

Final Report

Estimation of a Phosphorus TMDL for Lake Okeechobee

prepared for

**Florida Department of Environmental Protection
&
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by

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1.0 Introduction

This report describes modeling efforts that have been undertaken to estimate the long-term-average external phosphorus load required to achieve eutrophication-related water-quality objectives for Lake Okeechobee. The restoration goal endorsed by the Lake Okeechobee Technical Advisory Committee (LOTAC) is a long-term annual-average total phosphorus concentration of 40 ppb in the pelagic (open-water) zone. Monitoring data collected by South Florida Water Management District (SFWMD) show that phosphorus concentrations increased from ~40 ppb in 1973 to ~100 ppb in 1999. This trend was accompanied by an apparent increase in algal blooms in both the littoral (near-shore) and pelagic (open-water) zones of the Lake (Figure 1). The 40-ppb goal is based primarily upon correlations between bloom frequency and phosphorus concentration in littoral zones (Walker & Havens, 1995).

Although the estimated phosphorus load is a long-term average, it is described here as a “Total Maximum Daily Load” (TMDL) for consistency with U.S. Environmental Protection Agency terminology (USEPA, 1999a). Given the 2-8 year hydraulic retention time of the Lake and considerable phosphorus storage in its sediments, the long-term average load is more relevant than the maximum daily load as a factor driving lake phosphorus concentrations and eutrophication processes.

The USEPA (1999b) developed a TMDL estimate of 198 mtons/yr using a mechanistic model calibrated to 1983-1996 conditions (Jin et al., 1998). The estimates developed below are based upon simpler mass-balance models that place greater emphasis on recent monitoring data. Both the mechanistic and empirical models represent the Lake as a single, continuous stirred-tank reactor (CSTR). The dominant spatial pattern in the Lake is a decreasing gradient from the pelagic to the littoral zones (Havens et al., 1995; Walker & Havens, 1997). The CSTR representation is adequate for simulating spatially-averaged concentration in the pelagic zone, provided that the model is calibrated to concentrations measured in that region. Although flow-weighted-mean outflow concentrations tended to be higher than the pelagic-zone concentrations prior to the mid 1980's, the CSTR assumption is supported by the fact that outflow and pelagic concentrations converged in later years, when the outflow monitoring data were more complete (Walker, 2000).

Between 1973 and 1999, the phosphorus load averaged 498 mtons/yr and the Lake phosphorus concentration increased from ~40 to ~100 ppb. TMDL estimates to achieve a steady-state lake concentration of 40 ppb are derived below using three models of increasing complexity:

- Phosphorus Balance (Water Column)
- Coupled Phosphorus & Calcium Balance (Water Column)
- Coupled Phosphorus & Calcium Balance (Water-Column & Sediment)

Considering calcium and sediment helps to differentiate controlling mechanisms and improves the simulation of historical water column phosphorus concentrations. Results support adoption of a TMDL in range of 120 to 160 mt/yr. Refinement of the model(s) and TMDL estimates can proceed in parallel with the design and implementation of methods to accomplish the required load reductions.

2.0 Data

The models developed below are calibrated to phosphorus data collected by SFWMD between 1973 and 1999 (Germain, 1998). SFWMD staff has provided data files summarizing lake-mean concentrations, water-balance terms, and mass-balance terms on a monthly basis. These have been summarized on a calendar year basis for use in model calibration (Table 1). Morphometric, hydrologic, and phosphorus loading variables are plotted in Figure 3. The precision of inflow load estimates prior to the mid 1980's was probably lower because some of the stations were infrequently monitored (Walker, 2000). Because of the apparent increasing trend in lake phosphorus concentration, data from recent years (1995-1999) are of greatest importance in calibrating the models and estimating TMDL's. Data describing the forms and quantities of phosphorus stored lake sediments in the 1980's to early 1990's are also used in calibrating the coupled water-column and sediment model (Steinman et al., 1999; Reddy et al., 1995; Olila & Reddy, 1995; Brezonik & Engstrom, 1998).

3.0 Phosphorus Mass-Balance Model

The following differential equation describes the water-column phosphorus balance for a single CSTR:

$$dM / dt = L - Q_o C - K_{net} A C \quad (1)$$

$$\text{Change-in-Storage} = \text{Input} - \text{Output} - \text{Net Sedimentation}$$

where,

M	=	Phosphorus Mass in Water Column (metric tons)
t	=	Time (years)
L	=	Total External Load (Watershed + Atmospheric) (mtons/yr)
Q _o	=	Lake Outflow (10 ⁹ m ³ / year)
C	=	Average Lake Concentration (ppb)
K _{net}	=	Net Settling Rate (m/yr)
A	=	Lake Surface Area (10 ⁹ m ²)

Net sedimentation is assumed to be proportional to the water-column concentration and surface area (Chapra, 1975; Vollenweider, 1975). The proportionality constant or "net settling rate" reflects the combined result of all physical, chemical, and biological processes influencing phosphorus retention and recycling within the Lake.

Calibrating the model involves estimating K_{net} based upon historical monitoring data. The following equation can be used to compute approximate K_{net} values from historical yearly time-series:

$$K_{\text{net}} = (L - dM / dt) / AC - Q_0 / A \quad (2)$$

The change-in-storage term in each year is computed from monthly water levels and lake P concentrations. Because it is based upon monthly (vs. yearly) lake-mean concentrations, the measurement error for this term (which is a dominant mass-balance term in some years, Table 1) is likely to be relatively large. Relative standard errors of measured monthly and yearly-mean lake concentrations are ~16% and ~9%, respectively. The relative standard errors of yearly K_{net} values listed in Table 1 (averaging ~13%) underestimate the true values because they do not consider uncertainty in the change-in-storage term. Because of the magnitude of the storage term, it would be futile to model the Lake with a yearly time step while assuming that the mass balance is at steady-state with the external load in each year.

An apparent decreasing trend in K_{net} is largely responsible for the increasing trend in phosphorus and complicates model calibration (Figure 4). The net settling rate decreased from 5-8 m/yr in 1973-1974 to 0-2 m/yr in 1993-1999. Approximately half of the apparent decrease occurred between 1974 and 1975. Havens & James (1997) noted a similar trend in the phosphorus sedimentation coefficient, σ (yr^{-1}), which is mathematically equivalent to the ratio of K_{net} to mean depth. K_{net} variations are weakly correlated with mean depth ($r=-0.28$), but are uncorrelated with depth when the long-term trend ($r = -0.74$) is removed.

The 0-4 m/yr range of net settling rates observed in 1975-1999 is well below the 10-16 m/yr range reported for (generally deeper) lakes in the northern temperate zone (Chapra, 1975; Dillon & Kirchner, 1975; Chapra & Tarapchak, 1976; Vollenweider, 1975). Walker (1999b) showed that the range for Lake Okeechobee is generally consistent with predictions of empirical models that consider the dependence of settling rate on concentration, depth, water load, and/or sediment accumulation rate (Vollenweider, 1976; Sas, 1989; Canfield & Bachman, 1981; Walker & Kuhner, 1978; Walker, 1985;1996).

Given the absence of a strong external loading trend (Figure 3), the reasons for the apparent trends in K_{net} and lake concentration are unclear. Four potential factors have been discussed at LOTAC meetings:

1. Recycling of accumulated phosphorus from bottom sediments. With progressive accumulation and enrichment of the sediments (Brezonik & Engstrom, 1998; Reddy et al., 1995), the sediments and water column gradually approached equilibrium with external loads over the 1973-1999 period. Sediment data indicate that external loads increased by about a factor of four, relative to pre-

- 1900 conditions. Mechanistic models described by Jin et al. (1998) and Pollman (2000b) simulate this mechanism.
2. Effects of increases in the mean and variance of water levels over this same period (Figure 3). A variety of hypotheses have been proposed to explain the apparent correlation (Canfield & Hoyer, 1988; Maceina & Soballe, 1990; Havens, 1997).
 3. Effects of increases in average wind speeds, which are correlated with rainfall and lake water level (Maceina & Soballe, 1990; Havens, 1997);
 4. Effects of declining calcium concentrations on phosphorus deposition and recycling in the Lake (James et al., 1995); and
 5. Potential problems with earlier historical data related to incomplete sampling of inflows. Dominant inflows were sampled over the entire record, however. Limitations of the loading data would not influence the apparent trend in lake concentrations. Each of the eight pelagic stations was sampled monthly over the entire record.

Regardless of the precise mechanism, the most reliable data from recent years reflect the Lake's current condition and provide one basis for calculating the TMDL. The apparent long-term trend in K_{net} can be fit by the following empirical equation:

$$K_{net} = K_0 + (K_1 - K_0) \exp[-b(t - 1973)] \quad (3)$$

This equation reflects a first-order decline at a rate $b \text{ yr}^{-1}$ from an initial value K_1 to a lower asymptote, $K_0 \text{ m/yr}$. The latter provides an estimate of the steady-state net settling rate (K_{SS}) for use in TMDL calculations. Hypothetically, this gradual decline would reflect equilibration of phosphorus cycling processes in the sediments and water column with current external loads and hydrologic conditions.

Using yearly K_{net} values computed from equation (2), a time series of lake concentrations can be generated by numerically integrating the dynamic mass-balance equation (1) with initial concentrations set at measured 1973 values. Model parameters (K_0 , K_1 , b) have been selected to minimize the sum of squares of the differences between the observed and predicted concentrations. The least-squares solution has been found using the Solver routine in the Microsoft Excel program.

Figure 4 shows model parameter estimates, along with observed and predicted settling-rate and concentration time series. The model explains 58% of the settling-rate variance with a residual standard error of 1.0 m/yr and 46% of the concentration variance with a residual standard error of 16 ppb. The model significantly over-predicts observed concentrations in 1985 & 1986, but tracks the remainder of the time series fairly well. The steady-state setting rate is estimated at $K_{SS} = 0.69 \pm 0.22 \text{ m/yr}$. A lower bound for the standard error is estimated from standard error of the mean K_{net} residual. The actual

standard error (likely to be larger) could be estimated by considering the full parameter covariance matrix. This would require additional efforts to evaluate. The 80% confidence interval for the net settling rate is approximately 0.4 to 1.0 m/yr.

An alternative set of parameter estimates can be derived by minimizing the residual sum of squares for K_{net} (vs. concentration). This yields a slightly higher K_{SS} estimate (0.89 vs. 0.69 m/yr) but explains less concentration variance (41% vs. 46%). Since the ultimate objective of the exercise is to predict concentration, it seems more appropriate to base the least-squares objective function on concentration than on K_{net} . This concept is supported by the facts that (a) equation (2) for computing observed K_{net} values is an approximation and (b) the relative standard errors of observed K_{net} values are greater than those of the lake mean concentrations, as discussed above.

Once the phosphorus-balance model is calibrated, the steady-state solution for the lake concentration can be derived by setting $dM/dt = 0$ in equation (1) and solving for C:

$$C = L / (Q_0 + K_{SS} A) \quad (4)$$

This equation can be solved for the long-term average load required to achieve a given lake concentration target:

$$TMDL = (Q_0 + K_{SS} A) C_{TARGET} \quad (5)$$

$$SE(TMDL) = SE(K_{SS}) A C_{TARGET} \quad (6)$$

Where,

TMDL = “Total Maximum Daily Load” (actually long-term-average) (mtons/yr)

C_{TARGET} = Target Lake Concentration = 40 ppb

SE = Standard Error of the TMDL (metric tons/yr)

Based upon LOTAC consensus, 1973-1999 average hydrologic conditions are used in computing the TMDL. The average lake area over this period was $1.733 \times 10^9 \text{ m}^2$. To account for reductions in EAA backpumping to the Lake (see below), the 1973-1999 average outflow has been reduced from 1.68 to $1.57 \times 10^9 \text{ m}^3/\text{yr}$. This has the effect of lowering the TMDL estimate by ~4 mtons/yr.

As shown in Figure 4, the resulting TMDL estimate is:

$$TMDL = 115 \pm 16 \text{ mtons/yr}$$

The corresponding 80% confidence interval is approximately 102 to 128 mtons/yr.

Since the K_{SS} estimate is controlled primarily by observations at the end of the 1973-1999 time series (Figure 4), the above TMDL estimate reflects lake conditions in recent years. Depending upon the actual reason(s) for the decline in settling rate, changes in the lake sediment storage (e.g., dredging or other disturbance), calcium content, water levels, and/or water-level fluctuations could cause a shift in K_{SS} and the appropriate TMDL. Additional research would be needed to sort out these mechanisms. To the extent that low settling rates measured in recent years reflect climatologic variations (rainfall, water level, wind speed, etc., as opposed to long-term effects of nutrient enrichment), actual K_{SS} and TMDL values would exceed those derived above.

4.0 Potential Roles of Calcium

Declining trends in the phosphorus net settling rate may be related to decreases in lake calcium concentration observed in recent years (James et al., 1995; Reddy et al., 1995). Pelagic calcium levels dropped from 45-50 ppm to 30-35 ppm between 1973 and 1999 (Figure 5). On an annual basis, calcium concentrations are positively correlated with phosphorus settling rate ($r^2 = 0.32$). Simultaneous long-term trends in phosphorus, calcium, water level, sediment accumulation, and climatologic factors make it difficult to determine the relative importance of calcium as a factor controlling lake phosphorus levels using empirical methods. Independent evidence for the importance of calcium is discussed below.

Olila et al. (1995) reported that calcium & magnesium-bound phosphorus accounted for 58% (0-5 cm), 70% (5-10cm), and 79% (10-20 cm) of the total phosphorus in mud-zone sediments, where most of the sediment accumulation and net phosphorus deposition is thought to occur (Brezonik & Engstrom, 1998). Based upon graphs shown by Brezonik & Engstrom (1998) apatite P accounted for about 30-40% of the total P in sediments that accreted in the mud zone between 1980-1987. The vertical gradient in Ca-P content suggests a recent decrease in Ca-P accretion rate that is consistent with the declining trend in water-column calcium concentration. Lake phosphorus and calcium deposition may be related through various mechanisms, including precipitation of apatite or other calcium phosphate compounds and adsorption of inorganic and organic phosphorus to settling calcite particles and surface sediments (Wetzel, 1975; Olila & Reddy, 1995; Dierberg, 2000). To the extent that these mechanisms are reversible, they may act as phosphorus buffers rather than permanent phosphorus sinks. Calcium cycling in areas of exposed limestone on the lake bottom outside of the mud zone and in littoral periphyton and submersed aquatic vegetation communities may facilitate these mechanisms.

Based upon application of the Seasonal Kendall test (Hirsch & Slack, 1984), there were significant ($p < .05$) decreasing trends in calcium, magnesium, alkalinity, and chloride at each of the 8 pelagic stations in 1973-1999. Decreasing trends in pH and increasing trends in temperature are indicated at 3 (different) stations. Trends in factors controlling calcite and apatite solubility are shown in Figure 6. Calcite solubility is influenced by calcium concentration, pH, water temperature, and CO_2 concentration (Stumm & Morgan, 1970). These solubility calculations assume CO_2 saturation and ignore effects

of variations in ionic strength. The declining calcium trend is accompanied by a slight decrease in pH and slight increase in water temperature. The combined result is a decrease in the driving force for calcite formation (expressed as Ion Activity Product (Ca/Ca^*) or the $\text{Ca}-\text{Ca}^*$, where Ca^* = soluble calcium level computed from pH and temperature). Results are qualitatively consistent with calculations performed independently by Pollman (2000a).

Most of the IAP decrease apparently occurred around 1982. Calcium exceeded soluble levels ($\text{IAP} > 1$ or $\text{Ca} > \text{C}^*$) in 71% of the monitored months between 1973 and 1982, as compared with 34% between 1983 and 1999. The median IAP decreased from 1.21 to 0.88 and the median Ortho P solubility (vs. apatite) increased from 74 to 146 ppb. Ortho P solubility is computed from Ca and pH using an equation given by (Golterman, 1982); this equation does not include the potential effects of water temperature. Both sets of calculations should be refined using methods that account for ionic strength, alkalinity, and other controlling variables. These preliminary results suggest that calcium levels were generally super-saturated early in the record and were generally under-saturated or near equilibrium late in the record. A coincident decrease in driving forces for calcium-related phosphorus-retention mechanisms is indicated.

Seasonal patterns provide additional evidence that calcium is an important factor controlling phosphorus concentration in the Lake. Figure 7 shows monthly variations in total phosphorus and stage over the 1973-1999 period. Within-year variations in phosphorus are very large. Pelagic-average concentrations often varied by as much as a factor of two to three over a one- to two-month interval. The patterns are not explained by variations in stage. Given the long hydraulic residence time of the Lake, they cannot be attributed to temporal variations in external loads. Given their scale, a biological mechanism seems unlikely. Physical (sediment re-suspension) and chemical mechanisms (precipitation and/or adsorption) represent possible explanations, given the potentially rapid kinetics of such mechanisms. .

Seasonal variations in monthly-mean phosphorus, pH, calcium, calcite IAP, & wind speed are summarized in Figure 8. A sharp decline in total phosphorus occurs when pH and calcium IAP increase in late Spring. A decline in calcium content occurs over this same period. Given the timing, it is likely that the pH increase is triggered by photosynthetic activity. Elevated calcium levels at the end of the dry season (May) could reflect dissolution of calcite over the Winter when the calcite IAP remains below one, as well as the effects of evaporation (see calcium model below).

Short-term & seasonal variations in total phosphorus have also been attributed to wind-driven re-suspension of bottom sediments (Maceina & Soballe, 1990; Havens et al, 1995; James et al., 1997). Monthly-average wind speeds vary from 2 km/hr in Summer to 3.5 km/hr in Winter (Havens et al., 1995) and are generally correlated with phosphorus levels (Figure 8, wind data from Havens et al. 1995). A statistical analysis that considers both calcium-related and wind factors simultaneously would help to evaluate the relative importance of these mechanisms.

Given the strong seasonal dynamics, a long-term trend in calcium concentration and/or pH could have a significant impact on lake phosphorus dynamics. Seasonal swings in phosphorus concentration driven by calcite and/or calcium-phosphate equilibria are consistent with the calcium “homeostasis” hypothesis presented by Pollman (2000a). The role of “photosynthetically-induced epilimnetic decalcification” in hardwater lakes has been documented for some time (Wetzel, 1975). The extents calcite and calcium phosphate saturation may exceed those computed from water-column pH because of the potential for elevated pH levels adjacent to phytoplankton, periphyton, and macrophyte surfaces.

Based upon mud-zone accretion data reported by Brezonik & Engstrom (1998), the ratio of apatite P to calcium in the sediments that accreted between 1980-1987 was approximately 3-6 mg/g. This ratio was approximately 7 mg/g in a 0-5 cm mud-zone core collected in 1989 by Olila & Reddy (1995). The seasonal analysis (Figure 8) indicates that average calcium concentrations decrease from 48 to 39 ppm between May and July as Total P concentrations decrease from 99 to 64 ppm. The ratio of the decrease in phosphorus to the decrease in calcium (3.9 mg/g) is consistent with the accretion data. It is also consistent with the ratio reported by Kleiner (1988), 3.4 ± 0.2 mg/g, based upon measurements of phosphorus and calcite deposition in Lake Constance.

Since these ratios are substantially lower than the P/Ca ratio of hydroxyapatite (>400 mg/kg), adsorption to calcite particles seems more likely than apatite formation as the mechanism responsible for the apparent correlation between calcium and phosphorus net deposition. A portion of the adsorbed or otherwise calcium-associated phosphorus removed from the water column may eventually be converted to apatite or other stable calcium phosphate forms in the sediments. Olila & Reddy (1995) discuss the potential importance of these mechanisms in the Lake.

One simple method of adjusting the TMDL for the effects of changes in calcium would be to use the average net phosphorus settling rate for 1983-1999 (1.6 ± 0.25 m/yr, Table 1). Although calcium levels continued to decline within this period, the calcium IAP and Ortho P solubility were relatively stable (Figure 6). Using a K_{net} value of 1.6 m/yr would result in a TMDL of 173 mt/yr (80% confidence interval = 150 to 196 mt/yr). This probably represents an upper-bound estimate, however, because it attributes all of the apparent decline in K_{net} to reductions in calcium, rather than effects of sediment accumulation and enrichment. This approach would be risky without differentiating phosphorus cycling mechanisms and without understanding the reasons for the decline in calcium.

The following factors (among others) may have contributed to the decline in calcium content:

1. Changes in Water Management. In an effort to reduce phosphorus loads to the Lake, backpumping of runoff from the Everglades Agricultural Area (EAA) decreased substantially over the 1973-1999 period. The program was gradually phased in between ~1979 and ~1986. Based upon water budget information provided by SFWMD, EAA backpumping (S2 + S3) accounted for 13% of the total lake inflow in 1973-1978, 9.8% in 1979-1985, and 1.9% in 1986-1999. Because the calcium content of EAA runoff is approximately 4-5 times that of the other inflows, the average inflow calcium concentration to the Lake decreased from ~32 ppm in 1973-1978 to ~24 ppm in 1986-1999 (see below). Using a settling rate for 1986-1999 (1.36 ± 0.26 m/yr, Table 1) would account for changes in backpumping and calcium chemistry. This would result in a TMDL of 157 mtons/yr (80% CI = 133 to 182 mtons/yr).

2. Climatologic Variations. A general trend from dry to wet conditions occurred over the 1973-1999 period (Figures 1 & 9). The sequence of wet years at the end of this period was relatively unusual in the context of the 1900-1999 record derived from regional data reported by the National Climatic Data Center (NCDC, 2000). On the average, the Lake retained only ~14% of its 1973-1999 external load (see below). For a fixed external load or inflow concentration, the steady-state concentration of a conservative constituent would be inversely proportional to the net inflow (watershed inflow + rainfall – evaporation). Higher calcium concentrations would be expected to occur in dry periods, when evaporation is a larger portion of the water budget. On average, evaporation accounts for 65% of the Lake's total outflow (Table 1). As shown in Figure 9, net inflow is highly correlated with rainfall. It is likely that a portion of the decline in calcium content (particularly between 1990 and 1999) reflects increases in rainfall and net inflow.

A calcium mass-balance model is developed below to evaluate the combined effects of these factors on recent variations in calcium and phosphorus.

5.0 Calcium Mass-Balance Model

Yearly calcium loads have been estimated by applying the yearly arithmetic average concentration to the yearly average flow for each tributary (Table 2). Missing concentration values have been filled by interpolating between adjacent years with data. Concentration data were relatively sparse early in the record, although major inflows were sampled. The total load to the Lake in each year has been multiplied by the ratio of the average load across years to the product of the average flow and average inflow concentration across years (0.97). This procedure approximately adjusts for the fact that the yearly-average concentrations for each tributary are not flow-weighted. Future refinement of these calculations (including flow-weighting within each year) is recommended. Compared with phosphorus loads, calcium loads can be estimated with greater precision because temporal variations in tributary concentrations are smaller. Year-to-year variations in lake calcium loads are relatively insensitive to handling of the

concentration data because they are controlled more by year-to-year variations in the inflow volume distribution (% of inflows from EAA backpumping, Figure 10) than by year-to-year variations in the concentration of the each tributary. The assumed rainfall calcium concentration (1.1 ppm) is based upon measurements made by Peters & Reese (1995) near the Lake shore. To check the water budget and load estimates, a corresponding set of chloride loads have been estimated using the identical procedure

Figure 10 shows that yearly inflow calcium concentrations are strongly correlated with EAA backpumping rate (expressed as a fraction of the total lake inflow, $r^2 = 0.86$). Average inflow concentrations ranged from ~24 ppm in years without backpumping to ~60 ppm in 1981, the year with the highest backpumping (43%). The average inflow concentration decreased from 32 ppm in 1973-1998 (backpumping = %) to 24 ppm in 1986-1999 (backpumping = 1.9%). The algorithm described in Table 2 has been applied to develop a time series of yearly flows and calcium loads adjusted to reflect 1986-1999 backpumping rates. With such adjustments, the 27-year average calcium load decreased from 69 to 58 x 10³ metric tons/yr and the average lake outflow decreased from 1.68 to 1.57 x 10⁹ m³/yr. Regardless of whether calcium loads and chemistry influence lake phosphorus dynamics, the reduction in lake outflow volume alone attributed to less backpumping would cause a small reduction the TMDL (~4 mtons/yr) because outflow appears in the mass-balance equation (5).

The dynamic mass-balance equation (1) can be integrated to predict a yearly time series of lake chloride and calcium concentrations, assuming conservative behavior (no net sedimentation). Observed & predicted values are plotted in Figure 11. Concentrations are initialized at steady-state concentrations predicted by mass balance for the first three years of the simulation (1973-1975). The chloride simulation ($r^2 = 0.82$) supports the validity of the load estimates, water balance, and mass-balance framework. Calcium concentrations are over-predicted by ~20 ppm early in the simulation, but converge at the end. Apparent net deposition rates are computed based upon the difference between the observed & predicted calcium concentrations. Results indicate that calcium net deposition rates decreased from ~15 g/m²-yr in 1973-1976 to ~0 g/m²-yr in 1995-1999. This decrease is consistent with the apparent reduction in calcium retention from 35% in 1973-1978 to 1% in 1985-1999 (Table 2) and with significant reductions in calcite IAP observed over the same period (Figure 6).

