REPORT TO

UNIVERSITY OF WYOMING
NATIONAL PARK SERVICE RESEARCH CENTER

on

EVALUATION OF WATER QUALITY AND RATE OF SEDIMENTATION IN BIGHORN LAKE, BIGHORN CANYON NATIONAL RECREATION AREA

Submitted by

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EXECUTIVE SUMMARY

Bighorn Reservoir and some of its associated lands are part of the Bighorn Canyon National Recreation Area. The National Park Service rangers managing this area have grown increasingly concerned about two problem areas: siltation of the upper part of the reservoir, and excessive fertilization of the reservoir, especially in the upper half. Both of these problems appeared to be of sufficient magnitude to warrant their definition and evaluation. A cooperative study was initiated in the spring of 1980 between some of the rangers, principally R. Hougham of the Bighorn Canyon National Recreation Area, and the authors (Lee and Jones). The project was originally approved to have three years of funding. Funds, however, were abruptly shut off in the spring of 1981. This report presents the results of the study that was conducted to that time on the siltation and eutrophication-related water quality problems of Bighorn Reservoir.

Bighorn Reservoir was constructed in the late 1960s as a hydroelectric power, agricultural water supply impoundment. It is an approximately 60 mile (96 km) long reservoir located in north central Wyoming, south central Montana. The water in the reservoir is primarily derived from the Shoshone and Bighorn Rivers which drain forest and grazing lands as well as a small amount of irrigated agricultural land. Within the watershed about 3,000 people discharge domestic wastewaters to the Shoshone and Bighorn Rivers. The watersheds of these rivers consist of easily eroded land, principally of volcanic ash origin. This situation results in large amounts of erosional materials being transported to the reservoir. These materials cause the upper parts of the reservoir to be highly turbid and to generally have a muddy appearance. This is especially true in the Horseshoe Bend area of the reservoir which is one of the principal recreation areas of the reservoir.

The National Park Service staff have considered the

construction of a marina and other water-oriented recreational facilities at Horseshoe Bend. They express concern, however, about the rates of siltation in this part of the reservoir since it could interfere with boating. At the time this study was initiated no work had been done on the rate of sediment accumulation within the reservoir. Based on visual sightings during low pool elevation it appeared that sediment was rapidly accumulating in Horseshoe Bend. This study has shown through the use of depth sounding and Bureau of Reclamation sediment range maps that approximately 40 ft (12 m) of sediment had accumulated throughout the Horseshoe Bend region of Bighorn Reservoir. The curtailment of funding at the end of the first year precluded any determination of current rates of sediment accumulation in this area of the reservoir. The morphometric characteristics of Bighorn Reservoir in the Horseshoe Bend region, however, are such that sediment depth in this region may be steady state, where no further sediment accumulation will occur. Just beyond Horseshoe Bend the reservoir depth increases rapidly. Sediment accumulation in that area is of a lesser concern. It is possible that the sediment added to Horseshoe Bend each year from upstream sources is lost to the deeper parts of the reservoir, thereby creating a steady state condition in the sediment accumulation in the Horseshoe Bend region.

Before any further work is done on developing a marina at Horseshoe Bend, it is recommended that a sediment depth monitoring program be initiated which would determine current rates of sediment accumulation in the Horseshoe Bend region. If sediment is continuing to accumulate in this region to any significant extent, then provisions would have to be made to either reduce sediment input to the reservoir in general, and specifically this part of the reservoir, and/or remove sediment by dredging of a navigation channel from the boat landing areas to the deeper parts of the reservoir just beyond Horseshoe Bend.

The eutrophication of Bighorn Reservoir has been a subject of several previous studies. At the time of the dam closure in 1968 a study was conducted by Soltero and others at Montana State University on the limnological characteristics of the reservoir. In 1975 the U.S. Environmental Protection Agency (US EPA) included Bighorn Reservoir as one of the national eutrophication survey waterbodies. Both of these previous studies provide data on the aquatic plant nutrient loads and eutrophication response of Bighorn Reservoir. In 1980 as part of this study a monitoring program was conducted on the amounts of nitrogen and phosphorus added to Bighorn Reservoir by the Shoshone and Bighorn Rivers. Also, the eutrophication-related water quality of the middle and upper parts of the reservoir were monitored. All three sets of data, 1968-1971, 1975, and 1980, clearly show that the Horseshoe Bend region of Bighorn Reservoir is highly eutrophic, with severe blue-green algal blooms occurring during July and August. The eutrophication-related water quality of Bighorn Reservoir near the dam is generally quite good. As expected, the long thin nature of Bighorn Reservoir causes significant longitudinal water quality gradients, with the poorest water quality occurring near the upper end where the Shoshone and Bighorn Rivers enter the reservoir.

The 1980 studies show that phosphorus is the element most likely limiting phytoplankton growth in the reservoir in the summer months. Examination of phosphorus sources for the reservoir shows that it is primarily derived from non point sources such as land runoff, with the grazing and forest lands of the watershed being the dominant sources. Domestic wastewaters and irrigated agriculture represent insignificant, i.e., less than a few percent, sources of total phosphorus for the reservoir. However, the hydrologic characteristics of the upper parts of Bighorn Reservoir and its tributaries are such that most of the phosphorus that enters Bighorn Reservoir has limited impact on eutrophication-related water quality problems that occur each summer in the reservoir.

Phosphorus added to the reservoir during fall, winter and spring is largely transported beyond Horseshoe Bend and therefore does not contribute significantly to the excessive fertilization problems that occur each July and August in the upper part of the reservoir. Further, the large amounts of total phosphorus added to the reservoir during the spring - early summer high flow period for the Shoshone and Bighorn Rivers is in a particulate form which is not readily available to support algal growth. A good correlation was found between the soluble orthophosphate loads to Bighorn Reservoir during July and August of the three study periods for which there is data and the planktonic algal chlorophyll found at Horseshoe Bend. While domestic wastewater inputs represent an insignificant part of the total annual phosphorus loads to the reservoir, they are a significant source of the soluble orthophosphate loads during July and August. It is possible that removal of soluble orthophosphate from the domestic wastewaters could reduce the magnitude of the planktonic algal blooms which cause significant water quality deterioration in the upper parts of Bighorn Reservoir.

The results of the U.S. Organization for Economic Cooperation and Development (US OECD) eutrophication study program provide a basis by which it will be possible to ascertain the impact of removal of phosphorus during the summer months from municipalities discharging wastewaters to the Bighorn and Shoshone Rivers. The abrupt curtailment of funds at the end of the first year prevented the implementation of studies designed to obtain the data necessary for use in conjunction with the OECD eutrophication study results from this reservoir. Of particular importance is the need for information on the current morphological characteristics of Bighorn Reservoir above Horseshoe Bend. The rapid siltation that has occurred in this part of the reservoir prevents the use of the original U.S. Geological Survey (USGS) and Bureau of Reclamation maps of the reservoir prepared prior to dam closure.

The key to applying the OECD eutrophication study program results to the impact of altering phosphorus loads to Bighorn Reservoir is information on the hydraulic residence time, mean depth, and available phosphorus loads. These characteristics, loads and sources were to be ascertained during the second and third years of this project. However, a shift in funding priorities by the University of Wyoming National Park Service Research Center prevented the acquisition of the data necessary to determine the impact that controlling any particular phosphorus load, such as that associated with a particular municipality's domestic wastewater effluent, on the eutrophication-related water quality in various parts of Bighorn Reservoir. Information on the morphologic, hydrologic characteristics of the upper half of Bighorn Reservoir and the amounts of available phosphorus derived from various potentially controllable sources must be collected in order to formulate a technically valid, cost-effective eutrophication-related water quality management program for Bighorn Reservoir. It is possible that selective phosphorus removal from domestic wastewater sources and the selective application of alum to the Horseshoe Bend region of the reservoir could significantly improve the eutrophication-related water quality of this part of the reservoir at a relatively small cost.

PREFACE

In the spring of 1980 the National Park Service Research Center at the University of Wyoming approved the initiation of a research project devoted to water quality management in the Bighorn Canyon National Recreation Area. The total funding involved was $10,000 per year and the project was scheduled to be a three year project with review of progress to take place each year and renewal to be granted if funds and satisfactory progress were available and achieved. In accord with the proposal submitted for funding, this project was to follow a course of effort in which shortly after award of funds the principal investigators (G. Fred Lee and R. Anne Jones) would meet with the supervisor and his recreation area ranger staff to discuss water quality problems at Bighorn Reservoir and formulate a research plan to utilize the funds available to develop the technical base of information that could be used to minimize and where possible solve these problems. At this meeting with H. Rouse and his staff in April 1980 it was ascertained that the greatest problem of concern to management of the Bighorn recreation area was what appeared to the area rangers to be excessive sediment accumulation in the Horseshoe Bend region of the reservoir. This area of the reservoir is extensively used by Wyoming residents for boat-oriented recreation. Consideration is being given to developing a major marina at this location. Excessive siltation in this region could significantly impair marina development. It was decided that the highest priority be given in this study to sediment accumulation extent in the Horseshoe Bend region.

The second most important problem for the use of the reservoir and recreation area is excessive fertilization of the upper half of the reservoir, especially in the region of Horseshoe Bend. Discussions with area rangers and a review of the literature yield that the water during late summer in this region was a pea-soup green character and that there were questions raised about the human safety related to allowing swimming at the beach of Horseshoe Bend. The overall approach with respect to this problem was to use the funds available after defining sediment accumulation in the Horseshoe Bend area to initiate a monitoring program on nutrient sources and impact on the reservoir with the cooperation of R. Hougham, District Ranger at the south end of the reservoir at Lovell. A monitoring program was initiated in December 1980, in which samples of water were taken of the two major tributaries to the reservoir as well as at Horseshoe Bend and about mid-lake and shipped via bus to Fort Collins for analysis. While desirable, sampling near the dam was not necessary since it was rare that eutrophication-related water quality problems occurred in that part of the waterbody. The source of nutrients for the lake were the tributaries near the south end where the problems were primarily manifested.

This report presents the results of the study that was conducted during the first budget year of this project. The project was supported in part, less than 30 percent of the total funding, from a grant from the University of Wyoming National Park Service Research Center. The remainder of support was derived from the Department of Civil Engineering, Colorado State University, and EnviroQual Consultants and Laboratories, Fort Collins, Colorado. Special recognition must be given to R. Hougham and his associates of the Bighorn Canyon National Recreation Area, Lovell, Wyoming for sampling and data acquisition. Without his assistance and voluntary contributions of time the nutrient source eutrophication monitoring program that was undertaken would not have been possible. Special note should also be given to the assistance of H. Rouse who, until he transferred to another position at another National Park Service facility, provided valuable support for this study.

The assistance of Jose Ortiz, Juan Avilés and Jerry Snyder in conducting the bathymetric surveys of sediment accumulation in Horseshoe Bend was greatly appreciated. Several members of the Water Power and Resources Service staff also provided valuable assistance in this project. Of special note is the assistance by Rick Gold, Regional Hydrologist of the Billings, Montana office and Jim Thomas of the Services Research Center in Denver.

Various members of the U.S. Geological Survey staff provided valuable assistance by making available data on stream flows and other characteristics of the tributaries of the Bighorn Reservoir. The assistance of C. Cooper of the State of Wyoming Engineers Office in providing information on the irrigation diversions from the Bighorn and Shoshone Rivers is greatly appreciated. Another person who deserves a special note of gratitude for assisting in this project is J. Wagner of the Wyoming Department of Environmental Quality who provided information on past and current populations and flows of point source discharges to the Bighorn and Shoshone Rivers and/or their tributaries. Also, E. Fanning of that department critical review of this report is greatly appreciated. The assistance of Dr. R. Soltero in making available reprints, reports and his PhD dissertation is also appreciated.

G. Phillips of the State of Montana Water Quality Bureau assistance in providing a draft report covering the work he had conducted at Montana State University on the mercury content of fish collected in Bighorn Reservoir is greatly appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

PART A

INTRODUCTION

The research plan for this study involved three phases of activity. The first of these was to be a site visit to the area to discuss with National Park Service Bighorn Canyon National Recreation Area staff, water quality problems of Bighorn Reservoir. The second phase of this project was to conduct a critical review of the previous studies that are pertinent to the water quality problem area of Bighorn Reservoir. The third phase of the project was to be devoted to utilizing the limited funds available to gather additional information on the nature of the water quality problems of Bighorn Reservoir and their causes. Therefore, the first year was largely devoted to problem definition, while the second and third years were to be devoted to problem refinement and developing approaches for problem solution. This chapter presents a summary of the site visit to the Bighorn Canyon National Recreation Area, made for the purpose of determining the nature of the water quality problems in Bighorn Reservoir. Subsequent chapters of this report present the results of the first year's effort in this project.

WATER QUALITY PROBLEMS OF BIGHORN RESERVOIR

In April 1980, shortly after funds became available to initiate this project, a site visit was made to Bighorn Canyon National Recreation Area. During this visit, extensive discussions were held with area rangers and their supervisor, H. Rouse, concerning water quality problems of the reservoir. Subsequent to this visit contacts were made with several individuals in Wyoming and Montana who might provide information on water quality problems and management in Bighorn Reservoir. Based on a review of the information obtained, it was concluded that there are two substantial water quality problems of this reservoir that deserve immediate attention. These are excessive siltation (sediment accumulation) in the upper parts of the reservoir and excessive fertilization (eutrophication) in the upper half of the reservoir. It is clear that both siltation and eutrophication of the upper Wyoming part of the reservoir are of sufficient magnitude to cause impairment of beneficial uses of the reservoir for visitors to Bighorn Canyon National Recreation Area.

SILTATION

Many of the rangers who have been at Bighorn Canyon National Recreation Area for many years indicated that they felt they could perceive a rapid filling of the upper parts of the reservoir over the past few years. This was especially evident in the Horseshoe Bend area of the reservoir. They were concerned that if the siltation continued at the rate which they perceived it was occurring it might significantly impair the ability of the public to use the Horseshoe Bend region of the reservoir. Since this area is one of the prime recreation areas of the reservoir, this situation could represent a significant detriment to further development and even continued maintenance of established recreational uses of this area by the public.

According to the rangers, preliminary plans were being developed to construct a major recreational marina complex at Horseshoe Bend. The apparent high rates of siltation in this region, however, were sufficient to cause question of the advisability of construction of additional water-oriented facilities, such as a marina in the Horseshoe Bend area, since further siltation could cause these facilities to be of limited use without an extensive sediment removal program. It was obvious that an estimation of the amount of siltation that had occurred in the Horseshoe Bend region was needed. Further, there is need to initiate a program to determine the current rates of sediment accumulation in the Horseshoe Bend area. Part A of this report presents the results of the studies on sediment accumulation in the Horseshoe Bend region of Bighorn Reservoir.

EUTROPHICATION

The eutrophication problems of Bighorn Reservoir seem to be focused in the Horseshoe Bend region of the reservoir. The rangers characterized water in this part of the reservoir during some summers as "pea-soup green, with strong offensive odors, and some floating algal scum." The growth of planktonic algae has been sufficient in some summers to cause H. Rouse to consider closing the beach in the Horseshoe Bend area because of alleged public health implications of excessive algae. It appeared that the eutrophication-related water quality problems were significantly diminished as one proceeded down the reservoir. Some problems were noted at Barry's Landing, while few problems of this type were reported near the dam. It was obvious that what was needed was a determination of the current trophic state of the upper parts of the reservoir, a definition of the factors primarily limiting algal growth in these areas, and a determination of the aquatic plant nutrient loads and specific sources for the reservoir. Part B of this report presents the results of the studies that have been done on eutrophication in Bighorn Reservoir.

OTHER WATER QUALITY PROBLEMS

From discussions with pollution control officials and others in Wyoming and Montana, it does not appear that this reservoir has other major water quality problems. Of primary concern is the sports fishery. There appears to be no evidence of toxic chemical limitation of this fishery through either toxicity to fish or impairment of their reproduction. While the data available was very limited, it did not appear that there were any problems with the wholesomeness of the fish which would render them unsuitable for use as human food because of the accumulation of toxic chemicals within their tissue. It was therefore decided that the limited funds made available for this project would be devoted to work on the two readily identifiable water quality problems of the reservoir, excessive siltation and eutrophication. No attempt would be made to try to define other water quality problems during the first year of this project. Work in this area would be considered during the second and third years of this project if at some subsequent time it was found that funds were available for this purpose.

PART B

SEDIMENT ACCUMULATION IN HORSESHOE BEND AREA OF BIGHORN RESERVOIR

The Bighorn Canyon National Recreation Area rangers indicated that sediment accumulation in the Horseshoe Bend area of Bighorn Reservoir was the water quality problem of greatest concern to them. Their concern centered around navigability of that part of the reservoir. It was quickly found after initiating this project that no one had been systematically making measurements of water depth in the Horseshoe Bend region, and therefore, there were no historical records of sediment accumulation for that area of the reservoir. However, shortly after initiating this project, it was learned that the Bureau of Reclamation had, prior to closing the dam for Bighorn Reservoir, prepared a series of sediment range maps of the Bighorn River and its "flood plain" which would be inundated with the establishment of the reservoir. These range maps, showing the elevations of the land across various cross sections or transects across the river and flood plain, were referenced to benchmarks established using precise surveying techniques on both sides of the river above the full pool elevation of the projected impoundment. Copies of these sediment range maps were obtained; these would be useful in determining sediment deposition in the reservoir since the closing of the dam.

In June 1980 a field study team consisting of six individuals conducted a study to determine the current water depth - sediment contour at selected locations in the Horseshoe Bend region of the reservoir for comparison with elevations presented in sediment range maps. The Bureau of Reclamation benchmarks in the Horseshoe Bend area were located by positioning individuals at both benchmarks for a particular transect and having several individuals in a boat on the reservoir determine through line-of-sight navigation and range finders the location of the Bureau of Reclamation's transect and the boat's position along the transect. By measuring the water depth at known positions along each of the transects in the Horseshoe Bend area (Figure 1) using a metered line and weight, the current sediment contour was determined.

Figures 2 through 5 show the sediment accumulation at the Horseshoe Bend transects over the past 13 years, since closing of the dam. These figures illustrate the fact that in some areas of Horseshoe Bend as much as 12 m of sediment have accumulated during this time, a rate which, if maintained, could have serious ramifications on the recreational use of the Horseshoe Bend area of Bighorn Reservoir. Figure 6 shows the sediment accumulation in the old river bed between sediment ranges 14 and 17 and indicates that the sediment appears to have deposited primarily in the bend area, with substantially less deposition as the reservoir narrows at sediment range 14.

