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WATERSHED LAND USES AND PHOSPHORUS EXPORT COEFFICIENT RELATIONSHIPS: A PLANNING TOOL FOR LAKE RESOURCES MANAGEMENT

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ABSTRACT

Relationships between nonpoint source pollutant loadings and water quality degradation in lakes have been established. However, practical methodologies necessary to identify and manage nonpoint sources in accordance with lake water quality indices have been lacking. Objectives of the current study were as follows: (1) to compare predicted model values for in-lake total phosphorus (TP) concentrations with actual values; and (2) to determine the applicability of areal phosphorus loading models for lake resources management. The research site was located 19 km west of the City of Little Rock in the Lake Maumelle basin. Areal total phosphorus (TP) loadings in g $m^{-2}yr^{-1}$ were calculated for existing and projected watershed land uses for the period of 1985 to 2005. Model predictions for in-lake TP concentrations yielded .0204 mg 1^{-1} and .0223 mg 1^{-1} for the years 1985 and 2005, respectively. An average summertime TP value of .0280 mg 1^{-1} was measured in Lake Maumelle. The predicted TP value was not significantly different from the measured TP value. This model offers a practical planning approach for managing lake resources when phosphorus limited conditions are present.

INTRODUCTION

The role of nonpoint source pollutants in relationship to surface water degradation has been clearly established (Overcash and Davidson, 1984; Wilken and Jackson, 1983-84; Swank, 1984; USEPA, 1984). Research concerning impacts of nonpoint source pollutants on lake resources can be categorized: (1) research focusing on trophic status measurement and related lake indices; (2) in-lake water quality modeling techniques; (3) areal phosphorus loading methodologies for predicting water quality trends.

Carlson's (1977) trophic state index provided a methodology for comparing lake water quality using three parameters: secchi disc reading, total phosphorus and chlorophyll *a* concentration. This approach was employed in several related lake research studies (Junes and Bachman, 1976; Oglesby and Schoffner, 1978; Aika, et al., 1980; Smith and Shapiro, 1981; Smith, 1983). The modeling of in-lake water quality parameters presents an additional category of lake resources research. Higgin and Kim (1981) developed phosphorus retention models for Tennessee Valley Authority reservoirs. These models were not designed to operate interactively with watershed input models. A final category of lake resource research includes areal phosphorus loading models which combine in-lake water quality with watershed factors (Logan, 1980; Hill, 1981; Davis and Swartz, 1983; Lehman and Edmondson, 1983; Reckhow and Chapra, 1983).

Lake resource managers face a difficult task in selecting an appropriate planning strategy. A need exists for a practical methodology to identify and manage nonpoint sources in accordance with lake water quality indices. This paper reports a study designed: (1) to compare predicted model values for in-lake total phosphorus concentrations with actual values; and (2) to determine the applicability of areal phosphorus loading models (Reckhow and Chapra, 1983) for lake resources management.

STUDY SITE DESCRIPTION

The research site is located 19 km west of the City of Little Rock in the Lake Maumelle basin (Figure 1). Primary inflow to Lake Maumelle is provided by the Big Maumelle River. A total watershed area of 31,900 ha drains into the lake. Forestland represented 85.5 percent of total land use within the watershed. Silvicultural activities are commonplace with 43 percent of forested areas owned by private timber companies. An additional 21 percent of forestland, located in the western end of the watershed is owned by the U.S. Forest Service. Private land ownership and land owned by the City of Little Rock represents 19 percent and seven percent of the total watershed area, respectively. Agricultural land use represents 2.9 percent which consists of cultivated, non-cultivated and livestock production categories. Residential and related urban land uses account for 1.4 percent of the Lake Maumelle watershed. Demographic data indicates an estimated increase of 756 residents in the watershed between the years of 1985 to 2005. Based on these population estimates, land use changes were projected for the Lake Maumelle watershed (Table 1).

