



The chemical limnology and limnetic primary production of the Tongue River Reservoir, Montana
by Stephen Charles Whalen

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
in Botany

Montana State University

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Abstract:

The Tongue River Reservoir is a shallow, warmwater impoundment in southeastern Montana. Water stored in the reservoir is used primarily for irrigation, but recreational use of the reservoir is becoming increasingly popular. The Tongue River provides the only significant source of inflowing and outflowing surface water to and from the reservoir. The water chemistry and limnetic primary production of the reservoir system were studied from June 1975 through November 1976 to assess the early operational impact of surface coal mining activity on selected physical, chemical and biological parameters of the system. Data collected will also provide information against which future studies can be compared to detect any long-term changes resulting from continued and expanded mining activity.

The Tongue River Reservoir acted as a sediment trap for the in-flowing Tongue River. A thermal gradient and a density current were present in the reservoir from late May through most of June in 1976. However the reservoir was typically polymictic due to the deepwater penstock of the outflow structure. Although no thermal or chemical stratification was generally evident, a mild oxygen deficit developed in the bottom water late in the summers of 1975 and 1976. The Tongue River and Tongue River Reservoir waters were a calcium-magnesium bicarbonate-sulfate type. The annual surface nutrient loading rates of 4.1 g total-P.m⁻² and 22.0 g total-N.m⁻² were indicative of a hypereutrophic system. However, the water withdrawal characteristics, temporal nutrient loading pattern and flushing rate of 7.78.yr⁻¹ held the average phytoplankton standing crop to 8.91 cm³.m⁻² and the average photosynthetic rate to 0.77 g C.m⁻².day⁻¹. The typical algal standing crop was dominated by the Bacillariophyceae.

The dominant cation in the West Decker Mine discharge water was sodium while the most abundant anions were bicarbonate and sulfate. From June 1975 through November 1976 the mean percent contribution of the West Decker Mine discharge water to the Tongue River volume of flow was 0.09%; no change in river water quality was noted. The effluent discharged from three mines operating simultaneously should not significantly alter the water quality of the Tongue River or Tongue River Reservoir with respect to the parameters measured.

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OF THE TONGUE RIVER RESERVOIR, MONTANA

by

STEPHEN CHARLES WHALEN

A thesis submitted in partial fulfillment
of the requirements for the degree

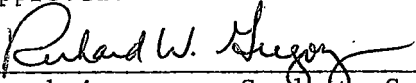
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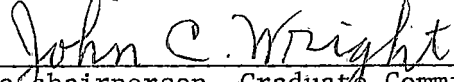
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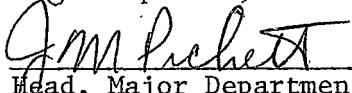
Approved:



Co-chairperson, Graduate Committee



Co-chairperson, Graduate Committee



Head, Major Department



Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

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TABLE OF CONTENTS

	Page
VITA.....	ii
ACKNOWLEDGMENTS.....	iii
TABLE OF CONTENTS.....	iv
LIST OF TABLES.....	vii
LIST OF FIGURES.....	x
ABSTRACT.....	xv
INTRODUCTION.....	1
DESCRIPTION OF THE STUDY AREA.....	6
METHODS AND MATERIALS.....	11
Inflow, Outflow, and Mine Discharge Waters.....	11
Temperature and Dissolved Oxygen.....	11
Specific Conductance, pH, and Alkalinity.....	12
Turbidity.....	13
Additional Water Chemistry.....	13
Reservoir.....	17
Light.....	18
Temperature and Dissolved Oxygen.....	18
Specific Conductance, pH, and Alkalinity.....	19
Turbidity.....	19
Additional Water Chemistry.....	19
Phytoplankton Standing Crop and Chlorophyll α	20
Phytoplankton Primary Production.....	22

	Page
Statistical Analyses.....	25
RESULTS AND DISCUSSION.....	26
Hydrology.....	26
Inflow and Outflow Waters.....	34
Turbidity.....	34
Temperature and Specific Conductance.....	36
Major Cations and Anions.....	38
pH.....	41
Nutrient Concentrations and Loads of the Inflowing and Outflowing Tongue River.....	44
Reservoir.....	58
Turbidity and Light.....	58
Temperature and Specific Conductance.....	61
Dissolved Oxygen and pH.....	66
Major Cations and Anions.....	70
Nutrients.....	75
Phytoplankton Standing Crop and Chlorophyll <i>a</i>	90
General Taxonomic Analysis.....	90
Horizontal Distribution.....	91
Class Composition of the Standing Crop.....	103
Seasonal Succession and Periodicity.....	105
Chlorophyll <i>a</i> and Cell Volume Relationships.....	122

	Page
Analysis of Factors Governing Standing Crop.....	124
Phytoplankton Primary Production.....	129
Evaluation of the Trophic Status of the Tongue River Reservoir.....	150
Mine Discharge.....	166
SUMMARY AND CONCLUSIONS.....	184
REFERENCES CITED.....	195

vii
LIST OF TABLES

	Page
Table 1. Morphometric data for the Tongue River Reservoir at maximum pool elevation.....	8
Table 2. Summary of hydrologic data for the Tongue River Reservoir during the calendar years 1975 and 1976.....	33
Table 3. Ranges and averages of some chemical and physical parameters of the inflow and outflow waters from November 1975 through November 1976.....	39
Table 4. Average seasonal distribution of cations and anions ($\text{me}\cdot\text{L}^{-1}$) in the inflow water from November 1975 through November 1976.....	42
Table 5. Average seasonal distribution of cations and anions ($\text{me}\cdot\text{L}^{-1}$) in the outflow water from November 1975 through November 1976.....	43
Table 6. A summary of the nitrogenous nutrient loads (kg of nitrogen) of the inflow and outflow waters from 15 November 1975 through 15 November 1976.....	56
Table 7. A summary of the phosphorus loads (kg of phosphorus) of the inflow and outflow waters from 15 November 1975 through 15 November 1976 and a comparison of molar ratios of some inorganic nutrients.....	56
Table 8. Monthly mean daily solar radiation ($\text{langley}\cdot\text{day}^{-1}$) from several sources compared with that recorded at the Tongue River Reservoir. Also, monthly mean extinction coefficients and monthly mean euphotic depths for the entire Tongue River Reservoir.....	62
Table 9. Ranges and averages of some chemical and physical parameters of the Tongue River Reservoir from November 1975 through November 1976.....	71

	page
Table 10. Average seasonal distribution of cations and anions ($\text{me}\cdot\text{L}^{-1}$) in the Tongue River Reservoir from November 1975-November 1976.....	73
Table 11. Phytoplankton species observed at all sampling stations in the Tongue River Reservoir from June 1975 through November 1976 with the corresponding mean volume of each organism.....	92
Table 12. A comparison of the areal class composition of the phytoplankton standing crops ($\text{cm}^3\cdot\text{m}^{-2}$) at three Tongue River Reservoir stations.....	104
Table 13. The Bray-Curtis Measure of Dissimilarity applied to the 1976 Tongue River Reservoir growing season standing crop data. Causative factors are indicated in parenthesis for values greater than 0.5.....	118
Table 14. Rank of the major phytoplankton taxa in the euphotic zone of the Tongue River Reservoir according to absolute mean cell volume ($\text{cm}^3\cdot\text{m}^{-2}$).....	119
Table 15. Rank of the major phytoplankton taxa in the euphotic zone of the Tongue River Reservoir according to frequency of occurrence (%).....	120
Table 16. Results of Spearman's Rank Correlation Test as applied between the 1976 growing season areal whole lake standing crop ($\text{cm}^3\cdot\text{m}^{-2}$) and several environmental parameters of the Tongue River Reservoir.....	128
Table 17. Results of Spearman's Rank Correlation Test as applied between <i>in situ</i> ^{14}C determined assimilation ratios ($\text{g C}\cdot\text{g Chl}\text{a}\cdot\text{hr}^{-1}$) and several environmental parameters.....	135

	Page
Table 18. A statistical analysis (Paired t -tests) of several mean estimates of photosynthetic production ($\text{gC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) at Station 2 of the Tongue River Reservoir.....	142
Table 19. A comparison of two estimates of photosynthetic production ($\text{g C}\cdot\text{m}^{-2}$) at Station 2 of the Tongue River Reservoir from November 1975 through November 1976.....	143
Table 20. A summary of the means of several parameters measured in the Tongue River and Tongue River Reservoir from November 1975 through November 1976.....	152
Table 21. An analysis of the seasonal loading patterns of inorganic and organic nutrients in the inflow and outflow waters.....	162
Table 22. The calculated and measured effects of the mine discharge upon the Tongue River with respect to several parameters.....	171
Table 23. Contribution of the mine discharge to the Tongue River flow rate from June 1975 through November 1976.....	174
Table 24. Calculated chemical influence of mean monthly mine discharge on mean monthly Tongue River Flow.....	176
Table 25. Calculated chemical influence of maximum predicted flow of highly mineralized mine effluent on average Tongue River Flow.....	179
Table 26. Calculated chemical influence of maximum predicted flow of highly mineralized mine effluent on minimum Tongue River Flow.....	180
Table 27. Average values of selected parameters measured in the mine discharge water and in the Tongue River above and below the site of discharge from June 1975 through November 1976.....	182

x
LIST OF FIGURES

	Page
Figure 1. Location map.....	2
Figure 2. Map of the Tongue River Reservoir detailing the study area.....	3
Figure 3. Mean water discharge rates ($m^3 \cdot sec^{-1}$) of the Tongue River Reservoir inflow and outflow waters.....	29
Figure 4. Pool elevation and storage capacity of the Tongue River Reservoir in 1975 and 1976.....	31
Figure 5. Water storage history of the Tongue River Reservoir from 1956 through 1977.....	32
Figure 6. Turbidity of the inflow and outflow waters of the Tongue River Reservoir versus the inflow rate.....	35
Figure 7. Annual temperature regime of the inflow and outflow waters of the Tongue River Reservoir..	37
Figure 8. Annual specific conductance regime of the inflow and outflow waters of the Tongue River Reservoir.....	37
Figure 9. Seasonal concentrations of inorganic and organic nitrogen in the inflow.....	45
Figure 10. Seasonal concentrations of orthophosphorus and organic + hydrolyzable phosphorus in the in- flow.....	45
Figure 11. Seasonal concentrations of inorganic and organic nitrogen in the outflow.....	49
Figure 12. Seasonal concentrations of orthophosphorus and organic + hydrolyzable phosphorus in the outflow.....	49

	Page
Figure 13. Seasonal loads of inorganic nitrogen ($\text{NO}_2 + \text{NO}_3 + \text{NH}_3\text{-N}$) and inorganic phosphorus ($\text{PO}_4\text{-P}$) carried by the inflow and outflow waters.....	52
Figure 14. Seasonal loads of organic nitrogen and organic + hydrolyzable phosphorus carried by the inflow and outflow waters.....	54
Figure 15. Average turbidity profiles in the Tongue River Reservoir from June 1975 through November 1976	60
Figure 16. Penetration of total visible light, mean extinction coefficients (k) and euphotic zone depths in the Tongue River Reservoir from 6/75 - 11/76.....	60
Figure 17. Seasonal isotherms ($^{\circ}\text{C}$) in the Tongue River Reservoir.....	64
Figure 18. Seasonal conductivity ($\mu\text{mhos}\cdot\text{cm}^{-1}$) isoclines in the Tongue River Reservoir.....	64
Figure 19. Seasonal dissolved oxygen ($\text{mg}\cdot\text{L}^{-1}$) isopleths in the Tongue River Reservoir.....	68
Figure 20. Seasonal oxygen saturation (%) isopleths in the Tongue River Reservoir.....	68
Figure 21. Seasonal pH isopleths in the Tongue River Reservoir.....	74
Figure 22. Seasonal total alkalinity ($\text{me}\cdot\text{L}^{-1}$) profiles in the Tongue River Reservoir on selected dates.....	74
Figure 23. Seasonal $\text{NO}_3\text{-N}$ ($\mu\text{g}\cdot\text{L}^{-1}$) isopleths in the Tongue River Reservoir.....	76
Figure 24. Seasonal $\text{NH}_3\text{-N}$ ($\mu\text{g}\cdot\text{L}^{-1}$) isopleths in the Tongue River Reservoir.....	76

	Page
Figure 25. Seasonal PO ₄ -P (µg·L ⁻¹) isopleths in the Tongue River Reservoir.....	80
Figure 26. Seasonal total -P (µg·L ⁻¹) isopleths in the Tongue River Reservoir.....	80
Figure 27. Variation in chemical composition of water overlying sediment in the Tongue River Reservoir during the summers of 1975 and 1976.....	84
Figure 28. Seasonal storage of inorganic nitrogen, orthophosphorus, and organic + hydrolyzable phosphorus in the Tongue River Reservoir.....	88
Figure 29. Seasonal variations in the volumetric phytoplankton standing crop and chlorophyll <i>a</i> concentration at three Tongue River Reservoir sampling sites.....	98
Figure 30. Seasonal variations in the areal phytoplankton standing crop and chlorophyll <i>a</i> concentration at three Tongue River Reservoir sampling sites.....	100
Figure 31. Seasonal variations in class composition of the phytoplankton standing crop at Station 2 in the Tongue River Reservoir.....	107
Figure 32. Seasonal variation and successional pattern of phytoplankton at Station 2 in the Tongue River Reservoir.....	108
Figure 33. Seasonal succession of <i>Aphanizomenon flos-aqua</i> and <i>Glenodinium gymmodinium</i> in 1976 at three sampling sites in the Tongue River Reservoir..	115
Figure 34. Mean relative standing crops of the five major phytoplankton species in the Tongue River Reservoir during the 1976 growing season plotted against the absolute areal phytoplankton standing crop.....	121

