An Optimized Network for Phosphorus Load Monitoring for Lake Okeechobee, Florida

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ABSTRACT

Phosphorus load data were evaluated for Lake Okeechobee, Florida, for water years 1982 through 1991. Standard errors for load estimates were computed from available phosphorus concentration and daily discharge data. Components of error were associated with uncertainty in concentration and discharge data and were calculated for existing conditions and for 6 alternative load-monitoring scenarios for each of 48 distinct inflows. Benefit-cost ratios were computed for each alternative monitoring scenario at each site by dividing estimated reductions in load uncertainty by the 5-year average costs of each scenario in 1992 dollars. Absolute and marginal benefit-cost ratios were compared in an iterative optimization scheme to determine the most cost-effective combination of discharge and concentration monitoring scenarios for the lake.

If the current (1992) discharge-monitoring network around the lake is maintained, the water-quality sampling at each inflow site twice each year is continued, and the nature of loading remains the same, the standard error of computed mean-annual load is estimated at about 98 metric tons per year compared to an absolute loading rate (inflows and outflows) of 530 metric tons per year. This produces a relative uncertainty of nearly 20 percent. The standard error in load can be reduced to about 20 metric tons per year (4 percent) by adopting an optimized set of monitoring alternatives at a cost of an additional $200,000 per year. The final optimized network prescribes changes to improve both concentration and discharge monitoring. These changes include the addition of intensive sampling with automatic samplers at 11 sites, the initiation of event-based sampling by observers at another 5 sites, the continuation of periodic sampling 12 times per year at 1 site, the installation of acoustic velocity meters to improve discharge gaging at 9 sites, and the improvement of a discharge rating at 1 site.

INTRODUCTION

Nutrient loading has a direct effect on the trophic state, diversity, and stability of aquatic ecosystems and is a major focus of many ecosystem restoration efforts. Because of the interest in nutrient loading rates for the evaluation of trends and ecological effects, the accuracy and precision of load estimates remain a continuing source of concern. Load monitoring at multiple inflow-outflow points around a lake can present an enormous task and expense for data collection and computation.

Various optimized decision-making approaches have been used to increase the efficiency with which information is collected in water-quality monitoring networks (Harmancioglu and Alpasian, 1992). These approaches have most often attempted to maximize information in hydrologic data (measurable changes in water quality) relative to noise. Generally, efforts to optimize load-monitoring networks have focused on minimizing uncertainty to concentration data; network-optimization studies have not considered cost in their optimization schemes. Potential errors in the determination of discharge are often ignored or assumed to be unimportant.

The measure and control of uncertainty in loading estimates is critical to the effective management of the ecological resources. The statistical ability of the monitoring networks to identify differences between sites or trends with time can be expressed as the statistical power of the network. Generally, this power is directly related to the extent to which the observed variation in measured loads can be explained by or attributed to relevant biological or chemical processes. Temporal variation can be explained when it can be predictably related to some time-dependent process or pattern (Box and Jenkins, 1970). Variation that cannot be empirically or theoretically related to some relevant process produces uncertainty in any inference derived from time-series data. The statistical power of the network increases as the ratio of explained to unexplained variation increases.

The ratio of explained to unexplained variation in measurement techniques is often expressed in terms of the accuracy and precision of the technique. This characterization can be usefully extended from the evaluation of instrument performance (as is most common) to the performance of an entire methodology. Accuracy, which generally refers to the relative systematic deviation of a measured quantity from its "true" value, can be likened in statistical terms to a measure of relative bias. Precision, which is held to be a measure of the random deviation of a measured quantity in relation to its "average measured" value, can be likened in statistical terms to the coefficient of variation (CV) of a sample distribution. Generally, of the two, accuracy is the more difficult to verify because of the uncertainty in obtaining a "true" value for comparison. Precision is somewhat easier to quantify because of its reliance on an "average measured" value, which can be readily obtained from a sample distribution.

This report describes a method to help prioritize load-monitoring effort and to increase the statistical power of the network for Lake Okeechobee, Florida. The uncertainty associated with a suite of monitoring alternatives was evaluated for each of 48 discrete nutrient discharges into the lake in a cooperative effort between the U.S. Geological Survey (USGS) and the South Florida Water Management District (SFWMD). An optimized set of monitoring practices was developed to produce the least uncertainty in total load rates for the least additional effort or cost.

Purpose and Scope

This report presents an approach for evaluating the components of error in loading rates associated with uncertainty in discharge and concentration data. Benefit-cost ratios are determined for each of seven alternative monitoring scenarios, where benefits are measured in terms of an overall reduction in uncertainty in loading rates. An optimized network for water-quality sampling and discharge gaging is derived to minimize random uncertainty in load estimates for a given level of effort measured in 1992 dollar costs. In contrast to other optimization methods in the literature, the approach presented here optimizes on both discharge and concentration in comparable terms of load for each of several discrete levels of instrumentation and expense. Although temporal covariance in concentration is addressed to a limited extent in this evaluation (by frequency-domain filtering), spatial covariance is not taken into account as a source of uncertainty in loading rates. Spatial covariance is not considered here because the existing models for load computation fail to incorporate spatial terms and are, therefore, insensitive to optimization in the spatial domain. Although loads of various nutrient chemical species might be considered in a similar analysis, this application is limited to total phosphorus data available from the USGS and SFWMD data bases.

Network optimization encompasses three operations—first, an evaluation of the explained and unexplained variations in daily mean loading rates based on available data; second, the computation of uncertainty estimates for each of several potential monitoring alternatives; and third, the selection of the most cost-effective combination of monitoring alternatives to produce the greatest overall decrease in uncertainty for the least increase in monitoring expense.

Background on Lake Okeechobee

Lake Okeechobee is the second largest lake in the coterminous United States and is an important part of the hydrologic system of the Everglades in south Florida. The lake is 675 square miles (mi^2) in area and contains about 4 million acre-feet (acre-ft) of water at a typical stage of 15 feet (ft) above mean sea level. Because much of the water flowing through the Everglades originates in or passes through Lake Okeechobee, the trophic status of the lake and the rates of nutrient loading in surface-water discharges from surrounding basins have become the focus of public attention. Consequently, a loading target has been established for the lake as part of Florida law (Storm Water Management Model (SWMM), 1992). To meet this target, maximum permitted nutrient-loading rates have been established by SFWMD for each of numerous tributaries to the lake.

The size of the lake and the complexity of hydrologic inputs and outputs make a comprehensive evaluation of nutrient loads for the entire lake difficult and expensive. Surface-water drainage can enter or leave the lake through any of 48 distinct sources (fig. 1, table 1). Most of these are controlled by structures at the lakeward end of a complex system of canals that are used alternately to provide irrigation or drainage depending on the weather and season. Only discharge to the lake from the west through Fisheating Creek remains uncontrolled. Back-pumping of drainage water from agricultural land can significantly increase the concentrations of nutrients in a rim canal around the lake from which water may enter the lake in small quantities at any of numerous locations. Concentrations of phosphorus in back-pumped water may be high in some agricultural discharges, but concentrations are not consistently high throughout the basin and vary substantially with season (Dickson and others, 1978). The SFWMD computes daily and annual loads for each of the 32 larger sources of nutrient inflow (SWMM, 1992).

Inflows into Lake Okeechobee may be divided into nine subbasins (table 1). These subbasins are hydrologic units that tend to have similar discharge characteristics and within which drainage systems are often hydraulically connected through a series of linking canals. This is particularly true in subbasins 7, 8, and 9 where agricultural ditching has completely altered the natural drainage. Because of the connectivity within subbasins, the sizes of contributing areas and area-based yields are difficult to determine. As a result, precise load estimates require discharge and concentration data for all major discharges to the lake.

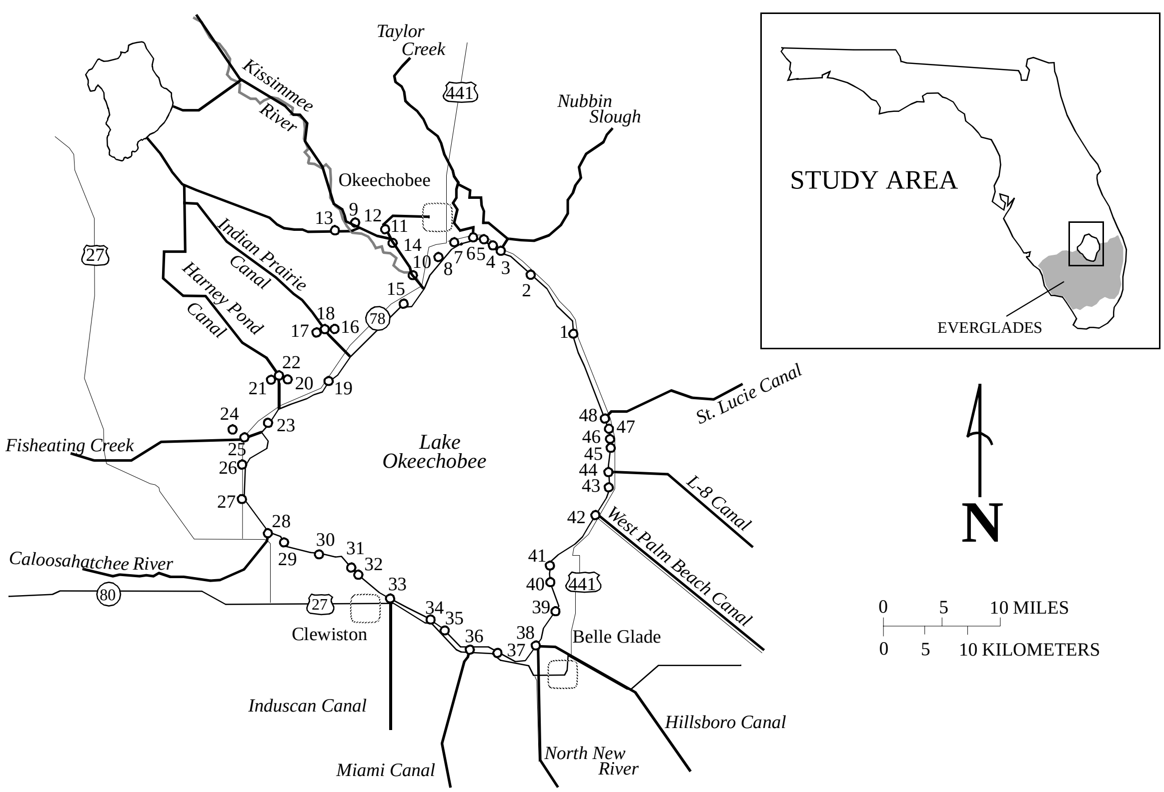

Figure 1. Lake Okeechobee, Florida, and location of numbered inflow and outflow points.

Table 1. Points of discharge and data collection around Lake Okeechobee

[HGS, Hurricane Gate Structure; ft^3/s, cubic feet per second; Do., ditto. Discharge rating: T, theoretical; M, measured; **, no rating. Discharge record: L, log; R, recorder; U, ungaged. Water quality analysis: I, inorganic constituents; N, nutrients. Water quality agency: SFWMD, South Florida Water Management District; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey]

Sub-basin	Site number	USGS site number	Site name	Latitude/ longitude	Type of control	Discharge			Water quality	
						Rating	Record	Agency	Analysis	Agency
1	1		S-135	270510 0803941	4-125 ft^3/s pumps, 15’ lock, 2-10’ lift gates	T	L	SFWMD	N, I	SFWMD
	2	02275705	Henry Creek Lock (HCL)	270943 0804304	15’ lock	M	R	USGS		Do.
2	3	02275606	S-191 on Nubbin Slough	271136 0804545	4-27’ lift gates	T	L	SFWMD	N, I	SFWMD
	4		C-9	271149 0804619	3 flap gates on 3-10’ culverts	T	L	USACE		Do.
	5		C-8	271207 0804649	3 flap gates on 3-10’ culverts	T	L	USACE		Do.
	6	02275503	S-133 on Taylor Creek	271224 0804753	5-125 ft^3/s pumps, 30’ lock	M	R	USGS	N, I	Do.
	7		HGS-6	271224 0804753	30’ lock	M	R	USGS	N, I,	Do.
	8		C-7	271220 0804805	3 flap gates on 3-10' culverts	T	L	USACE		Do.
3	9	02273000	S-65E on Kissimmee River	271332 0805746	6-27' lift gates, 30' lock	M	R	USGS	N, I	USGS, SFWMD
	10		C-6	270951 0805254	1 lift gate on 1-10' culvert	T	L	USACE		Do.
	11		C-38W	271159 0805436	1 lift gate on 1-10' culvert	T	L	USACE		Do.
	12		S-154 and S-154C	271241 0805506	2-10' lift gates	T	L	SFWMD	N, I	SFWMD
	13	02273300	S-84 on C-41A	271255 0805855	2-27' lift gates	M	R	SFWMD	N, I	USGS, SFWMD
	14		L-59E	271130 0805412	1 flap gate on 1-10' culvert	T	L	USACE	N, I	SFWMD
4	15		S-127 at Buckhead Lock	270719 0805346	5-125 ft^3/s pumps, 15' lock, 1-10' lift gate	T	L	SFWMD	N, I	SFWMD
	16		L-59W at S-72	270533 0810023	2 flap gates on 2-10' culverts	T	L	USACE	N, I	Do.
	17		L-60E at S-72	270533 0810027	2 flap gates on 2-10' culverts	T	L	USACE	N, I	Do.
	18		L-60W at S-71	270157 0810413	2 flap gates on 2-10' culverts	T	L	USACE	N, I	Do.
	19	02259200	S-72 on Indian Prairie Canal	270535 0810025	2-27' lift gates, 1-125 ft^3/s pump	M	R	SFWMD	N, I	USGS, SFWMD
	20		S-129	270147 0810006	3-120 ft^3/s pumps, 1-10' lift gate	T	L	SFWMD	N, I	SFWMD
	21		L-61E at S-71	270157 0810417	2 flap gates on 2-10' culverts	T	L	USACE	N, I	Do.
	22	02257800	S-71 on Harney Pond Canal	270200 081045	3-27' lift gates, 1-125 ft^3/s pump	M	R	SFWMD	N, I	USGS, SFWMD
	23		S-131 at Fisheating Lock	265842 0810524	2-120 ft^3/s pumps, 15' lock, 1-10' lift gate	T	L	SFWMD	N, I	SFWMD
5	24		L-61W at Hoover Dyke	265806 0810811	2-10' flap gates	T	L	USACE	N, I	SFWMD
	25	02257000	Fisheating Creek (FEC) at SR-78	265744 0810715	no structure-lake level control outflow	**	U	USGS	N, I	Do.
6	26		C-5	265508 0810722	3 flap gates on 3-10' culverts	T	L	USACE	N, I	SFWMD
	27		C-5A	265305 0810722	2 flap gates, 1 lift gate on 3-10' culverts	T	L	USACE		Do.
7	28	02292001	S-77 on Caloosahatchee River	265020 0810508	4-27' lift gates, 30' lock	M	R	USGS	N, I	SFWMD
	29		C-1	264938 0810356	2 flap gates on 2-10' culverts	T	L	USACE		Do.
	30		C-1A	264855 0810035	3 flap gates on 3-10' culverts	T	L	USACE		Do.
	31		S-4	264722 0805743	3-860 ft^3/s pumps	T	L	SFWMD	N, I	Do.
	32		C-2	264725 0805747	5 flap gates, 1 lift gate on 6-10' culverts	T	L	USACE		Do.
	33		S-310 and HGS-2 on Induscan Canal	264514 0805508	30' lock	**	U	SFWMD	N, I	Do.

