PHASE I DIAGNOSTIC/FEASIBILITY STUDY OF LAKE LUXEMBOURG, BUCKS COUNTY, PENNSYLVANIA

Final Report

Grant No. CL-003509-01-0

Submitted to:

U.S. EPA, Region III
841 Chestnut Building
Philadelphia, PA 19107

Submitted by:

Bucks County Conservation District
924 Town Center
New Britain, PA 18901-5182

Prepared by:

Coastal Environmental Services, Inc.

2 Research Way
Princeton, New Jersey 08540
●
1099 Winterson Road, Suite 130
Linthicum, Maryland 21090

May 1993
Revised: April 1994

Table of Contents

Table of Contents (Continued)

Section **Page**

Table of Contents (Continued)

List of Tables

List of Figures

Executive Summary

A Phase I diagnostic-feasibility study of Lake Luxembourg was completed under the U.S. EPA Clean Lakes Program. The study was initiated in September 1990 and all project elements were completed by June 1993. The Lake Luxembourg Phase I study examined a variety of lake and watershed characteristics and resulted in the development of a lake and watershed restoration plan for Lake Luxembourg. Some of the key findings of the Lake Luxembourg Phase I report are summarized below.

Conclusions

Lake Luxembourg is exhibiting symptoms of accelerated productivity, or eutrophication, brought on by sedimentation and high nutrient levels. Approximately 299,000 cubic meters (392,000 cubic yards or 243 acre-ft) of sediment have accumulated in Lake Luxembourg since it was impounded in 1977. The current sedimentation rate is approximately 11,800 cubic meters (9.6 acre-ft) per year, which is less than half of the sedimentation rate that occurred prior to 1987.

Nutrient levels in the lake are well in excess of those required to support algal growth and cause heavy algal blooms throughout much of the year. Phosphorus is the nutrient which appears to limit algal growth at the present time. Algal densities were high throughout the year, with the predominant species varying with season.

The transparency in Lake Luxembourg is low as a result of suspended silt and clay particles entering the lake from the watershed and frequent algal blooms. The low transparency prevents the growth of aquatic macrophytes and may partially limit algal growth.

Sediment and nutrients enter Lake Luxembourg primarily by runoff from the watershed. Pollutant loadings from runoff were calculated with both the unit areal loading method, based on land use, and from watershed monitoring data. The annual pollutant loadings calculated from the unit areal loading method were 2,340 kg (2.6 tons) of phosphorus, 45,500 kg (50.2 tons) of nitrogen and 3,596,000 kg (3,960 tons) of total suspended solids. Pollutant loadings calculated from monitoring data were 3,365 kg (3.7 tons) of phosphorus, 70,800 kg (7.8 tons) of nitrogen and 2,173,000 kg (2,400 tons) of total suspended solids. Because both methods involve a number of assumptions, and because monitoring data was limited, the agreement between the two methods is within expected limits. Runoff from crop land is the major contributor of nutrients and suspended solids.

The total nonpoint source pollutant loadings to Lake Luxembourg were determined by adding contributions from direct precipitation, internal loading, waterfowl and nonpoint source runoff. Runoff contributes more than 91 percent of the total phosphorus, more than 96 percent of the total nitrogen and more than 99 percent of the total suspended solids to Lake Luxembourg. Internal regeneration contributes approximately 6.5 percent of the total phosphorus load to Lake

Luxembourg, while all other sources contribute less that 2 percent each of total pollutant loadings.

An analysis of the trophic state of Lake Luxembourg indicated that the lake is hypereutrophic, or excessively productive, at the present time. Reductions in total phosphorus loadings of 91 percent would be required to bring water quality into the mesotrophic range, although the desired recreational uses of the lake could be maintained without this full degree of phosphorus reduction.

Recommendations

A three-year Phase II program is recommended to provide some immediate water quality benefits and to initiate watershed management activities. The availability of funding may determine which elements of the management program are implemented first.

The recommended management plan for Lake Luxembourg concentrates on the implementation of agricultural best management practices (BMP's) to reduce pollutant loadings. Reductions in annual soil loss of 25,200 yons/yr would be acheived if all of the recommended restoration measures are implemented.

In-lake management alternatives are recommended to alleviate some of the existing water quality problems and to enhance recreational use of the lake. Recommended in-lake restoration measures include a lake drawdown for sediment consolidation and fishery rehabilitation and a limited dredging program for the portion of the lake north of Woodbourne Road to increase sediment trapping efficiency.

In view of the heavy use of Core Creek Park, several measures were recommended to enhance lake access and use. These include environmental landscaping for duck and goose control, completion of the bicycle path around the lake, installation of an additional fishing pier and the installation of fish attractant devices to provide cover and increase the success rate for shoreline anglers.

The total costs for the recommended restoration efforts are $1,492,520; additional dredging, if desired, would significantly increase this figure. Potential funding sources are available to supplement County resources for the implementation of the recommended management plan. These include State conservation programs, as well as the U.S. EPA Clean Lakes Program (Section 314 of the Clean Water Act) and the Nonpoint Source Control Program (Section 319). Cost share funding for the implementation of BMP's may be available from the Soil Conservation Service (SCS) and the Agricultural Stabilization and Conservation Service (ASCS). The performance of in-kind services can be used as part of the required local match for many of these programs to help defray cash requirements.

1.0 Introduction

1.1 Project Background

Lake Luxembourg is the recreational and aesthetic focal point of the popular, multi-use Core Creek Park, part of the Bucks County Park System located in Middletown Township, Bucks County, Pennsylvania (Figure 1.1). The reservoir was built in the 1970's under Public Law 566 funding through the Soil Conservation Service. Flood control was the primary function of the reservoir, with recreation and water supply as secondary uses. Core Creek Park has the greatest attendance of any county park in Bucks County, and water-based recreation is one of the reasons for this high usage. Both fishing and boating are popular activities at Lake Luxembourg.

Water quality problems began to arise in Lake Luxembourg within just a few years after its impoundment. These problems have interfered with the suitability of Lake Luxembourg for both recreation and water supply. Reduced depth and turbid water have curtailed recreational usage of the lake. The lake is also eutrophic and excessive algae growth further limits the use of the lake. Problems caused by siltation and the excessive growth of algae have reduced the quality of aquatic and lakeside activities, preventing the entire park from reaching its full recreational potential.

Lake Luxembourg was designed to have enough capacity to store 100 years worth of sediment while still maintaining full flood storage. Unfortunately, the reservoir has reached its full 100-year sediment capacity in just 9 years. Construction activities associated with the rapid urbanization of the Lake Luxembourg watershed and agricultural practices are major sources of the high sediment load. Many soils in the watershed are erodible, and disturbed areas contribute high sediment loads during storm events.

Lake Luxembourg, Core Creek Park, and the Lake Luxembourg watershed are unique and valuable assets to Lower Bucks County. The Lake Luxembourg watershed contains some of the last actively farmed agricultural land remaining in Lower Bucks County. Core Creek Park is a valuable open space amid a rapidly expanding residential area and provides recreational facilities and opportunities for nearly half a million people each year. In recognition of the importance of Lake Luxembourg, the Bucks County Conservation District (BCCD) decided to take steps to restore the intended flood control and recreational uses of the lake.

The BCCD applied for funding to perform a Phase I Diagnostic/Feasibility Study of Lake Luxembourg under the U.S. EPA Clean Lakes Program in February 1990. The U.S. EPA Region III awarded Grant No. CL-003509-01-0 to the Pennsylvania Department of Environmental Regulation on 11 September 1990 to fund the Lake Luxembourg Phase I Study, and the BCCD selected Coastal Environmental Services, Inc. (Coastal) to perform the Phase I Study in May 1991.

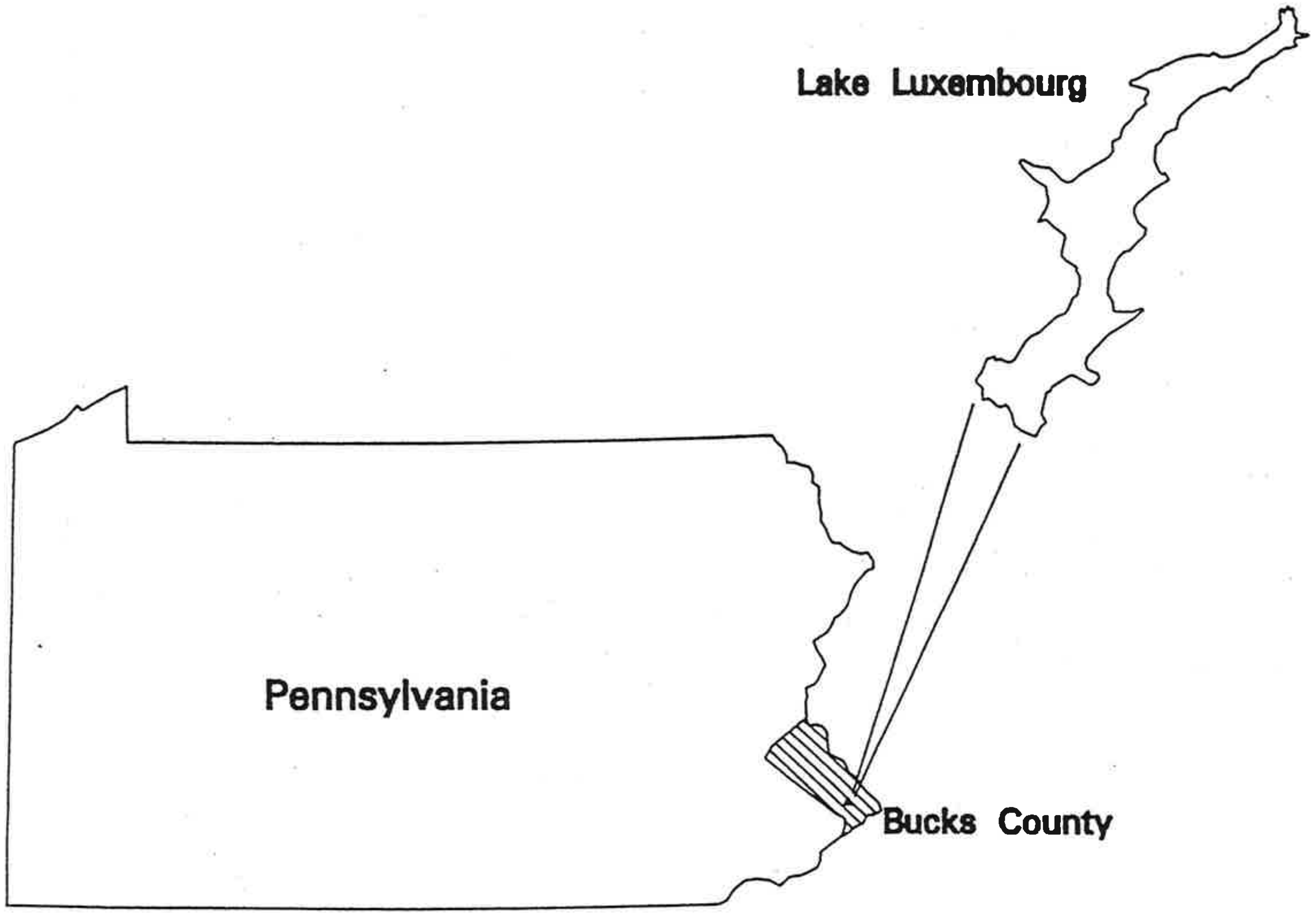


Figure 1.1. Location of Lake Luxembourg, Bucks County, Pennsylvania.

COASTAL
ENVIRONMENTAL SERVICES INC

1.2 Project Objectives

The Lake Luxembourg Phase I Diagnostic-Feasibility Study was designed to meet all applicable criteria set by the U.S. EPA Clean Lakes Program, as listed in Appendix A (40 CFR Chapter 1, § 35, Subpart H). The objectives of the diagnostic portion of the study were to assemble existing data and to develop a current data base for use in the review and selection of potential restoration and management alternatives. The Feasibility section of the study was designed to objectively assess the utility of potential lake restoration and watershed management alternatives. The overall objective of the Lake Luxembourg Phase I Study was the development of a Restoration/Management Plan that will serve as the blueprint for the protection and enhancement of the lake.

Based on a preliminary review of available water quality, limnological and socioeconomic data, the specific objectives of the Lake Luxembourg Phase I Study were:

1. the proper design of a sampling plan to assess in-lake, tributary, and stormwater quality and to identify existing water quality problems and pollutant sources,
2. an accurate quantification of the annual sediment and nutrient loads that originate from various identified watershed sources,
3. the accurate interpretation of these data relative to the trophic state and water quality of the lake,
4. an evaluation of lake and watershed management alternatives with respect to their effectiveness, costs, environmental impacts, and applicability, and
5. the development of a feasible Restoration/Management Plan for Lake Luxembourg and its watershed which is technically, fiscally and environmentally sound, suitable for Phase II implementation, meets the needs and requirements of regulatory agencies such as the U.S. EPA and the Pennsylvania Department of Environmental Regulation (PaDER), and responsive to the needs of park users and the surrounding community.

1.3 Project Expenditures

The total cost of the Lake Luxembourg Phase I Diagnostic-Feasibility Study was $62,858. Federal funding was provided by a grant of $44,000 from the U.S. EPA Clean Lakes Program. In addition, the Bucks County Conservation District provided a cash grant of $12,400 and in-kind services valued at $6,458 to meet the required 30 percent local match for the project. In-kind services were documented in the quarterly reports prepared by the BCCD. Costs and task descriptions are listed in Table 1.1.

Table 1.1 - Task Descriptions and Expenditures for the Lake Luxembourg Phase I Study

Task - Description	Costs
1 - Development of a Detailed Work Plan	$1,000
2 - Study of Lake and Watershed Characteristics	$1,000
3 - Study of Social, Economic, and Recreational Characteristics	$500
4 - Lake Monitoring Program	$21,358
5 - Bathymetric Analysis	$2,000
6 - Watershed Monitoring Program	$11,000
7 - Data Analysis and Development of Annual Pollutant Budgets	$4,500
8 - Evaluation of Restoration Alternatives	$4,000
9 - Environmental Impact Assessment	$1,000
10 - Development of a Lake and Watershed Management Program	$6,000
11 - Public Participation Program	$2,500
12 - Project Documentation	$8,000

2.0 Lake and Watershed Characteristics

Lake Luxembourg was constructed as a multi-purpose reservoir under Public Law 566 funding. Core Creek Dam (PA 620) was designed by E.H. Bourquard Associates, Inc., Pickering, Corts and Summerson, Inc., and Justin & Courtney for the Soil Conservation Service. Construction work was performed by James D. Morrissey and the dam was completed on 30 June 1976. Lake Luxembourg was filled in the summer of 1977.

Core Creek Dam was built under Public Law 566 funding through the Soil Conservation Service. The principal spillway is a reinforced concrete drop inlet structure with an ungated weir maintaining the recreation pool at a level of 102.5 feet above mean sea level (MSL). Gated water supply intakes are located at elevations of 91 and 88 feet, and the pond drain is located at an elevation of 71 feet above MSL. The emergency spillway is located at an elevation of 111.9 feet above MSL (Woodward-Clyde Consultants, 1978).

2.1 Lake Characteristics

Lake Luxembourg is located in Middletown Township, with approximately equal portions of the watershed located in Middletown, Lower Makefield and Newtown Townships. The approximate coordinates of the dam are 40° 11′ 45" north latitude and 74° 55′ 12" west longitude. Core Creek is the main inlet and outlet for Lake Luxembourg; it enters Neshaminy Creek approximately 21.6 km (13.5 miles) upstream of the Delaware River. Existing lake and watershed characteristics are summarized in Table 2.1.

Table 2.1 - Lake and Watershed Characteristics

Parameter	Value
Lake Surface Area	70.2 hectares (174 acres)
Watershed Area	2,514 hectares (6,209 acres)
Mean Depth	2.1 m (6.9 ft)
Maximum Depth	8.4 m (27.7 ft)
Lake Volume	1.48×10^6 m3 (1,196 acre-ft)
Mean Discharge	1.18×10^7 m3/yr (9,600 acre-ft/yr)
Hydraulic Residence Time	0.125 yr (45.5 days)
Flushing Rate	8.0 times/yr
Watershed Area/Lake Surface Area	35.8

The watershed area listed in Table 2.1 is greater than the value of 2,480 hectares (6,125 acres) used in previous reports. Changes in drainage patterns created by the rapid development of the watershed are the primary reason for this difference. The lake surface area includes approximately 63.3 hectares (156 acres) of surface water in the main body of the lake and an additional 7.0 hectares (17 acres) of surface water to the north of Woodbourne Road.

2.1.1 Bathymetric Analysis

The volume of Lake Luxembourg reported in the original Phase I Dam Inspection Report was 1,476 acre-ft (1.82 x 10^6 m^3) when the lake is filled to the normal recreation pool at an elevation of 102.5 feet above MSL (Woodward-Clyde Consultants, 1978). The original design included a conservation pool with a volume of 261 acre-ft (3.22 x 10^5 m^3) for sediment storage.

A bathymetric survey of Lake Luxembourg was conducted in 1987 by the Bucks County Conservation District and the USDA, Soil Conservation Service (Benton, 1988) because of concerns about sedimentation. Water and sediment depths were measured along 23 transects of the lake and used to calculate water and sediment volumes. The current and original water volumes calculated by that survey were 1,361 (1.67 x 10^6 m^3) and 1,614 acre-ft (1.99 x 10^6 m^3), respectively, for a sediment volume of 253 acre-ft (3.12 x 10^5 m^3).

The original lake volume calculated in the 1987 bathymetric survey of 1,614 acre-ft (1.99 x 10^6 m^3) is considerably greater than the known volume of 1,476 acre-ft (1.82 x 10^6 m^3). As a result, both volumes from the 1987 survey were recalculated by multiplying the volumes by the ratio of the known to the calculated original volumes. This resulted in revised volumes of 1,244 (1.53 x 10^6 m^3) and 232 acre-ft (2.86 x 10^5 m^3) for the 1987 lake and sediment volumes, respectively. The average sedimentation rate obtained from these figures is 23 acre-ft/year (2.84 x 10^4 m^3) for the period 1977 to 1987.

A bathymetric survey of Lake Luxembourg was performed as part of the Phase I study on 3 and 4 March 1992. A global positioning system (GPS) was used to determine position, and a recording fathometer was used to determine water depth along 40 transects. A calibrated rod was used to determine water depth and sediment thickness at an additional 37 locations. A Geographic Information System (GIS) was used to develop a bathymetric map for Lake Luxembourg (Figure 2.1) by integrating the depth and locational data. The bathymetric survey indicated the lake volume and mean depth were 1.48 x 10^6 m3 (1,196 acre-ft) and 2.1 m (6.9 ft), respectively. The maximum depth is approximately 8.4 m (27.7 ft) near the outlet structure at the dam.

An estimate of the original lake volume was obtained by digitizing as-built plans for the reservoir (Bourquard et al., 1971). The volume calculated by this method was 1,439 acre-ft (1.77 x 10^6 m3) was in good agreement with the volume of 1,476 acre-ft reported in the original Phase I Dam Inspection Report (Woodward-Clyde Consultants, 1978). Original contours for Lake Luxembourg are shown in Figure 2.2.

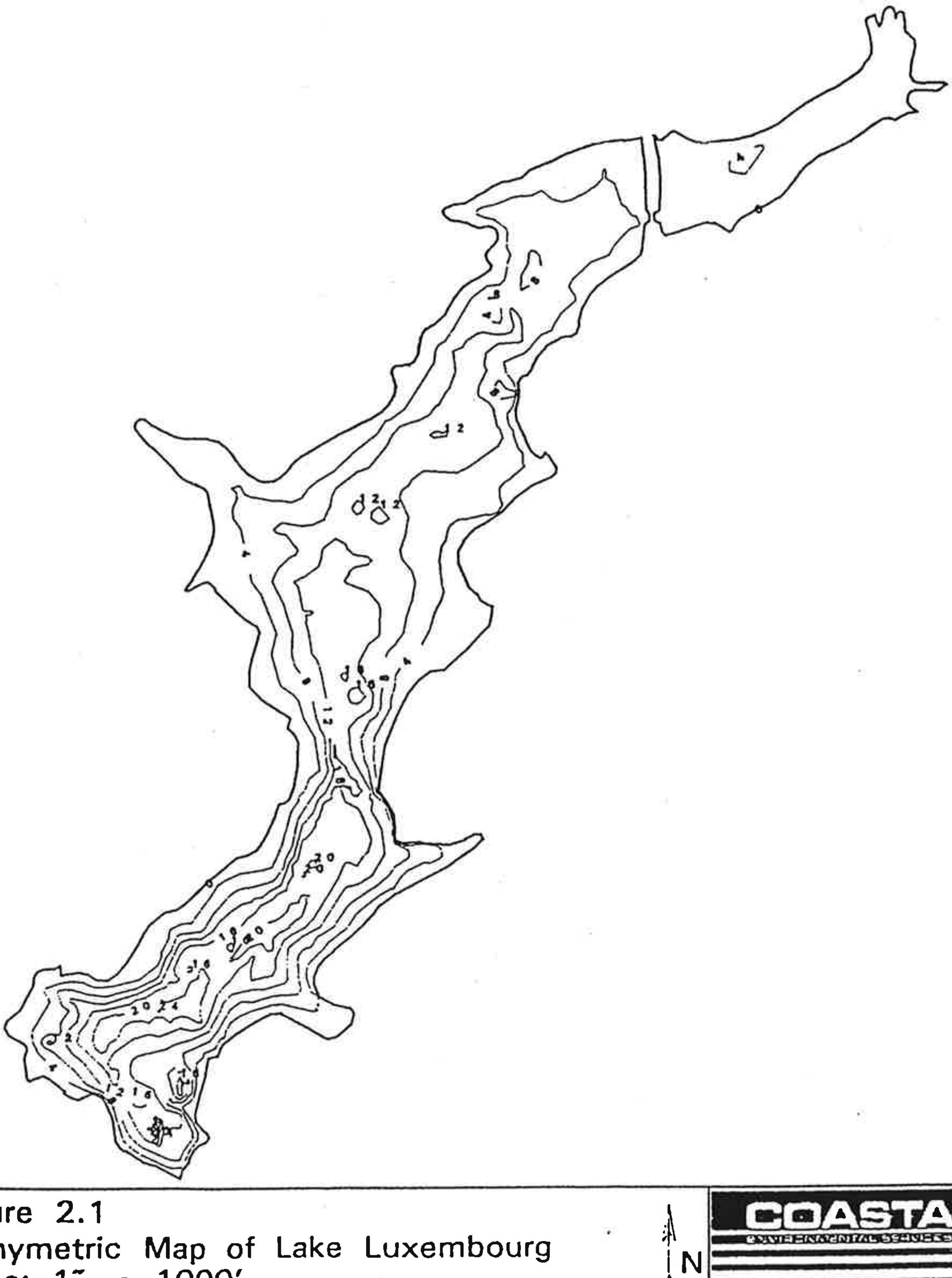


Figure 2.1
Bathymetric Map of Lake Luxembourg
Scale: 1" = 1000'
Contour Interval = 4'

COASTAL
ENVIRONMENTAL SERVICES INC

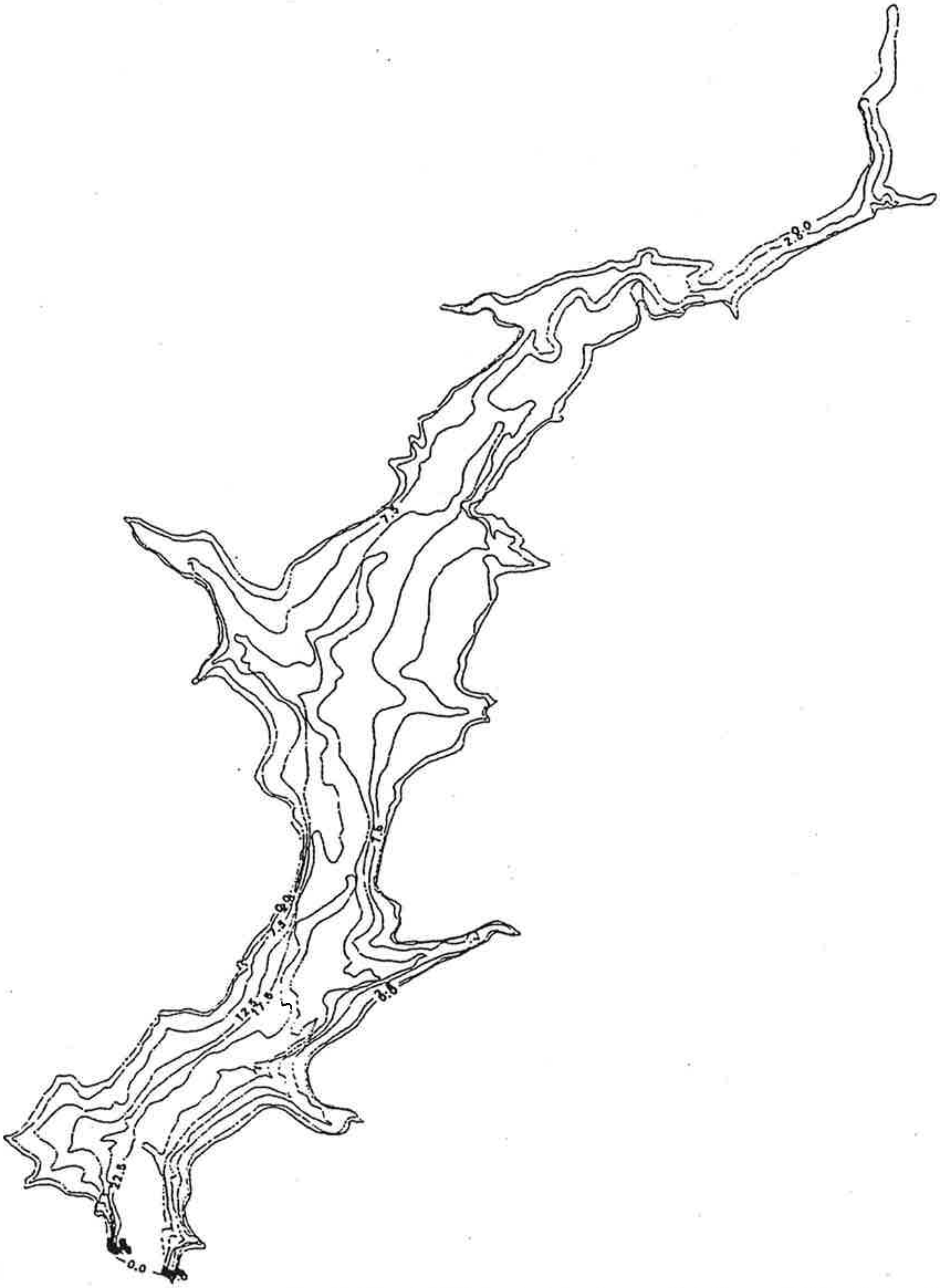


Figure 2.2
Original Lake Luxembourg Bathymetry
Source: USDA, SCS, Drawing #PA-620-P
Scale: 1" = 1000' : Contour Interval = 5'

N

COASTAL
ENVIRONMENTAL SERVICES INC

The current (1992) sediment volume was estimated by comparing the existing lake volume with the volumes obtained by digitizing the as-built plans because water depth made accurate assessments of sediment thickness difficult over much of the lake surface. Shallow water prevented access to approximately 5.0 acres near the lake inlet. An average sediment depth of 3 ft (1 m) was assumed for this area. Sediment volumes calculated by this method were 2.81 x 10^5 m^3 (3.68 x 10^5 yd^3 or 228 acre-ft) for the main body of the lake and 1.82 x 10^4 m^3 (2.39 x 10^4 yd^3 or 15 acre-ft) for the portion of the lake north of Woodbourne Road; total sediment volume was 2.99 x 10^5 m^3 (3.92 x 10^5 yd^3 or 243 acre-ft).

Comparison of the current, 1987 and original water volumes results in a calculated total sediment volume of 2.99 x 10^5 m^3 (280 acre-ft) and an additional accumulation of 5.92 x 10^4 m^3 (48 acre-ft) in the past five years. The current sedimentation rate calculated from these figures is 1.18 x 10^4 m^3/yr (9.6 acre-ft/year), or about half of the 1977 to 1987 rate. Tighter controls on construction practices and the implementation of some agricultural best management practices (BMP's) are possible reasons for the reduction in sedimentation rate.

The bathymetric survey indicated that sediment thicknesses of more than 1 m (3 ft) were common in the area of the lake north of Woodbourne Road. Water flow in this area is constricted by the culvert under the road, causing this portion of the lake to function as an in-lake sediment basin. The existing contours for this portion of the lake are shown in Figure 2.3.

2.1.2 Lake Uses

Lake Luxembourg is one of eight reservoirs currently comprising the Neshaminy Basin Flood Control System and represents about 16 percent of the flood storage capacity of the Neshaminy Basin. The lake impounds almost 99 percent of the Core Creek Basin in southern Bucks County. Flood control was the primary function of the reservoir, with recreation and water supply as secondary uses. There are currently no plans to use Lake Luxembourg as a water supply.

Lake Luxembourg has become a major recreational asset for the Bucks County Parks Department and is the focal point of Core Creek Park. Construction of Core Creek Park was completed in 1979, and the park quickly became the most widely used park in Bucks County. Attendance averaged 240,936 between 1980 and 1985 (Bucks County Planning Commission, 1986) and reached 355.275 by 1985 (Bucks County Department of Parks and Recreation, 1985). Park use is estimated to be increasing by over 10 percent each year and reached 1,273,014 in 1992 (Pfanstiel, 1993). Core Creek Park attendance figures are summarized in Table 2.2.

Core Creek Park offers a wide range of land and water-based recreational opportunities. Boat ramps, boat docks, a mooring beach and fishing piers are available for lake users. Fishing and boating are the most popular lake uses, and sailboats, rowboats, sail boards and canoes are common on the lake in the summertime. Boats

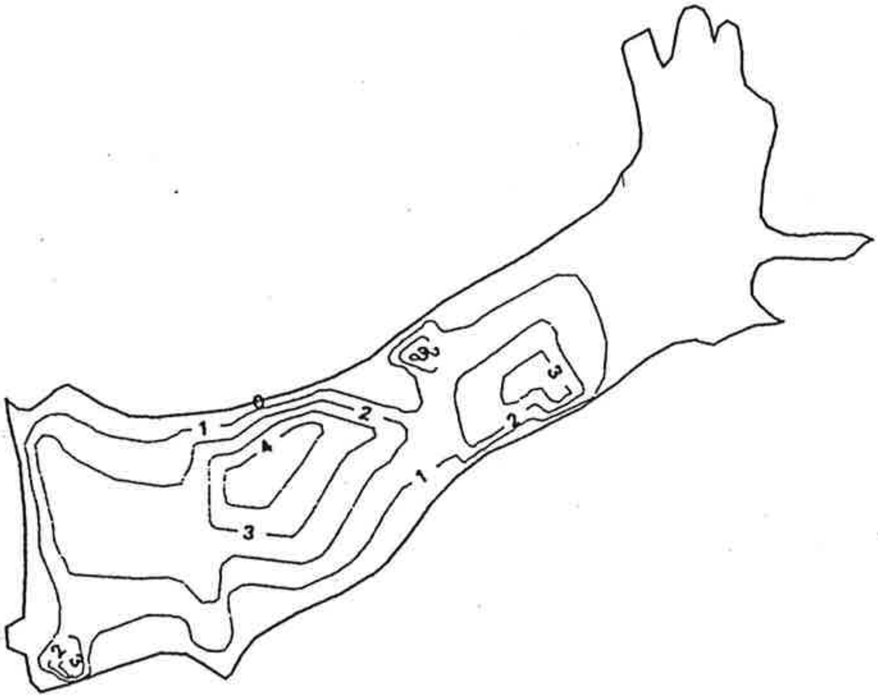


Figure 2.3
Existing Bathymetry of Lake Luxembourg
North of Woodbourne Road
Scale: 1" = 400' : Contour Interval = 1'

N

COASTAL
ENVIRONMENTAL SERVICES INC

are limited to 16 feet and only electric motors are permitted. The lake is used for ice skating and ice fishing during the winter months when conditions permit.

Table 2.2 - Core Creek Park Attendance

Year	Attendance
1980 - 1985 (average)	240,936
1985	355,275
1990	884,038
1991	1,060,845
1992	1,273,014

Land-based recreational activities in the park include picnicking, hiking, jogging and horseback riding. Tennis courts, playgrounds and athletic fields are also available for park users. Group camping areas are available to groups larger than 200. A complete listing of park facilities is included in Table 2.3.

A number of special events draw additional users to Core Creek Park. The annual Kite Day draws over 10,000 spectators. A popular concert series is held in the summer in the outdoor amphitheater. In addition, various community groups use the facilities at Core Creek Park for special events and activities. These include the Courier Times Classic, walkathons, pet shows, YMCA day camps, and Viet Nam Veterans' ceremonies.

Some other public lakes in Pennsylvania within a 80 km (50 mile) radius of Lake Luxembourg are listed in Table 2.4. Although many of these lakes offer a range of recreational opportunities, planners generally agree that over 75 percent of leisure activities occur within 20 miles (32 km) of home. Because of this fact, the popularity of Core Creek Park and the rapid population growth in the Lake Luxembourg watershed, none of these lakes receives the recreational use that Lake Luxembourg does.

2.1.3 Public Access

Core Creek Park is readily accessible to residents of Lower and Central Bucks County, as well as Northeast Philadelphia. The park is located just two miles northwest of the Interstate 95 and U.S. Route 1 interchange and less than one mile east of PA Route 413.

There are two access points to the main park road. One is from Old Bridgetown Pike, which links Route 413 and Langhorne-Yardley Road along the southern edge of the park, and the other is from Tollgate Road in the northwest section of the park.