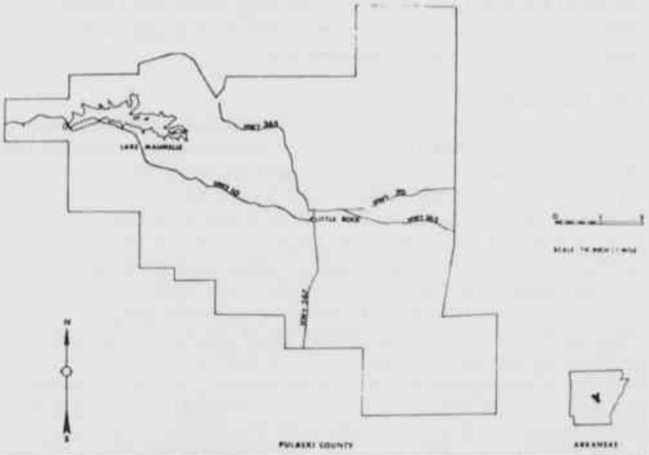

Figure 1. Location map for the Lake Maumelle basin, Pulaski County, Arkansas.

Four major sub-watersheds (SW) and associated tributaries were delineated for the Lake Maumelle basin (Figure 2). The Lower Maumelle (SW3) contained approximately 22,705 ha with 95 percent of this land area forested. Severe to moderate development limitations were identified in SW3 due to soils and slope conditions. These development

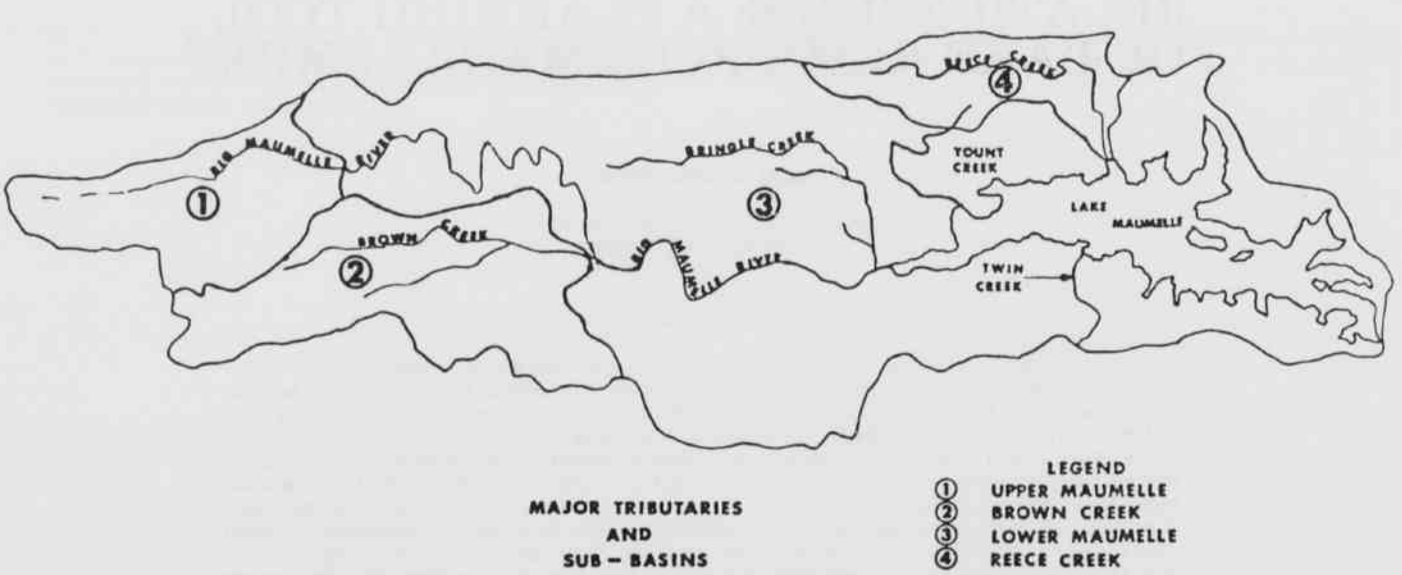

Figure 2. Lake Maumelle watershed with delineation of major sub-watersheds and tributaries.

limitations were apparent throughout the total watershed. The remaining sub-watersheds included the upper Maumelle (SW1), Brown Creek (SW2), and Reece Creek (SW4) with 9.9 percent, 13 percent and six percent of the total Lake Maumelle watershed, respectively. Reece Creek (SW4) contains the highest degree of urban development with 1.6 percent of its area devoted to this land use.

