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Assessment Of Total Phosphorus Concentration As A Predictor And Determinant Of Fishery Productivity In Southern Appalachian Reservoirs: Application To Smith Mountain Lake, Virginia

by

Jeffrey J. Yurk

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APPROVED:

John J. Ney, Chairman

Richard J. Neves

Donald J. Orth

Jackson R. Webster

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(ABSTRACT)

Phosphorus is often the limiting nutrient of primary productivity in southern Appalachian reservoirs, but its impact on higher trophic levels has not been assessed. Regression analysis was used to examine the relationship between total phosphorus concentrations and estimates of fish standing stock in Smith Mountain Lake (SML) over time and for 22 southern Appalachian reservoirs (SAR) at the same time. In SML, which had responded to a nutrient reduction program, total phosphorus concentration and fish biomass concurrently declined over an 12-year period; phosphorus concentration accounted for one-third (cove-specific) and two-thirds (whole-lake) of the annual variation in fish standing stock. Total phosphorus concentration was also the best predictor of fish abundance in SARs, accounting for 84% of the variation in standing stock despite great diversity in reservoir physical, chemical, and biological characteristics. Predictive power was generally higher at lower levels of the food chain (i.e. planktivores, younger fish) than for piscivores. Planktivore response to phosphorus was found to be immediate. Piscivore biomass did not vary significantly with phosphorus, owing in part to poor energy transfer up the food chain and variable management practices. Phosphorus concentration and total fish standing stock appear to have stabilized in SML since 1980. Losses in fish standing stock due to deceased fertility in SML have been partly offset by an increase in coolwater habitat. Aesthetic versus fishery benefits and the complexity of dealing with a longitudinal trophic gradient need to be considered for future management of SML.

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INTRODUCTION

Prediction of Fishery Productivity

A major challenge to fisheries managers is to determine fish population abundance and potential yield of lakes and reservoirs. A manager is constrained by both time and money, restricting the number of water bodies which can be directly assessed. An accurate estimator of the capacity of a given waterbody to support various fish populations would provide managers with a quantitative basis for resource planning (Jones and Hoyer 1982).

Two methods have been used to predict fishery biomass and harvest in lakes and reservoirs. The first is the explanatory or whole ecosystem approach (Walters 1980). This method requires extensive analysis including estimates of fish biomass, dietary requirements of fish, and energy flow among trophic levels (Kitchell et. al. 1974). These are difficult to determine, and estimates lose accuracy in more complex systems (Ploskey and Jenkins 1982).

The second method used to assess fishery parameters is empiricism. Empirical prediction is prediction based on observation and experience. It is the use of a known independent variable or variables to predict an unknown dependent variable without reference to causal relationships (Rigler 1982). Good independent variables are those that are easily attained and reliably measured. Empiricism could provide biologists with a fast, cost-efficient way to predict fish biomass and harvest, thus investing them with an invaluable tool in their efforts to design stocking programs and set harvest regulations.

The first attempts at empirically predicting fishery productivity in lentic waters stressed abiotic factors as predictors of fishery productivity (defined here as either standing stock biomass or sustained yield). These included physical measures, such as lake basin morphometry (Thienemann 1927 as cited in Galat 1982), lake surface area (Rounsefell 1946), and mean depth (Rawson 1952, 1955; Hayes 1957), as well as chemical measures such as nutrients (Moyle 1946; Hrbacek 1969; Hanson and Leggett 1982), and total dissolved solids (Northcote and Larkin 1956). All these abiotic predictors were found to be strongly correlated to fishery productivity for particular sets of lakes (Table 1).

Ryder (1965) combined a physical (morphometric) and chemical (edaphic) variable into what is now known as the morphoedaphic index (MEI). The MEI is simply the ratio of the concentration of total dissolved solids (mg/l) to mean depth (in meters). This simple index has been shown to be a successful predictor of potential fish standing stock and yield in many lakes throughout the world (Ryder et. al. 1974; Jenkins 1967, 1977, 1982; Jenkins and Morais 1971; Henderson et al. 1973; Regier and Henderson 1973; Toews and Griffith 1979).

The MEI is developed for a set of lakes and then used as a predictor of yield for other lakes which are similar physically, chemically, and biologically. Requirements to set up an MEI-fish relationship for a particular set of lakes or reservoirs are: 1) homogenous climatic conditions; 2) fairly constant ionic ratios; 3) approximately the same hydraulic flushing time; 4) inorganic turbidity on the same order of magnitude for all lakes; and 5) moderate to intensive fishing effort on a spectrum of species for a number of years (Ryder et. al. 1974). When these requirements are met, the MEI has been shown to account for 60 to 81% of the variation in fish yields among natural lakes (Ryder 1965, Jenkins 1967,1977,1982, Henderson and Welcomme 1974; see Table 1).

Ryder et al. (1974) concluded that reservoirs are generally unsuitable for morphoedaphic index analysis because they combine both lentic and lotic characteristics, thereby reducing the effectiveness of the MEI in estimating biomass or yield. Jenkins (1982) supported these conclusions and noted that the greatest departures from MEI predictions occurred in the first ten to fifteen years of impoundment.

Biotic parameters have also been used as predictors of fishery productivity in lentic waters. They should be better predictors than simple physico-chemical parameters because they are directly involved in the trophic chain leading to fish, but they are more expensive and time consuming to measure. Predictors such as primary production (Hrbacek 1961; Wolney and Grygierek 1972; Henderson et al. 1973; Melack 1976; McConnell et al. 1977; Oglesby 1977a;

Table 1. Empirical predictors of fish standing stock and yield.

AUTHOR	WATER BODIES	N	PREDICTOR	COEFFICIENT OF DETERMINATION (R^2)
		Yield		
Ryder 1965	Canadian Lakes	23	MEI	0.74
Jenkins 1967[1]	Large Temperate Reservoirs	210	MEI/biomass	0.27-0.54
Henderson and Welcomme 1974	African Lakes	31	MEI	0.26
Melack 1976	African Lakes	8	Gross Photosynthesis	0.5
McConnell et al. 1977	Research Ponds	6	Gross Photosynthesis	0.933
Liang et al. 1981	Chinese Lakes and Ponds	18	Gross Photosynthesis	0.76
Oglesby 1977	Temperate Ponds	22	Phytoplankton Standing Crop	0.84
Toews and Griffith 1979	African Lakes	8	Gross Primary Production	0.69
Hecky et al. 1981	Lake Tanganyika	1	Phytoplankton Standing Crop	NS
Nakashima and Leggett 1975	Lake Memphremagog	1	Phytoplankton Standing Crop	NS
Jones and Hoyer 1982	Midwest Lakes and Reservoirs	25	Chlorophyll-a	0.82
Smith and Swingle 1939	Small Excavated Ponds	15	Invertebrate Standing Crop	S
Matuszec 1978	North Temperate Lakes	22	Benthos Standing Crop	0.83
Hanson and Leggett 1982	North Temperate Lakes	26	Total Phosphorus	0.84
Rawson 1952	Large North American Lakes	10	Mean Depths	0.92
Moyle 1946	Minnesota Lakes and Ponds	218	Nutrients	S
Young and Heimbuch 1982	Large Bodies of Water	27	Surface Area	0.94
		Standing Stock		
Jenkins 1977[1]	Reservoirs	166	TDS/biomass	0.63-0.81
Jenkins 1982	Large U.S. Reservoirs > 202ha	294	MEI	0.21-0.72
Hanson and Leggett 1982	North Temperate Lakes	26	Total Phosphorus	0.71
Aggus and Lewis 1978	Southeastern U.S. Reservoirs	26	Retention Time, Surface area	0.09-0.31

[1] Various fish standing crop biomasses from reservoirs within study
NS: Non-significant relationship found
S: Significant relationship found; coefficient of determination not reported

Toews and Griffith 1979; Hecky et al. 1981; Liang et al. 1981), phytoplankton standing stock (Nakashima and Leggett 1975; Oglesby 1977a), chlorophyll-a (Jones and Hoyer 1982), and benthic invertebrate standing stock (Smith and Swingle 1939; Hrbacek 1969; Matuszek 1978; Hanson and Leggett 1982) have all proven to be effective (r^2=0.50-0.93) at predicting fish yield and/or standing stock in particular situations.

The empirical relationship between biotic parameters and fishery productivity, as cited above, has been extensively investigated in natural lakes by regression analysis. This is not the case for large (> 200 ha) reservoirs, which total more than four million surface hectares in the U.S. and receive 40% of the freshwater sportfishing pressure annually (Fisher et al. 1986). Reservoirs are inherently more unstable than natural lakes in physical factors (water level, discharge, turbidity) and biological characteristics (species composition, reproductive success, food availability); their fisheries may respond less predictably to various biotic conditions. Until all sources of stress can be sorted out and their effects adequately determined, empirical prediction by a few key environmental factors could provide the best means with which to assess reservoir fishery productivity, help identify perturbed environments, and provide guidelines for management of the fishery (Jenkins 1977).

The best correlations between standing stock and predictive indices in reservoirs were derived for the MEI when 290 U.S. reservoirs were divided into subsets of similar operational and chemical groups (r^2 = 0.72; Carline 1986). Other abiotic and biotic parameters have yet to be evaluated in regression analysis against standing stock estimates for reservoir subsets. The best correlations between fish yield and predictive indices in reservoirs to date has been with chlorophyll-a in a set of shallow midwestern U.S. lakes and reservoirs (r^2 =0..82; Jones and Hoyer 1982). Simple models for predicting fish yield are likely to be specific for the climatic zone from whence the data set originates (Hanson and Leggett 1982). Accurate predictors of fishery productivity in southern Appalachian reservoirs have yet to be established and may vary among operational and chemical characteristics of these systems.

Kerr and Martin (1980) noted that primary production is directly proportional to fish production up until optimal fish production is reached in a lake. Primary production is the rate at which radiant energy is stored by photosynthetic and chemosynthetic activity of producer organisms in the form of organic substances which can be used as food materials (Odum 1971). It is difficult to accurately measure primary production due to weak analytical methodologies and spatial-temporal variability (Oglesby 1977a). Consequently, parameters which influence primary production and are more stable and measurable are sought as potential predictors for biomass, yield, and ultimate management of a fishery. Nutrients such as phosphorus and nitrogen influence primary production, are relatively stable and measurable, and should provide for accurate predictions of fishery productivity.

Two approaches have been used to empirically predict fishery productivity in lakes and reservoirs. The first approach evaluates the relationship between fishery parameters and a putative predictor over time for a single lake (temporal prediction, e.g. Nakashima and Leggett 1975). The second evaluates the same relationship, but for a group of lakes with the same paired data (spatial prediction, e.g. Jenkins 1982). In this study, I was able to use both approaches.

Fish Production in Smith Mountain Lake

Smith Mountain Lake (SML) is a 8933 hectare hydroelectric reservoir in south-central Virginia impounded in 1963. It is located on the Roanoke River, forty miles southeast of Roanoke, Virginia. During the early years of its impoundment, Smith Mountain Lake developed into a prime recreational fishery. Fishing pressure increased almost exponentially from 1965 to 1975 (Whitehurst 1984). Over the next decade however, harvests of black basses and striped bass, the major piscivorous game species in the reservoir, declined sharply (Whitehurst 1984). A possible reason for this drop is the reduction of nutrient inputs into the reservoir and consequent effects upon trophic interactions. A National Eutrophication Survey (USEPA 1975) found phosphorus to be the limiting nutrient for primary production in Smith Mountain Lake. This conclusion was substantiated by Gregory et al. (1978).

In 1975, an advanced waste treatment facility (AWTF) went into operation in the upstream city of Roanoke. This facility accounts for removal of 81% of the previous phosphorus discharged at this point source and an estimated 35% of the total phosphorus load to Smith Mountain Lake (Obenshain and McLeod 1981). An additional 4% removal of total phosphorus load to the reservoir is expected as the city of Vinton has recently (1985) gone on line with the AWTF, rather than discharging its secondary-treated sewage into the Roanoke River.

Total phosphorus concentration in Smith Mountain Lake has declined since installation of this facility, and estimated fish standing stock in Smith Mountain Lake has also dropped sharply (Whitehurst 1984). Because phosphorus is the limiting nutrient and has declined concomitant with the fishery, it appears that phosphorus concentration might be responsible for some of the decline as well as be a good predictor of fish standing stock in the reservoir.

Total phosphorus concentrations have been highly correlated with fishery productivity parameters in Minnesota lakes (Moyle 1946) and north temperate lakes (Hanson and Leggett 1982). In a phosphorus-limited system such as Smith Mountain Lake, phosphorus dynamics are assumed to be significantly related to lake productivity (Schindler,1978) and should provide a simple, easily measured basis for the prediction of fish standing stock and yield.

Goal and Objectives

The overall goal of this study is to assess the degree to which total phosphorus concentration predicts and determines the fishery productivity (standing stock and harvest) for southern Appalachian reservoirs in general and Smith Mountain Lake in particular. The predictive relationship can be evaluated by regression analysis of mean annual total phosphorus concentration paired by year with fishery productivity data. The causality of the relationship has significant bearing on the future management of the Smith Mountain Lake fishery but, in the absence of experimental manipulations, can only be judged by inference.

Because of similar environmental conditions which occur within a given geographic region, a phosphorus-fishery productivity relationship described for Smith Mountain Lake might also apply to other impoundments in the southern Appalachian region of the U.S. Development of total phosphorus-fishery productivity models for southern Appalachian reservoirs (SARs) will indicate the robustness of phosphorus as a predictor over such variables as morphometry, chemistry, operational characteristics, and species complex. These results will also either substantiate or dispute the existence of a causal relationship between changes in total phosphorus concentrations and fish standing stock or harvest in Smith Mountain Lake.

The specific objectives of this study are to:

1. Develop total phosphorus-fishery data sets matched by year (SML) and lake (SAR):

2. Describe the predictive relationship between total phosphorus concentrations and fish standing stock and harvest matched by year for Smith Mountain Lake:

3. Evaluate the robustness of total phosphorus concentration as a predictor of fishery productivity for southern Appalachian reservoirs:

4. Assess the significance of phosphorus loading as an influence on present and future fishery productivity in Smith Mountain Lake.

METHODS

Study Area

Smith Mountain Lake is a hydroelectric impoundment of the Roanoke and Blackwater Rivers in Bedford, Franklin, and Pittsylvania Counties, Virginia. Riverine Roanoke and Blackwater arms extend 65km and 32km, respectively, from a broad deep lower lake which itself extends 10km above the dam (Figure 1). Smith Mountain Lake has 805 km of shoreline, maximum pool elevation of 242 meters, maximum depth of 61 meters, and mean depth of 17 meters (Simmons and Neff 1969). The reservoir's surface level fluctuates about 1 meter weekly due to hydroelectric operations.

Smith Mountain Lake is oligotrophic at its lower end but, mesotrophic at the confluence of its tributary upper arms and eutrophic further upstream (Obenshain and Mcleod 1981). Littoral areas ($<$5m in depth) of the lower lake are limited to within a few meters of shore at which point lake depth drops off steeply. Upper lake arms slope more gradually to the main channel, providing a more extensive littoral zone. The hypolimnion in these tributary arms becomes anoxic during summer months (Benfield and Hendricks 1975; Ney et al. 1988; Figure 1).

Largemouth bass (*Micropterus salmoides*) and, to a lesser extent, smallmouth bass (*M. dolomieui*) are the lake's major self-sustaining sportfish. Major forage species of the reservoir are gizzard shad (*Dorosoma cepedianum*), native to the river system, and alewife (*Alosa pseudoharengus*) which was introduced in 1965. Striped bass (*Morone saxatilis*), walleye (*Stizostedion vitreum*), and muskellunge (*Esox masquinongy*), have been stocked on a put-grow-take basis starting in the late 1960's to crop gizzard shad populations and diversify the fishery.

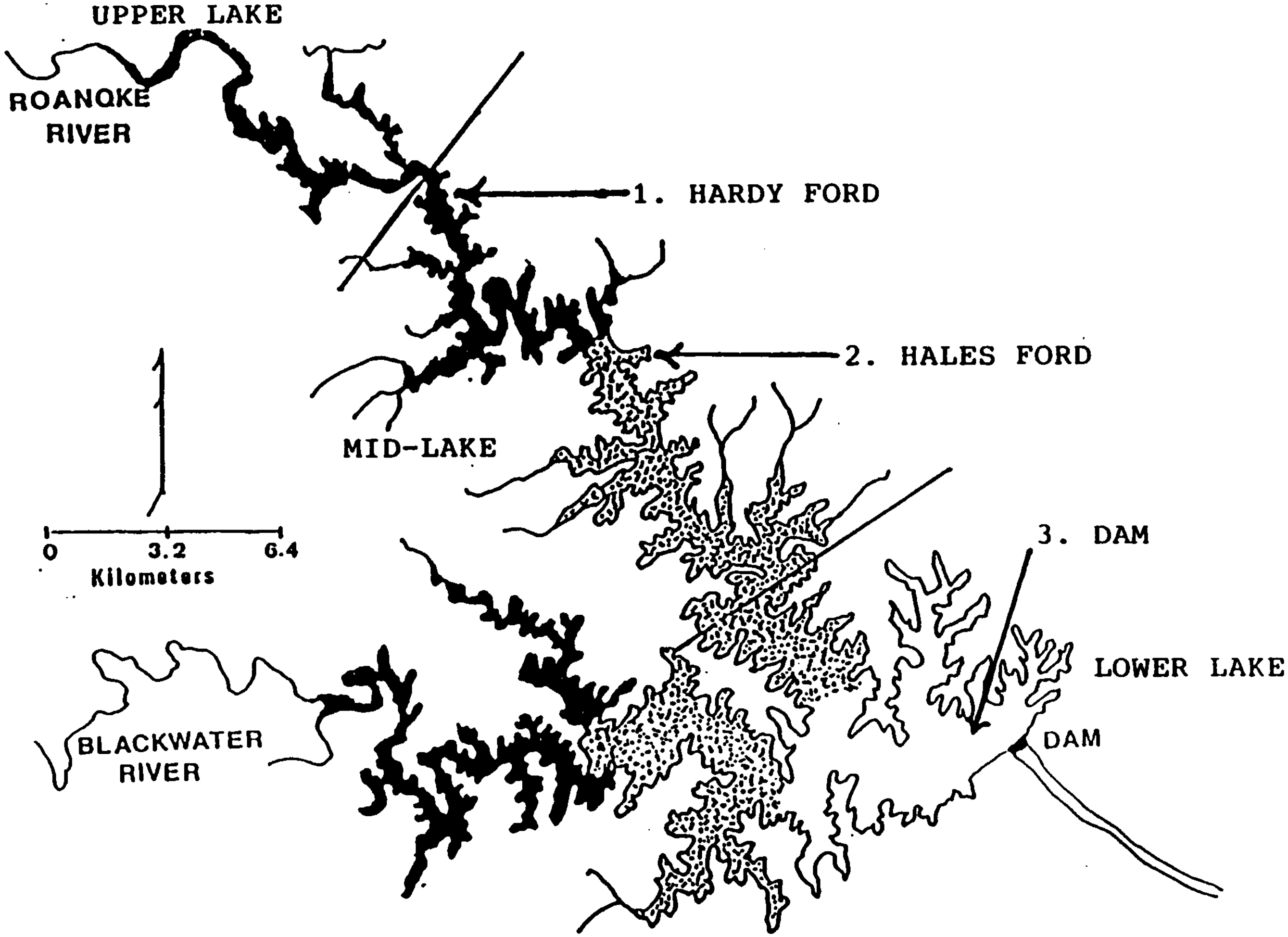

FIGURE 1. Smith Mountain Lake, Virginia. Stippled and darkened areas experienced summer hypolimnetic oxygen deficits in 1974. Only darkened areas experienced these deficits in 1984. (VWCB sampling sites numbered).

