A LIMNOLOGICAL SURVEY OF LAKE LAURA, VIRGINIA

by

James Parker

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
Environmental Science and Engineering

APPROVED:

Dr. T. J. Grizzard

Dr. J. L. Malanchuk

Dr. A. Evans, Jr.

May 1987

Blacksburg, VA

A Limnological Survey of Lake Laura, Virginia

by

James Parker

Committee Chairman: Dr. Thomas J. Grizzard

Civil Engineering

(ABSTRACT)

A limnological survey of Lake Laura and its tributary streams was conducted from June to October 1986 to evaluate causes of excessive algal blooms experienced in past years.

Lake Laura was classified as mesotrophic based upon total phosphorus surface water, chlorophyll a, and secchi disc levels measured. Due to atypical meterological conditions experienced during the study, the Vollenwieder model was utilized to evaluate the impact of various nutrient sources on Lake Laura under more typical conditions. Nonpoint source runoff from agricultural and pasture land and effluent from the Orkney Springs wastewater treatment plant were determined to be the main sources of nutrient inputs to Lake Laura.

A description of lake and drainage basin monitoring methods, model results, and an analysis of recommended lake management practices to control future algal blooms is included.

ACKNOWLEDGEMENTS

I would like to thank my Committee Chairman Dr. Tom Grizzard for his guidance and constant encouragement throughout this study. I would also like to thank my other committee members, Dr. John Malanchuk, Dr. Barry Weand, and Dr. Andrew Evans for their time and guidance. I also wish to acknowledge and all the staff at the Occoquan Watershed Monitoring Laboratory for their support in the field and in the laboratory, and for her word processing support. Finally, I would like to thank my wife for her constant encouragement and support for almost five years.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Purpose of Study

Lake Laura, located at the Bryce Mountain Resort in Shenandoah County, Virginia, has experienced excessive algal blooms over the past several years during the spring and summer seasons. The cause of the algal blooms is suspected as being the nutrient-rich effluent from the wastewater treatment plant located in the Town of Orkney Springs, Virginia. The effluent from this wastewater treatment plant is the only known source of pollutants which discharges to Lake Laura. The apparent deterioration of the water quality in Lake Laura over the past years has spurred interest by the Bryce Mountain Homeowners Association to investigate the cause of the decreased water quality, especially since one of the primary uses of the lake at the resort is for recreational purposes (i.e., swimming, boating, fishing). The purpose of this study, therefore, was to perform a limnological survey, with particular emphasis on physical and chemical factors, of Lake Laura and its associated drainage basin, in an effort to identify the potential causes of the algal blooms.

LITERATURE REVIEW

Lakes are self-contained in terms of the various biological components which are contained within the lake waters (i.e., aquatic plants and animals). However, the rate of metabolism and relative stability over years of these biological components is dependent on the input of light (i.e., radiant energy) and especially the rate of inflow and outflow of water and materials from the watershed. When an excessive amount of nutrients are introduced into lakes productivity is observed to increase substantially.

The process of eutrophication is a complex phenomenon which is affected by a number of physical, biological, and chemical factors (Rast, et al., 1983). The physical factors that influence the quantity of nutrients entering a watershed include the amount of nutrients in soils, topography, vegetative cover, quantity and duration of runoff flow, land use, and point source pollution (Wetzel, 1983). Most surface soils are relatively rich in nutrients from plant debris in different states of decomposition. The topography of the land within a lake basin or watershed will influence the extent of erosion of soils and the resulting export of nutrients. For example, flat lands with little runoff and high filtration rates (i.e., sandy soils) will contribute lower nutrient loads to runoff as compared to similar lands with steeper gradients (Sonzogni, et al., 1980). The relative amounts of erosion of soils during runoff periods is influenced by soil type, vegetation, and use of the land surrounding a lake. Many studies have quantified the relative amounts of nutrients that could be expected from a given land use (Rast and Lee, 1983; Sonzogni, et al., 1980; Daniel, et al., 1982). The land use types evaluated by these studies generally fall into four categories: rural (agriculture), urban, forest, and wetlands. In general, the nutrient loads from intensive agriculture and urban uses were found to be much greater than forested lands.

The most significant point sources of nutrient loads to lakes are generally domestic wastewater treatment plant effluents that are discharged directly to the lake, or, more commonly, to a tributary of the lake (Rast and Lee, 1983). However, the extent of nutrient loading to a lake from a wastewater treatment plant varies greatly with the density of population, the extent of treatment of the sewage for nutrient removal, and the proximity of the points of discharge of wastewater treatment plant effluent to the lake (Wetzel, 1983).

Two other physical factors which affect the process of eutrophication are atmospheric precipitation and groundwater. In particular these two physical factors could also be responsible for the transport of nutrients into a lake. The input of nutrients to a lake from atmospheric precipitation will be extremely variable depending upon many factors including: local meteorological conditions, wind patterns, and location of the lake in relation to industrial outputs. In light of this variability, studies have estimated atmospheric precipitation and dry fallout loadings of nutrients to be significant compared to other land uses (Daniel, et al., 1982; Rast and Lee, 1983). The phosphorus content of atmospheric precipitation is less than that of nitrogen (Wetzel, 1983; Rast and Lee, 1983).

The basic composition of groundwater depends upon its contact with soils, minerals, and rocks, and will vary depending upon the geographic location of the lake drainage basin and the associated geological make-up of the basin. The significance of nutrient loadings to lakes from groundwater has not been quantified primarily due to the inadequate methods of monitoring groundwater (Novotny and Chester, 1981). However, the limited information available regarding groundwater characteristics shows that nitrate nitrogen is the most common nutrient identified in groundwater (Wetzel, 1983; Novotny and Chesters, 1981). Further, the phosphorus content of groundwater is generally found to be low (Wetzel, 1983).

Biological factors also play an important role in the process of eutrophication. In particular, lake phytoplankton, which include truly aquatic single-celled photosynthetic algae and blue-green algae (or Cyanobacteria) play critical roles in nutrient cycles (Wetzel, 1983). These roles include decomposers and recyclers in food chains, as agents in biogeochemical cycles, and as links in detritus communities (Cole, 1983).

Within the basic physiological requirements of temperature and light, various chemical factors are critical to the growth and succession of lake phytoplankton. Particularly the nutrients carbon, nitrogen and phosphorus have been cited as being the elements most necessary for growth of aquatic algae and macrophytes (Cole, 1983; Wetzel, 1983; Lee, et al., 1978). Due to the fact that carbon, nitrogen and phosphorus play significant roles in aquatic plant growth in lakes, control of these nutrients has received much study over the years with respect to lake eutrophication.

According to the "Liebig Law of Minimum," the growth of a plant will be limited by the nutrients least present to the plant, relative to its needs. For growth and reproduction, the ratio of essential nutrients algae typically need is 106 carbon atoms to 16 nitrogen atoms to 1 phosphorus atom. The large algal demand for carbon, compared to nitrogen and phosphorus, would lead one to believe that carbon would be the limiting factor in algal growth. However, several authors have shown that it is phosphorus that is usually the limiting nutrient for algal growth in freshwater systems (Lee, et al., 1978; Rast, et al., 1983; Wetzel, 1983; Cole, 1983).

The potential for limitation of algal growth by carbon availability in lakes is small. This is primarily due to the adequate supply of carbon to lakes in its available forms, i.e., CO_2 and carbonate species (Lee, et al., 1978). Diffusion of atmospheric CO_2 is generally adequate to sustain the carbon requirements of phytoplanktonic communities in lakes (Wetzel, 1983). The only situation that would have the potential for carbon limiting algal growth in a waterbody would be under very fertile conditions, where nitrogen and phosphorus are available beyond the demands of the algal population. One such example of a highly fertile waterbody where carbon could be limiting would be a sewage lagoon (Wetzel, 1983).

Although algae would require almost ten times as much nitrogen for growth as phosphorus (based on mass), natural waters typically contain this relative amount of available nitrogen over phosphorus

(Lee et al., 1978). This is especially true for unproductive oligotrophic lakes. However, as phosphorus loading to fresh waters increases which results in increased productivity, nitrogen will become more important as a growth-limiting nutrient (Wetzel, 1983). Nitrate and ammonia are the forms of nitrogen that are generally utilized for algal growth. Dissolved nitrogen gas is also utilized by certain types of algae as a nitrogen source (Wetzel, 1983; Lee, et al., 1978). The natural sources of nitrogen to a lake includes dry fallout and precipitation, nitrogen fixation both in lake waters and in lake sediments and surface and groundwater drainage (Wetzel, 1983).

Perhaps the most significant nutrient which affects algal growth in lakes is phosphorus. This is due primarily to the fact that phosphorus is normally the controlling nutrient for algal growth in lakes. Typically, only small amounts of the biologically available forms of phosphorus are available, relative to the other nutrients required for algal growth in lakes (Lee, et al., 1978; Rast and Lee, 1978). Soluble orthophosphate is the fraction of total phosphorus which is directly utilizable for algal growth in most instances (Wetzel, 1983). The actual amount of biologically available phosphorus in a lake has been found to be approximately equal to the soluble orthophosphate content plus 20 percent times the differences between the total phosphorus and soluble orthophosphorus content (Lee, et al., 1978). Two natural mechanisms are primarily responsible for the accumulation of soluble orthophosphate in lakes; decomposition of sedimented lake plankton, and reduction of phosphate-containing trivalent iron precipitates. Phosphorus also enters lakes naturally from atmospheric precipitation, groundwater, and surface water runoff (Wetzel, 1983).

As discussed previously, man's activities can result in increased or excessive nutrient loadings to a lake. In particular, domestic wastewater discharges and agricultural and urban drainage have been recognized as sources of nutrient loadings to lakes (Lee, et al., 1978; Daniel, et al., 1982; Wetzel, 1983).

Domestic wastewater has been of particular concern as a phosphate source. The loadings from domestic wastewaters will vary depending upon the population density, the level of treatment (i.e., primary, secondary) and extent of nutrient removal at a wastewater treatment plant, and the point of discharge to a lake (Wetzel, 1983; Rast and Lee, 1983). It has also been estimated that approximately 20-25 percent of the phosphorus in domestic wastewaters is derived from the use of phosphate-built detergents (Lee and Jones, 1986).

The way in which agricultural land is utilized will directly affect the quality of the runoff water from the land. Two sources of excessive nutrients from agriculture practices are from croplands and pastureland (U.S. Environmental Protection Agency, 1984). The loading of nutrients from cropland has been directly related to tillage and other crop-management techniques. In particular, as the erosion potential presented by a given tillage practice increases, nutrient loadings in associated runoff will increase due to the attachment of nutrients to eroded sediments (U.S. Environmental Protection Agency, 1984; Sonzogni, et al., 1980). Improper or excessive application of commercial fertilizers or manure to cropland can also result in increased nutrient levels in runoff waters (Novotny and Chesters, 1981; Sonzogni, et al., 1980).

Pastureland can also contribute significant amounts of nutrients to water bodies either directly or via runoff from pasture areas. The extent of nutrient loadings from pastureland areas will depend upon pasture practices (i.e., direct animal access) and the density of animals. In one study, where animal concentrations were greater (i.e., barnyard areas), runoff contained approximately 10 times higher loadings of soluble phosphorus and ammonium nitrogen than other agricultural land uses (Daniel, et al., 1982). Another study found an exponential increase in total P, total N, and ammonium nitrogen associated with an increase in percent pasture area of a watershed (Smart, et al., 1985).

Runoff from urban areas also contributes nutrients to a water body. The contributions of nutrients from urban runoff depends upon the degree of impervious cover, the density of populations, and the degree of industrialization (Sonzogni, et al., 1980). Overall, the nutrient levels generally present in urban runoff are not as high in comparison with other possible discharges to a stream. In particular, average annual nutrient loads were found to be around an order of magnitude less than average annual loads expected from a well run secondary treatment plant (U.S. Environmental Protection Agency, 1983).

The control of eutrophication of a water body has received a vast amount of attention in the past and still does today. The most cost effective approach to managing the process of eutrophication is usually to control the supply of nutrients to a water body. Due to the fact that phosphorus has been found to be the most limiting and controllable nutrient, the control of phosphorus has been the focal point of much of the research to date (Gillion, 1984; Smith and Shapiro, 1981; Antosch, 1984). To assess the impact of the various options to control phosphorus inputs to lakes, various mathematical models have been developed. The most well known model is that of Vollenweider (1968). The Vollenweider Model states that the essential elements that control the trophic status of a lake include the mean depth of the lake, the rate at which phosphorus and water flow through the lake, and the loading of phosphorus per unit time. Utilizing these parameters, the Vollenweider Model can predict the trophic status of lakes.

Other models have been developed which relate water-quality variables to lake eutrophication. Dillon and Rigler (1974) and Oglesby and Schaffner (1978) used mean values for several lakes to derive relationships between spring total phosphorus levels and summer chlorophyll a levels. Rast and Lee (1978) developed a regression relationship between annual mean total phosphorus and Secchi disc transparency. The relationships derived from these models show that a reduction in total phosphorus levels results in reduction of lake productivity (as measured by chlorophyll a and/or Secchi disc transparency).

DESCRIPTION OF STUDY AREA

Lake Laura Morphology

Lake Laura (38° 47'N, 78° 47'W) is a small man-made lake located approximately 2.2 miles northeast of the Town of Orkney Springs, in Shenandoah County, Virginia. The lake, built in 1971, serves as a floodwater control structure for the Stony Creek Watershed (Potomac Basin) and as a recreational lake for the Bryce Mountain Resort. Lake Laura is owned and operated by the Bryce Mountain Corporation.

Table 1 provides the morphometric characteristics of Lake Laura. The main tributary to Lake Laura, Stony Creek, discharges into the south end of the lake. The minimum depth of the lake, 2.1 meters (m), is present at the south end of the lake. Lake Laura then gradually deepens towards the northern end and reaches a maximum depth of 11.3 m near the dam (see Figure 1). Excess water under normal conditions discharges from Lake Laura via a 91.4 centimeters (cm) diameter spillway, located just south of the dam, and flows back into the northern section of Stony Creek. The design flow of this principle spillway under normal conditions is 5.7 cubic meters per second (m^3/sec). Under flood conditions, an emergency spillway, 53.3 m wide and 1.6 m deep, can be utilized. The design flow of the emergency spillway is 143.8 m^3/sec.

Drainage Basin and Tributaries

The 1889.7 hectare (ha) basin surrounding Lake Laura is drained predominantly by four streams; Stony Creek, Rinker Run, Anderson Run,

TABLE 1. MORPHOMETRIC CHARACTERISTICS OF LAKE LAURA

Shoreline	
meters	2,926.1
feet	9,600.1
Surface Area (Recreation Pool)	
hectares	17.8
acres	44.0
Surface Area (Flood Pool)	
hectares	38.1
acres	94.0
Volume (Recreation Pool)	
1 x 10^6 cubic meters	0.8
acre-feet	660.0
Volume (Flood Pool)	
1 x 10^6 cubic meters	1.6
acre-feet	1,278.0
Maximum Depth	
meters	11.3
feet	37.2
Mean Depth (Recreation Pool)	
meters	4.5
feet	14.7
Drainage Area	
hectares	1,889.7
acres	4,666.0

(Source: Bryce Mountain Homeowners Association)