Lake Maumelle

Lake Maumelle (Figure 3) exhibits characteristics associated with a warm monomictic lake (Wetzel, 1983). Stratification occurred in the summer with a fall turnover and free circulation during the winter. Water depths in Lake Maumelle varied from 2.5 m in the western end to 13.7 m near the center of the lake. The maximum length of Lake Maumelle is 19 km with 114 km of shoreline. The ratio of the lake watershed area to lake surface area is 9:1. Hydrologic budget calculations revealed an average annual runoff inflow of 124,300 ac-ft (174.8 cfs) with an annual water loss of 33,304 ac-ft attributed to evaporation and water supply demands (Forest and Cotton, 1972). Based on these calculations, an annual flushing rate between 25.2 cfs and 104.2 cfs was determined. Selection of the appropriate rate was dependent on seasonal occurrences of spillway overflows. Table 2 contains a summary of morphometric and hydrologic characteristics for Lake Maumelle.

The area of Lake Maumelle west of the Highway 10 bridge (Figure 3) is relatively shallow (2.5 m) and exhibits high turbidity. An average secchi disc value of .96 m was recorded at this location during a 12-month observation period. During storms the Highway 10 bridge outlet tended to function as a weir. Inflow velocities from the Big Maumelle River were reduced with significant deposition of sediments occurring. Water quality in the remainder of Lake Maumelle has benefited from these hydraulic characteristics. However, this area was highly nutrient enriched with emergent vegetation evident near its shoreline.

Due to pre-reservoir characteristics of the Big Maumelle River channel, greater average depths were observed in the south-central areas of Lake Maumelle. The north shore areas tended to have more shallows with the exception of isolated coves.

METHODS

Data collection and analytical methods were divided into two sections: (1) sampling and analyses related to Lake Maumelle; and (2) development of areal phosphorus loadings and prediction of in-lake total phosphorus values.

Table 1. Existing and projected land uses in hectares for the period of 1985 to 2005, Lake Maumelle Basin, Pulaski County, Arkansas.

CATEGORIES	1985	1990	1995	2000	2005
AGRICULTURE	1,015.8	1,076.5	1,137.3	1,198.0	1,258.7
FOREST	30,323.1	30,208.5	30,085.0	29,993.5	29,815.0
URBAN	510.5	564.4	627.1	657.9	775.3
WATER	3,658.3	3,658.3	3,658.3	3,658.3	3,658.3
TOTALS	35,507.7	35,507.7	35,507.7	35,507.7	35,507.7

Sampling Site Selection

Six sampling sites were located on Lake Maumelle to assess current water quality conditions (Figure 3). Sampling site one was selected due to the isolated nature of this area from the main body of Lake Maumelle. Sampling site three provided an assessment of conditions for a typical cove. The remaining sampling sites were purposively located to assess conditions in the main body of the lake. Sampling sites two, five and six were located near the old Big Maumelle River channel.

Vertical discrete sampling was conducted at each sampling site from March, 1982, through February, 1983. Biweekly samples were collected during the summer (June-August) with monthly sampling for the remainder of the year. In-situ determination of dissolved oxygen, conductivity, and temperature was accomplished with a Hydrolab[1] unit. Discrete sampling was performed in accordance with the U.S. EPA lake sampling protocol. Sampling instrumentation included a Kemmerer bottle for discrete chemical and physical sample collection and a secchi disc for transparency measurement. Analyses of the Lake Maumelle samples were conducted at the University of Arkansas at Little Rock, Department of Biology. A quality assurance project plan approved by the U.S. EPA established the guidelines for analytical methods.