Data Acquisition

Phosphorus data for Smith Mountain Lake were assembled from the files of the Virginia State Water Control Board (VWCB). Water quality data for southern Appalachian reservoirs were obtained from National Eutrophication Survey (NES) reports (USEPA 1978a). The NES was initiated by the Environmental Protection Agency in 1972 to investigate the nationwide threat of accerated eutrophication to freshwater lakes and reservoirs. Its objective was to obtain information on nutrient sources and concentrations and their impact to selected waterbodies. This information was to then be used to manage point and nonpoint pollution.

In the NES study, reservoirs were sampled three times (spring, summer, and fall) during the open water season of 1973 by means of a pontoon-equipped Huey helicopter at several lake stations (USEPA 1975). Total phosphorus concentrations from water samples taken at various depths selected to characterize the water column were determined using a persulfate oxidation followed by colorimetric analysis to within 5μg/l (USEPA 1978b). Median total phosphorus concentration was calculated from the combined data set of all three sampling sites. Additional chemical and physical data obtained from the survey included surface area, mean depth, Secchi disk depth, retention time, chlorophyll-a, total nitrogen, phosphorus loading, and conductivity.

Fish standing stock (SML) and standing stock and harvest data (southern Appalachian Reservoirs) were obtained through written correspondence with Gene Ploskey of Aquatic Ecosystems Analysts, Fayetteville, Arkansas. Harvest data and gill net data for SML were obtained from the Virginia Commission (now Department) of Game and Inland Fisheries (VCGIF).

Smith Mountain Lake

Phosphorus Data

Total phosphorus concentration data (1973-1984) for three sites along the nutrient gradient of Smith Mountain Lake were obtained from the VWCB (Table 2). All samples were collected bimonthly from April to October at Secchi disk disappearance depth with a Kemmerer water sampler and were analyzed using colorimetric techniques by VWCBs Division of Ecological Studies. I averaged bimonthly data to estimate mean annual total phosphorus concentrations. Average whole-lake total phosphorus concentration was then estimated by taking a surface-area weighted average of these means. Weight given to each area's concentration was determined as a percentage of the whole lake's surface area. The lake was sectioned into three trophically different portions (eu-, meso-, and oligotrophic), with the divisions at Buoy R-14 and the mouth of Beaverdam Creek (Figure 1). The Blackwater River arm of the lake (1100 ha) was deleted from analysis due to insufficient phosphorus and fish data. The percent surface area of the whole lake (minus the Blackwater River arm segment) occupied by upper (11.1%), middle (39.7%), and lower (49.2%) lake portions was multiplied by phosphorus concentration for coinciding areas, and the three products were summed for each year in which total phosphorus data were available (8 of 12 years).

The VWCB total phosphorus data were inadequate (not measured at all three lake sites) for four of twelve years. Therefore, a second method was used to estimate missing values (four years) of whole-lake phosphorus concentrations. I used the model developed by Jones and Bachmann (1976) to estimate total phosphorus concentration in the reservoir, given the lake parameters of phosphorus loading, hydraulic flushing rate, and phosphorus sedimentation rate per year along with mean depth. This model was chosen because it is a direct method of predicting total phosphorus concentrations in a broad range of lakes (Jones and Bachmann 1976).

To use the Jones and Bachmann model, phosphorus loading had to be calculated; a loading model developed by the USEPA for their 1973 National Eutrophication Survey (NES)

Table 2. Total phosphorus concentrations ($\mu g/l$) and total fish standing stock estimates (kg/ha) in upper, middle, and lower Smith Mountain Lake, 1973-1984.

	Total Phosphorus			Total Standing Stock		
YEAR	UPPER	MIDDLE	LOWER	UPPER	MIDDLE	LOWER
1973	117.5	34.3	48.8	337.9	1586.9	414.4
1974	106.9	82.2	121.0	2367.4	2272.9	420.9
1975			260.0			266.9
1976	100.0			1534.6		
1977	240.0	80.0	130.0	2180.5	883.1	266.9
1978						
1979				379.7	112.3	57.9
1980	26.7	25.0	17.5	760.1	234.8	222.5
1981	52.5	20.0	21.7	384.6	256.8	127.9
1982	50.0	25.0	25.0	524.3	352.4	220.7
1983	54.0	32.5	30.0	353.3	251.8	174.3
1984	42.5	15.0	40.0	518.1	171.4	561.6

was used. Many models are available to calculate nutrient loading to a lake (e.g., Rast and Lee 1983; Dillon 1974). The NES model was chosen because it was previously used successfully on SML by Obenshain and McLeod (1981). The model uses flow rates and total phosphorus concentrations from incoming streams to estimate phosphorus load to the lake.

The NES equation used to estimate phosphorus load is:

$$\text{Average annual TP load (kg/mo)} = 74.604\bar{c}YS\sum_{i=1}^{12} NF_i$$

74.604 = factor including average number of days per month and conversion of concentration and flow to kilograms per day

$\bar{c}$ = mean total phosphorus concentration in the sampled stream

NF_i = Normalized flow (flow expected in an average year) for ith month

$Y = 10b\,(\overline{\log NF} - \overline{\log MF})$

$$S = \frac{\sum_{i=1}^{12} NF_i \cdot 10^{b(\log NF_i - \overline{\log NF})}}{\sum_{i=1}^{12} NF_i}$$

and:

$\overline{\log NF}$ = mean log normalized flow

$\overline{\log MF}$ = mean log monthly flow for year

b = -0.11 for phosphorus

Total phosphorus and orthophosphorus concentrations were obtained monthly for the major tributaries of Smith Mountain Lake (Roanoke River, Blackwater River, Back Creek) from VWCB data (1977-1982). Concentrations for the years 1973 and 1974 were obtained from the National Eutrophication Survey (NES) data collected by the Environmental Protection Agency. Concentrations were not available from the VWCB for the years 1975, 1976, 1983, or 1984. Stream flow data for the period 1973-1984 were obtained from USGS gauging stations located on the Roanoke River at Niagara, the Blackwater River at Rocky Mount, and Back Creek near

Dundee. Normalized flow data for these sites are taken from the 1973-74 NES study (USEPA 1975).

Total phosphorus concentration was not measured accurately because of high detection limits in the analytical equipment (TP>0.1 mg/L) for several years in Smith Mountain Lake's major tributaries. Orthophosphorus was measured accurately, in parts per billion, during these same years. The ratio of orthophosphorus to total phosphorus is remarkably constant in a large variety of lakes within the temperate zone (Wetzel 1983). To estimate the total phosphorus parameter required by the phosphorus loading model, a proportional relationship between total and orthophosphorus, for each major tributary, was calculated using data from 1973-74 and 1977-78 (Appendix Table 1). The proportional relationship was then used to estimate total phosphorus concentration, multiplying known orthophosphorus concentrations by the total phosphorus to orthophosphorus ratio. The calculated total phosphorus concentrations were then used in the NES equation to estimate total phosphorus loading from each major tributary.

Other sources contributing to the phosphorus load to Smith Mountain Lake include precipitation, direct runoff, and septic inputs. Loading due to precipitation was calculated using the Department of Commerce's climatological data for Roanoke, Virginia and average total phosphorus load to all of Smith Mountain Lake per inch of precipitation (42.76 kg) calculated by USEPA (1975). Immediate drainage total phosphorus load (runoff) was not measured in SML except during the 1973 NES and 1977 VWCB studies and had to be estimated as a percentage (26%) of the total load. This estimate was derived from the ratio of actual immediate drainage load to total loads calculated during 1977-1978, which was an average rainfall year (Obenshain and McLeod 1981). Loading from septic systems was estimated at 218 kg/year during 1977-78 (Obenshain and McLeod 1981), and this load was used for all years; no significant changes over time were assumed to have occurred in this minor point source (Robert Burnley, SWCB, personal communication).

Loading values were used in Jones and Bachmann's (1984) modification of Vollenweider's (1967) mass balance equation:

$$TP = L/[z(s + p)]$$

where:

TP = concentration of total phosphorus in the lake water (mg/m^3)

L = annual phosphorus loading per unit area of lake surface ($mg/m^2/year$)

z = mean depth of the lake in meters

s = phosphorus sedimentation rate per year, and

p = hydraulic flushing rate per year (constant)

Variables in the model include mean depth, estimated at 17 meters, hydraulic flushing rate, estimated at 0.3125 (Obenshain and Mcleod 1981) and phosphorus sedimentation rate. Modification to the Vollenweider model involved estimation of sedimentation rate, a value not available for many waters, including Smith Mountain Lake. Sedimentation rates in the range of 0 to 1 were used in the model to establish total phosphorus concentrations at various sedimentation rates. Concentrations obtained using various sedimentation rates were regressed with weighted whole-lake total phosphorus concentrations from VWCB data, for corresponding years (6), and evaluated for best fit using a coefficient of determination.

Fish Data

Cove-specific fish standing stock data for Smith Mountain Lake, 1973 to 1984, excluding 1978, were obtained from Gene Ploskey of Aquatic Ecosystems Analysts, Fayetteville, Arkansas (Table 2). Three representative coves on the lake (upper, middle and lower lake) were rotenoned annually by the Virginia Commission of Game and Inland Fisheries (VCGIF) in all years except 1978. Information gathered includes whole-lake estimates of pounds of fish per acre and number of fish per acre, by species and inch class. Fish standing stock data from these coves were combined to calculate whole-lake fish standing stock estimates. Data were converted to metric units and adjusted for open-water using the Douglas Lake correction factors developed for deep reservoirs (Hayne et al. 1968).

Fish harvest data for Smith Mountain Lake were obtained from the VCGIF (Hart 1976; LaRoche 1981). Harvest values, 1973 through 1977 and 1980, were estimated from creel surveys. Harvest values were not available in other years. From June 1973 to July 1976, harvest estimates were based strictly on a daytime survey. Estimates in 1977 and 1980 were based on both day and night-time survey.

Southern Appalachian Reservoirs

Standing stocks of fish in Appalachian reservoirs were taken from a data set provided by Gene Ploskey of Aquatic Ecosystems Analysis, Fayetteville, Arkansas (Table 3). Harvest data from seven of these reservoirs were also provided. Southern Appalachia is defined here as the area along the Appalachian mountain range from South Carolina north through West Virginia (Figure 2). Criteria for reservoir selection included: 1) location in or near the southern Appalachian mountains; 2) surface area greater than 400 hectares; and 3) availability of matching (i.e. same year $\pm$ 2 years) total phosphorus data with fish standing stock and/or harvest data. Standing stock data as obtained were given in pounds per acre by species for each reservoir. Twenty-two reservoirs met these criteria (Table 3).

Total phosphorus data for the reservoirs were obtained from the National Eutrophication Survey (USEPA 1978). This survey includes data taken only for the year 1973. Accordingly, matching fishery data were restricted to the period 1971-1975. Additional chemical and physical data available from the survey included surface area, mean depth, Secchi disk depth, retention time, chlorophyll-a, total nitrogen, phosphorus loading, and conductivity.

Table 3. Reservoirs included in the southern Appalachian data set, with key features of each.

Name	Surface area (ha)	Mean depth (m)	Retention (days)	Secchi disk depth (m)	Total phosphorus (mg/L)	Total nitrogen (mg/L)	Conductivity (μ/mhos)	Standing stock (kg/ha)
Kentucky								
Cumberland	16736	24.2	226	1.7	0.016	0.550	130	314
Dale Hollow	8939	14.4	438	4.3	0.010	0.490	180	228
Herrington	979	23.9	196	1.5	0.079	1.060	242	2,321
Kentucky	53388	5.2	22	1.0	0.081	0.680	144	855
North Carolina								
Badin	1989	14.2	28	0.8	0.042	0.070	68	908
Norman	10828	10.2	239	1.3	0.019	0.550	55	318
South Carolina								
Keowee	8711	15.2	402	3.3	0.008	0.320	32	166
Tennessee								
Holston	3068	26.4	370	2.4	0.014	0.855	166	529
Old Hickory	9106	5.6	11	0.8	0.058	0.550	148	1238
Cherokee	12262	14.9	190	1.3	0.051	1.270	265	2078
Chickamauga	14325	5.4	11	0.9	0.031	0.600	160	578
Fort Loudon	5909	7.6	15	0.9	0.054	0.960	210	809
Nickajack	4197	7.1	4	1.0	0.051	0.725	162	605
Watts Bar	15774	7.9	23	1.0	0.032	0.740	169	626
Douglas	12303	14.1	116	1.5	0.026	0.700	168	571
Woods	1611	5.7	85	1.8	0.017	0.710	150	338
Virginia								
Claytor	1819	29.0	63	1.5	0.031	0.730	90	340
John Kerr	19825	10.7	124	1.0	0.044	0.550	101	956
Flannagan	463	18.0	118	2.1	0.011	0.530	232	34
West Virginia								
Lynn	700	12.8	12	2.5	0.006	0.710	117	77
Summerville	1507	21.0	50	3.5	0.011	0.940	50	137
Tygart	799	17.4	20	3.1	0.006	0.640	82	104

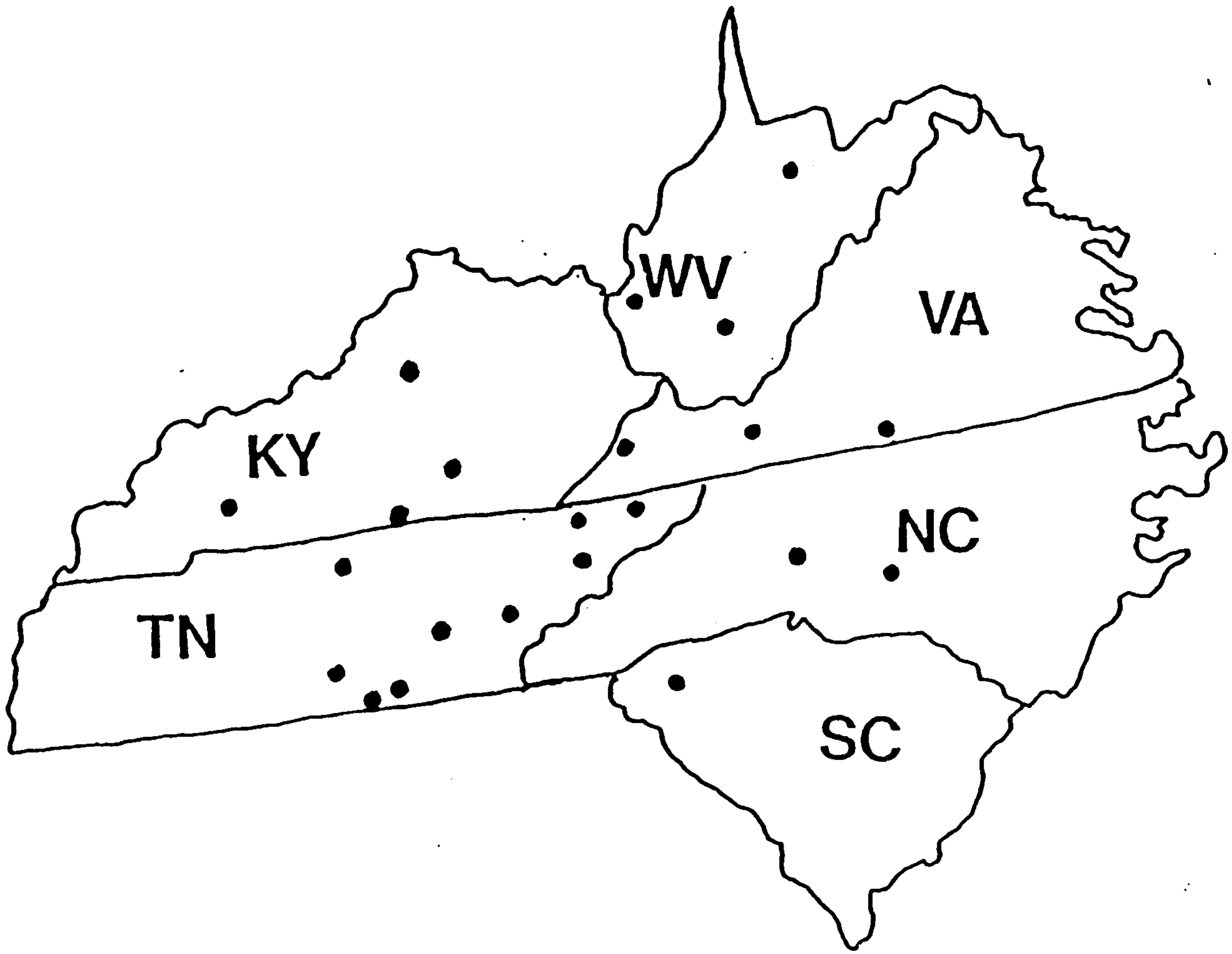

FIGURE 2. Location of southern Appalachain reservoirs included in SAR regression analysis.

Data Analysis

The phosphorus-fishery productivity relationship was analyzed by regression with total phosphorus concentration as the independent variable and fish standing stock or sportfish harvest as the dependent variable. Data analyses were divided into two major sections, Smith Mountain Lake (SML) and southern Appalachian reservoirs (SAR). Smith Mountain Lake data were analyzed at both cove-specific locations and for the lake as a whole. The SAR data were evaluated overall and in subsets based on physical and chemical distinctions, including mean depth, surface area, Secchi disk disappearance depth, and retention time.

The scatter plots of SML total fish standing stock (cove-specific) and phosphorus data were graphed to help identify any data transformations which might improve linearity, as measured by a coefficient of determination (r^2). Transformations on either a dependent variable, independent variable, or both variables are used to reduce curvature in the data and hence simplify data analysis (Ott 1984).

A series of common transformations of independent and dependent variables to increase linearity of the data set was assessed. Logarithmic transformations along with exponent variation of independent and dependent variables were evaluated in the phosphorus-total fish standing stock regression; the evaluation criterion was change in the r^2 value attained when regressing transformed data (Ott 1984). The various regression analyses tested on Smith Mountain Lake data are summarized in Table 4.

Phosphorus-fishery productivity relationships were assessed by two statistical characteristics of the regressions. Significance (P) measures the probability that a real relationship exists (i.e., the regression slope is not zero). In this study, the level of significance was set at $P=0.05$ for Type I error (the probability of rejecting a true null hypothesis). The coefficient of determination (r^2) is a measure of how well the independent variable explains differences in the dependent variable; i.e., how well the data fit the regression line. An r^2 of 0.80, for example, can be interpreted as explaining 80% of the scatter in the values of the

Table 4. Summary outline of data analysis.

