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Development and Application of a Phosphorus Balance Model for Lake Istokpoga, Florida

William W. Walker
1127 Lowell Road
Concord, Massachusetts 01742-5522
E-mail: wwwalker@wwwalker.net

Karl E. Havens
South Florida Water Management District
3301 Gun Club Rd.
West Palm Beach, Florida 33416
E-mail: khavens@stwmd.gov

ABSTRACT

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Hydrologic and phosphorus (P) mass balance models were constructed for Lake Istokpoga, a large shallow lake in Florida, USA. The objective was to use the models to determine whether there have been long-term trends in the processing of P by this lake, potentially impacting P exports to a downstream ecosystem (Lake Okeechobee). Higher lake P concentrations and outflow loads in recent years appear to be explained by higher runoff. A detailed basin survey will be needed to determine whether changes in land use in the predominantly agricultural and urban watershed also may have contributed to the increased P loads. Lake total P concentrations did not display a significant historical trend, nor did the lake's capacity to assimilate P. A number of statistical approaches are demonstrated that could have general application in establishing nutrient mass balances for lakes with sparse data sets for tributary flows and/or concentrations. Daily simulations of lake phosphorus and chloride levels demonstrate the feasibility of dynamic mass-balance modeling in shallow Florida lakes using simple first-order phosphorus removal kinetics. The model developed here could be used in setting a total maximum daily load (TMDL) for P, once an in-lake concentration goal has been specified.

Key Words: Phosphorus, mass balance modeling, Lake Istokpoga, Florida.

In the process of developing watershed management program for control of phosphorus (P) loading to Lake Okeechobee, Florida, it became apparent that consideration needed to be given to the P dynamics of upstream lakes and reservoirs (Harvey and Havens 1999). In particular, Lake Istokpoga, located approximately 20 km upstream, displayed a 3-fold (from 8 to 23 metric tons $\cdot y^1$) increase in its discharge P load between 1990-94 vs. 1995-99 (SFWMD 2001). Over the same time period, discharge P concentrations (5-yr averages) increased from 30 to 40 mg $\cdot L^{-1}$. In 2000, the Florida Legislature passed the Lake Okeechobee Protection Act (Chapter 373.4595 Florida Statutes), which called for a comprehensive program to control P inputs to that lake. It included a mandate to "*assess the sources of phosphorus from...Lake Istokpoga, and their relative contribution to Lake Okeechobee.*"

This paper focuses on the development of a P mass-balance model for Lake Istokpoga, as the first step in identification of potential P sources in the lake/ watershed, and for potential use in future management activities. Lake Istokpoga is on the Florida Department of Environmental Protection (FDEP) list of priority water bodies for development of a TMDL for total P, and the model developed here could be used in that process. In the present application, the model is used to evaluate mechanisms potentially responsible for apparent trends in Lake Istokpoga P concentrations and outflow P loads. Potential mechanisms include: (1) random climatologic variations (higher rainfall and runoff in recent years); (2) increasing trend in inflow loads attributed to watershed development and/or changes in management practices; and (3) a declining trend in lake assimilative capacity attributed to long-term accumulation and recycling of phosphorus within the lake. The third mechanism is thought to be largely responsible for increasing P trends in Lake Okeechobee (James et al. 1995, Havens and James 1997). Over the 1973-1999 period, Okeechobee phosphorus concentrations increased from ~50 ppb to ~120 ppb, while the phosphorus net settling velocity, a measure of assimilative capacity (Vollenweider 1969, Chapra 1975), declined from ~5 $m \cdot yr^{-1}$ to ~1 $m \cdot yr^{-1}$ (Walker 2000). This situation spawned the hypothesis that a similar process might be occurring in Lake Istokpoga since it is relatively common in lakes with a long history of excessive P loading (Sas 1989).

In addition to providing tools for addressing regional water-quality management questions, this paper demonstrates a variety of modeling techniques that are potentially applicable to developing TMDLs for other lakes and reservoirs. These techniques include:

1. estimation of daily tributary loads using low-frequency (bimonthly - quarterly) grab sampling data and continuous flow records;
2. dynamic simulation of chloride and phosphorus mass balances in a spatially-segmented system using simple first-order net removal kinetics; and
3. use of a lake chloride mass balance to test the water balance.

Study Site

Lake Istokpoga is a large (112 km^2), shallow (maximum depth 2.7 m, mean depth ~1.7 m) lake located Florida at 27°23'15"N Latitude 81°18'18"W Longitude in south central Florida, USA. The lake is a major sport fishing resource, being considered one of the premier locations for largemouth bass (*Micropterus salmoides*) fishing in the state. In a creel survey conducted by the Florida Fish and Wildlife Conservation Commission (FFWCC 1993) the hourly catch rate for this fish was 0.4 per hour, which was nearly double the state average. The lake also is used for recreational boating, waterfowl hunting, flood control, and agricultural water supply. The lake has a history of problems with exotic plants, particularly *Hydrilla*, and experiences regular applications of herbicide (O'Dell et al. 1995) to maintain open water. Beef cattle pasture, urban areas, pine forests, and natural wetlands (South Florida Water Management District [SFWMD] land use database for 1995) predominate in the watershed immediately surrounding Lake Istokpoga. There also are a number of citrus groves, row crop operations, and dairy farms in the watershed. The SFWMD has carried out a regular program of inflow, outflow, and lake water quality monitoring on Lake Istokpoga since the late 1980s. These data were used in the present analysis and modeling effort. Standard methods of sampling and laboratory analysis are described in detail in O'Dell et al. (1995).

Data Sources

We used the hydrologic and water quality data collected by SFWMD, along with supplemental hydrologic data from a U.S. Geological Survey monitoring station, for the period from January 1988 and September 2000. Stations were located at major inflow and outflow structures and at eight points within the lake (Fig. 1). Water and mass balance summaries are presented below for the October 1993 - September 2000 period, when flow records were complete. Missing flows occurring in years prior to October 1993 were estimated by interpolation.

The tributary monitoring stations were located on Arbuckle and Josephine Creeks (inflows) and at a water control structure known as S68 (outflow). Flow data were not available for the Istokpoga Canal, which connects the Lake to the Kissimmee River. SFWMD operations staff indicated that the gate was usually closed and that flows were relatively low (compared with S68 flows) when it was operated. Over the October 1993-September 2000 period, average discharges at watershed stations were 268, 54, and 360 $hm^3 \cdot day^{-1}$, respectively. Because of the flat topography and complex network of drainage canals, drainage areas have not been delineated. An additional ungauged inflow (mean flow = 55 $hm^3 \cdot day^{-1}$ or 17% of the total gauged inflow) is inferred below from the lake water budget. This additional input is likely to reflect groundwater seepage from areas surrounding the lake (particularly from the southeast, Fig. 1).

