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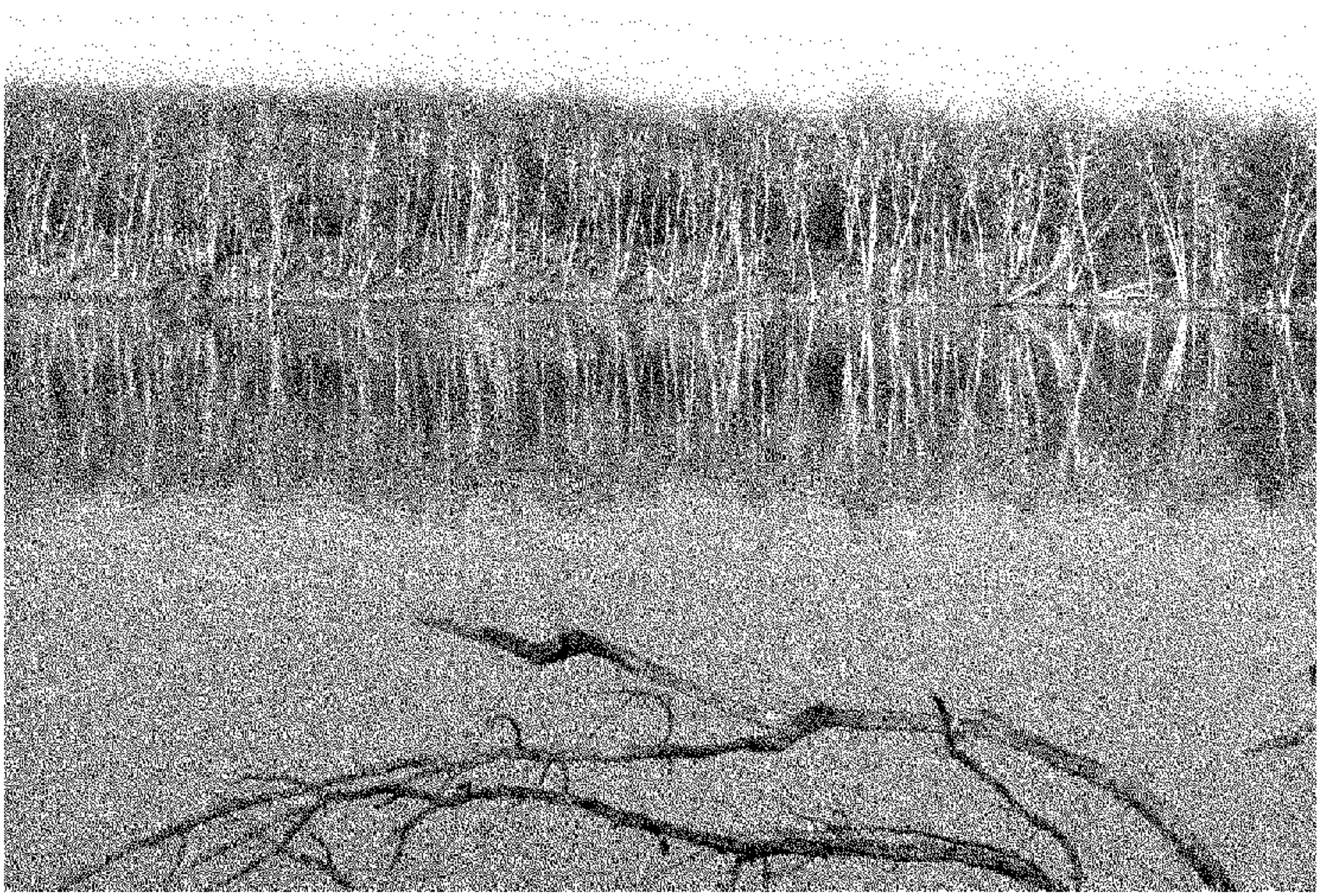


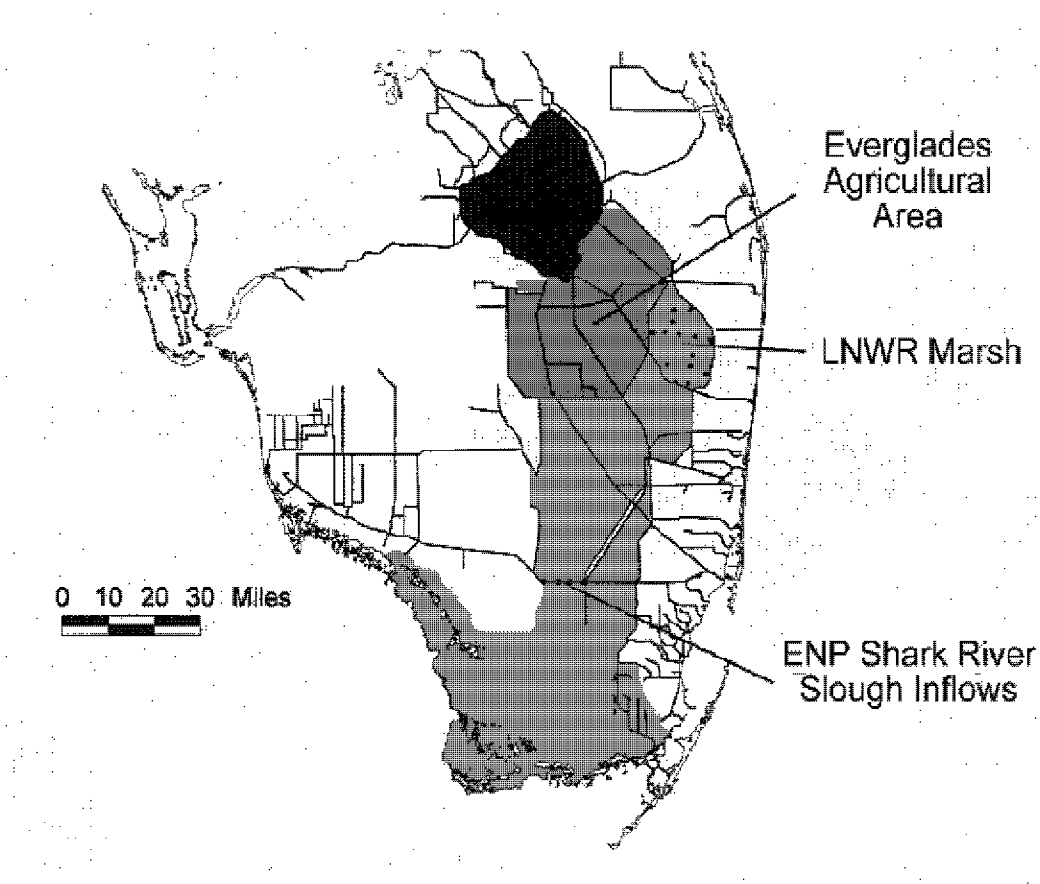
11. Interim Phosphorus Standards for the Everglades

