecedent periods of 1, 7, 30, 90, 180, 270, and 365 days are tested for each hydrologic factor. If a significant ($p < 0.10$) correlation is not found for any time scale, the corresponding hydrologic term (rainfall or elevation) is dropped from the equation. In this way, the hydrologic adjustment scheme is "guided" by the data set and only includes variables and time scales which are correlated with concentration.

Testing of alternative expressions indicates that a logarithmic transformation is preferable to a linear expression of antecedent rainfall, based upon explained concentration variance. Frequency distributions of antecedent rainfall values tend to be positively skewed, particularly at short lags. A small increment of 0.01 inch (lowest recorded daily rainfall) is added to antecedent rainfall in order to permit inclusion of zero values.

The elevation term reflects the water level upstream of S12C in Water Conservation Area 3A. Elevation measurements at this location are highly correlated with measurements at three stations monitored in the interior of WCA-3A ($r = 0.92$ to 0.97). The elevation term is included only for stations which are located at outlets from WCA-3A. A nine-station average daily rainfall from gauges in and around WCA-3A (see Figure 1) is used for analysis of the Shark River Slough stations. S332 and S18C rainfall records are derived from gauges located at these structures.

Because of intentional shifts in the distribution of flow across the outlets from WCA-3A during the study period, flow terms are not included in the hydrologic adjustment model. As noted by Mattraw *et al.* (1987), consideration of flow would be more appropriate for unregulated streams or for regulated reservoirs with fixed operating rules. Sensitivity analyses indicate that little additional concentration variance is explained by including flow terms, once rainfall and elevation terms have been considered. Conclusions regarding the presence or absence of trends are also insensitive to inclusion or exclusion of flow terms.

The objective of the hydrologic adjustment is to produce a time series of residuals which is uncorrelated with antecedent rainfall and marsh water elevation for each station and water quality component. Testing of such a series would reduce the risk that apparent trends are attributed to variations in rainfall or water level. Several modifications of this hydrologic adjustment scheme have been tested and found to give similar results (Walker, 1990).

In applying the seasonal Kendall test to each series, observations (or residuals) are first grouped by season and year. As implemented by Hirsch *et al.* (1982), "years" are defined based upon Water Year (October through September). Following Crawford *et al.* (1983), seasons are defined to provide 12 periods of equal length; these differ slightly from calendar months because of variations in the number of days per month. When multiple observations are available in a given season and year, the median value is used in the trend test. The data are arrayed in a two-way table of medians (seasons x years). Kendall's Tau test is applied separately to each season (Hirsch *et al.*, 1982). The procedure provides an estimate of trend and significance level for each season separately and for all seasons combined. Trend magnitude is expressed in units of percent per year:

$$T = (10^B - 1) \times 100\% \tag{2}$$

where,

T = trend (percent/year), and

B = Kendall slope estimator for $\log_{10}$-transformed data (or residuals).

This expression is used as a general indicator of trend magnitude which is independent of concentration units. It does not imply that the underlying distribution is increasing or decreasing at a fixed percentage per year. The seasonal Kendall test is for monotonic (generally increasing or generally decreasing) trends and does not distinguish among alternative trend forms or shapes (linear, log-linear, step change, complex).

RESULTS FOR S12 TOTAL PHOSPHORUS CONCENTRATION

The entire analysis involves testing 540 data sets for trend (9 stations x 20 components x 3 series). Detailed presentation and discussion of each test result would be infeasible. To demonstrate the methodology, results for total phosphorus at Station S12T (composite of gates A, B, C, and D) are discussed below. This choice of station and variable also reflects relative importance from a management perspective and the longest period of record. Results are tested for sensitivity to data subsets and to various aspects of the methodology. Results for other stations and variables are summarized and discussed in a subsequent section.

The test data set includes 281 daily composite total phosphorus concentrations computed from 991 samples collected at stations S12A, S12B, S12C, and S12D between December 1977 and September 1989; flow was released through at least one of the S12 structures on 257 out of 281 sampling dates. Sample concentration, upstream water elevation, and flow are plotted in Figure 3. Stepwise multiple regression against hydrologic factors, as specified in Equation (1), yields the following equation for use in Series C tests:

$$\log_{10}(C) = 1.857 - 0.213\,E_{30} - 1.091\log(P_{365} + 0.01) \qquad (3)$$

R^2 = 43.2%, Standard Error of Estimate = 0.236

Regression against E_{30} alone explains 40.6 percent of the concentration variance. Adding the P_{365} term explains another 2.6 percent and brings the total to 43.2 percent. Regression against antecedent rainfall alone yields an optimal lag of 270 days and explains 33.5 percent of the concentration variance.