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1. Smith Mountain Lake
    a. Statistical Approach
        1) Linear regression
        2) Linear regression with transformations
    b. Dependent Variables
        1) Cove-specific
            a) total standing stock
            b) species standing stock
            c) trophic groups standing stock
            d) age-groups standing stock
            e) time lags
        2) Whole lake
            a) total standing stock
            b) species standing stock
            c) trophic groups standing stock
            d) age-groups standing stock
            e) time lags
        3) Pelagic sportfish
        4) Total harvest
2. Southern Appalachian Reservoirs
    a. Regression Analyses
        1) Linear regression analysis
            a) total standing stock
                i. total phosphorus
                ii. other abiotic parameters
            b) species standing stock
            c) trophic groups standing stock
            d) time lags
        2) Multiple regression analysis
    b. Data Subsets

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dependent variable. Only coefficients of determination for significant ($P < 0.05$) relationships were assessed.

Smith Mountain Lake

Cove-Specific Analysis

Cove-specific analysis was conducted in Smith Mountain Lake (SML) for three reasons: 1) site-specific differences along the nutrient gradient of SML could be factored out; 2) sample size of cove-specific pairings was greater than that for whole-lake pairings of phosphorus and fish data; and 3) to determine if phosphorus is a robust predictor of fish standing stock over both space and time. Simple linear regression was the first technique used to define the total phosphorus-fishery productivity relationship in Smith Mountain Lake. Total standing stock estimates (dependent variable), based on data taken from coves located in the upper, middle, and lower portions of Smith Mountain Lake, were plotted against total phosphorus concentrations (independent variable) matched by lake area in each year. Several transformations of the data were attempted to improve fit of the data, measured by a coefficient of determination (r^2). Non-parametric regression of the data was also used as a means to linearize the data and was evaluated by Spearman's rank correlation test.

Fish standing stock estimates from coves in upper Smith Mountain Lake were matched by year over the period 1973-84 with total phosphorus concentrations taken at Hardy Ford. Those from mid-lake were matched with concentrations from Hales Ford, and stocks from lower Smith Mountain Lake were matched with concentrations from one of two locations near the dam (Figure 1). The data set consisted of 29 matched pairs (Table 2). The seven missing data pairs are a result of unavailable fish standing stock data in 1978 and unavailable nutrient data for some locations in each of three years.

I first used species-specific fish standing stock data to evaluate the total phosphorus/fish standing stock relationship. In a second series of tests, I partitioned the cove-specific data set by grouping standing stocks of fish of the same trophic level/diet. Fish were divided into groups of planktivores, benthophages, and piscivores (Table 5). Many fish in each of these categories are polyphagic within their lifetime and do not strictly follow the diet category under which they are grouped throughout life. Dietary group names were used here for consistency purposes. The purpose of these tests was to assess the robustness of the predictive relationship between phosphorus concentrations and different levels of the food chain.

Standing stock subsets containing several size interval combinations of gizzard shad and largemouth bass, the principal planktivorous and piscivorous species in the reservoir, were evaluated to assess the effect of grouping species by age on the total phosphorus/fish standing stock relationship. The VCGIF total standing stock data grouped fish, by species, in the 0 to 4 inch size class, and by one inch increments thereafter, following the pattern of data collected in cove rotenone studies. On the basis of VCGIF age analyses, I considered gizzard shad 0 to 5.0 inches to be age 0, 5.1 to 7.0 inches to be age-1, 7.1 to 10.0 inches to be age-2, and 10.1 inch or larger fish to be $\geq$ age 3. Largemouth bass were grouped as 0 to 6.0 inches for age 0 fish, 6.1 to 8.0 inches for age-1 fish, 8.1 to 10.0 inches for age-2 fish, 10.1 to 12.0 inches for age-3 fish, 12.1 to 16.0 inches for age-4 fish, and greater than 16.1 inches for age-5 fish. These tests were used to evaluate which size/age groups of fish responded most closely to changes in phosphorus levels.

The final analysis of the data, matched by cove, in the regression model considered the possibility of a time lag between change in phosphorus concentration and change in standing stock. Standing stock data were matched with total phosphorus concentrations from prior years. Regression analysis was conducted with 1 to 5 year time lags for total standing stock and for gizzard shad and largemouth bass, the principle planktivorous and piscivorous species in SML.

Table 5. List of fish species included in the categories of planktivorous fish, benthophagous fish, and piscivorus fish in Smith Mountain Lake and southern Appalachain reservoirs.

Planktivores[1]	Benthophagous fish	Piscivorous fish
Gizzard shad[2]	Quillback sucker	Largemouth bass
Rock bass	Hogsucker	Smallmouth bass
Redbreast sunfish	White sucker	Walleye
Pumpkinseed	Black bullhead	Striped bass
Bluegill	Brown bullhead	White bass
Black crappie	Yellow bullhead	
Yellow perch	Channel catfish	
	Redhorses	
	Suckers	
	Catfish	

[1]Alewife were excluded because no accurate measure of their abundance could be obtained.

[2] Scientific names in Appendix Table 2.

Whole-lake Relationships

A second approach to evaluating the regression data model of standing stock versus total phosphorus concentration involved whole-lake averages. Whole-lake averages reduce sampling variability which may occur in cove-specific sampling and also get rid of any time-space interaction, a potential confounding factor. Standing stock data from upper, middle, and lower lake sections were combined for the years 1973-1984, excluding 1978 (in which no rotenone sampling was carried out). Whole-lake standing stock was projected from this combined data set by Gene Ploskey of Aquatic Ecosytems Analysts, Fayetteville, Arkansas, based on adjustment factors for cove versus open water standing stock (Davies and Shelton 1983).

Total phosphorus concentration of the lake as a whole was determined using surface area weighted phosphorus concentrations from upper, middle, and lower SML for years in which data were available between 1973-1984 (8 years), but only matched fish data in seven of these years. A phosphorus loading model was useful in projecting whole-lake total phosphorus concentration for two of the four missing years. Whole-lake averages were used to decrease the amount of variability in the model, thereby increasing its coefficient of determination. However, this procedure also involved a decrease in sample size (29 to 9) which usually decreases significance (increases P-value) of the results.

Total fish standing stocks were first evaluated versus whole-lake total phosphorus concentration. Standing stock data were then divided into subsets of species and trophic groups (planktivores, benthophages, piscivores). For largemouth bass and gizzard shad, standing stock data was further partitioned by age group and evaluated as was done in cove-specific analyses. One, two, and three year time lags of total phosphorus concentrations behind standing stock data were also evaluated in the model for total fish standing stock, gizzard shad and largemouth bass. Lag periods longer than three years reduced data sets to less than five pairs and therefore were not analyzed in the regression model.

Whole-lake total phosphorus values were also regressed against relative abundance estimates of striped bass and walleye from gill netting catch-per-unit-effort (CPUE) data collected yearly (1974-1984) by the Virginia Commission of Game and Inland Fisheries. Gill nets were set annually overnight (3 net-nights) during the first week of October, November, and December at prescribed locations in both the upper and lower reservoir. Experimental monofilament gill nets (150 meter) with mesh sizes of 3.8, 5.1, and 10.2 cm stretch mesh were set alternating 3.8 and 10.2 cm stretch meshes perpendicular to the shoreline (Hart 1976). Catch-per-unit-effort was reported as number of fish per 9.29 m^2 of gill net (one unit of effort) for all samples combined and by age class of fish. Catch-per-unit-effort was converted to weight of fish per 9.29 m^2 of gill net using standard weight-length relationships developed for Smith Mountain Lake by Tisa (1988). Age of fish captured in nets was determined by scale analysis. Gill net CPUE was used as an index of abundance for these two pelagic piscivores because they are not representatively sampled by cove rotenone studies.

Total phosphorus concentrations were first regressed with total CPUE of striped bass and walleye separately. Striped bass and walleye biomasses were then combined, assuming these two pelagic species to be trophic equivalents (Ney et al. 1988), and regressed with total phosphorus concentration. One to three year time lags of total phosphorus concentrations behind gill net biomass estimates were also tested in a regression model to assess any delayed response of walleye and striped bass to changes in phosphorus concentrations.

Striped bass CPUE data were further partitioned into ages 0, 1, 2, and 3 fish and regressed with both whole-lake total phosphorus concentrations and whole-lake total phosphorus concentrations and stocking rates. This was done because striped bass diet and distribution change with age and abundance, and younger fish are probably more vulnerable to starvation and predation. Stocking and total phosphorus data were then lagged one year behind age-1 striped bass to evaluate the effect of changing total phosphorus concentrations on striped bass survival after stocking. Fish older than age 3 were not accurately sampled due to small sample size ($<$3 fish/1000 m^2 net). Catch-per-unit-effort data for walleye were not partitioned by age because no stocking took place in 1976 or from 1980-84.

Total harvest and harvest of four major game species (striped bass, walleye, largemouth bass, smallmouth bass) in SML were also regressed with whole-lake total phosphorus concentration for the six years in which creel census data were available. This was done to assess phosphorus as a predictor of fish harvest as well as fish biomass.

Southern Appalachian Reservoirs

Regression Analyses

Linear regression analysis was conducted matching fish standing stock data and total phosphorus concentration for each southern Appalachian reservoir (N=22). Fish standing stock data used in this analysis were from 1973, or the closest year in which data were available within a two-year time span of 1973 (1971-75), and were developed by conventional cove rotenone techniques described by Davies and Shelton (1983). The data set was then narrowed to include only reservoirs with standing stocks from 1973 (N=12) to assess how much more of the phosphorus/fishery relationship could be explained using data from the same year. Ninety percent confidence intervals were set to estimate the robustness of the model and to determine if any outliers existed in the data. Confidence intervals were determined according to procedures described by Ott (1984).

Next, multiple stepwise regression (R-square procedure, SAS 1985) was used to evaluate the importance of total phosphorus concentration in comparison to and in conjunction with other physical and chemical factors in the prediction of total standing stock for southern Appalachian reservoirs. The R-square procedure evaluates all independent variables separately and in all combinations in a regression model. Independent variables of total phosphorus concentration, surface area, Secchi disk depth, retention time, phosphorus loading, chlorophyll-a concentration, total nitrogen concentration, and mean depth were obtained from the NES directly. Additional independent variables were derived from these data and tested, including MEI, total phosphorus/surface area, total phosphorus/mean depth, and total phosphorus/ Secchi disk depth X surface area. These variables combine both morphometric and edaphic reservoir characteristics. Total dissolved solid (TDS) data were not available; therefore the equation, conductivity (μMHO's) X 0.65 = TDS (mg/l), was used to calculate the MEI (Rainwater and Thatcher 1960). This conversion has been used in lakes throughout the world (Oglesby 1977a, Schlesinger and Regier, 1982).

For comparison to SML data, total phosphorus was next regressed with individual fish species and trophic group subsets of total standing stock. Groups evaluated in the linear model included planktivorous fish, benthophagous fish, and piscivores. Standing stocks of most individual species were excluded from SAR analyses because species composition was highly variable among reservoirs. Also, subsets of total standing stocks from the years 1974 and 1975 were regressed separately for each year with 1973 total phosphorus concentrations to evaluate one and two year time lag effects. Sportfish harvest data from southern Appalachian reservoirs could only be obtained for 7 reservoirs. For this reason and because of the characteristic variability of creel survey data, due to differing data collection methods, sportfish harvest in southern Appalachian reservoirs were not evaluated in this study.

Data Subsets

Southern Appalachian reservoir fish standing stock and phosphorus data were divided into subsets to evaluate the effect of potentially influential factors on model variability and predictive strength. These tests grouped reservoirs based on high and low values of mean depths, surface areas, Secchi disk depths, and retention times to determine if the phosphorus-fish relationship varied predictably with reservoir characteristics. The SAR data set was split at or near where disjunctions in the independent variables occurred and allowed for balanced sample size for both high and low-valued subsets.

RESULTS

Smith Mountain Lake

Relationships between total phosphorus concentrations and phosphorus load, fish harvest, and fish standing stock in Smith Mountain Lake are described. Phosphorus load, fish harvest and gill net data were collected as whole-lake values, and therefore their relationships to total phosphorus concentrations are analyzed as whole-lake paired data over time. To analyze the relationship between fish standing stock and total phosphorus concentrations, both cove-specific and whole-lake data pairings were used. In both instances, fish standing stock data were partitioned into total standing stock, individual species standing stock, trophic groups, and age groups. The fishery productivity-phosphorus relationship was also analyzed for a time delay effect, lagging phosphorus data one to five years behind fishery data.

Total Phosphorus-Phosphorus Load Relationship

Determination of annual phosphorus load into Smith Mountain Lake involved the estimation of: 1) incoming stream total phosphorus concentrations (mg/l) from incoming stream orthophosphorus concentrations (mg/l); and 2) sedimentation rate of total phosphorus in the reservoir. The proportional relationship between ortho- and total phosphorus for 1973 versus 1978 data (mean values) were within 10% of each other for the Roanoke River and Back Creek and within 2% of each other for the Blackwater River and so were judged to be typical for these systems. Conversion factors used to predict total phosphorus concentration from orthophosphorus were orthophosphorus concentration times 2.04, 1.89, and 4.12 for the Roanoke River, Back Creek, and the Blackwater River, respectively.

Based on microshed (areas of similar land use within the same watershed) storm and base flow samples, Obenshain and McLeod (1981) found orthophosphorus to make up 50% of total phosphorus in SML. Conversion factors calculated for the Roanoke River and Back Creek both fall in this range (0.49 and 0.53). The conversion factor for the Blackwater River however, shows orthophosphorus to make up only 24% of the total phosphorus concentration in this stream.

The sedimentation rate giving the highest correlation ($r^2=0.91$) between total phosphorus concentrations predicted by the phosphorus loading model and measured total phosphorus concentrations weighted by surface area for eight years was 0.2. The sedimentation term is a correction factor used along with hydraulic flushing rate (i.e. the inverse of retention time) to adjust phosphorus load coming into the reservoir by that leaving the reservoir when calculating total phosphorus concentration. The sedimentation term incorporates sedimentation with the errors of all other variables in the phosphorus loading model and should not be interpreted to mean that 20% of the phosphorus load to the lake ends up in the sediments.

Using the above estimates of incoming stream total phosphorus concentrations and reservoir sedimentation rates, phosphorus loading per year into Smith Mountain Lake was estimated from the NES equation. Estimated total phosphorus loading into Smith Mountain Lake decreased from 69,000 kg/year in 1973-74 to 48,500 kg/year in 1977-78, and in the early 1980's has fluctuated between 25,000 and 35,000 kg/year (Table 6). Overall loading in the Roanoke River has decreased from 42,500 kg/year to 7,500 kg/year, which is an 82% decline. During this same period, loading to the lake from the Blackwater River has quadrupled, increasing from 4000 to 16,000 kg/year (Table 6). Phosphorus load for 1975, 1976, 1978, 1983, and 1984 could not be determined due to missing tributary phosphorus and/or orthophosphorus concentration data.

Table 6. Estimated phosphorus loading to Smith Mountain Lake in kilograms per year.

Source	Phosphorus loading (kg/yr)					
	1974	1977	1979	1980	1981	1982
Roanoke River	42636	21532	7612	8767	7524	7490
Blackwater River	4730	9090	6596	5946	11654	15979
Back Creek	1858	2538	2851	1725	1783	1957
Immediate Drainage	18001	12930	6654	6268	8095	9638
Precipitation	1931	2243	1639	1163	1834	1755
Septic Tanks	218	218	218	218	218	218
Total Load	69175	48551	25570	24087	31108	37037

Total Phosphorus - Standing Stock Relationship

Cove - Specific Analysis

Simple linear regression indicated that cove-specific total fish standing stock and some individual species' standing stock in coves varied significantly ($P<0.05$) with total phosphorus concentration. However, the predictive value of the relationship is limited as the amount of variation in total standing stock explained by differences in total phosphorus concentrations is low ($r^2=0.21$; Figure 3).

Data transformation was performed to improve the model's predictability. Attempted transformations of both the independent (total phosphorus concentrations) and dependent (total standing stock) variables included logs, squares, square roots, inversions, and other standard practices. Of 17 different combinations of transformations, the highest correlation was achieved when both standing stock and total phosphorus were log-ten transformed (Table 7). Nonparametric regression showed coefficients of determination approximately matching those arrived at using a log/log transformation ($r^2=0.43$). Parametric tests have more power, the probability of correctly rejecting a false hypothesis, than nonparametric tests (Hollander and Wolfe 1973) and therefore log-ten transformations of both variables were used throughout the remaining tests of the total phosphorus-fishery relationship.

The total standing stock - total phosphorus relationship evaluated in the transformed data model had a coefficient of determination of 0.38 (Figure 3). Standing stocks of abundant species (those occurring in 15 or more of the 29 samples) that were found to significantly vary with phosphorus concentrations in the log transformed model were gizzard shad, bluegill (*Lepomis macrochirus*), channel catfish (*Ictalurus punctatus*), and redhorses (*Moxostoma sp.*; Table 8). Tests grouping standing stock by trophic level resulted in significant r^2 values for forage fish and benthophagous fish, but no relationship for piscivorous fish (Table 8).