Table 1. Points of discharge and data collection around Lake Okeechobee

[HGS, Hurricane Gate Structure; ft^3/s, cubic feet per second; Do., ditto. Discharge rating: T, theoretical; M, measured; **, no rating. Discharge record: L, log; R, recorder; U, ungaged. Water quality analysis: I, inorganic constituents; N, nutrients. Water quality agency: SFWMD, South Florida Water Management District; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey]

Sub-basin	Site number	USGS site number	Site name	Latitude/ longitude	Type of control	Discharge			Water quality	
						Rating	Record	Agency	Analysis	Agency
8	34		S-236	264340 0805111	3-85 ft^3/s pumps	T	L	SFWMD	N, I	SFWMD
	35		C-3	264315 0805030	1 flap gate, 1 lift gate on 2-10’ culverts	T	L	USACE		Do.
	36	02286400	S-3 and HGS-3 on Miami Canal	264155 0804825	3-860 ft^3/s pumps, 2-27’ lift gates	M	R	USGS	N, I	Do.
	37		C-4A	264056 0804502	1 flap gate on 10’ culvert, private pump	T	L	USACE	N, I	Do.
	38	02280000	S-2 and HGS-4 on North New River	264200 0804300	4-900 ft^3/s pumps, 3-27’ lift gates	M	R	USGS	N, I	Do.
	39		C-12	264455 0804105	2 flap gates, 1 lift gate on 3-10’ culverts,	T	L	USACE	N, I	Do.
	40		C-12A	264634 0804137	1 flap gate on 1-7’ culvert, private pump	T	L	USACE	N, I	Do.
	41		C-10	264753 0804146	1 flap gate, 1 lift gate on 2-10’ culverts	T	L	USACE	N, I	Do.
9	42	02278000	S-352 and HGS-5 on West Palm Beach Canal	265150 0803755	2-27’ lift gates	M	R	USGS	N, I	SFWMD
	43		C-13	265359 0803644	1 lift gate on 1-10’ culvert	T	L	USACE		Do.
	44		C-10A on L-8 Canal	265501 0803649	4 flap gates, 1 lift gate on 5-10’ culverts	M	R	USGS	N, I	Do.
	45		C-14	265635 0803641	1 lift gate on 1-10’ culvert	T	L	USACE		Do.
	46		C-16	265709 0803641	1 lift gate on 1-10’ culvert	T	L	USACE		Do.
	47		C-11	265756 0803644	1 lift gate on 1-10’ culvert, private pump	T	L	USACE		Do.
	48	02276870	S-308B and S-308C on St. Lucie Canal	265900 0803700	4-27’ lift gates, 30’ lock	M	R	USGS	N, I	Do.

Phosphorus management goals are outlined by the SFWMD in the Lake Okeechobee SWMM Plan which sets forth target performance standards for inflow phosphorus concentrations for each of the 32 monitored inflows within the district. The target standards were established to produce in-lake phosphorus concentrations below the eutrophic range indicated by a modification of the Vollenweider model. The concentration target for each inflow is set at the lesser of an annual flow-weighted concentration of 0.18 milligram per liter (mg/L) or the flow-weighted average of historical data. When the flow-weighted concentration target of 0.18 mg/L or less is met consistently at all inflows, the overall target phosphorus load of 397 tons per year for the lake also should be met (SWMM, 1992).

Phosphorus concentrations and surface-water discharges are monitored at each of the 32 inflow and outflow sites around the lake. Discharges are monitored continuously and concentrations are sampled on 2- to 4-week intervals. From these data, daily and annual loading estimates and flow-weighted concentrations are computed. Discharge at many of the monitoring points is intermittent and samples are periodic. The natural variability in both the discharge and concentration data presents problems in comparing daily and long-term loading rates to SWMM standards.

Loading estimates for Lake Okeechobee generally have been computed using a time-weighted average interpolation method to determine concentration. Daily mean nutrient concentrations have been interpolated from periodic sample data (typically biweekly). These interpolated concentrations are then multiplied by gaged discharges to compute a daily load which is averaged for a given period. Automatic samplers have been used to increase sample frequency at some sites, but samplers can be costly to operate and have not been employed throughout the monitoring network. The computed average loads incorporate the variability associated with the sample concentration data and daily discharge. The effects of natural variability on computations of overall lake-loading rates have not previously been taken into account in evaluations of temporal trends and compliance with loading standards.

APPROACH AND METHODOLOGY

Network-monitoring optimization presented here is based on: (1) an evaluation of uncertainty in computed loads due to variability and uncertainty in both discharge and concentration data, and (2) an evaluation of potential changes in uncertainty in these data given each of several selected monitoring alternatives employed at each of the 48 flow points identified around the lake. Benefit-cost ratios computed for each monitoring alternative at each network site can then be compared and the most cost-effective set of monitoring alternatives for all sites can be selected. Because variations due to measurement and natural variability are cumulative, the uncertainties described in this report refer to a composite of measurement and sampling (representation) errors.

Daily discharge data for many tributaries were obtained from the USGS data base and were computed using standard USGS methods (Rantz and others, 1982). Discharge data at several other structures were obtained from the SFWMD data base and were computed from operator records at several hydraulic structures and theoretical structural ratings. Daily discharges for many of the smaller inflow points were estimated by comparison to adjacent sites.

Evaluation of Uncertainty

Tributary loading may be viewed as the integrated product of two time series, one consisting of sequential observations of discharge and the other of sequential observations of concentration. Within each of these time series, the observed value is an approximation of the true, or expected, value at any point in time. Differences between measured and expected time series may result from both systematic and random errors (a combination of measurement and sampling errors). Systematic differences, or biases, are difficult to identify and measure but can be reduced by rigorous quality-assurance standards. Random errors tend to increase the observed random variability in calculated loads but can be reduced by averaging. The aggregate uncertainty in loads due to random processes can be estimated from the observed variability of discharge and concentration data after an estimate of expected variation has been subtracted.

The standard approach to computing the load time series is given by equation 1:

$$L_t = C_t \times Q_t \,, \qquad (1)$$

where

C_t is measured concentration at time *t*,

Q_t is measured discharge at time *t*,

L_t is a computed load based on measured values of concentration (C_t) and discharge (Q_t).

Assuming random errors in estimating the expected values of discharge and concentration (errors are independent of any covariance in C_t and Q_t), measured values can be related to expected values by equations 2 and 3:

$$C_t = c_t + e_{c_t} , \qquad (2)$$

$$Q_t = q_t + e_{q_t} , \qquad (3)$$

where

c_t is expected concentration at time *t*,

q_t is expected discharge at time *t*,

e_{c_t} is random error in the measurement of (*c*) at time *t*, and

e_{q_t} is random error in the measurement of (*q*) at time *t*.

The error terms e_{c_t} and e_{q_t} can generally be assumed to be independent and random in *Q* and *C* time series so by substitution of equations 2 and 3 into equation 1, and the expression for measured load becomes:

$$L_t = \left(c_t + e_{c_t}\right)\left(q_t + e_{q_t}\right) , \qquad (4)$$

which can be factored to an expression of expected load:

$$qc_t = L_t - \left(ce_{q_t} + qe_{c_t} + e_{q_t}e_{c_t}\right) , \qquad (5)$$

where

qc is the expected load at time *t*,

ce_q is the partial error in L_t associated with e_{q_t} at time *t*,

qe_c is the partial error of L_t associated with e_{c_t} at time *t*, and

$e_q e_c$ is the product of errors in Q_t and C_t at time *t*.

Equation 5 explains the partitioning of uncertainty in load estimates into partial products. This also is illustrated by the square in figure 2. The partial error associated with uncertainty in concentration (concentration load error) and the error associated with uncertainty in discharge (discharge load error) are independent and random. Even where the expected values of discharge and concentration are covariant, the random errors in these terms are independent. The product of errors ($e_q\, e_c$) varies in proportion to discharge and concentration load errors, but tends to be small for coefficients of variation less than 1.

Given that errors in e_c and e_q are assumed to be independent, the standard error of measured loads can be approximated by the joint probability of partial error terms expressed in equation 5 by substituting standardized errors (s_c and s_q) for discrete errors (e_{c_t} and e_{q_t}) in each partial error term, and estimating expected values from the mean of measured values.

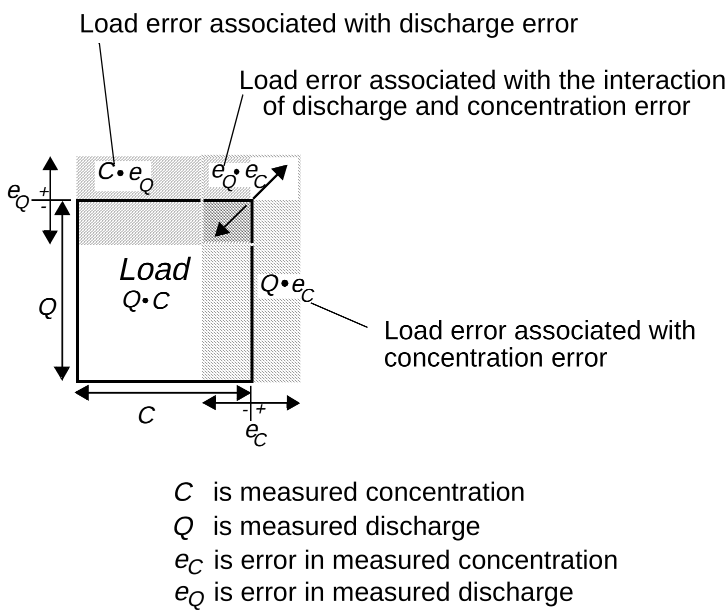

Figure 2. Partitioning of load error into discharge and concentration components—load is represented in the area formed by the product of discharge and concentration, errors in load are represented by shaded rectangles.

The joint probability of summed errors can then be estimated as:

$$s_L = \sqrt{(\bar{Q} \times s_c)^2 + (\bar{C} \times s_q)^2 + (s_c \times s_q)^2} \quad , \qquad (6)$$

where

s_L is the estimated standard error of measured loads,
s_q is the standard error of measured discharge,
s_c is the standard error of measured concentration,
$\bar{Q}$ is average measured discharge, and
$\bar{C}$ is average measured concentration.

This simplification ignores the errors in estimating the expected values of *q* and *c* by $\bar{Q}$ and $\bar{C}$; however, these errors are assumed to be small for large sample sizes.

Standard errors s_q and s_c are determined as the average difference between each measured value and the mean of all measurements (the estimated expected value). When the expected value of a time series is stationary, the random uncertainty can be estimated as the standard deviation of the observed data set. However, when a time series varies with some expected frequency, periodic variation is included in the measured deviation of the time series. As a result, the standard deviation of the time series overestimates actual random uncertainty. To improve estimates of uncertainty, estimates of s_c and s_q were refined by indentifying and removing periodic variation in the expected time series.

Continuous time series of *Q* and *C* are not actually measured at the temporal scale needed for load estimation. Instead, models are used to interpolate from observations of *Q* and *C*, based on the observed or assumed behavior of the expected time series *q* and *c*. As a class, models include any implied or explicit assumptions made about the behavior of *q* and *c*—including assumptions about simple straight-line relationships between successive observations. Conceptual models are then calibrated against periodic measurements *Q* and *C*. Standard errors of estimates ($s_{\hat{q}}$ and $s_{\hat{c}}$) for the modeled time series can be computed as the average squared difference between periodic observations and model predictions at a given time. This provides a composite measure of error associated with both the modeling and the measurement of *q* and *c*.

