Reprinted from the *Journal of Environmental Quality*
Vol. 22, no. 4, October-December 1993, Copyright © 1993, ASA, CSSA, SSSA
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Estimating Daily Nutrient Fluxes to a Large Piedmont Reservoir from Limited Tributary Data

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ABSTRACT

Physically based models of lakes require estimates of daily, spatially varied water and nutrient fluxes into the lake from surrounding watersheds. Often, however, only a selected set of streams are periodically (monthly or biweekly) sampled. The objective of this study was to develop and test a method for estimating daily flux of nutrients into a large reservoir using data from sampling of selected watersheds. Flow rate, nitrate (NO_3–N), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), and chemical oxygen demand (COD) were measured monthly during 1991 for eight watersheds that feed Lake Lanier in northern Georgia. Daily stream flow in the eight streams was correlated to data from nearby USGS gauged stream stations, and daily nutrient concentrations were related to watershed land use and monthly variation in measured concentrations. Fraction of agricultural land in the watershed (AG) was the only land use parameter that correlated to nonpoint-source loads. Coefficients of determination for linear regressions between AG and NO_3–N, TN, SRP, TP, and COD were 0.74, 0.73, 0.47, 0.84, and 0.52, respectively. The relationships were tested on an independent data set consisting of two samples from 19 additional streams. Coefficients of determination (r^2) between measured and predicted data for the independent test data was 0.77, 0.52, 0.66, 0.64, 0.69, and 0.76 for stream flow, NO_3–N, TN, SRP, TP, and COD, respectively. Percentages of nutrient loads attributable to nonpoint-source loads ranged between 76% for TN to 92% for TP and COD, whereas those attributable to agricultural nonpoint source were about 15% for COD, 28% for TN, 34% for NO_3–N, 40% for TP, and 70% for SRP.

PHYSICALLY BASED MODELS used for assessing water quality in lakes and reservoirs use mass-balance continuity equations for tracking water and dissolved constituents within and between lake segments. The USEPA Water Quality Analysis Simulation Program (WASP4; Ambrose et al., 1990) model was selected for modeling in-lake processes in Lake Lanier. The program requires estimates of daily flux of water and dissolved constituents into each lake segment from the surrounding land area. This study was undertaken to provide that information for the Lake Lanier–WASP4 application. Several methods exist for estimating daily fluxes of water and nutrients from watersheds based on periodic stream sampling (Reckhow et al., 1980). Also, several studies related annual export of nutrients to watershed characteristics such as land use, either through stream sampling (Hill, 1981; Dillon and Kirchner, 1975) or by using models (Walker et al., 1989).

For large reservoirs and lakes, particularly where nonpoint-source loads are major contributors to nutrient loading, periodic sampling of every stream that feeds the lake may not be possible. To apply a water quality model such as WASP in that case, reliable estimates of daily loads for all of the streams must be derived using the data from periodic sampling of a subset of the streams feeding the lake.

The objective of this study was to develop and test a method for estimating daily, spatially varied, nonpoint-source, and tributary nutrient loadings to Lake Lanier, located in the Piedmont area of northern Georgia, from the lower portion of the lake drainage basin for the year 1991. Information available for making these estimates included periodic sampling from selected watersheds, general land use information, and gauged stream data from nearby (but not in the study area) streams.

MATERIALS AND METHODS

Monthly flow and nutrient samples were taken from eight watersheds, ranging in size from approximately 320 to 5870 ha, to develop relationships for calculating daily loads. Samples were also taken in June and September from 19 additional streams to use for testing the method. The procedure involved relating measured water flux to nearby USGS gauged station data, calculating annual export coefficients for loads of nitrate (NO_3–N), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), and chemical oxygen demand (COD) from the eight monthly measured streams accounting for monthly variation in nutrient concentrations in the streams, and making an inventory and accounting for the effects of land use in the lower drainage basin. The resulting relationships were programmed into a spreadsheet to aid calculation of estimated daily fluxes of water and nutrients into each lake segment from all the surrounding land areas.