	Page
Figure 35. Seasonal euphotic zone phytoplankton chlorophyll <i>a</i> /cell volume ratios in the Tongue River Reservoir.....	123
Figure 36. Regression line correlating euphotic zone phytoplankton cell volumes and euphotic zone chlorophyll <i>a</i> concentrations in the Tongue River Reservoir during the 1976 growing season.....	125
Figure 37. Differences in day rate estimates of photosynthesis at Station 2 in the Tongue River Reservoir as estimated by the ¹⁴ C technique and the method of Ryther and Yentsch (1957)...	132
Figure 38. Regression line correlating <i>in situ</i> derived assimilation ratios and euphotic zone temperatures at Station 2 in the Tongue River Reservoir from November 1975 through November 1976.....	136
Figure 39. Regression line correlating theoretical assimilation ratios (based on ¹⁴ C estimates of diel photosynthesis) with euphotic zone temperatures at Station 2 in the Tongue River Reservoir from November 1975 through November 1976.	139
Figure 40. Comparisons of ¹⁴ C estimates of diel photosynthesis with estimates obtained by two modifications of the Ryther and Yentsch (1957) formula. Modifications incorporate a temperature dependent assimilation ratio.....	140
Figure 41. A. Comparison of estimates of day rate photosynthesis at Station 2. Estimates were obtained by the ¹⁴ C method and by a modified Ryther and Yentsch (1957) formula. B. Diel photosynthesis at three Tongue River Reservoir sampling sites during the growing season of 1976 as estimated by Equation 2.....	144

	page
Figure 42. Vollenweider's (1970) model for the trophic classification of lakes based on annual surface loading of total phosphorus as a function of mean depth.....	154
Figure 43. Vollenweider's (1970) model for the trophic classification of lakes based on annual surface loading of total nitrogen as a function of mean depth.....	155
Figure 44. Schematic representation of the origin and fate of the West Decker Mine discharge water.....	168
Figure 45. Ionic polygonic diagrams of the mean relative concentrations in equivalent percentages of the major cations and anions at several sampling sites. The number in parenthesis represents the sum of the cations ($\text{me}\cdot\text{L}^{-1}$).....	169
Figure 46. Ammonia and nitrate concentrations in the mine discharge water from June 1975 through November 1976.....	172

ABSTRACT

The Tongue River Reservoir is a shallow, warmwater impoundment in southeastern Montana. Water stored in the reservoir is used primarily for irrigation, but recreational use of the reservoir is becoming increasingly popular. The Tongue River provides the only significant source of inflowing and outflowing surface water to and from the reservoir. The water chemistry and limnetic primary production of the reservoir system were studied from June 1975 through November 1976 to assess the early operational impact of surface coal mining activity on selected physical, chemical and biological parameters of the system. Data collected will also provide information against which future studies can be compared to detect any long-term changes resulting from continued and expanded mining activity.

The Tongue River Reservoir acted as a sediment trap for the inflowing Tongue River. A thermal gradient and a density current were present in the reservoir from late May through most of June in 1976. However the reservoir was typically polymictic due to the deepwater penstock of the outflow structure. Although no thermal or chemical stratification was generally evident, a mild oxygen deficit developed in the bottom water late in the summers of 1975 and 1976. The Tongue River and Tongue River Reservoir waters were a calcium-magnesium bicarbonate-sulfate type. The annual surface nutrient loading rates of $4.1 \text{ g total-P}\cdot\text{m}^{-2}$ and $22.0 \text{ g total-N}\cdot\text{m}^{-2}$ were indicative of a hypereutrophic system. However, the water withdrawal characteristics, temporal nutrient loading pattern and flushing rate of $7.78\cdot\text{yr}^{-1}$ held the average phytoplankton standing crop to $8.91 \text{ cm}^3\cdot\text{m}^{-2}$ and the average photosynthetic rate to $0.77 \text{ g C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. The typical algal standing crop was dominated by the Bacillariophyceae.

The dominant cation in the West Decker Mine discharge water was sodium while the most abundant anions were bicarbonate and sulfate. From June 1975 through November 1976 the mean percent contribution of the West Decker Mine discharge water to the Tongue River volume of flow was 0.09%; no change in river water quality was noted. The effluent discharged from three mines operating simultaneously should not significantly alter the water quality of the Tongue River or Tongue River Reservoir with respect to the parameters measured.

INTRODUCTION

The surface mining of coal has become an increasingly important industry in the Northern Great Plains and adjacent western states in recent years. Because the mining and combustion of fossil fuels will be essential to meet the nation's projected energy needs, future exploitation of the largely untapped coal reserves underlying this region is certain.

In the past, considerable effort has been directed toward the documentation of the ecological impact of strip mining operations on the aquatic and terrestrial resources of the eastern United States. However, the effects of surface coal mining on the semi-arid environment of the western United States are not well defined.

The Tongue River Reservoir is located near Decker, Montana, just north of the Montana-Wyoming border (Figure 1). In the summer of 1972 an open pit coal mining operation was initiated on the southwest side of the reservoir (Figure 2) by the Decker Coal Company, a subsidiary of Peter Kiewit Sons' Company. In the summer of 1977 a second mine was started on the southeast shore of the reservoir, and a future northward extension of the West Decker site is planned (Figure 2). Present mining operations at the West Decker Mine are discharging wastewater into the Tongue River immediately above the Tongue River Reservoir. When in full operation, all three mine sites will discharge effluent, either directly or indirectly, into the Tongue River

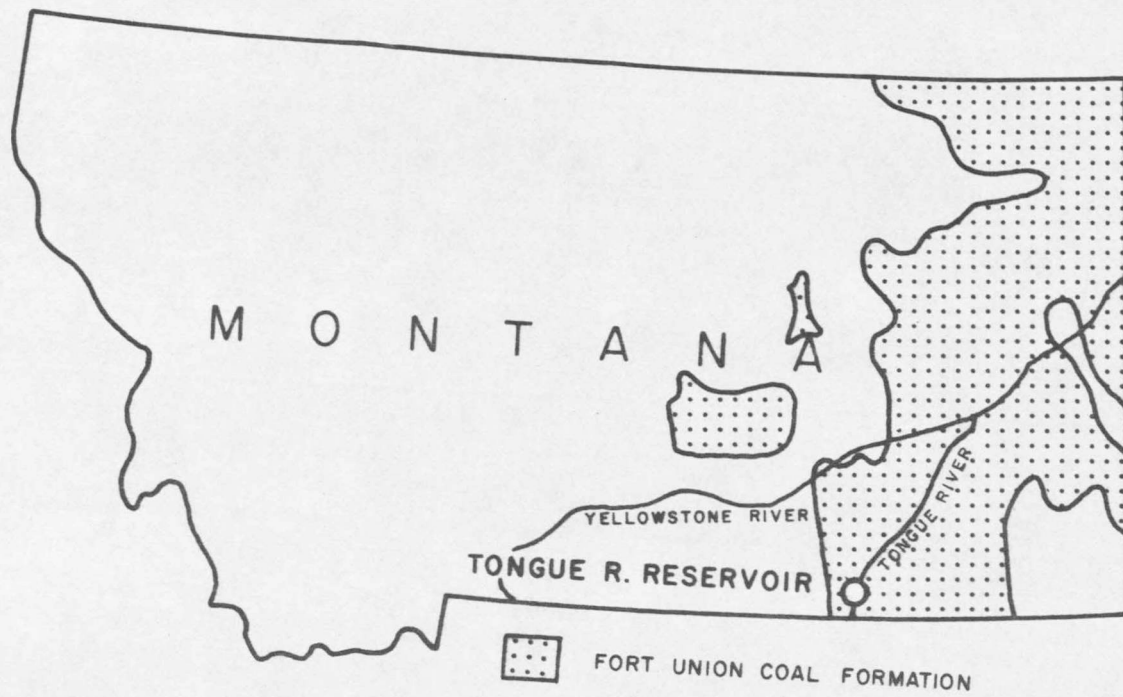


Figure 1. Location map.

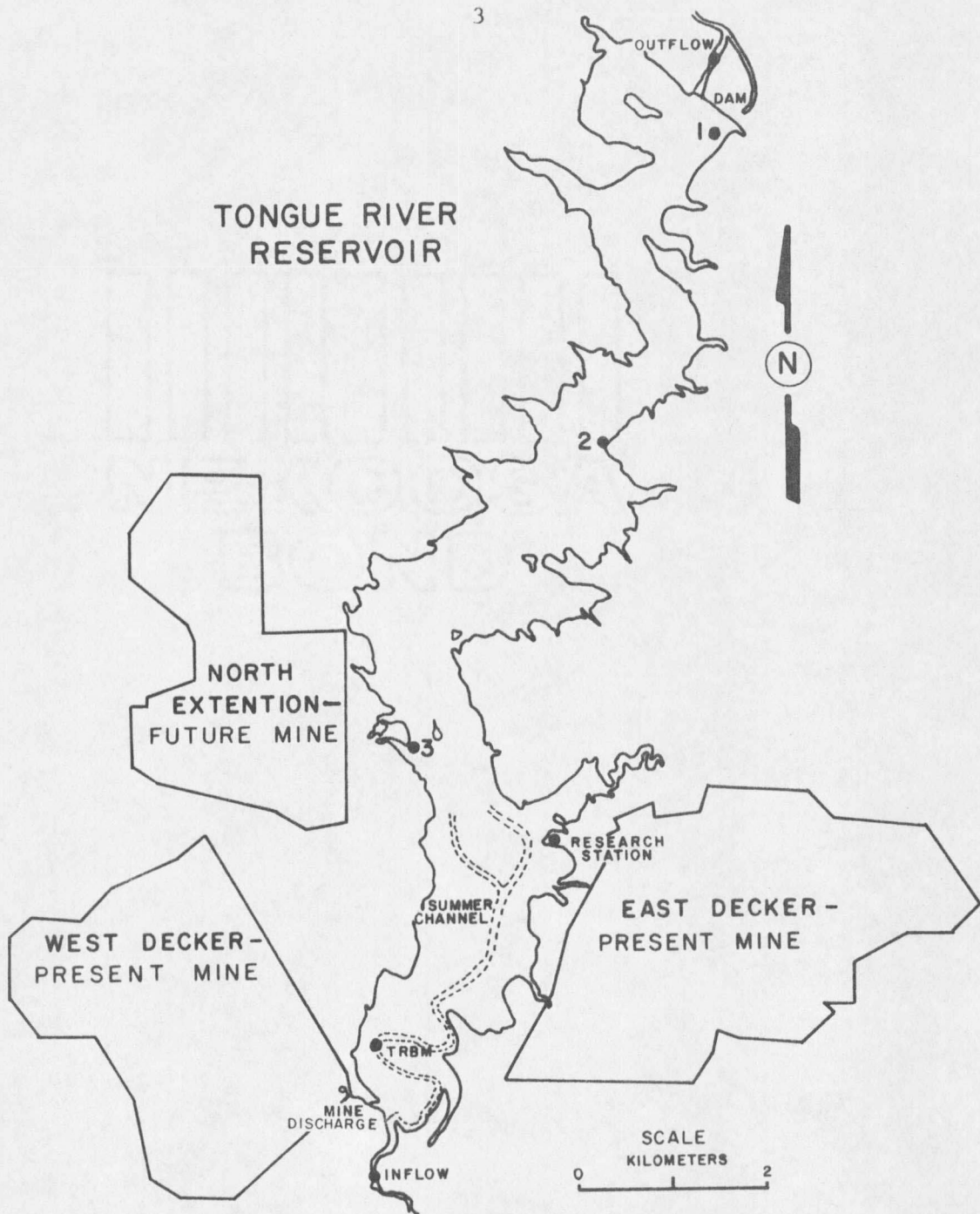


Figure 2. Map of the Tongue River Reservoir detailing the study area.

Reservoir.

In April 1975 the Montana Cooperative Fishery Research Unit initiated a program that included several detailed studies encompassing numerous aspects of the aquatic resources of the Tongue River and Tongue River Reservoir. The objective of this program is to assess the early operational impact of mining activity on selected physical, chemical and biological parameters of the river-reservoir system. Biological and chemical data are being secured to provide information against which future studies may be compared to detect any long-term changes resulting from continued and expanded mining activity. As part of the Tongue River Reservoir research program, the present study was conducted from June 1975 through November 1976 with the following specific goals:

(1) To relate the chemical, physical and hydrologic characteristics of the Tongue River-Tongue River Reservoir system and to define their effects on the limnological status of the reservoir. This goal includes; (a) characterization of the common anions and cations of the river and reservoir, (b) determination of the nutrient (nitrogen and phosphorus) loads of the Tongue River flowing in and out of the Tongue River Reservoir, (c) delimitation of the storage of these nutrients within the reservoir, (d) determination of factors affecting the fate of various forms of nutrients within the reservoir.

(2) To identify phytoplankton species present in the reservoir, to follow seasonal changes in the phytoplankton standing crop, and to examine factors affecting the size, species composition and primary productivity of the standing crop.

(3) To make a general assessment of the trophic status of the reservoir.

(4) To characterize the chemical nature of the West Decker Mine effluent water discharged into the Tongue River immediately above the reservoir, and to determine the immediate impact of this effluent, on the chemical limnology of the river and reservoir.

(5) To predict possible long-term effects of continued and expanded mining on the ecology of the Tongue River Reservoir.