The classic model for the computation of *q*, applied within the USGS, is the shifting-control method and rating-curve approach (Rantz and others, 1982). This approach can be extended somewhat to include structural ratings at hydraulic control structures. In either case, the discharge rating provides an estimate of the behavior of *q* over time against which measurements of *Q* are compared and an estimate of $s_{\hat{q}}$ derived. Random errors in estimated *q*, based on continuous record of stage, are due to random, transient changes in streamflow hydraulics in natural channels and at hydrologic control structures, and attributed to channel scour and deposition and the accumulation of debris.

The history of discharge measurements at sites around Lake Okeechobee and at sites on other low-gradient streams in Florida gives an indication of the random error in discharge models. Discharge measurements generally are rated in accuracy between 5 and 10 percent but may deviate from a given discharge rating by as much as 30 percent. Some of the measurement deviation from ratings can be attributed to systematic changes or shifts in control conditions, which are predictable and are corrected in discharge computations. However, the extent of measurement deviations from rating that is caused by random uncertainties can be substantial in terms of total discharge. This uncertainty typically is estimated to be as much as 20 percent.

Models for predicting $\hat{c}$ are not as well established as those for discharge; no single model has gained complete acceptance. The SFWMD has adopted a linear-interpolation model for computing loads to Lake Okeechobee. This model is only one of several possible alternatives and may be no better or worse than others. However, the interpolation model without modification is over parameterized and lacks the necessary degrees of freedom to evaluate $s_{\hat{c}}$. For the purposes of this analysis, a linear-regression model was used to predict *c* for all major tributaries except those for which reliable estimates of *q* were unavailable. Average concentrations for remaining discharge points were computed from available concentration data.

Concentration models were developed for each major tributary to Lake Okeechobee based on the following relation in which load $\hat{l}$ is obtained using least-squares regression in the following general form:

$$\hat{c} = \frac{\hat{l}}{\hat{q}} , \qquad (7)$$

and

$$\hat{l} = 10^{\left(\beta_0 + \beta_1 Log_{10}\hat{q} + \beta_2 T + \beta_3 D + \beta_4 S_1 + \ldots + \beta_{n+3} S_n + \frac{\sigma_L^2}{2}\right)} \quad (8)$$

where

$\hat{l}$ is modeled estimate of expected load,

β is a linear coefficient,

$\hat{q}$ is estimated daily mean discharge,

T is cumulative time,

D is the flow direction,

S is a seasonal term composed of sine and cosine terms, and

σ is the standard error of regression.

In linear form, $\hat{l}$ and $\hat{q}$ are expressed in log units. The data are log-transformed to remove the tendency toward increasing variance with increasing discharge. Log-transformation bias is corrected by the addition of 1/2 of the variance of the load. This corrected value provides a minimum-variance unbiased estimator (MVUE) of the mean phosphorus load (Gilbert, 1987). Multiple seasonal terms can be added to account for variations in expected concentration for periods less than or greater than 1 year.

Load-estimation models can be grouped into several general types (Preston and others, 1989), including averaging estimators, ratio estimators, and regression estimators. The accuracy and precision of each of these types depends to a large extent on the population distribution of the data. Although one estimation method may produce unbiased estimates of nutrient load, those estimates may be of such large variance that they are of little practical value; other estimates of greater precision may be biased. The regression method was confirmed by Preston and others (1989) to be a robust and precise method. It has been applied with modification in several load-modeling studies and has been used as a linear filter technique for trend analysis (Hirsch and others, 1992).

The standard error of estimated concentration ($s_{\hat{c}}$) is directly proportional to the standard error of $\hat{l}$ from equation 8. The general equation from Neter and Wasserman (1974) explains that the standard error of a linear model is determined by the standard error of the regression, the number of observations included in the regression analysis, and the difference between the considered value of the independent variable for a given estimate and the mean of the independent variable included in the regression analysis.

$$s_{\hat{Y}} = SER\left[\frac{1}{n} + \frac{(X - \bar{X})}{\Sigma(X - \bar{X})^2}\right] . \quad (9)$$

Equation 9 reduces to the standard error of the mean of regression residuals at the mean of the independent variable (X). Substituting the estimated load ($\hat{l}$) for Y and discharge ($\hat{q}$) *for X* in equation 9, the standard error of the mean load estimate at a mean discharge becomes:

$$s_{\hat{l}} = \frac{SER}{\sqrt{n}} , \quad (10)$$

the standard error of estimated concentration is then:

$$s_{\bar{c}} = \frac{s_{\hat{l}}}{\bar{q}} , \quad (11)$$

and is strictly proportional to the standard error of the mean of loads in equation 10.

Network Optimization

The network was optimized by minimizing the random and systematic errors in total load estimates for a given level of monetary investment. The goal of optimization was to produce the most cost-effective reduction in discharge-load and concentration-load errors by determining at which sites and for which instrumentation and sampling methods the greatest reduction in overall load error could be expected. This is achieved conceptually by minimizing equation 6, after summing for all sites and normalizing for cost. Equation 12 represents the summation of partial error terms for all 48 sites:

$$s_{\hat{l}_{TOTAL}} = \sqrt{\sum_{i=1}^{48} \frac{\left(\bar{q}_i \times s_{\bar{c}_i}\right)^2}{f_{c_i}} + \frac{\left(\bar{c}_i \times s_{\bar{q}_i}\right)^2}{f_{q_i}} + \frac{\left(s_{\bar{c}_i} \times s_{\bar{q}_i}\right)^2}{f_{c_i} \times f_{q_i}}} , \quad (12)$$

where

$s_{\bar{c}_i}$ is the standard error of mean *c* at site *i* for a given period of time,

$s_{\bar{q}_i}$ is the standard error of mean *q* at site *i* for a given period of time,

f is the dollar cost of the alternative, and

i is an index of inflow point.

Squared error terms are divided by costs (f_c) to obtain a measure of variance per unit cost. These terms are then summed to obtain the overall weighted variance per unit cost. The goal of optimization as expressed in equation 12 is to identify sampling and monitoring practices that produce the greatest possible reduction in variance for a given cost, where the sum of costs is limited by management prerogatives (eq. 13):

$$\sum_{i=1}^{n} \left(f_{c_i} + f_{q_i}\right) = COSTLIMIT \quad . \quad (13)$$

Because the monitoring alternatives considered in this analysis represent discrete levels of effort, standard errors for each monitoring alternative are discontinuous (stepping). This precludes the solution of equation 12 by standard linear or nonlinear techniques. As an alternative approach, a discrete solution utilizing an iterative selection process was developed.

Various feasible monitoring alternatives to the current flow- and concentration-sampling network were identified. These alternatives included a range of options for both discharge and concentration. Sampling costs and benefits for each alternative were then evaluated for each of the 48 sites around the lake. The Orlando Subdistrict of the USGS averaged 5-year costs (in 1992 dollars) for installation and operation of standard stream-gaging and water-quality sampling equipment. Benefits were determined as a difference in the squared mean standard errors of partial error terms summed as in equation 6.

By partitioning the loading error into partial terms involving discharge and concentration (partial products involving $\bar{q}_i$ and $\bar{c}_i$ in eq. 12), we directly compared costs and benefits of possible modifications to the discharge-monitoring network with the costs and benefits of possible alternatives to the concentration-monitoring network. Standard errors of discharge were determined from experience with various measurement and gaging techniques of the USGS and the observed success of various techniques in low-velocity streams in Florida (Sloat and Gain, 1995). Partial standard errors from concentration were calculated as in equations 9 and 10 and based on an expected replication factor (*n*) determined for each sampling alternative for a given sample period. A sample period of 1 year was assumed—based on the need for annual load estimates.

Benefit-cost ratios were computed for marginal differences between all monitoring alternatives for each site and for both concentration and discharge monitoring alternatives.

An optimized set of network enhancements was selected from among various monitoring alternatives by use of a manual, iterative selection process similar in nature to dynamic programming. The selection algorithm is illustrated in figure 3 and comprises the following steps: (1) rank marginal benefit-cost ratios for all sites and monitoring alternatives comparing each alternative to the existing baseline condition (the baseline may be an existing practice at a given site or any assumed minimal level of monitoring), (2) identify the maximum ratio and substitute the alternative for the baseline condition at that site, (3) re-rank benefit-cost ratios comparing baseline and possible alternatives and incorporate the new baseline substituted in the previous step, (4) identify the maximum marginal benefit-cost ratio and again substitute the alternative for the baseline, and (5) sum the total cost of monitoring. This selection process is repeated in the same manner until a predetermined cost limit is reached. Ultimately, the cost limit is affected by optimization and may be based on the marginal benefit of loading information relative to other management initiatives.

The schematic in figure 3 is simplified to show only two sites and three alternatives; however, the process is the same regardless of the number of sites and alternatives. The slopes of line segments in figure 3 represent benefit-cost ratios. By sequentially selecting the line segments of greatest slope (greatest marginal benefit-cost ratio), the resultant curve will have the most rapid increase in overall benefit for a given increase in total cost. The inverse of this curve (fig. 3) indicates the most rapid decrease in error for a given increase in cost.

The example in figure 4 illustrates the process of selection in tabular form. Numbered selections indicate the order in which a given site and monitoring alternative is implemented. Selection starts with the highest benefit/cost ratio of 43.4 and continues to a low of 0.72. After the initial selection of alternative 2

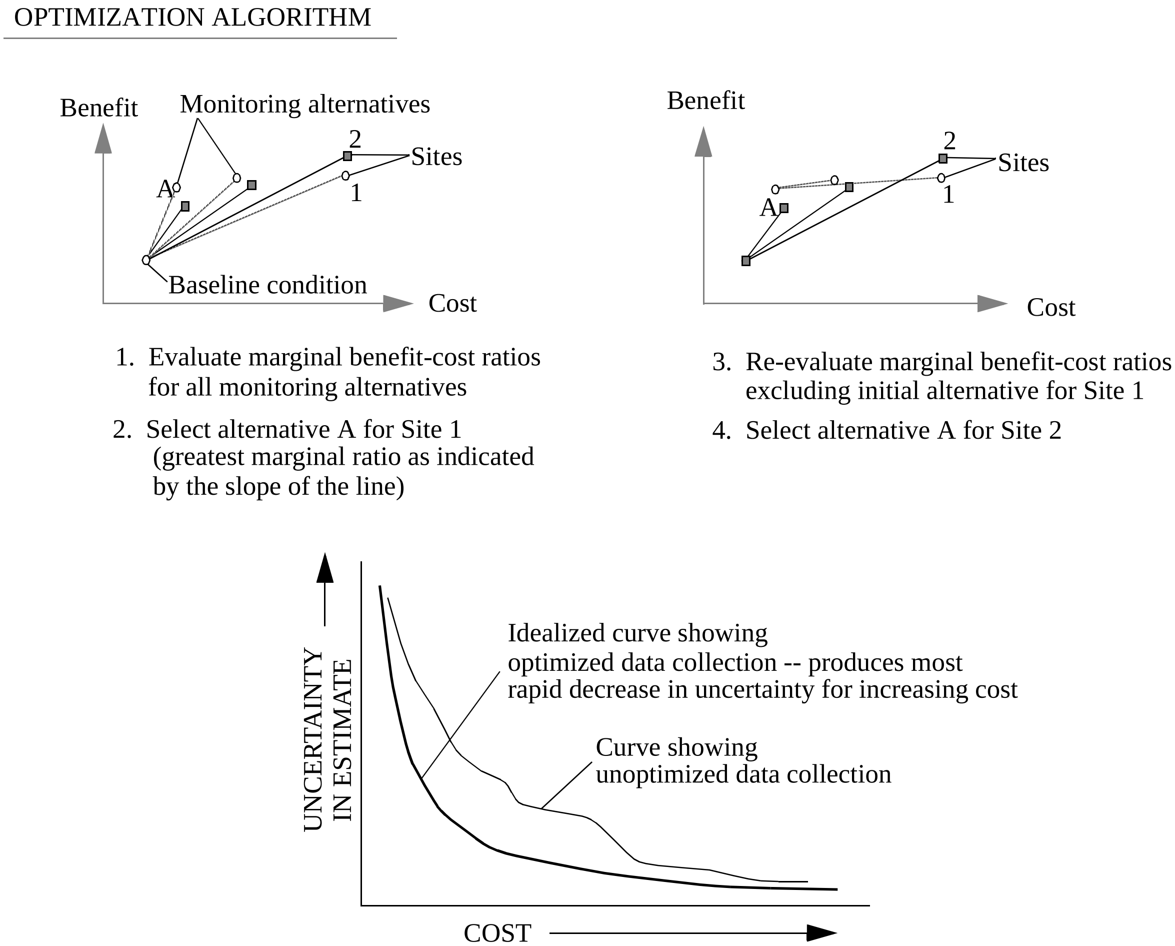

Figure 3. Optimization routine and resultant relation of uncertainty to cost.

on site C, the process continues with the implementation of 10 other monitoring alternatives on other sites until the highest remaining benefit-cost ratio is the marginal ratio of alternative 3 compared to the new baseline alternative 2 on site C (2.26 benefit /cost ratio). At this point, monitoring on site C is upgraded from alternative 2 to 3 (shown by the shaded arrow in fig. 4) as is monitoring on 4 subsequent sites (I, J, M, and Q) upgraded to more costly monitoring alternatives. The benefit/cost ratios computed are limited to marginal differences between mutually exclusive alternatives (i.e., sampling 12 times per year compared to sampling only twice per year). Marginal benefit-cost ratios are not computed for alternatives 1 and 2 because these alternatives are not mutually exclusive (as, for instance, discharge monitoring and concentration sampling can both be implemented concurrently).

As previously noted, the final limitation on this process is cost. Ultimately, with unlimited cost, the most expensive alternatives will be selected on all sites so long as these alternatives produce some marginal reduction in error. The object of this procedure is not to minimize the error in load estimates, but to maximize the rate of reduction so as to achieve the greatest possible reduction in error for some minimum desirable cost.