Study Area

Lake Lanier is an important flood control, recreational, and water supply lake in the Piedmont area of northern Georgia. The drainage basin of the lake is 269 500 ha, and the lake surface area is 15 600 ha. Lake Lanier is fed by the Chattahoochee River to the northeast and the Chestatee River to the north. The study area for this nonpoint-source assessment was 81 900 ha of land on the lower portion of the drainage basin, which drains directly into the lake below the entry points of the Chattahoochee and Chestatee rivers. Thus, the study area covered 30% of the total land area in the Lake Lanier basin.

Most of the Lake Lanier basin, including the entire nonpoint-source study area, is located in the Piedmont Geologic Province. A portion of the upper Lanier basin is located in the Blue Ridge Province. Valleys are V-shaped and relief is relatively steep, though less incised in the lower portion of the basin than in the upper end. The entire basin is underlain by metamorphosed, acid-crystalline rocks. Soils are derived from crystalline material and tend to have a thin loamy topsoil ranging in thickness from an average of 11.4 cm for the eroded soils to an average of 16.5 cm for the less eroded material (USDA, 1989).

Land use in the lower basin area is approximately 63% forest, 23% pasture, 13% residential and urban, and 1% cropland. Prior to about 1840, the entire Chestatee and upper Chatta-

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Published in J. Environ. Qual. 22:666–671 (1993).

Abbreviations: TN, total nitrogen; SRP, soluble-reactive phosphorus; TP, total phosphorus; COD, chemical oxygen demand; AG, fraction of agricultural land; WASP4, USEPA Water Quality Analysis Simulation Program; USGS, U.S. Geological Survey.

hoochee River basins were forested. Cotton (*Gossypium hirsutum* L.) production from 1840 until around 1940 caused severe erosion of much of the upland soils. Cotton is no longer grown in the area, and much of the land has been converted to forest and pasture. The cropland that remains in the lower Lanier basin is located northeast and across the lake from the city of Gainesville, GA. The predominant cropping system is conservation tilled corn (*Zea mays* L.) or sorghum [*Sorghum bicolor* (L.) Moench] with a winter cover of small grain. The pasture land supports primarily cattle, but is used extensively for disposal of dry litter from poultry production. The Lake Lanier basin in 1982 contained a total of approximately 75 million poultry (USDA, 1989).

There are two major land-application systems for wastewater in the lower Lanier basin. One, located in the 930-ha Squirrel Creek watershed, is owned and operated by a poultry processing plant. The second, located in the Six Mile Creek watershed, is owned and operated by a rendering plant.

Flat Creek has historically been a major source of pollutants to Lake Lanier. The waste water treatment plant for the city of Gainesville, GA, is located on Flat Creek. Though the wastewater plant has been upgraded and the effluent quality improved, Flat Creek remains the tributary with the largest measured pollutant concentrations for the lake. Since the influence of the point source was so predominant, none of the Flat Creek data were used in the nonpoint-source analysis herein, though the stream was sampled and loadings were calculated for comparison to the nonpoint-source loads.

Sampling Program

Stream flow and water samples were obtained from eight stations on a monthly basis and from 19 test data sections in June and September. The eight monthly stations were selected because the watersheds above those stations have land use that is representative of the lower Lanier basin. Flat Creek was selected because it is the principal point source in the area. Balus and Six-Mile creeks were chosen because they contained wastewater spray application facilities.

The 27 measured streams in this study were all of the perennial streams on the lower Lanier basin that could be measured. They drain a combined land area of 41 300 ha, which is 50% of the total lower basin area. Of the other 50% of the area, 6350 ha were drained by two perennial streams that could not be accessed. The remainder of the lower basin area drained directly into the lake, either through subsurface flow or storm water runoff.

