A LIMNOLOGICAL INVESTIGATION OF LAKE MANASSAS, VIRGINIA

by

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LIMNOLOGICAL PROFILE OF LAKE MANASSAS (VIRGINIA)

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(ABSTRACT)

Lake Manassas is a man-made impoundment in the Northern Virginia suburbs of Washington, D.C. The lake currently supplies drinking water at a rate of 6.7 million gallons per day to the City of Manassas, Virginia. The lake discharges, via the stream Broad Run, to the Occoquan Reservoir. The Occoquan Reservoir supplies potable water to over 750,000 people in the Northern Virginia area.

As the population of Washington, D.C., continues to increase, the development of the surrounding suburbs changes the quality of surface runoff water into existing reservoirs. These reservoirs can become enriched with both toxic and biomass inducing nutrient pollutants. The result can be less desirable and less dependable supplies of drinking water.

A State of Virginia mandated Environmental Monitoring Program is in force in this area to ensure the Occoquan Watershed remains a dependable supply of potable water. A computerized database, containing the results of the environmental monitoring program, allows for a quantitative

estimate of the overall water quality of the reservoirs to be made.

This thesis presents the results of a limnological analysis of Lake Manassas. The analysis techniques used are established limnological techniques to arrive at a profile which can be compared to accepted scales of ranking.

One conclusion from the analysis is that Lake Manassas is eutrophic, which means that the production of biomass in the lake is at a higher than desired rate. The result of this eutrophic condition is that the water quality of the lake will decline rather rapidly. Another conclusion is that Broad Run is the major supplier of nutrients into Lake Manassas, but that conditions are also affected by a point source discharge from a sewage treatment plant. These conclusions are consistent with previous studies done on Lake Manassas.

In summary, Lake Manassas is an important water resource in the Northern Virginia area, and it is important to continue to closely monitor and manage runoff practices in the watershed to ensure the lake does not degrade to unacceptable conditions.

ACKNOWLEDGEMENTS

The author wishes to thank his wife,   , for her constant encouragement and support during the long period required to write this paper. Poor family health conditions frequently required the author to "drop" the project for a period and then "pickup where it was left" at some time later. This cycle was encountered many times before the completion of this paper, and at times the author greatly doubted his ability to finish it. However, by following his wife's determination and bravery to face all of the challenges, the author completed the required task.

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Chapter I

INTRODUCTION

Groundwater became an undependable supply of potable water in the area around the City of Manassas, Virginia, in the mid-1960's. The expanding population increased the demand for water to the point where the aquifer experienced an overdraft condition. Because the population was expected to continue to increase at a relatively rapid rate, the overdraft condition would continue to worsen.

In response to this problem, the City of Manassas began a study for alternative supplies of water. The result of this study was the recommended development of a man-made impoundment, Lake Manassas, by constructing a dam on Broad Run, approximately 10 miles west of the City of Manassas. In 1968 the construction process began and by 1971 the lake and a new water treatment plant were supplying water to the City of Manassas.

The lake was designed for a capacity of 5.8 billion gallons and a surface area of approximately 780 acres. However, more recent studies indicate these design figures may be ten to twenty percent higher than the actual size of the lake. The issue of lake size, will be discussed in subsequent sections of this report. The water treatment plant was initially designed for a capacity of 4 million gallons per day (MGD), but the continued expansion of the surrounding population necessitated a doubling of the output capacity to 8 MGD in 1987. Figure 1 shows the location of Lake Manassas in the north-eastern corner of Virginia, approximately 30 miles due west of Washington, D.C.

Lake Manassas lies in the upper reaches of a major watershed for Northern Virginia: the Occoquan River watershed. The Occoquan River is impounded by a dam near its discharge into the Potomac River, south of Washington, DC. The Occoquan Reservoir is one of the largest potable water reservoirs in the northern Virginia area. Because of this, the Occoquan Reservoir and its watershed have been monitored and studied extensively.

Lake Manassas has grown in popularity as a recreational facility since its construction. The lake is stocked with fish, and the State Game Commission allows access to the lake for fishing on a permitted basis. No gasoline engines are allowed on the lake, and no swimming is permitted. A further example of the popularity of the lake is the recent acquisition of a significant portion of the land on the north-western shoreline for construction of a large golf resort and convention center. Current plans include the

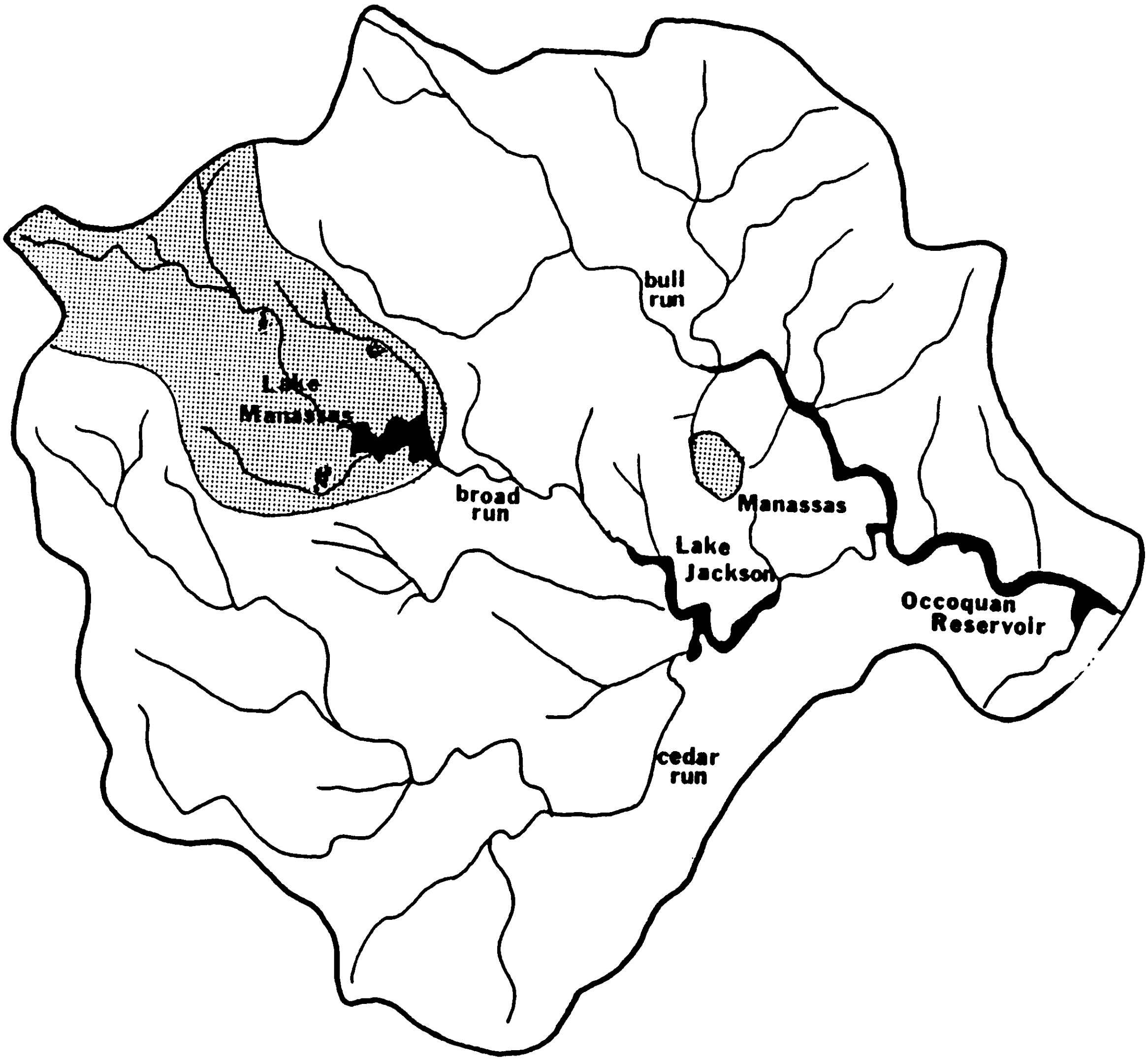

Figure 1 - Geographic Location of Lake Manassas

construction of three 18 hole golf courses, and an accompanying hotel and convention facility.

Limnological principles show that as the development of a watershed proceeds, the increased input of nutrients and other pollutants results in the gradual decline of the quality of the receiving water body. This decline is typified by an increase in algal growth, known as lake productivity. Typically, taste and odor problems and filtration overloading, all caused by these microorganisms, make it difficult and uneconomical to treat the water. As the lake productivity continues to increase, the water body can no longer be a useful supply of potable water. However, there are land management practices that can be implemented to minimize or control this undesirable environmental process.

It can be expected that as the population of this geographic region continues to increase, there will be an accompanying increased demand for potable water. Therefore, it is important that all existing water supply resources continue to be protected from any decline in quality.

The objectives of this study are to present a comprehensive analysis of the existing conditions in Lake Manassas. These existing, or baseline, conditions can be used in a comparative fashion to track the changes in the lake as the watershed development continues. These comparisons can be a useful way to monitor land management practices in the watershed so that their maximum effectiveness is achieved.

Specific objectives of this study were (1) to investigate the limnological characteristics of Lake Manassas including the morphology, stratification due to thermal effects, nutrient input and distribution, and lake productivity; (2) to use existing models to predict the magnitude of eutrophication in the lake; and (3) to characterize the major input streams to the lake.

Chapter II

LITERATURE REVIEW

History of Lake Manassas

Lake History

In 1962, the Town Council of Manassas requested that the Northern Virginia Soil Conservation District make a survey of possible sites for a water reservoir that would replace the increasingly unreliable groundwater supply. The community was undergoing rapid development, and the overdraft condition in the aquifer would only worsen with time. The survey proposed the development of an impoundment on Broad Run by placing a dam just south of the confluence of Broad Run and the North Fork tributary to Broad Run. The land in this area was purchased, and a bond referendum provided the funds to construct the dam. (1) Construction began in November of 1968, and the dam was completed in 1970. Parallel with construction of the dam, a water treatment plant at the base of the dam was designed and constructed. The treatment plant began supplying water in 1971 to the City of Manassas through a seven mile long, 24-inch diameter water main (2).

Water Treatment

The water treatment plant was initially designed to operate at a capacity of 4 MGD, and did so until 1987 when a plant expansion doubled its capacity to 8 MGD. Currently, the plant is operating at a nominal capacity of 6.7 MGD supplying water to the City of Manassas, and to the Prince William County Service Authority for other areas of Prince William County, Virginia. In addition to this withdrawal of water from Lake Manassas, a small hydroelectric plant at the base of the spillway was completed in 1987. This hydroelectric plant is designed to supplement local peak electricity demand. The hydroelectric plant is therefore only operated intermittently. Current plans are to operate the hydroelectric plant 3 to 7 hours per day, 5 to 10 days per year. (2)

Raw water is withdrawn from the lake by an intake system at depths of 5, 15, 25, 35, 45, and 55 feet below the lake surface. The spillway elevation of the lake is 285 feet above sea level. Typically, all water is drawn from the 5-foot level except during summer when some water is drawn from the 15-foot level and mixed with the shallower water to achieve an acceptable temperature. Deeper water is rarely withdrawn because experience has shown that the higher level of dissolved iron and manganese of the deeper waters causes processing problems. The water is then conveyed via an underground pipeline to the treatment plant. Pumps are available to pump water from the lake, but normal lake levels provide sufficient head for gravity flow. The raw water enters the plant in a rapid mix chamber where typically, the following chemicals are added; potassium permanganate for oxidizing iron and manganese, liquid alum to enhance flocculation, caustic soda for pH control, hydrofluorous salaic acid for fluoridation purposes, hexametaphosphate for corrosion protection, and some gaseous chlorine for preliminary disinfection. After the mix chamber, the water is sent to one of the two identical processing systems to complete treatment. (The plant expansion of 1987 essentially built an identical processing system parallel to the existing system.) The water flows through a series of settling basins which contain rotating flocculators to enhance flocculation and settling. The water then flows into dual media filters consisting of a bed of granular activated carbon (GAC) overlying sand. GAC is used because of problems with taste and odor control. The water from Lake Manassas has had taste and odor problems since the opening of the reservoir. As a historical note, this water treatment plant was the second facility in the State of Virginia to use GAC for taste and odor control. (2)

Finished water is held in one of two 205,000 gallon clearwells, which form the structural foundation of the water treatment plant buildings. The water is then withdrawn from the clearwells, and pumped into a 24-inch main which carries the water to water tanks nearer the city. To complete the disinfection process, and to provide the necessary chlorine residual for the distribution system, gaseous chlorine is added just before the water enters the main.