Table 2.3 - Recreational Facilities at Core Creek Park

Facility	Number/Size
Lake Facilities	
Boat Ramps	2
Boat Docks	2
Fishing Piers	4
Mooring Beach	1
Picnic Facilities	
Pavilions	9
Group Picnic Areas	4
General Picnic Areas	2
Other Facilities	
Tennis Courts	8
Athletic Fields	3
Paved Court with Basketball Backstops	1
Playground	1
Tot Lots	2
Comfort Stations	5
Paved Bicycle/Jogging Trails	1 mile
Hiking/Horseback Riding/Cross-country Skiing Trails	6 miles
Park Roads	2 miles

Table 2.4 - Public Lakes Within 80 km (50 miles) of Lake Luxembourg in Pennsylvania

Lake Name	Distance from Lake Luxembourg km (miles)	Recreational Uses
Churchville Reservoir	8 (5)	Fishing
Lake Afton	8 (5)	Fishing
Levittown Lake	10 (6)	Fishing
Silver Lake (Bristol)	13 (8)	Boating and Fishing
Loch Alsh Reservoir	26 (16)	Fishing
Lake Galena	29 (18)	Boating and Fishing
Lake Nockamixon	38 (24)	Boating and Fishing
Lake Towhee	43 (27)	Boating and Fishing
Trout Run Reservoir	61 (38)	Fishing
Marsh Creek Lake	69 (43)	Boating and Fishing

An additional access road for a fishing pier and boat launch areas is provided from Tollgate Road near the upper portion of the lake. Facilities providing access for fishing and boating activities are listed in Table 2.3. Shoreline access is also available for fishermen along much of the lake shore, and the Bucks County Parks Department has plans to complete the bicycle and jogging trail around the entire lake to provide pedestrian access to all areas of the lake.

2.1.4 Lake User Characteristics

Recent data indicates that Bucks County was the fastest growing county in Pennsylvania for the period 1980 to 1988 (Bucks County Planning Commission (1989). In addition, the three municipalities containing the Lake Luxembourg watershed are among the fastest growing in the county. Newtown Township had the greatest percentage population increase in the Central Bucks region, and Lower Makefield and Middletown Townships had the largest increases for the Lower Bucks region for the period 1980 to 1988. Population data for these municipalities is summarized in Table 2.5. Information on Bucks and Philadelphia Counties is also included because Lake Luxembourg and Core Creek Park are used primarily by residents of Central and Lower Bucks County, as well as residents of the northeast section of Philadelphia. Additional demographic information on residents of the Lake Luxembourg watershed is presented in Table 2.6.

Table 2.5 - Population Data

Municipality	1980 Population	1990 Population	2000 Population Projection*	
			Low	High
Lower Makefield Township	17,351	25,083	21,850	36,250
Middletown Township	34,246	43,063	42,650	48,850
Newtown Township	4,527	13,685	11,200	14,300
Bucks County	479,211	541,174	552,206	645,957
Philadelphia County	1,688,210	1,647,020	--	--

*BCPC, 1989.

2.1.5 Impaired Uses

Lake Luxembourg began to experience severe environmental problems almost immediately following its impoundment in 1977. Sedimentation has been a continuing problem in the lake. The conservation pool was intended to contain 100 years worth of sediment, but this sediment volume has already accumulated in the lake. The

Table 2.6 - Additional Demographic Information*

Municipality	Per Capita Income ($/yr)	Minority Population (%)	High School Graduates (%)	College Graduates (%)	Occupation	
					% White Collar	% Blue Collar
Lower Makefield Township	28,853	4.73	90.7	46.7	81.8	18.0
Middletown Township	17,479	3.48	80.5	19.6	61.8	38.1
Newtown Township	23,768	3.83	88.5	37.1	74.1	23.9
Bucks County	18,292	4.98	--	--	56.2	42.5

*BCPC, 1989

reduced flood capacity of Lake Luxembourg may eventually threaten flood control plans for the Neshaminy Creek watershed. The useful life of the lake will also be severely reduced if the sediment loading to Lake Luxembourg is not controlled.

In addition to reducing the lake storage capacity, sedimentation also has adverse effects on recreation. Siltation interferes with fish spawning and can also make it difficult for game fish to locate suitable food. A decrease in water clarity is also one of the factors making a lake less desirable for most recreational activities.

Algal blooms are a continuing problem in Lake Luxembourg. Although they are partially masked by the high turbidity in the lake, the decomposition of algal cells leads to low dissolved oxygen concentrations in the bottom waters of the lake. This reduces available fish habitat and further stresses game fish. Dissolved oxygen concentrations in Lake Luxembourg are very low during the summer months and would increase water treatment costs if the lake were to be used as a water supply reservoir at some future date.

2.2 Watershed Characteristics

The Lake Luxembourg watershed encompasses a total area of 2,512 hectares (6,209 acres) in a rapidly developing area of Buck County, Pennsylvania. The watershed lies within the Triassic Lowland Section of the Piedmont Physiographic Province. The Triassic Lowlands consist predominately of small ridges and valleys underlain by red Triassic sediments. A map of the Lake Luxembourg watershed is presented in Figure 2.4; highway numbers and road names are included to provide reference points.

2.2.1 Topography

The Bucks County area is predominantly an undulating plain characterized by low hills and ridges, and the topography of the Lake Luxembourg watershed is gently to moderately rolling. Elevations range from a maximum of 295 feet above MSL in northern portions of the watershed to a normal pool elevation of 102.5 feet above MSL at the lake surface.

2.2.2 Geology

The area is predominantly underlain by Triassic Age rocks of the Stockton geologic formation. The Stockton formation consists primarily of micaceous red shale and siltstone. The rock types which compose the Stockton formation do not exhibit high permeability, through they do contain fracture zones. The bedrock upon which Core Creek Dam was constructed consists of interbedded conglomerate, arkosic sandstone and shale (Woodward-Clyde Consultants, 1978).

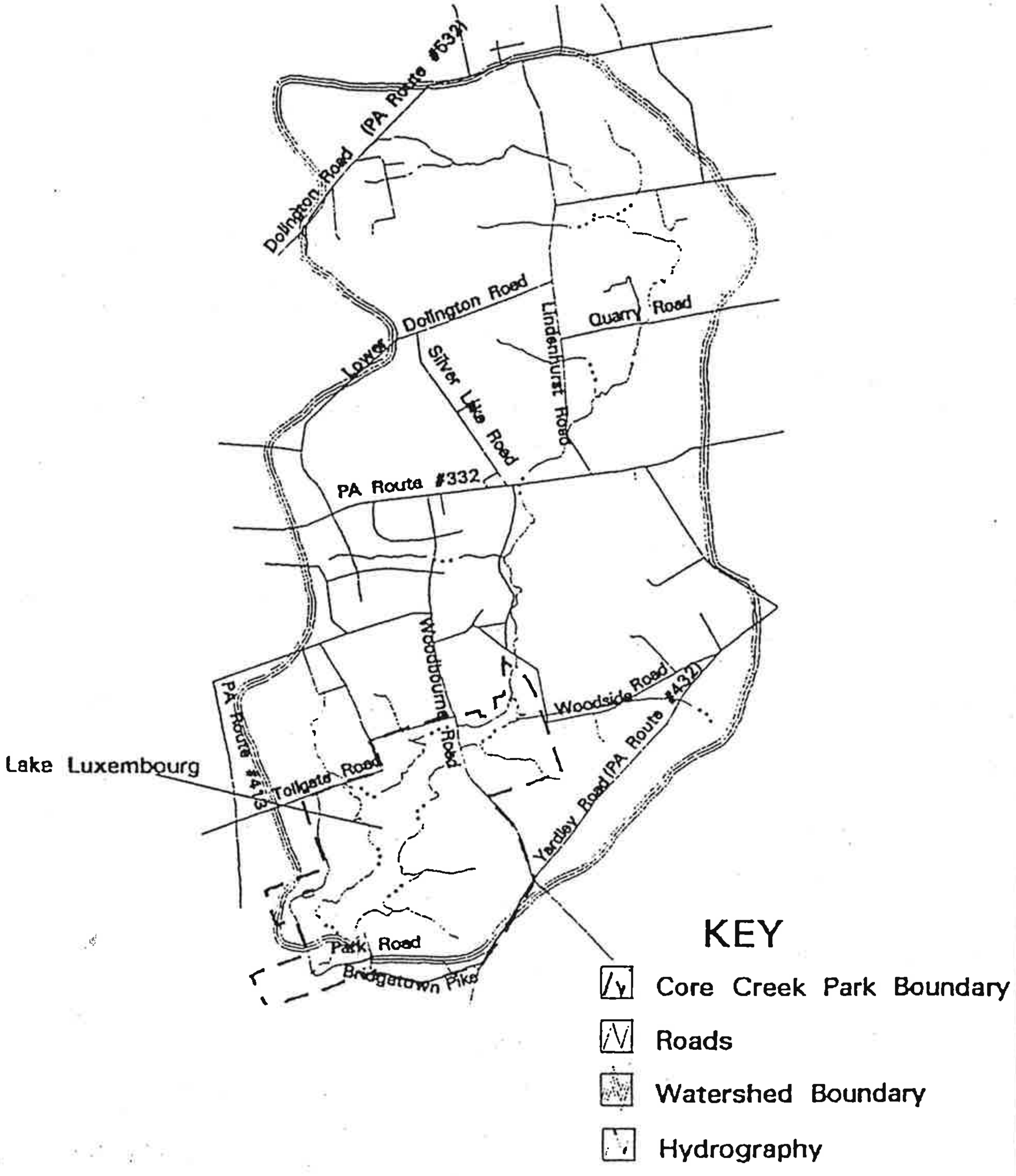


Figure 2.4
Lake Luxembourg Watershed
Scale: 1" = 4500'

COASTAL
ENVIRONMENTAL SERVICES INC

A small area in the northern portion of the watershed is underlain by the Lockatong formation. The Lockatong formation is composed chiefly of argillite, which gives rise to a rather heavy textured soil and generally makes a fair aquifer.

The rocks underlying Bucks County had their origin millions of years ago as layers of deposited sand, gravel, silt and lime materials. These layers were subjected to pressure, cementation and heat for long periods of time, causing the layers to evolve into gneiss, schist, shale, quartzite, sandstone and conglomerate, which would become the parent material for the soils within the County.

2.2.3 Soils

The majority of the Lake Luxembourg watershed is located within the Lansdale-Lawrenceville soil association. A small area of the northern portion of the watershed is within the Abbottstown-Readington-Reaville soil association. The soils of the Lansdale-Lawrenceville association consist of nearly level to sloping, moderately well-drained and well-drained soils on uplands. The soils formed in material weathered from shale and sandstone and in silty windblown deposits. This association consists of about 35 percent Lansdale soils, 15 percent Lawrenceville soils, and 50 percent minor soils.

The Abbottstown-Readington-Reaville soil association consists of nearly level to sloping, moderately deep, to deep, somewhat poorly drained, and moderately well-drained soils on uplands. This soil association is about 18 percent Abbottstown soils, 12 percent Readington soils, 10 percent Reaville soils and 60 percent minor soils. The soils in this association formed in loamy material weathered from shale and sandstone. A description of each of the soil series encountered within the Lake Luxembourg watershed follows:

Abbottstown series

Abbottstown soils are deep, somewhat poorly drained, nearly level to sloping soils, formed in loamy material weathered from red and brown shale and sandstone. The Abbottstown soils are located on the base of slopes, on side slopes and broad ridgetops. Typically, these soils have a dark brown silt loam surface layer with medium acidity. The upper subsoil is a reddish-brown silt loam. The lower subsoil contains portions of reddish-brown silt loam, shaly silt loam, and shaly clay loam. The lower subsoil has pink, yellow, brown, and gray mottles. Runoff from the Abbottstown soils is generally slow, and the erosion hazard is slight to moderate. The soil permeability is typically slow. The water table generally rises to within 6 to 18 inches of the soil surface during wet seasons. The slow permeability and wetness are the principle limitations to most non-agricultural use of the Abbottstown soils.

Bedington series

Bedington soils are deep, well-drained soils formed in loamy material weathered from brown, gray, and yellowish-brown shale. Bedington soils are located on convex sides of ridges and ridgetops. The surface layer of the Bedington soils is a dark yellowish-brown, medium acid, silt loam. The upper portion of the subsoil is a brown silt loam. The middle portion is a strong brown and brown shaly silt loam. The lower subsoil is a dark brown, very shaly silt loam and very shaly loam. The fractured shale bedrock generally occurs at a depth of 70 inches. The Bedington soils have a medium runoff rate and a slight to moderate erosion hazard. In addition, Bedington soils are characterized by a high available water capacity and moderate permeability. Slope and erosion hazard present limitations to most non-agricultural uses of the Bedington soils.

Bowmansville series

Bowmansville soils consist of deep, poorly drained, nearly level soils located on the floodplain. The Bowmansville soils formed in loamy alluvium washed from upland soils underlain by red and brown shale and sandstone. Most areas of these soils are along small meandering streams. The surface layer of the Bowmansville soils are a dark brown, medium acid, silt loam. The upper subsoil is reddish-brown silt loam that has reddish-yellow and pinkish-gray mottles. The lower subsoil is reddish-gray and dark reddish-gray heavy silt loam that has strong brown and pinkish-gray mottles. The upper substratum is a pinkish-gray silt loam that has reddish-yellow mottles. The lower substratum consists of stratified sand and gravel. Bowmansville soils have a slow runoff rate and slight erosion hazard. These soils have a high available water capacity and moderately slow permeability. The Bowmansville soils typically flood annually late in winter and spring. Flooding, restricted permeability, and wetness are limitations to non-agricultural uses of the Bowmansville soils.

Chalfont series

Chalfont soils are deep, somewhat poorly drained soils formed in a silty windblown mantle that overlies loamy material weathered from red and brown shale and sandstone. The Chalfont soils are located on concave positions of the landscape. The surface layer of the Chalfont soils are medium acid, brown silt loam. The upper subsoil is a brown silt loam and silty clay loam that has light brownish-gray and strong brown mottles. The middle portion of the subsoil is compact, firm and brittle with dark yellowish-brown and grayish-brown silt loam with many mottles. The lower subsoil is firm and brittle, dark brown and brown, mottled shaly loam. The firmness and brittleness within the lower and middle subsoil is due to the presence of a fragipan within these soil horizons. The substratum of the Chalfont soils is a brown shaly silt loam with many brown and strong brown mottles. These soils possess a slow to medium runoff rate and a slight to moderate erosion hazard. In addition, these soils have a moderate available water capacity and slow permeability. The Chalfont soils possess a seasonal high water within 6 to 18 inches of the surface during wet seasons.

Doylestown series

Doylestown soils are deep, poorly drained soils formed in silty material, predominantly windblown deposits that overlie a variety of loamy materials weathered from shale and sandstone. Typically, these soils are located on broad flats, in depressions, and at the base of slopes. The surface layer of the Doylestown soils are a dark grayish-brown, medium acid, silt loam. The upper subsoil is a grayish-brown silty clay loam with brownish-gray and strong brown mottles. A fragipan layer in this portion of the soil makes the soil firm with prismatic structure. The lower subsoil is also firm, dense, and brittle due to the presence of a fragipan. The lower subsoil is strong brown, dark brown, and brown silty clay loam and silt loam with prismatic and platy structure with many light brownish-gray and strong brown mottles. Fractured shale bedrock generally occurs at a depth of 53 or more inches. Doylestown soils have a slight to moderate erosion hazard. The surface layer is ponded at times, and the water table is at or near the surface during wet seasons. Limitations to non-agricultural uses of the Doylestown soils include restricted permeability and wetness.

Duncannon series

Duncannon soils are deep, well-drained soils formed in silty wind deposited sediment that overlies shale, sandstone and occasionally other materials. These soils are located on upper elevations in areas of low relief. The surface layer is a strongly acidic, brown silt loam. The upper subsoil is a yellowish-brown silt loam, the lower portion is a dark brown silt loam. The substratum is a dark brown and dark reddish-brown shaly silt loam. Duncannon soils have a medium runoff rate with a moderate to high erosion rate. The hazard to erosion presents a limitation to most non-agricultural uses of this soil.

Lansdale series

Lansdale soils consist of deep, well-drained, nearly level to very steep soils formed in loamy material weathered primarily from brown and yellowish-brown shale and sandstone. The surface layer of the Lansdale soils is a medium acid, dark brown loam. The upper subsoil is strong brown loam, the middle portion is a brown loam, and the lower portion is a brown, fine sandy loam. The substratum is brown and yellowish-brown channery fine, sandy loam and channery loamy sand. The runoff rate is medium to rapid and the erosion hazard is slight to high. The available water capacity is moderate and permeability is moderately rapid. Slope and stoniness can be limitations to non-agricultural uses of these soils. Included within those areas of Lansdale soils within the watershed are areas of Lansdale extremely stony loam. This soil is similar to the other Lansdale soils, however, the surface layer is thin and the subsoil is thinner and contains more coarse fragments. In addition, about 5 to 25 percent of the surface is covered by stones of mainly sandstone and some conglomerate.

Lawrenceville series

The Lawrenceville soils consist of deep, moderately well-drained soils formed in silty, windblown deposits underlain by a variety of material weathered chiefly from shale and sandstone. The Lawrenceville soils are located on middle and lower elevations in low relief areas. The surface layer of the Lawrenceville soils is a neutral dark brown silt loam. The upper subsoil is a yellowish-brown silt loam, the lower portion contain a fragipan and is a compact, very firm, yellowish-brown and strong brown silt loam that has light brownish-gray and strong brown mottles. The lower subsoil is a brown sandy loam. The runoff rate of these soils is medium and the erosion hazard is slight to high. The water table of the Lawrenceville soils usually rises to within 18 to 36 inches of the surface during wet seasons.

Penn series

The Penn soils consist of moderately deep, well-drained soils formed in loamy material weathered from red shale and sandstone. These soils are located on sides and tops of hills and ridges. The surface layer of the Penn soils is a dark medium acid, reddish-brown silt loam. The upper subsoil is a reddish-brown silt loam, the lower portion is a dark reddish-brown and reddish-brown shaly silt loam. Generally, at a depth of 35 inches, weak red, fractured shale bedrock is encountered. The Penn soils have a medium to rapid runoff rate and a moderate to high erosion rate. Depth to bedrock and slope present limitations to most non-agricultural uses of these soils.

Penn-Lansdale Complex

This complex consists of about 55 percent Penn silt loam and Penn shaly silt loam, 40 percent Lansdale loam, and 5 percent included soils. The Penn and Lansdale soils within the complex have been described previously. These soils are located on upper sides of hills and ridges. Areas of these soils are mapped as a complex because the two soils are so interspersed it was not practical to separate them.

Readington series

Readington soils consist of deep, moderately well-drained soils formed in loamy material weathered from shale, siltstone and sandstone. The Readington soils are located on all slope positions, even broad ridgetops. The surface layer is typically a slightly acid dark brown silt loam. The upper subsoil is a reddish-brown heavy silt loam. The lower subsoil contains a fragipan. The soil within the portion of the profile is a firm, brittle, reddish-brown silty clay loam with white, pinkish-white, and pale red mottles. The substratum is reddish-brown, very shaly clay loam. Fractured, dusky-red shale bedrock is at a depth of approximately 60 inches. Readington soils have a slow to medium runoff rate with a slight to moderate erosion hazard. The permeability of these soils is moderately slow. The water table generally rises to within 18 to 36 inches of the soil surface during wet seasons. Limitations to non-agricultural uses of the Readington soils are restricted permeability and wetness.

Reaville series

The Reaville soils consist of moderately deep, moderately well-drained to somewhat poorly drained soils formed in loamy materials weathered from red and brown shale. These soils are located on broad ridgetops and side slopes. The surface layer of the Reaville soils is a dark strongly acidic, reddish-brown shaly silt loam. The subsoil is a reddish-brown shaly and very shaly silt loam with pink and pinkish-white mottles in the lower portion. The substratum is mottled, reddish-brown very shaly silt loam. Red fractured shale bedrock occurs at a depth of approximately 26 inches.

Reaville soils have a slow to medium runoff rate, a slow permeability and slight to moderate erosion hazard. The water table rises to within 12 to 24 inches of the surface during wet seasons. The depth to bedrock, slow permeability and wetness are limitations to most non-agricultural uses of these soils.

Steinsburg series

Steinsburg soils consist of moderately deep, well-drained soils formed in loamy material weathered chiefly from sandstone and conglomerate. Steinsburg soils are located on slopes and tops of hills. The surface layer of the Steinsburg soils is a strongly acid, a brown gravelly loam. The subsoil, is a brown sandy loam. The substratum is a yellowish-red gravelly sandy loam. Brownish-yellow sandstone conglomerate bedrock at approximately 30 inches. Steinsburg soils have a medium runoff rate and moderate to high erosion rate. Depth to bedrock and slope present limitations to non-agricultural uses of these soils.

Urbanland-Lansdale Complex

This mapping unit consists of an intricate pattern of Urbanland and Lansdale soils that is impractical to separate for mapping purposes. This complex is 60 percent Urbanland, 35 percent Lansdale soils, and 5 percent included soils. This complex is semi-built-up areas that are mainly underlain by sandstone bedrock. The Urbanland is present in highly developed areas of the County. Most Urbanland is on terraces of the uplands and Coastal Plain; however, some occurs on the flood plain. Urban structures and works cover so much of this land type that identification of the soils is not practical. Most areas of Urbanland have been graded, and the original soil material has been disturbed, filled over or otherwise destroyed prior to construction. The Lansdale component of this complex is similar to the one described previously.

This complex is characterized by good drainage and is nearly level to slightly sloping. The complex is only slightly limited for non-agricultural use.

2.2.4 Groundwater

Groundwater is that part of the total water resource that is currently stored in, and moving through, the interstices between the solid materials that constitute the earth's crust. Most areas in Bucks County currently rely at least partially on groundwater obtained from wells for water supply (BCPC, 1985).

Water supply users in the Lake Luxembourg watershed use both the Stockton sandstone and Lockatong argillite for water supply wells. Average yields from these formations are 500,000 to 600,000 gallons/day/square mile and 300,000 to 400,000 gallons/day/square mile, respectively (BCPC, 1985). Available yields vary considerably.

The Stockton formation is the best bedrock source of groundwater in the area because it is coarse grained, weakly cemented, and fragmented. Water from this formation is moderately hard and mineralized. Some areas of this aquifer, including some in the Newtown area, are under artesian pressure. The fine grained rocks of the Lockatong formation have a low capacity to store and transmit water. Water from this aquifer is hard and frequently has excess mineralization. Typical well depths are 400 feet in the Stockton formation and 200 feet in the Lockatong formation (Martin, 1975).

2.2.5 Land Use

Many areas in the Lake Luxembourg watershed are undergoing a transition from agricultural land to residential developments. Current land use was initially evaluated using a Geographic Information System (GIS) and 1990 aerial photographs of the watershed obtained from the Bucks County Planning Commission. Aerial photographic interpretation and field reconnaissance was used to identify different land uses, and the GIS was used to calculate the land area associated with each use. These aerial photographs were not rectified, which may introduce some error in the calculated land use areas. Additional information supplied by the USDA, Soil Conservation Service, the ASCS and the BCCD was used to identify current conditions and to update information from the aerial photographs.

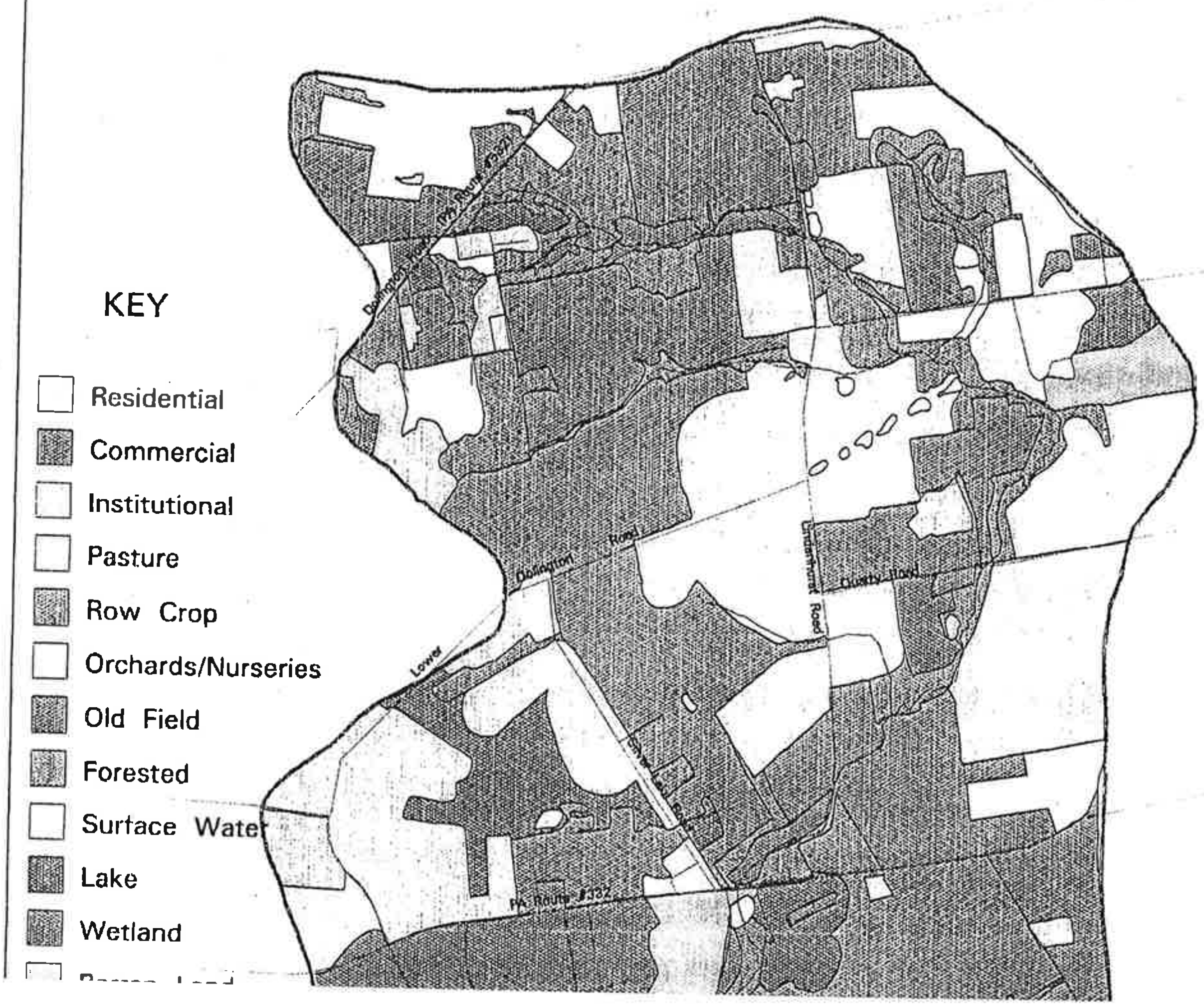
Information on land use in the watershed is summarized in Table 2.7. Approximately 60 percent of the land in the Lake Luxembourg watershed is farmland and includes most of the land use categories in Table 2.7, with the exception of residential, commercial and park land. A land use map for the Lake Luxembourg watershed is provided in Figure 2.5.

Table 2.7 - Land Use in the Lake Luxembourg Watershed

Land Use Category	Area*		Area (% of Total)
	Hectares	Acres	
Residential	726.3	1,794	28.9
Commercial	184.4	455	7.3
Park Land	60.0	148	2.4
Row Crop	817.1	2,019	32.5
Pasture/Grass	83.4	206	3.3
Nurseries	124.0	306	4.9
Old Field	127.8	316	5.1
Forested	257.1	635	10.2
Barren	14.3	35	0.6
Wetland	41.4	102	1.6
Open Water	6.9	17	0.3
Lake Surface	70.2	173	2.8
Total	**2,512.6**	**6,206**	**100.0**

*Totals do not agree with areas listed in Table 2.1 as a result of roundoff errors and the use of conversion factors.

Figure 2.6. Lake Luxembourg Watershed Land Use Map



3.0 Limnological Survey

A comprehensive limnological survey of Lake Luxembourg was conducted by Coastal with the assistance of the Bucks County Conservation District and the Bucks County Parks Department. Lake, stream and sediment samples were collected from June 1991 through June 1992 at the locations shown in Figure 3.1.

3.1 Monitoring Program

3.1.1 Lake Monitoring Program

Lake water quality samples were collected from one location in the deepest part of the lake near the dam (Station 1) and at a second location in the upper part of the lake (Station 2). Samples were collected bimonthly from June to August 1991 and in May 1992. Samples were collected monthly from September 1991 to April 1992. The December and January samples were collected from fishing piers near the main sampling locations because the lake was partially frozen. The lake sampling program also included a macrophyte survey on 5 August 1991 and the collection of sediment cores on 4 March 1992. Complete results from the lake sampling program are included in Appendix A.

Secchi depth measurements and profiles of temperature, dissolved oxygen concentration, pH and conductivity were made in the field on each sampling date. Additional Secchi depth measurements were made by Mr. Charles Pfanstiel of the Bucks County Parks Department from June to September 1991 from a fishing pier near the boat ramp (Figure 3.1). Samples for chlorophyll *a* analyses were collected on each sampling date, filtered in the field, placed on ice, and shipped frozen to Dr. Gregory Boyer at the State University of New York College of Environmental Science and Forestry for analysis. Lake water samples were collected from the surface, middle and bottom of the water column (0, 4 and 8 m at Station 1 and 0, 2 and 4 m at Station 2) and were delivered to the QC Inc. laboratory in Southhampton, Pennsylvania for the analysis of total phosphorus (TP), soluble orthophosphate, total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate+nitrite-nitrogen (NO_3^-+NO_2^--N), alkalinity and total suspended solids (TSS).

Phytoplankton were collected at both lake stations on each sampling date. Composite samples from the photic zone were collected and preserved with Lugol's solution. Zooplankton samples were collected in June, September and December 1991 and March and May 1992 by making vertical tows through the water column at Station 1. Zooplankton samples were preserved in a sucrose-formaldehyde solution (Prepas, 1978). Phytoplankton and zooplankton samples were sent to Dr. Kenneth Wagner of Wilbraham, Massachusetts, for identification and enumeration.

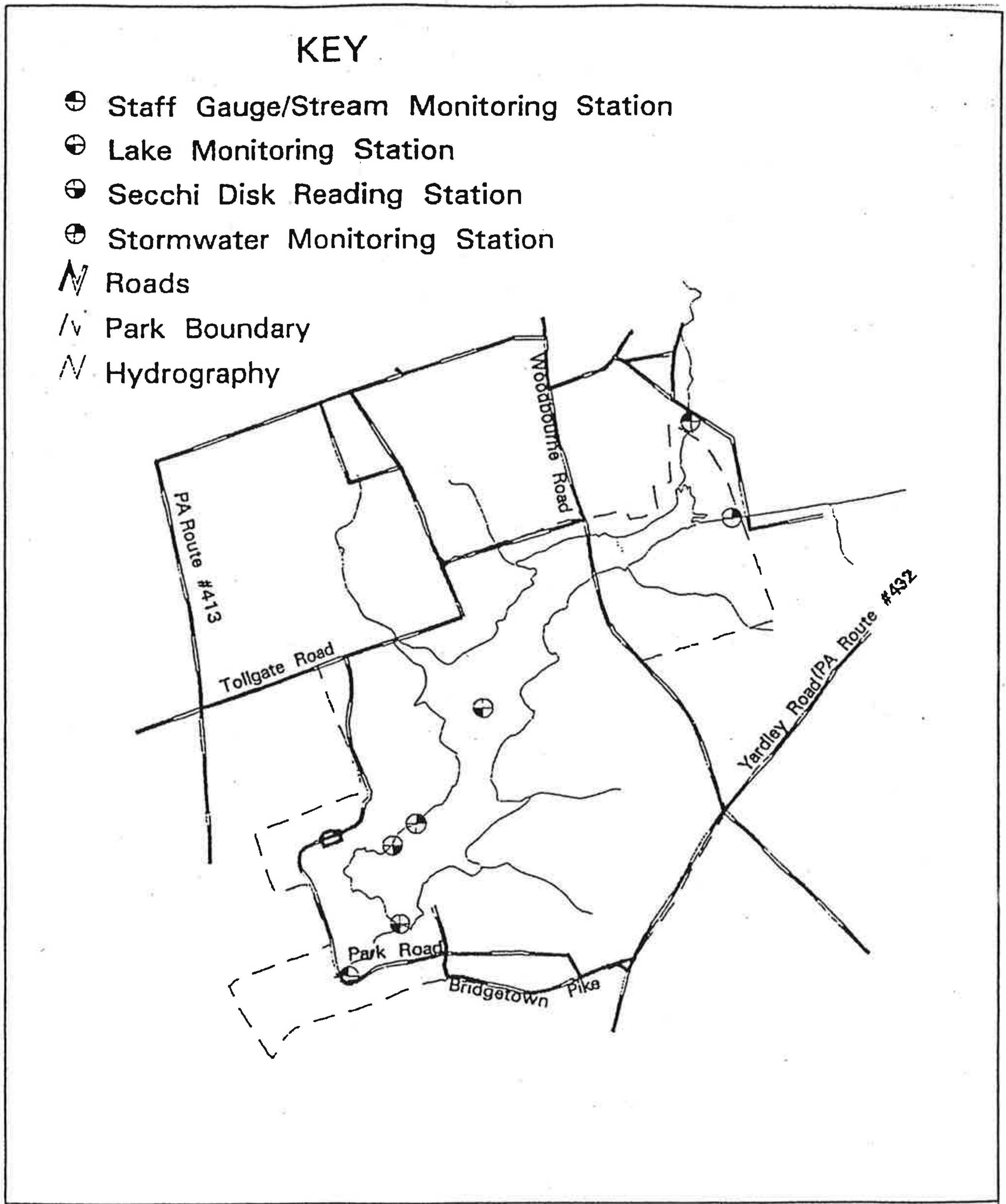


Figure 3.1
Sampling Station Locations
Approximate Scale: 1″ = 2400′

COASTAL
ENVIRONMENTAL SERVICES INC

3.1.2 Watershed Monitoring Program

Stream flow measurements and stream water quality analyses were included as part of the sampling program. Coastal erected staff gages at the lake outlet and at the major inlet on Core Creek in June 1991 and calibrated the gages through periodic stream flow measurements. Mr. Michael Brandt of the Bucks County Conservation District read staff gages on a regular basis and also collected storm event and well water samples.