by William W. Walker, Jr.

Eutrophication induced by anthropogenic phosphorus loads poses a long-term threat to Everglades ecosystems. Substantial shifts in macrophyte and microbial communities have been observed in regions located downstream of agricultural discharges (Belanger et al., 1989; Nearhoof, 1992; Davis, 1994). This problem developed over a period of three decades following construction of the Central and Southern Florida Flood Control Project and drainage of wetland areas south of Lake Okeechobee to support intensive agriculture (Figure 1).

In 1988, a lawsuit was filed by the federal government against the local regulatory agencies (Florida Department of Environmental Regulation and South Florida Water Management District (SFWMD)) for not enforcing water quality standards in Loxahatchee National Wildlife Refuge (LNWR) and Everglades National Park (ENP). The lawsuit ended in an out-of-court Settlement Agreement (SA) (USA et al., 1991) and federal consent decree in 1992.

Figure 1: Projects in South Florida



The SA establishes interim and long-term requirements for water quality, control technology, and research. Generally, interim standards and controls are designed based upon existing data and known technologies The interim control program includes implementation of agricultural Best Management Practices (BMP's) and construction of wetland Stormwater Treatment Areas (STA's) to reduce phosphorus loads from the Everglades Agricultural Area (EAA) by approximately 80 percent, relative to a 1979-1988 baseline.

Subsequently, SFWMD adopted the EAA Regulatory Rule (SFWMD, 1992; Whalen and Whalen, 1994), which requires implementation of BMP's in the EAA to achieve an annual-average phosphorus load reduction of at least 25 percent. The State of Florida (1994) passed the Everglades Forever Act, which defines a construction project and funding mechanism for STA's. Interim phosphorus standards will apply after interim control technologies are in place (1999-2006 for LNWR and 2003-2006 for ENP Shark Slough Inflows). Long-term standards (>2006) and control technologies will be developed over a period of several years and require a substantial research effort to develop supporting data.

Specific statistical procedures for tracking progress of the restoration effort and for determining compliance with interim and long-term objectives are built into the Settlement Agreement, EAA Regulatory Rule, and Everglades Forever Act. These procedures provide measures of performance that are important from technical, political, and legal perspectives. This report describes the general model upon which these procedures are based. Specific applications include:

- P standards for inflows to ENP (2 basins)
- P standards for marsh stations in LNWR
- Load-reduction requirements for the EAA

Each tracking procedure was developed within the constraints of historical data to accomplish a specific objective. They share a model structure which is generally applicable in situations where historical monitoring data are to be used as a frame of reference for interpreting current and/or future monitoring data. This would be the case when the management goal is to restore the system to its historical condition, to prevent degradation beyond its current condition, or to require improvement relative to its historical or current condition. This paper describes the model and its application to ENP Shark River Slough inflows. Other applications are briefly summarized.

General Model

Explicit consideration of variability is the key to formulating a valid tracking procedure. Procedures are developed by calibrating the following general model to historical data:

Response = Average + Temporal Effect + Hydrologic Effect + Random Effect (1)

The Response is the measurement to be tracked (e.g., concentration or load, averaged over appropriate spatial and temporal scales, linear or log-transformed). The Average represents the mean value of the Response during the calibration period. The Temporal Effect represents a long-term trend in the historical data (if present); this may reflect anthropogenic influences (e.g., land development, new point-source discharges, etc.). The Hydrologic Effect represents correlations of the Response with other measured variables, such as flow, water level, and/or rainfall (if present). The Random Effect is essentially an error term which represents all other sources of variance, including sampling error, analytical error, and variance sources not reflected in the Temporal or Hydrologic terms.

As demonstrated below, inclusion of Temporal and Hydrologic terms increases the statistical power of the tracking procedure (reduces risk of Type I and Type II errors). These terms can be excluded in situations where long-term trends are not present or where significant correlations between the response variable and hydrologic variables cannot be identified. In such a situation, the response would be treated as a purely random variable and the model would be identical to that described by Smeltzer et al. (1989)

for tracking long-term variations in lake water quality. The model can be expanded to include multiple Hydrologic Effects, interactions between Temporal and Hydrologic Effects, as well as other deterministic terms. Seasonal Effects (if present) can be considered by adding another term or eliminated by defining the Response as an annual statistic (average, median, etc.).