Gizzard shad comprised 58% by weight of all fish and 90% by weight of all prey species collected in SML cove rotenone collections, and largemouth bass contributed 60% of the total predatory game fish biomass in these studies. Due to their littoral zone occurance, gizzard

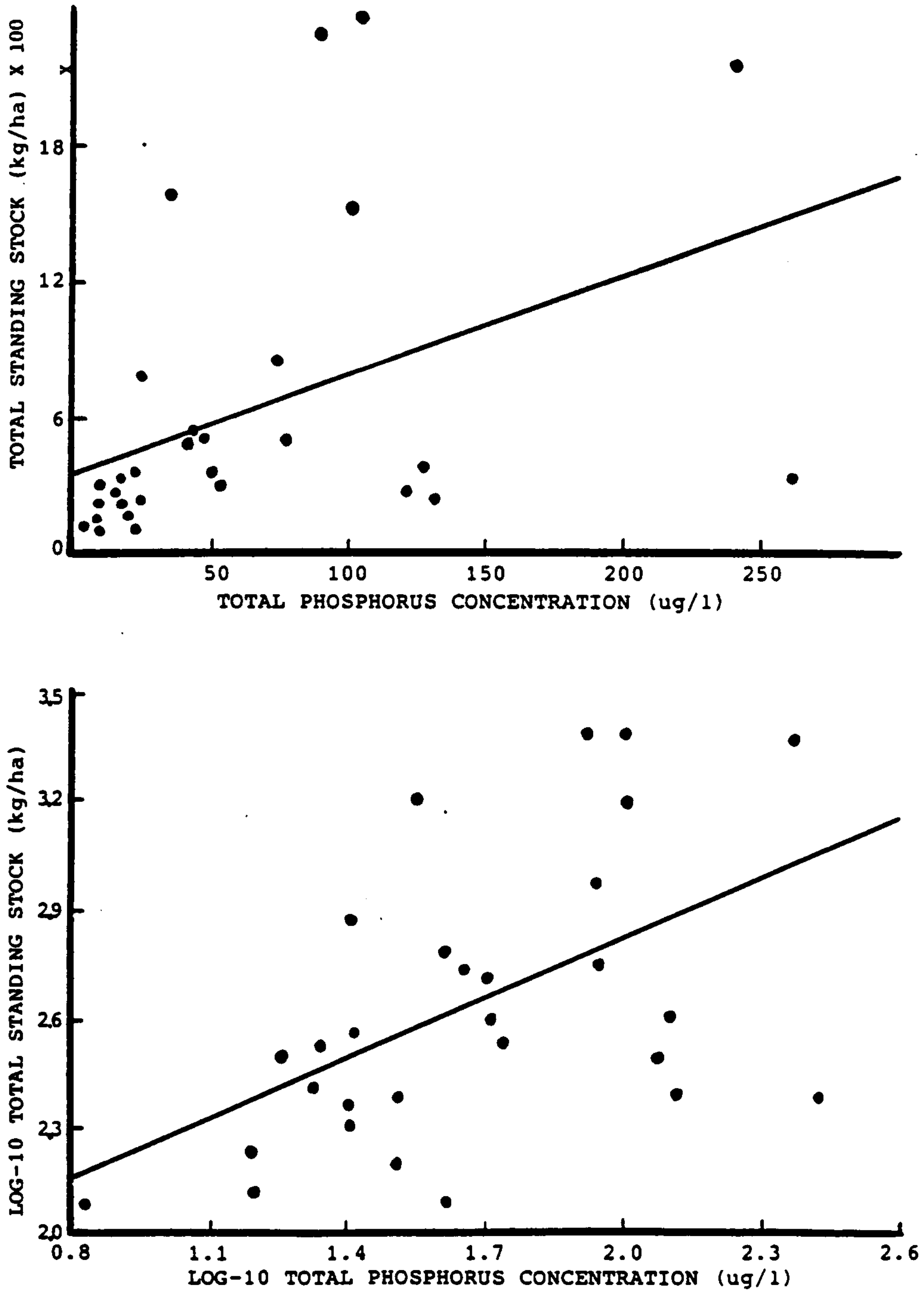

FIGURE 3. Regressions of cove-specific total phosphorus concentrations versus total fish standing stock in a untransformed (top) and transformed (bottom) linear model for Smith Mountain Lake.

Table 7. Transformations of total phosphorus concentration (x) and total standing stock (y) and resulting coefficients of determination in the simple linear regression model ($n=29$).

Transformation	r^2	P
x vs. y (untransformed)	0.24	0.0061
$1/x$ vs. y	0.18	0.03
$\frac{1}{\sqrt{x}}$ vs. y	0.21	0.01
x^2 vs. y	0.18	0.02
$\log_{10} x$ vs. $\frac{1}{\sqrt{y}}$	0.17	0.03
$\log_{10} x$ vs. $1/y$	0.07	0.17
$\log_{10} x$ vs. y^2	0.18	0.02
x vs. $\log_{10} y$	0.27	0.003
x vs. $1/y$	0.03	0.38
x vs. $\frac{1}{\sqrt{y}}$	0.09	0.11
$\frac{1}{\sqrt[3]{x^2}}$ vs. $\log_{10} y$	0.33	0.001
x^2 vs. $\log_{10} y$	0.15	0.03
$1/x$ vs. $\log_{10} y$	0.37	0.0004
$\frac{1}{\sqrt{x}}$ vs. $\log_{10} y$	0.38	0.0003
$\log_{10} x$ vs. $\log_{10} y$	0.38	0.0005

Table 8. Summary of log-10 linear regressions between cove-specific pairings of fish standing stock and total phosphorus concentration for Smith Mountain Lake, 1973-1984.

Category	r^2	P	Observations
Total Standing Stock	0.38	0.005	29
Trophic Groups			
Planktivores	0.32	0.001	29
Benthophages	0.23	0.01	29
Piscivores	0.02	0.42	29
Species			
Gizzard Shad	0.38	0.004	29
Redhorses	0.34	0.01	19
Bluegill	0.31	0.01	29
Channel Catfish	0.29	0.01	29
Smallmouth Bass	0.13	0.07	27
Largemouth Bass	0.01	0.55	29

shad and largemouth bass were sampled in sufficient quantities by cove rotenoning to further partition them by age. Total phosphorus concentration was significantly correlated with gizzard shad standing stock for all ages, explaining a maximum of 49% of the variation for age-1 fish. Largemouth bass biomass was not significantly correlated to phosphorus concentrations for any age subset (Table 9).

Time lags of one through five years of total phosphorus concentrations behind fish standing stock data did not significantly improve the model's predictability (Table 10). Total phosphorus concentration explained 4 to 37% less variation in total standing stock when lagged 1 to 5 years behind total standing stock data than in a no-lag situation. Correlations were found to increase slightly for gizzard shad, the principle forage species in SML, with a one year lag but, results were not significant past a one year lag. Standing stock of largemouth bass was not significantly correlated to total phosphorus concentration for matching years, and this did not change for 1 to 5 year time lags.

Whole - Lake Analysis

Evaluating Smith Mountain Lake as a whole in the total phosphorus-fish standing stock model decreased sample size from 29 cove-specific data pairs to seven for whole-lake values using surface area weighted phosphorus concentrations. An additional 2 data pairs were added when phosphorus loading data were used to obtain missing whole-lake total phosphorus concentrations (Figure 4). Total phosphorus concentrations could not be calculated for the years 1975 and 1976 due to the lack of data collection in both the lake and incoming streams for those years. Cove rotenone studies were not carried out in 1978 and; therefore, fish standing stock data were not available for that year (Appendix Table3).

In the whole-lake model, total phosphorus concentration explained 69% of the variation in total standing stock (Figure 5), a value almost twice that for cove-specific analysis. Four species also had significant correlations with phosphorus on a whole-lake level basis (Table 11) but only one of these, gizzard shad, is highly abundant in SML. Biomasses of largemouth

Table 9. Variation explained by cove-specific pairings of total phosphorus concentrations with gizzard shad and largemouth bass standing stock partitioned by age in a log-linear model.

Species	Age	N	r^2	P
Gizzard shad	0	29	0.137	0.048
	1	29	0.486	<0.001
	2	29	0.265	0.004
	3	29	0.195	0.016
	4	29	0.142	0.044
Largemouth bass	0	29	0.004	0.75
	1	28	0.078	0.15
	2	28	0.076	0.15
	3	29	0.082	0.13
	4	29	0.008	0.64
	5	27	0.005	0.72

Table 10. Results of cove-specific pairings of total phosphorus concentration behind standing stock of select fish species and total standing stock (lagged 1 to 5 years) in a log-linear model.

Fish Parameter	Lag (years)	N	r^2	P
Gizzard Shad	0	29	0.38	<0.01
	1	30	0.42	<0.01
	2	27	0.04	0.34
	3	23	0.06	0.23
	4	18	0.00	0.88
	5	14	0.25	0.07
Largemouth Bass	0	29	0.01	0.55
	1	29	0.06	0.21
	2	27	0.00	0.87
	3	23	0.03	0.46
	4	18	0.04	0.43
	5	13	0.15	0.17
Total Standing Stock	0	29	0.38	<0.01
	1	30	0.13	0.07
	2	28	0.07	0.18
	3	24	0.13	0.09
	4	19	0.01	0.70
	5	14	0.34	0.03

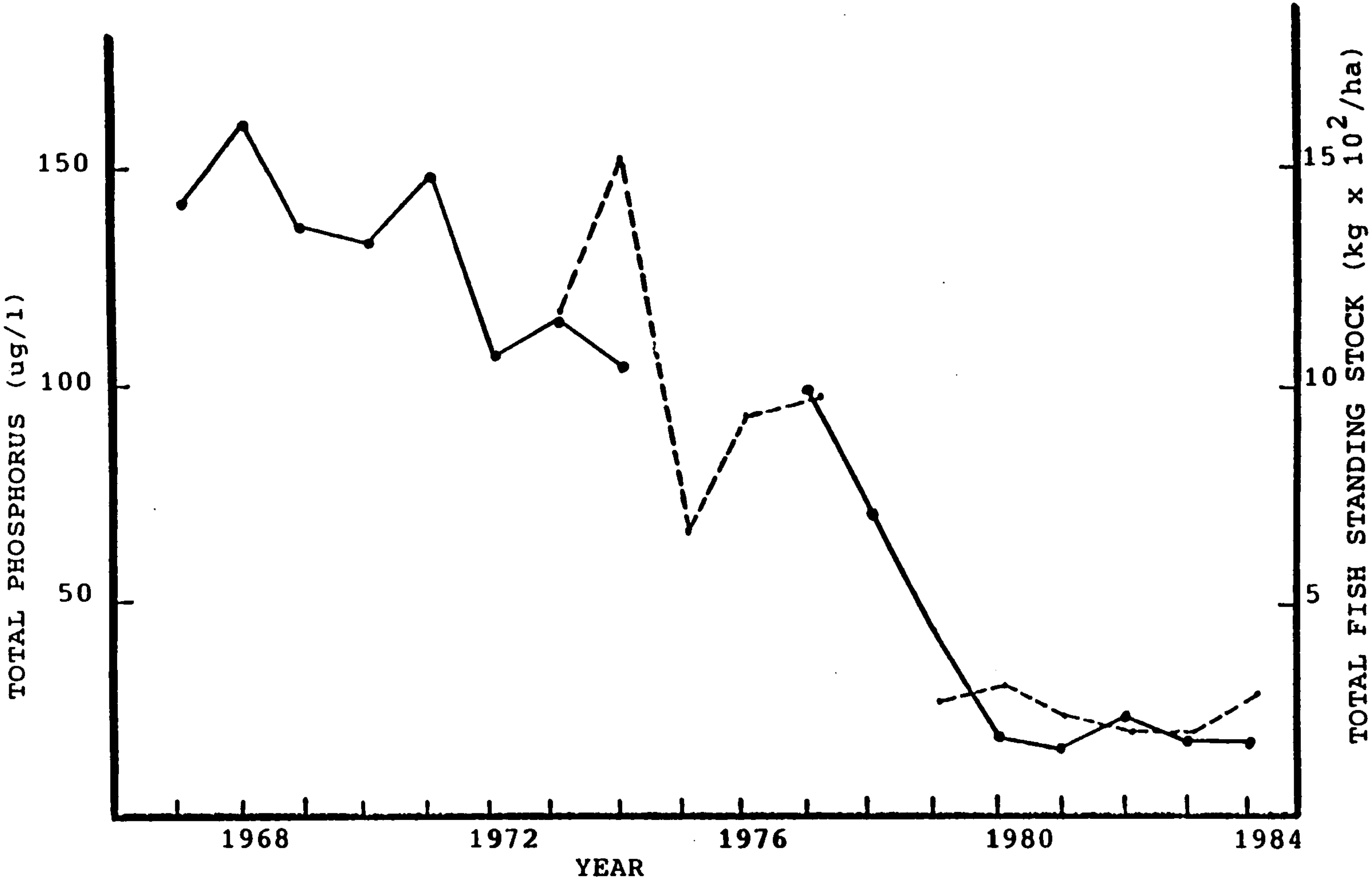

FIGURE 4. Mean annual total phosphorus concentration (solid line) and fish standing stock (dashed line) in Smith Mountain Lake over time.

bass and other game fish were not significantly correlated with whole-lake total phosphorus concentrations.

Trophic group analysis in the whole-lake total phosphorus-fish regression model resulted in a significant coefficient of determination for forage fish ($r^2=0.66$) and nonsignificant correlations for piscivorous and benthophagous fish. This contrasts with cove-specific results where benthophagous as well as planktivorous fish standing stock was significantly correlated to total phosphorus concentrations. The whole-lake age analysis was very similar to the cove-specific results for both gizzard shad and largemouth bass partitioned by age (Table 12). Both showed an increase in r^2 between age-0 and age-1 and a decrease at age-2 for gizzard shad. The amount of variation in largemouth bass standing stock grouped by age increased to statistical significance only for age-0 fish in comparison to cove-specific results.

Phosphorus data were lagged one, two, and three years behind largemouth bass, gizzard shad, and total standing stock data in the whole-lake model. Four and five year lags were not attempted here due to small sample size. Predictability of total standing stock or gizzard shad standing stock did not improve over 1 to 3 year lag periods, as correlations were nonsignificant for all lag periods. Largemouth bass correlation to total phosphorus was best with a three year lag ($r^2=0.17$), but this value was far from statistically significant ($p=0.59$) as were r^2 values for all time lag periods for this species (Figure 6).

Pelagic Sportfish

Pelagic sportfish (walleye and striped bass) are not adequately sampled using cove rotenone techniques (Henderson 1980). Estimates of relative abundance of these species were obtained from standardized gill netting samples over the period 1974-1984. Regressions plotting relative abundance (catch per unit effort) estimates of striped bass or walleye from gill net data against whole-lake total phosphorus concentrations were found to be nonsignificant (Table 13). Combining CPUE of striped bass and walleye by year and plotting

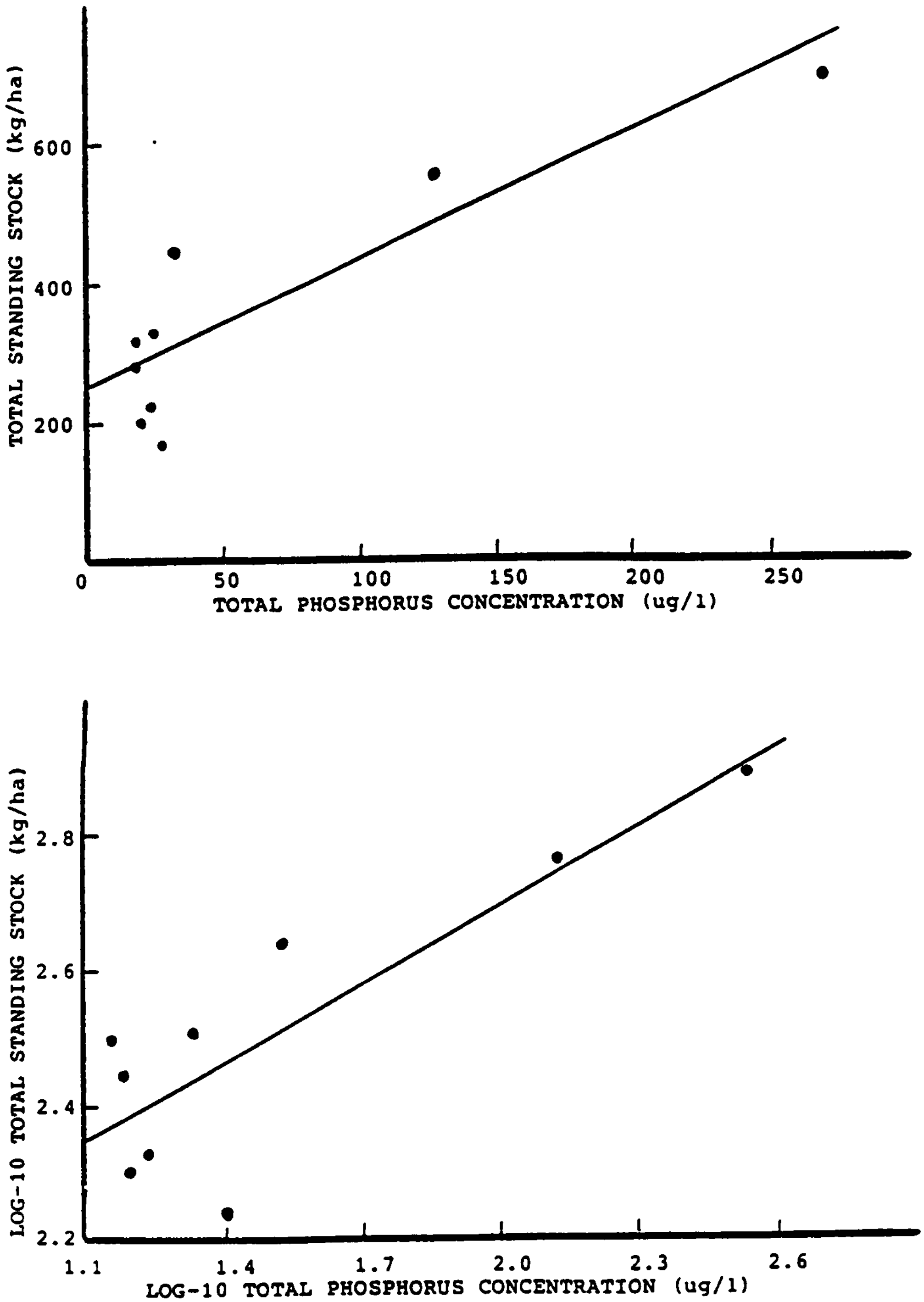

FIGURE 5. Regressions of whole-lake total phosphorus concentrations versus total fish standing stock in a untransformed (top) and transformed (bottom) linear model for Smith Mountain Lake.

Table 11. Summary of log-10 linear regressions between whole-lake pairings of fish standing stock and total phosphorus concentration for Smith Mountain Lake, 1973-1984 (N=9).

Category	r^2	P
Total Standing Stock	0.69	0.01
Trophic Groups		
Planktivores	0.66	0.01
Benthophages	0.14	0.31
Piscivores	0.03	0.68
Species		
Pumpkinseed	0.70	0.02
Gizzard Shad	0.66	0.03
Black Crappie	0.65	0.05
Yellow Perch	0.57	0.05
Bluegill	0.17	0.52
Channel Catfish	0.09	0.51
Largemouth Bass	0.01	0.92
Smallmouth Bass	0.01	0.96

Table 12. Variation explained by whole-lake pairings of total phosphorus concentrations with gizzard shad and largemouth bass standing stock partitioned by age in a log-linear model (N=9).