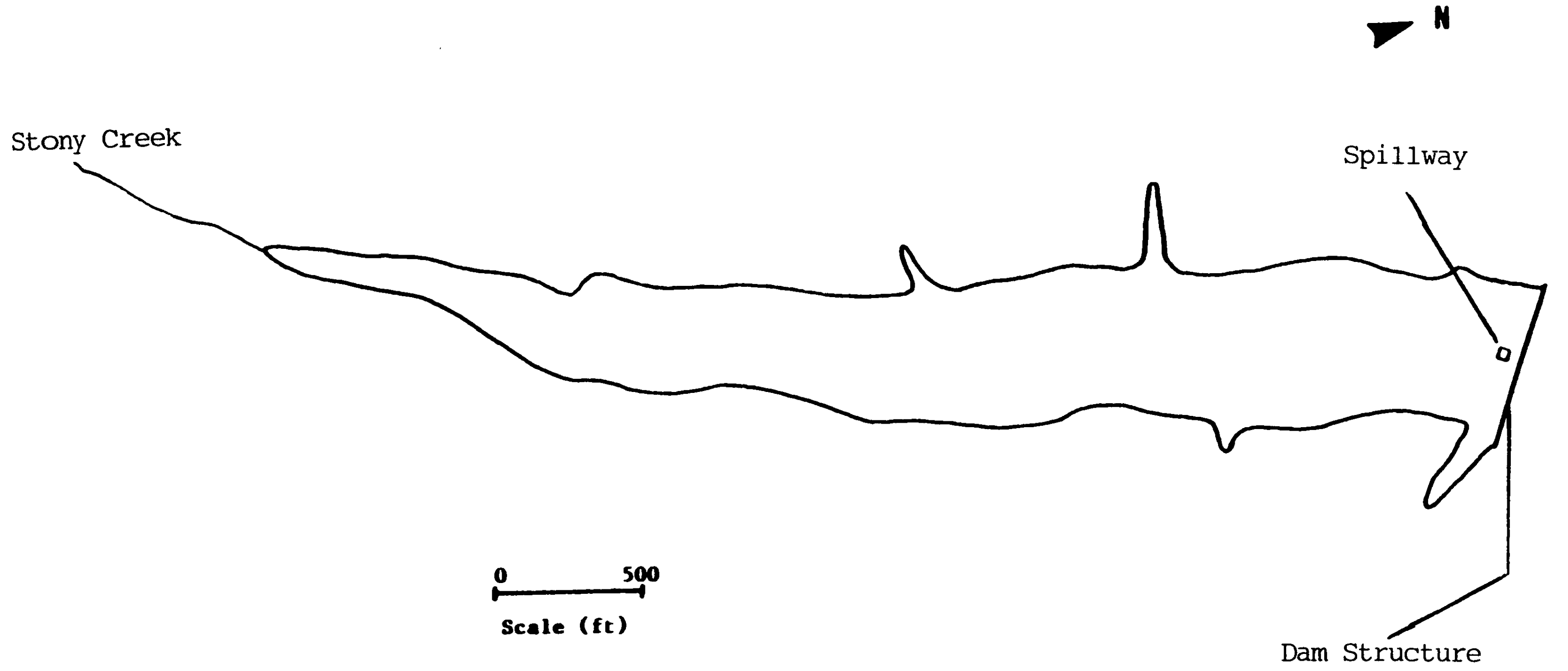
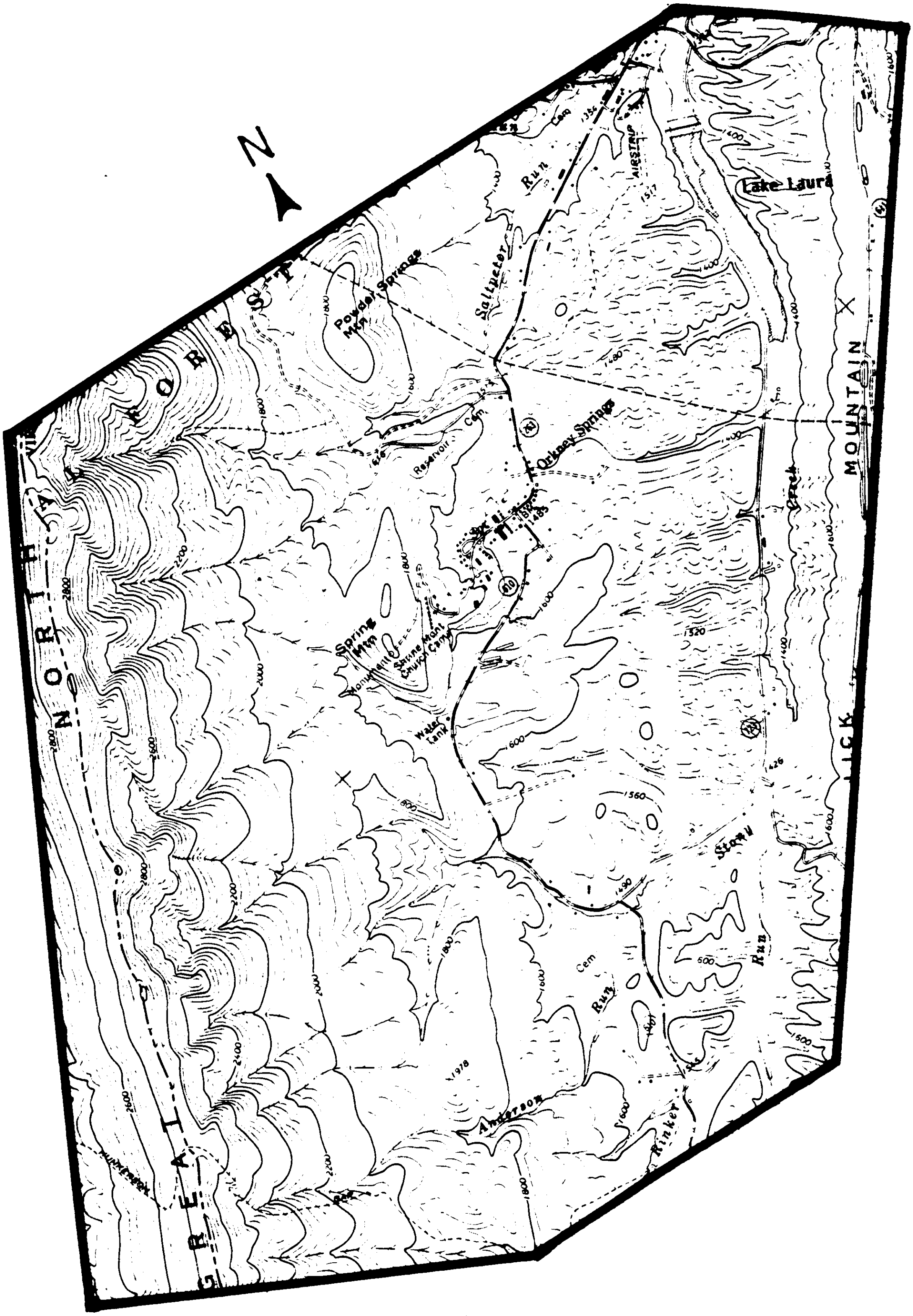


Figure 1. Lake Laura, Virginia

and an unnamed tributary of Stony Creek, hereafter referred to as "Orkney Springs Run" only for purposes of this study. In addition to these four streams, a small portion of the basin drains directly into Lake Laura via intermittent streams and direct runoff (see Figure 2). Table 2 presents estimated areas of the Lake Laura drainage basin served by each of the streams in the basin. These estimates were derived utilizing U.S. Geological Survey topographic maps (7.5 minute series) and familiarity of the drainage basin gained through a windshield survey performed during the study. Stony Creek is the only tributary which discharges directly into Lake Laura. In addition to the flow from the other streams in the drainage basin, Stony Creek receives drainage directly from eastern, southern, and western portions of the basin. Stony Creek drains approximately 35 percent of the total drainage basin area. Rinker and Anderson Run drain predominantly the southwest portions of the basin and discharge into Stony Creek approximately 2.5 km and 3.5 km downstream of Lake Laura, respectively. Rinker and Anderson Run drain approximately 25 and 10 percent, respectively, of the total drainage basin area. Portions of the northwest area of the Lake Laura basin drain into Orkney Springs Run, which drains approximately 20 percent of the total drainage basin area. The remaining ten percent of the basin, located along the eastern and western shores of Lake Laura, drain directly into the lake.

Drainage Basin Uses

The Lake Laura basin drains agricultural, forest, and urban land



(Source: U.S. Geological Survey, 1972)

Figure 2. Lake Laura Drainage Basin

TABLE 2. ESTIMATED DRAINAGE AREAS FOR THE STREAMS LOCATED IN THE LAKE LAURA BASIN

Stream	Estimated Percent of Total Drainage Basin Area (%)[1]	Approximate Drainage Area (ha)[2]	Approximate Drainage Area (acres)[2]
Stony Creek	35	661	1,632
Rinker Run	25	472	1,165
Orkney Springs Run	20	378	933
Anderson Run	10	189	467
Surrounding Lake Area	10	189	467

---

[1] Estimated from windshield survey and U.S. Geological topographic (7.5 minute series) maps

[2] Calculated by estimated percent times total drainage area (1,889.7 hectares/4,660.0 acres)

use areas. Based on USGS Land Use maps (U.S. Geological Survey, 1973-1977), forest lands constitute the major land use, estimated as covering almost 60 percent of the total area; agricultural lands are next comprising an estimated 35 percent of the total area; the remaining land in the basin is utilized for urban use.

The forest lands of the Lake Laura drainage basin are located throughout the basin. The majority of the drainage basin is covered by deciduous forest (U.S. Geological Survey, 1973-1977). However, evergreen and mixed forest cover can be found concentrated in the southeast corner of the drainage basin, adjacent to Stony Creek.

The agricultural areas of the Lake Laura drainage basin are concentrated along Stony Creek. In particular, there are several private dairy farms and a horse stable located in the basin areas drained by Stony Creek. Portions of Stony Creek actually meander through and along many of these farms and their associated pastures and barnyard areas. Much of the pasture land used by these farms allow for direct animal access to Stony Creek; only a limited portion of pasture land is fenced to keep pasture animals out of Stony Creek. The horse stable, which is operated by Bryce Mountain Resort, is located along the downstream section of Stony Creek, just prior to discharge into Lake Laura. Approximately 12 horses are kept at the stable for use by guests at the resort. Although no direct access to Stony Creek is allowed in the horse pastures adjacent to the creek, horse trails used for riding cross Stony Creek and are also located along the shores of Lake Laura itself.

The urban uses of the Lake Laura drainage basin include residential homes, a hotel and various roadways. There are over 50 residential homes located in the drainage basin, with the majority of them concentrated in and around the Town of Orkney Springs. The majority of the Bryce Mountain Resort, located north of the Lake Laura dam, is not in the Lake Laura drainage basin. However, there are several resort homes located around Lake Laura. Also located in the Town of Orkney Springs is the Orkney Springs Hotel. The hotel was not in full operation for the first half of the summer of 1986 due to rehabilitation of the hotel. Both the residential homes and the hotel in Orkney Springs are sewered, and connected to the Orkney Springs Hotels Sewage Treatment Plant (STP). The Orkney Springs Hotels STP operates under Virginia NPDES Permit No. VA0028401, which was issued on June 30, 1984, and expires on June 30, 1989 (see Appendix A). An aerated lagoon treatment system is utilized at the STP, which has a design flow of 0.0195 million gallons per day (mgd).

MONITORING METHODS

Sampling Site Locations

Both drainage basin and lake sampling sites were chosen for the study. Figures 3 and 4 present the locations of these sampling sites. A total of nine sampling sites were utilized. Four sites were located on Lake Laura (see Figure 3), each representing approximately one-quarter of the lake. Station LL01 was located at the northern and deepest end of Lake Laura, just prior to the spillway. Stations LL02 and LL03 were located in the middle quarters of the lake, in line with the small bay areas located along the western shoreline. Station LL04 was located at the south and shallowest end of the lake.

Four sampling sites were also located in the drainage basin of Lake Laura (See Figure 4). Station BM01 was located on Orkney Springs Run, at the point where Route 263 crosses over the stream, just upstream of the discharge from the Orkney Springs Hotels STP. Station BM02 was located on Stony Creek, at the point where Route 726 crosses over Stony Creek, and just after Rinker and Anderson Runs combine with Stony Creek. Station BM03 is located at a culvert on Orkney Springs Run, just prior to its discharge into Stony Creek near the horse stable, and downstream from the Orkney Springs Hotels STP. Station BM04 was located on Stony Creek, just prior to its discharge into Lake Laura, and downstream from the horse stable. The final sampling site, Station STP05, was the effluent from the Orkney Springs Hotels STP. Samples were taken just after chlorination at

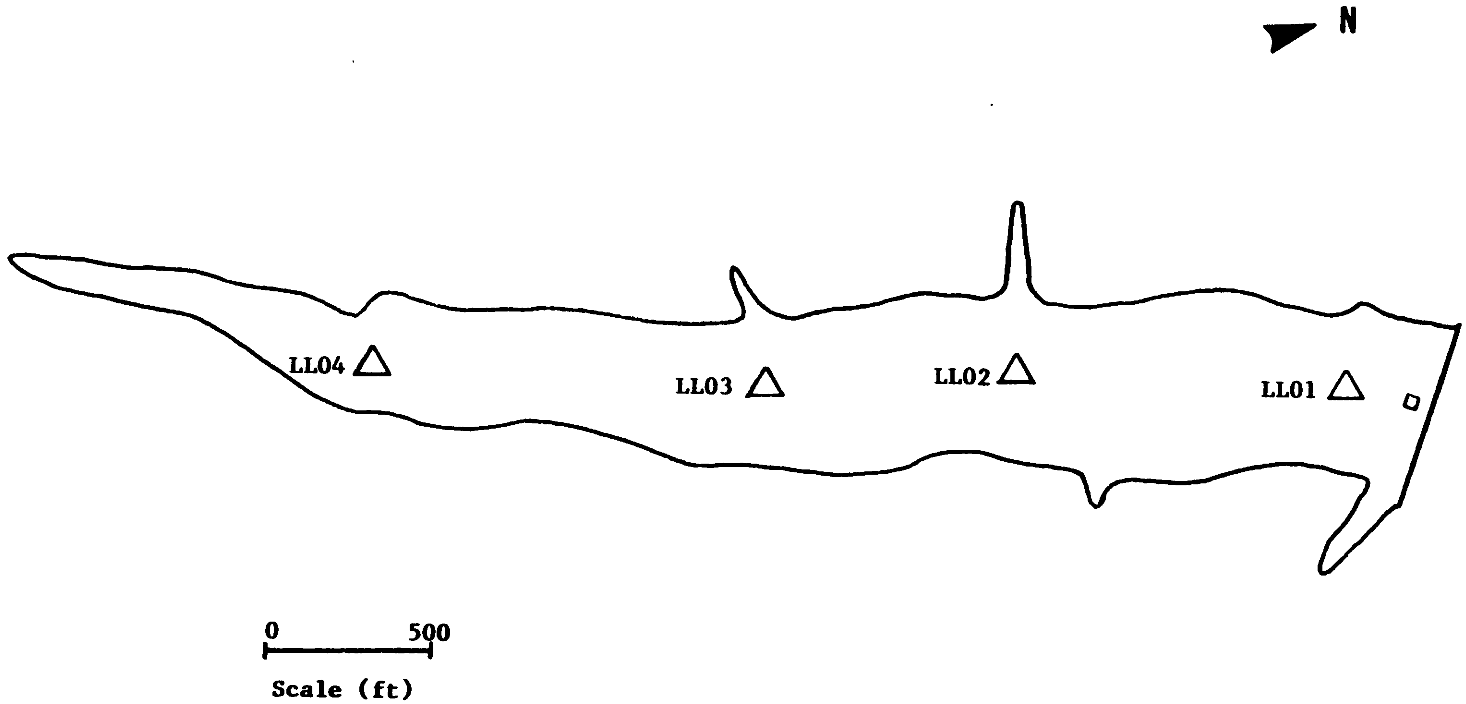
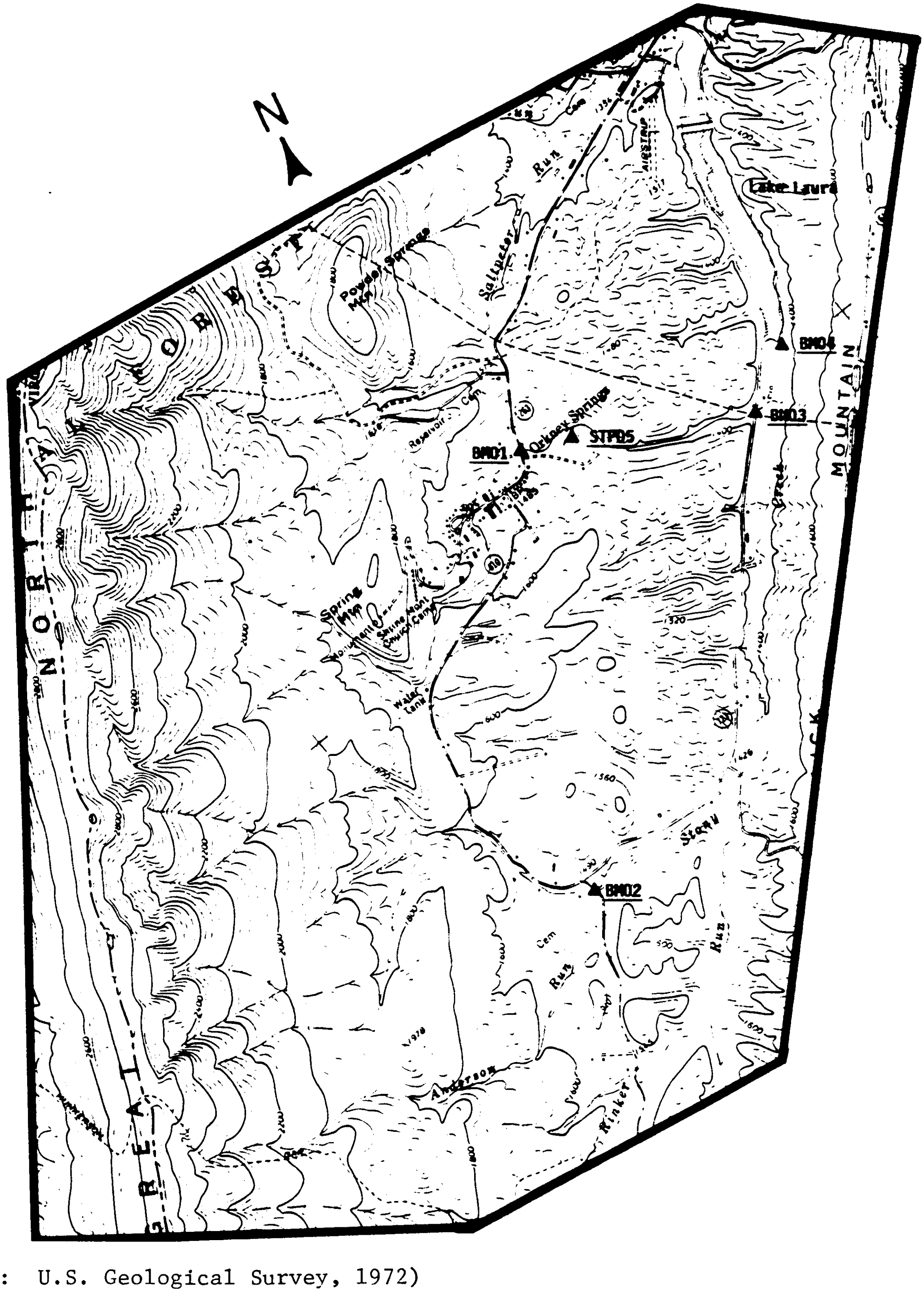


Figure 3. Lake Laura Sampling Sites



(Source: U.S. Geological Survey, 1972)

Figure 4. Lake Laura Drainage Basin Sampling Sites

the outfall cascade.