Over the October 1993-September 2000 period, rainfall accounted for ~29% of the total inflow and evaporation accounted for ~34% of the total outflow. Daily rainfall and evaporation rates were derived from monitoring stations adjacent to nearby Lake Okeechobee. Pan evaporation measurements were converted to lake evaporation rates by applying seasonally-varying pan coefficients estimated by Abtew (2001) for Lake Okeechobee. The resulting average evaporation rate (140 $cm \cdot yr^{-1}$) is typical of lakes in this region, based upon a nationwide contour map of evaporation rates presented by Linsley et al. (1975).

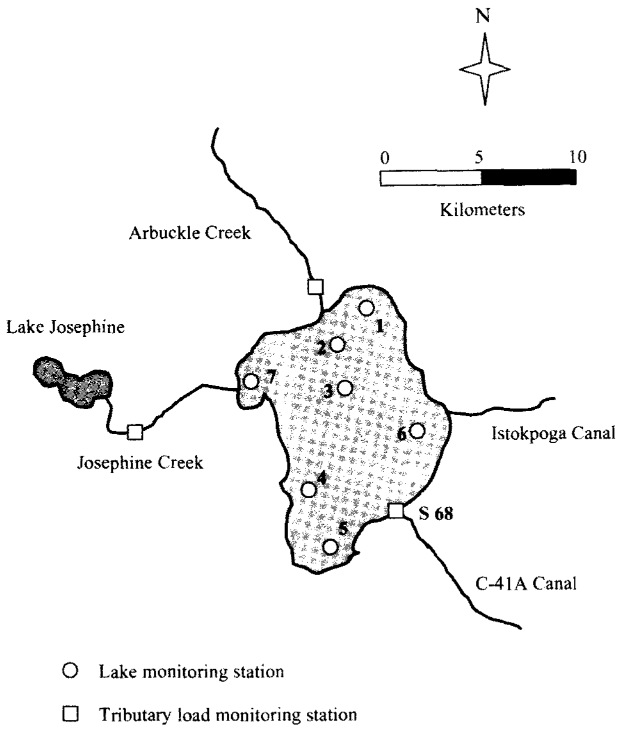

Figure 1.–Map.

Lake water levels were measured daily above the S68 outlet structure. Surface elevations fluctuated between 11.4 and 12.2 m NGVD and mean depths varied between 1.4 and 2.0 meters. At the mean depth of 1.7 m and mean outflow of 360 $hm^3 \cdot yr^{-1}$, the hydraulic residence time averaged 0.53 years and the net hydraulic load averaged 3.2 $m \cdot yr^{-1}$.

Grab samples were collected by SFWMD at watershed monitoring stations between January 1988 and September 2000 (Germain 1998). Sampling frequencies were low (bimonthly to quarterly) relative to those typically recommended to support estimation of nutrient loads (biweekly to weekly) (Walker 1999). Despite this limitation, load estimates developed below appear to be adequate to support mass-balance modeling. Lake water quality was monitored at frequencies from biweekly to quarterly and at seven locations between January 1984 and September 2000 (Germain 1998). Monitored variables included nutrient species, inorganic chemistry, chlorophyll a, and transparency.

We grouped the lake stations (Fig. 1) into two segments for modeling purposes (North = 1, 2, 3, and 7; South = 4,5, and 6). A modest spatial gradient in total P concentration (North = 0.058 ± 0.002 $mg \cdot L^{-1}$, South = 0.042 ± 0.002 $mg \cdot L^{-1}$) reflects relative proximity of North stations to inflows from Arbuckle and Josephine Creeks and is typical of patterns observed in reservoirs (Kennedy and Walker 1990). Exploratory data analysis indicates that nutrient concentrations are relatively homogeneous within each segment. Median values have been computed by segment to provide robust estimates of P and chloride (Cl) concentration on each sampling date for use in model calibration and testing.

Estimation of Tributary Loads

Daily total P and Cl loads from Arbuckle and Josephine Creeks were generated for use in mass-balance modeling (Figs. 2 and 3). Low sampling frequencies (bimonthly to quarterly) pose a challenge for the development of precise load estimates, particularly at a daily frequency. Precision can be promoted by applying stratification or regression techniques to remove a portion of the concentration variance (Walker 1999). Stratifying the data based upon flow can increase the precision of annual or seasonal loads (Bodo and Uny 1983), but would not be useful for estimating daily values. The method used here is based upon an algorithm contained in the FLUX program for generating daily load time series, given daily flow measurements and periodic grab samples (Walker 1999).

A multiple regression model representing concentration variations associated with flow, season, and year (trend) was fit to the data from each sampling date. This model was used to generate a daily series of predicted concentrations for the entire period of record. Interpolating residuals (observed – predicted values) between adjacent sampling dates generated another daily series of deviations from the regression. The predicted and residual time series were added together to generate daily concentration and load series for use in the lake modeling. Concentrations were log-transformed when appropriate to reduce skew and promote normality in model residuals. The regression models (Table 1) explained 10-58% of the variance in concentration and 33-95% of the variance in load on days when samples were collected. When the variance explained by the regression is small, the algorithm collapses to a direct interpolation of concentrations between sampling dates.

For Arbuckle Creek, the regression models explain 34% and 58% of the variance in total P and chloride concentrations, respectively (Fig. 2). Phosphorus concentrations are positively correlated with flow, but the trend term (0.7%/yr) is not significantly different from zero. Chloride concentrations are negatively correlated with flow and have a weak declining trend (-3%/yr, $p<.05$). The differences in flow response reflect that fact that phosphorus levels are highest in surface runoff,