Species	Age	r^2	P
Gizzard shad	0	0.04	0.60
	1	0.57	0.02
	2	0.09	0.44
	3	0.56	0.02
	>4	0.60	0.01
Largemouth Bass	0	0.47	0.04
	1	0.003	0.89
	2	0.03	0.66
	3	0.17	0.27
	4	0.008	0.82
	5	0.06	0.52

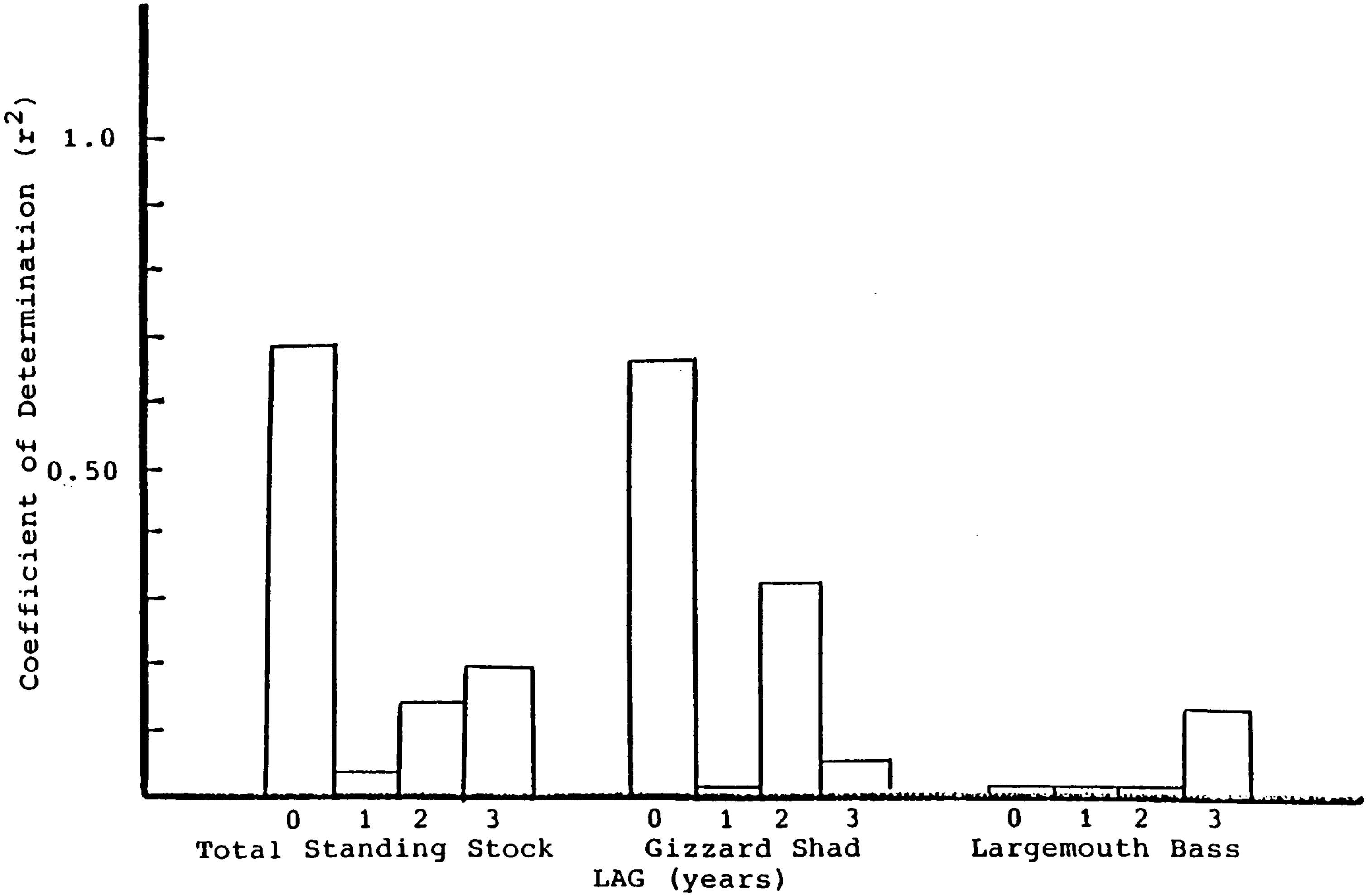

FIGURE 6. Percent of variation (r^2) in standing stock of fishes explained by lagging total phosphorus 0 to 3 years behind standing stock estimates.

against total phosphorus concentrations in matching years did not improve the fit of the model (r^2=0.08; P=0.47). Time lags of one to three years of total phosphorus concentrations behind walleye and striped bass standing stock resulted in nearly significant (P=0.06) coefficient of determination at one year for striped bass (Table 13).

Partitioning striped bass CPUE data by age resulted in nonsignificant correlations with whole-lake total phosphorus concentrations for all ages (Table 14). Use of stocking densities matched to appropriate cohorts along with total phosphorus concentrations as independent variables in a multiple regression did not significantly improve the regressions' predictability (Table 14). Lagging of total phosphorus concentration and striped bass stocking data one year behind age-1 striped bass also did not improve predictability (r^2=0.11; P=0.69).

Total Phosphorus-Fish Harvest Relationship

The whole-lake fish harvest data relationship to whole-lake total phosphorus concentration was not significant in the transformed regression model (r^2=0.02; P=0.92). This is not surprising as only four years of harvest data could be matched to whole-lake total phosphorus concentrations, and these data were collected by two different sampling techniques. Harvest data were not further partitioned to the species level because sample size was deemed too small to make species-specific inferences. Striped bass and walleye populations exploded via stocking during this time period, confounding attempts to relate harvest to fertility. However, a two-fold total harvest decline was noted between 1973 and 1980. During this same period, harvest of largemouth bass declined ten-fold (Figure 7).

Table 13. Results of whole lake total phosphorus concentration lagged 0 to 3 years versus walleye and striped bass relative abundance estimates from gill netting data.

Fish Parameter	Lag	N	r^2	P
Striped Bass	0 year	9	0.21	0.22
	1 year	9	0.61	0.06
	2 years	7	0.26	0.23
	3 years	7	0.01	0.87
Walleye	0 year	6	0.02	0.77
	1 year	5	0.01	0.90
	2 years	5	0.12	0.57
	3 years	4	0.60	0.23
Walleye	0 year	9	0.08	0.47
and	1 year	9	0.07	0.49
Striped Bass	2 years	7	0.01	0.90
	3 years	7	0.20	0.26

Table 14. Striped bass CPUE subsetted by age versus total phosphorus and total phosphorus with stocking densities of matching cohorts in a log-linear model ($n=9$).

Independent Variable(s)	Age	r^2	P
Total phosphorus	0	0.06	0.52
	1	0.25	0.17
	2	0.07	0.50
	3	0.12	0.37
Total phosphorus, Stocking	0	0.08	0.81
	1	0.30	0.35
	2	0.29	0.15
	3	0.13	0.28

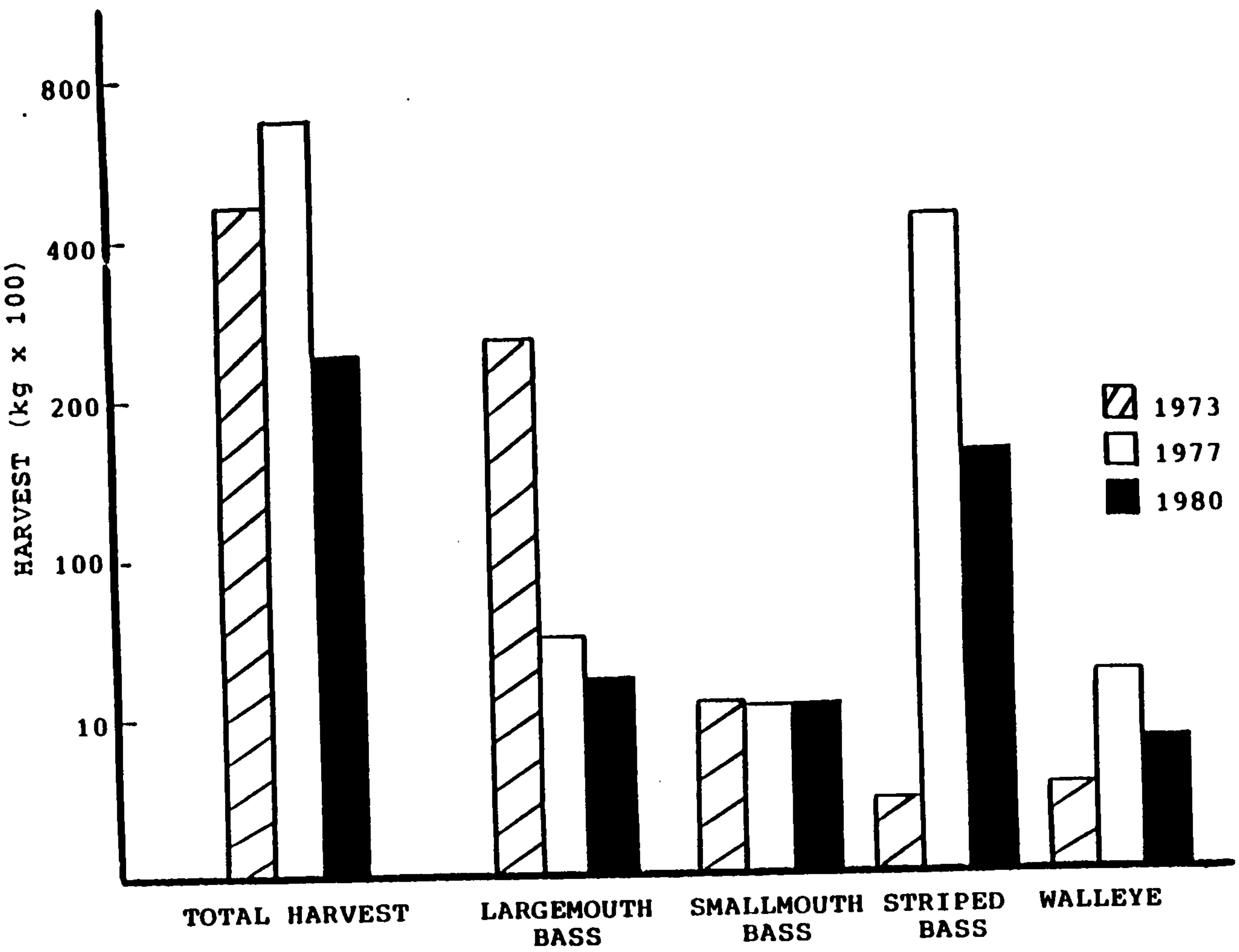

FIGURE 7. Estimated sportfishing harvest in Smith Mountain Lake.

Southern Appalachian Reservoirs

Regression Analyses

Twenty-two reservoirs in six states met the criteria of size, location, and availability of synchronous water-quality and fish data stipulated for the southern Appalachian reservoir data set (Figure 2). Reservoirs ranged in size from 463 ha to 53,388 ha, in mean depth from 5.2 m to 29 m, and in total standing stock from 34 kg/ha to 2321 kg/ha (Table 3). Physical and chemical lake parameters were regressed against log-ten transformed total standing stock of fish for the southern Appalachian reservoir (SAR) data set. Standing stock data were log-ten transformed to be consistent with Smith Mountain Lake regressions so that predictions from SAR data could be compared to reality in SML. Transformation of the data increased the explanatory power of the regression from 59% in the untransformed model to 75% in the log-10 transformed model of total phosphorus versus total fish standing stock (Figure 8). Regression analysis revealed an outlier (greater than 2 standard deviations away from the predictive line) reservoir in the data set (Flannagan Reservoir, Virginia). It was subsequently discarded, reducing the SAR data set to 21 reservoirs and raising the coefficient of determination to 0.83.

Independent variables were measured in 1973 (NES 1975), while fisheries data were obtained within two years of this time (1971-1975). Log-ten transformed total phosphorus was the best predictor of total fish standing stock (Table 15). Ninety percent confidence intervals were within 3.8% of predicted total fish standing stock in the log-10 transformed model (Figure 8). Ninety percent predictive limits fell within 11.1% of predicted total fish standing stock. All 21 points fell within 11.05% of the predicted, log-10 transformed standing stock (mean deviation 4.5%). Mean square error used to develop confidence limits is 0.03621. The regression equation developed for southern Appalachian reservoirs is:

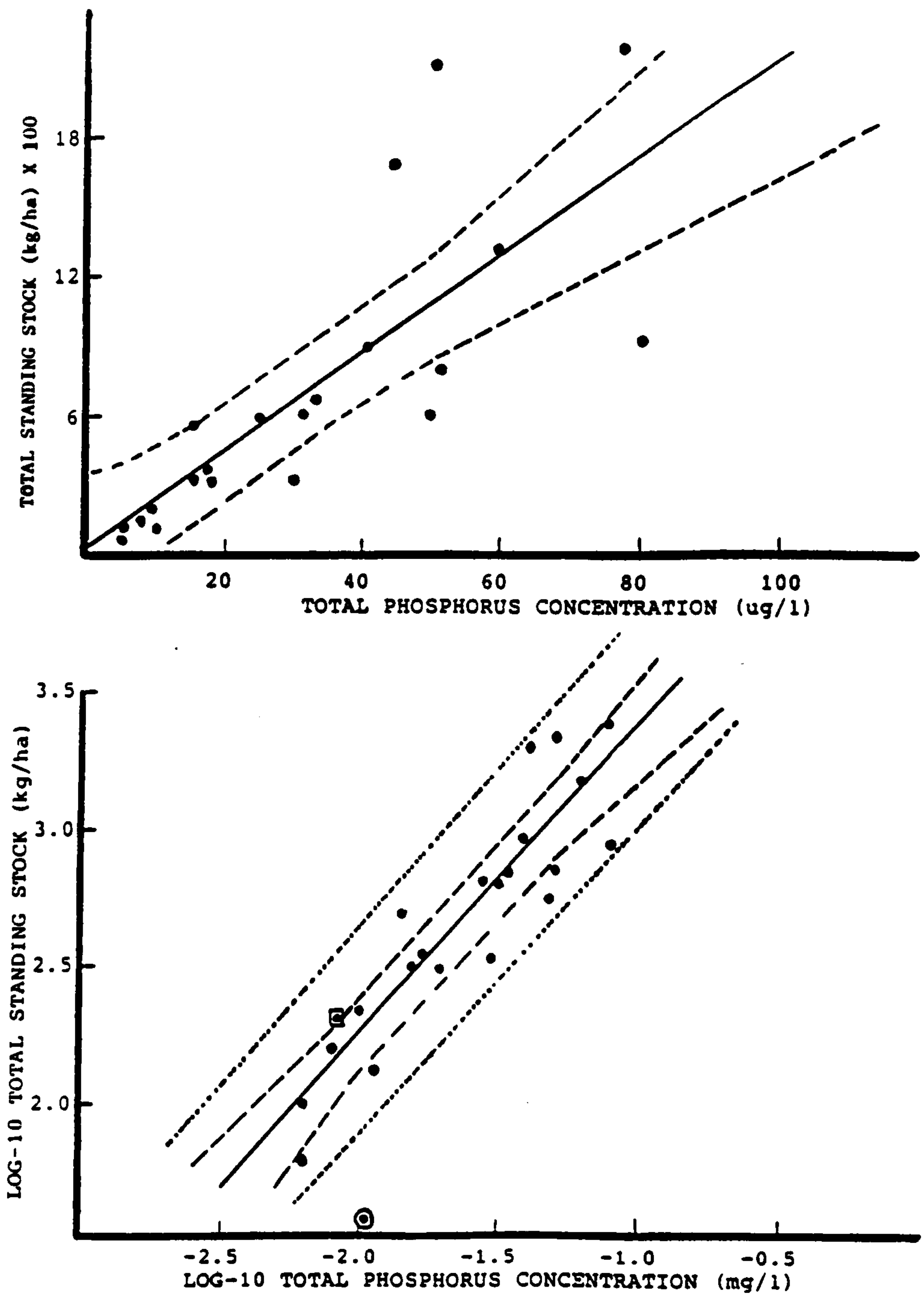

FIGURE 8. Regressions of total phosphorus concentration versus total fish standing stock in a untransformed (top) and transformed (bottom) linear model with 90% confidence intervals (dashed lines) and predictive limits (dotted lines) for 22 southern Appalachian reservoirs. Flannagan Reservoir, Virginia is circled as outlier. The dot in the square indicates the fit of Smith Mountain Lake data (1981-1983) to the SAR regression.

$$\log_{10}(\text{Total SS}) = 4.369 + 1.050 \log_{10}(\text{TP})$$

where standing stock (SS) is expressed in kg/ha and total phosphorus (TP) concentration is in mg/l.

Weaker but significant relationships were evident between total standing stock and some independent variables that have shown good predictive value in temperate natural lakes, notably chlorophyll-a, but were nonsignificant for others, notably MEI (Table 15). Correlations between fish standing stock and physico-chemical parameters were slightly higher when the reservoir data set was restricted to 1973 standing stock estimates. Again, total phosphorus concentration was found to be the best predictor, of variables tested, of total fish standing stock ($r^2=0.94$) for the 1973 data set.

Log-10 total phosphorus concentrations (1973) were regressed with log-10 individual species and trophic group standing stocks (Appendix Table 4) for the year closest to 1973 for 21 southern Appalachian reservoirs (Table 16). Only species reported for 15 or more systems were included. Significant results were found for three planktivorous fish (gizzard shad, threadfin shad, and bluegill) and one benthophage (channel catfish). Coefficients of determination for trophic group relationship to total phosphorus showed standing stocks at lower levels of the food chain to be more predictable than standing stocks at higher levels. Coefficients of determination were highly significant for planktivores ($r^2 = 0.79$) and benthophages ($r^2 = 0.41$), but no relationship was evident for piscivores (Table 16). Lagging of total phosphorus concentration one and two years behind total, trophic group, and individual species standing stock data reduced the model's predictability over a no-lag situation (Table 17).

Use of several independent variables to predict fish standing stock in multiple stepwise regression analysis resulted in improvement of only a maximum of 5.5% using two independent variables and 7.6% using three independent variables over predictive capabilities of log-10 phosphorus concentrations alone (Table 18). Additional variation in fish standing stock could be explained by retention time and log-10 chlorophyll-a concentration.

Table 15. Regressions of total standing stock (kg/ha) versus potential determinant variables in southern Appalachian reservoirs. Standing stock data obtained over the 1971-75 period (N=21). Regressions with standing stock data obtained only in 1973 (year of phosphorus data) are also included (N=11).

	1971-1975 S.S. Data Set		1973 S.S. Data Set	
Independent Variable	r^2	P	r^2	P
Log_{10}TP	0.83	<0.0001	0.94	<0.0001
Secchi Disk Depth	0.51	0.0002	0.46	0.022
Log_{10}Chlorophyll-a	0.47	0.001	0.49	0.017
Log_{10}TP/Surface Area	0.42	0.001	0.27	0.102
Log_{10}P-Load	0.39	0.003	0.46	0.022
Surface Area	0.07	0.236	0.10	0.346
Total Nitrogen	0.07	0.255	0.19	0.246
Mean Depth	0.03	0.427	<0.01	0.872
Log_{10}TP/Mean Depth	0.01	0.757	0.07	0.429
Retention Time	0.01	0.673	0.03	0.622
MEI	<0.01	0.957	0.24	0.125

Table 16. Summary of log-10 regressions between fish standing stock and total phosphorus concentration for 21 southern Appalachian reservoirs.

Category	r^2	P	Observations
Total Standing Stock	0.83	<0.01	21
Trophic Groups			
Planktivores	0.79	<0.01	21
Benthophages	0.41	<0.01	21
Piscivores	0.01	0.68	21
Species			
Threadfin Shad	0.44	<0.01	18
Channel Catfish	0.37	0.01	16
Bluegill	0.30	0.02	19
Gizzard Shad	0.25	0.05	16
Largemouth Bass	0.09	0.19	21
Carp	0.06	0.32	19

Table 17. Comparison of total phosphorus concentrations from southern Appalachian reservoirs lagged 0 to 2 years versus fish standing stock partitioned by species and trophic group in a log-linear model.