Sampling Program

Samples were taken during the period from June 1986, at the beginning of the lake growing season and after the lake had began to stratify, through October 1986, just after the lake had experienced a turnover and was almost completely mixed. In particular, seven sampling runs were performed at all nine sampling sites: June 13, July 12, July 26, August 9, September 6, September 20, and October 25. In addition, storm water samples were taken by Bryce Mountain Resort personnel at BM01, BM02, BM03, and BM04 on November 17.

Table 3 presents the parameters monitored at each sampling site. For Lake Laura sampling sites, both surface and bottom water samples were taken at each site. Surface water samples were grabbed from the boat, and bottom samples obtained using a Kemmerer water sampler. Drainage basin samples were grabbed, using a plastic bucket and rope at most sites.

One-liter plastic bottles were used to collect water samples for general chemistry analyses. Chlorophyll samples were taken in one-liter brown plastic bottles. All samples were properly labeled and stored in coolers on ice until delivery to the laboratory for analysis.

Flow measurements were also taken at STP05 during each sampling run by measuring the head in the primary device (30^o V-notch weir) located in the effluent channel at the STP. Flow measurements at the drainage basin sampling sites were taken on the last sampling run,

TABLE 3. LAKE LAURA SURVEY SAMPLING PARAMETERS

Sampling Sites	Parameters Sampled	Sample Depth (ft)
LL01	Dissolved Oxygen and Temperature	1.0, 2.5, 5.0, 7.5, 10.0, 15.0, 20.0, 25.0, Bottom
	Chlorophyll	Surface
	Transparency (Secchi)	--
	Water Chemistry*	Surface, Bottom
	pH	Surface, Bottom
	Alkalinity	Surface, Bottom
	Conductivity	Surface, Bottom
LL02	Dissolved Oxygen and Temperature	1.0, 2.5, 5.0, 7.5, 10.0, 15.0, 20.0, 25.0, Bottom
	Chlorophyll	Surface
	Transparency (Secchi)	--
	Water Chemistry*	Surface, Bottom
	pH	Surface, Bottom
	Alkalinity	Surface, Bottom
	Conductivity	Surface, Bottom
LL03	Dissolved Oxygen and Temperature	1.0, 2.5, 5.0, 7.5, 10.0, 15.0, Bottom
	Chlorophyll	Surface
	Transparency (Secchi)	--
	Water Chemistry*	Surface, Bottom
	pH	Surface, Bottom
	Alkalinity	Surface, Bottom
	Conductivity	Surface, Bottom
LL04	Dissolved Oxygen and Temperature	1.0, 2.5, 5.0, Bottom
	Chlorophyll	Surface
	Transparency (Secchi)	--
	Water Chemistry*	Surface, Bottom
	pH	Surface, Bottom
	Alkalinity	Surface, Bottom
	Conductivity	Surface, Bottom
BM01,BM02, BM03,BM04, STP05	Dissolved Oxygen	Surface
	Temperature	Surface
	Water Chemistry*	Surface
	pH	Surface
	Alkalinity	Surface
	Conductivity	Surface

---

* Water chemistry parameters include orthophosphorus, total phosphorus, ammonia nitrogen, total Kjeldahl nitrogen, and oxidized nitrogen.

October 25. Discharge measurements were made by the velocity-area method using a Pygmy velocity meter.

Analytical Methods

Dissolved oxygen (DO), conductivity, and temperature were all measured in the field using portable Yellow Springs oxygen and conductivity meters. All meters were calibrated in the field during each visit prior to use. Alkalinity was also measured in the field using a portable Hach water quality analysis kit. Field measurements for pH were made using a portable pH meter. The pH meter was checked and calibrated before measurements were taken at each site. Water transparency was determined using a 20-cm-diameter Secchi disc.

Water chemistry and chlorophyll analyses were performed by the Occoquan Watershed Monitoring Laboratory (OWML) located in Manassas, Virginia. Sample holding times and analyses were carried out according to Standard Methods (American Public Health Association, et al., 1985). Water chemistry included analyses for orthophosphorus (OP), total phosphorus (TP), ammonia nitrogen (NH_3), total Kjeldahl nitrogen (TKN), and oxidized, or nitrate plus nitrite, nitrogen (OX-N). Table 4 presents a summary of the OWML quality assurance/quality control program. In particular, Table 4 presents the current accuracy, precision, and detection limits for the analyses performed for the nutrient analyses.

TABLE 4. OCCOQUAN WATERSHED MONITORING LABORATORY

Quality Assurance/Quality Control

Current Accuracy, Precision, and Detection Limits

March 1987

PARAMETER	ACCURACY (%)				
	lcl	lwl	$\bar{x}$	uwl	ucl
OP	85	90	100	110	115
TP	73	85	109	133	145
NH_3	62	73	96	119	131
TKN	79	91	113	136	147
OXN	61	74	100	126	138

	PRECISION (mg/l)		
	$\bar{x}$	uwl	ucl
OP	0.0009	0.0029	0.0039
TP	0.0033	0.0078	0.0101
NH_3	0.0023	0.0063	0.0083
TKN	0.0301	0.0761	0.0991
OXN	0.0117	0.0338	0.0449

	DETECTION LIMIT (mg/l)
OP	0.01
TP	0.01
NH_3	0.01
TKN	0.01
OXN	0.01

---

lcl = lower control limit
lwl = lower warning limit
$\bar{x}$ = mean
ucl = upper control limit
uwl = upper warning limit

MONITORING RESULTS

Lake Laura

A summary of the data collected for Lake Laura is presented in Table 5. This summary was prepared using the raw data provided in Appendix B. It is important to note that the data summarized and presented in Table 5 represents data collected only during June-October 1986.

Generally, samples taken just off the lake bottom contained slightly higher concentrations of nutrients (phosphorus and nitrogen compounds) than surface water samples. The median surface water total phosphorus value was 0.02 milligrams per liter (mg/l). The median bottom water total phosphorus value was 0.06 mg/l. The predominate form of nitrogen found in Lake Laura waters was total Kjeldahl nitrogen. Surface waters had a median concentration of 0.37 mg/l, and bottom waters had a median concentration of 0.99 mg/l. Surface and ammonia nitrogen median concentrations were found to be 0.02 mg/l and 0.01 mg/l, respectively. Oxidized nitrogen was only detected once at each sampling site, each value being just above analytical detection limits.

During the entire sampling period, Lake Laura was not visually turbid. Secchi disk readings averaged 2.2 meters for the sampling period. The secchi readings were consistently were lower at the southern end of the lake, particularly at sites LL03 and LL04. The lower readings at these sites is probably due to their proximity to Stony Creek, the main tributary to Lake Laura. The median

TABLE 5. SUMMARY OF RESULTS FOR LAKE LAURA SAMPLING SITES: JUNE TO OCTOBER 1986

Parameter	Median	Number of Samples	Range
Total Phosphorus (mg/l)			
Surface	0.02	28	<0.01-0.04
Bottom	0.06	28	0.01-0.30
Orthophosphorus (mg/l)			
Surface	<0.01	27	<0.01-0.02
Bottom	<0.01	26	<0.01-0.06
Ammonia Nitrogen (mg/l)			
Surface	0.02	27	<0.01-0.06
Bottom	0.01	28	0.01-1.65
Total Kjeldahl Nitrogen (mg/l)			
Surface	0.37	28	0.21-0.65
Bottom	0.99	28	0.25-2.23
Oxidized Nitrogen (mg/l)			
Surface	<0.01	28	<0.01-0.02
Bottom	<0.01	28	<0.01-0.03
Chlorophyll _a_ (ug/l)			
Surface	5.7	24	1.1-23
Alkalinity (mg/l as $CaCO_3$)			
Surface	47.7	28	42.7-53.9
Bottom	53.5	28	36.3-77.5
Conductivity (umhos)			
Surface	109	28	95-119
Bottom	100	28	60-119
pH (standard units)			
Surface	--	28	6.9-8.5
Bottom	--	28	6.0-8.0
Secchi (m)	2.2	28	1.6-3.1

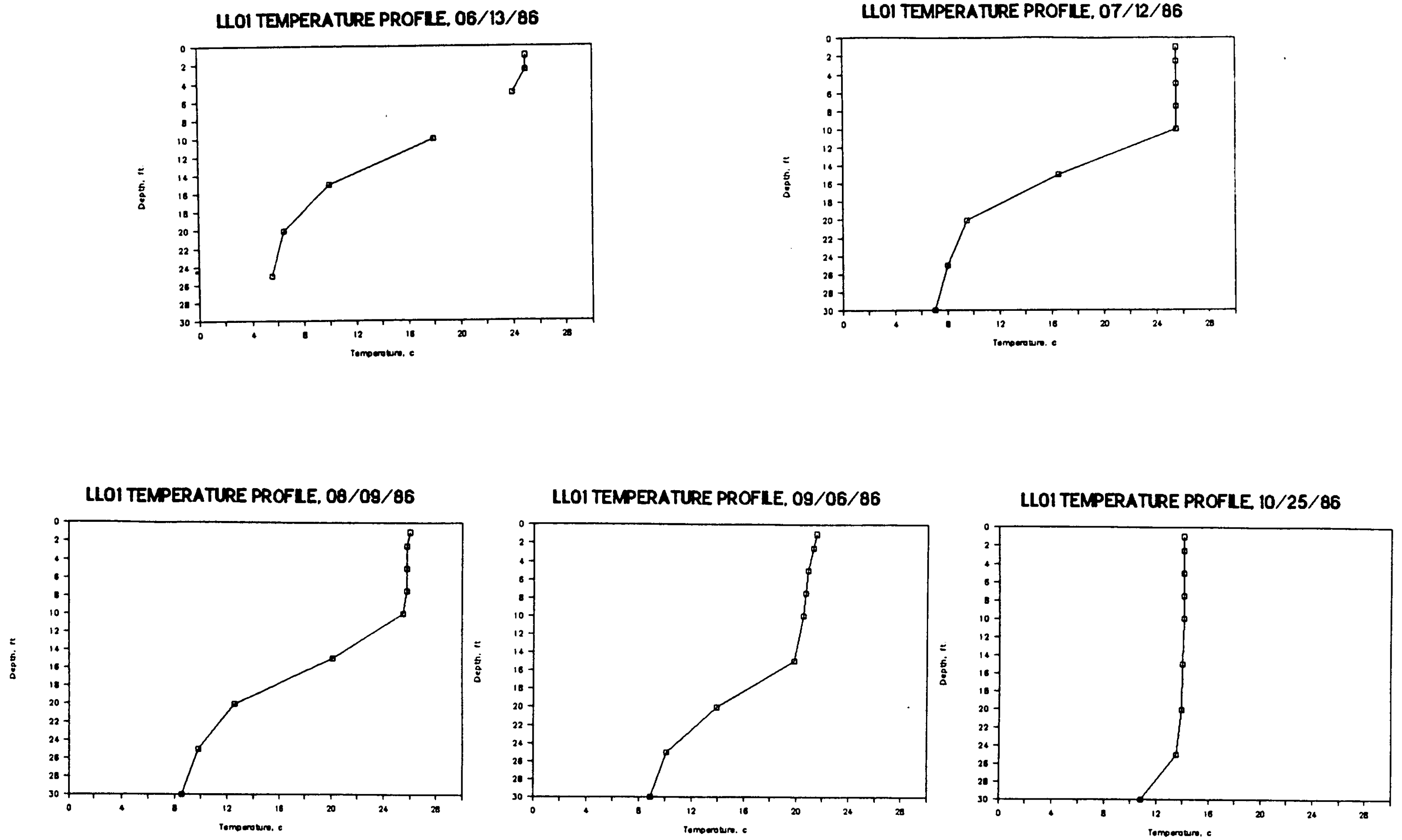
concentration of chlorophyll a was 5.7 ug/l over the sampling period in the lake surface waters.

Figure 5 provides a temperature profile for the deepest sampling site on Lake Laura, LL01. By the second month of the study (July 1986), the lake had fully stratified for the summer. Surface temperatures at this time averaged 27.5°C, the warmest observed during the entire sampling period. Bottom temperatures at the northern and deepest end of Lake Laura were around 9°C, increasing to about 14°C at LL03 and 25°C at LL04, at the shallow end of the lake. The stratum during summer stratification in Lake Laura is roughly estimated according to the temperature profiles as follows:

Epilimnion: 0-10 feet (approximately 0-3 meters)
Metalimnion: 10-16 feet (approximately 3-5 meters)
Hypolimnion: 16 feet-bottom (approximately 5 meters-bottom)

However, LL04 at the headworks of the lake and where the minimum depth of the lake is found (2.1 m), no stratification occurred. During the last sampling visit (October 1986), the lake was experiencing its fall turnover, and was for the most part, completely mixed. Average temperatures at all sampling sites throughout the water columns at fall turnover averaged just above 14°C.

Figure 6 provides a dissolved oxygen profile for the deepest Lake Laura sampling site, LL01. At LL01, the dissolved oxygen profile in the summer approach what would be considered a clinograde curve. However, the hypolimnion was never found to be anoxic (i.e., absent of oxygen), which would be found in a true clinograde oxygen profile. During summer stratification, dissolved oxygen concentrations were at or near 100 percent saturation in the


LL01 TEMPERATURE PROFILE, 06/13/86

LL01 TEMPERATURE PROFILE, 07/12/86

LL01 TEMPERATURE PROFILE, 08/09/86

LL01 TEMPERATURE PROFILE, 09/06/86

LL01 TEMPERATURE PROFILE, 10/25/86

Figure 5. LL01 Temperature Profiles

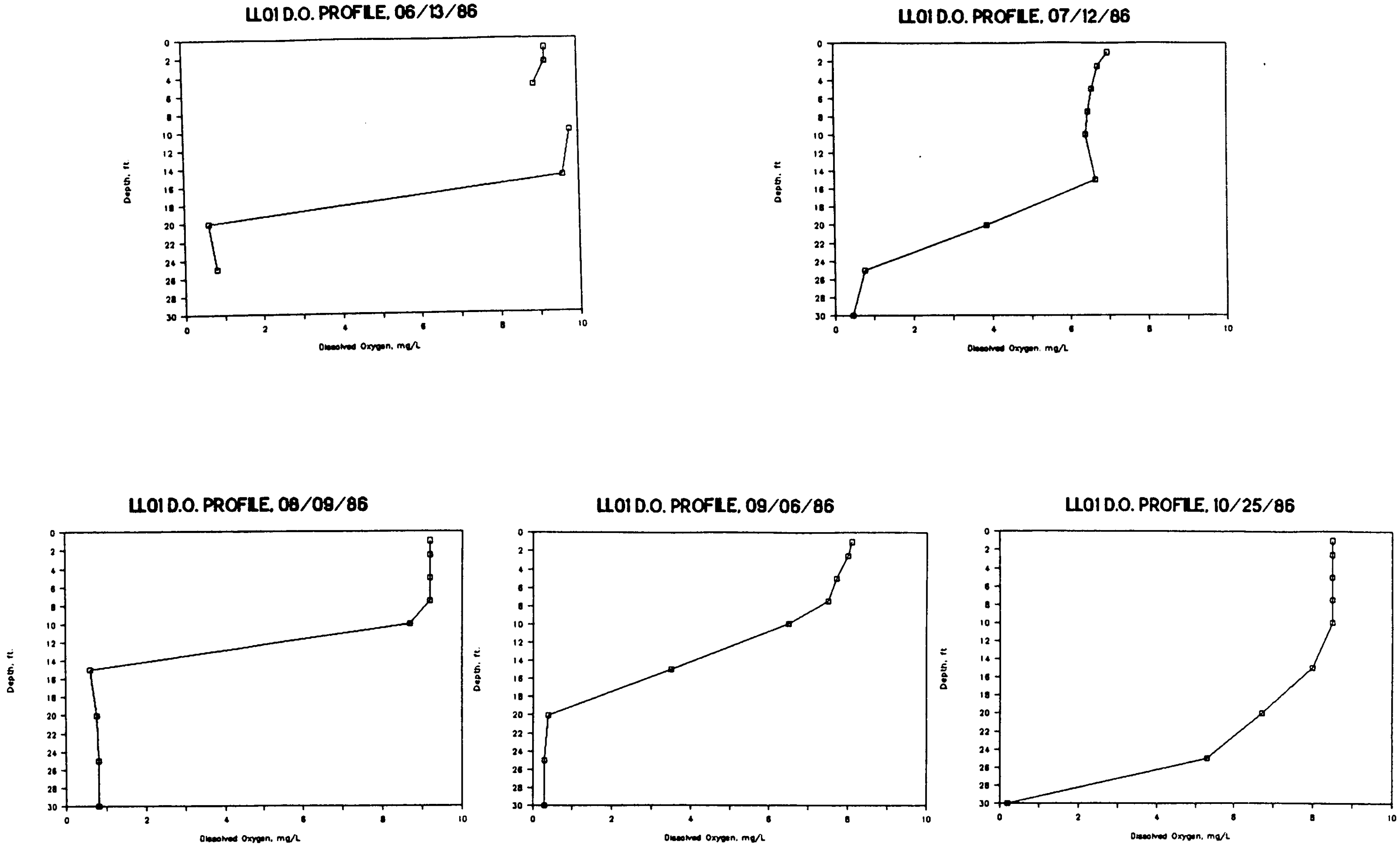


Figure 6. LL01 Dissolved Oxygen Profiles

epilimnion. At the metalimnion or thermocline (at a depth of approximately 15 feet or 4.5 meters) dissolved oxygen concentrations declined and became undersaturated (approximately 40-50 percent). In the hypolimnion, the dissolved oxygen concentrations became progressively more reduced and undersaturated, with all values less than 10 percent saturated. Dissolved oxygen at LL04 was fairly constant throughout the lake depth, which was consistent with the completely mixed condition at that location in the lake.

