

CHEMICAL LIMNOLOGY, ALGAL GROWTH POTENTIAL, AND
NUTRIENT LIMITATION FACTORS OF THE UPPER NEW RIVER,
VIRGINIA, AND PREDICTIONS CONCERNING TROPHIC STATUS
FOR THE PROPOSED BLUE RIDGE RESERVOIRS,

by

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To _____ and to my parents

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PREFACE

Mankind, and more importantly his political institutions, have finally begun to grasp the "spaceship earth" concept. There now seems to be an awareness of the finiteness of natural resources, coupled with an appreciation of their value and a sense of responsibility for their preservation.

Particularly important to the preservation of our water resources is a need for planning -- planning based on interdisciplinary systems approaches that seek to maximize the beneficial uses of water resources, including their inherent assimilative capacities, without abusing them.

As a result of this increased awareness and sense of responsibility, pre-construction water quality surveys (ecological reconnaissance) often precede water resource development. Properly performed studies of this nature create substantial data bases describing the chemical, physical, and biological condition of the system under consideration. These data bases are primarily used 1) to determine the feasibility of a site for development, 2) to serve as tools in making predictive statements about the environmental impact of development, and 3) when coupled with a post-construction data, to determine the environmental consequences of the development. Cairns et al. (1972) suggested that developers benefit from pre-construction surveys in many additional ways. They are provided with data that (1) enables them to anticipate and interpret their operations to minimize

environmental impact, (2) enables them to derive the assimilative capacity of the system, (3) identifies other stresses on the system, both man made and natural, (4) dispels or confirms beliefs of local inhabitants about fish productivity, (5) indicates ways of eliminating potential problems before they occur, and (6) lends credibility to statements about interest in the environment.

GENERAL INTRODUCTION

In 1965 the Appalachian Power Company filed application with the Federal Power Commission for a license to construct a twin-dam pumped storage hydroelectric facility on the New River, in Grayson County, Virginia, with reservoirs extending into North Carolina. The proposed facility, known and hereinafter referred to as the Blue Ridge Power Project, would require inundation of 40,000 acres of land, flooding 44 miles of the New River and 212 miles of tributaries.

In 1970, with funding from the Appalachian Power Company, members of the Biology Department and Center for Environmental Studies at VPI & SU began a pre-impoundment water quality survey on portions of the New River located above, in, and below the proposed impoundments. The objective of the study was to establish a biological, chemical, and physical baseline of conditions in the New River and associated tributaries prior to construction, and to provide a data base sufficient to allow for sound ecological predictions concerning water quality in the proposed impoundments. This ongoing survey has continued for 5 years, involving biweekly or monthly monitoring of 28 chemical and physical parameters, and yearly sampling of the macrobenthos and fish populations.

The purpose of the investigation reported here is to critically evaluate the water chemistry, algal growth potential and nutrient limitation data, and to formulate sound ecological predictions concerning the nutrient budgets and trophic status of the proposed reservoirs. In order to most clearly present the stated objectives, the

dissertation is divided into 6 sections as follows: 1) a historical, geological, geographical, and geochemical description of the Upper New River Basin; 2) a summary and discussion of the chemical limnology of the Upper New River and selected tributaries; 3) a discussion of algal growth potential studies; 4) discussion and modeling of the limiting nutrient situation in the 6 primary tributaries to the proposed impoundments; 5) a description of water quality and associated biotic changes which might be expected to occur if these lotic waters are impounded; and 6) predictive statements and models concerning the nutrient budgets, productivity, and trophic status of the proposed reservoirs.

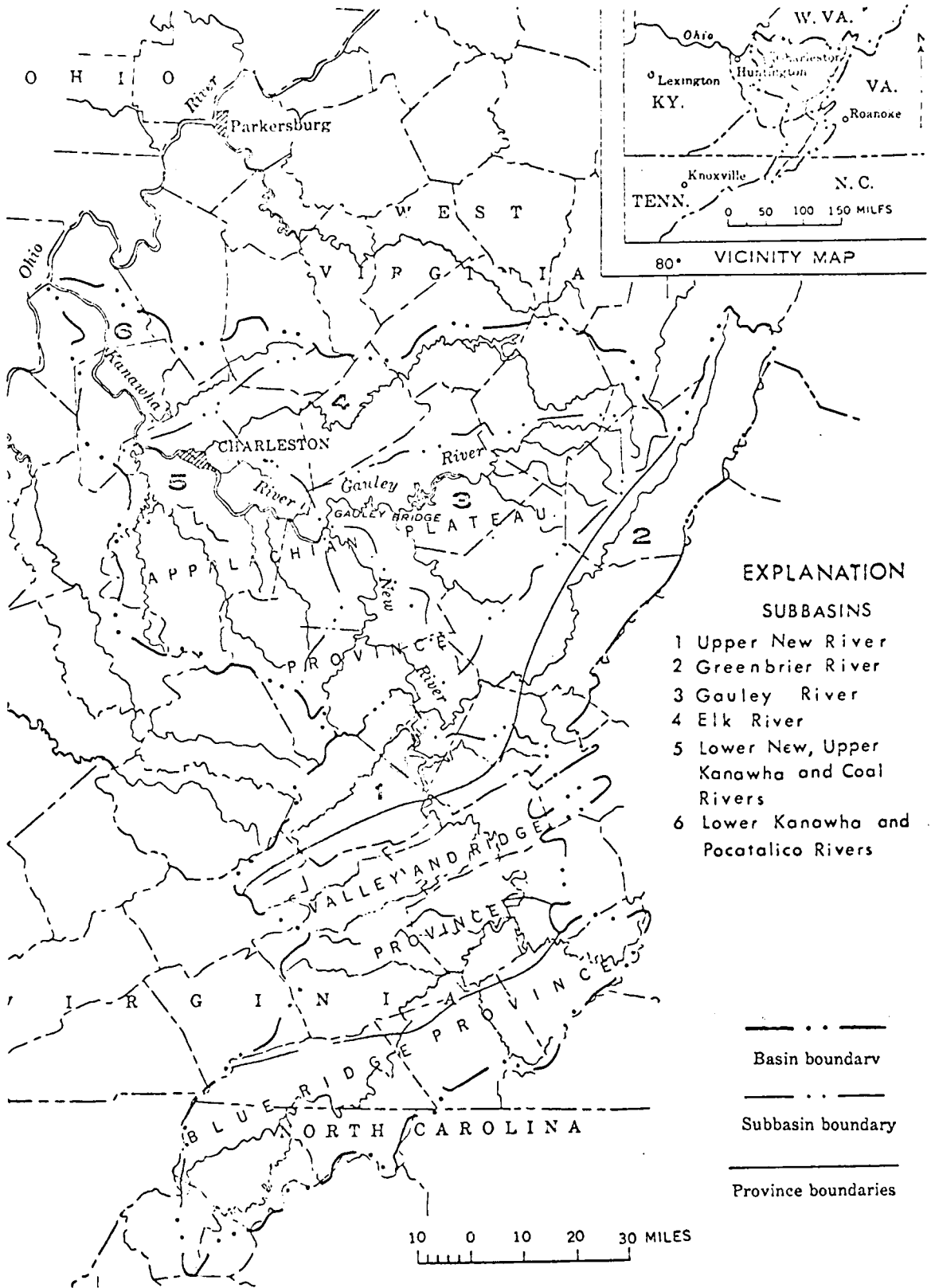
I. HISTORICAL, GEOLOGICAL, GEOGRAPHICAL, AND GEOCHEMICAL DESCRIPTION OF THE UPPER NEW RIVER BASIN

The New River of North Carolina and Virginia is one of the oldest rivers in the world, possibly second in age only to the Nile (Choquette and DeLalla, 1975). It is geologically unique in that it is the only existing major river in North America that flows north. Geologists explain this peculiarity by the fact that the river's course was determined prior to the uplifting of the Appalachian Mountains. The uplifting simply caused the river's bed to be narrowed and its flow rate to be increased.

The New River Valley was originally occupied by the Canawhay Indian Tribe, whose hunting trails followed the river north to the Ohio. White settlers later named the northern reaches of the river after the Indians, calling it the "Kanawha" from its confluence with the Gauley River in Fayette County, West Virginia, to Point Pleasant on the Ohio. (Kanawha River Basin Coordinating Committee (KRBCC), 1971)

The New River is the largest of the 6 major subbasins comprising the Kanawha River Basin (Fig. I-1). The entire basin drains some 31,857 square km, extending generally south to north from the Blue Ridge Parkway at Blowing Rock, N. C. to the Ohio River at Point Pleasant, W. Va. About 21,885 square km are in West Virginia, 8,003 in Virginia, and 1,994 in North Carolina.

After rising in northwestern N. C., the New River flows northeasterly into Virginia through and between spurs of the Blue Ridge Mountains, parallel to the main divides of this range and the



EXPLANATION

SUBBASINS

- 1 Upper New River
- 2 Greenbrier River
- 3 Gauley River
- 4 Elk River
- 5 Lower New, Upper Kanawha and Coal Rivers
- 6 Lower Kanawha and Pocotalico Rivers

— · · —

Basin boundary

— · · —

Subbasin boundary

— — —

Province boundaries

10 0 10 20 30 MILES

Fig. I-1. Index map of the Kanawha-New River Basin.

Alleghanies, until it reaches a point known as the "Horseshoe" near Little River (the proposed site of the lower dam). Here the River turns abruptly to the northwest, breaking through the 5 ranges of the Alleghany Mountains, and keeps the same general direction to its confluence with the Gauley. From the source at about elevation 1158 m to the mouth at elevation 198, the New River has a total fall of 960 m in its length of about 402 km or an average slope of 2.4 m per km. (KRBCC, 1971). The River follows deep, narrow valleys and has a channel that is, in general, narrow and tortuous with numerous rapids and falls.

The Kanawha Basin comprises 3 physiographic provinces the smallest of which is the Blue Ridge, embracing little more than the 3 counties in which the proposed impoundment would lie (Fig. I-1). This province is underlain by distorted metamorphic and igneous rocks of Precambrian origin, and the surface consists of irregularly disposed, rugged mountains, interspersed with irregular areas of hilly country. The lowest elevation in this province is just under 610 m, where the New River leaves the province. Upland areas range from elevations of 732 m upward to 1220 m, with several peaks in excess of 1525 m (KRBCC).

The headwaters of the South Fork New River receive runoff and ground-water discharge from the Blowing Rock Gneiss and tributaries that drain the Flattop Schist, Cranberry Gneiss, and a small section of the Unicoi formation, composed of sandstone, quartzite, and conglomerate. The South Fork is 105 km long and has an average fall

of 2.65 m per km. The North Fork drains similar geologic terrain, but is 56 km long with an average fall of 11.2 m per km. Despite their differences in length and profile, the 2 streams have similar low flow characteristics. Analyses of water from wells in the area show a total dissolved solids content similar to that in the 2 forks (KRBCC, 1971).

Big Wilson Creek and Fox Creek join the New River just below the confluence of the North and South Forks. These creeks drain an area underlain primarily by granitegneisses, although the upper reaches of both extend into areas underlain by rocks of the Mount Rogers Volcanic Group. Little River (Virginia) enters from the south and drains an area along the slopes of the Blue Ridge Mountains similar to those of Big Wilson and Fox Creeks. Elk Creek, in eastern Grayson County, Virginia, also drains an area underlain principally by gneisses and granites, although a few of its minor northern tributaries drain sandstone and quartzite of Cambrian age. Discharge from these Cambrian rock sequences may account for the slight increase in total dissolved solids in Elk Creek and in the New River downstream from its confluence with Elk Creek (KRBCC, 1971).

As the river flows northeasterly, tributaries entering from the north drain areas underlain mostly by Paleozoic sedimentary rocks and their water is rather hard. Tributaries from the south drain mainly gneisses, schists, and minor amounts of sandstone, shale, and dolomite and the water is fairly soft. The next major tributary of the New River is Cripple Creek, which drains shaly dolomite,

shales, and sandstones from Rome Formations of Cambrian age. The change in geological environment is reflected by marked increases in hardness and total mineral concentrations.

Just prior to its confluence with Cripple Creek, the New River itself passes into dolomite or limestone (carbonate) formations of Cambrian age, causing a significant increase in hardness. Reed Creek, the next major tributary, drains Paleozoic sediments in the northern portion of the basin, bringing in more hard water. The river then winds northeasterly through shale and sandstone deposits for approximately 40 km before again entering an area of limestone and dolomite at the confluence with Peak Creek, and the headwaters of Claytor Lake. This impoundment, as well as the remainder of the Upper New River Subbasin, lies in an area of Cambrian dolomite and limestone.

Although there is some discharge of untreated and partially treated industrial and municipal wastes in this subbasin, the greatest pick-up of minerals is due to increments from streams draining sedimentary rocks. The total dissolved solids concentration at Radford, Virginia is less than $1\frac{1}{2}$ times that of the New River at the confluence of the North and South Forks in North Carolina (KRBCC, 1971).

II. CHEMICAL LIMNOLOGY OF THE UPPER NEW RIVER AND SELECTED TRIBUTARIES

Introduction

The Greek philosopher Heraclitus (ca 500 B.C.) observed that "You cannot step twice into the same river, for fresh waters are ever flowing upon you." Lotic waters are set apart from all other aquatic ecosystems in that the water is continually entering and leaving, and is in almost constant motion. There is a continual mixing of the watery medium and a constant erosion of the substrate, with concomitant changes in the characteristics of the stream bed, and little or no opportunity for the accumulation and retention of the dissolved nutrients (Krumholtz and Neff, 1970).

In most natural waters physico-chemical parameters vary significantly through both time and space. Almost all parameters exhibit variation or patchiness within a given habitat, with small, undisturbed, spring fed streams providing the only exception (Hynes, 1972). Many parameters, such as dissolved oxygen and pH, also exhibit distinct annual and diurnal cycles.

Hynes (1972) points out that the chemical content of natural running waters varies enormously from region to region, reflecting the local geology, geography and climate. Usually much of the water entering a stream does so as subsurface run-off in mineral soil, and only when there is heavy precipitation or a considerable amount of snow melt does a large proportion enter as direct surface runoff.

A major part of this pre-impoundment survey has involved the monitoring of physico-chemical water quality in the New River

and selected tributaries above, in, and below the proposed impoundments. A total of 28 parameters were monitored at each of 12 sites (Fig. II-1). A description of these sites is as follows:

- Station 1 - South Fork, New River at N. C. State Route 88 near West Jefferson, N. C.
- Station 2 - North Fork, New River at the junction of N. C. State Route 88 and Lou Jones Road near Warrensville, N. C.
- Station 3 - North Fork, New River at low water bridge approximately 0.08 miles downstream from Sprague Electric Company near Lansing, N. C.
- Station 4 - Main channel, New River at low water bridge on Va. State Road 601 near Cox Chapel, Va.
- Station 5 - Peach Bottom Creek at U. S. 221-58 bridge, 1.0 mile below Independence, Va.
- Station 6 - Main channel, New River, 1.0 mile downstream from U. S. 221-58 highway bridge near Galax, Va.
- Station 7 - Main channel, New River, behind Fries High School, Fries, Va., approximately 0.5 miles below dam at
- Station 8 - Main channel, New River, 0.50 miles upstream from U. S. 52 highway bridge near Austinsville, Va.
- Station 9 - Main channel, New River at Va. State Road 114 highway bridge near Radford, Va.
- Station 10 - Wilson Creek, 0.25 miles upstream from confluence with New River, near Mouth of Wilson, Va.
- Station 11 - Fox Creek, 0.1 miles upstream from confluence with New River, at U. S. 58 bridge
- Station 12 - Little River, 1.5 miles upstream from confluence with New River, at Va. State Road 629 low water bridge near Galax, Va.

UPPER NEW RIVER BASIN

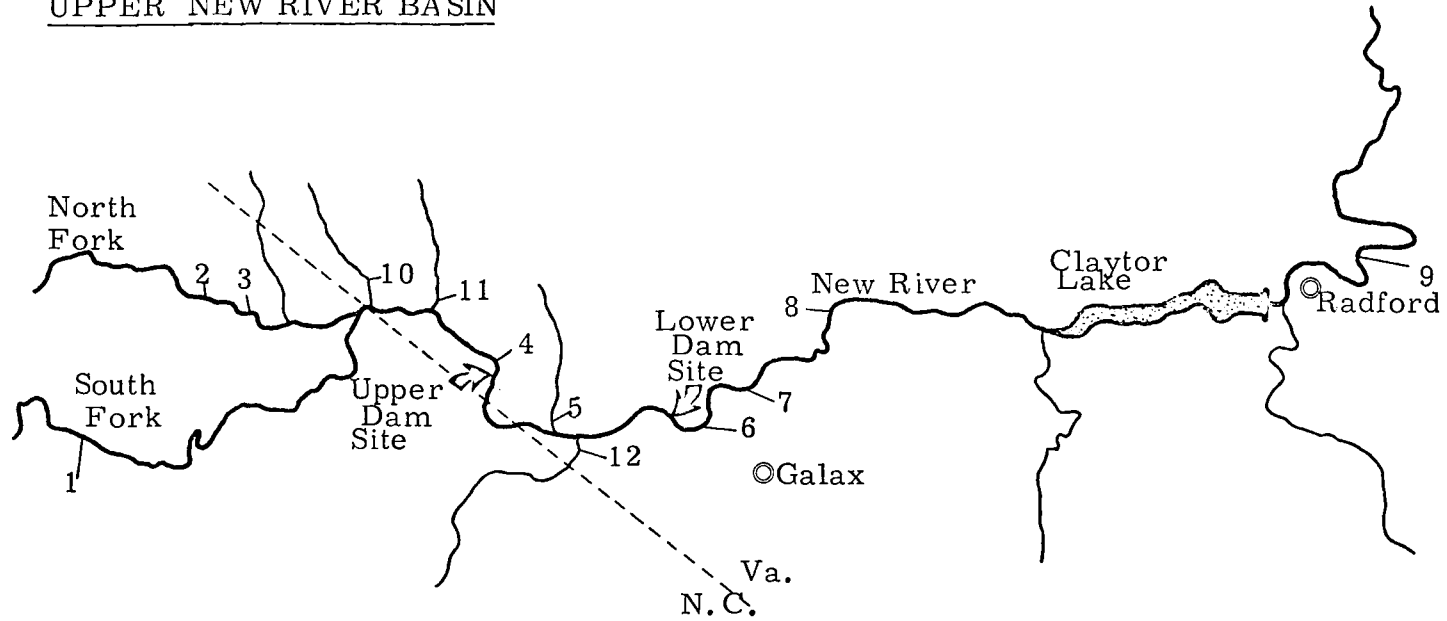


Fig. II-2. Location of the 12 physico-chemical sampling sites in the upper New River Basin.

Physico-chemical monitoring was initiated in the summer of 1970, however collections at Stations 10, 11, and 12 did not begin until October of 1973.

Materials and Methods

Collections were made biweekly during the 1970-71 USGS water year (Oct. 1, 1970 - Sep. 30, 1971), and monthly during the following three water years. Samples were collected by submersing acid-cleaned gallon jugs under the water surface until filled. Samples to be analyzed by the Appalachian Power Company water chemistry lab in Huntington, W. Va., were boxed and deposited at the Appalachian Power Company's office in Christiansburg, Va. for transportation to Huntington. Samples to be analyzed in the Aquatic Ecology Water Chemistry Laboratory at VPI & SU were transported from the field on ice and refrigerated upon return to the laboratory.

Analyses conducted by the Appalachian Power Company's Huntington laboratory included the following: Ca, Mg, Na, K, Fe, Mn, Al, Cr, Cu, Pb, Hg, Ni, Zn, SiO₂, HCO₃⁻ (alkalinity), SO₄⁻², Cl⁻, hardness (as CaCO₃), dissolved solids, total solids, specific conductance, turbidity, and pH.

Analyses conducted at VPI & SU included 5-day biochemical oxygen demand (BOD₅); nitrate nitrogen (phenoldisulfonic acid method); and ortho, condensed, acid hydrolizable and total (persulfate digestion) phosphate. Analytical procedures performed in both laboratories were according to Standard Methods for the Examination of Water and Wastewater (APHA, 1971).

Dissolved oxygen (Winkler method, azide modification) and temperature were monitored on site upon collection. Hardness, alkalinity, and pH were also periodically monitored on site in order to confirm the accuracy of measurements performed after holding at the Huntington laboratory.

The chemical limnology of the study area will be briefly summarized in the subsequent section. Only N and P, the 2 elements most likely to influence the productivity of the proposed reservoirs, will be discussed in detail.

Results and Discussion

Water throughout the entire upper New River Basin is soft. With the exception of Station 3, (immediately downstream from Sprague Electric Company, a firm engaged in electroplating processes) all stations located within the proposed impoundment area have yearly means of around 13 ppm hardness (as CaCO_3). Significant increases occur at downstream stations, reflecting a transition from areas underlain by crystalline rocks and sandstone into areas underlain predominantly by limestone and dolomite. Nevertheless the waters remain soft.

The pH in the upper basin normally ranges from 6.0 to 7.5, with the exception of the area immediately downstream of Sprague Electric Company on the North Fork of the River. Annual mean pH in the proposed impoundment area is around 6.8, but increases to around 7.1 downstream as a result of the aforementioned change

in bedrock composition. Waters throughout the area are relatively bicarbonate poor, ranging from around 18 ppm in headwater regions to around 50 ppm downstream of Claytor Lake.

Throughout the study area the New River is generally shallow and rapidly flowing with a frequently recurring series of riffles and falls. This physical nature, coupled with substantial photosynthetic activity and a relatively small amount of external organic loading, results in oxygen concentrations equal to, near, or above saturation throughout the entire year at most locations. Temperature is the dominant factor controlling concentrations and yearly maxima are normally attained in January and February. Although concentrations reach a minimum during the summer months, they generally equal or exceed saturation as a result of increased photosynthetic activity, especially in the shallower areas.

As is the case in many lotic waters, there is a general downstream trend of increasing dissolved solids and conductivity. Increases are steady and gradual until the river passes into areas containing limestone and dolomite, at which point there is a sudden increase from around 40 ppm total dissolved solids to around 55 ppm. Hart et al. (1945) reported that the range for dissolved solids in most rivers of the United States is from 72-400 ppm, with a median value of 169 ppm. The range within our study area was from 5-179 ppm (5-125 excluding Station 3) indicating that these waters are relatively low in dissolved solids content.

Waters in the proposed impoundment area are often very opaque and muddy in appearance after periods of any significant rainfall. Undoubtedly almost all of this suspended solids loading is due to non-point source run-off, and could perhaps be reduced through initiation of efficient erosion control methods. The level of suspended solids transported downstream is reduced to some extent by the small dam at Fries, Virginia, and is substantially reduced by Claytor Lake.

With the exception of waters located immediately downstream of the Sprague Electric Company, concentrations of SiO_2 , Fe, Mn, and K present in the study area are typical of those found in most rivers (Livingstone, 1963). Concentrations of Cl^- , $\text{SO}_4^{=}$, and Na present are substantially lower than mean concentrations for North American rivers (Altman and Dittner, 1966), however it is unlikely that they are present in such short supply as to limit productivity.

Concentrations of Al, Hg, and Zn found within the study area may at times be detrimental to aquatic communities. Yearly mean concentrations of Al throughout the basin occasionally exceed the Water Quality Criteria (EPA, 1973) recommended upper limit (0.1 ppm), and levels below the Sprague Electric Company may be 65 times higher than this recommended limit. Mercury concentrations throughout the basin are much greater than those expected to occur naturally, and consistently exceed recommended EPA Water Quality Criteria levels. Concentrations of Zn are generally within the range reported as normal by Durum et al. (1971), however current

mean levels below the Sprague Electric Company are likely to produce avoidance reactions in certain species (EPA, 1973)

It is almost axiomatic that either N or P is the nutrient most likely limiting primary productivity in natural waters (Keeney, 1972). For this reason, and in light of the objectives of this study, these 2 elements will be discussed in greater depth than were the preceding physico-chemical parameters.

Nitrogen, usually in the form of dissolved nitrate, is a major macronutrient for all types of plants, both aquatic and terrestrial. It is the element which transforms organic compounds into the compounds of life (Martin and Goff, 1972).

The concentration of various N species in waters is the net result of numerous environmental factors that influence the rate of nitrogen immobilization, mineralization, nitrification, denitrification, and fixation (Keeney, 1972). Assimilation of N, i.e. the incorporation of ammonium, nitrate, atmospheric N, or organic N into living biomass, is a necessary life process. Opposing mineralization processes are occurring simultaneously in most systems, and the net change in N status is reflected in the biomass level of N at a given time. The relative roles of bacteria, fauna, and flora, responsible for nitrogen assimilation and release, will vary with the system and with changes in morphological, physical, and chemical variables within the system (Johannes, 1968).

The major sources and forms of N vary from watershed to watershed. However in swift, shallow, well aerated waters such

as those of the upper New River, N is present almost exclusively as nitrate. Waters below the Sprague Electric Company contain by far the highest levels of nitrate in the basin, with annual means of around 1-3 ppm as nitrogen. Annual means throughout the remainder of the basin range from 0.2-0.5 ppm (as N). More detailed results are presented in Table II-1.

Hynes (1972) reports that normally the concentration of nitrate in stream or river waters is low because the ions are rapidly taken up by plants. However in the upper New River nitrate concentrations appear to be in excess of what indigenous plant populations can assimilate.

A concentration of 0.3 parts per million inorganic N has been suggested by Sawyer (1947) as the critical level at or above which noxious algal blooms can be expected to occur in natural waters, premised of course on the fact that all other essential nutrients are present in excess. The general applicability of this value has been verified by Vollenweider (1968) and Lueshow et al. (1970). Based on Sawyer's criterion, one could postulate that the proposed reservoirs would have ample inorganic N supplies for plant growth problems to develop, especially in view of the fact that freshly inundated soils are likely to contribute quite a bit of nitrogen. This hypothesis will be dealt with in greater detail in section VI.

The major sources of P to surface waters are groundwater, rainfall, land runoff, and wastewaters (Keup, 1966). While

Table II-1. A summary of nitrate data collected from 12 sampling sites in the upper New River basin. (Results are reported as ppm N.)

Station #	1970-71			1971-72			1972-73			1973-74		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1	0.195	0.059	0.319	0.269	0.136	0.417	0.316	0.134	0.609	0.266	0.051	0.477
2	0.211	0.066	0.405	0.334	0.123	0.477	0.362	0.121	0.647	0.417	0.199	0.637
3	1.781	0.053	4.955	2.971	0.334	6.189	1.364	0.162	2.273	2.062	1.022	3.028
4	0.232	0.127	0.382	0.363	0.163	0.788	0.415	0.202	0.636	0.380	0.072	0.601
5	0.222	0.076	0.421	0.332	0.180	0.570	0.429	0.181	0.693	0.419	0.111	0.770
6	0.196	0.073	0.350	0.306	0.154	0.589	0.358	0.070	0.569	0.407	0.189	0.597
7	0.212	0.069	0.360	0.354	0.138	0.522	0.401	0.100	0.712	0.393	0.224	0.586
8	0.232	0.070	0.366	0.354	0.165	0.548	0.415	0.194	0.595	0.405	0.207	0.648
9	0.210	0.071	0.392	0.324	0.145	0.466	0.429	0.244	0.799	0.360	0.044	0.603
10										0.240	0.065	0.467
11										0.250	0.065	0.565
12										0.205	0.038	0.318

acknowledging that the former 2 sources may be significant in isolated cases, Keup identifies the latter 2 as the major contributors.

Phosphorus undergoes several changes once it enters a flowing waterway. Suspended solids often settle to the bottom and may be incorporated, at least temporarily, into bottom or bank deposits. Soluble phosphate ions may either combine chemically with certain metallic cations and precipitate, may be adsorbed by suspended particulate materials, or may be taken up by the various flora occupying the stream. Odum (1971) reports that the majority of a waterway's P is tied up in organic materials, probably not over 10 % ever being in a soluble form at one time. Ball and Hooper (1963), using ^{32}P radioactive tracers, showed that the periphyton was the primary source of rapid biological uptake of P in stream ecosystems. Keup (1968) concludes that a stream's benthos is its primary net remover of P, responsible for the significant and rapid "drop out" of total P (T-P) often observed in flowing masses of water. The rates at which P is removed varies, of course, from river to river, within sections of a river, and with seasonal changes.

Phosphorus has a restricted biogeochemical cycle compared to nutrients such as N and carbon (C) which have gaseous forms and cycles open to the atmosphere. Lack of an atmospheric escape route restricts P to the waterway and the watershed, unless discharged from the basin. High or flood-stage waters allow for

deposition of large amounts of organic and inorganic adsorbed P on the surrounding floodplain. Other proposed mechanisms of removal include the emergence of aquatic insects and the harvesting of fishes.

Phosphorus compounds of a wide variety are encountered in natural waters. For purposes of analysis, however, the following three major forms are recognized; ortho-, poly- and organic phosphates. Both poly- and organic forms of P are converted to orthophosphate for measurement in the laboratory; and in natural waters, after hydrolysis and mineralization respectively, they are likewise converted to orthophosphate. Orthophosphate consists of four possible solute species: H_3PO_4 (aq), H_2PO_4^- , HPO_4^{2-} , and PO_4^{3-} . These are the forms of P normally assimilated by plants. The relative abundance of these four species is a function of the pH of the water which is buffered somewhat by their presence. In a natural water whose pH is 7.21, the phosphate activities would be evenly divided between H_2PO_4^- and HPO_4^{2-} . Polyphosphates are molecularly dehydrated forms of ortho- which are commonly added to synthetic detergents as "builders" and to public water supplies as a means of controlling corrosion in pipes. They are not immediately available for assimilation by plants in this form, but they are normally hydrolyzed in natural waters within a matter of several hours, or possibly days, to yield orthophosphate. Organic P, the third major form of P, may be present as nucleic acids,

lipids, cell fragments, whole cells, clumps of cells from partially mineralized organic matter, or even as whole planktonic and microscopic organisms (Keup, 1968).

Phosphorus is classified as an essential macronutrient for all plants and animals as well as the Monera, and is indispensable to life. Some of its primary vital functions can be appreciated when one realizes that it is a structural component of nucleic acids, coenzymes, phospholipids, and ATP (Keeton, 1972).

Although both N and P are frequently cited for causing excessive growths of algae and aquatic weeds, most attempts to control these growths have focused upon reducing inputs of phosphorus. This approach is based on the premises that (1) phosphates are present in only trace amounts in unproductive waters, (2) P additions by natural processes (rain, runoff, stream flow) are low relative to N, (3) P is more readily eliminated from sewage treatment plant effluents than is N, (4) N additions to waters are more difficult to control, and (5) the internal N cycle in waters is more self-regulating (Keeney, 1972). Two other factors which would seem to implicate P as the primary aquatic limiting nutrient are 1) the fact that the ratio of N to P within plants is about 15 to 1 (Ketchum, 1969) while the ratio in most natural waters is about 22 to 1 (Hem, 1970), and 2) there seems to have been a startling increase in the rate of eutrophication of natural waters since the advent of phosphate builders for synthetic detergents and the greatly accelerated mining of this mineral.