DESCRIPTION OF THE STUDY AREA

The Tongue River Reservoir is formed from impoundment of the Tongue River by the Tongue River Dam which is located at lat. $45^{\circ}08'29''$, long. $106^{\circ}45'15''$, in NE 1/4 Sec. 13, T. 8 S., R. 40 E. in Big Horn County, Montana, approximately 32 km (20 mi) north of Sheridan, Wyoming. The Tongue River originates in the Big Horn Mountains of Wyoming and flows northeasterly for 105 river kilometers (65 mi) until reaching the Tongue River Reservoir. The drainage area above the reservoir encompasses 4584 km^2 or 1770 mi^2 (U.S.G.S., 1977). The principal soils of the drainage area are sandy loam to clay loam, underlain by a bedrock of clay, shale, sandstone with coal, and limestone. The river continues for 270 kilometers (168 mi) beyond the reservoir to its confluence with the Yellowstone River at Miles City, Montana.

The Tongue River Reservoir was formed by an earthfill dam completed in May, 1939. The dam is owned by the Montana Department of Natural Resources and Conservation, but is operated by the Tongue River Water Users' Association. The Tongue River Dam was initially constructed for flood control and irrigation purposes, but water impounded by the structure provides recreational benefits as well. The reservoir had an estimated initial storage capacity of 894×10^5

m^3 or 72,450 acre-ft (Dendy and Champion, 1973). Based on calculated sedimentation rates, the 1975 usable capacity was estimated by U.S.G.S. and the Montana Department of State Lands (1977) to be $740 \times 10^5 m^3$ (60,000 acre-ft) between elevation 1028.5 m (3,374.4 ft) at the bottom of the outlet and elevation 1043.7 m (3,424.4 ft) at the spillway crest. Dead storage is $17.3 \times 10^5 m^3$ (1400 acre-ft) below elevation 1028.5 m (Mt. Dept. Nat. Res. and Cons., unpublished data).

The maximum reservoir depth is 18 m (59 ft) at storage capacity. At the maximum pool elevation the reservoir has an average depth of 5.9 m (19.5 ft), a maximum length of 12.5 km (7.8 mi) and a maximum breadth of 1.4 km (0.9 mi). Morphometric data for the Tongue River Reservoir is found in Table 1.

The Tongue River is the only significant source of inflowing and outflowing water to the Tongue River Reservoir, although several ephemeral streams make a minor contribution during spring runoff. The flow of the Tongue River above the reservoir is regulated by several small reservoirs in Wyoming with a combined storage capacity of $185 \times 10^5 m^3$ (15,000 acre-ft). There are diversions for irrigation of about $260 km^2$ (64,300 acres) between the headwaters in the Big Horn Mountains of Wyoming and the Tongue River Reservoir (U.S.G.S., 1977). The rate of release of water held by the reservoir is regulated at the outflow structure in response to spring runoff and

Table 1. Morphometric data for the Tonguè River Reservoir at maximum pool elevation (1043.7 m).¹

Maximum depth ²	18.0 m (59.1 ft)
Mean depth	5.9 m (19.5 ft)
Depth of outlet ³	15.2 m (49.9 ft)
Maximum length ²	12.5 km (7.8 mi)
Maximum breadth ²	1.4 km (0.9 mi)
Surface area ³	1277 ha (3156 acres)
Usable capacity ⁴	$740 \times 10^5 \text{ m}^3$ (6.0×10^4 acre-ft)
Volume ⁵	$757 \times 10^5 \text{ m}^3$ (6.14×10^4 acre-ft)
Length of shoreline ³	60 km (37.3 mi)
Shoreline development ³	4.74

¹ Definition and discussion of these parameters can be found in Ried and Wood (1976) or Welch (1948).

² Garrison, *et al.* (1975).

³ Penkal (1976).

⁴ U.S.G.S. and Mt. Dept. of State Lands (1977).

⁵ Usable capacity and dead storage volume.

summer irrigation needs. At times when exceptionally large volumes of spring runoff enter the reservoir, excess water is discharged from the spillway at the crest of the dam. Annually, the rate of runoff from the reservoir's watershed (and hence the rate of flow of the Tongue River to the reservoir) peaks in May and June. The lowest rates of flow of the Tongue River above the reservoir are typically encountered in the winter months. River gaging stations are maintained by the United States Geological Survey at about 4 km upstream from the reservoir (Tongue River at state line, near Decker) and at about 2 km downstream from the spillway structure (Tongue River at Tongue River Dam, near Decker) to monitor inflowing and outflowing water discharges.

A total of seven permanent sampling stations were established, three of which were located within the Tongue River Reservoir (Figure 2). The reservoir stations were referred to as Station 1 (located at the north end of the reservoir, 0.4 km from the dam), Station 2 (mid-reservoir station, 4.3 km south of the dam) and Station 3. Station 3 was mobile to accommodate fluctuations of reservoir stage in the late fall. For the month of October it was necessary to move Station 3 approximately one kilometer north to facilitate sampling.

An additional sampling site was located at the east end of a culvert which passes beneath Montana Highway 314. This sampling

station was named "Mine Discharge". Water collected at the Mine Discharge station was a combination of water pumped from disturbed ground water aquifers at the West Decker Mine and leachate through disturbed overburden at that mine site. The Mine Discharge effluent was collected in a settling pond and summarily discharged into the Tongue River via the Tongue River flood plain. Two permanent sampling stations were situated on the Tongue River above the Tongue River Reservoir. One station (Inflow) was located at the county bridge on the county road running northeast off Montana Highway 314. This site was approximately two kilometers south of the Tongue River Reservoir and was situated above the Mine Discharge station. The other sampling site was established on the inflowing Tongue River below the Mine Discharge station and was designated "TRBM" (Tongue River Below Mine). The single sampling location on the Tongue River below the Tongue River Reservoir (Outflow) was located about 0.5 km north of the spillway. All four non-reservoir sampling sites described above can be located in Figure 2.

METHODS AND MATERIALS

Inflow, Outflow and Mine Discharge Waters

Water samples were collected twice monthly from all previously described non-reservoir stations during the 17 June - 14 November 1975 and the 16 April - 21 November 1976 periods. In addition, samples were taken at monthly intervals from December, 1975 through March, 1976.

All samples were obtained by either lowering a rinsed 8-liter polyethylene bucket into the water or by directly filling sample containers with the water to be analyzed. Water was extracted from the main current when collecting river water samples regardless of the method used in procuring the sample. Four glass stoppered Pyrex bottles (1 each, 500-ml, 300-ml, 250-ml and 125-ml) and one 100-ml screw cap polyethylene bottle were filled with water from each station. All sample bottles were rinsed with deionized, distilled water in the laboratory, and with river water prior to sample collection.

Temperature and Dissolved Oxygen

Temperature and dissolved oxygen determinations were made immediately following sample collection on water in the 300-ml BOD bottle. The temperature of the water sample was taken with an E.H. Sargent & Co. -10° to 100°C mercury thermometer. Alternatively, a Yellow Springs Instrument Co., Inc. YSI Model 54 Dissolved Oxygen Meter equipped with a thermistor probe was used.

The dissolved oxygen concentration of the water sample was analyzed with the previously mentioned YSI Model 54 Dissolved Oxygen Meter. Prior to each sampling session the instrument was calibrated against a dissolved oxygen determination by the Alsterberg Azide Modification of the Winkler Method (APHA, 1971). The dissolved oxygen concentration is reported as $\text{mg O}_2 \cdot \text{L}^{-1}$.

Specific Conductance, pH and Alkalinity

The specific conductance of the water sample was measured at a frequency of 60 cps with a Yellow Springs Instrument Co., Inc. Model 31 AC conductivity bridge equipped with a Yellow Springs Instrument Co. Model 3401 dipping cell. Samples of high electrical conductivity were measured at a frequency of 1 KC. Specific conductance is reported as $\mu\text{mhos} \cdot \text{cm}^{-1}$ @ 25°C.

The hydrogen ion concentration was determined with a Beckman Model 76 Expanded Scale pH Meter equipped with a Corning Triple Purpose pH Electrode, a Corning Calomel Reference Electrode and a Beckman Model 76 and 96 Thermocompensator.

The alkalinity of each sample was determined potentiometrically (APHA, 1971) using 0.1 N standard H_2SO_4 as a titrant. A pH of 8.3 was chosen as the carbonate endpoint and pH 4.5 was selected as the bicarbonate endpoint. Total alkalinity is expressed as $\text{mg} \cdot \text{L}^{-1} \text{CaCO}_3$. Alkalinity and pH measurements were taken within a few hours of

sample collection.

Turbidity

The turbidity of each sample was determined using a Hach Laboratory Turbidimeter (Model 2100) and is reported as Standard Jackson Turbidity Units (JTU). Unfiltered water from the 250-ml glass stoppered bottle was used for the analyses of turbidity, specific conductance, pH and alkalinity.

Additional Water Chemistry

Sample preparation. At the laboratory most of the water in the 500-ml glass bottles was filtered through Millipore^R membrane filters with a pore size of 0.45 microns. This water was used for the following analyses: soluble inorganic phosphorus, nitrate, nitrite, ammonia, silica, calcium, magnesium, sodium, potassium, sulfate, fluoride, chloride and soluble iron. Unfiltered water from the 125-ml glass bottles was used for the analysis of Kjeldahl nitrogen and unfiltered, acidified samples collected in the 100-ml polyethylene vials were analyzed for organic carbon content. Total phosphorus determinations were made on the unfiltered portion of water reserved from the 500-ml glass bottle.

Phosphorus. Total phosphorus and soluble inorganic phosphorus concentrations were determined using the Single Reagent Method described by the Environmental Protection Agency (1971). Soluble

inorganic phosphorus was defined as that measured by direct colorimetric analysis on a filtered sample. Soluble inorganic phosphorus was referred to as orthophosphorus ($\text{PO}_4\text{-P}$) or inorganic phosphorus, although, strictly speaking, inorganic phosphorus should include polyphosphates that would have been trapped by the 0.45μ filter. Total phosphorus included all forms present in an unfiltered sample as measured by acid persulfate digestion followed by direct colorimetric analysis. Total phosphorus included soluble inorganic phosphorus, acid hydrolyzable phosphorus (inorganic polyphosphates and some organic phosphorus) and all oxidizable organic phosphorus. $\text{Org.-P} + \text{hydro.-P}$ was calculated as the difference between total phosphorus and soluble inorganic phosphorus and included all acid hydrolyzable and organic phosphorus of the unfiltered sample. Phosphorus concentrations are reported as $\mu\text{g P}\cdot\text{L}^{-1}$.

Nitrogen. The nitrite concentration was determined using Hach Chemical Company's NitriVer^R reagent. The method of Mullen and Riley as described by Barnes (1959) was used in the analysis of nitrate. The ammonia concentration was determined by the direct procedure outlined by Strickland and Parsons (1972). This technique proves satisfactory when concentrations of amino acids are low. Because the ammonia and nitrate tests include nitrite in the analyses, appropriate corrections were made to report the true nitrate and ammonia concentrations. Total

soluble inorganic nitrogen was referred to as inorganic nitrogen and included soluble $\text{NO}_3\text{-N} + \text{NO}_2\text{-N} + \text{NH}_3\text{-N}$.

An additional nitrogen test was performed on unfiltered water by Kjeldahl digestion (Strickland and Parsons, 1972). Total Kjeldahl nitrogen (TKN) was defined as the sum of the free ammonia and organic nitrogen compounds which were converted to ammonium sulfate by acid digestion. The ammonia test described above was used to measure TKN following digestion, hence the nitrite concentration was also included in the analysis. Total nitrogen was calculated as the sum of the nitrogenous forms determined by Kjeldahl digestion plus nitrate. Total nitrogen included total soluble inorganic nitrogen, as well as dissolved and particulate organic nitrogen. Organic nitrogen (Org.-N) was computed as the difference between total nitrogen and soluble inorganic nitrogen and included dissolved and particulate forms. All nitrogenous species are reported as $\mu\text{g. N}\cdot\text{L}^{-1}$.

Major cations. Measurements of calcium and magnesium concentrations were made using atomic absorption spectrophotometry with an Instrumentation Laboratory Inc. Model IL 151 Atomic Absorption-Flame Emission Spectrophotometer.

Sodium and potassium determinations were made using flame emission spectrophotometry and the previously mentioned instrumentation. Procedures followed are outlined by APHA (1971) and the IL Instruction

Manual. All cation concentrations are reported as $\text{mg}\cdot\text{L}^{-1}$.

Major anions. The Turbidimetric Method (APHA, 1971), utilizing Hach Chemical Company's SulfaVer^R IV, was employed to measure the sulfate concentration.

Chloride was determined titrimetrically by the Mercuric Nitrate Method (APHA, 1971) utilizing Hach Chemical Company's standard 0.0141 N mercuric nitrate as the titrant and diphenylcarbazone indicator-buffer.

The fluoride concentration was measured by the SPANS Method (APHA, 1971) utilizing Hach Chemical Company's acid zirconyl SPANS reagent.

Methodology in determination of the carbonate and bicarbonate concentrations has been previously described. All anions are reported as $\text{mg}\cdot\text{L}^{-1}$.

Silica. The silica concentration was detected using the Colorimetric Molybdosilicate Method (APHA, 1971). Results are expressed as $\text{mg SiO}_2\cdot\text{L}^{-1}$.

Organic carbon. The organic carbon content was determined by feeding an acidified, unfiltered sample into a Beckman Model IR 315 Infrared Carbonaceous Analyzer. Concentrations are reported as $\text{mg C}\cdot\text{L}^{-1}$.