Treatment plant operators have been experimenting by varying chemical addition rates to reduce the level of trihalomethanes (THM's) produced by the chlorination process. In general, the THM production level is controlled by the amount of pretreatment chlorination. Some experiments have shown that with minimal pretreatment chlorination, the level of THM's leaving the plant can be maintained below 30 parts per billion. (2) Current drinking water regulations require THM's to be held to less than 100 parts per billion.

Algae from Lake Manassas have historically caused significant processing problems. Filter clogging was very predominant, as were taste and odor problems. In order to control these problems, Lake Manassas is treated with copper sulfate, an algicide. The copper sulfate is applied from a moving boat in powder form and is typically applied four times per year, twice in the spring and twice in the fall. The application of copper sulfate to Lake Manassas has been practiced for approximately 14 years. (2)

The water from Lake Manassas is rather soft, with an average total hardness of less that 40 milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$). Therefore, the treatment plant does not perform any processing for hardness reduction.

Watershed Management

As previously stated, Lake Manassas and its watershed are part of the larger Occoquan River watershed. The Occoquan River is impounded by a dam near its outlet into the Potomac River. The Occoquan Reservoir is a very important water resource in the Northern Virginia area because it supplies potable water to over 750,000 people and regional businesses (3).

In 1971, the Commonwealth of Virginia State Water Control Board issued a policy statement titled "Waste Treatment and Water Quality Management in the Occoquan Watershed" (3). This policy statement was the result of research into the increasing pollution content of the

Occoquan Reservoir. In the early 1970's, the major sources of pollution into the watershed were point source discharges from sewage treatment plants. The new policy statement instituted the following major programs:

1. New high-performance wastewater treatment facilities in the watershed were to be constructed to replace some of the existing low efficiency plants.
2. The Occoquan Watershed Monitoring Program was established to continue to monitor the water quality of the reservoir and its watershed.
3. Erosion and sediment control standards were invoked.

The State Water Control Board revised the Occoquan Watershed Policy in 1980 to include more detailed requirements for the performance of new treatment plants and the expansion of existing treatment plants in the watershed (3). Most of the analytical data used in this document were obtained from the Occoquan Watershed Monitoring Program.

Current Watershed Development

In November, 1985, a golf resort development company requested permission from the Prince William County, Virginia, Planning Commission to build a golf resort on the northern shores of Lake Manassas. The golf resort plans include golf courses, 800,000 square feet of office space, a 500 unit full service hotel, and a residential community of 400 detached single family homes, 200 condominium homes, and 200 townhouse homes. (4) The placement of this resort is shown in Figure 2, with the golf courses nearest to the lake areas.

The land that the resort would be placed on is essentially undeveloped forest and pasture land with minimal population currently present. In order to obtain a preliminary understanding of the potential impact this resort community may have on Lake Manassas, the Prince William County Planning Commission contracted with the Northern Virginia Planning District Commission for a technical analysis. In April of 1986, the Planning District Commission published the results of their analysis (5). The following statements summarize the qualitative results of the analysis;

> "Results of the Watershed Model simulations showed that, due to the very small size of the site [the proposed resort] compared to the total area that drains to Lake Manassas, the proposed development would have only a slight effect on the lake. The fact that the model showed any effect at all, however, indicates that additional development within the watershed without adequate controls could result in significant adverse impacts on water quality in the lake." (5)

That report also recommended that runoff control measures and structures be built around the proposed resort to minimize nutrient and pollutant loadings into Lake Manassas (5).

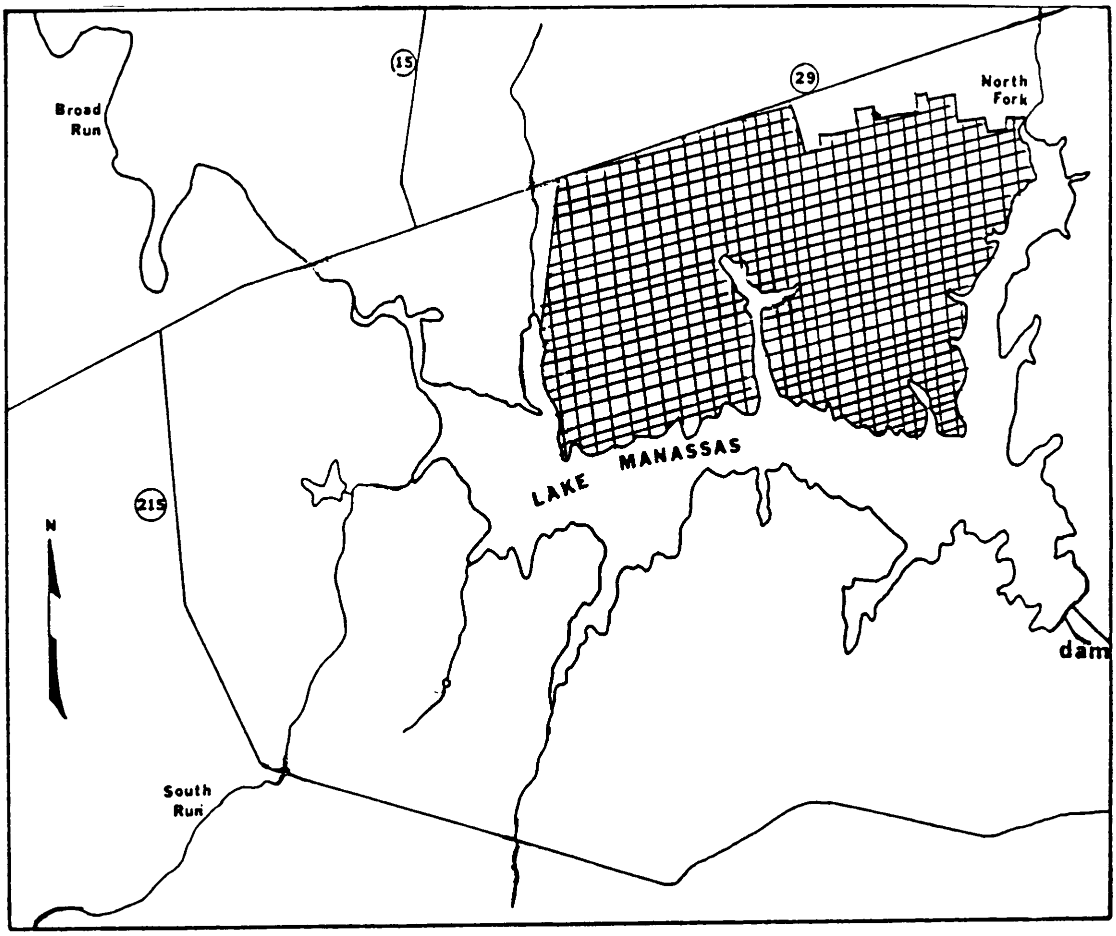

Figure 2 - Development of the Lake Manassas Watershed

Limnological Principles

The Lake as an Ecosystem

The study of fresh water bodies, their ecosystems, and their response to environmental changes is termed limnology. Limnology is a complex discipline because of the dynamic and extreme diversity of conditions that exist in the freshwater bodies of the world. Lakes are ecosystems with the metabolism of the resident species (herein termed a lake's metabolism) dependent on and responsive to the inputs of the entire drainage basin of the lake, the atmosphere, and the sun(6). As with any scientific discipline, there are "yardsticks" which have been developed to measure parameters and thereby enable comparisons between different lakes. These parameters will be presented along with a discussion of their effects on a lake.

Morphology

The size and shape of a lake is highly dependent on the mechanism by which the lake was created (6). Examples of the processes which create freshwater lakes include: tectonic movement resulting in the creation of huge basins, volcanic activity which produce lava flows that can distort as they cool to form cavities and dams, landslides which create natural dams in existing drainage pathways, glacial activities which carve out earthen soil and bedrock and subsequently deposit these materials as dams when the glaciers recede, meandering rivers which can have entire sections cut off by sedimentation processes, solution lakes caused by the dissolution of certain bedrock, shoreline lakes which result from the cyclic erosion and deposition actions of wave activity, and manmade lakes which are often formed by damming existing drainage ways. (7)

Examples of parameters which are used to describe the morphological characteristics of a lake include lake area: lake volume, maximum, mean, and relative depths, lake length, shoreline length, and shoreline development. The final term, shoreline development, is defined as the ratio of a lake's shoreline length to the radius of a circle whose area is that of the lake. Therefore, a perfectly circular lake would have a shoreline development of 1.00. Typically, natural lakes have a shoreline development of around 2.00 with some manmade impoundments approaching a value of 5.0 (6). Shoreline development is of interest because it reflects the potential for greater development of littoral communities (shallow shoreline areas with a higher preponderance of life forms) in proportion to the volume of the lake (8).

The volume of a lake is an important parameter because it controls the concentration of constituents within the lake and therefore the lake's metabolism. These data are often presented in the form of a hypsographic curve which plots the depth of a lake versus the percent of the total lake area for a particular depth. The shape of this curve can help indicate whether a lake has a substantial portion of its volume at a depth where light could penetrate and provide energy for photosynthetic organisms (9).