The model is not constrained to any particular mathematical form. For example, Hydrologic Effects can be predicted by a simulation model, provided that uncertainty associated with such predictions (Random Effects) can be quantified. The applications described below invoke relatively simple, multiple regression models which provide direct estimates of parameter uncertainty. The Hydrologic term provides a basis for adjusting historical and future monitoring data back to an average hydrologic condition, so that changes in the long-term mean (typically reflecting anthropogenic influences) can be tracked and not confused with random climatologic variability (e.g., wet-year vs dry-year differences).

Table 1 outlines three applications of the model to the Everglades. Data from a consistent, long-term monitoring program are desirable for calibrating and applying the model. Ideal data sets are rarely encountered, however, particularly if historical monitoring programs were not designed explicitly to collect data for this purpose. Everglades applications are based upon data sets ranging from 7 to 11 years in duration with monitoring frequencies ranging from biweekly to monthly. One strength of the data is that sampling and analyses have been consistently performed by a single agency (SFWMD). The following sections describe calibration and application of the model to ENP Shark River Slough inflows.

Model Calibration to Historical Monitoring Data

Interim standards for ENP Shark River Slough were designed to provide annual, flow-weighted-mean concentrations equivalent to those measured between March 1, 1978, and March 1, 1979, the legally established base period consistent with ENP's designation as an Outstanding Florida Water (OFW). Analysis of monitoring data collected between December 1977 and September 1989 collected at five inflow structures (S12A,B,C,D & S333) revealed significant increasing trends in phosphorus concentrations and negative correlations between concentration and flow (Walker, 1991). To reduce possible influences of season and shifts in the flow distribution across the five inflow structures, the annual-average, flow-weighted-mean concentration across all five structures was selected as a response variable and basis for the interim standard. Annual values for Water Years 1978-1990 (October-September) were used to calibrate a regression model of the following form:

$$Y = Ym + b_1 (T - Tm) + b2 (Q - Qm) + E \qquad (2)$$

where

Y = observed annual, flow-weighted-mean concentration (ppb)
T = water year (1978-1990)
Q = basin total flow (1000 acre-ft/yr)
E = random error term
m = subscript denoting average value of Y, T, or Q in calibration period

Prior to calibration, biweekly concentration data used to calculate annual flow-weighted means were screened for outliers from a log-normal distribution while accounting for correlations between concentration and flow (Snedocor & Cochran, 1989); a single sample was rejected on this basis. Data from Water Years 1985 and 1986 were excluded from the calibration because of unusual operating conditions which promoted discharge of high-phosphorus canal flows (vs. marsh sheet flows) through the inflow structures. The flow-weighted-mean concentrations were 33 and 21 ppb, respectively, as compared with a range of 7 to 18 in other Water Years. These unusual operating conditions are not expected to be repeated in the future.

Table 1: Model applications to the Everglades

Location	Everglades Agricultural Area	ENP Shark Slough Inflows	Loxahatchee National Wildlife Refuge
Reference	EAA Regulatory Rule (1992) Whalen & Whalen (1994)	Interim Standards Settlement Agreement (1991)	Interim Standards Settlement Agreement (1991)
Objective	25% Load Reduction vs. Oct 1979-Sept 1988	1978-79 conditions; baseline period for outstanding Florida waters	1978-79 conditions; baseline period for outstanding Florida waters
Response variable	Total P load	Total P concentration	Total P concentration
Temporal averaging	May-April water year	Flow-weighted mean Sept-Oct water year	Monthly
Spatial averaging	Total EAA thru 18 structures, adjusted for inputs from other basins & releases from Lake Okeechobee	Combined inflows from 5 structures in Shark River slough	Geometric mean across 14 marsh stations
Calibration period	May 1979-April 1988 9 water years 2058 samples	Oct 1977-Sept 1990 11 water years 222 sampling dates 1115 samples	July 1978-July 1983 14 sampling rounds 191 samples
Samples excluded	3 statistical outliers	Oct 1984-Sept 1986 (2 water years, unusual operation) 1 statistical outlier	2 dates with mean stage < 15.42 ft (missing values; marsh sampling difficult)
Temporal effect	None	Linear trend	Step change after base period
Hydrologic effect(s)	Basin rainfall, 9 stations Thiessen average Rainfall statistics: annual total, CV of monthly totals, skewness of monthly totals	Basin total flow Total thru 5 structures	Stage (water surface elev) Average of 3 stations
Transformation	Natural logarithm	None	Natural logarithm
Variance explained	90%	80%	67%
Residual standard error	0.18 (~18%)	1.87 ppb (~16%)	0.31 (~31%)
Base period	Water years 1980-88	Water years 1978-79	June 1978-May 1979 First full year of data
Target	75% of base period (25% load reduction)	100% of base period	100% of base period
Limit	90th percentile	90th percentile	90th percentile
Exceedence condition	> limit in any year, or > target in ≥ 3 consecutive years	> limit in any year	> limit in > 1 month in any consecutive 12-month period

Table 2 lists calibration data and results. The model explains 80% of the variance in the historical data set with a residual standard error of 1.87 ppb. The fit is illustrated in Figure 2. Figure 2A plots observed and predicted concentrations against time. The 80 percent prediction interval (10th, 50th, and 90th percentiles) are shown in relation to the observed data. Both regression slopes are significant at $p < .05$. The partial regression concept (Snedocor & Cochran, 1989) is applied below to illustrate the importance of each term in the model.