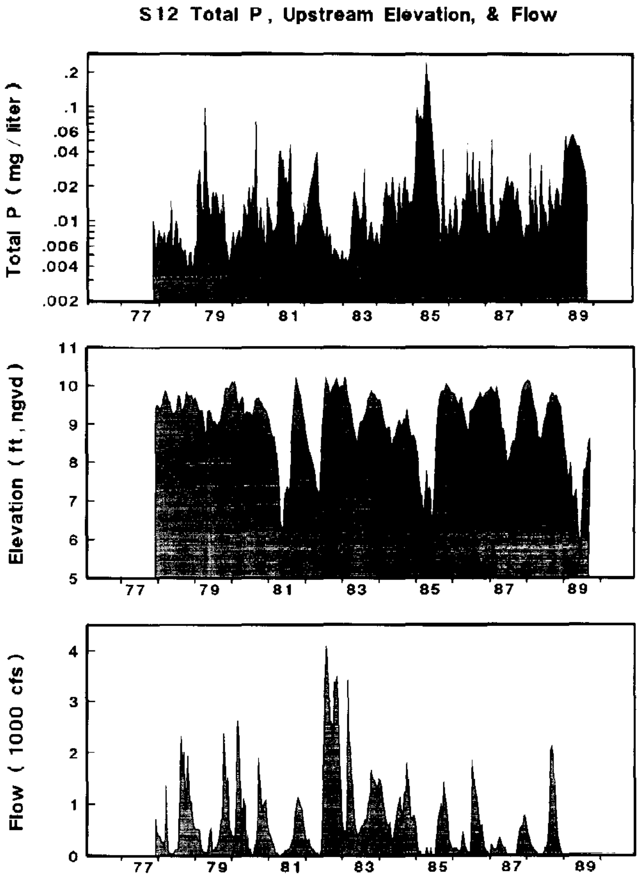

Figure 3. S12 Total Phosphorus, Upstream Elevation, and Flow.

The negative correlation between S12 total phosphorus concentration and upstream marsh elevation may be related to three mechanisms: (1) variations in WCA-3A hydraulic residence time (influencing phosphorus trap efficiency); (2) relative importance of canal flow (e.g., along L-67) vs. marsh sheet flow at lower water elevations; and (3) inherent tendency for phosphorus concentrations in Everglades marshes to increase at lower water elevations because of evaporation and increased mineralization of plant detritus and peat (Worth, 1988; Walker, 1990). The apparent significance of relatively long rainfall time scales (270-365 days) may reflect the hydraulic residence time of the WCA-3A marsh (averaging 0.73 years, SFWMD, 1990). Causal interpretations of the individual regression terms are difficult, however. The reason for performing the regression is not to determine precisely which hydrologic factors and time scales cause variations in concentration, but to generate a time series of residuals which is statistically independent of antecedent rainfall and elevation for subsequent trend testing.

Application of the seasonal Kendall test to S12 phosphorus data for each series is illustrated in Table 2. Based upon sampling date, each observation is assigned to a season (approximately corresponding to calendar month) and water year. A separate time series is constructed and tested for each season. Test results include the Kendall slope, corresponding trend (from Equation (2)), and the mean and variance of the Kendall's S statistic (Hirsch *et al.,* 1982). To develop the yearly test, the mean and variance of the S statistics are totaled across seasons. A separate calculation yields an estimate of the covariance of the S statistics across seasons (Hirsch and Slack, 1984). Overall significance levels are computed both with and without seasonal covariance.

A positive trend is calculated for each time series (original data and elevation/rainfall residual) and for each season. Trend estimates for individual seasons range from 1.7 to 9.2 percent/year. Overall trend estimates are 7.0, 5.7, and 5.3 percent/year for Series A, B, and C, respectively. Significance levels are $< 10^{-4}$, 10^{-4}, and $< 10^{-4}$, respectively, for the test which ignores seasonal covariance. Serial correlation coefficients for detrended monthly medians are 0.71, 0.66, and 0.29, respectively. This suggests that results from the more conservative test which accounts for serial correlation (Hirsch and Slack, 1984) should be given greater weight. Significance levels for this test are 0.0437, 0.0603, and 0.0093, respectively. These results indicate that a two-tailed null hypothesis (no trend) can be rejected at confidence levels of 95.6 percent, 94.0 percent, and 99.1 percent, respectively; a one-tailed null hypothesis (no increasing trend) can be rejected at confidence levels of 97.8 percent, 97.0 percent, and 99.5 percent, respectively. An increasing trend in total phosphorus at the S12 inflows to Everglades National Park is highly probable.

Based upon simulation studies, Hirsch and Slack (1984) found that actual Type I errors for their test exceeded nominal values for 10-20 year time series with unusually high persistence (first-order autoregressive coefficient > 0.60). The serial correlation coefficients (r_1) for Series A ($r_1 = 0.71$) and B ($r_1 = 0.66$) are in the range where this may be a factor. Simulations at a nominal significance level of 0.10 yielded empirical significance levels of ~ 0.12 (autoregressive coefficient = 0.60) and ~ 0.26 (autoregressive coefficient = 0.90) (Hirsch and Slack, 1984, Table 1). If we interpolate between these limits, actual Type I error levels would be 0.17 for $r_1 = 0.71$ and 0.15 for $r_1 = 0.66$ for a nominal significance level of 0.10. These represent error inflation rates of 70 percent and 50 percent, respectively. Applying these rates to the estimated significance levels for Series A (0.0437) and Series B (0.0603) yields adjusted significance levels of 0.074 and 0.090, respectively. The adjusted results indicate that a two-tailed null hypothesis of no trend can be rejected at > 90 percent confidence level.

The elevation/rainfall regression (Series C) has two impacts on the trend analysis. First, it reduces concentration variance by 43.2 percent. Second, it reduces residual serial correlation from 0.66 to 0.29. Both of these impacts would be expected to increase power for trend detection. As a result, the overall significance level for the Series C test (0.0093) is much lower than the significance level for the Series B test (0.0603). The hydrologic adjustment has a minor impact on the magnitude of the trend estimate (5.7 to 5.3 percent/year). Both the trend magnitude and conclusions regarding the presence or absence of a trend are insensitive to the hydrologic adjustment. An increasing trend of 5.1 percent/year (standard error = 1.0 percent/year) is estimated by multiple regression (Walker, 1990).