Net deposition of calcium can be modeled using a first-order expression of the following form:

$$S_{ca} = K_{ca} (Ca - Ca^*) \quad (6)$$

where,

$$\begin{aligned} S_{ca} &= \text{Net calcium sedimentation rate (g/m}^2\text{-yr)} \\ K_{ca} &= \text{First-order calcium settling velocity} = 2.61 \text{ m/yr} \\ Ca &= \text{Lake calcium concentration (ppm)} \end{aligned}$$

Ca^* = Equilibrium concentration = 38 ppm

Least-squares estimates of model parameters (Ca^* & K_{ca}) have been developed using the Excel Solver routine. Observed & predicted concentrations are shown in Figure 12. The model explains 75% of the variance in the observed values with a residual standard error of 2.3 ppm.

Model results are consistent with the hypothesis that calcium variations are controlled by calcite solubility. The Ca^* value (38 ppm) is similar to the median calcium solubility computed from pH and temperature measurements (36.5 ppm, Figure 6). The decline in net calcium deposition rates (Figure 11) can be attributed to decreases in calcium concentration to values approaching equilibrium.

The dashed line in Figure 12 shows predicted calcium time series with input flows and loads adjusted to current EAA backpumping rates (Table 2). Simulation results indicate that excess calcium contributed by backpumping was mostly deposited to lake sediments. The decreasing trend in the adjusted simulation is attributed to increasing trends in average precipitation and net inflow during this period (Figure 9). Results suggest that low calcium levels measured in 1990-1999 will increase with a return to periods of low to average rainfall, assuming that inflow calcium concentrations remain relatively constant.

6.0 Coupled Calcium & Phosphorus Model

The simplest way of coupling the phosphorus and calcium mass balances is to express the phosphorus net settling rate as linear function of calcium deposition rate:

$$K_{net} = K_0 + (K_1 - K_0) \exp [- b (t - 1973)] + K_3 (Ca - Ca^*) \quad (7)$$

The first two terms are identical to the trend model developed above. They represent the steady-state settling rate when calcium levels are at saturation ($Ca = Ca^*$). These simulate a decline in the settling rate towards steady state, possibly attributed to sediment accumulation, enrichment, and recycling. The third term represents that portion of the settling rate that is correlated with the driving force for calcite deposition or dissolution. Yearly values for K_{net} predicted from the above equation can be substituted into the phosphorus-balance equation(1) and integrated numerically to generate a time series of predicted phosphorus concentrations. Yearly calcium concentrations and the saturation concentration (Ca^*) are derived from the calcium balance model described above.

Using the Excel Solver routine, phosphorus parameters (K_0 , K_1 , b , & K_3) have been selected to minimize the concentration residual sum of squares. Observed & predicted settling rates and concentrations are shown in Figure 13. Adding the calcium term to the mass-balance model improves the concentration fit slightly ($R^2 = 0.51$ vs. $R^2 = 0.46$, Figure 4)

The steady-state net settling rate depends on the average lake calcium concentration predicted by the calcium-balance model with the historical calcium inputs adjusted for reductions in backpumping ($C_{aSS} = 38.5$ ppm). The revised K_{SS} and TMDL estimates are as follows:

$$K_{SS} = K_0 + K_3 (C_{aSS} - Ca^*) = 1.23 + 0.06 = 1.29 \text{ m/yr}$$

$$\text{TMDL} = 152 \text{ mtons/yr} \quad (80\% \text{ CI} = 126 \text{ to } 178 \text{ mtons/yr})$$

The contribution of the calcium-portion of the net settling rate (0.06 m/yr) is small relative to K_0 (1.23 m/yr), which represents the combined effects of other retention mechanisms. This reflects the predicted calcium concentrations under existing EAA backpumping regimes fluctuate around equilibrium values.

Water, phosphorus, and calcium balances under historical and TMDL conditions are listed in Table 3. The arithmetic mean phosphorus concentration over the 27-year period of record is 39.7 ppb. This is slightly below the target because the TMDL is derived from a steady-state approximation of the 27-year mass balance. Simulations indicate that the calcium retention coefficient would be only 2% under TMDL conditions, as compared with 11% under historical conditions.

If the slope of the trend term in equation 7 ($b = 0.13 \text{ yr}^{-1}$) is assumed to reflect a first-order equilibration process between the water column and sediment following a change in external load, 90% of the response to a new steady state (or dynamic equilibrium) would occur within ~20 years after a significant step change in load. The calibration of b was during a period of increasing sediment enrichment, however, and may not apply in the reverse direction.

Figure 14 shows phosphorus and calcium simulations with historical phosphorus loads rescaled to the TMDL and calcium loads adjusted to reflect current EAA backpumping rates. Variations in hydrology, external loads, and the long residence time of the lake complicate interpretation of yearly variations concentration. The general decline in calcium levels reflects the pattern of increasing rainfall. The bottom of Figure 14 shows the high correlation between the net deposition rates for phosphorus and calcium, as simulated by the model. Deposition rates are, in turn, inversely correlated with rainfall and net inflow to the Lake.

7.0 Coupled Water-Column & Sediment Model

The effects of sediment-water interactions are implicit in the parameter estimates of the water-column models discussed above. Direct simulation of accumulated sediments and their interactions with the water column is an alternative approach. The major advantages of including both water-column and sediment compartments are that a more complete mass balance is established, sediment measurements can significantly constrain

parameter estimates, and the time scales of lake and sediment responses to reductions in external phosphorus load can be estimated. The major disadvantage is that model complexity is increased and several simplifying assumptions must be made. Initial attempts at development of such a model are described below. Preliminary results support a TMDL in the range estimated with the simpler models discussed above.

The structure of a phosphorus-balance model that considers calcium and sediment-enrichment effects is shown in Figure 15. The model considers three stored phosphorus pools:

1. Ca-P (fraction related directly or indirectly to calcium cycling)
2. Organic (potentially decomposed to labile pool & subsequently recycled)
3. Labile (potentially recycled to water column)

These pools provide temporary storage of phosphorus that serves to buffer variations in water-column phosphorus levels. Burial of phosphorus from these pools represents the only long-term retention mechanism. A total calcium storage pool is also included.

Storage pools are assumed to be physically located in the biota, litter, sediment floc, and surface sediments distributed throughout the lake. Because of their heterogeneity, storage pools are not directly measureable or useful for calibration. Lake inputs and model parameters calibrated to the water-column and soil accretion data ultimately determine the magnitude of the simulated storage terms. For simplicity, storage is assumed to be distributed spatially throughout the Lake. Simulations are insensitive to this assumption because of compensation in the parameter-estimation process (e.g., assuming 50% area would result in a doubling of the calibrated settling and recycling rates, but no net change in the simulated fluxes). To initialize simulations, storage pools are estimated from the measured phosphorus contents of historical mud-zone sediments and applied to a 5-cm active sediment layer distributed over the entire lake area. Simulations of 1973-1999 conditions in the water column are insensitive to the assumed initial conditions. Sensitivity to the 5-cm assumption is explored.

Phosphorus and calcium in each storage pool is buried at a computed velocity. Burial velocity is determined by bulk density and gross soil accretion rate ($\text{g/m}^2\text{-yr}$). The latter is modeled as a power function of gross phosphorus sedimentation from the water column. Brezonik & Engstrom (1998) found that gross sediment accretion rates in the mud zone increased by ~2-fold between 1910 and 1980-1987, while phosphorus accretion rates increased by ~4-fold. This implies that gross sedimentation varies roughly with the square root of phosphorus accretion rate. Similar relationships between sediment accretion and phosphorus accretion have been found for wetland soils in Water Conservation Area-2A (Walker & Kadlec, 1996; Kadlec & Walker, 1999). With a linear dependence on phosphorus sedimentation rate (slope = 1 vs. 0.5), simulated sediment phosphorus contents would be nearly independent of external phosphorus load, a result that seems unrealistic.

Sediments buried by the storage pools (Figure 15) are reflected in soil cores and therefore useful for calibration purposes. They are assumed to be located in the mud zone, where most of the net accretion is thought to occur as a consequence of sediment focusing (Brezonik & Engstrom, 1998). The total mud zone comprises approximately 44% of the lake surface area. There is considerable spatial variability in accretion rates within the mud zone. The total mud thickness varies from 0 to ~80 cm (Reddy et al, 1995). Accretion rates were 1-3 mm/yr before 1910 and 2-6 mm/yr in 1980-1987 (Brezonik & Engstrom, 1998). As noted by these authors, it is difficult to compute a mud-zone-average accretion rate from the spatially-variable data. Because of the tendency to collect sediment cores in regions where more sediment is found, the average of the measured rates is likely to over-estimate the true spatial average over the mud zone and over the entire lake.

Figure 16 shows mud-zone core locations in relation to mud thickness. The cores were collected in regions where mud thickness ranged from 20-80 cm. Approximately 40% of the mud zone is located in unsampled regions where the mud thickness is less than 20 cm. Assuming that the mud depth is proportional to accretion rate, the average accretion rate over the entire mud zone would be about 70% of the average measured accretion rate. Similarly, the lake-wide average (assuming no accretion outside of the mud zone) would be ~31% (70% x 44%) of the measured rates. Therefore, measured accretion rates of 2-6 mm/yr between 1980 and 1987 correspond to a lake-wide average of 0.6–1.8 mm/yr. The preliminary model calibration assumes an average rate of ~1 mm/yr between 1980 and 1987. This value is consistent with that assumed in the Lake Okeechobee Water Quality Model (Jin et al., 1998).

If the water-column phosphorus balance is established, the soil accretion rate determines the average total phosphorus content of the accreted sediments. The measured composition of sediments accreted over a defined time interval (e.g., 1980-1987 for data reported by Brezonik & Engstrom, 1980-1987) is therefore useful for verifying the soil accretion rate estimate and overall mass balance. The measured range of soil P contents (1200-1600 mg/kg) agrees with the average predicted phosphorus content of net deposition from the water column between 1980-1987 (net deposition / soil accretion, 1500 mg/kg).

Measurements of phosphorus fractions are somewhat useful for calibrating the individual phosphorus pools (Reddy et al, 1995; Olila et al, 1995; Brezonik & Engstrom, 1998). They are only somewhat useful because fractions are operationally defined and do not necessarily represent the functional fractions simulated by the model. Olila et al. (1995) report the following mud zone sediment composition, based upon the 0-5 cm portion of a core collected at station K8 (Figure 16) in 1989:

Total P = 1197 ± 93 mg/kg		
	<u>Measured Fraction</u>	<u>Model Pool</u>
2%	NH ₄ CL-P (Loosely-bound)	~Labile
7%	NaOH-P (Fe-Al Associated)	~Labile

58%	HCL-P (Ca-Mg Associated)	~Ca-P
0.9%	NaOH-OP (Moderately-Highly Organic)	~Labile
32%	Residual (Refractory Organic)	~Organic

At the 2–6 mm/yr accretion rates reported by Brezonik & Engstrom (1998), the 0-5 cm depth interval represents about 8-25 years of accreted sediment.

The above assignments to model pools are imperfect. For example, the model's "Ca-P" pool (related to water-column calcium levels) may contain some organic P because calcite precipitation could induce deposition of both inorganic and organic P through adsorption mechanisms (Olila & Reddy, 1995). The HCL-P fraction increased with depth from 58% at 0-5 cm to 79% at 10-20 cm, while the residual organic fraction decreased with depth from 32% to 14%. This pattern is consistent with a long-term trend towards increased enrichment and decreased calcium carbonate precipitation, possibly linked to the declining calcium levels discussed above.

Brezonik & Engstrom (1998) reported the following composition for mud zone sediments that accreted between 1980 and 1987:

Total P = 1200-1600 mg/kg	
<u>Measured Fraction</u>	<u>Model Pool</u>
~29% Citrate+HCO ₃ (Non-Apatite Inorg.)	~Labile
~36% HCl (Apatite P)	~Apatite
~25% Residual (Organic)	~Organic

The measured values are imprecise because they have been estimated from tiny graphs in the cited reference. At the reported 2-6 mm/yr accretion rates, the 1980-1987 sediment layer would be about 1.6-5.0 cm thick. The large difference in apatite content between these results and those reported by Olila et al.(1995) for the 0-5 cm range (58% vs. 36%) may be attributed to differences in extraction techniques and/or to a declining vertical gradient.

With simulations starting in 1973, model calibration to 1973-1999 data would be sensitive to the assumed initial values for each phosphorus storage pool. This would be problematical, given the fact that the storage pools are not directly measureable and given the weak correspondence between the functional phosphorus pools and the measured sediment fractions. To reduce sensitivity to assumed initial conditions, model simulations start in 1900 using estimates of historical sediment phosphorus content derived from the 10-20 cm portion of the core collected at station K8 in 1989 by Olila & Reddy (1995).

The initialization scheme requires estimation of a 1900-1972 yearly time series of lake water budgets, phosphorus loads, and calcium loads. Preliminary calibration of the hydrologic time series derived from long-term rainfall records is shown in Figure 17. Based upon inferences drawn by Brezonik & Engstrom (1998), the pre-development (~1940) inflow phosphorus concentration is set at 25% of the average 1973-1999 value.

Based upon the intercept of the regression equation in Figure 10, the pre-development inflow calcium concentration is set at 22.7 ppm. Inflow concentrations between 1940 and 1973 are estimated by interpolation, accounting for the fact that EAA backpumping started around 1958. While there is considerable uncertainty and room for refinement in the estimated historical budgets, this approach is preferable to initializing the storage compartments in 1973. It also provides a framework for simulating the entire history (base condition, eutrophication following development, & recovery following implementation of phosphorus load controls).

Simulations are run for 200 years comprised of the following intervals:

1900-1942	Pre-Development (inputs estimated by simulation & sediment record)
1941-1972	Development (inputs estimated by simulation & interpolation)
1973-1999	Monitored Period (inputs observed, model calibrated)
2000-2100	Recovery Period (TMDL loads achieved starting in 2000)

The recovery period is simulated by repeating the 1973-1999 hydrologic time series with the average load rescaled to the TMDL and with calcium inflow concentrations adjusted to reflect current EAA backpumping regimes. An alternative TMDL simulation uses a 100-year hydrologic time series generated from the 1900-1999 rainfall record and calibrated to reflect recent inflow vs. rainfall and outflow vs. depth relationships (Figure 17)

Most of the model parameters are estimated using a constrained least-squares fit of the water-column concentration data collected between 1973 and 1999. Constraints include agreement (in most cases $\pm 20\%$) with a variety of sediment and water-column measures made in the 1980's to early 1990's (Reddy et al, 1995; Olila et al, 1995; Brezonik & Engstrom, 1998). The most important constraint is based upon the phosphorus content of sediment that accreted between 1980 and 1987 (1200-1600 mg/kg, Brezonik & Engstrom, 1998). Another constraint is based upon measured recycling ("internal loading") rates (mean = 0.8, range = 0.7 – 1.1 mg/m²-day, Reddy et al, 1995). The calibration is at the upper end of this range (~1 mg/m²-yr) and is possibly influenced by the facts that the measurements do not reflect all mechanisms (wind-driven resuspension, for one) and that portions of the storage pools simulated by the model may be located outside of the sediment (e.g., biota). In addition, it is not clear whether the measured recycling rates reflect calcium-related mechanisms, which are more likely to occur in the winter months (Figure 8). A sediment organic P decay rate of 0.005 yr⁻¹ is assumed based upon diagenesis modeling (Pollman, 1991). The fraction of gross phosphorus sedimentation that enters the organic storage pool (20%) has been calibrated to provide agreement between observed and predicted sediment organic P measurements (Olila et al., 1995). Other sediment parameter estimates are listed in Figure 15.

Although derived from a single mud-zone station, sediment composition measurements made in 1989 by Olila et al. (1995) are useful for calibration. Based upon accretion rates predicted by the model and adjusting for the relative surface area of the sampled mud

zone (~31%, see above), a 0-5 cm core collected in the mud zone during 1989 would reflect net accretion that occurred between 1974 and 1989. For calibration purposes, the measured composition of the 0-5 cm cores is compared with the average composition of sediments deposited from the water column or buried from the storage compartments between 1974 and 1989. Similarly, the 5-10 cm horizon in 1989 can be paired with average results for 1956-1974. These comparisons assume no net transport or transformation of phosphorus once it is buried from the storage pools.

Preliminary calibration results are shown in the following figures:

Figure 18	200-Year Simulation Results
Figure 19	Observed & Predicted Sediment & Water-Column Phosphorus
Figure 20	Comparisons with Soil Core Sampling Results
Figure 21	Observed & Predicted Sediment Composition
Figure 22	Observed & Predicted Accretion Rates
Figure 23	Phosphorus & Calcium Balances for 1973-1999

The model explains 60% of the variance in the observed concentrations with a residual standard error of 13 ppb (Figure 19). This is an improvement over the water column model without sediment storage ($R^2 = 51\%$, Figure 13).

The calibration generates a relatively small pool of labile phosphorus with a high turnover rate (Figure 23). The model's labile P is in better agreement with the sum of the exchangeable P, Fe-Al P, and loosely-bound organic P fractions reported by Olila et al (1995) than with the NAIP (non-apatite inorganic P) fraction reported by Brezonik & Engstrom (1998). The labile pool accounted for 11% of the average total P storage in 1973-1999. It is only about 4 times larger than the average phosphorus storage in the water column. The size and high turnover rate (2.6 yr^{-1}) suggest that labile pool is comprised largely of readily absorbed/desorbed P and biological components (e.g., plant biomass in the littoral zone).

Preliminary TMDL simulations using the coupled sediment and water-column model are shown in the following figures:

Figure 24	TMDL Mass Balances at Steady-State
Figure 25	TMDL Simulation Driven by Observed 1973-1999 Hydrology
Figure 26	TMDL Simulation Driven by Simulated 1990-1999 Hydrology
Figure 27	Mud Zone Vertical Profile Generated by Model for Year 2100
Figure 28	Rain-Driven Variations in Calcium & P Under TMDL Conditions

The TMDL is computed from the steady-state solution of the dynamic mass-balance equations under 1973-1999 hydrologic conditions (Figure 24). The TMDL estimate (139 mtons/yr, 80% CI = 115-163 mtons/yr) is based upon 1973-1999 hydrology adjusted to current backpumping regimes. This is similar to the 126-178 mtons/yr interval derived from the water-column model discussed above (Figure 13).

The TMDL estimate derived from the steady-state solution of the mass-balance equations (Figure 24) is verified by direct simulation. The simulated average water-column concentration in the last 27-year hydrologic cycle (2074-2100, when the system is closest to steady state) is 39.8 ppb (Figure 25). The simulation using a 100-year time series of rainfall-driven water budgets and lake levels produce an average concentration of 35 ppb with an average load of 139 mt/yr (Figure 27). The difference between the 27-year and 100-year simulations may reflect differences in rainfall characteristics (1973-1999 vs. 1900-1999), but should not be considered significant, pending further refinement of the 100-year rain-driven hydrologic series.

The model predicts a relatively rapid recovery of water column concentrations following TMDL implementation. The first yearly-mean concentrations less than 50 and 40 ppb occur ~8 and ~16 years, respectively, after TMDL implementation. The Ca-P storage pool declines slowly and does not reach steady-state within the 100-year simulated recovery period. The rapid water-column recovery reflects the relatively small size and high turnover rate of the available P pool. The model does not provide a mechanism for recycling of buried P. Such a mechanism would extend the recovery period and may be required for a realistic simulation.

Figure 27 translates the 200-year time series of accreted sediment composition into a hypothetical vertical profile collected in the year 2100. The vertical scale is stretched to reflect the relative surface area the sampled mud zone (i.e., to reflect a typical measured mud core). The bulge in the Ca-P pool between 20 and 30 cm reflects the excess calcium load from backpumping that occurred between ~1960 and ~1985. With the exception of the backpumping period, sediment calcium levels decline throughout the simulation. Inflow calcium loads estimated from recent data are not sufficient to maintain the 1990 calcium content (~140 g/kg) estimated from the calcium carbonate contents of dated cores (Brezonik & Engstrom, 1998). It is possible that the initial condition reflects geologic history (i.e., the sediment was not built by the Lake but was there when the Lake was formed) or that the historical inflow calcium concentration (22.7 ppm, Figure 10) is underestimated. With decreases in calcium deposition, a greater fraction of the total phosphorus deposition enters the labile and organic pools. As a result, the Ca-P content decreases and the organic P content remains relatively constant, despite the substantial decrease in external P loads.

Net Ca-P deposition accounts for only 22% of the long-term-average net phosphorus deposition under the TMDL (Figure 23). Year-to-year variations in phosphorus levels are controlled largely by calcium deposition, in turn driven by rainfall. Figure 28 shows 3-year rolling average results from the 100-year TMDL simulation. Inverse correlations between rainfall and the deposition of both calcium and phosphorus are apparent. Periods of low rainfall and relatively high evaporation cause lake calcium concentration levels to increase above saturation and trigger both calcium and phosphorus deposition. These processes are reversed under wet conditions. According to the model, this recycling mechanism was largely responsible for the decreases in sediment phosphorus

content and increases in water column phosphorus concentration during the wet period experienced in the mid to late 1990's (Figure 19). Changes water management that alter the net inflow to the Lake (inflow + rainfall – evaporation) could have direct impacts on calcium and phosphorus concentrations. It is possible that rainfall-driven variations in calcite deposition are partially responsible for the apparent correlation between water levels and lake phosphorus (Canfield & Hoyer, 1988; Havens, 1997).

8.0 Sensitivity Analysis

Results of alternative calibrations developed with different structural assumptions are listed in Table 4. Combining the labile & organic pools eliminates two model coefficients (K_o & f_o), fits the data about as well as the complete model, lowers the TMDL estimate by about 20 mtons/yr, and lengthens the response time by 2-3-fold. This sensitivity reflects the low turnover rate of the organic pool (0.024 yr^{-1}) relative to that of the labile pool (2.6 yr^{-1}). If the calcium pool is excluded (with or without the organic pool) and the remaining coefficients are re-calibrated, the TMDL increases by 20-40 mtons/yr, but the model is unable to simulate the observed concentration trend ($r^2 < 0$).

Assuming an active sediment thickness ranging 2.2 to 10 cm, the concentration fit is similar and the median TMDL estimate varies from 148 to 125 mtons/yr. Based upon the estimated ratio of the sampled mud zone area to the total lake area (~31%, Figure 16), an active sediment thickness in the range of 2.2 to 10 cm corresponds to a thickness of 7 to 32 cm in the actual mud-zone profile.

The TMDL is relatively sensitive to future inflow calcium concentrations or calcite saturation values (Ca^*). This suggests accuracy would benefit from refinement of the calcium budgets and development of a fundamental understanding of calcium chemistry and pH variations in the Lake. Potential reductions in calcium loads resulting from future diversion of inflows from the 298 Districts along the south shore of the Lake (associated with the Everglades Construction Project) should be also considered.

Given the number of parameters, it is likely that alternative sets of parameters would provide successful calibrations and different TMDL estimates. Recommended future efforts include investigation of alternative calibrations and development of more accurate estimates of uncertainty.

9.0 Discussion

While there is considerable room for refinement, the coupled water-column and storage model is an improvement over the water-column models and generates a TMDL estimate of similar magnitude. Additional sensitivity testing is needed to quantify the range of TMDL's potentially generated from alternative calibrations and structural refinements.

The sediment measurements used to calibrate the model are derived from two published papers (Brezonik & Engstrom, 1998; Olila et al, 1995) and probably represent only a

fraction of all the sediment data collected in recent years. Similarly, pre-1973 water quality data (for calcium, for example) may be available from STORET or other sources. Refinements to the calibration should be developed after a more complete data compilation. Refinements to the model structure and calibration can also be developed based upon feedback from LOTAC members and other reviewers.

TMDL estimates derived from the water-column or sediment & water-column models increase when the apparent effects of calcium are considered. The TMDL estimates increase because a portion of the recent increase in phosphorus is attributed to climatologic variations and reductions in calcium loads, rather than sediment enrichment and recycling. Given the simultaneous trends in calcium, phosphorus, rainfall, and water depth over the 1973-1999 monitoring period, however, mechanistic inferences are difficult. While residuals from the calcium-based models are independent of water level and inflow volume, the calcium-related parameter estimates derived from the data could be biased because of trends in other factors. The roles of calcium and related variables are further discussed below as they may relate to TMDL estimation.