Trophic status determination for Lake Maumelle was accomplished in accordance with Carlson (1977). Input parameters included biweekly summer (June-August) sampling results for secchi disc readings, chlorophyll *a* concentration and total phosphorus. Total phosphorus input values represented an average of vertical discrete[2] sample analyses for each sampling site and a total lake average representing all six sampling sites. Secchi disc and chlorophyll *a* values were determined by averag-

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[1] Manufactured by the Hydrolab Corp., Austin, Texas.

[2] Total phosphorus samples collected at .5 m beneath the surface, each additional 1.5 m in depth and .5 m above the lake bottom.

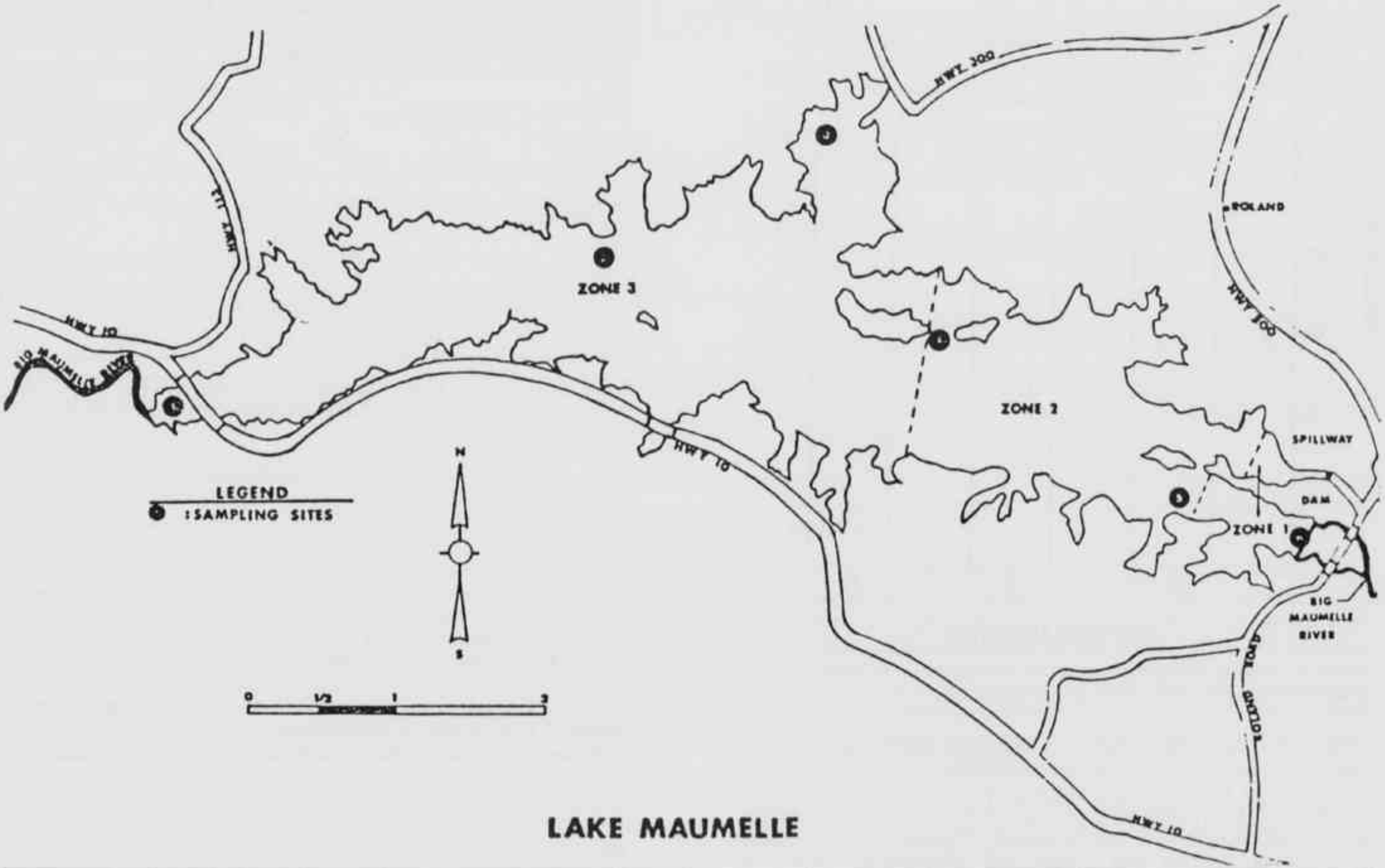

Figure 3. Map of Lake Maumelle, Arkansas, with sampling site locations.

ing results for the six sampling sites. Chlorophyll *a* samples were collected in the epilimnion .5 m beneath the surface. Analytical results for chlorophyll *a* were corrected for the presence of phaeophytin *a*.