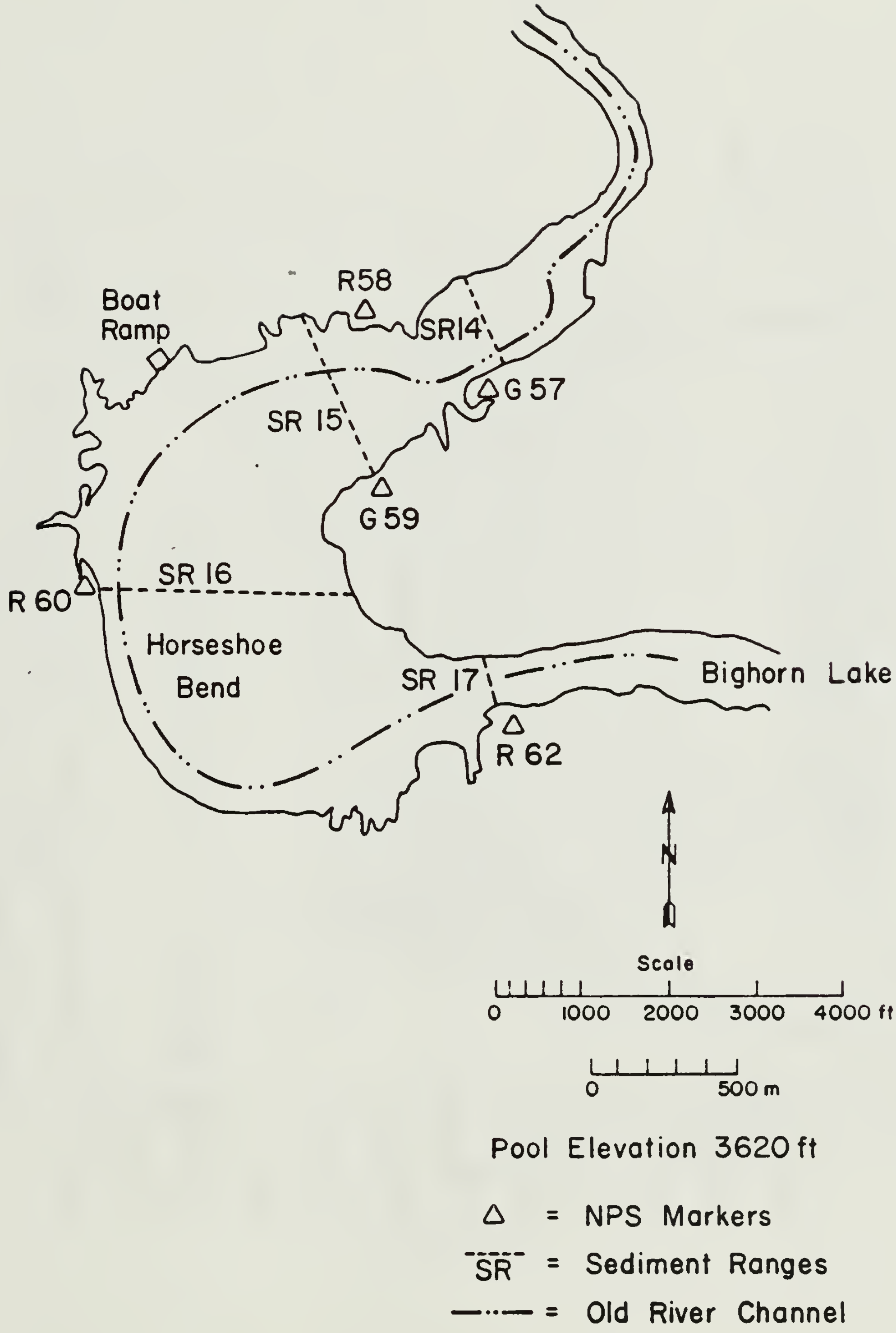


Figure I. Horseshoe Bend area of Bighorn Lake

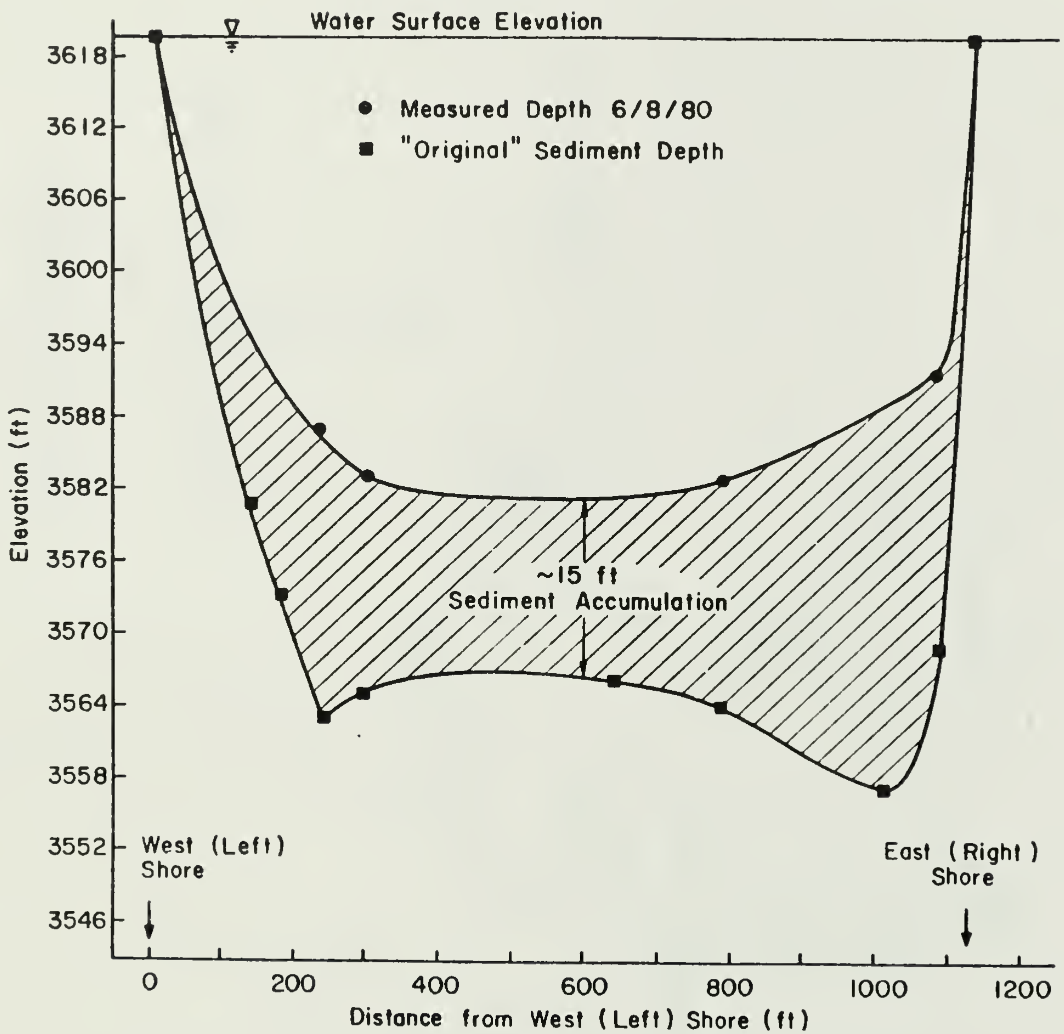


Figure 2. Sediment profiles at SR 14

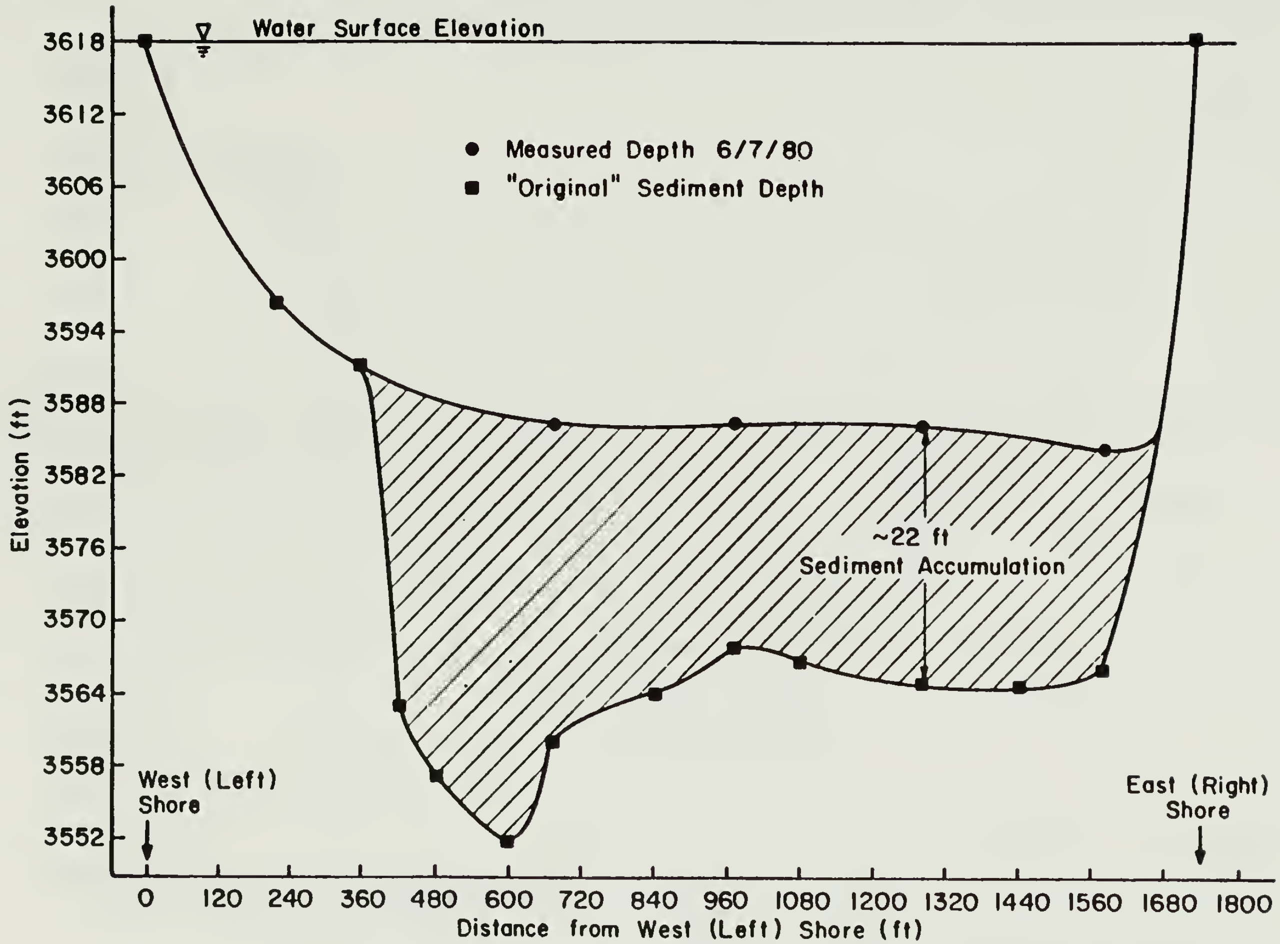


Figure 3. Sediment profiles at SR 15

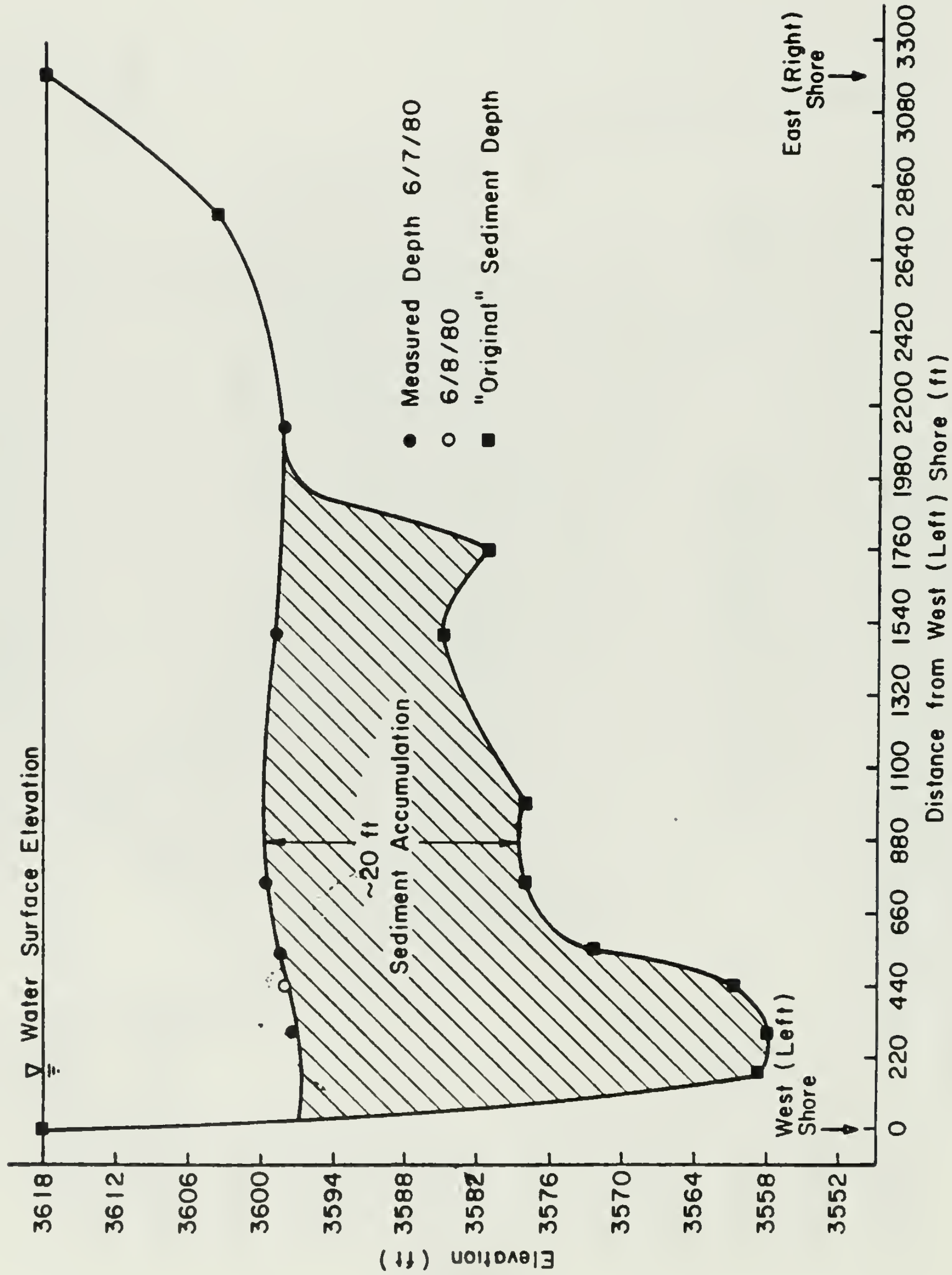


Figure 4. Sediment profiles at SR 16

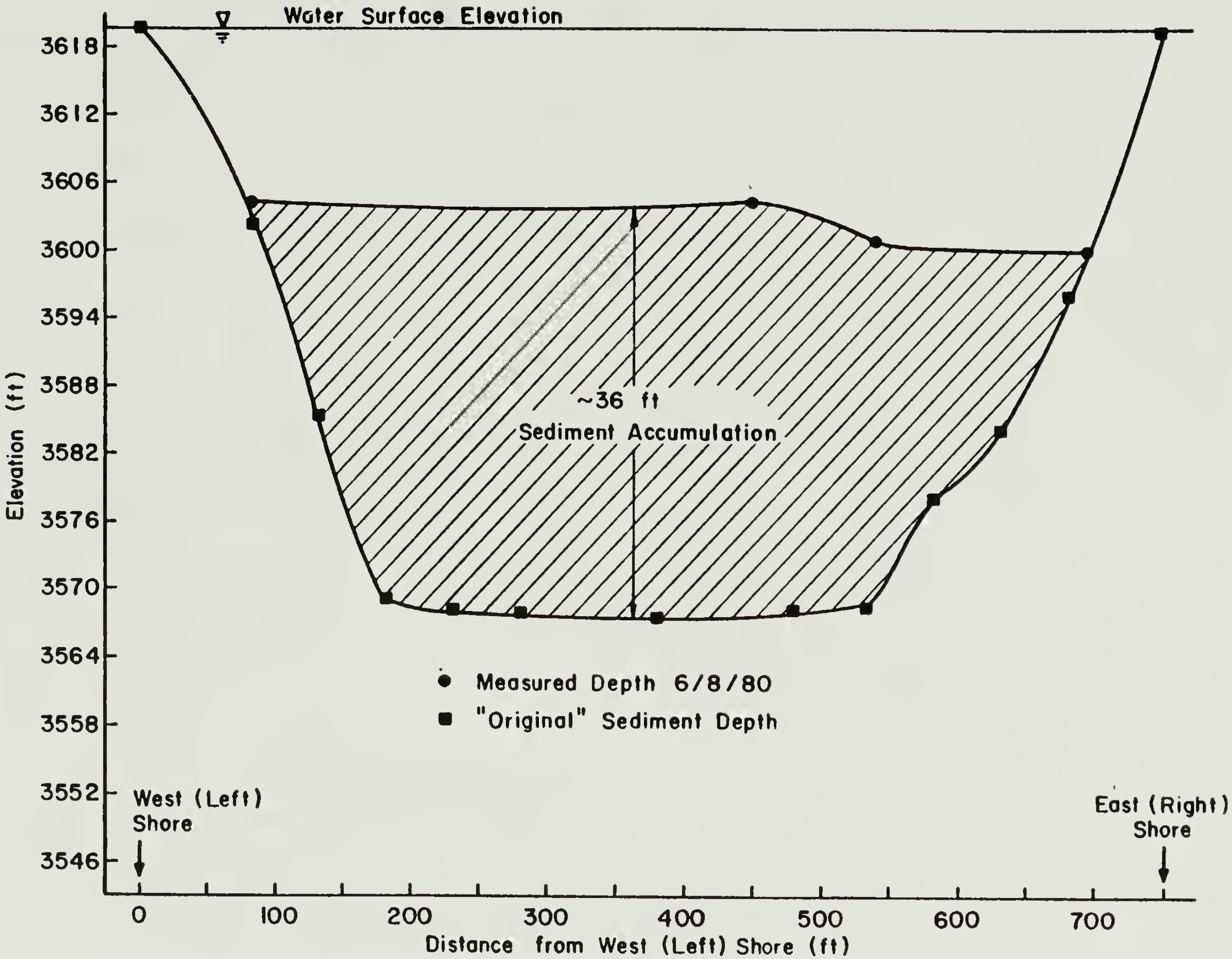


Figure 5. Sediment profiles at SR 17

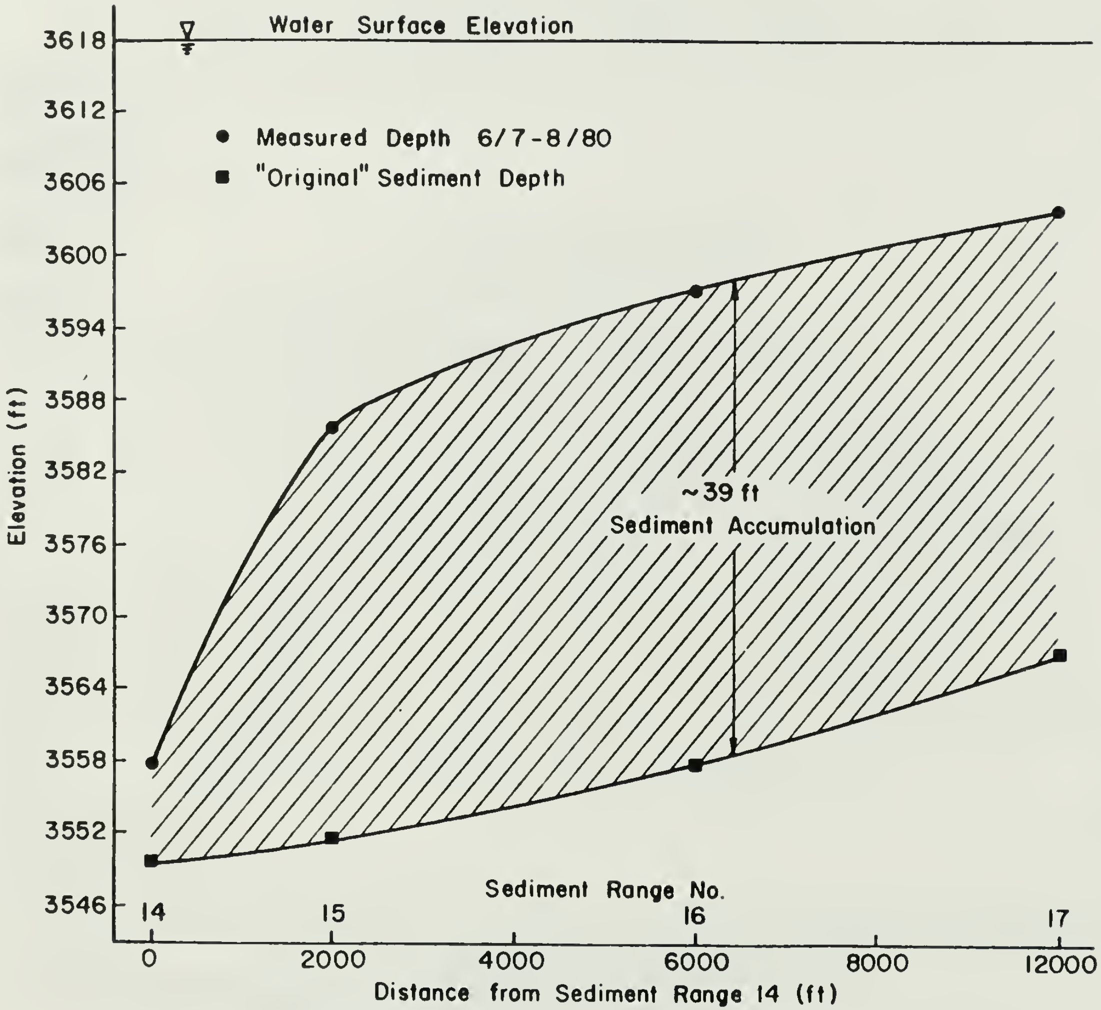


Figure 6. Sediment profile down old river channel

DISCUSSION

It is evident from the results of this study that the Bighorn Canyon National Recreation Area rangers' observations that there appears to be rapid sediment accumulation in the Horseshoe Bend area were correct. Since there appeared to be accumulation of over a meter per year of sediment in some parts of this area, this is of concern and raises serious questions about the advisability of future capital expenditures for increased National Park Service facilities at Horseshoe Bend.

There are several aspects of this situation that need to be considered. First, one should not extrapolate the average sediment accumulation rate over the past thirteen years to future situations. Sediment deposition patterns in the upper ends of new reservoirs are highly variable and depend on many factors. This would be especially true in the Horseshoe Bend region since the character of the reservoir changes just below the bend. At the "narrows" just below the Horseshoe Bend water depth increases significantly and the width of the canyon is much less. As shown in Figure 6, sediment accumulation at the narrows is only about 3 m. It is highly likely that once sediment gets to the narrows it will not accumulate there to any significant extent but will be transported on down the reservoir. It is also possible that sediment accumulation within Horseshoe Bend is at or near steady state. While it would be expected that sediment accumulation in this area would vary from year to year, from a longer term period, i.e., a 5 to 10 year period, the sediment added from upstream sources will be passed on down reservoir. Actually, it is likely that there might be sediment accumulation in that area over the year or over several years which would give the appearance of long term sediment buildup. However, associated with a major storm and/or high river flow conditions, especially under low pool elevation, most of the recently accumulated sediments would slough off and be carried out of Horseshoe Bend down the canyon beyond the narrows.

It is evident that the National Park Service should initiate a water depth monitoring program where once a month during the summer the depth of the water under known pool elevations should be measured at selected locations in Horseshoe Bend and just upstream and downstream thereof. A simple fathometer of the type used by fishermen, costing a few hundred dollars, would provide sufficient reliability for these measurements. A weight on the end of a graduated line would serve this purpose equally well. Precise positioning in the reservoir is not needed since in general the accumulated sediment forms a fairly flat surface in which readings taken at one location are the same as those taken tens to hundreds of meters away. The exception to this is in the region of rapid accumulated sediment dropoff shown in Figure 6. This occurs on the north side of Horseshoe Bend. In this region marker buoys or on-shore stations, which can be readily seen from a boat, should be used to locate the position of sediment - water depth measurements. A hand-held sextant or line-of-sight with shoreline markers would be adequate for this purpose. It is recommended that these measurements be made along the old river channel. The reason for following this route is that it would likely be the path of most boats leaving Horseshoe Bend boat ramp who are going into the canyon through the northern narrows. Marker buoys placed a few hundred meters apart located along the old channel would provide a convenient method of providing depth measurements within the reservoir. During the winter the above-surface buoys could be removed and replaced with a wooden pole in order to prevent ice damage to them.

POSSIBLE REMEDIAL PROGRAMS

Funding of the second and third years of this project as originally planned would, in addition to making several years' measurements on sediment accumulation in Horseshoe Bend, have enabled further exploration of methods for alleviating the sediment accumulation problem. A limited amount of work was done in this area during the first budget period. While preliminary, it does not appear that sediment control at the source is a viable remedial measure. Further information on the sources of sediment and possible remedial control measures for Bighorn Reservoir is provided in the 208 Water Quality Management Plan (Cooper, 1979). At the request of the principal investigators the Bureau of Reclamation Water Power Research Center staff in Denver conducted a preliminary investigation involving the feasibility of using a preimpoundment to trap sediment before it gets to Horseshoe Bend. According to J. Thomas this does not appear to be feasible because of the large spillway that would be needed to pass some of the high flows that occur in the tributary rivers. If funds had been made available, another area that would have been investigated is the dredging of a channel between the Horseshoe Bend boat ramp and the lower narrows. Such dredging could become a regular procedure of the National Park Service. This approach would probably be the most economical over time.

PART C

EUTROPHICATION

REVIEW OF PREVIOUS STUDIES ON BIGHORN RESERVOIR

There have been a number of studies on Bighorn Reservoir that provide data that is pertinent to water quality management in this waterbody. A summary of the key findings of these studies is presented below.

In 1968, 1969 and 1970, Soltero (1971) conducted limnological surveys of Bighorn Reservoir. This work represented the PhD dissertation of Soltero. It was conducted under the supervision of Dr. John C. Wright of the Department of Botany at Montana State University. The study consisted of detailed monitering of the major tributary inputs and of the reservoir during all or part of 1968, 1969 and 1970. Key parts of the data which are pertinent to this investigation are reproduced in this report.

Another fairly comprehensive study of Bighorn Reservoir and its tributaries was conducted in 1975 by the U.S. Environmental Protection Agency (US EPA) as part of their National Eutrophication Survey.

In the early to mid 1970s the US EPA conducted studies on approximately 800 lakes and impoundments located in various part of the U.S. One of these waterbodies was Bighorn Reservoir. The US EPA called Bighorn Reservoir Yellowtail Reservoir. The report covering this work was published by the US EPA (1977a).