During fall turnover dissolved oxygen concentrations were not totally equal throughout the depth profile. At the northern deep end of the lake, at sites LL01 and LL02, dissolved oxygen concentrations were approximately 80 percent saturated to a depth of around 20 feet (6 meters). Below 20 feet, dissolved oxygen concentrations became progressively undersaturated, with waters at less than 5 percent saturation. At the shallower end of Lake Laura, where fall turnover was more complete, dissolved oxygen concentrations were fairly constant throughout water depth. At LL03, dissolved oxygen concentrations were around 70-80 percent saturated throughout. At LL04, dissolved oxygen concentrations were slightly higher, approximately 90 percent saturation throughout.

The pH of the surface water was slighty higher than that found in the bottom water at Lake Laura. Surface water pH ranged from 6.9-8.5, only very slightly alkaline or above neutral. Bottom water pH ranged from 6.0-8.0, right around neutral. No variability between the pH measured at the four sampling sites was noted.

Conductivity, an indirect measure of the amount of ions present in water, was found slightly higher in the surface waters (median = 109 umhos) than in the bottom waters (median = 100 umhos). There were no differences found between the conductivity measured at the four sampling sites. Alkalinity, the capacity of a water to neutralize a strong acid, was found higher in the bottom waters (median = 53.5 mg/l as $CaCO_3$) than in the surface waters (median = 47.7 mg/l as $CaCO_3$). The only difference noted between lake sampling sites was that water alkalinity was slightly higher at the northern end of the lake at LL01, than at any other site location.

Drainage Basin

Table 6 presents a summary of the data collected from the Lake Laura drainage basin. This summary was prepared using the raw data presented in Appendix C. It should be noted that the data summarized and presented in Table 6 only represents data collected during the period from June-October 1986.

Nutrient (phosphorus and nitrogen compounds) concentrations measured in the main tributary to Lake Laura (BM04) were approximately equal to those concentrations found in the lake itself. The highest concentrations of nutrients found in all streams sampled, excluding STP05, was at BM03, downstream from the sewage treatment plant. Median total phosphorus and orthophosphorus concentrations at BM03 were 0.52 mg/l and 0.42 mg/l, respectively. The median concentration of total Kjeldahl nitrogen was 0.72 mg/l and the median oxidized nitrogen (nitrate plus nitrite) concentration was 3.67 mg/l at BM03. As would be expected, the highest concentrations of

TABLE 6. SUMMARY OF RESULTS FOR LAKE LAURA DRAINAGE BASIN SAMPLING SITES : JUNE TO OCTOBER 1986

Parameter	BM01	BM02	BM03	BM04	STP05
Total Phosphorus (mg/l)					
Median	<0.01	0.02	0.52	0.03	7.61
Number	7	7	7	7	6
Range	<0.01–0.05	< 0.01–0.04	0.32–0.94	0.01–0.04	4.06–9.18
Orthophosphorus (mg/l)					
Median	<0.01	<0.01	0.42	0.01	4.06
Number	7	6	7	7	5
Range	—	<0.01–0.01	<0.01–0.94	<0.01–0.04	0.03–6.26
Ammonia Nitrogen (mg/l)					
Median	0.02	0.02	0.02	0.02	6.99
Number	7	7	7	5	4
Range	0.01–0.03	<0.01–0.04	0.01–0.04	<0.01–0.03	0.05–19.63
Total Kjeldahl-N (mg/l)					
Median	0.29	0.15	0.72	0.16	33.83
Number	7	7	7	7	7
Range	0.05–0.84	<0.01–0.32	0.38–1.01	<0.01–0.30	19.56–41.48
Oxidized Nitrogen (mg/l)					
Median	0.41	0.06	3.67	0.22	0.20
Number	7	7	7	7	7
Range	0.01–0.49	<0.01–0.15	0.04–4.16	0.05–1.88	<0.01–0.93
Alkalinity (mg/l as $CaCO_3$)					
Median	62.1	112.8	90.7	103.5	298.8
Number	7	7	7	7	6
Range	57.2–68.2	75.2–123.7	63.2–147.6	73.8–126.4	264.9–339.4
Conductivity (umhos)					
Median	250	175	332	183	725
Number	7	7	7	7	6
Range	225–272	130–190	240–400	140–200	670–880
pH (standard units)					
Number	6	6	6	6	6
Range	6.2–6.9	7.0–7.7	6.7–7.3	7.0–7.8	6.9–7.5
Dissolved O_2					
Median	7.7	8.8	7.6	9.1	3.4
Number	7	7	7	7	6
Range	6.4–8.5	8.2–9.8	7.0–8.5	7.3–9.8	2.2–5.9

TABLE 6. SUMMARY OF RESULTS FOR LAKE LAURA DRAINAGE BASIN SAMPLING SITES: JUNE TO OCTOBER 1986 (Continued)

Parameter	BM01	BM02	BM03	BM04	STP05
Temperature (°C)					
Median	19.0	18.0	19.1	20.5	19.4
Number	7	7	7	7	6
Range	11.5–21.5	11.0–19.0	11.2–21.5	11.0–22.1	13.9–25.1
Flow (mgd)					
Mean	0.015	0.267	0.023	0.467	0.009
Number	1	1	1	1	7
Range	—	—	—	—	0.0028–0.0138

nutrients was measured at the effluent of the Orkney Springs Hotels sewage treatment plant.

The highest stream temperatures (approximately 21°C) were measured at the end of July, in the middle of the summer. The lowest stream temperatures (approximately 11°C) were measured during the last sampling visit in October. All temperature values measured at STP05 were slightly higher than the other stream temperatures.

Dissolved oxygen concentrations in all stream sites were always close to saturation levels. Sampling sites BM02 and BM04 were the higher of sites sampled, with median dissolved oxygen levels of 8.8 mg/l and 9.1 mg/l, respectively. During late July and early August, these streams approached supersaturation, experiencing dissolved oxygen concentrations of greater than 9.0 mg/l (at temperatures around 20°C). Sampling sites BM01 and BM03 located upstream and downstream of the sewage treatment plant, experienced lower dissolved oxygen concentrations with median values of 7.7 mg/l and 7.6 mg/l measured , respectively. The lowest dissolved oxygen values were found in the effluent of the sewage treatment plant (STP05) which had a median concentration of 3.6 mg/l.

The pH of all the drainage basin sites were found to be all around seven or neutral. The only site that a pH equal or greater than seven was not measured was at BM01, where the pH range measured was 6.2-6.9. The pH measured at sites BM02 and BM04 were always between a pH of seven and eight. No pH trends were noted over the time of the sampling period.

Conductivity values varied among drainage basin sites. BM02 and

BM04 had the lowest median conductivity measurements at 175 umhos and 183 umhos, respectively. The highest measurements of conductivity were found at STP05, with a median of 725 umhos. The highest conductivity found in the stream sites was at BM03, just downstream from STP05. The median conductivity measured at BM03 was 332 umhos.

Alkalinity concentrations were fairly consistent among stream sites with the exception of BM01. The median alkalinity measured at BM02, BM03, and BM04 were all approximately 100 mg/l as $CaCO^3$. The alkalinity at BM01 was lower than the other stream sample sites, with a median concentration of 62.1 mg/l as $CaCO_3$. Generally, the alkalinity at all stream sampling sites increased slightly from the summer months to the fall months. The highest alkalinity measured was at STP05, which had a median alkalinity of 298.8 mg/l as $CaCO_3$.

Table 7 presents the results of the samples taken on November 17, 1986, during a storm event. The data presented in Table 7 indicates the nutrient concentrations found during runoff conditions which occurred on November 17. Nutrient concentrations measured in runoff would be expected to be variable between any given number of storm events. In general, however, nutrient concentrations were found to be higher than the median concentrations presented in Table 6 at all stream locations except at BM03.

TABLE 7. NUTRIENT CONCENTRATIONS MEASURED AT LAKE LAURA DRAINAGE BASIN SAMPLING SITES DURING RUNOFF CONDITIONS ON NOVEMBER 17, 1986

Parameter	Sampling Sites			
	BM01	BM02	BM03	BM04
Total Phosphorus (mg/l)	0.08	0.05	0.22	0.14
Orthophosphorus (mg/l)	<0.01	0.02	0.21	0.06
Ammonia Nitrogen (mg/l)	0.05	0.02	0.03	0.04
Total Kjeldahl Nitrogen (mg/l)	0.67	0.34	0.50	0.41
Oxidized Nitrogen (mg/l)	0.13	0.64	1.39	0.56

DISCUSSION AND DATA ANALYSIS

Trophic State of Lake Laura

The first step in trying to identify the cause of eutrophication of Lake Laura would be to describe its water quality in terms of its trophic state. Table 8 presents a comparison of Lake Laura data to the general trophic states of lakes. Based upon surface nutrient values alone, Lake Laura would be classified between the oligotrophic and mesotrophic states. However, according to bottom nutrient, chlorophyll a, and Secchi values, Lake Laura would be classified between the mesotrophic and eutrophic states. Another widely used measure of the trophic state of lakes is the Trophic State Index (TSI) developed by Robert Carlson (Carlson, 1977). The Carlson index can be computed from Secchi disc transparency, chlorophyll, or total phosphorus measurements as follows:

$$\text{TSI (SD)} = 10 \left[6 - \frac{\ln SD}{\ln(2)} \right]$$

$$\text{TSI (Chl)} = 10 \left[6 - \frac{2.04 - 0.68 \ln Chl}{\ln(2)} \right]$$

$$\text{TSI (TP)} = 10 \left[6 - \frac{\ln (48/TP)}{\ln (2)} \right]$$

Use of Carlson's TSI is dependent on one assumption; the lake being studied is phosphorus limited. According to Wetzel (1983),

TABLE 8. COMPARISON OF LAKE LAURA DATA TO THE GENERAL TROPHIC STATE OF LAKES IN RELATION TO LITERATURE WATER QUALITY PARAMETERS

Water Quality Parameter[1]	Lake Laura[2]	Trophic State			
		Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophic
Total Phosphorus (ug/l)	20.0(S) 60.0(B)	8.0	26.7	84.4	>750.0
Total Nitrogen (ug/l)	370.0(S) 990.0(B)	661.0	753.0	1,875.0	--
Chlorophyll a (ug/l)	5.7	1.7	4.7	14.3	>100.0
Secchi (meters)	2.2	9.9	4.2	2.45	>0.5

[1] Median values as measured from June to December 1986.

[2] (S) = Surface water
(B) = Bottom water

(Modified from Wetzel, 1983)

freshwater plants require nitrogen and phosphorus for growth in a ratio of approximately 9:1. The median total nitrogen and phosphorus concentration of surface waters measured in Lake Laura were 0.37 mg/l (inorganic nitrogen concentrations were below detection limits) and 0.02 mg/l, respectively. These concentrations result in a ratio of approximately 18:1. Assuming that these concentrations were readily available for freshwater plant growth, and no other parameters (e.g., light) were limiting, phosphorus would appear to be considered limiting in Lake Laura and Carlson's TSI can be utilized.

Using surface median values for all three parameters to calculate a TSI for Lake Laura results in the following:

TSI (SD) = 48.6
TSI (Chl) = 50.8
TSI (TP) = 47.4

Generally, TSI values greater than 50 are considered eutrophic and values less than 40 are considered oligotrophic. Using all three parameters, a TSI of approximately 49 would be assigned to Lake Laura, thus, classifying it as a mesotrophic lake.

The algal blooms that have been observed in the past in Lake Laura did not occur during this study, which covered the algal growing season. However, based on data collected during this study, Lake Laura would be considered mesotrophic, or on the border of experiencing eutrophic conditions. Perhaps then, Lake Laura was also on the border of experiencing an algal bloom this year. The main cause of cultural eutrophication has been documented to be the excessive input of nutrients to a waterbody (Wetzel, 1983; Cole, 1983; Lee, et al., 1979; Antosch, 1984; Rast and Lee, 1983).

Therefore, the lack of an algal bloom this year in Lake Laura, given all other growth conditions (e.g., light, temperature, etc.) were not limiting, is assumed to be due to a decrease of nutrient input to Lake Laura. The following discussions will focus primarily on why algal blooms may not have occurred this year in Lake Laura, utilizing the data collected during this study. It should be noted here that no additional data regarding Lake Laura water quality was available at the local, State or Federal agency levels.

Lake Stratification

Both the temperature and dissolved oxygen profiles indicate stratification during the summer months. Temperature profiles in the northern, deeper end of Lake Laura showed stable thermal stratification throughout the summer months. In early fall, when turnover of the lake began, these thermal strata became less pronounced, and the temperatures throughout the water columns were similar (the lake had begun to mix). The thermal stratification which occurred during the summer months resulted in similar stratification of dissolved oxygen in Lake Laura. Basically, a thermal barrier was formed at the thermocline (found approximately at a depth of 10 feet or 3 meters) which prevents the migration of dissolved chemical species (e.g., dissolved oxygen) between the epilimnion and hypolimnion. Therefore, the waters were not replenished with dissolved oxygen as the surface waters are from atmospheric diffusion.

The oxygen profiles for Lake Laura further indicate that Lake

Laura is, or approaching, eutrophic conditions. In particular, the dissolved oxygen concentrations in the hypolimnion fell below 1.0 mg/l during the summer months at LL01, LL02, and LL03. The dissolved oxygen curve that resulted at these sites would be considered approaching clinograde, and is indicative of eutrophic lake conditions. The depletion of dissolved oxygen in the hypolimnion of shallow, eutrophic lakes is predominantly due to the oxidation of organic matter, especially at the sediment-water interface, where bacterial decomposition is greater (Wetzel, 1983). Therefore, the lack of dissolved oxygen in the hypolimnion in Lake Laura during the summer months when no algal bloom occurred, points to a past history of high organic matter levels in the lake, or fertile conditions.

The organic matter responsible for the depletion of hypolimnetic dissolved oxygen in Lake Laura is probably contributed from both internal and external sources. The internal source of organic matter in Lake Laura are the algae that are typically produced during the summer growing season, then die and sink to the lake . If indeed algal blooms in the past were as extensive as stated by lake owners, then these blooms could account for a large portion of the lake organic matter. External sources of organic matter to Lake Laura that should be considered include stormwater runoff and effluent from the wastewater treatment plant. The Lake Laura drainage basin, as previously discussed, is made up predominantly of forest and agricultural land. Leaf litter from forested areas and manure from pasture areas are particularly suspect as contributing to the organic matter loading to Lake Laura via stormwater runoff. Finally, direct discharges from the Orkney Springs Hotels STP to Lake Laura are likely to contribute as well to the organic matter load.

Meterological Conditions

In light of the fact that the water chemistry is indicative of eutrophic conditions, the probable reason for lack of algal blooms this year in Lake Laura could be related to the year's meterological conditions. Figure 7 provides total monthly rainfall for 1984, 1985, and 1986. Rainfall totals represent the average rainfall measured at rainfall metering stations located just north of Lake Laura in Mount Jackson, Virginia, and just south of Lake Laura in Cootes Stare, Virginia. Rainfall data was provided by the National Oceanic and Atmospheric Administration, Washington River District Office. As shown in Figure 7, there were two important occurrences which probably had an affect on the lack of algal blooms this year; the flooding conditions which occurred during November 1985, and the drought-like conditions experienced in the summer of 1986, as compared to 1984 and 1985.