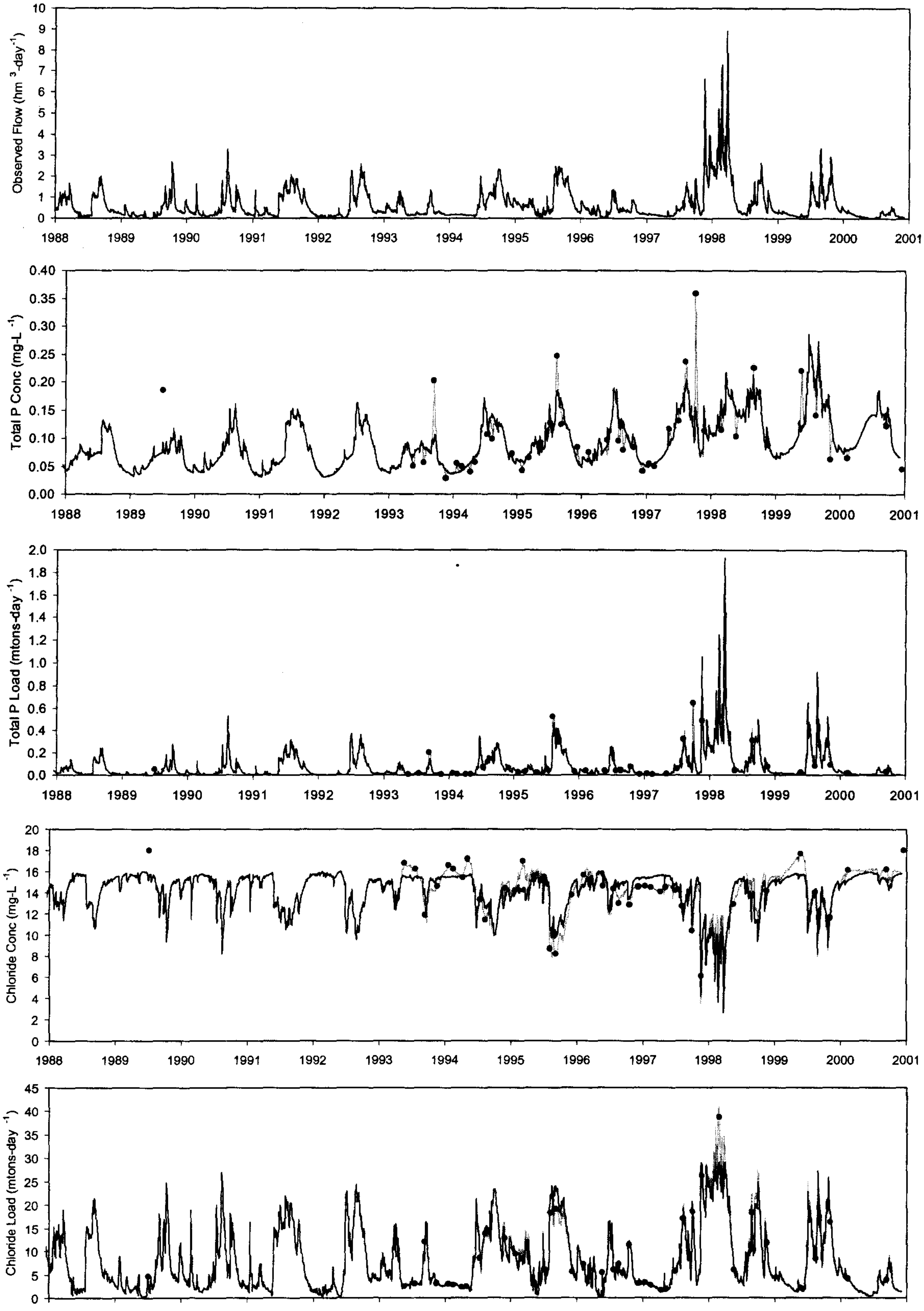

Figure 2.–Arbuckle Creek Time Series. Dark Lines = predictions of regression models relating concentrations to flow, season, and year; Light Lines = regression model prediction + interpolated residual (used in lake simulation); symbols = observed values.