Table 2: Derivation of interim standards for ENP Shark River Slough inflows

		Flow-Weighted-Mean Total P Concentration					
Water year	Basin Flow kac-ft/yr	Observed ppb	Predicted ppb	Flow-Adjusted ppb	Detrended ppb	50% target ppb	90% limit ppb
78	522.8	6.7	8.4	6.7	7.0	8.4	11.7
79	407.0	9.8	9.6	9.2	9.5	9.0	12.3
80	649.2	10.6	9.0	11.2	9.7	9.6	11.1
81	291.7	12.4	11.3	11.4	11.0	10.2	12.9
82	861.3	8.4	9.2	10.0	6.3	10.8	10.1
83	1061.3	7.0	8.9	9.5	4.4	11.4	9.4
84	842.8	12.0	10.5	13.4	8.7	12.0	10.2
87	276.6	15.9	14.9	14.8	10.9	13.8	13.0
88	585.5	15.6	14.1	15.9	10.0	14.4	11.4
89	116.9	13.5	16.9	11.6	7.3	15.0	14.0
90	148.2	18.1	17.3	16.3	11.2	15.6	13.8
Mean	523.9	11.8	11.8	11.8	8.7	8.7	11.8

Variables: Y = observed TP (ppb), T = water year, b_1,b_2 = regression slopes, m = subscript denoting mean value, Q = observed flow (kac-ft/yr), E = random error (ppb), SE = regression standard error of estimate (ppb), m = subscript denoting mean value..

Regression model: $Y = Y_m = b_1(T - T_m) + b_2 (Q - Q_m) + E$

$= 11.8 + 0.5932 (T - 83.7) - 0.00465 (Q - 523.9) + E$

Regression results: $R^2 = 0.80$, SE = 1.873 ppb, $Y_m = 11.8$ ppb, $T_m = 83.7$, $Q_m = 523.9$ kac-ft/yr, $b_1 = 0.5932$, $Var(b_1) = 0.02366$, $b_2 = -0.00465$, $Var(b_2) = -0.0046$, $Cov(b_1,b_2) = 0.00013$, $t_{,dof} = 1.397$, n = 11.

Y_Q = Flow-adjusted TP $= Y + b_2 (Q_m - Q) = Y - 0.00465 (523.9 - Q)$

Y_T = Detrended TP $= Y + b_1 (T_o - T) = Y + 0.5932 (78.5 - T)$

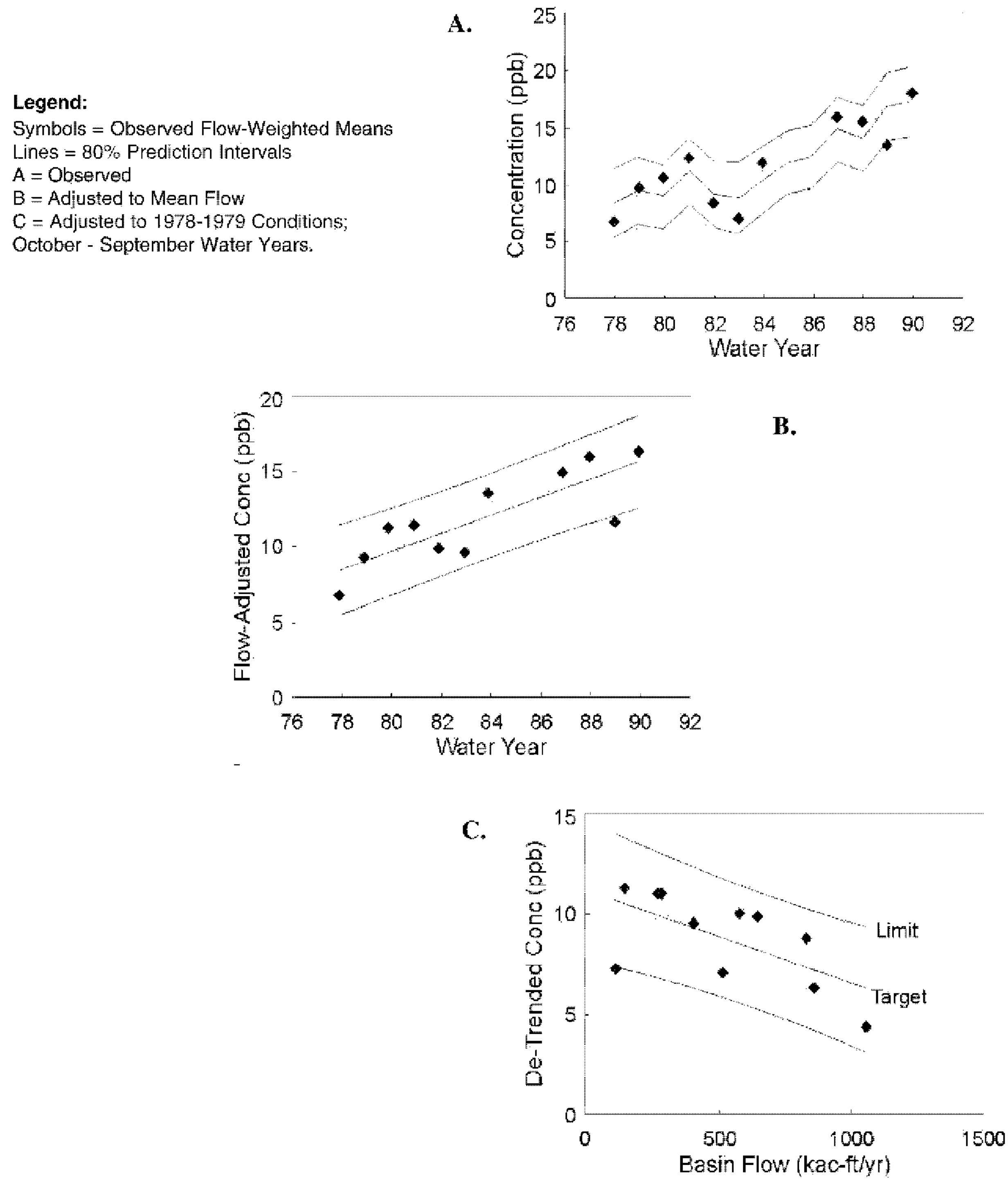
Target = $Y_m + b_1 (78.5 - T_m) + b_2 (Q - Q_m) = 11.16 - 0.00465 Q$