Based on the experience of the investigators (Lee and Jones), the US EPA National Eutrophication Survey studies on a waterbody generally provided reliable estimates of nutrient (nitrogen and phosphorus) loads to a waterbody. However, in many instances because of the limited sampling program used during the summer months, where normally only one set of samples was collected for this period, the characterization of the waterbody's eutrophication response was sometimes poorly done. Therefore, caution must be used in interpreting the US EPA lake or reservoir data since it may not properly represent the trophic conditions during the year of the study. The authors and their associates have developed a number of techniques which enable evaluation of the reliability of waterbody data based on the results of the U.S. Organization for Economic Cooperation and Development (OECD) eutrophication study. In the early 1970s the U.S. and about 20 other countries in Western Europe, North America, Japan and Australia initiated a 5 year, 200 waterbody study designed to investigate the nutrient load eutrophication response relationships for lakes and reservoirs. The U.S. part of this study consisted of approximately 40 waterbodies or parts thereof which were examined for a variety of phosphorus load eutrophication response relationships. Rast and Lee (1978) authored a US EPA report covering the U.S. part of the OECD eutrophication studies. Lee et al. (1978) have published a summary of the key findings in the US OECD eutrophication studies.

Basically, it was found that a normalized phosphorus load to a waterbody (lake or impoundment) could be used to predict the waterbody's planktonic algal chlorophyll, Secchi depth and hypolimnetic oxygen depletion rates. Recently, Jones and Lee (1981) have updated the US OECD eutrophication study data and have approximately doubled the number of waterbodies that have been found to fit the phosphorus load eutrophication response relationships developed by Rast and Lee (1978). Further, these relationships have been expanded by Lee and Jones (1979) to correlate fish yield to its normalized phosphorus load. These relationships are shown in Figures 7 and 8. As discussed by Rast and Lee (1978), Lee et al. (1978) and Jones and Lee (1981), the relationships shown in these figures can be used as a basis to predict the impact of altering phosphorus loads to a waterbody on the waterbody's eutrophication-related water quality. Discussed in a subsequent section of this report is the application of this approach to the management of excessive fertilization of Bighorn Reservoir.

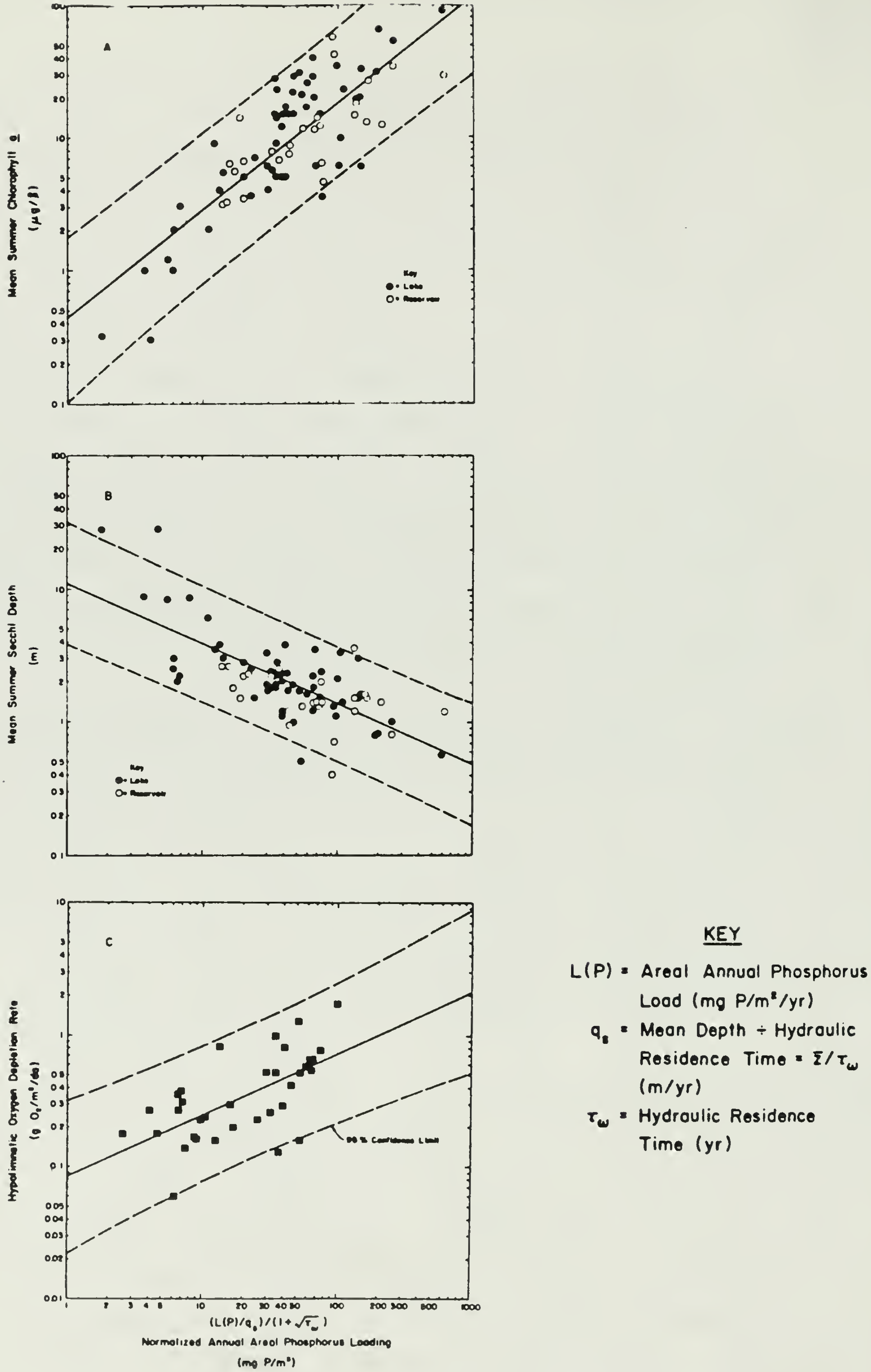
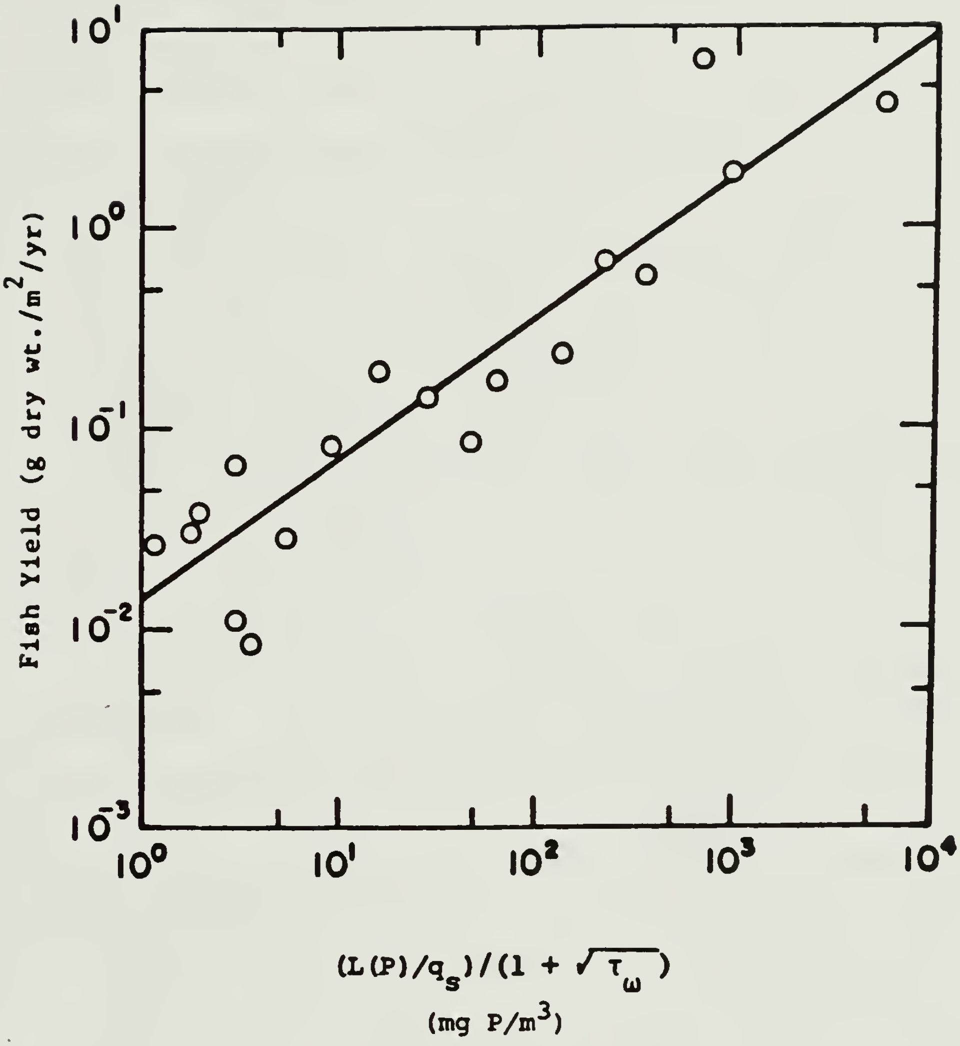


Figure 7. Updated P load - eutrophication-related water quality response relationship for U.S. waterbodies (After Jones and Lee, 1981)



Line of best fit:

$$\text{Log Fish Yield} = 0.7 \log [(L(P)/q_s)/(1 + \sqrt{\tau_\omega})] - 1.86$$

$(r^2 = 0.86)$

Figure 8. Relationship between normalized P load and fish yield (After Lee and Jones, 1979)

CHARACTERISTICS OF BIGHORN RESERVOIR WATERSHED

Data pertinent to the application of the US OECD eutrophication modeling results to Bighorn Reservoir were presented by the US EPA (1977a). Selective parts of this data are presented in Table 1. A map developed by the US EPA is shown in Figure 9. This figure shows the tributary and lake sampling sites used by the US EPA in their 1975 National Eutrophication Survey.

Table 1 shows that the primary tributaries to Bighorn Reservoir are the Bighorn and Shoshone Rivers. Almost 90 percent of the flow to the reservoir is derived from these two tributaries. As shown in Figure 9, both of these tributaries enter at the south end of the reservoir. Both tributaries have impoundments located in their headwaters which would play an important role in reducing phosphorus loads to the reservoirs from the headwater areas. For example, Boysen Reservoir was studied by the US EPA (1977b) as part of the National Eutrophication Survey. It was found that this reservoir removes about 90 percent of the phosphorus entering from its tributaries. If Boysen Reservoir was not present, the total phosphorus load to Bighorn Reservoir would increase significantly.

Tables 2 and 3 present the US EPA's estimates of phosphorus inputs of domestic and industrial wastewater to the Bighorn Reservoir. Similar data is presented for nitrogen loads in Table 4. The US EPA, in setting up the National Eutrophication Survey, arbitrarily selected a distance from the reservoir beyond which they would not monitor domestic and industrial wastewater inputs. This means that the phosphorus input from the towns of Powell, Cody, Worland and Thermopolis is incorrectly listed in the EPA report as being part of the non point source phosphorus load. The study planned for the second year of this investigation called for a detailed evaluation of the potential significance of these towns' wastewater discharges as factors contributing to the excessive

TABLE 1. CHARACTERISTICS OF BIGHORN RESERVOIR

Reservoir and Drainage Basin Characteristics

Morphometry*:

Surface area: 51.34 kilometers^2

Mean depth: 26.8 meters

Maximum depth: 146.3 meters

Volume: 1,375.912 x 10^6 m^3

Mean hydraulic retention time: 158 days (based on outflow)

Tributary and Outlet:

Tributaries -

Name	Drainage area (km^2)*	Mean flow (m^3/sec)*
Bighorn River	40,831.3	64.66
Shoshone River	6,086.5	29.48
Dry Head Creek	197.6	0.30
Crooked Creek	300.4	0.30
Minor tributaries & immediate drainage	3,470.4	11.44
Totals	50,886.2	106.18

Outlet -

Bighorn River	50,937.5	100.78

Precipitation:

Year of sampling (1975): 50.7 centimeters

Mean annual: 40.3 centimeters

(After US EPA, 1977a)

*Anesi (1975)

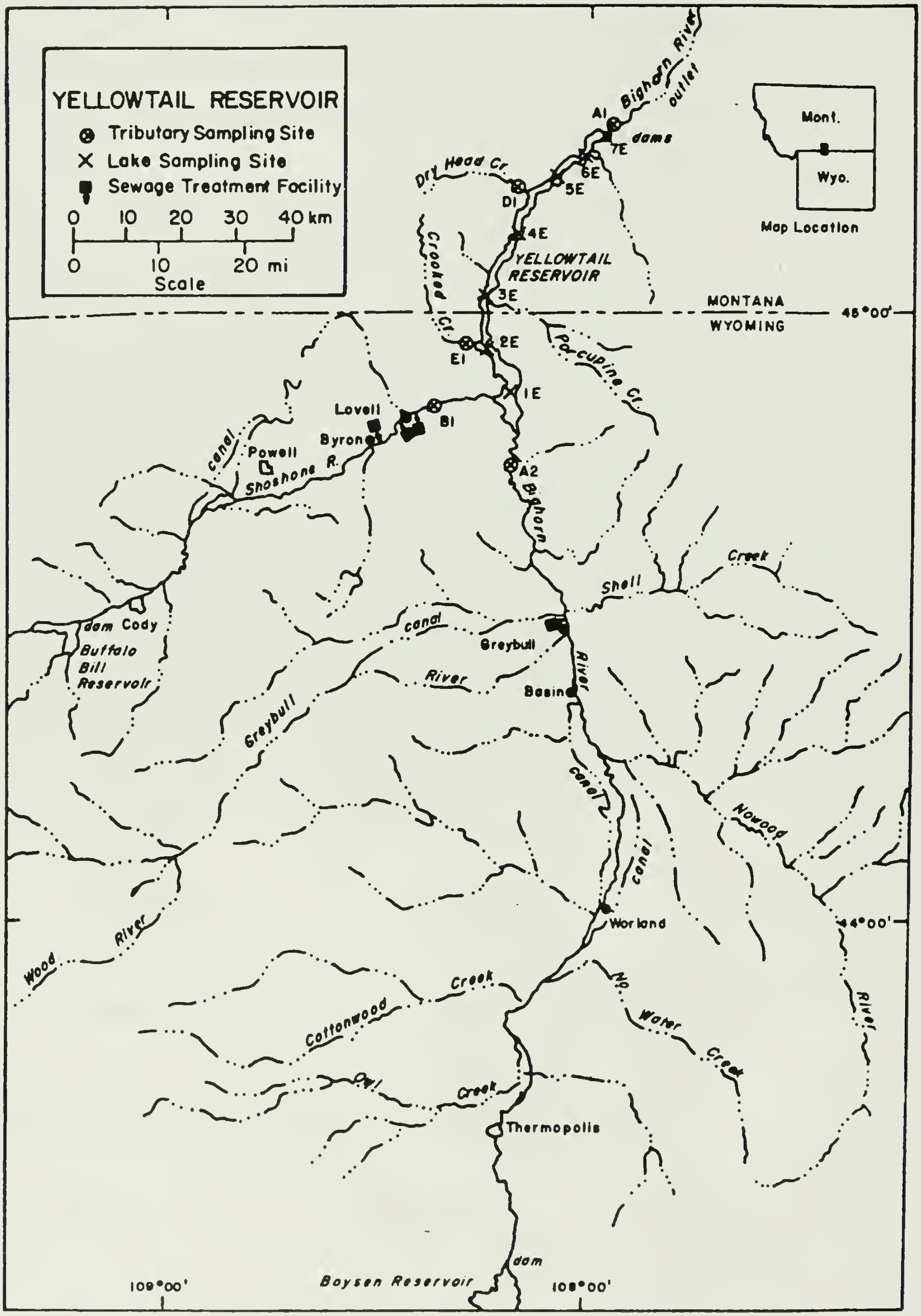


Figure 9. Map of the Bighorn Reservoir watershed (After US EPA, 1977a)

TABLE 2. DOMESTIC AND INDUSTRIAL WASTEWATER SOURCES FOR BIGHORN RESERVOIR

Known Municipal:

Name	Pop. Served	Treatment	Mean Flow (m^3/d)	Receiving Water
Greybull	140	stab. pond	770.8	Bighorn River
Byron	400	stab. pond	1,412.7	Shoshone River
Lovell	2,371	stab. pond	1,514.2	Shoshone River

Known Industrial:

Name	Type Waste	Treatment	Mean Flow (m^3/d)	Receiving Water
Great Western Sugar Co., Lovell	sugar processing	none	20,030.2	Shoshone River

(After US EPA, 1977a)

TABLE 3. US EPA DETERMINED PHOSPHORUS LOADING - 1975

Annual Total Phosphorus Loading - Average Year:

Inputs -

Source	kg P/yr	% of total
Tributaries (non point load) - considered by US EPA		
Bighorn River	671,595	64.1
Shoshone River	345,055	32.9
Dry Head Creek	1,195	0.1
Crooked Creek	480	<0.1
Minor tributaries & immediate drainage (non point load) -	20,820	2.0
Known municipal STP's* -		
Greybull	1,015	0.1
Byron	1,610	0.2
Lovell	3,430	0.3
Septic tanks - Unknown	?	-
Known industrial -		
Great Western Sugar Co.	2,125	0.2
Direct precipitation -	900	0.1
Total	1,048,225	100.0

Outputs -

Reservoir outlet - Bighorn River 66,965

Net annual P accumulation - 981,260 kg

(After US EPA, 1977a)

*STP - sewage treatment plant

TABLE 4. US EPA DETERMINED NITROGEN LOADING - 1975

Annual Total Nitrogen Loading - Average Year:

Inputs -

Source	kg N/yr	% of total
Tributaries (non point load) -		
Bighorn River	3,085,225	57.7
Shoshone River	1,880,125	35.2
Dry Head Creek	13,670	0.3
Crooked Creek	8,855	0.2
Minor tributaries & immediate drainage (non point load) -	239,460	4.4
Known municipal STP's*-		
Greybull	2,335	<0.1
Byron	4,940	0.1
Lovell	8,560	0.2
Septic tanks - Unknown	?	-
Known industrial -		
Great Western Sugar Co.	48,840	0.9
Direct precipitation -	55,425	1.0
Total	5,347,435	100.0
Outputs -		
Reservoir outlet - Bighorn River	5,064,620	

Net annual N accumulation - 282,815 kg

(After US EPA, 1977a)
*STP = sewage treatment plants

fertilization of Bighorn Reservoir. This point is discussed further in a subsequent section of this report.

According to R. Brenten of Great Western Sugar Company (1981), their Lovell facilities no longer discharge wastewaters to the Shoshone River. The discharges at this time are limited to cooling water to which they add no phosphorus. Therefore, the US EPA's 1975 measured phosphorus loads due to Great Western Sugar of 2,125 kg P/year are no longer occurring.

Examination of Tables 2 and 3 shows that in 1975 less than 1 percent of the annual phosphorus load entering Bighorn Reservoir was derived from US EPA measured point sources. Since, as discussed below, in general there is little or no possibility of significantly controlling non point source phosphorus loads, this situation means that conventional eutrophication control methods will have little impact on the eutrophication-related problems of Bighorn Reservoir.

Fanning of the Wyoming Department of Environmental Quality, Water Quality Division, has indicated (personal communication, 1982) that "there is a possibility of reducing the high phosphorus load attributed to Bitter Creek if irrigation efficiency and fertilization rates are improved as a result of the Bitter Creek Demonstration Project being conducted at the Powell Research and Extension Center. This project, therefore, addresses approximately 11% of the total phosphorus load carried by the Shoshone River." Fanning feels that by disseminati .. of research information on irrigation efficiency, fertilization rates based on soil and plant tissue tests and minimum tillage concepts that a substantial reduction in phosphorus loads to Bighorn Reservoir can be achieved. It is important, however, to emphasize as discussed by

Lee *et al*. (1980) that non point source phosphorus control programs be directed towards controlling algal available forms of phosphorus that are causing the excessive fertilization of Bighorn Reservoir. As discussed elsewhere in this report, substantial parts of the total phosphorus added to Bighorn Reservoir are in particulate forms which are expected to be largely unavailable in supporting algal growth in Bighorn Reservoir.

The US EPA (1977a) has developed nutrient land use export coefficients for various parts of the Bighorn Reservoir watershed. The values are presented in Table 5. Also presented in Table 5 are the nutrient land use export coefficients developed by Rast and Lee (1978) as reported by Lee *et al*. (1978) and Jones and Lee (1981). It is of interest to compare the US EPA derived nutrient land use export coefficients for the Bighorn Reservoir Watershed with those developed by Rast and Lee for the US OECD eutrophication study waterbodies. Based on a site visit to the Bighorn and Shoshone River watersheds, it was found that they are predominantly forest-prairie with a small strip of irrigated agriculture along the rivers. Much of the prairie is grazed by cattle. This should give a nutrient land use export coefficient for the watershed between the Rast and Lee coefficients for forest and agriculture with forest predominating. J. Rawlings, personal communication, U.S. Department of the Interior, Bureau of Reclamation (1980) estimated that there are approximately 64,544 irrigated acres in the Shoshone River Basin, 117,255 irrigated acres in the Bighorn River Basin between Boysen Reservoir and Bighorn Reservoir, and 64,544 irrigated acres in the Greybull River Basin. Examination of Table 1 shows that for the Shoshone River Basin the irrigated acreage is about 4 percent of total land area within the Shoshone

TABLE 5. NON POINT NUTRIENT EXPORT COEFFICIENT

Estimated by the US EPA:

Tributary	Export Coefficient $gP/m^2/yr$	Export Coefficient $gN/m^2/yr$
Bighorn River	0.016	0.076
Shoshone River	0.057	0.309
Dry Head Creek	0.006	0.069
Crooked Creek	0.002	0.029

(After US EPA, 1977a)

Estimated by the US OECD:

Land Use	Export Coefficient $gP/m^2/yr$	Export Coefficient $gN/m^2/yr$
Urban	0.1	0.5 (0.25)*
Rural-agriculture	0.05	0.5 (0.2)*
Forest	0.01	0.3 (0.1)*

(After Jones and Lee, 1981)

*Values applicable to the west coast and Rocky Mountain region

River Basin. For the Bighorn River Basin the irrigated area is about 1 percent of the total land use. Examination of Table 5 shows that the phosphorus and nitrogen nutrient export coefficients, as measured by the US EPA, for the Bighorn and Shoshone Rivers are in the appropriate range of values that are predicted by Rast and Lee (1978) and Jones and Lee (1981).

It is evident that the phosphorus loadings to the Bighorn Reservoir during 1975 as measured by the US EPA are in accord with those expected based on land use in the reservoir's watershed. Rast and Lee (1978), utilizing an approach suggested by Vollenweider (1976), have shown that for waterbodies in which the phosphorus load is rapidly mixed throughout the waterbody, i.e., bowl-shaped waterbodies, that the reliability of the phosphorus load can be checked by the relationship shown in Figure 10. As discussed by Rast and Lee (1978) and Jones and Lee (1981), in order to apply this relationship to a long, thin waterbody of the Bighorn Reservoir type, it is necessary to estimate the hydraulic residence time of the various parts of the waterbody. Of particular concern in Bighorn Reservoir is the area of most intense use from Barry's Landing southward. For most reservoirs, a bathymetric map of water depth coupled with flow information for the tributaries provides an adequate basis for estimating hydraulic residence time for various parts of the reservoir. In the case of Bighorn Reservoir, however, the very high sediment accumulation (12 m in 13 years in some locations) requires current mapping in order to define water depth. This was one of the scheduled activities for the second year of this project; however, curtailment of funds means this mapping will not be done. Therefore, it is impossible at this time to reliably apply the relationship shown in Figure 10 to Bighorn Reservoir.