Analyses for 4 different forms of phosphate were performed during the four year study period. Analyses conducted for the entire period included: ortho- acid hydrolyzable filtered (condensed), and acid hydrolyzable unfiltered. Total soluble and particulate (unfiltered, persulfate digested) phosphate analyses were initiated in April, 1972. From the standpoint of water quality management, the 2 most important of the various forms are ortho- and total: the former because it is the form instantaneously available to aquatic plants, and the latter because it represents the level of phosphate potentially available. Results of analyses for these 2 forms are presented in Tables II-2 and II-3. The rate of flux between total phosphate and soluble ortho- is of course a function of many environmental factors. However, since T-P serves as a reservoir for available phosphate, it is the form which must be considered in terms of P criteria and standards.

Water Quality Criteria (FWPCA, 1968) recommends that T-P levels not exceed 0.1 ppm in rivers, or 0.05 ppm where rivers enter lakes or reservoirs. During the 3 years in which T-P was monitored, mean annual levels were in excess of 0.1 ppm at least once at Stations 1, 2, 3, 4, 5, 6, 7, and 9. At Stations 3 and 5, annual means exceeded 0.1 during all 3 years. Of the 6 tributaries which would feed into the proposed reservoirs, 5 have annual means in excess of the proposed 0.05 ppm standard, and all 6 have yearly maxima exceeding this level.

Table II-2. A summary of orthophosphate data collected from 12 sampling sites in the upper New River basin. (Results reported as ppm P.)

Station #	1970-71			1971-72			1972-73			1973-74		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1	0.017	0.002	0.054	0.022	0.009	0.034	0.023	0.008	0.050	0.017	0.008	0.031
2	0.009	0.000	0.043	0.019	0.011	0.044	0.017	0.000	0.029	0.020	0.007	0.051
3	0.016	0.002	0.067	0.013	0.001	0.045	0.025	0.009	0.051	0.025	0.007	0.047
4	0.013	0.000	0.021	0.012	0.012	0.037	0.019	0.005	0.036	0.016	0.012	0.023
5	0.201	0.059	0.525	0.261	0.092	0.586	0.201	0.078	0.479	0.166	0.076	0.255
6	0.015	0.002	0.037	0.023	0.005	0.042	0.025	0.010	0.052	0.020	0.016	0.025
7	0.011	0.000	0.042	0.020	0.006	0.034	0.024	0.003	0.041	0.017	0.012	0.027
8	0.013	0.000	0.039	0.017	0.004	0.025	0.031	0.000	0.041	0.015	0.012	0.018
9	0.017	0.000	0.056	0.031	0.005	0.051	0.034	0.014	0.057	0.025	0.009	0.046
10										0.013	0.009	0.199
11										0.014	0.010	0.018
12										0.017	0.012	0.027

Table II-3. A summary of total PO₄-P data collected from 12 sampling sites in the upper New River basin. (Results reported as ppm P.)

Station #	1970-71			1971-72			1972-73			1973-74		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1	----	----	----	0.146	0.044	0.322	0.094	0.037	0.202	0.048	0.035	0.064
2	----	----	----	0.105	0.045	0.238	0.065	0.042	0.107	0.073	0.027	0.252
3	----	----	----	0.150	0.085	0.273	0.147	0.060	0.301	0.135	0.079	0.214
4	----	----	----	0.138	0.055	0.276	0.088	0.039	0.147	0.050	0.034	0.078
5	----	----	----	0.442	0.193	0.682	0.261	0.071	0.546	0.236	0.152	0.349
6	----	----	----	0.104	0.042	0.290	0.150	0.030	0.734	0.063	0.041	0.121
7	----	----	----	0.081	0.044	0.115	0.129	0.027	0.539	0.059	0.033	0.125
8	----	----	----	0.072	0.045	0.098	0.088	0.028	0.319	0.049	0.040	0.085
9	----	----	----	0.106	0.064	0.160	0.110	0.039	0.286	0.058	0.029	0.134
10										0.028	0.011	0.051
11										0.035	0.020	0.061
12										0.053	0.028	0.192

Conclusions

1. Waters in the upper New River Basin are well oxygenated, soft, bicarbonate-poor, and relatively low in dissolved solids content.
2. Water quality appears to be generally good, although concentrations of heavy metals present are often in excess of recommended water quality standards (EPA, 1973), especially in water immediately below the Sprague Electric Company, on the North Fork.
3. Concentrations of N and P present are relatively high, and although of no consequence in fast flowing waters, they may constitute a potential post-impoundment enrichment problem.

III. ALGAL GROWTH POTENTIAL (AGP) STUDIES

Introduction

In studies concerned with productivity of natural waters, it is important to know the potential capacity of the water to support algal growth. Chemical analysis provides information on the quantity of plant nutrients and/or toxicants present in water, but supplies no insight into its sum nutritional and inhibitional qualities, and therefore does not allow for adequate quantitative assessment of its growth quality. However controlled experiments, performed in the laboratory, will give reliable information of this nature. The objective of this study was to determine the AGP of selected waters in the New River Basin through use of static laboratory bioassays.

Materials and Methods

Water on which assays were to be performed was collected in acid-washed glass bottles and transported back to the laboratory in the dark and on ice. Upon arrival at the laboratory the water was filtered through pre-rinsed 0.45 μ Millipore[®] filters and stored in the dark at approximately 4C until ready for use. A unicellular green alga, Selenastrum capricornatum Printz (Chlorococcales, Chlorophyceae), obtained from the U. S. Environmental Protection Agency (Corvallis Oregon) was used as the assay organism. Assays were conducted in a growth chamber at 24C on an 18 hr. -6 hr. light-dark cycle at a light intensity of

400 ft. -candles (cool white fluorescent). Assays were carried out in 30-ml culture tubes, and growth was monitored as optical density using either a Klett-Summerson colorimeter (#42 filter) or a Perkin-Elmer Dual Beam Spectrophotometer (600 nm). Growth was monitored at 1 to 3 day intervals and incubation was continued until maximum biomass was achieved. Optical density readings obtained with the spectrophotometer were subsequently transformed into dry weight values using a previously calculated linear regression equation. The equation was calculated from data points created by centrifuging, drying, and weighing large aliquots of cultures with known optical densities.

Results and Discussion

AGP of primary sampling sites:

An assay was conducted on waters collected in February, 1973, (1) to determine the relative AGP of waters at the 8 primary sampling stations located above, in, and immediately below the proposed impoundments, and (2) to determine if differences in AGP between stations could be explained on the basis of the chemical content of the water.

After inoculation, the alga grew in all waters except those from Station 3, which is located approximately 50 meters below the lagoons of the Sprague Electric Company on the North Fork of the River. Cells inoculated into water from this station were destroyed shortly after incubation began. The AGP of 11 replicates was monitored for each of the 7 stations at which growth occurred.

At the conclusion of the assay, growth curves for each station were plotted (Fig. III-1) and a Student-Newman-Keuls (S. N. K.) a posteriori multiple range analysis was performed in order to determine at which stations, if any, the AGP was significantly different from other stations. Results of this analysis (Table III-1) demonstrated that the stations which exhibited growth could be divided into 4 significantly different groups ($\alpha = .05$) according to AGP. Water from Peach Bottom Creek had a growth potential significantly higher than that from any other station. The waters with the next significantly different growth potential were from Stations 2 and 7, located on the North Fork above Sprague Electric Co., and just below Washington Mills Dam, respectively. The growth potential at these 2 stations was significantly less than that at Peach Bottom Creek but significantly greater than that at all other stations. Next, in order of decreasing AGP, were Stations 1 and 6, located on the South Fork and New River below the proposed spillways, respectively. Waters from Station 4, near Cox Chapel, and Station 8, near Austinville had a growth potential significantly lower than that at Stations 1 and 6.

The high AGP of the water from Station 5 was somewhat expected because, as is often the case at this station, the level of P present was almost as high as that found in many synthetic algal media. Phosphorus and nitrogen concentrations were, respectively, 12.3 and 1.9 times higher than those reported by Sawyer (1947) to be present in "well-behaved" lake waters. The N and P ratio

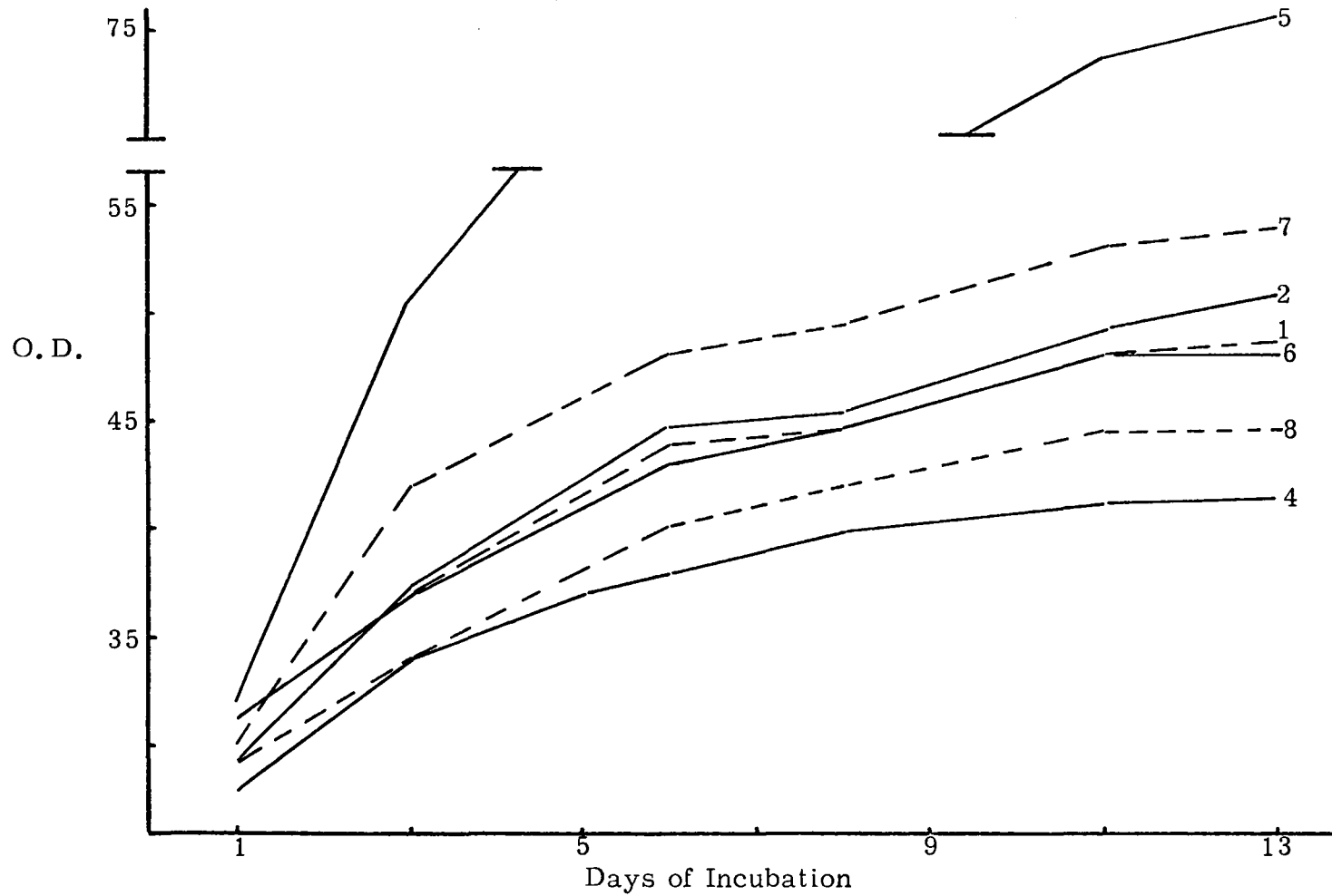


Fig. III-1. AGP of water from the 8 primary sampling sites in the upper New River basin.

Table III-1. Relationship between AGP and selected chemical parameters at the 8 primary sampling stations in the upper New River Basin. (brackets group means which are not significantly different, $\alpha = .05$ as determined by the Student-Newman-Kuels (S. N. K.) test)

Station #	O. D. (Colorimeter)	S. N. K. Analysis	PO ₄ -P (ppm)	NO ₃ -N (ppm)	Detectable * Toxicant
5	76.0		.123	.553	none
7	54.0	]	.014	.382	none
2	51.0		.018	.528	none
1	48.5	]	.023	.366	none
6	48.0		.014	.425	none
8	44.0	]	.015	.435	none
4	41.0		.013	.485	none
3	0.0		.023	1.411	Cu, Al

* Any parameter present at concentration in excess of levels recommended by Water Quality Criteria (EPA, 1973) for the protection of aquatic organisms.

in the water was 4.5:1, indicating that the lack of additional N may have prevented an even greater algal growth.

It was expected that the AGP of the water from Station 3 would be relatively low, although death of the cells within 24 hours was not anticipated. A comparison of the water chemistry at Station 3 with that at Station 2, located 5 miles upstream gives some insight into the possible causes of this death. On the sampling date, chlorides at Station 3 were 12 times higher; Al, 20 times higher; Hg, 5 times higher; Cu, 2 times higher, Zn, 33% higher, and the pH was 0.8 units lower. Levels of Cu and Al present were, respectively, 10 and 3 times higher than maximum levels recommended for surface waters in Water Quality Criteria (EPA, 1973).

The relatively low AGP of the water at Station 1 cannot be explained in terms of its chemical composition. The N to P ratio of 16:1 indicated that P might have been limiting, and yet this water contained the second highest P content of all the stations assayed. There was apparently some type of synergistic or antagonistic interaction exerting influence on the AGP, or there was some type of toxicant present which was undetectable in our routine chemical analyses. The latter may have been the case, due to the presence of a garage and service station immediately upstream from the sampling site. Here we have an example of a situation in which the AGP of a water could not be accurately predicted through evaluation of chemical data.

In order to examine the relationship between the AGP and available N and P levels present at the various stations, AGP was plotted as a function of orthophosphate-P (O-P) and nitrate-N (N-N) (Figures III-2 and III-3, Appendix A). The scatter of the points and the relatively low correlation coefficients (r) for the 2 regression lines indicate that the AGP differences cannot be explained entirely on the basis of P or N content.

AGP of selected tributaries:

Most of the water to be impounded by the proposed reservoirs would be supplied by the following 6 tributaries: North Fork, New River; South Fork, New River; Wilson Creek; Fox Creek; Peach Bottom Creek; and Little River. AGP bioassays were performed seasonally for a period of 1 year on waters collected from each of these tributaries. Seven replicates for each treatment were incubated and monitored for a period of 12 days, and results are reported as the maximum biomass recorded during this period. The objectives of these assays were (1) to determine the relative AGP of waters from the different tributaries at various times of the year and (2) to examine the relationship between AGP and N and P availability.

Assay data demonstrated that waters from Peach Bottom Creek consistently had the greatest AGP (Table III-2), and S. N. K. analyses indicated that the AGP there was significantly greater ($\alpha = .01$) than at the other 5 tributaries. Phosphorus concentrations in Peach Bottom Creek were generally an order of magnitude

Table III-2. Seasonal AGP , orthophosphate phosphorus concentration, and nitrate nitrogen concentration of the six major tributaries to the proposed impoundments. (brackets group non-significant subsets)

Season	Tributary	Biomass (mg l ⁻¹ dry wt.)	S.N.K ($\alpha = .01$)	Ortho-PO ₄ -P (ppm)	NO ₃ -N (ppm)
Fall (1973)	P. Bottom Cr.	3.5	]	.255	.257
	Little R.	.65		.017	.219
	South Fork	.60		.016	.136
	North Fork	.60		.010	.329
	Wilson Cr.	.53		.011	.215
	Fox Cr.	.48		.007	.565
Winter (1974)	P. Bottom Cr.	14.3	]	.142	.641
	North Fork	9.2		.039	.603
	Little R.	.73		.013	.244
	South Fork	.68		.012	.364
	Wilson Cr.	.67		.016	.287
	Fox Cr.	.46		.010	.339
Spring (1974)	P. Bottom Cr.	2.9	]	.200	.111
	South Fork	.72		.021	.342
	North Fork	.72		.016	.421
	Little R.	.68		.017	.185
	Wilson Cr.	.66		.013	.238
	Fox Cr.	.52		.014	.088
Summer (1974)	P. Bottom Cr.	2.7	]	.190	.307
	Wilson Cr.	.63		.007	.197
	Little R.	.63		.007	.197
	Fox Cr.	.57		.005	.160
	North Fork	.40		.003	.370
	South Fork	.35		.004	.139

greater than at all other stations and were presumably responsible for the significantly greater AGP. Fox and Wilson Creeks, the 2 smallest tributaries, generally had the lowest AGP as well as the least amount of phosphorus.

In order to examine the relationship between AGP and the N and P present in the respective waters, maximum biomass was plotted as a function of N-N and O-P concentrations for each of the seasonal assays, and a least squares regression line was calculated for each of the plots (Appendix A). The correlation coefficient for each of the lines is presented in Table III-3. Phosphorus concentration appeared to account for a great deal of the variation in AGP, while N concentrations appeared to account for very little. Consequently simple linear regression models with O-P concentrations as the only dependent variable can be used to closely approximate the AGP of these waters (Appendix A). Although high correlation and predict ability are not necessarily indicative of a cause-effect relationship, these results suggest that P availability may control the potential productivity of the tributaries assayed.

Table III-3. Correlation coefficients relating AGP to $\text{NO}_3\text{-N}$ and ortho $\text{PO}_4\text{-P}$ concentrations for each of the four assays.

	Fall	Winter	Spring	Summer
N	0.13	0.92	-0.38	0.46
P	0.99	0.94	0.99	0.99

IV. NUTRIENT LIMITATION STUDIES

Introduction

In studies concerned with the productivity and potential trophic status of natural waters, it is important to identify the element(s) that limits algal growth and the concentration of this element that must be maintained before other elements become limiting. There are 7 potential approaches to this problem: (1) short-term enrichment experiments utilizing indigenous populations of aquatic plants (e.g. Goldman, 1960, 1963), (2) short-term enrichment experiments utilizing a selected assay organism (e.g. EPA, 1971; Skulberg, 1966), (3) analysis of the nutrient composition of representative indigenous plants (e.g. Holm-Hansen et al., 1968; Coombs et al., 1967), (4) analysis of the enzymatic composition of representative indigenous plants (e.g. Fitzgerald, 1969; Eppley et al., 1969), (5) comparison of the relative abundance of essential plant nutrients present in the water with the relative abundance of these elements reportedly required by aquatic plants, (6) long-term studies in which nutrient levels within the euphotic zone are correlated with concurrently determined productivity and/or biomass data, and (7) long term studies in which calculated or measured nutrient inputs to the ecosystem are correlated with concurrently determined productivity and/or biomass data. Although the methods mentioned above have primarily been used in lacustrine environments, the objectives of this study were (1) to utilize as many of them as

possible to evaluate nutrient limitation in the upper New River Basin, and (2) to create empirical models which will allow prediction of AGP based on the nutrient composition of the water.

Assay utilizing indigenous periphyton

A short-term enrichment experiment utilizing indigenous algae was performed using a modification of a method suggested by Kobayasi (1961). Mats of Spirogyra-like algae were collected from the river and returned immediately to the lab where the algal filaments were meticulously separated from soil and debris. These "cleaned" algal filaments, undoubtedly colonized by various species of epiphyton, were placed in a blender with filtered river water, and blended until a homogeneous suspension of filaments and cells resulted. This suspension was then poured through layers of cheese cloth to remove any clumps of cells, and 20-ml aliquots were pipetted into each of four flasks containing 700 ml of filtered river water. Fifteen milligrams of NaHCO_3 were added to each flask as a buffering agent and to minimize the possibility of inorganic C concentrations limiting the rate of photosynthesis. One flask served as a control, and each of the other 3 were enriched with either P, N or a solution of micronutrients. Table IV-1 describes the contents of each enrichment. Control and treatment flasks were then incubated on a shaker table for 48 hours at 24C. After this initial incubation, the cultures were placed in 300-ml BOD bottles (1 light and 1 dark bottle per treatment) and inoculated with $1\mu\text{Ci}$ of $\text{Na}_2^{14}\text{CO}_3$, after which they were incubated for an additional

Table IV-1. Description of the 3 enrichment spikes added to solutions of filtered New River water and indigenous periphyton.

Treatment	Contents
Phosphate spike	0.186 ppm $\text{PO}_4\text{-P}$ (as K_2HPO_4)
Nitrogen spike	4.2 ppm $\text{NO}_3\text{-N}$ (as NaNO_3)
Trace metal spike	32 ppb B, 115 ppb Mn, 15.7 ppb Zn, 0.35 ppb Co, .004 ppb Cu, 2.9 ppb Mo, 33 ppb Fe, and 300 ppb Na_2EDTA

6-hour light period. Post-incubation treatments included withdrawal of triplicate samples from each of the treatment bottles, acidification and bubbling, after Schindler et al. (1972), pipetting 2.5 ml. of each sample into 15 ml. of a xylene-based scintillation cocktail (Aquasol[®]), and counting with a Packard Model 3310 Tri-Carb Scintillation Spectrometer. Samples were counted 3 times for a period of 10 minutes. All samples were counted in the presence of an external standard (Radium 226), and individual counting efficiencies were determined using a previously calibrated quench curve.

Results and Discussion:

Results, reported as carbon assimilation (mg C/liter) are presented in Table IV-2. The following formula was used for calculation of these values:

$$C_o = \frac{(C_1) (14C_a) (V_b)}{14C_b (V_a)} \times 1.06$$

where C_o = assimilation in mg C/l, C_1 = the concentration of dissolved inorganic carbon (12C in mg/l), $14C_b$ = the activity of 14C added to the incubation bottle (cpm), $14C_a$ = the activity (cpm) of the aliquot counted (light minus dark bottle), V_b = the volume of the incubation bottle (ml), V_a = the volume of the aliquot counted (ml), and 1.06 = the factor to correct for the difference in weight between the 2 carbon isotopes. C_1 was estimated from the conversion table of Bachmann (Saunders et al., 1962).

Hynes (1972) has discussed the many problems associated with attempts to obtain accurate measurements of primary productions in lotic waters. These problems remain bothersome, and I have concerned myself only with relative differences in productivity among treatments, not attempting in any way to define rates of in situ primary productivity.

Results (Table IV-2) indicate that enrichment with both N-N and O-P resulted in a significant increase in the rate of carbon assimilation over the control. Enrichment with the solution of micronutrients resulted in an increase in the mean rate of production, however multiple range test analysis (S. N. K.) indicated that the increase was not statistically significant at the $\alpha = 0.05$ level.

It still remains questionable, however, whether in situ primary productivity is nutrient limited in the upper New River. At the time of sampling, the river water contained 0.071 ppm PO_4 phosphorus and 1.22 ppm NO_3 nitrogen. Considering that the New River is a rapidly flowing stream in which nutrient supplies to plants are continually being replenished, it seems more probable that a physical factor such as light, temperature, or suitable substrate is limiting in situ production. Nevertheless *in vitro* algal bioassays, whether performed in situ or in the laboratory, provide a valuable tool for determining what nutrients might become limiting if physical factors were optimized or if these waters become impounded.

Table IV-2. Assimilation (mgC/liter) for the respective treatments during a 6-hour incubation period, 30-36 hours after treatment began. (Bracket groups means which are not significantly different, $\alpha = .05$)

Treatment	Assimilation (mgC/l)	Mean Assimilation (mgC/l)	S. N. K. Analysis
Control	4.812	4.55	
	4.449		
	4.382		
Micronutrient Spike	4.696	4.69	
	4.699		
	4.688		
N. Spike	6.262	6.16	
	6.082		
	6.122		
p Spike	9.100	9.08	
	9.249		
	8.878		

Assay utilizing indigenous plankton

A second short-term enrichment experiment was performed in June, 1974, using water and indigenous potomoplankton, and/or tytoplankton. Plankton samples were collected by holding an oceanic plankton net (mesh size 35 μ) in the river approximately 25 m below an extensive riffle area. Excess water was forced out of the net at approximately 1 minute intervals, and the contents of the net were emptied into acid-cleaned glass jugs approximately every 10 minutes. The resulting samples containing concentrated numbers of plankton were returned to the laboratory. After agitation to obtain a homogeneous suspension, the mixture was distributed in 250-ml aliquots into 500-ml Erlenmeyer flasks. Randomly selected flasks served as controls, and other randomly selected flasks were enriched with O-P, N-N, or a solution of micronutrients. Enrichment concentrations were the same as those reported earlier in Table IV-1. A small amount of NaHCO_3 was also added to each flask to serve as a buffering agent and to minimize the possibility of inorganic C concentrations limiting the rate of photosynthesis. Control and treatment flasks were then incubated on a shaker table for 12 hours at 24 C. After the initial incubation, 600-ml aliquots of each treatment were withdrawn and transferred to 2 300-ml BOD bottles (1 light and 1 dark bottle per treatment). The BOD bottles were then inoculated with 5 μCi of $\text{Na}_2^{14}\text{CO}_3$, after which they were incubated for an additional 6-hour period. Post incubation treatment of the samples and

calculation of production for the respective treatments were conducted as reported in the assay utilizing periphyton. The remainder of each of the treatment flasks was incubated for an additional 36 hours, after which an additional 600-ml aliquot was withdrawn and treated just as above.

Results and Discussion:

Carbon assimilation data for the respective treatments, after a total of 18 and 54 hours of incubation, are reported in Table IV-3. Results after an incubation period of 18 hours indicated that algae in waters enriched with P had the greatest production. However, results of the S.N.K. analysis revealed that none of the 4 treatments demonstrated a production significantly higher or lower than the other 3 ($\alpha = .05$). Results after a total incubation period of 54 hours revealed that again algae in waters enriched with P demonstrated the greatest production, and S.N.K. analyses indicated that production with this treatment was significantly greater than that exhibited in other treatments.

Results of this assay seem to add further credence to the hypothesis that nutrients are not limiting in situ primary production in the upper New River basin, considering the fact that none of the nutrient-enriched waters exhibited a significant increase in production until 2 days after incubation began. At the end of this 2 day incubation period, waters enriched with P and N exhibited production values which were, respectively, 9.2% and 3.4% greater than that in the control water. However S.N.K. analysis

Table IV-3. Assimilation (mgC/l) for the respective treatments 12-18 hours after treatment began and 30-36 hours after treatment began. (brackets group means which are not significantly different, $\alpha = .05$)

Treatment	Production (mgC/l) 12-18 hours	mean (mgC/l)	S. N. K. analysis	Production (mgC/l) 30-36 hours	mean (mgC/l)	S. N. K. analysis
Control	1.65	1.56		1.57	1.53	
	1.45			1.51		
	1.58			1.51		
Micro-nutrient spike	1.58	1.57		1.56	1.56	
	1.64			1.56		
	1.47			1.57		
N spike	1.59	1.54		1.59	1.58	
	1.50			1.59		
	1.54			1.56		
P spike	1.64	1.60		1.68	1.67	
	1.58			1.67		
	1.60			1.65		

revealed that only in the P-enriched waters was production significantly greater. Regardless of whether or not nutrient factors presently limit in situ production in these waters, results of this assay indicate that P would be the first nutrient to limit production if physical factors were optimized, or improved to the extent that they were no longer limiting. There is also a slight indication that in such a case N might become limiting for some members of the community.

Water assayed in this experiment had an inorganic N to O-P ratio of 19, assuming no $\text{NH}_4\text{-N}$ was present. This N:P ratio, which falls within the range of ratios reported to occur in aquatic flora (Ketchum, 1969) indicates that either P or N might be likely to limit productivity. One might question the exclusive use of inorganic forms of N and P in calculating the elemental ratios present in these waters. This was done because the inorganic forms of these nutrients are assimilated preferentially, and the extent to which heterotrophic algal growth takes place is open to question. Lund (1965) cited numerous references indicating that dissolved organic matter can be utilized by algae but concluded that photosynthesis was primarily responsible for energy generation. Hobbie (personal communication) has found that small amounts of algal heterotrophy may occur in the presence of high levels of organic matter, but at normally occurring levels the algae are unable to compete with the bacteria.

Assays utilizing a selected, cultured organism

A series of 4 bioassays, utilizing a selected, cultured assay organism, were conducted on water collected from each of the major tributaries to the proposed impoundments. The objective of these assays was to evaluate nutrient limitation in the tributaries utilizing water samples collected during 2 different seasons of the year (autumn and spring).

Water from the tributaries (collected in November, 1973 and March, 1974) was returned to the lab on ice in acid-cleaned glass jugs and filtered through pre-rinsed 0.45u Millipore[®] filters. Control and treatment waters were inoculated within 48 hours with a selected assay organism, Selenastrum capricornutum Printz, and procedures used were generally those described in the "Algal Assay Procedure Bottle Test" (EPA, 1971). Algal growth was monitored as optical density, and later converted to biomass (as mg/l dry wt.).

Factorial Assays:

The purpose of these assays was to determine whether productivity in the major tributaries was most likely to be limited by N and P, macronutrients other than N and P, or micronutrients. These 3 "groups" of nutrients were added to each of the respective waters alone and in all possible combinations, creating a 2^3 factorial experimental design. This experimental layout is shown in Table IV-4.

Table IV-4. Design for the 2^3 factorial experiment to determine limiting nutrients.

Enrichment	Treatment							
	Presence (+)				Absence (-)			
Macronutrients	+				-			
P and N	+		-		+		-	
Micronutrients	+	-	+	-	+	-	+	-
	1	2	3	4	5	6	7	8

Three replicates were used for each of the 8 treatments (i.e., a total of 24 samples for each water tested). The elemental composition of each of the 3 "groups" of enrichment spikes is given in Table IV-5.

After inoculation, each of the samples was allowed to grow until its maximum biomass was achieved (or until increases were less than 5% per day).

Results and Discussion:

The maximum biomass (mean) achieved by each of the treatments during both assays is reported in Table IV-6 and IV-7. It is quite evident from these data that either N or P, or both, is (are) the nutrient factor(s) most likely to limit growth in each of the 6 tributaries. Algae in waters which received only macronutrient and/or micronutrient enrichment did not achieve a maximum biomass significantly greater than the controls. On the other hand, algae in all waters enriched with N and P achieved a significant increase in biomass over controls.

Table IV-5. Elemental composition and concentration for the three "groups" of enrichment spikes used in factorial assays.