Stream samples were collected at irregular intervals and analyzed from the major inlet to Lake Luxembourg on Core Creek and at the lake outlet (Figure 3.1) from June 1991 through June 1992. Stream samples were collected under normal flow conditions on five sampling dates and during two storm events. Additional sampling locations for the storm events included a storm sewer in Core Creek Park near the boat ramp and a storm sewer draining agricultural land to the northeast of the park. All stream samples were analyzed for total phosphorus, total nitrogen (total Kjeldahl nitrogen and nitrate+nitrite-N) and total suspended solids.

Samples from two area wells were collected on 19 March 1992. Well samples were analyzed for total phosphorus and total nitrogen. Watershed monitoring results are included in Appendix B.

3.2 Chemical and Physical Characteristics of Lake Luxembourg

Water quality in a lake is determined by a complex interaction of a number of chemical, physical, and biological factors. The amounts of nutrients (phosphorus and nitrogen) and sediments delivered to a lake through runoff are major factors affecting lake water quality, while variations in ambient temperature and sunlight are also important. Some of the key water quality characteristics of Lake Luxembourg are discussed in the following sections. Summary water quality data for Stations 1 and 2 are presented in Tables 3.1 and 3.2, respectively. Analytical results from the watershed monitoring program are included in Table 3.3.

3.2.1 Temperature and Dissolved Oxygen

Temperature affects a number of physical, chemical, and biological processes in natural waters. The temperature regime of a lake is a function of ambient air temperatures, and the morphometry and setting of the lake. One of the most biologically important temperature effects is the decrease in oxygen solubility with increasing temperature. Temperature is controlled primarily by climatic conditions, but human activity can also have an influence.

The dissolved oxygen (DO) concentration of a lake is an important indicator of the "health" of a lake. A great amount of information can be obtained solely through the analysis of this parameter. Dissolved oxygen concentrations are related to the photosynthetic activity of algae and weeds and, therefore, provide insight into lake productivity. Dissolved oxygen gradients provide an indication of mixing patterns and

Table 3.1 - Summary Water Quality Data for Station 1

Date	Ortho P mg/L	Total P mg/L	NH3-N mg/L	NO2+NO3-N mg/L	TKN mg/L	Alk mgCaCO3/L	TSS mg/L	Chl. a µg/L	SD m
05Jun91	0.02	0.03	0.1	1.35	2.2	46	21	56.8	0.35
20Jun91	< 0.01	0.06	1.0	0.80	3.3	59	18	--	0.45
10Jul91	0.02	0.05	1.5	0.13	3.9	50	29	77.9	0.25
25Jul91	0.01	0.23	1.3	0.07	2.8	47	36	45.0	0.50
05Aug91	0.07	0.40	1.9	0.12	4.7	56	19	42.3	0.40
23Aug91	0.02	0.32	0.4	0.27	3.7	14	75	72.5	0.20
18Sep91	0.01	0.20	0.1	0.32	4.2	33	24	81.4	0.25
31Oct91	0.02	0.57	0.1	0.62	3.1	34	0	46.2	0.15
21Nov91	0.04	0.47	0.1	0.78	3.3	47	10	43.5	0.20
19Dec91	0.03	0.14	0.2	1.29	1.2	43	18	42.8	--
31Jan92	0.02	0.11	0.2	2.02	1.3	71	15	35.5	--
20Feb92	0.01	0.11	0.1	2.11	1.1	40	10	28.6	0.20
05Mar92	0.02	0.09	0.2	2.23	1.1	44	12	17.1	0.60
20Apr92	0.05	0.11	0.1	1.74	1.2	48	16	34.4	0.50
04May92	< 0.01	0.18	< 0.1	1.45	1.1	48	18	52.8	0.40
19May92	< 0.01	0.13	0.6	0.83	1.0	70	16	83.0	0.35
Mean	0.02	0.20	0.5	1.01	2.4	47	21	50.7	0.34

Table 3.2 - Summary Water Quality Data for Station 2

Date	Ortho P mg/L	Total P mg/L	NH3-N mg/L	NO2+NO3-N mg/L	TKN mg/L	Alk mgCaCO3/L	TSS mg/L	Chl. a µg/L	SD m
05Jun91	0.02	0.07	0.2	1.95	2.7	28	25	41.8	0.30
20Jun91	< 0.01	0.05	0.3	0.88	2.9	43	27	49.6	0.60
10Jul91	0.01	0.10	0.5	0.11	2.8	41	33	91.6	0.30
25Jul91	0.01	0.17	0.4	0.07	1.9	41	24	55.2	0.55
05Aug91	0.01	0.18	0.2	0.13	2.9	38	22	51.1	0.50
23Aug91	0.02	0.20	0.2	0.17	3.0	18	45	71.4	0.25
18Sep91	0.01	0.09	0.2	0.32	2.6	22	28	89.3	0.30
31Oct91	0.02	0.05	0.1	0.70	1.5	39	0	46.2	0.15
21Nov91	0.03	0.16	0.1	0.84	2.6	42	13	44.8	0.20
19Dec91	0.05	0.10	0.1	1.45	0.7	42	21	46.9	--
31Jan92	0.02	0.11	0.1	2.02	1.4	53	60	38.8	--
20Feb92	0.01	0.16	0.1	2.13	1.3	46	65	21.2	0.20
05Mar92	0.01	0.11	0.2	2.38	1.0	41	9	16.6	0.60
20Apr92	0.05	0.11	0.1	1.86	0.9	49	17	36.8	0.50
04May92	< 0.01	0.17	< 0.1	1.48	1.3	45	22	63.2	0.40
19May92	0.01	0.14	0.1	0.83	0.9	54	17	50.4	0.35
Mean	0.02	0.12	0.2	1.08	1.9	40	27	50.9	0.37

Table 3.3 - Summary of Watershed Sampling Results

Location	Date	Total P mg/L	NO2 + NO3-N mg/L	TKN mg/L	TSS mg/L
Routine Samples					
Lake Inlet	20Jun91	0.08	6.3	2.4	30
	10Jul91	0.70	8.5	4.5	22
	17Oct91	0.20	0.7	1.6	34
	20Feb92	0.07	6.0	1.7	8
	19May92	0.31	5.1	1.2	71
Park Drain Tile	19May92	0.08	8.6	1.3	27
	Mean	0.24	5.9	2.1	34
Lake Outlet	20Jun91	0.07	1.0	2.7	18
	10Jul91	0.50	0.5	3.0	14
	17Oct91	0.20	0.6	2.0	16
	20Feb92	0.09	2.1	1.4	10
	19May92	0.17	0.7	0.9	14
	Mean	0.21	1.0	2.0	14
Well 1	19Mar92	0.02	30.0	0.3	--
Well 3	19Mar92	0.04	5.5	7.1	--
Storm Samples					
Lake Inlet	05Jun92	1.70	1.4	2.0	2000
	29Mar92	0.06	3.4	1.1	35
Park SS	29Mar92	0.15	< 0.05	0.9	4
Ag Drain	29Mar92	0.97	0.6	3.2	630
	Mean	0.72	1.3	1.8	667
Rain	29Mar92	0.41	< 0.05	1.0	43
Lake Outlet	05Jun92	0.18	0.0	0.9	25
	29Mar92	0.07	2.2	1.3	14
	Mean	0.13	1.1	1.1	20

the effectiveness of mixing processes in a lake. Dissolved oxygen concentrations also have an important bearing on the physical-chemical properties of lakes and the composition of a lake's biota.

The amount of oxygen which can dissolve in water is subject to fluctuations caused in part by variations in temperature, photosynthetic activity, and stream flow. Respiratory processes, oxidation of inorganic wastes, and the decomposition of organic matter deplete oxygen, while photosynthesis and re-aeration by contact with the atmosphere increase oxygen concentrations in water. Dissolved oxygen concentrations are of concern because oxygen is essential for the survival of fish and many other aquatic organisms. Most desirable aquatic organisms require a dissolved oxygen concentration of 4.0 mg/L or greater for long-term survival.

Typical temperature and dissolved oxygen profiles for Lake Luxembourg are shown in Figure 3.2. Temperatures in Lake Luxembourg followed expected seasonal variations, with the highest temperatures of 28.36 °C at Station 1 and 28.83 °C at Station 2 observed on 25 July 1991. Minimum temperatures of 2.09 °C at Station 1 and 2.75 °C at Station 2 were observed on 19 December 1991. Strong thermal stratification was evident throughout the summer months at Station 1, with typical temperatures differences between surface and bottom waters of about 10 °C. Thermal stratification was not as pronounced at Station 2, where the maximum depth was only about 4.2 m (14 ft). Typical temperature differences between surface and bottom waters at Station 2 were 2 to 3 °C, with a maximum difference of 5.4 °C observed on 25 July 1991.

Severe oxygen depletion occurred in the bottom waters of Lake Luxembourg throughout the summer stratification period. Dissolved oxygen concentrations were less than 1 mg/L at all depths below 4 m at Station 1 from June through September. The water column remained oxygenated from the time the lake mixed in October 1991 through April 1992. Dissolved oxygen concentrations were less than 1 mg/L at depths of 7 and 8 m on 4 May 1992, and at all depths below 4 m by 19 May 1992. Oxygen depletion was not as severe at the shallower Station 2; however, dissolved oxygen concentrations of less than 1 mg/L were observed at the 4 m depth in June, July and August 1991. The dissolved oxygen concentrations observed in the bottom waters of Lake Luxembourg during the summer months are low enough to adversely impact fish and other aquatic organisms.

3.2.2 pH

The hydrogen ion activity in water provides an indication of the balance between acids and bases in solution. Hydrogen ion activity in water is usually reported as its negative logarithm, or pH. The pH of a water is an important general water quality indicator because pH is a major factor affecting most chemical and biological reactions. Accepted water quality criteria (U.S. EPA, 1976) indicate a pH of less than 6.5 units may be harmful to many species of fish. The pH observed in water is determined by a number of complex interactions and provides an overall measure of the intensity of the various acid/base interactions which are occurring.

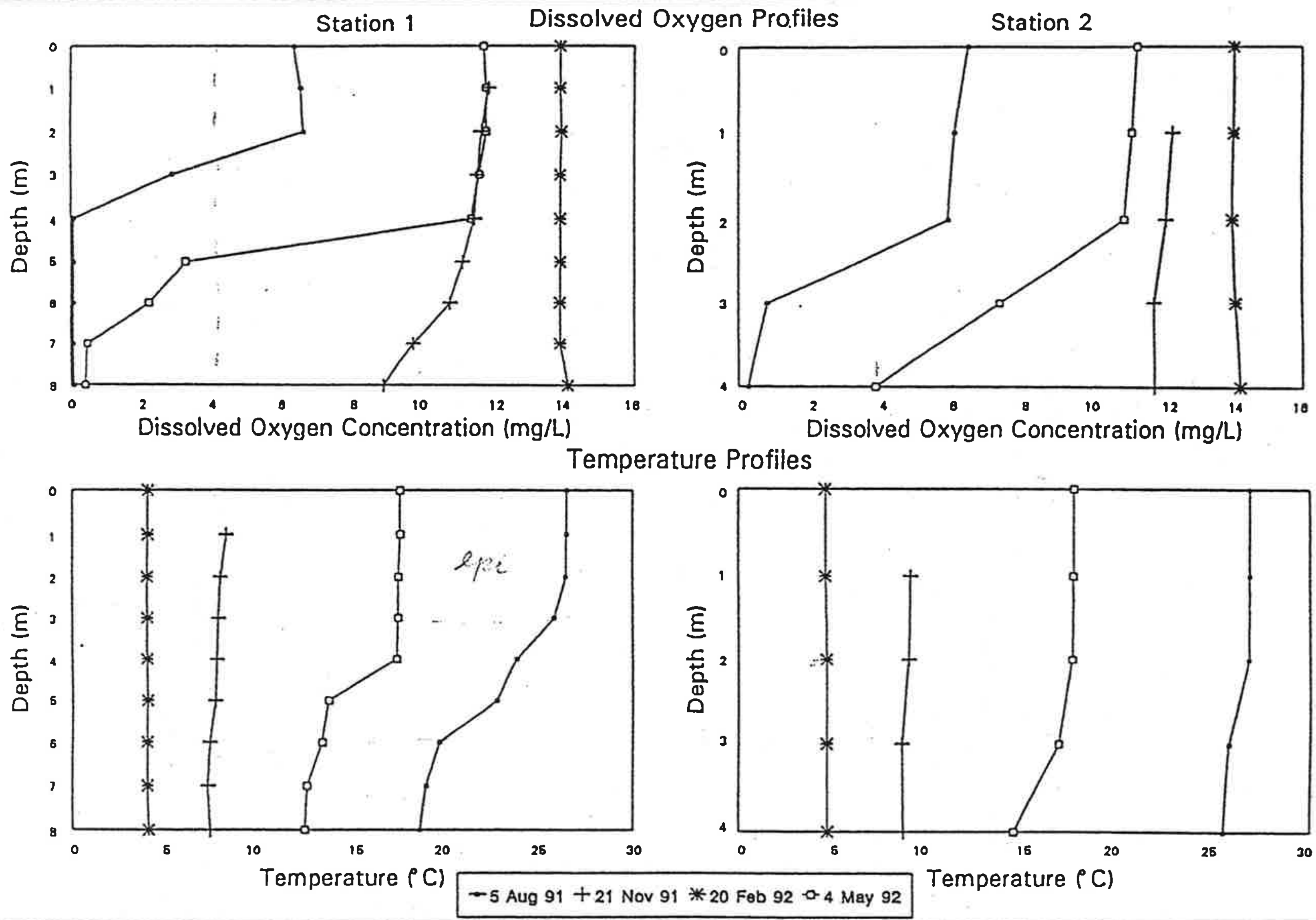


Figure 3.2. Seasonal temperature and dissolved oxygen profiles for Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

The pH scale ranges from 1 to 14 standard units. A pH of 7 indicates neutral conditions, while waters with a pH less than 7 are acidic and those with pH values greater than 7 are basic. Since pH is expressed on a logarithmic scale, each 1 unit change in pH represents ten-fold increase or decrease in hydrogen ion concentration. Therefore, a pH of 6 would be 10 times more acidic than a pH of 7 and 100 times more acidic than a pH of 8. The pH of normal rainwater (containing no pollutants) is about 5.6, and the average pH in most areas of Pennsylvania is about 4.5. As the rainwater travels over and through rocks and soil, chemical reactions with minerals affect the pH and buffering capacity of the water.

The pH levels in Lake Luxembourg reflected the high productivity of the lake. Typical pH profiles are shown in Figure 3.3. The pH levels in Lake Luxembourg were usually between 7 and 8 when the lake was mixed, with extreme levels observed during the summer stratification period. The pH in the surface water was elevated during the summer months, when high algal productivity results in the removal of free carbon dioxide, a weak acid, from the lake water. The maximum surface pH of 9.29 at Station 1 and 9.24 at Station 2 was observed on 10 July 1991, and many other readings above 8.5 were also observed during the summer months.

Low pH values are frequently encountered in the hypolimnion, the unmixed bottom layer of water, of a lake during the summer stratification period. Anaerobic decomposition processes result in the production of carbon dioxide and weak organic acids during this period. The minimum pH levels observed were 6.38 at Station 1 on 5 August 1991 and 6.68 at Station 2 on 20 June 1991. The pH was usually less than 7 in the hypolimnion during the stratification period.

3.2.3 Conductivity

Conductivity is a measure of the ability of water to conduct an electric current and is dependent on the number of dissolved ions in solution. Conductivity is closely related to, and highly correlated with, the concentration of dissolved solids. Observed conductivities in lake waters vary widely, and are largely a function of geology and soils in the watershed. Conductivity varies significantly with temperature and to a lesser extent with the nature of the individual ions present. Because temperature has a relatively large effect on conductivity, conductivity is typically corrected to 25 °C and reported as specific conductance (μmhos/cm @ 25 °C) to allow direct comparison of samples collected at different temperatures.

Typical conductivity profiles for Lake Luxembourg are shown in Figure 3.3. Average conductivities were 218 and 210 for Stations 1 and 2, respectively. The minimum conductivities at both stations, 121 μmhos/cm at Station 1 and 120 μmhos/cm at Station 2, were observed on 23 August 1991 following a heavy rain; rainwater has a much lower dissolved solids concentration than typical lake or stream water. Conductivity usually increases in the hypolimnion of a lake during the summer months as decomposition processes result in the accumulation of salts. The maximum conductivity of 276 μmhos/cm at Station 1 also occurred on 23 August.

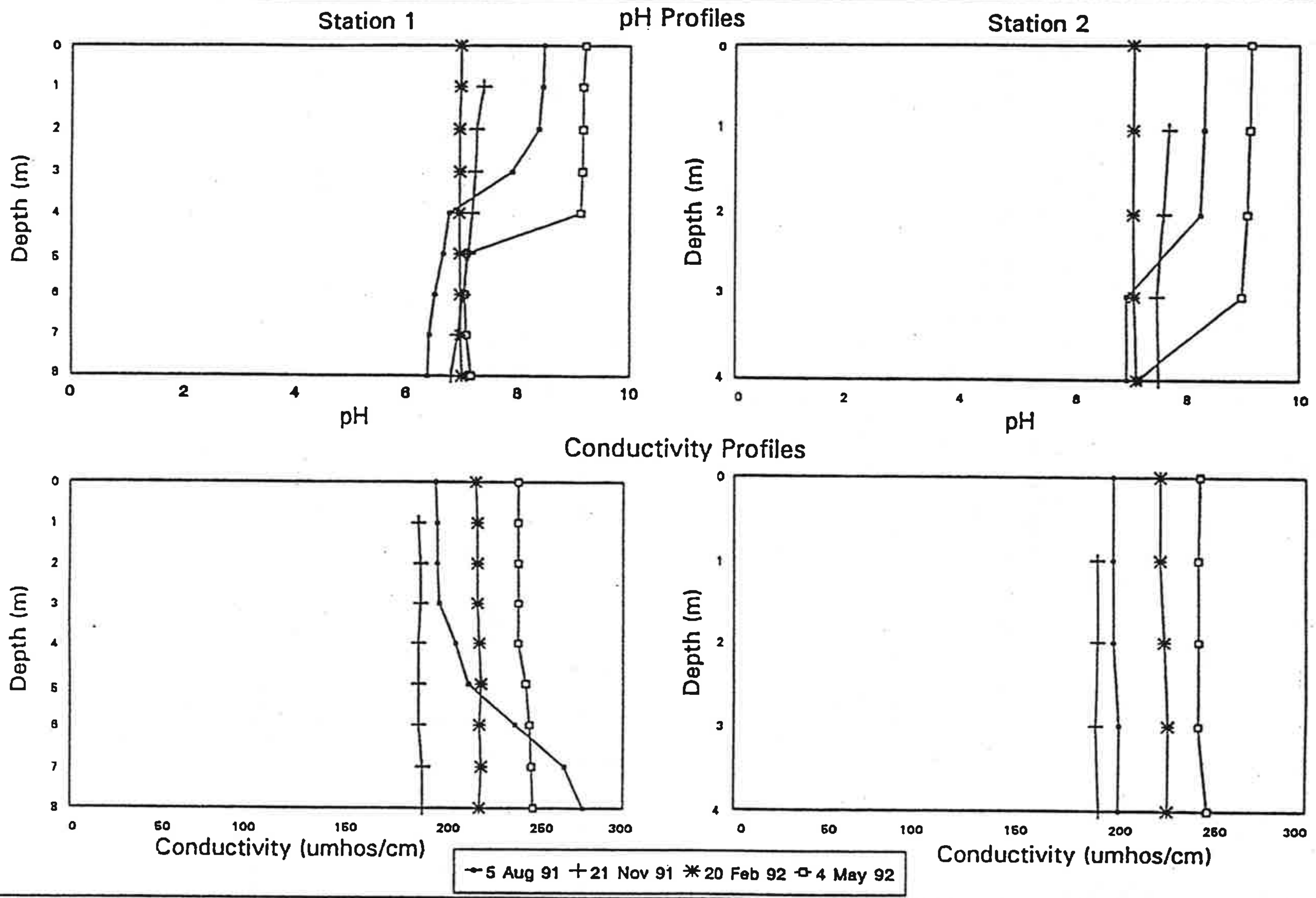


Figure 3.3. Seasonal pH and conductivity profiles for Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC

3.2.4 Alkalinity

Alkalinity is a measure of the capacity of water to neutralize bases. Alkalinity is a capacity factor and is directly related to pH, which is a measure of the overall intensity of acid and base reactions in water. Carbonate minerals are the major source of alkalinity in most waters, with bicarbonate ion representing the major form of alkalinity in natural waters at neutral pH levels. As a result, alkalinity is usually expressed as mg $CaCO_3$/L. The salts of other weak acids, such as borates, silicates and phosphates can be significant is some cases, particularly in more arid regions.

Alkalinity levels in Lake Luxembourg are graphically illustrated in Figure 3.4. The water in Lake Luxembourg appears to be well-buffered and the overall average alkalinity of 43 mg $CaCO_3$/L is typical of surface waters in Bucks County. Fluctuations in alkalinity were relatively minor; however, very low alkalinities were observed on 23 August 1991, when a heavy rainfall prior to sampling caused anomalous results for alkalinity and many other water quality parameters.

3.2.5 Total Suspended Solids

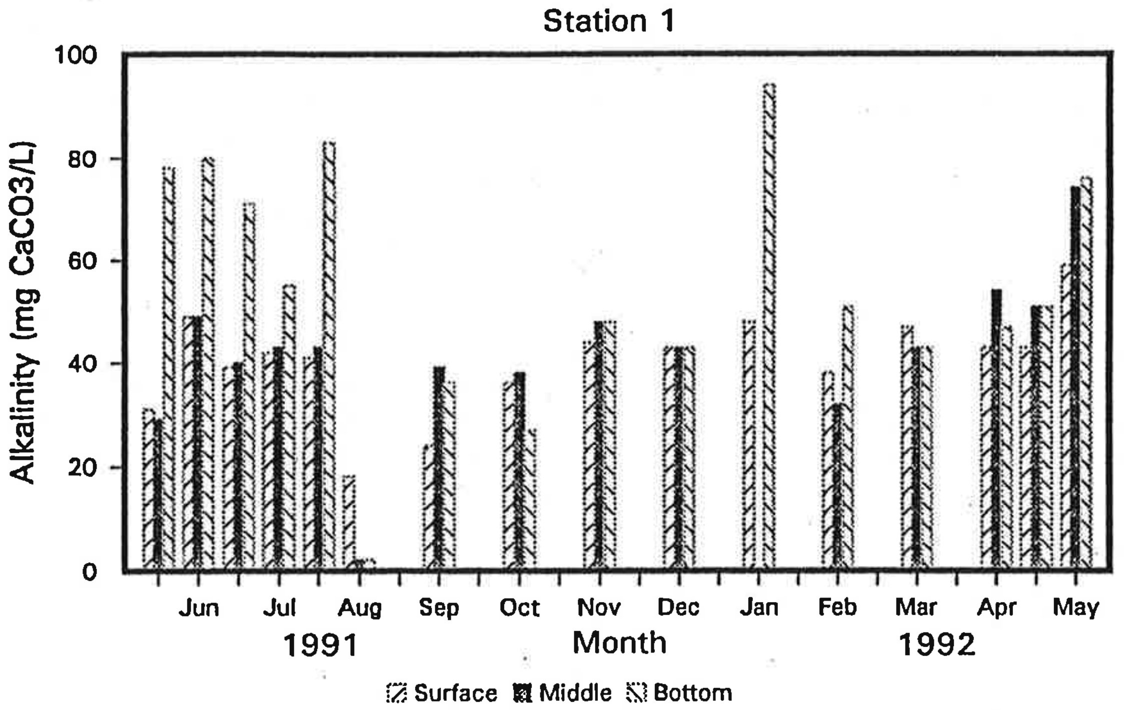
The total suspended solids concentration provides a measure of water clarity and the amount of particulate matter in the water column. Suspended solids include both organic matter, such as algae and other plant material, and inorganic material, including sand, silt, and clay particles.

Concentrations of total suspended solids in Lake Luxembourg are shown in Figure 3.5. Suspended solids levels in Lake Luxembourg were high, with average concentrations of 21 mg/L and 27 mg/L at Stations 1 and 2 (Tables 3.1 and 3.2), respectively. The high suspended solids concentrations can be attributed to a combination of suspended silt and clay particles originating from construction and agricultural activities in the watershed and high algal productivity in the lake itself.

The total suspended solids concentrations in the runoff samples were higher than those in the lake samples. Inlet total suspended solids concentrations averaged 33 mg/L for the routine samples and 667 mg/L for the storm samples, while outlet concentrations averaged 27 mg/L for routine samples and 20 mg/L for storm samples. These high concentrations indicated that there is still a significant amount of erosion in the Lake Luxembourg watershed. Differences between inlet and outlet concentrations demonstrate the effectiveness of the lake as a sediment trap.

3.2.6 Nutrient Concentrations

Phosphorus and nitrogen compounds are major nutrients required for the growth of algae and macrophytes in lakes. The lake monitoring program that was developed for Lake Luxembourg included the analysis of lake samples for both total and dissolved inorganic forms of both nutrients. The dissolved inorganic nutrients, soluble orthophosphorus and nitrate, nitrite and ammonia nitrogen, are regarded as the forms



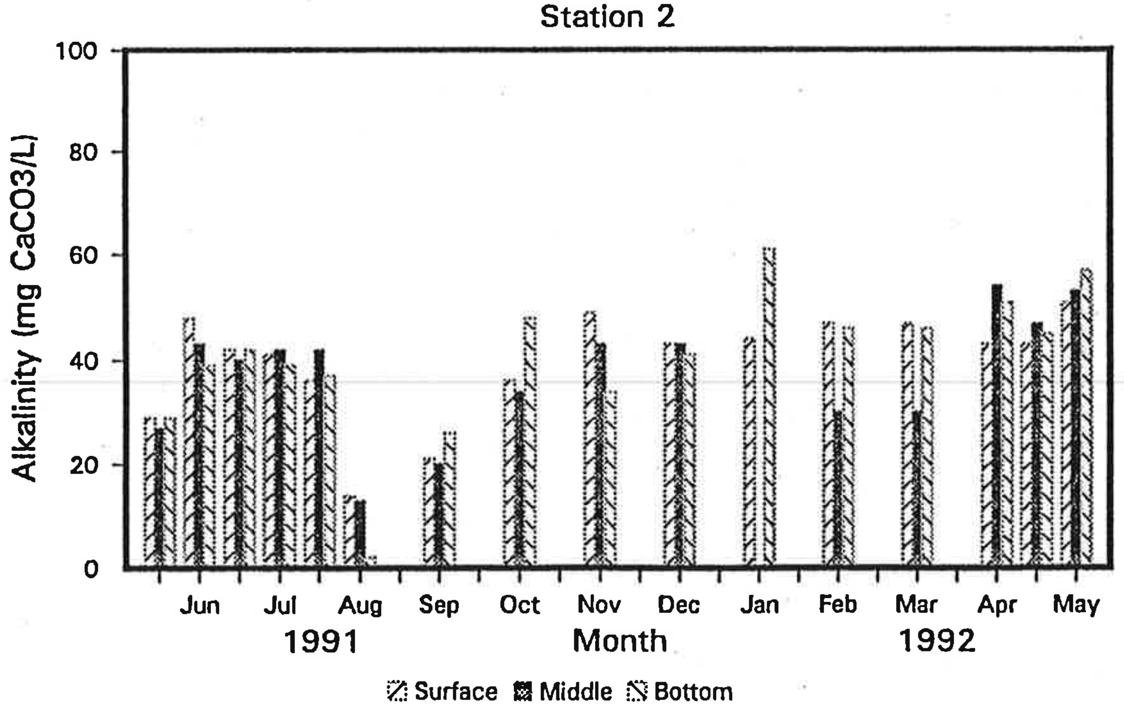
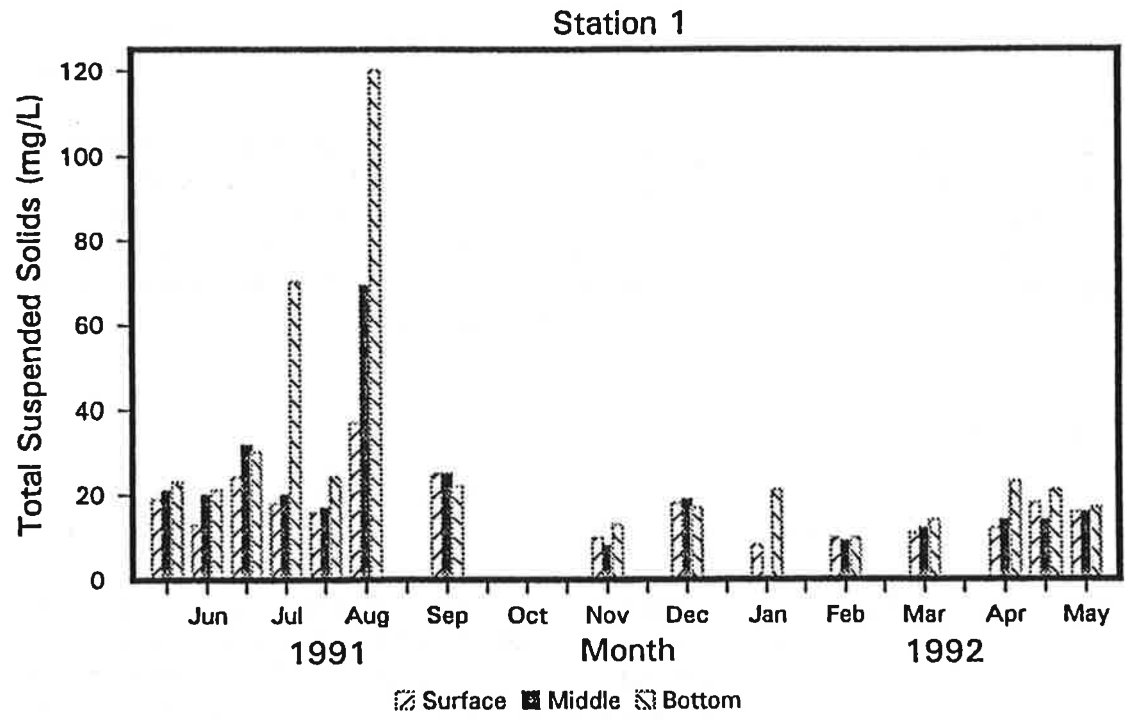


Figure 3.4. Alkalinity levels in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.



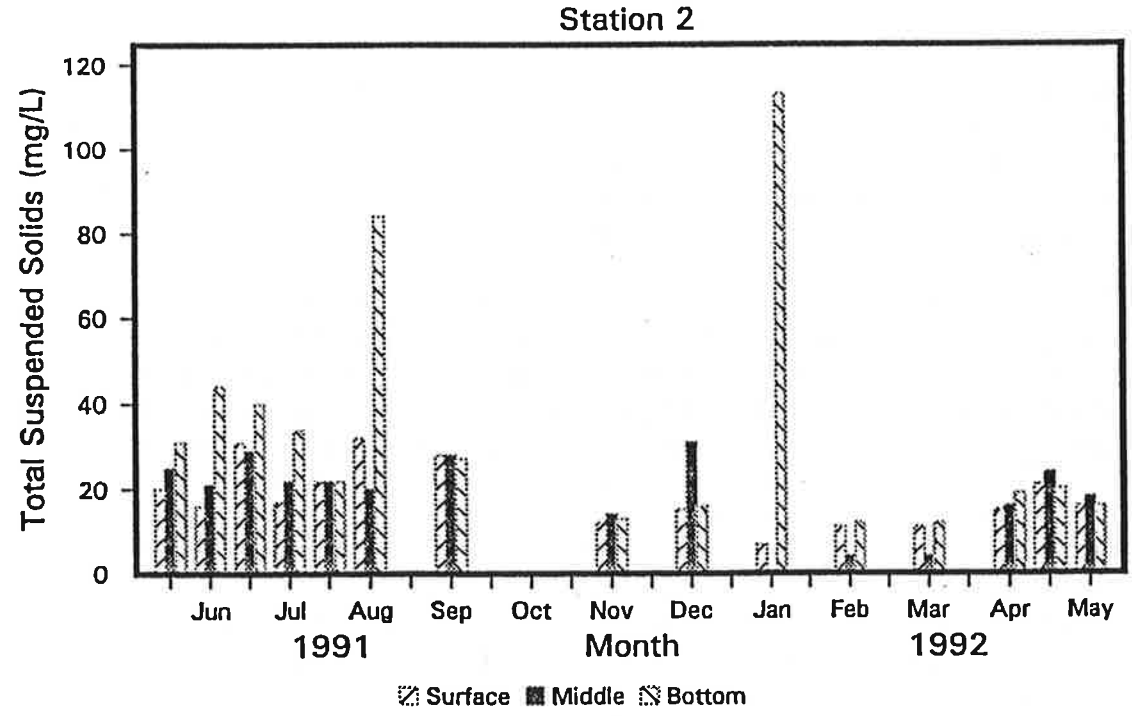


Figure 3.5. Concentrations of total suspended solids in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

readily available to support aquatic growth, while total phosphorus and total nitrogen concentrations provide an indication of the maximum growth which could be achieved.