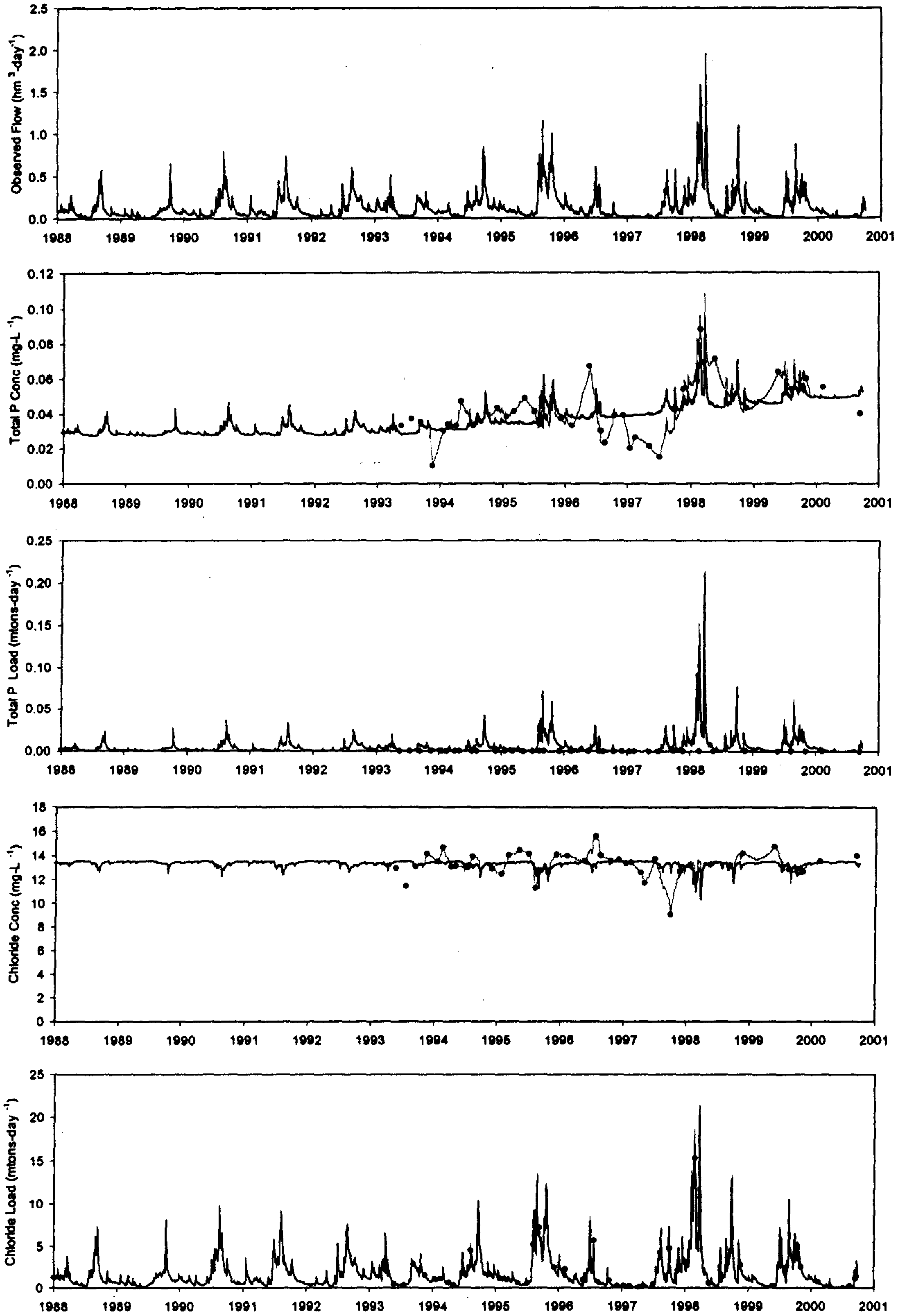

Figure 3.–Josephine Creek Time Series. Dark lines = predictions of regression models relating concentrations to flow, season, and year; light lines = regression model prediction + interpolated residual (used in lake simulation); symbols = observed values.

whereas highest chloride levels are highest in groundwater and base flow.

For Josephine Creek, the regression models explain 11% and 10% of the variance in total P and chloride concentrations, respectively (Fig. 3). Buffering of flow and concentration variations in upstream Lake Josephine may account for the low strength of correlations, as compared with Arbuckle Creek. With these low R^2 values, daily concentration time series generated by the load-calculation algorithm are controlled primarily by the interpolation terms. Weak declining trends are indicated for phosphorus (-2.4% $\cdot yr^{-1}$) and chloride (-1.0% $\cdot yr^{-1}$). Deviations from the regression (Fig. 3) indicate that most of the apparent trend in phosphorus occurred prior to 1998. Higher concentrations in 1998-2000 were associated with periods of higher runoff, particularly in 1998.

Water Balance Model

The following water-balance equations were used to generate a daily time series of predicted outflows for the January 1988 through September 2000 period:

$$Q_o = Q_i + P\,A - E\,A + V_s - V_e$$

$$Q_i = Q_a + Q_j + Q_u$$

$$Q_u = 0.17\,(Q_a + Q_j)$$

where,

Q_o = Lake Outflow ($hm^3 \cdot day^{-1}$)
Qi = Total Inflow ($hm^3 \cdot day^{-1}$)
P = Precipitation ($m \cdot day^{-1}$)
E = Evaporation ($m \cdot day^{-1}$)
A = Surface Area (km^2)
V_s = Volume at Start of Day (hm^3)
V_e = Volume at End of Day (hm^3)
Q_a = Arbuckle Creek Flow ($hm^3 \cdot day^{-1}$)
Q_j = Josephine Creek Flow ($hm^3 \cdot day^{-1}$)
Q_u = Ungauged Flow ($hm^3 \cdot day^{-1}$)

Starting and ending volumes were computed from measured lake elevations on adjacent days. Precise measurement of the change-in-storage term is difficult on a daily basis because it depends upon small differences in elevation of the lake. This factor caused negative computed outflows on some dates. To remove this high-frequency error term, rolling-average outflow volumes (14-day and 90-day) were used in model testing. The ungauged inflow was computed as a constant fraction (17%) of the gauged inflows from Arbuckle and Josephine Creeks. This fraction was calibrated based upon a comparison of average observed and

Table 1.–Regression models for tributary phosphorus and chloride concentrations.

	Regression Coefficients					Mean Flow	Concentration ($mg \cdot L^{-1}$)			Load ($mt \cdot day^{-1}$)			Trend	
	B0	B1	B2	B3	B4	$hm^3 \cdot d^{-1}$	Mean	R2	SE	Mean	R2	SE	$\% \cdot yr^{-1}$	
Arbuckle Creek (n = 91)														
Total P	-15.56	0.0067	0.2463	0.0381	-0.3039	0.641	0.125	34%	46%	0.080	76%	77%	0.7%	
Chloride	52.58	-0.0251	-0.0788	0.0810	0.0194	0.641	13.14	55%	16%	8.421	81%	40%	-2.5%	*
Josephine Creek (n = 89)														
Total P	45.21	-0.0242	0.0602	0.0930	-0.0761	0.125	0.047	11%	33%	0.006	78%	95%	-2.4%	*
Chloride	16.46	-0.0069	0.0170	0.0390	0.0061	0.125	68.70	8%	12%	8.589	97%	20%	-0.7%	*

Model

Ln (Conc) = B0 + B1 Y + B2 ln(Q) + B3 Sin + B4 Cos
Q = Flow ($hm^3 \cdot day^{-1}$)
Y = Calendar YearRange 1988.1 - 2000.7
Sin = Sin ($2\pi J / 365.25$),
Cos = Cos ($2\pi J / 365.25$)
J = Julian Day
SE = Standard Error of Estimate for Daily Concentration or Load

* Trend significant at $p < .05$.