Enrichment	Salt	Elemental composition and concentration		
			<u>Fall Assay</u>	<u>Spring Assay</u>
Macronutrient (mg/l)	MgSO ₄	Mg	2.9	2.9
	MgSO ₄	S	1.9	1.9
	CaCl ₂	Ca	1.2	1.2
	NaNO ₃	Na	11.0	11.0
	KCl	K	0.47	0.47
N and P (mg/l)	NaNO ₃	N	4.2	2.1
	K ₂ HPO ₄	P	0.19	0.01
Micronutrient (ug/l)	H ₃ BO ₃	B	32.5	32.5
	MnCl ₂	Mn	115.4	115.4
	ZnCl ₂	Zn	15.7	15.7
	CoCl ₂	Co	0.35	0.35
	CuCl ₂	Cu	0.004	0.004
	NaMoO ₄	Mo	2.8	2.8
	FeCl ₃	Fe	33.1	33.1

Table IV-6. Results of the 2³ factorial enrichment experiment performed on waters collected from 6 tributaries November 26, 1973. (brackets group means which are not significantly different, $\alpha = .05$)

Station #	Treatment* A B C	Max. Biomass Dry wt. (mg/l)	S.N.K. Test	Station #	Treatment A B C	Max. Biomass Dry wt. (mg/l)	S.N.K. Test
1	- - -	0.69]	10	- - -	0.63]
	- - +	0.69			+ - +	0.66	
	+ - -	0.72			+ - -	0.67	
	+ - +	0.72			- - +	0.69	
	- + +	129.]		- + -	123.]
	- + -	130.			- + +	125.	
	+ + -	137.			+ + -	133.	
	+ + +	137.			+ + +	134.	
2	- - -	0.69]	11	- - +	0.52]
	+ - -	0.69			+ - +	0.52	
	- - +	0.71			- - -	0.57	
	+ - +	0.71			+ - -	0.57	
	+ + -	106.]		+ + -	100.]
	- + +	111.			- + -	103.	
	- + -	113.			- + +	132.	
	+ + +	130.			+ + +	133.	
5	+ - -	3.7]	12	+ - +	0.69]
	- - -	3.8			- - +	0.71	
	- - +	3.8			- - -	0.74	
	+ - +	3.8			+ - -	0.74	
	+ + -	165.]		- + -	72.]
	- + -	166.			- + +	78.	
	+ + +	172.			+ + -	106.	
	- + +	174.			+ + +	131.	

* + = nutrient spike added
 - = nutrient spike withheld
 A = Macronutrients, B = P & N, C = Micronutrients

Table IV-7. Results of the 2^3 factorial enrichment experiment performed on waters collected from five tributaries on 19 March 1974.

Station #	Treatment* (Mac., N&P, Mic.)			Maximum Biomass Dry Wt. (mg/l)	S. N. K. Analysis
2	+	-	+	9.1]
	-	-	-	9.2	
	-	+	-	56.7	
	+	+	-	56.7	
	-	+	+	57.3	
	+	+	+	58.0]
5	-	-	-	14.7]
	+	-	+	14.7	
	-	+	-	73.3	
	+	+	-	74.3	
	-	+	+	74.6	
	+	+	+	78.7]
10	+	-	+	0.63]
	-	-	-	0.69	
	-	+	+	53.6	
	-	+	-	54.0	
	+	+	-	54.3	
	+	+	+	57.0]
11	+	-	+	0.40]
	-	-	-	0.46	
	+	+	-	55.7	
	-	+	-	56.0	
	+	+	+	57.0	
	+	+	+	57.3]
12	-	-	-	0.74]
	+	-	+	0.74	
	-	+	-	48.6	
	-	+	+	52.0	
	+	+	+	59.6	
	+	+	-	60.3]

* + = nutrient spike added
 - = nutrient spike withheld

In water from all tributaries, the greatest biomass was obtained either when the water was enriched with all 3 groups of nutrients or when enriched with N and P in conjunction with 1 of the other 2 groups. S. N. K. analysis of the fall data revealed that at Stations 2, 11, and 12, the maximum biomass achieved in waters receiving all 3 groups of nutrients was significantly greater ($\alpha = .05$) than in those same waters enriched with only N and P. This significant increase in growth observed in Station 11 water was primarily due to the addition of micronutrients, and in Station 12 water primarily due to addition of macronutrients. In Station 2 water, the additional significant increase was apparently the result of a synergistic interaction involving micronutrients and macronutrients. S. N. K. analysis of the spring data revealed that the biomass achieved in water receiving P and N in conjunction with other nutrients was significantly greater ($\alpha = .05$) at Stations 5 and 12 than that same water enriched with only N and P. The significant increase in the water from Station 12 was primarily due to the addition of macronutrients. In Station 5 water, the additional significant increase was apparently the result of synergism involving macronutrients and micronutrients. These data indicate that if quantities of N and P equivalent to concentrations added in this assay were added to the waters of the respective tributaries, nutrient factors other than N and P could become limiting.

Assays to evaluate N and P limitation:

In order to further evaluate the limiting nutrient situation in the 6 tributaries, waters collected in the fall and spring were enriched with various concentrations of N and P, and in some cases, combinations of the two. The purposes of these assays were (1) to determine whether N or P was the primary nutrient limiting greater productivity in each of the tributaries, and (2) to estimate the concentration of this primary nutrient that could be added before it no longer limited production.

Results and Discussion:

The maximum biomass achieved by each of the treatments in waters from each of the respective tributaries is reported in Tables IV-8 and IV-9. Data from these assays indicated that P was the primary nutrient factor limiting the productivity in water from Stations 1, 2, 10, 11, and 12, and N was the primary factor at Station 5. Waters in which P was limiting generally required an addition of only 0.03 mg/l P or less before it became present in excess of need. This was indicated by the fact that enrichment with P concentrations greater than 0.03 mg/l did not enable a greater biomass to be produced. However water collected at Station 11 in November required an enrichment of between 0.03 and 0.06 mg/l P before the demand of the algae for P was met. Following the addition of sufficient P, nitrogen became the limiting nutrient in all of the waters.

Table IV-8. Results of N and P enrichment bioassay performed on water collected from the 6 major tributaries to the proposed impoundments in November, 1973. (brackets group means which are not significantly different, $\alpha = .05$)

Station #	Enrichment (mg/l)	Max. Biomass Dry wt. (mg/l)	S.N.K. Analysis
1	0.225N	0.50]
	---(control)	0.55	
	0.675N	0.55]
	0.01P	0.80	
	0.03P	5.9	
	0.06P	5.9	
	0.10P	5.9	
0.03P, .675N	13.4		
2	0.675N	0.52]
	---(control)	0.55	
	0.01P	1.3]
	0.06P	9.0	
	0.03P	9.1	
0.06P, .675N	19.6		
5	---(control)	3.3]
	0.03P	3.4	
	0.225N	12.5	
10	0.675N	0.42]
	0.225N	0.44	
	---(control)	0.46	
	0.01P	0.89]
	0.03P	7.1	
	0.06P	7.2	
11	0.675N	0.38]
	---(control)	0.42	
	0.01P	0.93	
	0.03P	9.2	
	0.06P	13.6	
12	0.675N	0.57]
	---(control)	0.59	
	0.01P	0.84]
	0.03P	6.2	
	0.06P	6.2	
	0.03P, .675N	11.1	

Table IV-9. Results of N and P enrichment bioassay performed on water collected from the 6 major tributaries in March 1974. (brackets group means which are not significantly different, $\alpha = .05$)

Station #	Enrichment (mg/l)	Max. Biomass Dry wt. (mg/l)	S. N. K. Analysis
1	---(control)	0.63]
	0.8N	0.63	
	0.03P	9.1	
	0.06P	9.1	
	0.03P, 0.8N	11.2	
2	0.8N	8.9]
	---(control)	9.1	
	0.03P	14.83	
	0.06P	14.87	
	0.03P, 0.8N	18.9	
5	0.06P	14.2]
	---(control)	14.3	
	0.03P	14.4	
	0.08N	33.7	
	0.03P, 0.8N	33.7	
10	---(control)	0.66]
	0.8N	0.69	
	0.06P	6.8	
	0.03P	7.0	
	0.03P, 0.8N	9.1	
11	---(control)	0.46]
	0.8N	0.49	
	0.03P	9.13	
	0.06P	9.37	
	0.03P, 0.8N	11.67	
12	---(control)	0.71]
	0.8N	0.71	
	0.03P	7.13	
	0.06P	6.97	
	0.03P, 0.8N	9.3	

Table IV-10 gives the ratio of N-N to O-P present in each of the waters assayed and compares this with what the previously described assays determined to be the limiting nutrient. Nitrogen to phosphorus ratios between 10 and 20 are commonly cited as occurring in aquatic flora (e. g. Redfield et al., 1963; Ketchum, 1969; Gakstatter et al., 1975), therefore one might expect waters containing ratios in this range to be limited by either N or P, or both. In waters with ratios lower than 10, N would be expected to limit production, and in waters with ratios greater than 20, P limitation would be expected.

Data from these assays seem to partially confirm the validity of predicting nutrient limitation based on N:P ratios present. Only fall assay results at Station 1 contradicted the expected result; however, as noted in Table IV-10, the N:P ratio calculated for this station was based on only 1 N-N sample (replicates were lost), and, therefore, this ratio may be erroneous. If in fact it is accurate, however, one could postulate, based on results of this bioassay, that waters in this basin containing a N-N to O-P ratio of 8.5 or greater are limited by P.

Models Describing Nutrient Limitation

In each of the assays described above, N and P were found to be the primary nutrient factors limiting algal productivity. Only when these nutrients were present in excessive amounts were other nutrients found to limit or control algal productivity. Thus it would seem possible to construct simple linear regression

Table IV-10. N:P ratios in waters assayed, and the nutrient determined to be limiting productivity.

Station #	N to P Ratio		Limiting Nutrient
	Fall	Spring	
1	8.5	30.3	P
2	32.9	15.5	P
5	1.0	4.5	N
10	19.5	17.9	P
11	80.7	33.9	P
12	12.9	18.8	P

*only one sample was analyzed for NO_3 -N content

models which will allow prediction of the AGP of these waters given the concentrations of available N and P present. However attempts to plot AGP (biomass *S. capricornutum*) as a function of N concentrations proved to be a meaningless endeavor at all stations except #5, where correlation was good up to the point at which N alone was no longer limiting. Similarly, attempts to plot AGP as a function of P concentration produced significant correlation for the other stations only at low P concentrations where P alone was the limiting nutrient. Thus attempts to predict AGP as a function of available P (or N) would require a large number of different models, 1 for each different range of N (or P) concentrations. Once the primary limiting nutrient is present in excess, N and P, as well as other nutrients in some cases, act synergistically to control the AGP. Functions of this type can only be adequately described through the use of multiple regression models which allow simultaneous regression of a dependent variable on a number of independent variables.

A stepwise multiple regression analysis was performed on the data, using a program from the Statistical Analysis System (Barr and Goodnight, 1972). In these analyses AGP served as the dependent variable, and the concentrations of the following nutrient factors served as the independent variables: N-N, O-P, Ca, Mg, Na, K, S, Fe, and Mn. The data were analyzed by station for each of the 4 "Bottle Test" enrichment assays performed and also by stations with data from all 4 assays lumped into 1 matrix.

Models produced by the latter are of more value as a predictive tool, due to the fact that the data matrices are larger, the range of concentrations of $x_1 \dots x_k$ are greater, and they represent data on water samples collected at different times of the year.

Models produced were of the form

$$Y = \hat{\beta}_\phi + \hat{\beta}_1 x_1 + \dots + \hat{\beta}_k x_k$$

where Y = the AGP, $\hat{\beta}_\phi$ = the Y intercept, $x_1 \dots x_k$ = the nutrient factors which were significant ($\alpha = 0.01$) in determining the AGP of the given water, and $\hat{\beta}_1 - \hat{\beta}_k$ = the regression coefficients for the respective significant nutrient factors. Data for these models are presented in Table IV-11.

Results indicate that a model to predict the AGP of water at Station 1 would need to include the concentrations of P, N and K present. The concentrations of these 3 nutrients explained 98.4% of the variation in the AGP of these waters, while none of the other nutrients monitored were significant. In waters from Station 2, concentrations of P, N. and Fe accounted for 97.2% of the variation in AGP. In waters from Station 5, only N and P were significant in determining the AGP, accounting for 98% of the variation. In waters from Station 10, concentrations of P, N, Ca, and Fe were all significant, and accounted for 98.6% of the variation. P, N and Mn were significant at Station 11, accounting for 97.9% of the variation, and P, N and Na were significant at Station 12, accounting for 94.6% of the variation.

Table IV-11. Results of stepwise multiple regression analysis relating AGP to nutrient factors. Analysis was performed on data from all four "Bottle Test" assays.

Station #	$\hat{\beta}_0$	Significant nutrients (x) $\alpha = .01$	$\hat{\beta}_i - \hat{\beta}_k$	Prob > |T|	R ²	ANOVA F value	Prob > F
1	-2.71	P	205.1	0.0001	.984	1478.	0.0001
		N	22.5	0.0001			
		K	14.4	0.0001			
2	-5.64	P	264.9	0.0001	.972	878.	0.0001
		N	14.8	0.0001			
		Fe	218.1	0.0001			
5	-3.24	N	32.7	0.0001	.980	1641.	0.0001
		P	115.8	0.0001			
10	-3.38	P	296.6	0.0001	.986	1331.	0.0001
		N	16.9	0.0001			
		Ca	3.8	0.0050			
		Fe	52.5	0.0051			
11	-1.32	P	337.8	0.0001	.979	1150.	0.0001
		N	12.5	0.0001			
		Mn	81.7	0.0001			
12	-1.36	P	238.9	0.0001	.946	450.	0.0001
		N	12.1	0.0001			
		Na	1.3	0.0001			

The preceding data suggest that if these waters are impounded, the concentrations of N, P, Ca, Na, K, Fe and Mn present may play a role in determining the AGP in the resulting reservoirs. However it must be noted that regression of a dependent variable upon independent variable(s) is by no means proof of a cause-effect relationship.

Empirical models are of predictive value only when they have been verified, and only when the values of independent variables substituted are within the range of values used to formulate the models. Table IV-12 presents the nutrient ranges within which each of the above models is valid, and also gives the correlation coefficient (r) relating AGP's determined in bioassays to those predicted by the respective models.

Theoretically the preceding models can be used to predict the AGP of the various tributaries and to predict changes in AGP as a result of nutrient addition or removal. Such uses are based on the following assumptions: (1) that the waters assayed during model formulation were "typical" of those normally present in the tributaries, and (2) that methods outlined in the "Algal Assay Procedure: Bottle Test" (EPA, 1971) are acceptable as the procedure by which the AGP of a given water body is determined. The validity of these models can be further tested if additional AGP values are determined and correlated with those predicted by the models.

Table IV-12. Nutrient ranges within which models are valid, and correlation coefficients (r) relating AGP's predicted by the models to those determined in bioassays.

Station #	Significant Nutrients	Range (ppm)	r
1	P	0.012-0.202	.992
	N	0.136-4.34	
	K	0.8 -1.6	
2	P	0.010-0.196	.986
	N	0.329-4.53	
	Fe	0.18 -0.24	
5	N	0.257-4.46	.990
	P	0.142-0.441	
10	P	0.011-0.197	.993
	N	0.215-4.42	
	Fe	0.05 -0.17	
	Ca	3.5 -5.5	
11	P	0.007-0.193	.990
	N	0.339-4.77	
	Mn	0.001-0.116	
12	P	0.013-0.203	.973
	N	0.219-4.42	
	Na	2.0 -13.0	

V. THE INFLUENCE OF IMPOUNDMENT ON WATER QUALITY A GENERAL REVIEW

Up to this point, I have concerned myself primarily with the chemical limnology, AGP and limiting nutrient situation as it presently exists in the lotic waters of the upper New River Basin. The purpose of this section is to summarize the major physical, chemical, and biological changes which may be expected to occur if these waters are impounded.

A. Physical Effects

1. Thermal stratification:

The onset of thermal stratification is perhaps the greatest physical change which takes place when lotic waters become impounded. Lotic waters in the upper New River basin, for the most part, are thermally homogeneous, kept in this state by their shallow depths and a frequently recurring series of turbulent riffle areas. Impoundments of any depth, however, may become thermally stratified, a phenomenon caused by differences in the density of water at differential temperatures. In temperate areas, waters at or near the surface are warmed by solar radiation and warm air temperatures in the summer and chilled or frozen by cold air temperatures in the winter. These changes near the surface are in drastic contrast to changes in the temperature of bottom waters insulated from the atmosphere and solar radiation. The temperature differential between the upper waters (epilimnion) and the lower waters (hypolimnion) results in a density induced

separation of these waters. Waters within the epilimnion may be mixed by the wind, while waters within the hypolimnion become stagnant. This stagnation within the hypolimnion often results in the stratification of oxygen and many other dissolved substances. (These will be discussed further in a later section). Only when water temperature within the epilimnion approximates that in the hypolimnion, normally in the fall and spring, is the wind able to mechanically mix waters to an appreciable depth. Some lakes and impoundments in temperate regions become thermally stratified only in the summer (thus classified as monomictic). Whether or not these waters become inversely stratified is determined by the severity of winter weather.

2. Turbidity:

A second physical change which normally accompanies impoundment is a reduction in turbidity. Reservoir pools serve as settling basins and are especially effective in reducing the turbidity resulting from intense summer rains of short duration. Nevertheless heavy, protracted, winter rains, producing relatively large volumes of runoff in relation to storage capacity, occasionally produce significant turbidity (Churchill, 1958).

3. Color:

If present in significant amounts, color is also often drastically reduced following impoundment. In free-flowing streams, the only means of abating color (usually imparted due to pollution) is dilution. In impoundments, the bleaching action of solar

radiation, biological action, and coagulation and sedimentation are thought to be primarily responsible for this reduction (Churchill, 1958).

4. Odor:

While impoundments are normally effective in decreasing turbidity and color, there are circumstances under which they may impart objectionable odors to water. One of the most serious odor problems is likely to occur immediately after impoundment, when the uncleared flora exerts a tremendous oxygen demand, leading to anaerobiosis and the subsequent production of hydrogen sulfide. Vick (personal communication) indicates that these odors are often "obnoxious and intolerable" in the vicinity of the dam for quite some time following closure, and waters from the tailrace often contain enough hydrogen sulfide to darken the paint on nearby buildings. The length of time for which this condition persists as a direct result of inundation is a function of the amount of organic matter which must be decomposed, the flushing rate of the reservoir, and the depth of the power intakes. If following inundation, plant production in the euphotic zone is sufficiently high, theoretically this condition could persist forever.

Another type of odor problem in impoundments is produced by growths of algae and/or actinomycetes. These growths frequently cause taste and odor problems in water supplies in many areas of the U. S.

B. Bacteriological Effects

From a sanitary engineering standpoint, storage impoundments serve as desirable barriers between upstream bacterial pollution and downstream sites of water use. This bacterial reduction is one of the classical "beneficial" uses listed by engineers for multipurpose dams. (The author questions whether or not the reduction is substantially higher than that which would have occurred in an equidistant reach of lotic water). Churchill (1958) points out that the greatest reduction in bacterial concentrations takes place in the summer months when waters entering the impoundment are stored for extended periods of time (assuming penstocks are below the thermocline).

C. Chemical Effects

1. Dissolved oxygen and BOD:

Another classical "benefit" of storage impoundments frequently cited by engineers is a reduction in the BOD. While it is true that the BOD of water leaving an impoundment is often lower than when it entered, it is also true that the oxygen resources of the impoundment may be reduced in the process.

Impoundments that are productive, or that receive significant inputs of allochthonous organic matter, often exhibit a marked stratification of dissolved oxygen, especially during the summer months. Concentrations in the trophogenic zone approaching saturation may exist concomitantly with concentrations at or near

zero in the hypolimnion. Storage impoundments with low level penstocks release waters during these periods which contain lower concentrations of dissolved oxygen than those entering the impoundment. This phenomenon persists until such time as the thermocline and epilimnion extend down to the level of the penstocks (usually in late summer or early fall, depending upon the depths of the penstocks). Again in the late fall or early winter, when thermal density underflows exist, waters released from the dam contain less oxygen than waters entering the impoundment. As the pool cools even further, underflows cease and vertical circulation allows for increased oxygen levels both within the impoundment and in downstream releases.

Little (personal communication) and Churchill (1958) indicate that there is enough organic loading in most southeastern U. S. reservoirs to lower the late summer hypolimnetic oxygen concentration to near zero, even without point-source municipal and industrial discharges. In such cases substantial point source loadings of either organics or nutrients (especially N and P) may lead to hypolimnetic anaerobiosis. Extended anaerobiosis may, in turn, lead to production of hydrogen sulfide and a lowering of the redox potential to such a point that nutritive substances are released from the sediment, as described in the classic papers of Mortimer (1941, 1942). Such releases often lead to increased autochthonous production and an even further deterioration of water quality.

2. Alkalinity, pH, and free carbon dioxide (CO₂)

As is the case with dissolved oxygen and temperature, there is often a vertical stratification of pH, alkalinity, and free CO₂, most prevalent during the warmer months of the year. The carbonate-bicarbonate buffering system in natural waters forms a reservoir of inorganic C (CO₂, HCO₃⁻, CO₃⁻²) and CO₂ is also produced by biochemical mineralization of organic materials. Much of the CO₂ produced in the epilimnion is released to the atmosphere, and in the warmer months a great deal may be consumed by photosynthetic activity of autotrophic organisms. In the hypolimnion, the free CO₂ is kept in solution by the greater hydrostatic pressure and lack of contact with the atmosphere. These phenomena often cause pH differentials of 1-3 units from lake surface to bottom, and correspondingly significant differences in free CO₂ and alkalinity.

3. Iron:

The water of a flowing stream at or near neutral pH cannot contain, at equilibrium, significant concentrations of uncomplexed dissolved ferrous iron. Iron normally present in such waters occurs either as much less soluble particulate ferric hydroxide or as some form of organic complex (Hem, 1970).

In reservoirs, the variables of principal importance influencing Fe solubility include pH, redox potential, concentration of dissolved CO₂, and concentrations of S species (Sillen and Martel, 1964). Because many of these variables exhibit seasonal

stratification, the form and quality of Fe present is not likely to be vertically homogeneous.

Iron distribution is primarily reflected in the vertical distribution of redox potentials. When the oxygen curve of an impoundment is orthograde, Fe is likely to occur in very small amounts throughout the water column. In impoundments with clinograde oxygen curves, a microzonal oxygen deficit may develop and allow ferrous ions to diffuse into the hypolimnion. If any oxygen is present, ferric hydroxide may be formed and may remain dispersed. When the hypolimnion is essentially free of oxygen, considerable amounts of ferrous iron usually accumulate in the deepest water (Hutchinson, 1957).

The quantity and form of iron present (in conjunction with dissolved oxygen, sulfur, and redox potential) can play a major role in determining the productivity and trophic status of a reservoir. If when autumnal circulation occurs there is adequate Fe present to precipitate out hypolimnetic P as ferric phosphate, this P will not be available to the aquatic flora. If, however, Fe is not present in adequate quantities or is tied up as insoluble ferric sulfide, hypolimnetic P may substantially enrich the photic zone of the impoundment.

4. Nitrogen:

[The sources and forms of N in lotic waters were discussed in detail in section II and will not be repeated here.] Although molecular N_2 may become dissolved at the surface of a lake,

and distributed homogeneously throughout, the primary sources of combined N in lakes are the inflowing groundwater and surface streams. Ammonia and nitrate are readily assimilated by autotrophic organisms, and ammonia is produced by practically all heterotrophic bacteria in the course of organic decomposition.

During periods of stratification, ammonia may accumulate in the hypolimnion due to the cessation of nitrification and the disappearance of the oxidized microzone at the sediment interface. In the subsequent period of vertical circulation, this ammonia is distributed throughout the lake, and is thus available for assimilation by photoautotrophs in the trophogenic zone.

Nitrification appears to proceed most rapidly in winter, and nitrate reduction most rapidly in summer. Therefore, maximal amounts of nitrate tend to be present at the end of winter or at the vernal circulation periods. In some unproductive lakes with orthograde oxygen curves, little nitrate stratification develops. Usually in these lakes nitrate is removed from the trophogenic zone in the summer, but little increase occurs in the hypolimnion. In more productive lakes with clinograde oxygen curves, nitrate is removed by assimilation in the trophogenic layer and also by reduction near the bottom, producing a marked dichotomic distribution with a maximum in the middle waters (Hutchinson, 1957).

5. Phosphorus:

[The reader is referred to section II for a discussion of P in lotic waters.] Phosphorus has no gaseous states, and enters

lakes or impoundments via groundwater, surface waters, precipitation or allochthonous solids. In unproductive impoundments there is an increase of soluble P in the oxygen-deficient part of the hypolimnion, due in part to mineralization, but primarily due to liberation of P from reduced sediments.

When soluble P is added to a lake, primary productivity is initially increased, but usually only for a short time. The P is rapidly assimilated by the phytoplankton and then sedimented (although in shallow lakes there may be substantial assimilation by littoral plants). Experiments with radiophosphorus have demonstrated a horizontal movement between sediments and water, and Hutchinson(1957) postulates that within certain limits the chemical relations of P in sediments and water constitute a self-regulatory system. Einsele (1941) examined the P cycle in the Schleinsee by artificially enriching the lake with superphosphate. Fourteen kg were added to the trophogenic zone, and 2 days later only 7.1 kg remained there. The soluble P was taken up very rapidly by the phytoplankton and sedimented as sestonic phosphorus. By the end of the summer the P content of the lake had returned to normal, even though it had been artificially doubled in July.

The role of sediments as a potential source and/or trap for P is still not completely understood. Many researchers have classified the sediments as a trap, especially under aerobic conditions (e. g. Mortimer, 1941, 1942; Mackereth, 1965;

Fitzgerald, 1970). Others have postulated that the sediments act as a phosphate buffer, keeping the concentrations of P in water constant (e. g. Harter, 1968; Pomeroy et al., 1965; Hutchinson, 1957). Hendricks and Silvey (1973) postulated that sediments in shallow areas of a lake or reservoir play an important role in enhancing the level of productivity of the water, while sediments in deeper areas act as nutrient traps. It appears that most lakes and reservoirs have a large assimilative capacity for P, especially those that are deep and do not contain extensive littoral plants and sediments.

D. Biological

Leantvaar (1966), Funk and Gaufin (1971), Wright and Soltero (1973), Rodhe (1964), Biswar (1969) all report drastic changes in floral composition following impoundment, usually accompanied by blooms of dominant new species.

Zhadin and Gerd (1961) relate the following about new Russian reservoirs formed on rivers: the phytoplankton populations of the upper portions of the impoundment were initially very similar to the river potamoplankton. If the velocity of the current was sufficiently high, this type of flora persisted; otherwise, the phytoplankton species common to the more open waters slowly encroached and became dominant. Algal blooms were quite common during the first summers, culminating with blooms of blue-greens (unless the reservoirs remained highly turbid, in

which case phytoplankton development was limited). Mats of Cladophora often developed on bottom sediments in the littoral zone if water levels were constant.

Odum (1971) reports that the developmental stages of new ecosystems are characterized by open mineral cycles, a rapid exchange rate between organisms and the environment, and a relatively unimportant role of detritus in nutrient regeneration. Armitage (1974) concludes that the productivity of new impoundments is initially quite high, but assuming no cultural allochthonous inputs of nutrients, is expected to decline after several years.

E. The effects of pumped-storage operations

Operation of a pumped-storage power project involves the transfer of water from one impoundment to another. During periods of peak power demand, water is drawn from an upper reservoir to a lower reservoir and electrical power is produced. As power demands decrease, the excess power in the system is used to pump water from the lower reservoir back into the upper reservoir in order to maintain a maximum head of water. Operations of this nature are designed to increase the power system's load factor and to permit the system to accommodate daily, weekly, and seasonal peak capacity requirements at lower costs. Recent improvements in the design of reversible pump turbines have made pumped-storage schemes more attractive than ever before to the power industry (Chen and Orlob, 1972).

Many attempts have been made by engineers and limnologists to alleviate the detrimental effects of summer stratification and stagnation in lakes and reservoirs. As an additional advantage to pumped-storage electric power generation, it was hoped that recirculation of waters would improve overall water quality through destruction or disruption of thermally induced stratification.

Simmons and Neff (1969) conducted a study to determine the effects of the operation of the Smith Mountain, Virginia pumped-storage plant on the primary productivity of the upper impoundment, and to ascertain what effect the recycled water might have on its limnological characteristics. Results indicated that the reservoir was mesotrophic, and was rapidly developing the characteristics of older, eutrophic, main-stream reservoirs despite the recycling of large quantities of water. The anticipated beneficial effects appeared to be limited and in fact, seiche action begun by the recycling seemed to increase carbon assimilation rates in the vicinity of the dam due to eddy diffusion of nutrients across the metalimnion.

Chen and Orlob (1972) subsequently utilized an "ecologic" model to simulate different operational modes for the Smith Mountain plant, and to evaluate the environmental consequences of such operations. Results indicated that certain operational modes could be utilized which would improve water quality by deepening the epilimnion, i. e. driving the thermocline downward in the reservoir.

It appears that pumped-storage operation may be either detrimental or beneficial to water quality in impoundments. The chemical constituency of the water and the operational modes employed in operation of the facility play major roles in this determination.

Discussion

Only the major transformations occurring when waters are impounded have been dealt with here. For a more detailed and comprehensive discussion of the biology, physics, and chemistry of impoundments, the reader is referred to Churchill (1958), USPHS (1965), AFS (1967), Symons (1969), AFS (1971), IGU (1972), and Varga et al. (1973).

There is no objective manner in which to classify impoundments as beneficial or detrimental to water quality. Each case must be dealt with based on its own merit, and the decision is ultimately subjective, qualitative and political.

VI. PROJECTED NUTRIENT BUDGET AND TROPHIC STATUS FOR THE PROPOSED RESERVOIRS

Introduction

Much has been written and said about the causes and consequences of eutrophication (e.g. NAS, 1969; Lee, 1970; ASLO, 1972) and as well about its possible corrective measures (e.g. NAS, 1969; Dunst et al., 1974). The term eutrophic means "well-nourished," and eutrophication is the process through which aquatic environments reach this state. Some authors have described this as a natural process (e.g. Strom, 1928; Lindeman, 1942; Hasler, 1947; Hutchinson, 1973). However most of these authors, and many others, have quickly cited man's role in the rapid acceleration of this process - an acceleration often referred to as "cultural eutrophication."

Brezonik and Putnam (1968) pointed out that the trophic status of a lake is often affected by chemical factors such as pH, turbidity, and dissolved oxygen, and by physical factors such as depth, depth to surface area ratios, steepness of bottom contour, shoreline irregularity, % littoral area, temperature, and degree of circulation. However, by its very definition, the trophic status of a body of water is primarily a function of the composition and quantity of nutrients present. Therefore the development of plans for the proper management of a water resource requires, among other things, an accurate evaluation of its nutrient sources.

Historically, certain potential nutrient sources have been considered as natural or generally uncontrollable. Sources of this type include precipitation, drainage from urban areas, runoff from forest, pasture, and crop lands, return irrigation flows, decaying vegetation, and wastes from wild animals (Loehr, 1974). Generally it has been assumed that such non-point sources are small relative to point sources such as municipal and industrial waste discharges, however recent information on the magnitude of the non-point sources has led to questioning of the validity of this assumption. With the emphasis of the national water pollution control policy now centered on the amount of wastes that can be kept out of surface waters, it is pertinent to examine the magnitude of natural and non-point nutrient sources.

Although many nutrients are essential for plant growth, the nutrients usually considered to be most significant for aquatic plants are nitrogen and phosphorus. Although many studies have been conducted on the sources of N and P, and their dynamics within aquatic ecosystems, historically N or P budgets have been prepared for lakes only after cultural activities led to damaging, or at least aesthetically distasteful, events.

The objectives of this study were (1) to calculate (a priori) N and P budgets for the proposed Blue Ridge Project reservoirs and (2) using these projections in conjunction with nutrient budget models, to predict the trophic status of the reservoirs.