Carlson's (1977) methodology required the calculation of indices for total phosphorus (TP), secchi disc depth (SD) and chlorophyll *a* (CHLA). Equations required for calculation of the trophic state index (TSI) are listed below:

Secchi Disc TSI (TSISD) = 60-14.41 ln(SD)
Chlorophyll *a* TSI (TSIC) = 9.81 ln (Chl *a*) + 30.6
Total Phosphorus TSI (TSITP) = 14.42 ln (TP) + 4.15
where: SD = secchi disc transparency in meters
Chl *a* = chlorophyll *a* concentration in ug l^{-1}
TP = total phosphorus concentration in ug l^{-1}

Lake Phosphorus Loading and Response

Based on methods developed by Reckhow and Chapra (1983), a relationship was established between total phosphorus inputs and predicted values for total phosphorus concentrations in Lake Maumelle. Watershed land uses provided the total phosphorus loading data which was a function of selected phosphorus export coefficients. The following steps (Reckhow and Chapra, 1983) were used to calculate phosphorus loading and lake response parameters: (1) determination of areal water loadings (q_s); (2) calculation of areal phosphorus loading (L); and (3) determination of predicted lake phosphorus concentrations.

RESULTS AND DISCUSSION

Trophic Status Determination

An analysis of existing water quality in Lake Maumelle yielded an average total phosphorus concentration of .028 mg l^{-1} (Figure 4). This value represents an average of vertical discrete analyses for each sampling site and an overall average consisting of all six sampling sites. The decision to use averages for vertical discrete total phosphorus was based on data of Reckhow and Chapra (1983) which indicated a greater potential for error when using only samples collected from the epilimnion. Secchi disc depth averaged 2.5m with chlorophyll *a* averaging 6.05 mg l^{-1}. Total phosphorus, secchi disc. and chlorophyll *a* values were derived from biweekly summer (June-August) samples. Summer measures were selected to coincide with the growing season and fulfill model input data requirements of Carlson (1977) and Reckhow and Chapra (1983).

Table 2. Summary of Morphometric and hydrologic characteristics for Lake Maumelle, Pulaski County, Arkansas.

PARAMETER	MEASUREMENTS
SURFACE AREA	3,603 HA
MAXIMUM DEPTH	13.72 M
AVERAGE DEPTH	7.53 M
VOLUME	27.07 x 10^7--M^3
HYDRAULIC RESIDENCE TIME	628 DAYS
AREA OF WATERSHED	354.8 KM^2

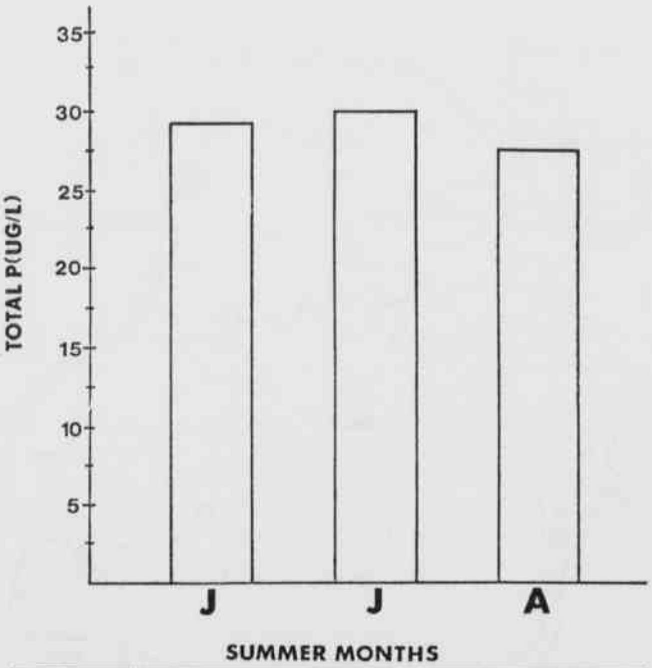

Figure 4. Average total phosphorus concentrations for all sampling sites combined, June-August, 1983, Lake Maumelle, Arkansas.