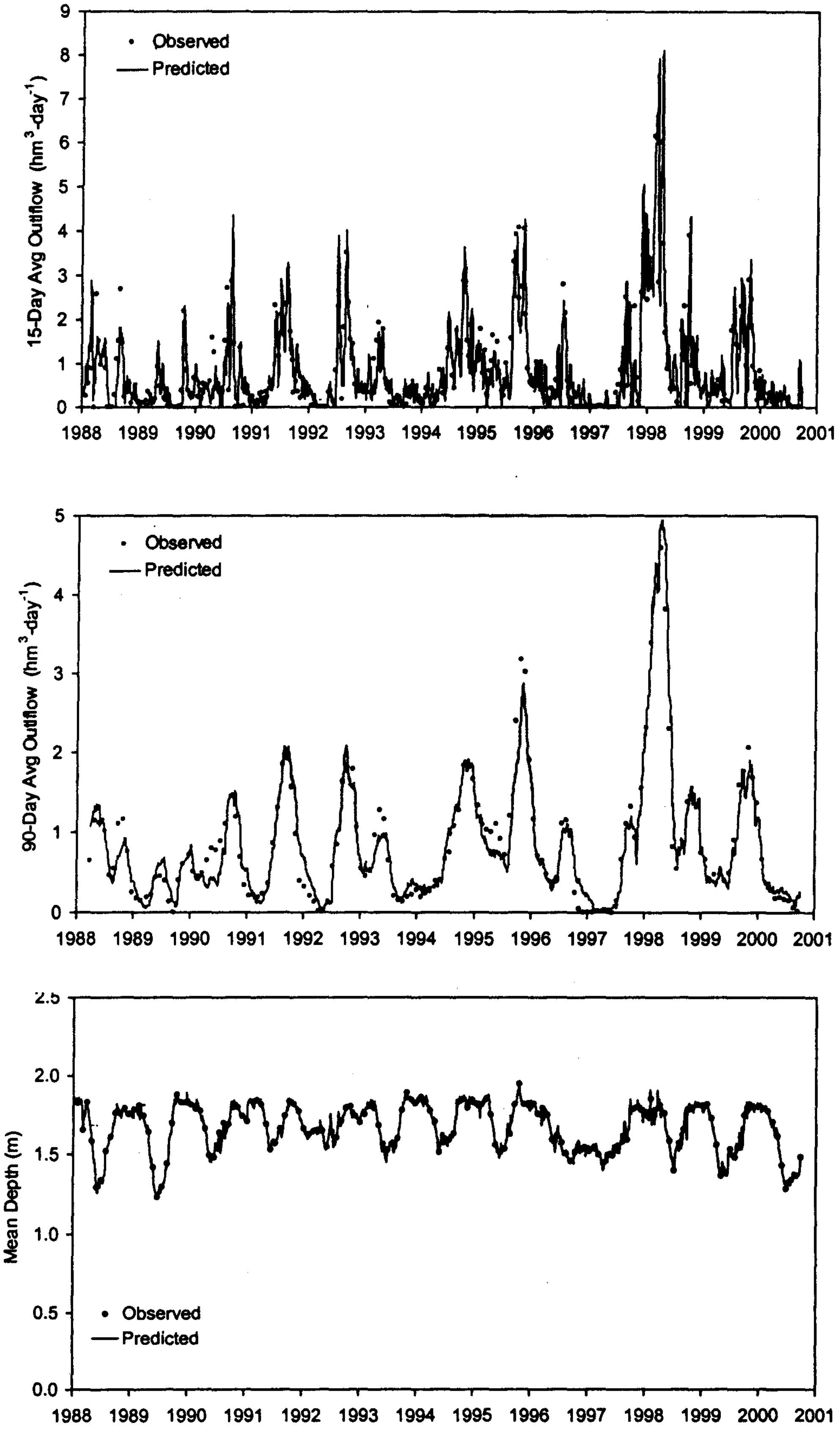

Figure 4.–Outflow and Mean Depth Time Series. Top panel: 14-day rolling average outflow volumes ($r^2 = 0.86$); middle panel: 90-day rolling average outflow volumes ($r^2 = 0.96$); bottom panel: daily mean depths ($r^2 = 1.00$, forced).

predicted outflows over the October 1993-September 2000 period. Data prior to October 1993 were reserved for model testing. All other water-balance terms were directly measured (inflows, volumes) or estimated independently (rainfall and evaporation).

The model explains 86% and 96% of the variance in the 14-day and 90-day rolling average outflows, respectively (Fig. 4). Small departures from the observed mean depths occur during periods when the predicted outflow is negative. The applicability of ungauged inflow estimates over the entire period is indicated by the fact that flow residuals are uncorrelated with date. Future watershed studies should provide drainage area delineations and direct estimates of ungauged inflows for comparison with those estimated here. The water budget appears to be sufficiently accurate to support mass-balance modeling, such as that required for TMDL development.

Mass Balance Model

Mass-balance models for Cl and P were developed to simulate variations in concentrations in each lake segment (North and South). Chloride was assumed to