Projected N and P inputs

Prior to any cultural activities which might occur within the vicinity of the reservoirs following impoundment, significant sources of N and P will include (1) tributary streams, (2) leachates from the inundated soils, (3) surface runoff from the surrounding watershed, and (4) precipitation. Groundwater inflow, which may represent a significant nutrient source in some impoundments, will not be significant in Blue Ridge due to the impervious nature of the bedrock and the distance of the reservoirs above the water table (Sears, personal communication). The purpose of this section will be to evaluate the composition and magnitude of the 4 significant nutrient sources.

1. Input from tributary streams:

Qualitative and quantitative determinations of nutrient input from tributary surface waters were calculated using chemical data collected in the present study in conjunction with flow data collected concurrently by the USGS. Potential N and P loadings for each tributary were determined using the following equation from Omernik (1974):

$$\text{Annual Load X} = (C) (F) (2446.4) (365) \\ (\text{gm yr}^{-1})$$

where: C = mean annual concentration of X in mg/l

F = mean annual stream flow in cfs

2446.4 = factor adjusting concentration and flow data to obtain loads in gm/day

Annual loads of T-P, inorganic (condensed) $\text{PO}_4\text{-P}$, and N-N were calculated for the 6 tributaries using data from each of the 4 water years monitored. Mean annual stream flows for the South Fork New River were taken from the USGS gauging station (3-1610) at Jefferson, N. C., and mean annual stream flows for the remaining tributaries were calculated based upon their drainage area ratios and flow data collected by the USGS gauging station (3-1640) on the New River near Galax, Virginia. Mean values calculated from the 4 years of data are reported in Table VI-1.

It is interesting to note the influence waters at Station 5 exert on the inorganic P budget. Although they comprise only 3.4% of the mean annual tributary flow, they will contribute an estimated 26.5% of the inorganic P loading to the reservoirs.

Nutrient retention models and trophic status models for the proposed reservoirs require estimates of the areal (L) and volumetric loading rates (L_v) for nitrogen and phosphorus. These values, along with the mean annual nutrient loading from all of the tributaries are presented in Table VI-2.

Areal and volumetric loading rates were calculated on the basis of a combined twin-reservoir area of 139.5 km^2 and a combined volume of $3.27 \times 10^9 \text{ m}^3$ (mean operational size of the proposed project).

2. N and P input from surface runoff:

Considerable effort has been expended recently to study the effects of land use on N and P runoff. In general, these

Table VI-1. Mean annual N and P concentrations, stream flows, and nutrient loadings for the 6 tributaries to the proposed Blue Ridge impoundments.

Station #	Mean Annual Flow (cfs)	Mean Annual Conc Inorg-P (ppm)	Mean Annual Loading Inorg-P (gms/yr) x 10 ³	Mean Annual Conc Total-P (ppm)	Mean Annual Loading Total-P (gms/yr) x 10 ³
1	431	.028	10,776.0	.0973	37,446.4
2	312	.022	6,129.1	.0826	23,012.0
5	42	.229	8,588.2	.313	11,738.5
10	67	.015	892.4	.028	1,675.1
11	124	.015	1,660.8	.035	3,875.3
12	245	.020	4,375.4	.053	11,594.8

Station #	Mean Annual Conc. NO ₃ -N (ppm)	Mean Annual Loading NO ₃ -N (gms/yr) x 10 ³	% of Inorg-P Loading	% of Total-P Loading	% of NO ₃ -N Loading
1	.265	101,986.7	33.2	41.9	34.8
2	.330	91,936.7	18.9	25.8	31.4
5	.350	13,126.2	26.5	13.1	4.5
10	.24	14,358.4	2.8	1.9	4.9
11	.25	27,681.0	5.1	4.3	9.5
12	.20	43,753.9	13.5	13.0	14.9

Table VI-2. Projected nutrient loading to the proposed Blue Ridge Reservoirs from the 6 primary tributaries.

Nutrient species	Annual Loading (gm/yr)x10 ³	L (gm/m ² /yr)	L (gm/m ³ /yr)
Inorganic P	32,426.9	.232	.010
Total P	89,342.1	.640	.027
NO ₃ -N	292,842.9	2.09	.089

efforts have intensified in the past 3 years, with the increased concern for developing methods of quantifying and monitoring nutrient export from non-point sources. Findings from some of the more frequently cited studies are presented in Table VI-3, Appendix B. Unfortunately many of the studies have been limited to investigations of 1 lake and a small geographical area, and little consistency can be found in these land use-nutrient export relationships, with the exception of the uniformly high total P export rates from urban areas.

Two recent works have addressed the problem on a larger scale, attempting to develop systems for estimating nutrient runoff from land-use based on export rates developed partially or entirely from literature reviews. Dillon and Kirchner (1974) defined land use by geological classification and determined ranges and mean values of T-P export from a study of 31 watersheds in Southern Ontario and 12 additional watersheds from literature sources (Table VI-4).

Table VI-4. Ranges and mean values for export of total P from 43 watersheds (Dillon and Kirchner, 1974).*

Land Use	Geological Classification			
	Igneous range	Igneous mean	Sedimentary range	Sedimentary mean
Forest	2-23.	12.2	14.-47.	30.3
Forest & Pasture	15-42.	26.4	29.-96.	60.3

*kg/mi²/yr

Uttormark et al. (1974) presented typical values of nutrient runoff from an extensive literature review conducted for the Environmental Protection Agency (Fig. VI-5). While suggesting that these values might be useful in estimating nutrient loading to lakes, the authors warned that they were obtained without regard to geographical location, and might not be representative of all parts of the country.

The great variation among export values presented in the respective studies makes one question the validity of choosing an export value from the literature. In addition, the lack of uniformity in procedure among the studies limits the validity of comparing results or of using combined results. It seems apparent that parameters such as soil type, soil pH, slope of the watershed, and climate must be taken into account before literature-derived export rates will provide sufficient predictive capability.

Gakstatter (personal communication) suggested that the most valid export rates for land in the upper New River Valley

Table VI-5. Ranges and mean value for export of total P and total N from watersheds (from Uttormark et al., 1974).

Land Use	Total P (kg/mi ² /yr)		Total N (kg/mi ² /yr)	
	range	mean	range	mean
Forest	13. -207.	52.	259. -1295.	648.
Agriculture	26. -259.	78.	518. -2591.	1295.
Urban	259. -1295.	389.	648. -2591.	1295.

could best be determined by using chemical data collected at Station 6 in the mainstream of the river in conjunction with flow data collected concurrently by the USGS gauging station located immediately upstream. This procedure eliminated problems involved with attempting to choose valid rates from the literature.

Export rates for inorganic P, T-P, and N-N were determined by dividing the mean annual quantity of each species discharged from the watershed at Station 6 by the number of square miles in the watershed above this site. The calculated export rates were subsequently multiplied by the area of the watershed which will drain directly to the reservoir (465 mi²) in order to project the nutrient loadings due to surface runoff. These values, along with corresponding areal and volumetric loading rates, are presented in Table VI-6.

Total P export rates calculated for land in the upper New River watershed were similar to those reported by Sawyer (1947) for "general farmland" in southern Wisconsin, and fell within

Table VI-6. Projected nutrient loading to the proposed Blue Ridge reservoirs due to surface runoff.

Nutrient Species	Mean Loading	Annual Load	L	L
	Rate (kg/mi ² /yr)	(gm/yr)	(gm/m ² /yr)	(gm/m ² /yr)
Inorganic P	40.	1.9.x10 ⁶	136.	.0058
Total P	130.	0.62.x10 ⁶	444.	.0189
NO ₃ -N	606.	2.87.8x10 ⁶	2.06	.0880

the range reported by Uttormark et al. (1974) for agricultural lands. Nitrogen export rates were similar to those reported by Taylor et al. (1971) for forests in central Ohio, and fell within the ranges reported for forests and agricultural lands by Uttormark et al. (1974).

3. N and P input from inundated soils:

Brezonik (1973) pointed out that the role of lake sediments as nutrient reservoirs or sinks needs further clarification, and suggested that experiments involving laboratory model systems should be undertaken to gain insight into this phenomenon. Once a reservoir is constructed, this becomes a difficult task. However, pre-impoundment studies provided a unique opportunity for obtaining un-inundated soil samples which can then be used in laboratory model studies.

Keup et al. (1970) performed soil leachate studies as part of a pre-impoundment survey by placing 400 gm of well mixed soil into carboys, adding water, and monitoring the water

chemistry until an equilibrium was reached. I feel that this is not an accurate method for obtaining estimates of in situ nutrient release rates, but rather gives estimates of the highest possible rates under disturbed conditions.

In order to obtain estimates of nutrient release from undisturbed soils, 6-inch diameter soil cores were collected from the impoundment area and returned to the laboratory where they were tested intact. The soil cores collected were representative of the 3 major alluvial and 3 major residual soils present in the proposed impoundment area. Information on the composition and relative abundance of the soils which the proposed reservoirs would inundate was obtained from Mr. Pat Trew, soil scientist with the District Office of the Soil Conservation Service (USDA) in Daleville, Virginia.

Experimental Design:

Three cylindrical soil cores (6" x 6") were collected for each of the 6 soils to be tested. One of these was used for analysis of soil chemistry, a second was used for determining the nutrient release rate under aerobic conditions, and the third for determining release rates under anaerobic conditions.

Chemical analysis of the soils was performed by the Soils Testing Laboratory, Extension Division, VPI & SU. Results of these analyses and a brief description of the 6 soils are presented in Table VI-7.

Table VI-7. Description of the 6 major soils to be inundated by the proposed Blue Ridge reservoirs.

Name	Type	Texture	% Organic Matter	PO ₄ (ppm as P ₂ O ₅)	NO ₃ (ppm)	pH	Mg (ppm as MgO)	Ca (ppm as CaO)
Tusquitee	Residual loam	med.	9.3	138+	12	6.5	199	1651+
Porters	Residual Brown loam	med.	8.5	21	13	5.5	176	1142
Ashe	Residual Yellow Brown loam	med.	5.6	5	15	5.5	169	605
Congaree	Alluvial Brown loam	light	1.1	42	13	6.0	78	344
Chewacla	Alluvial Red-brown loam	med.	1.5	138+	6	6.4	199+	812
Wehadkee	Alluvial Gray silt loam	Heavy	2.3	71	7	5.8	136	812

Nutrient release rates under aerobic and anaerobic conditions were determined as follows: intact soil cores were inserted into the bottom of 6-inch diameter Plexiglas[®] columns, and the columns were then mounted onto wooden bases and sealed (Fig. VI-1). Approximately 22 l. of New River water were slowly added to each of the columns in such a manner as to prevent disturbance of the soil. A piece of small diameter tubing capped with an air diffusing stone was then lowered into each column and secured so that the diffusing stone was positioned in the center of the column approximately 1 inch above the soil core. A second piece of tubing was placed in the column above the water level to serve as a vent. The columns were capped and sealed and the vent tubes inserted into water traps. Air or N₂ was bubbled into columns at a rate of approximately 2 cc/min in order to maintain aerobic or anaerobic conditions. Columns of river water (minus soil) maintained under aerobic and anaerobic conditions served as controls. Water samples (app. 500 ml) were withdrawn weekly through a port located 10 inches above the surface of the soil, and the following parameters monitored: dissolved oxygen, O-P, T-P, N-N, NO₂-N, NH₃-N, pH, alkalinity and hardness. Analyses for organic-N were also performed at periodic intervals, but measurable amounts were never detected.

Results:

Treatment and sampling were continued until levels of N and P in the water column stabilized for a period of a least 4 weeks. Plots of the release of O-P, T-P, and total (inorganic) N through time

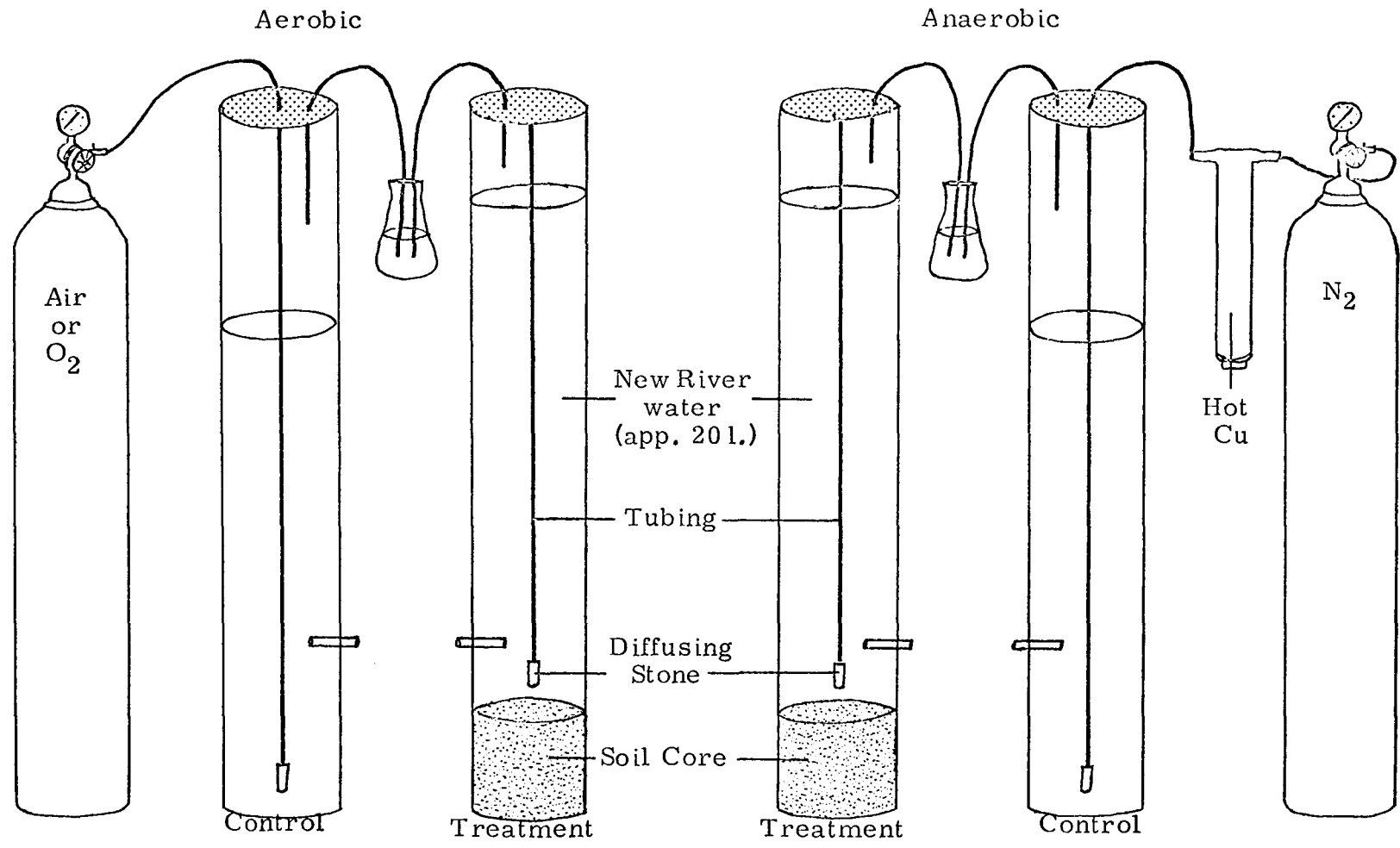


Fig. VI-1. Diagram of the treatment apparatus utilized in determining N and P release rates from the soils to be inundated by the proposed Blue Ridge Reservoirs.

for each of the soils and conditions tested are presented in Appendix C.

Release rates for each nutrient species from each soil type were determined as follows:

$$\text{Release Rate (mg/m}^2\text{/yr)} = \frac{(C_T - C_C) \cdot V_T \cdot T}{.0182 \cdot 365}$$

where C_T = the mean concentration (mg/l) present in the treatment column after stabilization

C_C = the mean concentration (mg/l) present in the control columns after stabilization

V_T = the mean volume of water present at the onset of stabilization

T = time (days) from beginning of treatment to onset of stabilization

0.0182 = area (m²) of soil core

Release rates of O-P, T-P and total (inorganic) N for each type of soil and treatment were then multiplied by the area of that soil to be inundated, yielding projected annual nutrient export for each soil under conditions of continual hypolimnetic oxygenation or continual anaerobiosis. These results are presented in Table VI-8.

Limnological data from Claytor Lake, a reservoir located downstream from the proposed impoundments, indicated that hypolimnetic anaerobiosis might be expected to last anywhere from 30 to 90 days (Simmons, 1968). Consequently projected export (gm/yr) of O-P, T-P and total (inorganic) N was calculated for each soil type simulating 30, 60 and 90 day periods of hypolimnetic anaerobiosis. These results are presented in Table VI-9.

Table VI-8. Projected nutrient export from the various soil types to be inundated based on continual aerobic or anaerobic conditions.

Soil	Hypolimnion	Ortho PO ₄ -P*	Total P*	Total N*	Inundation Area (km ²)
Tusquitee	aerobic	1,068	1,301	148,541	16.188
	anaerobic	26,499	37,329	410,932	
Porters	aerobic	2,104	2,185	742,705	80.94
	anaerobic	12,869	35,775	1,836,690	
Ashe	aerobic	641	655	445,623	48.56
	anaerobic	7,186	22,145	1,147,421	
Chewacla	aerobic	431	615	29,052	5.395
	anaerobic	2,217	4,871	103,152	
Congaree	aerobic	307	798	4,148	5.395
	anaerobic	615	1,791	126,280	
Wehadkee	aerobic	490	739	88,931	5.395
	anaerobic	1,726	4,003	152,365	

* = x 10³ gm/yr

Table VI-9. Projected nutrient export* from each of the six soil types based on different periods of hypolimnetic anaerobiosis.

Nutrient	Soil Type	Period of Hypolimnetic Anaerobiosis		
		30 days	60 days	90 days
Inorganic P	Tusquitee	3,158	5,246	7,336
	Porters	2,988	3,872	4,758
	Ashe	1,179	1,716	2,255
	Chewacla	578	724	871
	Congaree	332	358	383
	Wehadkee	591	693	795
Total P	Tusquitee	4,262	7,220	10,181
	Porters	4,946	7,704	10,464
	Ashe	2,421	4,186	5,952
	Chewacla	965	1,314	1,664
	Congaree	880	961	1,043
	Wehadkee	1,007	1,275	1,544
Total N (inorganic)	Tusquitee	170,109	191,652	213,220
	Porter	832,630	922,446	1,012,372
	Ashe	503,311	560,928	618,616
	Chewacla	35,143	41,226	47,317
	Congaree	14,187	24,214	34,253
	Wehadkee	94,145	99,353	104,567

* gm/yr x 10³

Export rates presented in Table VI-9 were then used to project total nutrient loadings to the proposed reservoirs from the inundated soils. These projections, simulating anaerobiosis for periods of 0, 30, 60 and 90 days, are presented in Table VI-10. Aereal and volumetric loading rates for the reservoirs were also calculated for each of the respective nutrients and periods of anaerobiosis, and are presented in the aforementioned table.

4. N and P input from precipitation:

Nutrients contributed directly by precipitation must be taken into account in analyzing the sources of nutrients to a lake. Precipitation normally contains a substantial quantity of solutes, due to the dissolution of gasses and scavenging of particles as it falls through the atmosphere.

In the past 15 years, rainfall has received a good deal of attention as a source of nutrients. Nenzel and Spaeth (1962) correlated the ammonia content of surface waters in the Sargasso Sea with the rainfall content of the previous 5 days, and Gambell (1963) found rainfall to be a major source of NO_3^- and SO_4^{-2} in several Virginia and North Carolina streams. Chalupa (1965) found significant rainfall contributions of phosphate to a Czechoslovakian reservoir, and Parker (1968) found bloom stimulating concentrations of vitamin B_{12} in rainfall of the St. Louis area.

Some of the most frequently cited data on N and P levels in precipitation are presented in Table VI-11. The data demonstrate that both N-N and NH_3 -N occur in significant amounts, but the latter

Table VI -10. Projected total nutrient loadings to the proposed reservoirs from inundated soils.

Nutrient	Parameter	Days of Anaerobiosis			
		0	30	60	90
Inorganic P	Total loading (gm/yr) x 10 ⁶	5.041	8.823	12.609	16.398
	Areal loading (L) (gm/m ² /yr)	0.036	0.063	0.090	0.117
	Volumetric loading (L _v) (gm/m ³ /yr)	0.0015	0.0027	0.0038	0.0050
Total P	Total loading (gm/yr) x 10 ⁶	6.293	14.481	22.660	30.848
	Areal loading (L) (gm/m ² /yr)	0.045	0.103	0.162	0.221
	Volumetric loading (L _v) (gm/m ³ /yr)	0.0019	0.004	0.0069	0.0094
Total N	Total loading (gm/yr) x 10 ⁹	1.459	1.649	1.839	2.030
	Areal loading (L) (gm/m ² /yr)	10.458	11.820	13.182	14.551
	Volumetric loading (L _v) (gm/m ³ /yr)	0.446	0.504	0.562	0.620

Table VI-11. Representative data from the literature on the N and P content of precipitation.

Reference	Mean Nutrient Levels mg/l				
	Inorganic P	Total P	NH ₄ -N	NO ₃ -N	Total N
Brezonik, 1973	0.009	0.033	0.21	0.21	0.63
Aulenbach & Clesceri, 1973		0.010			1.1
AWWA Task Group, 1967		0.050			1.5
Aulenbach & Clesceri, 1970		0.01			1.35
Feth, 1966			1.01	0.1	1.11
Weibel et al., 1964		0.08			1.3
Muir et al., 1973					2.0
Voight, 1960		0.01			0.07
Putnam et al., 1969	0.027	0.033	0.208	0.209	0.742
Armstrong & Schindler, 1971		0.014			0.378
Schindler & Nighswander, 1970	0.014	0.034	0.578	0.258	
Loehr, 1974		0.020			1.22
Cooper, 1969				0.14	
Hobbie & Likens, 1973		0.008	0.30	0.16	
Joyner, 1971		0.04			0.73

is usually higher. Nitrate is said to be somewhat more important in tropical than in temperate rains, but even there $\text{NH}_3\text{-N}$ is usually higher (Hutchinson, 1957). Total N concentrations frequently approach 1 mg/l., and both natural and cultural sources are responsible. Although a number of cultural sources (e.g. ammoniated fertilizers, nitrogen oxides of auto emissions) would seem to make important contributions to atmospheric fixed N, there is conflicting evidence regarding the correlation of high rainfall N levels with areas of cultural or industrial activity (Vollenweider, 1968; Feth, 1966). Putnam and Olsen (1960) and Weibel et al. (1964) have described rainfall as a cleansing agent for the atmosphere. Nutrient and particulate concentrations in precipitation were generally found to decrease during the course of an extended rainfall and to increase with the length of antecedent drought.

If data available in the literature have confirmed anything, it is that while precipitation may constitute a significant source of nutrients, the concentrations are highly variable through time and space. It becomes apparent that estimation of nutrient contributions to lacustrine environments via precipitation is not as simple as one might first have thought. However, in the absence of any field data collected in the immediate study area, mean concentrations of inorganic P, T-P, and total N from the literature will be employed to calculate projected loadings of these nutrients to the reservoirs.

Results:

Mean precipitation concentrations from the literature cited above were as follows: inorganic P, 0.016 mg/l; T-P, 0.0285 mg/l; and total N, 1.011 mg/l. Assuming that 44 inches of annual precipitation (60 year mean at Galax, Virginia; Independence, Virginia and Jefferson, North Carolina) falls on 34,458 acres of water surface, projected nutrient loadings to the proposed reservoirs are those presented in Table VI-12.

Summary of N and P inputs to the proposed reservoirs

Prior to any cultural activities within the vicinity of the reservoirs following impoundment, significant sources of N and P will include (1) the 6 tributary streams, (2) leachates from the inundated soils, (3) surface run-off from the surrounding watershed, and (4) atmospheric precipitation. Projected total nutrient loadings to the reservoirs from these 4 sources were tabulated and are presented in Table VI-13.

The largest projected contributions of inorganic and T-P were from the 6 tributaries, followed in decreasing order by surface runoff, the inundated soils, and atmospheric precipitation.

The largest projected N contributor was the inundated soil, contributing more N than all other sources even under conditions of year-round aerobic hypolimnetic waters. The next largest contributor was the 6 tributaries, followed by surface runoff and atmospheric precipitation.

Table VI-12. Projected N and P inputs to the proposed Blue Ridge reservoirs due to precipitation.

Nutrient	Annual Input ₃ (gm/yr) x 10 ³	L gm/m ² /yr	L ₃ gm/m ³ /yr
Inorganic P	2,493	.0178	.0008
Total P	4,441	.0318	.0014
Total N	157,555	1.1294	.0482

Table VI-13. Projected total nutrient loadings to the proposed Blue Ridge reservoirs.

Nutrient	Parameter	Minus Soils Input	Including Soils Input			
			Days of Anaerobiosis			
			0	30	60	90
Inorganic P	Total loading (gm/yr) x 10 ⁶	53.9	58.9	62.7	66.5	70.2
	Areal loading (L) (gm/m ² /yr)	.386	.422	.447	.476	.503
	Vol. loading (L _v) (gm/m ³ /yr)	.0165	.0180	.0192	.0203	.0215
Total P	Total loading (gm/yr) x 10 ⁶	155.8	162.	170.	178.4	186.
	Areal loading (L) (gm/m ² /yr)	1.11	1.16	1.21	1.27	1.33
	Vol. loading (L _v) (gm/m ³ /yr)	.047	.049	.052	.054	.057
Total N	Total loading (gm/yr) x 10 ⁶	738.1	2197.	2390.	2580.	2770.
	Areal loading (L) (gm/m ² /yr)	5.29	15.7	17.13	18.49	19.86
	Vol. loading (L _v) (gm/m ³ /yr)	.226	.672	.731	.789	.847

Now that all of the N and P inputs to the system have been projected, we must deal with the question of retention of these nutrients.

C. Nutrient Budget Models

Interest in and effort spent on nutrient modeling is growing at an increasing rate. From just a few papers published in the mid-sixties, the number of publications has soared, reflecting an increasing concern with the role of nutrients in the eutrophication process, and an expanding belief that some of these problems can be investigated in a quantitative manner (Dillon, 1974). Many of these publications include complex computer simulation models requiring information and involving sophistication beyond the scope of this study. However many of the relationships brought into focus during the formulation and verification of these models are helpful in understanding the relationship between nutrient input and nutrient retention in reservoirs. The objective of this study is to utilize 4 different models to predict N and P concentrations for the proposed Blue Ridge reservoirs.

1. Conservative substance model:

One obvious model which can be used to estimate the concentration of substances in lakes involves treating the substances as though they were conservative, i.e., the mean residence time of the substance is equal to the mean residence time of the water in the lake. Assumptions of this model are as follows: (1) the supply

of the substance to the lake is constant, (2) the substance is completely mixed within the entire lake volume, i. e. the lake is a continuously stirred tank reactor (CSTR), (3) all strata of the lake are assumed to have equal probability of being flushed at all times, and (4) the substance is lost from the lake only by flushing.

Based on a total discharge of $1.620 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ and a mean volume of $3.27 \times 10^9 \text{ m}^3$ (mean proposed operational specifications supplied by APCO, Appendix D), the twin-reservoir system would have a hydraulic residence time, or filling time, of 2.0 years. Employing a conservative substance model, the concentration of a substance within the reservoir system at any given time would be calculated as follows:

$$\text{Concentration of } x = \frac{(2.0) (\text{annual loading of } x)}{V}$$

where V is the volume of the reservoirs. Using the above formula, concentrations of inorganic P, T-P, and total N were projected and are presented in Table VI-14.

Table VI-14. Projected nutrient concentrations for the proposed Blue Ridge reservoirs based on a conservative substance model, with inundated soils serving as a nutrient source.

Nutrient	Annual Loading* (gm/yr ⁻¹) x 10 ⁶	Projected Concentrations* (gm/m ³)
Inorganic-P	58.9 - 70.2	0.0360 - 0.0429
Total-P	162. - 186.	0.0991 - 0.1137
Total-N	2179. -2770.	1.343 - 1.694

* range projected based on 0 and 90 days of anaerobiosis

If at some time following inundation the submerged soils no longer continue to function as a nutrient source, the following concentrations can be projected for the reservoirs based on the conservative substance model: inorganic P, 0.0329 gm m^{-3} ; T-P, 0.0952 gm m^{-3} ; and total N, 0.4574 gm m^{-3} .

Some of the criticisms commonly associated with conservative substance models are that (1) the assumption of consistent nutrient loading through time is often violated, (2) the CSTR assumption cannot adequately characterize stratified lakes, and (3) that only maximum possible concentrations are predicted. While the first 2 criticisms point out recognized possible weaknesses, the third is not necessarily valid. O'Melia (1972) points out that, to the contrary, the nonconservative behavior of substances such as P often leads to their accumulation in lakes.

2. Hydraulic residence time/nutrient residence time model:

Perhaps the most critical assumption of CSTR models is that substances behave conservatively, - an assumption which ignores the role that chemical and biological reactions play in determining the residence time of a substance. In actuality, chemical and biological reactions may play a major role, and the residence time for a given nutrient may differ significantly from the hydraulic residence time.

Lee (1974) has compared the hydraulic residence times and P residence times for several lakes (Table VI-15). Hydraulic residence times were calculated by dividing the lake volume (m^3)

Table VI-15. Relationship between hydraulic residence time and P residence time for several lakes (Lee, 1974).

Lake	Hydraulic Residence Time (yrs)	P Residence Time (yrs)	Ratio, P:Hydraulic
Washington	3.2	0.8	.25
Minnetonka	25.0	0.9	.04
Sebasticook	3.5	1.4	.40
Norrsviken	0.6	0.3	.50
Clear	6.0	2.0	.33
Mendota	4.8	3.2	.67

into the total hydraulic discharge (m^3/yr). Phosphorus residence times were calculated by dividing the annual P loading ($gm/m^3/yr$) into the mean annual steady state P content (gm/m^3).

Among these lakes, P residence times ranged from 4 to 67% of the hydraulic residence times, with a mean of 37%. If we assume that 37% of the hydraulic residence time of the proposed reservoirs is a valid estimate for nutrient residence times, we can calculate projected concentrations for the reservoirs as follows:

$$\text{Conc. of } x \text{ (gm/m}^3\text{)} = \frac{0.74 \text{ (annual loading of } x\text{)}}{V}$$

Results of the calculations are presented in Table VI-16.

If at some time following inundation the submerged soils no longer continue to function as a nutrient source, the following nutrient concentrations can be projected for the reservoirs: inorganic P, $0.0122 gm/m^3$; T-P, $0.0352 gm/m^3$; and total N, $0.1670 gm/m^3$.

Table VI-16. Projected nutrient loadings and concentrations for the proposed Blue Ridge reservoirs based on a nutrient residence time of 0.74 years.