RESULTS AND DISCUSSION

Discharge

A summary of average annual discharge in and out of Lake Okeechobee for the period 1982-91 shows the sources of inflow and the potential magnitude of errors (table 2). Atmospheric fluxes were adopted from James and others (1995) for a 20-year period

Structure Name	BENEFIT-COST RATIOS Alternative No. 1	Alternative No. 2	Alternative No. 3-Alternative No. 2, Marginal Benefit-Cost Ratio	Alternative No. 3
Site A	0.0	0.0	0.44	0.31
Site B	0.02	0.1	0.02	0.04
Site C	0.36	*1* 43.4	*12* 2.26	→ 14.01
Site D	0.57	0.1	0.16	0.87
Site E	0.17	*9* 3.0	0.16	1.71
Site F	0.0	0.1	0.02	0.05
Site G	0.06	*16* 1.2	0.23	0.53
Site H	0.01	*13* 1.8	0.12	0.62
Site I	0.36	*6* 10.1	*14* 1.79	→ 4.23
Site J	0.40	*3* 15.3	*15* 1.44	→ 5.55
Site K	0.01	0.1	0.01	0.05
Site L	*18* 0.82	0.3	0.01	0.10
Site M	0.14	*5* 14.4	*17* 0.86	→ 4.78
Site N	0.0	*10* 2.5	0.19	0.86
Site O	0.39	*7* 6.2	0.53	2.18
Site P	0.08	*4* 14.9	*19* 0.72	→ 4.84
Site Q	0.0	0.1	0.03	0.04
Site R	0.08	*2* 28.3	0.65	8.70
Site S	0.05	*11* 2.3	0.42	0.96
Site T	0.038	*8* 4.8	0.604	1.83

Figure 4. Schematic of selection order for optimum benefit-cost improvement in monitoring—numbered boxes indicate the order in which an alternative on a particular site is selected for implementation based on a comparison of relative and marginal benefit-cost ratios.

from 1973 to 1992. This hydrologic budget is similar to that reported by Joyner (1974) and Maddy (1978) and the surface-water fluxes are similar to those reported by James and others (1995). Lake evapotranspiration estimates also are similar to a previous regional estimate by Farnsworth and others (1982). From 1982 to 1991, inflow to the lake averaged 4,380 cubic feet per second (ft^3/s). Of this, more than one-third (about 1,710 ft^3/s) is derived from rainfall alone. Of the 4,550 ft^3/s of outflow, evaporation comprised the largest single sink (2,800 ft^3/s), followed by surface-water discharge (1,480 ft^3/s) flowing largely through three structures: S-77, on the Caloosahatchee River to the southwest; S-308, on the St. Lucie Canal to the east; and S-2, flowing south through the Hillsboro Canal to the Everglades agricultural area.

The intra-annual distribution of daily mean surface-water discharges within the year is driven by a combination of stormwater runoff and agricultural withdrawal and releases (fig. 5), and the daily balance of inflows and outflows varies seasonally. In the example shown in figure 5 (water year 1986), daily discharges entering the lake range from 0 to more than 8,000 ft^3/s and daily discharges leaving the lake range from near 0 to more than 4,000 ft^3/s. During periods of high rainfall, inflow to the lake is increased by both surface-water runoff upstream and the return of water from inundated agricultural land, or backpumping. Backpumping from agricultural land usually is greatest from May through September (Dickson and others, 1978). Large releases from the lake are usually made in April and May to increase the flood-control capacity of the lake before the wet season of July through September.

Estimated standard errors in discharge (table 2) reflect an average error for gaged inflows of about 20 percent but vary by site according to the demonstrated reliability of the existing data at each site. The total error for all inflows (given the joint probability of errors) reduces to about 5 percent. Annual discharge data using standard gaging practices typically are considered to be accurate only to within a range of about

Table 2. A hydrologic budget for Lake Okeechobee for water years 1982 to 1991

[--, no data; HGS, Hurricane Gate Structure; ft^3/s, cubic feet per second]

Subbasin	Site name	Source	Inflow (ft^3/s)	Inflow estimated standard error (ft^3/s)	Outflow (ft^3/s)	Outflow estimated standard error (ft^3/s)
1	S-135	Gaged	23	2	--	--
	HCL	Estimated	3	2	--	--
2	S-133	Gaged	28	3	--	--
	S-191, C-9, C-8, HGS-6, C-7	Estimated	131	29	--	--
3	S-65E	Gaged	1,230	180	--	--
	S-84	Gaged	169	25	--	--
	C-6, C-38W, S-154, S-154C, L-59E	Estimated	52	25	--	--
4	S-127	Gaged	22	5	--	--
	S-72	Gaged	35	5	--	--
	S-129	Gaged	14	2	--	--
	S-71	Gaged	222	44	--	--
	S-131	Gaged	6	1	--	--
	L-59W, L-60E, L-60W, L-61E	Estimated	8	4	--	--
5	FEC	Gaged	246	40	--	--
	L-61W	Estimated	2	2	--	--
6	C-5, C-5A	Estimated	30	7	--	--
7	S-77	Gaged	13	5	467	70
	S-4	Gaged	26	3	--	--
	C-1, C-1A, C-2, S-310, HGS-2	Estimated	--	--	53	25
8	S-236	Gaged	5	1	--	--
	S-3, HGS-3	Gaged	51	7	180	31
	C- 4A	Gaged	8	1		--
	S-2, HGS-4	Gaged	98	15	320	48
	C-12	Gaged	10	1	--	--
	C-12A	Gaged	11	1	--	--
	C-10	Gaged	7	3	--	--
	C-3	Estimated	3	2	--	--
9	S-352, HGS-5	Gaged	3	2	82	14
	C-10A	Gaged	68	10	57	9
	S-308B, S-308C	Gaged	134	40	326	98
	C-13, C-14, C-16, C-11	Estimated	12	6	--	--
All	Surface water	Gaged	2,429	196	1,432	134
		Estimated	241	39	53	25
	Atmospheric		1,712	86	2,806	140
	Change in storage (4 ft)				262	--
Total			4,382	217	4,553	195
Residual	(Inflow-outflow)				171	

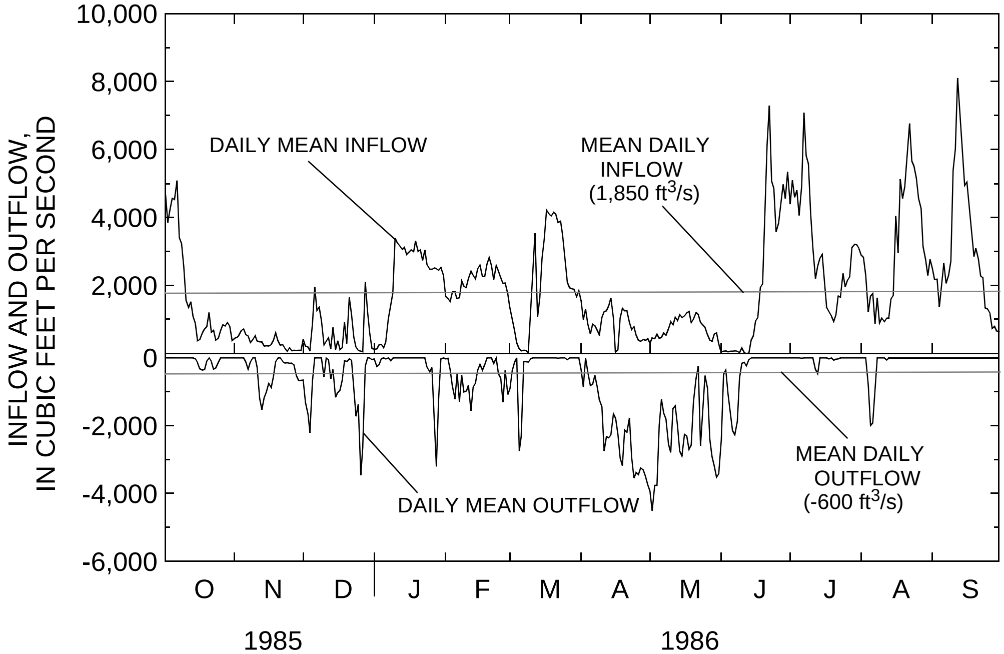

Figure 5. Hydrograph of inflow and outflow for Lake Okeechobee, water year 1986.

5 to15 percent based on the accuracy of individual discharge measurements (within about 5-8 percent) and the magnitude of stage-shift corrections in low-gradient streams (typically 5-20 percent). The standard error of budget residuals reported in James and others (1995) for the period 1982 to 1991 was 255 ft^3/s. When assuming equal errors in the measurement of inflow and outflow, the standard error of each component can be estimated as the square root of one-half the squared standard error of the budget residuals. From the data of James and others (1995), this amounts to about 180 ft^3/s for total inflow and total outflow, which is similar to the standard errors reported for inflow (217 ft^3/s) and outflow (195 ft^3/s) in table 2.

An average annual flux into lake storage of +260 ft^3/s occurred during 1982 to 1991; subtraction of outflow from inflow indicates a net overage in outflows of about 170 ft^3/s. Meyer (1971) estimated that about 22 ft^3/s of the outflow may be accounted for by levee seepage into the lake. The remaining residual hydrologic flux may represent an accumulation of errors in unmeasured sources or poorly measured sinks over the period of study. The annual water budget from James and others (1995) shows a similar overage in outflow (190 ft^3/s). Although the magnitude of this budget residual is relatively small compared to total inflow and outflow (only about 4 percent), it is notable that the overage is about equal to the combined inflow from all but the twelve largest tributaries to the lake (204 ft^3/s).

The greatest part of the random error in hydrologic budgets can be attributed to errors in the measurement and estimation of surface-water discharge. Though rainfall is spatially and temporally variable, rainfall is spatially diffuse and can be measured accurately and independently at numerous random locations with relatively little bias. Evaporation from the surface of a lake—though subject to bias, particularly where measured in pans (Winter, 1981)—is spatially uniform and temporally predictable. A similar point can be made for ground-water seepage for which changes in hydrostatic head over time are relatively small. Furthermore, though small changes in lake stage equate to large differences in equivalent discharge, changes in lake storage can be measured very precisely—especially when accumulated over a 10-year period.

Phosphorus Concentrations and Loads

Phosphorus-concentration data collected by the USGS in periodic samples from the Kissimmee River (S-65E), Fisheating Creek (FEC), and Harney Pond Canal (S-71), during the period 1982 to 1991, were compared to SFWMD data from these streams for the same period and differed by only 0.01 mg/L on average. This was not statistically significant so the USGS sample data are used in combination with SFWMD data from these streams and 31 other flow-control points around the lake.

Although the Kissimmee River is disproportionately the largest source of discharge to Lake Okeechobee, loads are more evenly distributed around the lake because of the spatial variability of phosphorus concentrations (fig. 6). Standard errors of regression represent the magnitude of uncertainty in instantaneous loading estimates due to uncertainties in the concentration model. The standard error of regression is greatest for the Kissimmee River (85 metric tons per year (tons/yr)), although this is not strictly in proportion to discharge. For example, discharge from the Kissimmee River is four times that of the combined inflow and outflow of the North New River (S-2 and HGS-4) on the south side of the lake. The standard error of regression, in contrast, is only about 60 percent larger for the Kissimmee River compared to that of the North New River.

Total-phosphorus concentration data for major inflow sites are separated by flow direction into three categories: no-flow, inflow, and outflow (table 3). Samples are identified as no-flow if they were collected on days for which a net discharge of 0.0 ft^3/s was computed. Net daily discharges were not determined for all sites. The large proportion of no-flow samples indicated at some sites reflects the episodic temporal distribution of discharge around the lake and the difficulty inherent in periodic sampling schemes in which samples are collected according to a schedule rather than hydrologic conditions. Although most of the differences in concentration with respect to flow direction are small in absolute terms, phosphorus concentrations were marginally higher in flow samples than in no-flow samples at 8 out of 12 inflow sites for which net flows were determined. Notable exceptions to this are average phosphorus concentrations in Fisheating Creek (FEC) and Fisheating Lock (S-131), and at two inflow-outflow sites—C-10A and S-308B and S-308C (St. Lucie Canal)—where concentrations were greater in no-flow samples. Small differences in mean phosphorus concentrations for no-flow and inflow samples may appear to be insignificant when compared to the standard deviations of the data; however, a difference of only 0.02 mg/L when compared to a mean of 0.08 mg/L can induce a bias in load computations of as much as 25 percent.

The standard deviations of combined phosphorus data over the 10-year period range from 0.03 mg/L at S-135 to 0.73 mg/L at S-154. Standard deviations in proportion to the mean were high, ranging from about 50 to 100 percent. The highest concentrations and largest errors were in estimates for the Nubbin Slough (S-191) and Taylor Creek (S-133) Basins to the north of the lake and east of the Kissimmee River. At 13 of the 30 sites listed in table 3, concentrations equalled or exceeded the 0.18 mg/L threshold established as a management goal for Lake Okeechobee. Without additional definition of expected concentrations and increased refinement of standard errors, uncertainties in concentration data make the detection of trends and evaluation of management effects very difficult.

Mean annual loading rates estimated for all streams, entering and leaving Lake Okeechobee, are summarized in table 4. The total load entering the lake from all surface-water discharge for the 10-year period was 404 tons/yr. The greatest single contribution of 103 tons/yr (25 percent) came from Kissimmee River (S-65E); the second largest was 84 tons/yr (20 percent) at Nubbins Slough (S-191). Harney Pond Canal (S-71) and Fisheating Creek (FEC) were next in order of load contribution and together accounted for about as much as the Kissimmee River (S-65E). Load contribution from all the remaining streams comprised only about another 110 tons/yr. The total load leaving the lake was only 129 tons/yr, the greatest part of which leaves through the Caloosahatchee River (S-77) and St. Lucie Canal (S-308B and S-308C).