Iron. Soluble iron was measured using Hach Chemical Company's FerroZine^R solution. Results are expressed as $\text{mg Fe}\cdot\text{L}^{-1}$.

Silica, sulfate and all nutrients except nitrite were analyzed with a Klett Summerson Model 900-3 Photoelectric Colorimeter with the proper filters. Analyses of sample waters were compared to standards of known concentration of the particular parameter being measured. Analyses of iron, fluoride, chloride and nitrite were performed with a Bausch and Lomb Spectronic 20 Colorimeter.

Tests for all nutrients except Kjeldahl nitrogen were performed within 12 hours of sample collection. The determination of fluoride, chloride, sulfate, soluble iron and silica concentrations was completed within 24 hours of sample collection. Analyses for calcium, magnesium, sodium, potassium, organic carbon and Kjeldahl nitrogen were performed within 96 hours of sample collection.

Water was collected at each station on each sampling date and all of the above described physical and chemical tests were performed on each sample.

Reservoir

All samples and *in situ* measurements were taken twice monthly during the periods of 17 June - 14 November 1975 and 16 April - 21 November 1976. Additionally, samples were collected at monthly intervals from December, 1975 through March, 1976 at Station 2.

Light

A vertical profile of light attenuation at each reservoir station on each sampling date was obtained by measuring the *in situ* light intensity with a Kahl Submarine Photometer. Light intensity was recorded at the surface and at 1-meter intervals to the depth at which 1% of the incident radiation penetrated.

Ruttner (1963) defined the compensation point as the depth at which assimilation was equal to dissimilation. At that point algal respiration was balanced by photosynthetic production. Verduin (1964) stated that the compensation depth was set at the depth to which 1% of the incident light penetrated. Therefore, the depth of 1% incident light penetration defined the lower limit of the euphotic zone.

The mean vertical extinction coefficient (m^{-1}) was computed as a measure of transparency of the euphotic zone at each station, on each sampling date, according to the formula of Hutchinson (1957).

Temperature and Dissolved Oxygen

Temperature and dissolved oxygen determinations were made using previously mentioned equipment. A 5-liter Van Dorn bottle was employed to obtain water samples at depth for these analyses. If a dissolved oxygen concentration proved to be $<2 \text{ mg } O_2 \cdot L^{-1}$ at a given depth, a BOD Sewage Sampler was used to obtain water at that depth and a Winkler titration was performed to verify the results. Temperature

and dissolved oxygen concentrations were measured at the water surface and at 1-meter intervals through the euphotic zone. Through the aphotic zone, water samples were collected at 2-meter intervals for dissolved oxygen and temperature determinations.

Specific Conductance, pH and Alkalinity

Previously discussed materials and methods were used for the measurements of specific conductance, pH and alkalinity. The vertical sampling scheme mentioned above for temperature and dissolved oxygen was followed relative to pH and alkalinity determinations. Specific conductance was measured at 2-meter intervals from the surface to the bottom of the water column.

Turbidity

Turbidity determinations were made at 2-meter intervals through the water column using previously mentioned methodology.

Additional Water Chemistry

All water samples were collected with a 5-liter Van Dorn bottle at 2-meter intervals from the surface to the bottom of the reservoir. Chemical parameters analyzed included all those tested on non-reservoir waters with the exception of the Kjeldahl nitrogen test. All methods and procedures were as previously delineated.

Timing relative to collection and subsequent analysis of samples was similar to that of non-reservoir waters. Water was collected in

the prescribed manner at each reservoir station on each sampling date (except where previously noted) and all of the above mentioned physical and chemical tests were performed on each sample.

Phytoplankton Standing Crop and Chlorophyll *a*

On every sampling cruise duplicate euphotic zone composite samples were collected at each reservoir station for a total of six composites per cruise. Each composite was formed by homogeneously mixing samples taken at 1-meter intervals from the surface through the euphotic zone. An aliquot of each composite was preserved with Lugol's solution and reserved for phytoplankton enumeration. A large volume of each composite sample was used for chlorophyll determinations.

In the laboratory the preserved plankton samples were shaken to homogeneously resuspend the algae. Subsamples ranging in volume from 2 to 75 ml were then withdrawn and prepared for microscopic analysis according to the Membrane Filter Concentration Technique (APHA, 1971). The stained plankton were identified and counted in transects along the diameter of the filter after the water and air in the matrix of the filter were replaced with immersion oil. This method has the advantage of providing a permanent phytoplankton mount (UNESCO, 1974).

One transect was counted at each of three different magnifications: 100X, 430X and 970X. The lower magnifications were sufficient to record the occurrence of larger forms while it was necessary to use

970X to identify and enumerate the microplankton. Algae were enumerated at the species level in most cases in ten randomly selected fields along the transects defined at both 100X and 430X. Twenty random fields were counted along the 970X transect for a total count of 40 fields.

A mean volume of each morphological unit (trichome, colony, cell, etc.) was calculated for most phytoplankton species by likening the alga to the appropriate geometrical figure (i.e. sphere, cylinder, cone, etc.) and averaging the mean linear dimensions of a large population of individuals (usually 100) as measured with a Whipple ocular micrometer. Literature values were used to estimate the mean cell volumes of rarely occurring species. A series of ratios involving the volume of water filtered, the magnification and the number of fields counted were used to extrapolate to cell volume per liter of water ($\text{mm}^3 \cdot \text{L}^{-1}$). The standing crop of phytoplankton is best expressed in these terms because numbers do not give a true evaluation of biomass due to the variability in size among species (Wetzel, 1975). A discussion of the statistical validity of the volumetric determination of plankton biomass may be found in Willén (1976) and a statistical treatment of the direct count method is presented in Lund, *et al.* (1958).

Algae were identified from living and preserved material collected

throughout the course of the study. Taxonomic references used to identify most groups included Smith (1950), Tiffany and Britton (1952), Taft and Taft (1971) and Prescott (1952, 1970). Keys by Hustedt (1930), Patrick and Reimer (1966), FWPCA (1966) and Hansmann (1973) proved helpful in identifying the Bacillariophyceae, as did Drouet (1959) for the Myxophyceae. All microscopic analyses were performed with a Bausch and Lomb Dynoptic Microscope.

The chlorophyll a concentration was determined by filtering a known volume of each euphotic zone composite through a Millipore^R membrane filter of 0.45 micron pore diameter. The filter was then placed in a 12-ml centrifuge tube to which 5 ml of 90% acetone was added. Chlorophyll was extracted by placing the tube in complete darkness in a freezer for 24 hours. The content of the tube was then centrifuged and the chlorophyll a concentration of the supernatant was measured with a Beckman DU Spectrophotometer according to the methods and equation of Strickland and Parsons (1972). The equation used to calculate the chlorophyll a concentration eliminated some of the photometric interferences due to chlorophyll degradation products. A rough estimate of the phytoplankton standing crop was obtained from the chlorophyll a analysis.

Phytoplankton Primary Production

An estimate of limnetic primary production was obtained at all

three reservoir stations through the use of chlorophyll and light data as outlined by Ryther and Yentsch (1957). This estimate proved to be unsatisfactory and the formula was modified to obtain a better estimate of gross primary production.

Data relative to total incident surface radiation which is a necessary component of the formula of Ryther and Yentsch (1957) and the modified empirical formula herein presented was obtained using either a Kip-Zonen Model CM-3 or a Kahl pyranometer and an Esterline Angus Model 80-M recorder. Daily radiation was converted to langley-day⁻¹ as described by the Kip-Zonen and Kahl manuals. The pyranometer was located on the east bank of the reservoir, opposite Station 3 (see Figure 2 for location of Station 3).

Primary production was also measured at Station 2 by the more accurate carbon-14 technique first described by Steemann-Nielsen (1952). Samples were collected at 1-meter intervals from the surface to the bottom of the euphotic zone and duplicate light and opaque 300-ml BOD bottles were used to resuspend the samples to their original depths. All samples were spiked with 5 μCi or 10 μCi of $\text{NaH}^{14}\text{CO}_3$ obtained from New England Nuclear prior to resuspension. A 3/4 inch diameter iron rod of 6 m length permanently attached to two styrofoam floats at Station 2 of the reservoir was used to incubate the samples in the absence of shading. These in situ ¹⁴C experiments lasted

approximately 4 hours and were conducted during the second and/or third photoperiods in a light day divided into 5 equal photoperiods. Vollenweider (1965) and Vollenweider and Nauwerck (1961) suggested that this procedure facilitated the day rate estimation of photosynthesis.

Upon completion of the experiment, the BOD bottles were fixed with 1 ml of 1% merthiolate and an aliquot of each sample (10-25 ml; depending upon the size of the standing crop) was then filtered through a 0.45 μ Millipore^R filter. The sides of the filter funnel and filter were then rinsed with 100 ml of 1% HCl to remove possible ¹⁴C precipitated extracellularly (Wetzel, 1965). Filters were then placed in a scintillation vial containing 4 ml of absolute methanol to eliminate the loss of activity during storage (Wallen and Geer, 1968). The above procedure was completed within 24 hours of sample collection. The scintillation vials were filled with a scintillation fluor similar to those suggested by Vollenweider (1969) consisting of 4 g 2,5 diphenyloxazole (PPO), 0.1 g p-Bis(2-(5-phenyloxazolyl))-benzene (POPOP) and 1 L toluene and were radioassayed within 96 hours of sample collection on a Packard Tricarb Liquid Scintillation Counter. An isotope effect of 6% was assumed in calculating activity (Steemann-Nielsen, 1955).

Statistical Analyses

Statistical methods employed in the analysis of the data collected during this study are found in Snedecor and Cochran (1967) or Steel and Torrie (1960). In the statistical analysis of all data, the 5% probability level was considered the critical value in determining whether the author rejected or failed to reject the null hypothesis (i.e. for $p \leq 0.05$ the null hypothesis was rejected). However, values of $p = 0.06-0.10$ are reported for reference purposes.

RESULTS AND DISCUSSION

One of the defined goals of the Tongue River Reservoir study program was to obtain data during the early operational stages of the West Decker Mine against which future comparisons may be made to evaluate the long range impact of coal mining on the reservoir ecosystem. As such, it was appropriate that the defined objectives of the immediate study be addressed for an "average" water year. An abnormally low reservoir stage was encountered during the first four months of this study (June - September 1975) because of the excessive reservoir drawdown undertaken to repair the outflow gate. The reservoir's hydrologic regime for the balance of the study approximated the norm. When compared with records for the previous eighteen years (unpublished data provided by Mt. Dept. Nat. Res. and Cons.), the period from ice-in (mid-November) 1975 to ice-in (mid-November) 1976 was chosen as an "average" water year. Nonetheless, some of the data collected in the summer of 1975 was used as supportive evidence for the interpretation and discussion of results. In establishing means of various parameters for the average water year, the pre-defined seasonal sampling regime has been taken into account and the data have been weighed accordingly.

Hydrology

Hydrologic data were supplied by the U.S. Geological Survey (1976, 1977 and unpublished data), the Montana Bureau of Mines and

Geology (unpublished data) and the Montana Department of Natural Resources and Conservation (unpublished data).

The Tongue River provided the only significant inflow of surface water into the Tongue River Reservoir. Ground water inflow was estimated to vary between $0.003 \text{ m}^3 \cdot \text{sec}^{-1}$ (0.1 cfs) at the southern end of the reservoir and $0.3 \text{ m}^3 \cdot \text{sec}^{-1}$ (10 cfs) at the northern end of the reservoir. The reservoir's only outflows were the gate at the bottom of the dam and the emergency spillway at the crest of the dam.

During this entire study, the maximum rate of water discharge of the Tongue River above the reservoir (near the inflow station) was $152 \text{ m}^3 \cdot \text{sec}^{-1}$ (5350 cfs), observed on 22 June 1975. The minimum rate of water discharge at this station during the study was $2.74 \text{ m}^3 \cdot \text{sec}^{-1}$ (97 cfs), recorded on 6 September 1976. At the Tongue River Dam (near the outflow station), the maximum rate of Tongue River water discharge during this study was $140 \text{ m}^3 \cdot \text{sec}^{-1}$ (4950 cfs), observed on 25 June 1975. The minimum rate of water discharge at this station was $0.42 \text{ m}^3 \cdot \text{sec}^{-1}$ (15 cfs), recorded on 5 November 1975. Averaged over the past 16 and 37 years, the mean rates of discharge of the reservoir's inflow and outflow waters were $14.5 \text{ m}^3 \cdot \text{sec}^{-1}$ (511 cfs) and $13.1 \text{ m}^3 \cdot \text{sec}^{-1}$ (461 cfs). During the two calendar years encompassing this study the mean rate of discharge of the inflow was $17.3 \text{ m}^3 \cdot \text{sec}^{-1}$ (611 cfs) while that of the outflow was $17.2 \text{ m}^3 \cdot \text{sec}^{-1}$ (607 cfs). These mean rates of discharge

represent departures of +19% and +31% from the long-term average inflow and outflow water discharge rates, respectively.

Figure 3 depicts the average monthly water discharge of the Tongue River, recorded at the previously mentioned gaging stations located above and below the Tongue River Reservoir. Peak runoff typically occurred in mid-June and, on an annual basis, the highest rates of discharge of the inflow water were recorded at that time. Correspondingly high rates of discharge of outflow water were recorded during spring runoff, upon attainment of reservoir storage capacity. The lowest rates of discharge of both the inflow and outflow water were noted during the winter months.