Over the three year period from 1984 to 1986, the highest total monthly rainfall occurred in November 1985. In particular, over seven inches of rain fell in the Lake Laura area over a period of just several days, resulting in flood conditions throughout the Lake Laura drainage basin. These flood conditions occurred in the fall, as primary production of phytoplankton lessened and surface water nutrient levels began to increase (due to decrease of algal utilization). A possible result of the flood in November 1985 was

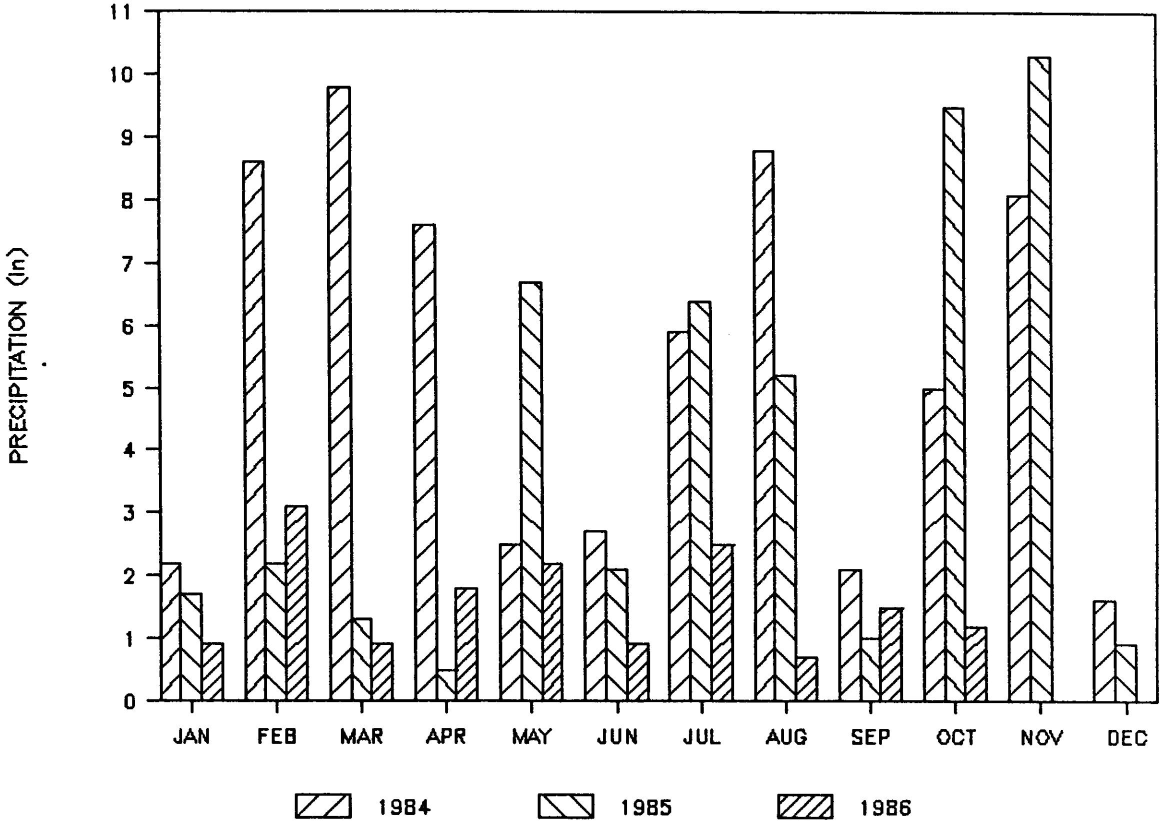


Figure 7. Comparison of Precipitation Data for Lake Laura

that it may have scoured and flushed out organic matter and nutrients from Lake Laura. If indeed sediments were scoured, a substantial fraction of a major internal source of nutrients may have been removed. Therefore, it is possible that this flood event was responsible for the improved water quality observed in the Lake Laura surface waters during the summer of 1986.

The spring and summer of 1986 was relatively dry compared to 1984 and 1985, especially during the summer months. The effect of this dry period was probably reduced runoff and associated streamflow to Lake Laura. Due to the relatively dry weather experienced at Lake Laura and the associated decrease in runoff, the total nutrient loadings to the lake were expected to be lower than that of previous years. This is evident upon comparison of the concentrations of nutrients measured at each drainage basin sampling site during baseflow and runoff conditions. Table 9 presents the concentrations of total phosphorus and organic and inorganic nitrogen for each drainage basin sampling site. As shown in Table 9, runoff concentrations for total phosphorus and organic and inorganic nitrogen are substantially higher, respectively, than baseflow concentrations measured at BM04. Given the dry conditions experienced during the study, it can be assumed that baseflow conditions predominated. This probably resulted in an overall reduction in loadings of nutrients to Lake Laura during 1986, compared to that which has been experienced over the past years.

TABLE 9. MEASURED NUTRIENT CONCENTRATIONS FOR LAKE LAURA DRAINAGE BASIN SAMPLING SITES UNDER BASEFLOW AND RUNOFF CONDITIONS

Sampling Sites	Under Baseflow Conditions[1]			Under Runoff Conditions[2]		
	Total Phosphorus Concentration (mg/l)	Organic Nitrogen Concentration (mg/l)	Inorganic Nitrogen Concentration (mg/l)	Total Phosphorus Concentration (mg/l)	Organic Nitrogen Concentration (mg/l)	Inorganic Nitrogen Concentration (mg/l)
BM01	<0.01	0.27	0.43	0.08	0.62	0.18
BM02	0.02	0.13	0.08	0.05	0.32	0.66
BM03	0.52	0.70	3.69	0.22	0.47	1.42
BM04	0.03	0.14	0.24	0.14	0.35	0.60
STP05	7.61	26.84	7.19	--	--	--

[1] Median Values for the Sampling Period From June to October 1986

[2] Based Upon One Sample Taken on November 17, 1986

Evaluation of Nutrient Sources

Due to the fact that algal blooms may reoccur at Lake Laura, an evaluation of the sources of nutrients to Lake Laura was performed so as to provide a basis for further study and/or future lake management practices.

Using baseflow discharge and nutrient concentration measurements taken during this study, total phosphorus and total nitrogen loadings were calculated for each drainage basin sampling site. Table 10 presents these calculated loadings.

The wastewater treatment plant effluent (STP05) represents the highest nutrient loading calculated. The effect of the wastewater treatment plant effluent nutrient loadings can be seen by examining the loadings at BM01 (upstream of STP05) and at BM03 (downstream from STP05). There is a substantial increase in loadings experienced from BM01 to BM03. However, the loadings at BM03, downstream from STP05, accounted for only about 20 percent of the loading expected from STP05. Therefore, Orkney Springs Run, which normally would be considered a very low flow stream, actually acted more as a nutrient trap or sink rather than a nutrient transport mechanism. This condition in Orkney Springs Run would not be expected, at least to the degree found during this study, under normal or average flow conditions. Under average flow conditions, the retention time of the wastewater treatment plant effluent in Orkney Springs Run would not be expected to be as long, giving less time for nutrients to be actually trapped or utilized within the stream. Average flow conditions would, therefore, probably result in larger nutrient

TABLE 10. CALCULATED BASEFLOW NUTRIENT LOADINGS FROM LAKE LAURA DRAINAGE BASIN SAMPLING SITES[a]

Sampling Site	Total Phosphorus Loadings (kg/yr)	Total Nitrogen Loadings (kg/yr)
BM01	0.2	14.5
BM02	7.4	77.5
BM03	16.5	139.5
BM04	19.4	245.2
STP05	94.6	423.1

[a] Calculated using median values from Table 6 and flow values measured on October 25, 1986

loadings to Stony Creek from the wastewater treatment plant.

As just discussed, the highest nutrient loadings were found at STP05, the effluent from the wastewater treatment plant. However, based on loadings calculated at BM03, they should not be considered the only significant nutrient source when compared with nutrient loadings found at BM02. At BM02, just downstream from pasture and forest land, total phosphorus loadings were about half the amount that was found at BM03, and total nitrogen loadings were slightly less than that at BM03, under baseflow conditions. However, under runoff conditions, nutrient concentration levels increased significantly to levels similar to what was found at BM03. Therefore, the barnyard and pasture areas adjacent to Rinker and Anderson Runs and pasture practices which allow direct cattle access to these streams, would appear to have a substantial effect on nutrient loads to Lake Laura.

In an effort to assess the relative impact of the sources of nutrients to the water quality of Lake Laura, a modified version of the Vollenweider input-output model was utilized to predict in-lake total phosphorus concentrations from total phosphorus loading rates. Based on the results from application of the model, a plot of the Vollenweider relationship and the Carlson TSI was used to assess water quality in terms of trophic state. The general Vollenweider input-output model with the phosphorus sedimentation coefficient for natural lakes developed by Canfield and Bachman (1981) was used in this analysis to predict the water quality of Lake Laura under the different phosphorus loading scenarios. The form of this model is as follows:

$$TP = \frac{L}{Z(\sigma + p)}$$

where:

TP = total phosphorus concentration in the lake waters(mg/m^3)
L = annual phosphorus loading per lake surface area($mg/m^2/yr$)
Z = lake mean depth (m)
σ = phosphorus sedimentation coefficient (yr^{-1})
= $0.162\ (L/Z)^{0.458}$
p = hydraulic flushing rate of the lake (yr^{-1})

This model was chosen because of its documented accuracy to predict total phosphorus concentrations, compared to other models (Antosch,1984; Canfield and Bachman, 1981).

Three different scenarios were evaluated using this model:

- o Scenario 1: 1986 baseflow conditions with baseflow total phosphorus loadings at BM04;
- o Scenario 2: 1986 baseflow conditions with baseflow total phosphorus loadings at BM04 plus the difference in loadings between STP05 and BM03; and
- o Scenario 3: Using nutrient export coefficients based upon land use in the drainage basin to predict nonpoint total phosphorus loadings during a normal year, plus the points source loadings from STP05.

Table 11 provides the nutrient export coefficients and associated drainage basin areas that were utilized to estimate in part, the total phosphorus loadings under the last scenario described above. These land use coefficients were extracted from Rast and Lee (1983), who developed the values and consider them as generally applicable to many lakes in the United States.

Table 12 and Figure 8 provide the results of the application of the modified Vollenweider input-output model for Lake Laura under the three scenarios. Under baseflow conditions and concentrations, the predicted total phosphorus concentration in Lake Laura was 4.7 mg/m^3. This total phosphorus concentration results in a TSI of 26 for Lake

TABLE 11. ANNUAL TOTAL PHOSPHORUS LOADINGS TO LAKE LAURA FROM NONPOINT SOURCES ESTIMATED USING NUTRIENT EXPORT COEFFICIENTS

Land Use	Estimated Percentage of Drainage Basin[a] Covered (%)	Total Area Within the Drainage Basin (ha)	Nutrient Export Coefficient[b] (g/m^2-yr)	Estimated Annual Phosphorus Loading (kg/year)
Agriculture/ Pasture	35	661.4	0.05	330.7
Forest	60	1,133.8	0.005	56.7
Urban	5	94.5	0.1	94.5
Atmosphere	--	17.8[c]	0.025	4.6

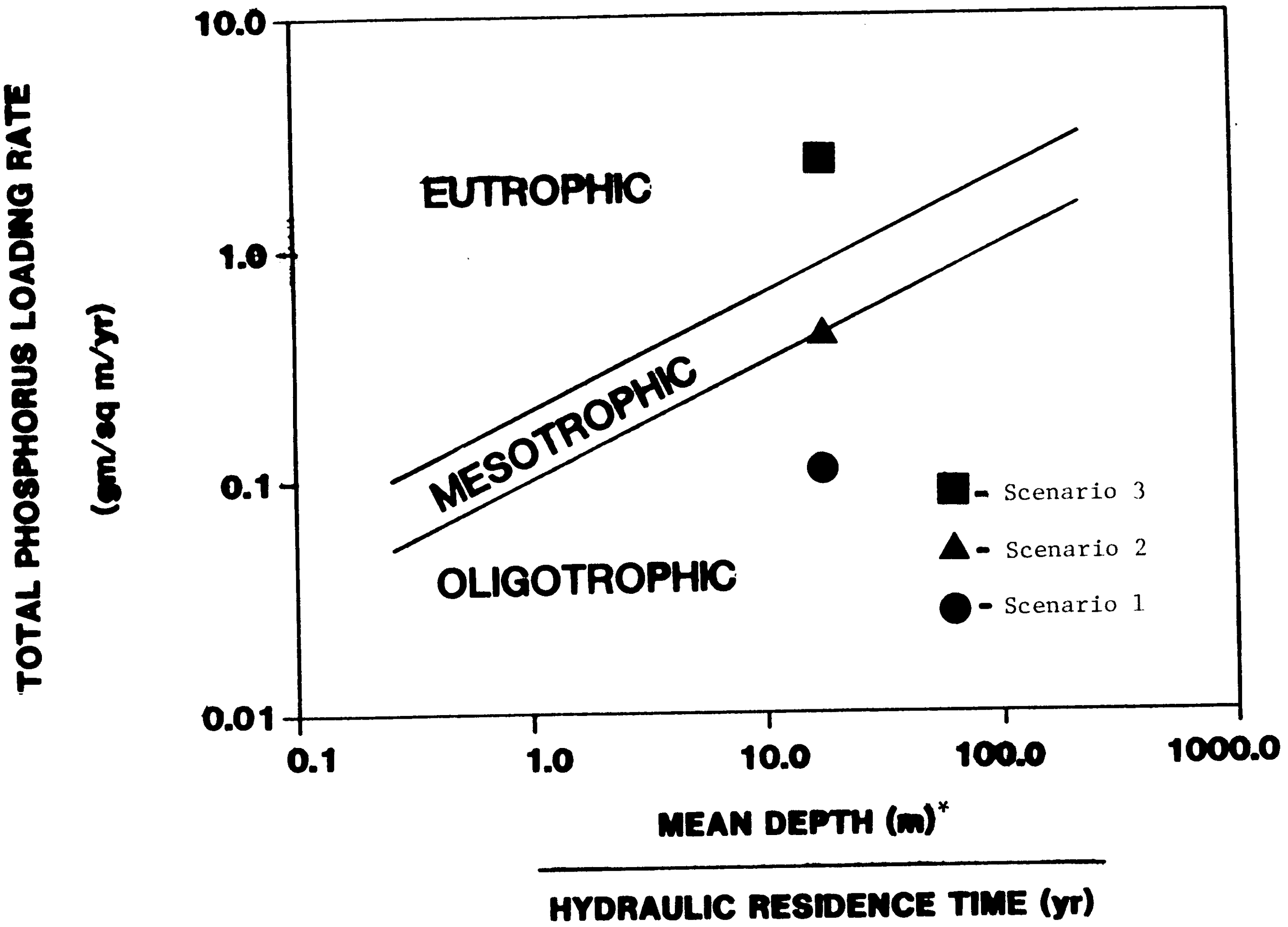
[a] Estimates based upon windshield survey performed during this study and use of USGS Land Use Maps (U.S. Geological Survey, 1973-1977)

[b] From Rast and Lee (1983)

[c] Lake surface area

TABLE 12. RESULTS OF MODEL APPLICATION TO LAKE LAURA UNDER THREE SCENARIOS

Scenario	Total Phosphorus Loading Rate ($g/m^2.yr$)	Predicted Total Phosphorus Concentration (mg/m^3)	Associated Carlson's Trophic State Index
1. Baseflow conditions, baseflow concentrations at BM04	0.11	4.7	26
2. Baseflow conditions, baseflow concentrations and STP05 loading	0.55	20.5	48
3. Nutrient export coefficients plus STP05 loading	3.17	90.9	69



*Recreation Pool

Figure 8. Plot of Results From Vollenweider Model Under Three Different Scenarios

Laura which would be considered indicative of oligotrophic conditions. Further, as shown in Figure 8, phosphorus loadings calculated under the first scenario result in oligotrophic status for Lake Laura on the Vollenweider relationship plot. It should also be noted that the nutrient loading from the wastewater treatment plant is included as a part of the baseflow conditions. However, due to the potential nutrient trap in Orkney Springs Run (as discussed previously), this may not be totally indicative of the effect of the treatment plant loadings on Lake Laura.

Assuming the entire nutrient loading from the wastewater treatment plant reached Lake Laura in addition to the baseflow condition loadings to Lake Laura, the predicted total phosphorus concentration in Lake Laura would be 20.5 mg/m^3. This concentration is higher than that predicted under the first scenario, and results in defining the lake conditions as mesotrophic (TSI = 48). Plot of the total phosphorus loading associated with this scenario shown in Figure 8, results in Lake Laura being classified as mesotrophic. Therefore, the addition of the entire wastewater treatment plant nutrient loadings, assuming it all reached the lake, could also result in near eutrophic conditions in Lake Laura. This assumption would not hold entirely true according to the results of this study performed during a low flow year. As discussed earlier, only about 20 percent of the loading from the wastewater treatment plant was measured downstream from the outfall at BM03. Therefore, although the wastewater treatment plant could be considered a significant nutrient source under more typical flow conditions, the wastewater treatment plant alone could not be considered the only source of nutrient loadings to Lake Laura.