Because of the large atmospheric component in the hydrologic budget, atmospheric deposition is a potentially large source of phosphorus to the lake (Joyner, 1974; Swift and others, 1987; James and others, 1995). Although wet deposition may account for a significant phosphorus load to the system, bulk deposition (wet plus dry) has proven difficult to measure accurately due to persistent problems with sample contamination (Peters and Reese, 1995). James and others (1995) inferred a constant phosphorus concentration of 0.03 mg/L in rainwater based on peat-accretion measurements made for the Everglades Water Conservation Area *2A* (Walker, 1993). This concentration, though reasonable as a long-term average, reflects a process of accumulation over such an extremely long period (hundreds of years) that annual estimates of load have little meaning. Atmospheric fluxes were not included in this analysis because of the difficulty in determining an annual atmospheric loading rate with any precision.

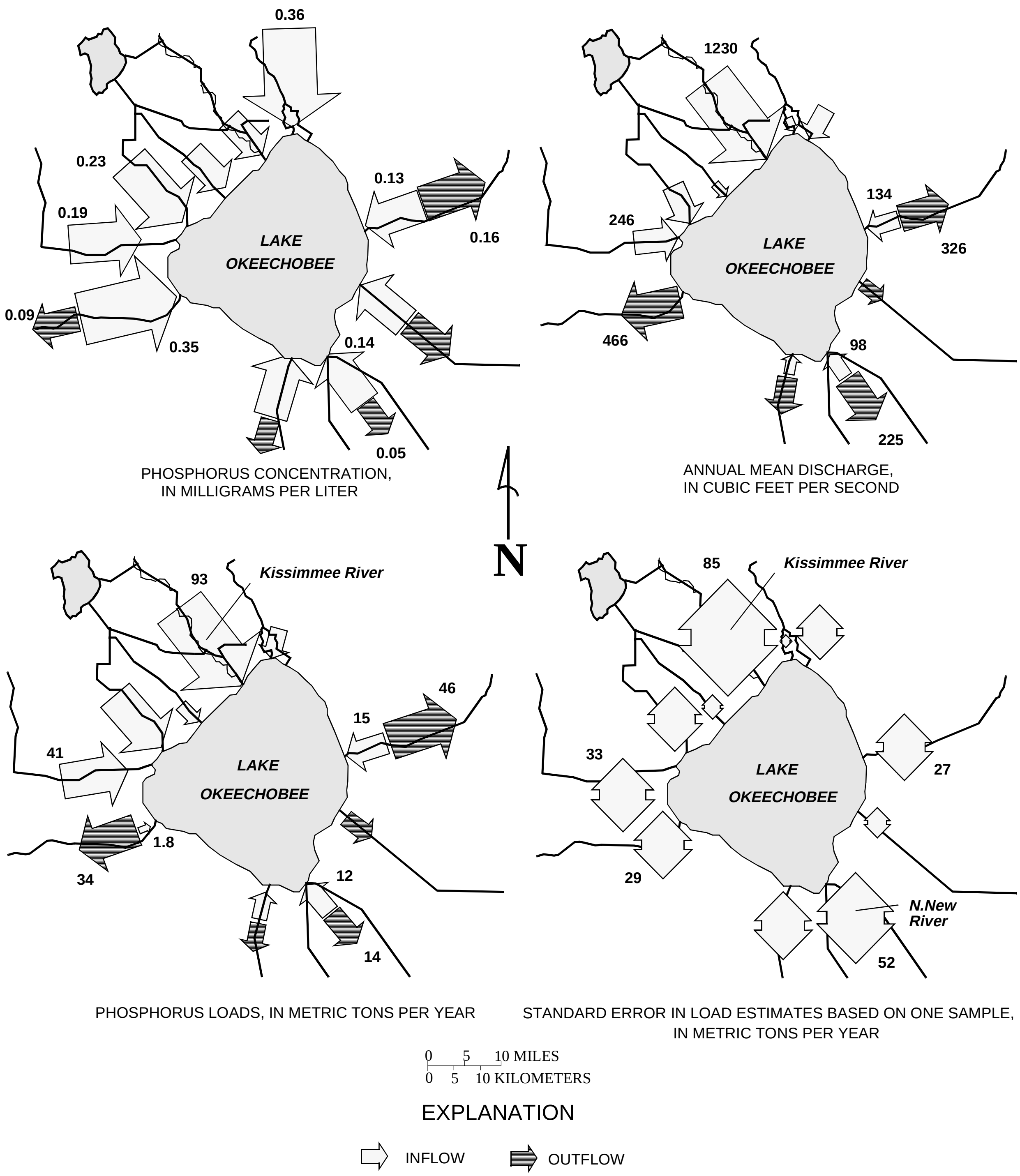

Figure 6. Spatial distribution of average phosphorus concentrations, discharge, computed phosphorus loads, and standard load errors for Lake Okeechobee, 1982-91.

Table 3. Mean and standard deviation of phosphorus concentration data for samples collected at selected discharge points around Lake Okeechobee

[Concentrations are in milligrams per liter. SD, standard deviation; N, number of samples collected; --, no data; HGS, Hurricane Gate Structure]

Site number	Site name	Phosphorus											
		No-flow samples			Inflow samples			Outflow samples			All samples		
		N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
1	S-135	119	0.07	0.03	24	0.09	0.03	0	--	--	143	0.07	0.03
3	S-191 on Nubbin Slough	--	--	--	--	--	--	--	--	--	216	.68	.23
6	S-133 on Taylor Creek	114	.19	.09	36	.33	.14	0	--	--	150	.22	.12
9	S-65E on Kissimmee River	0	--	--	217	.11	.08	0	--	--	217	.11	.08
12	S-154 and S-154C	--	--	--	--	--	--	--	--	--	181	.79	.73
13	S-84 on C-41A	58	.05	.05	59	.06	.04	0	--	--	117	.06	.05
14	L-59E	--	--	--	--	--	--	--	--	--	40	.25	.17
15	S-127 at Buckhead Lock	--	--	--	--	--	--	--	--	--	163	.26	.16
16	L-59W at S-72	--	--	--	--	--	--	--	--	--	42	.21	.17
17	L-60E at S-72	--	--	--	--	--	--	--	--	--	42	.17	.13
18	L-60W at S-71	--	--	--	--	--	--	--	--	--	44	.16	.14
19	S-72 on Indian Prairie Canal	84	.18	.14	45	.19	.09	0	--	--	129	.18	.12
20	S-129	124	.13	.09	24	.17	.12	0	--	--	148	.13	.09
21	L-61E at S-71	--	--	--	--	--	--	--	--	--	39	.14	.08
22	S-71 on Harney Pond Canal	62	.16	.12	88	.20	.15	0	--	--	150	.18	.13
23	S-131 at Fisheating Lock	115	.11	.06	19	.11	.05	0	--	--	134	.11	.06
25	Fisheating Creek (FEC) at SR-78	5	.24	.19	121	.18	.15	0	--	--	126	.18	.15
26	C-5	--	--	--	--	--	--	--	--	--	43	.07	.07
28	S-77 on Caloosahatchee River	0	--	--	0	--	--	148	0.09	0.06	148	.09	.06
31	S-4	--	--	--	--	--	--	--	--	--	122	.19	.20
33	S-310 and HGS-2 on Induscan Canal	--	--	--	--	--	--	--	--	--	51	.27	.29
36	S-3 and HGS-3 on Miami Canal	51	.08	.07	49	.15	.12	16	.05	.02	116	.11	.09
37	C-4A	--	--	--	--	--	--	--	--	--	85	.09	.04
38	S-2 and HGS-4 on North New River	60	.14	.08	79	.17	.10	13	.08	.03	152	.15	.10
39	C-12	--	--	--	--	--	--	--	--	--	65	.13	.08
40	C-12A	--	--	--	--	--	--	--	--	--	109	.24	.16
41	C-10	--	--	--	--	--	--	--	--	--	76	.28	.21
42	S-352 and HGS-5 on West Palm Beach Canal	71	.16	.10	0	--	--	56	.14	.06	127	.15	.09
44	C-10A on L-8 Canal	7	.16	.22	17	.06	.04	11	.12	.05	35	.10	.10
48	S-308B and S-308C on St. Lucie Canal	42	.15	.08	22	.13	.04	75	.15	.06	139	.15	.07

Table 4. Summary of phosphorus loads for tributaries to Lake Okeechobee

[ft^3/s, cubic feet per second; tons/yr, tons per year; mg/L, milligrams per liter; --, no data; ( ), estimated value; HGS, Hurricane Gate Structure}

Sub-basin	Site name	Source	No. of days in period	No. of no-flow days	Inflow: No. of inflow days	Inflow: Mean annual discharge (ft^3/s)	Inflow Phosphorus: Mean annual load (tons/yr)	Inflow Phosphorus: Load-weighted concentrations (mg/L)	Outflow: No. of outflow days	Outflow: Mean annual discharge (ft^3/s)	Outflow Phosphorus: Mean annual load (tons/yr)	Outflow Phosphorus: Load-weighted concentrations (mg/L)	Degree of freedom	Standard error mean load (units)
1	S-135	LSR	3,643	3,196	447	22.0	1.70	0.087	--	--	--	--	18	1.046
	HCL	Average	--	--	--	3	.24	(.09)	--	--	--	--	--	--
2	S-133	LSR	3,600	3,129	471	27.8	8.81	.355	--	--	--	--	32	1.067
	S-191, C-9, C-8, HGS-6, C-7	Average	--	--	--	131	84	.68	--	--	--	--	--	--
3	S-65E	LSR	3,652	450	3,202	1230	103	.093	--	--	--	--	204	1.039
	S-84	LSR	3,644	1,885	1,722	162	22.4	.155	37	-2.50	-1.11	0.496	53	1.067
	C-6, C-38W, S-154, S-154C, L-59E	Average	--	--	--	52	28	.62	--	--	--	--	--	--
4	S-127	Average	--	--	--	22	5.5	.28	--	--	--	--	--	--
	S-72	LSR	3,642	2,561	1,081	70	5.47	.088	--	--	--	--	40	1.060
	S-129	LSR	3,643	3,135	474	17.6	3.07	.195	34	-1.86	-.221	.133	17	1.109
	S-71	LSR	3,642	1,670	1,958	221	45.2	.230	14	-2.49	-.416	.187	82	1.055
	S-131	LSR	3,643	3,356	287	5.8	.57	.110	--	--	--	--	14	1.093
	L-59W, L-60E, L-60W, L-61E	Average	--	--	--	8	1.2	.17	--	--	--	--	--	--
5	FEC	LSR	3,594	168	3,426	245	40.8	.187	--	--	--	--	114	1.050
	L-61W	Average	--	--	--	2	.41	.101	--	--	--	--	--	--
6	C-5, C-5A	Average	--	--	--	30	1.9	.072	--	--	--	--	--	--
7	S-77	LSR	3,642	6	49	5.7	1.80	.352	3587	-474	-33.8	.080	141	1.038
	S-4	Average	--	--	--	26	4.4	.19	--	--	--	--	--	--
	C-1, C-1A, C-2, S-310, HGS-2	Average	--	--	--	--	--	--	--	-53	-9.0	.27	--	--
8	S-236	Average	--	--	--	5	.36	.08	--	--	--	--	--	--
	S-3, HGS-3	LSR	3,643	1,966	215	50.9	6.88	.151	1462	-182	-7.48	.046	59	1.068
	C-4A	Average	--	--	--	8	.57	.08	--	--	--	--	--	--
	S-2, HGS-4	LSR	3,643	2,034	290	97.5	11.9	.136	1319	-321	-14.5	.050	83	1.038
	C-12	Average	--	--	--	10	1.1	.12	--	--	--	--	--	--
	C-12A	Average	--	--	--	11	2.4	.24	--	--	--	--	--	--
	C-10	Average	--	--	--	7	1.6	.25	--	--	--	--	--	--
	C-3	Average	--	--	--	3	.7	(.25)	--	--	--	--	--	--
9	S-352, HGS-5	LSR	3,652	2,536	18	2.3	.20	.095	1098	-84.5	-9.76	.129	50	1.058
	C-10A	LSR	3,541	1,111	1,269	61.7	2.73	.050	1161	-58.4	-6.89	.132	21	1.082
	S-308B, S-308C	LSR	3,652	1,356	777	129	15.4	.134	1519	-326	-45.9	.157	91	1.040
	C-13, C-14, C-16, C-11	Average	--	--	--	12	1.4	.13	--	--	--	--	--	--
Basin		LSR	--	--	--	2348	270	.129	--	1453	120	.092	--	--
		Average	--	--	--	322	134	.465	--	53	9.0	.19	--	--
		Total	--	--	--	2670	404	.169	--	1506	129	.096	--	--

Standard errors of the mean in table 4 were calculated using equation 10 and represent an estimate of the standard error of average calculated loads from 1982 to 1991. Because the transformed model is exponential in form, the standard error of the mean is multiplicative rather than additive (table 4). The standard errors of average calculated loads range from about 1.04 (approximately 4 percent of the mean) at S-65E, S-77, S-2, and S-308C to 1.11 (approximately 11 percent) at S-129. About 67 percent (270 tons/yr) of the total inflow load was calculated by least-squares regression and may be characterized by standard errors ranging from 4 to 11 percent (table 4). Loading rates for Taylor Creek (S-133) and Nubbin Slough (S-191) were calculated from average concentrations and estimates of discharge, and consequently are two of the largest sources of uncertainty in overall loading estimates.