The Tongue River Reservoir is primarily a storage reservoir and, as such, exhibits widely fluctuating pool elevations on an annual basis in response to spring runoff and downstream irrigation needs throughout the growing season. The average annual reservoir surface elevation fluctuation is 3-6 meters, with storage peaking in late June or early July and reaching a minimum in late September. Storage is held constant at about $432 \times 10^5 \text{ m}^3$ (35,000 acre-ft) throughout the winter months. This figure represents about 60% of the storage capacity of the Tongue River Reservoir. During 1975 the pool elevation fluctuated 8 meters as a result of the previously mentioned reservoir drawdown.

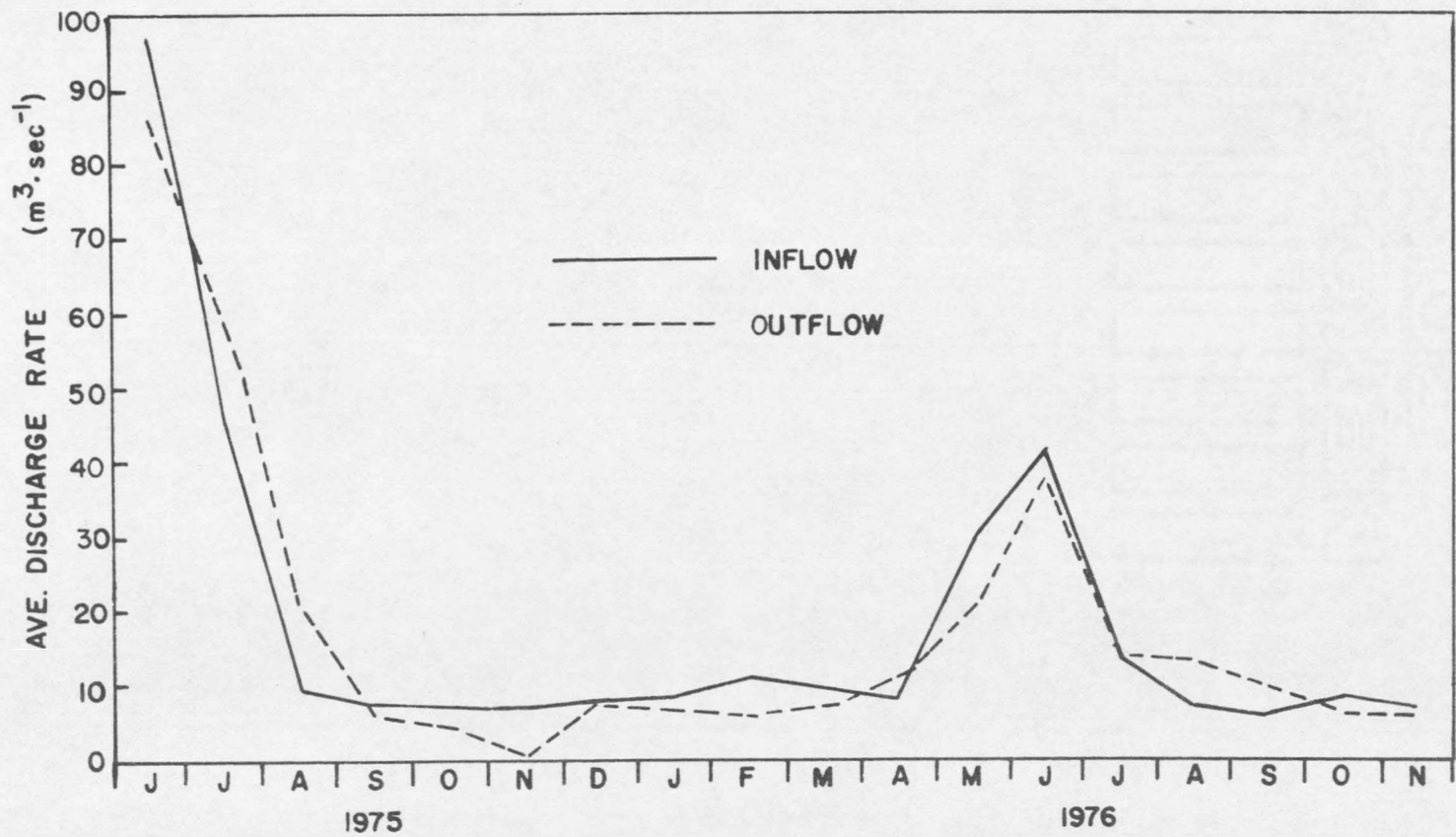


Figure 3. Mean water discharge rates ($\text{m}^3 \cdot \text{sec}^{-1}$) of the Tongue River Reservoir inflow and outflow waters. Data are averaged over monthly intervals from June 1975 through November 1976 (U.S.G.S., 1976, 1977 and unpublished data).

Figure 4 presents the annual pool elevation regime and storage capacity averaged over two week intervals for the years encompassed by this study. The maximum content observed was $889 \times 10^5 \text{ m}^3$ (72,100 acre-ft) on 24 June 1975 and the minimum storage was $159 \times 10^5 \text{ m}^3$ (12,900 acre-ft) on 19 September 1975. The reservoir volume on 24 June 1975 was 20.2% higher than the estimated usable capacity of $740 \times 10^5 \text{ m}^3$ (60,000 acre-ft). This followed abnormally high early June runoff (Figure 3) catalyzed by the rapid melting of excessive snowpack in the Big Horn mountains. At that time ambient temperatures were high and water crested the reservoir spillway. The minimum storage represented only 21.5% of the usable capacity, but was considerably greater than the dead storage volume of $17.3 \times 10^5 \text{ m}^3$ (≈ 1400 acre-ft).

The water storage history of the Tongue River Reservoir is depicted in Figure 5. Mean reservoir water storage from 1956-1977 was $440 \times 10^5 \text{ m}^3$ (35,705 acre-ft). Due to the annual extremes in pool elevation, submergent and emergent aquatic vegetation have not become established.

A summary of the hydrologic data for the Tongue River Reservoir during the 1975 and 1976 calendar years is in Table 2. The data for 1976 is probably more indicative of the annual hydrologic regime of the reservoir than the 1975 data. Unusually short retention times were

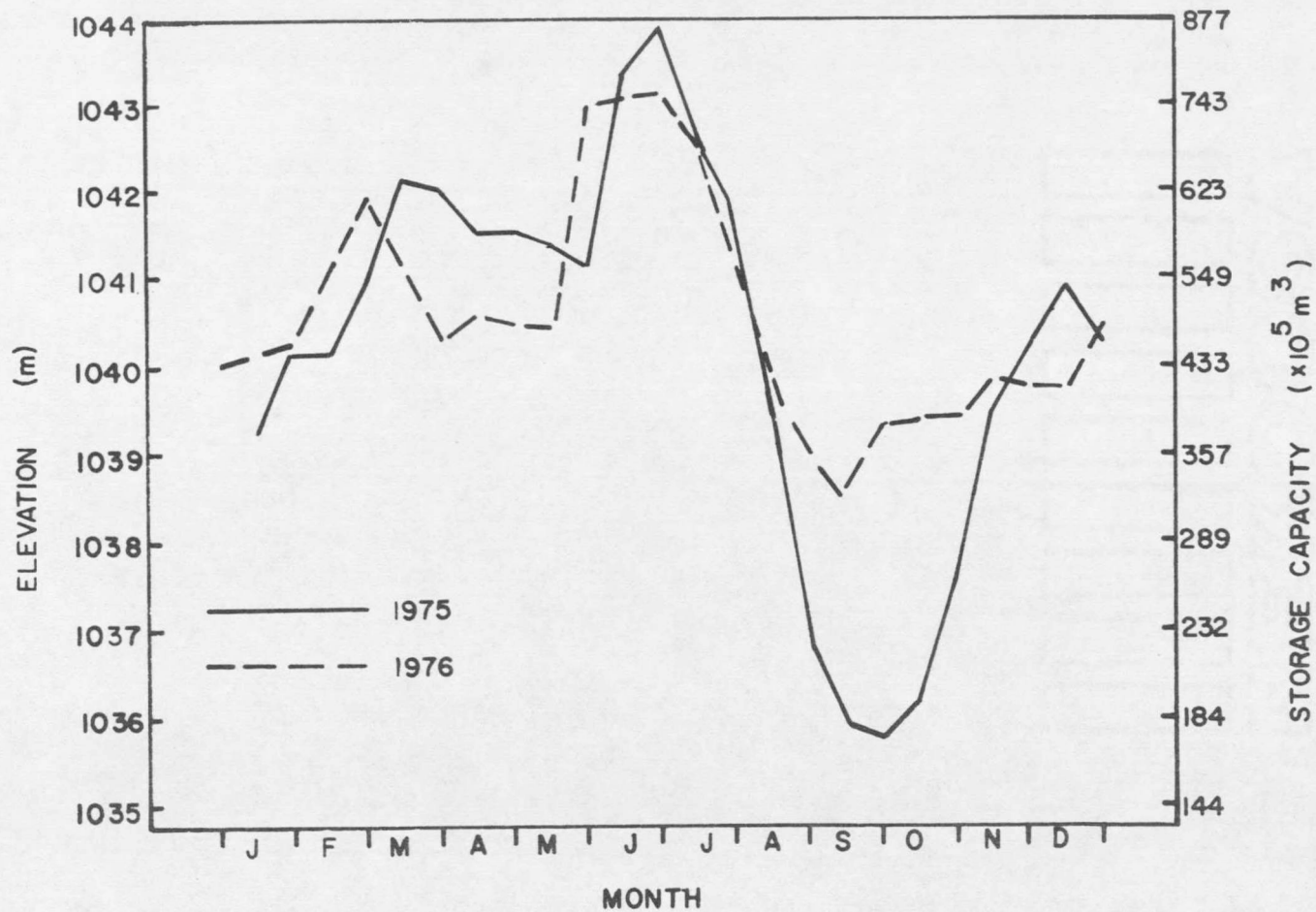


Figure 4. Pool elevation and storage capacity of the Tongue River Reservoir in 1975 and 1976 (Mt. Dept. Nat. Res. and Cons., unpublished data and U.S.G.S., 1977).

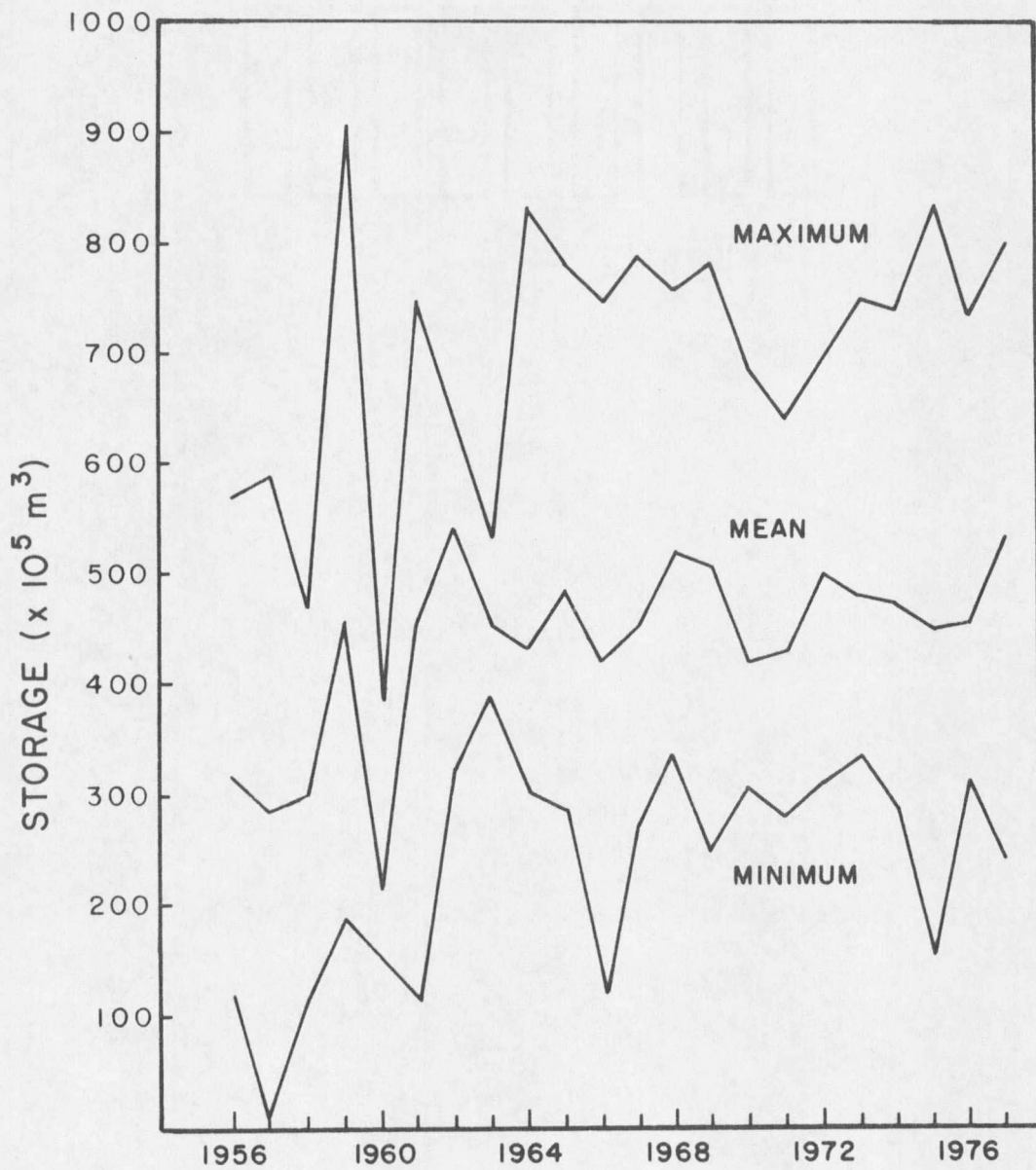


Figure 5. Water storage history of the Tongue River Reservoir from 1956 through 1977 (Mt. Dept. Nat. Res. and Cons., unpublished data derived from monthly averages).