Nutrient	Annual loading* (gm/yr x 10^6)	Projected Concentration* (gm/m ³)
Inorganic-P	58.9 - 70.2	0.0133 - 0.0158
Total-P	167. - 186.	0.0366 - 0.0420
Total-N	2197. - 2770.	0.4971 - 0.6268

*range based on 0 and 90 days of hypolimnetic anaerobiosis

3. Model employing loading rate to mean concentration ratios from the literature:

Several recent publications contain data concerning the P loading rates and/or mean spring P concentrations for a number of lakes. Both of these values were available for 18 lakes (4 of which are reservoirs in the southeastern U. S.) with mean depths similar to that of the proposed Blue Ridge Project (Table VI-17). From these data I calculated a linear regression model which allow for prediction of mean concentrations of total P at spring overturn based on total P areal loading. The model is as follows:

$$Y = .01652 + .00688 x \quad (r = .86)$$

where Y = concentration of total P at spring overturn (gm/m³)

x = areal load of total P (gm/m²/yr)

Table VI-18 contains projected concentrations of total P at spring overturn for the proposed reservoirs, both including and excluding P input from the inundated soils. Projections which include loading from the soils would be applicable for years immediately following inundation, and projections excluding soil input would be applicable after these soils have been covered with allochthonous and/or autochthonous detrital sediments.

4. Model of Dillon and Rigler (1974):

Dillon and Rigler (1974) monitored total P budgets for a number of lakes over a 20-month period. These data, combined with the lakes' morphometric characteristics and hydraulic budgets were used to create a nutrient budget model purporting to predict

Table VI-17. Data from the literature relating spring concentrations of P in lakes and reservoirs to their areal P loading rates.

Lake or Reservoir	Areal P Loading (gm/m ² /yr)	Observed Spring P (gm/m ³)
Oblong-Haliburton	0.124 ⁽¹⁾	0.0053 ⁽¹⁾
Aegerisse	0.160 ⁽²⁾	0.0076 ⁽²⁾
Bob	0.162 ⁽¹⁾	0.0085 ⁽¹⁾
Halls	0.217 ⁽¹⁾	0.0043 ⁽¹⁾
Eagle-Moose	0.232 ⁽¹⁾	0.0071 ⁽¹⁾
Turlersee	0.300 ⁽²⁾	0.0145 ⁽²⁾
Kalamalka	0.320 ⁽³⁾	0.020 ⁽⁴⁾
Okanagan	0.390 ⁽³⁾	0.030 ⁽⁴⁾
Ontario, 1969	0.680 ⁽²⁾	0.0264 ⁽⁵⁾
Ontario, 1972	0.680 ⁽²⁾	0.024 ⁽⁶⁾
Sempachersee	0.77 ⁽⁷⁾	0.0355 ⁽⁸⁾
Zurichsee	1.32 ⁽²⁾	0.032 ⁽²⁾
Skaha	2.19 ⁽³⁾	0.06 ⁽⁴⁾
Smith Mtn.	2.23 ⁽⁹⁾	0.03 ⁽⁹⁾
Osoyoos	4.20 ⁽³⁾	0.06 ⁽⁴⁾
Lake Hickory	6.08 ⁽¹⁰⁾	0.063 ⁽¹⁰⁾
Claytor Lake	10.00 ⁽¹¹⁾	0.041 ⁽¹¹⁾
High Rock Lake	14.78 ⁽¹²⁾	0.137 ⁽¹²⁾

References: (1) Dillon and Rigler, 1974 (2) Vollenweider, 1975 (3) Patalas and Salki, 1973 (4) Stein and Coulthard, 1971 (5) Shiomi & Chawla, 1970 (6) Dobson, 1974 (7) Imboden, 1973 (8) Perret, 1973 (9) NES, 1975 (10) NES, 1975 (12) NES, 1975

Table VI-18. Projected total P concentration at spring turnover for the proposed reservoirs based on loading/concentration ratio.

Condition	Projected Areal Loading (gm/m ² /yr)	Projected Conc. Spring Turnover (gm P/m ³)
Soil as reservoir		
0 days anaerobiosis	1.16	0.0245
30 days anaerobiosis	1.21	0.0248
60 days anaerobiosis	1.27	0.0253
90 days anaerobiosis	1.33	0.0257
Soil as neither reservoir nor sink	1.11	0.0242

the total P concentration in lakes. Data used in the model came from lakes with mean depths (\bar{z}) ranging from 1 to 27 m, and flushing rates from 0.2 to 55

With the exception of 2 very shallow lakes ($\bar{z} = 1$ m), concentrations of P predicted by this model were very close to those measured in the lakes at spring overturn. Additional data from the literature supported the belief that this model could be used effectively for other lakes (Dillon and Riger, 1974).

The model is as follows:

$$P = \frac{L(1-R)}{\bar{z} p}$$

where P = total P concentration at spring overturn (gm/m^3)
 L = areal loading rate of total P ($\text{gm}/\text{m}^2/\text{yr}$)
 R = phosphorus retention coefficient (retention/input)
 \bar{z} = mean depth (m)
 p = hydraulic flushing rate (yr^{-1})

The large expenditure of time and money required to calculate the P retention coefficient of a lake or reservoir largely negated the value of the model. Kirchner and Dillon (1975) later developed an empirical method of estimating the retention of P in lakes. Their model to accomplish the task is as follows:

$$R = 0.426 \exp(-0.271qs) + 0.574 \exp(-0.00949qs)$$

where R = P retention coefficient
 qs = areal hydraulic load (m/yr^1)

This model allows for prediction of P retention based on 2 easily obtainable hydrologic parameters (total discharge and lake surface area). Solution of the model for the proposed Blue Ridge reservoirs yields an R of 0.542.

Solution of the P model of Dillon and Rigler (1974) using an R of 0.54 allowed for projection of the total P concentration at spring turnover for the proposed reservoirs (Table VI-19).

Other values used in the model were as follows: mean depth (\bar{z}) of 24 m, flushing rate (p) of 0.5, and areal loading rates for T-P (L) as reported in Table VI-13.

Summary of Nutrient Budget Models:

Four models have been utilized to estimate the concentrations of P and/or N in the proposed reservoirs. These results are summarized in Table VI-20.

Concentrations of N and P projected by the 4 models cover a substantial range. This is not surprising, however, in light of the fact that the models were developed using different criteria, and 3 of the models were created using data collected from a diverse group of lakes, by a diverse group of people, undoubtedly using an equally diverse assortment of collection and analytical procedures. Perhaps different models could best describe nutrient levels during different stages of the reservoirs' life. One might suspect that initially, before the inundated soils become covered with allochthonous and/or autochthonous sediments and are thus able to function as a nutrient sink, the conservative substance model may be the most accurate predictive tool. Once this initial period has passed, the other models might provide more accuracy, due to the wealth of "experience" built into them, and due to the

Table VI-19. Projected total P concentration at spring turnover based on the model of Dillon and Rigler (1974).

Condition	Projected spring turnover conc. (gm P/m ³)
Soil as a reservoir	
0 days anaerobiosis	0.0442
30 days anaerobiosis	0.0461
60 days anaerobiosis	0.0484
90 days anaerobiosis	0.0507
Soil as neither reservoir nor sink	0.0423

Table VI-20. Summary of projected nutrient concentrations for the proposed Blue Ridge reservoirs derived using 4 different models.

Model	Nutrient	Projected Conc. Soils as Source * (gm/m ³)	Projected Conc. Minus Soil Source (gm/m ³)
Conservative Substance	Inorganic-P	0.0360 - 0.0429	0.0329
	Total-P	0.0991 - 0.1137	0.0952
	Inorganic-N	1.342 - 1.694	0.4514
Hydraulic Residence to Nutrient Residence	Inorganic-P	0.0133 - 0.0158	0.0122
	Total-P	0.0366 - 0.0420	0.0352
	Inorganic-N	0.4971 - 0.6268	0.1670
P loading to P concentration ratio	Total-P	0.0245 - 0.0257	0.0242
Dillon & Rigler	Total-P	0.0442 - 0.0507	0.0423

*range projected based on 0 and 90 days of anaerobiosis

fact that the data bases from which they were constructed dealt with older lakes.

D. Projected Trophic Status for the proposed reservoirs

Calculations in the proceeding sections have produced a number of projections concerning the probable concentrations of inorganic P, T-P, and total (inorganic) N in the proposed Blue Ridge reservoirs, as well as projected areal and volumetric loading rates for each of these nutrients. The purpose of this section is to predict the probable trophic status for the proposed reservoirs based on 10 different criteria.

1. Criteria of Sawyer:

The concentration of dissolved oxygen has been used extensively as a measure of the acceptability of water quality in streams. Sawyer (1942) has proposed an analagous approach to characterize water quality in lakes, with the concentrations of N and P replacing dissolved oxygen as the criteria of water quality. Sawyer noted that concentrations of inorganic N and P less than 300 and 10 g/l, respectively, during the spring generally produce satisfactory water quality throughout the year. At concentrations in excess of these levels, the waters are likely to deteriorate.

Projections of inorganic N and P concentrations using the conservative substance model are in excess of Sawyer's criteria for satisfactory water quality, regardless of whether nutrient loadings from the soils are included. Utilizing the

"hydraulic/nutrient residence time" model, projected levels of inorganic P exceed the criteria by 3-6 g/l with loadings from the soil included, while the projected level without soil input is almost on the border between satisfactory and deteriorating water quality. Projected N concentrations exceed the criteria only when the inundated soils are contributing, falling well below the critical level otherwise. The latter is a result of the fact that a large portion of the projected N input is from the inundated soils.

2. Trophic state - P relationships in lakes:

Miller et al. (1974) reported data concerning the chemical limnology and reported trophic status of 23 American lakes currently being studied as part of the USEPA National Eutrophication Survey (NES). These data indicate that lakes classified as oligotrophic have inorganic P concentrations ranging from 0.005 to 0.017 mg/l; those classified as mesotrophic have concentrations ranging from 0.008 to 0.041 mg/l; and those classified as eutrophic have concentrations ranging from 0.01 to 0.835 mg/l. There are, of course, no clearly defined boundaries between the 3 different classifications, for reasons too obvious and too numerous to discuss here. However analysis of these data indicates that there is only 1 oligotrophic lake which contains more than 0.010 mg/l inorganic P (it has a pH of 5.5), and only 2 eutrophic lakes which contain less than 0.020 mg/l inorganic P. Based on this data, one might generalize that lakes containing less than

0.010 mg/l inorganic P are likely to be oligotrophic, and that lakes containing more than 0.020 mg/l are likely to be eutrophic. Mesotrophic lakes could of course occupy the range between these extremes and would assuredly overlap in both directions.

Assuming the preceding criteria, inorganic P levels projected by the conservative substance model indicate that the reservoirs are likely to be eutrophic. On the other hand, concentrations of inorganic P projected by the "hydraulic/nutrient residence time" model indicate that the reservoirs are likely to be mesotrophic, perhaps bordering on oligotrophy when the inundated soils no longer serve as a P source.

3. Predicted AGP:

Miller et al. (1974) also reported data indicating the relationship between the AGP of a water [as determined using the Algal Assay Procedure Bottle Test, with S. capricornutum as the test organism (EPA, 1971)] and the trophic status of the lake from which the water was collected.

Utilizing a regression model developed for waters in the upper New River basin ($AGP = 1.2 + 282 (P) + 16 (N)$) and concentrations of inorganic P and N projected for the reservoirs, the AGP of the reservoirs under various conditions was predicted (Table VI-21).

Miller et al. (1974) defined 4 productivity groups based on the AGP values (mg dry wt/l.) obtained from the various lake waters: (1) low productivity (< 0.10), (2) moderate productivity (0.11 - 0.80), (3) moderately high productivity (0.81 - 6.0), and

(4) high productivity (> 6.0). The authors point out that their AGP values reflect the nutrient content of the waters at the time of assay and not necessarily the AGP of the lake. Interestingly enough, however, all water which were classified as having high productivity or moderately high productivity came from lakes which were reported to be eutrophic.

Based on the preceding criteria and the AGP projections presented in Table VI-21, we can predict that the waters in the proposed reservoirs will be highly productive, and that they would most likely be classified as eutrophic.

4. Vollenweider's Criteria for N and P concentrations:

Vollenweider (1968) has presented a "tentative" classification (empirically determined) allowing for estimation of the trophic status of lakes based on P and N concentrations. He prefaces this

Table VI-21. AGP* predicted for waters in the proposed Blue Ridge reservoirs.

Nutrient Model	Soils as nutrient source		Omitting nutrients from soils
	anoxic 0 days	anoxic 90 days	
Conservative substance	32.8	40.4	17.6
Hydraulic-nutrient retention ratio	12.9 x	15.6	7.3

* in mg S. capricornutum dry wt/liter

by writing that " it is admittedly not rigorous enough to meet the demands of theoretical limnology, and obviously cannot be followed to the letter; it does, however, provide guidelines for use in applied limnology." The classification is as follows:

<u>Trophic characteristics</u>	<u>Total P (mg/m³)</u>	<u>Inorganic N (mg/m³)</u>
ultra-oligotrophic	5	200
oligo-mesotrophic	5 - 10	200 - 400
meso-eutrophic	10 - 30	300 - 650
eu-polytrophic	30 - 100	500 - 1500
polytrophic	> 100	> 1500

Based on the above criteria for total P, the projected trophic status for the proposed reservoirs would be either meso-eutrophic, eu-polytrophic, or polytrophic, depending on which model projections were employed and whether or not the soils were serving as a P source.

Based on Vollenweider's N criteria and the N levels projected by the conservative substance model, the proposed reservoirs would be eu-polytrophic under conditions in which the inundated soils served as a source, and meso-eutrophic under conditions in which they did not serve as a source. Based on levels projected by the "retention ratio" model, the reservoirs would be respectively meso-eutrophic and oligotrophic depending on conditions.

5. Vollenweider's Criteria for N and P loading rates:

Vollenweider (1968) points out that nutrient concentrations must not be regarded as a rigid guideline for trophic status classification. In practice, he adds, " the key to the eutrophication problem lies not in the nutrient concentrations but in subsequent

nutrient loadings." Utilizing data from a large number of lakes, Vollenweider devised guidelines for "permissible" and "dangerous" loading levels for total N and total P as a function of the mean depth of the lake in question. For lakes with mean depths of between 10 and 50m, those guidelines estimate "permissible" loadings of up to 4.0 and 0.25 gm/m²/yr for N and P, respectively, and estimate as "dangerous" loadings in excess of 8.0 and 0.50 gm/m²/yr for N and P respectively.

Based on these guidelines, projected N loadings to the Blue Ridge reservoirs are in excess of both permissible and dangerous loadings under all conditions in which the soils serve as a N source. With the soils not serving as a source, projected loadings are above permissible levels but below dangerous levels. Projected P loadings for the reservoirs are in excess of both permissible and dangerous loading estimates under all conditions.

6. Vollenweider's modified model for P loading rates:

Edmondson (1970), in discussing the usefulness of the P loading-mean depth relationship, mentioned that the effect of a doubled P loading from a doubled flow rate must be different from the effect caused by a doubled P concentration in the inflow. Subsequently Vollenweider (1975) modified his initial relationship and based his revised model on considerations of a mass balance equation for P. The revised model allowed for prediction of trophic status based on the relationship between P loading rates and a mean depth/mean hydraulic retention time ratio (Fig. VI-1).

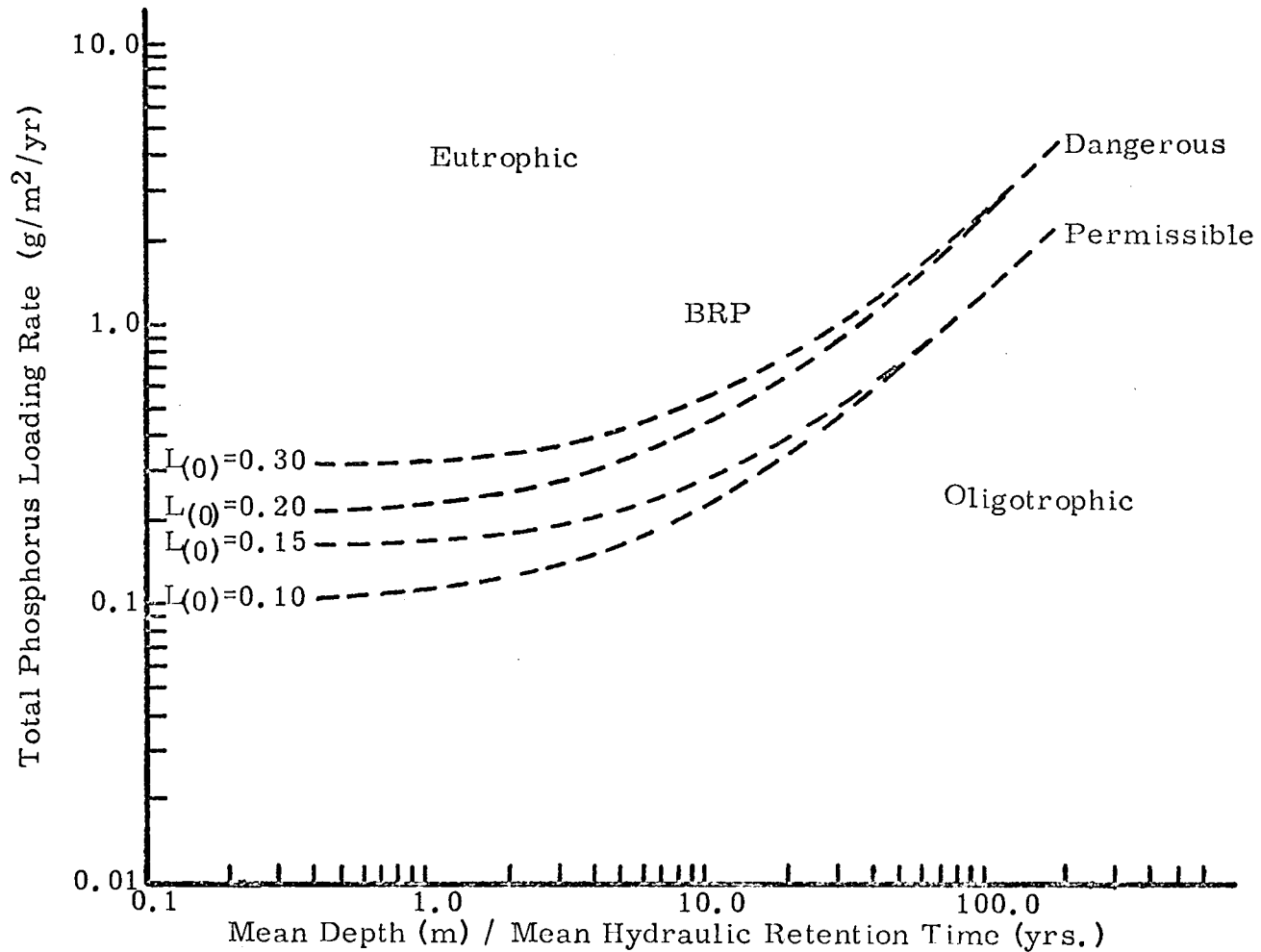


Fig. VI-7. Nomograph from the model of Vollenweider (1975) summarizing the relationship between (1) total P loading rate, (2) the ratio of mean depth to mean hydraulic retention time, and (3) the in-lake concentration of total P. (redrawn from Vollenweider, 1975)

Projected P loadings are between 1.11 and 1.33 gm/m²/yr for the proposed reservoirs. Based on a mean depth of 24 m and a mean hydraulic retention time of 2.0 years, Vollenweider's revised model estimates a permissible loading of approximately 0.27 gm/m²/yr and a dangerous loading of approximately 20.52 gm/m²/yr.

Utilizing either the 1968 or 1975 criteria of Vollenweider, water quality in the proposed reservoirs will not be good unless the nutrient loading is reduced.

7. Loading criteria of O'Melia:

O'Melia (1974) has created a predictive model for P in lakes which, when tested, shows excellent agreement between observed and predicted average P concentrations for lakes with a wide range of hydraulic retention times (1 to 700 years) and mean depths (14 to 313 m). Based on an areal hydraulic loading of 11 (m/yr) and a mean depth of 24 m, this model predicts a permissible areal total P loading of approximately 0.5 (gm/m²/yr). Using this criterion, total P loading to the proposed reservoirs would not be "permissible." (Note permissible loading rates as determined by this model are those which allow for a mean total P concentration of 0.020 mg/l).

8. Criteria of Dillon (1975):

The P loading vs. mean depth relationships formulated by Vollenweider (1968, 1975) have been widely accepted and used as a guide to the trophic status of lakes, and also as a guide to

the trophic status of lakes, and also as a guide to the permissible and dangerous loading levels of P in lakes. The loading relationships appears to have played a significant role in the Great Lakes Joint Commission's decisions to ban phosphates in detergents and to implement tertiary sewage treatment in the Lakes region (Int. J. Comm., 1969). Faith in this model stemmed from the fact that for lakes on which P loading data were available, the predicted status of the lake usually matched the observed status.

However Dillon (1975) found that a number of lakes in Southern Ontario were not accurately depicted by Vollenweider's P loading relationships. Using a mass balance modeling approach, Dillon derived a relationship relating lake mean depth to a factor which included annual P loading, hydraulic flushing time, and the P retention coefficient (Fig. VI-2). The lines drawn on this plot are lines of equal predicted P concentration; i. e., the prediction of the trophic status of a lake is based on a measure of the predicted P concentration in the lake rather than on its P loading. The closeness of this value for similar lakes has led Dillon to conclude that this parameter is more suitable than loading alone for describing a lake's trophic condition.

Calculation of $L(1-R)/p$ for the Blue Ridge project reservoirs gives a value of 1.0 (based on an areal loading rate of 1.11 gm/m²/yr, R of 0.542, and p of 0.5). A plot of this value vs. mean depth (24 m) places the proposed reservoirs in the "eutrophic" category.

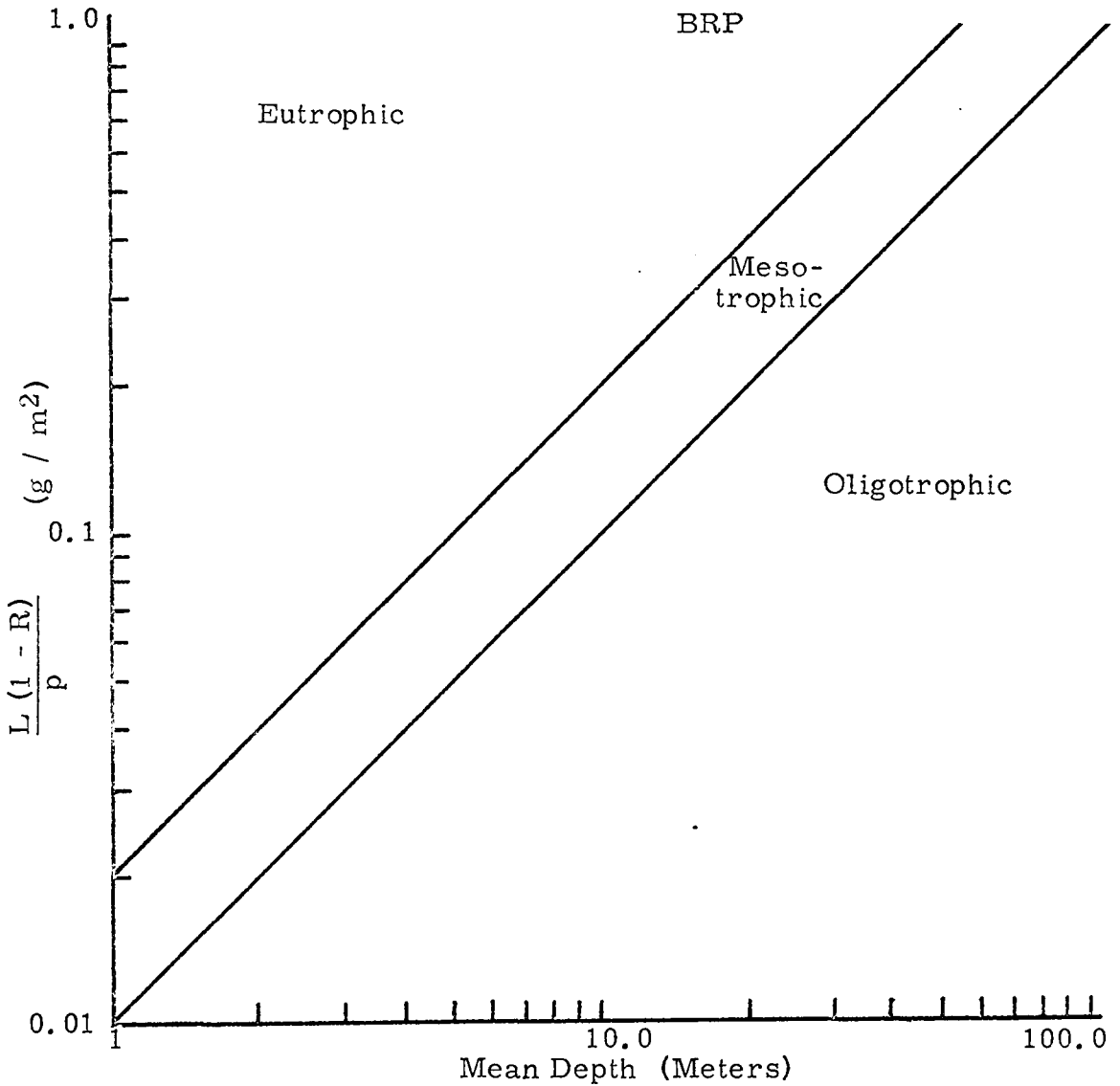


Fig. VI-8. Nomograph from the model of Dillon (1975) illustrating the relationship between (1) mean depth, (2) a factor which includes annual P loading, hydraulic flushing time, and the P retention coefficient, and (3) in-lake concentrations of total P. (redrawn from Dillon, 1975)

9. Criteria of Larsen and Mercier (1975):

Working independently of Dillon, Larsen and Mercier (1975) postulated that average influent P concentrations may be more appropriate than loading rates as a measure of the potential trophic status of a lake. This is based on the premise that the mean P influent concentration is a potential lake P concentration. The assimilative capacity of a lake, involving biological, chemical, and physical processes, normally reduces this potential to produce mean lake concentrations.

Kirchner and Dillon (1975), and Vollenweider (1975) developed empirical expressions which can be used to estimate the P retention capacity in lakes based on either areal hydraulic loading or the hydraulic washout coefficient. Subsequently, Larsen and Mercier (1975) developed an expression derived from the steady state solution of a P mass balance model relating mean lake P concentration to mean influent P concentration and the lake retention capacity. A graph of mean influent P concentration to mean lake P concentration and the lake retention capacity. A graph of mean influent P concentration vs. lake P retention capacity has been proposed to summarize this relationship (Fig. VI-3). Lines of constant lake P concentration have been drawn on the graph to delineate trophic states (based on concentration) and to facilitate prediction of trophic status when mean influent P concentration and/or P retention capacity are changed.

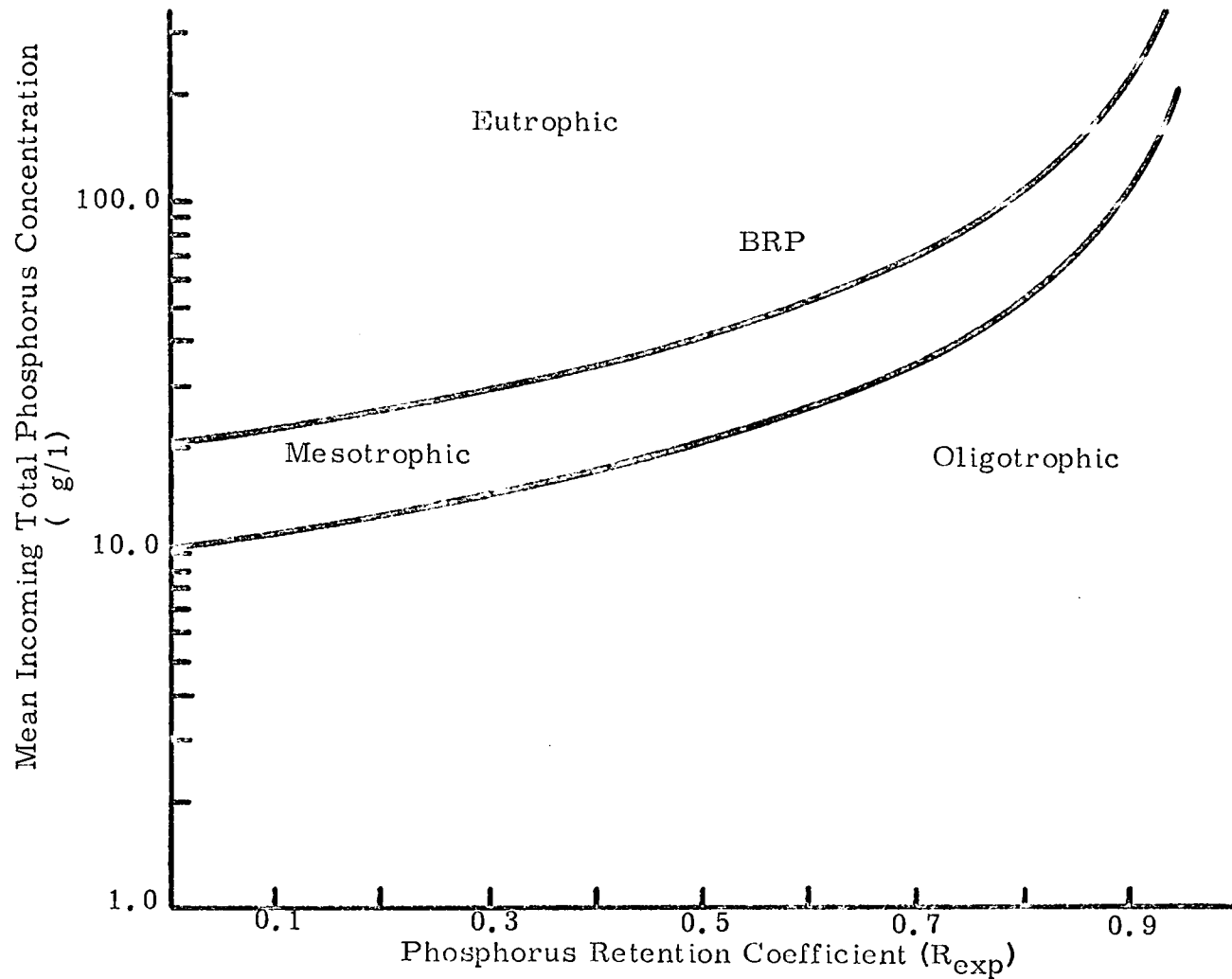


Fig. VI-9. Nomograph from the model of Larsen and Mercier (1975) summarizing the relationship between the P retention coefficient, mean incoming total P concentration, and in-lake concentrations of total P. (redrawn from Larsen and Mercier, 1975)

Based on a projected mean incoming total P concentration of 86.6 mg/m^3 (annual P load without soil input \div mean annual hydraulic load) and the retention coefficient of 0.54 projected earlier, we can predict a eutrophic status for the Blue Ridge reservoirs. At the same level of loading the reservoirs would require a retention coefficient of 0.76 in order to have a projected mesotrophic status, and a coefficient of around 0.88 for projected oligotrophic status.