Multiple regression coefficients for load models used in this analysis are listed in table 5. The log of discharge or squared log of discharge was statistically significant ($\alpha = .05$) in all models except that for S-129. Flow direction was significant in about half of the models to which this parameter was applied. Absolute time (indicating a long-term trend) and seasonal frequencies of the time-related variables on 1/2-year and 1-year cycles were typically found to be significant. Other temporal variables included on 1/4-year, 2-year, and 4-year cycles were not generally significant at more than two sites. Nonsignificant variables are included in predictive equations for comparability among sites, but have little contribution to the computed loads or load-error estimates.

Concern about spurious correlation in load-discharge regression occasionally has been raised in literature. Although the multiplication of discharge in the dependent variable load produces a higher correlation than in the relation of concentration to discharge, this does not produce spurious correlation, but rather serves to illustrate the dominant control of discharge on load. Figure 7 shows the relation of phosphorus-loading rate to both discharge and concentration for the periodic-sample data used to develop regression models on five of the principal tributaries to Lake Okeechobee. Only Harney Pond Canal (S-71) and North New River (S-2), of the five sites included, show a reasonably strong correlation between load and concentration. These also are the only sites of the five that show a significant relation of load to the squared-log of discharge.

The significant relation of load to discharge is to be expected because discharge is one of the operands in the computation of load. The relation of load to the higher order squared-log of discharge, however, indicates a relation between concentration and discharge. Though loads are determined to a large extent by discharge, much of the uncertainty in load remains a function of uncertainty in concentration (fig. 7).

As noted previously, the residual uncertainty in loads calculated from these regression models is directly proportional to the uncertainty in estimated concentration ($s_{\hat{c}}$). Figure 8 shows a time series of sample phosphorus concentrations (*C*) and estimated concentrations ($\hat{c}$) for the same sites shown in figure 7. Estimated concentrations were back-calculated from load estimates by dividing out discharge. The fit of the two time series shows the degree to which the models are capable of accounting for the temporal variations in expected phosphorus concentrations. The models fit best where concentrations can be functionally related to discharge (S-71, Harney Pond Canal; and S-2, North New River).

An Optimized Monitoring Network

Seven monitoring alternatives were compared for optimization:

Q0. Continue discharge gaging without change.

Q1. Double discharge-measurement frequency to improve discharge ratings.

Q2. Install an acoustic-velocity measuring device to improve discharge ratings.

C0. Continue monitoring at all sites at a reduced frequency of 2 times per year.

C1. Continue current sampling frequency without change (12 visits per year).

C2. Increase periodic sampling to 25 samples per year by employing observers at each site.

C3. Install automatic samplers to continuously collect sample in proportion to discharge.

Alternatives Q0 and C0 were held as baseline conditions against which absolute benefit-cost ratios were computed. Continued monitoring at the baseline condition was held as a no-cost alternative. Costs for other alternatives and the overall cost of the optimized network thus represent cost increases relative to the baseline condition. Alternative C0 was chosen as a minimum level of sampling to provide for minimal reconnaissance monitoring. Two samples, providing

Table 5. Coefficients for estimation of loads based on regression analysis loading data at major tributaries for the period October 1981 through September 1990

[--, no data; FEC, Fisheating Creek; HGS, Hurricane Gate Structure]

Site number	Site name	Intercept	Log of discharge	Squared log of discharge	Flow direction (binomial)	Absolute time (days since 1900)	Sine 1-year cycle	Cosine 1-year cycle	Sine 1/2-year cycle	Cosine 1/2-year cycle	Sine 1/4-year cycle	Cosine 1/4-year cycle	Sine 2-year cycle	Cosine 2-year cycle	Sine 4-year cycle	Cosine 4-year cycle	Log standard error of regression	Standard error of regression
1	S-135	0.0013	0.0593**	0.2436**	0.0013	-6.78E-06	-0.0389	0.0672	-0.0006	-0.0188	0.0089	0.0112	-0.0713	0.0115	0.0977	-0.0648	0.1566	1.43
6	S-133	.0089	.0744**	.2827**	--	-6.25E-07	-.0934*	.0187	.0740	.0478	.0012	.0453	.1062	.0709	-.0630	.0624	.1721	1.49
9	S-65E	-.0164**	.7740**	.0346	--	-2.41E-05**	-.1405	-.0264**	.0230	-.0452*	.0200	-.0054	.0361	.0600*	-.0400	-.0153	.2474	1.78
13	S-84	.0583**	1.0967**	-.0139	-.2011	-4.14E-05**	-.0590	-.0464	.0836*	.0363	.0206	-.1041*	-.0480	.0078	-.0179	-.0039	.2282	1.69
19	S-72	.1981**	1.4285**	-.0861*	---	-4.65E-05**	-.1462	.0529**	.0087	.0682	-.0375	.0115	-.0097	-.0392	.0243	-.0476	.1658	1.46
20	S-129	.7909	1.3683	-.0293	.7909	-9.53E-05	.1591*	.0755	.0382	.0117	.0848	-.0167	-.0572	.1607	.0518	-.3707	.2559	1.80
22	S-71	.7472	.3123	.1874**	--	-3.42E-05*	-.1307	-.0376**	.0548	.0373	.0053	.0272	.0150	-.0524	.0279	-.0343	.2188	1.66
23	S-131	-.0142	1.0669**	--	--	-3.52E-05*	.1667	-.0128	.0171	-.0407	.1389	-.1058	-.1756	.0639	-.0213	-.2458	.1599	1.44
25	FEC	-.1626	1.0625**	.0027	-.1626	-2.17E-05	.0830**	-.1575**	-.0070	.0240	.0048	.0012	.0306	-.0258	.0922**	-.2010**	.1855	1.53
28	S-77	-.0453**	1.0814**	-.0174	-.2138**	-3.09E-05**	-.1303**	-.1205**	.0627**	-.0837**	-.0268	.0625**	.0141	-.0328	-.0365	-.0604**	.1868	1.54
36	S-3 & HGS-3	.0235	.5429	.1177	-.1900**	-3.32E-05*	.0860	.0892	.1170*	.0863	-.0564	.0802	-.2058	.1837	-.4381	-.2022*	.2329	1.71
38	S-2 & HGS-4	-.6565**	-1.1232**	.4095**	-.1875**	7.134E-05**	.0927	.0446*	.0913*	.0535	-.0283	.0004	-.0289	.1575*	-.0920	.0688	.1607	1.45
42	S-352 & HGS-5	-.3683	-.4428	.2821**	-.3683*	5.095E-05*	-.0671	-.0717	-.0370	-.0620	-.0203	-.0181	.0284	-.0180	.0422	.0567	.1803	1.51
44	C-10A	.0172**	.8424**	--	.1959**	-2.49E-05**	.1136*	-.0728	.0747	.0069	.0458	.0119	.0256	.0477	.0937	-.1308*	.1680	1.47
48	S-308B & S-308C	.0361	.4817	.1057**	-.0235	-1.10E-05	.0249**	.0828	-.0307	.0502*	.0109	-.0078	.0749*	-.0419	-.0318	.0448*	.1653	1.46

* significant at = .1

** significant at = .01

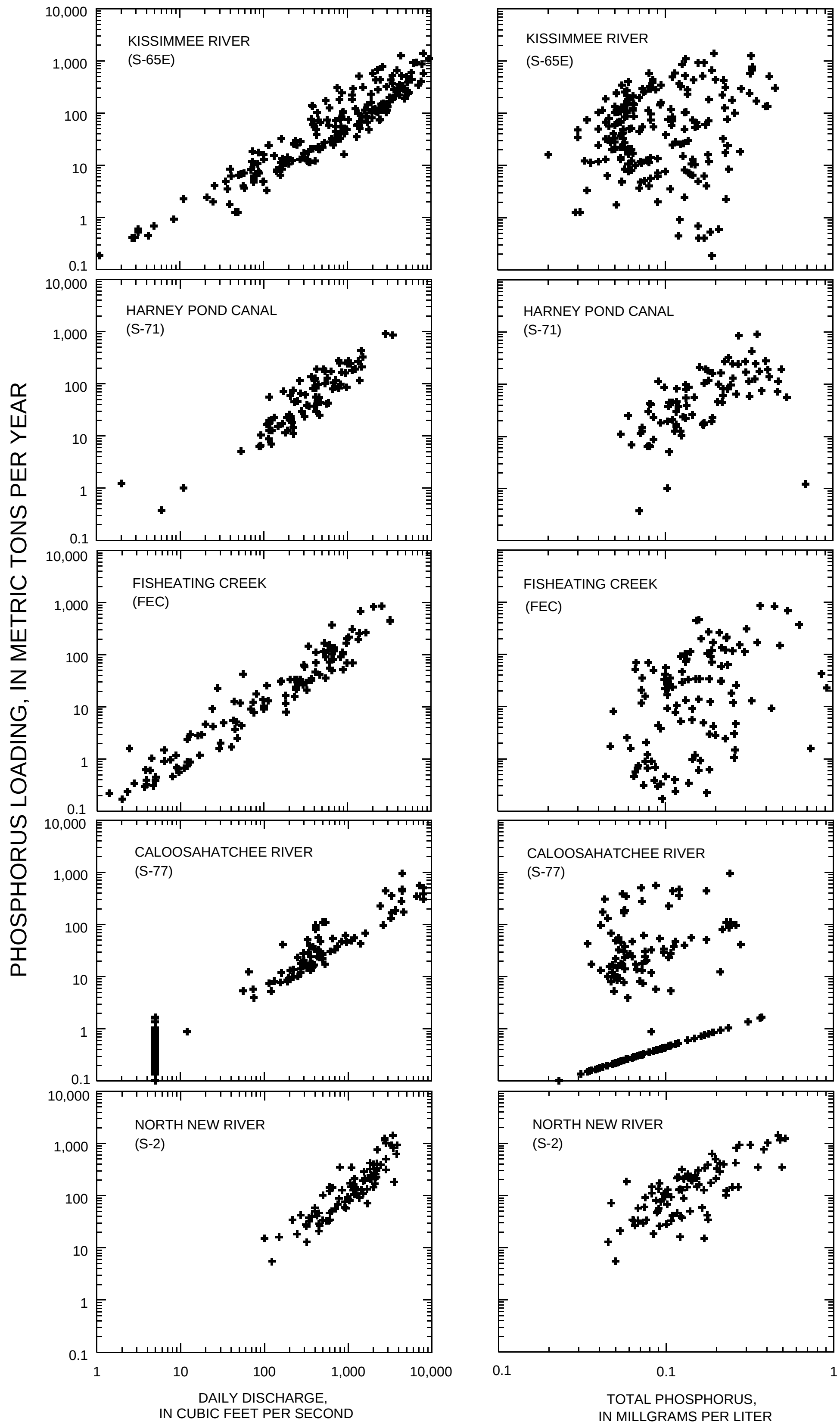

Figure 7. Relation of phosphorus-loading rate to discharge and concentration on five principal tributaries to Lake Okeechobee, 1981-92.

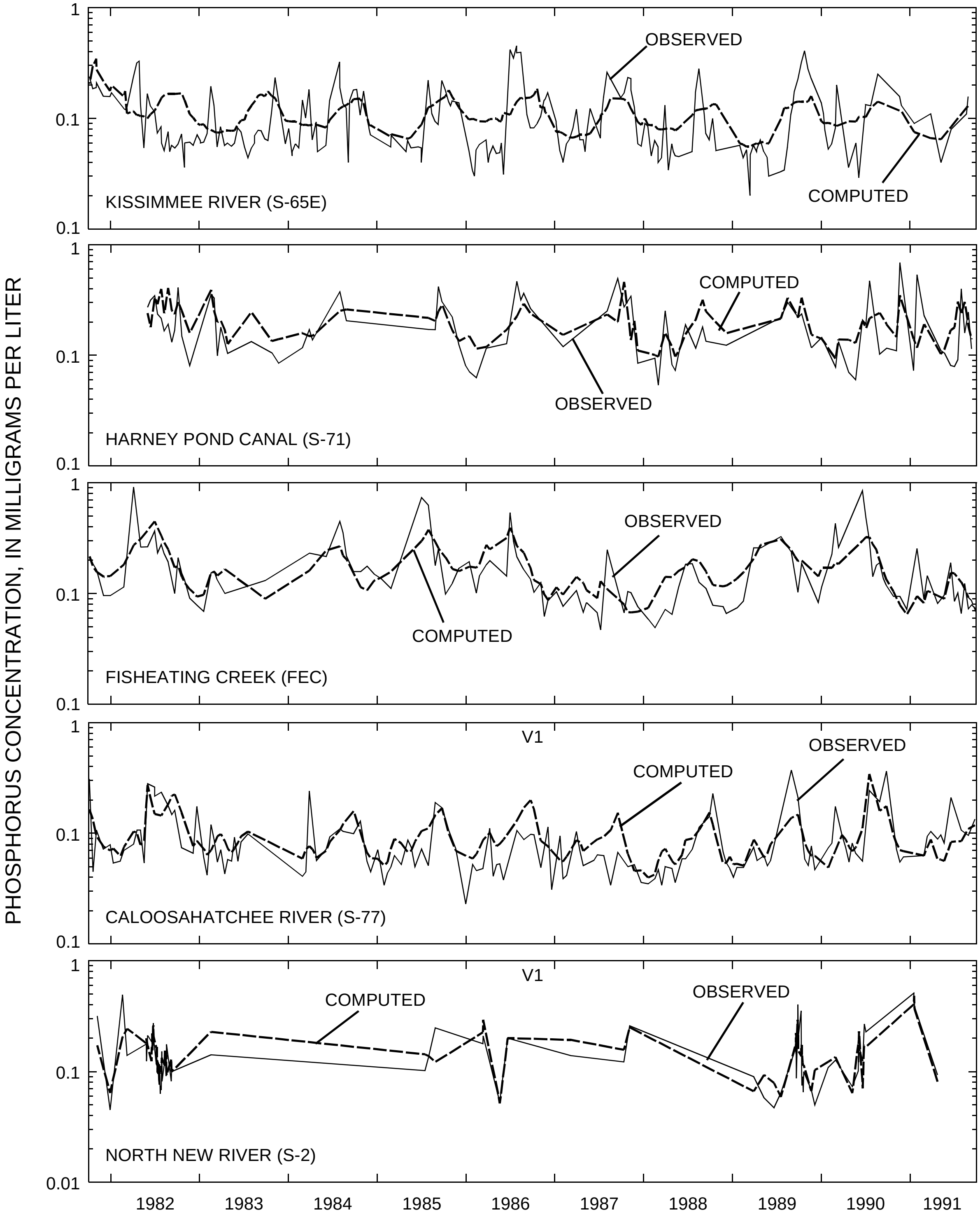

Figure 8. Observed phosphorus concentrations and estimates computed from regression of loads for five selected sites.

one degree of freedom, are thus the minimum number to identify a significant outlier from previously established sample distributions. The current discharge-gaging network was held as a minimum baseline condition (Q0) because much of the current network is required for other purposes.