SENSITIVITY ANALYSIS

Sensitivity of test results to various factors is examined in Table 3. The analysis of S12 total phosphorus data has been repeated using alternative regression models and data subsets. The following factors have been examined:

(1) Modifying the hydrologic regression model (Equation (1)) to include rainfall, flow, and elevation terms, both separately and simultaneously.

(2) Modifying the hydrologic regression model to permit inclusion of multiple lags for each variable category (NMAX in Table 3), subject to the constraint that each term is significant at $p < 0.10$.

(3) Using 26 instead of 12 seasons per year in the seasonal Kendall test to reflect the biweekly sampling frequency.

(4) Using alternative rainfall data sources in the hydrologic regression, including:

(a) nine-station average from gauges in and around WCA-3A,
(b) four-station average from gauges within WCA-3A, and

TABLE 2. Seasonal Kendall Tests Applied to S12T Total Phosphorus Data.

Season Month	Samples	Years	S	Var(S)	Median	Trend (percent/year)	RA	Prob
SERIES A – TEST CONCENTRATIONS, ALL DATA								
1 October	24	11	21	165	0.0081	7.8	0.04	0.1195
2 November	23	11	23	165	0.0091	9.2	0.08	0.0868
3 December	19	12	16	213	0.0075	6.1	–0.03	0.3036
4 January	25	12	24	213	0.0076	7.3	0.23	0.1147
5 February	25	12	18	213	0.0096	8.9	–0.16	0.2437
6 March	25	12	22	213	0.0103	6.0	–0.28	0.1498
7 April	25	12	18	213	0.0093	8.7	–0.10	0.2437
8 May	22	12	18	213	0.0178	5.7	–0.33	0.2437
9 June	21	12	18	213	0.0156	5.8	–0.05	0.2437
10 July	23	12	18	213	0.0143	8.0	–0.25	0.2437
11 August	23	12	24	213	0.0172	7.1	–0.08	0.1147
12 September	26	12	24	213	0.0127	6.7	–0.13	0.1147
Year	281	12	244	2457	0.0107	7.0	0.71	0.0000
Year*	281	12	244	14509	0.0107	7.0	0.71	0.0437
SERIES B – TEST CONCENTRATIONS, FLOWS > 0								
1 October	24	11	21	165	0.0081	7.8	0.04	0.1195
2 November	23	11	23	165	0.0091	9.2	0.08	0.0868
3 December	19	12	16	213	0.0075	6.1	–0.03	0.3036
4 January	24	11	17	165	0.0075	6.5	0.25	0.2129
5 February	23	11	9	165	0.0091	3.7	–0.16	0.5334
6 March	22	11	13	165	0.0100	4.4	–0.32	0.3502
7 April	22	11	9	165	0.0091	5.7	–0.03	0.5334
8 May	20	10	7	125	0.0147	3.4	–0.35	0.5914
9 June	17	10	19	125	0.0156	5.7	–0.14	0.1074
10 July	18	10	7	125	0.0116	4.9	–0.35	0.5914
11 August	21	10	11	125	0.0155	4.0	0.09	0.3710
12 September	24	11	17	165	0.0121	5.8	–0.10	0.2129
Year	257	12	169	1868	0.0102	5.7	0.66	0.0001
Year*	257	12	169	8001	0.0102	5.7	0.66	0.0603
SERIES C – TEST RESIDUALS FROM REGRESSION AGAINST ANTECEDENT ELEVATION & RAINFALL								
1 October	24	11	25	165	–0.0972	7.1	–0.01	0.0617
2 November	23	11	25	165	–0.0038	7.2	0.21	0.0617
3 December	19	12	24	213	–0.1146	4.1	0.47	0.1147
4 January	24	11	45	165	–0.0910	8.2	0.65	0.0006
5 February	23	11	15	165	–0.0939	8.0	0.19	0.2757
6 March	22	11	7	165	–0.0558	4.1	0.09	0.6404
7 April	22	11	19	165	–0.0814	3.7	0.34	0.1611
8 May	20	10	11	125	0.0058	1.7	–0.24	0.3710
9 June	17	10	11	125	0.1054	6.9	–0.03	0.3710
10 July	18	10	13	125	–0.0121	4.6	–0.05	0.2831
11 August	21	10	17	125	0.0585	7.5	–0.15	0.1524
12 September	24	11	9	165	0.0087	3.5	–0.25	0.5334
Year	257	12	221	1868	–0.0399	5.3	0.29	0.0000
Year*	257	12	221	7156	–0.0399	5.3	0.29	0.0093

NOTES:

MONTH = calendar month corresponding to season (approximate).
S, VAR(S) = mean and variance of Kendall's S statistic (Hirsch *et al.*, 1982).
MEDIAN = median concentration (Series A & B, mg/l) or residual (Series C, log10 units).
TREND = trend calculated from seasonal Kendall slope (Hirsch *et al.*, 1982), percent/year.
RA = first-order serial correlation of detrended seasonal values.
Year = summary computed without seasonal covariance (Hirsch *et al.*, 1982).
Year* = summary computed with seasonal covariance term (Hirsch and Slack, 1984).
PROB = two-tailed significance level.