The results of the model for the two scenarios discussed above provide an idea as to the relative impact of baseflow conditions and the wastewater treatment plant based upon data collected during 1986, which is considered not to be an average year in terms of rainfall. To assess nutrient loadings under more typical conditions, nutrient export coefficients were utilized to estimate nonpoint source loadings, which are related to the types of land use in the drainage basin. Utilizing these nutrient export coefficients plus the measured loading from the wastewater treatment plant, the predicted total phosphorus concentration in Lake Laura would be 90.9 mg/m^3, over 15 times higher than that predicted under the first scenario. This predicted total phosphorus concentration results in a TSI value of 69, indicative of eutrophic conditions. The calculated total phosphorus loading under this scenario was 3.17 grams of phosphorus per square meter of lake surface area per year. As shown in Figure 8, this loading results in an estimation of trophic status to be considered highly eutrophic. Although the use of nutrient export coefficients and land use is largely subjective, previous authors have stated that the approach can provide an estimate that is relatively accurate (Daniel, et al., 1982; Rast and Lee, 1983). Therefore, through the use of nutrient export coefficients, nutrient loadings during a normal year without discharges from the wastewater treatment plant would be expected to cause eutrophic conditions in Lake Laura.

Table 13 presents a summary of either estimated or measured loadings for all phosphorus sources to Lake Laura. Assuming all wastewater treatment plant effluent reached the lake and normal precipitation occurs, the total phosphorus loading to Lake Laura would be close to 600 kilograms per year. Based upon nutrient export coefficients from literature, runoff from the agriculture/pasture lands in the Lake Laura drainage basin would be expected to contribute over 50 percent of this total load. The remaining phosphorus load from each of the other phosphorus sources are approximately equivalent, accounting for approximately 10 to 15 percent of the total each.

Table 14 presents a breakdown of the phosphorus sources from the various land uses for each sub-drainage basin in the Lake Laura drainage basin. As would be expected, the Stony Creek drainage area, where the majority of agriculture/pasture activities take place, accounts for almost 50 percent of the total phosphorus load from these areas. The Orkney Springs Run drainage area, where the majority of urban land use can be found, accounts for almost 20 percent of the total phosphorus load to Lake Laura from these sources. The remaining sub-drainage basins, made up of a mixture of mostly forest and agriculture land, accounts for the remaining phosphorus loads to Lake Laura.

Another potential source of nutrients to Lake Laura, although not quantifiable, may be from within the lake itself. In particular, it has been stated that eutrophic lakes which exhibit clinograde oxygen curves during summer stratification, will also show an

TABLE 13. SUMMARY OF THE SOURCES OF PHOSPHORUS TO LAKE LAURA

Phosphorus Source	Total Phosphorus Load (kg/yr)	Percent of Total
Orkney Springs Hotels Wastewater Treatment Plant (measured)	94.6	16.3
Agriculture/Pasture Lands (estimated)	330.7	56.8
Forest Land (estimated)	56.7	9.8
Urban Land Uses (estimated)	94.5	16.3
Atmospheric Sources (estimated)	4.6	0.8
TOTAL	581.1	100.0

TABLE 14. SUMMARY OF SOURCE PHOSPHORUS LOADINGS TO LAKE LAURA BY SUB-DRAINAGE BASINS

	ESTIMATED PHOSPHORUS LOADINGS (kg/yr)[a]					
Phosphorus Source	Stony Creek	Rinker Run	Orkney Springs Run	Anderson Run	Direct Discharge	Totals
Agriculture/ Pasture Land	198.4	66.1	33.1	33.1	--	330.7
Forest Land	17.1	11.3	11.3	5.7	11.3	56.7
Urban Land	18.9	9.5	47.3	4.6	14.2	94.5
Atmosphere	--	--	--	--	4.6	4.6
TOTAL	234.4	86.9	91.7	43.4	30.1	486.5

[a] Loadings based upon percent of drainage area for each land use (see Table 11).

increase in nutrient content in the lower hypolimnion (Wetzel, 1983). This increase is due to the fact that the dissolved oxygen concentration in the hypolimnion also regulates the exchange of materials between lake sediments and lake waters. Particularly, as the dissolved oxygen content in the hypolimnion decreases, the redox potential also decreases, resulting in the release of nutrients that were bound-up in lake sediments. The results from this study indeed did show greater concentrations of reduced nitrogen and phosphorus forms in the waters of Lake Laura, compared to those levels found in the surface waters (see Table 5). Further, the median concentrations of nutrients measured in waters are similar to levels associated with eutrophic conditions, compared to levels associated with mesotrophic conditions measured in the surface waters (see Table 8). This increase in hypolimnetic nutrients would be of particular concern in the fall when Lake Laura experiences a turnover. This turnover destroys the stable thermal stratification experienced during the summer, as surface waters begin to cool to temperatures equivalent to the waters. The result of this turnover is usually complete mixing of the lake waters. Thus, the increased nutrient levels contained in the waters can be mixed with the surface waters, resulting in a net increase of nutrients in surface waters where they can contribute to the triggering of algal growth in the fall.

Lake Management to Control Algal Growth

Although Lake Laura did not experience algal blooms during the course of this study, data collected indicates past and potential future fertile conditions in the lake waters. Further, data collected during this study suggested that the growth of algae in Lake Laura is controlled or limited by phosphorus. Therefore, successful management of the water quality of Lake Laura, in an effort to avoid nuisance algal blooms in the future, will be highly dependent upon the ability to reduce the phosphorus levels in Lake Laura.

There are many control options available to control phosphorus in lakes. These options vary in both their costs for development, implementation, and maintenance and their overall effectiveness in controlling phosphorus in lakes. Personnel responsible for managing the water quality in Lake Laura must evaluate control options in light of their relative costs and their effectiveness in achieving the desired water quality for Lake Laura.

There are several potential phosphorus control options which could be utilized by the lake owners of Lake Laura. In increasing order of estimated cost, they are as follows:

- Oxidize shallow area sediments by lake drawdown;
- Modify dam operations to release the nutrient-rich waters;
- Implement Best Management Practices (BMPs) in the Lake Laura watershed;
- Apply algicides when algal blooms occur;
- Install a hypolimnetic aeration system;
- Oxidize shallow area sediments by chemical application;
- Remove accumulated sediments from the shallow waters of Lake Laura;and
- Undertake phosphorus removal at the Orkney Springs Hotels STP.

Table 15 presents a summary of the basic advantages and disadvantages of each control option described above. Following are brief discussions of these control options as they relate to use for

TABLE 15. ADVANTAGES AND DISADVANTAGES OF POTENTIAL LAKE LAURA WATER QUALITY MANAGEMENT OPTIONS[1]

CONTROL OPTION	ADVANTAGES	DISADVANTAGES
1. Oxidize shallow area sediments by lake drawdown	o Low cost development and implementation o Reduces internal lake nutrient levels	o External nutrient loads are not controlled or reduced o Downstream tributary may be overload during drawdown period
2. Modify dam operations to release nutrient-rich bottom waters	o Low cost development and implementation o Reduces internal lake nutrient levels	o External nutrient loads are not controlled or reduced o Potential downstream impacts from nutrient-rich waters
3. Implement watershed best management practices (BMPs)	o Low development and low to moderate implementation costs o Directly reduces nutrient loads from agricultural and urban areas o Has been documented to be very effective in reducing nutrient loadings	o Requires cooperation of several different basin land owners
4. Application of algicides during algal growth periods	o Option can be implemented rapidly o Water quality is improved in a relatively short period of time o Directly prohibits algae growth	o Moderate to high cost to implement o Results in high organic matter levels from algae die-off o Accumulation of toxics in lake sediments is possible o Considered only a short-term measure o Internal and external nutrient loads are not controlled or reduced
5. Installation of a hypolimnetic aeration system	o Reduces internal lake nutrient levels o Low to moderate maintenance costs	o Moderate to high development cost o External nutrient loads are not controlled or reduced
6. Application of chemical oxidizers in shallow lake areas	o Reduces internal lake nutrient levels	o Moderate to high implementation costs during application o External nutrient loads are not controlled or reduced

TABLE 15. ADVANTAGES AND DISADVANTAGES OF POTENTIAL LAKE LAURA WATER QUALITY MANAGEMENT OPTIONS[1] (Continued)

CONTROL OPTION	ADVANTAGES	DISADVANTAGES
7. Removal of accumulated sediments for shallow lake areas	o Directly removes nutrients bound to sediments o Reduces internal lake nutrient levels o Documented effectiveness in improving water quality	o Moderate to high cost to implement o Resuspension of nutrients may cause increase in available nutrient levels during removal o Disposal options for removed sediments may be limited o External nutrient loads are not controlled or reduced
8. Installation of nutrient removal processes at the Orkney Springs Hotels STP	o Direct reduction of nutrient loads to Lake Laura	o High development, implementation, and maintenance costs o May account for only small reductions in overall nutrient loading to Lake Laura

---

[1] In order of increasing estimated costs.

managing the water quality in Lake Laura.

Oxidizing shallow area sediments in Lake Laura can be effective in controlling the release of nutrients from these sediments under water. Shallow areas in the southern end and along the shoreline of Lake Laura can be exposed through the drawdown of the lake level via operation of the dam outlet structure. During exposure, the sediment oxygen demand is reduced and the oxidation state of the sediment surface layer increases, thereby retarding nutrient release upon lake filling. The effectiveness of this control option will depend upon how much of, and how long, Lake Laura can be kept at low levels during the recreational off-seasons (i.e., late fall, winter, early spring). The main advantage to this control option, other than reducing in lake nutrient levels, is the zero to low cost to develop and implement this practice. Control mechanisms already exist at the current dam structure that would allow lake drawdown. There are two main disadvantages to this control option. First, lake drawdown only assists in reducing the internal lake loading of nutrients. It doe not control the input of nutrients from external sources. Secondly, prolonged drawdown of Lake Laura could temporarily impact the water balance in the streams which currently receive overflow from the lake.

The second control option involves the removal of nutrient-rich waters from Lake Laura. The waters of Lake Laura can be removed by modification of the current dam structure to draw from the of the structure as opposed to utilizing the spillway which drains surface waters. At water concentrations measured during this study, this control option could result in the removal of internal nutrient loads equivalent to estimated external nutrient loads during periods of lake stratification. The removal of these waters will also reduce the availability of nutrients to algae during fall and spring turnover. This control option, in conjunction with other watershed BMPs, has been documented to be an effective control option and resulted in increased lake clarity of a eutrophic lake (ASIWPCA, 1985). The main advantage for this option is the zero to low cost associated with implementation. The existing dam structure would need only be modified slightly to accommodate the release of water from the lake . The primary disadvantage of this option is that the external sources responsible for increased nutrient loads to Lake Laura would not be controlled or reduced.

The third potential option for consideration is the implementation of watershed BMPs to manage the pollution generated by nonpoint sources to Lake Laura. The BMPs that should be considered as most important for the Lake Laura watershed, based upon information collected during this study, include the following:

- Dairy cattle and horses should be restricted from direct access to stream beds in the watershed. In particular, fences could be installed along stream beds to confirm both cattle and horses. Restriction of livestock has been shown to be very effective in reducing total phosphorus loads by 50-90 percent (U.S. Environmental Protection Agency, 1984).

- Manure stockpiling practices, particularly in the Stony Creek subdrainage basin, should be discontinued, or mechanisms to collect or divert runoff from these stockpiles should be installed. Manure storage runoff controls are very effective at reducing the total phosphorus content in runoff. Particularly, reduction of 75-100 percent have been documented (U.S. Environmental Protection Agency, 1984).

- Cropping and fertilization management practices in the Lake Laura watershed could be modified or improved. Certain cropping techniques (i.e., conservation tillage, contour) have shown to be very effective in reducing nutrient loads during runoff. Certain management techniques for fertilizer use have also shown to be effective in retaining nutrients in cropland soils (Novotny and Chesters, 1981).

The primary advantage of the implementation of the BMPs described above is that external nutrient loads to Lake Laura can be effectively reduced. The disadvantage to the use of the BMPs described above is that their effectiveness will depend upon the cooperation of the several different basin land owners and farmers. Even though development costs may be low to moderate for the BMPs, it will be these land owners and farmers who may have to bear some of the costs.

Application of algicides during algal growth, is another management technique that is widely used for control of algae growth. Some common algicides that are used include copper sulfate and cutrine. The reason that chemical control of algae is widely used is that algicides can be applied to infested areas rapidly, resulting in the die-off of algae over a short period of time. The disadvantages of chemical control of algae growth outweigh the advantages for use in Lake Laura. First, the cost of applying algicides can be very high depending upon the magnitude of the algal bloom experienced in Lake Laura. Second, the large die off of algae will result in the deposition of large quantities of organic matter. This high organic matter loading to the lake will increase the hypolimnetic oxygen demand and nutrient content in the lake sediments. Third, toxic pollutants contained in algicides (i.e., copper) can accumulate in lake sediments over time after several applications. The accumulation of toxic pollutants in Lake Laura sediments can result in harmful long-term effects to the lake environment and biota. Finally, the application of algicides would only be considered a short-term measure to control algae growth. Neither internal or external nutrient sources to Lake Laura are controlled.

The installation of a hypolimnetic aeration system in Lake Laura would result in the reduction of the loading of nutrients from release from the lake sediments by increasing dissolved oxygen levels in the hypolimnion. A hypolimnetic aeration system can also cause turbulence throughout the water column, resulting in continuous turnover of the lake waters. This turnover will breakup any thermal barriers which would effect internal nutrient transport during periods when stratification would normally occur (i.e., summer). Overall, the installation of a hypolimnetic aeration system should result in the net increase in the deposition and retention of nutrients in the lake sediments. This control option has been shown to be successful in application to lakes similar to Lake Laura in size and purpose (Stein, et al., 1985). The advantage to this control option is that the loads from the internal source of nutrients to Lake Laura are reduced. Another advantage is that implementation and maintenance costs of an aeration system would be low to moderate, made up of primarily costs to operate an air compressor. The disadvantage of this control option would be that external nutrient loads to Lake Laura would not be controlled or reduced. Another disadvantage of this option would be the moderate to high costs for development. Development costs would include engineering design and capital costs for the aeration equipment and distribution system.

The sixth potential control option for Lake Laura involves the application of chemical oxidizers (i.e., nitrate salts) in shallow areas of Lake Laura. These chemical oxidizers serve as alternate terminal electron acceptors and keep the redox potential in the waters relatively high. Under these oxidizing conditions, phosphorus remains a relatively insoluble compound and is controlled from being cycled back into lake waters. The advantage of using chemical oxidizers is that internal phosphorus loads are controlled. One of the disadvantages is that external sources of nutrients are not controlled or reduced. Further, the costs for application of chemical oxidizers can be moderate to high, depending upon the number of applications that would be needed to effectively control nutrient loads, especially during stratification periods.

The application of accumulated sediments from lakes (i.e., dredging) has become a widely used technique for lake water quality management. Dredging of lake sediments results in the removal of nutrients which have accumulated in sediments and the exposure of nutrient-poor materials to lake waters. Dredging has been documented to be very effective in improving lake water quality, especially when internal cycling of phosphorus between the lake sediments and water is considered a major phosphorus source. In particular, reduction of phosphorus concentrations by 90 percent in lake waters have been found (Dunst, et al., 1974). The primary advantages of nutrients associated with sediments can be reduced, resulting in a potential long-term solution to eutrophic conditions in a lake. The disadvantages of dredging include high cost, generation of spoils, and no reduction of external nutrient sources. For Lake Laura, dredging costs can be kept down at least initially by only dredging the shallow areas of the lake during lake drawdown. In particular, dredging during lake drawdown in shallow areas will allow the direct access to the lake sediments by removal equipment (i.e., front-end loaders). This method would be less expensive and more efficient as opposed to removal of sediments under water with external removal equipment (i.e., mechanical or hydraulic dredges). Regardless of dredging technique, dredged material will need to be disposed of properly. In particular, a spoil (dredged material) disposal site would have to be obtained, and runoff from the disposal site controlled to avoid discharge of removed pollutants back into a water body. Dredging of lake sediments can also result in the release of nutrients bound-up in sediments, making them available for algal growth. The degree of release will depend upon several factors including the type of dredging equipment used, the duration of dredging activities, and the actual quantity of sediment dredged. Finally, dredging of Lake Laura will only solve the immediate problem of algae growth. Dredging will not control the external nutrient sources to Lake Laura, which may be the primary cause of the algal blooms.

The final potential management option for Lake Laura involves the installation of nutrient removal processes at the Orkney Springs

Hotels STP. There are several processes that could be added to the current treatment processes at the Orkney Springs Hotels STP. The most common process utilized for phosphorus removal in wastewater treatment plants involves chemical precipitation using aluminum or iron coagulants, followed by lime settling. The addition of phosphorus removal processes can result in removal of 80-90 percent of the phosphorus load from the Orkney Springs Hotels STP (Hammer, 1975). However, based on the results of this study, the Orkney Springs Hotels STP only contributes approximately 15 percent of the total phosphorus load to Lake Laura (assuming the entire load discharged reached the lake). Further, Virginia legislation has banned the sale of phosphate detergents. The bill was recently passed by the Virginia General Assembly in early 1987. Various studies have shown that phosphate bans have resulted in a decrease in phosphorus loadings. In particular, it has been documented that wastewater treatment plants observed a 42 percent decrease in mean phosphorus effluent loadings as a result of phosphate-bans. Assuming the same relative effectiveness would apply to the Orkney Springs Hotels STP, the total loading of phosphorus to Lake Laura from what is currently estimated to be around 15 percent, would be reduced to somewhere around 7 percent. The primary disadvantage of installation of a nutrient removal system at the Orkney Springs Hotels STP is the high cost for construction, operation, and maintenance. These high costs need to be weighed against the fact that the overall reduction of nutrient loads to Lake Laura may not be significant enough to prevent algal blooms.