Large seasonal variations in phosphorus and calcium-related variables are evident in Figure 8. This suggests that a shorter time step may be appropriate for modeling lake calcium and phosphorus dynamics. Model complexity and data requirements would increase substantially, however. In any case, calcium-related mechanisms should be considered in any future updates of the existing lake model (Jin et al, 1998)

Figure 8 suggests that the late-spring increase in pH is an important factor controlling calcium and phosphorus deposition. Long-term variations in pH could influence calcite solubility, as represented by the Ca^* term in the models. A slight decreasing trend in pH over the 1973-1999 period is indicated in Figure 6. Applying the seasonal Kendall test (Hirsch & Slack, 1984) to data from each pelagic station separately indicates significant ($p < .05$) decreasing trends at three out of the eight stations (L003, L004, & L008, Figure 1). The median trend was on the order of -0.03 pH units per year. It is possible that this trend also reflected increases in rainfall (dilution of relatively alkaline/hard lake waters with relatively soft/acidic inflows and rainfall). Further analysis indicates that the trend at these stations was focused exclusively between February and April. There was no apparent trend in pH during the May-August period when calcite precipitation is most likely to occur. Lower pH levels in February-April may have promoted calcium dissolution and phosphorus recycling in later years.

If significant reductions in maximum chlorophyll-a concentrations accompany reductions in lake phosphorus concentrations, maximum pH levels would be expected to decrease, and minimum Ca^* levels, to increase. Both pH and chlorophyll-a levels in the pelagic zone are likely to be less sensitive to reductions in phosphorus, as compared with levels in the littoral zone, where most of the historical algal blooms have occurred. Because of the manner in which the 40-ppb phosphorus target was derived, a reduction in littoral-zone blooms is the major objective of the TMDL. As discussed above, winter pH levels declined slightly at 3 out of the 8 stations in the pelagic zone between 1973 and 1999,

while algal bloom frequencies increased (Figure 2). Since the pH trend is in the opposite direction than that predicted by the trend in chlorophyll-a, variations in pH must be controlled by factors other than algal blooms.

Lake monitoring over the next several years may help to differentiate mechanisms responsible for recent increases in phosphorus (calcium decline vs. sediment enrichment). With a return to dry or average hydrologic conditions, the calcium model predicts an increase in calcium and decrease in phosphorus levels, whereas the enrichment model predicts further increases or no change in phosphorus. Lake responses to recent changes in management (reduction in water level) may also help to differentiate mechanisms. Comparisons between observed and predicted lake responses provides a basis for interpreting monitoring data, refining the model(s), and targeting both monitoring and research efforts.

10.0 Summary of TMDL Estimates

Table 4 and Figure 29 compare historical phosphorus loads with the TMDL estimates derived above. The magnitude and variance of the latter are small in the context of historical loads. The model that best simulates historical sediment and water-column data (base run of the sediment/water-column model) estimates a TMDL of 139 metric tons per year with an 80% confidence interval of 115 to 163 metric tons/yr. Most of the other estimates overlap this range. Refinement of the model(s) and TMDL estimates can proceed in parallel with the design and implementation of methods to accomplish the required load reductions.

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Figure 1
Lake Okeechobee Pelagic Monitoring Stations

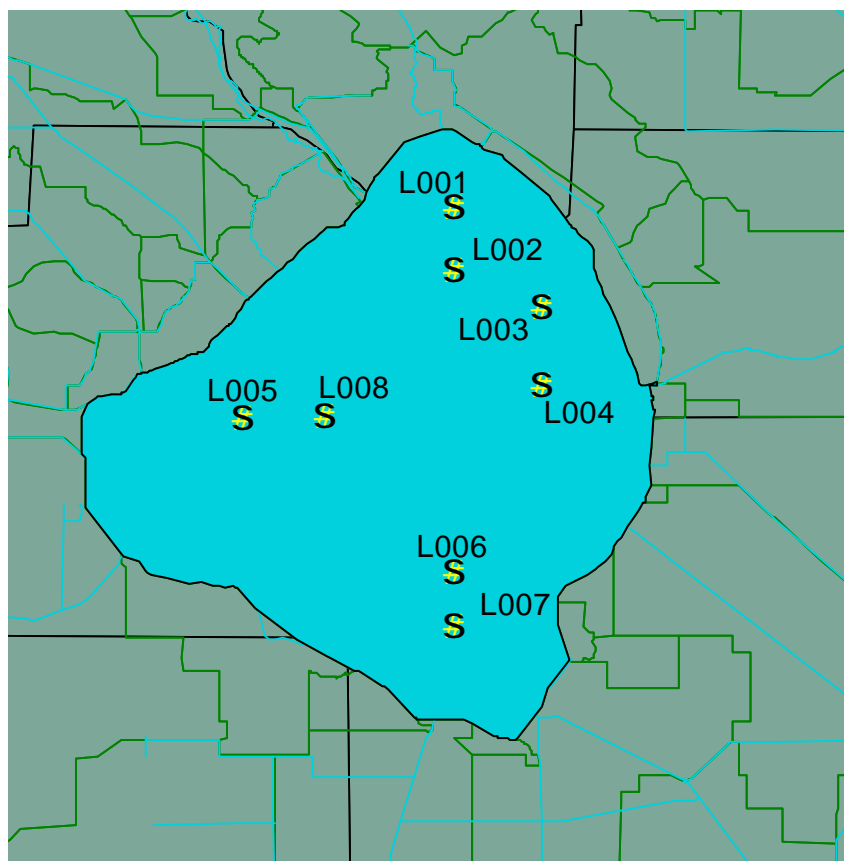


Figure 2
Long-Term Trends in Phosphorus & Algal Bloom Frequency

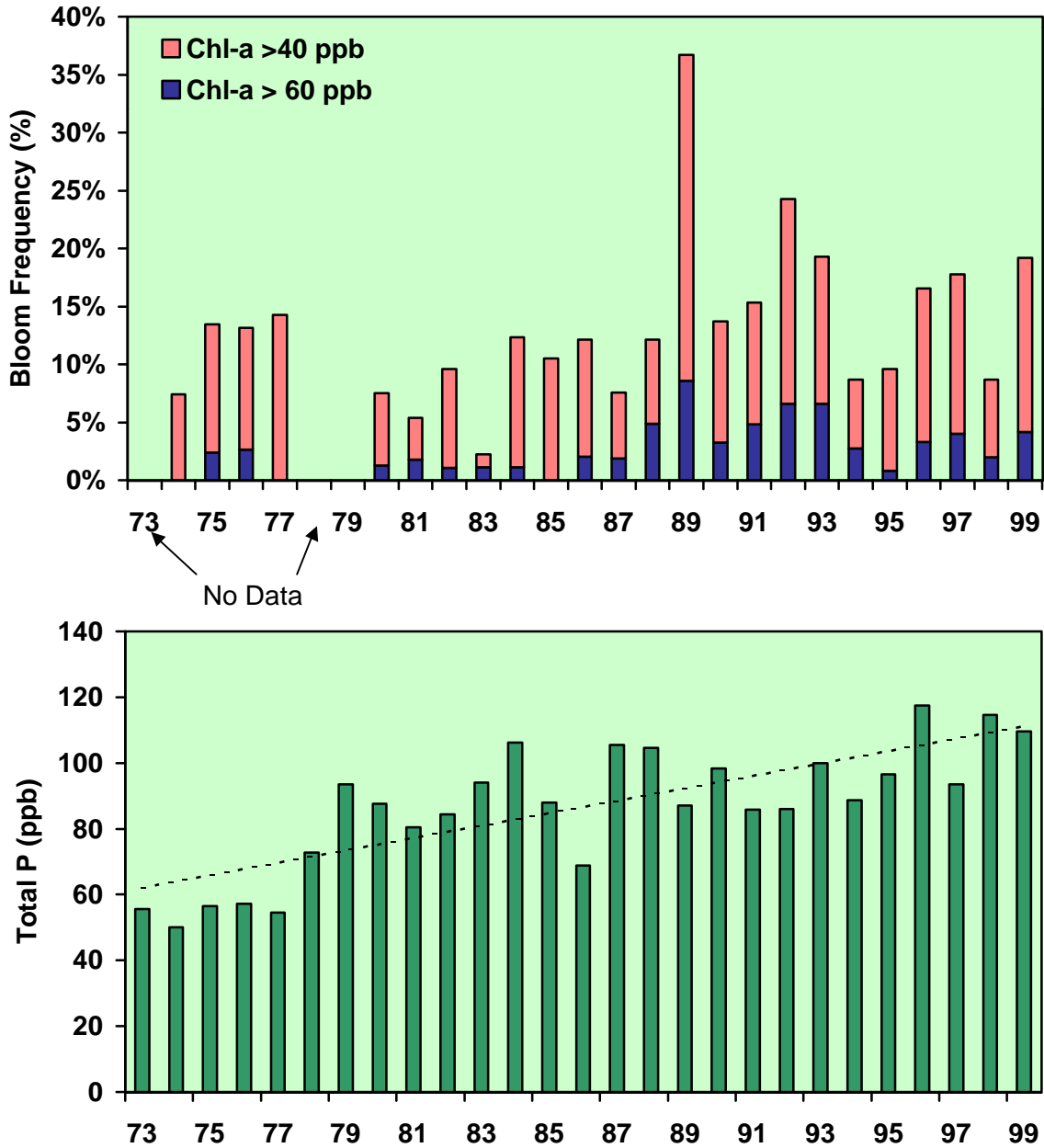


Figure 3
Hydrologic Time Series

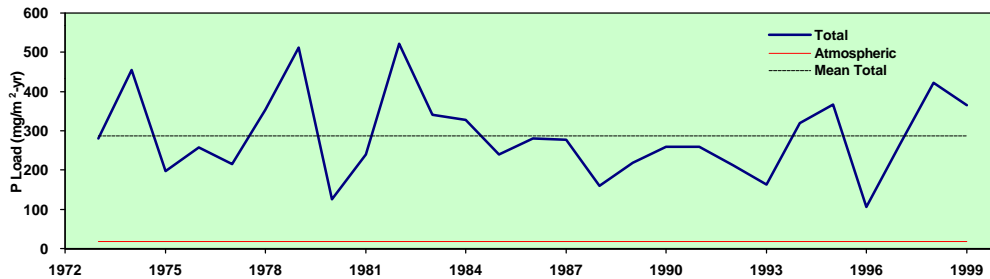
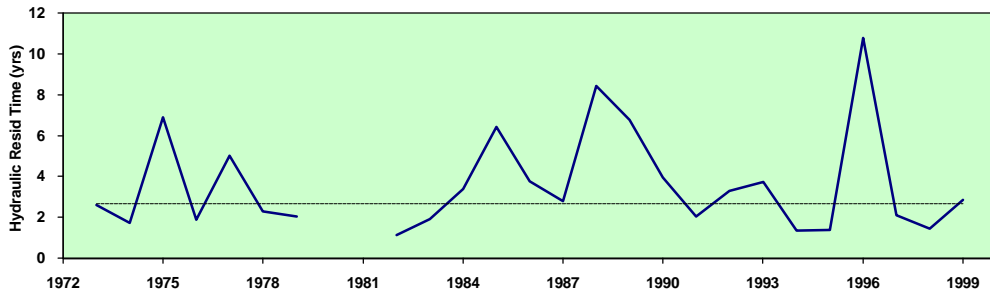
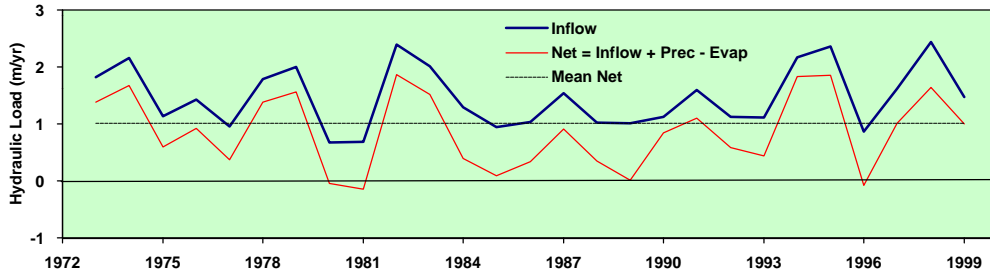
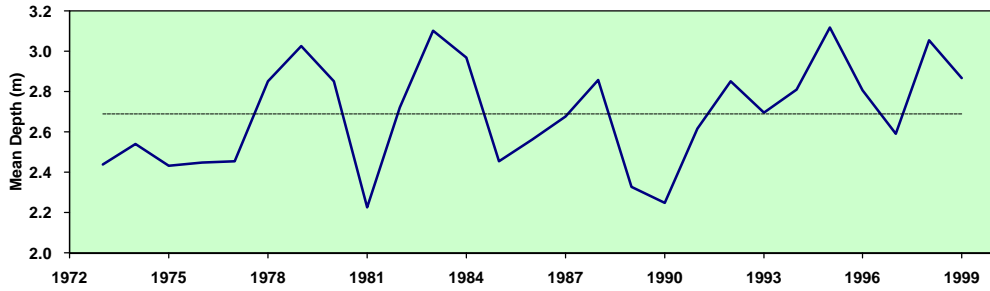
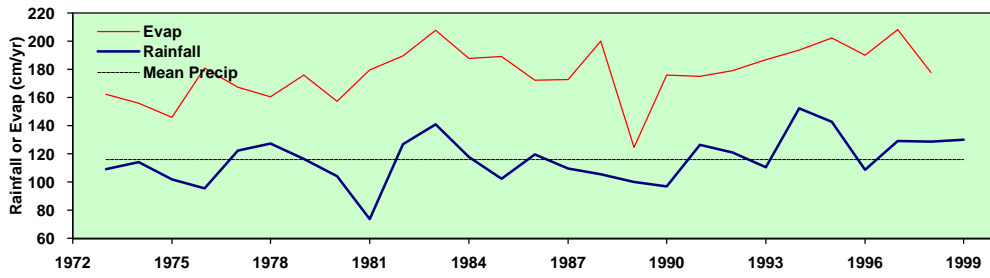
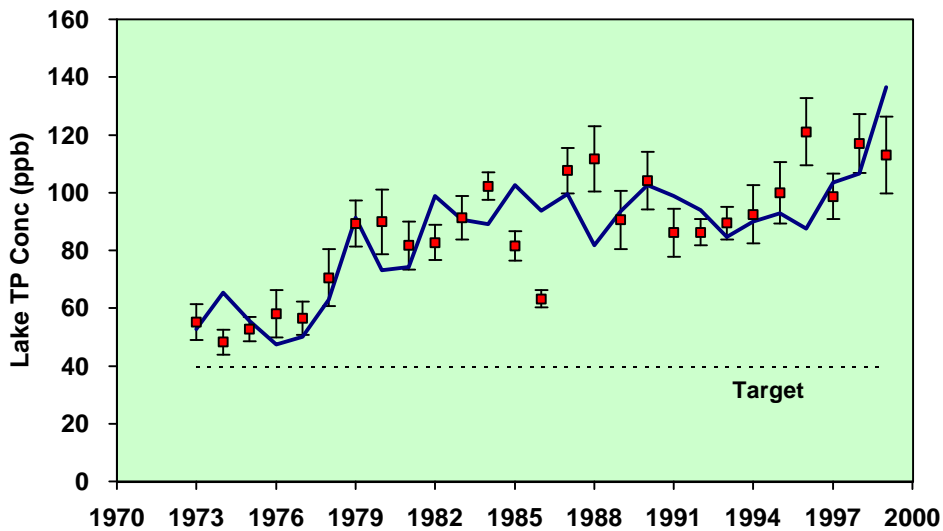
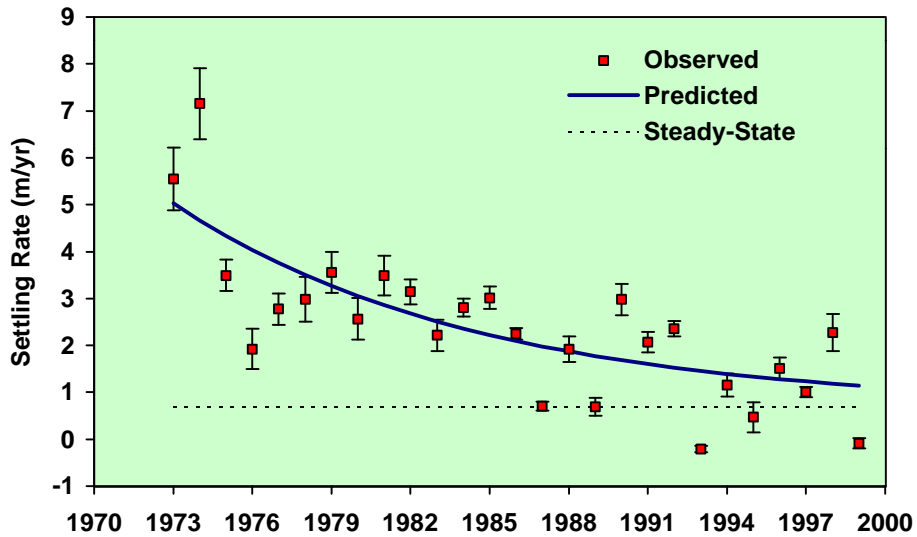


Figure 4
Trend Model Calibration



Observed $K_{net} = (L - dM/dt) / (\text{Area } C_{lake}) - Q_o/\text{Area}$ +/- 1 Standard Error

Model: $K_{net} = K_0 + (K_0 - K_1) \exp(-b(t - 1973))$

Knet $R^2 = 0.58$ SE = 1.03 m/yr

Conc $R^2 = 0.46$ SE = 15.2 ppb

Least Squares Parameter Estimates:

$K_0 = 0.693$ m/yr = K_{SS}

$K_1 = 5.026$ m/yr $b = 0.087$ 1/yr

TMDL Calculation:

$TMDL = C_{TARGET} (K_{SS} \text{ Area} + Q_o)$

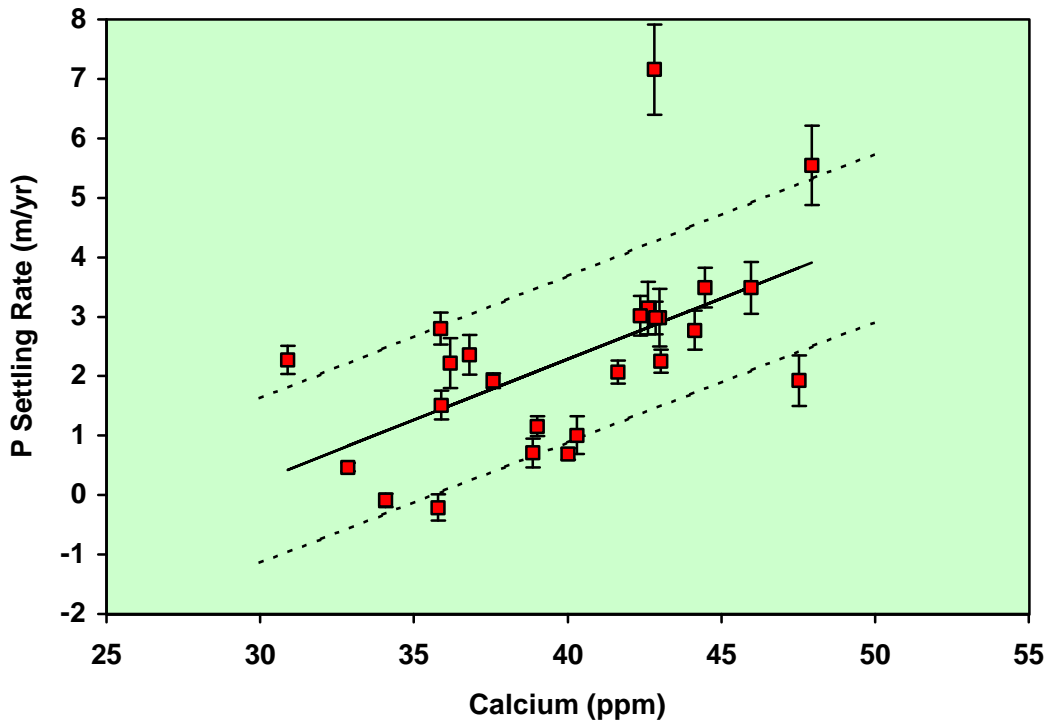
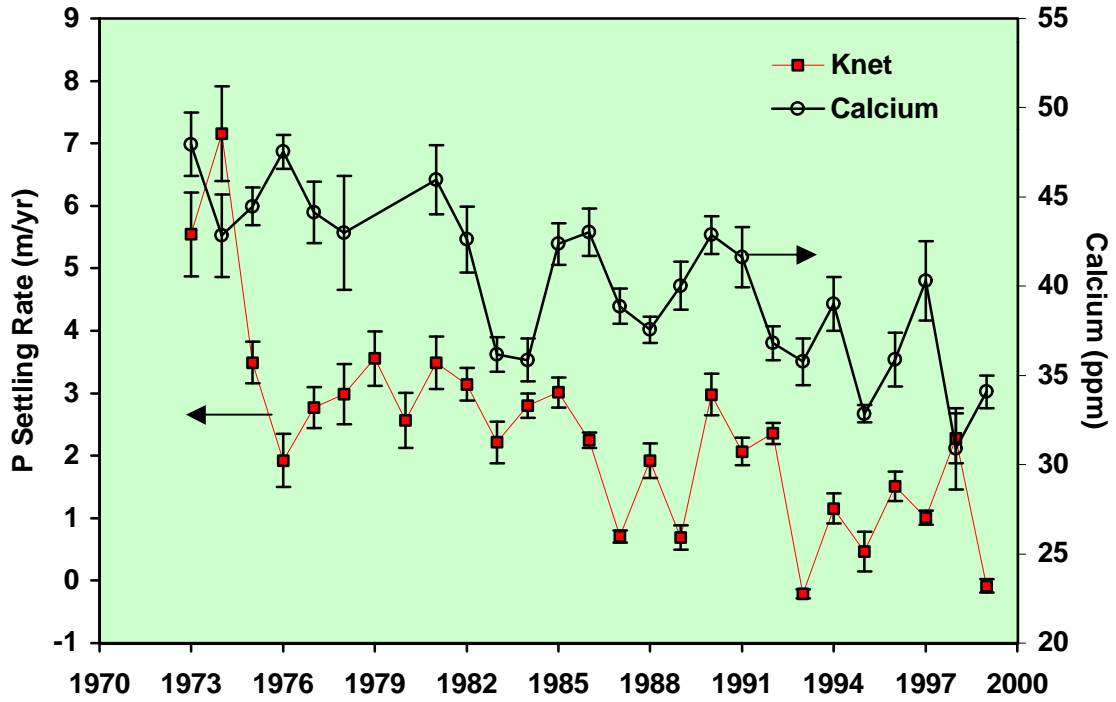
$C_{TARGET} = 40$ ppb $Q_o = 1.68 \times 10^9 \text{ m}^3/\text{yr}$