Limit = Target + S $t_{,dof} = 11.16 - 0.00465 Q + 1.397 S$

$S = [SE^2 (1 + 1/n) + Var(b_1) (T_o - T_m)^2 + Var(b_2) (Q_c - Q_m)^2 + 2 Cov(b_1,b_2) (78.5 - T_m)(Q_c - Q_m)]0.5$

$= [6.377 - 0.00591 Q + 0.00000436 Q^2]^{0.5}$

Figure 2: Model calibration to ENP Shark River Slough inflows



The concentration measured in any year (Y) can be adjusted back to an average flow condition (Qm) using the following equation for flow-adjusted concentration (YQ):

$$YQ = Y + b_2 (Qm - Q) \qquad (3)$$

Figure 2B plots observed and predicted flow-adjusted concentrations against time. The long-term trend is more readily apparent in this display because effects of flow variations have been filtered out.

Similarly, the concentration in any year can be adjusted back to any base period (To) using the following equation for a time-adjusted or de-trended concentration (YT):

$$YT = Y + b_1 (To - T) \qquad (4)$$

In this case, a base period value of To = 78.5 is used to represent the 1978-1979 OFW time frame. Using this equation, Figure 2C plots observed and predicted time-adjusted concentrations against flow. The inverse correlation between concentration and flow is apparent. The figure shows the predicted relationship between concentration and flow if long-term mean were equivalent to that experienced in 1978-1979.

The model can be used to evaluate the likelihood that current monitoring results (Yc, Qc) are equivalent to the 1978-1979 base period, while accounting for hydrologic and random variability. This is accomplished using the following terms which characterize the prediction interval for a 1978-1979 time frame under a given flow condition:

$$Target = Ym + b_1 (To - Tm) + b_2 (Qc - Qm) \qquad (5)$$

$$Limit = Target + S\ t\ ,dof \qquad (6)$$

$$S = [\ SE2\ (1 + 1/n) + Var(b_1)\ (To - Tm)2 + Var(b_2)\ (Qc - Qm)2 + 2\ Cov(b_1,b_2)\ (78.5 - Tm)(Qc - Qm)\ ].5 \qquad (7)$$

where

Target = 50th Percentile of Prediction Interval = Predicted Mean (ppb)
Limit = 90th Percentile of Prediction Interval (ppb)
S = Standard Error of Predicted Value (ppb)
SE = Regression Standard Error of Estimate (ppb)
t = One-tailed Student's t statistic
Significance Level = 0.10
dof = Degrees of Freedom = n - 3
n=Number of Years in Calibration Data Set = 11
Var = Variance Operator
Cov = Covariance Operator

In Figure 2C, the Target and Limit lines correspond to the 50th and 90th percentile predictions, respectively. The required parameter estimates and variance/covariance terms are derived from a standard multiple regression analysis. If the current long-term flow-weighted-mean is less than the 1978-1979 long-term mean (adjusted for hydrologic effects), there would be less than a 50 percent chance that the yearly mean (Yc) would exceed the Target and less than a 10 percent chance that Yc would exceed the Limit. The difference between the Target and Limit reflects the magnitude of the Random Effects term and uncertainty in model parameter estimates (b_1, b_2, Ym).