10. FWPCA Criteria for P:

Federal Water Quality Criteria (FWPCA, 1968) recommends that T-P concentrations not exceed 0.05 ppm where rivers or streams enter reservoirs. Influent concentrations greater than 0.05 ppm are likely to provide the potential for luxurious plant growth. Based on a projected mean influent T-P concentration of 0.086 ppm (see preceding section) or a projected concentration of 0.055 ppm (annual tributary loading of T-P \div annual hydraulic loading), the FWPCA recommended concentration is exceeded.

Summary

Ten different criteria have been employed in order to predict the most probable trophic status for the proposed Blue Ridge reservoirs. Table VI-22 summarizes the predictions of these criteria based on projected N and P loading rates and on the various projected nutrient concentrations derived from the use of 4 different nutrient budget models. Because the scientific community

Table VI-22. Summary of predictions* concerning the most probable trophic status for the proposed Blue Ridge Reservoirs.

Criteria	Loading Rate Conservative			Nutrient Residence vs.			Loading Dillon-		AGP		
	N	P	Substance Model	P _i	P _t	N _i	P _t	P _t			
Sawyer (1947)				P _i E	P _t	N _i E	P _i E	P _t	N _i M-E	P _t	
Miller et al. (1974)				E			M				
AGP											E
Vollenweider (1968)				E-P	M-P		EP	O-E	M-E	EP	
Vollenweider (1968)	M-E	EP									
Vollenweider (1968)		E									
O'Melia (1974)		E									
Dillon (1975)		M-E									
Larsen-Mercier (1975)		E									
FWPCA (1968)		E									

*Subjective designations: O = oligotrophic E = eutrophic
M = mesotrophic P = polytrophic

has not yet agreed upon objective criteria for identifying the trophic status of lakes, the designation O (oligotrophic), M (mesotrophic), E (eutrophic), P (polytrophic), and HE (hyper-eutrophic) are qualitative and subjective.

One might wonder why many of these criteria predict that waters previously described as having good water quality (Cairns et al., 1972; Benfield et al., 1974) will produce a mesotrophic or eutrophic reservoir if impounded. The N and P levels present in these waters are the foundation upon which these predictions stand, and this epitomizes a difference between lotic and lentic waters.

Many other factors are known to influence the effects of N and P enrichment on trophic status, including mean depth, steepness of bottom contour, shoreline irregularity, % littoral area, mean depth/surface area ratio, wind protection by surrounding terrain, temperature, insolation, circulation, pH, hardness, the balance of all nutrients needed for production, and transparency. On the basis of any one of these factors a prediction, with sound limnological basis, can be made concerning probable trophic status. Once this is completed, however, the task of properly weighting each factor and its corresponding prediction is confronted. This cannot be adequately accomplished, and for this reason practical limnologists must increasingly look to models to facilitate prediction.

Good lake models are formulated from large data bases, collected over long periods of time from a diverse group of lakes, and thus contain a wealth of latitude and "experience." In using these models to make predictions (such as I have attempted here) the following is assumed:

1. that the models were formulated from accurate data
2. that the test data used were accurate
3. that the analytical procedures employed for the determination of any given parameter were the same in the model data and in the test data
4. that the test lake does not contain any significant peculiarities not encountered in the lakes used in the model formulation

The predictions which I have made are only as sound as the models which I employed, and the degree to which the above assumptions have been met. It could be that all of the assumptions have not been met - perhaps the Blue Ridge Reservoir waters will be softer than any dealt with in the model formulations; perhaps suspended clay particles will give the reservoirs a higher P sedimentation capacity than any encountered in the model formulations; perhaps turbidity, common in many southeastern U. S. reservoirs, will prevent light penetration necessary to support the levels of productivity found in the data base lakes; or perhaps these models cannot accurately deal with pumped-storage operations.

Only inundation and time will tell.

Discussion

Gakstatler et al. (1975) reported that the trophic status of 23 selected NES lakes and reservoirs was predicted "quite well" by both the Dillon (1975) and Larsen-Mercier (1975) models. The trophic state designations in both models are based on a prediction of in-lake concentrations of total phosphorus. I do not question the capability of these 2 models to accurately estimate P concentrations, however I do not believe that P. J. Dillon, R. A. Vollenweider, H. T. Mercier, D. P. Larsen, C. N. Sawyer, or anyone else can formulate "magic" concentrations for nutrients applicable to all waters (lakes and reservoirs) in all parts of the world. The works of the above researchers are extremely important, not only because of the relationships they have demonstrated, but also because of the interest they have initiated in this field. I personally feel that empirical models need to be developed for the respective geographic areas of the world. The models should allow for determination of permissible regional loading rates and concentrations based on trophic state classifications determined by a number of limnologists employing a large number of criteria. I have already initiated the effort for accomplishing this task in the Tennessee Valley region of the U. S.

REFERENCES

- Aaronson, T. 1971. Mercury in the environment. *Environment*, 13(4): 16-27.
- AFS, Southern Div. 1967. Reservoir Fishery Resources Symposium. Reservoir committee, Southern Div., AFS. Univ. of Georgia, Athens. 569 p.
- AFS, 1971. Reservoir Fisheries and Limnology. Special pub. No. 8, Gordon E. Hall [ed.], American Fisheries Society, Washington, D. C. 511 p.
- Altman, P. L., and D. S. Dittner, ed. 1966. Environmental Biology. Federation of American Societies for Experimental Biology. Bethesda Md. 694 p.
- American Public Health Association. 1971. Standard methods for the examination of water and wastewater, 13th ed. APHA. New York. 874 p.
- American Society of Limnology and Oceanography, Inc. 1972. Nutrients and eutrophication: The limiting-nutrient controversy. In G. E. Linkins [ed.], Special Symposia Vol. I. Allen Press, Inc. Lawrence, Kansas. 328 p.
- Anonymous. 1971. Role of animal wastes in agricultural land runoff. Dept. of Biol. and Agric. Engr., N. C. St. U., Raleigh, EPA Rept. No. 13020 DGX 08/71, Washington, D. C.
- Armitage, B. J. 1974. An investigation of phytoplankton periodicity and primary productivity in a new reservoir, Lake Anna, Virginia. PhD. dissertation. VPI & SU. Blacksburg, Va. 195 p.
- Armitage, K. B. 1958. Ecology of riffle insects of the Firehole River, Wyoming. *Ecology*. 39: 571-580.
- Armstrong, F. A. J., and D. W. Schindler. 1971. Preliminary chemical characterization of waters in the Experimental Lakes area, northwestern Ontario. *J. Fish. Res. Bd. Con.* 28(2): 171-187.
- Aulenbach, D. B., and N. L. Clesceri. 1973. Nutrient inputs to a lake and their effects upon water quality. FWI Report 73-8. RPI. Troy, N. Y. 35 p.
- AWWA Task Group. 1967. Sources of N and P in water supplies. *JAWWA*. 59: 344-365.

- Ball, R. C., and F. F. Hooper. 1963. Translocation of phosphorus in a trout stream ecosystems, p. 217-228. In: V. Schultz and A. W. Klement [ed.], Radioecology. Reinhold Pub. New York.
- Bannister, T. T. 1972. Discussion on algal response to nutrients, p. 154. In: G. E. Likens [ed.], Nutrients and eutrophication: the limiting nutrient controversy. Am. Soc. Limnol. and Oceanogr. Allen Press Inc.
- Barr, A. J. and J. H. Goodnight. 1972. A user's guide to the statistical analysis system. Student Supply Stores, N. C. St. U., Raleigh, N. C. 260 p.
- Becker, C. D., and T. C. Thatcher. 1973. Toxicity of power plant chemicals to aquatic life. Compiled for U. S. Atomic Energy Commission by Battelle Pacific Northwest Laboratories. Richland, Washington.
- Benfield, E. F., and J. Cairns, Jr. 1974. Pre-impoundment ecological reconnaissance of the New River in the area of the proposed APCo Blue Ridge Project. Three year report, CES, VPI & SU. Blacksburg, Va.
- Bernstein, L. 1967. Quantitative assessment of irrigation water quality. Special technical publication 416. American Society for Testing and Materials. Philadelphia, Pa. p. 51-65.
- Biswar, S. 1969. The Volta Lake: some ecological observations on the phytoplankton. Verh. Int. Ver. limnol. 17: 259-272.
- Blum, J. L. 1960. Algal populations in flowing waters. Spec. publs. Pymatuning Lab. Fld. Biol. 2: 11-21.
- Brezonik, P. L. 1973. Nitrogen cycling and sources in natural waters. EPA 660/3-73-002. Washington, D. C. 167 p.
- Brezonik, P. L., and H. D. Putnam. 1968. Eutrophication: Small Florida lakes as models to study the process. Proceedings 17th Southern Water Resources and Pollution Control Conference. University of North Carolina, Chapel Hill, N. C. p. 315.
- Brungs, W. A. 1969. Chronic toxicity of zinc to the fathead minnow, *Pimephales promelas* Rafinesque. Trans. Am. Fish. Soc. 98(2): 272-279.
- Bryan, E. H. 1970. Quality of stormwater drainage from urban lands in North Carolina. Rept. 37, Water Resources Res. Inst., U. of North Carolina, Chapel Hill.

- Burm, R. J., D. F. Krawczyk, and G. L. Harlow. 1968. Chemical and physical comparison of combined and separate sewer discharges. *J. Water Poll. Contr. Fed.* 40(1): 112-126.
- Butcher, R. W. 1930. Variations in composition of river waters. *Int. Revue ges. Hydrobiol. Hydrogr.* 24: 47-80.
- Butcher, R. W. 1933. Idem. I. On the distribution of macrophytic vegetation in the rivers of Britain. *J. Ecol.* 21: 58-91.
- Butcher, R. W. 1938. The algae of the river. *Rep. Avon. biol. Res.* 5: 47-52.
- Cairns, J. Jr. 1968. We're in hot water! *Scientist and Citizen.* 10(8): 187-198.
- Cairns, J. Jr., D. W. Albaugh, F. Busey, and M. D. Chaney. 1968. The sequential comparison index: a simplified method for non-biologists to estimate relative differences in biological diversity in stream pollution studies. *J. Water Pollut. Control Fed.* 40(a): 1607-1613.
- Cairns, J. Jr., K. L. Dickson, and A. Hendricks. 1972. Pre- and post- construction surveys. *Indus. Water Eng.* 9(2): 33-35.
- Cairns, J. Jr., K. L. Dickson, D. P. Klarberg, and E. F. Benfield. 1972. A pre-impoundment water quality survey on the New River and associated tributaries related to Appalachian Power Co.'s Blue Ridge pumped storage project. First year report. Biology Dept. and Center for Environmental Studies, VPI & SU., Blacksburg, Va. 125 p.
- Cairns, J. Jr., and A. Scheier. 1958. The effect of periodic low oxygen upon the toxicity of various chemicals to aquatic organisms. 12th Indus. Waste Conf. Proc. Purdue Univ. Eng. Ext. Series.
- Chalupa, J. 1960. Eutrophication of reservoirs by atmospheric phosphorus. *Sbornik Vysoke Skoly Chem. Technol.* 29: 406.
- Chapman, W. H., H. L. Fisher, and M. W. Pratt. 1968. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564, Lawrence Radiation Laboratory, Livermore, Cal. 50 p.
- Chen, C. W., and G. T. Onlob. 1972. Predicting quality effects of pumped storage. *J. Power Div., Proceedings Am. Soc. Civil Eng.* 98(POL): 65-75.
- Choquette, S., and F. DeLalla. 1975. "Ol' Man New River"
In B. E. Watkins [ed.], *The New River Almanac.*

- Churchill, M. A. 1958. Effects of storage impoundments on water quality. *Trans. Am. Soc. Civil Eng.* 123: 419-464.
- Chu, S. P. 1942. The influence of the mineral composition of the medium on the growth of planktonic algae. I. Methods and culture media. *J. Ecol.* 30: 284-325.
- Chu, S. P. 1943. The influence of the mineral composition of the medium on the growth of planktonic algae. II. The influence of the concentration of inorganic nitrogen and phosphate phosphorus. *J. Ecol.* 31: 109-148.
- Clemens, H. P., and W. H. Jones. 1954. Toxicity of brine water from oil wells. *Trans. Amer. Fish. Soc.* 84: 97-109.
- Cooper, C. F. 1969. Nutrient output from managed forests. In *Eutrophication: Causes, consequences, correctives*. NAS, Washington, D. C. 404 p.
- Cummins, K. W. 1966. A review of stream ecology with special emphasis on organism-substrate relationships. *Spec. Publ. Pymatuning Lab.Fld. Biol.* 4: 2-51.
- Dillon, P. J. 1974. A critical review of Vollenweider's nutrient budget model and other related models. *Water Resources Bull., AWRA.* 10(5): 969-989.
- Dillon, P. J. 1975. The phosphorus budget of Cameron Lake, Ontario: The importance of flushing rate to the degree of eutrophy of lakes. *Limnol. Oceanogr.* 20(1): 28-39.
- Dillon, P. J., and W. B. Kirchner. 1974. The effects of geology and land use on the export of phosphorus from watersheds. *Water Res.* 9: 135-148.
- Dillon, P. J., and F. H. Rigler. 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. *J. Fish. Res. Bd. Can.* 31: 1771-1778.
- Doudoroff, P. and M. Katz. 1953. Critical review of the literature on the toxicity of industrial wastes and their components to fish. II. The metals, as salts. *Sewage Industr. Wastes.* 25: 802-839.
- Doudoroff, P., and D. L. Shumway. 1967. Dissolved oxygen criteria for the protection of fish. *Am. Fish. Soc. Spec. Pub.* 4: 13-19.
- Doudoroff, P., and C. E. Warren. 1965. D. O. requirements of fishes. In C. M. Tarzwell (ed.), *Biological problems in water pollution*. PHS Pub. 99-WP-25.

- Dunst, R. C., et al. 1974. Survey of lake rehabilitation techniques and experiences. Tech. Bull. No. 75. Dept. Nat. Resources, Madison, Wisconsin. 179 p.
- Durum, W. H., and J. Haffty. 1963. Implications of the minor element content of some major streams of the world. *Geochim. et Cosmochim. Acta.* 27: 1-11.
- Durum, W. H., J. D. Hem, and S. G. Heidel. 1971. Reconnaissance of selected minor trace elements in surface waters of the U. S. Geol. Survey Circ. No. 643. 49 p.
- Durfor, C. N., and E. Becker. 1964. Public water supplies of the 100 largest cities in the U. S. U. S. Geol. Survey Water Supply Paper, 1812. (U. S. Gov. Printing Office, Washington, D. C.)
- Edmondson, W. T. 1970. Book review. *Limnol. Oceanogr.* 15: 169-170.
- Einsele, W. 1941. Die Umsetzung von zugefuhrtem, anorganischen phosphat im eutrophen See und ihre Ruckwirkung auf seinen Gesamthaushalt. *Z. Fisch.* 39: 407-488.
- EIFAC. 1965. Working paper on water quality criteria for European freshwater fish. Report of finely divided solids and inland fish. *Air Water Pollution.* 9(3): 151-168.
- Ellis, M. M. 1937. Detection and measurement of stream pollution. *U. S. Bur. Fish. Bull.* 22: 365-437.
- EPA. 1971. Algal assay procedure bottle test. National Eutrophication Research Program, EPA, Corvallis, Oregon. 82 p.
- EPA. 1973. Water quality criteria 1972. EPA Ecological Research Series, EPA-R3-73-033-March 1973. Washington, D. C. 594 p.
- EPA. 1975. Report on Claytor Lake, Virginia. Working Paper No. 460. NERC, Las Vegas, Nevada. 50 p.
- EPA. 1975. Report on High Rock Lake, North Carolina. Working Paper No. 381. NERC, Las Vegas, Nevada. 57 p.
- EPA. 1975. Report on Lake Hickory, North Carolina. Working Paper No. 380. NERC, Las Vegas, Nevada. 45 p.
- EPA. 1975. Report on Smith Mountain Reservoir, Virginia. Working Paper No. 465. NERC, Las Vegas, Nevada. 54 p.
- Eppley, R. W., J. L. Coatsworth, and L. Solorzano. 1969. Studies of nitrate reductase in marine phytoplankton. *Limnol. Oceanogr.* 14: 194-205.

- Feth, J. H. 1966. Nitrogen compounds in natural water - a review. *Water Resources Research*. 2: 41-58.
- Fisher, D. W. 1968. Annual variations in chemical composition of atmospheric precipitation in eastern North Carolina and southeastern Virginia. U. S. Geol. Survey Water Supply Paper 1535-M. 21 p.
- Fitzgerald, G. P. 1969. Field and laboratory evaluations of bioassays for nitrogen and phosphorus with algae and aquatic weeds. *Limnol. Oceanogr.* 14: 206-212.
- Fitzgerald, G. P. 1970. Aerobic lake needs for the removal of phosphorus from lake waters. *Limnol. & Oceanogr.* 15(4): 550-555.
- Frink, C. R. 1967. Nutrient budget: rational analysis of eutrophication in a Connecticut Lake. *Environ. Sci. & Tech.* 1: 425-428.
- Frost, W. E. 1939. River Liffey survey II - the food consumed by the brown trout (*Salmo Trutta* Linn.) in acid and alkaline waters. *Proc. R. Ir. Acad.* 45B: 159-206.
- Frost, W. E. 1942. Idem IV - the fauna of the submerged 'mosses' in an acid and an alkaline water. *Proc. R. Ir. Acad.* 47B: 293-369.
- Fry, F.E. J. 1960. The oxygen requirements of fish. In C. M. Tarzwell [ed.], *Biological problems in water pollution*. (U. S. Dept. HEW, Robert A. Raft Sanitary Engineering Center, Cincinnati, Ohio) p. 106-109.
- Funk, W. H., and A. R. Gaufin. 1971. Phytoplankton productivity in a Wyoming coolin-water reservoir. p. 167-178. In G. E. Hall [ed.], *Reservoir fisheries and limnology*. Spec. Pub. No. 8. Am. Fish. Soc.
- FWPCA, USDI. 1968. Water quality criteria. Report of the Committee on Water Quality Criteria. Washington, D. C. 234 p.
- Gakstatter, Jack. Biologist, USEPA, Eutrophication and lake restoration branch, Corvallis, Oregon. (personal communication).
- Gakstatter, Jack. 1974. Relationships between drainage area characteristics and non-point source nutrients in streams. Working Paper No. 25. USEPA, NES. Corvallis, Or. 50 p.

- Gakstatter, J. H., M. O. Allum, and J. M. Omernik. 1975. Lake Eutrophication: Results from the National Eutrophication Survey. Presented, 26th Ann. AIBS Meeting, OSU, Corvallis, Oregon, August 17-22, 1975.
- Gambell, A. W. Jr. 1963. Sulfate and nitrate content of precipitation over parts of North Carolina and Virginia. Geol. Surv. Prof. Paper 475-C: 209-214.
- Gammon, J. R. 1970. The effect of inorganic sediment on stream biota. EPA Water Pollution Control Research Series No. 18050DWC. U. S. Gov. Print. Office. Washington, D. C. 141 p.
- Garrels, R. M., and C. L. Christ. 1964. Solutions, minerals, and equilibria. Harper and Row. New York. 450 p.
- Gerloff, G. C., and F. Skoog. 1954. Cell contents of nitrogen and phosphorus as a measure of their availability for growth of Microcystis aeruginosa. Ecology. 38: 551-556.
- Gessner, F. 1960. Investigations of the phosphate economy of the Amazon. Int. rev. Hydrobiol. 45: 339-345.
- Goldman, C. R. 1960. Primary productivity and limiting nutrient factors in three lakes of the Alaska peninsula. Ecol. Monogr. 30: 207-230.
- Goldman, C. R. 1961. Primary productivity and limiting factors in Brooks Lake, Alaska. Verh. int. Verein theor. angew. limnol. 14: 120-124.
- Goldman, C. R. 1963. The measurement of primary productivity and limiting factors in freshwater with ^{14}C . p. 103-113. In M. S. Doty [ed.], Proceedings of the conference on primary productivity measurement, marine and freshwater. USAEC, TID-7633.
- Gorham, E. 1961. Factors influencing supply of ions to inland waters, with special reference to the atmosphere. Bull. Geol. Soc. Am. 72: 795-840.
- Grant, N. 1971. Mercury in man. Environment. 13(4): 2-15.
- Gustafson, P. F. 1967. Comments on radionuclides in aquatic ecosystems. Proc. int. symp. radioecol. concent. process. 1966. Stockholm. 853-858.
- Hamilton, A. 1971. Mercury levels in Canadian fish. p. 73-90. In Mercury in man's environment, proceedings of a symposium. Royal Society of Canada, Ottawa.

- Hart, W. B., P. Daudoroff, and J. Greenbank. 1945. The evaluation of the toxicity of industrial wastes, chemicals, and other substances to freshwater fishes. Waste Control Laboratory. The Atlantic Refining Co. Philadelphia. 317 p.
- Harter, R. D. 1968. Adsorption of phosphorus by lake sediments. *Proc., Soil Sci. Soc. Amer.* 32: 514-518.
- Hasler, A. D. 1947. Eutrophication of lakes by domestic drainage. *Ecology.* 28: 383-95.
- Hem, J. C. 1968. Graphical methods for studies of aqueous aluminum hydroxide, fluoride, and sulfate complexes. U. S. Geol. Survey Water Supply Paper 1827-B. 33p.
- Hem, John D. 1970. Study and interpretation of the chemical characteristics of natural waters. Geological Survey Water Supply Paper 1473. U. S. Gov. Printing Off. Washington, D. C. 365 p.
- Hendricks, A. C., and J. K. G. Silvey. 1973. Nutrient ratio variation in reservoir sediments. *JWPCF.* 45(3): 490-497.
- Hepher, B. 1958. On the dynamics of P added to fishponds in Israel. *Limnol. Oceanogr.* 3: 84-100.
- Hobbie, John E. Associate Professor of Zoology, N. C. State University, Raleigh, N. C. Personal communication.
- Hobbie, J. E., and G. E. Likens. 1973. The output of phosphorus, dissolved organic carbon, and fine particulate carbon from Hubbard Brook Watershed. *Limnol. Oceanogr.* 18: 734-742.
- Holm-Hansen, O., W. H. Sutcliffe, Jr., and J. Sharp. 1968. Measurement of DNA in the ocean and its ecological significance. *Limnol. Oceanogr.* 13: 507-514.
- Horn, M. K., and J. A. S. Adams. 1966. Computer-derived geochemical balances and element abundance. *Geochim. et Cosmochim. Acta.* 30: 279-297.
- Hutchinson, G. E. 1957. A treatise on limnology. Vol. 1. John Wiley and Sons, Inc. New York. 1015 p.
- Hutchinson, G. E. 1973. Eutrophication. *American Scientist.* 61: 269-280.
- Hynes, H. B. N. 1972. The ecology of running waters. Liverpool University Press, Great Britain. 555 p.

- International Geophysical Union. 1972. Proceedings: International symposium on man-made lakes, their problems and environmental effects. Knoxville, Tennessee, USA, May 3-7, 1971.
- International Lake Erie and Lake Ontario - St. Lawrence River Water Pollution Boards. 1969. Pollution of Lake Erie, Lake Ontario, and the international section of the St. Lawrence River. 1: 1-151.
- Jaworski, N. A., O. Villa, Jr., and L. J. Hetling. 1969. Nutrients in the Potomac River Basin. Tech. Rept. 9, Middle Atlantic Region. Fed. Water Poll. Contr. Adm.
- Jaworski, N. A., and L. J. Hetling. 1970. Relative contributions of nutrients to the Potomac River basin from various sources. Tech. Rept. 31, Middle Atlantic Region, Fed. Water Poll. Contr. Adm.
- Johannes, R. E. 1968. Nutrient regeneration in lakes and oceans. Adv. Microbiol. Sea. 1: 203-212.
- Johnson, M. G., and G. E. Owen. 1971. Nutrients and nutrient budgets in the Bay of Quinte, Lake Ontario. J. Water Poll. Contr. Fed. 43(5): 836-853.
- Joyner, B. F. unknown. Appraisal of chemical and biological condition of Lake Okeechobee. U. S. Geol. Survey, Open File Rept. 71006.
- Kanawha River Basin Coordinating Committee (KRBCC). 1971. Kanawha River Comprehensive Basin Study. Vol. III, Appendix C, Hydrology. Huntington District, S. S. Army Corps of Engineers. Huntington, W. Va. 238 p.
- Kanawha River Basin Coordinating Committee (KRBCC). 1971. Kanawha River Comprehensive Basin Study. Vol. I. Main Report. Huntington District, U. S. Army Corps of Engineers, Huntington, W. Va. 185 p.
- Keeney, D. R. 1972. The fate of nitrogen in aquatic ecosystems. Literature review no. 3. Eutrophication Information Program, U. Wis. -WRRC. Madison, Wisconsin. 59 p.
- Keeton, W. T. 1972. Biological science. Second Edition, W. W. Norton and Co., Inc. New York. 88 p.
- Ketchum, B. H. 1969. Eutrophication of estuaries, pp. 197-209. In: Eutrophication: Causes, consequences, correctives. Nat. Acad. Sci./Nat. Res. Council, Publ. 1700.

- Keup, L. E. 1968. Phosphorus in flowing waters. *Water Research*, 2: 373-386.
- Keup, L. E., G. D. McKee, E. W. Raabe, and R. W. Warner. 1970. Water quality effects of leaching from submerged soils. *JAWWA*. 62(6): 391-396.
- Kilmer, V. J., J. W. Gilliam, J. F. Lutz, R. T. Joyce, and C. D. Eklund. 1974. Nutrient losses from fertilized grassed watersheds in western North Carolina. *J. Env. Qual.* 3(3): 214-219.
- Kirchner, W. B. 1975. An examination of the relationship between drainage basin morphology and the export of phosphorus. *Limnol. & Oceanogr.* 20(2): 267-270.
- Kirchner, W. B., and P. J. Dillon. 1975. An empirical method for estimating the retention of phosphorus in lakes. *Water Resources Res.* 11: 182-183.
- Kobayasi, H. 1961. Productivity in a sessile algal community of a Japanese mountain river. *Bot. Mag. Tokyo.* 74: 228-235.
- Kolehmainen, S., E. Haesaenen, and J. K. Miettinen. 1967. Cesium-137 in fish, plankton, and plants in Finnish lakes during 1964-65. *Proc. Int. Symp. Radioecol. Convent. Process.*, 1966, Stockholm. 913-919.
- Kopp, J. F. 1969. The occurrence of trace elements in water, in *Proc. 3rd An. Conf. on Trace Substances in Env. Health*, D. D. Hemphill, ed. (U. of Missouri, Columbia) p. 59-73.
- Krumholz, L. A., and S. E. Neff. 1970. The freshwater stream, a complex ecosystem. *Water Resources Bulletin.* 6(1): 163-174.
- Larsen, D. P., and H. T. Mercier. 1975. Lake phosphorus loading graphs: an alternative. EPA-ELRD, Working Paper No. 174. 30 p.
- Lee, G. F. 1970. Eutrophication. Occasional Paper No. 2. Eutrophication Information Program, University of Wisconsin Water Resources Center. 39 p.
- Lee, G. Fred. 1974. Diversion of wastewaters from Madison Lakes. *J. Env. Eng. Div., ASCE.* 100(EE1): 153-170.
- Leentvaar, P. 1966. The Brokopondo Lake in Surinam. *Verh. int. Ver. Limnol.* 16: 680-684.

- Lindemann, R. L. 1942. The trophic-dynamic aspect of ecology. *Ecology*. 23: 399-418.
- Little, J. A. Deputy administrator, USEPA, Region IV, Atlanta, Georgia. Personal communication.
- Livingstone, D. A. 1963. Chemical composition of rivers and lakes. In *Data of geochemistry* (6th ed.) U. S. Geol. Survey Prof. Paper 440-G, G1-664.
- Lloyd, R. 1961. Effect of dissolved oxygen concentration on the toxicity of several poisons to rainbow trout (*Salmo gairdnerii* Richardson). *J. Exp. Biol.* 38: 447.
- Loehr, R. C. 1974. Characteristics and comparative magnitude of non-point sources. *JWPCF*. 46(8): 1849-1872.
- Lowman, F. G., T. R. Rice, and F. A. Richards. 1971. Accumulation of radionuclides by marine organisms. In *Radioactivity in the marine env.* (NAS, Washington, D. C.) p. 161-199.
- Lueshow, L. A., J. M. Helm, D. R. Winter, and G. Karl. 1970. Trophic nature of selected Wisconsin lakes. *Wisc. Acad. Sci. Arts and Letters*. 58: 237-264.
- Lund, J. W. G. 1965. The ecology of freshwater phytoplankton. *Biol. Rev.* 40: 231-293.
- Mackenthun, K. M. 1965. Nitrogen and phosphorus in water, an annotated selected bibliography of their biological effects. Dept. of HEW, USPHS, Div. Water Supply and Pollution Control. PHS Pub. No. 1305.
- Mackenthun, K. M., L. E. Keup, and R. K. Stewart. 1968. Nutrients and algae in Lake Sebasticook, Maine. *J. Water Poll. Contr. Fed.* 40(2): R72-R81.
- Mackereth, F. J. H. 1963. Some methods of water analysis for limnologists. Scientific Pub. No. 21. Freshwater Biological Association. The Perry House, Ambleside, Westmoreland. 70 p.
- Mackereth, F. J. H. 1965. Some chemical observations on post glacial sediments. *Phil. Trans. Royal Soc. Ser. B.* 250: 165.
- Martin, D. M., and D. R. Foff. 1972. The role of nitrogen in the aquatic environment. Pub. No. 2. Dept. of Limnology, Academy of Natural Sciences of Philadelphia. Philadelphia, Pa. 46 p.

- Menzel, D. W., and J. P. Spaeth. 1962. Occurrence of ammonia in Sargasso Sea waters and in rain water at Bermuda. *Limnol. & Oceanogr.* 7: 159-162.
- Miller, W. E., T. E. Maloney, and J. C. Greene. 1974. Algal productivity in 49 lake waters as determined by algal assays. *Water Research.* 8: 667-669.
- Minshall, N. E., M. S. Nichols, and S. A. Witzel. 1969. Plant nutrients in base flow of streams in southwestern Wisconsin. *Water Resources Res., American Geophysical Union.* 5(3): 706-713.
- Morey, G. W., R. O. Fournier, and J. J. Rowe. 1962. The solubility of quartz in water in the temperature interval from 25° to 300°C. *Geochim. et Cosmochim. Acta.* v. 26, p.1029-1044.
- Mortimer, C. H. 1941. The exchange of dissolved substances between mud and water in lakes. I and II. *J. Ecol.* 29: 280-329.
- Mortimer, C. H. 1942. The exchange of dissolved substances between mud and water in lakes. III and IV. *J. Ecol.* 30: 147-201.
- Muir, J., E. C. Seim, and R. A. Olsen. 1973. A study of factors influencing the N and P content of Nebraska waters. *J. Env. Qual.* 2(4): 466-470.
- Müller-Haëcke, A. 1965. Tagesperiodik des Siliziumgehaltes in einem Fließgewässer. *Z. Morph. Okol Tiere.* 16: 232-233.
- Muss, D. L. 1962. Relation between water quality and deaths from cardiovascular disease. *J. Amer. Water Works Ass.* 54: 1371-1378.
- National Academy of Sciences. 1969. Eutrophication: causes, consequences, correctives. Proceedings of a symposium, June 11-15, 1967, University of Wisconsin, Madison. N.A.S. Washington, D. C. 661 p.
- Odum, E. P. 1971. Fundamentals of ecology, 3rd ed. W. B. Saunders Co. Philadelphia, Pa. 574 p.
- O'Melia, C. R. 1972. An approach to the modeling of lakes. *Schweizerische Zeitschrift für Hydrologie.* 34: 1-33.
- O'Melia, C. R. 1974. Phosphorus cycling in lakes. UNC-WRRI-74-97.