Some important external sources of phosphorus and nitrogen are fertilizers, septic leachate, sewage effluent, detergents and soaps, particulate material transported by stormwater, and precipitation. Lake sediments, particularly those which are highly organic or mucky, can serve as an internal source of nutrients, especially if the overlying waters become devoid of oxygen. The decomposition of dead algal cells or aquatic weed tissue is another internal source of nutrients.

Phosphorus Concentrations

Phosphorus is an essential nutrient and is often the factor limiting additional growth of aquatic organisms in lakes. Total phosphorus (Total P) represents the sum of all phosphorus forms, including dissolved and particulate organic phosphates from algae and other organisms, inorganic particulate phosphorus from soil particles and other solids, polyphosphates from detergents, and dissolved orthophosphates. Soluble orthophosphate (PO_4-P) is the phosphorus form that is most readily available for algal uptake. Total phosphorus levels are strongly affected by the daily phosphorus loads that enter the lake, while soluble orthophosphate levels are more likely to be affected by algal consumption during the growing season.

The EPA eutrophic criterion is a mean in-lake concentration of 0.02 to 0.03 mg/L for total phosphorus (U.S. EPA, 1980). Lakes with phosphorus concentrations below 0.01 mg/L are relatively unproductive, while lakes with total phosphorus concentrations above 0.03 mg/L can be expected to experience problems with nuisance algal blooms and/or aquatic weed growth.

Concentrations of soluble orthophosphate and total phosphorus in Lake Luxembourg are shown in Figures 3.6 and 3.7, respectively. The soluble orthophosphate concentrations in the surface waters at both stations were often below the detection limit of 0.01 mg/L, indicating that any available inorganic phosphate is rapidly taken up by algae and incorporated into cellular material. Elevated soluble orthophosphate concentrations were observed in the hypolimnion at Station 1 during the summer stratification period. This increase could result from either internal phosphorus loading or the decomposition of algal cells sinking from the surface.

The total phosphorus concentrations in Lake Luxembourg were relatively high (Figure 3.7), averaging 0.20 mg/L at Station 1 and 0.16 mg/L at Station 2. Total phosphorus concentrations were much higher than soluble orthophosphate concentrations, which indicates that most of the phosphorus in the water column is either incorporated in algal cells or attached to the clay particles which are responsible for the high turbidity in the lake water. The increased concentration in the hypolimnion was more pronounced for total phosphorus than for soluble orthophosphate, but the results can again be attributed to internal loading or the accumulation of algal cells and other particulate material.

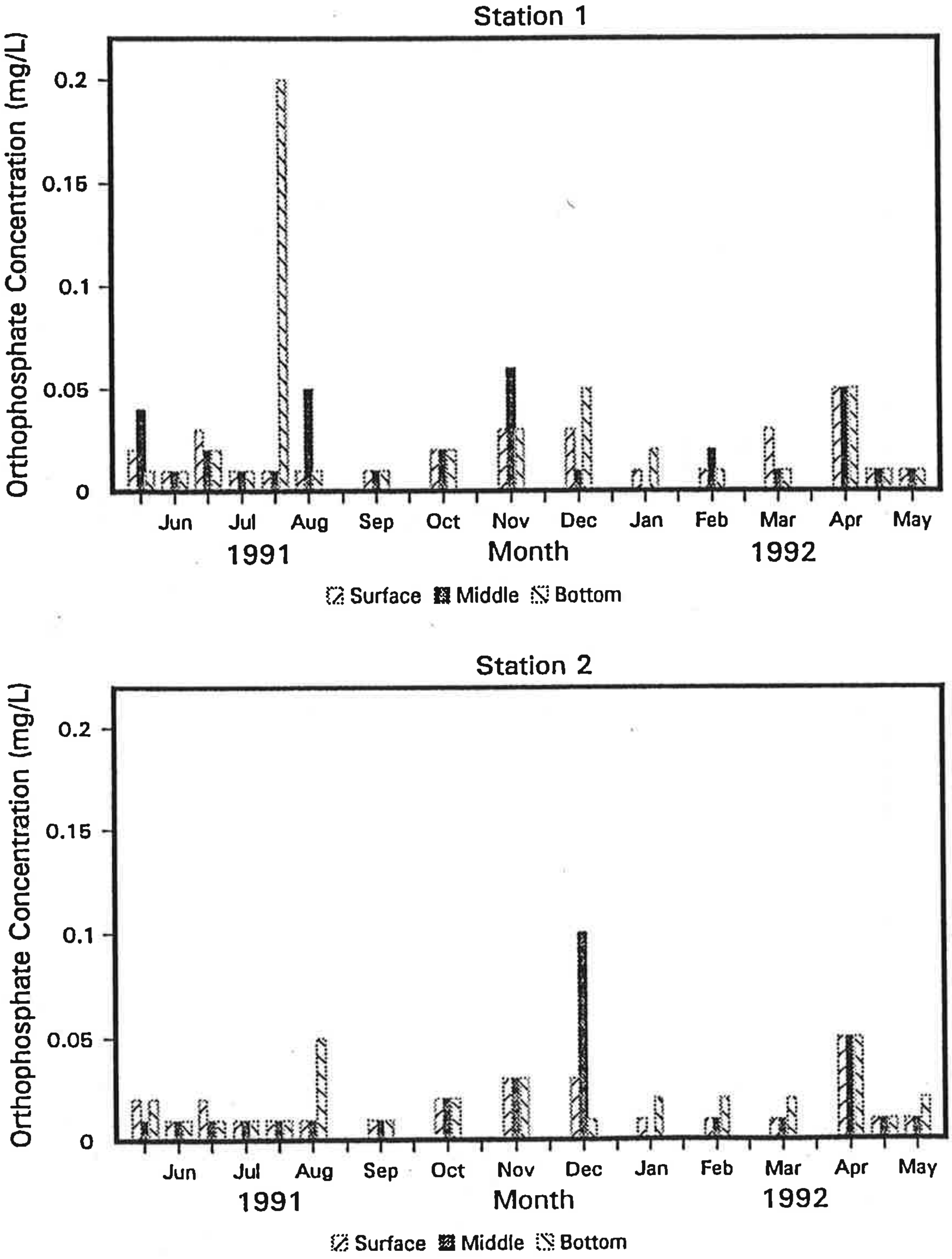


Figure 3.6. Concentrations of soluble orthophosphate in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

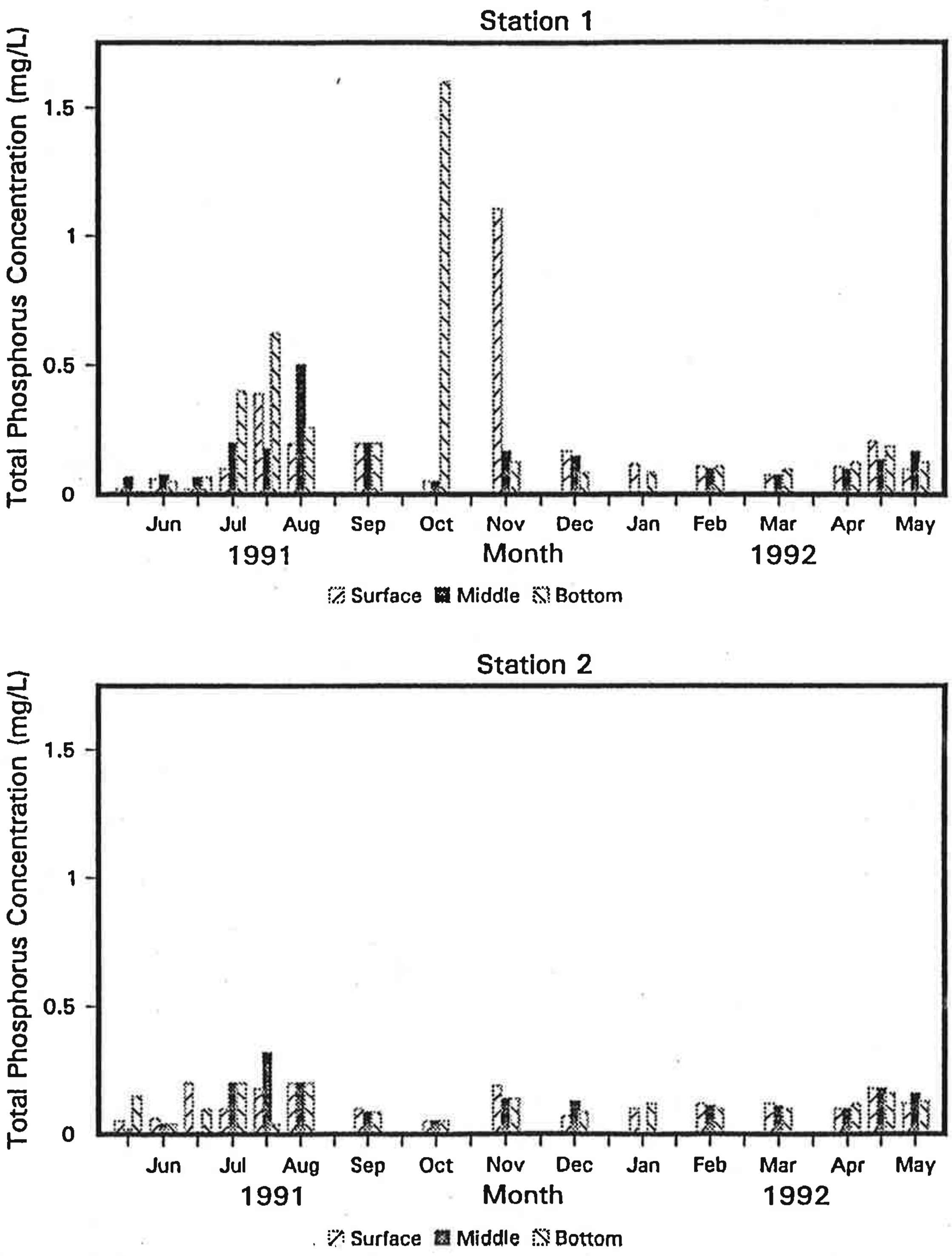


Figure 3.7. Total phosphorus concentrations in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

Total phosphorus concentrations in the runoff samples were higher than concentrations in the lake water, averaging 0.27 for the routine samples and 0.72 mg/L for the storm samples. Concentrations of total phosphorus at the lake outlet averaged 0.21 mg/L under routine conditions and 0.13 mg/L for the storm samples, indicating that much of the phosphorus entering the lake settles out with particulate matter. These results indicate the importance of the settling of sediment particles in reducing phosphorus concentrations in the lake water.

Total phosphorus concentrations in the well samples were relatively low. The average concentration of 0.03 mg/L was much lower than that of either the lake or stream samples. These results, coupled with the large Lake Luxembourg watershed, indicate that groundwater is of minor importance in the lake phosphorus budget.

Nitrogen Concentrations

The nitrogen cycle in lakes is considerably more complicated than the phosphorus cycle. Nitrogen can exist in either oxidized forms, usually nitrate (NO_3^-) or nitrite (NO_2^-), or reduced forms, including ammonia (NH_3) and organic nitrogen. Atmospheric nitrogen (N_2) can also be used as a nutrient source by some species of algae, and various other reduced forms of nitrogen can be produced by decomposition processes. The form of nitrogen present depends primarily on dissolved oxygen concentrations and plant growth. Nitrate is the most common form of nitrogen in surface waters, while ammonia is predominant in low oxygen environments. Ammonia, the nitrogen form that is most easily assimilated and utilized by phytoplankton, can be present as either un-ionized ammonia (NH_3) or as ammonium ion (NH_4^+); ammonium ion predominates below pH 9.3. Extensive algal blooms can deplete concentrations of the inorganic nutrients, nitrate and ammonia, as nitrogen is converted into organic nitrogen in the form of algal cells. Total Kjeldahl nitrogen (TKN) provides a measure of ammonia plus organic nitrogen.

The concentrations of nitrate/nitrite-N, ammonia-N and TKN are shown in Figures 3.8, 3.9 and 3.10, respectively. Nitrate exhibited clear seasonal variations (Figure 3.8), with high concentrations during the winter and spring and relatively low concentrations during the summer months. Concentrations of nitrate + nitrite-N (NO_3^- + NO_2^--N) averaged 1.01 mg/L and 1.08 mg/L at Stations 1 and 2, respectively, with concentrations above 2 mg/l occurring at both stations in January, February and March. High concentrations during these months may be indicative of fertilizer runoff from agricultural operations in the watershed. Low concentrations during the summer months are probably the result of algal uptake in the surface waters.

Ammonia concentrations peaked during the summer months, particularly in the bottom waters at Station 1 (Figure 3.9). The reduction of nitrate to ammonia and the decomposition of algal cells in the hypolimnion of the lake are the likely cause of the increased ammonia concentrations during this period. Total Kjeldahl nitrogen concentrations also peaked during the summer months. This is to be expected because TKN includes both ammonia and organic nitrogen. The incorporation of inorganic nitrogen into algal cells is a likely cause for the significant increase in TKN in the surface water of the lake during the summer months.

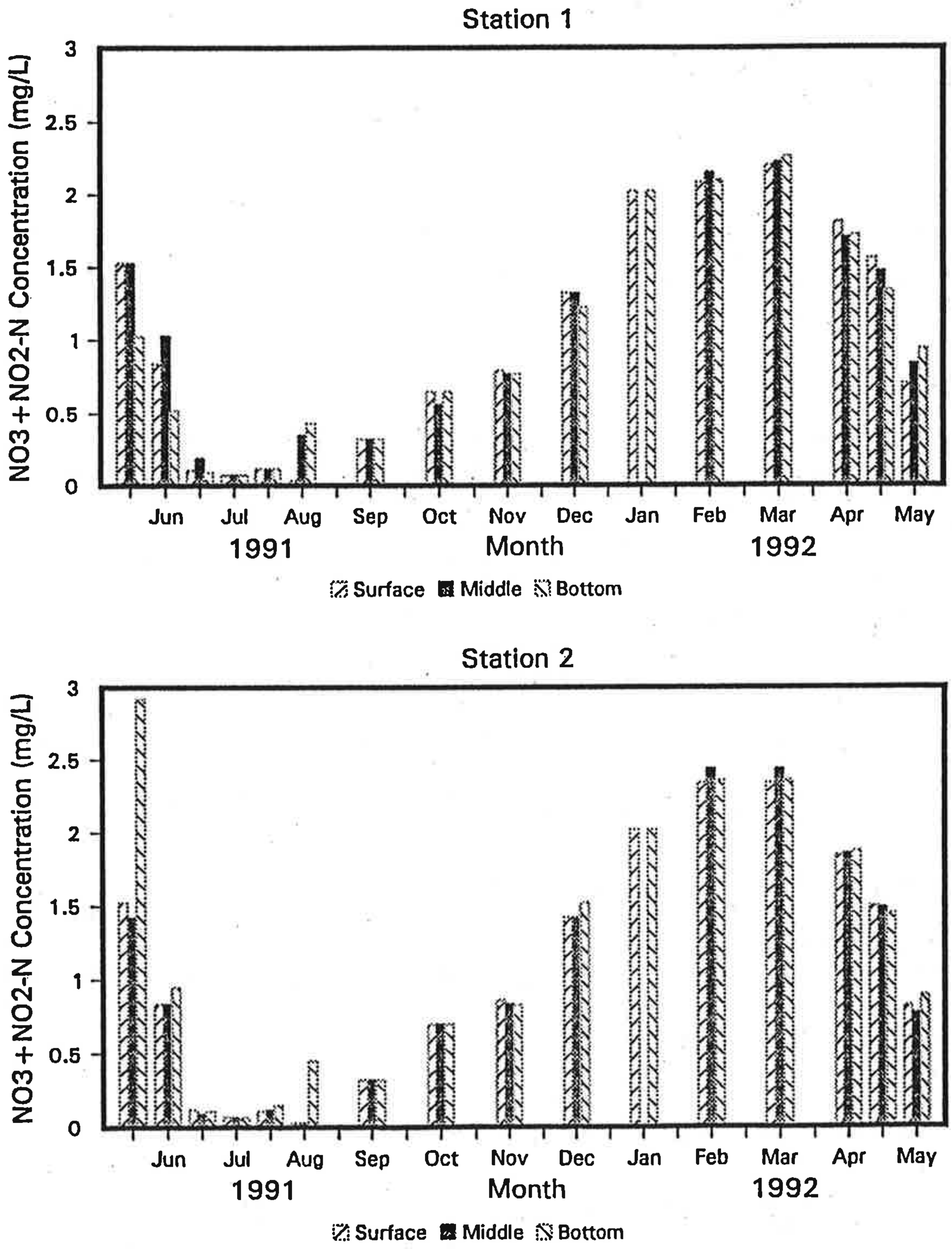


Figure 3.8. Nitrate + nitrite-N concentrations in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

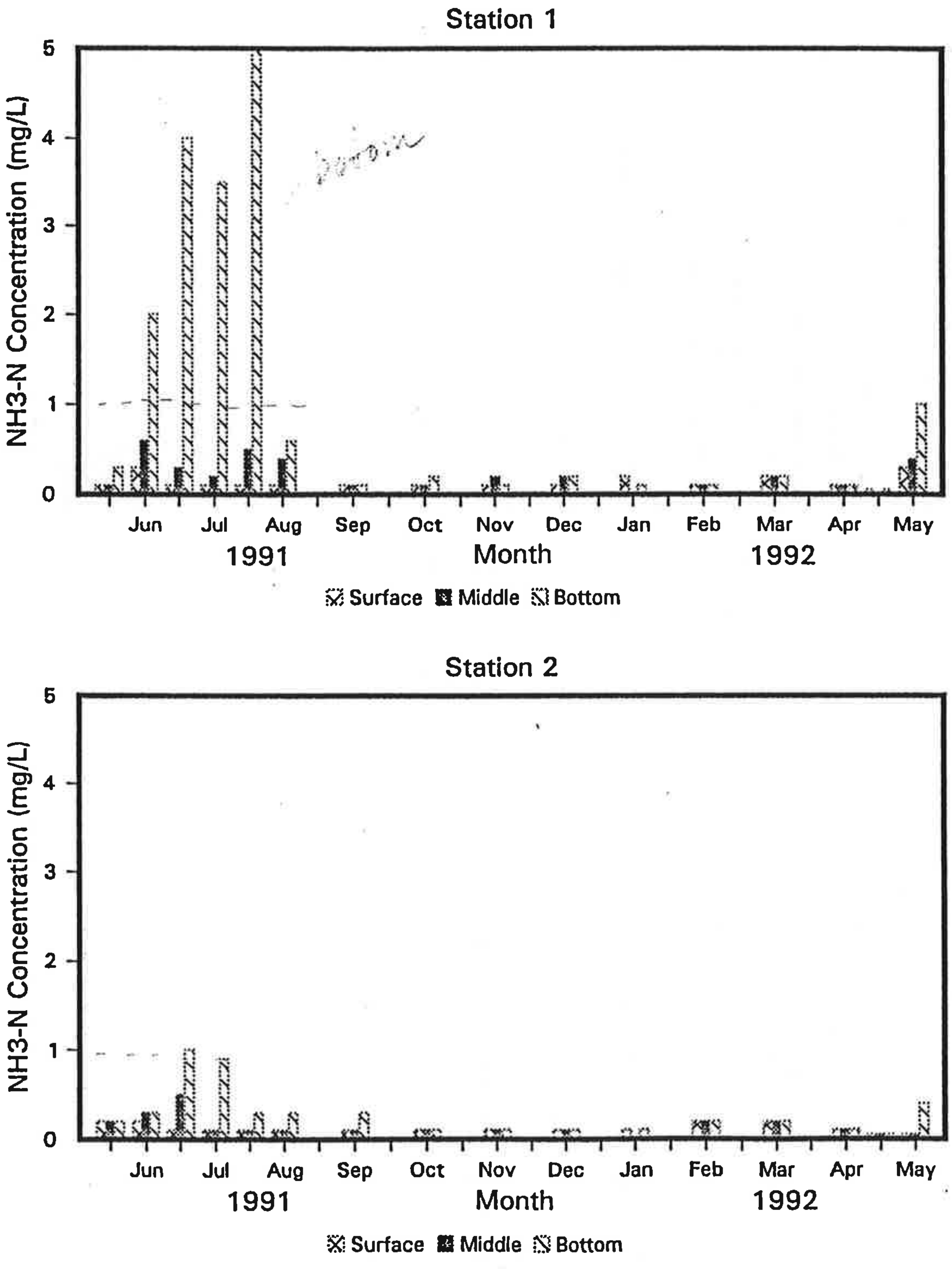
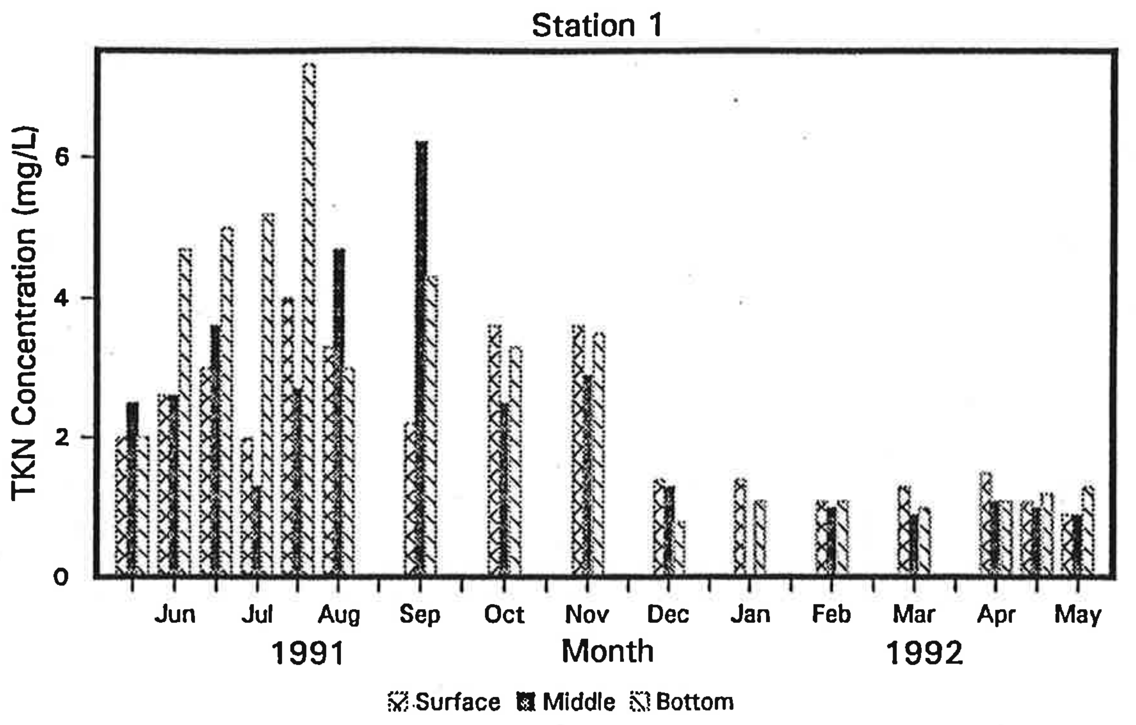


Figure 3.9. Concentrations of ammonia-N in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.



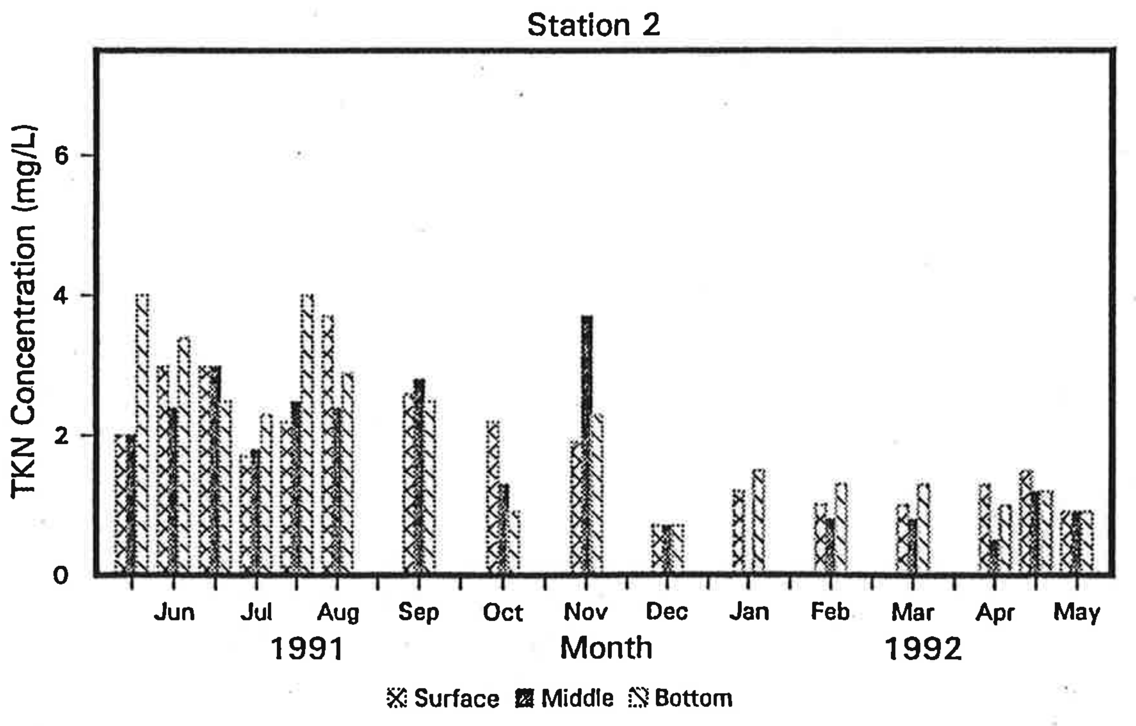


Figure 3.10. Total Kjeldahl nitrogen concentrations in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

Concentrations of both nitrate/nitrite-N and TKN were higher in the lake inlets (Table 3.3) for routine runoff samples (5.8 mg/L and 2.1 mg/L, respectively) than in the storm samples (1.3 mg/L and 1.8 mg/L, respectively). Nitrogen compounds are relatively soluble, and less dilution during periods of low runoff may be responsible for the observed results.

Nitrate concentrations in the well samples were very high, with concentrations of 30.0 mg/L in Well 1 and 5.5 mg/L in Well 3. The concentration in Well 1 far exceeds the maximum acceptable concentration of 10 mg/L for drinking water (U.S. EPA, 1976). Well 1 was located at Shadybrook Farm and Well 3 was located at Moon Nursery. The high levels may be indicative of excessive fertilizer use for agricultural operations in the Lake Luxembourg watershed.

Limiting Nutrient

Phytoplankton require both macronutrients, such as phosphorus, nitrogen, and carbon, and trace nutrients, including iron, manganese, and other minerals, for growth. Biological growth is limited by the substance that is present in the minimum quantity with respect to the needs of the organism. Nitrogen and phosphorus are the nutrients that usually limit algal growth in natural waters.

The ratio of nitrogen to phosphorus in algal cells is usually between 15 and 26 atoms of nitrogen for every atom of phosphorus (7 to 12 grams of nitrogen per gram of phosphorus on a mass basis), depending on the species. A total nitrogen to total phosphorus ratio of 15:1 is generally regarded as the dividing point between nitrogen and phosphorus limitation. Identification of the limiting nutrient becomes more certain as the total nitrogen to total phosphorus ratio moves farther away from the dividing point, with ratios of 10:1 or less providing a strong indication of nitrogen limitation and ratios of 20:1 or more strongly indicating phosphorus limitation (U.S. EPA, 1980). Ratios of inorganic nutrients, nitrate/nitrite-N plus ammonia-N (total inorganic nitrogen = TIN) to soluble orthophosphate (OP) may be an even better indicator of the limiting nutrient because the inorganic nutrients are the forms that can be utilized directly to support algal growth.

Nitrogen to phosphorus ratios in Lake Luxembourg are shown in Table 3.4. The average TN:TP ratios of 31:1 and 30:1 for Stations 1 and 2, respectively, are clearly indicative of phosphorus limitation. The ratios of the inorganic nutrients, with a TIN:OP of 75:1 at Station 1 and 82:1 at Station 2 provide even stronger support of phosphorus limitation in Lake Luxembourg. As a result, a management plan focusing on a reduction in the total phosphorus load to Lake Luxembourg will have the greatest impact on controlling nuisance algal growth in the lake.

3.2.7 Transparency

The transparency, or clarity, of water is most often reported in lakes as the Secchi depth. This measurement is taken by lowering a circular white or black-and-

Table 3.4 - Nitrogen to Phosphorus Ratios in Lake Luxembourg

Date	Station 1		Station 2	
	TN/TP	TIN/OP	TN/TP	TIN/OP
05Jun91	117	73	63	129
20Jun91	65	--	82	--
10Jul91	75	68	28	48
25Jul91	12	134	12	44
05Aug91	12	27	17	29
23Aug91	12	27	16	14
18Sep91	23	42	32	49
31Oct91	7	38	44	40
21Nov91	9	23	22	31
19Dec91	18	48	23	34
31Jan92	31	145	31	141
20Feb92	30	166	21	168
05Mar92	38	146	31	194
20Apr92	26	37	26	39
04May92	14	--	16	--
19May92	14	--	13	192
Mean	**31**	**75**	**30**	**82**

white disk, 20 cm (8 inches) in diameter, into the water until it is no longer visible. Observed Secchi depths range from a few centimeters in very turbid lakes to over 40 meters in the clearest known lakes (Wetzel, 1983). Although somewhat simplistic and subjective, this testing method probably best represents the conditions which are most readily visible to the common lake user. Secchi depths of less than 6.6 feet (2.0 meters) have traditionally been considered undesirable for recreational lake uses; however, lower clarity is usually tolerated in reservoirs .

Secchi disk transparency is related to the transmission of light in water, and depends on both the absorption and scattering of light. The absorption of light in dark-colored waters reduces light transmission. Light scattering is usually a more important factor than absorption in determining Secchi depths. Scattering can be caused by color, by particulate organic matter, including algal cells, and by inorganic materials, such as suspended clay particles in water.

Transparency in Lake Luxembourg was limited by both the silt and clay particles suspended in the water and frequent and extensive algal blooms. Secchi depths ranged from 0.15 to 0.6 m (Figure 3.11), with averages of 0.35 m at Station 1 and 0.38 m at Station 2. There was even less variability in the Secchi depth readings taken by the Bucks County Parks Department at the fishing pier near the boat dock; all readings at this site fell in the range of 0.2 to 0.4 m. The low transparency in Lake Luxembourg limits light penetration and may limit both algal and macrophyte growth.

3.2.8 Sediment Analyses

Six sediment cores were collected from the area of Lake Luxembourg north of Woodbourne Road on 4 March 1992. A gravity corer was used to collect samples of unconsolidated sediments; core lengths varied from 0.45 m (1.5 ft) to 1.0 m (3.3 ft). All cores were combined and analyzed for solids, nutrients, heavy metals and pesticides. Two cores with different textures were analyzed for particle size distribution.

None of the heavy metals detected were present at problem levels and metabolites of DDT were the only pesticides detected, and these were only present at low levels. Sediment characteristics are summarized in Table 3.5, and complete results of sediment analyses are presented in Appendix C. A toxicity characteristic leaching procedure (TCLP) test was also performed to determine if there were any toxic compounds which could be leached from the sediments; no metals were detected and no organic compounds were present at elevated levels.

Neither the U.S. EPA nor the Commonwealth of Pennsylvania has adopted sediment quality criteria. Medium specific concentrations (MSC's) for soils reported by the PaDER (1993) are included in Table 3.5 for comparison purposes. These MSC's are for soils in residential areas and are based upon exposure by ingestion.

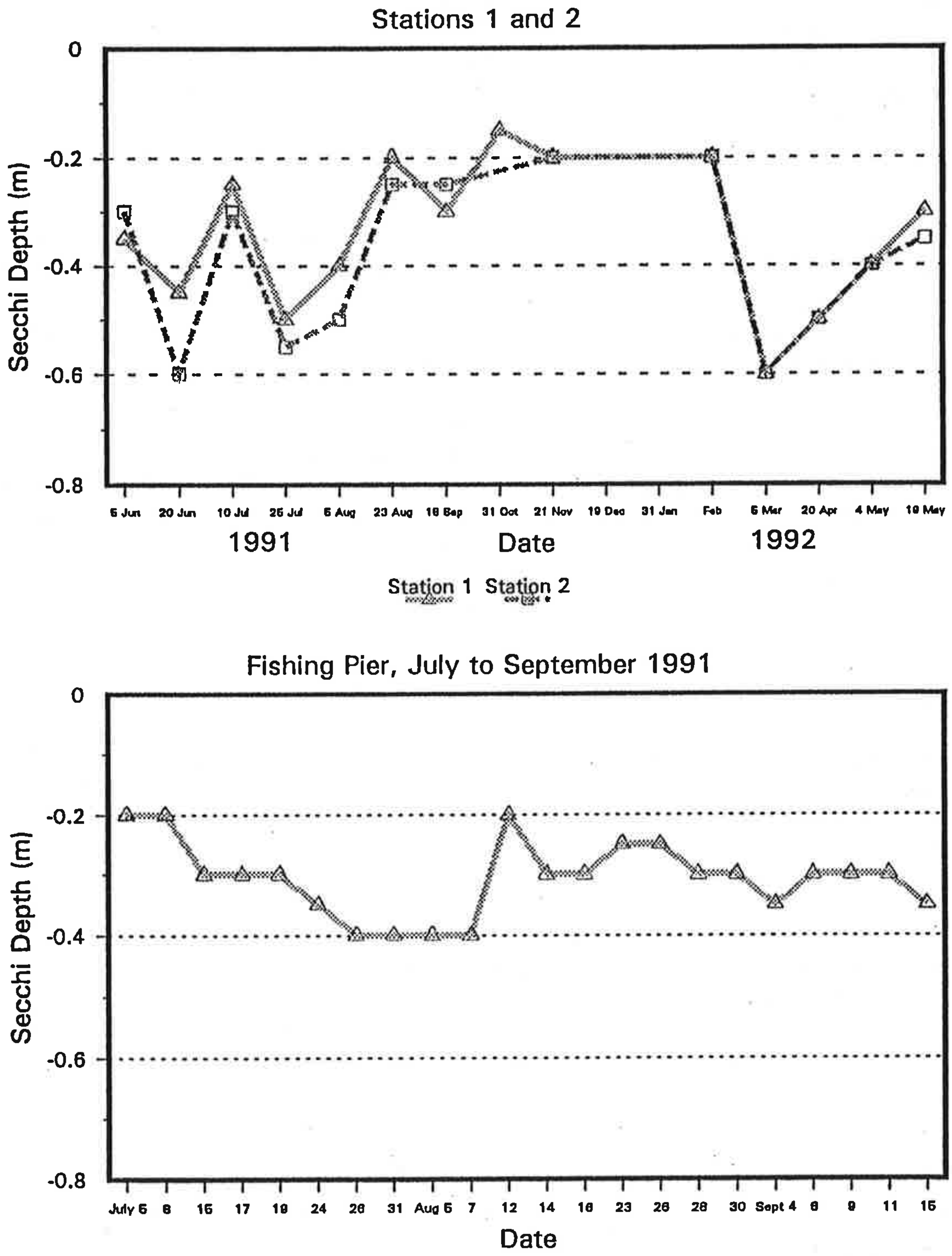


Figure 3.11. Secchi disk transparency in Lake Luxembourg.