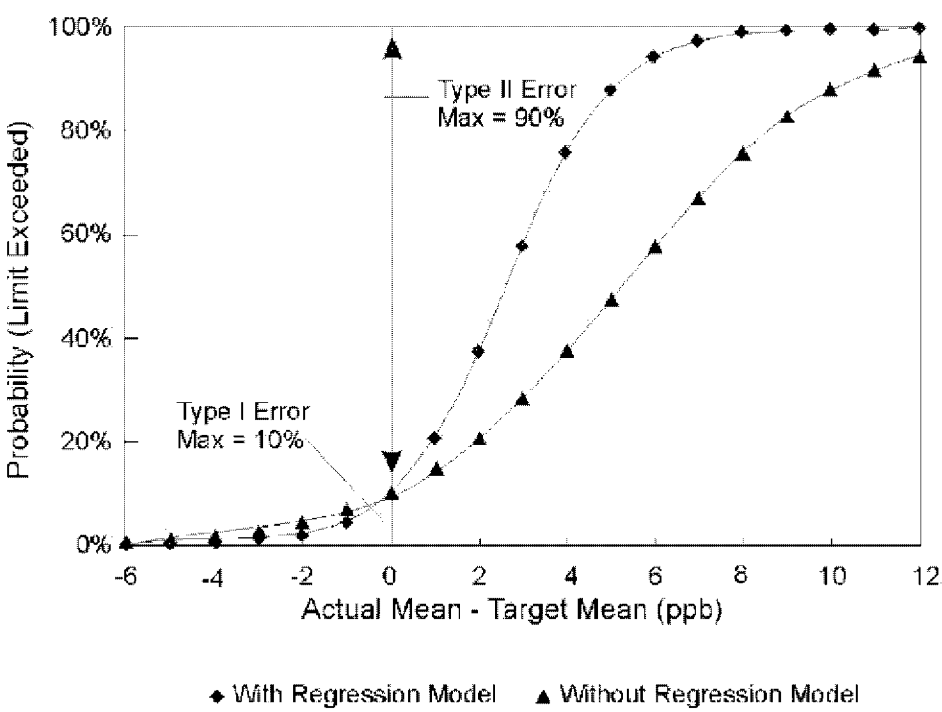
Type I and Type II Errors

Under the terms of the Settlement Agreement, an exceedence of the Limit in any year would trigger further scientific investigations which, in turn, may lead to implementation of additional phosphorus control measures. The significance level for the compliance test (.10) represents the maximum Type-I error rate (probability of exceeding the Limit if the future and 1978-1979 long-term means are exactly equal). Unless a model can be constructed to explain all of the variance in the data, there is no way to design a compliance test without explicitly adopting a maximum Type-I error. In this case, the .10 value was arrived at by negotiation and with the understanding that results of the test would be interpreted by a scientific panel in light of the inherent risk of Type I error.

Type II error (failure to detect an exceedence or excursion from the standard) is another unavoidable feature of compliance tests. In this case, a Type II error would occur when the actual long-term mean exceeds the 1978-1979 flow-adjusted mean but the measured annual mean is still below the Limit. Risk of Type II error depends upon the specified maximum Type I error (10%), model error variance (Random Effects Term), and the magnitude of the excursion from the long-term mean.

Figure 3 illustrates Type I and Type II error concepts. The probability that the annual mean exceeds the Limit is plotted against the difference between the actual long-term mean and the target. Probabilities are calculated using standard statistical procedures (Snedecor and Cochran, 1989; Walker, 1989). Type I errors (false exceedence) may occur when the actual long-term mean is below the target. The risk of Type I error equals the probability shown on the left-hand side in Figure 4 and has maximum value of 10 percent (by design). Type II errors (failure to detect exceedence) may occur when the actual mean exceeds the target. The risk of Type II error equals 100 percent minus the probability shown on the right-hand side of Figure 4 and has a maximum value of 90 percent. As deviation from the target increases, risks of Type I and Type II errors decrease.

Figure 3: Type I and Type II errors



Probability curves are shown for two values of residual standard error in Figure 3. Without applying the regression model, the Random Effects term in the model would have a standard deviation of 3.73 ppb (= standard deviation of annual flow-weighted-means in the calibration period). With the regression model, the standard deviation is reduced to 1.87 ppb. Removing variance associated with trend and flow increases the probability of exceeding the Limit when the long-term mean exceeds the target. For example, if the true long-term mean were 5 ppb above the target, the probability of detecting an excursion (measured annual value above Limit) would be ~90 percent with the regression model, but only ~50 percent without the regression model. Risk of Type I error when the actual mean is below the target is also lower with the regression model. The regression approach thus enables a more powerful compliance test than would result from treating the calibration data set as a random time series.

Model Application to Recent Monitoring Data

Figure 4 shows monitoring results for the Water Years 1991-1996 (6 years following the 1978-1990 calibration period). Although interim standards will not be enforced until 2003, the procedure is useful for tracking responses to control measures implemented over the 1991-2002 period. Such measures include adoption of the EAA Regulatory Rule (requiring a 25% reduction in EAA phosphorus load) in 1992 and operation of the Everglades Nutrient Removal Project (ENR, pilot scale STA removing an additional ~9% percdent of the EAA phosphorus load) (Guardo et al., 1995; SFMWD, 1997) starting in August 1994.

Figure 4A shows observed values before and after the calibration period in relation to the 80% prediction interval derived from the above regression model. Values in Figure 4A reflect both long-term trend and flow variations. Observed values in 1992-1996 fall near the lower boundary of the 80% prediction interval (10th percentile).

Figure 4B shows flow-adjusted concentrations (equation 3) in relation to the 80% prediction interval. The prediction interval extrapolates the increasing trend in the 1978-1990 data to the later years. Theoretically, flow-related variations are filtered from this time series, so that observed and predicted values reflect variations in the long-term mean. The plot suggests that the increasing trend present during the calibration period has been arrested in recent years.

Figure 4C plots concentrations against flow in relation to the 80 percent prediction interval for 1978-1979 conditions. Observed values during the 1978-1991 calibration period have been adjusted to the 1978-1979 time frame (equation 4). The middle and upper values in the prediction interval correspond to the Target and Limit values at any flow. Compliance with the interim standards (when they are in effect) will require that the observed (unadjusted) flow-weighted mean fall below the Limit line in every year.

Discussion

Extremely wet conditions experienced in recent years relative to the calibration period impose significant limitations on tracking results. Figure 5 plots annual basin flow against time. Flow exceeded the maximum value experienced in the base period (1061 kac-ft/yr) in 3 out of 6 Water Years after 1990. In these cases, the model is being extrapolated beyond the range of the calibration data set. The extrapolation is particularly large in Water Year 1995, when the average flow exceeded the calibration maximum by approximately 2.5-fold. Because of the extrapolation into high flow regimes, the model does not provide reliable assessments in recent wet years. Nonetheless, the model does provide the best currently available scientific assessment of long-term trends in phosphorus at these structures.