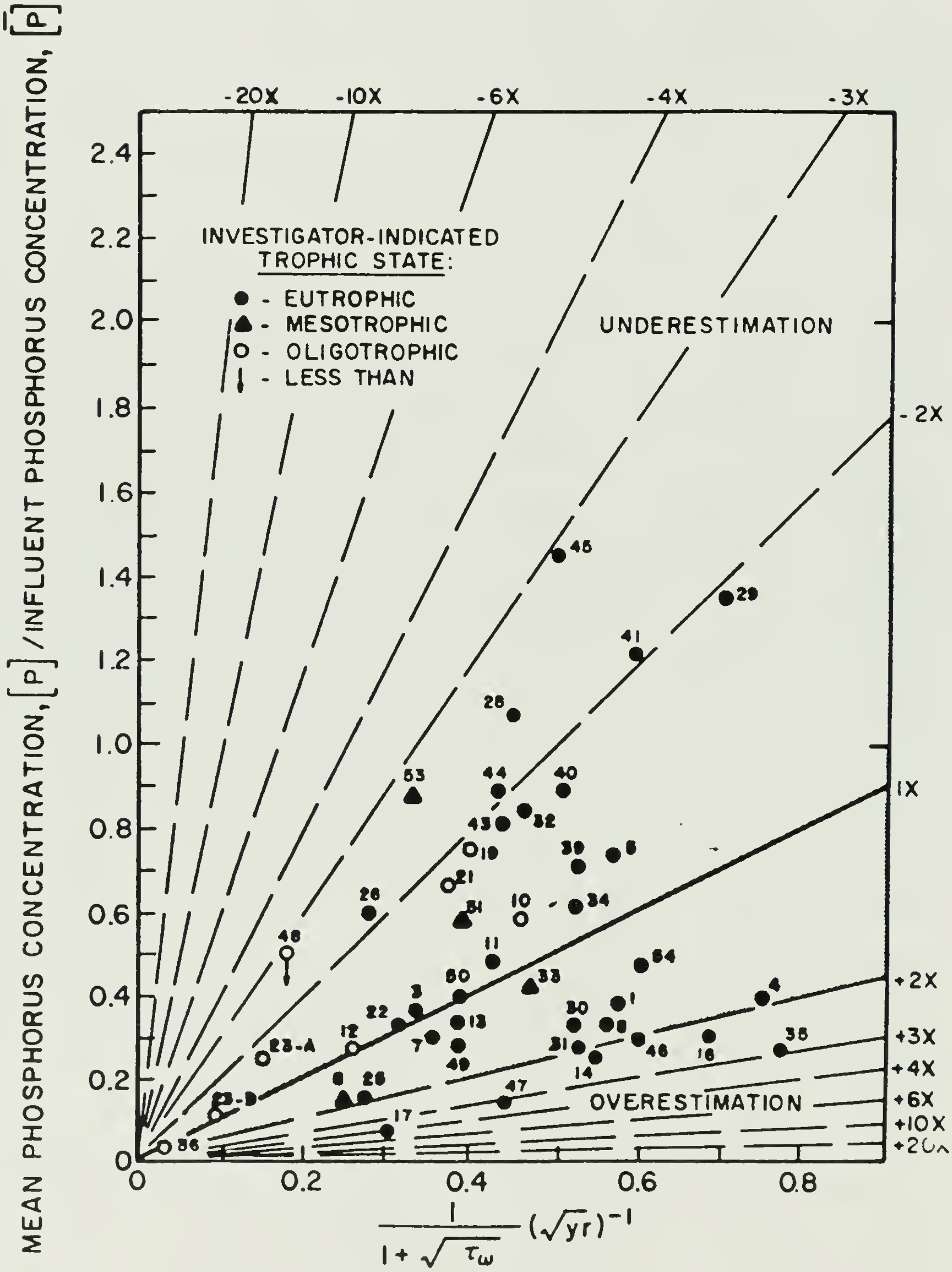


Figure 10. Evaluation of estimates of US OECD waterbody nutrient loadings: Vollenweider mean phosphorus/influent phosphorus and hydraulic residence time relationship (After Rast and Lee, 1978)

In 1968 and 1969, Soltero (1971) determined the concentrations of nitrogen and phosphorus compounds entering Bighorn Reservoir from the Shoshone and Bighorn Rivers. He also presented information on the U.S. Geological Survey (USGS) measured flows of these rivers near the points where they entered the reservoir. Tables 6, 7 and 8 present a summary of the Soltero data on the concentrations of nitrogen and phosphorus compounds entering Bighorn Reservoir during 1968 and 1969. The corresponding flows for the Bighorn and Shoshone Rivers are presented in Table 9. Using a three point moving average of the nitrogen and phosphorus concentrations presented in Tables 6, 7 and 8, and the average monthly flow data presented in Table 9, the estimated phosphorus and inorganic nitrogen loads to Bighorn Reservoir for 1968 and 1969 have been computed. Because of gaps in the concentration data for certain months and irregularly spaced sampling, the computations of these loads involved some interpretation of the data based on the authors' experience in making computations of this type on many other waterbodies. The results of these computations are presented in Tables 10, 11 and 12. The data presented in these tables is based on a monthly nutrient load in order to determine the influence of loads at certain times of the year on water quality in the reservoir. Similar types of nutrient monthly load data, based on the 1975 US EPA study of the reservoir as published by the US EPA (1977a), are presented in Tables 13, 14 and 15. The loads presented in these tables differ somewhat from those presented in the US EPA report of phosphorus and inorganic nitrogen loads to the reservoir for 1975. This is because the US EPA utilized normalized flows rather than actual flows in computing loads. As can be seen in Tables 3 and 13, the total phosphorus loads in 1975 were approximately 982,000 kg P/year. This is about two percent less than the total phosphorus load reported by the US EPA for that year. The US EPA normalized loads are an attempt to estimate the phosphorus loads that would occur in

TABLE 6. TOTAL PHOSPHORUS CONCENTRATIONS FOR BIGHORN AND SHOSHONE RIVERS 1968 AND 1969

Total Phosphate (mg/l P)					
1968			1969		
Date	Bighorn River	Shoshone River	Date	Bighorn River	Shoshone River
2/22	0.26	0.24	1/18	-	0.05
3/7	0.13	0.13	2/1	-	0.11
3/28	0.07	0.18	2/15	-	0.007
4/11	0.07	0.13	3/1	-	0.04
5/4	0.16	0.32	3/17	0.21	0.16
5/18	0.26	0.30	3/31	0.21	0.17
6/1	3.53	0.33	4/7	0.12	0.25
6/12	5.61	0.74	4/14	1.08	0.43
6/24	0.72	0.55	4/21	0.14	0.15
7/15	0.003	0.01	4/28	0.49	0.27
8/1	0.001	0.05	5/5	0.07	0.07
8/19	1.19	0.73	5/12	0.15	0.25
9/23	0.04	0.07	5/22	0.20	0.27
10/7	0.06	0.02	5/28	0.47	0.43
10/19	0.02	0.02	6/3	0.06	0.24
11/9	0.001	0.001	6/10	0.37	0.42
11/23	0.11	0.09	6/17	0.17	0.26
12/7	0.06	0.08	6/24	0.46	0.22
12/20	-	0.007	7/1	0.66	0.38
			7/8	0.21	0.27
			7/14	0.13	0.31
			7/21	0.37	0.11
			7/29	0.07	-
			8/5	0.08	0.26
			8/11	0.007	0.10
			8/18	0.07	0.21

(After Soltero, 1971)
Dash (-) indicates no data

TABLE 7. SOLUBLE ORTHOPHOSPHATE CONCENTRATIONS FOR BIGHORN AND SHOSHONE RIVERS 1968 AND 1969

Soluble Orthophosphate (mg/l P)					
1968			1969		
Date	Bighorn River	Shoshone River	Date	Bighorn River	Shoshone River
2/22	0.05	0.01	1/18	-	0.003
3/7	0.02	0.05	2/1	-	0.09
3/28	0.02	0.01	2/15	-	0.001
4/11	0.001	0.001	3/1	-	0.007
5/4	0.06	0.21	3/17	0.001	0.001
5/18	0.12	0.08	3/31	0.003	0.007
6/1	0.03	0.04	4/7	0.001	0.001
6/12	0.13	0.09	4/14	0.03	0.001
6/24	0.04	0.02	4/21	0.003	0.03
7/15	0.02	0.08	4/28	0.003	0.01
8/1	0.001	0.02	5/5	0.04	0.05
8/19	0.05	0.03	5/12	0.01	0.02
9/23	0.08	0.10	5/22	0.01	0.07
10/7	0.01	0.001	5/28	0.52	0.09
10/19	0.001	0.001	6/3	0.003	0.04
11/9	0.001	0.001	6/10	0.01	0.03
11/23	0.02	0.02	6/17	0.003	0.001
12/7	0.007	0.01	6/24	0.04	0.04
12/20	-	0.001	7/1	0.02	0.01
			7/8	0.02	0.03
			7/14	0.02	0.06
			7/21	0.02	0.03
			7/29	0.001	0.05
			8/5	0.003	0.02
			8/11	0.02	0.04
			8/18	0.02	0.02

(After Soltero, 1971)

Dash (-) indicates no data

TABLE 8. INORGANIC NITROGEN CONCENTRATION FOR BIGHORN AND SHOSHONE RIVERS 1968 AND 1969

Inorganic Nitrogen (NO_3^-, NO_2^-, NH_3 mg/l as N)					
1968			1969		
Date	Bighorn River	Shoshone River	Date	Bighorn River	Shoshone River
2/22	1.07	1.35	1/18	-	0.35
3/7	0.63	0.98	2/1	-	0.31
3/28	0.36	0.44	2/15	-	1.13
4/11	-	-	3/1	-	0.86
5/4	-	-	3/17	0.52	0.65
5/18	0.45	1.12	3/31	0.50	0.42
6/1	0.50	0.79	4/7	0.62	1.15
6/12	2.18	1.78	4/14	0.68	0.87
6/24	0.40	1.23	4/21	0.43	0.72
7/15	0.30	1.57	4/28	0.70	0.78
8/1	1.28	1.20	5/5	0.51	1.07
8/19	1.04	2.29	5/12	0.42	1.65
9/23	0.45	1.09	5/22	0.78	1.63
10/7	0.44	0.95	5/28	0.73	1.71
10/19	0.15	1.10	6/3	0.32	0.90
11/9	0.61	1.02	6/10	0.77	1.08
11/23	0.60	1.22	6/17	0.82	1.15
12/7	0.98	1.14	6/24	0.91	1.32
12/20	-	0.84	7/1	0.68	0.92
			7/8	0.70	0.90
			7/14	0.35	1.04
			7/21	1.01	0.76
			7/29	1.01	2.26
			8/5	0.47	1.65
			8/11	0.56	1.34
			8/18	0.68	1.24

(After Soltero, 1971)

Dash (-) indicates no data

TABLE 9. AVERAGE DAILY DISCHARGE OF BIGHORN AND SHOSHONE RIVERS IN 1968 AND 1969

	Discharge (m^3/sec)					
	1968			1969		
Month	Bighorn River at Kane	Shoshone River at Lovell	Total	Bighorn River at Kane	Shoshone River at Lovell	Total
Jan.	50.7	24.3	75.0	44.3	28.4	72.7
Feb.	64.6	20.4	85.0	72.1	22.9	95.0
Mar.	71.4	28.6	100.0	76.5	23.8	100.3
Apr.	61.7	26.9	88.6	69.5	25.0	94.5
May	59.6	21.6	81.2	67.8	15.6	83.4
June	186.1	32.8	218.9	97.3	40.0	137.3
July	57.8	19.6	77.4	71.2	37.0	108.2
Aug.	61.9	42.7	104.6	23.9	17.0	40.9
Sept.	67.4	34.5	101.9	31.2	23.1	54.3
Oct.	57.4	28.2	85.6	94.7	51.5	146.2
Nov.	67.1	32.4	99.5	122.2	46.2	168.4
Dec.	58.6	33.1	91.7	95.8	41.7	137.5

(After Soltero, 1971)

TABLE 10. TOTAL PHOSPHORUS LOADS TO BIGHORN AND SHOSHONE RIVERS IN 1968 AND 1969

1968	Bighorn River kg P/month	Shoshone River kg P/month	Total kg P/month
Jan.	35,591	15,746	51,337
Feb.	24,763	9,350	34,113
Mar.	17,350	11,326	28,676
Apr.	16,042	14,687	30,729
May	26,284	14,580	40,864
June	1,590,286	46,051	1,636,337
July	37,662	10,760	48,422
Aug.	66,518	30,360	96,878
Sept.	75,353	24,518	99,871
Oct.	6,199	2,716	8,915
Nov.	7,618	3,033	10,651
Dec.	9,493	5,273	14,766
1969			
Jan.	23,922*	4,269	28,191
Feb.	34,608*	2,876	37,484
Mar.	37,179	7,925	45,104
Apr.	82,670	17,875	100,545
May	40,731	10,741	51,472
June	67,040	29,640	96,680
July	55,365	26,723	82,088
Aug.	3,377	8,721	12,09[illegible]

(Based on Soltero, 1971 data)

*estimated value

TABLE 11. SOLUBLE ORTHOPHOSPHATE LOADS TO BIGHORN AND SHOSHONE RIVERS IN 1968 AND 1969

1968	Bighorn River kg P/month	Shoshone River kg P/month	Total Kg P/month
Jan.	6,845	656	7,501
Feb.	4,845	1,190	6,035
Mar.	2,635	1,570	4,205
Apr.	4,331	5,152	9,483
May	9,709	5,657	15,366
June	32,257	4,264	36,521
July	3,173	2,117	5,290
Aug.	3,955	4,995	8,950
Sept.	8,178	3,917	12,095
Oct.	4,701	2,589	7,290
Nov.	1,628	870	2,498
Dec.	2,136	923	3,059
1969			
Jan.	119*	230	349
Feb.	173*	1,722	1,895
Mar.	413	321	734
Apr.	1,671	682	2,353
May	26,544	2,422	28,966
June	3,542	2,886	6,428
July	3,114	3,596	6,710
Aug.	925	1,224	2,149

(Based on Soltero, 1971 data)

*estimated value

TABLE 12. INORGANIC NITROGEN LOADS TO BIGHORN AND SHOSHONE RIVERS IN 1968 AND 1969

1968	Bighorn River kg N/month	Shoshone River kg N/month	Total kg N/month
Jan.	146,472	88,574	235,046
Feb.	137,275	59,415	196,690
Mar.	95,426	54,826	150,252
Apr.	64,970*	54,553*	119,523
May	76,437	55,696	132,133
June	496,763	108,021	604,784
July	103,000	70,560	173,560
Aug.	145,960	194,456	340,416
Sept.	112,738	129,467	242,205
Oct.	53,726	79,693	133,419
Nov.	79,089	93,787	172,876
Dec.	124,994	95,328	220,322
1969			
Jan.	59,805*	26,838	86,643
Feb.	86,520*	39,571	126,091
Mar.	105,341	41,341	146,682
Apr.	109,775	57,200	166,975
May	111,667	63,812	175,479
June	178,730	115,700	294,430
July	144,180	117,482	261,662
Aug.	36,782	64,719	101,501

(Based on Soltero, 1971 data)

*estimated value

TABLE 13. TOTAL PHOSPHORUS LOADS TO BIGHORN AND SHOSHONE RIVERS IN 1975

Month	Bighorn River kg P/month	Shoshone River kg P/month	Total kg P/month
Oct.	7,922	14,171	22,093
Nov.	10,813	4,783	15,596
Dec.	5,191	14,534	19,725
Jan.	5,000*	5,258	10,258*
Feb.	5,000*	10,000*	15,000*
Mar.	10,000*	16,790	26,790*
Apr.	126,534	26,034	152,568
May	114,749	60,184	174,933
June	232,889	37,708	270,597
July	108,106	91,841	199,947
Aug.	29,862	21,277	51,139
Sept.	4,341	18,884	23,225

(After US EPA, 1977a)

*estimated value

TABLE 14. SOLUBLE ORTHOPHOSPHATE LOADS TO BIGHORN AND SHOSHONE RIVERS IN 1975

Month	Bighorn River kg P/month	Shoshone River kg P/month	Total kg P/month
Oct.	132*	6,664	6,796
Nov.	601	1,025	1,626
Dec.	104*	1,009	1,113
Jan.	500*	1,546	2,046*
Feb.	500*	2,000*	2,500*
Mar.	1,000*	3,498	4,498*
Apr.	5,442	2,072	7,514
May	9,780	1,837	11,617
June	15,526	7,802	23,328
July	6,995	9,433	16,428
Aug.	2,666	3,546	6,212
Sept.	543	2,361	2,904

(After US EPA, 1977a)
*estimated value

TABLE 15. INORGANIC NITROGEN LOADS TO BIGHORN AND SHOSHONE RIVERS IN 1975

Month	Bighorn River kg N/month	Shoshone River kg N/month	Total kg N/month
Oct.	37,761	60,896	98,657
Nov.	31,719	63,887	95,606
Dec.	33,844	68,293	102,137
Jan.	30,000*	57,156	87,156*
Feb.	30,000*	56,000*	86,000*
Mar.	40,000*	55,266	95,266*
Apr.	63,947	44,196	108,143
May	138,872	21,474	106,346
June	305,667	100,770	406,437
July	66,135	98,482	164,617
Aug.	36,261	55,852	92,113
Sept.	17,364	60,025	77,389

(After US EPA, 1977a)

*estimated value

a normal flow year. It is evident that in 1975 the loads reported are not atypical because of either high or low flows during that year.

CHARACTERISTICS OF BIGHORN RESERVOIR

From the data and information presented in Tables 1 and 16 and Figure 9, it can be seen that Bighorn Reservoir is a long, narrow waterbody with a maximum depth of 146.3 m occurring near the dam. It is located in an approximately 300 m deep canyon which, at the dam, is about half filled with water. There are three principal recreation entry points to the reservoir, Horseshoe Bend, Barry's Landing and Ok-a-bek. This means that the areas of the reservoir - upper (south) in the region of Horseshoe Bend and Barry's Landing, which have heaviest use by the public, also are the areas which have greatest impact from nutrient loads derived from the Shoshone and Bighorn Rivers, since both of these rivers enter the reservoir just above Horseshoe Bend.

Soltero (1971), as part of his studies, collected a considerable amount of data on the water quality characteristics of the reservoir from 1968 through part of 1970. Sections of his data pertinent to this study are reproduced in this report. His original report (PhD dissertation) should be consulted for the complete data and additional details on procedures used for sample collection and analysis.

In any review of the Soltero data, several aspects need to be considered. First, the 1968 data would not necessarily be considered representative of the characteristics of Bighorn Reservoir during the late 60s, since during that year the reservoir was being filled. As is discussed later, the pool elevation during the summer of 1968 was considerably less than normal pool elevation. The second factor to consider is that reservoirs typically age during the first few years after filling because appreciable nutrients are leached from the soil in the newly flooded areas. Normally, three to five years, dependent on hydraulic residence

TABLE 16. ADDITIONAL MORPHOMETRIC DATA FOR BIGHORN RESERVOIR AT MAXIMUM CAPACITY (ELEVATION 1,115.5 m)

Maximum length	98.4 km (61 mi)
Maximum effective length	9.8 km (6.1 mi)
Maximum width	3.2 km (2.0 mi)
Maximum effective width	3.2 km (2.0 mi)
Mean width	739 m (2,425 ft)
Maximum depth	140 m (459 ft)
Mean depth	24 m (80 ft)
Area	727×10^5 m^2 (17,958 acres)
Volume	176×10^7 m^3 (1,427,840 acre-ft)
Length of shoreline	206 km (128 mi)
Shoreline development	11.8
Slope of basin	0.14%

(After Soltero, 1971)

time, characteristics of the reservoir and the flooded soils, are needed to have the reservoir come to equilibrium. This means that the data developed by Soltero for 1968 through 1970 for Bighorn Reservoir may not represent the characteristics of the reservoir from the mid-1970s on.

A number of the key components of the Soltero data pertinent to eutrophication are presented and discussed in subsequent sections of this report, together with other data of a similar type such as that collected in this study. Presented below is a general review of the Soltero data for 1968 through 1970.

Table 17 summarizes the chemical composition of Bighorn Reservoir in the outlet waters for 1969 as determined by Soltero (1971). Examination of this table shows that this reservoir's waters have a high dissolved solids content, compared to most freshwater systems and that the water is of moderate hardness. Therefore, appreciable parts of the dissolved solids are derived from alkali metals such as sodium. The pH of the waters is in the neutral to slightly alkaline region. All other chemical characteristics measured by Soltero are normal for waters of this type in this part of the country. From an overall point of view, the Soltero data, such as that presented in Table 17, indicates that Bighorn Reservoir should provide a high value recreational asset near the dam, as a result of the fact that none of the chemical characteristics would impair aquatic organism growth in the reservoir.