Hydraulic retention time, or the average time an individual water molecule spends in a lake, is a useful parameter to relate a lake to its surrounding drainage basin. Long retention times indicate a stable lake metabolism, and short retention times indicate a propensity for quick changes in lake metabolism due to rapid changes in lake inputs. (6)

Energy Input to Lakes

A lake's metabolism is highly dependent on the input and distribution of energy within the lake. The food chain, be it terrestrial or aquatic, starts with the conversion of solar energy into chemical energy via the process of photosynthesis. Furthermore, most life forms need some form of thermal energy to keep their temperature in the range necessary for biochemical processes to proceed. Therefore, the amount of light impinging on a lake, the depth to which it penetrates, and the overall distribution of the resulting thermal energy is very important to a lake's metabolism. (6,9)

There is an array of physical, chemical, and biological properties which controls the absorption of solar energy. However, it is the distribution of this energy that is of most interest to limnological studies. As water becomes warmer, it also becomes less dense and therefore rises to the surface of the lake. The cooler, more dense water sinks and remains in the deeper portions of the lake. Figure 3 represents the change in the density of water with temperature. Other forces on the lake, such as wind, tend to promote mixing. However, during the spring and summer months, the heat input from solar radiation, and the often less windy conditions associated with the warmer seasons, create conditions where the heat induced density gradient remains quite evident, a condition known as stratification. The layer of warmer water on the top of the lake is termed the epilimnion, the layer with a relatively rapid temperature change with depth is termed the metalimnion, and the lower layer of colder water the hypolimnion. It is

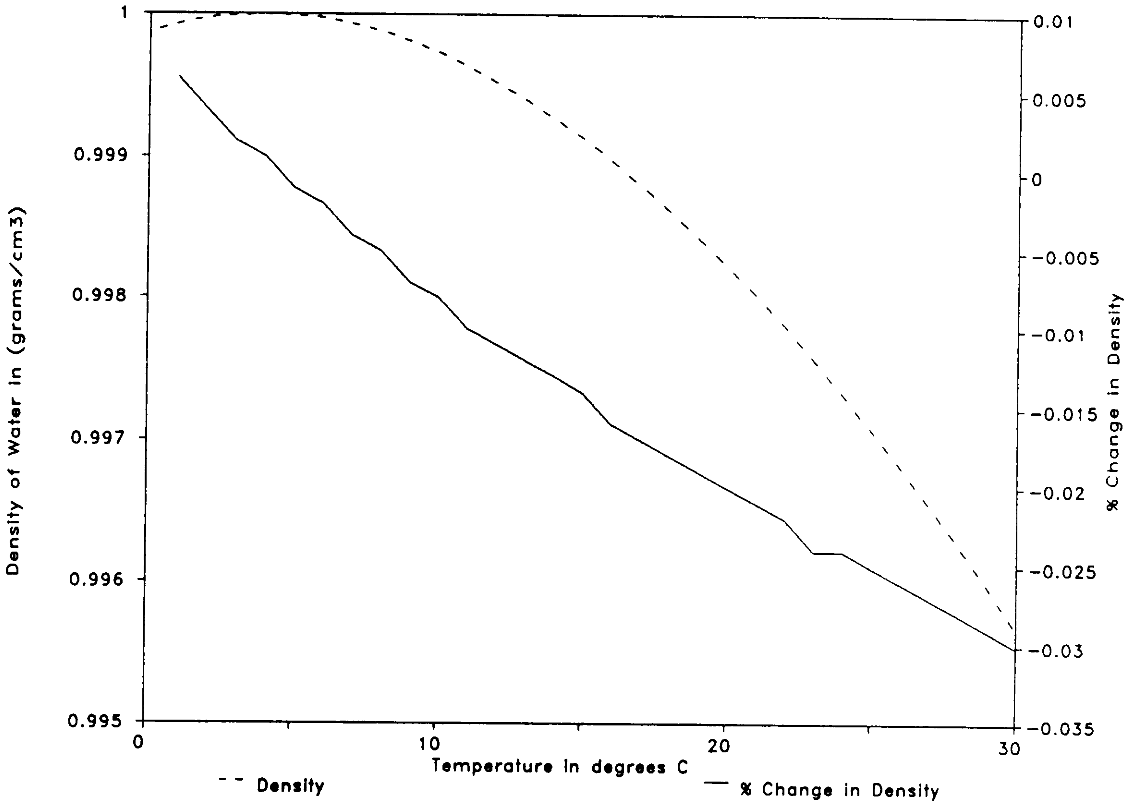

Figure 3 - Density of Water versus Water Temperature

easily seen that this set of conditions also acts as a barrier to mixing of dissolved materials between the layers of different density (6,9). The effects of this stratification will be developed further in later discussion.

With a change in seasons (summer to autumn), the epilimnion cools to a point where it's density is no longer significantly different from the rest of the lake. At that time, the action of wind can induce sufficient mixing action to create a condition known as turnover. The hypolimnion and its dissolved materials then mix with the rest of the lake to create essentially uniform chemical conditions throughout the lake. (10)

Depending on the climate of the lake's location, ice can form in winter. The ice cover then creates a small thermal gradient near the surface of the lake. However, this stratification condition is much less severe than the summer stratification. (6, 9)

With the onset of spring, the uniform temperature gradient develops again and spring turnover occurs. As the heat input of solar radiation increases in the spring, the entire stratification cycle is then repeated. A lake which experiences this type of repeated cycle is termed a dimictic lake, and is typical for the temperate zones of the planet (6, 9).

Other stratification cycles are also seen for other sets of environmental conditions, such as: polymictic lakes which experience frequent circulation cycles (typically found in equatorial regions with little seasonal weather changes), cold monomictic lakes which have water temperatures at or below 4°C most of the year and therefore little to no thermal stratification (typically found in Arctic and mountain areas), warm monomictic lakes which have temperatures always above 4°C and thus only stratify in the summer (typically found in temperate climates near oceans), and oligomictic lakes which are always above 4°C which have rare recirculation periods at irregular intervals (typically found in tropical areas). (6,9) The difference between oligomictic and warm monomictic lakes is that warm monomictic lakes undergo regular recirculation at the end of summer, but oligomictic lakes do not undergo a regular interval recirculation.

Lake Productivity

It is the metabolism of a lake, or more accurately the metabolism of the organisms living in the lake, that is the overriding concern of limnological studies (11). All lakes will go through a gradual process of building up sedimentary material, ultimately turning the lake into a soil column with surface water flowing over it (6, 9, 11). This process is called eutrophication. Some sedimentary material is always being added from the entrained sediment in the supply waters to the lake. However, depending on the propensity for organic life forms to exist in the lake, the buildup of the sediment may be much more rapid due to the addition of detritus from dead organisms. The usefulness and aesthetic qualities of the lake may also be severely impacted if too much organic life is present. For example, excessive algae growth makes the water difficult to treat for domestic use, and can inhibit recreational use of the lake (12). Therefore, it is the productivity of new biomass within the lake (its metabolism) that can drastically affect the useful lifetime of a lake (13). It is important at this point to ensure a useful terminology and technical approach is developed for this study. The underlined text in the following quote was added by the author of this thesis to emphasize key concepts.

> "Much of the confusion ...[of limnology]... emanates from early concepts that considered productivity as the maximum growth and development of organisms under optimal conditions. While the potential of organisms to produce and increase towards infinity may be a useful conceptual framework, in the real world <u>environmental constraints</u> regulate these increases. Optimal conditions for an organism, population, community, or ecosystem can, at best, only be

> approximated after extensive investigation. ... It is much more meaningful to define the terms production and productivity in relation to realized or actual production of organisms. Changes in production are related ...[to the]... _dynamics_ of environmental ... parameters." (6)

It is the environmental parameters such as oxygen content and nutrient availability, and their affects on lake organisms that will be discussed further in this study. This author does not intend that the above noted quotation over simplify limnology. Instead this author intends that the quotation help focus the scope of this study because limnology can involve so many complex interactive variables.

A lake that is low in biomass productivity is termed oligotrophic, and this condition most often corresponds to a low supply of nutrients for organic life. As the nutrient supply slowly increases, so does the biomass productivity and the lake becomes mesotrophic. Finally, a lake which is enriched in nutrients to a point where other parameters, such as the length of the warm season, control the biomass production is termed eutrophic (14).

Typically, the algal population in a eutrophic lake is high during the spring and summer seasons because there is adequate sunlight and because of the slower metabolism rate during the cooler seasons (9). Algae produce oxygen during photosynthesis, and it is quite common for the epilimnion waters to be supersaturated with oxygen (15). However, the thermal stratification prevents the oxygen from diffusing into the hypolimnion. The aerobic life forms in the hypolimnion rapidly decrease the oxygen content of the hypolimnion water to a point below which aerobic life can not be supported. Often, even fish can not survive at these locations (9). Anaerobic and anoxic bacteria then flourish as they decompose organic matter that settles from higher points in the lake. These hypolimnion conditions set up a reducing redox potential, which enables the sediment to release reduced forms of some metals such as iron (Fe^{2+}) and manganese (Mn^{2+}). These materials will remain in the hypolimnion waters until the lake experiences a turnover condition with the normal change of seasons (6).

Nutrients Necessary for Biomass Production

All living organisms require a diverse combination of chemical materials, or nutrients, in order to survive and flourish. All organisms have different nutritional requirements, but similar organisms have similar nutritional requirements (9, 11). The organisms of most interest to limnologists, with regard to a lake's productivity, are the phytoplankton communities referred to as algae (8, 11). These communities are actually a combination of many individual microbiological algae species, including the blue-green, green, yellow-green, red, brown, and golden-brown algae, as well as the diatoms and euglenoids. These organisms are photosynthetic, converting sunlight into chemical energy for their entire biochemical metabolism. Table 1 lists their basic nutritional needs and the sources of the nutrients (1, 6).

Studies have shown that the average stoichiometric cellular makeup of freshwater algae organisms is given by $C_{68}H_{124}O_{30}N_9P$ (16). From this molecular formula, and the biological data of Table 1, some conclusions can be made regarding the nutritional requirements of freshwater algae. First, carbon, hydrogen, and oxygen are needed in relatively large amounts for production of cellular biomass. Second, nitrogen and phosphorus are also needed but in lesser amounts.

A parallel concept concerning nutritional requirements and organism productivity is Leibig's "Law of the Minimum" (9). In 1840, Justus Leibig, while studying inorganic chemical fertilizers, found that crop growth was limited by whatever essential element was in shortest supply, regardless of whether the total amount required was large or small (1). Therefore, whatever nutrient is the

Table 1 - Nutritional Requirements(6)

Function	Source
Energy Source	Organic and inorganic compounds Sunlight via photosynthesis
Electron Acceptor from Respiration	O_2 Organic compounds NO_3^-, NO_2^-, SO_4^{-2}
Material for Cellular Biomass	CO_2, HCO_3^-, NO_3^-, NO_2^-, PO_4^{-2} Organic compounds Trace elements such as vitamins

least abundant, relative to an organism's need, is the controlling nutrient for organism productivity.

This concept is a useful and well proven predictive tool for limnologists and many other biological scientists (6, 9, 10, 14). However, it should be emphasized that it is a "relative law", subject to the level of detail of the analysis. For example, certain vitamins may be essential to an organism's biochemical pathways such that its absence, regardless of the supply of energy sources and electron receptors, could prevent that organism from flourishing. Also, as stated previously, the dynamic change in the characteristics of environmental parameters, including nutrients, also affect the productivity of lake ecosystems.

In lakes, the most necessary chemical elements are also the most prolific. Carbon is readily available from organic matter present, CO_2, and the dissolved forms of $CO_{2,}$ HCO_3^- and CO_3^{2-}. Hydrogen is readily available from organic matter present and water itself. Oxygen is reasonably available in the epilimnion from both dissolved atmospheric O_2, and O_2 produced from the photosynthesis process (6). For aerobic life forms, oxygen is the terminal electron acceptor in biochemical oxidation - the energy producing process. In anaerobic and anoxic life forms, other compounds can be the terminal electron acceptors. Since carbon, hydrogen, and oxygen are available in relatively large amounts, the availability of nitrogen and phosphorus controls the production of algae.

In summary, nutrients can be kinetically or stoichiometrically limiting. Although the assumptions for deriving limiting nutrients under either of these categories can be different, both should be considered when performing such analyses (10).

The above analysis stresses the production of algae and other similar biomass. This does not mean that in other areas of the lake different biochemical processes (or metabolic pathways) result in a prolific collection of different life forms, such as anoxic and anaerobic bacteria in lake sediment (6, 9). However, these other metabolic pathways are not as efficient in the production of biomass material (17).

Nitrogen is a common element in the environment, and its availability to freshwater lakes is the result of numerous sources. Limnological studies have yielded the following information regarding some of the pathways in a lake's nitrogen budget (6, 8, 9, 10, 14).