COASTAL
ENVIRONMENTAL SERVICES INC.

Table 3.5 - Lake Luxembourg Sediment Characteristics

Parameter (units)	Concentration	Soil MSC (Residential)*
Total Solids (percent)	65.12	n/a
Volatile Solids (percent)	1.20	n/a
Particle Size Distribution - Core 1 (percent)	Sand - 37 Silt - 46 Clay - 17	n/a
Particle Size Distribution - Core 2 (percent)	Sand - 63 Silt - 20 Clay - 17	n/a
Total Phosphorus (mg/kg)	685	n/a
Total Kjeldahl Nitrogen (mg/kg)	919	n/a
Nitrate-N (mg/kg)	<2.5	350,000
Arsenic (mg/kg)	2.6	12
Barium (mg/kg)	77	15.000
Cadmium (mg/kg)	<0.98	110
Chromium (mg/kg)	14	220,000 - Cr(III) 1,100 - Cr (VI)
Lead (mg/kg)	8.6	500
Mercury (mg/kg)	<0.016	19
Selenium (mg/kg)	0.18	1,100
Silver (mg/kg)	<0.98	1,100
DDE (mg/kg)	0.03	53
DDD (mg/kg)	0.006	75
Total DDT (mg/kg)	0.036	53

*Source: PADER (1993)

3.3 Biological Characteristics of Lake Luxembourg

3.3.1 Chlorophyll *a*

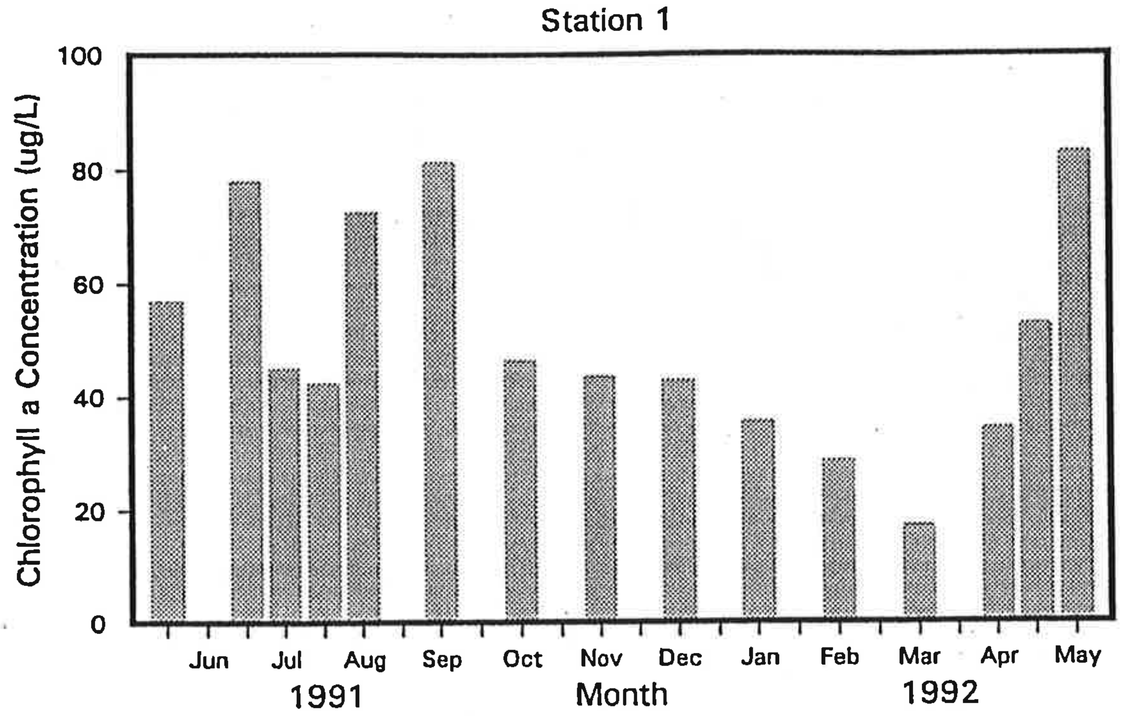
Chlorophyll *a* is the pigment that gives the green color to plants. It converts sunlight into chemical energy during the photosynthesis process. Water samples containing algal cells can be treated to extract chlorophyll *a* for analysis. Because it constitutes about 1 to 2 percent of the dry weight of planktonic algae, chlorophyll *a* provides an indicator of algal biomass in lake water samples. Chlorophyll *a* concentrations in Lake Luxembourg were very high, with averages of over 50 µg/L at both stations and peak values of 83.0 µg/L at Station 1 (19 May 1992) and 91.6 µg/L at Station 2 (10 July 1991). Although the highest levels occurred during the summer months (Figure 3.12), chlorophyll *a* concentrations exceeded the level of 30 µg/L generally associated with user perceptions of severe nuisance conditions (Walmsley and Butty, 1979) in all months except February and March.

Visitors to Lake Luxembourg encountered during the limnological survey did not voice complaints about algal blooms. The nuisance blooms occurring, as indicated by high chlorophyll *a* levels and phytoplankton counts, were generally not noticeable because of the high turbidity levels created by suspended clay particles in the water column. This inorganic turbidity is apparently high enough to at least partially mask the severe algal blooms occurring in the lake.

3.3.2 Phytoplankton

The algal community of Lake Luxembourg followed an annual seasonal succession typical of temperate, eutrophic lakes. In general, the blue-green algae (cyanobacteria) were the dominant algal group over the spring and summer months, and the diatoms (bacillariophytes) and/or green algae (chlorophytes) were the dominate algal groups over the fall and winter months. Data for algal populations is summarized in Tables 3.6 and 3.7 for Stations 1 and 2, respectively. The algal data are also shown graphically in Figure 3.13. Complete results from the phytoplankton sampling program are included in Appendix D.

The late spring samples of 5 June 1991 contained a mixed assemblage of phytoplankton. Blue-greens, diatoms and cryptomonads were all common; however, the green alga *Chlorella*, as well as other green algal species, were the dominant algae on this sampling date. The blue-greens were the predominant algal group in the number of cells/mL at both Stations 1 and 2 from 20 June through 18 September 1991. Algal concentrations on 10 July 1991 were estimated to be 173,126 cells/mL and 176,978 cells/mL for Stations 1 and 2, respectively. These were the highest cell counts observed during the entire study, and blue-green algae accounted for 99.9 percent of these algal cells. The extremely high concentrations of algal cells observed on this sampling date corresponded with some of the highest concentrations of chlorophyll *a* measured throughout this study, with chlorophyll *a* concentrations of 77.9 and 91.6 µg/L reported for Stations 1 and 2, respectively, on 10 July 1991.



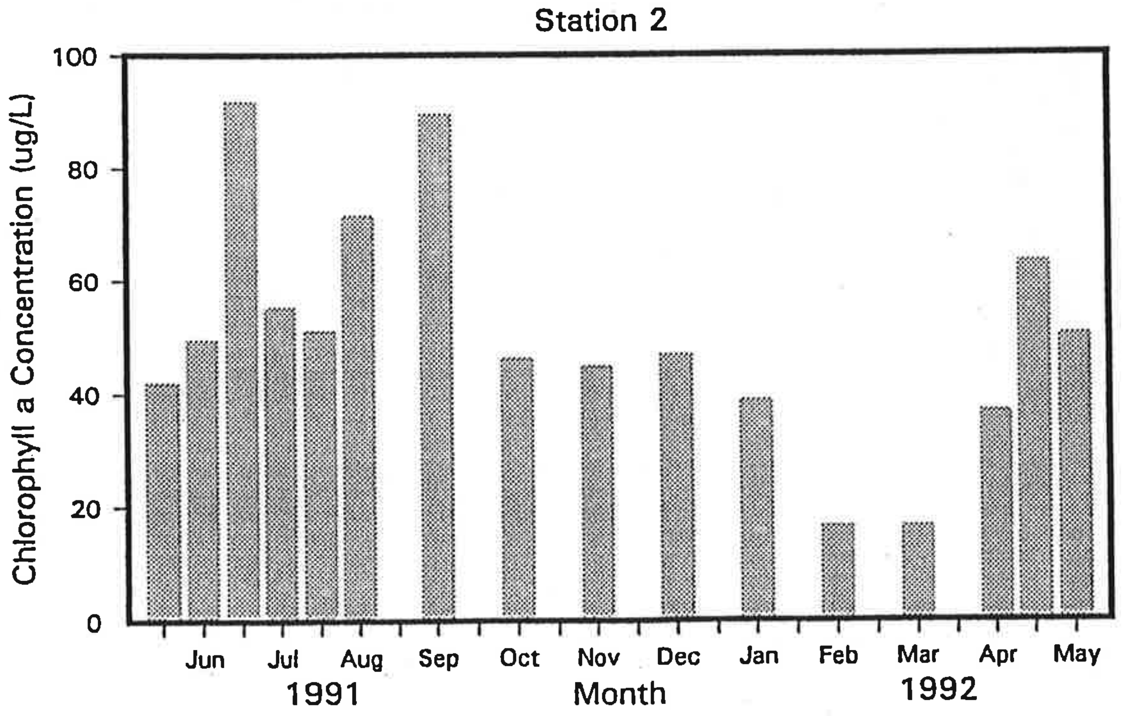


Figure 3.12. Chlorophyll *a* concentrations in Lake Luxembourg.

COASTAL ENVIRONMENTAL SERVICES INC.

Table 3.6 - Phytoplankton Population at Station 1

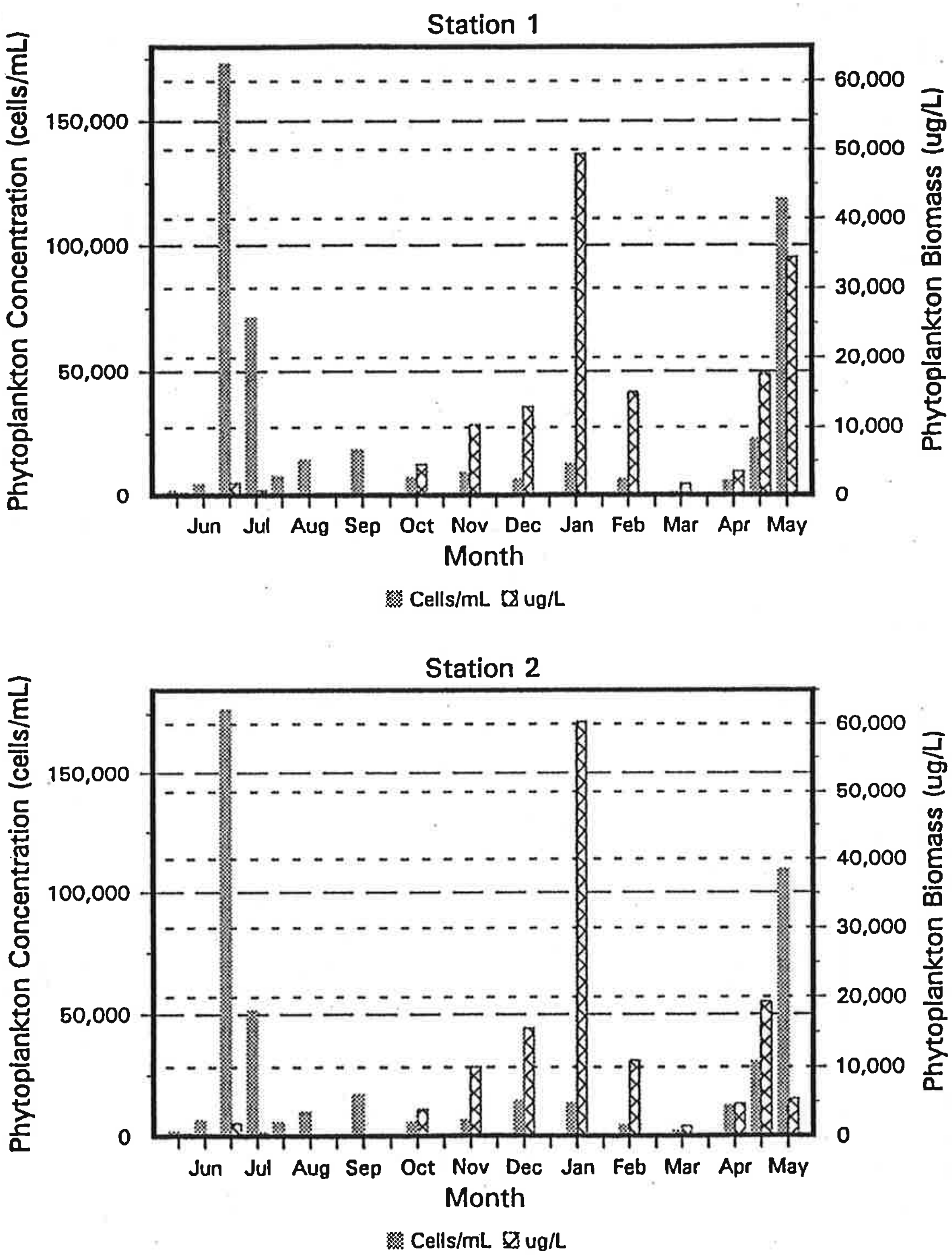
Date	Phytoplankton Family (cells/mL)							Total Concentration	
	Bacillario.	Chloro.	Chryso.	Crypto.	Cyano.	Euglen.	Pyrrho.	cells/mL	μg/L
06/05/91	248	788	0	216	440	84	0	1,776	383
06/20/92	213	213	0	57	3,848	0	0	4,332	363
07/10/91	38	36	0	44	173,000	8	0	173,126	1,779
07/25/91	34	76	0	36	71,200	0	0	71,346	754
08/05/91	24	86	0	12	7,240	4	0	7,366	135
08/23/91	36	140	0	0	13,872	0	0	14,048	242
09/18/91	20	120	0	12	18,128	0	0	18,280	212
10/31/91	2,160	2,196	0	216	2,160	36	0	6,768	4,507
11/21/91	4,686	814	0	308	3,344	0	0	9,152	10,343
12/19/91	3,200	930	0	310	1,960	100	0	6,500	12,917
01/31/92	9,594	1,782	18	36	1,224	36	0	12,690	49,357
02/20/92	3,419	884	13	156	1,638	0	0	6,110	14,892
03/05/92	234	221	104	39	598	13	0	1,209	1,654
04/20/92	594	432	0	252	4,464	126	0	5,868	3,470
05/04/92	1,536	9,996	240	120	10,704	84	0	22,680	17,545
05/19/92	2,256	19,644	168	120	96,192	24	0	118,404	34,428
Mean	1,768	2,397	34	121	25,626	32	0	29,978	9,561

*Bacillario. = Bacillariophyta (diatoms), Chloro. = Chlorophyta (green algae), Chryso. = Chrysophyta (chrysophyte algae), Crypto. = Cryptophyta (cryptophyte algae), Cyano. = Cyanophyta (blue-green algae), Eugleno. = Euglenophyta (euglenoid algae), Pyrrho. = Pyrrhophyta (golden-brown algae)

Table 3.7 - Phytoplankton Populations at Station 2

Date	Phytoplankton Family (cells/mL)							Total Concentration	
	Bacillario.	Chloro.	Chryso.	Crypto.	Cyano.	Eugleno.	Pyrrho.	cells/mL	µg/L
06/05/91	239	575	0	229	468	57	0	1,568	346
06/20/91	268	100	0	24	5,960	20	2	6,374	383
07/10/91	32	118	0	20	176,800	8	0	176,978	1,840
07/25/91	8	60	0	28	51,200	8	0	51,304	538
08/05/91	14	92	0	16	5,600	8	0	5,730	88
08/23/91	8	72	0	12	9,600	4	0	9,696	160
09/18/91	8	72	0	18	17,272	2	0	17,372	201
10/31/91	2,010	1,500	0	240	1,860	75	0	5,685	3,886
11/21/91	3,087	840	21	567	1,848	0	0	6,363	10,052
12/19/91	4,070	902	0	550	8,976	88	0	14,586	15,545
01/31/92	9,972	2,340	0	90	1,044	90	18	13,554	60,313
02/20/92	2,712	684	12	36	816	0	12	4,272	10,871
03/05/92	399	247	0	76	1,102	38	0	1,862	1,463
04/20/92	684	969	0	152	10,526	38	0	12,369	4,674
05/04/92	1,212	9,708	264	168	18,912	48	0	30,312	19,264
05/19/92	1,320	20,448	72	216	87,072	60	24	109,212	5,445
Mean	1,628	2,420	23	153	24,941	34	4	29,202	8,442

*Bacillario. = Bacillariophyta (diatoms), Chloro. = Chlorophyta (green algae), Chryso. = Chrysophyta (chrysophyte algae), Crypto. = Cryptophyta (cryptophyte algae), Cyano. = Cyanophyta (blue-green algae), Eugleno. = Euglenophyta (euglenoid algae), Pyrrho. = Pyrrhophyta (golden-brown algae)



Station 1

Station 2

Figure 3.13. Lake Luxembourg phytoplankton.

COASTAL
ENVIRONMENTAL SERVICES INC.

The blue-green algae were also the predominant algal group in terms of biomass over the summer months, with the exception of the 20 June 1991 sampling date. On that date, the diatom *Synedra* accounted for the majority of the total algal biomass. These data obviously indicate that the eutrophic conditions of Lake Luxembourg gave rise to an intensive blue-green algal bloom over the summer months of 1991. The non-nitrogen fixing blue-green algae *Merismopedia* and *Oscillatoria* accounted for a significant proportion of this summer bloom.

The blue-greens, greens and diatoms all made up approximately equal portions of algal community on 31 October 1991. Each of these groups accounted for about 32 percent of the total number of cells at Station 1, while the blue-greens, greens and diatoms accounted for 33, 35, and 26 percent of the total number of cells, respectively, at Station 2.

The diatoms *Melosira* and *Synedra* were the predominant algal species at both sampling stations from 11 November 1991 to 20 February 1992, both in terms of total algal cell numbers and biomass. On 19 December 1991, however, the algal species responsible for the majority of the algal numbers and biomass at Station 2 was the blue-green alga *Oscillatoria*, although *Melosira* and *Synedra* still made up a significant proportion of the phytoplankton community on this sampling date. Other commonly occurring algal species over the late fall and early winter months were the green algae *Ankistrodesmus*, *Chlamydomonas*, *Scenedesmus*, the blue-green algae *Merismopedia*, *Oscillatoria*, *Chroococcus* and *Anabaena*, and the cryptomonad alga *Cryptomonas*. *Melosira*, a large-celled, filamentous diatom, was the most common species in terms of both numbers and biomass during the late fall and early winter.

From 5 March to 20 April 1992 algal numbers and biomass were accounted for primarily by blue-green algae and diatoms, respectively, while algal numbers and biomass were accounted for primarily by blue-green and green algae, respectively, from 4 May to 19 May 1992. The shift in biomass dominance from diatoms to green algae was the result of a May bloom of the relatively large-sized, green alga *Scenedesmus*. The spring blue-green algal bloom of 1992 was relatively more diverse in the number of species it contained than the 1991 summer blue-green algal bloom.

The maximum amount of algal biomass per liter for both sampling stations was observed on 31 January, corresponding with the maximum number of diatom cells observed in this study. Diatoms tend to be relatively large organisms, especially when compared to most blue-green and green algae (Reynolds, 1986), which explains why the maximum algal biomass occurred during the winter diatom maximum and not during the summer blue-green maximum.

The cryptomonad *Cryptomonas*, the euglenoids *Euglena* and *Trachelomonas*, and the green alga *Eudorina* were all common in Lake Luxembourg. These algae are known to require a variety of organic compounds and/or vitamins, such as vitamin B-12, cyanocobalamin and thiamine (Sze, 1986), which indicates that Lake Luxembourg must contain relatively high concentrations of dissolved organic matter. The lake must also have a large, actively growing bacterial community, since heterotrophic bacteria are responsible for the production of compounds such as vitamin B-12 and thiamin.

A substantial number of the algal species commonly found in the Lake Luxembourg phytoplankton assemblage are known to exist and grow in "polluted water", high in organic matter. Besides the algal species mentioned above, other species include *Chlamydomonas*, *Chlorella*, *Chlorogonium*, *Merismopedia* and *Oscillatoria*. Lake Luxembourg also has a fairly large assemblage of algal species known to produce distinctive taste and odor problems, which include *Anabaena*, *Staurastrum*, *Mallomonas*, *Synedra* and *Ceratium*.

Secchi disk transparency recorded during the Phase I study was extremely low (0.15 to 0.60 m). The low light penetration, which could be caused by either algae or inorganic suspended solids, may lead to light limitation in the phytoplankton community. Light limitation could help explain the competitive success of the blue-green algae at Lake Luxembourg, since many of these organisms can regulate their position in the water column with the use of gas vacuoles (or pseudovacuoles). The relatively large nitrogen to phosphorus nutrient ratios would indicate that Lake Luxembourg is a phosphorus limited system however, light appears to be the overriding factor controlling algal growth in this ecosystem.

3.3.3 Zooplankton

Lake Luxembourg was sampled for zooplankton at Station 1 on five occasions over the course of the study. Zooplankton data are presented graphically in Figure 3.14, with complete results included in Appendix D.

Planktonic copepods were the dominant zooplankters in terms of both numbers and biomass on four out of the five sampling dates. These organisms made up between 77 to 92 percent of the total zooplankton numbers and 86 to 94 percent of the zooplankton biomass in June, September and December 1991 and May 1992. The calanoid copepod, *Diaptomus*, as dominant on 20 June and 19 December 1991, while the cylopoid, *Mesocyclops* , predominated on 18 September 1991.

The calanoid copepod *Diaptomus* feeds primarily on phytoplankton by a combination of raptorial and filter feeding, and the cyclopoid *Mesocyclops* is highly carnivorous, feeding on other members of the zooplankton community. Since the phytoplankton was composed almost entirely of the inedible blue-green alga *Oscillatoria* on 18 September 1991, the herbivorous copepod *Diaptomus* was at a competitive disadvantage, making the carnivorous copepod *Mesocyclops* the most common zooplankter in Lake Luxembourg at that time.

An extremely large "bloom" of the rotifer *Brachionus*, dominated the zooplankton community in both of numbers and biomass on 5 March 1992. Such population explosions of *Brachionus* in the early spring have been documented in other aquatic ecosystems (Wetzel, 1983). *Brachionus* was also observed in the 20 June 1991 sample; however, their numbers and biomass at that time were significantly lower than the values observed during the early spring of 1992. *Asplanchna*, a large predatory rotifer, was the most commonly occurring rotifer in the 20 June 1991 sample.

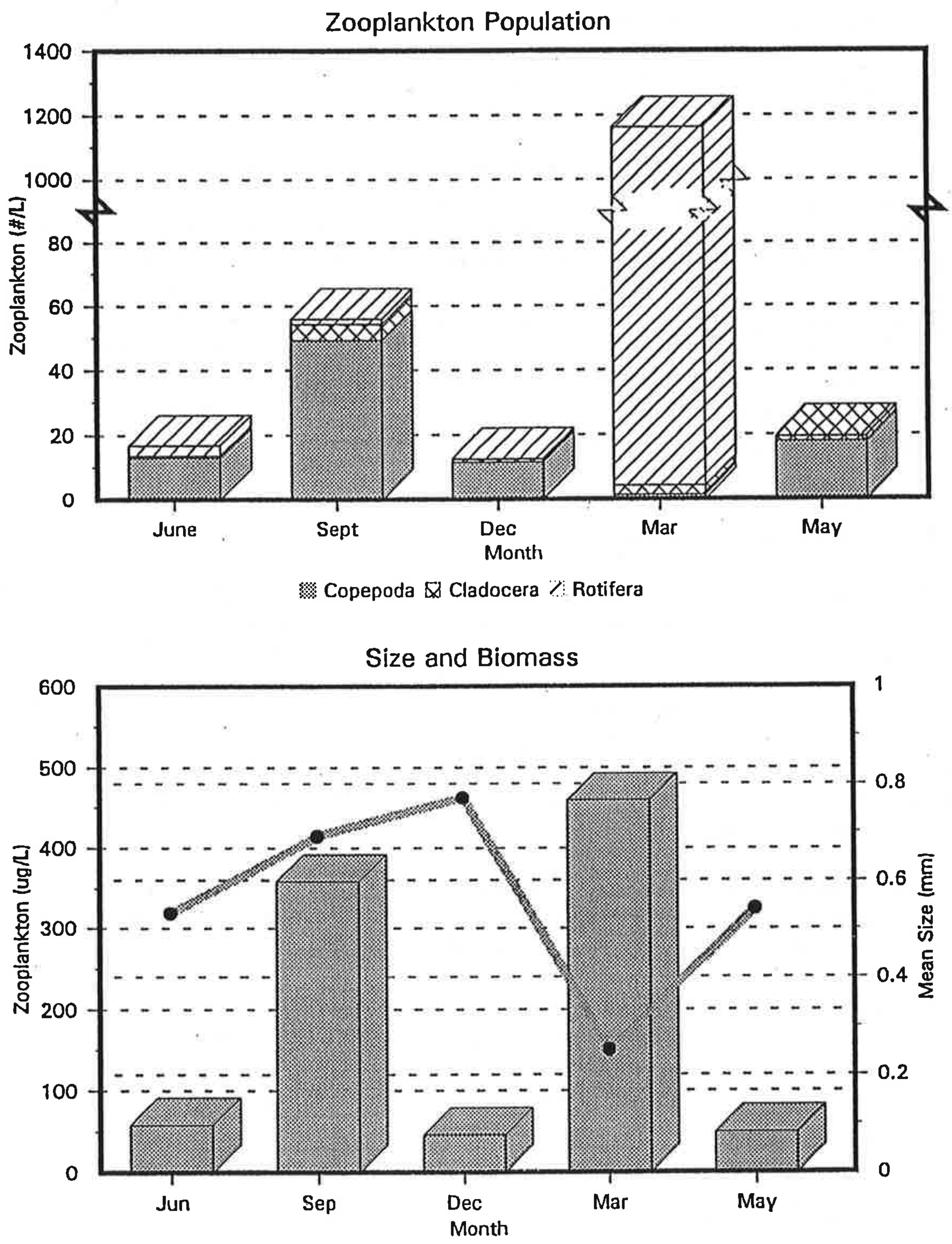


Figure 3.14. Lake Luxembourg zooplankton.

COASTAL
ENVIRONMENTAL SERVICES INC.

A simple oscillating predator-prey interaction has been well documented in many systems between *Asplanchna* and *Brachionus* (Wetzel, 1983). The early spring "bloom" of *Brachionus* in Lake Luxembourg stimulated an increase in the number of *Asplanchna*, which in turn, reduced the number of *Brachionus* by early summer.

The highly efficient herbivorous grazing cladocerans were relatively uncommon over the course of this study of Lake Luxembourg. A variety of factors may be responsible for this observation. Stocked fingerlings, as well as other fish already present in Lake Luxembourg, such as alewife and gizzard shad, are highly planktivorous and prefer large-bodied cladocerans, such as *Daphnia*, over other groups of zooplankton as a food source. In addition, the blue-green algae that make up a substantial proportion of the phytoplankton community, are a highly inedible source of food for cladoceran zooplankton. Some data have been documented to indicate that blue-green algae produce inhibitory compounds that reduce the growth or cause some sort of mortality to cladoceran zooplankton populations.

3.3.4 Macrophyte Survey

A macrophyte (aquatic plant) survey of Lake Luxembourg was conducted on 5 August 1991. Plants were identified and the species distribution within the lake was noted. Macrophytes in Lake Luxembourg occur only within narrow bands along approximately half of the lake shoreline. No plants were observed in water more than approximately 0.5 m (1.5 feet) deep. Common species encountered included cattail (*Typha latifolia*), various sedges (*Carex sp.*), purple loosestrife (*Lythrum salicaria*) and arrowhead (*Saggittaria latifolia*). Other species present included reed canary grass (*Phlaris arundinacea*), woolgrass (*Scirpus cyperinus*), water plantain (*Plantago cordata*) and black willow (*Salix nigra*) saplings.

The distribution of plants within a lake is a function of the water depth, substrate, water chemistry, available light, and species composition. These factors interact to create favorable niches for certain plant species.

Typically large, deep, turbulent lakes contain few macrophytes except in protected calm areas. The majority of macrophytes cannot tolerate physical stress of turbulent water and a shifting bottom. The openness and configuration of Lake Luxembourg does not favor the development of suitable habitat for aquatic macrophytes.

3.3.5 Fish Resources

Fishing is one of the most popular recreational activities in Lake Luxembourg. The lake has been regularly stocked since 1977 with a variety of warmwater fish species by the Pennsylvania Fish and Boar Commission (PFBC). Stocking records for Lake Luxembourg are summarized in Table 3.8. Lake Luxembourg is also stocked annually with adult trout in addition to warmwater fish species. Trout have been stocked in Lake Luxembourg since 1980 to provide a temporary source of recreation.

Table 3.8 - Stocking Record for Lake Luxembourg

Year	Species	Size	Number Stocked
1977	Largemouth Bass	Fingerling	4,000
1978	Walleye	Fry	425,000
	Largemouth Bass	Fingerling	4,250
	Black Crappie	Fingerling	4,250
1979	Walleye	Small Fingerling	4,000
	Largemouth Bass	Fingerling	4,000
	Black Crappie	Fingerling	4,000
1980	Walleye	Small Fingerling	5,000
	Black Crappie	Fingerling	4,000
1981	No Warmwater Fish Species Stocked		
1982	Walleye	Large Fingerling	4,150
	Chain Pickerel	Fingerling	1,650
1983	Chain Pickerel	Fingerling	1,200
1984	Walleye	Large Fingerling	4,150
1985	No Warmwater Fish Species Stocked		
1986	Channel Catfish	Fingerling	8,300
	Gizzard Shad	Adult	170
1987	White Catfish	Fingerling	8,300
	Channel Catfish	Fingerling	8,300
	Chain Pickerel	Fingerling	1,650

Table 3.8 - Stocking Record for Lake Luxembourg (Continued)

Year	Species	Size	Number Stocked
1988	Walleye	Small Fingerling	1,650
	Walleye	Large Fingerling	1,650
	White Catfish	Fingerling	6,550
	Channel Catfish	Fingerling	2,500
	Chain Pickerel	Fingerling	1,650
1989	Walleye	Large Fingerling	1,650
	Chain Pickerel	Fingerling	1,650
1990	Walleye	Small Fingerling	3,300
	Walleye	Large Fingerling	1,650
	Channel Catfish	Fingerling	2,500
1991	Walleye	Fry	124,500
	Walleye	Small Fingerling	3,300
	Largemouth Bass	Fingerling	3,300
1992	Walleye	Fry	124,500
	Walleye	Small Fingerling	4,950
	Largemouth Bass	Fingerling	4,150
1993*	Walleye	Fry	124,500
	Walleye	Small Fingerling	3,300
	Channel Catfish	Fingerling	5,800
	Largemouth Bass	Fingerling	4,150

*Proposed - Actual species and numbers will depend upon the availability of fish from the hatchery system.

Lake Luxembourg is currently included in the PFBC's spring, fall and winter trout stocking programs. The lake received 11,500 rainbow trout during the spring trout stocking program, 3,000 rainbow trout during the fall trout stocking program and 2,000 rainbow trout during the winter trout stocking program in 1992. Brook trout and brown trout have also been stocked in Lake Luxembourg in past years.

The last complete biological survey of Lake Luxembourg conducted by the Pennsylvania Fish and Boat Commission was done in 1985. That survey showed a small population of white perch, which had been introduced to the lake from angler's bait buckets, moderately large gamefish populations, and moderately large populations of crappies and bluegills. Crappies and bluegills exhibited a poor size distribution in the 1985 survey (Wnuk, 1992).

By-catches from species specific surveys at Lake Luxembourg since 1985 have shown overabundant gizzard shad and white perch populations, while crappie and bluegill populations have drastically declined. Recent surveys have also shown low abundance and minimal reproduction of largemouth bass in the lake. The Pennsylvania Fish Commission attempted to enhance the largemouth population through fingerling stockings, but that effort has met with little success to date. It is likely that overabundant gizzard shad and white perch are limiting gamefish and panfish populations in Lake Luxembourg through competition with and predation on the young of more desirable sportfishes. In addition, there is little available fish cover in Lake Luxembourg, and this may be an additional detriment to the lake's fishery.