Soltero made measurements of the reservoir at five stations, as shown in Figure 11. Station 0S is located near the dam; Station 5S is located just upstream from Horseshoe Bend. In this report, Station 5S will be considered equivalent to Horseshoe Bend. In his report, Soltero presents detailed data for all stations that he monitored during his three year study. In general, for the bulk characteristics, the water composition at all stations is similar to that

TABLE 17. RANGE AND MEAN OF CHEMICAL CHARACTERISTICS OF BIGHORN RESERVOIR AT THE RESERVOIR OUTLET DURING THE 1969 SAMPLING PERIODS

	Discharge
Ca^{++}(meq/l)	2.88-4.43 3.71
Mg^{++}(meq/l)	1.46-3.38 2.02
Na^{+}(meq/l)	2.73-4.50 3.53
K^{+}(meq/l)	0.06-0.16 0.12
HCO_3^- (meq/l)	2.25-3.70 3.05
Cl^- (meq/l)	0.27-0.45 0.34
$SO_4^=$ (meq/l)	4.33-6.21 5.47
F^- (meq/l)	0.02-0.06 0.04
Soluble organic C (mg/l)	5.3 -23.0 9.5
Particulate C (mg/l)	0.0 -30.8 5.0
NO_3^- -N (mg/l)	0.00-0.74 0.55
NO_2^- -N (mg/l)	0.000-0.015 0.004
NH_3 -N (mg/l)	0.02-0.55 0.21
Orthophosphate (mg/l P)	0.00-0.06 0.01
Turbidity (J.T.U.)	0-36 10
Silica (mg/l)	6.0-12.8 10.5

(Table continues)

(Table 17 continued)

	Discharge
Total iron (mg/l)	0.000-0.463 0.052
Mn^{++} (mg/l)	0.000-0.300 0.030
Cu^{++} (μg/l)	0.0-6.0 1.3
Zn^{++} (mg/l)	0.004-0.058 0.022
Conductance (μmhos/cm)	692-971 877
pH range	6.8-8.3

(After Soltero, 1971)

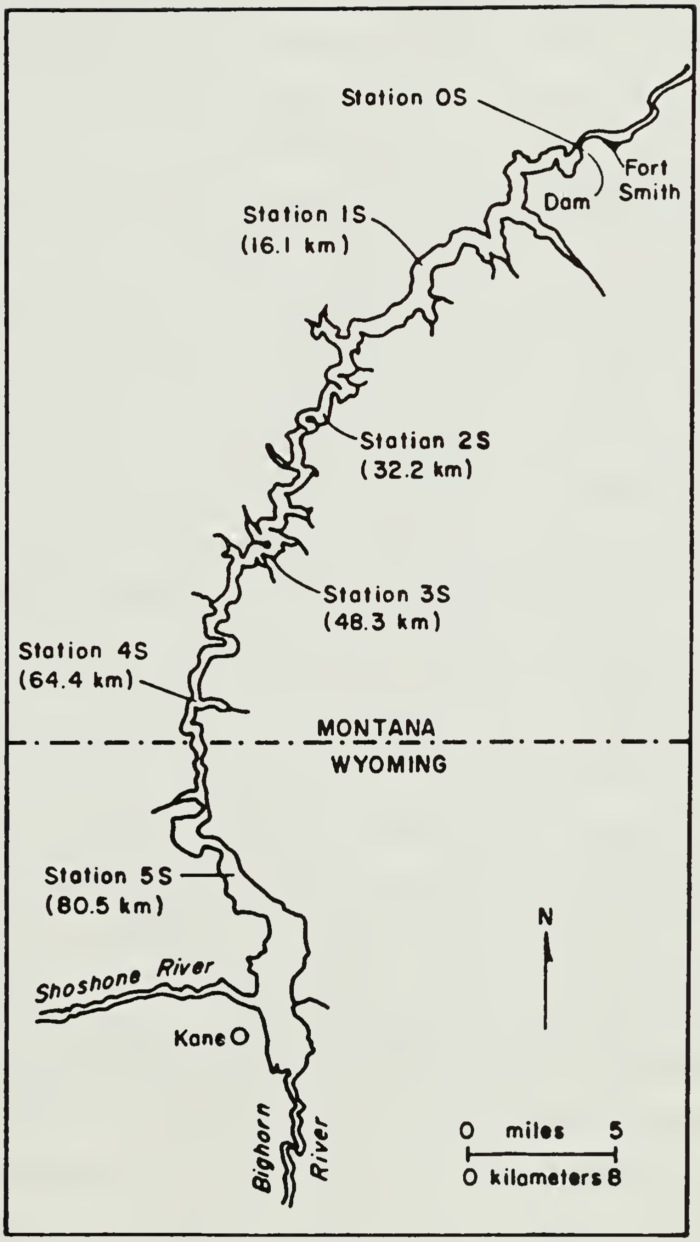


Figure 11. Map of Bighorn Reservoir (Bureau of Reclamation) showing location of the six permanent sampling stations used by Soltero (1971)

shown in Table 17. However, for eutrophication-related water quality parameters such as nitrogen and phosphorus species and planktonic algal chlorophyll, there are marked differences in the characteristics of the water from the upper ends to the dam. Tables 18, 19 and 20 present the average planktonic algal chlorophyll found by Soltero for each of the stations during 1968, 1969 and 1970. As discussed above, while this data is probably not representative of the reservoir once it has come to equilibrium with its flooded soils, it does show appreciable differences in the phytoplankton population from the Horseshoe Bend region of the reservoir to the waters of the dam. It further shows that during 1968 through 1970 the eutrophication-related water quality near the dam would have been considered to be quite good, while near Horseshoe Bend (Station 5S) the planktonic algal chlorophyll was sufficient to impair recreational use of this part of the reservoir. A further discussion of the Soltero chlorophyll data is presented in a subsequent section of this report.

Soltero (1971) also presents fairly detailed information on the numbers and types of algae that he collected. It should be noted that the numbers and types of algae present in a new reservoir are frequently not typical of what is present after the system comes to equilibrium. Soltero and Wright (1975) report that the bluegreen algae make up from 6 to 18 percent of the cell volume in the three year period 1968 through 1970. They noted that Aphanizomenon flos-aquae was the most predominant representative of this class and that bluegreens were typically present during the late summer months.

Soltero did not measure phosphate within the reservoir. He did measure what he labeled as orthophosphate, however, it is not clear whether the samples were filtered prior to phosphorus determinations. For the purposes of this report, it will be assumed that these were soluble orthophosphate measurements. Tables 21, 22 and 23 present summaries of the

TABLE 18. CHLOROPHYLL a CONCENTRATIONS (µg/l) IN BIGHORN RESERVOIR - SUMMER 1968

	Station					
Month	0	1	2	3	4	5
June						
Mean	3.5	6.6	8.9	5.6	5.9	19.2
S. dev.	1.0	2.3	1.9	2.7	2.0	9.3
No. obs.	4	4	4	4	4	4
July						
Mean	4.2	7.7	8.5	8.3	21.6	24.8
S. dev.	-	-	-	-	-	-
No. obs.	1	1	1	1	1	1
August						
Mean	2.1	4.5	7.1	8.7	11.3	28.3
S. dev.	1.6	2.2	2.6	3.1	9.7	19.6
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

Dash (-) indicates insufficient data available to compute standard deviation

TABLE 19. CHLOROPHYLL a CONCENTRATIONS (μg/l) IN BIGHORN RESERVOIR - SUMMER 1969

	Station					
Month	0	1	2	3	4	5
June						
Mean	1.4	7.7	3.9	5.8	6.6	1.8
S. dev.	-	-	-	-	-	-
No. obs.	1	1	1	1	1	1
July						
Mean	2.2	2.0	6.4	3.4	4.9	7.8
S. dev.	1.5	0.2	3.0	1.8	3.4	4.4
No. obs.	2	2	2	2	2	2
August						
Mean	2.8	2.7	6.6	6.0	31.4	32.75
S. dev.	0.8	-	2.7	0.3	0.6	9.8
No. obs.	2	1	2	2	2	2

(Based on Soltero, 1971)
Dash (-) indicates insufficient data available to compute standard deviation

TABLE 20. CHLOROPHYLL a CONCENTRATIONS (μg/l) IN BIGHORN RESERVOIR - SUMMER 1970

	Station					
Month	0	1	2	3	4	5
June						
Mean	3.6	10.1	14.9	26.2	30.3	8.9
S. dev.	2.5	14.3	16.1	2.8	2.9	-
No. obs.	2	2	2	2	2	1
July						
Mean	4.2	9.3	13.6	10.7	10.4	21.1
S. dev.	2.7	2.4	5.9	6.1	4.8	10.8
No. obs.	5	5	4	5	5	5
August						
Mean	4.0	4.0	7.1	10.8	13.1	9.4
S. dev.	2.2	1.7	0.0	2.6	3.2	3.1
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

Dash (-) indicates insufficient data available to compute standard deviation

TABLE 21. ORTHOPHOSPHATE CONCENTRATIONS (mg/l P) IN BIGHORN RESERVOIR - SUMMER 1968

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.047	0.047	0.05	0.047	0.043	0.07
S. dev.	0.033	0.027	0.043	0.03	0.04	0.073
No. obs.	4	4	4	4	4	4
July						
Mean	0.003	0.01	0.023	0.027	0.013	0.007
S. dev.	0.007	0.01	0.04	0.033	0.023	0.013
No. obs.	5	5	5	5	5	5
August						
Mean	0.013	0.007	>0.001	0.007	0.003	0.013
S. dev.	0.013	0.007	0.003	0.007	0.01	0.02
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

TABLE 22. ORTHOPHOSPHATE CONCENTRATIONS (mg/l P) IN BIGHORN RESERVOIR - SUMMER 1969

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.04	0.02	0.017	0.017	0.02	0.057
S. dev.	0.043	0.02	0.017	0.017	0.02	0.04
No. obs.	5	5	5	4	5	5
July						
Mean	0.003	0.003	0.003	0.003	0.003	0.003
S. dev.	0.003	0.00	0.003	0.00	0.003	0.003
No. obs.	2	2	2	2	2	2
August						
Mean	0.013	0.017	0.01	0.043	0.017	0.017
S. dev.	0.003	0.003	0.007	0.047	0.017	0.02
No. obs.	2	2	2	2	2	2

(Based on Soltero, 1971)

TABLE 23. ORTHOPHOSPHATE CONCENTRATIONS (mg/l P) IN BIGHORN RESERVOIR - SUMMER 1970

	Station					
Month	0	1	2	3	4	5
June						
Mean	-	-	-	-	-	-
S. dev.	-	-	-	-	-	-
No. obs.	-	-	-	-	-	-
July						
Mean	0.017	0.027	0.04	0.04	0.047	0.053
S. dev.	0.00	0.007	0.01	0.013	0.017	0.03
No. obs.	5	5	5	5	5	5
August						
Mean	0.01	0.013	0.01	0.023	0.017	0.01
S. dev.	0.01	0.01	0.01	0.007	0.01	0.013
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

Dash (-) indicates no data available

1968, 1969 and 1970 orthophosphate data. Little can be said about this data at this time except to indicate that the concentrations at Station 5S - Horseshoe Bend in some months tend to be higher than at other stations. If this is a soluble orthophosphate measurement, then during periods of algal blooms the concentrations at Station 5S should be the lowest of any part of the lake if phosphorus is limiting algal growth.

Tables 24 through 32 present summaries of the inorganic nitrogen data Soltero obtained for Bighorn Reservoir for the summers of 1968, 1969 and 1970. Examination of these tables shows that the concentrations of inorganic nitrogen are generally less than 2 mg/l N, with many of the values near 1 mg/l N. The predominant form is nitrate. The concentrations of ammonia and nitrite are such that they would not cause toxicity to fish and other aquatic life. From the data available it appears that phosphorus could be limiting phytoplankton growth during peak biomass of the summer months based on the fact that the soluble orthophosphate concentrations are reduced to growth rate limiting values.

Soltero (1971) and Soltero _et_ _al_. (1974) have reported on density currents in Bighorn Reservoir which were the result of subsurface withdrawal of water through the power penstocks at the dam. It does not appear however that this phenomenon has any impact on the water quality of Bighorn Reservoir.

Soltero made an extensive set of measurements of the depth of the euphotic zone using a submarine photometer in which he defined the euphotic zone in accord with conventional limnological practice, as the depth at which there is 1 percent of the surface light radiation. Since similar measurements of this type were not made by other subsequent investigators, the data of Soltero on the depth of the euphotic zone has been converted to an equivalent Secchi depth using a relationship where 3 x Secchi depth is equal to the depth of the euphotic zone. While many investigators use a factor of 2.5, it

TABLE 24. AMMONIA NITROGEN CONCENTRATIONS (mg/l NH_3-N) IN BIGHORN RESERVOIR - SUMMER 1968

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.16	0.17	0.11	0.15	0.13	0.19
S. dev.	0.29	0.31	0.18	0.27	0.16	0.28
No. obs.	4	4	4	4	4	4
July						
Mean	0.00	0.00	0.08	0.00	0.00	0.00
S. dev.	-	-	0.18	-	-	-
No. obs.	5	5	5	5	5	5
August						
Mean	0.09	0.08	0.08	0.09	0.17	0.12
S. dev.	0.11	0.11	0.11	0.12	0.25	0.14
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

Dash (-) indicates insufficient data to compute standard deviation

TABLE 25. AMMONIA NITROGEN CONCENTRATIONS (mg/l NH_3-N) IN BIGHORN RESERVOIR - SUMMER 1969

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.24	0.23	0.24	0.23	0.28	0.34
S. dev.	0.07	0.09	0.08	0.08	0.08	0.10
No. obs.	5	5	5	5	5	5
July						
Mean	0.29	0.38	0.21	0.23	0.21	0.34
S. dev.	0.26	0.39	0.14	0.19	0.13	0.01
No. obs.	2	2	2	2	2	2
August						
Mean	0.16	0.21	0.18	0.20	0.24	0.43
S. dev.	0.01	0.06	0.01	0.01	0.02	0.18
No. obs.	2	2	2	2	2	2

(Based on Soltero, 1971)

TABLE 26. AMMONIA NITROGEN CONCENTRATIONS (mg/l NH_3-N) IN BIGHORN RESERVOIR - SUMMER 1970

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.03	0.02	0.04	0.05	0.07	0.12
S. dev.	0.02	0.01	0.02	0.02	0.05	0.14
No. obs.	3	3	3	3	3	3
July						
Mean	0.03	0.03	0.03	0.04	0.04	0.03
S. dev.	0.01	0.00	0.01	0.01	0.01	0.02
No. obs.	5	5	5	5	5	5
August						
Mean	0.02	0.02	0.02	0.03	0.03	0.03
S. dev.	0.01	0.01	0.01	0.01	0.00	0.00
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

TABLE 27. NITRITE NITROGEN CONCENTRATIONS (mg/l NO_2^- - N) IN BIGHORN RESERVOIR - SUMMER 1968

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.025	0.013	0.01	0.018	0.01	0.015
S. dev.	0.019	0.005	0.008	0.022	0.008	0.01
No. obs.	4	4	4	4	4	4
July						
Mean	0.012	0.012	0.008	0.01	0.012	0.01
S. dev.	0.008	0.004	0.004	0.00	0.004	0.00
No. obs.	5	5	5	5	5	5
August						
Mean	0.01	0.005	0.013	0.015	0.01	0.013
S. dev.	0.00	0.006	0.005	0.006	0.00	0.005
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

TABLE 28. NITRITE NITROGEN CONCENTRATIONS (mg/l NO_2^- - N) IN BIGHORN RESERVOIR - SUMMER 1969

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.007	0.007	0.009	0.008	0.008	0.008
S. dev.	0.003	0.002	0.003	0.002	0.002	0.005
No. obs.	5	5	5	5	5	5
July						
Mean	0.02	0.011	0.008	0.006	0.002	0.010
S. dev.	0.02	0.004	0.002	0.006	0.001	0.001
No. obs.	2	2	2	2	2	2
August						
Mean	0.009	0.015	0.007	0.009	0.009	0.003
S. dev.	0.001	0.002	0.004	0.002	0.004	0.001
No. obs.	2	2	2	2	2	2

(Based on Soltero, 1971)

TABLE 29. NITRITE NITROGEN CONCENTRATIONS (mg/l NO_2^- - N) IN BIGHORN RESERVOIR - SUMMER 1970

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.005	0.011	0.018	0.016	0.014	0.011
S. dev.	0.003	0.003	0.002	0.001	0.001	0.004
No. obs.	3	3	3	3	3	3
July						
Mean	0.012	0.016	0.012	0.012	0.013	0.016
S. dev.	0.003	0.002	0.003	0.003	0.004	0.006
No. obs.	5	5	5	5	5	5
August						
Mean	0.012	0.008	0.004	0.006	0.017	0.022
S. dev.	0.002	0.002	0.003	0.002	0.008	0.005
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

TABLE 30. NITRATE NITROGEN CONCENTRATIONS (mg/l NO_3^- - N) IN BIGHORN RESERVOIR - SUMMER 1968

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.33	0.35	0.40	0.34	0.35	0.37
S. dev.	0.16	0.10	0.11	0.16	0.14	0.15
No. obs.	4	4	4	4	4	4
July						
Mean	0.26	0.16	0.12	0.17	0.29	0.48
S. dev.	0.06	0.05	0.04	0.04	0.13	0.14
No. obs.	5	5	5	5	5	5
August						
Mean	0.35	0.24	0.32	0.41	0.59	0.98
S. dev.	0.17	0.14	0.15	0.20	0.27	0.28
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

TABLE 31. NITRATE NITROGEN CONCENTRATIONS (mg/l NO_3^- - N) IN BIGHORN RESERVOIR - SUMMER 1969

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.40	0.41	0.45	0.44	0.49	0.60
S. dev.	0.28	0.35	0.34	0.15	0.22	0.20
No. obs.	5	5	5	5	5	5
July						
Mean	0.36	0.44	0.16	0.10	0.43	0.50
S. dev.	0.01	0.16	0.007	0.13	0.27	0.21
No. obs.	2	2	2	2	2	2
August						
Mean	0.31	0.36	0.12	0.10	0.14	0.24
S. dev.	0.01	0.07	0.04	0.04	0.08	0.19
No. obs.	2	2	2	2	2	2

(Based on Soltero, 1971)

TABLE 32. NITRATE NITROGEN CONCENTRATIONS (mg/l NO_3^- - N) IN BIGHORN RESERVOIR - SUMMER 1970

	Station					
Month	0	1	2	3	4	5
June						
Mean	0.33	0.62	0.54	0.48	0.51	0.56
S. dev.	0.26	0.02	0.16	0.15	0.03	0.07
No. obs.	3	3	3	3	3	3
July						
Mean	0.43	0.29	0.28	0.24	0.25	0.29
S. dev.	0.13	0.18	0.25	0.17	0.15	0.16
No. obs.	5	5	5	5	5	5
August						
Mean	0.26	0.11	0.06	0.09	0.25	0.46
S. dev.	0.12	0.06	0.02	0.01	0.16	0.12
No. obs.	4	4	4	4	4	4

(Based on Soltero, 1971)

appears that this factor varies from about 2.5 to 4 based on US OECD eutrophication studies (Rast and Lee, 1978), and therefore a factor of 3 seems to be more appropriate than the standard limnological relationship used. Tables 33 and 34 present the estimated Secchi depth based on the Soltero euphotic zone data. Examination of these tables shows that in general there is a marked increase in Secchi depth as one proceeds down the reservoir from Station 5S to Station 0S near the dam. This is a result of two factors. First, is a decrease in inorganic turbidity associated with the settling of the large amount of erosional material brought into the reservoir by the Bighorn and Shoshone Rivers. The other reason for the increased Secchi depth as one approaches the dam is the decreased phytoplankton that occurs in the reservoir as one proceeds from Station 5S to 0S. The OECD eutrophication relationships described earlier which relate phosphorus load to chlorophyll and Secchi depth can be used to estimate the Secchi depth that would be present in Bighorn Reservoir if it did not have a high erosional load added to it from the watershed. Estimates of this type are presented in a subsequent section of this report.

Rast and Lee (1978), Lee et al. (1980) and Jones and Lee (1981) have pointed out that the application of the OECD study results to long, narrow reservoirs of the Bighorn Reservoir type must be done in a way which reflects the fact that appreciable nutrient removal will take place in the upper parts of a reservoir as a result of phytoplankton growth in these areas. The US EPA, in their 1975 studies of the reservoir, established seven sampling stations along the length of the reservoir with Station 1E at the uppermost end of the reservoir and Station 7E located just above the dam (see Figure 9). Table 35 presents the planktonic algal chlorophyll data for Bighorn Reservoir for each of the US EPA stations. During the May, August and October samplings of the reservoir, examination of the data in this table shows that there is a marked gradation of chlorophyll from the upper end of

TABLE 33. ESTIMATED SECCHI DEPTH (m) FOR BIGHORN RESERVOIR FOR 1968

	Station					
1968	0	1	2	3	4	5
5/5	3.3	3.3	2.3	1.3	0.7	0.1
5/13	3.3	2.7	1.7	1.3	1.0	0.5
5/20	3.3	2.7	1.7	1.0	0.7	0.3
5/27	3.3	2.7	2.0	1.3	0.7	0.1
6/7	6.0	2.3	1.0	0.7	0.3	0.03
6/12	5.3	2.3	1.0	0.7	0.7	0.03
6/20	6.0	3.3	1.0	0.7	0.3	0.03
6/27	4.0	1.3	0.7	1.0	0.3	0.1
7/2	3.7	2.0	1.0	0.7	0.7	0.3
7/8	3.3	2.0	2.0	1.3	0.7	0.3
7/15	3.0	2.0	1.3	1.3	1.0	0.3
7/23	2.7	2.0	2.7	2.0	1.0	0.3
7/29	3.3	2.3	2.3	1.7	1.0	0.17
8/5	3.3	3.3	3.3	3.3	2.0	0.43
8/12	2.7	2.0	2.7	1.7	1.0	0.17
8/19	2.7	2.0	2.7	2.0	1.3	0.3
8/26	2.7	2.7	2.7	1.3	1.3	0.4
9/3	2.7	2.7	1.7	1.3	1.3	0.7
9/9	2.7	2.0	1.3	0.7	1.3	0.7
9/17	2.7	2.0	2.7	2.7	1.3	1.0
9/23	3.0	3.0	3.0	3.0	2.0	1.0
10/2	3.0	3.0	3.0	2.7	2.0	1.0
10/8	3.0	3.0	3.0	3.0	2.0	1.0
10/14	2.7	2.7	3.0	3.0	2.7	1.0
10/22	3.0	2.7	2.0	2.0	2.0	1.0
11/2	3.0	3.0	3.0	3.0	3.0	1.0

TABLE 34. ESTIMATED SECCHI DEPTH (m) FOR BIGHORN RESERVOIR FOR 1969-1970

	Station					
1969	0	1	2	3	4	5
4/15	4.0	3.3	2.7	2.0	1.0	0.1
4/21	3.3	3.3	2.7	2.0	1.0	0.43
4/28	3.7	3.3	2.7	1.7	0.7	0.47
5/5	4.0	3.3	2.7	2.0	1.3	0.53
5/12	4.7	2.7	2.0	1.3	1.0	0.43
5/21	4.7	2.7	2.0	2.0	1.3	0.7
5/27	3.3	2.7	2.3	1.3	1.3	0.7
6/3	3.3	3.3	1.3	1.3	1.3	1.0
6/13	3.3	3.3	2.0	2.0	1.3	0.6
6/18	4.0	2.7	2.0	2.0	1.3	0.7
6/24	3.3	2.7	2.0	2.0	1.3	1.0
6/30	4.0	2.0	2.0	1.3	1.3	1.0
7/22	3.3	2.0	2.0	2.0	2.0	1.0
7/28	2.7	2.0	2.0	1.3	1.3	1.0
8/4	2.7	2.0	1.0	0.7	0.7	0.37
8/11	2.7	2.7	1.3	1.3	1.0	0.5
1970						
6/11	4.3	2.7	1.7	1.3	1.3	1.3
6/18	4.3	2.3	1.7	1.7	1.3	1.0
6/24	4.7	2.0	1.7	1.7	1.3	1.0
7/2	4.3	1.7	1.7	0.7	1.0	0.7
7/8	2.3	1.7	1.0	1.0	1.3	0.7
7/16	2.3	1.7	1.0	1.0	1.3	1.0
7/23	5.0	2.0	1.7	1.3	1.3	1.0
7/29	2.0	1.7	1.3	3.7	1.7	1.3
8/4	2.3	2.0	1.7	2.0	1.3	1.0
8/10	3.3	4.3	4.0	3.3	3.7	1.3
8/18	2.3	2.0	2.0	1.7	1.3	1.3
8/24	3.0	2.0	2.0	1.7	1.7	1.3
9/1	3.0	2.0	2.3	1.7	2.0	1.3
9/18	3.0	2.3	2.3	2.3	1.3	0.7

TABLE 35. US EPA PLANKTONIC ALGAL CHLOROPHYLL a IN BIGHORN RESERVOIR

Chlorophyll a:

Sampling Date	Station Number	Chlorophyll a (μg/l)	Secchi Depth (cm)
05/21/75	1E	7.9	-
	2E	2.6	23
	3E	2.4	33
	4E	2.9	61
	5E	4.4	152
	6E	2.1	244
	7E	2.1	548
08/29/75	1E	16.9	61
	2E	41.8	61
	3E	2.6	168
	4E	3.1	229
	5E	1.5	305
	6E	1.9	488
	7E	2.7	1344
10/17/75	1E	3.5	30
	2E	6.9	213
	3E	2.2	305
	4E	1.6	610
	5E	1.3	610
	6E	1.6	238
	7E	1.6	610

(After US EPA, 1977a)

the reservoir to the dam. This is especially true during the August sampling where the planktonic algal chlorophyll in the upper part of the reservoir was 10 to 20 times that found near the dam. Table 35 also presents the Secchi depth data collected by the US EPA in 1975. As expected, there is an inverse relationship between planktonic algal chlorophyll and Secchi depth, with the least turbid waters located near the dam. This inverse relationship in Bighorn Reservoir is affected by the large amounts of inorganic suspended sediment transported to the reservoir by the Shoshone and Bighorn Rivers. The relationships developed by Rast and Lee (1978), based on the US OECD eutrophication study data, can be used to estimate the Secchi depth that should be present in the reservoir based on planktonic algal chlorophyll.