1. Aerobic decomposition processes are not present in an anaerobic hypolimnion.

2. The metabolism of epilimnion organisms can be a major source of organic nitrogen in lakes.

3. Many components of nitrogen input to lakes are either seasonal or intermittent in application and variable in magnitude. Examples of these sources include organic and ammonia nitrogen from water fowl excretions, and both organic and oxidized nitrogen from sewage treatment plant discharges.

4. Nitrogen uptake and release from sediments is a complex and not well understood process. One study showed that although there is a significant source of nitrogen present in lake sediments, it is not readily available for metabolism in a lake system. Therefore, the influent sources of nitrogen usually determine the quantity of nitrogen available in the water column of a lake.

In summary, for most lakes, nitrogen is available in sufficient quantities to not be the limiting nutrient for algae growth. However, because nitrogen is critical for biomass production, the amount of nitrogen present can have an affect upon the total amount of biomass produced. Therefore, minimizing the nitrogen input to a lake is still a desirable objective.

The magnitude of nitrogen in drinking water can also be an environmental health issue (18). Ammonia is toxic to many organisms when present in sufficient quantities, and nitrate is toxic to human infants (19). Therefore, control of nitrogen is important for both lake productivity and water resource usefulness.

The preceding discussion concludes that phosphorus is often the most kinetically and/or stoichiometrically limiting nutrient with respect to lake productivity. This has been demonstrated in numerous laboratory and natural environmental experiments. For example, one of the most dramatic experiments was performed on a natural lake in Ontario, Canada, which had a natural shape like a dumbbell (6). A partition was placed in the narrow section connecting the lobes of the lake. The partition prevented cross-flow between the two main lobes of the lake. One lobe was fertilized with phosphorus, nitrogen, and carbon, and the other lobe was fertilized with equivalent concentrations of nitrogen and carbon only. Algal biomass increased two orders of magnitude in the lobe which received the phosphorus, but it did not appreciably change from normal conditions in the other side. (6) Pre-experiment conditions returned in both lobes of the lake quickly after fertilization was stopped. Many other similar experiments demonstrate that phosphorus inputs to a lake ecosystem can drastically and rapidly change the biomass production rate (20).

Most of the phosphorus (often greater than 95 percent by mass) present in a lake at any time is not readily available for utilization by algae (11). This unavailable phosphorus is bound in organic phosphates and cellular constituents of organisms, both living and dead, and is absorbed by organic and inorganic colloids, and particulate compounds (6). Also, the highly reactive chemical properties of phosphorus further amplify the shortage of this nutrient, because any supply is rapidly depleted (9). Phosphorus exchange between lake water and sediment is highly dependent on the oxidation-reduction conditions at the sediment water interface, and on the mixing (turbulence) conditions of the lake (21). In general, studies have shown that the phosphorus budget of a lake is more complex than the nitrogen budget, partly due to the rapid kinetics of the phosphorus reactions which make measurements difficult (6).

Quantification and Prediction of Lake Productivity

The ability to quantify and predict the trophic status of a lake can be useful when it is desired to monitor, control, or correct the productive status of a lake (10, 14). Numerous models have been developed which insert easily measured parameters into empirically developed relationships. Most of these models have been developed based on the assumption that a lake is phosphorus limited. Since these models are empirically developed, their results must be tempered with appropriate professional judgement (6).

One of the first and most successful models developed was the Vollenweider model (6, 20). This model used annual mean concentration values of total phosphorus and chlorophyll a to assign a trophic status to a lake. Vollenweider then improved his model to use the annual loading rates of phosphorus to arrive at a trophic status. It is then easier to develop control measures to ensure loading rates do not exceed the desired level of productivity.

The Vollenweider model is a mass balance equation for phosphorus. The change in total phosphorus is equal to the influent loading of phosphorus minus the sum of the outflow of phosphorus and the sedimentation of phosphorus. The data are represented by graphing the annual phosphorus loading (mass/area/time) versus the mean depth (length) times the hydraulic retention time (years). The abscissa in this graph is the relative "flushing" term because it relates the rate at which water is changed in the lake to the amount of the lake which can produce algae due to light penetration. The resulting curve is shown in Figure 4. Vollenweider designated 'admissible' and 'dangerous' loading levels, which are depicted by the curves shown on Figure 4.

Vollenweider's assumptions were pointed out as important limitations by Dillion (20); 1) the lake is well mixed, thus ignoring stratification affects, 2) loading, flushing, and sedimentation rates are constant, 3) the sedimentation process is first order relative to the amount of phosphorus present, and 4) no credit is taken for internal loading of phosphorus.

A different type of model uses water transparency and other parameters to arrive at a "trophic index".

In 1977, Carlson published a scheme to classify lakes using three different Trophic State Indices (TSI) (22). He emphasized that a TSI was not a water quality index, but that the TSI could be useful for comparing lakes within a region, and as a management tool for predicting productivity

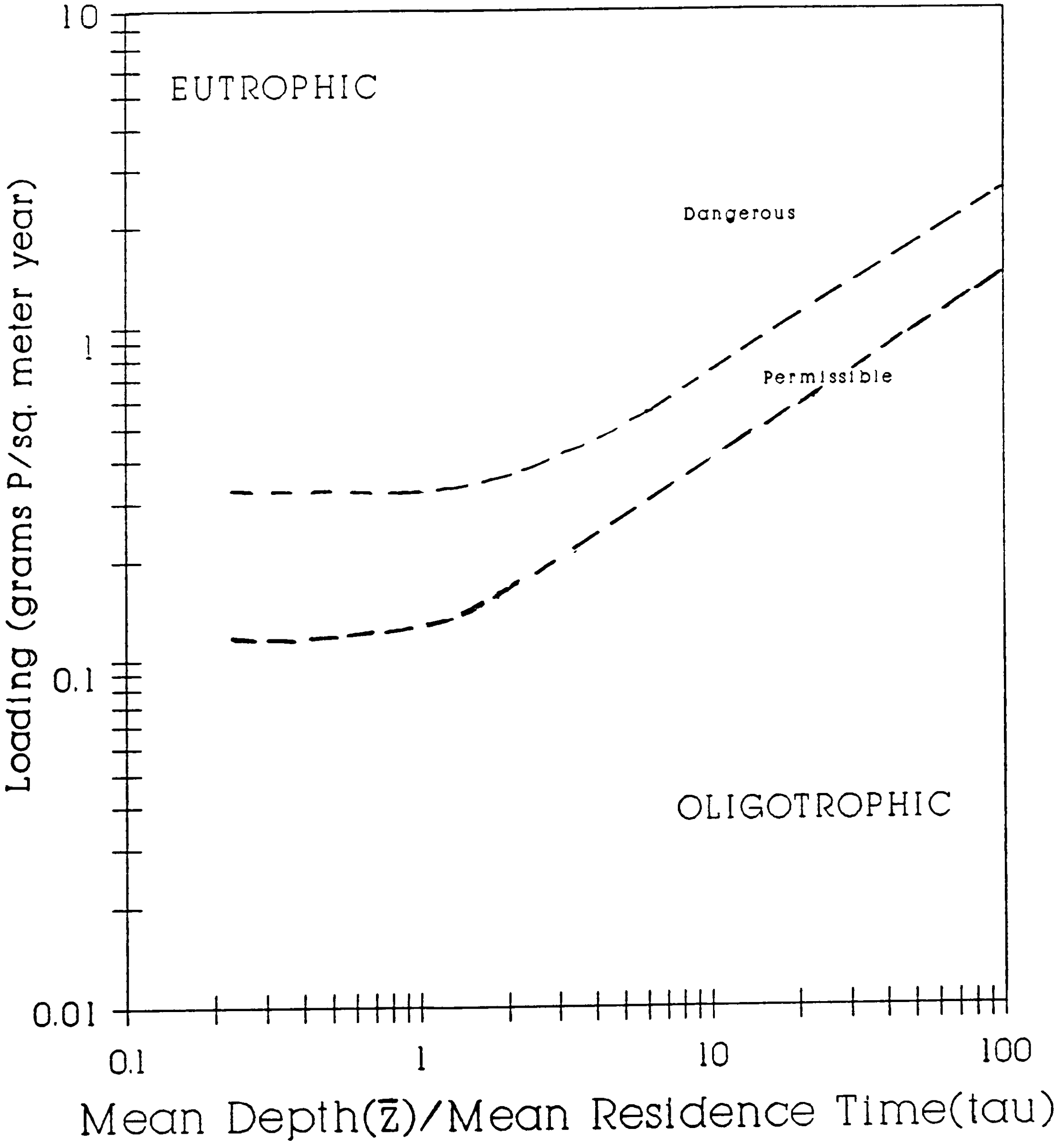

Figure 4 - The Vollenweider Model Relationship

changes when it is used in conjunction with nutrient loading concepts.

Carlson uses the epilimnion values of total phosphorus, chlorophyll a, and secchi disk reading to arrive at a TSI for a lake. Carlson's scale is based on the increase in algal biomass in response to an increase in the phosphorus concentration. Many factors can affect the ability of Carlson's model to accurately predict the trophic index of a lake, such as seasonal changes, and highly colored or turbid waters. He found that man-made impoundments showed different relationships than did natural lakes. Carlson speculated that man-made impoundments may be muddier than natural lakes, thus affecting the secchi disk results. (1, 22)

Carlson's model yields a TSI value between 0 and 100. However, he did not propose ranges of a TSI relative to the older oligotrophic-mesotrophic-eutrophic system other than to say that a higher TSI indicates an increased propensity for eutrophic conditions.

Tables 2, 3, and 4 present the TSI scales developed by Carlson, Sakamoto, Dobson, the National Academy of Sciences, and the U.S. Environmental Protection Agency. The parameter values provided are the epilimnion averages during the summer season. (23)

Table 2 - Carlson's Trophic State Index (22)

TSI	Secchi Dish Depth (m)	Surface Total Phosphorus (micrograms/liter)	Surface Chlorophyll a (micrograms/liter)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3.0	0.34
30	8	6.0	0.94
40	4	12	2.6
50	2	24	6.4
60	0.5	96	56
70	0.5	96	154
90	0.12	384	427
100	0.062	768	1183

Analytical equations to generate the table given above are:

$$\text{TSI Secchi } (S) = 10*(6-(\ln(S)/\ln(2)))$$

$$\text{TSI Total Phosphorus } (TP) = 10*(6-(\ln(48/TP)/\ln(2)))$$

$$\text{TSI Chlorophyll } \underline{a} \ (Cha) = 10*(6-((2.04-0.68*\ln(Cha))/\ln(2))$$

Table 3 - Trophic State Indices Based on Chlorophyll a
Chorophyll a in micrograms per liter (22)

Trophic Condition	Sakamoto	Academy	Dobson	EPA
Oligotrophic	0.3 to 2.5	0 to 4	0 to 4.3	<7
Mesotrophic	1 to 15	4 to 10	4.3 to 8.8	7 to 12
Eutrophic	5 to 140	>10	>8.8	>12

Table 4 - EPA Trophic State Index System (22)

Trophic Condition	Chlorophyll *a*	Total Phosphorus	Secchi Dish Depth (meters)
	(micrograms per liter)		
Oligotrophic	<7	<10	>3.7
Mesotrophic	7 to 12	10 to 20	2 to 3.7
Eutrophic	>12	>20	<2.0

Chapter III

METHODS AND MATERIALS

The City of Manassas has contracted with the Occoquan Watershed Monitoring Laboratory (OWML), located in Manassas, Virginia, to design and implement a monitoring program for the lake and its tributaries (24). Sampling of the lake began in October of 1984. Sampling of some of the tributaries to the lake began as early as 1975 as part of the greater Occoquan Watershed monitoring program. The OWML has established schedules and procedures for the Lake Manassas monitoring program, and the data generated from this program is stored at the OWML and on the mainframe computers of the Virginia Polytechnic Institute and State University.