(c) values from a single station closest to the S12's (southwest of S12A, Figure 1).

This series of regressions also considers extended rainfall lags beyond one year (1, 7, 30, 90, 180, 270, 365, 545, 730, and 910 days) and includes any regression term significant at $p < 0.10$.

(5) Excluding data from January 1-September 15, 1985 (duration of the phosphorus spike in Figure 3, associated with low WCA-3A water elevations and open S12 gates).

(6) Considering wet season (May-October) vs. dry season (November-April) data separately.

(7) Considering low-elevation (< 9.4 feet) vs. high-elevation (> 9.4 feet) observations separately; elevation cutpoint selected to divide data set roughly in half.

(8) Excluding periods of extreme low elevation (< 8 feet), associated with phosphorus spikes in Figure 3.

(9) Considering low-flow (< 500 cfs) vs. high-flow (> 500 cfs) data separately; flow cutpoint selected to divide data set roughly in half.

Test results are generally insensitive to these factors. Estimated trend magnitudes range from 3.3 to 7.0 percent/year. Significance levels for the more conservative test accounting for serial correlation are below 0.10 in 28 out of 33 tests summarized in Table 3.

Results are insensitive to modifications in the hydrologic regression model, number of seasons per year, rainfall data source, and wet-season vs. dry-season subsets. When flow alone is used in the hydrologic regression equation, the significance level increases to 0.2196. Flow explains only 21.1 percent of the variance of the concentration variance, however, as compared with 33.5 percent for antecedent rainfall and 40.6 percent for elevation. Adjustment based upon flow is complicated by increases in S333 flows and decreases in S12 flows which occurred in and after 1984 as a result of changes in water management strategies. The presence of a significant increasing trend when data from January 1-September 15, 1985, are excluded indicates that the trend is not explained by the phosphorus spike evident in Figure 3.

When the sensitivity analysis in Table 3 is repeated using the combined discharge to Shark River Slough (Station S12_334), significance levels are below 0.06 in every case except for the low-flow and low-elevation data sets. The relative weakness of trends in low-flow or low-elevation samples partially reflects the fact that concentrations are more variable under these conditions. For example, the log-scale standard deviation of the low-flow and high-flow data sets for S12T are 0.339 and 0.244, respectively. Higher variability makes it more difficult to identify trends. Another important factor contributing to higher significance levels is that the number of observations is cut in half when the data set is split; this reduces the power of the test. Despite differences in significance levels, estimates of trend magnitude are similar for the low-flow vs. high-flow data sets and for the low-elevation vs. high-elevation data sets. The fact that trends are more distinct under high-flow conditions is important because such conditions are primarily responsible for phosphorus transport into the Park. Analysis of S12 daily flow data for water years 1978-1989 indicates that flow rates exceeding 500 cfs accounted for 87 percent of the total discharge volume and 49 percent of the total days.

RESULTS FOR OTHER STATIONS AND COMPONENTS

The seasonal Kendall test has been applied to data for each station and water quality component. Detailed results are reported in Walker (1990). Table 4 summarizes the number of significant test results as a function of probability level (< 0.01, < 0.05, < 0.10), test method (with vs. without seasonal covariance), and test series (A, B, and C). Application of the more conservative test which accounts for serial correlation reduces the number of significant results, particularly at the 0.01 test level. The number of significant results in each category far exceeds that which would be expected based upon chance if no trends existed. For example, 52 Series B results out of 180 tests had significance levels less than 0.10. If no trends existed, the expected number of significant results would be 18 (= 0.10 x 180).

Table 5 lists estimated trend magnitudes for each station, variable, and series for all tests with two-tailed significance levels less than 0.10 using the more conservative test (Hirsch and Slack, 1984). Increasing trends in total phosphorus are indicated in at least one test series (A, B, or C) at eight out of nine stations (excluding S18C). With adjustments for antecedent elevation and rainfall (Series C), increasing trends are indicated at seven out of nine stations (excluding S333 and S18C). An increasing phosphorus trend (9.1 percent/year) is also likely at S18C, based upon the estimated significance level for Series B and C ($p = 0.1048$) and the tendency for the test to overestimate significance levels in time series less than 10 years in length (Hirsch and Slack, 1984). Trend magnitudes in residuals range from 4.2 percent/year for S12D to 20.6 percent/year for S332. Conclusions regarding the presence or absence of trend, as well as trend magnitudes, are insensitive to hydrologic adjustment of the time series (Series B vs. Series C) for the combined discharges to Shark River

TABLE 3. Seasonal Kendall Tests Applied to S12 Total Phosphorus Data – Sensitivity Analysis.