Area = $1.733 \times 10^9 \text{ m}^2$

	Mean	SE	10th%	90th%
K_{SS} m/yr	0.69	0.21	0.42	0.96
TMDL mt/yr	115	10	102	128

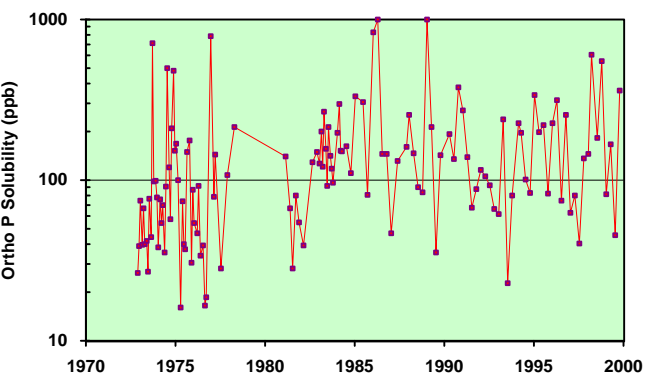
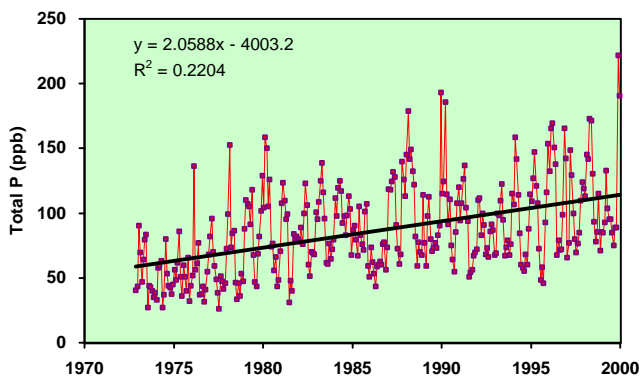
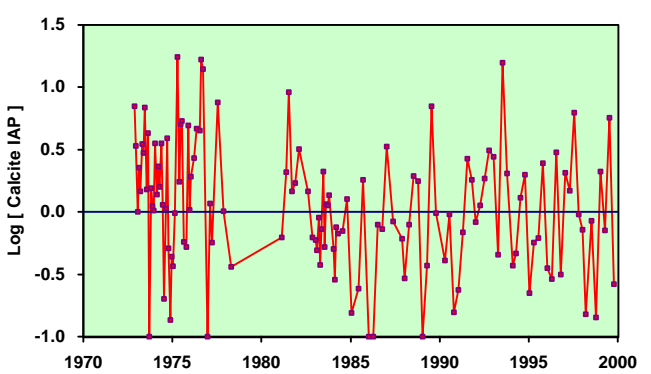
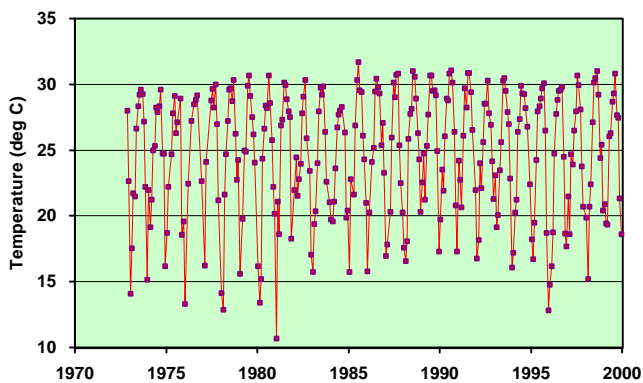
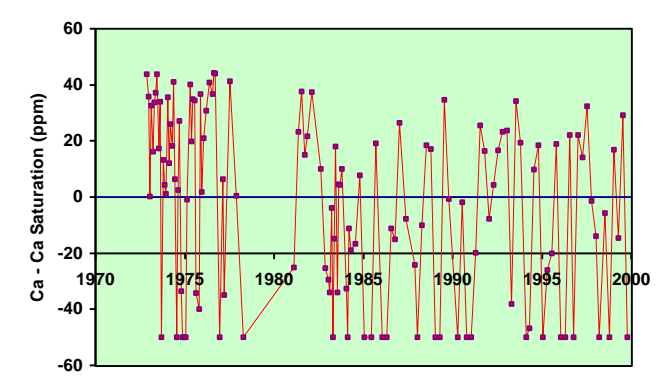
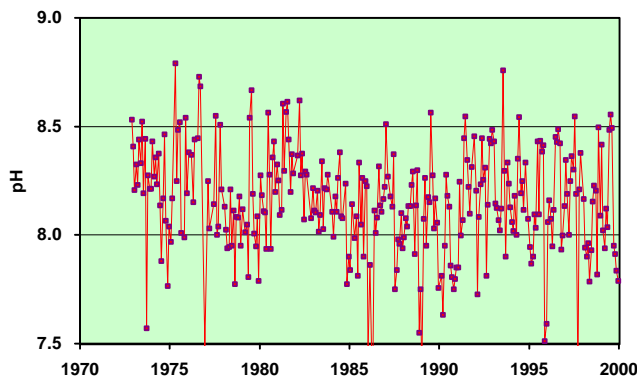
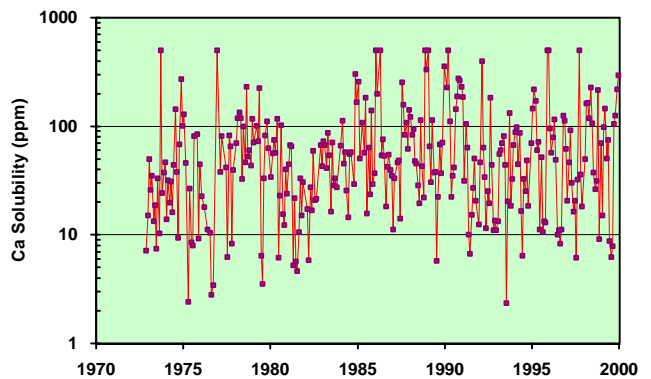
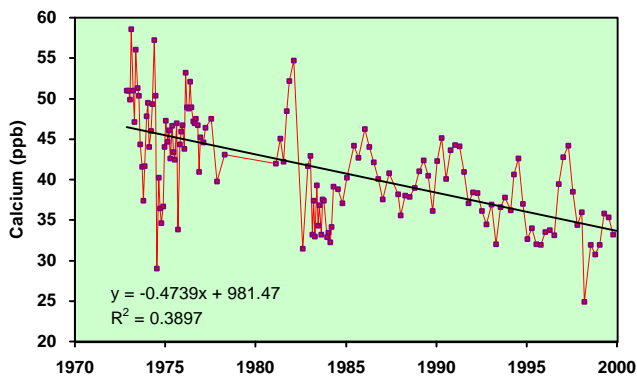
Time for 90% Response to New Steady State = $-\ln(.1) / b = 26.5$ years

Figure 5
Phosphorus Settling Rate vs. Calcium Concentration



$r^2 = 0.32$ $SE = 1.37$ $y = -5.882 + 0.204 X$

Figure 6
Trends in Calcium-Related Variables



Monthly Mean Values for Lake Okeechobee Pelagic Stations
 Calcite Solubility computed from Ca, pH, & Temperature (Stumm & Morgan, 1970)
 Ortho P solubility vs. apatite computed from Ca & pH (Golterman, 1982)

Figure 7
Monthly Variations in Phosphorus & Stage

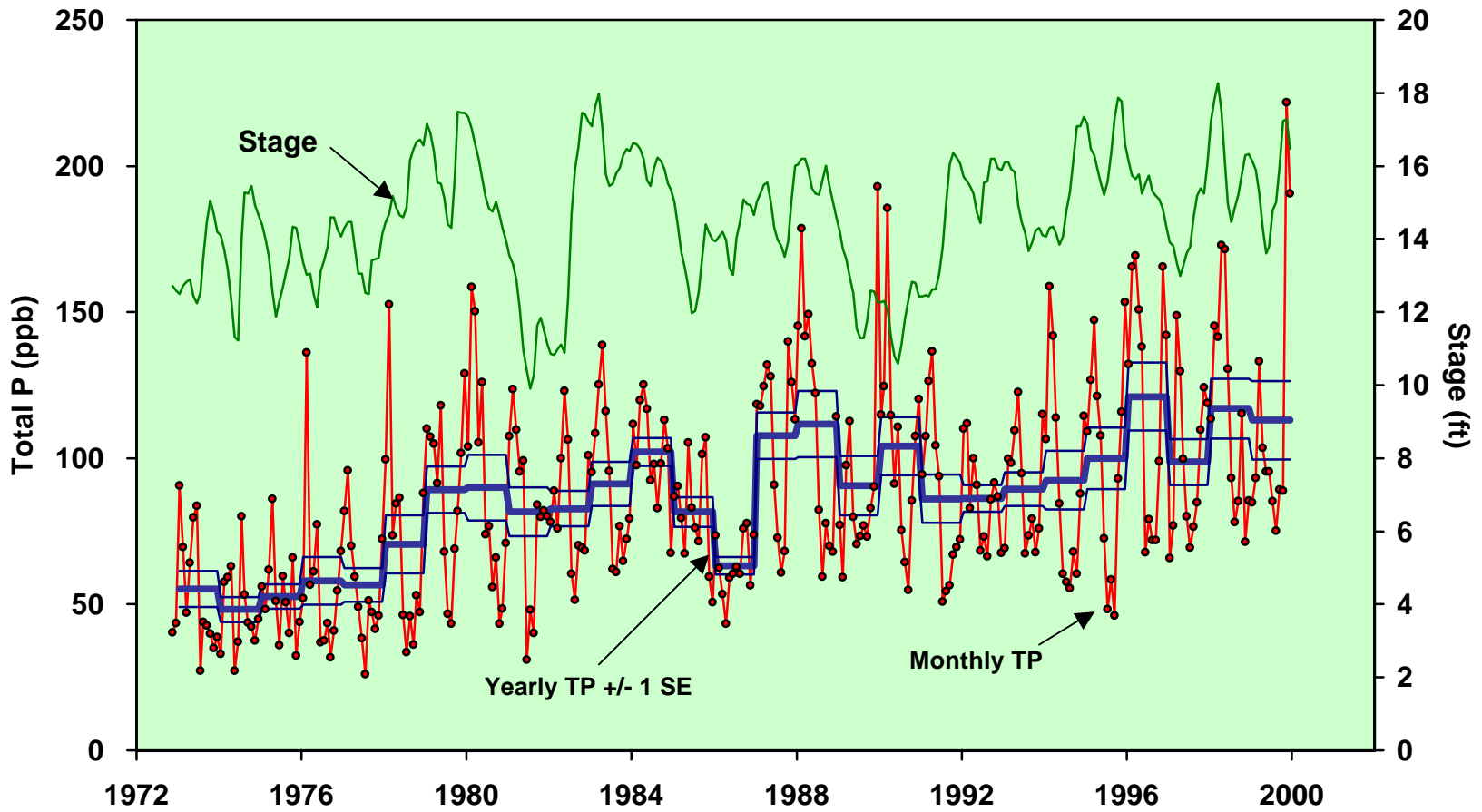


Figure 8
Seasonal Variations in Total P, Calcium, pH, & Calcite IAP

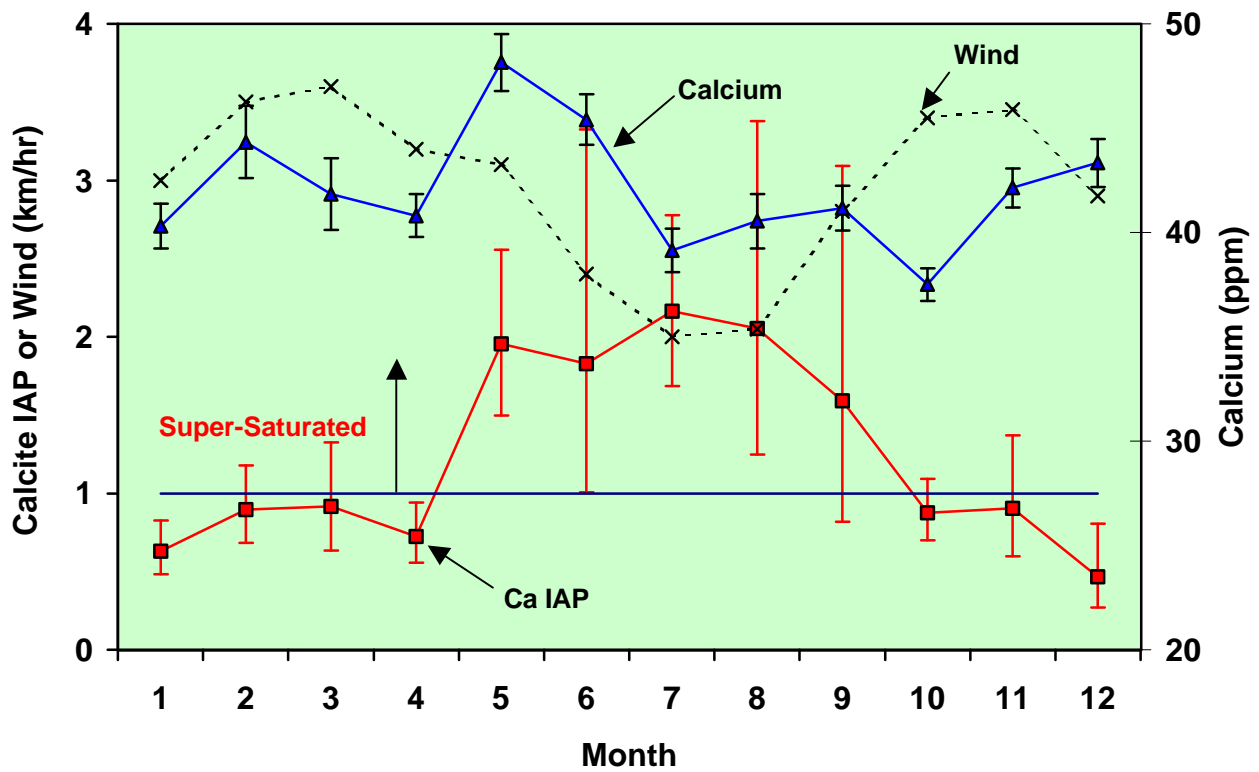
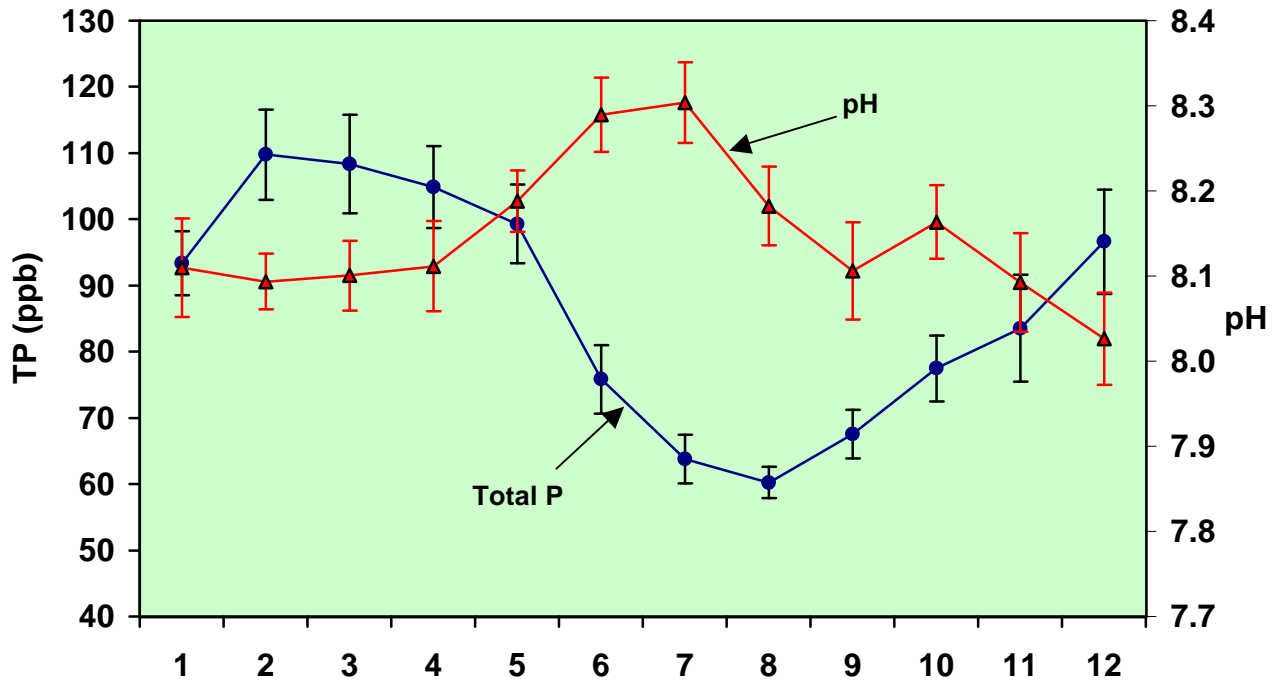
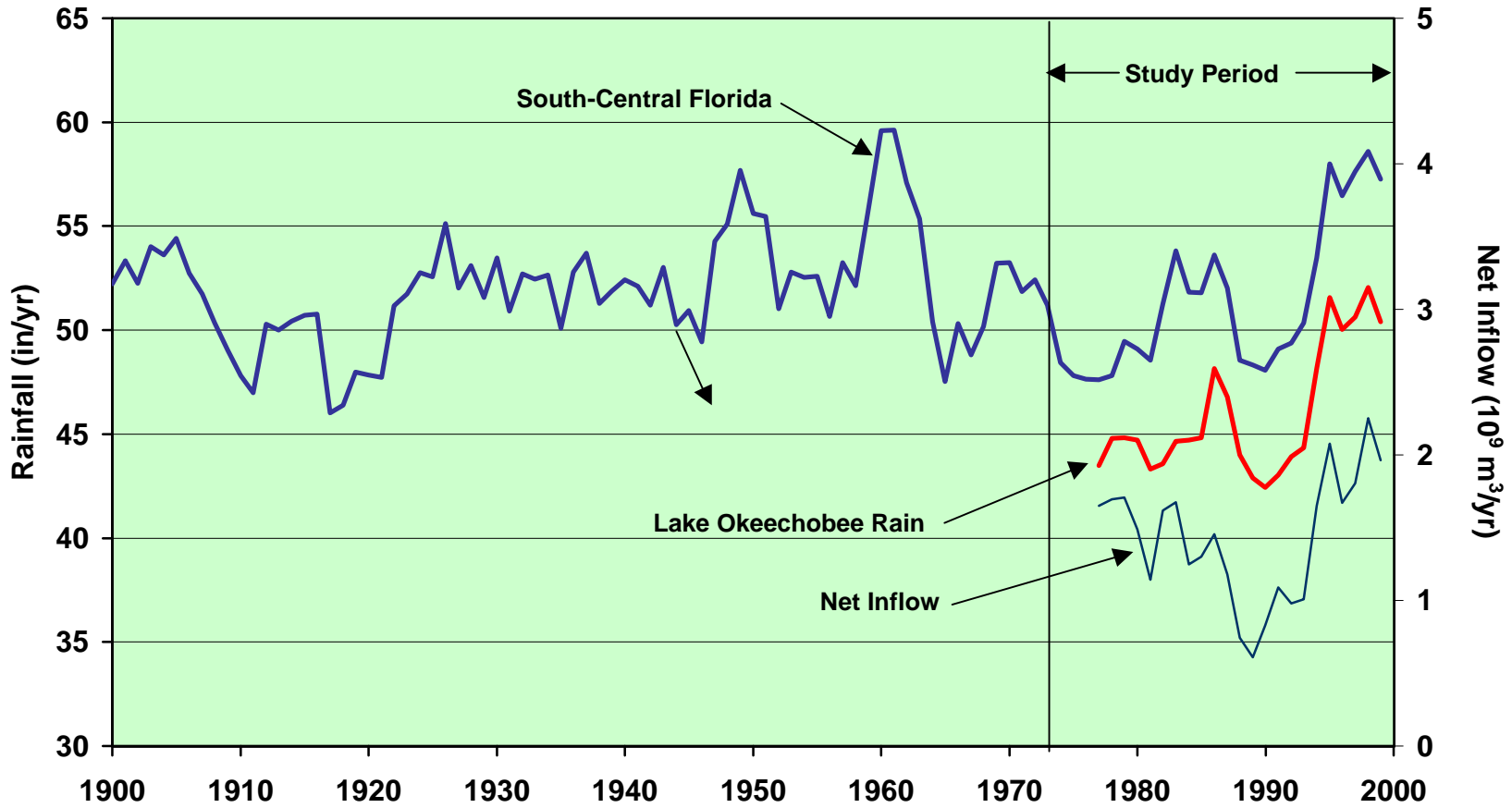


Figure 9
Long-Term Trends in Rainfall & Net Inflow



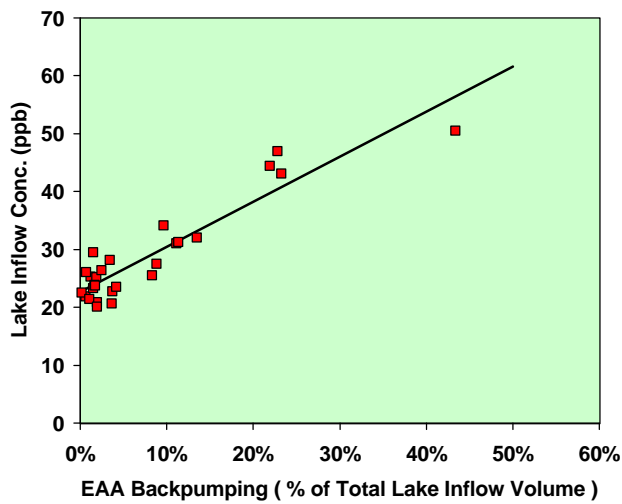
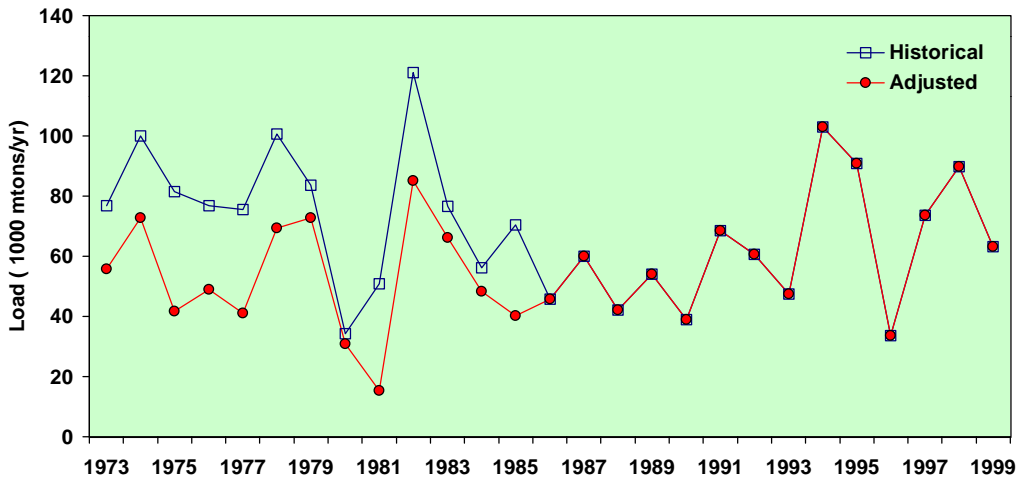
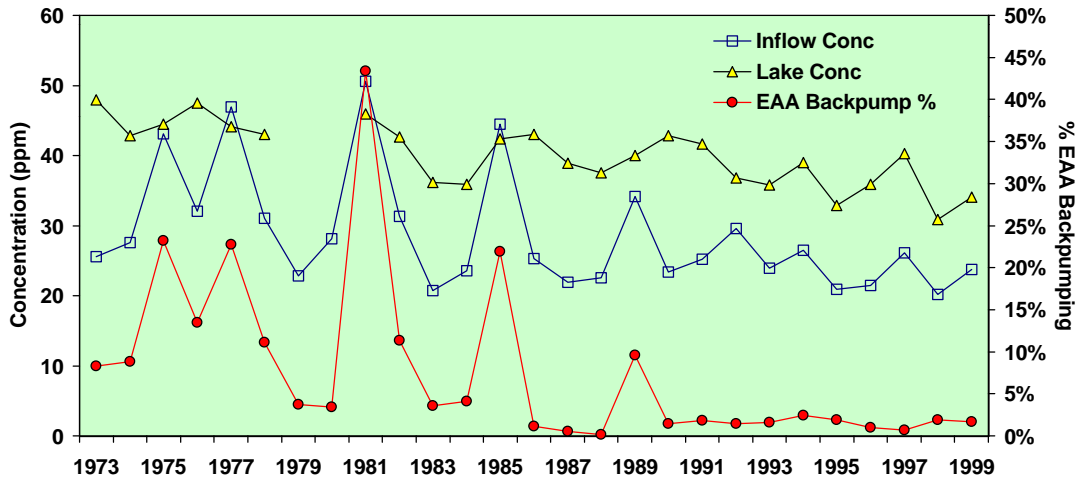
Five-Year Rolling Averages

1900-1999 Rainfall Record from National Climatic Data Center, Florida Regions 4 & 5, <http://www.???>

1973-1999 Rainfall & Net Inflow Record from Lake Okeechobee Water Budgets (SFWMD)