Each sampling station was located as near as possible to the outlet of the respective watershed to the lake. Measurements were taken of stream flow rate, NO_3–N, TN, SRP, TP, and COD. Data from Squirrel Creek for the month of July, data from the Flat Creek, and N data from Six Mile Creek were not used in developing the nonpoint-source loading functions. Reasons for excluding those data are discussed below.

Stream flow rate was measured on-site using a modified USGS midsection method (USDI, 1974). Chemical oxygen demand was measured using a twist-tube spectrophotometric method (Bioscience Management, 1986). A low-level titrimetric method (EPA Method 410.2, USEPA, 1983) was also used on selected samples to verify the spectrophotometric results.

Total P and SRP were measured following sample preparation methods outlined in *Standard Methods of Water and Wastewater* (Method 4500-P B, Clesceri et al., 1989). Soluble-reactive P was measured following filtration to remove particulates. Total P was determined following persulfate digestion of the unfiltered sample. After preparation, both TP and SRP were measured using an automated ascorbic acid colorimetric method (Method 4500-P, E, Clesceri et al., 1989).

Nitrate-N was measured using an automated cadium reduction method (Method 4500-NO_3^- F, Clesceri et al., 1989). Total N was measured following the method of Korleff (1983), using persulfate digestion to oxidize the N to NO_3^-, followed by automated cadium reduction (Method 4500-NO_3^- F, Clesceri et al., 1989).

ESTIMATING DAILY STREAM FLOW

Daily stream flow data were obtained from the U.S. Geological Survey (USGS) for gauged stations on the Chattahoochee River near Cornelia, GA, on the Chestatee River near Dahlonega, GA, on the North Oconee River near Arcade, GA, and on the Suwanee Creek near Suwanee, GA. These four stations are located east, north, south, and west of the study area, respectively. No gauged USGS or other daily stream flow data collected within the study area are available. A mathematical relationship was developed between the measured flow in the monthly sampling stations and the data from the USGS gauged stations. This relationship was then tested with the data from the 19 test data stations, which represented an independent data set.

The best overall relationship between the measured flow rates and the gauged stream data was of the form

$$q_d = aq_n^b \qquad [1]$$

where q_d (m^3) is the daily flow in the stream of interest, and a (m^3) and b are regression coefficients; q_n (unitless) is the average of the normalized flows in the four gauged stations: a value of q_n equal to 1.0 would be calculated if flow in all four gauges was the average value for the year at each station. Regression coefficients were obtained using linear regression between log q_d and log q_n. Equation [1] gave satisfactory results for five of the eight streams, for which the regression coefficients were different from zero at the 99% probability level. Equation [1] gave a poor fit with flow for streams draining the urban or suburban watersheds such as Limestone, Balus, or Flat Creek.

Flat Creek has a waste treatment plant on it that influences the flow rates in the stream. Limestone Creek has a relatively large reservoir located on it, which may be influencing the relationship between the gauged data and the measured data from the study. For the calculations of export coefficients on the Limestone Creek and Balus Creek, the average of the measured stream flows was used. Flat Creek, as discussed above, was not used in the nonpoint-source calculations.

Regression coefficients a and b were calculated to fit Eq. [1] for the five streams that followed the relationship. The coefficient a increased linearly ($r^2 = 0.99$) with the size of the watershed and the power coefficient; b decreased ($r^2 = 0.87$) as the size of the watershed increased (Fig. 1). Thus, it was possible to apply Eq. [1] to the other watersheds in the lower drainage basin area to estimate daily stream flows for the 1991 year. Figure 2 shows all the measured stream flow data vs. the daily flow predicted from the gauged data using the Eq. [1] and estimated values for a and b. Figure 3 shows the data for 19 test data stations from both sample times that were not used in developing the predictive equation or coefficients ($n = 32$; four flow measurements were not taken because flow was too small to measure in those streams on the sample day). The model explained 77% of the variance for those daily data.