Case	Hydrologic Variables	NMAX	OBS	TERMS	R2	SE	RA	TREND (percent/ year)	PROB1	PROB2
Flow>=0 Series A	None	0	281	0	0.000	0.333	0.71	7.0	0.0000	0.0437*
Flow>0 Series B	None	0	257	0	0.000	0.311	0.66	5.7	0.0001	0.0603*
Flow>0 Series C	Elev, Rainfall	1	257	2	0.432	0.236	0.29	5.3	0.0000	0.0093*
Modified Regressions	Elevation	1	257	1	0.406	0.241	0.33	5.5	0.0000	0.0340*
Modified Regressions	Rainfall	1	257	1	0.335	0.255	0.38	6.0	0.0000	0.0081*
Modified Regressions	Flow	1	257	1	0.211	0.278	0.53	3.3	0.0333	0.2196
Modified Regressions	Elev, Rainfall, Flow	1	257	3	0.447	0.234	0.26	4.6	0.0000	0.0096*
Modified Regressions	Elev, Rainfall	7	257	4	0.468	0.230	0.23	4.9	0.0000	0.0116*
Modified Regressions	Elevation	7	257	2	0.422	0.238	0.32	5.4	0.0000	0.0354*
Modified Regressions	Rainfall	7	257	3	0.407	0.242	0.30	5.3	0.0000	0.0163*
Modified Regressions	Flow	7	257	3	0.266	0.269	0.45	4.7	0.0012	0.0971*
Modified Regressions	Flow, Elev, Rainfall	7	257	5	0.478	0.228	0.19	4.8	0.0001	0.0210*
Seasons/Year = 26	None	0	257	0	0.000	0.311	0.59	6.5	0.0000	0.0515*
Seasons/Year = 26	Elev, Rainfall	1	257	2	0.432	0.236	0.26	5.6	0.0000	0.0065*
Rain Gauge–WCA-3A (9-st)	Rainfall (Extended Lag)	10	257	4	0.417	0.241	0.30	5.4	0.0000	0.0141*
Rain Gauge–WCA-3A (4-st)	Rainfall (Extended Lag)	10	257	3	0.321	0.259	0.42	6.3	0.0000	0.0124*
Rain Gauge–Tamiami Trail	Rainfall (Extended Lag)	10	257	3	0.379	0.248	0.40	5.0	0.0003	0.0558*
Excl. Jan. 1-Sept. 15, 1985	None	0	245	0	0.000	0.262	0.50	4.8	0.0008	0.0479*
Excl. Jan. 1-Sept. 15, 1985	Elev, Rainfall	1	245	2	0.292	0.223	0.20	4.9	0.0000	0.0080*
May-October	None	0	124	0	0.000	0.310	0.27	5.3	0.0049	0.0664*
May-October	Elev, Rainfall	1	124	2	0.359	0.252	0.10	4.8	0.0049	0.0574*
November-April	None	0	133	0	0.000	0.294	0.57	5.8	0.0076	0.1413
November-April	Elev, Rainfall	2	133	2	0.523	0.206	0.22	5.8	0.0000	0.0043*
Elevation > 9.4	None	0	134	0	0.000	0.249	0.20	5.3	0.0010	0.0641*
Elevation > 9.4	Elev, Rainfall	1	134	2	0.215	0.224	0.05	6.1	0.0000	0.0044*
Elevation < 9.4	None	0	126	0	0.000	0.319	0.55	6.7	0.0152	0.1676
Elevation < 9.4	Elev, Rainfall	1	126	2	0.479	0.234	0.20	4.6	0.0043	0.0921*
Elevation > 8	None	0	234	0	0.000	0.252	0.41	5.6	0.0000	0.0148*
Elevation > 8	Elev, Rainfall	1	234	2	0.230	0.223	0.17	4.9	0.0000	0.0046*
Flow > 500 cfs	None	0	122	0	0.000	0.244	0.28	5.5	0.0068	0.0748*
Flow > 500 cfs	Elev, Rainfall	1	122	2	0.282	0.211	–0.03	4.7	0.0012	0.0204*
Flow < 500 cfs	None	0	135	0	0.000	0.339	0.57	5.0	0.0737	0.3295
Flow < 500 cfs	Elev, Rainfall	1	135	1	0.440	0.257	0.32	4.8	0.0069	0.1596

NOTES:

NMAX = maximum number of terms included in hydrologic regression in each class (elev., rainfall, or flow), each term significant at $p < 0.10$.
OBS = number of water quality observations.
TERMS = total terms included in regression against hydrologic variables.
R2 = fraction of concentration variance explained by regression.
SE = standard error of estimate for hydrologic regression (log10 units).
RA = first-order serial correlation of detrended concentrations or residuals.
TREND = trend (percent/year) calculated from seasonal Kendall slope (Hirsch *et al.*, 1982).
PROB1 = significance level, 2-tailed test, without seasonal covariance (Hirsch *et al.*, 1982).
PROB2 = significance level, 2-tailed test, with seasonal covariance (Hirsch and Slack, 1984).
* = trend significantly different from zero, PROB2 < 0.10.

All tests run using data collected on days with positive flow and 12 seasons/year, unless otherwise noted.

TABLE 4. Number of Significant Trends vs. Significance Level, Test Method, and Series.

Seasonal Kendall Test	Two-Tailed Significance Level	Number of Significant Results			
		Series A	Series B	Series C	Expected
Without Seasonal Covariance	< 0.01	92	53	51	1.8
(Hirsch *et al.*, 1982)	< 0.05	109	77	74	9
	< 0.10	120	88	88	18
With Seasonal Covariance	< 0.01	6	5	16	1.8
(Hirsch and Slack, 1984)	< 0.05	49	34	43	9
	<0.10	70	52	58	18
Total Tests		180	180	180	

NOTES:

Tests include nine stations and 20 water quality components

Test Series:
Series A = all data.
Series B = flows > 0.
Series C = flows > 0, adjusted for antecedent water elevation and rainfall.
Expected = expected number of significant results if no trends existed.