Sampling Program

The Lake Manassas sampling program consists of eight sampling locations on the lake, and are designated on Figure 5 as LM01 to LM08. The Lake Manassas tributary monitoring program consists of eight sampling stations, designated on Figure 5 as BR02 to BR08 and ST70. Samples obtained at the stations denoted by the BR series are grab samples, whereas samples from the ST70 station consist of

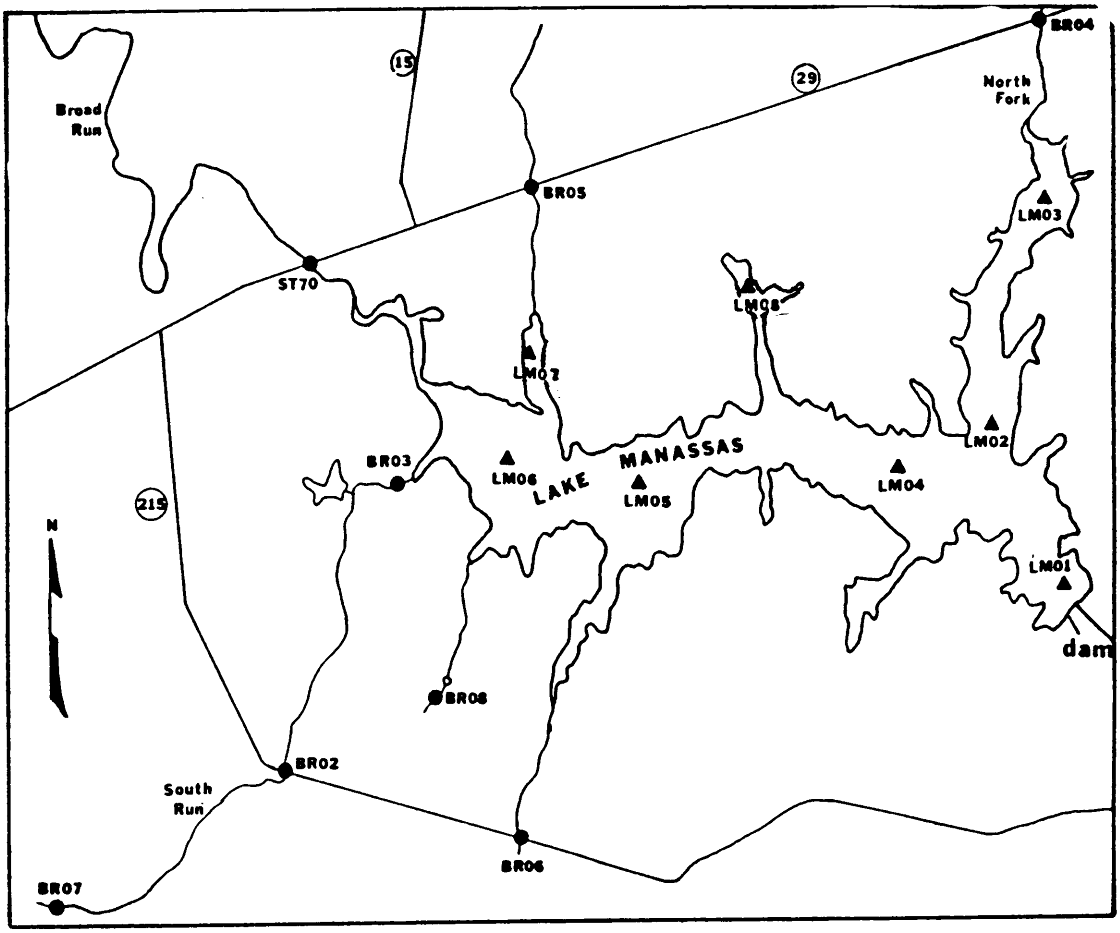

Figure 5 - Lake Manassas Sampling Stations

both flow weighted composite samples and grab samples. ST70 is the only tributary to the lake that is gauged.

There is a gauged monitoring station for the outlet from of Lake Manassas, ST30.

At the LM series lake sampling stations, field measurements are obtained at the one-foot, two-and-a-half-foot, and five-foot depths, and then at five foot increments until the bottom is reached. Sampling is typically done twice a month, slightly more often during the summer months and slightly less often during the winter months if ice is present. Field measurements include dissolved oxygen, temperature, pH, and Secchi disk reading. Samples are obtained from the one-foot depth and the bottom depth for later constituent analysis in the laboratory. These constituent analyses include phosphorus and nitrogen concentrations, solids concentrations, conductivity, chlorophyll a, and occasionally other pollutants such as metals.

Grab samples from the BR series tributaries are analyzed the same as the lake samples. The flow-weighted composite samples and grab samples from the ST70 and ST30 stations are also analyzed in a similar fashion.

One unique situation in the monitoring program is on the South Run tributary to the lake. The water from Lake

Brittle, a state owned impoundment used as a fishing reservoir, is monitored at location BR07 (2). All of the water from the South Run watershed flows through Lake Brittle. Downstream of BR07 and immediately downstream from the point where a discharge from the Vint Hill Farm Station, a U. S. Army Military Reservation, enters South Run is a monitoring station, BR02. The discharge from the Vint Hill Farm Station is from a sewage treatment plant, and is a State of Virginia permitted facility (24). Finally, South Run is monitored just before it enters Lake Manassas, at BR03.

Sample Analysis

All samples and measurements made are logged by using a unique sample identification number which is generated by the computerized data management system. All sample analysis techniques are performed in accordance with Standard Methods for the Examination of Water and Wastewater (31).

The computerized data management system which contains the results of this monitoring program is structured and maintained in an IBM-PC format database language, dBASE III+, a trademark database computer language. The field names for the database and the corresponding parameter which is represented by the database fieldname are listed in Table 5. All of the fields are stored as character fields except the fields containing date information which are stored as date fields. All of the fields have a length of 8 characters except the time fields which are 5 characters in length. The format for data in fields containing numerical information is for the decimal point to always occupy the third position from the right end of the field. If the parameter being measured is less than the analytical detection limit, the detection limit is entered as the value with a negative sign in front of it.

Data Analysis

Various IBM-PC software packages were used to perform the numerical analysis for this report and to generate the graphical data presentations of Chapters IV, V and VI.

Most of the numerical analysis performed on the data was done by extracting the appropriate data from the database and importing it into a Lotus 1-2-3 spreadsheet. Typical mathematical functions were then used to obtain the desired values such as average concentrations. Most of the graphs produced for this thesis are from the Lotus 1-2-3 graphing routine.

One set of graphs which were produced by another program are the contour graphs presenting lake data as a function of depth and time. For example the temperature profiles over the depth of the lake for the monitoring period. These graphs were produced using a software package called SURFER. This program takes numerical data from a Lotus 1-2-3 spreadsheet and uses contouring techniques to develope the subject graphs. Different techniques can be selected, and for this thesis the technique of inverse distance between individual data points was used by the program to splice contour lines between data points. SURFER also offers another optional contouring technique known as "krieging." This technique uses geostatistical equations to splice contour lines between data points. However, because the data analyzed in this case are not derived from geological processes (i.e. erosion, faulting, or other geologic process), this optional contouring technique was not used. One shortcoming of the SURFER contouring technique is that it attempts to close all contours over the abscissa data range. This can result in graphical anomalies. For example, in the case of temperature profiles with depth, there are some closed loop contours within the water column. Physically, this implies that warmer water is both above and below a "pocket" of cooler water. This is not physically possible, because the density of water increases steadily as temperature decreases for temperature above $4^{\circ C}$. The cooler water should sink, not float on top of warmer water. This limitation of the computer software does not have a serious affect on the analyses results of this thesis because the graphs developed are used almost exclusively in a qualitative manner.

Another computer package utilized for this thesis is a companion program to the Lotus 1-2-3 program (also called a Lotus add-in) called @RISK. This program provides Lotus 1-2-3 with additional mathematical functions used in statistical techniques. In this thesis, the Vollenweider model was converted into a computer "spreadsheet model" of Lake Manassas. This spreadsheet model used the hydrologic data determined for the lake input streams (discussed below) and the nutrient sampling data from these streams (the dBASE III+ database). The spreadsheet lake model used @RISK to enable the model parameters (e.g. nutrient concentration, stream flowrate) to be expressed as continuous distribution functions. The model, when executed, analyzes each variable separately according to the parameters listed in their respective distribution functions (27). The results for each iteration are tabulated, and another iteration of the model takes place.

Applying the Vollenweider analysis in this way allowed all of the environmental parameters in the model to vary across their respective ranges independently of each other. This methodology reduces induced biasing resulting from an arbitrary "averaging" technique that would be normally used in the Vollenweider analysis. Table 5 lists the various model parameters and the distribution functions chosen for them. The truncated lognormal distributions were chosen for the stream total phosphorus concentration based on the results of extensive environmental studies which showed this distribution to be the appropriate choice (25).

All of the distributions were truncated to both the highest and lowest observed values to ensure the model did not select concentrations that were outside the range of actual observed data (26). The model was executed 1000 times using a latin hypercube distribution to ensure adequate sampling of the entire range of any parameter value. The spreadsheet model used separate parameter distribution functions based on median values and average (mean) values for each parameter. This modification further reduces biasing of results. The results of this analysis technique are presented on the Vollenweider plot as a "box" instead of a point. Therefore, this analysis technique minimizes one of the shortcomings of the Vollenweider

Table 5 - Distribution Functions for Spreadsheet Model

Yearly Rainfall	Normally Distributed
Vint Hill Phosphorus Concentration	Normally Distributed
All other Stream Phosphorus Concentrations	Truncated Lognormal

analysis; forcing a real world dynamic system into a static model. The modeling technique used in this paper still results in a single set of parameter values for predicting the eutrophic status of Lake Manassas, but these predicted values are the result of allowing all parameters to vary "dynamically." A distribution of possible results is obtained with corresponding statistical properties, thereby producing a better understanding of the stability of the eutrophic status of the lake. A Latin Hypercube sampling technique was used for the parameter distribution functions. This sampling technique is different than the pure random technique of Monte Carlo sampling, but it allows for convergence on the "true mean" in fewer iterations than Monte Carlo. Latin Hypercube essentially constrains the sampling to the higher probablility values of the distribution functions.

This spreadsheet model analyzed Lake Manassas at "full pool" conditions and did not account for the yearly drawdown-refill cycle that can be encountered under normal operating conditions. If the model was modified to account for a changing volume and mean depth with time, the predicted results would a be a more accurate prediction of the lake's eutrophic status. However, in this case the proportional decrease in volume and mean depth would be approximately linear, (see the range of values in Figure 6) thereby cancelling each other out in the z/tau parameter. The z term is the mean depth of the lake, and the tau term is the mean residence time of a water molecule in the lake (e.g. flowrate divided by the volume). Furthermore, the lake drawdown level change is highly dependent on yearly rainfall (a normally distributed variable), and the end result should be a z/tau distribution of very similar values to that of the current model.

Finally, there was insufficient data in the existing database to quantify the magnitude and periodicity of the lake drawdown cycle.

Measurements of a geographical and hydraulic nature were made with a planimeter (27). U.S. Geological Survey Maps served as the templates for these measurements (28). For purposes of this study, the Lake Manassas watershed was divided into five separate basins, three of which compose approximately 90 percent of the total watershed area. The breakdown was based on the hydrology of the surface water inputs to Lake Manassas and on the database available from the existing environmental monitoring program. Planimetric techniques were employed to determine the basins areas.