Fish tissue analyses were performed as part of the limnological survey of Lake Luxembourg. A 13-year old, 6.4 kg (14 lb) carp (*Cyprinus carpio*) and a 2 to 3-year old, 0.060 kg (0.13 lb) white crappie (*Pomoxis annularis*) were collected on 18 December 1992 for these analyses. The carp is a bottom feeder that feeds on both vegetation and animal matter, while the crappie feeds on a wide variety of animal life. The fish were ground whole and analyzed for chlorinated pesticides and PCB's by Minnesota Valley Testing Laboratory, New Ulm, MN. Metabolites of DDT were detected in both fish, with a total concentration of 1.21 mg/kg in the carp and 0.04 mg/kg in the black crappie. These concentrations are below the action level of 2 mg/kg. These results demonstrate the persistence of this pesticide because it has been banned for nearly 20 years; however, its past use in a heavily agricultural watershed was expected to be high. Dieldrin was also detected in the carp at a concentration of 0.02 mg/kg. Complete results of the fish tissue analyses are presented in Appendix C.

4.0 Hydrologic and Pollutant Budgets

Pollutants can enter a lake either as discrete discharges from known sources or through runoff from a variety of sources within the watershed. Discrete discharges are referred to as point sources, and all other sources of pollutants are referred to as nonpoint sources. Nonpoint sources contribute pollutants through stormwater runoff, precipitation on the lake surface, and internal sources, such as groundwater inputs and release from lake sediments.

Hydrologic and pollutant budgets are required to quantify the impacts of various pollutant sources on lake water quality and to evaluate lake and watershed interactions. Analysis of pollutant budgets provides a means to identify and to quantify the magnitude of nitrogen, phosphorus, and sediment contributions from various sources and is a key component in the development and evaluation of lake and watershed management alternatives.

Pollutant budgets can be developed from an extensive sampling program or through the evaluation of land use practices in the watershed. The unit areal loading approach was used to generate initial pollutant budgets for Lake Luxembourg. The hydrologic budget developed for Lake Luxembourg and monitoring data collected during the the study were also used to calculate pollutant budgets for the lake.

4.1 Hydrologic Budget

The hydrologic budget provides a representation of the total amount of water annually contributed to and lost from a lake. It is a function of precipitation, overland runoff, soil type, vegetative cover, slope, ground water infiltration, evaporation, and discharge. The volume of water annually entering a lake has a profound effect on nutrient and pollutant loading and sedimentation rates. The loss of water from a lake will affect flushing rates, the formation of algal blooms and the settling of particulate pollutants. As a result, the development of an accurate hydrologic budget is a critical step in understanding the ecological status of a lake.

The Core Creek watershed was the focus of an intensive hydrologic modeling study conducted by Thomas H. Cahill Associates (THCA, 1989) in the 1980's as part of the Neshaminy Watershed Stormwater Management Program. The study made use of extensive stream monitoring data and a data file consisting of 2,550 one-hectare (ha) cells for the Core Creek watershed to develop flow information. The mean discharge for the Lake Luxembourg watershed calculated from the data presented in the THCA (1989) study was 1.02 x 10^6 m^3/yr (7.4 MGD or 1.2 cubic feet/second/square mile of watershed).

An annual hydrologic budget for Lake Luxembourg was calculated as part of the current study using current land use and watershed area data and mean annual precipitation (SCS, 1986). Direct runoff from storms was assumed to be approximately 10 percent of the total precipitation, which is typical of watersheds in this region that are not highly urbanized.

Baseflow was computed by subtracting the 10 percent runoff from monthly precipitation figures to determine input to baseflow. The Thornthwaite method was used to develop an evapotranspiration water balance from temperatures and adjustment factors for this latitude (SCS, 1985). The annual baseflow runoff predicted by the SCS model was 14.6 inches (0.37 m), or 7,322 acre-ft per year (9.03×10^6 m^3/yr). Surface runoff was calculated to be 4.4 inches (0.11 m), or 2,277 acre-ft per year (2.81×10^6 m^3/yr) over the entire watershed. The total annual yield is the sum of the baseflow and surface runoff, which is equal to 9,600 acre-ft/yr (1.18×10^7 m^3/yr) or 1.37 cubic feet/second/square mile of watershed area. The hydraulic residence time calculated from the mean flow and the lake volume is 0.125 years, indicating that water in the lake is replaced an average of eight times per year.

The annual runoff calculated for this study is higher than the values reported by THCA (1989) and the value of 1.3 cubic feet/second/square mile reported by the PADER (1983). An increase was expected over the runoff predicted in earlier studies because of an increase in the amount of impervious area in the watershed. The THCA (1989) study listed the impervious area in the Core Creek watershed of 12.58 percent in 1985, with a projected increase to 18.83 percent by 1995.

Staff gage readings during the study indicated the "flashy" nature of stream flow in the Lake Luxembourg watershed. Stream flows rapidly increased during rain events and quickly returned to normal conditions. The flow was so high on the lake inlet that the first storm flattened the post holding the original staff gage. The gage was replaced and a sturdier one was installed in a more sheltered location. Staff gage readings taken during the study are included in Appendix E.

4.2 Point Source Pollutant Loads

Point sources are discharges arising from discrete, identifiable sources. Effluent limits for pollutants of concern and a specific discharge number are assigned to point source discharges by the National Pollutant Discharge Elimination System (NPDES). There are no point source pollutant discharges within the Lake Luxembourg watershed, although several agricultural and nursery operations in the watershed do represent concentrated sources of pollutants.

4.3 Nonpoint Source Pollutant Loads

The majority of the annual nutrient and sediment loads contributed to lakes often originate from nonpoint sources (Dillon and Rigler, 1974). Overland runoff of stormwater has been demonstrated to be the primary vehicle of such pollutant loads (Uttormark et al., 1974) and, as a result, land use has an important impact on lake pollutant budgets. Varying land uses contribute substantially different amounts of both the sediment that is deposited in a lake to decrease depth and the nutrients that promote the growth of algae. Most sediment and nutrient transport occurs during storm events. Eroded soils, fertilizers, heavy metals, pesticides and petroleum hydrocarbons are all constituents of storm runoff. It has been demonstrated that the majority of pollutants in stormwater are attached to the surface of sediment particles through absorption and/or adsorption reactions (Wanielista et al., 1982).

Internal processes can also contribute to nutrient and sediment loads. The bacterial decomposition of plant and animal tissue and algal cells can generate a considerable amount of nitrogen and phosphorus and can lead to the accumulation of organic sediments. Nutrients can also be liberated from lake sediments or enter a lake through groundwater flow. Because Lake Luxembourg has a relatively large watershed, groundwater inputs are expected to have a limited effect on lake pollutant budgets.

4.3.1 Nutrient Inputs from Precipitation

The relatively large size of the Lake Luxembourg watershed limits the relative importance of precipitation compared to other pollutant sources. Rainfall analyses conducted during this study were used to estimate pollutant loadings from precipitation. Concentrations (mg/L = g/m^3) of total phosphorus, total nitrogen (nitrate-N plus total Kjeldahl nitrogen) and total suspended solids (Table 3.3) were multiplied by the mean annual precipitation (45 inches/yr or 1.14 m/yr) to develop annual areal loading rates. Areal loading rates (expressed in kg/ha/yr) were multiplied by the lake surface area of 70.2 ha to determine the annual inputs from precipitation (Table 4.2). The calculated loading rates to Lake Luxembourg from precipitation were 33 kg of phosphorus, 800 kg of nitrogen and 3,440 kg of total suspended solids.

4.3.2 Internal Loading

Internal regeneration represents a source of nutrient loading to lakes that is often overlooked. Examination of temperature and dissolved oxygen profiles for Lake Luxembourg (Figure 3.2) indicates the lake is strongly stratified and subject to complete hypolimnetic oxygen depletion during the summer months. Areas as shallow as 2 m experienced some oxygen depletion from June through September, with complete oxygen depletion usually occurring at depths of 3 to 4 m. As a result, the area of the lake below the 8 foot (2.4 m) contour was calculated to approximate that portion of the lake bottom most likely to significantly contribute to internal nutrient regeneration. This portion of the lake bottom has an area of 2.70×10^5 m^2 (66.8 acres).

A number of phosphorus release rates for anaerobic sediments were reviewed (Holdren and Armstrong, 1980; Nurnberg, 1984) and a release rate of 5.0 mg/m^2/day was selected for Lake Luxembourg. The nitrogen release rate was assumed to be five times the phosphorus release rate based on previous studies (Holdren, 1983; Holdren, unpublished data). Internal nutrient regeneration is expected to be most significant during the period of June through September (122 days) when hypolimnetic oxygen depletion was noted in Lake Luxembourg.

The annual internal nutrient loadings calculated from the above data were 165 kg of phosphorus and 824 kg of nitrogen. These rates are probably conservative because internal nutrient regeneration can occur throughout the year and also in more shallow water, although release rates are much lower under aerobic conditions (Holdren and Armstrong, 1980).

4.3.3 Nutrient Loadings from Waterfowl

Lake Luxembourg supports a resident population of ducks and Canada geese. Counts taken during the monitoring study indicated about 50 to 100 ducks and 20 to 30 geese inhabit the lake on a permanent basis. Larger numbers of geese use the lake during the winter, when flocks of approximately 1,000 geese were observed for brief periods. A previous study (Manny et al., 1975) found that the average daily nutrient load from Canada geese was approximately 1.4 grams of nitrogen and 0.4 grams of phosphorus. The nutrient loading from the smaller ducks was assumed to be 40 percent of the loading from geese, or 0.56 grams of nitrogen and 0.16 grams of phosphorus per day.

Annual pollutant loadings from waterfowl were calculated by assuming that 75 ducks and 25 geese inhabit the lake on a permanent basis, and that an additional 1,000 geese inhabit the lake for 30 days each year. The annual nutrient loadings calculated under these assumptions are 70 kg of nitrogen and 20 kg of phosphorus.

4.3.4 Calculation of Nonpoint Source Pollutant Loadings from Runoff

The unit areal loading (UAL) approach (Uttormark et al., 1974; U.S. EPA, 1980) has been widely accepted for the calculation of pollutant inputs from nonpoint sources. The unit areal loading approach can also be used to develop pollutant budgets and is based on the premise that different land uses contribute different quantities of pollutants through runoff. Unit areal loadings were used in this report for the calculation of nonpoint source pollutant budgets for nutrients and total suspended solids in Lake Luxembourg. The greatest utility of the UAL approach is in its use in quantifying changes in pollutant loading with watershed development (Souza and Perry, 1977) as well as in directing watershed management techniques to those areas contributing the greatest impact to water quality degradation.

Pollutant export coefficients compiled by Uttormark et al. (1974), Reckhow et al. (1980) and the U.S. EPA (1980) were evaluated, and the field validated unit areal loading coefficients developed in the U.S. EPA (1980) and modified by Souza and Koppen (1983) were used to compute annual phosphorus and nitrogen loadings from tributary and overland runoff. Export coefficients are typically reported in units of kg/ha/year, which are approximately 10 percent higher than the corresponding English units of lb/acre/year. Export coefficients for total suspended solids were derived from soil losses for southeastern Pennsylvania reported by the PADER (1983). The reported annual erosion rates of 12.2 tons/acre for row crops, 0.2 tons/acre for forest and 3.7 tons/acre for pasture and other uses were converted to export coefficients by assuming a 10 percent delivery ratio to the lake (Brzostek, 1992a). The calculated export coefficients were 2,735 kg/ha/yr, 45 kg/ha/yr, and 830 kg/ha/yr for row crops, forest and pasture/other, respectively.

The product of the area of each land use and the assigned export coefficient provided the total pollutant loading. Note that other ponds and wetlands in the watershed serve as sinks for suspended solids and total phosphorus, resulting in negative loadings for these land uses. Nonpoint source pollutant loadings for the Lake Luxembourg watershed determined by the unit areal loading method are summarized in Table 4.1. Annual pollutant loadings from runoff calculated by this method were 2,340 kg of phosphorus, 45,500 kg of nitrogen and 3,596,000 kg of total suspended solids.

Relative pollutant loadings from different land uses are summarized in Table 4.2. It is readily seen that agricultural land used for row crops contributes the majority of the nutrient and suspended solids loads to Lake Luxembourg. Row crops comprise about one third of the total area of the Lake Luxembourg watershed but contribute 55.9 percent of the phosphorus, 71.8 percent of the nitrogen and 62.1 percent of the total suspended solids that enter the lake through runoff. Residential and commercial land also contribute relatively large phosphorus loadings, with residential land also contributing a high solids load. Nurseries contribute a disproportionately high nitrogen load.

4.3.5 Pollutant Loadings Calculated from Monitoring Data

There was no significant correlation between nitrogen concentrations and streamflow measured during this study, but concentrations of both total phosphorus and total suspended solids generally increased during storm events. To account for these differences, pollutant concentrations measured in the routine samples were multiplied by the annual base flow of 9.03×10^6 m^3/yr and pollutant concentrations from storm samples were multiplied by the annual stormwater runoff of 2.81×10^6 m^3/yr calculated from the hydrologic budget. The mean concentrations reported in Table 3.3 were used for the storm samples, but the 10 July 1991 runoff samples were not used in determination of the average for routine samples because the total phosphorus and total Kjeldahl nitrogen concentrations on that date were not in line with values from other samples for similar flows.

The total annual pollutant loadings calculated from the monitoring data were 3,365 kg of phosphorus, 70,800 kg of nitrogen and 2,173,000 kg of total suspended solids. Both the phosphorus and nitrogen loadings were approximately 50 percent higher than those calculated from unit areal loading data, while the total suspended solids loadings was about 50 percent lower. Because both methods involve a number of assumptions, and because monitoring data was limited, the agreement between the two methods is within expected limits.

Results obtained from storm samples indicated that concentrations of total suspended solids increase with stream discharge but vary widely. Suspended solids

Table 4.1. Unit Areal Loadings for Lake Luxembourg

Land Use	Area (ha)	Parameter	Runoff Coeff. (kg/ha/yr)	Annual Load (kg/yr)
Row crops	817.1	Total P	1.6	1,307
	817.1	Total N	40.0	32,684
	817.1	TSS	2,735	2,234,769
Pasture/Grass	83.4	Total P	0.6	50
	83.4	Total N	14.0	1,168
	83.4	TSS	830	69,222
Nurseries	124.0	Total P	1.6	198
	124.0	Total N	40.0	4,960
	124.0	TSS	2,735	339,140
Park	127.8	Total P	0.3	38
	127.8	Total N	5.0	639
	127.8	TSS	830	106,074
Institutional	60.0	Total P	0.5	30
	60.0	Total N	7.0	420
	60.0	TSS	830	49,800
Residential	726.3	Total P	0.5	363
	726.3	Total N	4.0	2,905
	726.3	TSS	830	602,829
Commercial	184.4	Total P	1.6	295
	184.4	Total N	10.0	1,844
	184.4	TSS	830	153,052
Forested	257.1	Total P	0.2	51
	257.1	Total N	2.5	643
	257.1	TSS	45	11,570
Barren	14.3	Total P	1.2	17
	14.3	Total N	20.0	286
	14.3	TSS	2,735	39,111
Wetland	41.4	Total P	-0.25	-10
	41.4	Total N	0.0	0
	41.4	TSS	-200	-8,280
Open Water	6.9	Total P	-0.25	-2
	6.9	Total N	0.0	0
	6.9	TSS	-200	-1,380
Total Pollutant Load	2,442.7	Total P Load		2,339
	2,442.7	Total N Load		45,549
	2,442.7	Total SS Load		3,595,906

Table 4.2. Unit Areal Loading Summary for Lake Luxembourg

Land Use	Area (%)	Total Phosphorus (%)	Total Nitrogen (%)	Total Suspended Solids (%)
Row crops	33.5	55.9	71.8	62.1
Pasture/Grass	3.4	2.1	2.6	1.9
Nurseries	5.1	8.5	10.9	9.4
Park	5.2	1.6	1.4	2.9
Institutional	2.5	1.3	0.9	1.4
Residential	29.7	15.5	6.4	16.8
Commercial	7.5	12.6	4.0	4.3
Forested	10.5	2.2	1.4	0.3
Barren	0.6	0.7	0.6	1.1
Wetland	1.7	-0.4	0.0	-0.2
Open Water	0.3	-0.1	0.0	0.0
Total Watershed	100.0	100.0	100.0	100.0

concentrations in the storm samples averaged 667 mg/L, but ranged from 4 mg/L to 2,000 mg/L. Measured discharge also varied by several orders of magnitude. As a result of this variation, the pollutant budgets calculated from monitoring data are expected to have a much greater degree of uncertainty than those obtained from unit areal loadings.

4.3.6 Total Pollutant Loadings

The total nonpoint source pollutant loadings to Lake Luxembourg were determined by adding contributions from direct precipitation, internal loading and nonpoint source runoff. Total pollutant loadings are summarized in Table 4.3. Runoff contributes more than 91 percent of the total phosphorus, more than 96 percent of the total nitrogen and more than 99 percent of the total suspended solids to Lake Luxembourg. Internal loading during the summer stratification period accounts for approximately 6.5 percent of the total phosphorus loading and less than 2 percent of the total nitrogen loading to the lake. Nutrient loadings from precipitation and waterfowl each contribute less than 2 percent of the total nitrogen and phosphorus budgets for Lake Luxembourg.

Table 4.3 - Pollutant Budget Summary

Source	Total P Load (kg/yr)	Total N Load (kg/yr)	Total Solids Load (kg/yr)
Precipitation	33	800	3,440
Internal Loading	165	824	--
Waterfowl	20	70	--
Runoff (UAL)	2,340	45,500	3,596,000
Runoff (Monitoring Data)	3,365	70,800	2,173,000
Total (UAL)	2,560	47,200	3,599,000
Total (Monitoring Data	3,580	72,500	2,176,000

4.4 Trophic State Analysis

An information base consisting of lake morphometry, watershed characteristics, pollutant loading, hydrologic loading and lake water quality data was assembled in previous sections. This section integrates this information to quantify the trophic state of Lake Luxembourg. Trophic state is a relative description of biological productivity (U.S. EPA, 1980). That is, it is an expression of the amount of algae, plants, fish and other forms of life that can be supported in the lake. Emphasis is usually placed on transparency and on the growth of algae and aquatic plants since these are the factors that are used by most lake users to evaluate the recreational potential of a lake.

4.4.1 Trophic State Assessment

Eutrophication is the natural aging process which results from sediments and nutrients from the watershed accumulating in a lake. The eutrophication process is often accelerated by the activities of man. Eutrophication is characterized by an increase in the number of living organisms in a lake, but this biomass is usually comprised of relatively few species. In contrast, an oligotrophic lake is characterized by relatively small populations of many diverse organisms. Mesotrophic lakes have conditions intermediate between eutrophic and oligotrophic lakes.

The trophic state of a lake is a relative expression of the biological productivity of a lake. The Trophic State Index (TSI) developed by Carlson (1977) is among the most commonly used indicators of lake trophic state. The Carlson Trophic State Index is actually composed of three separate indices based on levels of total phosphorus concentrations, chlorophyll *a* concentrations, and Secchi depths from a variety of lakes. These variables were selected for the index because phosphorus often is the nutrient limiting algal growth, chlorophyll *a* provides an indication of algal biomass and Secchi depth is the most common measure of the transparency of lake water.

Mean values of total phosphorus, chlorophyll *a*, and Secchi depth for an individual lake are logarithmically converted to a scale of relative trophic state ranging from 1 to 100. Increasing values for the Trophic State Index are indicative of increasing trophic state, with indices of 40, 50, and 60 representing mesotrophic, meso/eutrophic, and eutrophic conditions, respectively. Index values above 70 can be considered indicative of hypereutrophic, or extremely productive, conditions. Higher numbers are associated with increased probabilities of encountering nuisance conditions such as aesthetic problems and algal scums.

Trophic state indices for Lake Luxembourg are presented in Table 4.4. These values were calculated using surface water data collected during the monitoring program for the months of May through September because Carlson (1977) suggested that summer average values may produce the most meaningful results. The trophic state indices indicate Lake Luxembourg would be considered hypereutrophic at the present time. The index based on chlorophyll *a* concentrations is lower than the other two indices, probably because the growth of algae in Lake Luxembourg is at least partially limited by light penetration as a result of the high turbidity in the lake.

Table 4.4 - Trophic State Indices for Lake Luxembourg

Location	Trophic State Index		
	Total Phosphorus	Secchi Depth	Chlorophyll *a*
Station 1	79.1	75.1	70.2
Station 2	74.4	73.6	71.2
Mean	76.7	74.3	70.7

Lake trophic state can also be assessed by comparing monitoring data to trophic state criteria, such as those developed by the U.S EPA (1980). Table 4.5 presents a comparison of monitoring data from Lake Luxembourg to EPA trophic state criteria. These criteria, like calculated trophic state indices, are based on somewhat arbitrary concentrations that are typically found when the average lake user perceives that water quality problems exist. Comparisons of monitoring data to trophic state criteria also clearly indicate that Lake Luxembourg would be considered hypereutrophic.

Table 4.5 - Comparison of Lake Luxembourg Monitoring Data to U.S. EPA Trophic State Criteria

Trophic State	Characteristic			
	Spring Total P (mg/L)	Chlorophyll *a* (μg/L) Summer	Secchi Depth (m)	Relative Productivity
Oligotrophic	< 0.005	< 2.0	> 8	Low
Mesotrophic	0.005 - 0.030	2.0 - 6.0	4 - 8	Moderate
Eutrophic	0.030 - 0.100	6.0 - 40.0	2 - 4	High
Hypereutrophic	> 0.100	> 40.0	< 2	Excessive
Lake Luxembourg	0.130	59.7	0.37	--

4.4.2 Trophic State Modeling

Although the use of trophic state variables and trophic state indices for classifying lake trophic state is straightforward, it is also somewhat flawed. These techniques may generate erroneous results for lakes that have significant internal phosphorus loading, lakes that are highly-colored or that have high amounts of inorganic turbidity, and lakes that support significant weed growth but little algae growth. Because of these limitations, lake managers and limnologists have developed a variety of mathematical models to quantitatively evaluate lake productivity. These models are designed to yield a value that can be used to rank and classify lake productivity with much less ambiguity than the use of trophic state variables.

Trophic state modeling consists of the quantification of a lake's relative potential productivity by regression analysis of nutrient, hydrologic and morphometric data (Uttormark et al., 1974). A number of different models have been developed for this purpose, but most are very similar in their mathematical origin. In general, these models can be used to evaluate the effects of land use and various pollutant sources on lake water quality without relying on extensive field studies (Coffey et al., 1989). The models generate a concise value and are less subjective and more precise than the use of trophic state indices. They also allow for the prediction of changes in water quality variables, such as transparency and productivity, that arise from changes in land use, pollutant loading or lake management strategies. As a result, these models can be used effectively as planning and management tools.

Most trophic state models are based on field measurements and empirical data. Since such data can be very site specific, the use of a model in a region other than where it has been verified can generate erroneous information. Several different models, each verified for use with northern temperate lakes, were used in this study. The morphometric, hydrologic, and nutrient loading data were used to model phosphorus retention in Lake Luxembourg using both mechanistic (Dillon and Rigler, 1974; Vollenweider, 1976) and empirical (Walker, 1977) models. The Walker model can be used to provide a quantitative prediction of lake trophic state. In addition, the Vollenwieder (1976) model for determining chlorophyll *a* productivity was also evaluated. Emphasis was placed on the role of phosphorus in determining the productivity because the monitoring program demonstrated that phosphorus is the limiting nutrient in Lake Luxembourg.

The Dillon and Rigler (1974) model is one of the most commonly-used models for the prediction of phosphorus concentrations in lakes and has the form:

$$[TP] = L(1-R)/\rho z \qquad (1)$$

where [TP] = annual mean phosphorus concentration (g/m^3), L = areal phosphorus loading (g/m^2/yr), R = phosphorus retention, ρ = flushing rate (yr^{-1}), and z = mean depth (m). Values for ρ and z for Lake Luxembourg are 8.0 year^{-1} and 2.1 m, respectively. Values for L calculated from total phosphorus loadings from UAL and watershed monitoring data are 3.65 and 5.10 g/m^2/yr, respectively. A value for R is calculated from the equation developed by Larsen and Mercier (1976):

$$R = 1/[1 + \sqrt{\rho}] \qquad (2)$$

The phosphorus retention coefficient for Lake Luxembourg calculated from Equation 2 is 0.26. When Equation 2 is used to calculate R, then the Dillon and Rigler (1974) model is identical to the Vollenweider (1976) model:

$$[TP] = (L/q_s)(1/[1 + \sqrt{(z/q_s)}]) \qquad (3)$$

where q_s = areal water load (m/yr) = z/τ_w = 16.9 m/yr and τ_w = hydraulic residence time (yr) = 0.125 yr. Since $z/\tau_w = \rho z$, Equations 1 and 3 are the same.

The total phosphorus concentrations calculated from this equation are 0.160 and 0.223 mg/L for the unit areal loading and monitoring data, respectively. The former is in excellent agreement with the observed total phosphorus concentration of 0.160 mg/L from the monitoring program.

The empirical model developed by Walker (1977) is considered to be very robust. That is, the model is capable of generating reasonably accurate results even when used with a limited database. The model has the form:

$$[P_s] = (L\tau_w/z) \times (1 + 0.824\tau_w^{0.454}) \quad (4)$$

where $[P_s]$ = spring phosphorus concentration (g/m^3), L = areal phosphorus load ($g/m^2/yr$), τ_w = hydraulic residence time (yr), and z = mean depth (m). Hydraulic residence time is the inverse of flushing rate and is equal to 0.125 yr.

The spring total phosphorus data is important in that it provides an estimate of the amount of phosphorus available for utilization by primary producers at the onset of the growing season. It provides a more representative estimate of potential lake productivity than the mean summer total phosphorus concentration, although there was little variation in total phosphorus concentrations observed in Lake Luxembourg (Figure 3.7). Phosphorus concentrations predicted by the Walker model were 0.164 and 0.229 mg/L for the unit areal loading and monitoring program total phosphorus loads, respectively, and are again in good agreement with observed results.

The above modeling results indicated that the Dillon and Rigler (1974), Vollenweider (1976) and Walker (1977) models can all predict phosphorus concentrations in Lake Luxembourg and can be used to evaluate potential management alternatives. The results also indicate that the phosphorus loadings calculated from unit areal loading data may be more representative of actual conditions that those calculated from the data collected during the monitoring program.

The Walker (1977) model can also be used to quantify the potential for a lake to reach a given degree of productivity by using the relationship:

$$X = L\,[q_s(1 + 0.824 \times \tau_w^{0.454})]^{-0.815} \quad (5)$$

where the logarithm of X, the trophic state value, can be used to determine the probability of a lake being eutrophic. Calculations indicate that current phosphorus loadings give Lake Luxembourg a 99.8 percent probability of being eutrophic and that reductions in phosphorus loadings of 91 percent would be required to bring water quality into the mesotrophic range. It should be noted that the desired recreational uses of the lake could be maintained without this full degree of phosphorus reduction.

It must be emphasized that this model calculates the probability of a lake being eutrophic, mesotrophic or oligotrophic, but it does not indicate the degree of eutrophication. Eutrophic lakes span a wide range of conditions and it is possible for two lakes with the same probability of eutrophication to have entirely different water quality, algal growth and weed growth conditions. This may in part be due to specific lake characteristics such as volume, surface area, mean depth and flushing rate.

Although limnologists and lake managers routinely use phosphorus concentrations as an indicator of lake quality, a more illustrative interpretation of trophic state can be achieved by determining the amount of productivity that can be sustained by a given amount of phosphorus loading. It is expected that higher phosphorus loadings will lead to additional algal growth.

Vollenwieder (1976) also presented a model for the prediction of chlorophyll *a* concentrations in lakes. The model is similar to the total phosphorus model presented in Equation 3 and has the form:

$$[\text{Chlorophyll } a] = 0.367 \times \{(L/q_s)(1/[1 + \sqrt{(z/q_s)}])\}^{0.91} \quad (6)$$

The model predicts a chlorophyll *a* concentration of 69.2 μg/L based on phosphorus loadings from unit areal loading data for Lake Luxembourg. This concentration is in good agreement with the observed summer chlorophyll *a* concentration of 59.7 μg/L, especially when considering that phytoplankton growth in Lake Luxembourg may be at least partially limited by light penetration.

To translate the impacts of different nutrient loading rates and chlorophyll *a* concentrations on water quality into terms that are meaningful to most recreational users is a complex task. Walmsley and Butty (1979) proposed some typical relationships between maximum chlorophyll *a* concentrations and observed impacts (Table 4.6) to describe lake user perception of water quality. The information presented in Table 4.6 indicates Lake Luxembourg currently has an excessive rate of productivity. Phosphorus loading reduction of nearly 60 percent would be required for improvement to less than severe nuisance conditions, and reductions of about 88 percent would be required before no problems were evident.

Table 4.6 - Impact of Chlorophyll *a* Concentrations on Perceived Water Quality

Chlorophyll *a* Concentration	Nuisance Value
0 to 10 μg/L	No problems evident
10 to 20 μg/L	Algal scums evident
20 to 30 μg/L	Nuisance conditions encountered
Greater than 30 μg/L	Severe nuisance conditions encountered

Tolerable loading = current annual load − 88%.
88% reduction

[illegible] [illegible] [illegible]
not [illegible]
[illegible]
[illegible]

max load can be 7 x 10 x 100
+ pull # out of hat.
max has to be 7
than [illegible]
[illegible]

5.0 Evaluation of Lake and Watershed Management Alternatives

Information from the limnological survey of Lake Luxembourg and the lake pollutant budgets identified water quality problems and pollutant sources. Existing water quality problems include eutrophic conditions leading to extensive algal blooms and oxygen depletion in lake bottom waters. Runoff from the watershed and algal blooms result in a very low transparency in Lake Luxembourg during all seasons.

A number of potential lake and watershed management alternatives were evaluated to improve lake water quality and control pollutant inputs from the watershed. Those alternatives deemed suitable for the restoration of Lake Luxembourg are discussed in detail in the following sections.

5.1 Watershed Management

Pollutants enter Lake Luxembourg primarily through runoff from the watershed. This source is responsible for nearly all of the phosphorus, nitrogen and suspended solids entering Lake Luxembourg. As a result, any management plan for Lake Luxembourg must focus on watershed management activities to provide meaningful results. Watershed management methodologies are typically aimed at correcting the primary causes of lake degradation (U.S. EPA, 1986). These methods attempt to limit the loading of sediments and nutrients entering the lake. They are often more costly than in-lake techniques, but have more long-term positive impacts.

The fundamental objective of watershed management activities is to reduce external nutrient, sediment and contaminant loadings. If a sufficient degree of control can be exerted over such sources, then long-term effective management and improvements of lake trophic state can be achieved. The restoration and management plan for Lake Luxembourg focuses on watershed management methods to reduce pollutant loadings to the lake. Proven management alternatives, including stormwater detention and retention basins and enforcement of existing regulations, are included in the suggested alternatives.

The implementation of a variety of agricultural BMP's is suggested to provide watershed management for the Lake Luxembourg Phase II project. The SCS and ASCS have identified potential sites for the installation of the suggested BMP's. Exact locations for the BMP's implemented during the proposed restoration project would be determined following discussions with local land owners.

5.1.1 Implementation of Agricultural BMP's

The pollutant budgets developed for Lake Luxembourg indicated runoff from crop land contributed the majority of the nutrients and suspended solids entering the lake. The USDA, Soil Conservation Service (Brzostek, 1992b), in cooperation with the Bucks County Conservation District and the ASCS also found that excessive soil erosion and associated soil nutrient loss were the principal problems In the watershed and developed an Agricultural Conservation Program (ACP) project application to address these problems. The findings and recommendations of the Brzostek (1992b) application are presented below.

Approximately 60 percent of the Lake Luxembourg watershed is farmland, and an estimated 2,100 acres (850 ha) of this farmland has inadequate treatment to control soil erosion. Soil erosion is a particular problem in this area because approximately 70 percent of the soils in the Lake Luxembourg watershed are classified as highly erodible, with an erodibility factor of 0.32 or greater (Brzostek, 1992a).

There are 42 owners of tracts who operate or lease their land to agricultural operators in the Lake Luxembourg watershed. Many of the operators in the area have intense agricultural operations, with principal crops consisting of vegetables, nursery stock, corn, soybeans and small grains. The USDA, Soil Conservation Service, the Bucks County Conservation District and the ASCS have all worked extensively in the Lake Luxembourg watershed and have identified those areas which would benefit from the implementation of agricultural BMP's.

The most cost-effective practices required to solve the conservation problems in the Lake Luxembourg watershed are the use of no-till or conservation tillage, cover cropping, terraces, diversions, waterways, structures for water and sediment control, buffer strips, streambank protection and, where feasible, stripcropping and seedings. With the exception of cover cropping and seedings, all of these practices are currently being used under the annual cost share program.

No-till and conservation tillage, stripcropping and contour farming all involve modifications to conventional agricultural practices to control erosion. No-till and conservation tillage control erosion by reducing the amount of barren ground, while stripcropping and contour farming reduce runoff velocities. In addition to erosion control, residual nitrogen from legume cover crops enhances the soil for commercial crops and may reduce requirements for fertilizations. Seedings also reduce erosion by increasing the amount of cover and slowing runoff velocities.

Terraces and diversions are earth embankments that intercept runoff water and control erosion. They are often used in conjunction with contouring, stripcropping and reduced tillage methods. The effectiveness of terraces for reducing sediment loss can range from 50 to 98 percent.

Grassed waterways are designed to facilitate the safe disposal and transmission of surface runoff. The effectiveness of grassed waterways to remove sediments from runoff has not been well documented. Buffer strips are also vegetated areas which intercept storm runoff, reduce runoff velocities, and filter out runoff contaminants. Their effectiveness in removing pollutants can range from 30 to over 95 percent, depending on local conditions.

Streambank erosion can be a significant source of direct soil loss. Streambank protection measures are designed to reduce erosion in these critical areas.