Observed frequency of significant results >> Expected number in each case ($p < 0.05$).

Slough (S12T and S12_334), for the discharge to Taylor Slough (S332), and for the discharge to the Coastal basin (S18C). Positive trends in ortho phosphorus are indicated at three stations for Series A and one station for Series B, although trend magnitudes cannot be quantified because of the high percentage of ortho phosphorus measurements at or below the lower detection limit (0.004 mg/liter).

Decreasing trends in total nitrogen are evident at five Shark River Slough stations (S12C, S12D, S12T, S333, and S12_S334) in each Series. Estimates of trend magnitude range from –2.7 to –4.4 percent/year. Results for individual nitrogen species suggest that decreases in total nitrogen are primarily attributed to the organic fraction, which accounts for 92 percent of the median total nitrogen measured at S12T (Table 1). For Series C, increasing trends in nitrate + nitrite nitrogen concentrations are indicated at S12A (11.9 percent/year) and S332 (21.9 percent/year), while a decreasing trend is ammonia nitrogen is indicated at S332 (–21.9 percent/year).

Decreasing trends in Total N/P ratio at seven stations (–7.1 to –15.3 percent/year) reflect the coincidence of increasing total phosphorus and decreasing total nitrogen levels. Declining N/P ratios have been associated with changes in lake microbial communities (Smith, 1983) and are consistent with eutrophication of the upstream marshes. Nitrogen losses through plant uptake and denitrification would be promoted by greater plant productivity and lower dissolved oxygen regimes characteristic of phosphorus-enriched zones (Belanger *et al.*, 1989). Changes in N/P load ratios to the WCA's could also cause decreases in outflow N/P ratios.

Trends in water quality components other than nutrients are identified in specific instances, but seem of less importance from a water-quality-management perspective. Compared with results for the individual and composite S12 structures, results for the composite discharge to Shark River Slough (S12_334) are less likely to be influenced by changes in the distribution of flows across the S12's and S333. Aside from nutrients, a trend is detected at S12_334 only in the case of sodium (–3.2 percent/year, Series B and C). This represents one significant result out of 12 tests of nonnutrient species and is not different from that which would be expected based upon chance for hypothesis tests conducted at the 0.1 significance level (1.2 = 0.1 x 12). The frequency of significant results for nutrients, particularly total phosphorus, total nitrogen, and total N/P ratio, far exceeds that which would be expected based upon chance. Trend magnitudes for each station, series, and nutrient are summarized in Figure 4.

CONCLUSION

Water quality data collected by the South Florida Water Management District at inflows to Everglades National Park have been examined for trends using the seasonal Kendall test (Hirsch *et al.*, 1982; Hirsch and Slack, 1984). Results indicate a pattern of

TABLE 5. Trend Magnitudes vs. Station, Variable, and Series.

Variable	ENP Inflow Station								
	S12A	**S12B**	**S12C**	**S12D**	**S12T**	**S333**	**S12_334**	**S332**	**S18C**
SERIES = A – RAW DATA, ALL SAMPLING DATES									
Total Phosphorus	6.9	9.0	8.5	4.4	7.0	4.4	8.4	23.3	
Ortho Phosphorus	>0.0				>0.0		>0.0		
Total Nitrogen			–3.0	–4.0	–3.2	–3.5	–2.9		
Total N/P Ratio	–7.6	–10.3	–9.9	–9.0	–10.0	–9.0	–10.5	–18.0	
Total Kjeldahl N			–2.8	–3.9	–3.0	–3.7	–2.9		
Organic Nitrogen			–3.3	–4.0	–3.4	–3.8	–3.3		
Ammonia Nitrogen									
Nitrate+Nitrite N	11.3							18.3	20.0
Turbidity (NTU)									
Color (Pt-Co Units)				–4.3	–3.8	–4.2			10.4
Temperature (deg-C)	0.4	0.3	0.4	0.2	0.3		0.3		1.5
Dissolved Oxygen			1.6						
pH									
Conductivity (umhos)				–3.3	–4.0	–3.0	–2.5		
Alkalinity				–2.4	–2.4	–2.0			
Chlorides	4.2			–4.2	–4.6	–4.1			
Calcium									
Magnesium				–7.9	–8.3	–5.4	–5.2		
Potassium				–6.3	–8.5				
Sodium				–7.5	–9.2	–6.6	–6.6		
SERIES = B – RAW DATA, DATES WITH POSITIVE FLOWS									
Total Phosphorus	9.9	8.4	8.4		5.7		7.4	23.0	
Ortho Phosphorus	>0.0								
Total Nitrogen			–3.2	–4.4	–3.3	–4.1	–2.7		
Total N/P Ratio	–9.8		–9.6	–7.0	–8.6		–9.5	–17.0	
Total Kjeldahl N			–3.0	–4.5	–3.1	–4.5	–2.7		
Organic Nitrogen			–3.2	–4.6	–3.2	–4.1	–2.7		
Ammonia Nitrogen									
Nitrate+Nitrite N	11.4							15.9	
Turbidity (NTU)									8.5
Color (Pt-Co Units)									
Temperature (deg-C)			0.2		0.3				
Dissolved Oxygen									
pH									
Conductivity (umhos)				–2.5	–3.9	–3.8			
Alkalinity				–1.7	–3.1				
Chlorides				–2.9	–3.9	–3.7			
Calcium				–1.8	–2.9				
Magnesium				–5.3	–7.6	–4.9			
Potassium					–7.2				
Sodium			–23.4	–4.6	–8.5	–4.6	–3.2		
SERIES = C – RESIDUALS FROM ELEVATION/RAINFALL REGRESSION									
Total Phosphorus	6.4	6.7	6.6	4.2	5.3		7.0	20.6	
Ortho Phosphorus									
Total Nitrogen			–3.6	–4.4	–3.5	–3.5	–2.9		
Total N/P Ratio	–8.9	–7.1	–8.4	–7.4	–8.5		–9.3	–15.3	
Total Kjeldahl N			–3.3	–4.2	–3.3	–4.1	–2.6		
Organic Nitrogen			–3.4	–4.5	–3.4	–4.2	–2.9		
Ammonia Nitrogen								–19.1	
Nitrate+Nitrite N	11.9							21.9	
Turbidity (NTU)									10.4
Color (Pt-Co Units)					–3.1				
Temperature (deg-C)		0.9							
Dissolved Oxygen									
pH									
Conductivity (umhos)				–2.5	–4.1	–2.7		2.5	
Alkalinity					–2.8				
Chlorides				–2.8	–5.0	–3.9		9.4	
Calcium				–1.4	–2.0				
Magnesium	4.6			–5.6	–6.9	–5.1			7.8
Potassium				–6.2	–7.0				
Sodium			–16.1	–5.4	–8.1	–4.6	–3.2		