Net Inflow = Watershed Inflow + Rainfall - Evaporation

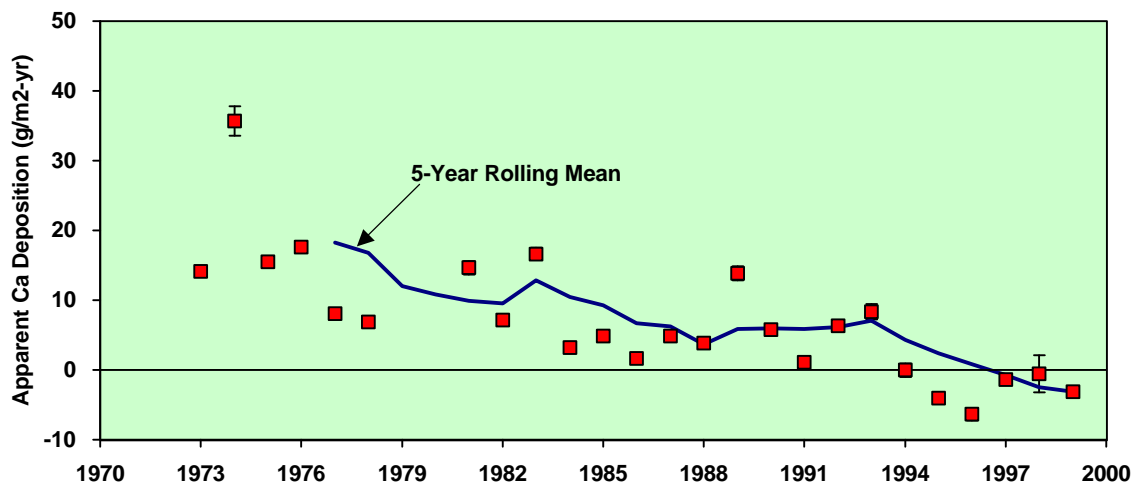
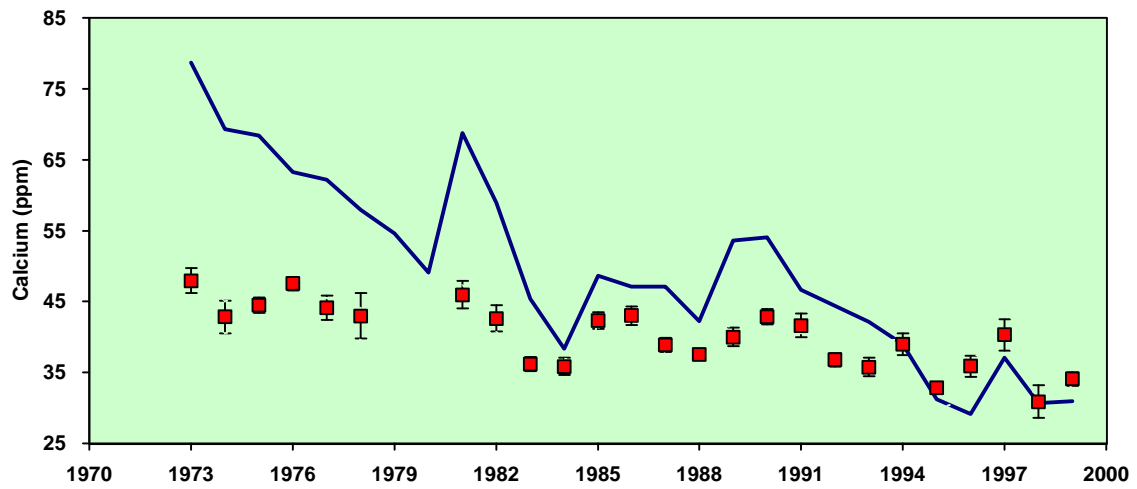
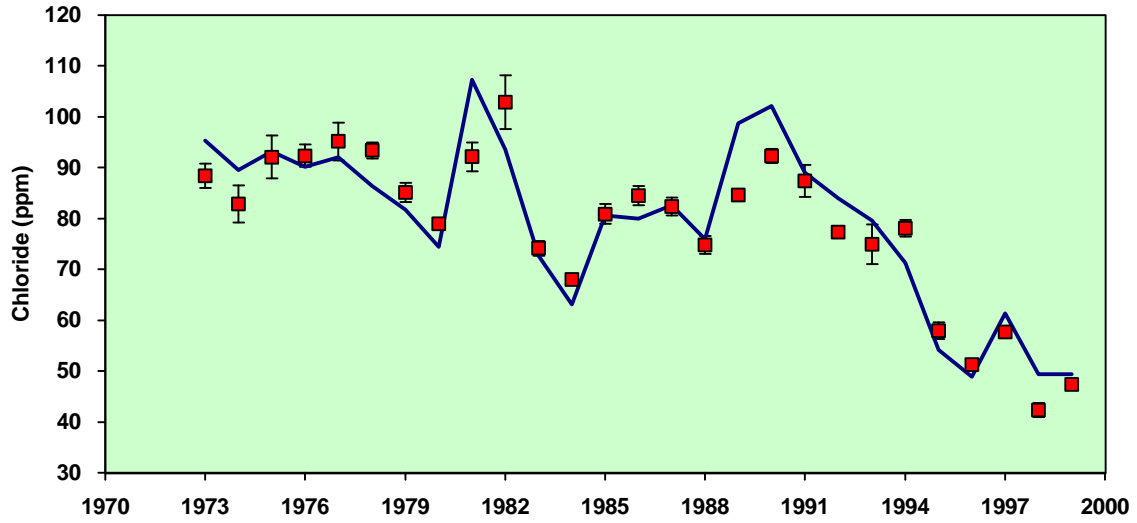
Figure 10
EAA Backpumping & Calcium Loads



$$\text{Inflow Conc (ppm)} = 22.7 + 77.9 \text{ EAA \%} \quad r^2 = 0.86$$

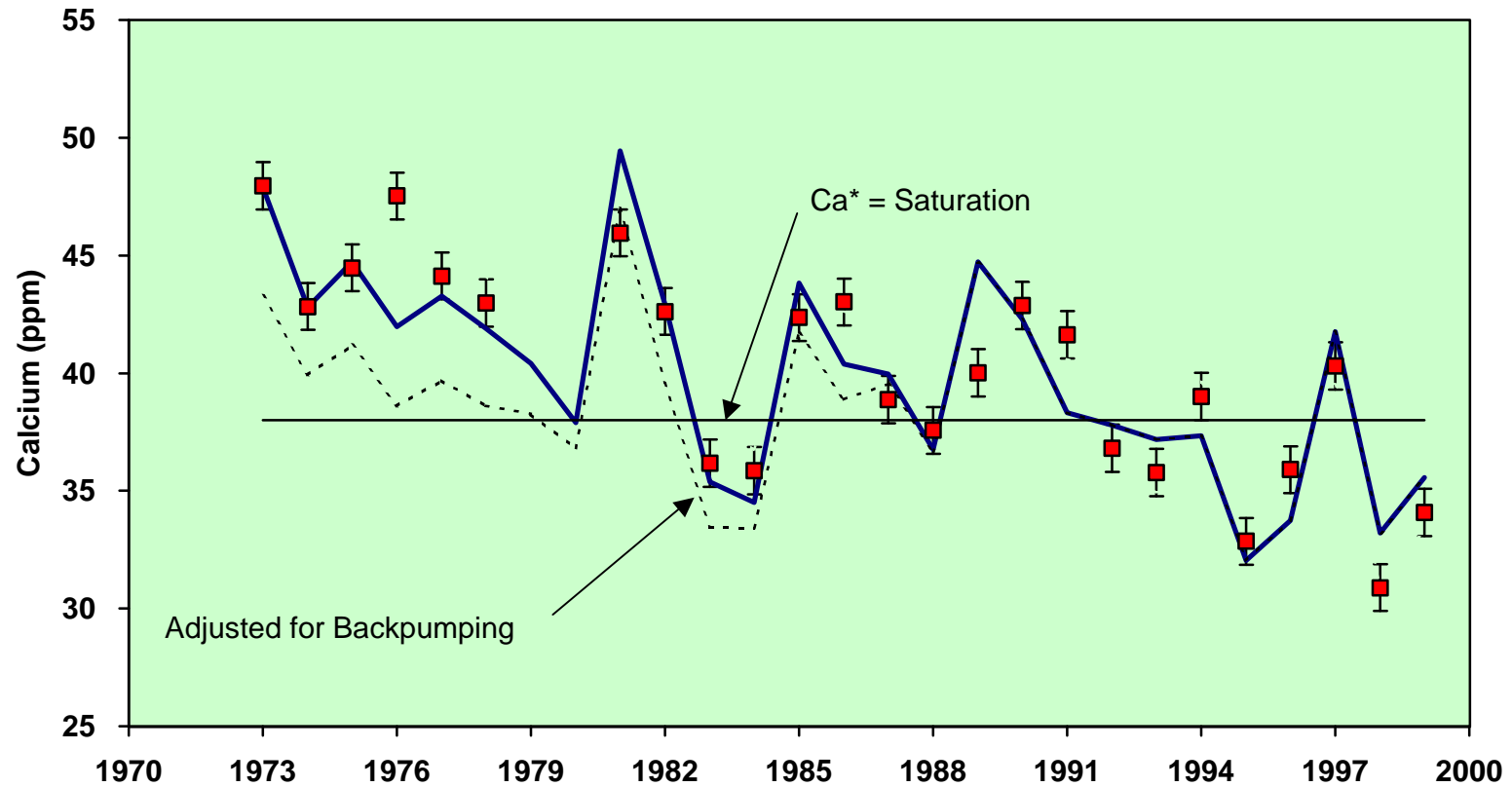
Adjusted = 1973-1985 loads adjusted to be consistent with 1986-1999 EAA backpumping rates

Figure 11
Chloride & Calcium Simulations



Simulations assume conservative behaviour (no net losses from water column)

Figure 12
Calcium Model Calibration



Solid Line: Predicted Historical Ca Conc

Observed +/- 1 Standard Error

Dashed Line: Inflows Adjusted for Reductions in EAA Backpumping

Model: $S_{CA} = K_{CA} (Ca - Ca^*)$

$R^2 = 0.75$

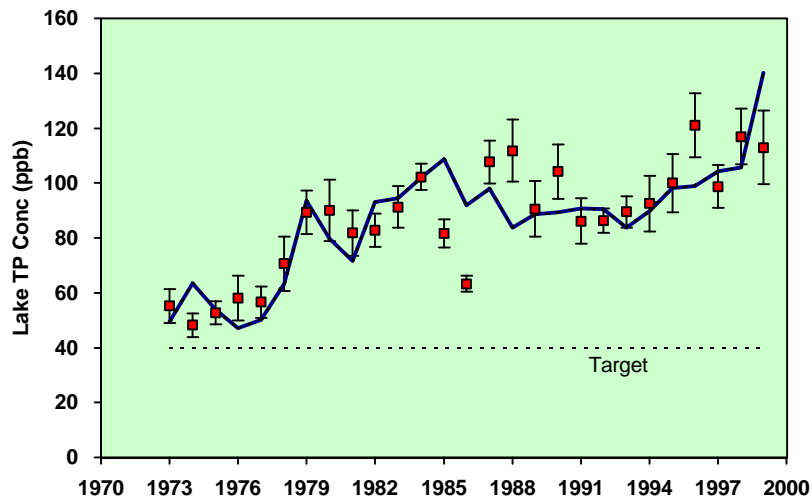
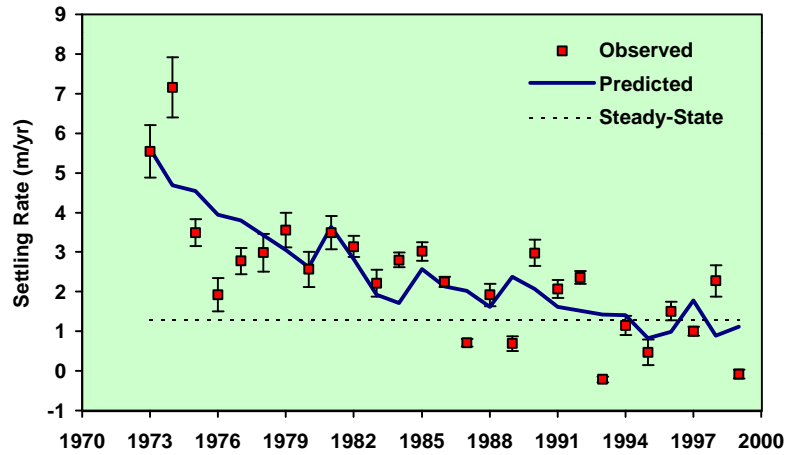
SE = 2.26 ppm

Least Squares Parameter Estimates:

$K_{CA} = 2.61$ m/yr

$Ca^* = 38.0$ ppm

Figure 13
Calibration of Calcium-Coupled Total P Model



Observed $K_{net} = (L - dM/dt) / (\text{Area } C_{lake}) - Q_o/\text{Area} \quad +/- 1 \text{ Standard Error}$

Model: $K_{net} = K_0 + (K_0 - K_1) \exp(-b(t - 1973)) + K_3(Ca - Ca^*)$

Knet $R^2 = 0.54 \quad SE = 1.08 \text{ m/yr}$

Conc $R^2 = 0.51 \quad SE = 14.4 \text{ ppb}$

Least Squares Parameter Estimates:

$K_0 = 1.234 \text{ m/yr} \quad K_3 = 0.103 \text{ m/yr / ppm}$

$K_1 = 4.590 \text{ m/yr} \quad K_{CA} = 2.61 \text{ m/yr}$

$b = 0.126 \text{ 1/yr} \quad Ca^* = 38.0 \text{ ppm}$

TMDL Calculation:

$TMDL = C_{TARGET} (K_{SS} \text{ Area} + Q_o)$

$K_{SS} = K_0 + K_3 (Ca_{SS} - Ca^*)$

$C_{TARGET} = 40 \text{ ppb} \quad Q_o = 1.57 \text{ } 10^9 \text{ m}^3/\text{yr}$

$\text{Area} = 1.733 \text{ } 10^9 \text{ m}^2 \quad Ca_{SS} = 38.5 \text{ ppm}$

	Mean	SE	10th%	90th%
K_{SS} m/yr	1.289	0.22	1.00	1.58
TMDL mt/yr	152	20	126	178

Time for 90% Response to New Steady State = $-\ln(.1) / b = 18.3 \text{ years}$

Figure 14
TMDL Phosphorus & Calcium Simulations

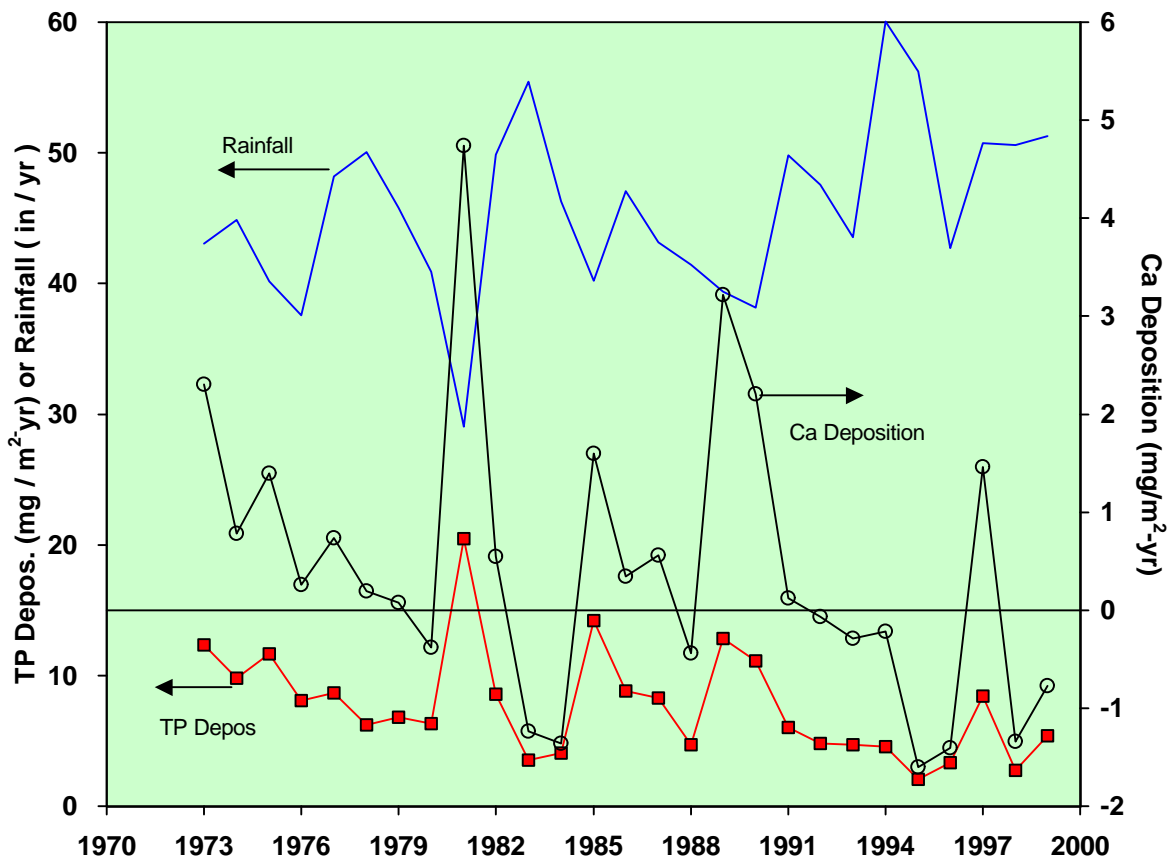
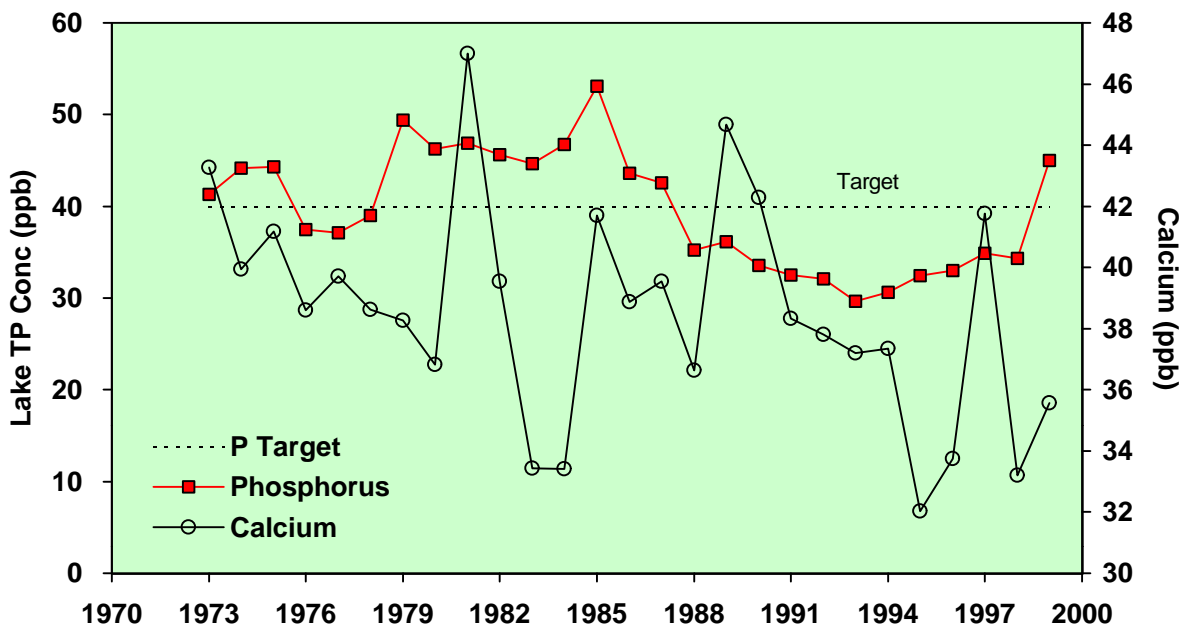
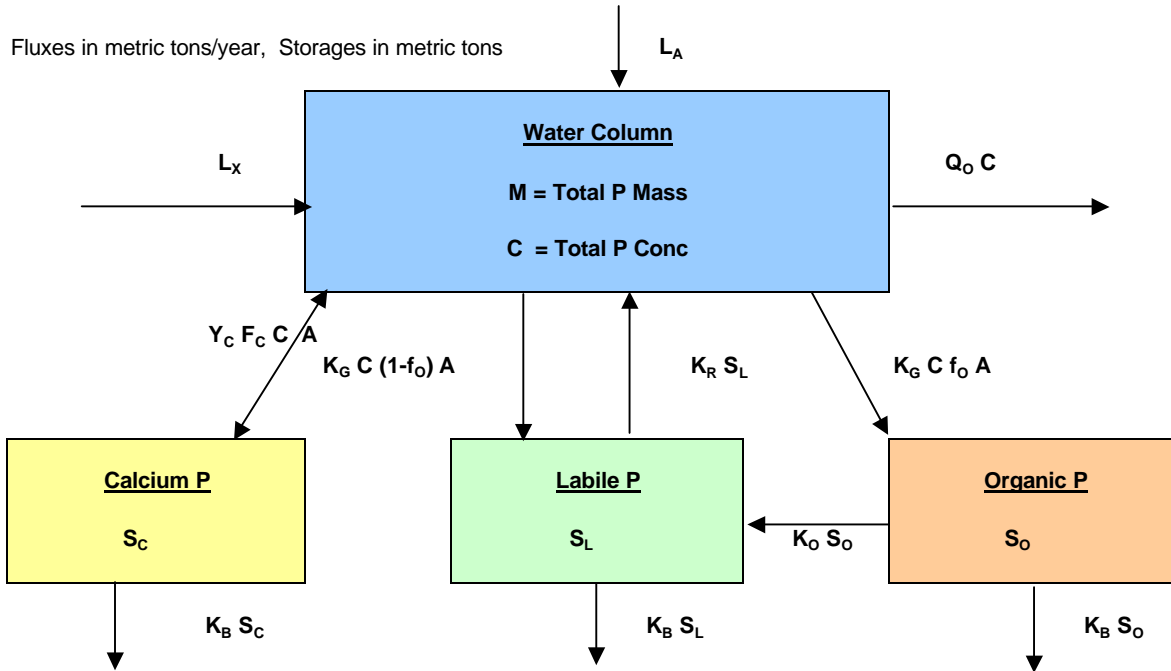


Figure 15
Model Structure & Parameter Estimates



<u>Parameter Estimates</u>		<u>Value</u>	<u>Units</u>	<u>Basis</u>
K_G	gross settling rate	5.004	m/yr	CLS = Constrained Least Squares
K_R	labile P recycle rate	0.369	1/yr	CLA
K_O	organic P decomposition rate	0.005	1/yr	Pollman (1991)
Y_C	C-P settling rate / Ca depos	0.187	m/yr/(g/m ² -y)	CLS
f_o	refractory organic p fraction	0.20	-	adjusted to fit mud zone data
d	soil bulk density	0.15	g/cm ³	mud zone sediment measurements
a	sediment deposition coef	6.50	-	CLS
b	sediment deposition slope	0.50	-	CLS
F_c	net calcium deposition rate	-	g/m ² -yr	calcium mass-balance model
Z_s	storage layer thickness	5	cm	assumed

<u>Burial Rate Model</u>		<u>Units</u>	<u>Equations</u>
K_B	stored p burial rate	yr ⁻¹	V_B / Z_s
V_B	burial velocity	cm/yr	$10^{-4} T / d$
T	sediment deposition rate	g/m ² -yr	$a G^b$
G	gross p sedimentation	mg/m ² -yr	$Y_C F_C C + K_G C$

Constrained Least Squares of Water Col P $R^2 = 0.62$ RSE = 12.6 ppb

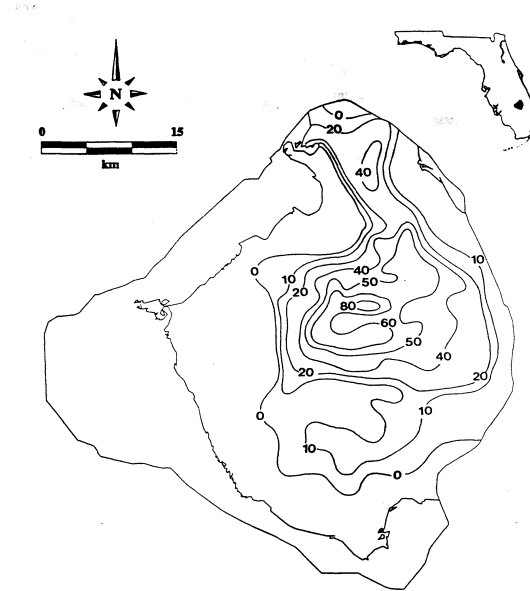
Sediment Constraints (1980-1987 Averages), +/- 20% Agreement

<u>Variable</u>	<u>Units</u>	<u>Model</u>	<u>Data</u>	<u>Parameters</u>	<u>Reference</u>
gross p recycle rate	mg/m ² -d	1.00	0.80	K_R, Y_C	Reddy et al., (1995)
accreted soil tp 80-87	mg/kg	1504	1400	a	Brez. & Engstr. (1998)
avg. sediment accm rate	mm/yr	1.00	1.00	a, K_G	Brez. & Engstr. (1998)
1900 / 1980-87 soil accr.	-	56%	50%	b	Brez. & Engstr. (1998)
1989, 0-5 cm Calcium	g/kg	85	94	a, K_{CA}	Olila et al (1995)
1989, 0-5 cm sed TP	mg/kg	1263	1197	a	Olila et al (1995)
1989, 0-5 cm sed Org P	mg/kg	385	383	a, f_o, K_O	Olila et al (1995)
1989, 0-5 cm sed Ca-P	mg/kg	719	694	a, Y_C	Olila et al (1995)
1989, 0-5 cm sed Avail P	mg/kg	159	63	a, K_R	Olila et al (1995)

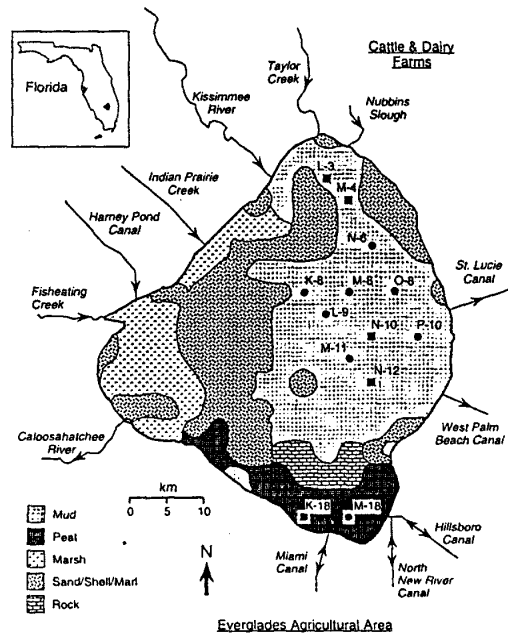
Figure 16 Mud Zone Thickness & Sampling Locations

Mud Zone Soil Thickness (cm) (SFWMD, 1997):

Figure 13. The thickness (cm) of mud sediments in Lake Okeechobee (Kirby *et al.* 1994).