Sediment basins detain stormwater and release it at a controlled rate. There are two types of impoundments. Detention basins that temporarily store runoff have typical sediment removal efficiencies of about 40 percent, while retention basins providing permanent water storage can have removal efficiencies of 80 percent or higher.

Some additional, more expensive BMP's are also recommended to meet some special needs in the watershed. These include animal waste storage structures, pesticide containment structures and wastewater filtration systems. Implementation of these BMP's will serve primarily to reduce nutrient loadings and to control potential sources of chemical contamination.

An animal waste storage structure can be either an above-ground fabricated structure or an excavated pond that is designed to reduce water pollution by controlling liquid and solid wastes. Wastes can be disposed of by controlled application to cropland. Animal waste storage structures can result in significant nutrient reductions because the wastes treated by these structures contains nutrients in mobile forms. Wastewater filtration systems are also designed to treat concentrated waste sources and can result in significant nutrient reductions.

Many agricultural operations involve the use of pesticides, and this is especially true in the Lake Luxembourg watershed because of the presence of several nurseries. Pesticide containment structures are recommended for some of the larger operations to a spill that could lead to chemical contamination of the lake.

The recommended agricultural BMP's for the Lake Luxembourg watershed are summarized in Table 5.1. The amount required, cost share and estimated soil loss reduction are provided for each practice.

It is estimated that average soil loss per acre per year on cropland in the Lake Luxembourg watershed is 15 tons (33,600 kg/ha/yr). The implementation of the conservation practices listed in Table 5.1 would reduce this rate to 3 tons per acre per year (6,700 kg/ha/yr) and would result in a reduction in annual soil loss of 25,200 tons (22,900 metric tons) for the watershed. If an average lifespan of 10 years is used for each practice, then the cost of each ton of soil saved is $1.01 (Brzostek, 1992b).

Table 5.1 - Recommended Agricultural BMP's for the Lake Luxembourg Watershed

Conservation Practices	Amount Required	Soil Loss Reduction (tons/acre/yr)	Cost Share	
			Rate	Total Cost
No-till/Conservation Tillage	700 acres	1 to 5	$12/acre	$8,400
Cover Cropping	1,500 acres	1 to 3	$17/acre	$25,500
Terraces	150,000 ft	3 to 20	$2.00/ft	$300,000
Diversions	50,000 ft	3 to 12	$1.50/ft	$75,000
Diversion Seeding	50 acres	-	$170/acre	$8,500
Waterways	20,000 ft	15 to 60	$1.90/ft	$38,000
Waterway Seeding	20 acres	-	$170/acre	$3,400
Structures	30	5 to 10	$618/unit	$18,540
Seedings	100 acres	-	$170/acre	$17,000
Stripcropping	100 acres	5 to 10	$11.00/acre	$1,100
Contour Farming	500 acres	3 to 5	$8.00/acre	$4,000
Sediment Basins	10	5 to 10	$3,500 each	$35,000
Buffer Strips	200 acres	5 to 10	$170/acre	$34,000
Streambank Protection	5,000 feet	15 to 60	$5/foot	$25,000
Animal Waste Storage Structures	5	-	$25,000 each	$125,000
Pesticide Containment Structures	5	-	$10,000 each	$50,000
Wastewater Filtration Systems	2	-	$25,000 each	$50,000
Total Cost				**$818,440**

5.1.2 Establishment of a Buffer Area for Waterfowl Control

Although waterfowl had only minor impacts on nutrient budgets for Lake Luxembourg, their droppings create both sanitary and aesthetic problems for lake users. The establishment of a vegetated buffer strip around Lake Luxembourg would represent a low-cost method of providing goose control while at the same time providing a buffer strip that would help reduce nutrient and sediment inputs from adjacent lands. The buffer area would serve primarily to help reduce the use of the lake by large congregations of Canada geese. The buffer strip would also help serve the functions of stabilizing the shoreline to prevent erosion, reducing other pollutant loads (i.e, bacteria, oil and grease), preventing wind-blown debris from entering the lake and serving as habitat for various wildlife species.

The buffer strip would consist of a combination of unmowed grass areas and clusters of shrubs in designated areas (Figure 5.1). The added shrubs would be plants of medium height (0.5 to 1 m or 1.5 to 3 ft) that would create a natural fence to limit easy passage of waterfowl to and from the lake. The plantings are designed to be high enough to screen the lake from geese in the grass and inhibit them from being on lawn areas.

The plantings are low enough so that pedestrians can see the lake and maintain aesthetic appeal for park users. Access paths are designed diagonally or on a curved path so fisherman can easily cross the buffer. The access paths and a strip between the lake edge and the shrubs are the width of a riding lawn mower so that maintenance is easy and requires no special equipment. Unmowed grass areas can be mowed once a year to be maintained as high grasses.

The shrub areas will average 20 to 30 feet (6 to 9 m) in width and would contain approximately 100 shrubs for every 1,000 feet (300 m) of shoreline. The cost for balled and burlapped, nursery grown shrubs is estimated to be $12 each, with an installed cost of $20 to $30 each. Planting shrubs bareroot would reduce the cost by one-fifth, or approximately $500 per 1,000 feet of shoreline. Therefore, total costs would range from $1,500 to $3,000 per 1,000 feet of shoreline. The unmowed areas would not have an additional cost and may actually result in reductions in maintenance costs.

It is recommended that 2,000 feet of identified areas with eroding shoreline receive these plantings to test their effectiveness and acceptance by the public. Total costs for the implementation of this alternative would be about $5,000, some of which could be contributed labor by Parks Department staff.

5.2 In-Lake Restoration Measures

In-lake restoration measures are aimed at enhancing the viability of lakes by alleviating specific symptoms of eutrophication (U.S. EPA, 1980). Although these

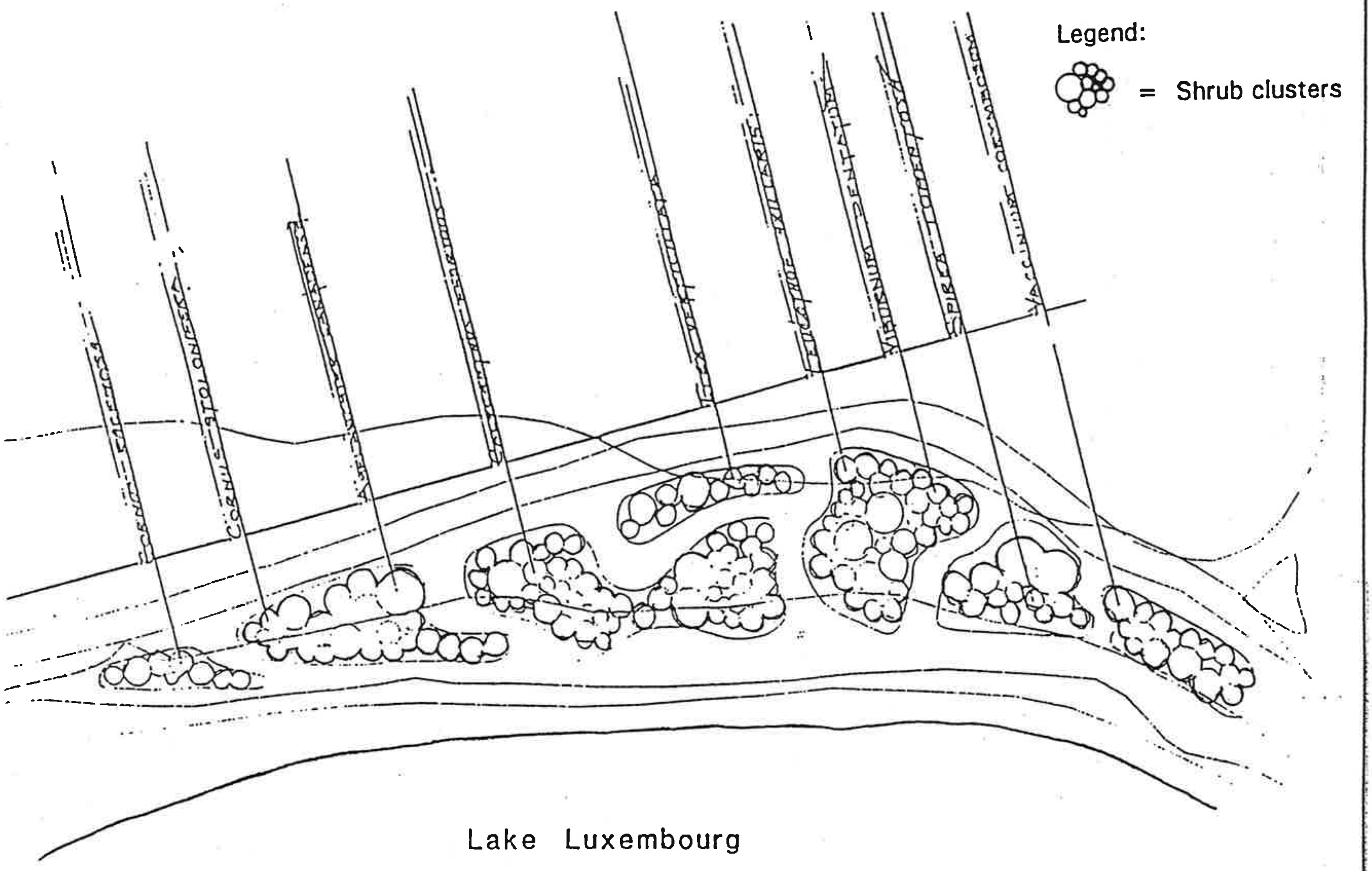


Figure 5.1. Planting Schematic for waterfowl control.

COASTAL

measures typically provide only short-term relief without controlling pollutant sources, they can substantially improve the aesthetic and recreational potential of the lake and help gain public support for the restoration program while long-term management practices are being implemented. Potential in-lake restoration measures for Lake Luxembourg are discussed below.

5.2.1 Dredging

Dredging projects have the immediate benefit of removing silt accumulations to restore portions of a lake to its original depth and can also produce some water quality benefits. Dredging is often relatively expensive when compared to other lake restoration methods; however, the costs of dredging are often offset by the long-term benefits.

The bathymetric survey of Lake Luxembourg indicated that significant amounts of sediment have accumulated in the lake. There are approximately 2.81×10^5 m^3 (228 acre-ft) of sediment in the main body of the lake and an additional 1.82×10^4 m^3 (15 acre-ft) of sediment in the portion of the lake north of Woodbourne Road. It is probably not economically feasible to remove all of this sediment; however, a selective dredging project could result in water quality benefits for Lake Luxembourg.

Dredging methods can be divided into the broad categories of in-lake dredging and drawdown and excavation. In-lake dredging includes methods which do not necessitate a complete drawdown of the lake, such as dragline and hydraulic dredging. Drawdown and excavation involves the actual drainage of the lake and the removal of sediment by the use of specialized earthmoving equipment. Costs and the availability of adequate disposal sites are usually the factors determining which method is more appropriate for any given situation. Either method would appear feasible for Lake Luxembourg, and it is likely that costs will determine which is the method of choice.

Dredging often has significant environmental impacts on lake ecosystems. Both types of dredging cause destruction of the benthic community, including fish food organisms. If the entire lake basin is dredged, two to three years may be required to re-establish the benthic fauna. Problems with hydraulic dredging often occur as a result of the resuspension of sediments and nutrients during the dredging operation, although the existing high turbidity in Lake Luxembourg and the continued improvement of hydraulic dredging equipment would minimize these adverse impacts.

Dredging to depths below the photic zone can also reduce aquatic weed growth by limiting the amount of available light. Dunst and Beauheim (1979) found the following empirical relationship could be used to estimate the maximum depth of macrophyte growth:

$$y = 2.73 + 1.22x \tag{7}$$

where y = maximum depth of growth (feet) and x = Secchi disk transparency (feet), for which the mean is 0.34 m or 1.1 feet in Lake Luxembourg.

There are currently no submerged macrophytes in Lake Luxembourg because of low transparency. Equation 7 predicts a maximum depth for macrophyte growth of 4.1 ft (1.2 m) in Lake Luxembourg, and most of the lake is deeper than this. Although dredging would not have a major effect on macrophyte growth under current conditions, dredging to prevent macrophyte growth could be an important benefit if watershed management practices succeed in controlling the sediment load to Lake Luxembourg.

The size and location of disposal areas is one of the major concerns with any dredging project. Hydraulic dredging usually requires a large disposal site to handle the large volume of water which is pumped along with the sediments. In addition, chemical treatment of the effluent from the disposal area is sometimes necessary to ensure that a sufficient portion of the nutrients and suspended solids precipitate out of the water. Sediments which have already been dewatered in the lake bottom do not need as much disposal area.

Dredging costs increase as the distance to the disposal area increases, especially for mechanical dredging projects where trucking costs are often greater than the cost of sediment removal. As a result, dredge spoil disposal sites should be located as close to the lake as possible. There are several areas near Lake Luxembourg that would appear to provide adequate disposal areas for either a mechanical or hydraulic dredging project. These areas include undeveloped parkland to the northeast of the lake and farmland near the northern end of the lake. The proximity of these sites to Lake Luxembourg would help minimize the costs of a dredging project.

Typical sediment removal costs for hydraulic dredging projects are $5/cubic yard. Earthmoving costs for mechanical dredging projects can also be in this range if the lake sediments can be adequately dried to allow access with conventional earthmoving equipment. Mobilization/demobilization and disposal site preparation costs would be expected to increase the cost to about $10/cubic yard if hydraulic dredging is selected for Lake Luxembourg. Trucking and sediment handling costs can increase the cost of a mechanical dredging project to $10 to $20/cubic yard, or even higher if the disposal site is in a remote location. Engineering and permitting costs typically raise the prices an additional 10 percent. Because adequate disposal areas are located near the lake, a total cost of $12/cubic yard would appear to be a conservative estimate for a dredging project.

The implementation of a mechanical dredging project following lake drawdown is recommended for Lake Luxembourg. The area of the lake north of Woodbourne Road has been acting as an in-lake sedimentation basin, and the return of this area to its original depth would improve sediment trapping efficiency and help protect water quality in the rest of the lake.

There are an estimated 23,900 cubic yards of sediment in the area of Lake Luxembourg north of Woodbourne Road. Total costs for the design and implementation of a dredging project in this part of the lake are estimated to be $286,800. Sediment could be stockpiled in areas adjacent to the lake and spread on nearby field for disposal. This disposal method would minimize costs and return some of the sediment to those areas from which it was eroded.

Additional sediments could be removed from shallow areas in the lake to help prevent nuisance macrophyte growth as water clarity in the lake improves. Additional sediment from the main body of the lake could be removed at a later date as finances allowed if Bucks County determines that it is worthwhile to restore some or all of the volume of the conservation pool. It should be noted that this additional dredging would have little benefit to water quality or to the recreational uses of the lake. Costs for a larger dredging project should decrease to the $5 to $10/cubic yard range because of the economies of scale involved.

5.2.2 Lake Drawdown

Lake drawdown is a low-cost management option that can have several benefits. Drawdown prior to a dredging project results in consolidation of the sediments to reduce the volume of material which would be removed. Consolidation is the gradual decrease in water content of a saturated soil under load and usually results in a significant decrease in volume and rearrangement of the soil structure. Consolidation of sediments is largely irreversible and little re-swelling occurs after a lake is refilled (Dunst et al., 1974). As a result, a complete drawdown of Lake Luxembourg would reduce sediment volumes even in those areas which are not dredged.

Recreation would be severely curtailed during the time that lake levels were low, but a winter drawdown would minimize the effects on recreation and would also permit a more detailed analysis of sediment accumulation in the lake.

One of the main advantages of lake drawdown is the low cost. Costs for lowering the water level in Lake Luxembourg would be minimal because the dam is equipped with a control structure that allows the lake to be drained. The only costs involved would be those associated with obtaining the necessary permit for lowering the lake level.

A complete drawdown is also the simplest and most effective management option for dealing with the unbalanced fish community in Lake Luxembourg. Drawing down and reclaiming the lake is the only viable way to eliminate the gizzard shad and white perch, as heavy predator stocking is not likely to achieve population control of these species. A full drawdown would also facilitate the recommended dredging program and would permit an assessment of sediment accumulations in deeper areas of the lake. In addition, drawdown would facilitate the placement of habitat improvement devices.

The Pennsylvania Fish Commission has indicated their support for a drawdown in Lake Luxembourg following a survey to confirm the current status of the lake's fishery (Wnuk, 1992). A drawdown of 6 to 8 feet (2 to 2.5 m) would be sufficient for dredging the area north of Woodbourne Road, while a more complete drawdown could be made if the fish survey confirmed the need for a complete rehabilitation of the fishery.

5.2.3 Environmental Landscaping and Shoreline Stabilization

There are 6,360 feet (1,940 m) of Lake Luxembourg shoreline that could benefit from erosion control. The landscaping recommended for waterfowl control (Section 5.1.2) would treat 2,000 feet of eroding shoreline, and additional environmental landscaping and public access improvements could be incorporated into some of the remaining area.

Shoreline stabilization would require redesign and regrading of eroding shoreline, which could be best accomplished during a lake drawdown. Lake access can be improved by the creation of a "scalloped edge" along about 500 feet of eroding shoreline. A section of the scalloped edge would produce 5 to 10 embayments, each about 25 feet wide with associated peninsulas also approximately 25 feet wide (Figure 5.2). The lakeward edge of the embayment should be two to three feet deep, and slope gently (three percent) up towards the shore. A combination of yellow flag, blue flag, pickerel weed and arrow arum, all planted as plugs, should be introduced along the shoreline. Approximately 8,400 square feet of these littoral plantings would be installed, with the greatest concentration of plants directly on the shoreline. These plantings will provide aesthetic appeal and also provide habitat for fish and aquatic organisms. The combination of plants and redesigned shoreline will also increase the visual appeal of the lake and create a better integration of the park and the lake than now exists.

The peninsulas created between the embayments should be seeded with a wetland grass seed mix and/or with grasses tolerant of foot traffic. These peninsulas will enable park use to expand out into the lake. The lakeward edge of the peninsulas should be rip-rapped to create approximately 11,780 square feet of hard surface for walking, standing or fishing. If desired, some of the access peninsulas could be decked and/or could be equipped with seating benches to ensure easy access for handicapped individuals.

The total cost of this option is $92,000. This includes $3,000 for design, $15,000 for creation of the scalloped edge and $78,000 for grading and seeding for shoreline stabilization.

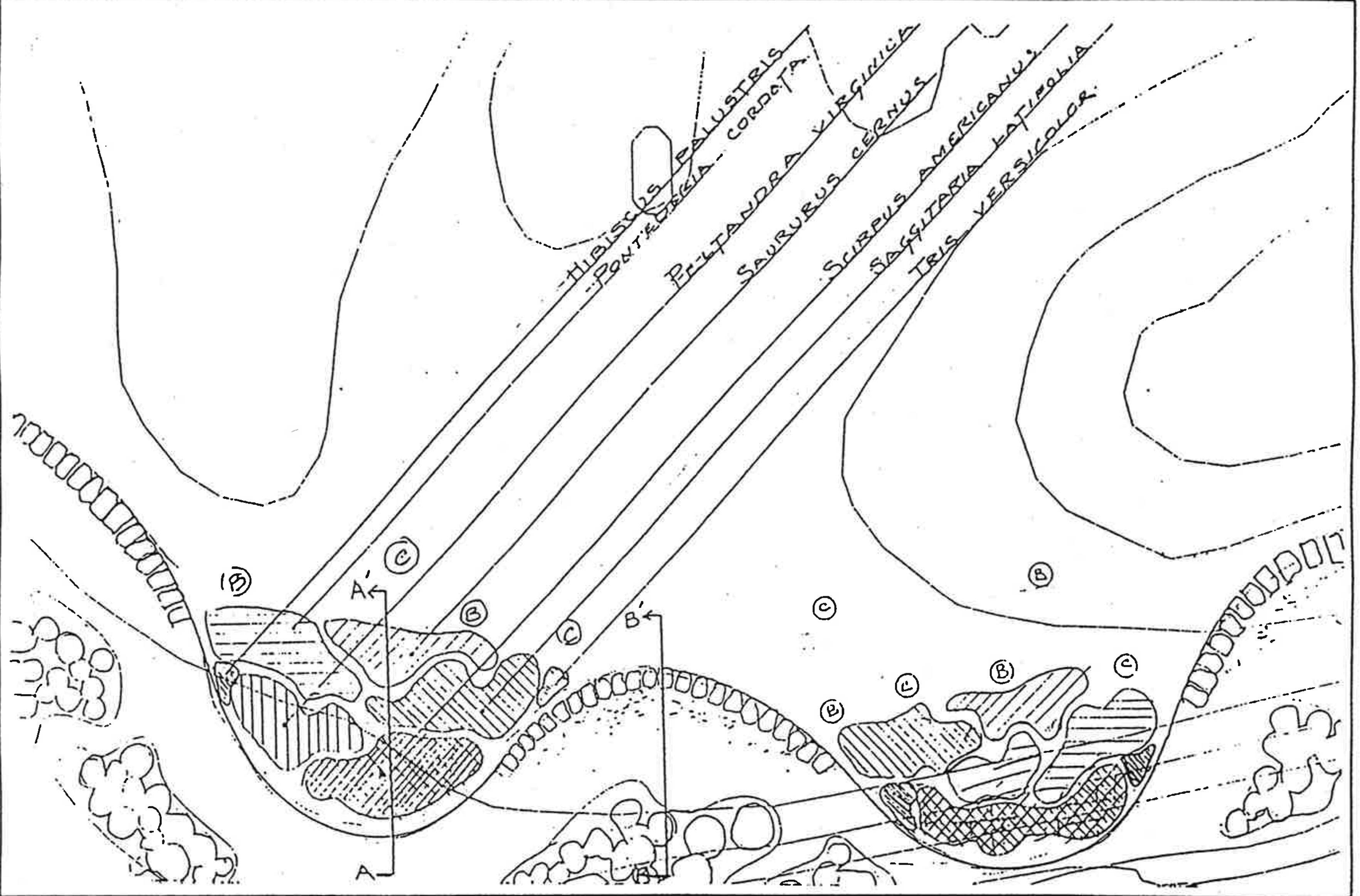
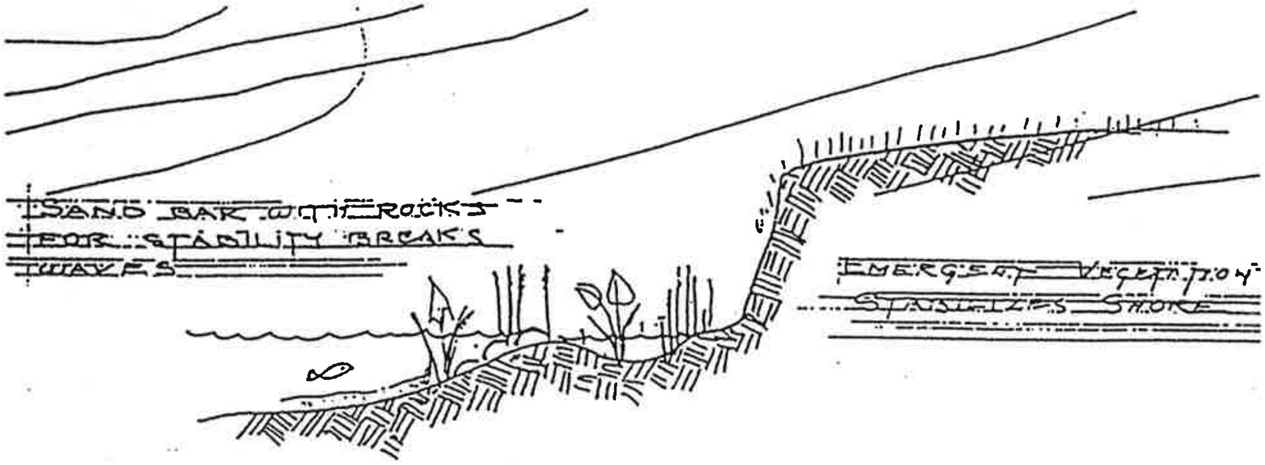
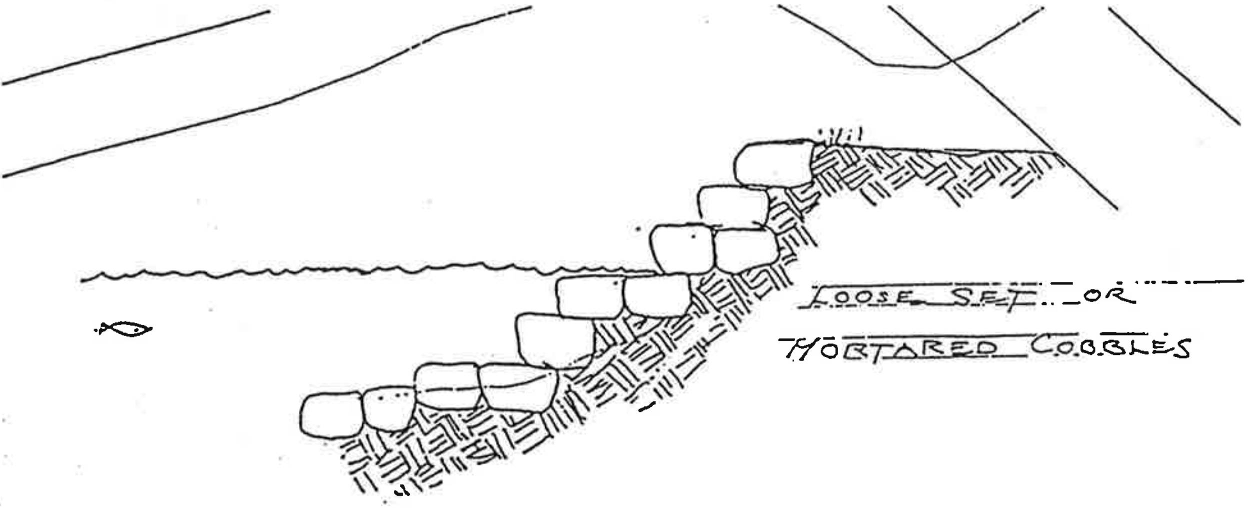


Figure 5.2. Scalloped edge design for public access and shoreline stabilization.

COASTAL



SECTION A-A'



SECTION B-B'

Figure 5.3. Scalloped edge details.

COASTAL
ENVIRONMENTAL SERVICES INC

5.2.4 Aeration

Aeration has often been used as a lake management option for lakes suffering from hypolimnetic oxygen depletion. For these lakes, aeration can increase oxygen concentrations, decrease sediment nutrient release, minimize iron and manganese concentrations, and prevent fish kills. Aeration systems can be designed to provide complete mixing throughout the water column, to increase oxygen concentrations in the hypolimnion without mixing the lake, or to aerate surface waters and provide aesthetic appeal.

Artificial circulation can have a number of positive effects on lake water chemistry. Aeration oxidizes sulfide and ammonia, which can be toxic to aquatic life, to sulfate and nitrate, respectively. The oxidation of the trace metals iron and manganese is a significant benefit of aeration in drinking water reservoirs. These metals are responsible for taste and odor problems and can also present aesthetic problems if they are present in high concentrations in finished water. For both iron and manganese, the reduced form is soluble while the oxidized form of the metal is insoluble. In recent years, the use of aerators to provide complete circulation of the water column has been shown to have some potential as a method of algal control in shallower lakes where low dissolved oxygen levels are not the major concern. Advances in compressor efficiency, the reported success of aeration as an algal control measure, and relatively low costs have led to increased interest in aeration as a lake restoration technique.

Artificial circulation has the effect of increasing the overall temperature of the water column. While this effect is limited in shallow lakes, the overall effects on lake biota can be significant for deeper lakes that normally stratify. The elimination of cold water habitat and increased microbiological activity are two of the major effects of this increase in temperature.

The cost of artificial circulation systems varies widely, depending on the supplier, the type of system installed, the type and availability of power supplies and the number of pumps or compressors recommended. Costs for an artificial circulation system in Lake Luxembourg are estimated at $60,000 because of the size and shape of the lake and the relatively large area of lake bottom experiencing oxygen depletion.

Hypolimnetic aeration systems are useful when the primary lake management goal is increasing oxygen levels in the bottom waters of a lake without causing destratification. Hypolimnetic aeration systems provide additional habitat for cold water fish. Hypolimnetic aerators maintain distinct thermal layers in the lake and focus on increasing dissolved oxygen concentrations in the lake's intermediate and/or deeper layers. In addition, they can reduce internal phosphorus loading and are useful in reducing iron and manganese levels in water supply reservoirs. Hypolimnetic aeration can be expensive, with the cost of hypolimnetic aeration systems for lakes the size of Lake Luxembourg typically ranging from about $100,000 to $250,000.

Some form of aeration system would enhance the probability that Lake Luxembourg could be used as a drinking water reservoir. Unless a decision is made to use the lake for that purpose, however, the relatively high cost and limited benefits of an aeration system limit the utility of this management option.

5.3 Public Access and Fishery Enhancements

The use of Core Creek Park has been growing very rapidly in recent years, as indicated in Section 2.1.2. Management options to improve lake access are suggested to meet this growing need.

5.3.1 Fishery Enhancement

Following a drawdown (Section 5.2.2), two additional activities are recommended to further enhance the Lake Luxembourg sport fishery and increase recreational opportunities. These are the installation of fish attractant devices (FADs) in 3 to 4 designated sites throughout the lake to provide cover and the installation of an additional fishing pier on the eastern shore of the lake. Placement of the FADs near the existing fishing piers would also attract fish to areas to increase the fishing success of shoreline anglers.

The FADs would be constructed from groups of 8 to 12 tires cabled together and ballasted in place with concrete. The FADs would function as devices to promote the congregation of larger bass that would be attracted to the area specifically to forage upon the smaller fish (bluegills and pumpkinseed) which would seek refuge in the tire reefs.

A sampling program would be implemented to quantify the benefits of these FADs. The program would entail systematic sampling of the area within a 25-foot radius of the FAD using electroshocking equipment. Open areas that lack structure will be used as controls and will also be sampled with electroshocking equipment. The results from the control and FAD areas, expressed in catch per unit effort (CPUE), will be compared and then used to make recommendations concerning the possible expansion of the FAD program and the benefits associated with the introduction of artificial habitat in Lake Luxembourg.

Total costs for the implementation of the proposed fishery enhancement measures would be approximately $15,000. This cost includes $10,000 for the installation and monitoring of the FAD's and $5,000 for a 6 foot x 20 foot fishing dock with railings. A grant for $7,500 could be sought from the FishAmerica Foundation for the recommended habitat creation program. This grant would also serve as part of the required local match for a Phase II project.

5.3.2 Completion of the Bicycle/Jogging Path

An existing bicycle/jogging path provides access to areas south and west of Lake Luxembourg. Park development plans include completion of this path to completely encircle the lake. Completion of the path would greatly increase lake access by opening the entire eastern shore of the lake to pedestrian traffic.

The total length of the new path would be 3.36 miles (5,410 m). The width of the path would be 6 feet (2 m) and the path would be classified by the American Association of State and Highway Transportation Officials (AASHTO) as a Class I bicycle path. Class I bicycle paths should have a smooth, nonslick surface and have a thickness capable of supporting vehicles for routine maintenance. Surfaces are asphalt, concrete, soil cement, stone chip aggregate or stabilized earth. Asphalt is recommended for the high traffic expected and to match the existing path.

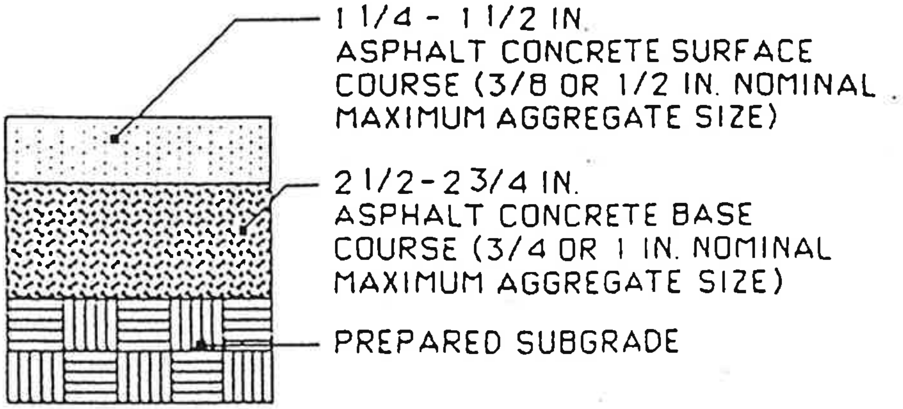
The bike path would have a total asphalt concrete thickness of 3 to 4 inches (75 to 100 mm) in a full depth or untreated aggregate design. Typical design details area shown in Figure 5.3. A 3" (7.5 cm) thick asphalt concrete pavement (1" asphalt concrete surface plus 2" asphalt concrete base course) on a 4" (10 cm) primed granular base with a compacted subgrade is recommended. Paving costs were estimated at $20/square yard for installation. The resulting total cost of the bicycle path is $236,680.