Figure 4B suggests that the increasing trend in the long-term mean present prior to 1991 has been arrested in years following adoption of the EAA Regulatory Rule in 1992 and operation of the ENR in 1994. For the 6-year period between May 1992 and April 1997, the tracking procedure for EAA phosphorus load (Table 1) indicates an average load reduction of 46% relative to the May 1979-April

Figure 4: Model Application to ENP Shark River Slough Inflows

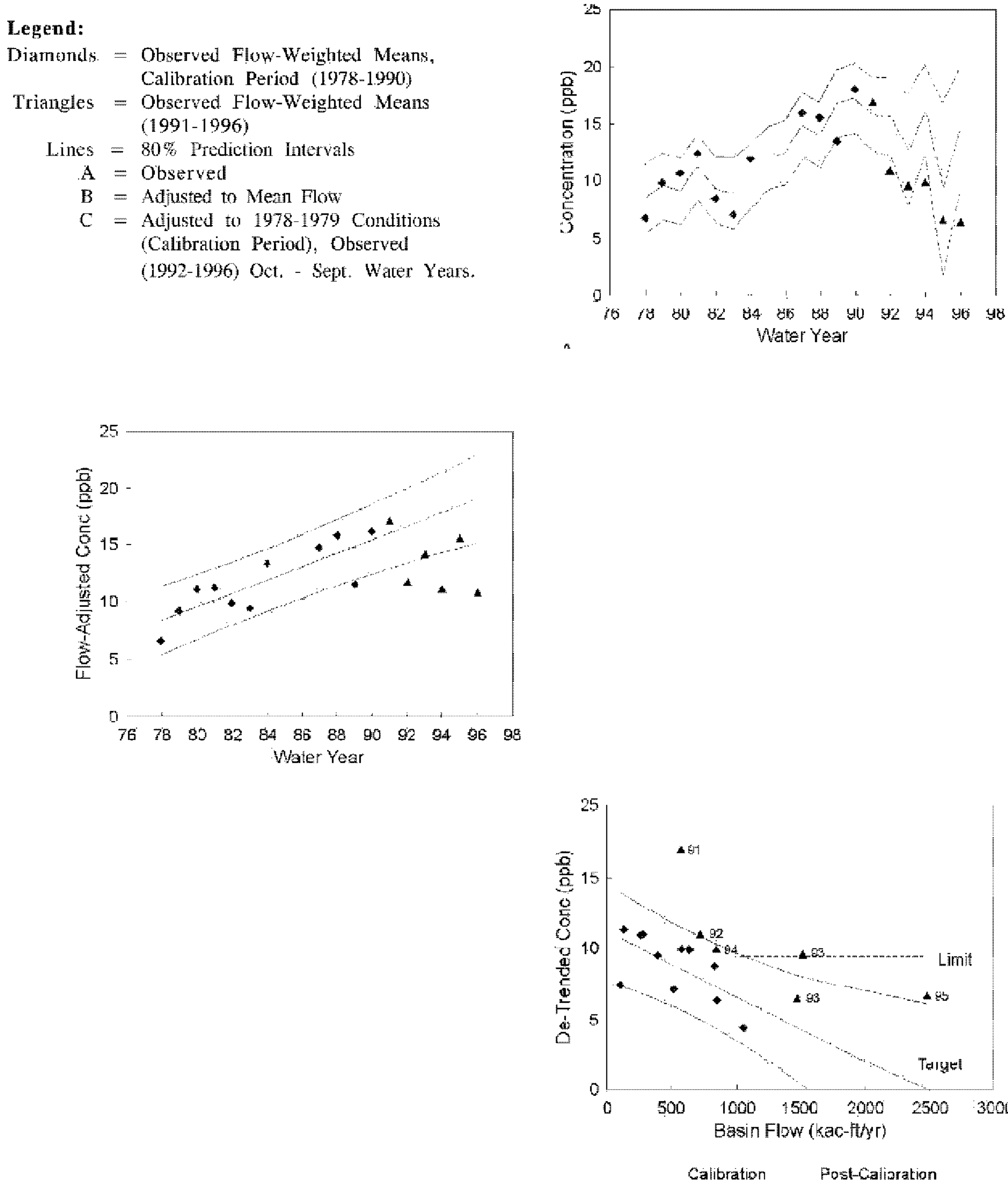
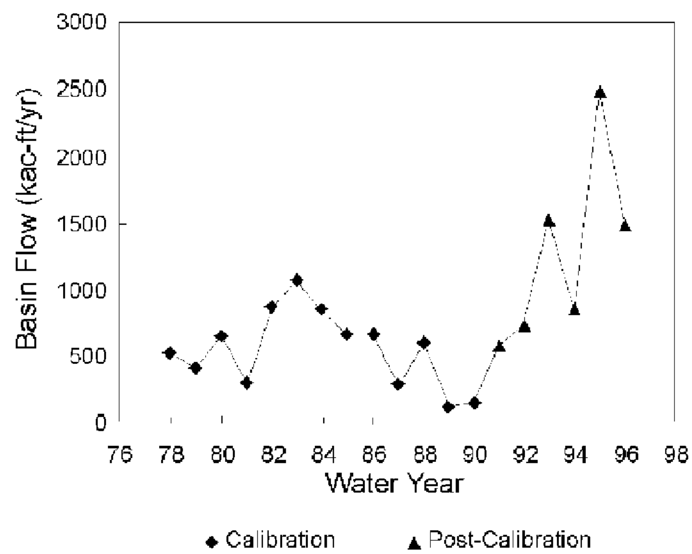


Figure 5. Flow variations.