CONCLUSIONS

Data collected during this study showed the surface waters of Lake Laura to be only moderately enriched, resulting in a mesotrophic classification (TSI = 49). The mesotrophic condition this year is believed to be due to the atypically dry hydrologic year experienced at Lake Laura. This lack of rainfall probably resulted in a decrease in nutrient loadings from drainage basin runoff. Further, the loadings from the Orkney Springs Hotels wastewater treatment plant were probably reduced from that experienced during normal years due to extreme low flow in the receiving stream.

In spite of this, a past history of fertile conditions in Lake Laura was evident. Hypolimnetic oxygen levels were found to be close to anoxic and dissolved oxygen profiles in the deeper areas of the lake resembled clinograde curves, characteristic of eutrophic lakes. Lake Laura also appeared to have a large mass of nutrients bound in sediments. The water concentrations of reduced nitrogen and phosphorus forms were both over twice as great than those in the surface waters. The release of these nutrients would be expected due to the reduced oxygen levels found in the hypolimnion during stratification.

Due to the atypical hydrologic conditions experienced during this study, an assessment of the sources from the upstream drainage basin was not entirely possible because little surface runoff occurred. In observing stream water quality, however, the highest nutrient concentrations were found in the Orkney Springs Hotels STP effluent. All other stream water quality was observed to be good in terms of nutrient levels and other water quality parameters. Samples taken during one stormwater event in late November 1986, however, indicated a substantial increase in nutrient concentrations in the tributaries to Lake Laura over concentrations measured during base-flow periods. Therefore, under more typical hydrologic years, the nonpoint source loadings would be expected to have a greater impact on Lake Laura water quality.

Nutrient export coefficients were utilized to examine potential nutrient sources from runoff from the various land uses in the Lake Laura drainage basin. Runoff from agriculture/pasture lands would be expected to contribute over 50 percent of the estimated total phosphorus loading to Lake Laura. This is not surprising in light of the location of the majority of agricultural/pasture land along Stony Creek (the main tributary to Lake Laura) and the practices of basin land-owners which include uncontained stockpiling of manure and allowing direct access of dairy cattle and horses to the lake tributaries.

Together, runoff from agriculture/pasture land and effluent from the Orkney Springs Hotels STP, which contributes around 15 percent of the total phosphorus load, would appear sufficient to maintain Lake Laura in a highly productive state. These external sources are also supplemented by internal (lake sediment) nutrient sources during stratification in the summer months. This will only intensify the potential for algal blooms in the future.

Based on results from this study, Lake Laura appeared to be phosphorus limited. Therefore, management options that should be considered to control future algal blooms should primarily focus on phosphorus controls. Several control options can be utilized to effectively control the algal blooms in Lake Laura. These control options range from simple, low cost options such as lake drawdown, implementation of watershed BMPs, and algicide application to more complex and expensive options such as lake dredging and the addition of phosphorus removal processes at the Orkney Springs Hotels STP.

RECOMMENDATIONS

The water quality of Lake Laura is greatly influenced by its role as a flood water control system. Runoff from agricultural/pasture lands appear to be the most significant source of nutrients to Lake Laura. Further, the effluent from the Orkney Springs Hotels wastewater treatment plant can also contribute up to 15 percent of the nutrient loadings to Lake Laura. The excessive nutrient loadings from these sources have affected the chemical and biological characteristics of the lake in the past, resulting in eutrophic conditions. These conditions need to be improved, especially when other uses for Lake Laura (e.g., recreation) are important.

The results of this study, which only covered the period from June to November, 1986, would make it difficult to recommend a full lake management plan for Lake Laura. Thus, the first recommendation would be to suggest further research of Lake Laura, particularly since this study was performed during an unusually dry year. Further studies should focus on the nonpoint source loadings of nutrients to Lake Laura, especially during runoff conditions and lake sediment nutrient concentrations and their effect on phosphorus loads and availability to the lake waters.

However, study results do point to the cause of the algal blooms in the past to be most-likely due to the excessive input of phosphorus into Lake Laura. Therefore, beginning to control the phosphorus inputs to Lake Laura, assuming a constant output from the lake is maintained, will probably assist in avoiding algal blooms in future years. Many control were discussed as being applicable to Lake Laura. Due to the uncertainty of the water quality of Lake Laura in the future (i.e., will the algal blooms occur next year?), it is recommended that a conservative approach to Lake Laura water quality management be taken. In particular, the zero- or low-cost control options be implemented first, keeping in mind that future water quality degradation (i.e., excessive algal bloom occurrence) require the investment of more costly and effective control measures.

Initially, it is recommended that the Bryce Mountain Resort consider implementation of the low cost control options including lake drawdown, hypolimnetic water release, and watershed BMPs. The first two options would be under the control of the Resort, would involve little to no cost to implement, and would provide a reduction in the internal release of nutrients to the lake waters. Virginia law will prohibit the use of phosphate detergents in the near future. Although this phosphate detergent ban will probably not result alone in a marked difference in Lake Laura water quality, the reductions of phosphate loads resulting from the ban in conjunction with other low-cost controls may prove to be adequate to control the algal blooms in Lake Laura. The final low-to-no cost control option that is recommended is the implementation of watershed BMPs. Although this control option would require further investigations into current practices within the basin and the cooperation of several basin landowners, it could have the largest impact on the improvement of the Lake Laura water quality. To assist in the evaluation of which

BMP practices would be most beneficial to Lake Laura, it is recommended that the Resort consult with local and State agencies responsible for the abatement and control of nonpoint pollution. Examples of such agencies include:

- Virginia Tech Cooperative Extension Service
- USDA Soil Conservation Service
- State Soil and Water Conservation District Offices.

The Resort can begin immediate implementation of some BMPs on their own. Specifically, horse access along the horse barn and headwaters of the lake should be restricted.

The remaining options discussed would require greater expenditures of resources then those described above. However, should algal blooms reoccur in Lake Laura, these options should be considered for use in Lake Laura. Only one of the remaining options, installation of nutrient removal at the STP, would result in the reduction of external sources of nutrients. However, as a control option alone, the costs for installation of nutrient removal would not merit the overall reduction of nutrients discharged to Lake Laura. The remaining options could be utilized if external nutrient sources could not be controlled. The addition of chemical oxidizers in shallow areas or installation of a hypolimnetic aeration system would reduce the internal phosphorus loads for the lake sediments. Dredging would remove the nutrient-rich sediments, and applications of algicides would kill-off algal blooms during growth periods.

LITERATURE CITED

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1985. Standard Methods for the Examination of Water and Wastewater; 16th Edition. American Public Health Association.

Antosch, L.M., 1984. Phosphorus Management to Protect Lake Water Quality. AWRA Water Resources Bulletin. 20:23-26.

ASIWPCA, 1985. America's Clean Water: The State's Nonpoint Source Management Experience. Association of State and Interstate Water Pollution Control Administrators. ND-1, MN-8.

Canfield, D.E., Jr. and R.W. Bachman, 1981. Prediction of Total Phosphorus Concentrations, Chlorophyll a, and Secchi Depths in Natural and Artificial Lakes. Canadian Journal of Fisheries and Aquatic Sciences. 38:414-423.

Carlson, R.E., 1977. A Trophic State Index for Lakes. Limnology and Oceanography. 22:361-369.

Cole, G.A., 1983. Textbook of Limnology, 3rd Edition. The C.V. Mosby Company. pp. 321-329.

Daniel, T.C., R.C. Wendt, P.E. McGuire, and D. Stoffel, 1982. Nonpoint Source Loading Rates from Selected Land Uses. AWRA Water Resources Bulletin. 18:117-120.

Dillion, P.J. and F.H. Rigler, 1974. The Phosphorus-Chlorophyll Relationships in Lakes. Limnology and Oceanography. 19:767-773.

Dunst, R.C., S.M. Born, P.D. Uttormark, S.A. Smith, S.A. Nichols, J.O. Peterson, D.R. Knaver, S.L. Serns, D.R. Winter and T.L. Wirth, 1974. Survey of Lake Rehabilitation Techniques and Experiences. Wisconsin Department of Natural Resources. Technical Bulletin No. 75.

Free, B.M. and G.G. Mulamoottil, 1983. The Limnology of Lake Wabukayne, a Storm-Water Impoundment. AWRA Water Resources Bulletin. 19:821-827.

Gillion, R.J., 1984. Relationships Between Water Quality and Phosphorus Concentrations for Puget Sound Regions Lakes. AWRA Water Resources Bulletin. 20:435-442.

Hammer, M.J., 1975. Water and Waste-Water Technology. John Wiley and Sons, Inc. pp. 452-455.

Lee, G.F. and R.A. Jones, 1986. Detergent Phosphate Bans and Eutrophication. Environmental Science and Technology. 20:330-331

Novotny, V. and G. Chesters, 1981. Handbook of Nonpoint Pollution Sources and Management. Van Nostrand Reinhold Company. pp. 535.

Oglesby, R.T. and W.R. Schaffner, 1978. Phosphorus Loadings to Lakes and Some of Their Responses. Part 2 - Regression Models of Summer Phytoplankton Standing Crops, Winter Total P, and Transparency of New York Lakes with Known Phosphorus Loadings. Limnology and Oceanography. 23:135-145.

Rast, W., R.A. Jones, and G.F. Lee, 1983. Predictive Capability of U.S. OECD Phosphorus Loading - Eutrophication Response Models. Journal Water Pollution Control Federation. 55:990-1003.

Rast, W. and G.F. Lee, 1978. Summary Analysis of the North American (U.S. Portion) OECD Eutrophication Project: Nutrient Loading - Lake Response Relationships and Trophic State Indices. U.S. Environmental Protection Agency. EPA-600/3-78-008, p. 455.

Rast, W. and G.F. Lee, 1983. Nutrient Loading Estimates for Lakes. Journal of Environmental Engineering. 109:502-516.

Smart, M.M., J.R. Jones, and J.L. Sebaugh, 1985. Stream-Watershed Relations in the Missouri Ozark Plateau Province. Journal Environmental Quality. 14:77-82.

Smith, V.H. and J. Shapiro, 1981. Chlorophyll-Phosphorus Relations in Individual Lakes. Their Importance to Lake Restoration Strategies. Environmental Science and Technology. 15:444-451.

Sonzogni, W.C., G. Chesters, D.R. Coote, D.N. Jeffs, J.C. Konrad, R.C. Ostry and J.B. Robinson, 1980. Pollution from Land Runoff. Environmental Science and Technology. 14:148-153.

Stein, S.M., G.K. Young, and J.T. Phillippe, 1985. A Water Quality Assessment of Lake Barcroft Aerators. GKY and Associates Inc. Springfield, VA.

U.S. Environmental Protection Agency, 1983. Results of the Nationwide Urban Runoff Program: Volume 1 - Final Report. NTIS:PB84-185552.

U.S. Environmental Protection Agency, 1984. Report to Congress: Nonpoint Source Pollution in the U.S. Office of Water, Water Planning Division.

U.S. Geological Survey, 1973-1977. Land Use and Land Cover, 1973-1977 Charlottesville, VA.; W. VA. Open File 79-403-1. Land Use Series.

U.S. Geological Survey, 1972. Topographic (7.5 minute series); Orkney Springs Quadrangle, VA.-W.V.

Vollenweider, R.A., 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus in Lake Eutrophication. OECD Technical Report, Paris. PAS/CSI/68, 27:1-182.

Wetzel, R.G., 1983. Limnology, 2nd Edition. Saunders College Publishing. pp. 223-297.

APPENDIX A

ORKNEY SPRINGS HOTELS NPDES PERMIT

COMMONWEALTH *of* VIRGINIA

STATE WATER CONTROL BOARD
2111 Hamilton Street

Richard N. Burton
Executive Director

Post Office Box 11143
Richmond, Virginia 23230-1143
(804) 257-0066

Permit No.: VA 0028401
Effective Date: 30 June 1984
Modification Date: 9 August 1985
Expiration Date: 30 June 1989

AUTHORIZATION TO DISCHARGE UNDER THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM AND THE VIRGINIA STATE WATER CONTROL LAW

1. In compliance with the provisions of the Federal Water Pollution Control Act and pursuant to the State Water Control Law and regulations adopted pursuant thereto,

   Orkney Springs Hotels, Inc. and
   Wilmer E. Moomaw, Treasurer

   is authorized to discharge from a facility located at Orkney Springs Hotels Sewag Treatment Plant (Point Source 001), Route 723, approximately 0.1 mile SE of Route 263/723 intersection, Orkney Springs, Shenandoah County
   to receiving waters named unnamed tributary of Stony Creek, Potomac Basin, Shenandoah Subbasin, Section 6, Class IV, Special Standards: pH 6.5-9.5

   in accordance with the effluent limitations, monitoring requirements, and other conditions set forth in this permit.

2. Design and operation of facilities and/or treatment works and disposal of all wastes shall be in accordance with the application filed with the State Water Control Board and in conformity with the conceptual design, or the plans, specifications and/or other supporting data approved by the Board. The facilities shall be operated in accordance with the conditions of the permit.

3. The approval of the treatment works conceptual design or the plans and specifications does not relieve the permittee of the responsibility of designing and operating the facility in a reliable and consistent manner to meet the facility performance requirements in the permit. If facility deficiencies, design and/or operational, are identified in the future which could affect the facility performance or reliability, it is the responsibility of the permittee to correct such deficiencies.

Executive Director, State Water Control Board

Date

Rev. 12-82

SWCB/1-83/M

PERMIT NO. VA 002. J1
Page 1 of 2

PART I

A. EFFLUENT LIMITATIONS AND MONITORING REQUIREMENTS

1. During the period beginning with the permit's effective date and lasting until the permit's expiration date, the permittee is authorized to discharge from outfall(s) serial number(s) 001.

Such discharges shall be limited and monitored by the permittee as specified below:

EFFLUENT CHARACTERISTICS	DISCHARGE LIMITATIONS Monthly Average		Weekly Average		Instantaneous Limitation Min.	Max.	MONITORING REQUIREMENTS Frequency	Sample Type
Flow (MGD)*	- -	- -	- -	- -	- -	- -	1/Day	Measured
BOD_5	24 mg/l	1.8 kg/d	36 mg/l	2.7 kg/d	- -	- -	1/Month	Grab
Suspended Solids	24 mg/l	1.8 kg/d	36 mg/l	2.7 kg/d	- -	- -	1/Month	Grab
Cl_2 Residual (mg/l)$^{(2)}$	- -	- -	- -	- -	- -	- -	1/Day	Grab
pH (standard units)	- -	- -	- -	- -	6.0	9.0	1/Day	Grab
Dissolved Oxygen (mg/l)	- -	- -	- -	- -	6.8	- -	1/Day	Grab

2. (a) All total chlorine residual analyses which are taken prior to dechlorination and after the chlorine contact time shall be greater than or equal to 1.0 mg/l.
   (b) At all times the total chlorine residual concentration in the final effluent from this facility shall be maintained at a level not to exceed 0.05 mg/l.

3. There shall be no discharge of floating solids or visible foam in other than trace amounts.

4. Samples taken in compliance with the monitoring requirements specified above shall be taken at the following location(s): PS 001.

*The design flow of this treatment facility is 0.0195 MGD. The permittee shall monitor flow as specified above (See the Board policy for Sewage Treatment Plant Loadings effective February 1, 1981).

B. SPECIAL CONDITION

1. This permit shall be modified or alternatively revoked and reissued to comply with or reflect the evaluations and/or recommendations of the Disinfection Task Force and any resulting effluent standard or limitation.