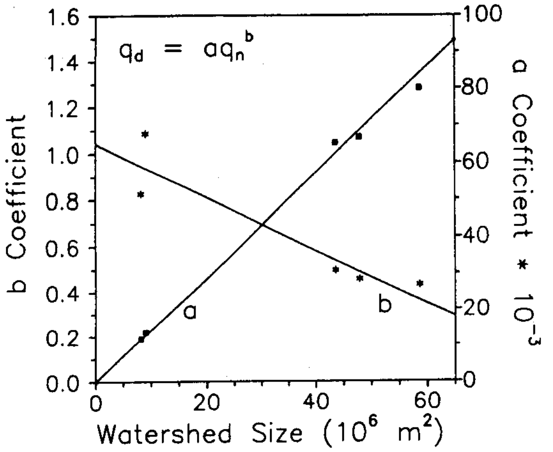

Fig. 1. Coefficients for computing daily stream flows from the gauged data as a function of watershed size.

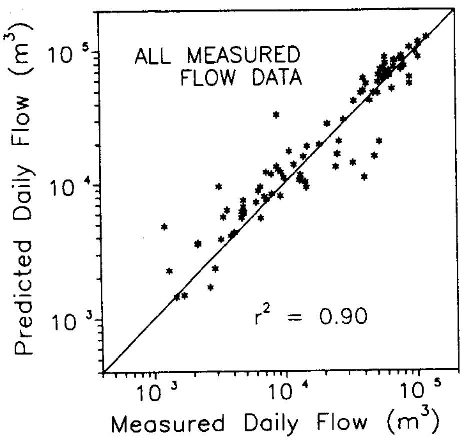

Fig. 2. Predicted vs. measured daily stream flow for the complete data set (n = 92).

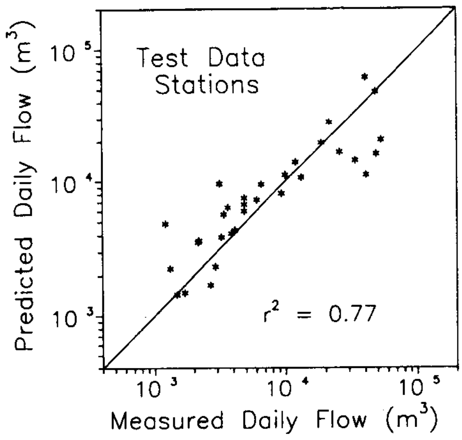

Fig. 3. Predicted vs. measured daily stream flow for the test data stations (n = 32).

Table 1. Export coefficients computed for the monthly sampled stations.

Stream	NO_3-N	Total N	SRP	Total P	COD
	kg ha^{-1} yr^{-1}				
W. Little	7.02	10.45	0.296	0.579	51.5
E. Little	5.41	7.77	0.144	0.460	45.3
Wahoo	3.81	5.80	0.098	0.370	49.6
Squirrel	6.05	8.43	0.124	0.383	50.8
Six Mile	34.26	35.70	0.049	0.388	41.2
Limestone	2.26	3.58	0.012	0.168	35.4
Flat	36.94	103.84	0.745	1.410	176.9
Balus	3.21	5.17	0.027	0.222	31.0

Table 2. Land use in the watersheds of the monthly sampled stations.

Stream	Forest	Pasture	Resid.	Crop	Urban	Total
	ha					
W. Little	2504	1897	137	246	0	4785
E. Little	2136	1640	281	287	0	4345
Wahoo	4096	1383	223	157	0	5860
Squirrel	507	213	95	7	0	823
Six Mile	491	381	18	0	0	891
Limestone	183	0	608	0	79	869
Flat	249	0	1123	0	254	1626
Balus	519	0	1134	0	0	1653

Table 3. Relationships used for estimating annual export coefficients for nutrients entering Lake Lanier during 1991 as a function of fraction of agricultural land in the drainage area.†

Nutrient	Equation¶	r^2	n
NO_3-N	NO_3 = 2.76 + 7.777 (AG)	0.74*	6
TN	TN = 4.35 + 10.494 (AG)	0.73*	6
SRP	SRP = 0.0182 + 0.333 (AG)	0.47**	7
TP	TP = 0.196 + 0.640 (AG)	0.84*	7
COD	COD = 35.57 + 29.95 (AG)	0.52**	7

*, ** Regression coefficients significantly different from zero at the 0.05 and 0.01% probability levels, respectively.