Category	Lag	N	r^2	P
Total Standing Stock	0 year	11	0.94	0.0001
	1 year	10	0.70	0.001
	2 years	9	0.74	0.003
Trophic Groups				
Planktivores	0 year	11	0.84	0.0001
	1 year	10	0.67	0.04
	2 years	8	0.51	0.27
Benthophages	0 year	11	0.44	0.02
	1 year	10	0.40	0.05
	2 years	9	0.37	0.03
Piscivores	0 year	11	0.51	0.01
	1 year	10	0.36	0.07
	2 years	9	0.05	0.56
Species				
Gizzard Shad	0 year	8	0.56	0.03
	1 year	7	0.15	0.40
	2 years	5	0.43	0.23
Largemouth Bass	0 year	11	0.50	0.01
	1 year	10	0.29	0.11
	2 years	9	0.09	0.42

Independent variables which did not improve the phosphorus-fish standing stock model were surface area, log-10 phosphorus load, Secchi disk depth, mean depth, and the MEI.

Data Subsets

Reservoir data sets split approximately in halves and their standard deviations are: 1) retention time: high (n=11, (228 days +/- 124)) vs. low (n=11, (23.5 days +/- 5.4)), 2) Secchi disk depth: high (n=10, (2.6 meters +/- 0.9)) vs. low (n=12, (1.1 meters +/- 0.25)), 3) mean lake depth: high (n=13, (18.9 meters +/- 5.4)) vs. low (n=9, (7.3 meters +/- 2.1)), and 4) surface area: high (n=12, (171.4 km^2 +/- 156.7)) vs. low (n=10 (17.4 km^2 +/- 11.9)). Results of phosphorus-fishery regressions for the high and low range of each of these split data sets are shown in Table 19. The explanatory power of the phosphorus-fishery model for data subsets increased over that found with the whole data set for lakes with a mean depth greater than 10 m, those with a surface area less than 50 km^2, and for lakes subset by retention time. These findings indicate total phosphorus to be a better predictor of fish standing stock in deep rather than shallow impoundments, in clear rather than turbid systems, and in those reservoirs with a surface area of less than 50 km^2. Smith Mountain Lake fits into the categories of: 1) high retention time (3.2 years); 2) high transparency (mean Secchi disk of 2 meters); 3) deep (mean depth = 17 meters); and 4) relatively large size (surface area = 80.94 km^2).

Table 18. Simple and multiple regression relationships of log-10 total fish standing stock (TSS) to chemical and physical variables in 21 southern Appalachian reservoirs.

Variables	MSE	r^2	Equation
Log-10 Total phosphorus (TP)	0.0362	0.83	TSS = 4.3688 + 1.04996(TP)
Secchi disk (SD)	0.0868	0.51	TSS = 3.18867 - 0.28714 (SD)
Log-10 chlorophyll-a (C)	0.0946	0.47	TSS = 1.8554 + 1.13164 (C)
Log-10 phosphorus load (PL)	0.1086	0.39	TSS = 0.78627 + 0.35220 (PL)
Total nitrogen (TN)	0.1654	0.07	TSS = 2.39323 + 0.42022 (TN)
Surface area (SA)	0.1644	0.07	TSS = 2.5973 + 0.00079 (SA)
Mean Depth (MD)	0.1714	0.03	TSS = 2.8237 - 0.0102 (MD)
Retention time (RT)	0.1757	0.01	TSS = 2.7178 - 0.00029 (RT)
MEI	0.1027	<0.01	TSS = 2.8410 + 0.00078 (MEI)
TP, RT	0.0215	0.87	TSS = 4.4426 + 1.15548 (TP) + 0.00076 (RT)
TP, RT, C	0.0205	0.89	TSS = 4.1095 + 1.04407 (TP) + 0.00065 (RT) + 0.2301 (C)

Table 19. Results of regressing total phosphorus concentrations (mg/l) versus total standing stock (kg/ha) in a log-linear model for southern Appalachian reservoirs partitioned based on abiotic characteristics.

Abiotic Subset	r^2	N	P	Equation
Retention time				
High (85-438 days)	0.92	10	<0.00001	TSS=4.809+1.2394(TP)
Low (4-63 days)	0.92	11	<0.00001	TSS=4.199+1.0124(TP)
Surface area				
High (59.09-648.71 km^2)	0.78	12	0.00013	TSS=4.208+0.9603(TP)
Low (4.63-30.7 km^2)	0.85	9	0.00042	TSS=4.393+1.0851(TP)
Mean depth				
High (3.9-8.8 meters)	0.89	12	<0.0001	TSS=4.681+1.2089(TP)
Low (1.6-3.5 meters)	0.57	9	0.01896	TSS=3.905+0.7893(TP)
Secchi disk depth				
High (1.5-4.3 meters)	0.65	9	0.00897	TSS=4.170+0.9540(TP)
Low (0.8-1.5 meters)	0.51	12	0.00896	TSS=4.231+0.9774(TP)

DISCUSSION

Smith Mountain Lake Phosphorus Loading

Prior to this study, phosphorus loading to Smith Mountain Lake (SML) had been estimated twice since impoundment in 1963. The first estimate, done in 1973 (USEPA 1975) concluded that: 1) the Roanoke River arm was eutrophic while the Blackwater River arm and main body of the lake were mesotrophic; 2) phosphorus was the limiting nutrient; and 3) 51.3% of the phosphorus load came from point sources, while 48.6% was accounted for from nonpoint sources. The second thorough measure of phosphorus loading to SML, conducted by the Virginia Water Control Board in 1978 (Obenshain and McLeod 1981), indicated that the lake as a whole was mesotrophic, phosphorus was still the limiting nutrient, and phosphorus loading to the lake had decreased by approximately 35% due to the installation of an advanced waste water treatment plant in the upstream city of Roanoke, Virginia.

Both studies used the NES phosphorus loading equation (USEPA 1975) to estimate phosphorus loading to SML. I also calculated phosphorus loading from incoming major tributaries of SML from 1979 to 1982 using the NES loading equation, but stream phosphorus concentrations had to be estimated from stream orthophosphorus concentrations for use in the equation. The proportion of orthophosphorus in total phosphorus is remarkably constant, but varies from site to site based on the amount of phosphorus in soils, topography, vegetative cover, quantity and duration of runoff flow, land use, and pollution (Wetzel 1983). Stream phosphorus and/or orthophosphorus concentrations were not recorded in 1983 and 1984; therefore, phosphorus loading estimates could not be calculated for these years.

Vollenweider (1968) found a 1:2 ratio of orthophosphorus to the total phosphorus which is exported as runoff. A study based on microshed storm and base flow samples found orthophosphorus to make up an average of 50% of the total phosphorus concentration in the

SML drainage basin (Obenshain and McLeod 1981). This agrees with estimates from the Roanoke River and Back Creek. The fraction of orthophosphorus making up total phosphorus in the Blackwater River differed possibly due to watershed characteristics. Differences between watersheds in SML, detailed in Obenshain and McLeod (1981), indicate the Blackwater watershed to be twice the size of the Roanoke watershed and percentage-wise to have less forested areas and more pasture land. Both the Roanoke River and Back Creek are in the same watershed. Alternatively, the ratio of 1:4 could be wrong. However, the ratio is based on data taken in two separate studies in 1974 and 1978 (USEPA 1975; Obenshain and McLeod 1981). Both studies indicate the orthophosphorus to phosphorus ratio to be within 2% of a 1:4 ratio.

Phosphorus load to SML from precipitation, septic input, and immediate drainage runoff also had to be estimated for 1979-1982. Average rainfall was estimated to contribute 0.02 $g/m^2/yr$ of total phosphorus to SML (USEPA 1975). This falls in the world-wide average range of 0.01 to 0.1 $g/m^2/yr$ cited by Wetzel (1983). Septic tank phosphorus load to SML was estimated to remain constant at 1977 levels for all years. This is questionable given the rate of urban development around the lake, but septic input made up less than 2% of the annual phosphorus load to SML, and slight errors in this estimate will have little effect on lake phosphorus concentrations.

To accurately estimate phosphorus loading to the immediate drainage, fixed interval sampling at each representative microshed would have to be measured along with additional samples taken corresponding to each storm in a given year. This was done in 1973 by the USEPA and in 1978 by the VWCB but is impractical to do every year. Immediate drainage phosphorus load to SML was therefore estimated as a percentage (26%) of total loading from the surrounding area based on 1978 measurements. This method assumes that changes in urbanization, land management practices, and precipitation affect the immediate drainage at the same rate they affect the incoming tributaries over time. This assumption cannot be verified, but seems reasonable given the relative geographical closeness of these areas.

Immediate drainage phosphorus load estimates followed the pattern of wet and dry years and varied 3000 kg/yr between 1979 and 1982.

Accuracy of the phosphorus load estimates was evaluated when results from the Jones and Bachmann (1984) model, which uses phosphorus load to estimate whole-lake total phosphorus concentration, were compared to whole-lake total phosphorus concentrations obtained by surface-area weighting actual sample concentrations from upper, middle, and lower SML. All estimates of whole-lake total phosphorus concentrations obtained using phosphorus loading estimates were slightly higher than those projected from surface area weighting of sample concentrations, but were within 10 μg/l (10% on average) in all cases. This indicates that the overall temporal pattern of SML total phosphorus concentration was accurately described.

Phosphorus loading to the lake decreased by a factor of two since the 1978 study and by a factor of three since the 1973 study. The 1973 study indicated a net annual phosphorus accumulation of 170,365 kg/yr in sediments (USEPA 1975). Continued decline from 1978 to about 1980 in phosphorus load was probably due to a decline in phosphorus from Roanoke River sediment re-entering the system (Obenshain and McLeod 1981). This is reflected in the 75% reduction in lake total phosphorus concentration between 1975 and 1984. Lake phosphorus concentrations have apparently stablized in the 1980's because concentrations have fluctuated between 14.4 and 20.3 μg/l from 1980 to 1984 with no apparent trend. This suggests that phosphorus surplus in sediments is either used up or trapped under new sediment.

Since 1980, phosphorus load to the lake has generally stabilized with a slight upturn in 1981 and 1982. This increase is due to a two-fold increase in loading to the Blackwater River. Both 1981 and 1982 were wet years, and some of this increase is attributable to this source of inter-annual variability. Runoff from agricultural activities and urban developments produces ten times the amount of phosphorus and five times the amount of nitrogen as forested areas (Omernik 1976). Increased urban development and agricultural land use along the Blackwater River may have also contributed to the phosphorus load increase in the early

1980's as over 15,000 ha (29%) of land in the watershed fell into the category of pasture or barren lands in 1977 (Obenshain and McLeod 1981). Further increases in phosphorus loading due to lakeshore development are likely to be balanced by point source reductions (either by secondary treatment of wastes or reductions from industry). Phosphorus loading is not expected to increase sharply in the foreseeable future (Robert Burnley, VWCB, personal communication).

Smith Mountain Lake Total Phosphorus-Standing Stock Relationship

The variation in total fish standing stock among coves and over years explained by total phosphorus concentrations was low. A scatter plot of the data indicated that a transformation of the data might improve the explanatory power of the relationship. Re-expression of independent and/or dependent variables follows an exponential pattern to decrease data curvature. Variables transformed in an increasing direction (e.g., x^2, x^3) tend to raise low and high data points (i.e., curve upward). Variables transformed in a decreasing direction (e.g., $\sqrt{x}$, log x, 1/x) tend to lower both high and low data points (i.e., curve downward).

A log-10 transformation of both variables was used in this study because it eliminated the most curvature of the data. Log-10 transformations to decrease curvature of the relationship between an abiotic predictor (e.g., total phosphorus, MEI) and fish standing stock data have been used by several researchers (Jenkins 1966; Ryder 1965; Carlander 1955; Rounsefell 1946). In my study, the amount of variation, in fish standing stock data explained by changes in total phosphorus concentrations increased 16 to 30% using log-10 transformations.

Cove-specific Analysis

The total phosphorus concentration versus total fish standing stock relationship was highly significant after data transformation, but the explanatory power was only moderate. There are at least three possible reasons for this: 1) inaccuracy in the measurement of total phosphorus concentrations; 2) variation in the effectiveness of cove rotenone sampling over time and space; and 3) the influence of other variables on fish abundance.

A principal impediment in using total phosphorus concentration to predict fish standing stock is the difficulty of obtaining accurate, representative measurements. Concentrations in the lake vary from sample site to sample site and from day to day, depending on precipitation and runoff in a given area. It is not practical to measure total phosphorus daily and at the hundreds of locations necessary to obtain a completely accurate picture of total phosphorus concentrations in the lake. The VWCB measured epilimnetic total phosphorus concentrations bimonthly from April through October (spring, summer and fall) at upper, middle, and lower SML sites in the same way. Apparent variation in total phosphorus concentrations should be reduced by the standardizing of sampling procedures and stations over seasonal changes. Nevertheless, total phosphorus measurements at a particular site varied by as much as 75% within the period April and October, with no discernible seasonal pattern.

Cove rotenone sampling, when executed properly, provides information on fish standing stocks (Davies and Shelton 1983) and fish distributions (Lambou 1962). Ideally, a random sampling design would eliminate bias caused by site selection or area sampled (Davies and Shelton 1983). This is not practical in most reservoirs, including SML which is too deep to sample in open water. Bias also exists among samples. Henderson (1980) lists several reasons why differences can occur among consecutive samples including variation in the:

1. size of the population from one sample time to the next;
2. distribution of fish from one sample place to the next;
3. behavior of the fish from one sample time to the next;

4. distribution of fish from one time to the next;
5. percent recovered (fish) from one sample to the next.

Sample size must be large enough to adequately address these differences. Davies and Shelton (1983) recommend the use of at least two fixed and two random sites. SML was sampled at 3 or more sites annually, with fixed stations in the upper, middle, and lower lake. The VCGIF used standardized data collection procedures to minimize bias, and total standing stock in the same cove varied no more than 30% between consecutive years.

The influence of changing total phosphorus concentrations on fish abundance, especially that of quality-sized piscivores, is mitigated in part by fish management practices such as regulations and stocking. Potential productivity is set with nutrient supply, but actual productivity depends on the cycling of nutrients and their allocation among populations with different growth rates (Carpenter et al. 1986). Fish abundance may also be greatly affected by variable reproductive success. Carline et al. (1984) found largemouth bass recruitment to fluctuate greatly on an annual basis which in turn strongly influenced size structure of the largemouth bass population.

Although both phosphorus concentration and fish biomass declined concurrently in SML (1973-84; Figure 4), this does not establish a causative relationship. Nor can statistical analysis be used to prove that fish biomass in SML is controlled by total phosphorus concentration. The relationship between total phosphorus and fish biomass, whether dependent or coincidental, must be inferred from evidence. Phosphorus is, however, the nutrient limiting primary production in SML, suggesting that it may have a large influence on annual fish reproduction, growth, and survival, the dynamic factors resulting in fish abundance and biomass.

Planktivorous fish had the most promising relationship when paired with total phosphorus concentration. There are two main reasons fish species at the lower end of the trophic food chain, notably gizzard shad, were highly correlated to total phosphorus concentrations. First, gizzard shad and other planktivores should be particularly responsive to changes in the limiting nutrient, because it affects their food supply directly. Second, gizzard shad is the most abundant species in SML cove samples, comprising 40 to 60% of the total standing stock, thereby allowing for more precise biomass estimates because of increased sample size.

Significant correlations between phosphorus and species standing stock were also found for bluegill, a planktivore-benthophage, and two benthophages, channel catfish and redhorses as well as the benthophagous group as a whole. This is also probably a function of the closeness of these species' diets to the lower end of the food chain and their relative abundance in cove samples. Piscivores were not significantly correlated to phosphorus concentrations in coves. Although some species, notably largemouth bass, are well represented in cove sampling in SML, piscivore diets are further removed from the direct impacts of changing phosphorus levels. They are also impacted more by harvest effort and regulations than other species.

Partitioning cove rotenone data by species or group of species does not take into account the change in species trophic position with age. To overcome this, data were partitioned into age classes for gizzard shad and largemouth bass, the most abundant forage fish and piscivore in SML. Biomass estimates of younger fish might be more responsive to changes in total phosphorus concentrations than older fish. Older fish tend to be better competitors, have a broader trophic niche, are more opportunistic, and are less susceptible to starvation (Adams et al. 1982;Jenkins and Moralis 1976). However, biomass estimates for age-1 shad were more highly correlated with total phosphorus concentrations than were age-0 fish biomass estimates. This may be an artifact attributable to inaccurate sampling of fish less than 100mm in length in cove rotenone studies. Alternatively, biomass of age-0 fish may be affected more by factors such as predation pressure and reproductive success. Moore (1988) found that age-0 gizzard shad were the primary food of largemouth and smallmouth bass in SML. Reproductive success of gizzard shad varies greatly based on size of an individual and variable climatic conditions (Drenner 1982).

Largemouth bass standing stock was not significantly correlated to total phosphorus concentrations for any age subset. This may be explained in part by highly variable reproductive success of black basses in reservoirs including SML (Carline et al. 1984; Whitehurst 1984). Young largemouth bass may also not be adequately sampled in cove rotenone samples which many times overlook fish below 100mm in length. Growth rates of largemoth bass have however, declined 10 to 16% for all age classes in SML between the 1970's and 1980's (Hart 1976; Whitehurst 1984). This indicates bass are food limited in SML, not necessarily phosphorus limited if the trophic pathway is not direct.

One to five-year time lags of phosphorus data behind cove-specific estimates of gizzard shad, largemouth bass, and total standing stock data were used in the phosphorus-fishery model. Lindeman (1942) stated that the lower ends of the food chain may be first to be affected by changes in phosphorus levels and would then in turn affect higher ends of the food chain over a longer period of time. Correlations between total phosphorus and gizzard shad standing stock dropped off sharply with only a one year lag. This implies that planktivore response to changing nutrient levels is immediate.

Correlations with largemouth bass standing stock and total phosphorus were not significant over the entire range of lag periods. This may be due in part to the variability of the SML largemouth bass population brought on by changes in harvest rates, increasing competition with walleye and striped bass, and the popularization of catch and release fishing in recent years. The amount of variation in total standing stock explained by total phosphorus concentrations, lagged one to five years behind it, declined for all lag periods. It is not surprising that total standing stock followed the pattern of gizzard shad, which comprise up to 60% by weight of total standing stock in SML.

Cove-specific analyses provided low, but still significant, coefficients of determination between total phosphorus and total fish standing stocks. This would be expected given the variability in cove-specific data. It also says that intra-lake matching of fertility and fish abundance (biomass) did not work well. Rather, fish are transient and move among locations, and energy flow affects the whole lake. Consequently, it may be more useful to take a whole-lake approach to this analysis.

Whole-lake Relationship

There are several advantages to modeling Smith Mountain Lake as a whole. First, future total phosphorus concentrations can be predicted using the mass balance phosphorus loading model modified by Jones and Bachmann (1984). These values may then be used to forecast probable future swings in the fishery. Second, whole lake values are averages, and averaging removes intra-lake (spatial) variation from the temporal analysis. Third, whole lake phosphorus values can also be tested in the model against gill net and harvest data which are not separable by location within the lake. The major disadvantage to modeling Smith Mountain Lake as a whole is the decrease of sample size which in turn increases the probability of both Type I error and Type II error.