- Omernik, J. M. 1974. Relationships between drainage area characteristics and non-point source nutrients in streams. Working paper #25. National Eutrophication Survey, EPA, PNERL, Corvallis, Oregon. 50 p.
- Omernik, James M. 1975. The influence of land use on stream nutrient levels. USEPA, CRD. pre-publication copy.
- Parker, B. C. 1968. Rain as a source of vitamin B₁₂. *Nature*. 219: 617-618.
- Patalas, K., and A. Salki. 1973. Crustacean plankton and the eutrophication of lakes in the Okanagan Valley, B. C. *J. Fish. Res. Bd. Can.* 30: 519-542.
- Pearsall, W. H. 1923. A theory of diatom periodicity. *J. Ecol.* 2: 165.
- Pickering, Q. H. 1968. Some effects of dissolved oxygen concentrations upon the toxicity of zinc to bluegill Lepomis macrochirus Raf. *Water Res.* 2(3): 187-194.
- Podubsky, V. and E. Stedronsky. 1948. Toxic effects of some metals on fish and river crabs. *SB Cesk. Akad. Zemed. Ved.* 21: 206-222.
- Pomeroy, L. R., E. E. Smith, and C. M. Grant. 1965. The exchange of phosphate between estuarine water and sediments. *Limnol. & Oceanogr.* 10: 167-172.
- Putnam, H. D., P. L. Brezonik, W. H. Morgan, and E. E. Shannon. 1969. Eutrophication factors in north central Florida lakes. Bull. No. 134 WRRC Pub. No. 5. Univ. of Florida, Gainesville, Fla. 101 p.
- Putnam, H. D., and J. A. Olsen. 1960. An investigation of nutrients in western Lake Superior. School of Public Health, Univ. of Minn., mimeo. 24 p.
- Redfield, A. C., B. H. Ketchum, and F. A. Richards. 1963. The influence of organisms on the composition of sea water, pp. 26-77. In M. N. Hill [ed.], *The sea*, v. 2. Interscience.
- Reid, G. K. 1961. Ecology of inland waters and estuaries. Reinhold Pub. Corp. New York, N. Y. 375 p.
- Rodhe, W. 1964. Effects of impoundment on water chemistry and plankton in Lake Ransaren (Swedish Lapland). *Verh. int. Ver. Limnol.* 15: 437-443.

- Round, F. E. 1964. The ecology of benthic algae. In D. F. Jackson [ed.], *Algae and man*. Plenum Press, New York. p. 138-184.
- Ruttner, Franz. 1963. *Fundamentals of limnology*. Univ. of Toronto Press. 295 p.
- Sawyer, C. N. 1947. Fertilization of lakes by agricultural and urban drainage. *J. New Eng. WWA*. LXI(2): 109-127.
- Schindler, D. W., and J. E. Nighswander. 1970. Nutrient supply and primary production in Cloar Lake, eastern Ontario. *J. Fish. Res. Bd. Con.* 27(11): 2009-2036.
- Schmitz, W. 1956. Salzgehaltsschwankungen in der Werra und ihre fischereilichen Auswirkungen. *Vom Wass.* 23: 399-418.
- Sears, Charles E. Jr. Associate Professor of Geology, VPI & SU. Personal communication.
- Shumway, D. L., and P. Doudoroff. 1970. Dissolved oxygen requirements of freshwater fishes. *FAO Tech. Paper 86* (FAO, Rome). 291 p.
- Shiomi, M. T., and J. K. Chawla. 1970. Nutrients in Lake Ontario. *Proc. 13th Conf. Great Lakes Res., Int. Assoc. Great Lakes Res.*, 715-732.
- Sillén, L. G., and A. E. Martell. 1964. Stability constants of metal-ion complexes. *Chem. Soc. [London]. Spec. Pub. #17*. 754 p.
- Simmons, G. M., Jr. 1968. Investigations of limnetic inorganic carbon assimilation in a mainstream and pumped storage impoundment. PhD dissertation. VPI & SU. Blacksburg, Va.
- Simmons, G. M., Jr., and S. E. Neff. 1969. The effect of pumped storage reservoir operation on biological productivity and water quality. *Bull. No. 21, VA-WRRC, Blacksburg, Va.* 47 p.
- Skulberg, O. M. 1966. Algal cultures as a means to assess the fertilizing influence of pollution. In *Proceedings, Third Int. Conf. on Water Pollution Res., Section 1, Paper No. 6*. Water Pollution Cont. Fed. Washington, D. C.
- Smith, R. L. 1971. Nutritional attributes as taxonomic tools in phycology, p. 31-46. In B. C. Parker and R. M. Brown, Jr. [eds.], *Contributions in phycology*. Allen Press, Inc. Lawrence, Kansas.

- Sollmann, T. H. 1957. A manual of pharmacology and its applications to therapeutics and toxicology. 8th ed. W. B. Saunders Co., Philadelphia.
- Sonzogni, W. C., and G. F. Lee. 1972. Nutrient sources for Lake Mendota. Report of the Water Chemistry Program MS, U. of Wisc., Madison.
- Sprague, J. B. 1968. Avoidance reactions of rainbow trout to zinc sulfate solutions. *Water Res.* 2(5): 367-372.
- Stein, J. R. and T. L. Coulthard. 1971. A report on the Okanagan water investigation 1969-70. *Water Inves. Br.*, British Columbia Water Res. Service, Victoria B. C., Canada. 176 p.
- Stiff, M. J. 1971. Copper/bicarbonate equilibria in solutions of bicarbonate ion at concentrations similar to those found in natural waters. *Water Res.* 5(5): 171-176.
- Ström, K. M. 1928. Recent advances in limnology. *Proc. Linn. Soc. London.* 140: 96-110.
- Study group on mercury hazards. 1971. Hazards of mercury: special report to the secretary's Pesticide Advisory Committee, U. S. Dept. HEW. *Environ. Res.* 4(1): 1-69.
- Stumm, W., and J. L. Morgan. 1970. Aquatic chemistry. John Wiley and Sons, Inc. New York, N. Y. 583 p.
- Sylvester, R. C. 1961. Nutrient content of drainage water from forested, urban, and agricultural areas. In *Algae and metropolitan wastes*. U. S. Dept. HEW, Pub. No. SEC-TR-W61-3, Cincinnati, Ohio.
- Symons, J. M. 1969. Water quality behavior in reservoirs. U. S. Dept. HEW, PHS Pub. No. 1930. Cincinnati, Ohio. 616 p.
- Taylor, A. W., W. M. Edwards, and E. C. Simpson. 1971. Nutrients in streams draining woodland and farmland near Coshocton, Ohio. *Water Resources Res.* 7(1): 81-89.
- USPHS. 1965. Symposium on streamflow regulation for quality control. April 3-5, 1963. Taft Eng. Cntr., Cincinnati, Ohio. USPHS Pub. No. 999-WP-30. 420 p.
- Uttormark, P. D., J. D. Chapin, and K. M. Green. 1974. Estimating nutrient loadings of lakes from non-point sources. EPA-660/3-74-020. Washington, D. C. 112 p.

- Vallee, B. L. 1957. Zinc and its biological significance. A.M.A. Arch. Indust. Health. 16(2): 147-154.
- Varga, Louis P., D. W. Toetz, and T. C. Dorris. 1973. Biogeochemistry of a reservoir ecosystem. Prepared for USAEC. Report No. ORO-4254-14. OSU, Stillwater, Oklahoma. 40 p.
- Vick, H. C. Environmental chemist, USEPA, Region IV. Athens, Georgia. Personal communication.
- Voight, G. K. 1960. Alteration of the composition of rainwater by trees. Am. Midl. Nat. 63: 321-326.
- Vollenweider, R. A. 1963. Scientific fundamentals of the eutrophication of lakes, with particular reference to N and P as factors in eutrophication. OECD Report, DAS/CSI: 68.27.
- Vollenweider, R. A. 1969. Möglichkeiten und Grenzen elementarerer modelle der stoffbilanz von seen. Arch. Hydrobiol. 66: 1-36.
- Vollenweider, R. A. 1975. Input-output models. Schweiz. Z. Hydrol. In press.
- Vollenweider, R.A. and P. J. Dillon. 1974. The application of the phosphorus loading concept to eutrophication research. Nat. Res. Council of Canada. Pub. No. 13690. 42 p.
- Wallace, R. A., W. Fulkerson, W. D. Schultz, and W. S. Lyon. 1971. Mercury in the environment: the human element. ORNL-NSF-EP-1. Oak Ridge Nat. Lab., Oak Ridge, Tenn. 61 p.
- Weibel, S. R., R. J. Anderson, and R. L. Woodward. 1964. Urban land runoff as a factor in stream pollution. J. Water Poll. Contr. Fed. 36(7): 914-924.
- Weibel, S. R., R. B. Weidner, A. G. Christianson, and R. G. Anderson. 1964. Urban land runoff as a factor in stream pollution. J.W.P.C.F. 36: 914-924.
- Whitford, L. A. 1960. Ecological distribution of fresh water algae. Spec. Publs. Pymatuning Lab. Fld. Biol. 2: 2-10.
- Williams, L. G. 1960. Uptake of caesium-137 by cells and detritus of Euglena and Chlorella. Limnol. Oceanogr. 5: 301-311.
- Witzel, S. A., N. E. Minshall, M. S. Nichols, and J. Wilke. 1969. Surface runoff and nutrient losses of Fenimore Watersheds. Trans. Amer. Soc. Agric. Engr. 12: 338-341.

Wright, J. C., and R. A. Soltero. 1973. Limnology of Yellowtail reservoir and the Bighorn River. USEPA, ORD. Project 18050 DBW. Washington, D. C. 105 p.

APPENDICES

Appendix A

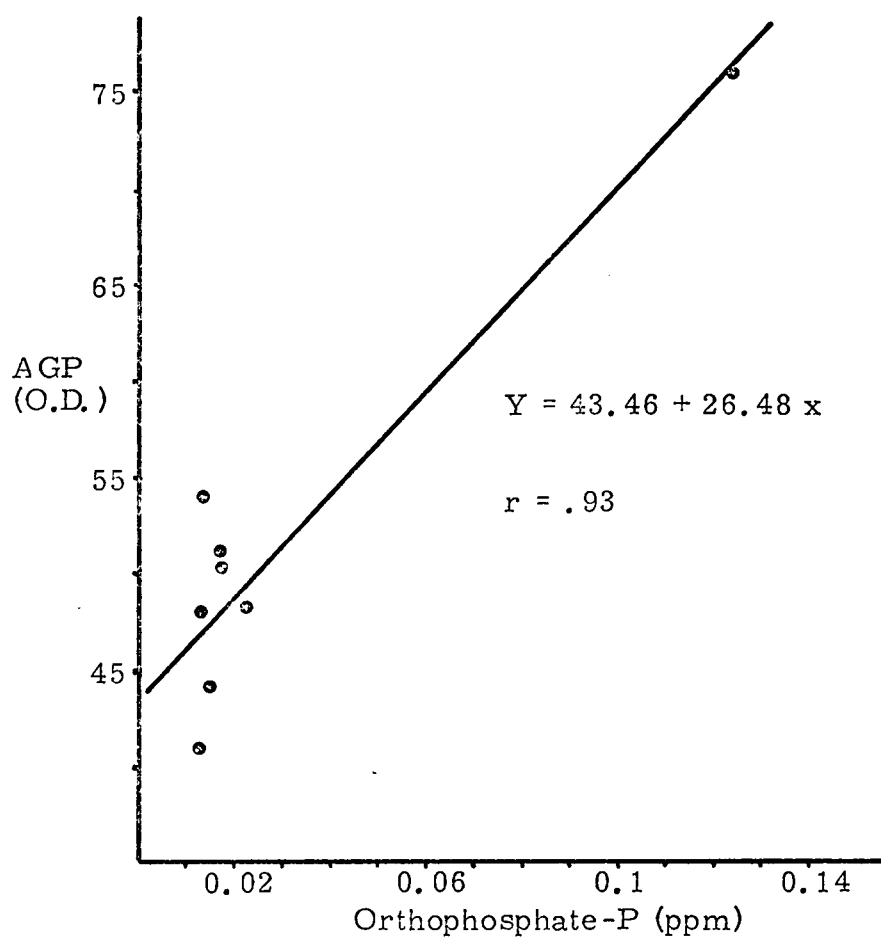


Fig. III-2. The relationship between AGP and the orthophosphate-P concentrations present at 7 primary sampling sites located above, in, and below the proposed Blue Ridge Reservoirs.

Appendix A

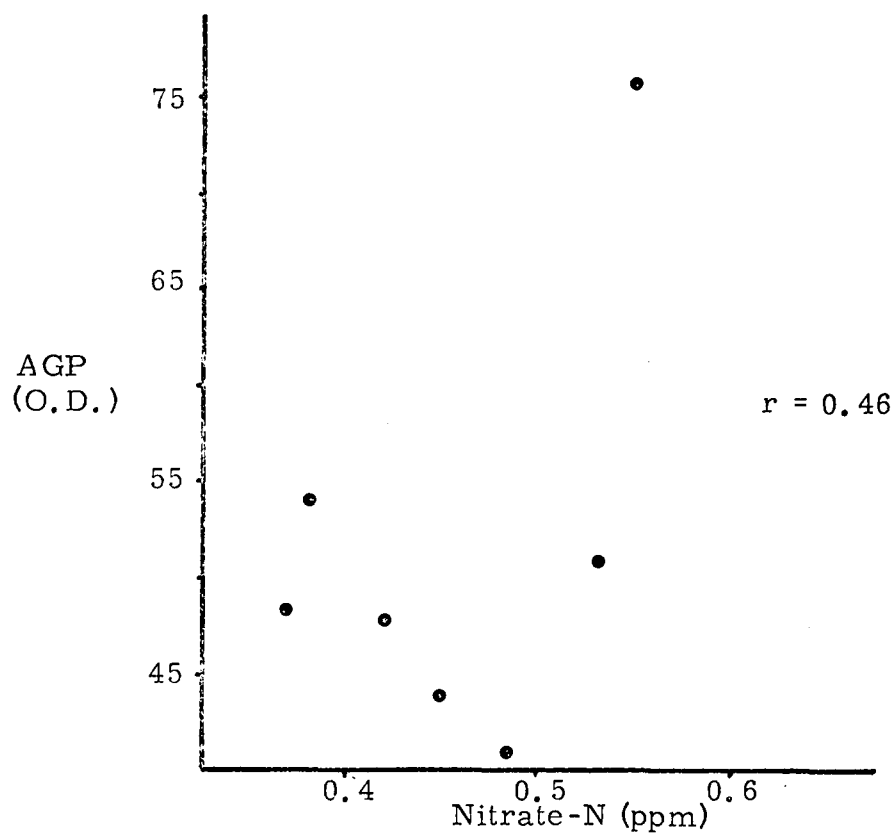


Fig. III-3. The relationship between AGP and the Nitrate-N concentrations present at 7 primary sampling sites located above, in, and below the proposed Blue Ridge Reservoirs.

Appendix A

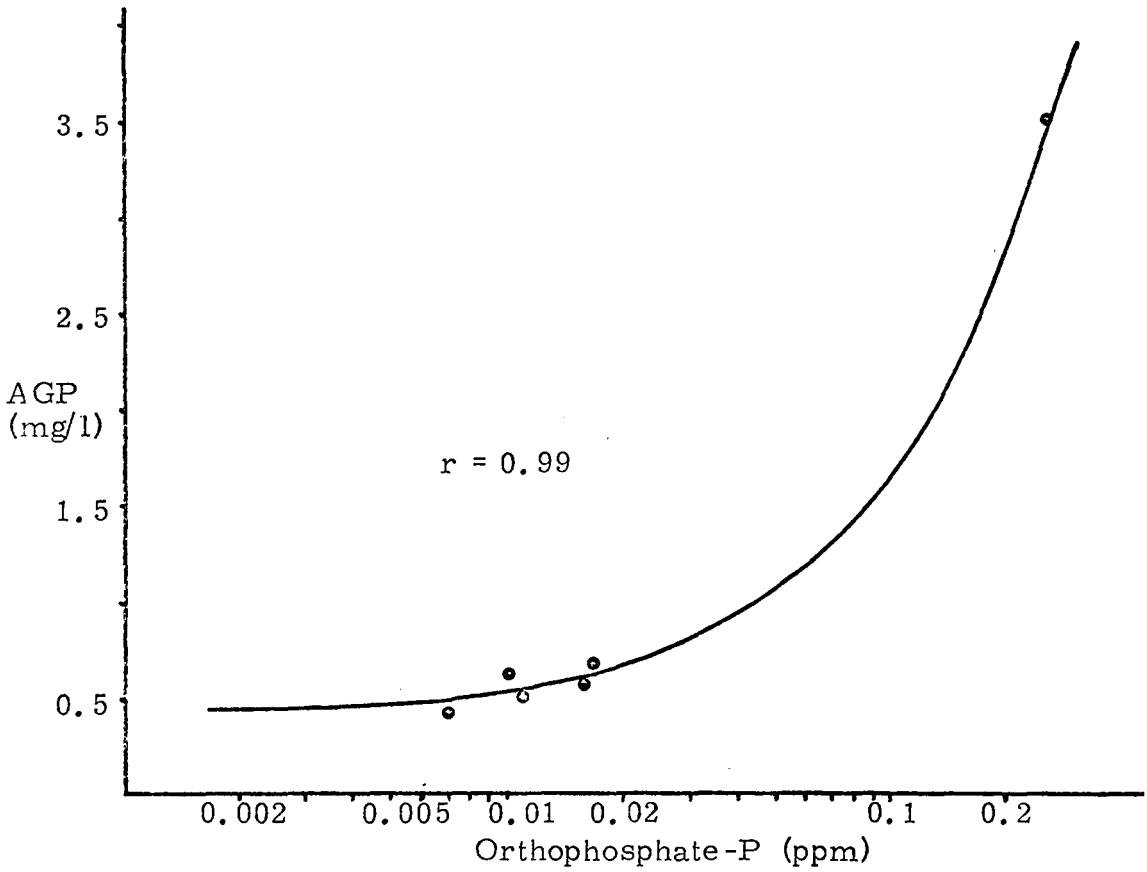


Fig. III-4. The relationship between AGP and the orthophosphate-P concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (fall, 1973).

Appendix A

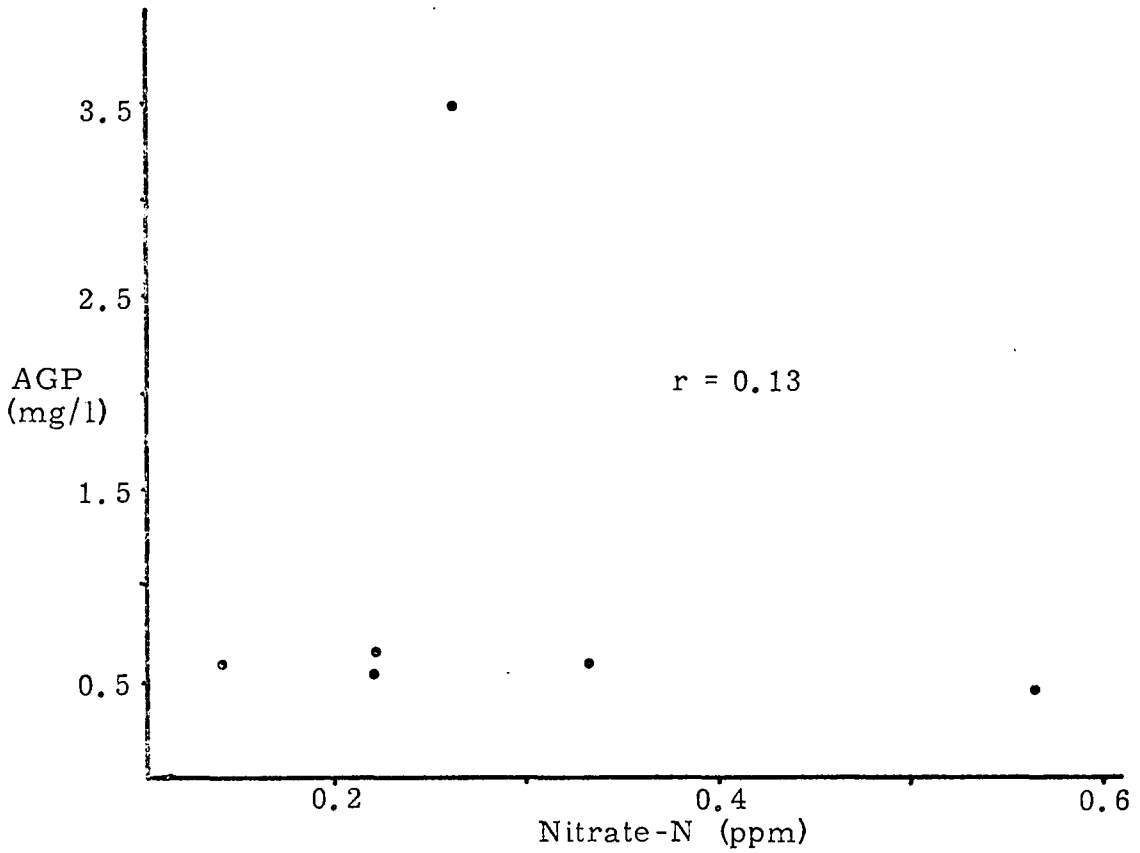


Fig. III-5. The relationship between AGP and the nitrate-N concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (fall, 1973).

Appendix A

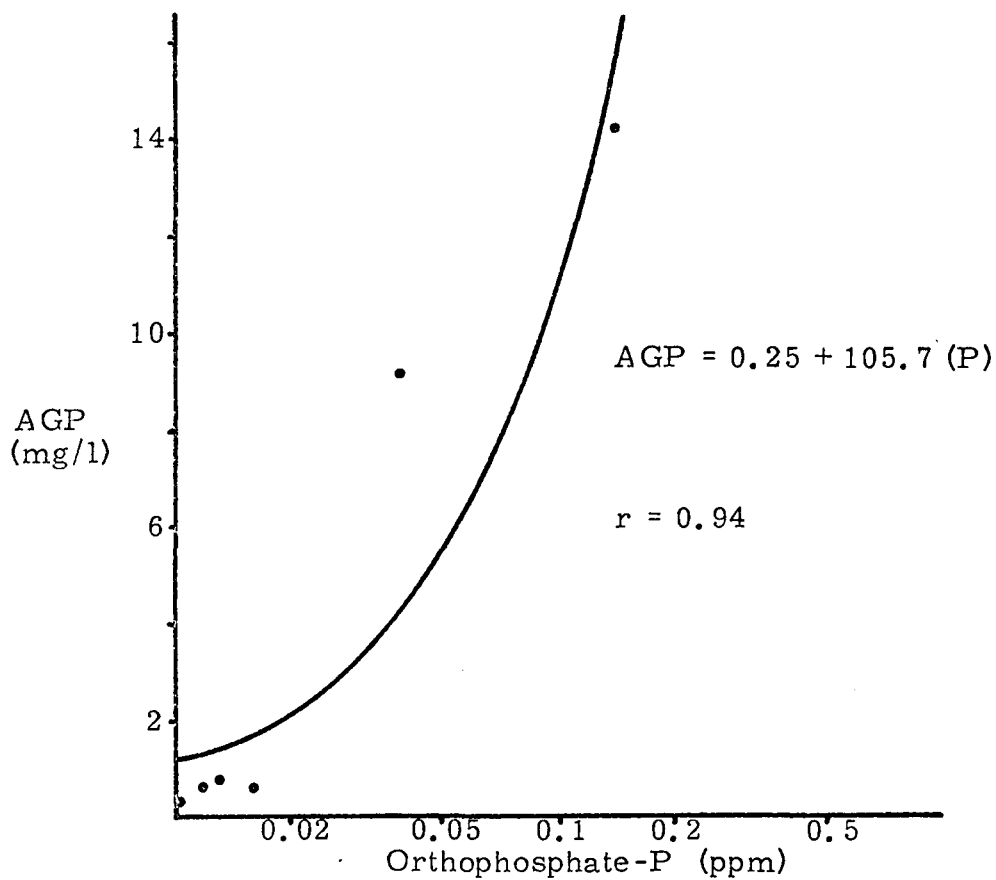


Fig. III-6. The relationship between AGP and the orthophosphate-P concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (winter, 1974).

Appendix A

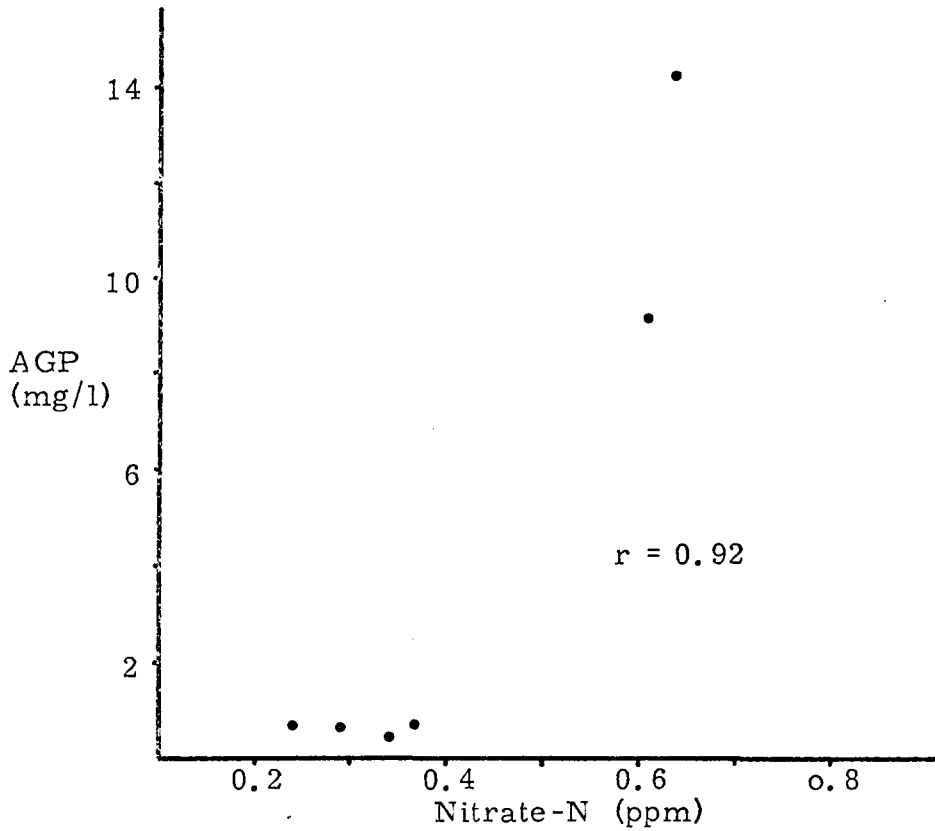


Fig. III-7. The relationship between AGP and the nitrate-N concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (winter, 1974).

Appendix A

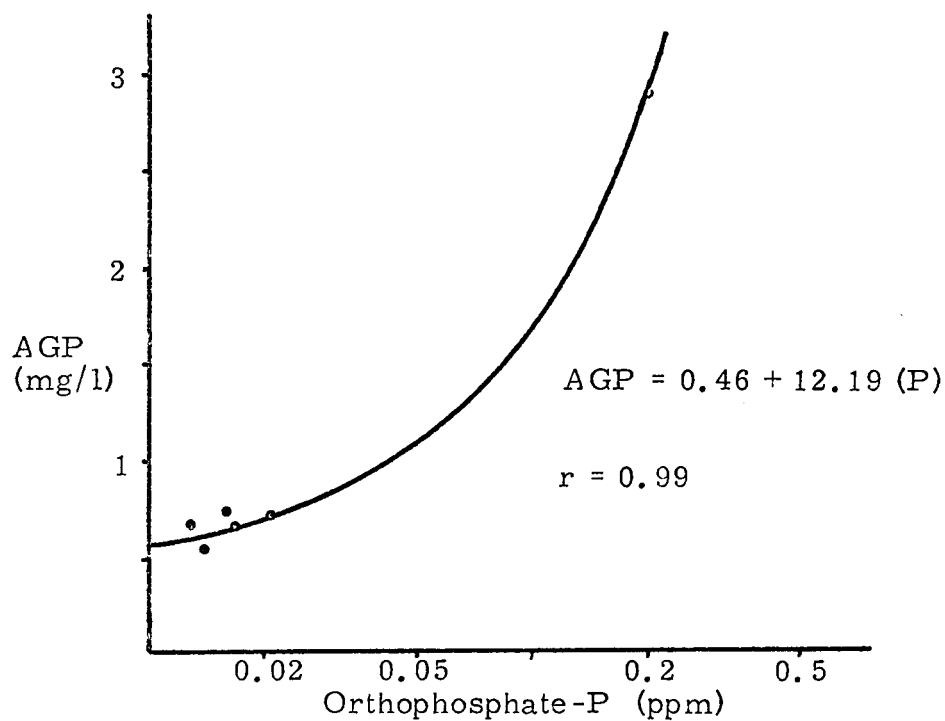


Fig. III-8. The relationship between AGP and the orthophosphate-P concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (spring, 1974).

Appendix A

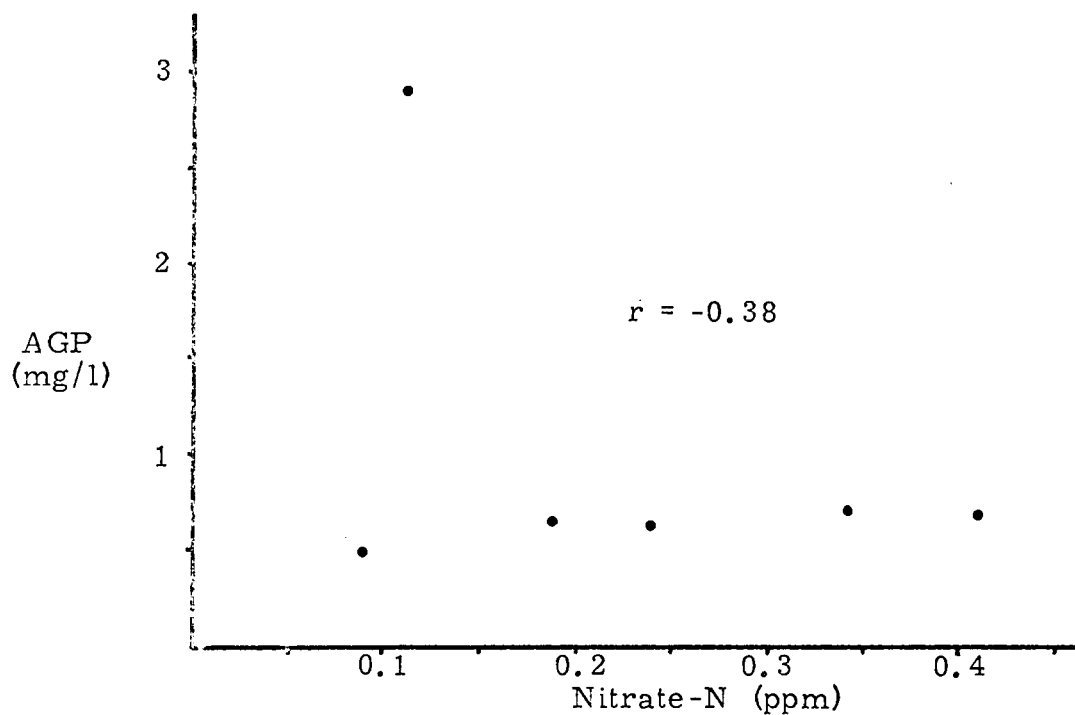


Fig. III-9. The relationship between AGP and the nitrate-N concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (spring, 1974).