† All values in (kg ha^{-1} yr^{-1}).

¶ AG = Fraction of agricultural land.

ESTIMATING NUTRIENT EXPORT COEFFICIENTS BY LAND USE

Annual watershed export coefficients (mass per unit area per year) were calculated for NO_3–N, TN, SRP, TP, and COD using data from each of the eight monthly sampled stations. Computations were performed by multiplying estimated daily flows from the watersheds by the measured concentrations for each month to obtain daily loads (mass per day) from each of the eight sampled watersheds (for Squirrel Creek, the July concentrations were assumed to be the average of that from June and August). The sum of the daily loads for the year was the annual load. This sum divided by the land area in the watershed above the sample station gave an estimate of the export coefficient for each stream for the year 1991 (Table 1).

The next step in estimating daily fluxes was to relate the export coefficient to land use above the data collection location in the monthly sampled watersheds. Land use was estimated from aerial photos and recent topographic maps of the area. Areas were classified as forest, pasture, residential, urban, cropland, or water (Table 2). Analysis of variance and multiple linear regression methods were used to evaluate relationships between nutrient export coefficients and land use in the monthly sampled watersheds (exceptions previously mentioned).

A definitive picture of all of the effects of land use on export coefficients was not obtainable from the data. It was impossible to assign a distinct value for the export coefficient for each type of land use. The data show, however, a correlation ($P < 0.10$) between export coefficients and total agricultural land area in the sampled watersheds (the sum of both cropland and pasture). The equations that best related nutrient export coefficients and land use are linear functions of the fraction of agricultural land in the watershed (Table 3). The constants of the equations match relatively well with the export coefficient values for sampled watersheds without appreciable agricultural land.

Although total percentage of agricultural land is related to nutrient loads, other factors may contribute to nutrient load levels in the Lake Lanier watersheds. In addition to the analysis of land use vs. export coefficients, correlations between land use and nutrient concentration data from all 27 measured watersheds for the months of June and September were also investigated. This analysis showed a correlation ($P < 0.10$) between percentage of cropland and NO_3–N, TN, and TP concentrations for the data, but no correlation between pasture land and concentrations. Two months of nutrient concentration data are insufficient to draw conclusions regarding annual export coefficients, but the correlations do suggest that more work and, specifically, a broader data set are needed to quantitatively delineate between pasture and cropland as nutrient nonpoint sources within the Lake Lanier basin. Nonetheless, the data are clear in the case of both export coefficients and June and September's concentrations: agricultural activity was related to nutrient loads for the Lake Lanier basin ($P < 0.10$).

Reckhow et al. (1980) published a list of nutrient export coefficients taken from the literature from a variety of sources. Values listed for forested watersheds of pine (*Pinus* spp.) or mixed pine and hardwood from the eastern USA had TP export coefficients that ranged from 0.20 to 0.36 kg ha^{-1} yr^{-1}. Values listed for mixed agricultural watersheds ranged from 0.1 to 5.4 kg ha^{-1} yr^{-1}, with 80% of the values between 0.26 and 1.53 kg ha^{-1} yr^{-1}. Using the equations in Table 3, values from the lower Lanier basin range from about 0.2 kg ha^{-1} yr^{-1} for completely forested areas to approximately 0.5 kg ha^{-1} yr^{-1} for watersheds with 50% agricultural use. Thus, the export coefficients established from this study fall well within the range of previously published results and tend toward the lower part of that range.