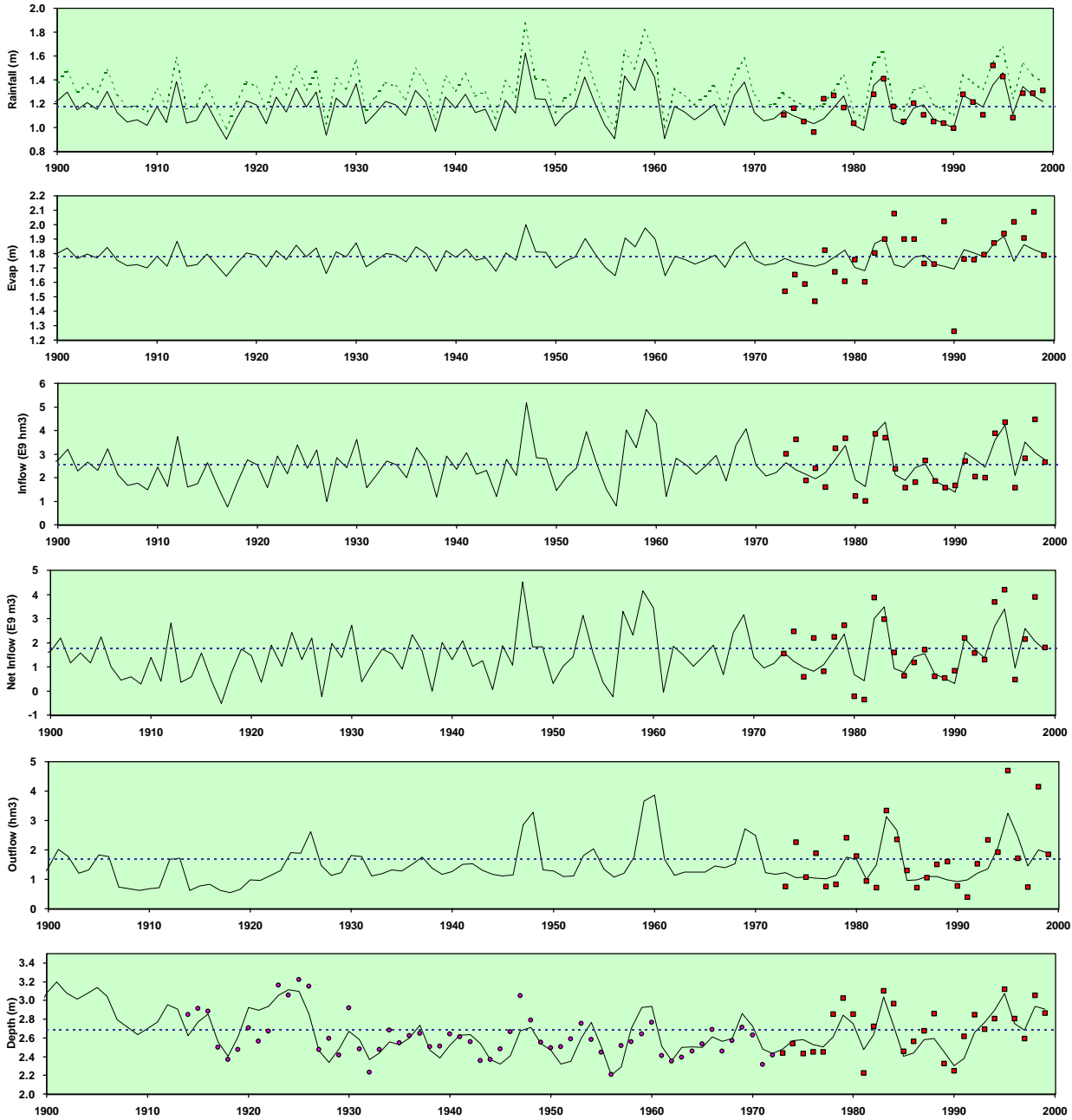


Core Locations (Brezonik & Engstrom, 1998):



Map of Lake Okeechobee showing sediment types. (from Reddy *et al.*, 1993), locations of cores collected in 1989 (circles with stars).

Figure 17
Simulated Historical Hydrologic Record



Solid Lines: Simulated Time Series Symbols:

Dashed Lines : 1973-1999 Means

Variable	Estimation Method	Mean	StdDev	Min	Max
Base Rain (m)	From NCDC, Average of FL Regions 4 & 5 (dashed line)	1.32	0.18	0.98	1.88
Lake Rain(m)	Correlated with Base Rain	1.17	0.14	0.90	1.62
Evap (m)	Correlated with Base Rain	1.78	0.07	1.64	2.00
Inflow (E9m3)	Correlated with Base Rain (3 Periods)	2.52	0.86	0.76	5.17
Outflow (E9 m3)	Stage/Discharge Correl (Separate for 1914-27, 28-73, 74-99)	1.47	0.66	0.55	3.87
Net Inflow (E9 m3)	Inflow + Rainfall - Evaporation	1.47	0.97	-0.52	4.51
Volume (E9 M3)	Water Balance	4.64	0.62	3.10	5.86
Depth (m)	From Volume, Based on Morphometry	2.66	0.23	2.20	3.20

Figure 18
200-Year Simulation Results

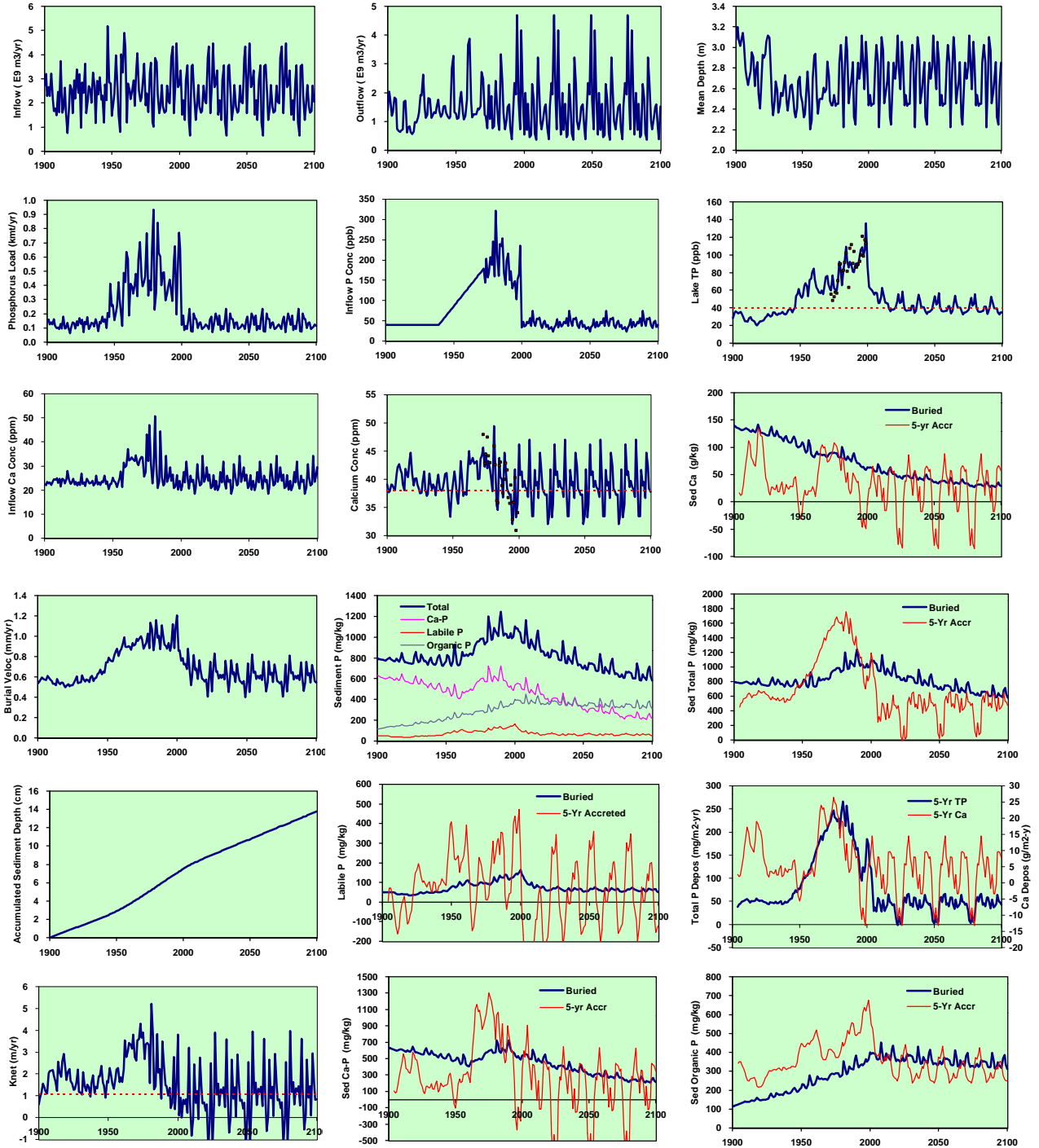
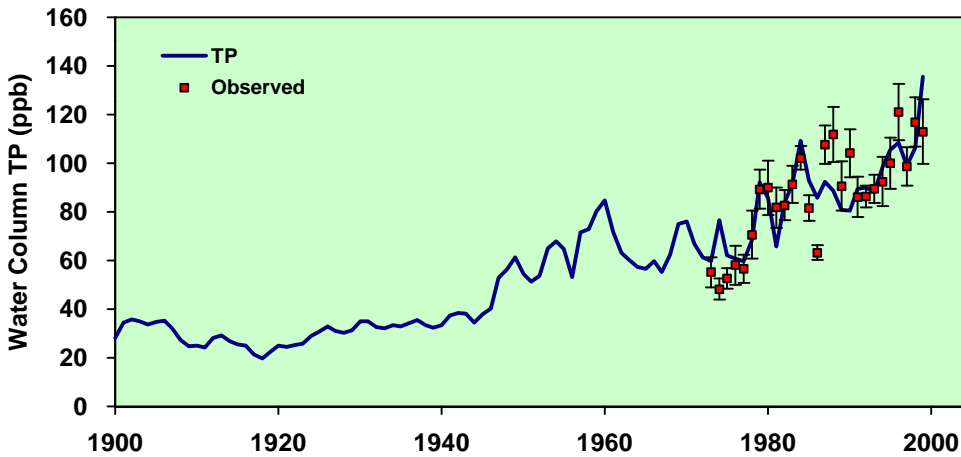
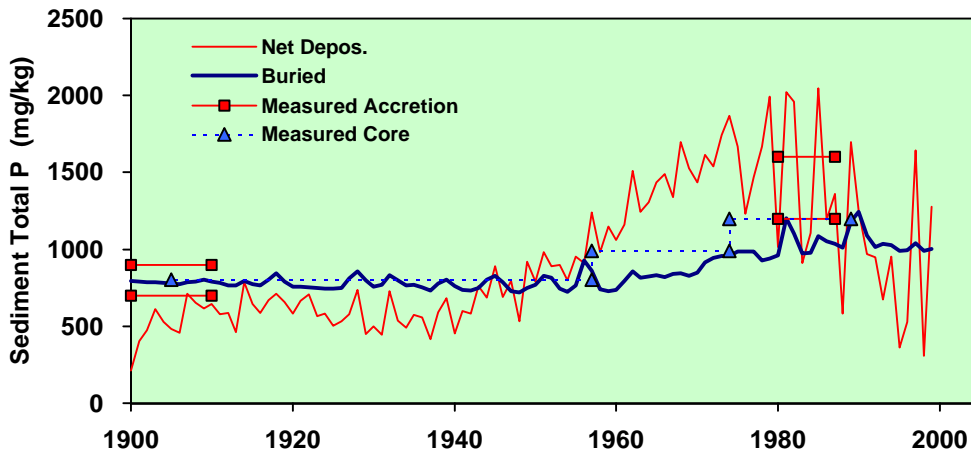
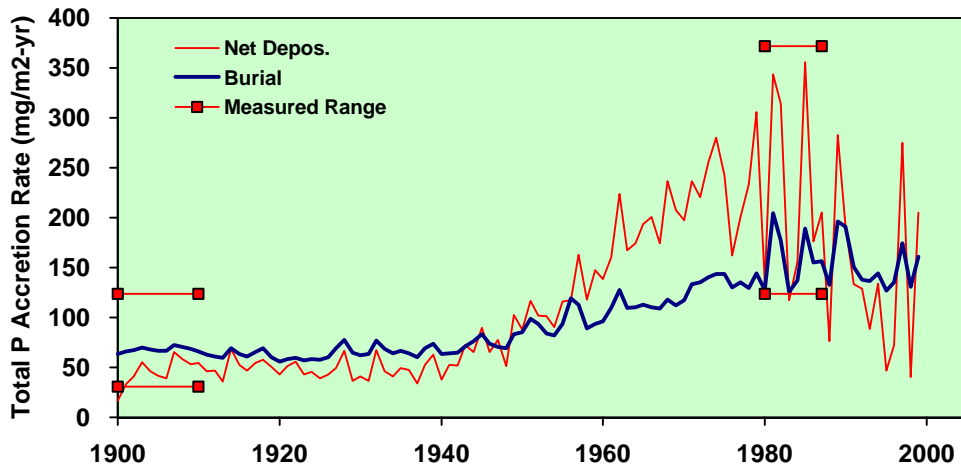


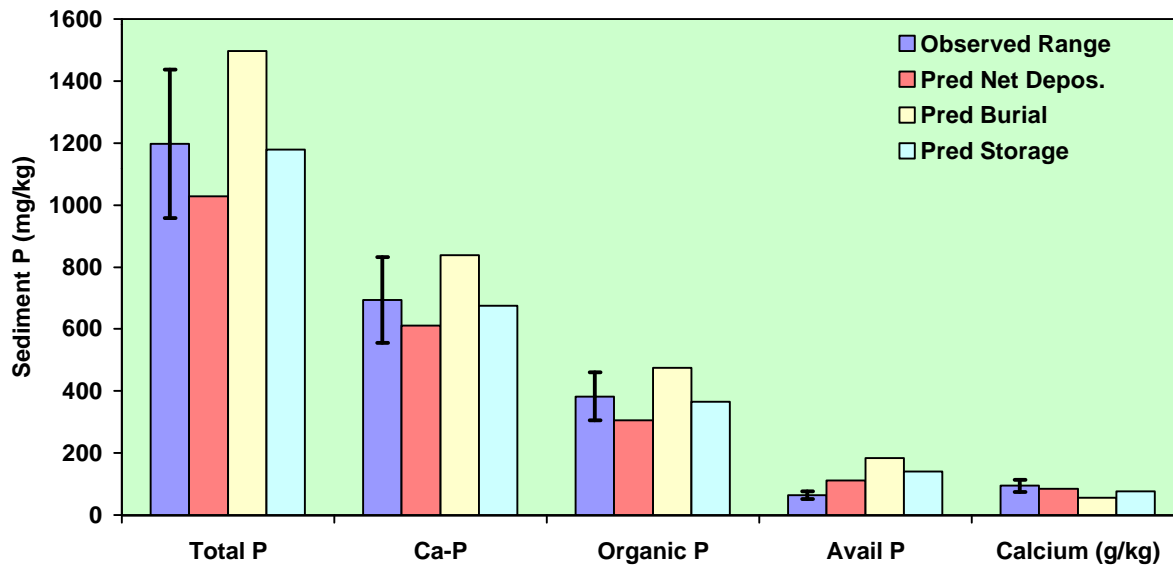
Figure 19
Observed & Predicted Sediment & Water-Column Phosphorus



$R^2 = 0.60$ $SE = 13.0$ ppb

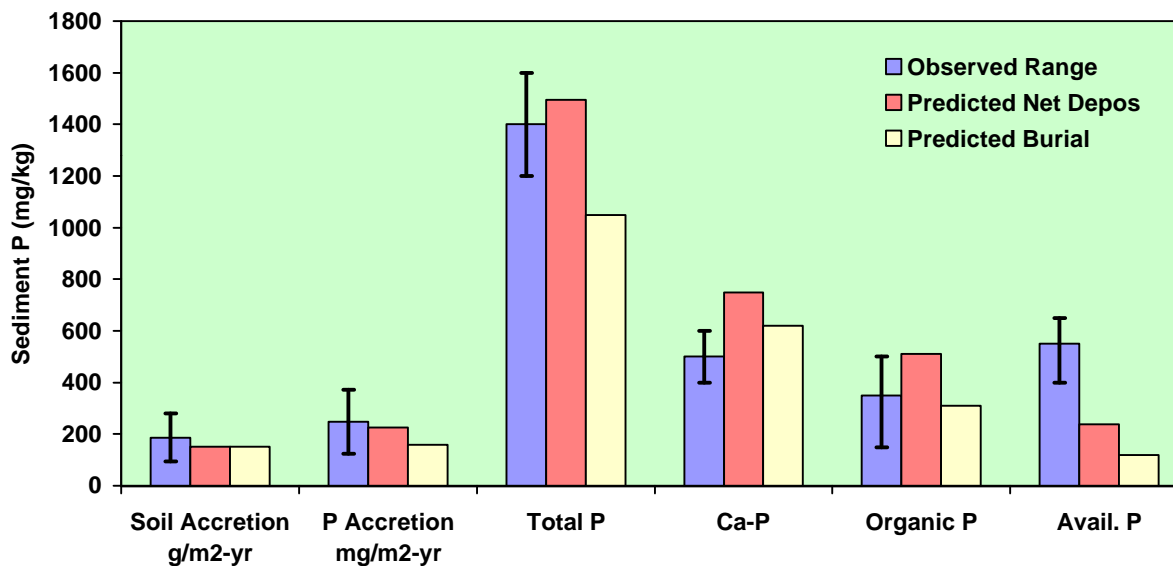
Figure 20
Comparisons with Soil Core Sampling Results

Mud Zone 0-5 Cm Core (~1989)



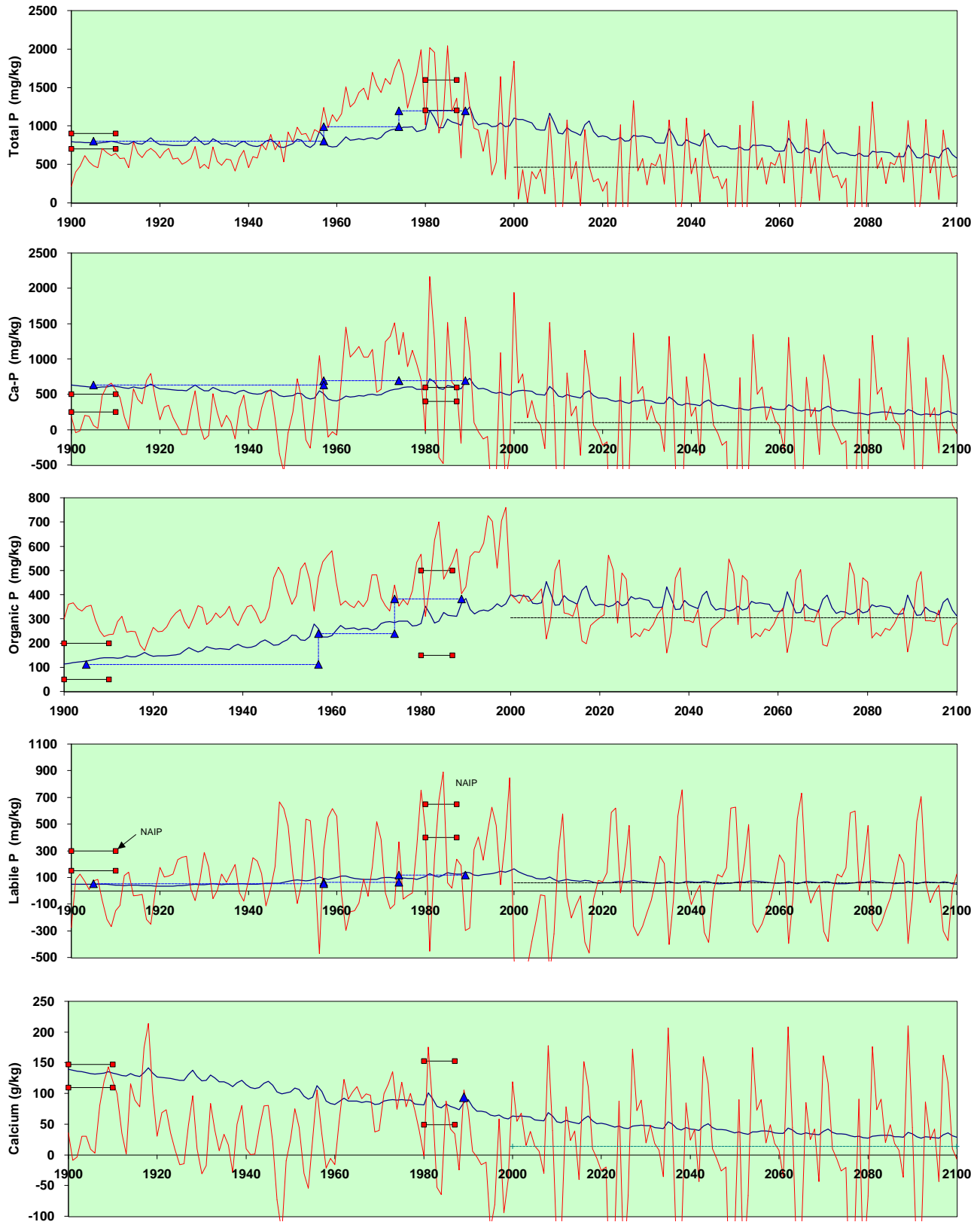
Observed values from 0-5 cm core collected in 1989 by Olila et al (1995) at Station K8 in mud zone; +/- 2 standard errors
 Model available P pool compared with measured NH₄CL-P + NaOH-P + Loose Organic P.
 Predicted composition of active storage, net deposition from water column, & burial from storage over time interval represented by core.
 Based upon accretion rates predicted by model, core date range= 1974 to 1989 adjusted for mud zone area = 31%

Mud Zone Sediment Accreted between 1980 & 1987



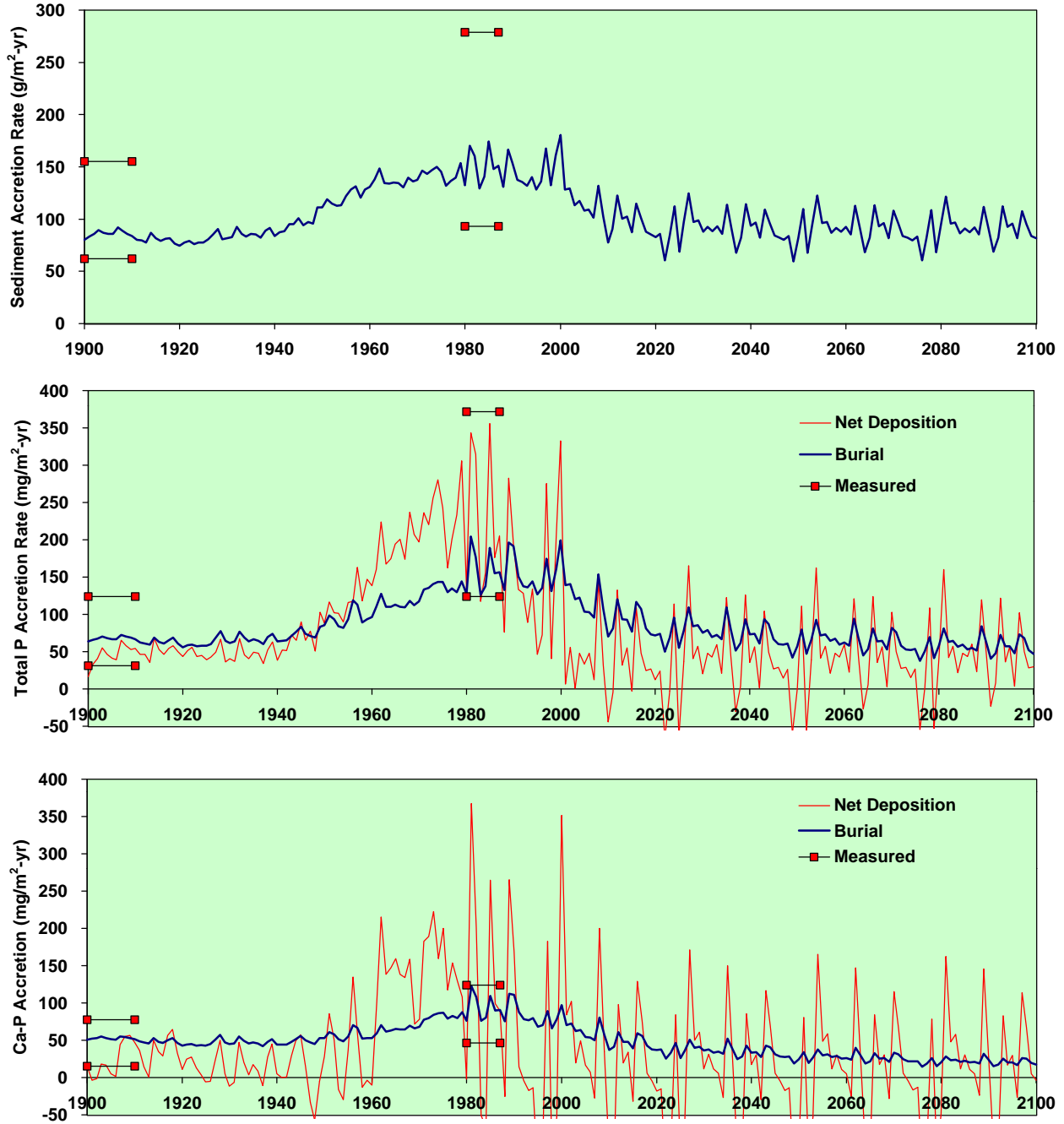
Observed values from 1980-1987 dated core collected by Brezonik & Engstrom (1998), range of values from 8 mud-zone stations.
 Model available P pool compared with measured NAIP (Non-Apatite Inorganic P)
 Predicted accretion rates & composition of net deposition from water column and burial from storage between 1980 & 1987.