Appendix A

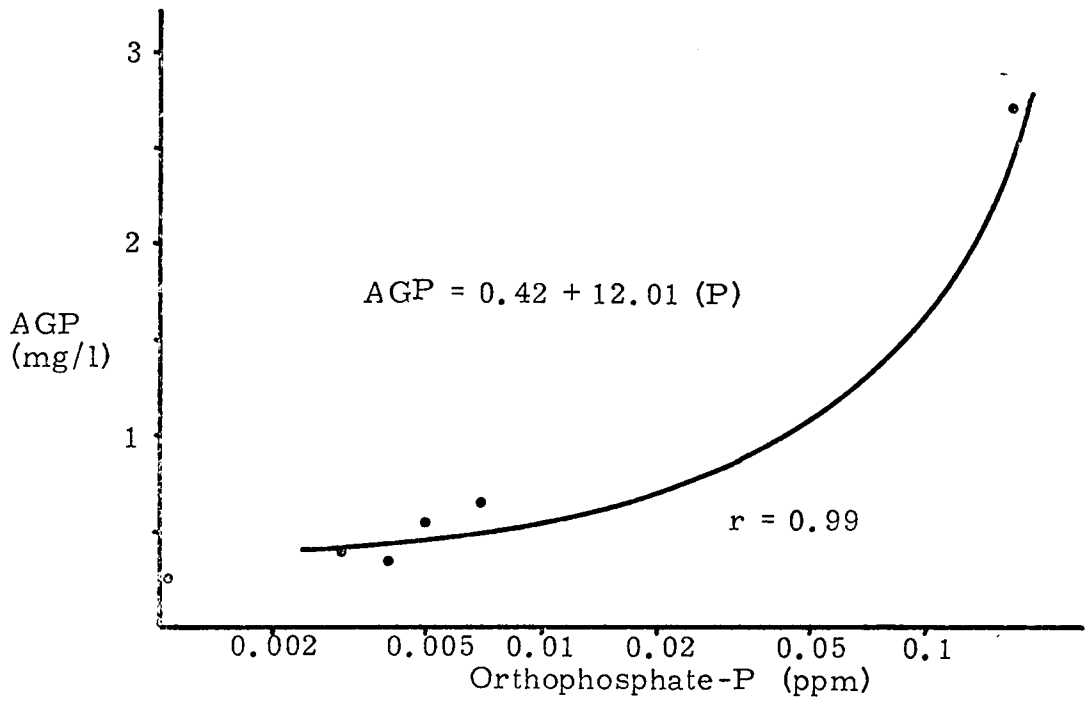


Fig. III-10. The relationship between AGP and the orthophosphate-P concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (summer, 1974).

Appendix A

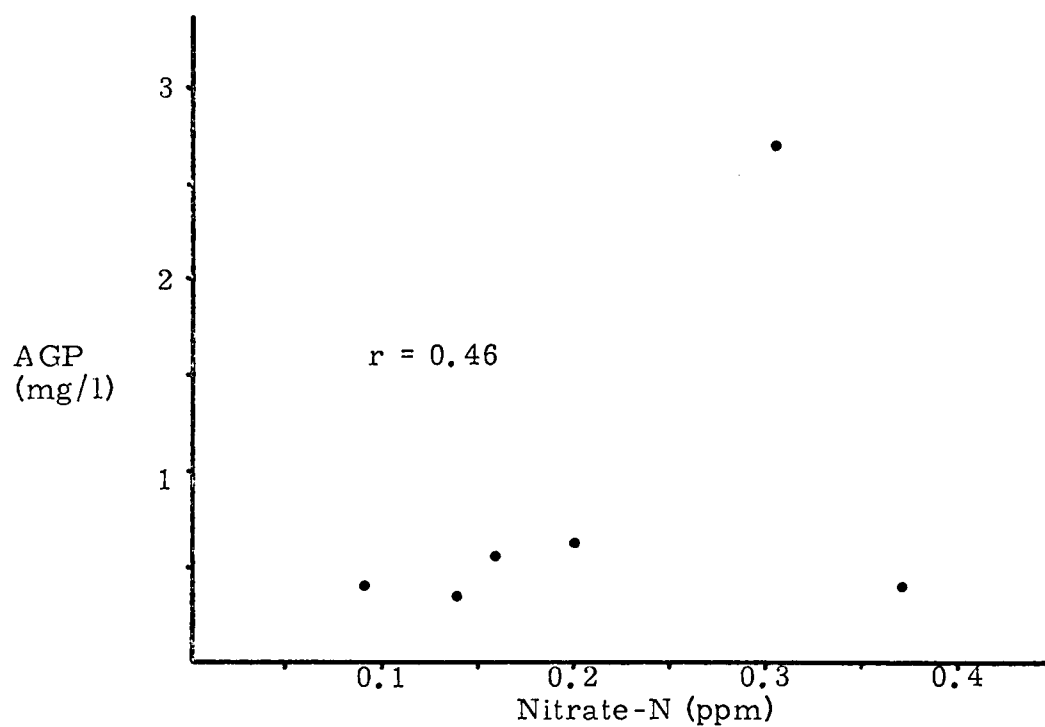


Fig. III-11. The relationship between AGP and the nitrate-N concentrations present in the 6 major tributaries to the proposed Blue Ridge Reservoirs (summer, 1974).

Table VI-3. Frequently cited data from the literature on N and P export for various types of land use.

General Land Use	Total N (kg/mi ² /yr)	Total P (kg/mi ² /yr)	Reference	Geographical Location
Forest		93	Sylvester (1961)	Washington
		860		
		377		
		1288	Cooper (1969)	N. Minnesota
		1153		
		341		
		863		
		397	Jaworski & Hetling (1970)	N. E. West Va.
		635		
			12	Taylor et al. (1971)	Cent. Ohio
Agric.	2025	116	Sawyer (1947)	S. Wisconsin
	1050	331	Witzel et al. (1969)	S. W. Wisconsin
	329	28	Minshall et al. (1969)	S. W. Wisconsin

Table VI-3. (Continued)

General Land Use	Total N (kg/mi ² /yr)	Total P (kg/mi ² /yr)	Reference	Geographical Location
Agric. cont'd	1110	70	Jaworski et al. (1969)	W. Cent. Md.
	996	55	Anon. (1971)	Cent. N. C.
Urban	2584	237	Weibel et al. (1964)	Cincinnati, Ohio
	552	265	Burm et al. (1968)	Ann Arbor, Mich.
		322	Bryan (1970)	Durham, N. C.
	563		Jaworski & Hedling (1970)	Washington, D. C. metro area
		284	Sonzogni & Lee (1972)	Madison, Wisc.
Mixed	936	64	Frink (1967)	Connecticut
	502	7	MacKenthun et al. (1968)	Maine
	553	29	Johnson & Owen (1971)	S. E. Ontario
	476	22		
	621	19		
780	37			

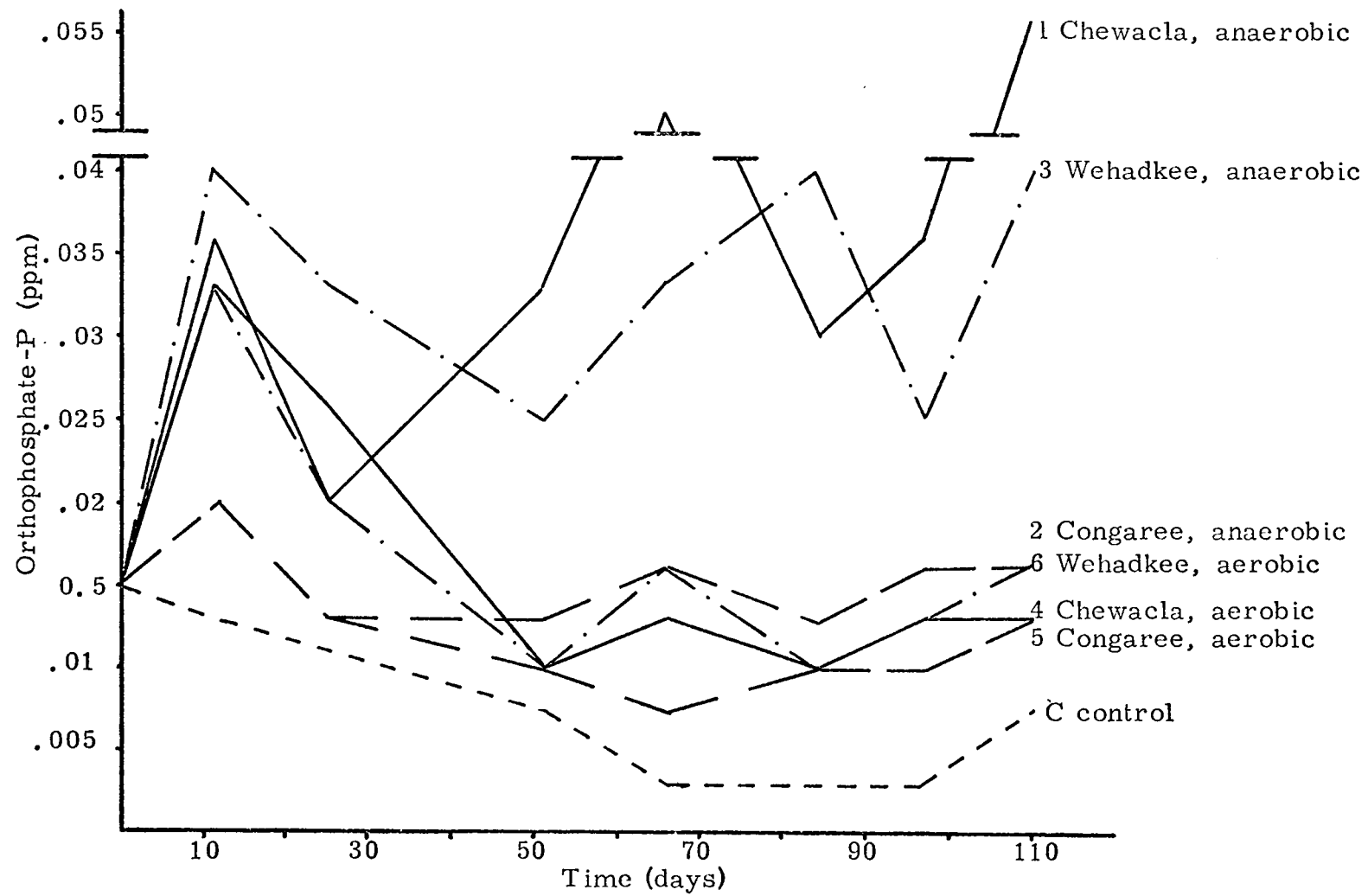


Fig. VI-2. Release of inorganic-P from the 3 alluvial soils to be inundated by the proposed Blue Ridge Reservoirs.

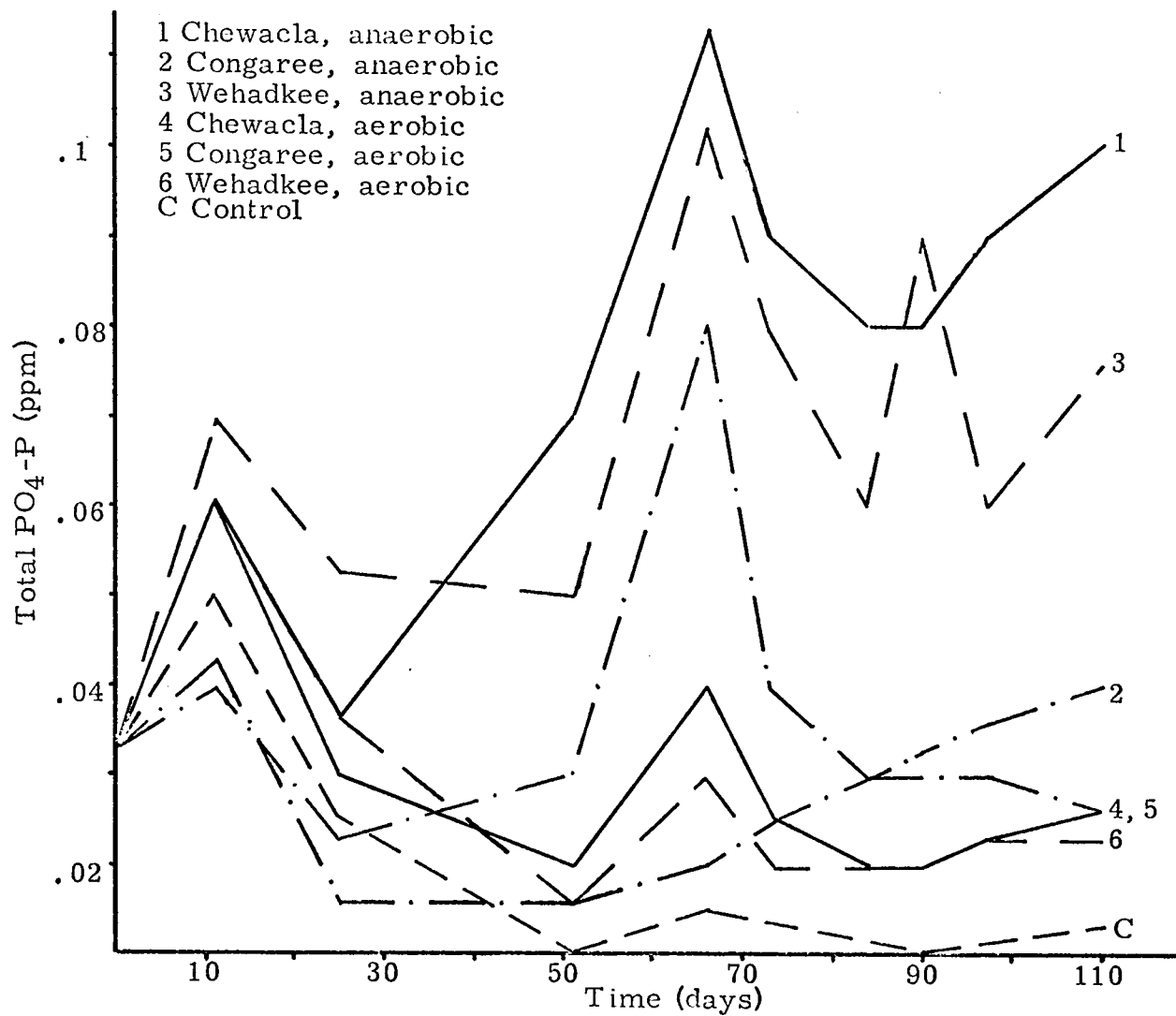


Fig. VI-3. Release of total $\text{PO}_4\text{-P}$ from the 3 alluvial soils to be inundated by the proposed Blue Ridge Reservoirs.

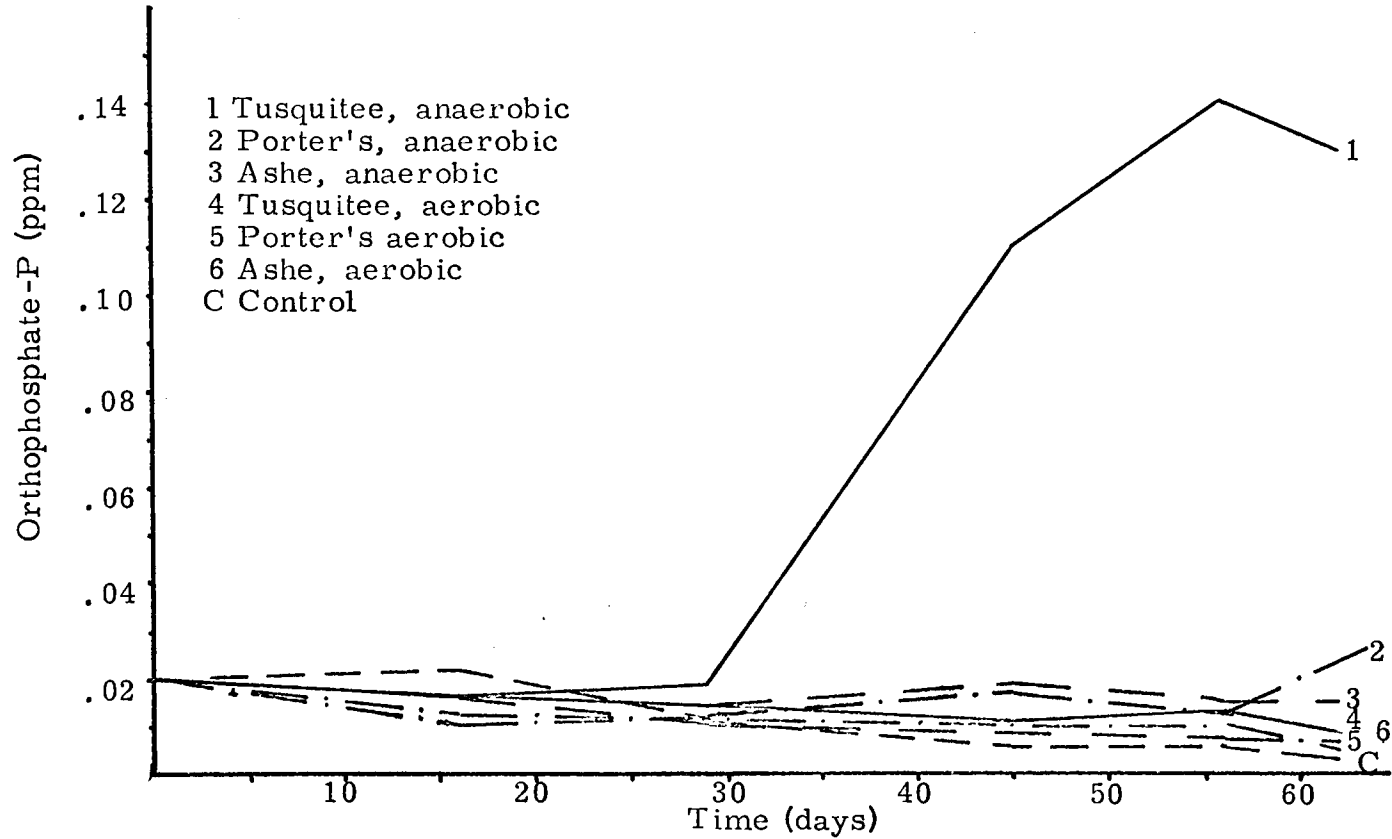


Fig. VI-4. Release of inorganic P from the 3 residual soils to be inundated by the proposed Blue Ridge Reservoirs.

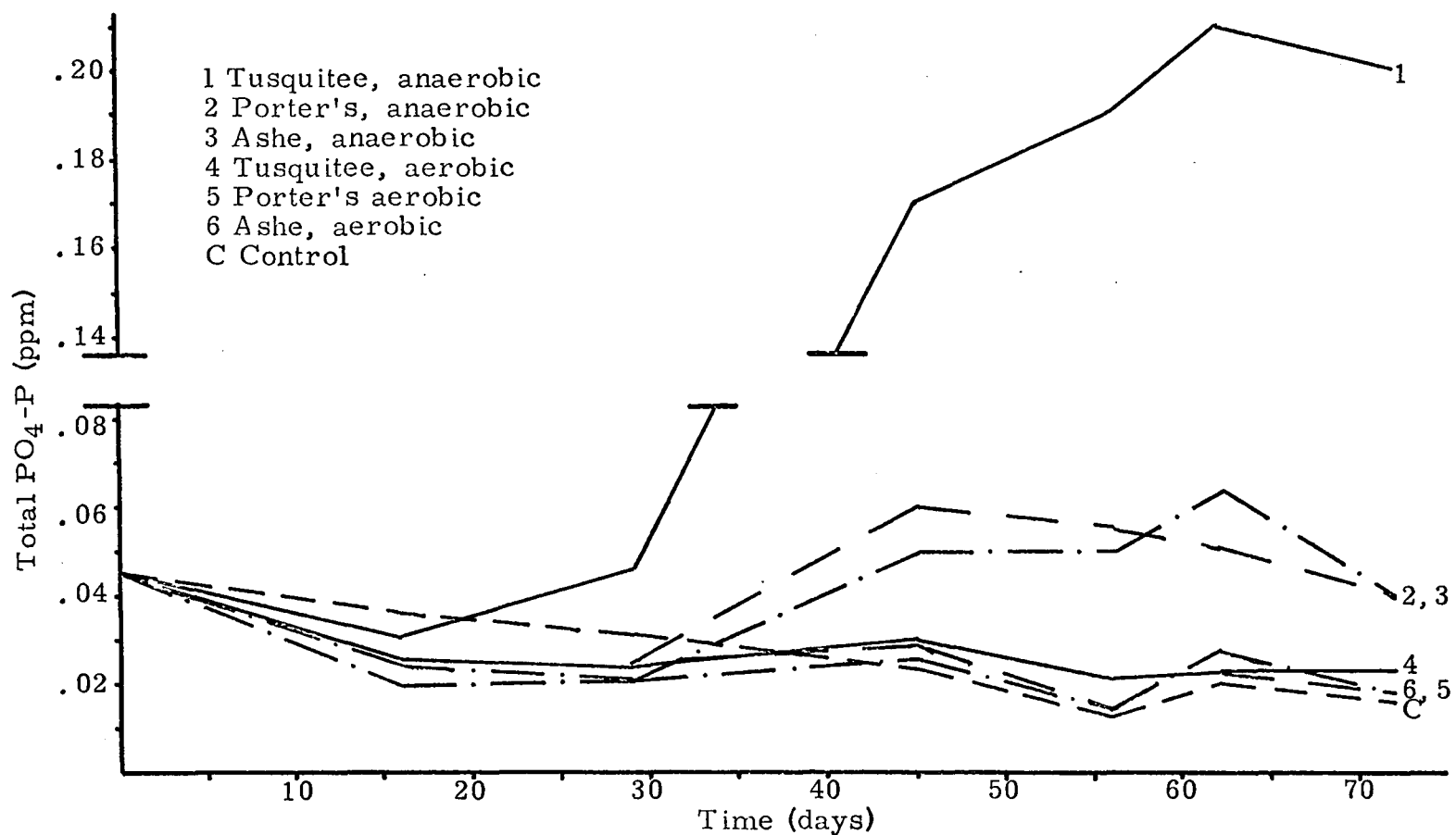


Fig. VI-5. Release of total PO₄-P from the 3 residual soils to be inundated by the proposed Blue Ridge Reservoirs.

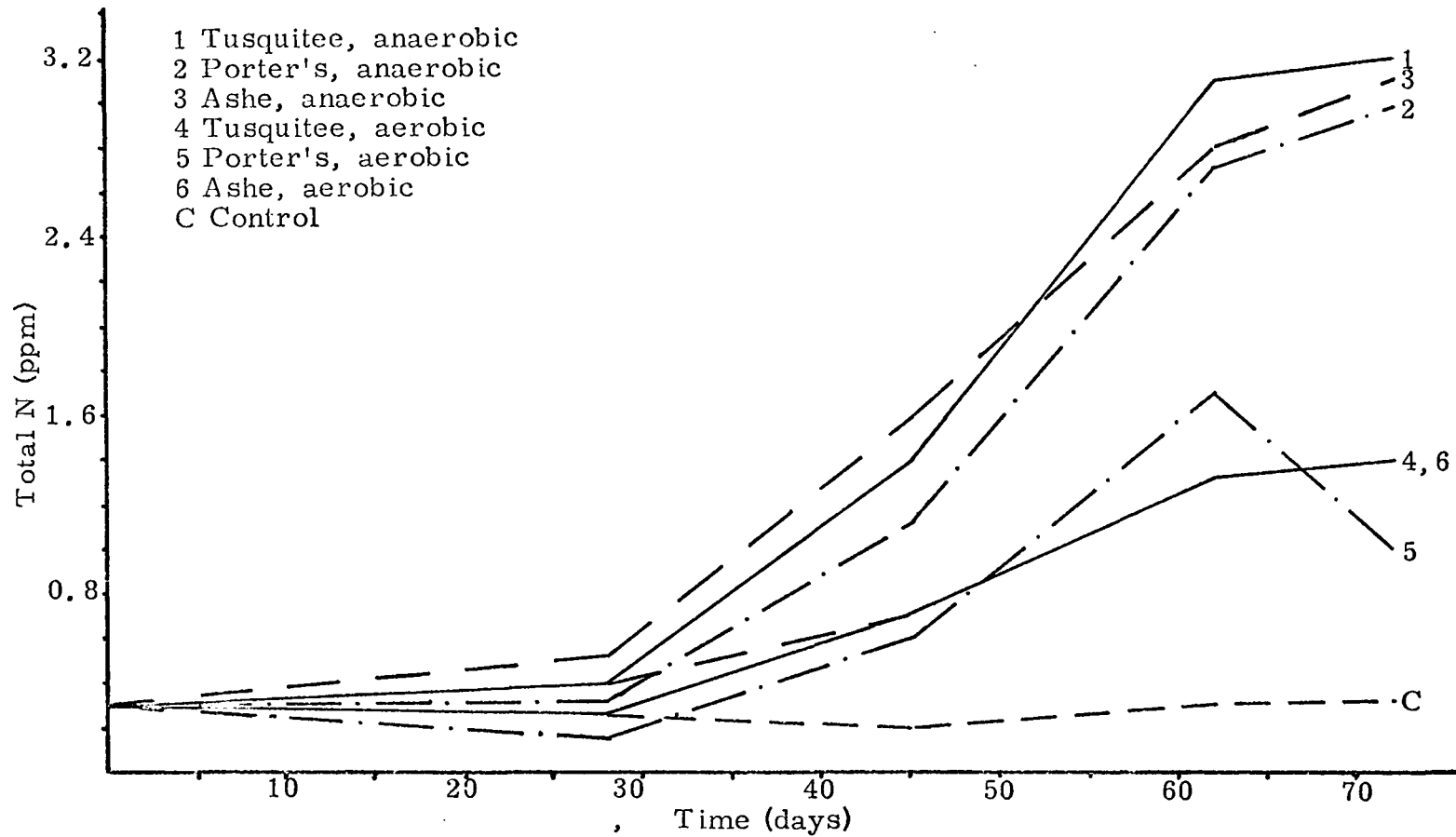


Fig. VI-6. Release of nitrogen from the 3 residual soils to be inundated by the proposed Blue Ridge Reservoirs.

Appendix D

Mean Operational Specifications for the Proposed Blue Ridge Reservoirs*

<u>Parameter</u>	<u>Symbol</u>	<u>Mean Value</u>
Drainage Area above lower dam site (km ²)	Ad	2878.
Lake Area (km ²)	Ao	139.5
Drainage Area: Lake Area Ratio		20.6
Volume (10 ⁶ m ³)	V	3270.
Depth (m)	Z	24.
Discharge (10 ⁶ m ³ yr ⁻¹)	Q	1620.
Flushing rate (yr ⁻¹) (= Q/V)	p	0.5
Areal loading (gm ⁻² yr ⁻¹)	L	see Table VI-13
Volumetric loading (gm ⁻³ yr ⁻¹)	L _v	see Table VI-13
Areal water load (m yr ⁻¹) (=Q/A.)	q _s	11.5
Hydraulic residence time (yr)		2.0
P retention coefficient	R	0.542
Drainage to reservoir following inundation (km ²)		1230.
Drainage to tributaries above sampling sites (km ²)		1484.

*All values were provided by Mr. J. C. Plunk, Supt. of Hydro Generation at the Appalachian Power Company, or were calculated from data provided by Mr. Plunk.

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CHEMICAL LIMNOLOGY, ALGAL GROWTH POTENTIAL, AND
NUTRIENT LIMITATION FACTORS OF THE UPPER NEW RIVER,
VIRGINIA, AND PREDICTIONS CONCERNING TROPHIC STATUS
FOR THE PROPOSED BLUE RIDGE RESERVOIRS

by

James Rhodes Wright, Jr.

(ABSTRACT)

Waters in the upper New River basin are well oxygenated, soft, bicarbonate poor, and relatively low in dissolved solids content. Water quality appears to be generally good, although concentrations of heavy metals present are often in excess of recommended water quality standards.

Algal growth potential tests performed on water from mainstream and tributary stations identified the waters in Peach Bottom Creek as having the greatest growth potential and indicated that P availability might control the potential productivity of water in the basin.

Nutrient limitation studies were conducted utilizing indigenous periphyton, indigenous plankton, and a selected, cultured organism (Selenastrum capricornutum). Uptake of ^{14}C by indigenous periphyton and phytoplankton was greatest in river water cultures enriched with phosphorus. Regardless of whether or not in situ primary productivity is nutrient limited in the upper New River, these experimental enrichment results suggest that P would become limiting if physical factors were optimized or if these

waters became impounded. Studies conducted on water from the 6 major tributaries to the proposed impoundments indicated that P was the primary nutrient factor limiting productivity in all tributaries except Peach Bottom Creek, where N was limiting. All waters in the basin containing a $\text{NO}_3\text{-N}$ to orthophosphate-P ratio of 8.5 or greater appear to be P limited. A multiple regression model was calculated to predict algal growth potential in these waters.

Impoundment of lotic waters often leads to a reduction in color, turbidity, BOD, and numbers of coliform bacteria. On the other hand, objectionable odors, higher levels of soluble Fe and Mn and loss of oxygen resources may result. Impoundments are often characterized by vertical stratification of O_2 , temperature, alkalinity, free CO_2 , pH, Fe, Mn, N, and P during different seasons of the year. As a result, the location of the penstocks can greatly influence downstream water quality during periods of stratification. Floral composition is drastically altered by impoundment, and often productivity is greatly increased. Algal blooms are common initially, and depending upon nutrient loading, may continue to occur or may subside within a few years.

If the proposed Blue Ridge Reservoirs are constructed, tributary streams inundated soils, surface runoff, and precipitation will contribute significant amounts of nitrogen and phosphorus. Based on projected inputs from these sources N and P budgets were calculated using 4 different models. Ten different

criteria were subsequently utilized to predict the trophic status of the proposed reservoirs. Indications are that the reservoirs will be mesotrophic or eutrophic, immediately following inundation and will remain in this state until N and P inputs are reduced.