5.4 Institutional Watershed Management Practices

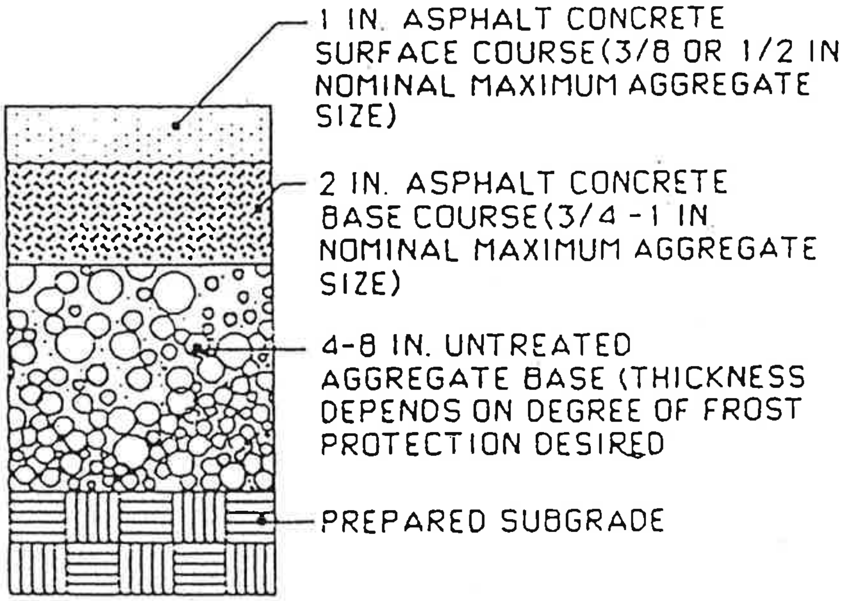
Institutional management practices consist of laws, ordinances and enforcement actions which are intended to provide controls on land use activities and to result in long-term improvements in water quality. The Bucks County Conservation District and the three townships in the Lake Luxembourg watershed, Lower Makefield, Middletown and Newtown Townships, have all implemented management practices that should lead to improvements in the water quality of Lake Luxembourg. Enforcement of these ordinances by the townships and the BCCD will help minimize future sediment and nutrient inputs to Lake Luxembourg. The U.S. Department of Agriculture, Soil Conservation Service and the Agricultural Conservation and Stabilization Service have also been actively involved in the implementation of measures to improve water quality in Lake Luxembourg; however, the activities of these agencies are covered under the implementation of agricultural BMP's.

5.4.1 Bucks County Conservation District

The Bucks County Conservation District (BCCD) has been actively involved in the management of the Lake Luxembourg watershed since at least 1986. The District assists with the implementation of erosion control plans and has an active inspection and enforcement program. The District administers all aspects of Title 25 - Chapter



FULL DEPTH DESIGN



AGGREGATE BASE DESIGN

Figure 5.4. Bicycle path design details.

COASTAL
ENVIRONMENTAL SERVICES INC

102 of the Pennsylvania Clean Streams Law and worked with the ASCS to develop an Agricultural Conservation Program (ACP) to provide cost-share assistance for the construction of soil conservation measures.

The review of erosion and sediment pollution control plans is another major activity of the BCCD. District staff reviewed 894 such plans in 1992 (BCCD, 1993). The BCCD performs inspections of approved land development activities to ensure compliance with applicable regulations and to minimize erosion and sediment pollution. Enforcement actions are pursued if voluntary compliance with guidelines is not achieved, and any penalties collected are paid to the Pennsylvania Clean Water Fund.

The BCCD has a major commitment to improving water quality in County lakes. In addition to erosion control programs, the District initiated the current Lake Luxembourg Phase I Diagnostic/Feasibility Study, and participated in Phase I studies of Lake Nockamixon and Lake Galena, as well as the Phase II Implementation Program for Lake Nockamixon.

5.4.2 Township Land Development Ordinances

All three townships in the Lake Luxembourg watershed have implemented land development ordinances to control erosion and stormwater runoff. The enforcement of these ordinances should lead to significant reductions in erosion as development proceeds in the Lake Luxembourg watershed.

Lower Makefield Township adopted a subdivision and land development ordinance (#261) in 1991 (Lower Makefield Township, 1991). The ordinance requires developers to provide drainage structures to prevent erosion and protect natural stream channels. Stormwater runoff after development must be no greater than the natural condition of the site for the same frequency storm. Any increased runoff from subdivision or land development must be controlled by permanent control measures which are capable of maintaining natural runoff conditions for the 100-year storm. Design criteria for stormwater detention basins are provided in the ordinance.

Soil erosion and sediment control is also a major component of the Lower Makefield Township ordinance. The ordinance requires that, as a minimum, erosion and sediment control measures meet the standards and specifications of the BCCD.

The Middletown Township subdivision and land development ordinance was adopted in 1986 (Middletown Township, 1986). Stormwater management provision encouraged percolation to recharge groundwater and preservation of natural drainage features. Runoff following development was not to exceed the original runoff. Required details for stormwater management plans and design criteria for stormwater management facilities were provided, with design criteria for stormwater detention basins based on TR-55 (SCS, 1985). The Middletown Township ordinance also requires that erosion and sediment control measures meet the standards and specifications of the BCCD.

The Middletown Township ordinance was modified in 1992 by the passage of Ordinances 92-14, 92-15, 92-16, 92-16 and 92-17 (Middletown Township, 1992). These ordinances were designed to make stormwater management activities in those areas of the Township in the Neshaminy Creek watershed also comply with the Pennsylvania Storm Water Management Act and the Neshaminy Creek Watershed Management Plan. These ordinances provided for the formation of stormwater runoff peak rate districts to establish differing erosion and sedimentation control design standards and criteria for different areas of the Township. All areas of the Township were required to provide a minimum detention of 24 hours for the one-year, 24-hour design storm of 2.7 inches.

Requirements of the Newtown Township subdivision and land development ordinance (Newtown Township, 1985) are similar to those of Lower Makefield and Middletown Townships. Design criteria for stormwater detention basins are also based on TR-55 (SCS, 1985). Detention basins are to be designed so that stormwater runoff neither exceeds nor decreases the runoff that existed before development.

Erosion and sediment control measures include the required review of erosion and sediment control plans by the BCCD. Acceptable design criteria for specific drainage facilities were provided.

The existing institutional watershed management practices appear to be able to meet the management needs of the Lake Luxembourg watershed at the present time. No additional institutional practices are recommended as long as existing laws and ordinances are actively enforced.

5.5 Evaluation of Management Alternatives

In order to objectively evaluate the applicability of various watershed management methods, a feasibility matrix was developed (Table 5.2). An ordinal ranking, based on a score of 1 to 5, was generated for each alternative. Those alternatives scoring the highest were given priority consideration. The feasibility of each option was judged on the basis of:

- Pollutant reduction - How substantial a decrease in nutrient and/or sediment loading could be expected from implementation of this method?
- Practicality - Can the method be practically implemented for Lake Luxembourg and/or its watershed?
- Effectiveness - Based on the scientific literature, how effective is this method is meeting desired management objectives?
- Cost - How does the cost of implementing the technique compare to the expected returns?

Table 5.2 - Management Alternatives Feasibility Matrix

Alternative	Pollutant Reduction	Practicality	Effectiveness	Cost	Environmental Impacts	Overall Rating
Implementation of Agricultural BMP's	5	5	5	2	4	21
Buffer Area for Waterfowl Control	2	4	3	4	5	18
Dredging	4	4	5	1	2	16
Lake Drawdown	1	5	4	5	1	16
Environmental Landscaping and Shoreline Stabilization	3	4	4	2	4	17
Aeration	1	3	3	2	3	12
Fishery Enhancement	1	4	3	5	4	17
Completion of Bicycle/Jogging Path	1	4	4	1	4	14
Institutional Watershed Management Practices Measures	4	5	5	5	4	23

- Environmental Impacts - Are there any adverse environmental impacts associated with implementation of the technique?

Review of the matrix scores (Table 5.2) indicates that the top five watershed management options are implementation of institutional watershed management practices, implementation of agricultural BMP's, establishment of a buffer area for waterfowl control, environmental landscaping and shoreline stabilization, and fishery enhancement, followed closely by dredging and lake drawdown. Completion of the bicycle/jogging path does not affect water quality and received a low score, but could still remain a feasible option because of the improved public access it would provide. Aeration is the only option considered which does not appear worthy of further consideration at this time.

Implementation of the recommended nanagement options would reduce nutrient and sediment loading to Lake Luxembourg and lead to long-term lake water quality improvements. Recommendations for implementing these options are presented in the following section.

6.0 Lake Luxembourg Restoration and Management Plan

The recommended management plan for Lake Luxembourg will need to be implemented over a period of several years to minimize impacts on County finances and to allow time for the implementation of the agricultural BMP's that are the key to the proposed restoration program. The proposed Phase II program will provide some immediate benefits to park users, while the suggested watershed management techniques will lead to long-term improvements in water quality. Funding to implement the proposed restoration project will be sought from the EPA Clean Lakes Program, as well as other federal, state and county sources.

6.1 Proposed Restoration Activities

The Lake Luxembourg restoration program is based on the alternatives discussed in Section 6. The initial stages of the Phase II project can be implemented as soon as funding is available. The major activities planned as part of the initial restoration efforts include the implementation of agricultural BMP's in the Lake Luxembourg watershed and the use of buffer strips to reduce shoreline erosion and to reduce access for ducks and geese around the lake perimeter. Locations of some of the proposed restoration activities are shown in Figure 6.1.

Additional restoration activities are recommended in future years. The activities include the implementation of more agricultural BMP's, a dredging project to remove existing silt accumulations, shoreline stabilization and the installation of fish habitat improvement devices and a restructuring of the lake fishery. The dredging program, shoreline stabilization and fishery improvement activities would take place following a complete drawdown of the lake.

Several of the recommended management activities will increase public access to the lake and improve the lake fishery. The completion of a bicycle path around the lake will make the entire lake readily accessible for cyclists and pedestrians. The construction of an additional fishing pier will increase direct lake access, and the installation of fish attractant devices will provide fish habitat and promote the congregation of fish in areas accessible to shoreline anglers.

The proposed restoration activities will result in reductions in annual soil loss of an estimated 25,200 tons/year (22,900 metric tons/year) at an average cost of only $1.01/ton. Phosphorus loadings to the lake would also be significantly reduced.

Associated activities, including a monitoring program to document the effects of the proposed restoration activities, a public education program to keep the public informed of project progress and the preparation of project reports are also included in the suggested Phase II implementation program to meet the requirements of the Clean Lakes Program. The proposed tasks for the Lake Luxembourg Phase II project are summarized in Table 6.1. Tasks 1 to 7 were discussed in the preceding chapter; the remaining tasks are discussed below.

Table 6.1 - Proposed Tasks for the Lake Luxembourg Phase II Project

Task	Description
1	Implementation of Agricultural BMP's
2	Establishment of Buffer Areas for Waterfowl Control
3	Dredging
4	Lake Drawdown
5	Environmental Landscaping and Shoreline Stabilization
6	Fishery Enhancement
7	Completion of Bicycle/Jogging Path
8	Public Education Program
9	Phase II Monitoring
10	Project Documentation

6.2 Public Education Program

A comprehensive public education program will be conducted as part of the Lake Luxembourg restoration project. The public education program will be coordinated through the Bucks County Conservation District and the Bucks County Department of Parks and Recreation. At least one public meeting will be held during each year of the project to inform interested citizens of project progress and to permit public input on possible new directions for improving public access the implementation of agricultural BMP's. The public education program will also include the development of educational materials for use at Core Creek Park. The annual cost of the public education program would be about $3,500.

6.3 Phase II Monitoring

A monitoring program is required for Phase II projects by the U.S. EPA to document changes in water quality occurring as a result of implementation of the lake restoration program. The Phase II monitoring program will be conducted throughout the restoration project and for at least one additional year following the implementation of all recommended management activities.

A limited lake and watershed monitoring program will be conducted during the implementation phase of the Lake Luxembourg Phase II project to evaluate the effectiveness of the lake and watershed management measures that are implemented and to document any changes in lake water quality.

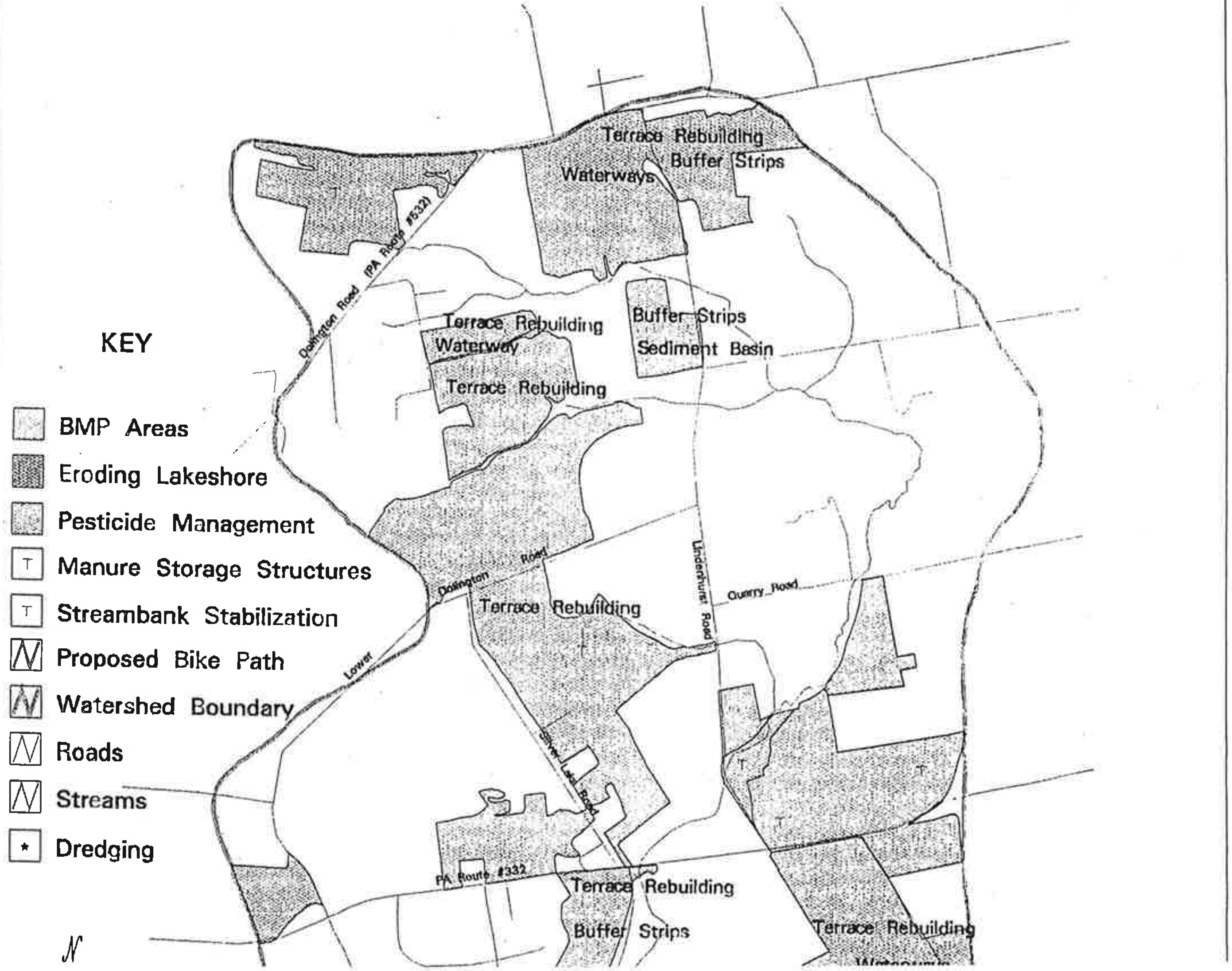


Figure 6.1. Locations Of Proposed Restoration Measures

Lake samples should be collected from the surface, middle and bottom of the water column from a single station near the dam. Samples should be collected once per month in June, July and August, and again in December or January of each year and analyzed for all of the parameters included in the Phase I study, including Secchi depth, profiles for temperature, dissolved oxygen, pH and conductivity, nutrients (soluble orthophosphate, total phosphorus, nitrate + nitrite-N, ammonia-N and total Kjeldahl nitrogen), total solids, total suspended solids, alkalinity, chlorophyll *a*, phytoplankton and zooplankton.

Additional samples should be collected from the watershed to monitor the progress of the restoration project and to help identify new potential problem areas. Watershed samples should be analyzed for total phosphorus, total nitrogen and total suspended solids. The annual cost of the monitoring program is estimated to be $5,200.

6.4 Project Documentation

A detailed work plan for the Lake Luxembourg Phase II project will be completed prior to the initiation of any project activities. The detailed work plan will include a Quality Assurance Project Plan (QAPjP) designed to meet all EPA requirements if funding is obtained from the U.S. EPA Clean Lakes Program. Regardless of the funding source, the work plan should meet all current EPA requirements for Phase II projects.

Quarterly progress reports will be prepared and submitted to the Bucks County Conservation District and all appropriate funding agencies to document project results. Each progress report will contain a description of project activities and copies of all data collected. A final report will be prepared at the conclusion of the Phase II project containing all information required by the EPA Clean Lakes Program.

Semi-annual reports will contain all information from the progress reports, a description of project expenditures, and a description of proposed activities and expenditures for the following six month period. A final report will be prepared at the conclusion of the Phase II project containing all information required by the EPA Clean Lakes Program. The total cost for project documentation is estimated at $12,500 over a three year period.

6.5 Proposed Phase II Budget

The proposed cost for the Lake Luxembourg Phase II project is approximately $828,900 over a three year period. Funding for 50 percent of the project costs will be sought from the U.S. EPA Clean Lakes Program. Part of the required local funding match can be met by the Bucks County Conservation District and cooperating agencies through the performance of in-kind services. The proposed project budget is shown in Table 6.2.

Table 6.2 - Lake Luxembourg Phase II Budget

Phase II Program Element	Cost
Implementation of Agricultural BMP's	$818,440
Establishment of a Buffer Area for Waterfowl Control	$5,000
Dredging	$286,800
Lake Drawdown	$0
Environmental Landscaping and Shoreline Stabilization	$92,000
Fishery Enhancement	$15,000
Completion of Bicycle/Jogging Path	$236,680
Public Education	$10,500
Phase II Monitoring	$15,600
Project Documentation	$12,500
Total Project Cost	**$1,492,520**

6.6 Implementation Schedule

The proposed implementation schedule for the Lake Luxembourg Phase II project is presented in Table 6.3. The project would begin as soon as funding was available and would continue for a three-year period. The implementation of agricultural BMP's and the establishment of buffer areas for waterfowl control could begin as soon as funding was available. Lake drawdown, dredging, shoreline stabilization and the implementation of fishery enhancement measures would be conducted during the second year of the project, and the bicycle path would be completed during the third year. Public education, monitoring and documentation would be conducted throughout the project period. Specific program elements could be implemented over a more extended period, if necessary, depending upon the availability of funding.

6.6 Lake and Watershed Improvements

The proposed restoration activities will result in significant reductions in pollutant loadings to Lake Luxembourg. Implementation of the recommended agricultural BMP's would reduce the average soil loss from cropland from 15 tons/acre/year to about 3 tons/acre/year. This would result in a total reduction in annual soil loss of about 25,300 tons for the Lake Luxembourg watershed. Although it is difficult to quantify the impact that this reduction will have on the annual suspended solids load to Lake Luxembourg, estimated reductions of about 25 percent

Table 6.3 - Proposed Implementation Schedule

Program Element	Months from Project Start
Implementation of Agricultural BMP's	0 to 36
Establishment of a Buffer Area for Waterfowl Control	0 to 6
Dredging	12 to 24
Lake Drawdown	12 to 24
Environmental Landscaping and Shoreline Stabilization	12 to 24
Fishery Enhancement	12 to 24
Completion of Bicycle/Jogging Path	25 to 36
Public Education	0 to 36
Phase II Monitoring	0 to 36
Project Documentation	0 to 36

of the suspended solids and total phosphorus loads would result if a delivery ratio of 5 percent is used for the eroding soil. Monitoring information gathered as part of the Phase II monitoring program will be used to further quantify the actual reductions achieved by the proposed management measures.

Significant reductions in nutrient loading to Lake Luxembourg would also occur. Total phosphorus concentrations are closely related to concentrations of suspended solids entering the lake. As a result, reductions in soil loss will reduce the concentrations of phosphorus entering the lake.

The limited groundwater monitoring conducted during the Phase I Study indicated that very high nitrate concentrations are found in shallow groundwater as a result of the current high fertilization rates and cropping practices. Improved fertilizer management practices and the recirculation of will help alleviate this problem and will also reduce the current nutrient load to Lake Luxembourg.

by how much ?

Fishing is one of the most popular activities in Lake Luxembourg. The revitalization of the lake fishery, improved access, installation of an additional fishing pier and the installation of fish attractant devices will all help increase fishing success.

As a final consideration, shoreline access to the lake will be significantly improved by the completion of a bicycle trail completely encircling the lake. The proposed extension of the existing mile trail will provide direct access to all areas of the lake to pedestrian traffic.

6.8 Technical and Financial Feasibility

Proposed restoration activities for the Lake Luxembourg Phase II project are technically and financially feasible. The implementation of agricultural BMP's has been shown to be an effective long-term lake management technique. Dredging, lake drawdown and shoreline stabilization are also proven management techniques.

Proposed restoration activities for the Lake Luxembourg Phase II project are technically and financially feasible. The implementation of agricultural BMP's and dredging programs have been shown to be effective long-term lake management techniques. The proposed measures to increase public access to the lake and enhance the lake fishery will help gain support for the project and maintain public interest while the less visible watershed management measures are being implemented.

While the proposed restoration project is expensive, the high use and visibility of Core Creek Park merit local funding for the project. Funds will also be sought from additional federal, state and local sources to implement the proposed management plan. In-kind services can be provided by County personnel in several areas of the restoration plan, and a grant from the FishAmerica Foundation will also help defray some of the necessary local match for the proposed project. The long-term benefits expected from the proposed project justify the expected costs of the proposed restoration program.

6.9 Permit Requirements

The Pennsylvania DER, the Pennsylvania Fish and Boat Commission and the Philadelphia Office of the U.S. Army Corps of Engineers (USACOE) were contacted to determine permit requirements for the proposed Phase II project. The permits required from the Pennsylvania DER will include GP-1 for the installation of fish enhancement structures, GP-2 for private recreational docks and GP-3 for the proposed shoreline stabilization activities. A permit from the Pennsylvania Fish Commission would also be needed for the lake drawdown.

The USACOE indicated that no determination could be made concerning the need for a Water Quality Certificate for a dredging program until specific details of the proposed project were provided. Dredging would require a stream encroachment permit from the Pennsylvania DER, and Nationwide permit GP-33 for the maintenance of dams may also be required.

6.10 Environmental Evaluation

Socio-economic and environmental impacts were considered as part of the alternatives analysis conducted as part of the Lake Luxembourg Phase I study. These impacts and their mitigative measures are presented below using the environmental evaluation checklist from the EPA Clean Lakes Program Guidance Manual (1980).

1. Will the project displace people?

   No.

2. Will the project deface existing residences or residential areas?

   No.

3. Will the project be likely to lead to changes in established land use patterns or an increase in development pressure?

   No. The Lake Luxembourg watershed is already undergoing rapid development. Any changes in land use patterns in the watershed which occur during the project would be unrelated to proposed project activities. Upgrading agricultural operations in the watershed through the implementation of agricultural BMP's may even reduce the likelihood of development for those farms which are affected.

4. Will the project adversely affect prime agricultural land or activities?

   No. The agricultural BMP's included as part of proposed project activities will lead to long-term improvements in agricultural land in the watershed.

5. Will the project adversely affect park land, public land or scenic land?

No. The planned restoration activities will enhance the recreational and aesthetic uses of the lake and adjacent park land. Public access to the lake and other areas of the park will also be improved.

6. Will the project adversely affect lands or structures of historic, architectural, archeological or cultural value?

The proposed project involves no modifications to existing structures or activities which will impact lands of historic, archeological or cultural value.

7. Will the project lead to a significant long-range increase in energy demands?

No. Earth moving activities required for the proposed dredging project will result in a short-term increase in energy usage, but this usage will be relatively minor and no long-term impacts are expected.

8. Will the project adversely affect short-term or long-term ambient air quality?

Earth moving activities required for the project may cause a short-term increase in emissions; however, no long-term effects on air quality are expected. All construction equipment will have proper emission controls and proper dust control practices will be used.

9. Will the project adversely affect short-term or long-term noise levels?

Noise levels will be temporarily affected by construction activities, but all construction vehicles and equipment will use noise control devices. Increased use of the lake and surrounding park will lead to increases in long-term noise levels; however, the park is be used primarily for passive recreation and these increases are not expected to have adverse impacts.

10. If the project involves the use of in-lake chemical treatment, will it cause any short-term or long-term effects?

The proposed restoration project does no include in-lake chemical treatments.

11. Will the project be located in a floodplain?

The dredging project, the installation of an additional fishing dock and the installation of fish attractant devices will all occur in the Lake Luxembourg floodplain, but no long-term adverse impacts are expected.

12. Will structures be constructed in the floodplain?

The additional fishing dock and fish attractant devices will be installed in a floodplain, but these structures will be placed in Lake Luxembourg and no adverse impacts are expected.

13. If the project involves physically modifying the lake shore, its bed, or its watershed, will the project cause any short or long-term adverse effects?

The project will have no adverse effects on aquatic life since all aquatic organisms were eliminated when the lake was drained. The dredging project will modify the lake bed, and proposed stabilization activities will slightly modify the shoreline, but both of these activities will result in positive long-term effects for the lake.

14. Will the project have a significant adverse effect on fish and wildlife, wetlands or other wildlife habitat?

The proposed lake drawdown would eliminate existing fish populations; however, the Pennsylvania Fish Commission has indicated significant problems with the existing lake fishery and concurs with the proposed drawdown. The project would result in a re-structuring of fish populations in the lake and would have a long-term beneficial effect.

Four species of special concern may occur in the Lake Luxembourg watershed (Martin, 1975). Threatened or endangered species of birds that might frequent the area during their migration include the southern bald eagle (*Haliaeetus leucocephalus leucocephalus*), Arctic peregrin falcon (*Falco peregrinus tundrius*) and American osprey (*Pandion haliaetus carolinensis*). None of these birds are permanent residents of the watershed and the proposed project would have no significant impacts on these species.

The bridle shiner (*Notropis bifrenatus*), has been reported for several areas in the Neshaminy Creek watershed. This species is listed as rare by the Pennsylvania Fish Commission, but not by the U.S. Department of the Interior. This species has not been reported for Lake Luxembourg.

15. Have all feasible alternatives to the project been considered in terms of environmental impacts, resource commitment, public interest and cost?

All feasible alternatives for the restoration of Lake Luxembourg have been thoroughly analyzed. The recommended plan should result in an improvement in lake water quality and will minimize negative environmental impacts.

16. Are there other measures not previously discussed which are necessary to mitigate adverse impacts resulting from the project?

There are no necessary mitigation measures known at the present time which have not been discussed.

7.0 Public Participation Program

Several meetings were held during the course of the Phase I project to obtain input from the Bucks County Conservation District, the Bucks County Parks Department, the USDA, Soil Conservation Service and the ASCS. Recommendations from those meetings were included in the proposed management plan.

A public meeting to discuss the findings and recommendations of the Lake Luxembourg Phase I study was held on April 14, 1994 at Core Creek Park (the Bucks County Parks Department Office). Comments received at the meeting concerning the Phase I and proposed Phase II project are included in this report.

8.0 Literature Cited

Benton, B. 1988. Bathymetric survey of Lake Luxembourg, letter report. USDA, SCS, Harrisburg, PA.

Bourquard, E.H. Assoc., Pickering, Corts and Newton, and Justin & Courtney. 1971. Neshaminy Creek water resources development plan, Bucks County, PA. Multi-purpose dam No. PA-620, Core Creek. USDA, SCS Drawing No. PA-620-P.

Brzostek, E. 1992a. Personal communication to C. Holdren, Coastal Environmental Services, Inc.

Brzostek, E. 1992b. Core creek special ACP project, Bucks County, Pennsylvania. Application prepared by the USDA, SCS, Chalfont, PA.

Bucks County Department of Parks and Recreation. 1985. Annual Report. Bucks County Department of Parks and Recreation, Doylestown, PA.

Bucks County Planning Commission. 1986. Park and Recreation Plan. Bucks County Planning Commission, Doylestown, PA.

Bucks County Planning Commission. 1989. Mini demographic profile of Bucks County. Bucks County Planning Commission, Doylestown, PA.

Carlson, R. E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22:361-369.

Coffey, S.W., W.S. Berryhill, Jr., D.W. Miller, and M.D. Smolen, 1989. Making molehills out of mountains: Using models to identify non-point sources. Virginia Regional Symposium, Lake Line 9(4):14-18.

Dillon, P. J., and F. H. Rigler. 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. J. Fish. Res. Board Can. 31:1771-1778.

Dunst, R. C., and R. Beauheim. 1979. Effect of dredging and nutrient inactivation at Lily Lake, Wisconsin. In: Limnological and Socioeconomic Evaluation of Lake Restoration Projects, Report No. EPA-600/3-79-005. U.S. EPA, Corvallis, OR.

Holdren, G. C. 1983. Estimation of internal nutrient loading in Laguna Lake, pp. 127-133. In Lake Restoration, Protection, and Management, EPA 440/5-83-001. U. S. EPA, Washington, D.C.

Holdren, G. C., and D. E. Armstrong. 1980. Factors affecting phosphorus release from intact lake sediment cores. Environ. Sci. Technol. 14:79-87.

Larsen, D. P., and H. T. Mercier. 1976. Phosphorus retention capacity of lakes. J. Fish. Res. Bd. Canada 33:1742-1750.

Lower Makefield Township. 1991. Subdivision and land development ordinance. Lower Makefield Township, Bucks County, PA.

Manny, B. A., R. G. Wetzel, and W. C. Johnson. 1975. Annual contribution of carbon, nitrogen and phosphorus by migrant Canada geese to a hardwater lake. Verh. Internat. Verein. Limnol. 19:949-951.

Martin, B. 1975. Neshaming Creek Watershed Project, Draft Environmental Impact Statement. Report No. USDA-SCS-WIS-WS-(ADM)-76-1-(D)-PA. USDA, SCS, Harrisburg, PA.

Middletown Township. 1986. Subdivision and land development ordinance. Middletown Township.

Middletown Township. 1992. Ordinance 92-14, Ordinance 92-15, Ordinance 92-16 and Ordinance 92-17. Middletown Township.

Newtown Township. 1985. Subdivision and land development ordinance. Newtown Township, Bucks County, PA.

Nurnberg, G. K. 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. Limnol. Oceanogr. 29:111-124.

PADER. 1983. The State Water Plan. Subbasin 2. Central Delaware River. Office of Resources Management, Bureau of Water Resources Management, State Water Plan Division, Harrisburg, PA.

PADER. 1993. Cleanup Standards for Contaminated Soils. Commonwealth of Pennsylvania, Department of Environmental Resources, Harrisburg, PA.

Pfanstiel, C. 1993. Personal communication to C. Holdren, Coastal Environmental Services, Inc.

Prepas, E. 1978. Sugar-frosted Daphnia: An improved fixation technique for Cladocera. Limnol. Oceanogr. 23:557-559.

Reckhow, K. H., M. N. Beaulac, and J. T. Simpson. 1980. Modeling phosphorus loading and lake response under uncertainty: A manual and compilation of export coefficients. Report No. EPA-440/5-80-011. U. S. EPA, Washington, D.C.

Reynolds, C. S. 1986. The Ecolohy of Freshwater Phytoplankton. Cambridge University Press, Cambridge, Great Britain.

SCS. 1985. National engineering handbook. Section 4 - Hydrology. Report No. SCS/ENG/NEH-4-2. USDA, Washington, D.C.

SCS. 1986. Technical Release 55. Urban hydrology for small watersheds, 2nd Edition. Report No. SCS/ENG/TR-55. Engineering Division, SCS, USDA, Washington, D.C.

Souza, S.J. and J.D. Koppen. 1984. The role of internal phosphorus loading on the trophic state of New Jersey's two largest lakes. Lake and Reservoir Management. EPA-440/5/84-001, 235-238.

Souza, S. J. and P. A. Perry. 1977. Land and Recreational Development at New Jersey Reservoirs. Water Resources Research Institute. Technical Publication A-043-NJ. Rutgers University, New Brunswick, NJ.

Sze, P. 1986. A Biology of the Algae. Wm C. Brown Publishers, Dubuque, Iowa.

THCA. 1989. Neshaminy Creek Watershed, Bucks and Montgomery Counties, PA, Stormwater Management Plan. Thomas H. Cahill Associates, West Chester, PA.

U.S. EPA. 1976. Quality criteria for water. Report No. EPA-440/9-76-023. U.S. EPA, Washington, D.C.

U.S. EPA. 1980. Clean lakes program guidance manual. Report No. EPA-440/5-81-003. U.S. EPA, Washington, D.C.

U.S. EPA. 1986. Methodology for analysis of detention basins for control of Urban Runoff Quality. Report No. EPA-440/5-87-001. Office of Water, Non-Point Source Branch, Washington, D.C.

Uttormark, P. D., J. D. Chapin, and K. M. Green. 1974. Estimating nutrient loading of lakes from nonpoint sources. Report No. EPA-660/3-74-020, U. S. EPA, Corvallis, OR.

Vollenweider, R. A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33:53-83.

Walker, W.W. 1977. Some Analytical Methods Applied to Lake Water Quality Problems. Ph.D. dissertation, Harvard University.

Walker, W. W. 1987. Phosphorus removal by urban runoff detention basins. Lake and Reservoir Management 3:314-326.

Walmsley, R.D. and M. Butty. 1979. Eutrophication of rivers and dams. VI. An investigation of chlorophyll-nutrient relationships for 21 South African Impoundments. Contributed Report, Water Res. Comm., Pretoria, South Africa.

Wanielista, M. P., Y. A. Youseff, and J. S. Taylor. 1982. Stormwater Management to Improve Lake Water Quality. Report No. EPA-600/52-82-048, U.S. EPA, Municipal Env. Res. Lab., Cincinnati, OH.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Co., Philadelphia, PA.

Wnuk, R.T. 1992. Pennsylvania Fish Commission, Area 6 Fisheries Management Office. Letter to C. Holdren, Coastal Environmental Services, Inc., 10 December 1992.

Woodward-Clyde Consultants. 1978. Phase I Inspection Report, National Dam Inspection Program. Core Creek Dam, National ID #PA 00802, DER ID #9-172. Department of the Army, Baltimore District, Corps of Engineers, Baltimore, MD.