Alternatives Q1 and Q2 represent two levels of increased effort for discharge gaging over the baseline network. Because all streams are not currently rated or gaged, alternative Q1 (rating improvement) represents a greater change in effort at some sites than at others. Alternative Q2 (acoustic velocity monitoring) represents an increase in effort and an improvement in data quality for all sites. Acoustic methods, by providing a continuous record of velocity, reduce uncertainty in estimated discharge $\hat{q}$ caused by temporal changes in ratings and backwater effects in low-gradient streams (Sloat and Gain, 1995).

Alternatives C1, C2, and C3 increase the frequency of water-quality sampling over the current baseline (C0). Alternative C1 is identified as the current practice of collecting periodic data at a frequency of about 12 samples each year. Because 12 visits do not produce 12 usable samples at all sites, alternative C1 has demonstrated a tendency to produce the uneven replication among sites identified in table 3. Alternatives C2 and C3 would increase the number of usable samples at all sites and as a result would tend to produce a more even distribution of samples. Trained observers, in visiting sites on a regular basis, are more likely to obtain samples under desirable flow conditions and have proven in USGS programs to be a reliable alternative to periodic or automated sampling methods. Automatic sampling (C3) is the most intensive means of sampling.

Partial-error terms and costs for each discharge and concentration-monitoring alternative are presented in table 6. Because sample replication is dependent on time, standard errors of the mean must be associated with a time interval. Estimates of partial and total errors computed for current and optimized networks in this analysis reflect uncertainty on a scale of annual averages. This analysis can be performed at other levels of temporal resolution as long as the estimated errors reflect the temporal scale. Although the magnitudes of estimated errors will decrease for longer averaging periods and increase for shorter intervals, the optimized network will not be greatly affected so long as increases and decreases are proportionate for all sites and monitoring alternatives.

Errors in discharge for baseline alternatives were taken from table 2 and reflect the current monitoring network (pre-1992). Errors in concentration for the baseline alternatives are computed from standard errors of regression for modeled sites and standard deviations of sample data on other sites. Errors for sites that were unmeasured or unsampled were estimated from other nearby sites (generally within the same subbasin). Standard errors for improvement alternatives (C1, C2, and C3) were computed using equations 9 and 10 and an effective sample-replication rate for each alternative based on expected performance. For alternative C1 (current sampling network), effective sample-replication rates were based on the proportion of flow samples in table 3.

Estimates of error for alternative C3 (automatic sampling) were based on an assumption of a minimum error of $\pm$3 percent. This is an arbitrary value based on a combination of factors. By frequent subsampling composites, automatic samplers increase the effective subsample replication toward infinity and reduce random components of subsampling error toward zero. However, other remaining random components inherent in laboratory analyses, sample handling, and sample representativeness are not reduced by automatic sampling. For example, the standard error of the mean caused by errors in laboratory analyses is dependent only on the number of composite samples analyzed, not the number of subsamples composited. Other systematic errors also may be induced by the positioning of the sampler intake or the methods by which samples are composited (Shih and others, 1994).

The costs of each of the various monitoring alternatives in table 6 are listed as similar or the same for all stations because of the necessities of operating a spatial and temporal network. Although one site may require more effort or be farther from a given base of operations than some other site, the specific costs of operating the two sites in a network are difficult to apportion. An average operating cost is usually calculated and applied in USGS gaging operations and has been applied in most cases in table 6. As a result, marginal changes in cost associated with the number and type of sites operated (based on economies of scale) were not reflected in this particular application of the optimization algorithm. However, the approach presented here could be readily adapted to include this feature, if a suitable costing algorithm were developed.

Table 6. Summary of benefits and costs for selected monitoring scenarios

[mg/L, milligrams per liter; ft^3/s, cubic feet per second; tons/yr, tons per year; mt/yr, metric tons per year; >, less than; HGS, Hurricane Gate Structure]

Site number	Site name	Mean phosphorus concentration (mg/L)	Potential discharge monitoring scenarios: Baseline		Rating improvement			Acoustic velocity meter		
			Discharge error (ft^3/s)	Discharge load error (tons/yr)	Cost ($)	Discharge error (ft^3/s)	Discharge load error (tons/yr)	Cost ($)	Discharge error (ft^3/s)	Discharge load error (tons/yr)
1	S-135	0.09	2	0.2	8,440	2	0.2	12,480	2	0.2
2	HCL	.68	5	3.1	8,440	5	3.1	12,480	1	.6
3	S-191	.68	25	15.3	8,440	20	12.2	12,480	11	6.7
4	C-9	.68	2	1.2	8,440	1	.6	18,440	1	.6
5	C-8	.68	2	1.2	8,440	1	.6	18,440	1	.6
6	S-133	.68	15	9.2	8,440	10	6.1	12,480	2	1.2
7	HGS-6	.36	3	1.0	8,440	3	1.0	18,440	3	1.0
8	C-7	.68	2	1.2	8,440	1	.6	18,440	1	.6
9	S-65E	.09	180	14.9	8,440	150	12.5	12,480	120	10.0
10	C-6	.21	2	.4	8,440	1	.2	18,440	1	.2
11	C-38W	.21	2	.4	8,440	1	.2	18,440	1	.2
12	S-154 and S-154C	.79	25	17.6	8,440	10	7.0	20,440	5	3.5
13	S-84	.16	25	3.5	8,440	10	1.4	12,480	10	1.4
14	L-59E	.25	2	.5	8,440	2	.5	16,440	2	.5
15	S-127	.26	5	1.2	8,440	2	.5	12,480	2	.5
16	L-59W	.21	2	.4	8,440	1	.2	16,440	1	.2
17	L-60E	.17	2	.3	8,440	1	.1	20,440	1	.1
18	L-60W	.17	2	.3	8,440	3	.4	12,480	3	.4
19	S-72	.09	5	.4	8,440	3	.2	12,480	3	.2
20	S-129	.20	2	.3	8,440	1	.2	20,440	1	.2
21	L-61E	.14	2	.3	8,440	1	.1	16,440	1	.1
22	S-71	.23	44	9.0	10,360	33	6.8	12,480	22	4.5
23	S-131	.11	1	.1	8,440	1	.1	12,480	1	.1
24	L-61W	.10	2	.2	8,440	1	.1	16,440	1	.1
25	FEC	.19	40	6.7	8,440	20	3.3	12,480	10	1.7
26	C-5	.07	5	.3	8,440	2	.1	12,480	2	.1
27	C-5A	.07	5	.3	8,440	1	.1	12,480	1	.1
28	S-77	.08	72	5.1	8,440	48	3.4	12,480	48	3.4
29	C-1	.19	2	.3	8,440	1	.2	18,440	1	.2
30	C-1A	.19	2	.3	8,440	1	.2	18,440	1	.2
31	S-4	.19	3	.5	8,440	3	.5	20,440	3	.5
32	C-2	.27	1	.2	8,440	1	.2	22,440	1	.2
33	S-310 and HGS-2	.27	25	6.1	8,440	25	6.1	12,480	5	1.2
34	S-236	.09	1	.1	8,440	1	.1	16,440	1	.1
35	C-3	.28	5	1.2	8,440	1	.2	12,480	1	.2
36	S-3 and HGS-3	.10	40	3.4	8,440	40	3.4	12,480	23	2.0
37	C-4A	.09	1	.1	8,440	1	.1	12,480	1	.1
38	S-2 and HGS-2	.09	62	4.9	8,440	60	4.8	14,480	42	3.3
39	C-12	.13	1	.1	8,440	1	.1	12,480	1	.1
40	C-12A	.24	1	.2	8,440	1	.2	12,480	1	.2
41	C-10	.28	1	.2	8,440	1	.2	12,480	1	.2
42	S-352 and HGS-5	.13	14	1.6	8,440	9	1.0	12,480	9	1.0
43	C-13	.13	3	.3	8,440	1	.1	13,440	1	.1
44	C-10A	.11	18	1.8	8,440	12	1.2	12,480	12	1.2
45	C-14	.11	3	.3	8,440	1	.1	13,440	1	.1
46	C-16	.11	3	.3	8,440	1	.1	13,440	1	.1
47	C-11	.11	5	.5	8,440	1	.1	13,440	1	.1
48	S-308B and S-308C	.15	150	20.2	8,440	50	6.7	12,480	50	6.7

Table 6. Summary of benefits and costs for selected monitoring scenarios--Continued

[mg/L, milligrams per liter; ft^3/s, cubic feet per second; tons/yr, tons per year; mt/yr, metric tons per year; >, less than; HGS, Hurricane Gate Structure]

		Potential concentration monitoring scenarios														
		Baseline			Periodic sampling			Event sampling			Observor sampling			Automatic sampling		
Site number	Site name	Absolute discharge (ft^3/s)	Concentration error (mt/yr)	Concentration load error (mt/yr)	Cost ($)	Concentration error (mt/yr)	Concentration load error (mt/yr)	Cost ($)	Concentration error (mt/yr)	Concentration load error (mt/yr)	Cost ($)	Concentration error (mt/yr)	Concentration load error (mt/yr)	Cost ($)	Concentration error (mt/yr)	Concentration load error (mt/yr)
1	S-135	23	0.03	0.7	1,700	0.02	0.4	2,660	0.01	0.2	3,050	0.01	0.1	5,866	>0.01	0.1
2	HCL	3	.23	.6	1,700	.15	.4	2,660	.08	.2	3,050	.05	.1	5,866	.02	.1
3	S-191	110	.23	22.4	1,700	.07	6.5	2,660	.07	6.5	3,050	.05	4.5	5,866	.02	2.0
4	C-9	2	.23	.4	1,700	.15	.3	2,660	.08	.1	3,050	.05	.1	5,866	.02	>.1
5	C-8	2	.23	.4	1,700	.09	.2	2,660	.07	.1	3,050	.05	.1	5,866	.02	>.1
6	S-133	15	.23	3.1	1,700	.12	1.6	2,660	.08	1.0	3,050	.05	.6	5,866	.02	.3
7	HGS-6	28	.15	3.6	1,700	.08	1.9	2,660	.05	1.2	3,050	.03	.7	5,866	.01	.3
8	C-7	2	.23	.4	1,700	.12	.2	2,660	.08	.1	3,050	.05	.1	5,866	.02	>.1
9	S-65E	1230	.06	62.2	1,700	.02	18.0	2,660	.02	18.0	3,050	.01	12.4	5,866	.01	5.7
10	C-6	2	.17	.3	1,700	.09	.2	2,660	.06	.1	3,050	.03	.1	5,866	.02	>.1
11	C-38W	2	.17	.3	1,700	.09	.2	2,660	.06	.1	3,050	.03	.1	5,866	.02	>.1
12	S-154 and S-154C	46	.73	29.9	1,700	.30	12.2	2,660	.23	9.4	3,050	.15	6.0	5,866	.07	2.7
13	S-84	169	.09	12.8	1,700	.04	5.3	2,660	.03	4.1	3,050	.02	2.6	5,866	.01	1.2
14	L-59E	2	.17	.3	1,700	.11	.2	2,660	.06	.1	3,050	.03	.1	5,866	.02	>.1
15	S-127	22	.16	3.2	1,700	.11	2.1	2,660	.06	1.1	3,050	.03	.6	5,866	.01	.3
16	L-59W	2	.17	.3	1,700	.11	.2	2,660	.06	.1	3,050	.03	.1	5,866	.02	>.1
17	L-60E	2	.14	.2	1,700	.09	.2	2,660	.05	.1	3,050	.03	>.1	5,866	.01	>.1
18	L-60W	2	.14	.2	1,700	.09	.2	2,660	.05	.1	3,050	.03	>.1	5,866	.01	>.1
19	S-72	35	.03	1.1	1,700	.02	.5	2,660	.01	.4	3,050	.01	.2	5,866	>.01	.1
20	S-129	14	.12	1.5	1,700	.08	1.0	2,660	.04	.5	3,050	.02	.3	5,866	.01	.1
21	L-61E	2	.08	.1	1,700	.05	.1	2,660	.03	>.1	3,050	.02	>.1	5,866	.01	>.1
22	S-71	222	.12	24.1	1,700	.04	8.1	2,660	.04	8.0	3,050	.02	4.8	5,866	.01	2.2
23	S-131	6	.04	.2	1,700	.03	.2	2,660	.01	.1	3,050	.01	>.1	5,866	>.01	>.1
24	L-61W	2	.06	.1	1,700	.04	.1	2,660	.02	>.1	3,050	.01	>.1	5,866	.01	>.1
25	FEC	246	.08	18.0	1,700	.02	5.2	2,660	.02	5.2	3,050	.02	3.6	5,866	.01	1.6
26	C-5	5	.07	.3	1,700	.03	.1	2,660	.02	.1	3,050	.01	.1	5,866	.01	>.1
27	C-5A	5	.07	.3	1,700	.05	.2	2,660	.02	.1	3,050	.01	.1	5,866	.01	>.1
28	S-77	480	.04	15.3	1,700	.01	4.4	2,660	.01	4.4	3,050	.01	3.1	5,866	>.01	1.4
29	C-1	1	.20	.2	1,700	.13	.1	2,660	.07	.1	3,050	.04	>.1	5,866	.02	>.1
30	C-1A	1	.20	.2	1,700	.13	.1	2,660	.07	.1	3,050	.04	>.1	5,866	.02	>.1
31	S-4	26	.20	4.7	1,700	.10	2.4	2,660	.07	1.7	3,050	.04	.9	5,866	.02	.4
32	C-2	1	.29	.3	1,700	.19	.2	2,660	.08	.1	3,050	.06	.1	5,866	.03	>.1
33	S-310 and HGS-2	50	.29	12.9	1,700	.13	5.9	2,660	.10	4.3	3,050	.06	2.6	5,866	.03	1.2
34	S-236	10	.05	.4	1,700	.02	.2	2,660	.02	.1	3,050	.01	.1	5,866	>.01	>.1
35	C-3	3	.21	0.6	1,700	.09	.3	2,660	.07	.2	3,050	.04	.1	5,866	.02	.1
36	S-3 and HGS-3	233	.05	11.2	1,700	.02	5.1	2,660	.02	3.7	3,050	.01	2.2	5,866	>.01	1.0
37	C-4A	8	.04	.3	1,700	.03	.2	2,660	.01	.1	3,050	.01	.1	5,866	>.01	>.1
38	S-2 and HGS-2	418	.03	12.6	1,700	.01	4.5	2,660	.01	4.0	3,050	.01	2.5	5,866	>.01	1.2
39	C-12	10	.08	.7	1,700	.03	.3	2,660	.03	.2	3,050	.02	.1	5,866	.01	.1
40	C-12A	11	.16	1.6	1,700	.07	.7	2,660	.05	.5	3,050	.03	.3	5,866	.01	.1
41	C-10	7	.21	1.3	1,700	.09	.6	2,660	.07	.4	3,050	.04	.3	5,866	.02	.1
42	S-352 and HGS-5	87	.05	4.2	1,700	.02	1.8	2,660	.02	1.3	3,050	.01	.8	5,866	>.01	.4
43	C-13	3	.14	.4	1,700	.07	.2	2,660	.05	.1	3,050	.03	.1	5,866	.01	>.1
44	C-10A	120	.04	4.6	1,700	.02	1.6	2,660	.01	1.4	3,050	.01	.9	5,866	>.01	.4
45	C-14	3	.10	.3	1,700	.05	.1	2,660	.03	0.1	3,050	.02	.1	5,866	.01	>.1
46	C-16	3	.10	.3	1,700	.05	.1	2,660	.03	0.1	3,050	.02	.1	5,866	.01	>.1
47	C-11	3	.10	.3	1,700	.05	.1	2,660	.03	0.1	3,050	.02	.1	5,866	.01	>.1
48	S-308B and S-308C	450	.06	23.8	1,700	.02	7.6	2,660	.02	7.2	3,050	.01	4.8	5,866	.01	2.2