The database also contains information on the amount of rainfall received in the area around Lake Manassas on a yearly basis. The rainfall data can be linked with the flow data for Broad Run at station ST70 to develop a runoff factor as a function of total rainfall on the ST70 basin area. An average %Runoff curve can be developed by dividing the yearly flow through a watershed by the yearly volume of rainfall on the watershed. This method assumes that the basins are of similar character with regards to runoff potential. The predicted flows can be combined with monitoring results for the other basins to yield loading rates for each basin (29).

TABLE 6 - Database Structure and Contents

Field name	Field contents
STA	Monitoring station number
LABID	Laboratory ID number
DATE1	Date of sample for grab samples, start of event period for composite samples
TIME1	Time of sample for grab samples, start time of event for composite samples
DATE2	Blank for grab samples, finish date of event for composite samples
TIME2	Blank for grab samples, finish time of event for composite samples
UPDATECHAR	Indicates which data has been updated
UPDATE	Date of data update or change
STRMNO	Storm number for composite samples during a storm event
SAMNO	Number of samples taken to makeup the composite sample
TYPE	Grab or composite sample
DEPTH	Depth of sample for lake samples
STAGE	Stage of stream based on gage height
POOLELEV	Height of water in lake at the dam gage
FLO	Flow rate of stream in (ft^3/sec)

TABLE 6 - continued

Field name	Field contents
TOTFLO	Total flow during event for composite samples in (ft^3)
TOTRAIN	Total rain in inches for event
WFDFVOL	Storm to base flow ratio
DO	Dissolved oxygen in mg/L as O_2
FIELDPH	pH of sample measured in field
LABPH	pH of sample measured in laboratory
TEMP	Temperature of sample in field in °C
COND	Conductivity of sample measured in field
COND25	Conductivity of sample corrected to 25 °C
PALK	Phenophtalein alkalinity in mg/L as $CaCO_3$
TALK	Total alkalinity in mg/L as $CaCO_3$
SECCHI	Secchi disk reading in inches
OP	Orthophosphorus concentration in mg/L as P
TSP	Total soluble phosphorus concentration in mg/L as P
TP	Total phosphorus concentration in mg/L as P
NH3_N	Ammonia nitrogen concentration in mg/L as N

TABLE 6 -continued

Field name	Field contents
SKN	Soluble Kedjadl nitrogen in mg/L as N
TKN	Total Kedjadl nitrogen in mg/L as N
NO2_N	Nitrite concentration in mg/L as N
NO3_N	Nitrate concentration in mg/L as N
OX_N	Total oxidized nitrogen concentration in mg/L as N
COD	Chemical oxygen demand (meq/l)
TOC	Total organic carbon concentration in mg/L as C
BOD5	BOD concentration in mg/L after 5 days
BOD5I	Inhibited BOD concentration in mg/L after 5 days
BOD20	BOD concentration in mg/L after 20 days
BOD20I	Inhibited BOD concentration in mg/L after 30 days
BOD40	BOD concentration in mg/L after 40 days
BOD40I	Inhibited BOD concentration in mg/L after 40 days
TURB	Turbidity in (n.t.u.)
TSS	Total suspended solids in mg/L

TABLE 6 - continued

Field name	Field contents
VSS	Volatile suspended solids in mg/L
TDS	Total dissolved solids in mg/L
TS	Total solids in mg/L
CHLA	Chlorophyll by the trichromatic method in micrograms per liter (ug/l)
CHLAM	Chlorophyll by the monochromatic method in ug/l
PHPA	Chlorophyll by the phenophatlein method in ug/l
TCOLI	Total coliforms as most probable number (MPN)
FCOLI	Fecal coliforms as MPN
TAG	Total silver in mg/L as silver
EAG	Extractable silver in mg/L as silver
SAG	Soluble silver in mg/L as silver

Other metals in the database include aluminum, cadmium, chromium, copper, iron, mercury, manganese, nickel, lead, and zinc. All are included as fields similar to silver, named by T, E, or S with their two letter chemical name following.

Chapter IV

RESULTS

This section presents the results of the analysis performed using the environmental database discussed in Chapter III. Results from lake data will be presented first, followed by results from stream data.

Lake Manassas Morphology

Planimetric measurements were conducted on standard 7.5 minute U.S. Geological Survey maps of the area comprising Lake Manassas. These area measurements were combined with elevation data to develop a hypsographic curve for Lake Manassas (Figure 6). Table 7 gives the other morphological characteristics measured for the lake.

Lake Manassas Thermal Stratification

Figures 7 through 14 represent the temperature profiles for Lake Manassas at lake monitoring stations LM01 through LM08. The figures were developed by contouring the measured temperature in °C at a given depth (the ordinate) over the monitoring period (the abscissa). Chapter III contains a more detailed description of the contouring technique. The figures are structured so that the surface of the lake is at

Table 7 - Morphological Characteristics of Lake Manassas

(at full pool of 285 feet above mean sea level)

Lake Volume	4.2	billion gallons
Lake Area	694	acres
Maximum depth	55	feet
Mean depth	11.5	feet
Length of lake	2.9	miles
Shoreline length	17.3	miles
Shoreline Development	29.5	

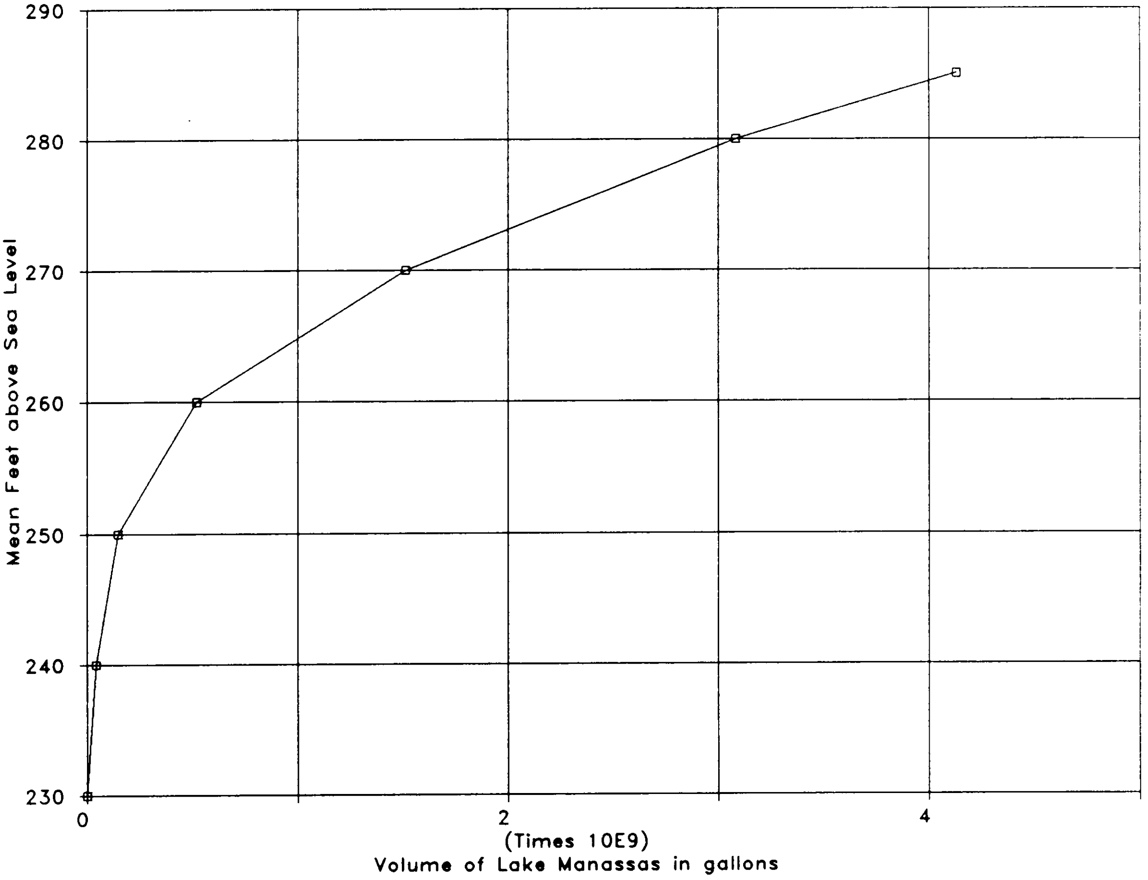

Figure 6 - Hypsographic Curve for Lake Manassas

the top of the graph, and the ordinate scale is denoted by water depth in feet. The abscissa is scaled in months from the start date of the measurements. For Figures 7 through 12, the start date was October 31, 1984. For Figures 13 and 14 the start date was August 13, 1986. The monitoring period for Figures 13 and 14 is shorter because sampling stations LM07 and LM08 were added to the monitoring program after it had been in place for some time.

As discussed in Chapter III, there may be some closed loop contours within the figures. This is a limitation of the computer software program used to develop the figures.