NOTE: Table lists trend magnitudes (percent/year) with two-tailed significant levels < 0.10 based upon seasonal Kendall test accounting for seasonal covariance (Hirsch and Slack, 1984).

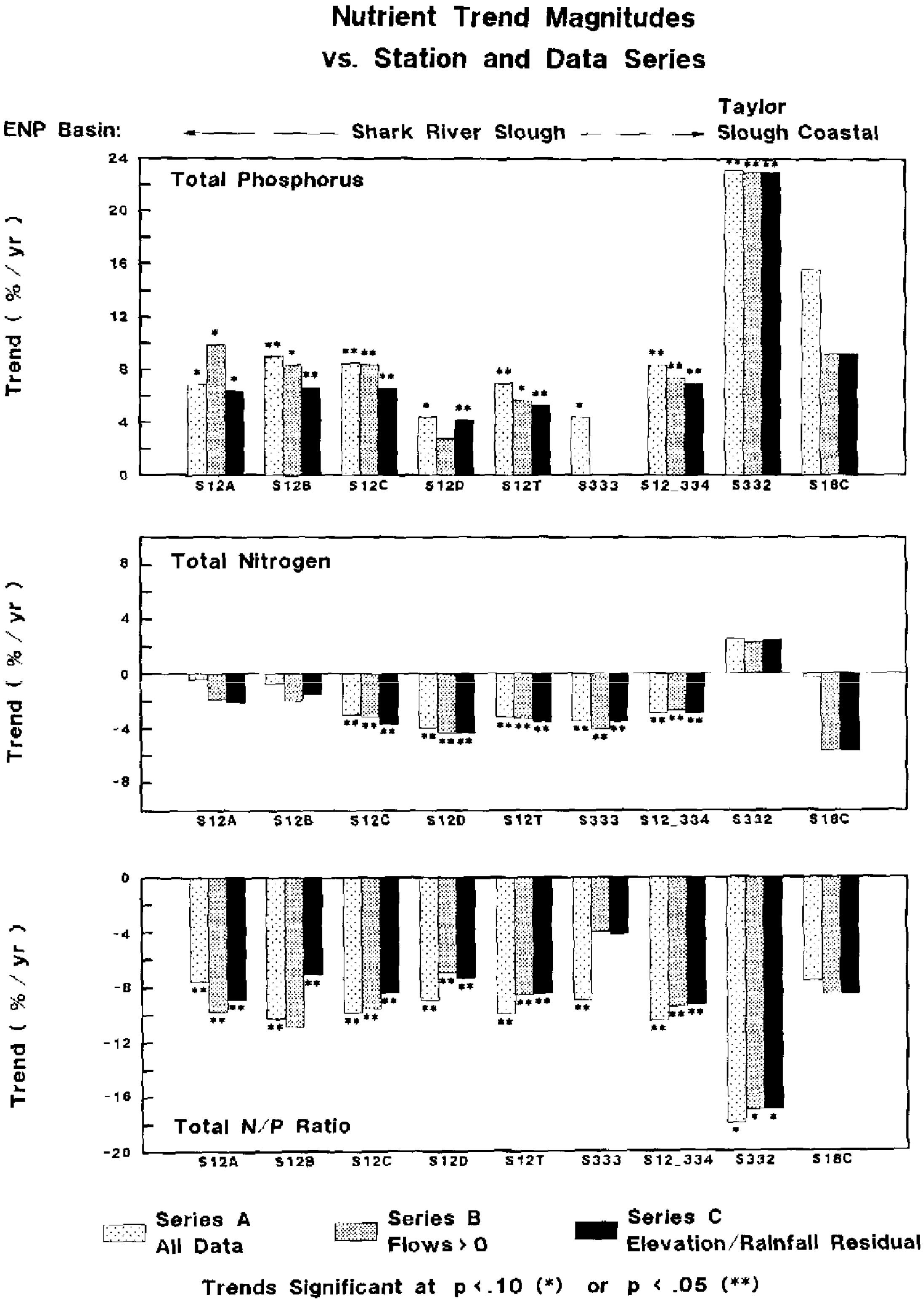

Figure 4. Nutrient Trend Magnitudes vs. Station and Data Series.