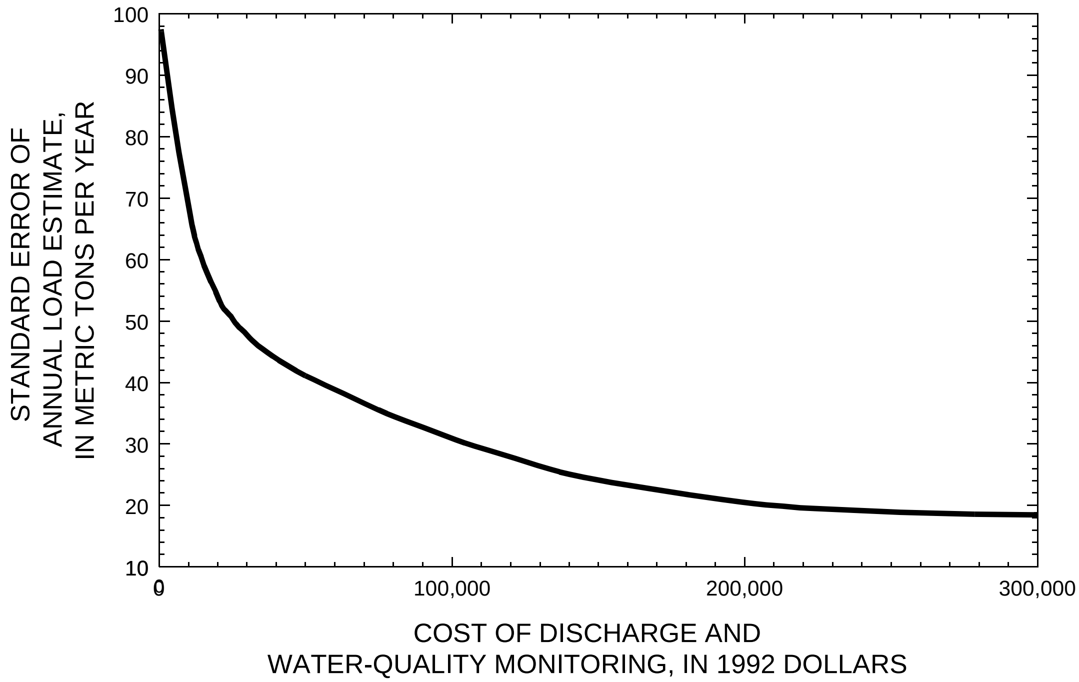

Figure 9. Uncertainty in annual load estimates as a function of increasing monitoring cost in 1992 dollars.

Total estimated uncertainty in annual absolute load estimates and monitoring cost determined by optimizing the network based on the values in table 6 is shown by the curve in figure 9. Where this curve intercepts the ordinate axis of the graph, monitoring cost is zero and baseline-network alternatives are the default for both discharge and concentration. At this intercept, overall error for an absolute load of 530 tons/yr is about 98 tons/yr or about 18 percent. As the iterative optimization routine proceeds to identify alternatives of greatest benefit for cost, alternative selections are reflected in increasing costs and decreasing errors. Decreases in error are most dramatic with the expenditure of the first $20,000 to $30,000 for alternative improvements. Most of the alternatives chosen for implementation in this range were increases in sampling frequency (C1 or C2). Error continues to decrease steadily with expenditures up to a cost of about $200,000 at which point the error curve appears to level off at about 20 tons/yr or about 4 percent of absolute load. Monitoring expenses from greater than $200,000 to $1,000,000 reduced load-estimate error only another 2 tons/yr to a minimum of 18 tons/yr.

The optimized set of network alternatives chosen for a cost level of about $200,000—where uncertainty levels off at 20 tons/yr—is given in figure 10. Only 17 of 48 inflow-monitoring sites around the lake are identified as contributing sufficiently to uncertainty in annual load estimates to warrant additional effort beyond the baseline network. Alternatives to baseline-discharge monitoring were indicated for 10 sites: 9 to be instrumented with acoustic velocity meters (Q2) and 1 to be improved by additional rating development (Q1). Alternatives to baseline sampling (twice per year) were identified as efficient improvements for all 17 sites: 11 to be instrumented with automatic samplers (C3), 5 to be sampled routinely by observers (C2), and 1 to be sampled 12 times per year (C1).

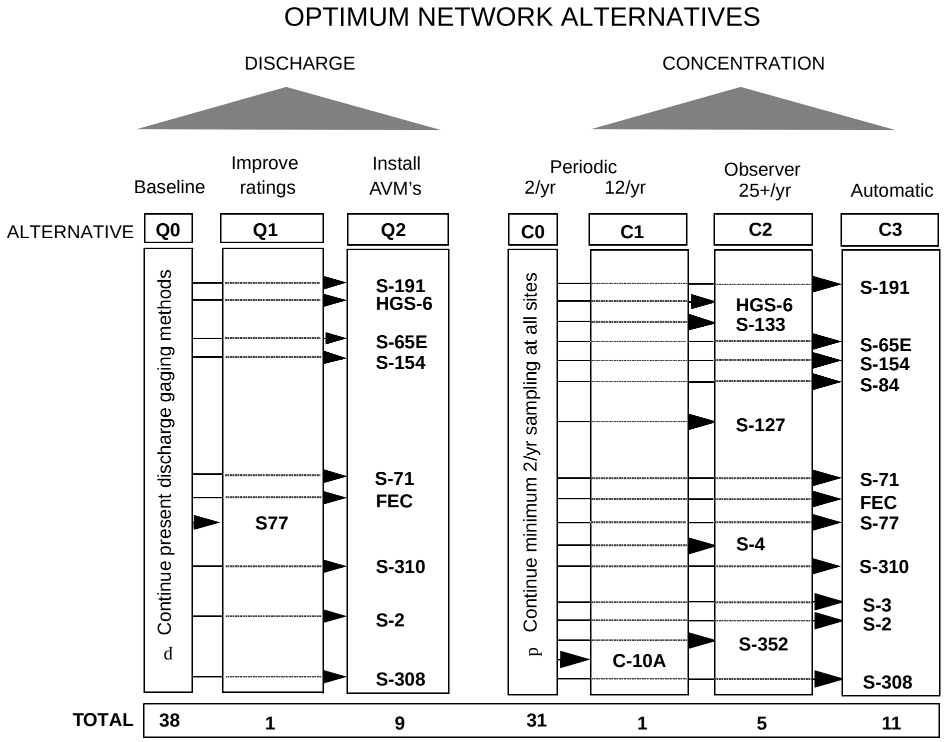

Figure 10. An optimized set of network changes decrease uncertainty in nutrient load estimates for Lake Okeechobee at a cost of $200,000 (1992 dollars).

SUMMARY AND CONCLUSIONS

A benefit-cost approach to monitoring phosphorus loads entering and leaving Lake Okeechobee at 48 discrete-discharge points was used to identify the most cost-effective means to improve load monitoring. Errors in load estimates were evaluated in terms of separate components of uncertainty associated with discharge and concentration. Uncertainty in discharge was estimated from the proven performance of various gaging methods used by the U.S. Geological Survey throughout Florida. Uncertainty in phosphorus-concentration time series was evaluated using phosphorus load models which were developed for principal tributaries to the lake based on a least-squares regression.

Partial errors in annual loading estimates were evaluated for each of two baseline conditions (one for discharge monitoring and one for concentration monitoring) and for five alternative monitoring options to reduce error. Marginal differences in error comparing each monitoring alternative were factored against cost to derive a benefit-cost ratio for each alternative at each site, and an iterative-selection routine was used to select the optimum set of monitoring alternatives for the 48 sites.

The selected set of network alternatives included changes to improve both concentration and discharge monitoring. These alternatives indicate the relative importance of monitoring at each of the various sites around the lake. Precision in annual load estimates for Lake Okeechobee was improved relatively little by effort above and beyond an additional $200,000 (1992 dollars) over and above the current discharge-gaging network and sampling at a continued frequency of twice per year. Likewise, the set of cost-optimized alternatives at an expense of $200,000 identified beneficial changes to the existing network at only 17 of the 48 sites around the lake.

One can infer from the limited selection in the optimized network that monitoring effort above the existing network is not of equal efficacy at all sites in a load-monitoring program and that monitoring effort should be tailored to reduce uncertainty where it is greatest. The remaining 32 unselected sites around the lake are of relatively little importance to the evaluation of loads and trends for the lake and probably can be estimated from adjacent sites with little loss of precision. Although this observation should not preclude monitoring at one or another of these sites for other scientific reasons, it does suggest that resources might be optimized by tailoring monitoring activities to the uncertainty in load estimates at each site.

The optimized monitoring network for Lake Okeechobee developed in this study is one realization of an almost infinite set of possibilities containing any number of other suites of monitoring alternatives. The particular monitoring alternatives chosen for optimization here were convenient options because they already exist in one way or another as part of an ongoing monitoring effort by the U.S. Geological Survey throughout Florida. However, the optimization approach presented here need not be limited to the specific alternative selected or to only discrete alternatives. The same approach might be adapted with only slight modification to evaluate the best distribution of samples among periodically sampled sites. It is also certain that the optimized network presented here is not fixed in time but will change and could benefit from continuous re-examination as additional information becomes available.

Optimization analysis was intended to provide a fairly simple tool to assess priorities for surface-water monitoring and so is limited in several important ways. First, it does not address atmospheric deposition which is thought to be a major source of phosphorus. This omission was principally because of difficulty in assessing error terms for atmospheric fluxes which are rarely measured without the near certainty of bias. Secondly, this approach ignores the covariance of discharge and concentration in the estimation of the standard error of concentration. Although this somewhat underestimates the overall load error, it probably does not have a large effect on the optimization results (relative error). This analysis makes no attempt to account for, or optimize on, spatial covariance. Until models are developed that utilize spatial covariance in the computation of load, there is no way to optimize data collection on that term. Finally, it is unlikely that substantial improvement can be made in load estimates by including spatial covariance in computational models. The bulk of uncertainty in total load estimates is already attributable to a relatively small set of streams. This analysis has shown that the temporal uncertainties on the larger contributing streams are sufficient to eliminate from consideration much of the spatial uncertainty between streams. It is likely that, had the tested monitoring alternatives not been discrete, this effect would have been even greater. Resolution of uncertainty on a few of the largest contributing streams would have demanded an even larger share of available resources and resulted in even less spatial definition.

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