Table 2. Summary of hydrologic data for the Tongue River Reservoir during the calendar years 1975 and 1976.

	Total Inflow $\times 10^5 \text{m}^3$	Total Outflow $\times 10^5 \text{m}^3$	Storage Change $\times 10^5 \text{m}^3$	Average Storage $\times 10^5 \text{m}^3$	Average Discharge $\times 10^5 \text{m}^3 \cdot \text{day}^{-1}$	Retention Time (days)	Average Surface Elevation (m)
Jan.	136.4	113.6	+ 22.8	363.3	3.7	98.1	1039.3
Feb.	121.1	102.0	+ 19.1	429.3	3.6	119.3	1040.2
Mar.	407.7	212.3	+258.4	618.2	6.9	89.5	1042.1
1 Apr.	302.9	361.6	- 58.7	558.0	12.1	46.1	1041.5
May	922.2	1015.7	- 93.5	482.5	32.8	14.7	1040.8
9 June	2521.1	2238.0	+283.1	999.8	74.6	13.4	1043.3
July	1268.8	1578.9	-310.1	724.1	50.9	14.2	1042.7
7 Aug.	253.2	581.4	-328.2	367.8	18.8	19.5	1039.5
Sept.	318.6	175.3	- 36.7	164.1	5.8	28.2	1035.8
5 Oct.	198.5	116.0	+ 82.5	179.6	3.7	48.5	1036.2
Nov.	186.3	29.7	+156.6	354.8	1.0	354.8	1039.3
Dec.	205.4	194.0	+ 11.4	479.7	6.3	76.1	1040.8
Ave.				476.7		76.8	
Total	6725.2	6718.5	+ 6.7				
Jan.	220.5	184.9	+ 35.9	431.7	6.0	71.9	1040.0
Feb.	259.4	160.9	+ 98.5	441.5	5.7	77.4	1040.2
Mar.	266.8	196.3	+ 70.5	518.1	6.3	82.2	1041.1
1 Apr.	222.2	272.8	- 50.6	466.9	9.1	51.3	1040.7
May	789.8	545.0	+244.8	451.4	17.5	25.7	1040.5
9 June	1100.0	985.1	+114.9	706.9	32.8	21.5	1043.0
July	344.8	379.7	- 34.9	729.9	12.3	59.3	1043.2
7 Aug.	186.5	348.7	-162.2	526.8	11.2	47.0	1041.4
Sept.	150.3	247.2	- 96.9	342.2	8.2	41.7	1039.1
6 Oct.	212.2	169.8	+ 42.4	354.8	5.5	64.5	1039.3
Nov.	168.7	135.7	+ 33.0	365.6	4.5	81.2	1039.4
Dec.	166.8	116.0	+ 50.8	397.2	3.7	107.3	1039.8
Ave.				477.7		60.9	
Total	4088.0	3715.1	+372.9				

observed in the summer of 1975 in preparation for repairs to the outflow gate.

Inflow and Outflow Waters

Turbidity

Turbidity in the Tongue River Reservoir inflow water ranged from 3.1-53.0 JTU and averaged 18.2 JTU over the course of a year. Turbidity has been defined as the degree of opaqueness produced in water by suspended particulate matter (Reid, 1961). Suspended particulates affecting turbidity may be biogenic or abiogenic in nature. In the Tongue River turbidity was due in part to suspended organics, but primarily to siltaceous matter.

Neel (1963) and Symons, *et al.* (1964) found that reservoirs may serve as sediment traps for inflowing water, leading to increased downstream transparency. The data of Figure 6 indicate that this phenomenon occurred in the Tongue River Reservoir. During peak runoff in May and June a large volume of silt-laden water flowed into the reservoir and a strong correlation ($n = 29$, $r = 0.63$, $p < 0.01$) was found between inflow rate and inflow turbidity throughout this study.

The deposition of suspended abiotic matter in the upper end of the reservoir accounted for decreased turbidity of the outflowing water relative to the inflowing water. The sudden increase in tur-

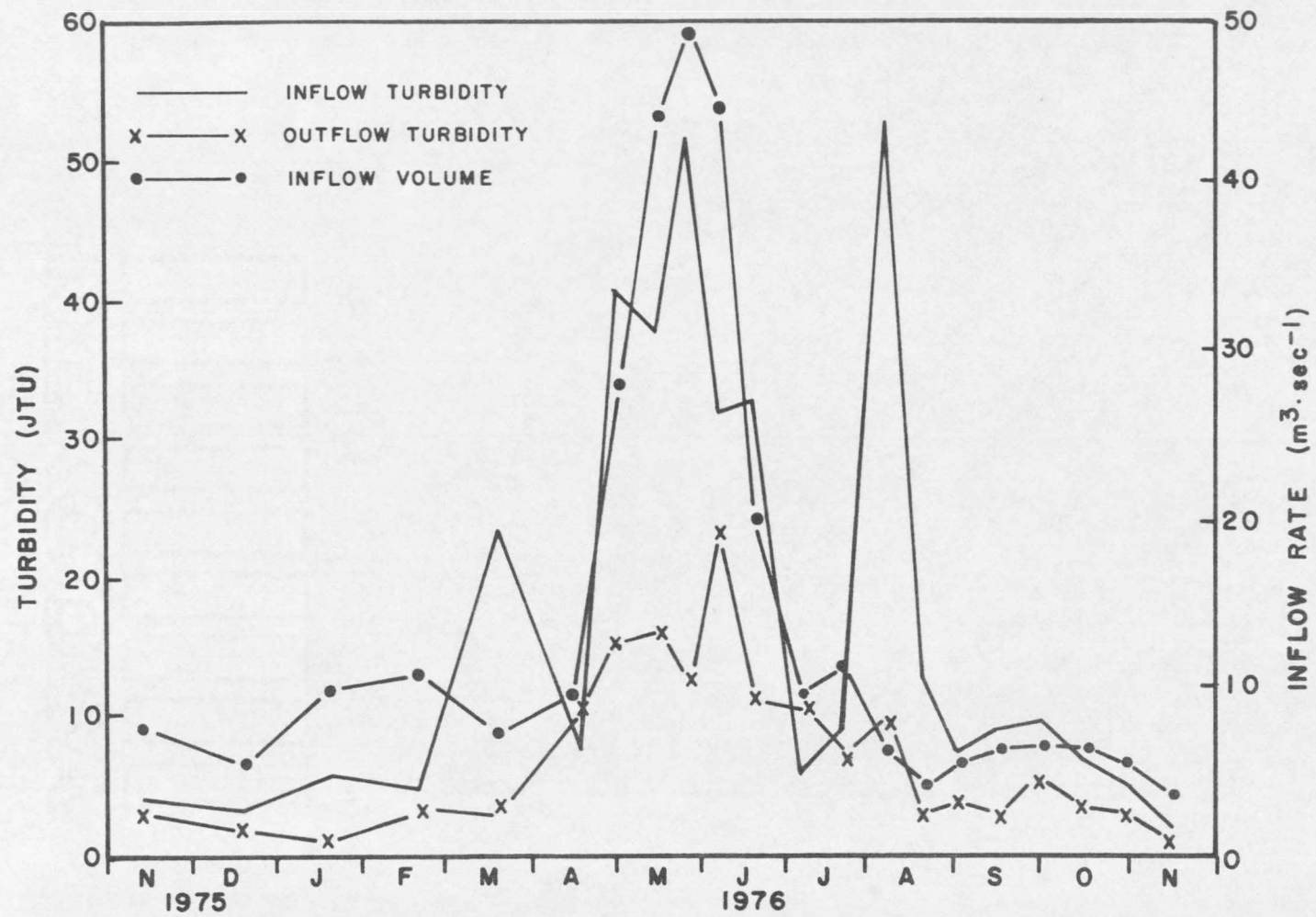


Figure 6. Turbidity of the inflow and outflow waters of the Tongue River Reservoir versus the inflow rate.

bidity of the inflow on 6 August 1976 was attributed to repair work on the County Bridge at the sampling site. The turbidity of the outflow ranged from 1.6 - 21.0 JTU and averaged 7.6 JTU. The turbidity of the outflow increased somewhat during spring runoff but the magnitude of the increase was not as substantial as that of the inflow, reflecting the deposition of silt.

Temperature and Specific Conductance

The annual temperature regime at the Inflow and Outflow stations is graphically illustrated in Figure 7. Winter water temperatures of both the inflow and outflow were close to the freezing point. A gradual warming trend began with the start of spring runoff in April and peak temperatures were reached in August at both the Inflow and Outflow stations. Due to the deepwater withdrawal, consistently lower water temperatures were observed at the outflow than the inflow on any given sampling date during the spring and summer. The highest outflow water temperatures were observed in the months of the warmest ambient temperatures and the lowest reservoir stages. The yearly range of water temperature of the inflow was 1.3-25.8°C and the average was 13.3°C. The annual temperature range of the outflow water was 1.0-20.3°C and the average was 11.2°C.

Figure 8 presents the specific conductance regime at the Inflow and Outflow stations for a year. Specific conductance fluctuated

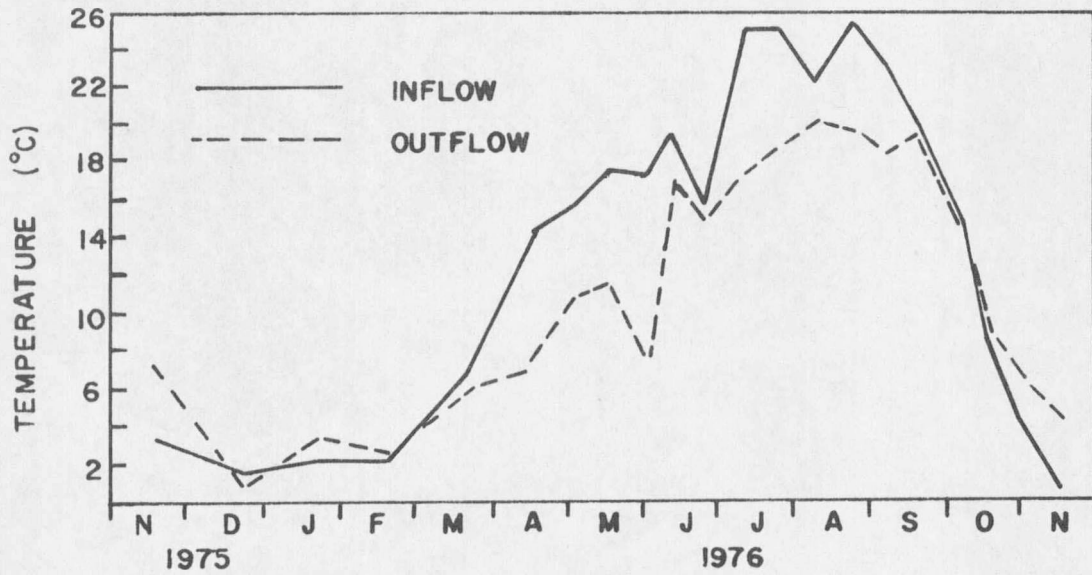


Figure 7. Annual temperature regime of the inflow and outflow waters of the Tongue River Reservoir.

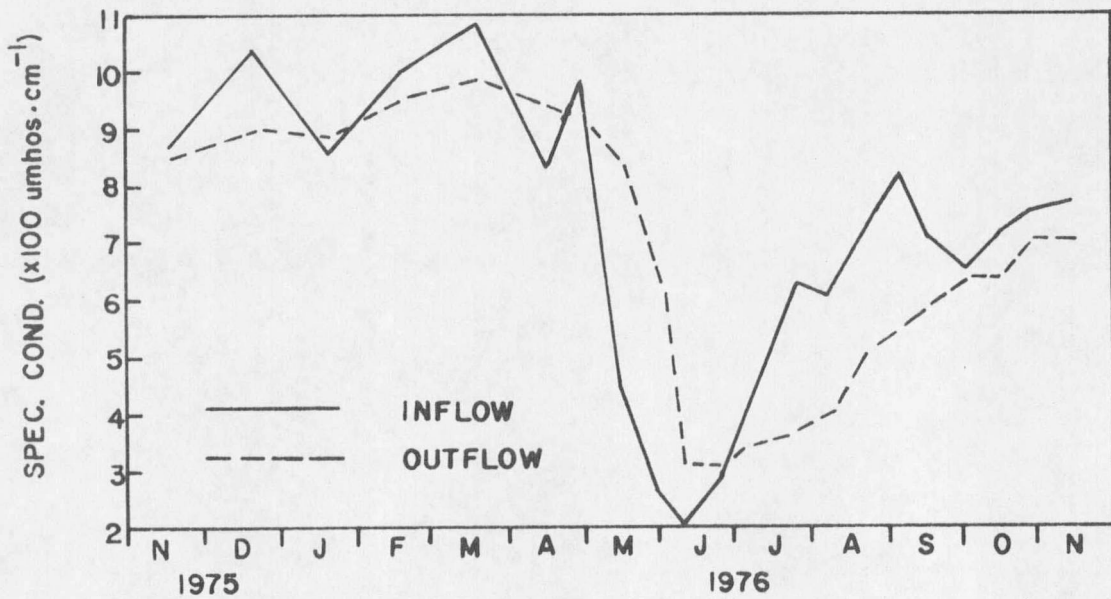


Figure 8. Annual specific conductance regime of the inflow and outflow waters of the Tongue River Reservoir.

around 875-1075 $\mu\text{mhos}\cdot\text{cm}^{-1}$ at the Inflow station during the fall and winter of 1975-1976. With the onset of spring runoff conductivity values dipped to a low of 199 $\mu\text{mhos}\cdot\text{cm}^{-1}$ on 10 June 1976 reflecting the low ionic content of snowmelt. Feth, *et al.* (1964) have recorded conductivity values of 2-42 $\mu\text{mhos}\cdot\text{cm}^{-1}$ for melted snow in the western United States. With the completion of spring runoff, specific conductance increased in the inflow water through the fall. A significant correlation ($n = 29$, $r = 0.79$, $p < 0.01$) was found between low inflow specific conductance and high inflow volume, which further illustrates the effect of spring runoff on specific conductance of the inflowing river. Specific conductance at the Outflow station followed a pattern similar to that of the Inflow, with the graph displaced one month to the right owing to the effect of impoundment. The ranges of specific conductance measured at the Inflow and Outflow stations were 199-1072 $\mu\text{mhos}\cdot\text{cm}^{-1}$ and 297-989 $\mu\text{mhos}\cdot\text{cm}^{-1}$ respectively. The mean conductivity of the inflowing water was 694 $\mu\text{mhos}\cdot\text{cm}^{-1}$, while that of the outflowing water was 662 $\mu\text{mhos}\cdot\text{cm}^{-1}$.