Figure 21
Observed & Predicted Sediment Composition



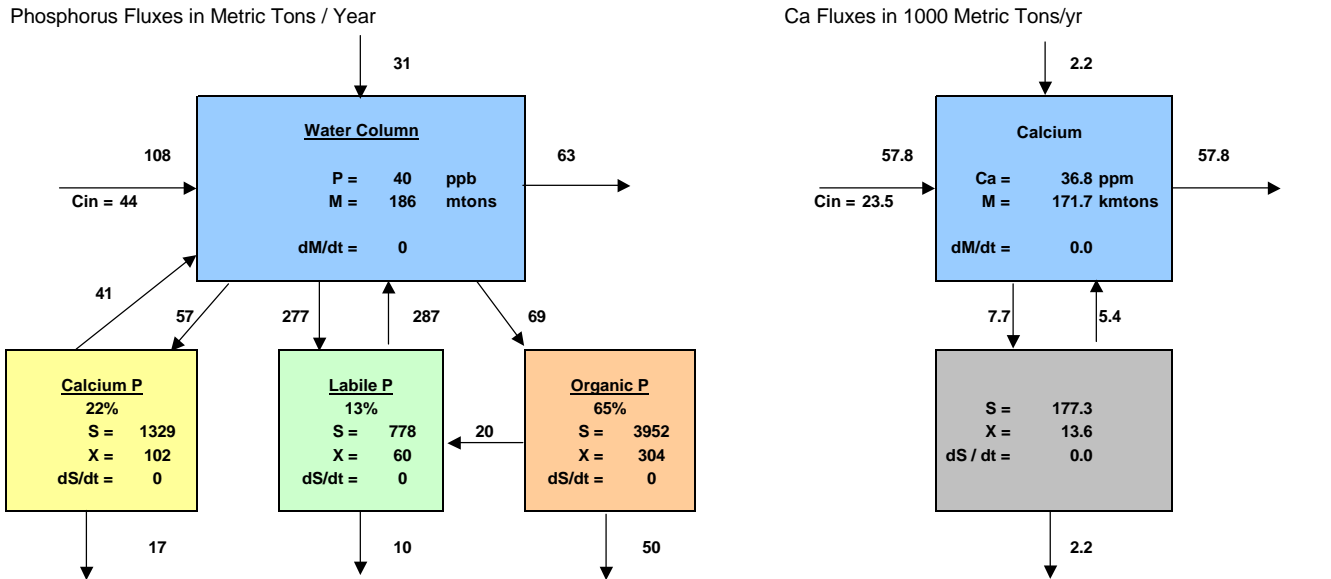
Horizontal bars show range of measurements from mud zone reflecting net accretion pre-1910 & 1980-1987 (Brezonik & Engstrom, 1998)
 Thin red lines show predicted average composition of net deposition from water column. Negative values indicate that recycle to water column exceeds gross deposition.
 Heavy blue lines show predicted composition of the active sediment layer (= composition of buried sediment)
 Blue triangles show 0-5-, 5-10-, & 10-20 cm mud zone sediment compos. (Ollila et al, 1995) dated using accretion rates predicted by model & adjusted for 31% sampled mud zone area
 Dashed lines show predicted steady-state under TMDL load.

Figure 22
Observed & Predicted Accretion Rates



Horizontal bars show range of measurements from mud zone reflecting net accretion between 1980-1987 (Brezonik & Engstrom, 1998)
 Measured rates multiplied by ratio of sampled mud zone to total lake area (0.31) to estimate lake-wide average rate predicted by model.
 Lines show predicted net deposition rates from water column and burial rates from storage

Figure 24 TMDL Mass Balance at Steady-State



Steady-State Solution:

C*	40	ppb	Assumed Lake Target Concentration
TMDL	139	mtons/yr	$C^* (K_{net} A + Q_0)$
TMDL SE	18	mtons/yr	Approx. Standard Error of TMDL
TMDL 10%	115	mtons/yr	Approx. Lower 10% Conf. Interval
TMDL 90%	163	mtons/yr	Approx. Upper 90% Conf. Interval
K_{net}	1.10	m/yr	Steady-State Net Settling Rate
SE(K_{net})	0.26	m/yr	Standard Error of Predicted Knet
Q_0	1.57	10^9 m ³ /yr	1973-1999 Outflow (*adjusted for reduced EAA inflows)
Lca	60.0	1000 mt/yr	1973-1999 Calcium Load *
Fcg	4.42	g/m ² -yr	1973-1999 Gross Calcium Sedimentation *
Fc	1.28	g/m ² -yr	1973-1999 Net Calcium Sedimentation *
A	1.73	10^9 m ²	1973-1999 Lake Area
Q_w	2.45	10^9 m ³ /yr	1973-1999 Watershed Inflows *
Ci	44	ppb	Inflow Conc. From Watershed Under TMDL

Calculations:

K_B	0.013	yr ⁻¹	V_B / Z_S
V_B	0.063	cm/yr	$10^4 T / d$
T	94	g/m ² -yr	$a G^b$
Ca	36.8	ppm	$(L_{CA} - F_C A) / Q_0$
X_{CA}	13.6	g/kg	$1000 F_C / T$
G	210	mg/m ² -yr	$Y_C F_C C^* + K_G C^*$
S_C	1329	mtons	$Y_C F_C C^* A / K_B$
S_O	3952	mtons	$f_0 K_G C^* A / (K_B + K_O)$
S _L	778	mtons	$[K_O S_O + (1 - f_0) K_G C^* A] / (K_B + K_R)$
N	7.5	kg/m2	$10 Z_S d$
$KNET_O$	0.72	m/yr	$f_0 K_G K_B / (K_B + K_O)$
$KNET_C$	0.24	m/yr	$Y_C F_C$
$KNET_L$	0.14	m/yr	$[f_0 K_G K_O / (K_O + K_B) + (1 - f_0) K_G] K_B / (K_B + K_R)$
K_{net}	1.10	m/yr	$KNET_O + KNET_C + KNET_L$

Check	Inputs	Outputs	Storage		Turnover			Storage	Storage	Burial	Net Depo
			Increase	Error	mtons	1/yr	90% Resp				
W Col	467	467	0.0	0.0	186	2.506	0.9	107.5			
Labile P	297	297	0.0	0.0	778	0.382	6.0	449.2	59.9	5.6	-5.8
Ca P	57	57	0.0	0.0	1329	0.043	53.3	767.0	102.3	9.6	9.6
Org P	69	69	0.0	0.0	3952	0.018	131.2	2280.7	304.1	28.6	40.0
Total Stor	424	424	0.0	0.0	6059	0.070	32.9	3497.0	466.3	43.9	43.9
Wtr+Lab	199	199	0.0	0.0	965	0.207	11.1	556.8			
Whole	139	139	0.0	0.0	6245	0.022	103.6	3604.5			
Ca W Col	65.45	65.45	0.0	0.0	102	0.640	3.6	59.1			
Ca Sed	7.67	7.67	0.0	0.0	177	0.043	53.3	102.3	13.6	1.3	1.3
Ca Total	60	60	0.0	0.0	280	0.215	10.7	161.4			

Figure 25
TMDL Simulation using 1973-1999 Hydrology

TMDL = 139 mtons/yr starting in 2000 T50 = 8 years

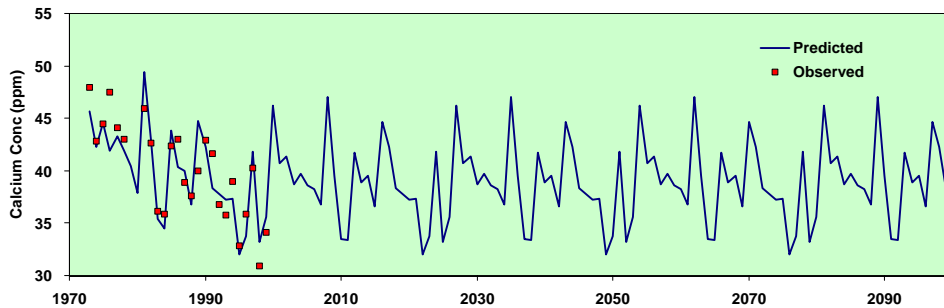
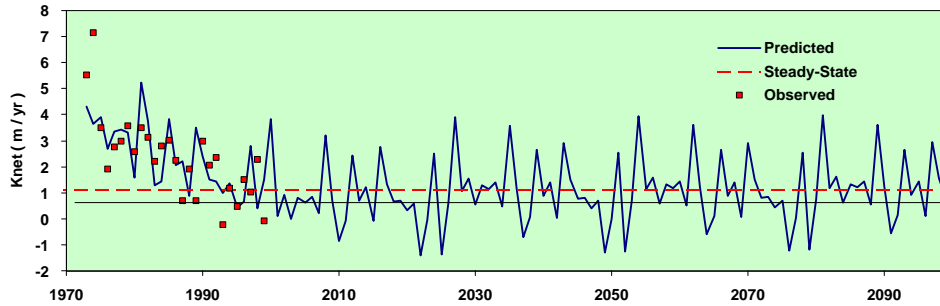
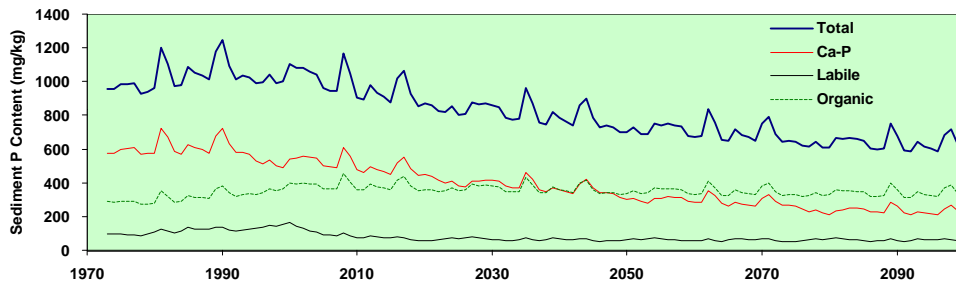
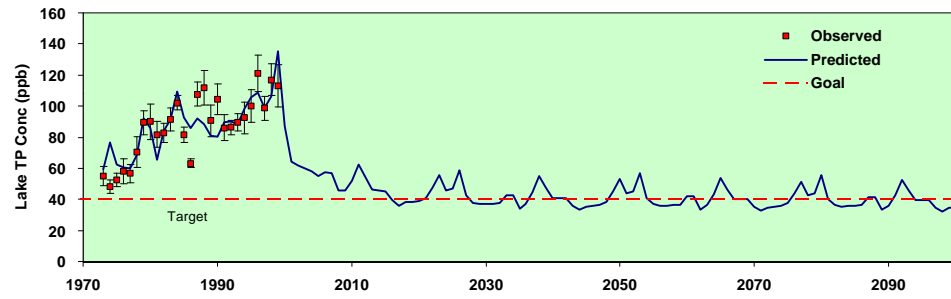
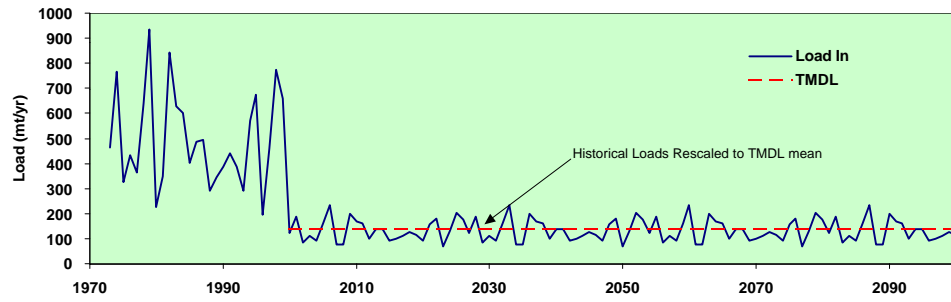


Figure 26
TMDL Simulation using 1990-1999 Simulated Hydrology

TMDL = 139 mt/ons/yr starting in 2000 T50 = 8 years

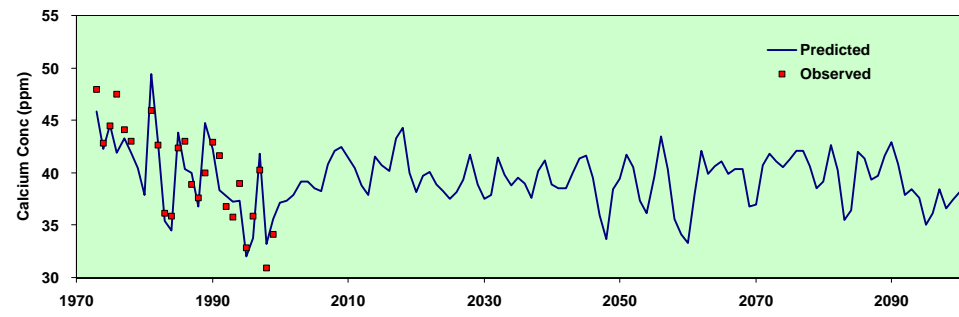
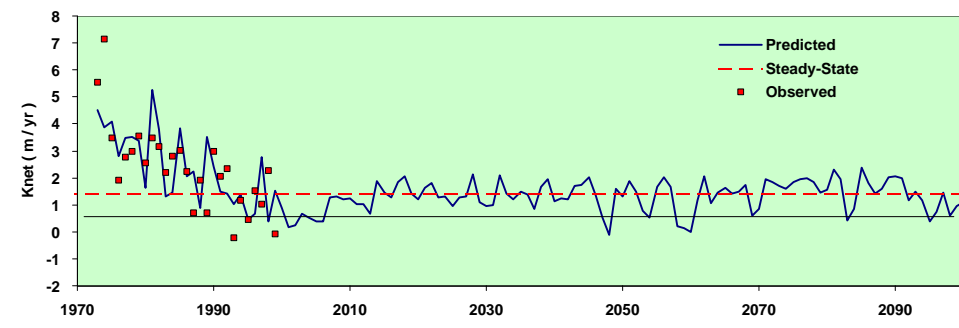
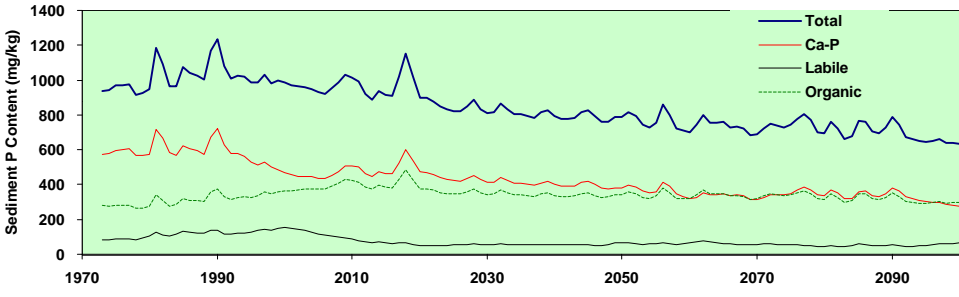
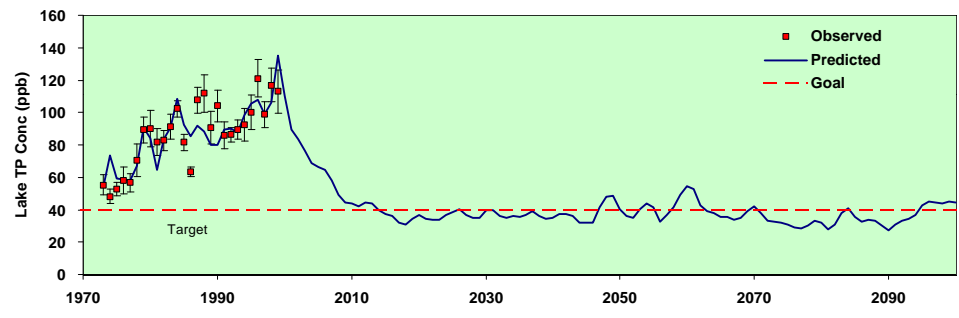
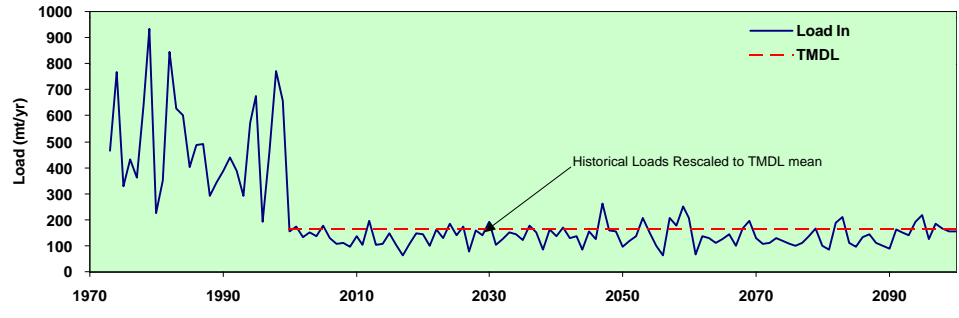
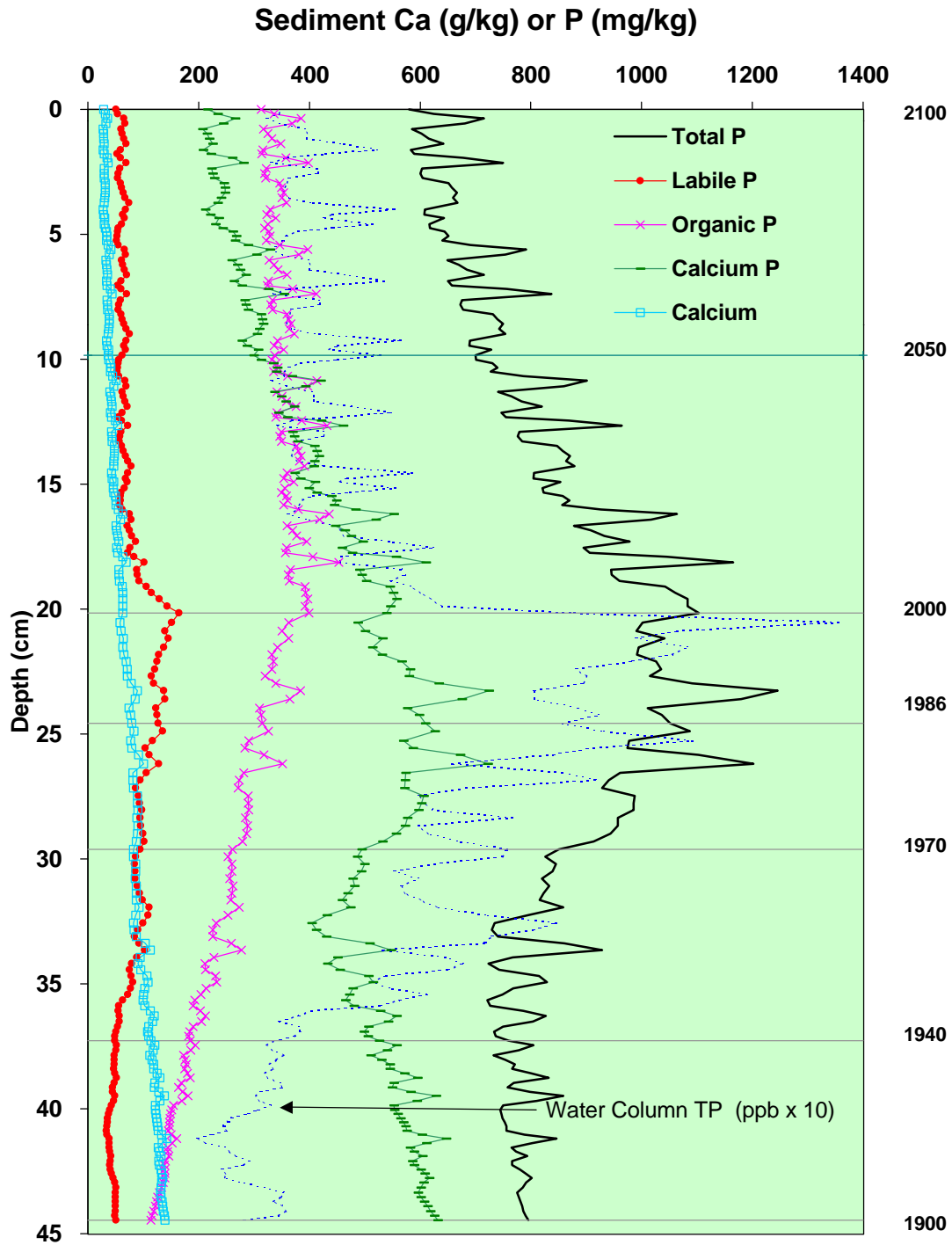


Figure 27
Mud Zone Vertical Profile Generated by Model for Year 2100



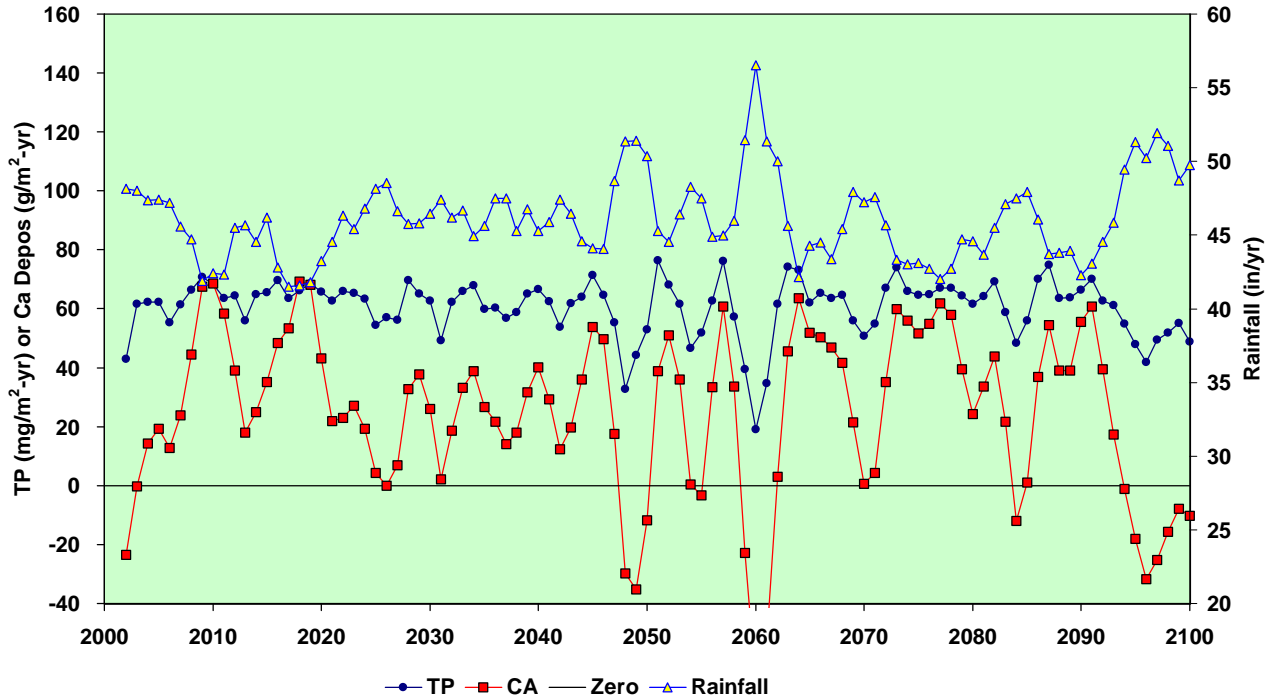
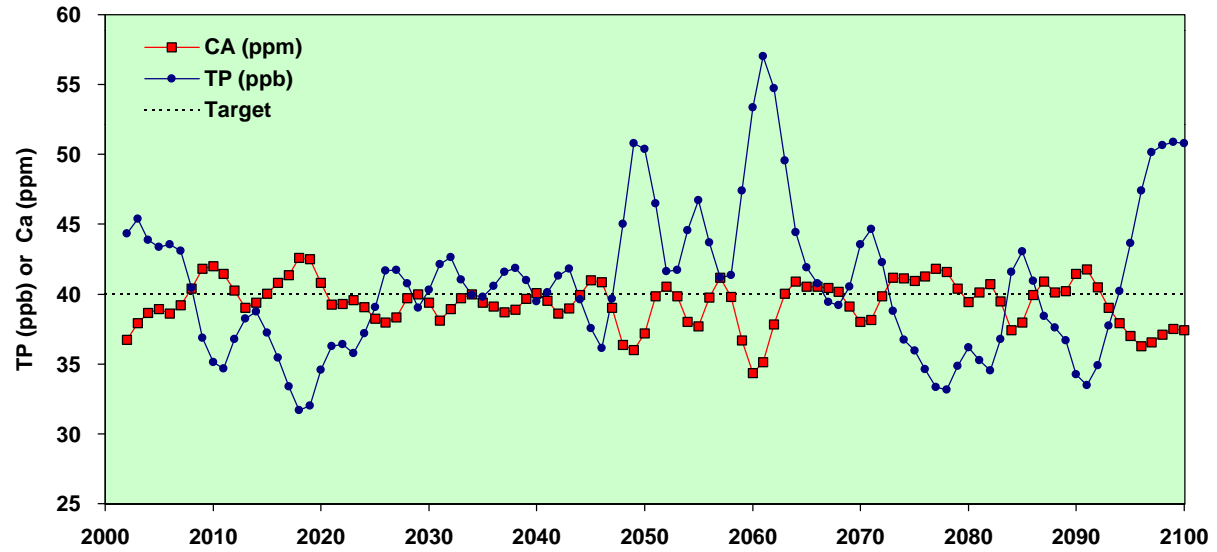
Historical Simulation (1900-1999) with TMDL achieved starting in year 2000, load =