From the relationship presented in Figure 7, a chlorophyll of 2 μg/l should have a corresponding Secchi depth of 4.75 m. As shown in Table 35, the Secchi depth for chlorophylls in the order of 2 μg/l range from 2.4 to 13 m with the preponderance of the data on the order of 5 to 6 m. It is evident that near the dam, where most of the 2 μg/l chlorophylls were observed, the higher inorganic turbidity found in lower parts of the reservoir is not significantly affecting chlorophyll - Secchi depth relationships. However, on the upper end of the reservoir the planktonic algal chlorophylls of 7, 17 and 42 μg/l should have associated Secchi depths of 2.5, 1.4 and 0.9 m, respectively. The Secchi depths measured by the US EPA ranged from 0.6 to 2.1 m. This difference can be accounted for by the inorganic turbidity. As discussed by Rast and Lee (1978), planktonic algal chlorophyll - Secchi depth relationships are fairly insensitive to chlorophyll concentrations above about 10 μg/l and therefore, while the differences between the expected chlorophylls and measured chlorophylls are small, they are of the appropriate magnitude based on the characteristics of the reservoir. Of note in Table 35 is the appreciable light inhibition of planktonic algal chlorophyll production at EPA Station 1E. This is to be expected from the turbid nature of the reservoir at this point.

Table 36 presents the dominant types of algae found by the US EPA in Bighorn Reservoir in 1975. During the August sampling in the upper ends of the reservoir, as expected, large numbers of bluegreen algae were found. Based on the experience of the authors, the US EPA's data for chlorophyll and dominant algal types indicate that the upper ends of the reservoir near Horseshoe Bend are highly eutrophic. During late summer it would be expected that the degree of eutrophication of this part of the reservoir is sufficient to seriously impair recreational uses of the water.

The US EPA (1977a) in their discussion of Bighorn Reservoir characterized the overall trophic quality of the reservoir as ranging from mesotrophic near the dam to eutrophic near Horseshoe Bend. As discussed by Jones and Lee (1981) and Lee et al. (1981a), the trophic state classification system used by the US EPA is not technically valid. Based on the OECD trophic state classification system as reported by Jones and Lee (1981), the upper end of the reservoir would be classified as hypereutrophic, while the waters near the dam would be classified as oligotrophic to mesotrophic.

Further, the US EPA (1977a) presents a discussion of "dangerous" and "permissible" phosphorus loads. These loads are based on Vollenweider's original assessment utilizing Sawyer's critical phosphorus concentration of 10 μg/l P. Rast and Lee (1978), Lee et al. (1978), Jones and Lee (1981) and Lee et al. (1981a) have discussed the problems with this approach. The US EPA found a 1975 phosphorus loading of 20.4 $g/m^2/yr$; the US EPA "permissible" loading should be 0.74 $g/m^2/yr$. Using this relationship, the actual loading is about 27 times more than it should be to attain a "permissible" phosphorus load.

It is the experience of the authors that in a Bighorn Reservoir-like setting the phosphorus loadings which the

TABLE 36. DOMINANT TYPES OF ALGAE IN BIGHORN RESERVOIR ON US EPA SAMPLING DATES 1975

Phytoplankton:

Sampling Date	Dominant Genera	Algal Units per ml
05/21/75	1. *Fragilaria* sp.	357
	2. *Melosira* sp.	268
	3. *Asterionella* sp.	223
	4. *Lyngbya* sp.	134
	5. *Navicula* sp.	134
	Other genera	359
	Total	1,475
08/29/75	1. *Aphanizomenon* sp.	1,728
	2. *Skeletonema* sp.	241
	3. *Carteria* sp.	201
	4. *Microcystis* sp.	201
	5. *Chroomonas* (?) sp.	201
	Other genera	201
	Total	2,773
10/17/75	1. *Chroomonas* (?) sp.	363
	2. *Navicula* sp.	161
	3. *Synedra* sp.	81
	4. *Nitzschia* sp.	81
	5. *Oscillatoria* sp.	40
	Other genera	100
	Total	826

(After US EPA, 1977a)

US EPA has characterized as "dangerous," can be exceeded to a considerable extent without significantly impairing beneficial uses of the reservoir. As warm water sports fishery is one of these primary uses, it should be noted that reduction of the phosphorus load to this reservoir to achieve the "permissible" phosphorus loading would greatly reduce the value of the sports fishery. According to the relationship shown in Figure 8, utilizing the US EPA data for phosphorus loads to Bighorn Reservoir found in 1975, fish yield would decrease in this reservoir by approximately a factor of 10. There is no doubt, however, that phosphorus load to the reservoir is far in excess of what it should be to optimize sport fisheries and other recreational uses of the reservoir.

There have been a number of other studies on Bighorn Reservoir and its tributaries that provide some data pertinent to this project. These include the paper by Soltero et al. (1973) which presents a review of the Soltero work on the characteristics of the Bighorn River and Reservoir, with particular emphasis on the effect of impounding the river on water quality. The information in this paper is also contained within the Soltero PhD dissertation (Soltero, 1971). Pertinent sections have been discussed in this report. Richards (1955) presents a review of the geology of Bighorn Canyon which provides limited information of direct applicability to this study. Lowry and Lines (1972) provide some information on the chemical characteristics of groundwaters in the Bighorn Basin, however, there is limited information presented in this report that is directly applicable to this study.

Kent (1977) reviews the Wyoming Game and Fish Department 1965 through 1975 data on Bighorn Reservoir. This reference is of particular importance in discussing the fisheries of this reservoir. As discussed by Kent, this reservoir has provided an excellent warm water fishery. Miller et al. (1981) has determined the mercury content of walleye taken from Bighorn Reservoir near Horseshoe Bend and Barry's Landing.

They have found that the mercury content in the axial muscle of the fish was a function of fish length. Fish that were on the order of 600 mm long contained between 0.5 and 0.8 μg Hg/g, with two of the approximately 50 fish that he examined having mercury in this muscle above the Food and Drug Administration guidelines of 1 μg Hg/g. While mercury is a problem in some of the reservoirs in Wyoming and Montana, it does not appear to be a problem in Bighorn Reservoir.

Additional data on the water quality characteristics of tributaries to Bighorn Reservoir and on the reservoir itself is provided in the 208 Water Quality Management Plant, Bighorn Basin, Wyoming (Cooper, 1979). Examination of the 208 data shows that in general it is in accord with the other data collected on the reservoir both before and after these studies. Table 36a presents the 208 master plan phosphorus loading from the various streams in the Bighorn watershed. It should be noted that there are some important differences in the phosphorus loading results in Bighorn Reservoir presented in this table and those reported by the US EPA (1975) based on their NES studies. The 208 study report 1.1×10^5 Kg P/year added to the reservoir by the Bighorn River at Kane. The US EPA found approximately 6.7×10^5 kg P/year added to the reservoir by the Bighorn River. Similarly, the US EPA reported a phosphorus load from the Shoshone River of 3.4×10^5 Kg P/year. The 208 study report indicated that 1.1×10^6 Kg P/year was added to the reservoir by this river. Since these two studies were conducted in different years it is likely that the differences noticed are due to different rainfall patterns between the two years within the major components (Bighorn and Shoshone River Basin) of the Bighorn Reservoir watershed. Based on the authors' experience of conducting nutrient load studies of this type, year to year differences of a factor of approximately two such as those found in the EPA and 208 studies in the amounts of total phosphorus contributed from watersheds of this type are to be expected.

TABLE 36a PHOSPHORUS (AS TOTAL P) LOADING TO BASIN STREAMS

STREAM	TOTAL PHOSPHORUS LOAD AT SEGMENT MOUTH (MEAN OF USGS, G&F, 208 DATA)		ACRES IN DRAINAGE		IRRIGATION LOADING		POINT SOURCE LOADING		UNACCOUNTED LOADING	
	Tons/day	Tons/year	Irrigated/Total		Tons/day	Tons/year	Tons/day	Tons/year	Tons/day	Tons/year
Big Horn River at Worland	.179	65.3	----	1,989,760	.106	9.6	DNA	DNA	.073	55.7
Nowood River	.071	25.9	14,610	1,280,000	.033	3.0	DNA	DNA	.038	22.9
Greybull River	.019	6.9	41,770	713,600	.101	9.1	DNA	DNA	----	----
Shell Creek	.010	3.7	10,560	358,400	.026	2.3	0	0	----	1.4
Big Horn River at Kane	.331	120.8	DNA	5,160,960	.266	23.9	.003	1.13	.062	95.77
Shoshone River below Buffalo Bill	.200	73	----	984,320	.083	7.5	0	0	.117	65.5
Whistle Creek	.010	3.7	10,800	64,640	.026	2.3	0	0	----	1.4
Bitter Creek	.161	58.9	57,600 *	51,520	.138	12.4	DNA	DNA	.023	40.4
Sage Creek	.021	7.7	23,516	DNA	.056	5.0	0	0	----	2.7
Shoshone River	3.30	1222	DNA	1,912,960	.377	3[illegible]	.015	5.48	2.91	1182.52
Clark's Fork River	.079	28.8	11,120	DNA	.028	2.[illegible]	0	0	.051	26.3

* Irrigated acres are greater than total acres in natural drainage of Bitter Creek because some of the irrigated acreage that is in the natural drainage of Shoshone River is artifically drained [illegible] Bitter Creek.

After Cooper (1979)

1980 STUDIES

INTRODUCTION

From a preliminary review of the literature and discussions with various individuals knowledgeable on Bighorn Reservoir water quality, it was apparent that there is need for updated information on the current characteristics of Bighorn Reservoir, especially the upper parts of the reservoir where the impact of water quality on recreational use is a major concern. Once the estimate of sediment accumulation in the Horseshoe Bend region of Bighorn Reservoir had been completed, it was decided to use the very limited funds remaining to initiate a water quality monitoring program designed to estimate current nutrient loads to the reservoir and the reservoir's eutrophication-related water quality. This section of the report presents the results of this program.

EXPERIMENTAL PROCEDURES

A cooperative sample collection program was developed with R. Hougham and other rangers located in the Bighorn Canyon National Recreation Area at Lovell, Wyoming to collect water samples from the Shoshone River near Lovell, the Bighorn River near Kane, and Horseshoe Bend and Barry's Landing in Bighorn Reservoir, and send them via bus to Fort Collins, Colorado. Samples were collected in the morning and received the same day in the evening. Samples were collected with a rope and bucket from convenient bridges or piers, placed in prewashed, acid rinsed plastic bottles, and transported in ice chests with two frozen Travel Ice packs. Upon arrival in Fort Collins, the samples were refrigerated and the next morning they were filtered for soluble orthophosphate and chlorophyll analyses. These analyses were consistently performed the day following sample collection.

At the time of sample collection the National Park Service staff measured the temperature with a mercury in glass thermometer and measured the Secchi depth of the reservoir samples using a 20 cm black/white quadrant painted disc.

All chemical analyses were performed in accord with procedures listed in Standard Methods APHA et al. (1976). The specific analytical procedures are listed below.

Total phosphorus was determined on unfiltered water samples. Samples were digested following the APHA et al. (1976) Section 425 C-III Persulfate Digestion Method and the P concentration determined using the APHA et al. (1976) Section 425 F Ascorbic Acid Method. Soluble orthophosphate was measured on water samples which had been filtered through a 0.45 μm pore size membrane filter (prerinsed with dilute HCl and distilled water) following the APHA et al. (1976) Section 425 F Ascorbic Acid Method.

Total ammonia was determined using the method of Solorzano (1969), and nitrate by the APHA et al. (1976) Section 419 C Cadmium Reduction Method.

Total alkalinity determinations were made according to the APHA et al. Section 403 procedure using bromcresol green-methyl red mixed indicator. APHA et al. (1976) Section 309 B EDTA Titrimetric Method was used to determine water hardness. A Fisher Model 150 portable pH meter was used to measure pH; a Hach 2100 A turbidimeter for turbidity; and a YSI Model 33 S-C-T meter was used to measure specific conductance. Specific conductance values were corrected mathematically to 20°C assuming a 2.5 percent change in specific conductance for each C° difference in temperature.

Chlorophyll concentration analyses were made following the APHA et al. (1976) Section 1002 G 1 Spectrophotometric (Trichromatic) Method. Between 100 and 500 ml of the samples were used; absorbance was read using a 5 cm light path length.

Chlorophyll, soluble ortho P, and pH were generally measured the day following sample collection. The remaining unfiltered sample was stored at about 4°C in the dark; the remaining filtered sample was acidified to about pH 2 with H_2SO_4.

1980 NUTRIENT LOADS

A sampling program was initiated on the Shoshone River at Lovell and Bighorn River at Kane in order to estimate the amounts of inorganic nitrogen and phosphorus entering Bighorn Reservoir. The data from this study are presented in Table 37. The kilograms per month contributed to the reservoir by these rivers were computed from the concentration data obtained in this study and the U.S. Geological Survey (USGS) discharge data shown in Table 38. The USGS data is provisional at this time and subject to revision. The results of these computations for total phosphorus, soluble orthophosphate and inorganic nitrogen are presented in Tables 39, 40 and 41 respectively. Summary load data with total phosphorus, soluble orthophosphate and inorganic nitrogen loads for June, July and August for 1968, 1969, 1975, and 1980 are presented in Tables 42, 43, and 44 respectively. These tables summarize all of the data available on the nitrogen and phosphorus loads during the summer months. Examination of these tables reveals that the month to month and year to year loads of these nutrients to the reservoir is highly variable. This variability appears to be primarily related to the flow of the rivers. Interestingly, the percent soluble orthophosphate of the total phosphorus load varies from 1 percent to 18 percent, as shown in Table 45. In general, the smallest percentage orthophosphate occurs during months with the greatest loads. This is to be expected because for most natural water systems the difference between total phosphorus and soluble orthophosphate is predominantly particulate phosphorus. As with most sediment transport

TABLE 37. CHARACTERISTICS OF MAJOR TRIBUTARIES TO BIGHORN LAKE

Date (mo-da-yr)	Temp (C°)	pH	Specific Conductance (μmhos/cm at 20° C)	Turbidity (NTU)	Soluble Ortho P (mg P/l)	Total P (mg P/l)	Total NH_3 (mg N/l)	NO_3^- (mg N/l)	Alkalinity (mg/l as $CaCO_3$)
Bighorn River									
06-09-80	17.5	7.7	585	425	0.026	3	0.061	0.68	197
07-09-80	21.0	8.1	494	91	0.02	0.27	0.12	3.4	172
07-23-80	23.0	8.0	667	46	0.024	0.14	0.15	2.0	204
08-06-80	19.0	8.0	-	-	0.020	0.22	0.058	0.67	-
08-20-80	-	7.8	675	330	0.031	-	0.1	-	-
09-03-80	17.0	8.1	698	72	0.016	-	-	-	175
09-17-80	12.5	8.1	605	6400	0.024	-	-	-	160
10-16-80	6.0	8.1	686	32	0.001	-	0.068	-	177
11-26-80	0.0	8.2	679	48	0.002	-	-	-	-
01-08-81	-1.0	-	-	-	0.005	-	-	-	-
02-19-81	0.0	-	-	-	0.006	-	-	-	-
04-01-81	6.0	8.1	-	-	0.008	-	-	-	-
Shoshone River									
06-09-80	17.0	7.2	838	95	0.020	0.30	0.018	0.68	224
07-09-80	17.0	7.2	439	63	0.057	0.24	0.018	0.62	159
07-23-80	17.0	8.1	652	55	0.041	0.23	0.045	1.4	209
08-06-80	16.0	7.8	-	10	0.050	0.28	0.051	1.0	-
08-20-80	-	7.8	694	66	0.045	-	0.093	-	186
09-03-80	14.0	8.1	765	46	0.028	-	-	-	190
09-17-80	11.0	8.0	668	2400	0.034	-	0.074	-	176
10-16-80	4.0	7.6	690	125	0.007	-	0.080	-	196
11-26-80	-1.0	8.1	878	18	0.011	-	-	-	-
01-08-81	-1.0	-	-	-	0.018	-	-	-	-
02-19-81	2.0	-	-	-	0.020	-	-	-	-
04-01-81	6.0	8.1	-	-	0.015	-	-	-	-

Dash (-) indicates no measurement made

TABLE 38. AVERAGE DAILY DISCHARGE OF BIGHORN AND SHOSHONE RIVERS IN 1979-1980

Month	Discharge (m^3/sec) Bighorn River at Kane	Shoshone River at Lovell	Total
Oct.	35.8	16.7	52.5
Nov.	39.4	16.6	56.0
Dec.	34.9	15.1	50.0
Jan.	35.0	14.6	49.6
Feb.	42.4	14.6	57.0
Mar.	61.8	13.4	75.2
Apr.	47.1	16.7	63.8
May	59.7	16.0	75.7
June	124.2	39.1	163.3
July	103.7	42.7	146.4
Aug.	48.4	23.2	71.6
Sept.	59.3	21.8	81.1

(Based on USGS data)

TABLE 39. TOTAL PHOSPHORUS LOADS TO BIGHORN AND SHOSHONE RIVERS IN SUMMER 1980

Month	Bighorn River kg P/month	Shoshone River kg P/month	Total kg P/month
June	968,760	30,498	999,258
July	57,398	27,093	84,491
Aug.	28,750	17,539	46,289

TABLE 40. SOLUBLE ORTHOPHOSPHATE LOADS TO BIGHORN AND SHOSHONE RIVERS IN SUMMER-FALL 1980

Month	Bighorn River kg P/month	Shoshone River kg P/month	Total kg P/month
June	8,396	2,033	10,429
July	6,160	5,649	11,809
Aug.	3,332	2,975	6,307
Sept.	3,084	1,757	4,841
Oct.	97	316	413
Nov.	205	475	680

TABLE 41. INORGANIC NITROGEN LOADS TO BIGHORN AND SHOSHONE RIVERS IN SUMMER 1980

Month	Bighorn River kg N/month	Shoshone River kg N/month	Total kg N/month
June	239,284	70,959	310,243
July	793,772	120,075	913,847
Aug.	95,135	65,835	160,970

TABLE 42. TOTAL PHOSPHORUS LOADS FROM BIGHORN AND SHOSHONE RIVERS TO BIGHORN RESERVOIR (kg P/month)

Month	1968		1969		1975		1980	
	Bighorn River	Shoshone River	Bighorn River	Shoshone River	Bighorn River	Shoshone River	Bighorn River	Shoshone River
June	1,590,286	46,051	67,040	29,640	232,889	37,708	968,760	30,498
July	37,662	10,760	55,365	26,723	108,106	91,841	57,398	27,093
Aug.	66,518	30,360	3,377	8,721	29,862	21,277	28,750	17,539

TABLE 43. SOLUBLE ORTHOPHOSPHATE LOADS TO BIGHORN RESERVOIR (kg P/month)

Month	1968			1969			1975			1980		
	Bighorn River	Shoshone River	Total	Bighorn River	Shoshone River	Total	Bighorn River	Shoshone River	Total	Bighorn River	Shoshone River	Total
June	32,257	4,264	36,521	3,542	2,886	6,428	15,526	7,802	23,328	8,396	2,033	10,429
July	3,173	2,117	5,290	3,114	3,596	6,710	6,995	9,433	16,428	6,160	5,649	11,809
Aug.	3,955	4,995	8,950	925	1,224	2,149	2,666	3,546	6,212	3,332	2,975	3,307
	Total 3 months:		50,761	Total 3 months:		15,287	Total 3 months:		45,968	Total 3 months:		25,545
	Total July and August:		14,240	Total July and August:		8,859	Total July and August:		22,640	Total July and August:		15,116

TABLE 44. TOTAL INORGANIC NITROGEN LOADS FROM BIGHORN AND SHOSHONE RIVERS TO BIGHORN RESERVOIR (kg N/month)

Month	1968		1969		1975		1980	
	Bighorn River	Shoshone River	Bighorn River	Shoshone River	Bighorn River	Shoshone River	Bighorn River	Shoshone River
June	496,763	108,021	178,730	115,700	305,667	100,770	239,284	70,959
July	103,000	70,560	144,180	117,482	66,135	98,482	793,772	120,075
Aug.	145,960	194,456	36,782	64,719	36,261	55,852	95,135	65,835

TABLE 45. PERCENT SOLUBLE ORTHOPHOSPHATE OF TOTAL PHOSPHORUS LOAD TO BIGHORN RESERVOIR

Month	1968	1969	1975	1980
June	2%	7%	9%	1%
July	11%	8%	8%	14%
Aug.	9%	18%	12%	7%

in rivers, the greatest concentrations are found under periods of high flow. The combination of high flow with elevated concentrations leads to the much greater loads of total phosphorus occurring in June. The lower flow months of July and August generally have a greater percentage of the phosphorus in the soluble orthophosphate form. This is of importance in reviewing the nutrient load eutrophication response in Bighorn Reservoir because the soluble orthophosphate load to a reservoir is generally the primary factor controlling eutrophication-related water quality of a waterbody.

Lee et al. (1980) have reviewed the information available on algal available phosphorus present in rivers and lakes. They have found that, in general, in the absence of site-specific information, the algal available phosphorus in a river may be estimated by the sum of the soluble orthophosphate plus 20 percent of the difference between the total phosphate and soluble orthophosphate. For Bighorn Reservoir, it is evident that a substantial part of the total phosphorus load associated with the high flow months of late spring and early summer is in a form that will not likely support algal growth in the reservoir. This is an extremely important factor in formulating a eutrophication control program for Bighorn Reservoir. This point is discussed further in a subsequent section of this report.