Major Cations and Anions

Table 3 includes a list of the ranges and averages of the concentrations of major anions and cations at the Tongue River Reservoir Inflow and Outflow stations. The chemical composition of soil and rock and the ionic exchange capacity of the parent material in the

Table 3. Ranges and averages of some chemical and physical parameters of the inflow and outflow waters from November 1975 through November 1976.

Parameter	Inflow	Outflow
Ca ⁺⁺ (me·L ⁻¹)	1.05-4.79 3.04	1.40-4.24 2.84
Mg ⁺⁺ (me·L ⁻¹)	0.79-4.69 3.18	1.23-4.24 2.97
Na ⁺ (me·L ⁻¹)	0.31-2.39 1.35	0.51-1.97 1.27
K ⁺ (me·L ⁻¹)	0.03-0.16 0.10	0.05-0.16 0.10
Total alkalinity (me·L ⁻¹)	1.61-5.87 3.92	1.95-5.31 3.64
SO ₄ ⁼ (me·L ⁻¹)	0.65-6.25 3.56	1.12-5.68 3.46
Cl ⁻ (me·L ⁻¹)	0.03-0.16 0.09	0.05-0.14 0.08
SiO ₂ (mg·L ⁻¹)	3.1-12.6 7.7	1.8-11.9 6.3
NH ₃ -N (μg·L ⁻¹)	0-175 20	0-86 32
NO ₃ -N (μg·L ⁻¹)	0-173 38	0-143 32
NO ₂ -N (μg·L ⁻¹)	0-14 3	0-8 3
Total-N (μg·L ⁻¹)	67-620 377	67-610 417
PO ₄ -P (μg·L ⁻¹)	4-70 23	0.37 10
Total-P (μg·L ⁻¹)	36-164 67	12-61 40
Spec. cond. (μmhos·cm ⁻¹ @ 25°C)	199-1072 694	297-989 662
pH	7.9-8.8 8.4	7.8-8.6 8.3
Turbidity (JTU)	3.1-53.0 18.2	1.6-21.0 7.6
Temperature (°C)	1.3-25.8 13.3	1.0-20.3 11.2

drainage area influence the rate of weathering and ion supply to surface waters of the drainage area (Wetzel, 1975). General processes of weathering that control ion supply include solution, redox reactions, pH changes, and the formation of complexes (Gorham, 1961). Rodhe (1949) has pointed out that the ionic composition of surface water ultimately reflects the changes that occur after the initial solution of ions from the parent material as well as the lithological considerations described above.

Hutchinson (1957) stated that the interaction of the above processes led to the following cationic order of abundance in the river waters of the world: $\text{Ca}^{++} > \text{Mg}^{++} > \text{Na}^+ > \text{K}^+$. In both the inflow and outflow waters the order of abundance of cations was $\text{Ca}^{++} \approx \text{Mg}^{++} > \text{Na}^+ > \text{K}^+$. This was probably due to the preponderance of dolomite $[\text{CaMg}(\text{CO}_3)_2]$ in the drainage area. Upon solution, dolomite should yield nearly equal concentrations ($\text{me}\cdot\text{L}^{-1}$) of calcium and magnesium, barring the precipitation of calcium and calcium carbonate (Hem, 1970).

An analysis of a hardwater system should yield the following anionic ranking of abundance: $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{=}$ (Hutchinson, 1957). Bicarbonate should clearly dominate the anionic chemical analysis of most waters due to the formation and subsequent dissociation of carbonic acid into bicarbonate when atmospheric CO_2 comes into contact with natural water. However, in both the inflowing and outflowing

waters the order of abundance of anions was $\text{HCO}_3^- \geq \text{SO}_4^{=} > \text{Cl}^-$. Natural systems in contact with gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), anhydrite (CaSO_4), pyrite (FeS_2), or drainage waters through arid soils high in sodium sulfate (Na_2SO_4) could be expected to contain high concentrations of sulfate. For this reason the millequivalent concentration of sulfate was nearly equal to that of bicarbonate in the river water above and below the reservoir. The Tongue River inflow and outflow could be characterized as calcium-magnesium bicarbonate-sulfate waters.

Tables 4 and 5 illustrate the seasonal distribution of cations and anions ($\text{me} \cdot \text{L}^{-1}$) in the inflow and outflow. In both cases, the millequivalent concentrations of the anions and cations followed the same seasonal trends. The concentrations of anions and cations were high from the fall through the early spring and reached a low in the early summer, reflecting the dilution effect of spring runoff. Increases in the concentrations of anionic and cationic species were noted through the late summer and fall due to evaporative concentration and the lack of rainfall.

pH

The pH of the Tongue River directly above the reservoir ranged from 7.9-8.8 and the mean pH was 8.4. The range of pH for the outflowing Tongue River water was 7.8-8.6 with a mean of 8.3. No seasonal trends in pH values were noted at either the Inflow or Outflow

Table 4. Average seasonal distribution of cations and anions ($\text{me}\cdot\text{L}^{-1}$) in the inflow water from November 1975 through November 1976.

Date	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Total Cations	Alk.	Cl ⁻	F ⁻	SO ₄ ⁼	Total Anions
15 Nov. 75	3.80	4.15	1.69	0.12	9.76	5.55	0.10	0.02	4.32	9.99
18 Dec	4.77	4.90	1.98	0.15	11.80	5.95	0.16	0.01	5.55	11.67
17 Jan. 76	3.80	3.70	1.36	0.12	8.98	4.95	0.10	0.02	3.89	8.96
21 Feb.	4.13	4.24	1.85	0.15	10.37	5.17	0.12	0.02	5.06	10.35
22 Mar.	4.31	4.69	2.39	0.16	11.55	5.06	0.07	0.02	6.25	11.40
16 Apr.	3.23	3.60	1.67	0.10	8.60	4.26	0.10	0.02	4.45	8.83
1 May	3.69	4.19	2.20	0.14	10.22	4.49	0.12	0.02	5.05	9.68
14 May	2.00	2.22	0.85	0.07	5.14	2.73	0.07	0.01	2.17	4.98
29 May	1.26	1.07	0.39	0.04	2.76	1.68	0.05	0.01	0.84	2.58
10 June	1.09	0.79	0.31	0.03	2.22	1.58	0.03	0.01	0.66	2.28
25 June	1.31	1.17	0.41	0.04	2.93	1.94	0.04	0.01	1.05	3.04
8 July	2.04	1.52	0.61	0.05	4.22	2.61	0.01	0.05	1.45	4.12
22 July	2.84	2.73	1.23	0.10	6.90	3.90	0.02	0.05	3.15	7.12
6 Aug.	2.52	2.69	1.48	0.10	6.79	3.62	0.02	0.07	3.04	6.75
20 Aug.	3.50	3.80	1.57	0.13	9.00	4.61	0.01	0.10	4.08	8.80
2 Sept.	3.32	4.12	1.75	0.16	9.35	4.59	0.01	0.09	4.55	9.24
16 Sept.	3.32	3.50	1.55	0.12	8.49	4.52	0.03	0.08	4.02	4.65
2 Oct.	2.89	3.32	1.23	0.15	7.59	3.98	0.03	0.10	3.50	7.61
16 Oct.	3.55	3.52	1.34	0.11	8.52	4.56	0.02	0.09	3.60	8.27
30 Oct.	3.49	3.68	1.36	0.10	8.63	4.80	0.02	0.09	3.92	8.83
12 Nov.	3.55	3.68	1.43	0.10	8.76	4.76	0.03	0.08	4.02	8.89

Table 5. Average seasonal distribution of cations and anions ($\text{me}\cdot\text{L}^{-1}$) in the outflow water from November 1975 through November 1976.

Date	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Total Cations	Alk.	Cl ⁻	F ⁻	SO ₄ ⁼	Total Anions
15 Nov. 75	3.71	4.00	1.70	0.13	9.54	4.78	0.10	0.02	4.95	9.85
18 Dec.	3.80	3.95	1.67	0.14	9.56	5.05	0.10	0.01	4.80	9.96
17 Jan. 76	3.89	4.15	1.70	0.14	9.88	5.19	0.10	0.02	4.82	10.13
21 Feb.	4.01	3.95	1.66	0.14	9.76	5.35	0.10	0.01	4.46	10.28
22 Mar.	4.25	4.29	1.97	0.15	10.66	5.26	0.09	0.01	5.68	11.04
16 Apr.	3.56	4.04	1.76	0.12	9.48	4.69	0.12	0.02	4.87	9.70
1 May	3.69	4.03	1.87	0.12	9.71	4.58	0.12	0.03	4.91	9.64
14 May	3.62	4.24	1.90	0.16	9.92	4.39	0.14	0.02	5.15	9.70
29 May	2.49	2.72	1.14	0.08	6.43	3.11	0.10	0.02	3.04	6.27
10 June	1.46	1.23	0.51	0.05	3.25	1.92	0.05	0.01	1.31	3.29
25 June	1.42	1.23	0.45	0.05	3.15	1.98	0.04	0.01	1.12	3.15
8 July	1.71	1.30	0.47	0.05	3.53	2.10	0.01	0.04	1.27	3.42
22 July	1.64	1.40	0.52	0.05	3.61	2.25	0.01	0.03	1.39	3.68
6 Aug.	1.84	1.73	0.73	0.06	4.36	2.70	0.01	0.06	1.68	4.45
20 Aug.	2.26	2.10	0.87	0.09	5.32	2.95	0.01	0.05	2.15	5.16
2 Sept.	2.28	2.59	1.13	0.11	6.11	3.05	0.01	0.07	2.79	5.91
16 Sept.	2.32	2.76	1.39	0.11	6.58	3.13	0.02	0.07	3.40	6.62
2 Oct.	2.76	3.22	1.32	0.15	7.45	3.61	0.02	0.08	3.62	7.33
16 Oct.	2.89	3.16	1.38	0.12	7.55	3.81	0.02	0.09	3.70	7.62
30 Oct.	3.01	3.45	1.34	0.10	7.90	4.22	0.02	0.11	3.77	8.12
12 Nov.	3.06	3.26	1.37	0.11	7.80	4.13	0.02	0.08	4.02	8.25

stations. Rada (1974) observed reduced values of pH in the spring and rising pH values over the course of the summer in the Missouri River above Canyon Ferry Reservoir in Montana. He attributed this phenomenon to turbid runoff water and the scouring of periphyton in the spring, followed by increased periphyton productivity in the summer. Low periphyton activity and high buffering capacity in the Tongue River discourage an increase in pH during the summer growing season.

Nutrient Concentrations and Loads of the Inflowing and Outflowing Tongue River

The natural nutrient input into a water system is a function of the drainage basin geochemistry, drainage basin size, hydrology and precipitation pattern (Hynes, 1970). Additional considerations include the drainage basin land use pattern and the human population characteristics within the area (Brezonik, 1972).