APPENDIX B

LAKE LAURA SAMPLING RESULTS

LAKE LAURA SAMPLING DATA
STATION LL01

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
SECCHI (ft)	9.2	8.0	7.9	8.1	5.4	10.1	8.0
ALK. SURF. (mg/l CaCO3) [phtl]	49.4 [1.1]	42.7 [2.4]	44.5 [2.3]	47.0 [2.1]	47.4 [1.8]	49.4	52.3
ALK. BOTT. (mg/l CaCO3)	50.8	55.9	58.9	62.9	56.0	77.5	77.2
COND. SURF. (umhos)	100	110	119	115	108	109	95
COND. BOTT. (umhos)	65	90	95	99	115	112	119
pH SURF.	ND	7.9	7.9	7.9	7.2	7.9	7.3
pH BOTT.	ND	6.3	6.2	6.3	6.4	6.7	6.7
TEMPERATURE (C)							
1.0 ft.	25.0	25.5	27.5	26.0	21.5	20.5	14.1
2.5 ft.	25.0	25.5	27.5	25.8	21.3	20.3	14.1
5.0 ft.	24.0	25.5	27.5	25.8	20.9	20.1	14.1
7.5 ft.	ND	25.5	27.5	25.8	20.7	20.1	14.1
10.0 ft.	18.0	25.5	26.0	25.5	20.5	19.8	14.1
15.0 ft.	10.0	16.5	19.0	20.1	19.8	19.0	14.0
20.0 ft.	6.5	9.5	12.6	12.6	13.9	16.1	13.9
25.0 ft.	5.5	8.0	9.3	9.8	10.1	11.1	13.5
Bottom	ND	7.0	8.5	8.5	8.9	9.2	10.8
D.O. (mg/l)							
1.0 ft.	9.2	7.0	8.0	9.2	8.1	8.3	8.5
2.5 ft.	9.2	6.7	7.9	9.2	8.0	8.4	8.5
5.0 ft.	8.9	6.6	8.1	9.2	7.7	8.4	8.5
7.5 ft.	ND	6.5	7.9	9.2	7.5	8.2	8.5
10.0 ft.	9.8	6.4	7.2	8.7	6.5	8.0	8.5
15.0 ft.	9.6	6.7	3.4	0.6	3.5	6.0	8.0
20.0 ft.	0.6	3.9	1.0	0.8	0.4	0.9	6.7
25.0 ft.	0.8	0.8	0.8	0.8	0.3	0.3	5.3
Bottom	ND	0.5	0.7	0.8	0.3	0.2	0.2
Ortho-P (mg/l)							
Surface	BDL	0.04	0.02	0.02	ND	BDL	BDL
Bottom	0.02	0.06	ND	0.04	0.04	ND	0.03
Total P (mg/l)							
Surface	0.02	0.04	BDL	0.02	0.03	0.02	0.02
Bottom	0.06	0.13	0.07	0.10	0.07	0.08	0.06
Ammonia-N (mg/l)							
Surface	BDL	0.02	0.06	0.04	0.03	0.02	0.02
Bottom	0.60	0.83	1.11	1.49	0.93	1.65	1.23
TKN (mg/l)							
Surface	0.26	0.44	0.32	0.28	0.65	0.39	0.44
Bottom	0.91	1.78	1.50	1.53	1.37	2.23	1.93
Oxidized-N (mg/l)							
Surface	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bottom	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Chl a (ug/l)	ND	1.1	5.3	4.8	23.0	6.4	8.2

BDL=BELOW DETECTION LIMITS
ND=NO DATA

LAKE LAURA SAMPLING DATA
STATION LL02

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
SECCHI (ft)	6.3	7.3	7.8	8.1	5.8	9.3	7.5
ALK. SURF. (mg/l CaCO3) [phtl]	47.8	43.0 [2.3]	45.9 [2.3]	44.7 [1.8]	47.7 [1.8]	49.4	53.7
ALK. BOTT. (mg/l CaCO3)	45.6	54.5	54.1	52.9	64.3	64.5	58.0
COND. SURF. (umhos)	105	110	117	118	109	109	98
COND. BOTT. (umhos)	60	85	91	95	99	111	101
pH SURF.	ND	7.9	7.8	8.0	7.4	7.9	7.2
pH BOTT.	ND	6.3	6.1	6.6	6.1	6.7	6.5
TEMPERATURE (C)							
1.0 ft.	25.5	25.0	27.5	26.0	21.6	20.6	14.2
2.5 ft.	25.5	25.0	27.3	26.0	21.5	20.3	14.2
5.0 ft.	25.0	25.0	27.3	25.6	20.9	20.1	14.2
7.5 ft.	ND	25.0	27.1	25.6	20.7	20.0	14.1
10.0 ft.	19.5	23.0	26.2	25.3	20.5	19.8	14.1
15.0 ft.	13.5	15.5	19.8	21.0	20.0	19.1	14.0
20.0 ft.	10.0	9.0	12.7	12.8	14.3	16.7	14.0
25.0 ft.	9.5	7.0	9.5	9.5	10.1	10.6	12.8
Bottom ft.	ND	7.0	8.7	8.9	9.5	9.8	12.2
D.O. (mg/l)							
1.0 ft.	8.9	6.7	7.9	9.2	8.1	8.5	8.6
2.5 ft.	8.9	6.5	7.9	9.2	8.1	8.6	8.5
5.0 ft.	9.1	6.5	7.9	9.3	8.2	8.5	8.6
7.5 ft.	ND	6.4	8.0	9.2	8.1	8.3	8.6
10.0 ft.	9.8	6.4	7.0	8.9	7.5	8.0	8.4
15.0 ft.	10.5	6.2	2.9	1.9	4.0	7.1	8.1
20.0 ft.	0.5	1.2	0.9	0.9	0.4	1.1	7.4
25.0 ft.	0.4	0.6	0.8	0.9	0.4	0.4	1.6
Bottom ft.	ND	0.4	0.7	0.8	0.3	0.2	0.5
Ortho-P (mg/l)							
Surface	BDL	0.02	BDL	BDL	BDL	0.02	0.02
Bottom	BDL	0.02	0.02	0.02	0.02	0.02	BDL
Total P (mg/l)							
Surface	0.01	0.04	BDL	0.03	BDL	0.02	0.02
Bottom	0.09	0.08	0.06	0.08	0.10	0.05	0.02
Ammonia-N (mg/l)							
Surface	0.01	0.02	0.03	0.02	0.03	0.01	0.02
Bottom	0.10	0.66	1.06	0.98	1.24	0.98	0.29
TKN (mg/l)							
Surface	0.26	0.43	0.25	0.28	0.50	0.22	0.43
Bottom	0.85	1.50	1.19	1.06	1.84	1.41	0.72
Oxidized-N (mg/l)							
Surface	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bottom	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Chl a (ug/l)	ND	1.3	5.4	5.5	22.0	6.4	7.4

BDL=BELOW DETECTION LIMITS
ND=NO DATA

LAKE LAURA SAMPLING DATA
STATION LL03

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
SECCHI (ft)	5.5	7.3	7.5	8.0	5.9	8.8	6.8
ALK. SURF. (mg/l CaCO3) [phtl]	49.6 [9.2]	45.0 [2.5]	44.8 [2.1]	47.9 [2.1]	49.3 [1.7]	48.6	52.6
ALK. BOTT. (mg/l CaCO3)	44.6	36.3	42.1	43.0	48.9	51.0	53.9
COND. SURF. (umhos)	95	110	118	119	110	110	99
COND. BOTT. (umhos)	65	80	82	91	98	102	101
pH SURF.	ND	7.9	8.0	7.9	7.0	8.0	7.3
pH BOTT.	ND	6.0	6.3	6.3	6.5	7.1	7.0
TEMPERATURE (C)							
1.0 ft.	24.5	25.0	27.3	26.0	21.9	20.6	14.1
2.5 ft.	24.5	25.0	27.2	26.0	21.7	20.2	14.2
5.0 ft.	24.0	25.0	27.2	25.6	21.3	20.1	14.2
7.5 ft.	ND	24.5	27.1	25.5	21.1	20.0	14.2
10.0 ft.	19.0	23.0	26.0	25.3	20.8	20.0	14.1
15.0 ft.	12.5	15.5	19.8	21.0	19.6	18.9	14.0
17.0 ft.	13.0	11.0	14.0	16.5	16.8	18.0	14.0
D.O. (mg/l)							
1.0 ft.	9.0	7.2	8.6	9.1	8.2	8.5	8.7
2.5 ft.	9.0	6.9	8.6	9.2	8.1	8.6	8.5
5.0 ft.	8.9	6.8	8.6	9.3	8.1	8.5	8.6
7.5 ft.	ND	6.8	8.6	9.3	7.9	8.5	8.5
10.0 ft.	7.1	6.8	7.6	8.8	7.6	8.3	8.3
15.0 ft.	9.0	6.3	1.7	2.4	5.6	5.3	7.8
Bottom ft.	10.5	1.4	0.7	0.7	0.4	2.5	6.9
Ortho-P (mg/l)							
Surface	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bottom	BDL	BDL	0.01	BDL	BDL	BDL	BDL
Total P (mg/l)							
Surface	0.02	0.03	BDL	0.02	BDL	0.01	0.02
Bottom	0.03	0.10	0.06	0.05	0.01	0.02	0.02
Ammonia-N (mg/l)							
Surface	0.01	0.03	ND	0.02	0.02	0.03	0.03
Bottom	0.02	0.09	0.13	0.08	0.05	0.05	0.02
TKN (mg/l)							
Surface	0.35	0.50	0.30	0.21	0.51	0.23	0.45
Bottom	0.34	0.83	0.55	0.48	0.51	0.28	0.38
Oxidized-N (mg/l)							
Surface	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bottom	BDL	BDL	0.02	BDL	BDL	BDL	BDL
Chl a (ug/l)	ND	1.1	5.8	4.8	23.0	6.6	6.2

BDL=BELOW DETECTION LIMITS
ND=NO DATA

LAKE LAURA SAMPLING DATA
STATION LL04

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
SECCHI (ft)	6.8	5.8	5.5	5.5	5.8	6.0	5.1
ALK. SURF. (mg/l CaCO3) [phtl]	44.6	44.0 [2.7]	44.8 [1.6]	45.5 [1.2]	48.9 [2.2]	50.5	53.9
ALK. BOTT. (mg/l CaCO3)	54.4	44.9	46.0 [2.0]	46.9 [1.2]	49.6	49.5	54.3
COND. SURF. (umhos)	105	110	119	119	112	112	100
COND. BOTT. (umhos)	105	120	121	119	112	111	100
pH SURF.	ND	8.5	7.9	7.8	6.9	7.8	7.3
pH BOTT.	ND	8.0	7.9	7.8	6.9	7.8	7.2
TEMPERATURE (C)							
1.0 ft.	24.5	25.0	27.8	26.0	22.5	20.6	14.2
2.5 ft.	24.3	24.5	27.5	26.0	22.0	20.1	14.2
5.0 ft.	24.0	24.5	27.2	25.5	21.9	20.0	14.2
7.5 ft.	24.0	24.0	27.2	25.5	21.9	20.0	14.2
D.O. (mg/l)							
1.0 ft.	8.9	7.4	8.6	9.1	8.1	8.3	9.6
2.5 ft.	8.8	7.3	8.6	9.1	7.9	8.3	8.9
5.0 ft.	8.8	7.2	9.8	9.1	7.8	8.6	9.0
7.5 ft.	8.3	7.1	9.8	9.3	7.8	8.5	9.0
Ortho-P (mg/l)							
Surface	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bottom	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Total P (mg/l)							
Surface	0.02	0.04	BDL	0.02	BDL	0.01	0.02
Bottom	0.30	0.21	0.02	0.02	0.20	0.02	0.02
Ammonia-N (mg/l)							
Surface	0.01	0.02	0.03	0.02	0.04	0.04	0.02
Bottom	0.05	0.01	0.02	0.02	0.02	0.04	0.02
TKN (mg/l)							
Surface	0.39	0.43	0.27	0.29	0.46	0.23	0.39
Bottom	1.75	1.25	0.30	0.25	1.51	0.25	0.43
Oxidized-N (mg/l)							
Surface	BDL	BDL	BDL	BDL	BDL	BDL	0.02
Bottom	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Chl a (ug/l)	ND	2.6	3.8	7.2	22.0	5.5	4.5

BDL=BELOW DETECTION LIMITS
ND=NO DATA

APPENDIX C

LAKE LAURA DRAINAGE BASIN SAMPLING RESULTS

LAKE LAURA SAMPLING DATA
STATION BM01

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
ALKALINITY (alk/100 ml)	67.4	57.2	58.8	60.9	62.1	67.5	68.2
CONDUCTIVITY (umhos)	225	238	255	250	269	272	242
TEMPERATURE (C.)	21.0	19.5	21.5	19.0	17.2	16.0	11.5
D.O. (mg/l)	7.6	8.5	7.7	8.1	7.3	6.4	8.0
pH	ND	6.9	6.4	6.2	6.4	6.5	6.6
Ortho-P (mg/l)	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Total P (mg/l)	0.03	0.05	0.02	BDL	BDL	BDL	BDL
Ammonia-N (mg/l)	0.03	0.03	0.02	0.01	0.02	0.03	0.01
TKN (mg/l)	0.84	0.38	0.29	0.05	0.38	0.09	0.28
Oxidized N (mg/l)	0.49	0.29	0.34	0.01	0.29	0.49	0.41

ND=NO DATA
BDL=BELOW DETECTION LIMIT

LAKE LAURA SAMPLING DATA
STATION BM02

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
ALKALINITY (alk/100 ml)	75.2	102.2	99.8	112.8	117.1	122.8	123.7
CONDUCTIVITY (umhos)	130	175	171	185	181	190	175
TEMPERATURE (C)	19.0	18.0	19.7	18.0	15.3	15.5	11.0
D.O. (mg/l)	8.5	8.2	8.8	9.5	8.3	9.6	9.8
pH	ND	7.6	7.0	7.2	7.6	7.7	7.6
Ortho-P (mg/l)	0.01	0.01	BDL	BDL	BDL	BDL	BDL
Total P (mg/l)	0.02	0.04	0.02	0.02	BDL	0.01	0.01
Ammonia-N (mg/l)	0.02	0.02	0.02	0.04	0.01	BDL	BDL
TKN (mg/l)	0.23	0.32	0.15	0.07	0.10	BDL	0.17
Oxidized-N (mg/l)	0.09	0.06	0.06	BDL	0.04	0.07	0.15

ND=NO DATA
BDL=BELOW DETECTION LIMIT

LAKE LAURA SAMPLING DATA
STATION BM03

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
ALKALINITY (alk/100 ml)	63.2	81.9	90.7	112.4	83.4	147.6	100.0
CONDUCTIVITY (umhos)	240	325	352	395	325	400	332
TEMPERATURE (C)	21.5	19.5	21.2	19.1	16.8	16.5	11.1
D.O. (mg/l)	8.5	7.2	7.1	7.6	7.0	7.9	8.0
pH	ND	7.1	6.7	6.9	7.0	7.3	7.2
Ortho-P (mg/l)	0.21	0.30	BDL	0.44	0.94	0.55	0.42
Total P (mg/l)	0.32	0.34	0.48	0.53	0.94	0.67	0.52
Ammonia-N (mg/l)	0.02	0.02	0.02	0.04	0.03	0.04	0.01
TKN (mg/l)	0.38	0.60	0.72	0.83	0.81	1.01	0.72
Oxidized-N (mg/l)	0.89	0.70	0.04	3.67	4.16	4.07	4.02

ND=NO DATA
BDL=BELOW DETECTION LIMIT

LAKE LAURA SAMPLING DATA
STATION BM04

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/25/86)
ALKALINITY (alk/100 ml)	73.8	94.2	86.3	103.5	126.4	117.3	117.7
CONDUCTIVITY (umhos)	140	200	183	197	199	180	178
TEMPERATURE (C)	21.0	22.0	22.1	20.5	18.0	16.5	11.0
D.O. (mg/l)	9.1	7.3	9.0	9.6	8.3	9.8	9.1
pH	ND	7.7	7.0	7.2	7.5	7.8	7.4
Ortho-P (mg/l)	0.02	0.04	0.01	BDL	0.03	0.01	BDL
Total P (mg/l)	0.04	0.06	0.04	0.02	0.03	0.01	0.01
Ammonia-N (mg/l)	BDL	0.02	0.02	ND	0.03	ND	BDL
TKN (mg/l)	0.17	0.30	0.19	0.10	0.16	BDL	0.14
Oxidized-N (mg/l)	0.22	0.28	1.88	0.05	0.29	0.10	0.19

ND=NO DATA
BDL=BELOW DETECTION LIMIT
k2S

LAKE LAURA SAMPLING DATA
STATION STP05

	DATE (6/13/86)	DATE (7/12/86)	DATE (7/26/86)	DATE (8/9/86)	DATE (9/6/86)	DATE (9/20/86)	DATE (10/26/86)
ALKALINITY (alk/100 ml)	ND	291.0	306.5	308.0	339.4	290.9	264.9
CONDUCTIVITY (umhos)	ND	670	850	880	750	700	670
TEMPERATURE (C)	ND	16.0	25.1	23.9	19.5	19.2	13.9
D.O. (mg/l)	ND	2.2	2.4	2.8	3.9	4.6	5.9
pH	ND	6.9	6.9	7.0	7.2	7.5	7.3
FLOW (mgd)	0.0028	0.0138	0.0138	0.0054	0.0076	0.0104	0.0064
Ortho-P (mg/l)	3.85	4.78	0.03	ND	ND	6.26	4.06
Total P (mg/l)	4.16	ND	8.19	8.85	9.18	7.03	4.06
Ammonia-N (mg/l)	13.86	ND	0.12	0.05	ND	ND	19.63
TKN (mg/l)	19.56	34.90	41.11	33.83	41.48	30.42	24.28
Oxidized-N (mg/l)	0.20	BDL	BDL	BDL	0.45	0.93	0.91

BDL=BELOW DETECTION LIMITS
ND=NO DATA

The vita has been removed from
the scanned document