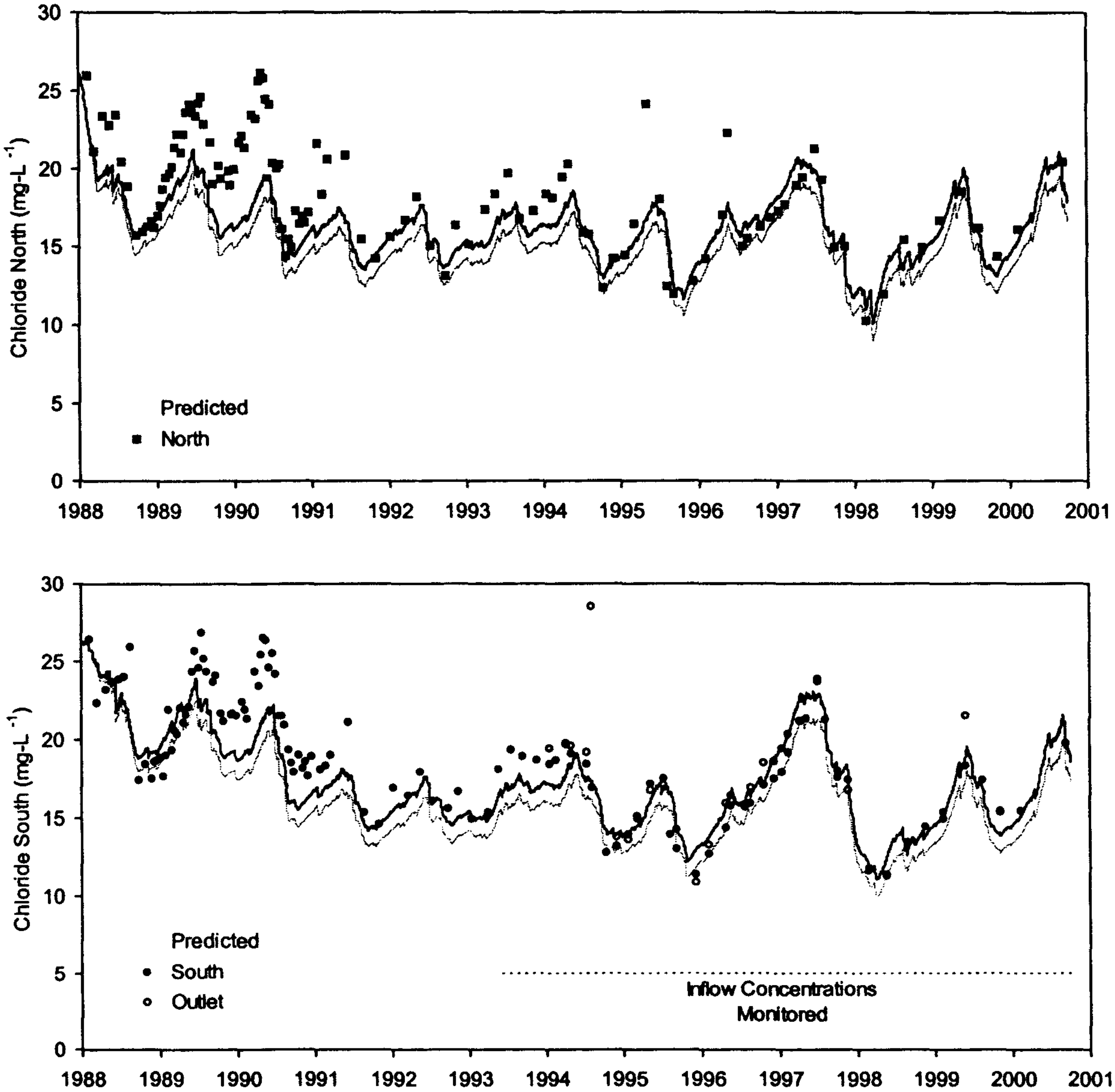

Figure 5.–Lake and outflow chloride concentration time series. Top panel: north lake (r^2 =0.41, s_p/s_o =0.60); bottom panel: south lake (r^2 = 0.75, s_p/s_o = 0.81); s_p/s_o = predicted / observed standard deviation statistics for model calibration period (January 1993-Sept 2000). Light line = prediction with ungauged inflow concentration = 16 mg·L^{-1} (initial hypothesis); dark line = prediction with ungauged inflow concentration = 21 mg·L^{-1} (Calibrated); Symbol = median observed value in each lake segment.

be a conservative tracer that provides a basis for further testing of the water balance and load-computation methods. Two lake segments were incorporated to reflect the observed spatial gradients in P concentration. Predictions of south-lake concentrations are of particular interest because they are more directly correlated with outflow concentrations, as compared with north-lake or lake-mean values.

Daily mass balances are simulated by analytically integrating the following set of linear differential equations:

$$dM_1/dt = L_i + A_1\ D + P\ A_1\ C_p - Q_{12}\ C_1 - K\ A_1\ C_1$$
$$dM_2/dt = Q_{12}\ C_1 + A_2\ D + P\ A_2\ C_p - Q_o\ C_2 - K\ A_2\ C_2$$
$$C_1 = M_1 / V_1$$
$$C_2 = M_2 / V_2$$
$$Q_{12} = (Q_i + Q_o) / 2$$
$$L_i = L_a + L_j + Q_u\ C_u$$
$$A_1 = A_2 = A / 2$$
$$V_1 = V_2 = V / 2$$

Where,

t = time (days)

M_1, M_2 = mass in segments 1 and 2 (metric tons)

A_1, A_2 = segment surface areas (km^2)

V_1, V_2 = segment volumes (hm^3)

C_1, C_2 = segment concentrations (mg $\cdot$ L^{-1})

Q_{12} = flow from segment 1 to segment 2 (hm$^3 \cdot$ d^{-1})

L_i = total inflow load (metric tons $\cdot$ d^{-1})

L_a = Arbuckle Creek load (metric tons $\cdot$ d^{-1})

L_j = Josephine Creek load (metric tons $\cdot$ d^{-1})

L_u =ungauged load (metric tons $\cdot$ d^{-1})

C_u = concentration in ungauged inflows (mg $\cdot$ d^{-1})

D = dry atmospheric deposition rate (g . m^{-2}-d)

C_r = concentration in rainfall (mg $\cdot$ L^{-1})

K = first-order net settling velocity (m $\cdot$ d^{-1})

The two lake segments are assumed to be of equal area and volume. The area assumption is consistent with the spatial distribution of sampling stations (Fig. 1). Although estimates of mean depth within each segment are not available, simulations are insensitive to depth because the P removal term is dependent only on surface area. Flow and volume terms used in the mass balance model are derived from the water balance model.

Consideration of dispersive transport (e.g, wind-driven mixing) between the two lake segments would add another unknown parameter to the model. Wind-driven mixing is known to occur in other shallow Florida lakes, including nearby Lake Okeechobee (Jin et al. 2000). Some degree of numerical dispersion is associated with the spatial segmentation scheme (Walker 1999). While the model appears to provide adequate simulation of lake and outflow concentration dynamics without explicit consideration of dispersion, future refinements to the model could include a calibrated dispersion term if P estimates of concentrations at the north end of the Lake are of particular interest.

Estimates of dry atmospheric deposition rates (0 g $\cdot$ m^{-2}-yr for Cl and 0.01 g $\cdot$ m^{-2}-yr for P) and rainfall concentrations (1.4 mg $\cdot$ L^{-1} for Cl and 0.007 mg $\cdot$ L^{-1} for P) were derived from various regional data and consistent with values used in modeling for Lake Okeechobee (Walker 2000). Given the flat topography, ungauged inflows to be primarily in the form of seepage. Concentrations were initially assigned to values measured in Arbuckle Creek under low-flow conditions (16 mg $\cdot$ L^{-1} Cl and 0.05 mg $\cdot$ L^{-1} total P). Concentrations of Cl and P at the start of the simulation (January 1, 1988) were assigned to values measured on the first sampling date (February 1988). Water and mass balances derived from the model for the October 1993 – September 2000 period are summarized in Table 2.

As expected for a conservative constituent (K = 0 m $\cdot$ d^{-1}), average Cl concentrations in the North and South segments of the Lake are not significantly different (Fig. 6). Predicted Cl concentrations are shown using two assumed values for the Cl concentration in non-gauged inflows. With a non-gauged inflow concentration of 16 mg $\cdot$ L^{-1} (low-flow value for Arbuckle Creek), the model under-predicts observed Cl by 11% and 5% in the North and South segments, respectively over the 1993-2001 period. Adjusting the non-gauged inflow concentration from 16 to 21 mg $\cdot$ L^{-1} reduces the biases to 5% and 0%, respectively, and closes the chloride balance. The Cl adjustment may reflect higher concentrations in seepage, as compared with surface canal flows. The adjustment may also reflect consistent bias in one or more of the water balance terms, particularly in rainfall and/or evaporation estimates derived from Lake Okeechobee data. The validity of the load estimates and mass-balance framework is supported by the fact that model tracks observed Cl dynamics in both regions of the lake over the entire period of record (Fig. 5).