Legend: Diamonds = calibration period (1978-1990); triangles = after calibration period (1991-1996); horizontal line = maximum flow in calibration period Oct-Sept water years.

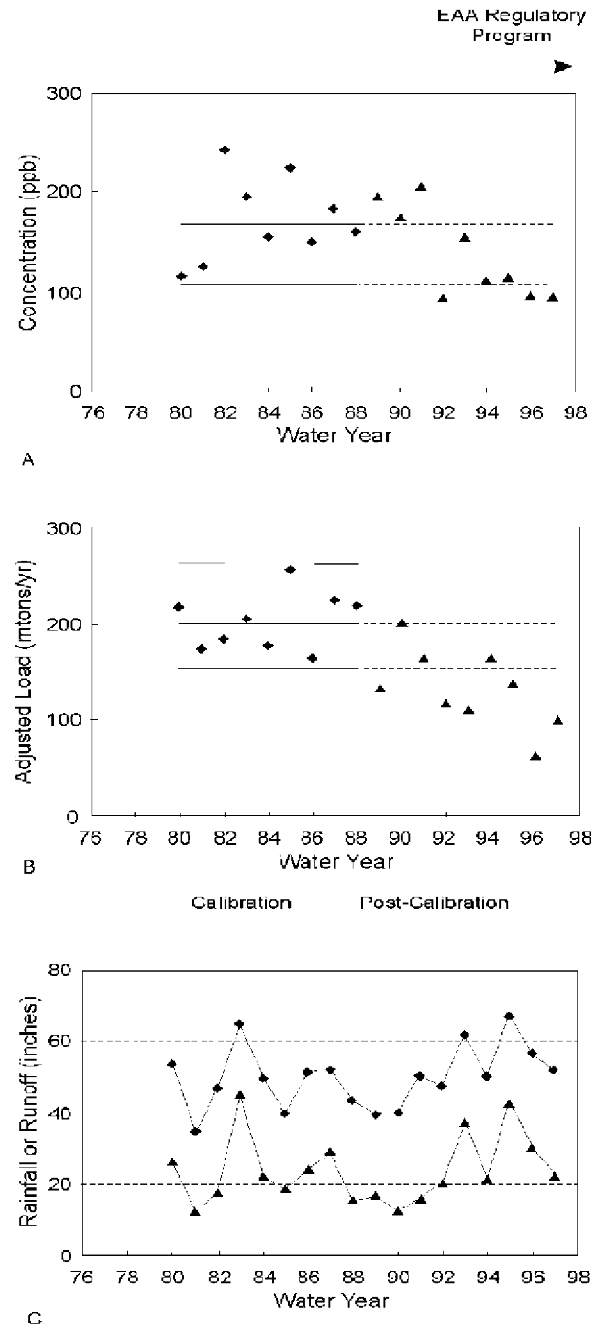
1988 base period for the Rule and adjusted for variations in rainfall. Figure 6 shows annual variations in phosphorus concentration and adjusted load from the EAA. Compared with the model discussed above, the model for tracking EAA phosphorus loads is calibrated to a slightly different base period and employs a different Water Year definition (May-April). A regression against rainfall statistics (Table 1) is used to adjust measured loads to average hydrologic conditions during the base period. The accuracy of EAA adjusted load estimates is also limited by wet conditions experienced in recent years, however.

EAA runoff concentrations are not adjusted because they are weakly correlated with rainfall. Prediction intervals for concentration are derived by assuming that the Random-Effects term of the model follows a log-normal distribution calibrated to base-period results.

Other possible factors contributing to water quality improvements at ENP inflows during recent wet years include (1) increased phosphorus retention under high-stage conditions in the Water Conservation Areas and (2) shifts in the distribution of flow across the Tamiami Trail. A higher percentage of flow is released through the S12's (western) as opposed to S333 (eastern) in wet years because of flow-control constraints in the Eastern Everglades. Historically, P concentrations at S333 have been higher than those at measured at the S12's, because flows passing through S333 contain a higher percentage of canal flow (vs. marsh sheet flow). Because of limitations in the tracking methodology during recent wet years, several years of monitoring under average and dry conditions will provide a more reliable assessment of ENP inflow water quality conditions in relation to the 1978-1979 OFW period.

Despite signs of improvement, it is unlikely that the interim control objective for ENP Shark Slough inflows has been achieved, since the flow-adjusted means in recent years are consistently above the 1978-1979 flow-adjusted mean (~ 8 ppb, Figures 2B, 4B). Observed concentrations in 1992-1996 cluster

Figure 6. Variations in EAA runoff P concentratin and adjusted load



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Legend: Diamonds = calibration period (1980-88); triangles = after calibration period (1989-97); lines = 80% prediction intervals; A = flow-weighted-mean total P concentration; B = total P load, adjusted for variations in rainfall; C = average rainfall and runoff.. May-April water years.

around the Limit line in Figure 4C. If the interim objectives were achieved, the observed values would be expected to cluster around the Target line (center of distribution).

Under the provisions of the Settlement Agreement, the maximum flow during the calibration period (1061 kac-ft/yr) will be used to calculate the Limit in years when the observed flow exceeds that value. This essentially prevents extrapolation of the regression beyond the calibration range. The dashed line in Figure 3C shows the Limit calculated according to this procedure. One could argue whether this procedure provides a better estimate of the 90th percentile at high flows than the extrapolated (solid) line. The distribution of observed values after 1991 is such that the determination of "compliance" (if the standard were in effect) would be influenced only in the case of the extreme high-flow year (1995). In the remaining years, the system would have been in compliance in 2 out of 5 years (1994 and 1996), regardless of which limit line is used.

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