increasing phosphorus concentrations and decreasing N/P radios at ENP inflow points. Conclusions regarding the presence or absence of nutrient trends are insensitive to adjustment of the time series to account for variations in hydrologic factors (rainfall, water elevation, or flow). Trends detected for the 1977 to 1989 period cannot be extrapolated into the past or into the future. The analysis does not distinguish among alternative trend shapes (linear, exponential, step change at a specific date) or identify specific causes. Increasing phosphorus concentrations and decreasing N/P ratios are symptoms of eutrophication, a process which must be avoided if the unique water quality and ecology of ENP marshes are to be preserved.

ACKNOWLEDGMENTS

This analysis was supported by the U.S. Department of Justice, Environment and Natural Resources Division. Daniel Sheidt, Robert Johnson, and David Sikkema of the Everglades National Park Research Laboratory assisted in supply data and reviewing the manuscript. Comments by Dennis Helsel, James Slack, and Aaron Higer of the U.S. Geological Survey, James Loftis of Colorado State University, Robert Gerzoff of Environ Corporation, and AWRA reviewers are also gratefully acknowledged.

LITERATURE CITED

Belanger, T. V., D. J. Scheidt, and J. R. Platko, 1989. Effects of Nutrient Enrichment on the Florida Everglades. Lake and Reservoir Management 5(1):101-112.

Berryman, D., B. Bobee, D. Cluis, and J. Haemmerli, 1988. Nonparametric Tests for Trend Detection in Water Quality Time Series. Water Resources Bulletin 24(3):545-556.

Crawford, C. G., J. R. Slack, and R. M. Hirsch, 1983. Nonparametric Tests for Trends in Water-Quality Data Using the Statistical Analysis System. U.S. Geological Survey, Open-File Report 83-550.

Germain, G. J. and J. E. Shaw, 1988. Surface Water Quality Network. South Florida Water Management District, Technical Publication 88-3.

Gilbert, R. O., 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand.

Hipel, K. W., A. I. McLeod, and R. R. Weiler, 1988. Data Analysis of Water Quality Time Series in Lake Erie. Water Resources Bulletin 24(3):533-544.

Hirsch, R. M. and J. R. Slack, 1984. A Nonparametric Trend Test for Seasonal Data with Serial Dependence. Water Resources Research 20(6):727-732.

Hirsch, R. M., J. R. Slack, and R. A. Smith, 1982. Techniques of Trend Analysis for Monthly Water Quality Data. Water Resources Research 18(1):107-121.

Lake Okeechobee Technical Advisory Council (LOTAC II), 1990. Final Report to State of Florida.

Lettenmaier, D. P., 1976. Detection of Trends in Water Quality Data from Records with Dependent Observations. Water Resources Research 12(5):1037-1046.

Loftis, J. C., R. C. Ward, R. D. Phillips, and C. Taylor, 1989. An Evaluation of Trend Detection Techniques for Use in Water Quality Monitoring Programs. U.S. Environmental Protection Agency, Office of Acid Deposition Environmental Monitoring and Quality Assurance, Washington, D.C., EPA/600/3-89/037.

Mattraw, H. C., D. J. Scheidt, and A. C. Federico, 1987. Analysis of Trends in Water-Quality Data for Water Conservation Area 3A, The Everglades, Florida. U.S. Geological Survey, Water Resources Investigations Report 87-4142.

Montgomery, R. H. and K. H. Reckhow, 1984. Techniques for Detecting Trends in Lake Water Quality. Water Resources Bulletin 20(1):43-52.

Reckhow, K. H. and C. Stow, 1990. Monitoring Design and Data Analysis for Trend Detection. Lake and Reservoir Management 6(1):49-60.

Smith, R. A., R. M. Hirsch, and J. R. Slack, 1982. A Study of Trends in Total Phosphorus Measurements at Stations in the NASQAN Network. U.S. Geological Survey, Water Supply Paper 2190.

Smith, V., 1983. Low Nitrogen to Phosphorus Ratios Favor Dominance by Blue-Green Algae in Lake Phytoplankton. Science 221:669-671.

Snedecor, G. W. and W. G. Cochran, 1989. Statistical Methods, 8th Edition. The Iowa State University Press, Ames, Iowa.

South Florida Water Management District, 1988. Access to the South Florida Water Management District Hydrologic Data Base. Data Management Division, Version 3.1.

South Florida Water Management District, 1990. Everglades SWIM Plan (draft).

U.S. Geological Survey, 1989. Water Resources Data for Florida. Miami, Florida, Office.

Van Belle, G. and J. P. Hughes, 1984. Nonparametric Tests for Trend in Water Quality. Water Resources Research 20(1):127-136.

Walker, W. W., 1990. Water Quality Trends at Inflows to Everglades National Park. Prepared for U.S. Department of Justice, Environment and Natural Resources Division, Washington, D.C.

Worth, D. F., 1988. Environmental Response of WCA-2A to Reduction in Regulation Schedule and Marsh Drawdown. Technical Publication No. 88-2, South Florida Water Management District.