Whole-lake analyses provided generally higher correlations between total phosphorus concentrations and fish standing stock in SML than did cove-specific regressions. P-values also increased for whole-lake analyses, but were still significant in most cases. Both data sets establish the fact that phosphorus concentrations and fish standing stocks (1973-84) do vary together in SML and that roughly two-thirds (whole-lake) and one-third (cove-specific) of the variation in fish standing stocks can be explained in a statistical sense by changes in total phosphorus concentrations. The general pattern of the phosphorus-fish relationship was similar in cove and whole-lake regressions for standing stock partitioned by trophic, species and age groupings.

Results using the whole-lake model and partitioning whole-lake cove rotenone fish data by fish species, fish trophic group, and age for gizzard shad and largemouth bass support conclusions drawn using the cove specific model. These are: 1) that planktivore biomass, (primarily gizzard shad) in Smith Mountain Lake is more closely correlated to total phosphorus concentration than are other fish trophic levels and that piscivore (gamefish) biomass shows no relationship; 2) biomass estimates of younger fish are more closely correlated to total phosphorus concentrations than biomass estimates of older fish. Lagging of whole-lake data also support cove-specific results. Both whole-lake and cove-specific lagging indicated that planktivorous fish were immediately affected by changes in phosphorus concentrations.

Pelagic Sport Fishes

Relative abundance estimates of walleye and striped bass standing stock obtained through gill netting were regressed against whole-lake phosphorus concentrations. Biases using gill net data include net saturation (Kennedy, 1951), mesh size selectivity (Pope et al. 1975; Hamley and Regier 1973), net visibility and flexibility (Jester, 1977), and bias resulting from environmental fluctuations (May et al. 1976). Standardizing sampling from year to year (i.e. same season, time, depth, and location of set) should minimize temporal variability resulting from these biases.

No regressions using gill net data were statistically significant, in part due to small sample size ($n=8$). However, walleye and striped bass CPUE data were highly correlated to total phosphorus concentration ($r^2=0.60$) when lagged one year (striped bass) or three years (walleye). Although these results were not significant, a lag period between changes in phosphorus concentrations and their effect on the biomass of piscivores should be expected as energy level changes pass from one level of a food chain to the next (Carpenter et al. 1986). With a larger data set (more years), total phosphorus concentration might be a useful tool to predict the relative abundances of walleye and striped bass.

Striped bass CPUE was partitioned by age and regressed with total phosphorus concentrations. Total phosphorus concentrations explained 25% of the variation in age-1 striped bass CPUE. Age subsets were also regressed with total phosphorus and the appropriate stocking density for each cohort in a multiple regression. Again results were not significant, but age-1 fish were the most highly correlated ($r^2=0.30$) of the ages sampled. This supports the conclusion from largemouth bass age subsets that younger fish are more affected by changes in total phosphorus concentrations than older fish. Striped bass first-year survival rate has been shown to be inversely correlated to stocking density in SML (Moore 1988), indicating that their survival may be food limited. Because phosphorus explains two-thirds of the variation in planktivore biomass, and planktivores are the principle food of juvenile striped bass (Moore 1988), the phosphorus-juvenile striped bass CPUE relationship would not be surprising. Lagging of total phosphorus one year behind age-1 striped bass CPUE did not result in a significant relationship. A negative relationship was found when stocking density was used with total phosphorus concentration in a multiple regression versus age-1 striped bass ($r^2=0.30$) however, this relationship was also not significant ($P=0.35$).

Harvest

A basic need of fisheries management is the ability to predict the potential yield of sportfish from a lake or reservoir (Jones and Hoyer 1982). The most successful methods used to predict fish harvest to date have been the MEI in Canadian Lakes (Ryder 1965), the MEI subsetted by retention time in large temperate reservoirs (Jenkins 1967,1982), summer chlorophyll-a and total phosphorus concentrations in in midwest lakes (Jones and Hoyer 1982), and phytoplankton standing crop in temperate lakes (Oglesby 1977a). No significant relationship between phosphorus concentrations and fish harvest in Smith Mountain Lake was indicated by regression analysis. This could be a result of insufficient fishing effort to accurately estimate fishery productivity from yield in SML. Also, harvest data were collected by day and day-night surveys during different years, and estimates are therefore not consistent over time. A small sample size ($n=4$) and a large fluctuation in number of stocked fish also prevented any significant relationship to be drawn between total phosphorus and the decline in total harvest in the reservoir.

Southern Appalachian Reservoirs

Flannagan Reservoir (Virginia) was an extreme outlier in the southern Appalachian reservoir total phosphorus-total standing stock regression and was discarded from further analysis. Flannagan Reservoir has a history of acid mine drainage problems (Gary F. Martel, Virginia Department of Game and Inland Fisheries, personal communication) which may be the cause of the poor relationship between total phosphorus and fish standing stock in this lake. Satisfyingly, the phosphorus-standing stock regression isolated this dysfunctional system. Good empirical predictors of fishery productivity should have this ability (Ryder et al. 1974; Jenkins 1988).

The strength of the phosphorus-standing stock relationship in southern Appalachian reservoirs demonstrates that total phosphorus concentration is a robust predictor of fishery productivity for these systems. Total phosphorus concentration explained five-sixths of the variation in total fish standing stock for 21 southern Appalachian reservoirs using standing stock estimates within two years of phosphorus measurements. The 90% confidence interval for this relationship was within 3.8% of the predicted line. This indicates that the average log-10 standing stock for a given log-10 total phosphorus level can be predicted to within 11.1% 9 out of 10 times. Ninety percent prediction limits for total standing stock, given a total phosphorus concentration, were within 11.1% of the predicted line. That is total standing stock can be predicted to within 51% of cove rotenone fish biomass estimates 9 out of 10 times.

Narrowing the southern Appalachian reservoir data set down to 11 reservoirs for which phosphorus concentration could be paired to the same year's fish standing stock data increased percent variation explained by the model to 94%. Phosphorus-standing stock is a remarkably strong relationship in southern Appalachian reservoirs, considering the physical, chemical, and biological diversity of lakes in the sample. Physical differences include; surface area, ranging from 400 to 55000 hectares; and mean depth, ranging from 5.2 to 29 meters. Chemical variability includes phosphorus concentrations, ranging from 6 to 81 μg/l, and nitrogen concentrations ranging from 70 to 1270 μg/l. Total fish standing stocks of the reservoirs used in the regression ranged from 30 to 2323 kilograms per hectare. Retention time also varied by two orders of magnitude, reflecting differences in operational characteristics (i.e., flood control versus hydropower).

Hanson and Leggett (1982) found 71% of the variation of standing stock estimates in the same year to be explained by total phosphorus concentrations for 26 north temperate lakes. They also found total phosphorus to explain 84% of the variation in commercial fish yield from these lakes. Using their phosphorus-fish biomass model developed for Canadian lakes, Hanson and Leggett projected fish biomass for five Tennessee Valley Authority reservoirs to within 30% of that estimated using cove rotenone techniques. They concluded that "total phosphorus concentration may have considerable potential as a predictor of fish standing crop in reservoirs."

Moyle (1956) was the first to report a positive relationship between fish biomass and total phosphorus concentration. He found yields of yellow perch (*Perca flavescens*) to be low in lakes and ponds with total phosphorus concentrations below 50 μg/l and to increase at higher phosphorus concentrations up to 200 μg/l. Jones and Hoyer (1982) measured the total phosphorus-fish yield relationship in shallow midwestern U.S. lakes and reservoirs and found total phosphorus concentrations to explain 52% of the variability in fish yield. Jenkins (1988) has also investigated the total phosphorus-fishery productivity relationship in 112 U.S. reservoirs. He found total phosphorus to be positively correlated to weight of fish harvested/hour and to yields of catfish (*Ictalurus sp.*) and white bass (*Morone chrysops*). He also found total clupeid standing stock and standing stocks of sportfish to be positively correlated to total phosphorus concentrations, but did not report a coefficient of determination.

The phosphorus-fishery relationship in southern Appalachian reservoirs compares very favorably with other empirical indices of fish standing stock and yield. Indices which have been successfully used to predict fishery productivity in reservoirs include alkalinity ($r^2=0.69$; Carlander 1955), the MEI ($r^2=0.40$; Jenkins 1967) and dissolved solids ($r^2=0.63$-0.81; Jenkins 1977) for standing stock, and chlorophyll-a ($r^2=0.83$; Jones and Hoyer 1982) for fish yield. These indices were developed either for reservoirs in a particular geographic region (e.g., midwestern U.S.; Jones and Hoyer 1982) or for particular reservoir types (e.g., hydropower reservoirs; Jenkins 1977).

Ryder (1982) stated that empirical indices have their greatest utility at the regional level where growing season may be considered a constant. Brylinsky and Mann (1978) found that globally, solar energy inputs have the greatest impact on lake productivity, but in lakes within a narrow range of latitude, nutrient-related variables assume greater importance. The 0.83-0.94 coefficient of determination found for the total phosphorus-fish standing stock relationship in southern Appalachian reservoirs indicates it may be the single best abiotic predictor of fishery productivity in U.S. reservoirs when grouped by region.

Several other physical-chemical variables for which data were available were also regressed against total fish standing stock for the southern Appalachian reservoir data set. Correlations of fish standing stock with more direct measures of primary production (Secchi disk disappearance depth, chlorophyll-a) in southern Appalachian reservoirs were considerably weaker than with total phosphorus. Fish standing stock was positively correlated to chlorophyll-a concentrations and phosphorus loading estimates and negatively correlated to Secchi disk disappearance depth. This is not surprising as Secchi disk disappearance depth is an inverse measure of lake trophic state (Lambou et al. 1982). Chlorophyll-a (Jones and Hoyer 1982) and Secchi disk disappearance depth (Jenkins 1976) have both proven to be valid estimators of fish yield in reservoirs in some situations. Accurate measure of these variables is difficult because of temporal and spatial variation (e.g., turbidity, patchiness), which are characteristic of reservoirs, and therefore, sampling error may have obscured true relationships. Phosphorus loading estimates may not be a reliable predictor of fishery productivity in reservoirs because of the different pathways for phosphorus deriving from different retention times, dilution rates, and sediment trapping. Phosphorus loading does, however, directly affect total phosphorus concentration in a reservoir and may be useful as an index of how fishery productivity may change with decreased phosphorus loading from a point source, as for Smith Mountain Lake.

Surface area, mean depth, retention time, total nitrogen concentration, and the MEI were not significantly correlated to fish standing stock for this data set. Variation in surface area and mean depth have both been found to be effective predictors of fish yield in natural lakes (Rounsefell 1946; Rawson 1952). Rounsefell's (1946) theory that smaller lakes have proportionally more littoral area and are therefore more productive often does not hold true in reservoirs, where banks may drop over 10 meters right next to shore. Rawson (1952), who found mean depth to be negatively correlated to fish yield in natural lakes, also was not dealing with reservoirs, in which mean depth may change as much as 10 meters throughout a year.

Retention time also showed no relationship to fishery productivity in southern Appalachian reservoirs. Riverine impoundments with high flushing rates might be expected to support less primary productivity than more lacustrine reservoirs (Oglesby 1977b). However, Jenkins (1967) reported a nonsignificant relationship between fish standing stock and retention time in regression analysis of 127 U.S. reservoirs. The fact that total nitrogen concentrations were not significantly correlated to fishery productivity is not surprising in that most of the reservoirs in the southern Appalachian data set were phosphorus limited.

The most widely used empirical index to date has been the morphoedaphic index (MEI). The MEI, developed for predicting yield in natural lakes, explained 54 to 73% of the variation in fish harvest in 23 Canadian Lakes (Ryder 1965). However, Jenkins (1982) found that the MEI explained only 8% of the variation in fish harvest and 21% of the variation in fish standing stock in 294 large U.S. reservoirs. He concluded that this was due to large variability in habitat, which ranges from sluggish river to near natural lake conditions. His data set also did not fit the criteria of homogenous climatic conditions (Ryder et al. 1974) required for use of the MEI.

Partitioning his data by operational characteristics (storage capacity and retention time) and water chemistry differences (carbonate ions dominant versus sulfate-chloride ions dominant), increased MEI explanatory power to a range of 21 to 72% of the variation in fish standing stocks. Due to the diversity of southern Appalachian reservoirs in operational characteristics and water chemistry, the lack of an MEI relationship to total standing stock was not unexpected.

Biotic indices which have shown explanatory power in natural lakes are benthic biomass ($r^2=0.83$; Matuszek 1978) and phytoplankton standing crop ($r^2=0.84$; Ogelsby 1977a). Data were not available for these biotic indices in southern Appalachian reservoirs. In general, time and effort needed to accurately measure these variables does not appear to be justified.

To better compare the southern Appalachian reservoir fishery-phosphorus relationship with that found in Smith Mountain Lake, data were analyzed by species, trophic groupings, and for effects of a time lag. In most cases, predictability of fish standing stock was higher for the southern Appalachian reservoir data set. This may be due to varying time lag responses of different trophic levels to changing nutrient levels occurring in SML, whereas nutrient levels are assumed stable for the spatial reservoir data set. Gizzard shad in particular and planktivores in general were highly correlated to total phosphorus concentrations in both Smith Mountain Lake and the southern Appalachian reservoir data sets. Benthophagous fish were also significantly correlated to total phosphorus concentrations for both data sets.

There was no apparent relationship between piscivore standing stock and total phosphorus concentrations for either southern Appalachian reservoirs in general or Smith Mountain Lake in particular. This could be interpreted to suggest that energy flow is unimportant to piscivores (i.e., is not a limiting factor or doesn't transfer that far up the food chain). However, Ploskey and Jenkins (1982) found that 95% of the annual losses of piscivore biomass in Beaver Lake, Arkansas was largely the result of seasonal prey deficiences (i.e. food was limiting).

The main reason for poor total phosphorus-piscivore relationships may be a weak energy transfer link in these reservoirs. Most forage fish in southern Appalachian reservoirs are gizzard shad, but much of their biomass is too big to be eaten by piscivores. In SML, Moore (1988) examined 1800 piscivore stomachs and found only four shad that were not age 0. But older (age 1+) shad made up 80% by weight of shad standing stock. In SAR systems, gizzard shad was usually the most abundant forage fish (average of 40% of total fish standing stock). Strong relationships between total phosphorus and planktivore standing stock are not transmitted to piscivores in SAR systems either. Noble (1981) pointed out that although gizzard shad are the principle prey species in southern reservoirs, they reach lengths of 400mm and rapidly grow too large to be eaten by most predators. It therefore seems quite credible that gizzard shad are functioning as an energy trap. The poor relationship between total phosphorus and piscivore standing stock may also be due in part to the confounding influence of management (e.g., harvest regulations, stocking, water level fluctuations), expanding coolwater habitat (in SML), and exploitation (e.g., fishing pressure, catch and release fishing). Logic dictates that in an unexploited reservoir, piscivore biomass should correlate with system productivity if energy transfer is efficient at each step of the trophic pathway. Total phosphorus may not be a good predictor of piscivore biomass in reservoirs. However, if alewife or threadfin shad can be quantified in reservoirs, the strong total phosphorus-planktivore relationship may be useful in predicting seasonal prey deficiencies and potential piscivore abundance.

Lagging phosphorus data behind fish standing stock data did not improve correlations using either Smith Mountain Lake or southern Appalachian reservoir data. Lagging of southern Appalachian data logically would not improve fit of the regression model unless sharp contrasts existed in year-to-year phosphorus concentrations. This would be unlikely as eutrophication is usually a slow process, except under conditions of severe perturbations, and varies from reservoir to reservoir.

Inclusion of additional variables in a multiple stepwise regression did not greatly improve explanatory power, but there was also not much room for improvement (17%). Log-10 total phosphorus concentrations matched with retention time resulted in the highest second order regression equation explaining an additional 5.5% of the variation in fish standing stock.

However, retention time by itself was poorly correlated to fish standing stock. This suggests that the influence of total phosphorus and retention time on fish standing stock are mostly independent of each other. Only one third order regression equation was significant: the matching of log-10 total phosphorus with retention time and log-10 chlorophyll-a. Chlorophyll-a is a measure of primary productivity and has been found to be highly correlated ($r^2=0.90$) to total phosphorus (Jones and Bachmann 1976). Probably because chlorophyll-a concentrations are not completely independent from total phosphorus concentrations, only a slight improvement (2.1%) over the second order equation of total phosphorus and retention time occurred. Jones and Hoyer (1982) found chlorophyll-a by itself to be highly correlated ($r^2=0.82$) to fish harvest in shallow Iowa lakes. Both chlorophyll-a and retention time were positively correlated to fish standing stock in the higher order expressions. No higher order regression equations were significant.

Southern Appalachian reservoirs were partitioned to determine if the total phosphorus-fish standing stock relationship could be improved by grouping reservoirs by either similar surface areas, mean depths, Secchi disk disappearance depths or retention times. This process decreased sample size by approximately one-half, but results remained highly significant ($P<0.01$) for all subsets. Partitioning the reservoirs into groups indicated phosphorus to be a better predictor in deep rather than shallow impoundments. This difference is probably due to the fact that shallow lakes are more environmentally unstable, and community structure will be more affected with swings in weather conditions than in deeper lakes. Partitioning also revealed phosphorus to be a better predictor in clear rather than turbid lakes. This would be expected because most lakes with high turbidity are not phosphorus limited, turbid systems are usually nutrient rich (Lambou et al. 1983). Increases in turbidity may also result in lower primary production due to decreases in light penetration. Finally, turbid lakes tend to be shallower than non-turbid lakes, linking turbidity with depth.

An increase in the predictive power of phosphorus was noticed in the partitioning of reservoirs based on retention time. Correlation values increased to explain over 90% of fish standing stocks variability, in reservoirs both with less than 75 day retention times and greater than 75 day retention times. This implies that fish standing stock in reservoirs with low or high retention times respond similarly to changing phosphorus concentrations within their respective group, but differently than each other. One possible reason for this is that phosphorus may transfer at different rates up the food chain, brought about by differing functional responses at various flow rates (i.e., retention times).

Jenkins (1982) divided reservoirs into similar operational groups (i.e., hydropower mainstream, hydropower storage, and chemical types of nonhydropower reservoirs). These subsets grouped reservoirs by operational characteristics and water chemistry characteristics. Retention times were similar within operational groups and hence this method also partitioned reservoirs based on retention time. Jenkins found higher correlations of fish standing stock to the MEI when reservoirs were partitioned in the above manner (r^2=0.21-0.72) in comparison to using the data set as a whole (r^2=0.08-0.21). Although Jenkins coefficients of determination were smaller than those of this study, his reservoir data set covered a much larger and more diverse geographical area.

Jenkins (1982) results suggest that reservoirs with lower retention times are more productive (greater fish biomass) than reservoirs with high retention times. In this study, reservoirs with a high retention time were found to be more productive. Soballe and Kimmel (1987) found that algal abundance per unit phosphorus increased with an increase in retention time. This suggests that more stable systems (those with high retention times) can better utilize phosphorus in the water column. Phosphorus limited systems, such as those found in the southeastern United States, should therefore be more productive as retention time in a reservoir increases.