139 mt/yr

Vertical scale = depth below active sediment layer, computed from predicted sediment accretion rates

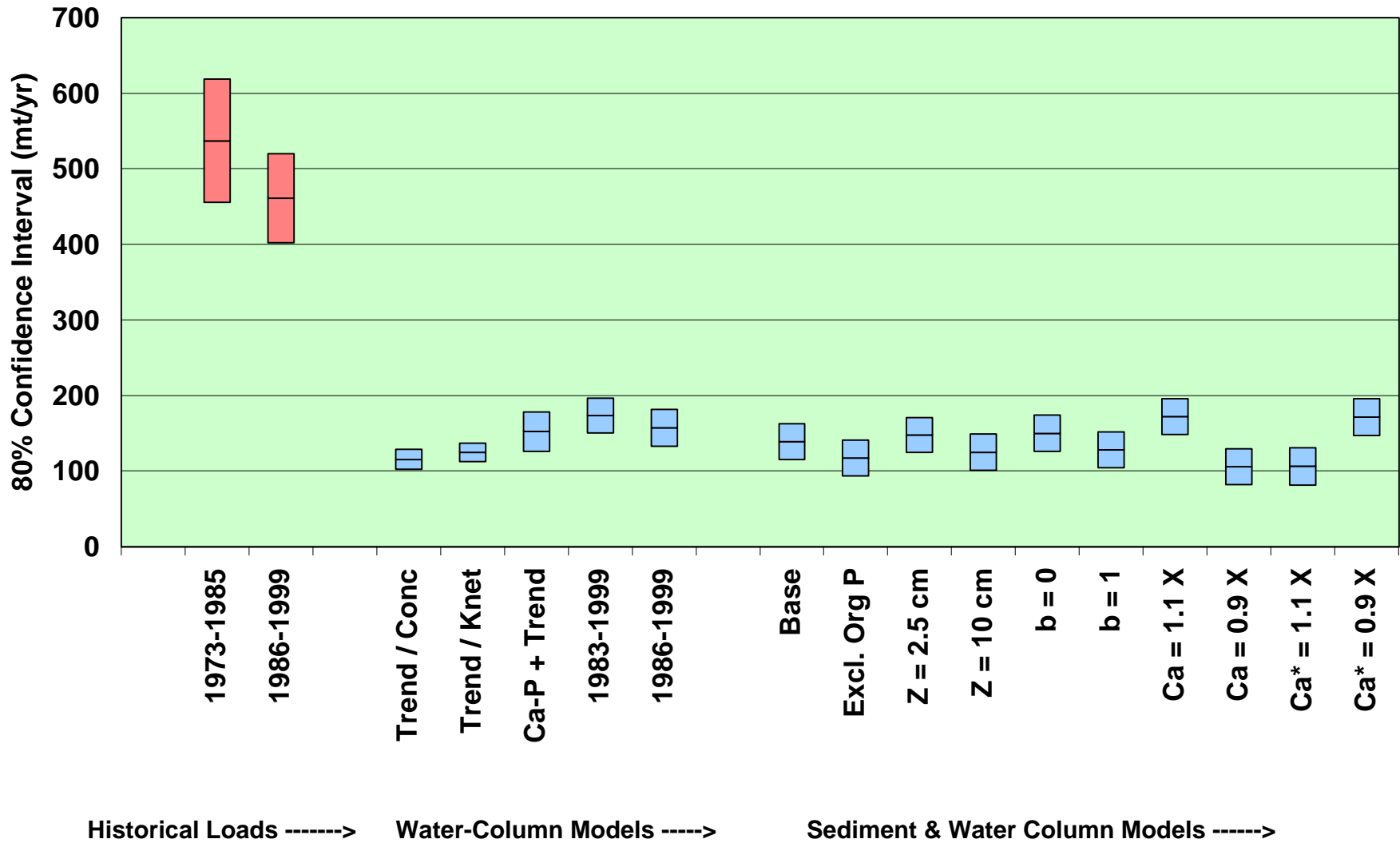
Figure 28

Rain-Driven Variations in Calcium & Phosphorus Under TMDL Conditions



Three-Year rolling averages using simulated hydrology based upon 1900-1999 rainfall record

Figure 29
Confidence Intervals for TMDL's Compared with Historical Phosphorus Loads



List of Tables

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- 2 Estimated Calcium Budgets
- 3 Water & Mass Balances
- 4 Sensitivity Analysis Results

Table 1
Lake Hydrologic, Morphometric, & Phosphorus Load Data

<u>Year</u>	<u>Water Balance (10⁹ m³/yr)</u>						<u>P Load (metric tons/yr)</u>				<u>Area Zmean</u>		<u>T</u>	<u>Cin</u>	<u>UAL</u>	<u>Lake P</u>		<u>Knet</u>	
	<u>Rain</u>	<u>Evap</u>	<u>Qin</u>	<u>Qout</u>	<u>dV/dt</u>	<u>Error</u>	<u>Inflow</u>	<u>Atmos</u>	<u>Total</u>	<u>dM/dt</u>	<u>10⁹m²</u>	<u>m</u>				<u>ppb</u>	<u>mg/m²/h</u>	<u>ppb</u>	<u>ppb</u>
1973	1.8	2.5	3.01	0.76	0.80	0.73	434.4	29.8	464.2	-84.7	1.656	2.44	2.59	145	280.3	55.2	6.2	5.54	0.67
1974	1.9	2.7	3.63	2.27	0.21	0.33	737.3	30.4	767.6	75.5	1.686	2.54	1.73	203	455.2	48.3	4.3	7.16	0.76
1975	1.7	2.6	1.89	1.08	-0.49	0.40	297.0	29.9	327.0	-35.9	1.664	2.43	6.88	157	196.5	52.7	4.3	3.49	0.33
1976	1.6	2.5	2.40	1.88	0.31	-0.65	403.0	30.2	433.2	136.4	1.678	2.45	1.88	168	258.1	58.1	8.1	1.92	0.43
1977	2.1	3.1	1.61	0.76	0.07	-0.21	332.6	30.3	362.9	55.3	1.686	2.45	5.00	207	215.3	56.6	5.8	2.77	0.33
1978	2.3	3.0	3.24	0.83	1.42	0.27	608.1	32.7	640.7	200.0	1.814	2.85	2.30	188	353.2	70.6	9.9	2.98	0.48
1979	2.1	2.9	3.66	2.41	0.31	0.13	900.9	32.9	933.8	138.4	1.826	3.03	2.03	246	511.5	89.3	8.0	3.56	0.44
1980	1.9	3.2	1.22	1.79	-2.01	0.12	193.8	32.6	226.3	-352.3	1.809	2.85		159	125.1	89.9	11.2	2.56	0.44
1981	1.1	2.3	1.01	0.94	-1.28	0.14	324.0	26.2	350.3	-142.2	1.458	2.22		322	240.3	81.7	8.3	3.49	0.42
1982	2.0	2.9	3.86	0.71	3.15	-0.85	814.6	29.1	843.7	364.8	1.616	2.72	1.14	211	522.2	82.7	6.1	3.14	0.26
1983	2.6	3.5	3.70	3.33	-0.36	-0.18	594.6	33.1	627.8	-48.9	1.842	3.10	1.92	161	340.9	91.3	7.6	2.22	0.33
1984	2.2	3.8	2.38	2.35	-0.75	-0.88	569.0	33.1	602.1	-164.7	1.838	2.97	3.40	239	327.7	102.2	4.8	2.80	0.19
1985	1.7	3.1	1.58	1.30	-0.66	-0.49	371.0	30.1	401.0	-115.8	1.670	2.45	6.43	234	240.1	81.6	5.2	3.02	0.24
1986	2.1	3.3	1.81	0.72	0.47	-0.60	457.0	31.4	488.5	194.4	1.747	2.56	3.77	253	279.6	63.3	3.0	2.25	0.12
1987	2.0	3.1	2.74	1.06	0.65	-0.09	460.3	32.0	492.4	242.5	1.781	2.68	2.78	168	276.5	107.7	7.9	0.71	0.10
1988	1.9	3.2	1.86	1.51	-0.89	0.01	260.2	32.9	293.1	-267.1	1.825	2.86	8.44	140	160.6	111.7	11.3	1.92	0.28
1989	1.6	3.1	1.59	1.60	-1.06	-0.52	314.9	28.2	343.1	100.4	1.565	2.33	6.77	198	219.2	90.5	10.1	0.69	0.19
1990	1.4	1.9	1.67	0.77	0.08	0.41	360.6	26.8	387.4	-155.1	1.490	2.25	3.95	216	260.0	104.2	9.9	2.98	0.33
1991	2.1	3.0	2.71	0.39	1.81	-0.32	409.8	30.6	440.4	104.5	1.699	2.62	2.02	151	259.3	86.1	8.3	2.07	0.22
1992	2.2	3.2	2.05	1.52	0.06	-0.52	353.5	32.8	386.3	-116.1	1.824	2.85	3.29	172	211.8	86.3	4.5	2.36	0.17
1993	2.0	3.2	1.99	2.33	-1.04	-0.52	258.2	32.1	290.2	115.3	1.781	2.70	3.71	130	162.9	89.4	5.7	-0.21	0.07
1994	2.7	3.3	3.89	1.93	1.76	-0.41	539.3	32.2	571.5	201.5	1.790	2.81	1.36	139	319.3	92.5	10.0	1.16	0.24
1995	2.6	3.6	4.35	4.69	-0.50	-0.78	642.7	33.2	675.8	120.7	1.842	3.12	1.37	148	366.9	100.0	10.6	0.47	0.32
1996	2.0	3.7	1.57	1.72	-1.25	-0.61	160.9	32.7	193.6	-347.0	1.819	2.81	10.78	103	106.5	121.1	11.7	1.51	0.24
1997	2.2	3.3	2.82	0.73	1.42	-0.39	427.4	31.3	458.7	213.8	1.741	2.59	2.10	152	263.5	98.7	7.8	1.01	0.11
1998	2.4	3.8	4.46	4.16	-0.25	-0.91	739.5	32.9	772.4	-201.3	1.830	3.05	1.43	166	422.1	117.0	10.2	2.28	0.40
1999	2.3	3.2	2.66	1.85	-0.03	0.00	626.1	32.5	658.6	467.2	1.805	2.87	2.85	235	365.0	113.0	13.3	-0.08	0.11
73-99	2.02	3.07	2.57	1.68	0.07	-0.24	466.3	31.2	497.5	25.9	1.733	2.69	2.66	182	287.1	86.7	7.9	2.36	0.31
73-77	1.82	2.67	2.51	1.35	0.18	0.12	440.8	30.1	471.0	29.3	1.674	2.46	2.70	176	281.3	54.2	5.7	4.18	0.96
86-99	2.11	3.20	2.58	1.78	0.09	-0.38	429.3	31.5	460.9	48.1	1.753	2.72	2.55	166	262.9	98.7	8.9	1.36	0.26
95-99	2.31	3.51	3.17	2.63	-0.12	-0.54	519.3	32.5	551.8	50.7	1.807	2.89	2.08	164	305.3	109.9	10.7	1.04	0.41
83-99	2.12	3.25	2.58	1.88	-0.03	-0.40	443.8	31.6	475.5	20.3	1.758	2.74	2.61	172	270.5	97.4	10.8	1.60	0.25

**Table 2
Estimated Calcium Budgets**

Year	Historical Data								Adjusted for Reductions in EAA Backpumping					
	Atmos			Watershed					EAA		EAA Watershed			
	Lake	Load	Outflow	Inflow	Conc	Load	Retained	BackP	BackP	Inflow	Conc	Load	Outflow	
ppm	1000 mt	10 ⁹ m ³ /yr	10 ⁹ m ³ /yr	ppm	1000 mt	1000 mt	%	%	%	10 ⁹ m ³ /yr	ppm	1000 mt	10 ⁹ m ³ /yr	
1973	48.0	2.13	0.76	3.01	25.5	76.8	42.4	54%	8.3%	1.2%	2.79	20.0	55.9	0.55
1974	42.8	2.17	2.27	3.63	27.6	100.1	5.0	5%	8.8%	1.3%	3.36	21.7	72.8	2.00
1975	44.5	2.14	1.08	1.89	43.1	81.6	35.6	43%	23.2%	3.3%	1.51	27.6	41.8	0.70
1976	47.5	2.16	1.88	2.40	32.1	76.9	-10.5	-13%	13.5%	1.9%	2.12	23.1	48.9	1.61
1977	44.1	2.17	0.76	1.61	47.0	75.5	44.2	57%	22.8%	3.2%	1.29	31.7	41.1	0.45
1978	43.0	2.34	0.83	3.24	31.0	100.6	67.2	65%	11.1%	1.6%	2.93	23.6	69.3	0.52
1979		2.35	2.41	3.66	22.8	83.6			3.7%	0.7%	3.55	20.5	72.8	2.31
1980		2.33	1.79	1.22	28.1	34.2			3.4%	0.7%	1.18	26.0	30.8	1.76
1981	46.0	1.88	0.94	1.01	50.6	51.0	9.7	18%	43.4%	8.6%	0.66	23.5	15.4	0.59
1982	42.6	2.08	0.71	3.86	31.3	121.0	92.9	75%	11.3%	2.2%	3.51	24.2	85.1	0.36
1983	36.2	2.37	3.33	3.70	20.7	76.5	-41.7	-53%	3.6%	0.7%	3.59	18.5	66.2	3.23
1984	35.9	2.37	2.35	2.38	23.6	56.1	-25.9	-44%	4.1%	0.8%	2.30	21.0	48.3	2.27
1985	42.4	2.15	1.30	1.58	44.4	70.3	17.4	24%	21.9%	4.3%	1.30	30.7	40.1	1.02
1986	43.0	2.25	0.72	1.81	25.3	45.7	17.1	36%	1.2%	1.2%	1.81	25.3	45.7	0.72
1987	38.9	2.29	1.06	2.74	21.9	60.0	21.1	34%	0.6%	0.6%	2.74	21.9	60.0	1.06
1988	37.6	2.35	1.51	1.86	22.6	42.1	-12.3	-28%	0.1%	0.1%	1.86	22.6	42.1	1.51
1989	40.0	2.02	1.60	1.59	34.1	54.1	-7.9	-14%	9.6%	9.6%	1.59	34.1	54.1	1.60
1990	42.9	1.92	0.77	1.67	23.4	38.9	7.8	19%	1.4%	1.4%	1.67	23.4	38.9	0.77
1991	41.6	2.19	0.39	2.71	25.2	68.5	54.4	77%	1.9%	1.9%	2.71	25.2	68.5	0.39
1992	36.8	2.35	1.52	2.05	29.6	60.6	7.0	11%	1.5%	1.5%	2.05	29.6	60.6	1.52
1993	35.8	2.29	2.33	1.99	23.9	47.5	-33.7	-68%	1.6%	1.6%	1.99	23.9	47.5	2.33
1994	39.0	2.31	1.93	3.89	26.5	102.9	30.0	28%	2.4%	2.4%	3.89	26.5	102.9	1.93
1995	32.9	2.37	4.69	4.35	20.9	90.8	-61.0	-66%	1.9%	1.9%	4.35	20.9	90.8	4.69
1996	35.9	2.34	1.72	1.57	21.5	33.7	-25.7	-71%	1.0%	1.0%	1.57	21.5	33.7	1.72
1997	40.3	2.24	0.73	2.82	26.1	73.6	46.5	61%	0.7%	0.7%	2.82	26.1	73.6	0.73
1998	30.9	2.36	4.16	4.46	20.1	89.9	-36.2	-39%	1.9%	1.9%	4.46	20.1	89.9	4.16
1999	34.1	2.32	1.85	2.66	23.8	63.3	2.7	4%	1.7%	1.7%	2.66	23.8	63.3	1.85
1973-78	45.0	2.19	1.27	2.63	32.4	85.2	30.62	35%	13.0%	1.9%	2.33	23.5	54.9	0.97
1979-85	40.6	2.22	1.83	2.49	28.3	70.4	10.48	14%	9.4%	1.9%	2.30	22.3	51.3	1.65
1986-99	37.8	2.26	1.78	2.58	24.1	62.3	0.69	1%	1.9%	1.9%	2.58	24.1	62.3	1.78
1973-99	40.1	2.23	1.68	2.57	27.1	69.5	9.83	14%	6.3%	1.9%	2.45	23.5	57.8	1.57

Regression:

$$\text{Inflow Conc (ppm)} = 22.7 + 77.9 \text{ EAA \%} \quad r^2 = 0.86$$

EAABackp = Percent of Total Lake Inflow from S2 & S3

Adjustment Procedure Applied to 1973-1985 Data:

$$\text{Adjusted EAA Backp\%} = \text{EAA Backp} \quad K = 1973-78 \quad 0.14 \quad 1979-85 \quad 5.06 \quad 1986-99 \quad 1.00$$

$$\text{Adjusted Inflow} = \text{Inflow} \times (1 - \text{Reduction in EAA Backp})$$

$$\text{Adjusted Conc.} = \text{Historical Conc.} - \text{Reduction in EAA Backp} \times \text{Slope of above Regression} = 77.9$$

$$\text{Adjusted Load} = \text{Adjusted Inflow} \times \text{Adjusted Concentration}$$

$$\text{Adjusted Outflow} = \text{Outflow} + \text{Adjusted Inflow} - \text{Historical Inflow}$$

1999 EAA backpump fraction set to 1994-1998 average (1.6%, data not available)

Atmospheric Deposition: 1.3 g/m²-yr Bulk Rainfall Conc = 1.1 ppm (Peters & Reese, 1995) @ 46.0897673720453 in/yr

Flow-Weighted-Mean Inflow Concentrations by Source

C10	C12	C12A	C4A	FECR	HGS5	INDS	L59E	L59W	L60E	L60W	L61E	L61W
99	98	102	80	13	52	84	167	39	37	23	23	43
L8	NIC	S127	S129	S131	S133	S135	S154	S191	S2	S236	S3	S308
59	39	75	67	52	55	71	24	33	93	121	78	45
S4	S65E	S71	S72	S77	S84							
78	14	23	32	51	14							

**Table 3
Water & Mass Balances**

<u>Term</u>	<u>Flow</u>		<u>Total P</u>				<u>Calcium</u>			
	<u>Volume</u> <u>10⁹m³</u>	<u>Volume</u> <u>%</u>	<u>Load</u> <u>mt/yr</u>	<u>Load</u> <u>%</u>	<u>Conc</u> <u>ppb</u>	<u>UAL</u> <u>mg/m²-y</u>	<u>Load</u> <u>kmt/y</u>	<u>Load</u> <u>%</u>	<u>Conc</u> <u>ppm</u>	<u>UAL</u> <u>g/m²-y</u>
Historical Conditions (1973-1979)										
Watershed	2.57	56%	488.4	98%	190.2	281.9	69.47	97%	27.1	40.1
Rainfall	2.02	44%	31.2	6%	15.4	18.0	2.22	3%	1.1	1.3
Total Inflow	4.59	100%	497.5	100%	108.4	287.1	71.69	100%	15.6	41.4
Evaporation	3.07									
Outflow	1.68	37%	150.8	30%	89.6	87.0	64.15	89%	38.1	37.0
Net Retention			326.2	66%		188.3	7.73	11%		4.5
Ca-P Recycle			-18.9	-4%		-10.9	-4.70	-7%		-2.7
Ca-P Deposition			36.2	7%		20.9	12.43	17%		7.2
Other Net P Depo.			308.9	62%		178.3		0%		0.0
Storage Increase	0.07	2%	20.5	4%		11.8	-0.19	0%		-0.1
Water Bal Error	-0.24	-5%								
Arith. Mean Conc					86.1				39.9	
TMDL (1973-1999, Adjusted for Reductions in EAA Backpumping & TP Loads)										
Watershed	2.45	55%	120.9	79%	49.3	69.8	57.78	96%	23.5	33.3
Rainfall	2.02	45%	31.2	21%	15.4	18.0	2.22	4%	1.1	1.3
Total Inflow	4.48	100%	152.1	100%	34.0	87.8	60.00	100%	13.4	34.6
Evaporation	3.07	69%								
Outflow	1.57	35%	61.0	40%	38.9		57.66	96%	36.8	33.3
Net Retention			88.1		4.9		1.58	3%		0.9
Ca-P Recycle			-8.2	-2%		-4.7	-5.44	-8%		-3.1
Ca-P Deposition			11.5	2%		6.7	7.02	10%		4.1
Other Net P Depo.			84.8	17%		48.9		0%		0.0
Storage Increase	0.07	2%	3.03				0.77	1%		
Water Bal Error	-0.24	-5%								
Arith Mean Conc					39.7				38.5	

Table 4
Sensitivity Analysis Results

<u>Basis</u>	<u>K_{NET} (m/yr)</u>		<u>TP Load (mt/yr)</u>			<u>Conc.</u> <u>R²</u>	<u>Response Time</u>		<u>Description</u>
	<u>Mean</u>	<u>SE</u>	<u>50th%</u>	<u>10th%</u>	<u>90th%</u>		<u>50 ppb</u> <u>Yrs</u>	<u>40 ppb</u> <u>Yrs</u>	
<u>Historical Loads - Confidence Intervals for Means</u>									
1973-1985			537	455	618				
1986-1999			461	402	520				
<u>TMDL Estimates Based upon Water Column Models</u>									
Trend / Conc	0.69	0.21	115	102	128	0.46	8	-	Knet Trend Model Calib to Concentration
Trend / Knet	0.89	0.20	125	112	146	0.41	6	-	Knet Trend Model Calib to Knet
Ca-P + Trend	1.29	0.22	152	126	178	0.51	6	-	Coupled Ca & P Balance, with Trend
1983-1999	1.60	0.25	173	150	196	-	-	-	Observed Knet, ~Stable Calcium Chemistry
1986-1999	1.36	0.26	157	133	182	-	-	-	Obs.Knet ~Stable Ca Chem. & EAA Backpumping
<u>TMDL Estimates based upon Coupled Water-Column & Sediment Model</u>									
Base	1.10	0.26	139	115	163	0.60	8	16	Base Calibration, Sed Depth = 5 cm
Excl. Org P	0.79	0.26	117	93	141	0.58	17	44	Excluding Organic P Pool
Z = 2.5 cm	1.23	0.26	148	124	171	0.59	8	17	Active Sediment Depth = 2.5 cm
Z = 10 cm	0.89	0.27	125	100	149	0.60	8	16	Active Sediment Depth = 10 cm
b = 0	1.26	0.27	150	126	174	0.60	8	17	Burial Rate Indep. Of P Accretion Rate
b = 1	0.94	0.26	128	104	152	0.60	8	16	Burial Rate Proportional to P Accretion
Ca = 1.1 X	1.57	0.26	172	148	196	0.60	8	16	Future Inflow Ca x 1.1 (Calibration Unchanged)
Ca = 0.9 X	0.62	0.26	106	82	130	0.60	8	17	Future Inflow Ca x 0.9 (")
Ca* = 1.1 X	0.63	0.28	106	81	132	0.35	8	17	Future Ca Saturation x 1.1 (")
Ca* = 0.9 X	1.57	0.27	171	147	196	0.43	8	16	Future Ca Saturation x 0.9 (")
<u>TMDL Estimates based upon Coupled Water-Column & Sediment Model (Rejected Because of Poor Fit)</u>									
Excl Ca Pool	1.69	0.27	180	155	205	-0.28	15	47	Excluding Calcium P Pool
Excl Ca +Org	1.42	0.27	161	136	186	-0.29	20	49	Excluding Calcium & Organic P Pool