A settling velocity for P of 0.0096 m $\cdot$ d^{-1} (3.5 m $\cdot$ yr^{-1}) was calibrated to match the observed mean concentration in the south segment between 1993 and 2001. Data prior to October 1993 were reserved for model testing. While agreement between observed and predicted values is poor in some years (Fig. 6), the model tracks the response to the major loading pulse in 1998 (Figs. 2 and 3). Overall r^2 statistics are low (<0.10), but do not adequately reflect model performance. Small differences in the timing of observed and predicted phosphorus pulses (phase shifts) can result in low r^2 values, even when the model generally tracks the observed range of values. Phase shifts on a daily scale do not limit the utility of the model for simulating long-term variations in P concentration and outflow load. The ratio of predicted to observed standard deviation is an alternative measure of fit that is insensitive to phase shifts. Values close to 1.0 (1.05 North, 0.96 South) indicate that observed and predicted variations have similar scales.

Observed and predicted outflow P loads (Fig. 7) are plotted in linear and logarithmic scales; the latter provides better resolution over the entire range of loads. The model explains 84% and 64% of the variance in the observed loads computed from measured flows and concentrations measured at S68 and the South lake segment, respectively. Ratios of predicted to observed load standard deviation are 0.86 and 1.23, respectively. Deviations between observed and predicted P concentrations during the 1989-1990 drought have little influence on the load simulation because of the low flows that occurred during that period. Given no apparent trend in the P model residuals (observed – predicted concentrations) over the 1988-2001 period, there is no indication of a long-term increasing or decreasing trend in the lake P assimilative capacity. Higher lake P concentrations in recent years appear to be explained by higher runoff volumes, particularly in 1998 (Figs. 2, 3).

Table 2.–Water and mass balance summary.

	Flow		TP Load		TP Conc	Chloride Load		CL Conc
Term	$hm^3 \cdot yr^{-1}$	%	$mt \cdot yr^{-1}$	%	$mg \cdot L^{-1}$	$mt \cdot yr^{-1}$	%	$mg \cdot L^{-1}$
Arbuckle	268.2	52%	34.9	82%	0.130	3265	61%	12.2
Josephine	54.2	11%	2.7	6%	0.049	709	13%	13.1
Ungauged	54.8	11%	2.7	6%	0.050	1151	22%	21.0
Total Watershed	377.2	73%	40.3	95%	0.107	5125	96%	13.6
Rainfall	137.0	27%	2.1	5%	0.015	192	4%	1.4
Total Inflow	514.2	100%	42.4	100%	0.082	5316	100%	10.3
Evaporation	158.3	31%						
Outflow	361.4	70%	21.4	51%	0.059	5434	102%	15.0
Storage Increase	-5.5	-1%	-0.5	-1%		-118	-2%	
Net Retention	0.0	0%	21.5	51%		-0	0%	
Mean Surface Area	112.7 km^2				Hydraulic Res. Time	0.53 yrs		
Mean Volume	188.2 hm^3				Water Load	3.2 $m \cdot y^{-1}$		
Mean Depth	1.7 m				Net Settling Rate	3.2 $m \cdot yr^{-1}$		
Water Years	1994-2000							

Conclusions

Empirical phosphorus models often are formulated to simulate the steady-state response to external loads averaged over seasonal, yearly, or long-term average time scales (Vollenweider 1969, Chapra 1975, Canfield and Bachman, 1981, Walker 1999). Although such models are simpler computationally, their inherent structures and data requirements are similar to the daily, dynamic simulations demonstrated here. One advantage of the dynamic simulation is that it explicitly accounts for the change-in-storage term of the mass balance and therefore does not assume that measured lake concentrations are in equilibrium with external loads in each season or year. Measured within-year variations provide a calibration signal for dynamic models that is not available for yearly models. Given the high outflow concentration variance and low sampling frequency in this case, the calibration basis for a yearly model would be limited by the low precision of the observed yearly-average values. Daily simulation of a deeper lake in more northern climates may require additional complexity and calibration parameters, however, to account for effects of season and/or vertical stratification.