Future Productivity in Smith Mountain Lake

Fertility and fishery parameters in Smith Mountain Lake have undergone dramatic changes between the 1970's and 1980's. Phosphorus concentrations in the lake appear to have stabilized since 1980, indicating not only that loading has stabilized, but also suggests that sediment release of phosphorus is no longer a significant contribution to water-borne phosphorus. It is difficult to predict whether fish standing stock in the reservoir has reached a nutrient-fish steady state due to variability in dynamic factors such as stocking and fishing effort but, it has varied only 25% in the 1980's.

It is not expected that phosphorus loading to Smith Mountain Lake will increase or decrease much over the next decade. The city of Vinton has recently gone on line with the advanced wastewater treatment plant in Roanoke, VA and a projected 4% decrease in the phosphorus load from this point source is expected. Further reductions in point source discharge of phosphorus are likely to be balanced by increases associated with lake development; neither is expected to change sharply as in the past (Robert Burnley, VWCB, personnel communication).

Using the regression equation developed for southern Appalachian reservoirs (Page 50), the projected total standing stock of fish for the period 1981-83 is 328 kg/ha. This is only about 19% lower than that estimated by whole-lake cove rotenone procedures over the same period, which is itself right on the 90% confidence interval lines drawn for the southern Appalachian reservoir data set and well within the prediction limits of the model(Figure 8). The closeness of this projection indicates that SML does not differ in its response to total phosphorus concentration when compared to other southern Appalachian reservoirs. It is, therefore, reasonable to assume that SML has reached a steady-state condition and that the current lower phosphorus concentrations, as compared to the early 1970's, will continue to promote lower fish standing stocks over the next decade than those realized ten years previous. Using the total standing stock-total phosphorus equation developed for southern Appalachian reservoirs, the effects of a projected 20% increase in SML total phosphorus concentration ("worst-case" scenario, until the end of the century) was estimated to be a 21% increase in total standing stock to 397 kg/ha. This is still far below (as much as four-fold) standing stocks of the early 1970's.

The sport fishery in SML cannot be projected as confidently as total standing stock or planktivore standing stock. This is due to the lack of a statistically significant relationship between piscivore standing stock and total phosphorus concentrations in southern Appalachian reservoirs in general and SML in particular. A confounding factor in SML is that the lake follows a eutrophic gradient ranging from a highly eutrophic state in its upper reaches to an oligotrophic state near the dam. Large areas of the lake in the tributary arms are effectively off-limits to coolwater fishes in the summer due to oxygen deficits in the hypolimnion (Ney et al. 1988). Reductions in phosphorus load to SML, while reducing overall productivity in the lake, also have resulted in additional coolwater habitat for species such as striped bass, walleye, and their forage counterpart, the alewife (Figure 1).

A further complicating factor in SML is that the resulting change in distribution of coolwater species may result in altered predator/prey relationships within the reservoir. In SML, striped bass and largemouth bass are now largely compatible, in part due to habitat segregation; largemouth dominate in the tributary arms while striped bass use the broader and deeper reaches during most of the growing season (Ney et al. 1988). Changing nutrient levels will affect the distributional overlap of these two dominate sportfish species, thereby influencing the interspecific competition and predation which now is minimal. Similarly, habitat expansion of the abundant alewife to upper lake arms could affect sunfish and black bass species through trophic competition (Kelso and Ney 1982) or predation (Kohler and Ney 1980).

Another complication in the attempt to predict piscivore standing stock is that abundance of walleye and striped bass are not accurately represented in cove rotenone studies, and consequently, total piscivore standing stock could not be precisely estimated. Results were also variable between total phosphorus concentrations and CPUE data for these pelagic piscivores; it is not recommended that total phosphorus concentration be used to project optimal stocking densities for these species.

Despite the apparent inability of phosphorus to predict piscivore abundance, the future of Smith Mountain Lake's sport fishery will ultimately depend on nutrient load to the lake. Except in cases of hyper-eutrophication, reduced nutrients will result in lower fishery productivity (Swenson 1980). In assessing the cost/benefit of nutrient reductions in SML, the eutrophic gradient needs to be considered. To manage for a mesotrophic upper lake will probably result in an oligotrophic lower lake. Mesotrophic conditions in the lower lake will probably occur when the upper lake arms are in the eutrophic state. A balance between the oligo-mesotrophic aesthetic benefits of an increase in fishery productivity should be carefully considered when managing nutrient load to this reservoir.

SUMMARY AND CONCLUSION

1. Phosphorus load to Smith Mountain Lake was calculated from tributary phosphorus concentration and discharge. Estimated phosphorus load to Smith Mountain lake ranged from a high of 69,175 kg/yr in 1974 to a low of 24,087 kg/yr in 1981.

2. Estimated phosphorus load to the Roanoke River declined 82% from 42,500 kg/year in 1974 to 7490 kg/year in 1983. Estimated phosphorus load to the Blackwater River during this same time period quadrupled from 4730 kg/year to 15,979 kg/year.

3. Mean annual total phosphorus concentration and fish standing stock parameters were matched in regression analysis over the period 1974-84. Smith Mountain Lake data were first evaluated in log-linear regressions matching total phosphorus concentrations with fish standing stock estimates by lake section (upper, middle, and lower SML). Then whole-lake total phosphorus concentrations were regressed with whole-lake standing stock estimates, harvest, and CPUE of walleye and striped bass from gill net samples. Attempts to relate phosphorus concentrations to fish standing stock by lake area (cove-specific analysis) resulted in generally poorer fits of the log-linear model than in considering the lake as a whole (whole-lake analysis).

4. Total phosphorus concentration consistently had the highest correlations to total fish standing stock in Smith Mountain Lake. Phosphorus concentrations explained one-third (cove-specific) and two-thirds (whole-lake) of the variation in total fish standing stock. Gizzard shad comprised 58% by weight of total standing stock in cove rotenone studies, and had the highest coefficient of determination of an individual species with total phosphorus concentrations ($r^2 = 0.38$,coves; $r^2 = 0.69$, whole-lake).

5. Biomass of younger fish was more closely correlated to total phosphorus concentrations than that of older fish for largemouth bass. Significant relationships occurred for age-1 and age 3+ or older gizzard shad but not for any age group of largemouth bass.

6. Grouping of fish species in Smith Mountain Lake by trophic levels indicated that standing stock of fish at lower levels of the food chain (i.e., zooplanktivores and benthophages) were significantly correlated with total phosphorus concentration but that piscivore standing stocks were not.

7. Total phosphorus concentrations lagged 1 through 5 years behind total and species standing stock data in Smith Mountain Lake resulted in no significant correlations higher than those found with no time lag.

8. Total phosphorus was not a good predictor of fish harvest in Smith Mountain Lake. This may be a result of both small sample size (n=4), and variable management and angler practices, including striped bass and walleye stocking; bias in harvest estimates; changing harvest regulations; and the recent popularity of catch-and-release fishing. Total estimated sportfish harvest has declined by half since phosphorus concentrations have been declining (1973-1985).

9. Southern Appalachian reservoir (SAR) fish standing stock data were paired with total phosphorus as well as with other abiotic parameters in linear models to test the robustness of total phosphorus as a predictor of fish standing stock. Log-10 total phosphorus was found to have the highest coefficient of determination ($r^2=0.83$) followed by Secchi disk disappearance depth ($r^2=0.51$), and log-10 chlorophyll-a ($r^2=0.47$). The MEI, mean depth, surface area, and total nitrogen concentration provided weak or nonsignificant correlations when paired with fish standing stock in southern Appalachian reservoirs.

10. When fish standing stock of southern Appalachian reservoirs was partitioned by species and regressed with total phosphorus concentration, a significant relationship ($p < 0.05$) was found for one benthophage, channel catfish ($r^2 = 0.37$) and three forage species; threadfin shad ($r^2 = 0.44$), bluegill ($r^2 = 0.30$), and gizzard shad ($r^2 = 0.25$).

11. Grouping fish species in southern Appalachian reservoirs by trophic levels in a linear model indicated, as in Smith Mountain Lake, that standing stock estimates of fish from lower levels of the food chain were correlated to phosphorus concentration, but piscivore biomass estimates were not.

12. Using multiple stepwise regression, I tested several abiotic parameters in conjunction with total phosphorus to predict fish standing stock. Only retention time (5.5%) and log-10 chlorophyll-a concentration (2.6%) were found to account for additional variation in the total phosphorus-total fish standing stock model.

13. Reservoir data sets were split in two by low and high values of mean depth, surface area, Secchi disc depth, and retention time, and were then evaluated separately in the total phosphorus-total fish standing stock model. Results indicate total phosphorus to be a better predictor of fish standing stock in deep rather than shallow lakes, in clear rather than turbid lakes, and in lakes grouped by retention time whether high or low. Surface area did not greatly affect model predictability.

14. Phosphorus concentrations and total fish standing stocks appear to have stabilized in Smith Mountain Lake (SML) since 1980. Losses in fish standing stock due to decreased fertility in SML have been in part mitigated by an increase in coolwater habitat. Aesthetic versus fishery benefits and the complexity of dealing with a longitudinal trophic gradient need to be considered for future management of SML.

The strong relationship found between total phosphorus concentration and total fish standing stock in southern Appalachian reservoirs demonstrates that phosphorus concentration is an excellent empirical index over a wide range of reservoir physical and chemical variability. Total phosphorus should therefore be a good predictor of fish standing stock in general for reservoirs in a given geographical region. It was found to work best for deep (mean depth > 10m) rather than shallow lakes, in lakes with a surface area > 50km^2, and in lakes grouped by operational characteristics (i.e., retention time). The geographical closeness of the southern Appalachian reservoir data set suggests that phosphorus works well in a climatically similar area.

The total phosphorus-fish standing stock relationship was strongest at the lower end of the food chain (i.e., for planktivores). Younger fish were also more affected than older fish by changes in total phosphorus. Total phosphorus did not work well as a predictor of piscivore biomass in southern Appalachian reservoirs. This may be the result of an energy transfer trap formed by gizzard shad too large to be eaten by most piscivores. However, food supply is the ultimate limiting factor for sportfish in most freshwater systems (Jenkins and Moralis 1976), and to the degree that young planktivores (which are highly correlated to total phosphorus concentrations) are a major food source for piscivores, phosphorus should affect their abundance. The sportfish harvest-total phosphorus concentration relationship was not evaluated for southern Appalachian reservoirs, but Hanson and Leggett (1982) found total phosphorus to be highly correlated to commercial harvest and the same relationship might hold here.

Hanson and Leggett (1982) applied their phosphorus-standing stock regression, derived for natural lakes, to predict fish standing stock in five Tennessee Valley Authority reservoirs. Their predictions ranged from 73-131% of estimates obtained by cove rotenone sampling. The regression line developed by Hanson and Leggett ran nearly parallel to and below the line generated by the southern Appalachian reservoir data. This suggests the relationship between total phosphorus and fish standing stock is consistent and will shift up or down probably based on growing season length.

Total fish standing stocks in the southern Appalachian reservoir data set, determined by cove rotenone sampling, were within 50% of those predicted with an average deviation of only 26%. Based on this robust and precise correlation in the large and diverse southern Appalachian reservoir data set, I believe the relationship between total phosphorus concentration and fish standing stock to be causative rather than coincidental. This is supported by the obvious logic that phosphorus affects primary production which in turn supports the fish community.

The apparent causative relationship between total phosphorus and fish standing stock in southern Appalachian reservoirs suggests that the concomitant decline of fish standing stock and total phosphorus concentrations in Smith Mountain Lake (SML) are also not coincidental. The high levels of fish standing stock and harvest of the early 1970's will not return because of reduced phosphorus levels. This is mitigated in part by the expansion of coolwater habitat used by striped bass, walleye, and their forage counterpart the alewife.

Planktivore biomass and distribution have been most directly affected by changes in the fertility of Smith Mountain Lake. Biomass estimates of gizzard shad have declined to near extinction in the oligotrophic lower lake and 50 to 75% in the lake overall since the early 1970's (Whitehurst 1984). Alewife populations have changed from exclusively lower lake inhabitants during late summer months to lower and mid-lake inhabitants (Ney et al. 1988). Biomass of alewife is not accurately assessed in cove-rotenone studies (Davies and Shelton 1983), and therefore no conclusions can be drawn about their biomass shifts since the early 1970's.

Piscivore standing stocks did not decline in parallel with total phosphorus concentrations in Smith Mountain Lake. However, largemouth bass (a major piscivore in SML) partitioned by age showed that total phosphorus concentrations explained almost 50% of changes in standing stock of age-0 fish. Other researchers have found mortality of age-0 largemouth bass to be directly related to food availability (Gutreuter and Anderson 1985, Toneys and Coble 1980). The affect of nutrient availability on the top carnivores in SML was probably mitigated in part a poor energy tranfer past the planktivore trophic level and by changing fishery management actions (stocking, regulations, water level manipulations) and exploitation rates (fishing pressure, catch and release).

Smith Mountain Lake falls right on the 90% confidence band of the SAR regression line, indicating that the lake is near steady-state, and that overall fishery productivity should remain relatively stable for the foreseeable future. Deviations from steady-state may result from increases in species overlap of piscivorous species (i.e., striped bass and walleye with largemouth bass) and planktivorous species (i.e., gizzard shad with alewife) if coolwater habitat expands further upstream. Alewife have been shown to adversely affect centrarchid populations via competition (Kelso and Ney 1982) and predation (Kohler and Ney 1980). Consequences of trophic interactions between striped bass, walleye, and the black basses are uncertain.

The fishery in SML should be managed on the basis of the present standing stock of fish, which has been relatively stable over the past five years. Managers are challenged to be more efficient and innovative in order to optimize fishing in SML (e.g., matching piscivore stocking densities to food supply, non-wasteful harvest regulations). Also, angler expectations and attitudes may require adjustment. There is a growing recognition that anglers judge satisfaction based on expectations (Hudgins and Davies 1984). As fishing pressure continues to increase on SML (Whitehurst 1984), expectations may have to be changed in order to optimize angler satisfaction.

Smith Mountain Lake follows a fertility gradient and has shown mixed results to nutrient reduction. Eutrophication has been curtailed in the upper lake, but, this has been accompanied by a more oligotrophic lower lake and a decline in overall fishery productivity. Increasing nutrient inputs to the upper lake would probably increase fishery productivity in the lake, but upper lake arms could be expected to revert back to a hyper-eutrophic state which is unacceptable. Fertilization of the lower lake could increase productivity at this end (Axler et al. 1988), but it would have to be done annually and would probably not be cost effective.

The evidence accumulated in this and other studies of the nutrient/primary production-fishery productivity relationship demonstrates that "clean," oligotrophic waters will generally support less fish biomass than more fertile systems. Excessive fertility can result in an increase in algal and weed nuisances and a depletion of hypolimnetic oxygen which can also impair fish production. Clearly, each water body has optimum nutrient levels at which fishery and aesthetic benefits can be maximized, but the optimum level for each is likely to differ. Determining the nutrient level to maximize fishery productivity is a major challenge facing fishery managers.

Collaboration between limnologists and fisheries scientists will be required to permit informed decision-making regarding the fisheries-clean water trade-off. Such collaborations have been rare, although the benefits are obvious and urgently needed (Rigler 1982). Lakes cannot be too clean for fish, but they can certainly be too infertile for good fishing. Appreciation of the nutrient-fishery productivity relationship is fundamental to effective management of lakes as multi-use recreational resources.

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Appendix Table 1. Relationship of total phosphorus to orthophosphorus in major tributaries of Smith Mountain Lake, Virginia.

Tributary	OP:TP	Year		Total phosphorus (ppm)	Orthophosphorus (ppm)
Roanoke River	1:2.04	1973	mean	0.28	0.153
			range	(0.05-0.32)	(0.02-0.227)
		1978	mean	0.14	0.062
			range	(0.04-0.32)	(0.015-0.125)
Blackwater River	1:4.12	1973	mean	0.088	0.022
			range	(0.02-0.23)	(0.01-0.038)
		1978	mean	0.17	0.040
			range	(0.05-1.08)	(0.008-0.089)
Back Creek	1:1.89	1973	mean	0.11	0.059
			range	(0.063-0.165)	(0.035-0.087)

Appendix Table 2 Scientific names of fish found in tables.

Common Name	Scientific Name
Alewife	*Alosa pseudoharengus*
Black bullhead	*Ictalurus melas*
Black crappie	*Pomoxis nigromaculatus*
Bluegill	*Lepomis macrochirus*
Brown bullhead	*Ictalurus nebulosus*
Carp	*Cyprinus carpio*
Catfish	*Ictalurus* sp.
Channel catfish	*Ictalurus punctatus*
Gizzard shad	*Dorosoma cepedianum*
Hogsucker	*Hypentelium nigricans*
Largemouth bass	*Micropterus salmoides*
Pumpkinseed	*Lepomis gibbosus*
Quillback carpsucker	*Carpiodes cyprinus*
Redbreast sunfish	*Lepomis auritus*
Redhorses	*Moxostoma* sp.
Rockbass	*Ambloplites rupestris*
Smallmouth bass	*Micropterus dolomieui*
Striped bass	*Monroe saxatilis*
Suckers	*Catostomidae*
Threadfin shad	*Dorosoma petenense*
Walleye	*Stizosstedion vitreum*
White bass	*Monroe chrysops*
White sucker	*Catostmus commersoni*
Yellow bullhead	*Ictalurus natalis*
Yellow perch	*Perca flavescens*

Appendix Table 3. Whole-lake total and trophic group standing stocks (kg/ha) in Smith Mountain Lake (1973-1984).

Year	TSS	Planktivore	Benthophage	Piscivore
1973	533.2	330.92	48.30	9.73
1974	1115.5	625.99	42.47	8.51
1975	437.8	231.41	37.09	9.44
1976	694.7	296.97	65.45	8.19
1977	818.1	474.70	56.93	11.30
1978				
1979	301.9	64.88	43.93	10.68
1980	411.4	154.09	71.61	10.46
1981	277.9	90.21	45.83	6.72
1982	400.3	74.41	65.78	13.12
1983	346.8	136.16	45.05	8.90
1984	352.6	218.19	67.91	12.18

Appendix Table 4. Standing stocks (kg/ha) of trophic groups in southern Appalachian reservoirs.

Name	Planktivore Standing Stock	Benthophage Standing Stock	Piscivore Standing Stock
Kentucky			
Cumberland	85.04	42.80	9.78
Dale Hollow	67.96	31.86	6.52
Herrington	753.18	38.44	35.86
Kentucky	283.73	52.24	8.10
North Carolina			
Badin	173.83	93.22	13.78
Norman	121.48	25.66	7.84
South Carolina			
Keowee	9.08	22.92	7.36
Tennessee			
Holston	172.24	53.46	35.97
Old Hickory	489.11	200.04	8.48
Cherokee	774.31	188.90	46.85
Chickamauga	139.89	103.70	10.86
Fort Loudon	252.03	114.98	11.77
Nickajack	209.45	59.40	6.61
Watts Bar	162.72	111.17	8.85
Douglas	35.52	167.98	69.48
Woods	47.55	200.04	26.17
Virginia			
Claytor	85.43	62.14	16.59
John Kerr	391.78	134.90	22.60
West Virginia			
Lynn	9.04	4.75	36.24
Summerville	33.17	1.04	28.65
Tygart	10.43	18.86	6.81

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