1980 WATER QUALITY CHARACTERISTICS OF THE UPPER PARTS OF BIGHORN RESERVOIR

The reservoir sampling program during summer-fall 1980 focused the funds available on obtaining information that is pertinent to eutrophication-related water quality problems of Horseshoe Bend. The data obtained in this study are presented in Table 46. The key eutrophication-related water quality parameter presented in Table 46 is the uncorrected chlorophyll a. It is evident that the summer of 1980 was similar to the summers of the late 1960s studied by Soltero (1971) in that the greatest phytoplankton populations in the Horseshoe Bend region of Bighorn Reservoir were found in late July - early August. It should

TABLE 46. CHARACTERISTICS OF BIGHORN RESERVOIR AT HORSESHOE BEND AND BARRY'S LANDING

Date (mo-da-yr)	Temp (C°)	pH	Specific Conductance (µmhos/cm at 20° C)	Turbidity (NTU)	Secchi Depth (cm)	Uncorrected Chlorophyll (µg/l)	Soluble Ortho P (mg P/l)	Total P (mg P/l)	Total NH_3 (mg N/l)	NO_3^- (mg N/l)	Alkalinity (mg/l as $CaCO_3$)
Horseshoe Bend											
6-09-80	17.5	8.1	620	9.6	50	2	0.011	0.06	0.016	0.63	186
7-09-80	22.0	8.0	445	3.6	103	13	0.003	0.05	0.021	0.18	170
7-23-80	23.0	8.0	500	13.0	53	69	0.003	0.09	<0.010	0.21	155
8-06-80	23.0	7.9	-	-	70	10	0.060	0.24	0.097	0.15	
8-20-80	23.0	-	-	10.0	35	39	0.005				
9-03-80	18.0	8.2	673	7.0	35	29	0.003				
9-17-80	17.0	8.3	656	6.0	80	14	0.002				
10-16-80	12.0	7.7	686	17.0	30	11	0.006				
11-26-80	4.0	8.0	585	2.5	150	4	0.006				
Barry's Landing											
7-09-80	21.0	7.8	451	2.1	170	9	0.013	0.05	0.028	0.28	168
7-23-80	22.0	7.0	472	3.5	127	15	0.003	0.05	0.130	0.46	165
8-06-80	22.0	7.9	-	-	310	3	0.020	0.05	0.063	0.10	
8-20-80	22.0	-	-	-	280	7	0.012				
9-03-80	19.0	8.1	445	1.0	240	3	0.016				
9-17-80	18.5	8.1	540	1.0	330	1.5	0.019				
10-16-80	12.0	7.9	518	1.0	250	1.6	0.017				
11-26-80	10.0	7.7	656	1.0	315	0.8	0.014				

Dash (-) indicates no measurement made

Blank space indicates analysis not yet completed be noted that the data of Soltero is more comparable to the 1980 data of this study, since both studies involved sampling every week or two over the study period. The US EPA, on the other hand, took only one set of samples during the summer. Therefore, the single value for 1975 chlorophyll may not be representative of the summer 1975 characteristics of that part of the reservoir. Figure 12 presents the summer chlorophyll data obtained by Soltero and by this study for the stations at or near Horseshoe Bend. It includes the single value obtained by the US EPA on August 29, 1975. It is evident upon examination of this figure that, as expected, the planktonic algal chlorophyll is highly variable, with large changes in chlorophyll occurring in a relatively short period of time. For example, sampling on either side of the 1980 chlorophyll peak that occurred in mid-July would have yielded the impression that the July 1980 water quality was good when actually it was the worst of the year. While one cannot be certain that this is an appropriate general conclusion from the data available, it is interesting that in 1980 the worst chlorophyll of the summer was observed earlier than in other years for which there is data.

In some years, as seen in Figure 12, Soltero's sampling of Bighorn Reservoir was somewhat irregular. For example, in 1968, no samples were taken for over a month in late June through July. Based on the chlorophyll time patterns when more frequent samples were taken, it is possible that a major algal bloom could have occurred during this period and not been detected. It is evident that sampling frequencies of no less than two week intervals and preferably weekly intervals should be used in the Horseshoe Bend region of the reservoir for the period late June through early September.

In general, the greatest concentrations of chlorophyll were found in July and August, which coincides with that part of the year with the greatest water contact recreational use of this part of the reservoir. It should be noted that the public generally starts to complain about impairment of beneficial uses of a lake or reservoir when the planktonic

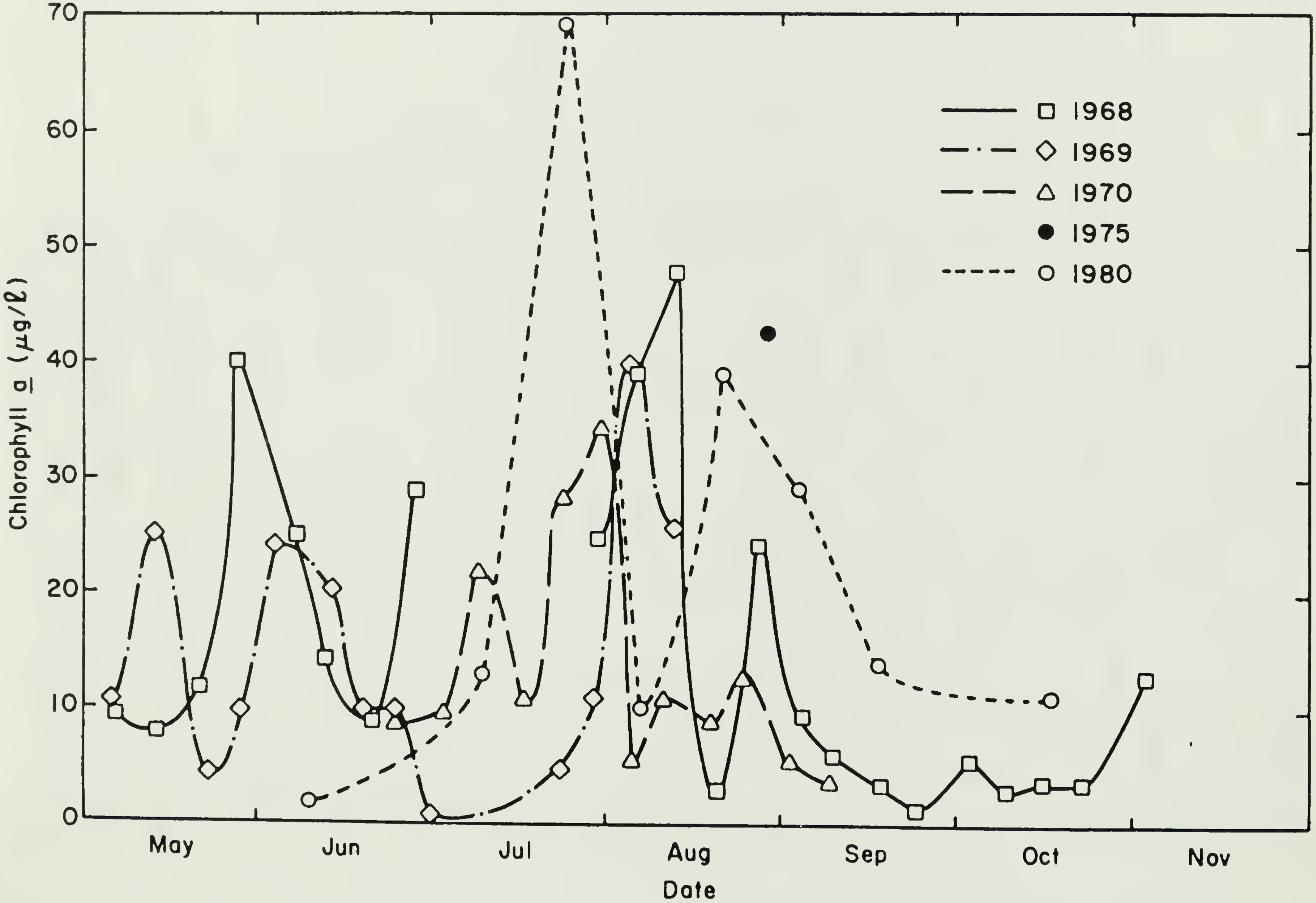


Figure 12. Planktonic algal chlorophyll at Horseshoe Bend, Bighorn Reservoir

algal chlorophyll is above about 10 µg/l. Values above 30 µg/l represent significantly deteriorated water quality which would cause some members of the public not to use a waterbody for recreational purposes.

Microscopic examination of the Bighorn Reservoir samples during the summer of 1980 showed that the dominant algal type was bluegreen algae with Aphanizomenon the dominant alga. This is similar to what was found by the US EPA in their 1975 studies.

The summer data for Secchi depth obtained in the various studies for the sampling stations at or near Horseshoe Bend is presented in Figure 13. In general, the data available shows that the Secchi depth varied at Horseshoe Bend from 0.1 m to be about 1.3 m in the summer months. A comparison of the actual and predicted Secchi depth for Bighorn Reservoir is shown in Table 47. It is evident that the ratio of the actual to the predicted Secchi depth is, in general, considerably less than 1.0. As noted earlier, this situation is an indication that part of the decreased Secchi depth that is found at Horseshoe Bend is due to inorganic turbidity brought into the reservoir by the tributaries, as well as stirred up by wind from the sediments in the shallow part of the reservoir.

It is evident that the eutrophication-related water quality data for Horseshoe Bend from summer 1980 is not atypical of data collected in this part of the reservoir in the late 1960s and 1975. Further, examination of the soluble orthophosphate inorganic nitrogen data for the summer of 1980 shows that phosphorus is the element most likely limiting maximum phytoplankton biomass. As shown in Table 46, the data obtained at Horseshoe Bend shows that the soluble orthophosphate data, in general, was in the order of a few µg/l which are generally recognized to be growth rate limiting concentrations. Further, the inorganic nitrogen (ammonia + nitrate) soluble orthophosphate ratio during the summer months showed, in general, a significant surplus of available nitrogen compared to phosphorus, although

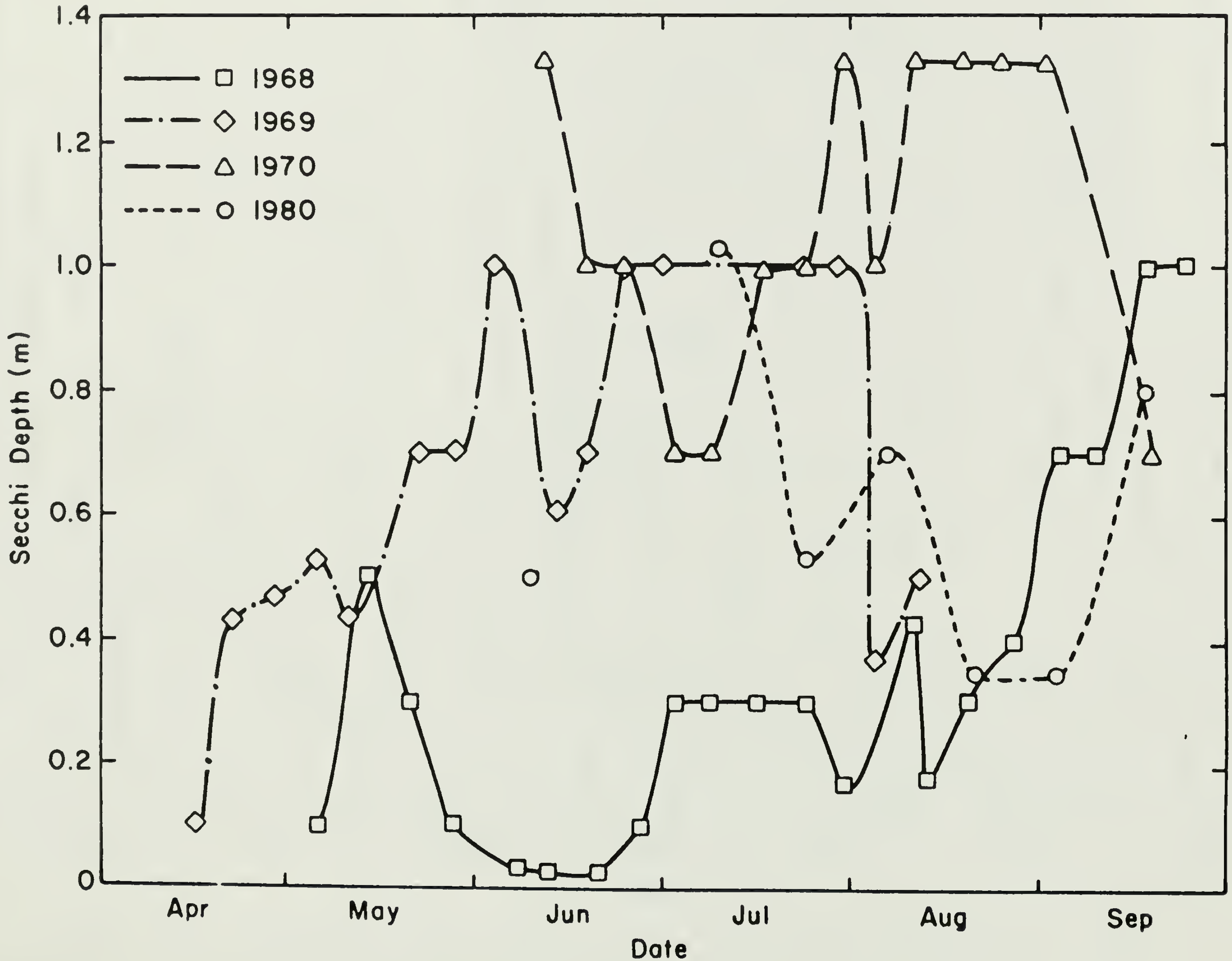


Figure 13. Secchi depth at Horseshoe Bend, Bighorn Reservoir

TABLE 47. COMPARISON OF ACTUAL AND PREDICTED SECCHI DEPTH FOR BIGHORN RESERVOIR - HORSESHOE BEND

1980	Actual Secchi Depths (m)	Predicted Secchi Depths (m)	Ratio = Actual / Predicted
6/9	0.50	4.5	0.11
7/9	1.03	1.5	0.69
7/23	0.53	0.7	0.76
8/6	0.70	1.8	0.39
8/20	0.35	0.9	0.39
9/3	0.35	1.4	0.25
9/17	0.80	1.5	0.53
10/16	0.30	1.7	0.18
11/26	1.50	3.0	0.50

by early August the ratio and the absolute concentrations of inorganic nitrogen were such that planktonic algal growth could be limited by both nitrogen and phosphorus. This supports similar conclusions based on data collected in the late 1960s and 1975.

The second year of this project was to include a complete water year's monitoring of nutrient load eutrophication response relationships for the upper part of the Bighorn Reservoir. Based on indicated funding availability by H. Rouse, this monitoring program was initiated in the fall of 1980 and carried through until spring 1981. It was terminated when it became evident that no funding would be available for the summer 1981 studies. The data obtained by this part of the monitoring program are presented in Table 37. Little can be said about this data since it was designed to be part of a year long monitoring study. Without the corresponding summer data it has little relevance to developing information that is pertinent to water quality management in Bighorn Reservoir.

Pool Elevation

One of the factors that could significantly affect the eutrophication-related quality at Horseshoe Bend during the summer is the rate of filling of the reservoir each year.

Figure 14 presents water level - pool elevation for 1968, 1969, 1970, 1975 and 1980. It is evident upon examination of this figure that there is considerable year to year variation in the filling pattern of the reservoir during the period May through July. It is not possible at this time, however, to assess the potential significance of reservoir filling pattern on summer eutrophication-related water quality because the data needed for this assessment are not available due to failure to fund the second and third years of the project.

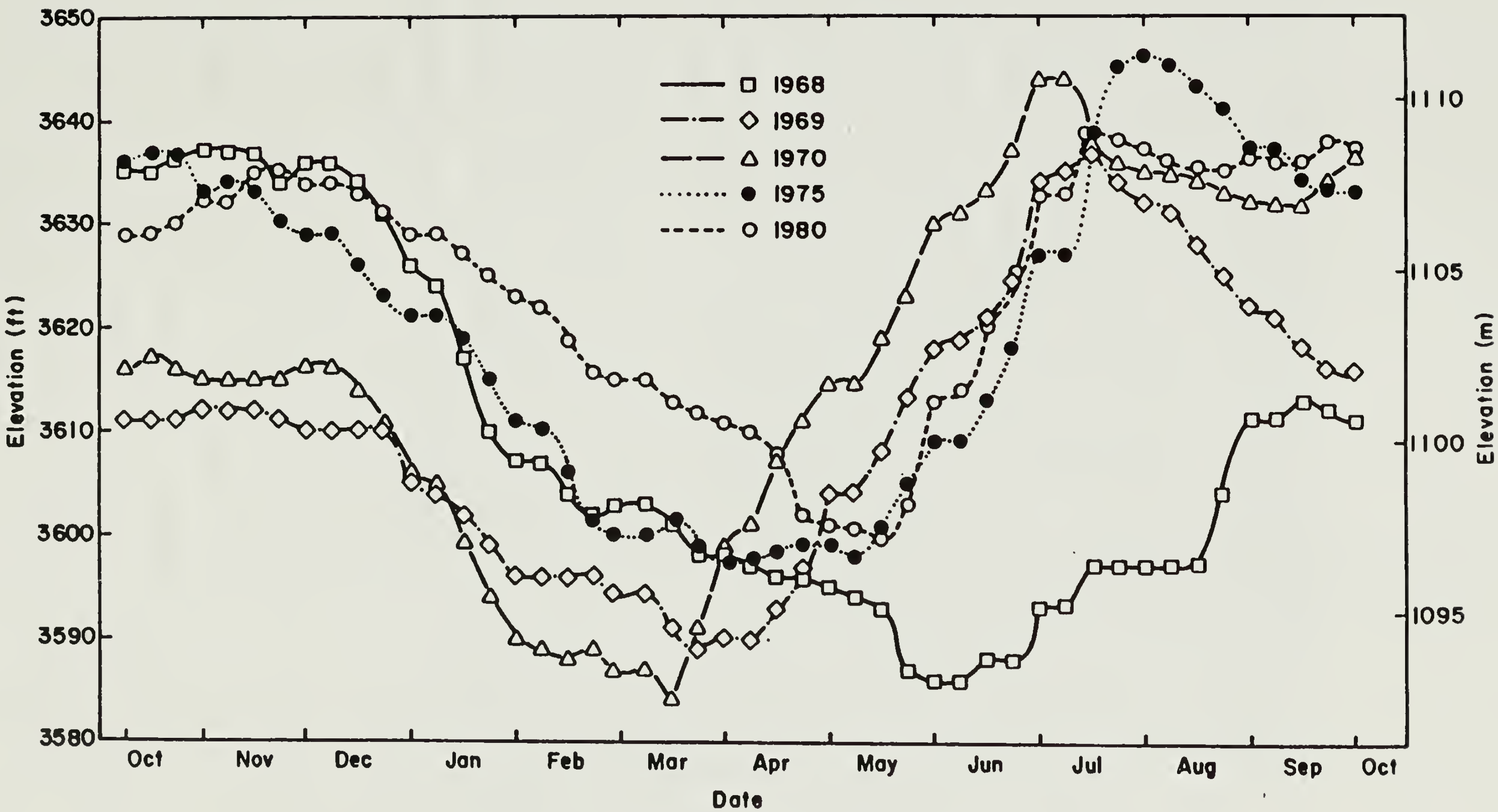


Figure 14. Bighorn Reservoir pool elevation

EVALUATION OF THE POTENTIAL SIGNIFICANCE OF DOMESTIC WASTEWATER PHOSPHORUS AS A CAUSE OF EUTROPHICATION-RELATED WATER QUALITY PROBLEMS IN HORSESHOE BEND

The US EPA concluded that in 1975 domestic wastewater contributed only 0.8 percent of the total phosphorus load to Bighorn Reservoir. However, as discussed previously, they did not include some of the major upstream communities in their surveys. Cooper (1979), in the Bighorn Basin 208 Plan, has reported that approximately 1% of the Bighorn River at Kane phosphorus loads is derived from point sources. For the Shoshone River, Cooper (1979) estimates that approximately 0.5% of the phosphorus load is derived from point sources. It is evident that only a small part of the phosphorus load contributed to Bighorn Reservoir is derived from readily controllable sources.

In order to estimate the contribution of all communities' domestic wastewater phosphorus discharges to the Shoshone and Bighorn Rivers or their tributaries, and the amounts of phosphorus which reach Bighorn Reservoir, one must obtain information on the populations of each of the communities and the hydrology of the two river systems. Information of this type for 1975 and 1980 was made available by J. Wagner of the Wyoming Department of Environmental Quality, C. Cooper of the Wyoming State Engineers Office, and various individuals associated with the U.S. Geological Survey in Cheyenne.

When one examines the morphology, hydrology and water quality information for the upper end of Bighorn Reservoir, it becomes apparent that one should note the potential impact of domestic wastewater derived phosphorus on eutrophication-related water quality in the Horseshoe Bend region based on total annual phosphorus loads. The shallow nature of the reservoir in this region and the anticipated very small volume of this region compared to the total volume of the reservoir, coupled with the appreciable drawdown of the reservoir pool elevation each year and the fact that appreciable amounts of the flow enter the reservoir during short periods of time each spring, leads to a situation where most of the annual load of phosphorus entering the reservoir from the Bighorn and Shoshone Rivers is being transported past the Horseshoe Bend region at times when it has little or no impact on eutrophication-related water quality. Based on the experience of the authors, the primary factor controlling eutrophication-related water quality in Horseshoe Bend will be the soluble orthophosphate loads added to the reservoir from the Shoshone and Bighorn Rivers during the summer months. Therefore, the computations presented below of the significance of domestic wastewater phosphorus loads to Bighorn Reservoir focus on the summer months, especially July and August. Justification for this approach will become apparent in subsequent sections of this report.

DOMESTIC WASTEWATER PHOSPHORUS SOURCES

J. Wagner (1981) provided information on population and municipal wastewater discharges for each of the municipalities present in the Bighorn and Shoshone watersheds below Buffalo Bill and Boysen Reservoirs. Communities located upstream from these reservoirs were considered to contribute insignificant amounts of phosphorus to the rivers below the reservoirs as a result of their small size and the high phosphorus trapping efficiency of reservoirs. Table 48 presents the 1975 and 1980 populations and domestic wastewater discharges to the Bighorn and Shoshone Rivers or their tributaries below Buffalo Bill and Boysen Reservoirs. Since the phosphorus concentrations of domestic wastewaters for many of these communities is not measured, it was necessary to utilize the population information and a population equivalent phosphorus loading factor of 1.1 kg P per person per year to estimate the phosphorus loads discharged by these communities. Lee et al. (1981b) and Rast and Lee (1981) have found that this value generally provides a reliable base for estimating the amount of phosphorus derived from domestic wastewaters for sewered populations in the U.S. The US EPA (1977a) provided data that could be used to compute a population equivalent phosphorus load for Lovell, Wyoming based on monitoring the Lovell wastewater treatment plant discharge in 1975. Using the populations provided by J. Wagner (1981) for Lovell in 1975 and the US EPA measured phosphorus discharge from the Lovell treatment plant, a phosphorus load population equivalent of 1.4 kg P per person per year is computed. This value provides support for the 1.1 kg P per person per year developed by Rast and Lee (1981). The US EPA

TABLE 48. DOMESTIC WASTEWATER INPUTS TO TRIBUTARIES OF BIGHORN RESERVOIR*

Municipality	1975 Population	1975 Wastewater Treatment Plant Discharge (MGD)	1980 Population	1980 Wastewater Treatment Plant Discharge (MGD)
Bighorn River				
Basin	1,145	0.22	1,338	0.23
Greybull	1,953	0.21	2,250	0.22
Meeteetse	459	0.23	521	0.30
Ten Sleep	729	0.07	859	0.087
Thermopolis	3,063	0.40	3,849	0.49
Worland	5,055	0.45	6,379	0.495
Shoshone River				
Byron	397	0.24	635	0.25
Cody	5,161	0.50	6,661	0.61
Deaver	112	0.02	178	0.03
Lovell	2,371	0.24	2,445	0.25
Powell	4,807	2.10	5,302	2.30

*Information supplied by J. Wagner, Wyoming Department of Environmental Quality, 1981

(1977a) also provided information for phosphorus loads for Greybull and Byron for 1975. The population equivalent phosphorus load for these communities is appreciably different than the 1.1 kg P per person per year. 4 and 7 kg P per person per year are computed for these communities. These values are thought to be in error.