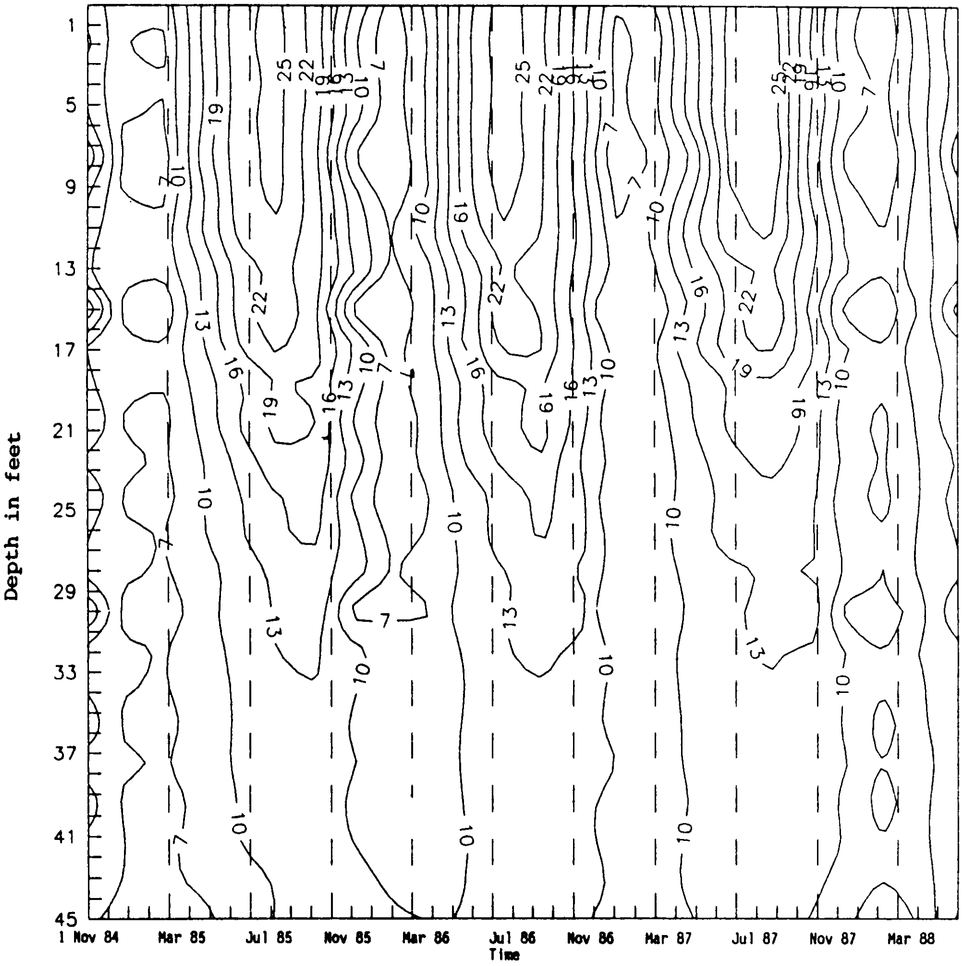

Figure 7 - Temperature Profile at Monitoring Station LM01

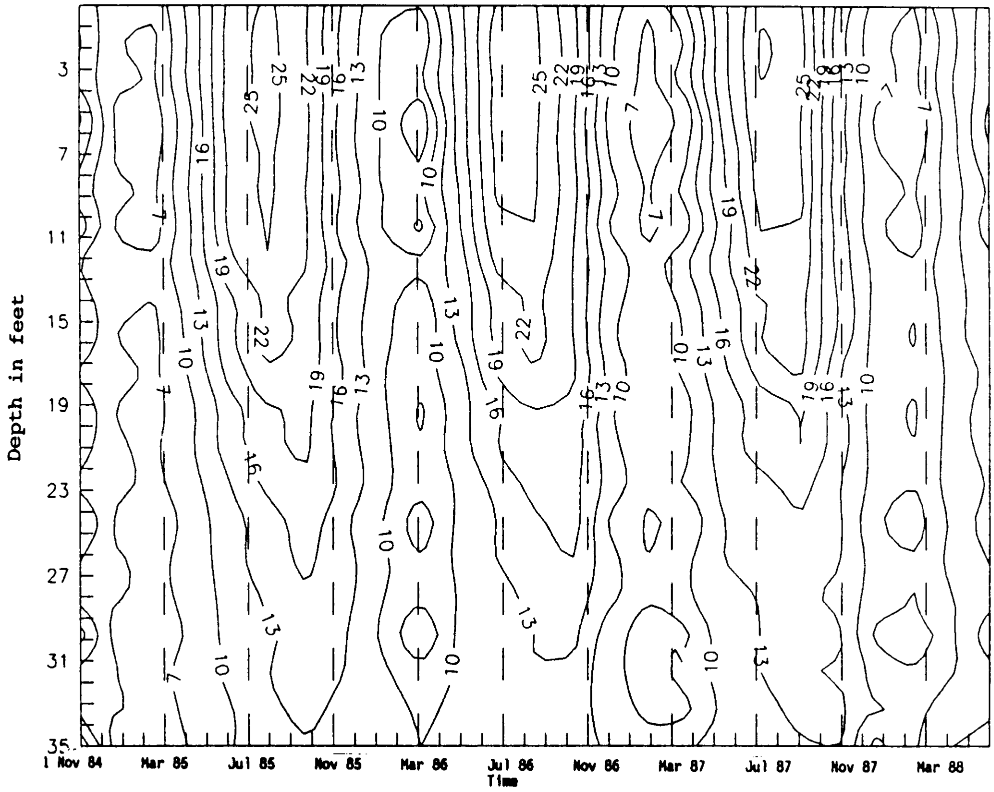

Figure 8 - Temperature Profile at Monitoring Station LM02

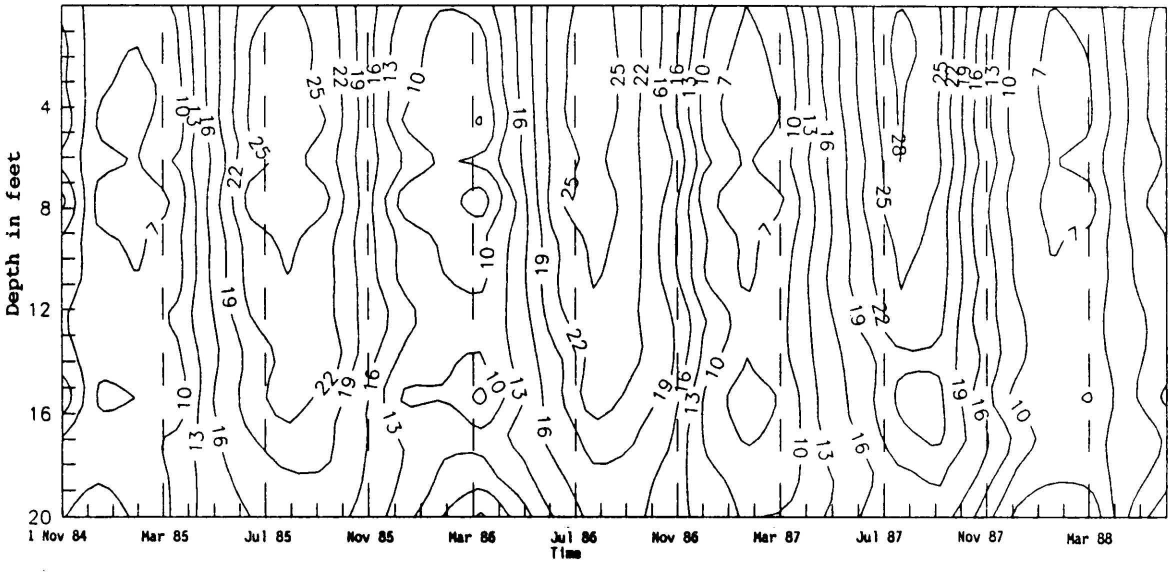

Figure 9 - Temperature Profile at Monitoring Station LM03

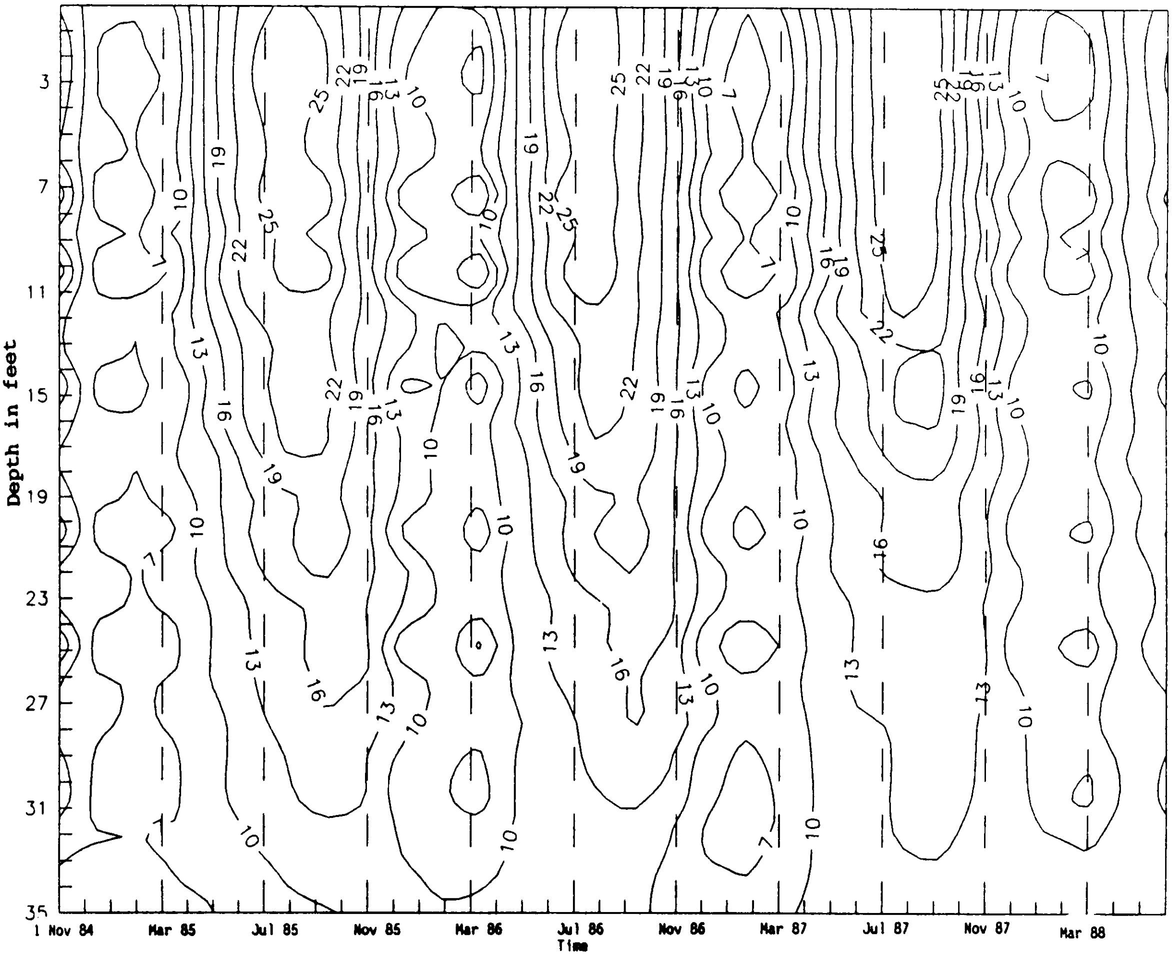

Figure 10 - Temperature Profile at Monitoring Station LM04

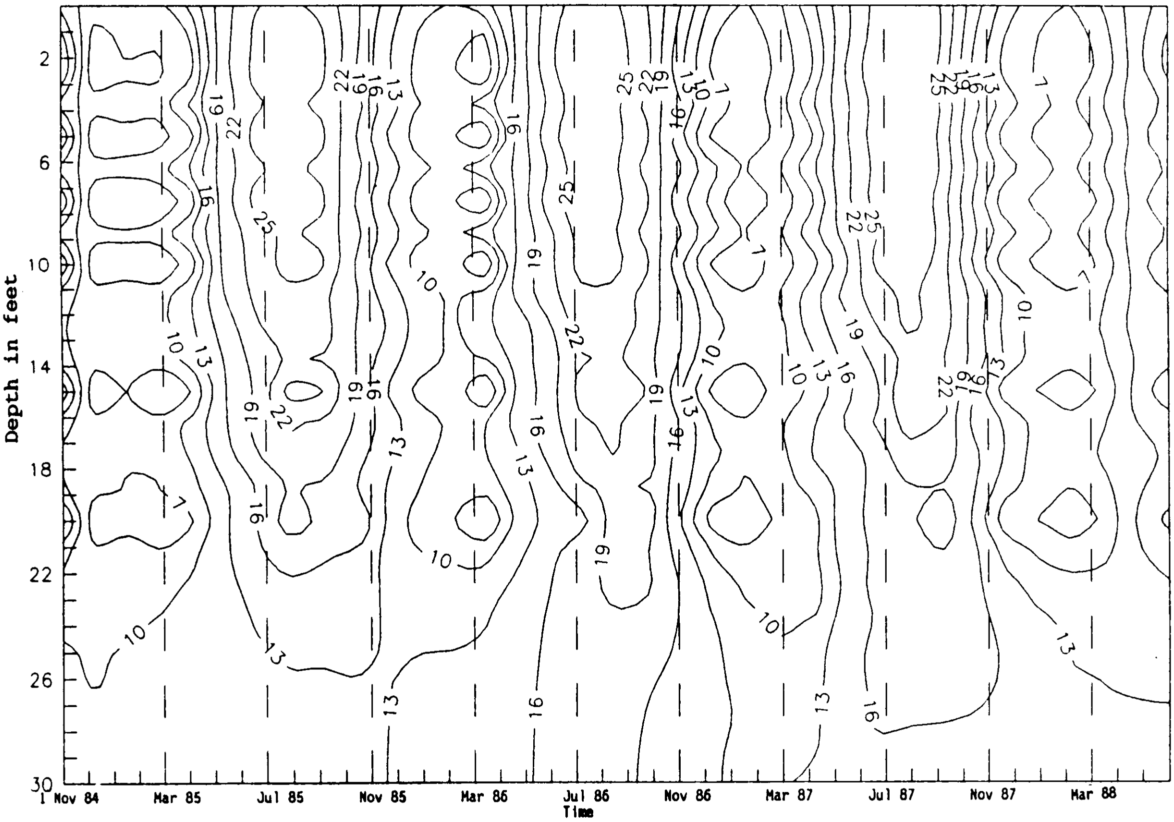

Figure 11 - Temperature Profile at Monitoring Station LM05

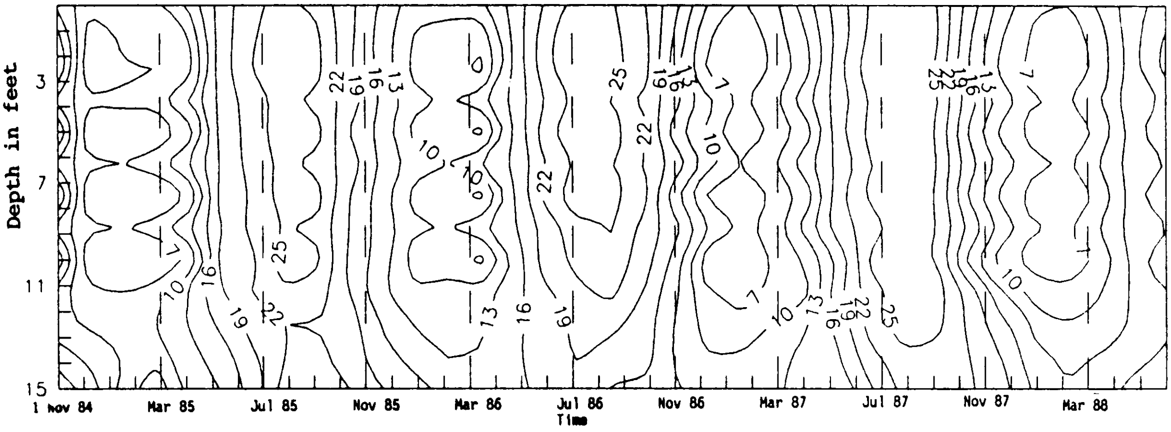

Figure 12 - Temperature Profile at Monitoring Station LM06

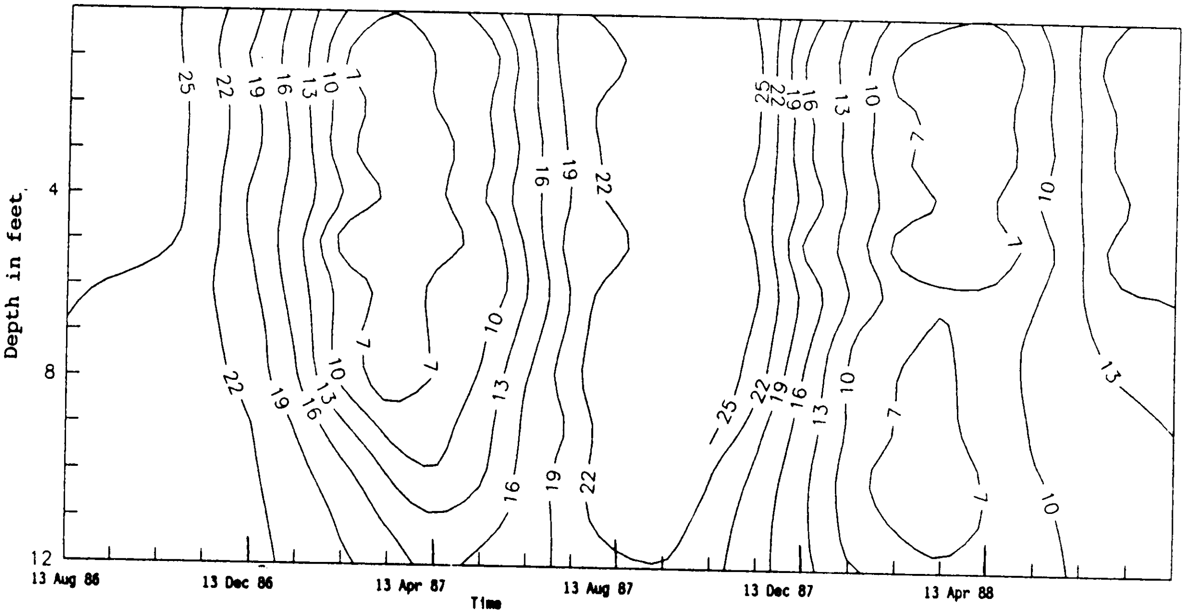

Figure 13 - Temperature Profile at Monitoring Station LM07

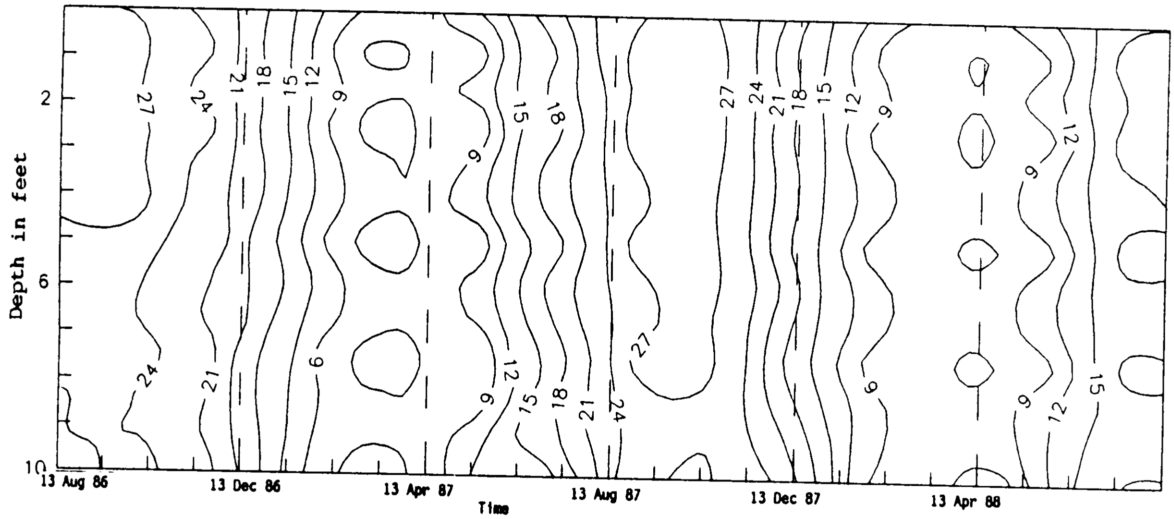

Figure 14 - Temperature Profile at Monitoring Station LM08

Lake Manassas Dissolved Oxygen Profiles

Figures 15 through 22 represent the dissolved oxygen profiles for Lake Manassas at lake monitoring stations LM01 through LM08. The figures are developed by contouring the measured dissolved