Figures 9 and 10 depict the seasonal variations in the concentrations of inorganic-N, inorganic-P, organic + hydrolyzable-P, and organic-N in the inflowing water. The highest concentrations of inorganic nutrients in the inflow were observed during the winter months. No reasonable explanation is offered for this phenomenon. However, this pattern may represent the norm as Leathe and Whalen (1978) found high levels of nitrate and orthophosphorus at the Inflow

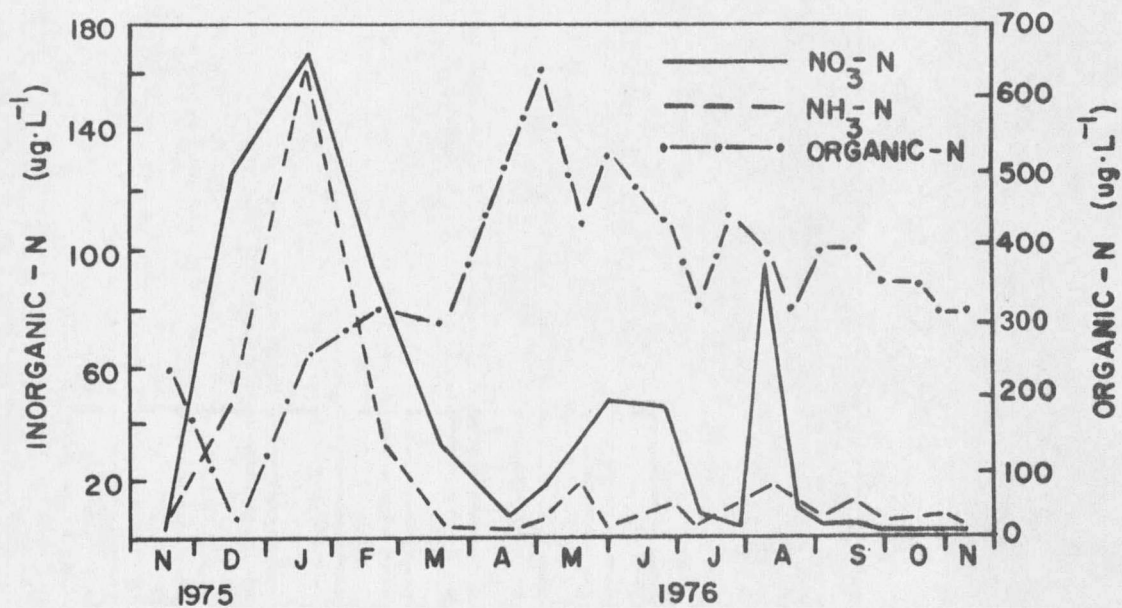


Figure 9. Seasonal concentrations of inorganic and organic nitrogen in the inflow.

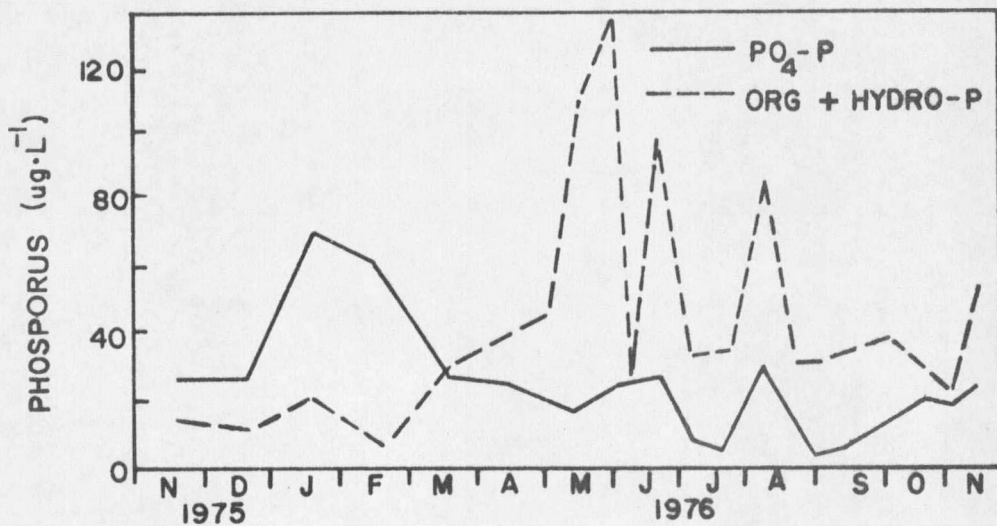


Figure 10. Seasonal concentrations of orthophosphorus and organic + hydrolyzable phosphorus in the inflow.

station during a single winter sampling session conducted on 20 March 1978.

The role of spring runoff in enhancing nutrient levels of the inflow with respect to particulate forms becomes readily apparent by comparing Figures 9 and 10 with Figure 6. The highest concentrations of organic-N and organic + hydrolyzable-P in the inflow were achieved during spring runoff. As previously discussed, the turbidity in the Tongue River was partially due to suspended organics and suspended inorganic particulates, especially silt. Hynes (1970) stressed the role of runoff in supplying organic nitrogen to lotic systems and Sawyer (1947) found that drainage from agricultural lands contributed heavily to the organic nutrient loads carried by streams. The main land uses of the Tongue River drainage above the reservoir are agriculture and grazing. A strong correlation ($n = 29$, $r = 0.56$, $p = 0.02$) was found between high turbidity values and high concentrations of organic nitrogen at the Inflow station. In contrast, no statistically significant correlations existed between inflow turbidity values and inflow ammonia concentrations ($n = 29$) or between inflow turbidity values and inflow nitrate concentrations ($n = 29$).

Wright and Soltero (1973) and Rada (1974) found significant correlations between high turbidity and high orthophosphorus in the Big Horn and Missouri Rivers respectively. A base exchange equilibrium

between water and suspended sediments with the concomitant release of orthophosphorus was hypothesized to explain this observation. This mechanism apparently did not operate in the inflow water of the Tongue River Reservoir as no statistically valid relationship ($n = 29$) was noted between inflow turbidity values and inflow orthophosphorus concentrations. However, a statistically significant correlation ($n = 29$, $r = 0.36$, $p = 0.04$) was observed between high turbidity values and high concentrations of org. + hydro.-P at the Inflow station. The mode of phosphate sorption onto silt has been discussed by Syers, *et al.* (1973) and the role of silt relative to phosphorus loading in rivers has been reviewed by Golterman (1973).

The anomolous peaks displayed by several parameters of Figures 9 and 10 on 6 August 1976 are ancillary to the previously described bridge construction.

Seasonal concentrations of inorganic and organic nitrogen in the outflowing water are depicted in Figure 11. The chemistry of the outflow water necessarily reflected biogeochemical processes occurring in the reservoir sediment, interstitial water, and bottom water due to deepwater withdrawal at the outflow gate. A roughly bimodal curve (excepting the $\text{NH}_3\text{-N}$ concentration on 2 October 1976) was observed for ammonia and nitrate concentrations in the outflow water with seasonal peaks occurring beneath ice cover and in the early

summer. The first peak was attributed in part to the autochthonous microbial decomposition of sedimented organic matter, but also to the high inflow concentration of inorganic nitrogen during the winter months (Figure 9). During the winter, low water temperatures suppressed the assimilation of nutrients by algae, and, in essence, incoming nutrients flowed through the reservoir. Factors contributing to the second peak included wind-generated agitation of the sediment during reduced reservoir stage (Figure 4) and accelerated bacterial decomposition in the presence of favorable water temperatures.

Figure 12 shows the seasonal variations in the concentrations of inorganic-P and org. + hydro.-P in the outflow. Redox conditions were never conducive to the release of mineralized phosphorus trapped in the sediment. The winter peak of orthophosphorus was attributed to a high winter inflow concentration (Figure 10) flowing through the reservoir in the absence of appreciable planktonic mediation; summer peaks were probably caused by wind activity.

Evidence for the winter inorganic nutrient flow-through theory is gained from examination of the peaks of the winter inorganic phosphorus concentration in Figures 10 and 12. The hydraulic retention time through the winter months of 1975-76 was approximately 75 days (Table 2). In the absence of biological perturbation, the highest concentration of a given nutrient in the outflow should have been noted

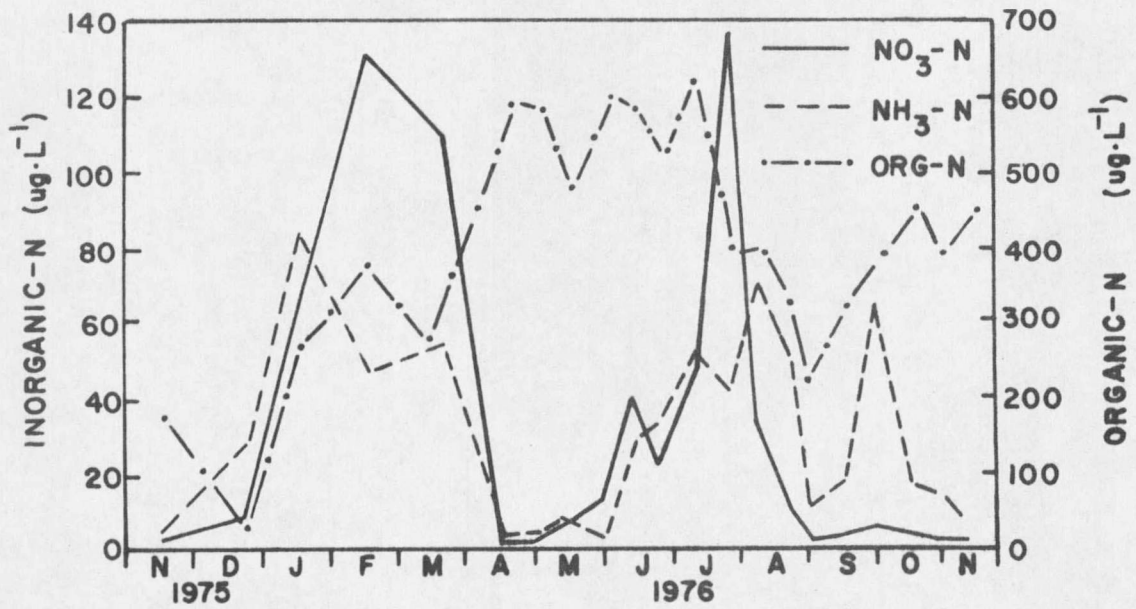


Figure 11. Seasonal concentrations of inorganic and organic nitrogen in the outflow.

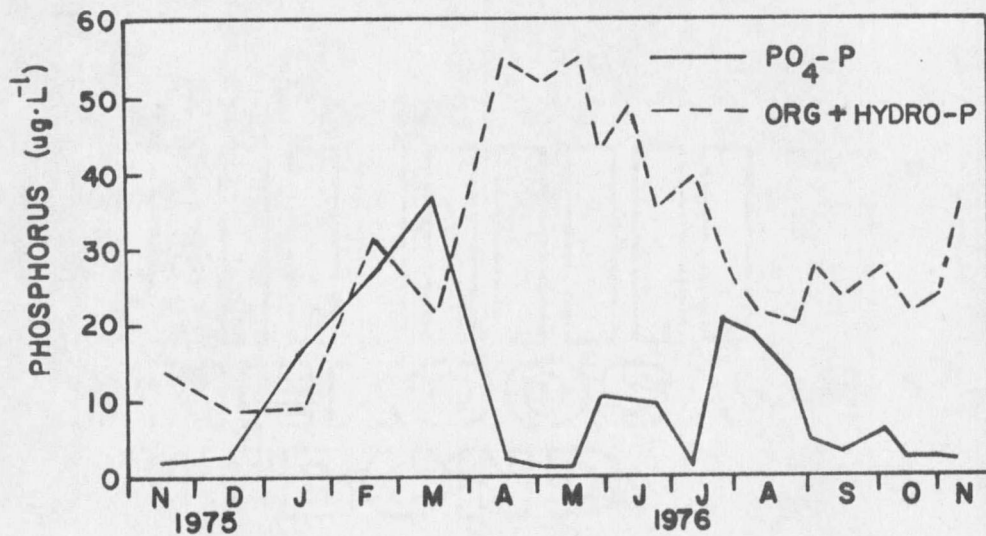


Figure 12. Seasonal concentrations of orthophosphorus and organic + hydrolyzable phosphorus in the outflow.

about 75 days following the highest recorded inflow concentration. Although a monthly sampling scheme through the winter precluded accurate detection of peak concentrations, the peak concentration of orthophosphorus in the outflow was detected 60 days following the inflow maximum (Figures 10 and 12). The outflow nitrate and ammonia maxima were noted 30 and 0 days, respectively, following the inflow peaks (Figures 9 and 11), which seemingly contradicts the theory. However, nitrogen was more mobile than phosphorus, especially in the sediment and interstitial water, which could easily explain these apparent anomalies.

Note the sharp drops encountered in Figures 11 and 12 relative to inorganic nutrient concentrations in April. The declines were attributed to increased phytoplankton activity in the reservoir upon ice-out. Considering the hydraulic retention time, it is obvious that the winter input of inorganic nutrients was not completely lost to algal consumption.

The concentrations of org. + hydro. - P and organic-N in the outflow water peaked during runoff (Figures 11 and 12) reflecting the short hydraulic retention time of the reservoir in the spring.

The nutrient load carried by a lotic system is contingent upon the volume of flow and the concentration of nutrients species in that flow. When seasonal nutrient loads borne by the reservoir's inflow and out-

flow waters were plotted (Figure 13), two major peaks were obtained relative to inorganic nitrogen and inorganic phosphorus. The first maxima of the inflow inorganic-N and inorganic-P plots temporally correspond with their counterparts in Figures 9 and 10. Although the flow rate was low in the inflowing water during the winter months, the concentrations of inorganic nutrient species in that flow were high enough that a significant fraction of the annual inorganic nutrient load delivered by the Tongue River to the reservoir was realized during that time. Winter loads of inorganic nitrogen and inorganic phosphorus were also high in the outflow water (Figures 13B and D) and reflect favorably upon the data presented in Figures 11 and 12 relative to winter concentrations of outflowing inorganic nutrients. Figures 13A-D lend support to the winter inorganic nutrient flow-through theory presented in the discussion of Figures 9-12.

The second peak of the inorganic nutrient loads of the inflow and outflow (Figure 13) occurred during the spring-summer months. The volume of inflowing water was greatest during spring runoff (Figure 3) but inorganic nutrient concentrations in that water were low (Figures 9 and 10). As a result the inorganic nutrient load carried by the inflowing river in the spring was of a lesser consequence when compared to the winter input (compare data from December-March with data from May-July in Figures 13A and C).