ESTIMATING DAILY NUTRIENT AND CHEMICAL OXYGEN DEMAND LOADS

Three factors were used to estimate the daily loads to Lake Lanier from the watersheds in the lower drainage basin: the annual export coefficients, K; the estimated daily flows into the lake, q_d; and the average monthly variation in concentrations of the nutrients. Consideration of monthly variations was particularly important for SRP and COD, which showed much greater concentrations in December and January. Monthly concentrations were represented in a normalized form in Table 4. These values were calculated using the data from the monthly sampled stations. A value of 1.00 represents the average concentration for the year, values greater than 1.00 indicate concentrations in that month exceed average, and values less than 1.00 indicate concentrations in that month are less than the yearly average. Note that Table 4 does not indicate that SRP concentrations were sometimes greater than those for TP, it only indicates that the ratio of monthly to average annual SRP concentrations were sometimes greater than the same ratio for TP.

Table 4. 1991 Lake Lanier normalized monthly nutrient concentrations. Values represent the ratio of monthly concentrations to average annual concentrations for each constituent.

Month	NO_3-N	TN	SRP	TP	COD
January	1.15†	1.38	3.41	1.46	2.19
February	1.23	1.08	1.22	0.38	0.63
March	1.06	1.03	0.72	0.47	0.75
April	0.96	0.88	1.00	1.12	0.53
May	0.98	0.84	0.36	1.40	0.77
June	1.03	1.04	0.49	1.58	0.83
July	0.96	1.03	0.74	1.57	1.07
August	0.79	1.02	0.57	1.46	0.35
September	0.82	1.11	0.48	1.57	0.30
October	0.93	0.72	0.22	0.17	0.42
November	1.02	0.83	0.31	0.11	0.90
December	1.06	1.04	2.48	0.70	3.27

† A value of 1.00 represents the average annual concentration for the corresponding nutrient.

Given the annual export coefficient and daily flows from a source area and the normalized monthly concentrations in Table 4, the yearly average concentration of each nutrient for each source area, c_y (g m^{-3}) may be calculated as

$$c_y = L/\sum(N_i q_i) \qquad [2]$$

where N_i is the normalized (nondimensional) value for month i from Table 4, q_i (m^3) is the monthly flow calculated as the sum of the daily flows using Eq. [1], and L (g) is the annual export of nutrient calculated using the export coefficient for the source area (Table 3).

Given the average concentration for a source area, daily loads are calculated as

$$y_d = c_y N_i q_d \qquad [3]$$

where y_d (g) is the daily yield of a particular nutrient from a source area.

The above method of estimating daily loads from source areas was tested on the test station data from the other 19 watersheds sampled. These data were independent from the data used in developing the prediction relationships . Figures 4, 5, 6, 7, and 8 show the measured vs. predicted daily loads from the test data stations for NO_3–N, TN, SRP, TP, and COD, respectively.

Daily nutrient loads were estimated for the entire lower drainage basin for Lake Lanier using the relationships described above and land use data for each land area. The basin area was divided into 77 contributing areas, based on the segmentation scheme for the lake model, and land use in each area was identified.

DISCUSSION

This method of calculating daily loads from watersheds surrounding Lake Lanier does not attempt to

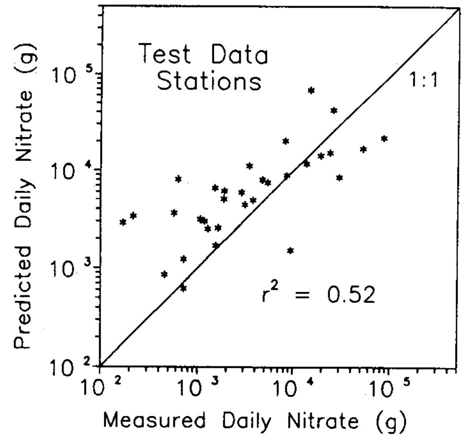

Fig. 4. Predicted vs. measured daily NO_3^- flux for the test data stations (n = 32).