Using the values presented above, trophic state indices (Carlson, 1977) were calculated for Lake Maumelle. Index values of 46.8, 48.3 and 52.2 were obtained for secchi disc, chlorophyll *a*, and total phosphorus, respectively. An average trophic state index value of 49.1 indicated mesotrophic conditions in Lake Maumelle. Comparative index values presented by Carlson (1977) were 45.0 (mesotrophic) and 53.0 (eutrophic). However, the total phosphorus index value (52.2) was very close to a eutrophic level. For a 12-month observation period, the ratio of total nitrogen (TN) to total phosphorus (TP) was 19:1. This ratio indicates that Lake Maumelle was phosphorus limited. Based on this value, it is apparent that phosphorus loading is critical for maintaining water quality in Lake Maumelle.

Phosphorus Loading and Lake Response

Calculation of areal phosphorus loadings required application of phosphorus export coefficients to land uses in the Lake Maumelle watershed. High, most likely and low phosphorus export coefficients (Table 3) were selected from values presented in Reckhow and Chapra (1983). These coefficients were used to calculate mass phosphorus loadings for the Lake Maumelle basin (Table 4). Based on these loadings, a phosphorus budget was developed for Lake Maumelle. Total phosphorus inputs for 1985 of 10,696.5 kg yr^{-1} were compared to phosphorus outflows which consisted of 1,364.1 kg yr^{-1} and 1,272.3 kg yr^{-1} attributed to water supply demand (41.7 cfs) and spillway overflows (4.3 cfs), respectively. An additional total phosphorus sink was likely to be lake bottom sediments, especially in the area west of the Highway 10 bridge (Logan, 1980). This analysis assumed a most likely mass total phosphorus loading.

Table 3. High, most likely and low phosphorus export coefficients for land use categories, precipitation and septic tank inputs.

SOURCE	*UNITS	HIGH	MID	LOW
AGRICULTURE	KG/ (HA-YR)	3.0	.95	0.10
FOREST	KG/ (HA-YR)	0.45	0.225	0.02
PRECIPITATION	KG/ (HA-YR)	0.60	0.35	0.15
URBAN	KG/ (HA-YR)	5.0	2.0	0.50
SEPTIC TANK INPUTS	KG/ (CAPITA-YR)	1.8	0.675	0.30

*KILOGRAMS OF TOTAL PHOSPHORUS PER HECTARE PER YEAR AND KILOGRAMS OF TOTAL PHOSPHORUS PER CAPITA-YR AS APPLIED TO SEPTIC TANK INPUTS.

SOURCE: RECKHOW AND CHAPRA, "ENGINEERING APPROACHES FOR LAKE MANAGEMENT", 1983, P. 278.

Table 4. Mass total phosphorus loadings (W) for the period of 1985 to 2005, Lake Maumelle basin, Pulaski County, Arkansas. High, most likely and low mass loadings are shown.

LEVELS	*MASS PHOSPHORUS LOADING (W) KG/YR				
	1985	1990	1995	2000	2005
HIGH	23,524.2	24,158.5	24,881.0	25,528.2	26,641.1
MOST LIKELY	10,696.5	10,905.6	11,144.6	11,347.4	11,725.5
LOW	1,689.6	1,740.9	1,800.5	1,851.1	1,949.5

$*W = (Ec_F \times AREA_F) + (Ec_{AG} \times AREA_{AG}) + Ec_U + AREA_U) + (Ec_A \times A_S) + (Ec_{ST} \times \#$ OF CAPITA YEARS $\times (1-S.R.)) + PSI$

Table 5. High, most likely and low areal phosphorus loadings (L) for the period of 1985 to 2005, Lake Maumelle basin, Pulaski County, Arkansas.