Table 49 presents the estimated 1975 and 1980 phosphorus loads from each of the communities located in the Bighorn and Shoshone River basins. It is evident that the towns of greatest potential impact are Thermopolis, Worland, Cody and Powell, with Greybull and Lovell also of potential concern. Because appreciable amounts of the Bighorn and Shoshone Rivers are diverted during the summer months for irrigation purposes, the phosphorus discharge from some of these communities has to be adjusted.

Examination of Table 50 shows that in June 1975 approximately 70 percent of the average monthly flow released from Buffalo Bill Reservoir is diverted in the canals between Cody and Powell. During July 1975 about 40 percent of the water released from Buffalo Bill Reservoir was diverted in irrigation canals, while in August there was complete diversion of all water released from the reservoir. This means that in June, approximately 70 percent of the phosphorus discharged from Cody in its wastewater treatment plant effluent is diverted from the Shoshone River before Powell's wastewater effluent reaches the river via Bitter Creek. The corresponding figure for July was 40 percent and for August none of Cody's domestic wastewater phosphorus would reach the Garland gage. These computations are not completely accurate because the river receives appreciable water input from ungaged sources such as irrigation return water. Also, as discussed below, some of the canals in the Bighorn-Shoshone River system return excess irrigation water to the river. Table 50 shows that the flow at the Garland gage, based on the release from Buffalo Bill Reservoir and the diversions, should have been 676 cfs. The measured flow was

TABLE 49. DOMESTIC WASTEWATER INPUTS OF PHOSPHORUS TO TRIBUTARIES OF THE BIGHORN RIVER

Municipality	1975 kg P/yr	1980 kg P/yr
Bighorn River		
Basin	1,260	1,472
Greybull	2,148	2,475
Meeteetse	505	573
Ten Sleep	802	945
Thermopolis	3,369	4,234
Worland	5,560	7,017
Shoshone River		
Byron	437	698
Cody	5,677	7,327
Deaver	123	196
Lovell	2,608	2,690
Powell	5,288	5,832

TABLE 50. IRRIGATION DIVERSIONS OF THE SHOSHONE RIVER 1975

Wastewater Discharges (cfs)	Shoshone River Measured Discharge (cfs)				Shoshone River Canal Diversions (cfs)		
	June	July	Aug.		June	July	Aug.
	2,161	3,996	1,434	Buffalo Bill Reservoir (USGS Gage)			
0.77				Cody			
				→ Garland Canal	838	848	863
				→ Willwood Canal	288	326	336
	1,464	3,387	861	Willwood (USGS Gage)			
				→ Elk-Lovell Canal	359	328	337
	1,091	3,137	571	Garland (USGS Gage)			
3.20				Powell			
				→ Sidon Canal	243	257	264
0.37				Byron			
				→ Globe Canal	52	47	55
				→ Hunt Canal	124	126	132
0.03				Deaver			
	1,573	3,650	1,018	Lovell (USGS Gage)			
0.37				Lovell			
				Bighorn Reservoir			

1,091 cfs, therefore, there was a 415 cfs pickup of water from ungaged sources. The corresponding values for July and August are 643 cfs and 673 cfs, respectively.

As shown in Table 49, Powell adds an average of about 15 kg P per day to the Shoshone River at the point where Bitter Creek enters the river. A similar amount was added by Cody during 1975, however, as noted above, approximately half of Cody's wastewater effluent phosphorus reaches the Garland gage in July and little or none of this phosphorus reached this point in the river in August of that year. Therefore, it is estimated that approximately 20 kg P per day, derived from wastewater sources, was present in July 1975 at the point at which the Sidon Canal diverts water. The corresponding value for August 1975 is 15 kg P per day. Using the flows at the Garland gage and Sidon Canal, it is concluded that for June, July and August, 22, 8 and 46 percent diversion of this phosphorus takes place before the river reaches Byron. At Byron, about 1 kg P per day is added to the river in wastewater discharges. Below Byron an additional 16, 6 and 33 percent of the flow at the Garland gage is diverted during June, July and August, respectively.

This means that the 1975 June, July and August phosphorus from domestic wastewater sources in the Shoshone River at the point just above where Deaver's wastewater enters the Shoshone River via Sage Creek is 13, 18 and 5 kg P per day, respectively. Deaver and Lovell together added about 7.5 kg P per day to the Shoshone River. Therefore, the June 1975 point source phosphorus load for Bighorn Reservoir was around 600 kg P per month. For July 1975 the corresponding value was 806 kg P per month, and for August 1975 it was 372 kg P per month. A comparison of these values with those in Table 13 shows that the total phosphorus inputs from the Shoshone River domestic wastewater sources to Bighorn Reservoir during these three months was negligible. For example, in August 1975 approximately 21,000 kg P per month were added to the reservoir via Shoshone River.

The point sources of phosphorus amounted to about 2 percent of the total. However, similar calculations for the soluble orthophosphate load show that in August 1975 about 10 percent could be accounted for by point sources if all point source phosphorus were discharged in soluble orthophosphate form, and it remained in this form during transportation to the reservoir. For July 1975 about 8 percent of the soluble orthophosphate load was added to Bighorn Reservoir via the Shoshone River from point sources. In 1980, the domestic wastewater inputs to the Shoshone River were estimated to be 15 and 17 percent of the soluble orthophosphate load added to the reservoir for July and August, respectively, based on information provided in Table 51.

Using generally the same approach for the Bighorn River, as used for the Shoshone River described above, the information presented in Table 52 shows that approximately 50 percent of the average monthly flow released from Boysen Reservoir is diverted in irrigation canals between Thermopolis and Worland. The corresponding values for July and August 1975 are 30 and 58 percent. This means that between 30 and 60 percent of the phosphorus discharged by Thermopolis in wastewater effluent is diverted before it reaches Worland. Since there are no further significant irrigation diversions below Worland, it is possible to estimate the domestic wastewater phosphorus input to Bighorn Reservoir from the Bighorn River as the sum of the contributions by all downstream communities and about half of the Thermopolis input. In 1975 these wastewater phosphorus contributions were approximately 15 kg P per day from Worland, 2 kg P per day from Ten Sleep, 3 kg P per day from Basin, 1 kg P per day from Meeteetse and 6 kg P per day from Greybull. For June, July and August 1975 the total phosphorus per month added to Bighorn Reservoir from domestic wastewater input is approximately 990 kg P per month. While the phosphorus inputs from domestic wastewater sources represent a small part of the total phosphorus load during the summer months, it is a significant part (approximately 40 percent) of the August soluble

TABLE 48. DOMESTIC WASTEWATER INPUTS TO TRIBUTARIES OF BIGHORN RESERVOIR*

	1975		1980	
Municipality	Population	Wastewater Treatment Plant Discharge (MGD)	Population	Wastewater Treatment Plant Discharge (MGD)
Bighorn River				
Basin	1,145	0.22	1,338	0.23
Greybull	1,953	0.21	2,250	0.22
Meeteetse	459	0.23	521	0.30
Ten Sleep	729	0.07	859	0.087
Thermopolis	3,063	0.40	3,849	0.49
Worland	5,055	0.45	6,379	0.495
Shoshone River				
Byron	397	0.24	635	0.25
Cody	5,161	0.50	6,661	0.61
Deaver	112	0.02	178	0.03
Lovell	2,371	0.24	2,445	0.25
Powell	4,807	2.10	5,302	2.30

*Information supplied by J. Wagner, Wyoming Department of Environmental Quality, 1981

TABLE 51. IRRIGATION DIVERSIONS OF THE SHOSHONE RIVER 1980

Wastewater Discharges (cfs)	Shoshone River Measured Discharge (cfs)				Shoshone River Canal Diversions (cfs)		
	June	July	Aug.		June	July	Aug.
	1,852	2,271	1,170	Buffalo Bill Reservoir (USGS Gage) ↓			
0.94				Cody			
				→ Garland Canal	850*	850*	850*
				→ Willwood Canal	233	340	302
	1,464	3,387	861	Willwood (USGS Gage)			
				→ Elk-Lovell Canal	343	351	336
	1,091	3,137	571	Garland (USGS Gage) ↓			
3.50				Powell			
				→ Sidon Canal	201	258	253
0.38				Byron			
				→ Globe Canal	65	74	61
				→ Hunt Canal	48	98	90
0.05				Deaver ↓			
	1,573	3,650	1,018	Lovell (USGS Gage) ↓			
0.38				Lovell ↓			
				Bighorn Reservoir			

*Assumed to be the same as 1975

TABLE 52. IRRIGATION DIVERSIONS OF THE BIGHORN RIVER 1975

Wastewater Discharges (cfs)	Bighorn River Measured Discharge (cfs)				Bighorn River Canal Diversions (cfs)		
	June	July	Aug.		June	July	Aug.
	2,276	4,315	2,151	Boysen Reservoir (USGS Gage)			
0.62				Thermopolis			
				→ Lucerne Pump Ditch	39	68	68
				→ Kirby Canal	51	67	54
				→ Upper Hanover	445	482	468
				→ Lower Hanover	160	192	175
				→ Bighorn Canal	417	502	490
0.69				Worland			
0.11				Ten Sleep			
0.34				Basin			
				→ Tillard Canal	20	20	18
0.35				Meeteetse			
0.32				Greybull			
	6,168	7,152	2,118	Kane (USGS Gage)			
				Bighorn Reservoir			

orthophosphate load. Therefore, if the Shoshone and Bighorn River domestic wastewater inputs to Bighorn Reservoir are computed, it is found that about 20 percent of the soluble orthophosphate for August 1975 added to Bighorn Reservoir could be derived from this source. For August 1980, based on information provided in Table 53, the corresponding value would be about 50 percent. The increase from 1975 is due to increased populations in Bighorn Basin. (See Table 48.)

Based on discussions with C. Cooper, Wyoming State Engineers Office Water Division Superintendent Water Division No. 3, Riverton, Wyoming, many of the canals in the Bighorn-Shoshone system divert water into their systems which is used for carrying their appropriation completely through the canal. This "carriage water" is not applied to the land, but rather is spilled or finds its way back into the river downstream from where it was diverted. This means that the computations made above for the losses of domestic wastewater phosphorus by irrigation canals are less than what actually takes place because part of the irrigation canal water is returned to the river. At this time there is insufficient information available to estimate the amount of error involved in these computations as a result of this situation.

A factor that has to be evaluated, which was scheduled to be examined in the second and third years of this project, was that of the amount of available phosphorus entering Bighorn Reservoir from its tributaries. Lee et al. (1980) have summarized the current information on algal available phosphorus. This has been discussed in an earlier section of this report. Of particular importance to this section, however, are the discussions by Lee et al. (1980) on the transformations of algal available forms of phosphorus discharged from point sources in river systems. It is now clear that the further the point source of phosphorus is away from the reservoir, the greater the probability that the available phosphorus discharged by the point source, such as a domestic wastewater treatment plant, will become refractory - unavailable to support

TABLE 53. IRRIGATION DIVERSIONS OF THE BIGHORN RIVER 1980

Wastewater Discharges (cfs)	Bighorn River Measured Discharge (cfs)				Bighorn River Canal Diversions (cfs)		
	June	July	Aug.		June	July	Aug.
	3,074	3,796	1,846	Boysen Reservoir (USGS Gage) ↓			
0.75				Thermopolis			
				→ Lucerne Pump Ditch	55	62	50
				→ Kirby Canal	49	53	46
				→ Upper Hanover	455	486	467
				→ Lower Hanover	177	201	161
				→ Bighorn Canal	427	459	391
0.76				↓ Worland			
0.13				↓ Ten Sleep			
0.35				↓ Basin			
0.46				↓ Meeteetse			
0.34				↓ Greybull			
	4,385	3,662	1,709	↓ Kane (USGS Gage)			
				↓ Bighorn Reservoir			

algal growth in the reservoir. Per unit phosphorus, the Cody and Thermopolis wastewater phosphorus loads will have less impact on Bighorn Reservoir than phosphorus loads from Lovell or other communities located near the reservoir. At this time, insufficient information is available on this topic to enable reliable predictions of the impacts of "upstream" phosphorus loads on the reservoir. It could be that the "upstream" point sources such as Cody, Thermopolis, etc., could spend a lot of money for phosphorus removal and have little or no impact on Bighorn Reservoir water quality. Before any management plan is put into effect involving phosphorus removal from communities in Bighorn Reservoir's watershed, site-specific studies should be conducted to determine the relative significance of various point sources of phosphorus in impairing beneficial uses of Bighorn Reservoir.

Table 54 presents the data obtained for the chlorophyll a concentration at Horseshoe Bend and soluble orthophosphate load for July and August to Bighorn Reservoir. It is evident that for the five years for which there is data, that there is an essentially constant ratio of the July and August planktonic algal chlorophyll at Horseshoe Bend and the soluble orthophosphate load during that year. From this type of relationship it can be argued that the primary factor governing planktonic algal chlorophyll for the primary recreation period at Horseshoe Bend, i.e., July and August, is the amount of soluble orthophosphate added to Bighorn Reservoir during those months. From a hydrologic point of view this conclusion is in accord with what would be expected. Since the phosphorus added to Bighorn Reservoir for October to June of each year would be expected to be carried downstream in the reservoir past Horseshoe Bend by the high spring flows, it is reasonable to conclude that the available phosphorus load, i.e., soluble orthophosphate, to the reservoir during the summer months would be the primary factor governing phytoplankton growth in the upper parts of the reservoir. The data presented in Table 54 strongly support this conclusion.

TABLE 54. SUMMARY OF CHLOROPHYLL a CONCENTRATIONS AND SOLUBLE ORTHOPHOSPHATE LOADS FOR HORSESHOE BEND IN JULY AND AUGUST

	1968	1969	1970	1975	1980
Average Chlorophyll a near Horseshoe Bend (µg/l) (July, August)	28	20	16	42*	33
July, August Soluble Orthophosphate (kg P/summer)	14,240	8,859	-	22,640	15,116
Ratio of Average Summer Chlorophyll to July and August Phosphorus Load $\times 10^3$	2.0	2.3	-	1.9	2.2

*Single value

Dash (-) indicates no data available

In order to evaluate whether this conclusion is appropriate, it would be necessary to compute the monthly hydraulic residence time of the upper part of Bighorn Reservoir. While the Bureau of Reclamation range maps provide cross sections of the original shape of the reservoir at and above Horseshoe Bend before dam closure, these cross sections provide no information on the current topography.

As noted in this report, at least 12 m of sediment had accumulated in parts of Horseshoe Bend since dam closure in 1968. No information is available at this time on sediment accumulation in other parts of Bighorn Reservoir above Horseshoe Bend. Actually, from a water quality point of view with respect to eutrophication control, the amount of sediment that has accumulated in this area is of little interest. What is needed is the volume of the reservoir above Horseshoe Bend as a function of pool elevation. With tributary river flow information during the summer months, and the current volume of the reservoir as a function of reservoir stage, it is possible to compute a monthly or weekly hydraulic residence time of that part of the reservoir and thereby assess the amount of phosphorus present at Horseshoe Bend during July and August that is derived from the inputs of soluble orthophosphate to the reservoir during these months. The premature termination of the project prevented the collection of data which could have been used to provide the needed information on the relationships between the soluble orthophosphate loads during the summer months to the reservoir and the excessive algal growths that occurred in July and August of each year.

IMPLICATION OF RESULTS FOR EUTROPHICATION-RELATED WATER QUALITY MANAGEMENT IN BIGHORN RESERVOIR

The action of the National Park Service University of Wyoming Research Center in diverting funds which had been originally set aside for support of this project during its second and third years, to other National Park Service areas, prevented completion of this project to the point where definitive conclusions or recommendations could be made on the approaches that should be adopted for management of eutrophication-related water quality in the Horseshoe Bend region of the reservoir. This project did proceed to the point of developing sufficient information to formulate preliminary information in this area. A discussion of the implications of the results of this study for water quality management for Bighorn Reservoir is presented below.

The results of this investigation point to the potential importance of the June and July soluble orthophosphate loads to Bighorn Reservoir from the Shoshone and Bighorn Rivers in influencing the eutrophication-related water quality in the Horseshoe Bend area of the reservoir. If the preliminary conclusions are supported by more detailed studies then consideration should be given to adopting remedial programs which would limit the amount of available phosphorus discharged to these rivers during these months. It has been found that phosphorus removal to about 1 mg/l effluent phosphorus can be readily achieved at domestic wastewater treatment plants by the addition of iron or aluminum salts at a cost of less than a quarter of a cent per person per day for the population served. These costs are generally associated with treatment plants serving more than 10,000 people. Since all of the treatment plants in the Bighorn Reservoir watershed are less than this size, the cost would be increased somewhat. Even at a cent per person per day for the total population served by treatment plants located in the reservoir's watershed, for treatment only during July and August, the annual cost would be about $300.

At this time, there is insufficient information available to judge the potential impact of practicing phosphorus removal during the summer months, at all or selected domestic wastewater treatment plants in the Bighorn Reservoir watershed, on the improvement of water quality that will occur at Horseshoe Bend. The results of a research program as originally planned for years two and three of this project are needed to develop phosphorus load eutrophication response relationships for this waterbody. It is anticipated that the OECD eutrophication modeling approach described earlier in this report, modified to consider only the upper portion of the reservoir and summer phosphorus loads, would be a suitable basis for estimating the impact of altering the phosphorus loads derived from domestic wastewaters on eutrophication-related water quality in the Horseshoe Bend region of the reservoir. It is important to emphasize, however, that studies need to be conducted to verify that this modeling approach is applicable to this part of the reservoir.

Many Wyoming communities are showing rapid increases in population. Generally, a 10 to 20 percent increase in population was observed for the communities located in the Bighorn Reservoir watershed between 1975 and 1980. As these communities develop, and as they upgrade their sewage collection and wastewater treatment plant systems, their importance in influencing water quality deterioration in Horseshoe Bend will increase. With increased populations in these communities water quality in Horseshoe Bend will continue to deteriorate. Detailed studies of the type recommended in this report are needed to determine the relationships between the phosphorus discharged by a particular community in its domestic wastewaters and water quality in Bighorn Reservoir.

In addition to consideration of phosphorus removal by addition of iron or aluminum salts at the wastewater treatment plants, consideration should be given to direct addition of alum to the Bighorn and Shoshone Rivers during late June, July and August. This could prove to be highly effective in improving water quality in the upper parts of Bighorn Reservoir during the critical period of recreational use of the reservoir. Direct alum addition to lakes and reservoirs has been shown to be highly effective in controlling eutrophication-related water quality in some waterbodies. The physical setting of the Bighorn and Shoshone Rivers relative to Horseshoe Bend and the high turbidity of these waters due to erosional materials provide an almost ideal setting for this approach. This approach has proved to be highly successful in West Germany in managing eutrophication-related water quality at the Wahnbacht Reservoir near Bohn. (Clasen, 1978) The complete tributary stream to this reservoir is passed through a phosphorus removal plant. By understanding the role of the various forms of phosphorus present in the Bighorn and Shoshone Rivers, as well as upper parts of the reservoir, in causing excessive fertilization of the Horseshoe Bend region of the reservoir during July and August, it is possible that highly selective phosphorus removal could be practiced. Preliminary cost estimates indicate that direct treatment of the tributaries may be cost prohibitive. However, it may be possible to selectively treat Horseshoe Bend at a greatly reduced cost and significantly improve water quality in that part of the reservoir. It is important to emphasize that before any further work can be done on developing water quality management programs in Bighorn Reservoir, the studies which were originally planned for the second and third years of this project must be completed by individuals who are thoroughly familiar with phosphorus load eutrophication response relationships for lakes and reservoirs. Further, those conducting these studies must be familiar with the use of information of this type in developing public policy for eutrophication management.

PART D
CONCLUSIONS AND RECOMMENDATIONS

1. In order to develop a technically valid eutrophication management plan for Bighorn Reservoir it will be necessary to conduct studies that were originally planned for the second and third years of this project. Particular attention must be given to obtaining current bathymetric information on Bighorn Reservoir from a kilometer or so north of Horseshoe Bend to the upper end of the reservoir. It is recommended that bathymetric mapping of this part of the reservoir be completed. This information is needed to estimate rates of sediment accumulation and to apply the US OECD eutrophication study model to the upper parts of the reservoir and thereby determine the cost-effectiveness of phosphorus control programs in managing eutrophication-related water quality in the upper parts of the reservoir.

2. The current populations and amount of phosphorus discharged by municipalities and industry to the Shoshone and Bighorn Rivers and their tributaries should be determined. Particular emphasis should be given to the period May through August. Also, studies should be conducted on the Bighorn and Shoshone Rivers to determine the amounts of phosphorus that are discharged to these rivers or their tributaries by communities in the watershed that reach the Horseshoe Bend area of the reservoir during the summer months and are available to support algal growth in that area. This information is needed to determine the efficacy of phosphorus removal programs at the municipal wastewater treatment plants while improving water quality in the upper parts of Bighorn Reservoir.

3. Domestic wastewaters discharged to the Shoshone and Bighorn Rivers represent a potentially significant source of phosphorus for the excessive algal growth

that occurs in the summer in the upper parts of Bighorn Reservoir. As these communities discharging domestic wastewaters increase in population their significance in the excessive fertilization of Bighorn Reservoir will become increasingly important. It is recommended that before any phosphorus removal programs are initiated, that site-specific studies be conducted to determine the impact of each communities' wastewater discharges of phosphorus on impairing beneficial uses of Bighorn Reservoir. Particular attention should be given to determining the amount of algal available phosphorus entering Bighorn Reservoir during July and August that contributes to the excessive fertilization of Horseshoe Bend. Further, the sources of this algal available phosphorus should be determined with particular emphasis on the potentially controllable sources such as domestic wastewater inputs.

4. It has been found that rapid siltation of the upper parts of Bighorn Reservoir has been occurring since closure of the dam. Over 12 m of sediment has accumulated in Horseshoe Bend in 13 years. It is recommended that a water depth monitoring program be established for Horseshoe Bend which would determine on an annual basis the rate of sediment accumulation in this part of the reservoir. With this type of information it should be possible to determine whether or not further site accumulation is to be expected in this part of the reservoir. If sufficient sediment accumulation is occurring to impair the use of Horseshoe Bend for recreational boating purposes, then any development of additional public recreational facilities, such as a marina, should only be done if long term funding of sediment removal can be accomplished. It does not appear at this time that any technically valid, economically feasible procedures are available to control sediment

input to Horseshoe Bend. Therefore, the long range sediment accumulation problems must be based on removal of sediment at the point where sediment accumulation interferes with desired beneficial uses.

PART E

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