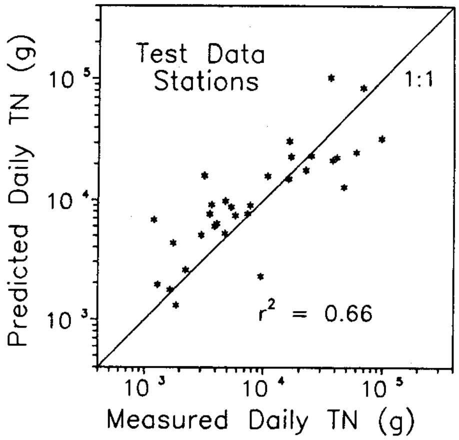

Fig. 5. Predicted vs. measured daily total N flux for the test data stations (n = 32).

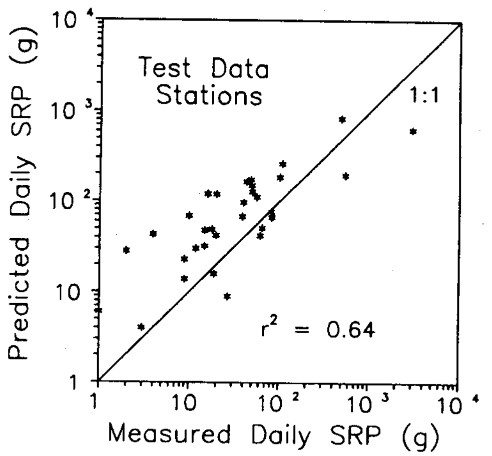

Fig. 6. Predicted vs. measured daily soluble reactive P flux for the test data stations (n = 32).

differentiate between base flow loads and event loads. These watersheds contain principally forest and pasture land, and respond relatively slowly to storm events. Surface runoff is rare. Also, the data show no correlation between flow rates and concentrations of N or P.

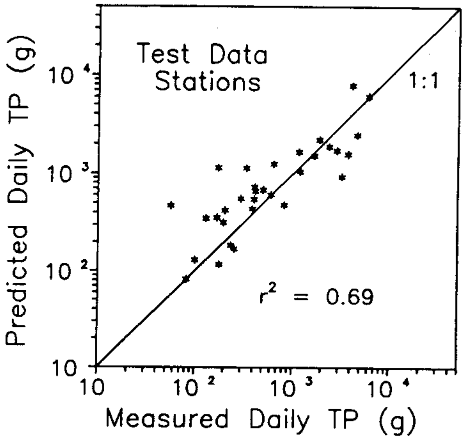

Fig. 7. Predicted vs. measured daily total P for the test data stations (n = 32).

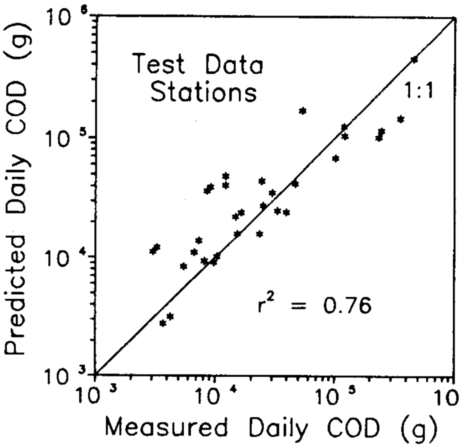

Fig. 8. Predicted vs. measured daily COD flux for the test data stations (n = 32).

Flow rates, concentrations of COD, and suspended solids concentrations were extremely high for Squirrel Creek in July. Flow in the creek for the size of the watershed was too great to be accounted for by natural hydrologic processes. The COD concentrations approached that of raw or somewhat diluted sewage water. In addition, the creek had a very strong odor of raw sewage on the July sampling date. Given documented problems with the waste treatment facility in the Squirrel Creek watershed, including discharge of partially treated or raw sewage directly into Squirrel Creek, it was considered likely that the system was failing that day and acting essentially as a point source. Thus, this data point was eliminated from the analysis of nonpoint sources.