LEVELS	AREAL PHOSPHORUS LOADINGS (L) G/M^2-YR				
	1985	1990	1995	2000	2005
HIGH	.653	.670	.691	.709	.740
MOST LIKELY	.297	.302	.310	.315	.326
LOW	.047	.048	.050	.051	.054

$*L=W/A_S$ (A_S =AREA OF LAKE MAUMELLE IN M^2)

Table 6. Predicted in-lake total phosphorus (P) concentrations for the period of 1985 to 2005, Lake Maumelle, Pulaski County, Arkansas. High, most likely and low total phosphorus concentrations are indicated.

LEVELS	*LAKE PHOSPHORUS CONCENTRATION (P) MG/L				
	1985	1990	1995	2000	2005
HIGH	.0446	.0457	.0472	.0484	.0510
MOST LIKELY	.0204	.0206	.0213	.0215	.0223
LOW	.0032	.0033	.0034	.0035	.0037

$*P=L/11.6 + 1.2\ qs$ (QS=AREAL WATER LOADING M/YR)

Areal phosphorus loadings (Table 5) were used as inputs for the phosphorus model ($P = L/11.6 + 1.2\ qs$) of Reckhow and Chapra (1983) to predict existing and projected in-lake phosphorus concentrations for Lake Maumelle (Table 6). An actual summer period total phosphorus concentration of .0280 mg l^{-1} was measured in Lake Maumelle. When compared to the predicted value of .0204 mg l^{-1}, a difference of .0076 mg l^{-1} existed. This difference was not statistically significant $P \leq .05$ (Table 7).[3] Modifications of the above analyses by using the high phosphorus export coefficient for forestland while leaving the remaining coefficients at the most likely level, resulted in a predicted in-lake total phosphorus concentration of .033 mg l^{-1}. This modification was reasonable based on the area devoted to forestland and silvicultural ac-

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[3] A t-test was used for all analyses comparing differences between actual and predicted average total phosphorus concentrations.

Table 7. Comparison of actual and predicted summer average total phosphorus (P) concentrations using most likely and high phosphorus export coefficients for forestland areas, Lake Maumelle, Pulaski County, Arkansas.

EXPORT COEFFICIENTS FORESTLAND	TOTAL PHOSPHORUS (P) MG L^{-1} ACTUAL	PREDICTED
MOST LIKELY*	.0280 ± .0062	.0204 ± .0100
HIGH*	.0280 ± .0062	.0330 ± .0135

*DIFFERENCES ARE NOT STATISTICALLY SIGNIFICANT $P \leq .05$, DF = 5

tivities in the Lake Maumelle basin (Swank, 1984). The difference between the predicted total phosphorus concentration (.033 mg l^{-1}) and the actual value (.028 mg l^{-1}) for the second analysis was not statistically significant $P \leq .05$ (Table 7).

The phosphorus model applied to Lake Maumelle was originally developed from data representative of lakes in the north temperate climatic zone (Reckhow and Chapra, 1983). Validation of this empirical model for Lake Maumelle supports its potential application to lakes in the south-central climatic zone. Model predictions also compared very favorably with the trophic state index results. Since this model depends on areal phosphorus loadings, it emphasizes the role of watershed management for protecting lake resources. Water quality planners can utilize this model (Davis and Swartz, 1983) to develop cost-effective strategies for reduction of lake phosphorus inputs. Prioritization of watershed problem areas based on phosphorus contributions can be easily accomplished (Hill, 1981; Lemon and Edmondson, 1983). Best Management Practices (BMPs) and related costs can be identified for the priority areas. Based on the BMP phosphorus reduction capabilities, changes in areal phosphorus loadings and in-lake phosphorus concentrations can be calculated.

In summary, the areal phosphorus loading model based on Reckhow and Chapra (1983) provided statistically significant predictions of total phosphorus concentrations in Lake Maumelle. Furthermore, the model proved to be applicable to lake watershed planning strategies.

ACKNOWLEDGMENTS

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