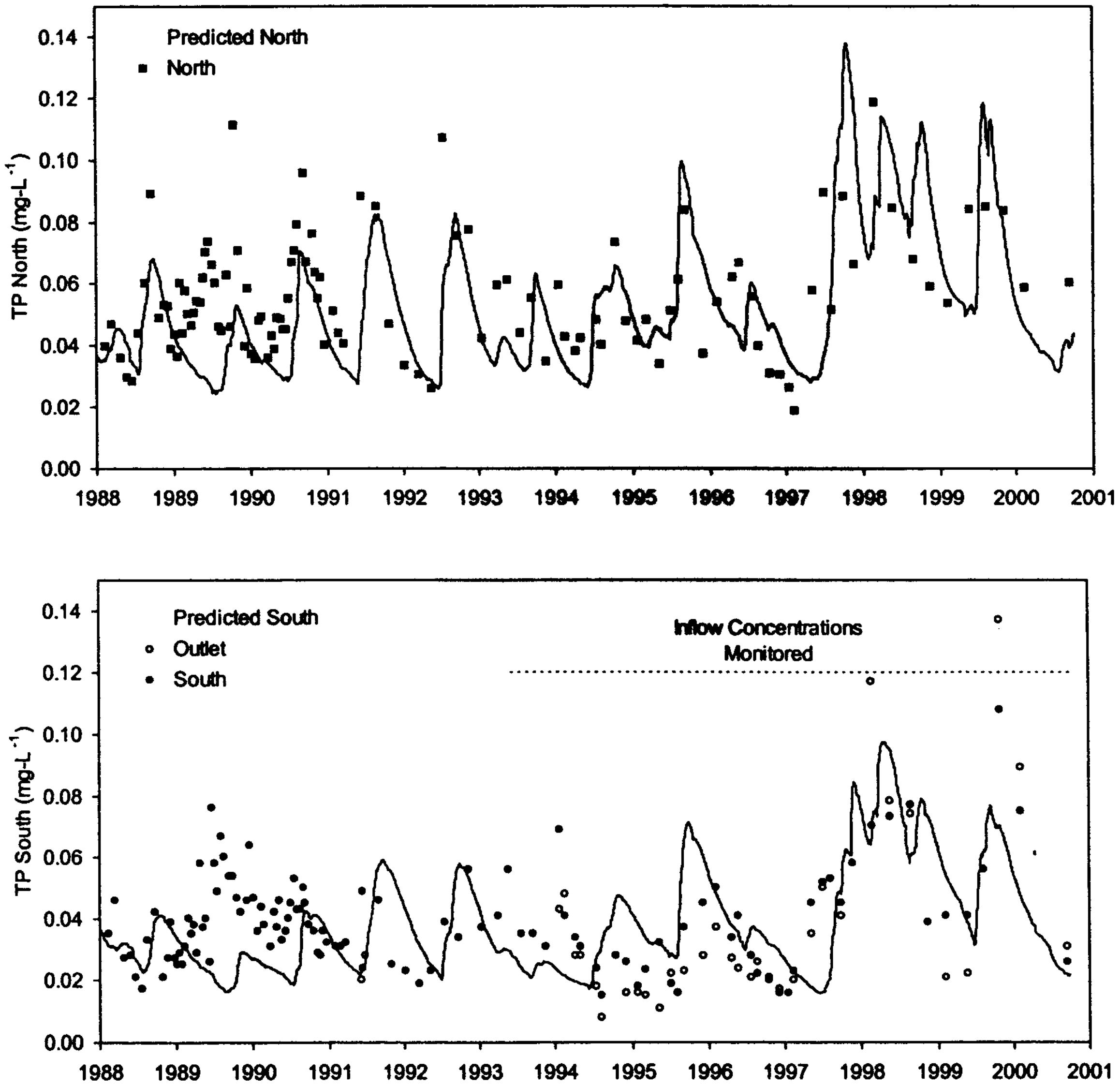

Figure 6.–Lake and outflow phosphorus concentration time series. Top panel - north lake (r^2 = -0.03, s_P/s_O = 1.05); bottom panel - south lake (r^2 = -0.10, s_P/s_O = 0.96); statistics for model calibration period (Jan 1993 - Sept 2000); Line = model prediction; symbol = median observed value in each lake segment.

The data analysis and modeling results indicate the following:

(1) The regression/interpolation algorithm demonstrated here is useful for estimating daily tributary loads based upon sparse concentration data. In our experience, sparse data often are a concern to managers when faced with such issues as TMDL development.

(2) In the specific case of Lake Istokpoga, the water and P mass-balance models developed here could be used by the FDEP in setting a lake TMDL for total P, once an in-lake concentration goal is specified.

(3) The modeling and monitoring results provide no evidence of a decline in lake assimilative capacity or an increase in the long-term-average phosphorus load.

(4) Apparent increases in inflow and outflow P concentrations and loads between 1993-2000 may reflect climatologic variations. Future monitoring and watershed diagnostic efforts will help to identify specific causal factors. Development and application of watershed models relating phosphorus loads to rainfall would help to identify any long-term loading trends in the presence of hydrologic variability.

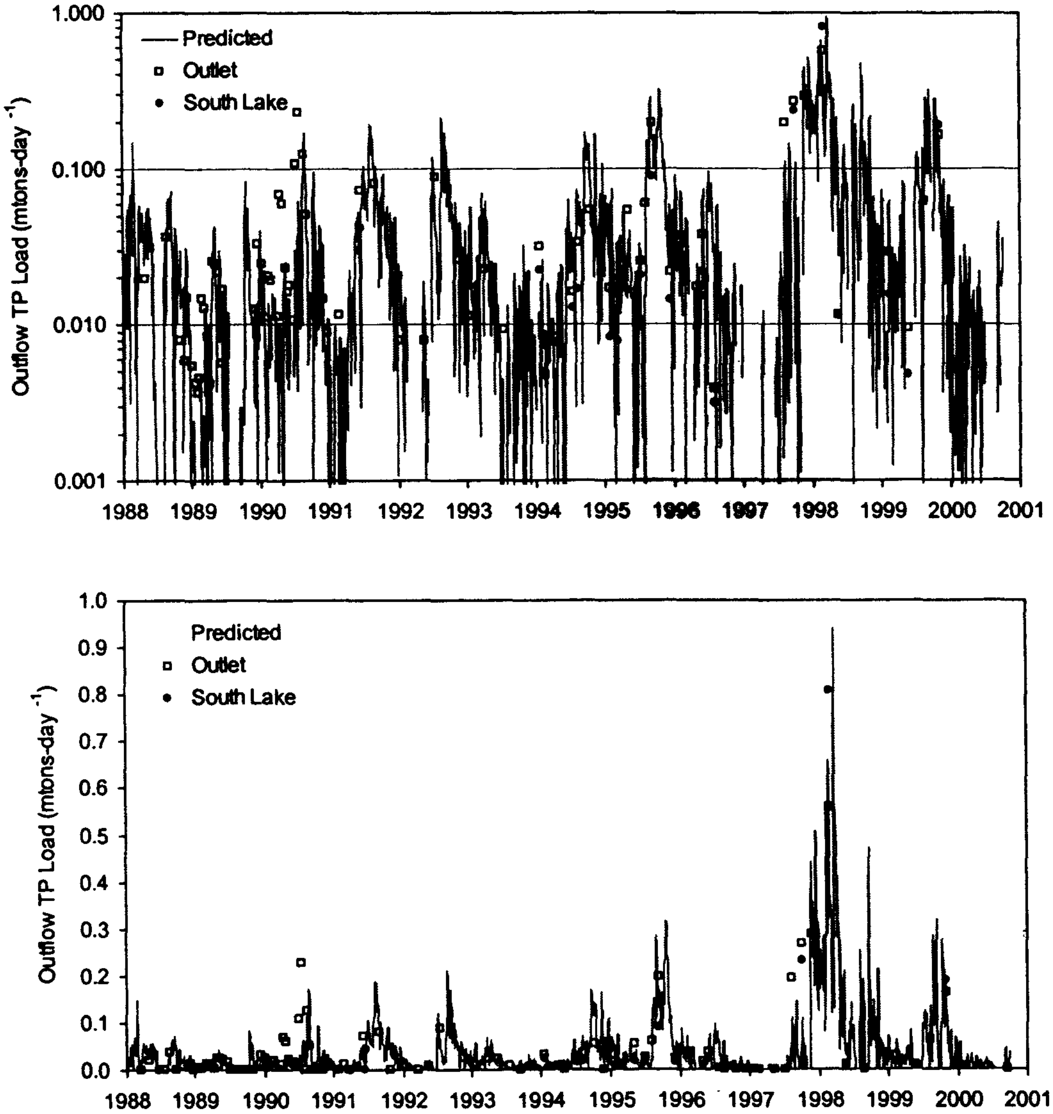

Figure 7.–Observed and predicted outflow phosphorus loads. Lines = predicted outflow x predicted south-lake conc., 7-day rolling average; squares = observed outflow x observed outflow conc. ($r^2 = 0.84$, $s_p/s_O = 0.86$); circles = observed outflow x observed south-lake conc. ($r^2 = 0.64$, $s_p/s_O = 1.23$).

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