Nitrogen concentrations from Six Mile Creek were greater ($P < 0.01$) than those for the other streams (except for Flat Creek). Most of the N from Six Mile Creek was in the soluble and very mobile form of NO_3–N. It was suspected that the spray application facility mentioned previously may have been the source of the higher N levels at Six Mile Creek, and thus those data were omitted in developing the predictive equations for other watersheds. At no time did a measured NO_3–N or TN levels in Six Mile Creek exceed 10 mg L^{-1}.

The estimated loadings from the entire lower Lanier

Table 5. Estimated nutrient loads from surface waters in the Lake Lanier study area.

Nutrient	Estimated loading 1991	Flat Creek	Total nonpoint source	Agricultural nonpoint source	Background nonpoint source
	Mg			%	
NO_3-N	440 ± 215†	14	86	34	51
TN	737 ± 301	24	76	28	48
SRP	9 ± 14	14	86	70	16
TP	31 ± 12	8	92	40	52
COD	3797 ± 1194	8	92	15	77

† Range about the mean calculated using the 95% confidence interval for the slope of the linear regression equations in Table 3. Percentages by source reflect only mean values of predictions.

drainage basin are presented in Table 5. The confidence range on the estimated loadings is based on the 90% confidence range for the coefficients in the regression equation between land use and export coefficients. In general, nonpoint source loads account for 80 to 90% of the total loadings of nutrients to the lake. The point source at the Flat Creek is significant, however, since it is the only major nutrient point source in the lower drainage basin. For NO_3–N, TN, and TP, natural (nonagricultural) nonpoint sources account for approximately half of the total load to the lake. For COD they account for about three-quarters of the total. The results suggest that agriculture is contributing a greater proportion of SRP than other sources; however, the low confidence in the overall SRP loading estimate precludes making definitive statements about SRP sources. Agricultural nonpoint sources account for approximately 40% of the TP loads.

The TN/TP ratio estimated from this data is greater than 20. This indicates a strong P-limiting situation for algal growth in Lake Lanier. Using the overall SRP and TP loads to the lake and the estimated water inflow, average overall concentrations of incoming SRP and TP was approximated at 0.02 and 0.07 g m^{-3}, respectively. These P loadings are somewhat high, but high sedimentation rates in the lake embayments may be maintaining low P levels in the main body of the lake which thus reduces the potential for excessive algal growth. Raschke et al. (1985) found that sedimentation rates of TP in Lake Hartwell, a Piedmont lake very similar to Lake Lanier, were responsible for a greater loss of TP and subsequent reduction in eutrophication potential than was expected from experience in other lakes. More work is needed in Lake Lanier to establish P sedimentation rates in embayments.

The results indicate three potential areas of concern in terms of tributary loads to Lake Lanier in the lower drainage basin: Flat Creek, the land application system on Squirrel Creek, and agricultural nonpoint sources. The Flat Creek sewage plant continues to contribute an inordinate amount of pollutants to Lake Lanier (Table 5). The intermittent problem of partly treated sewage release on the Squirrel Creek should be addressed. It would be possible to accurately quantify this problem only if a continuous monitoring station were placed on Squirrel Creek. However, the data from July of 1991 indicate that a problem exists on Squirrel Creek.

Elimination of agricultural nonpoint-source pollution would reduce P loads to Lake Lanier. Before remedial measures are taken with regard to agriculture, further work is needed to delineate agricultural sources of the P. Export coefficients for pasture and cropland need to be delineated.

Another significant finding of this research is that COD loads are apparently due to natural nonpoint-source loads. Our data do not indicate that alteration of land use wold greatly affect oxygen demanding loads to Lake Lanier.

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