oxygen concentration (in mg/L) at a given depth over the monitoring period. The figures are structured so that the surface of the lake is at the top of the graph, and the ordinate scale is denoted by water depth in feet. The abscissa is scaled in months after the start date of the measurements, as in Figures 7 through 14.

Figures 23 through 30 represent the percent saturation of dissolved oxygen for Lake Manassas at lake monitoring stations LM01 through LM08. These graphs are a combination of the temperature profile graphs and the dissolved oxygen profiles. The percent oxygen saturation corresponding to each dissolved oxygen measurement was calculated based on the measured temperature at that location. These graphs are structured the same as Figures 15 through 22.

Note that for these figures closed loop contours are both possible and expected because of the presence of submerged microorganisms (algae) producing oxygen by photosynthesis.

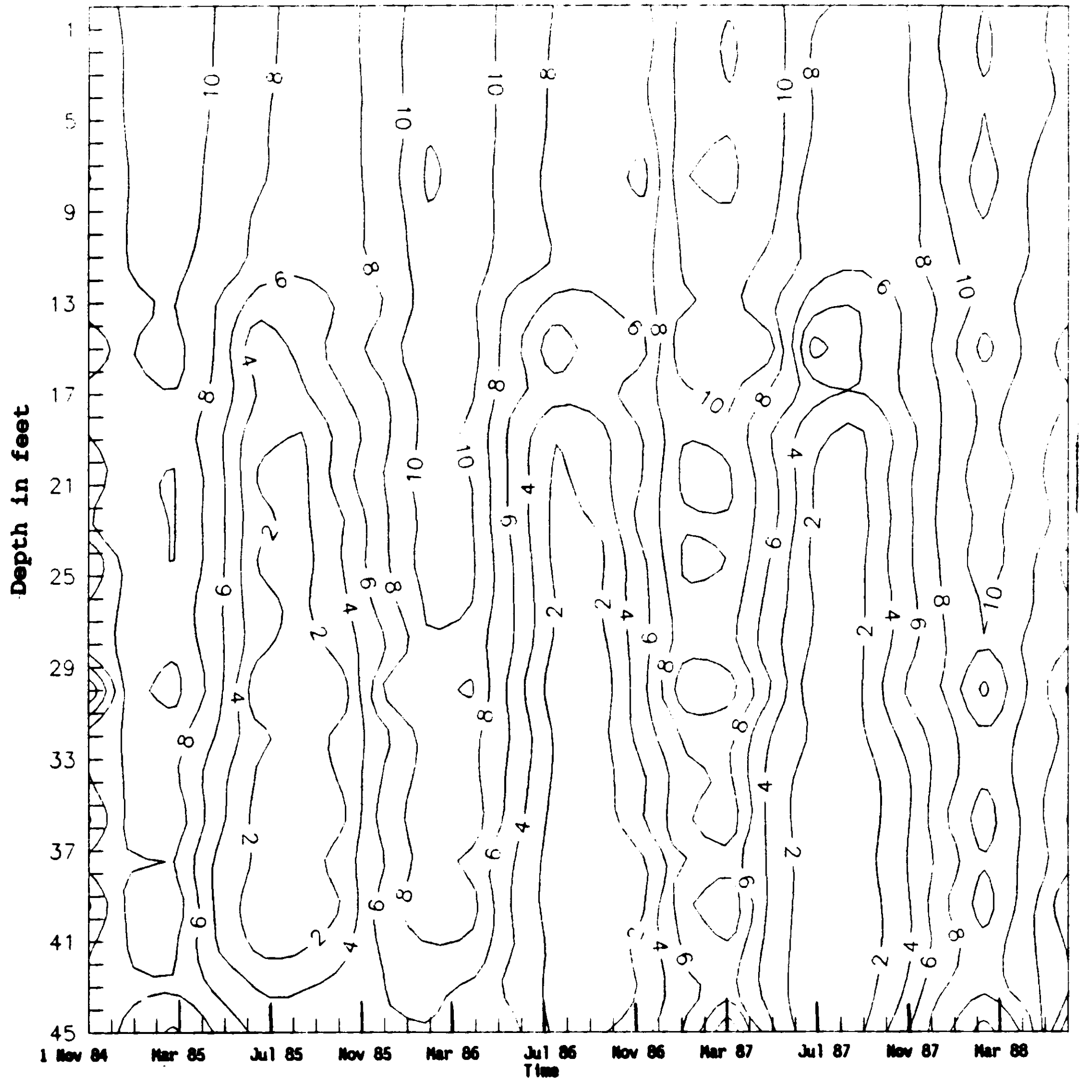

Figure 15 - Dissolved Oxygen Profile at Station LM01

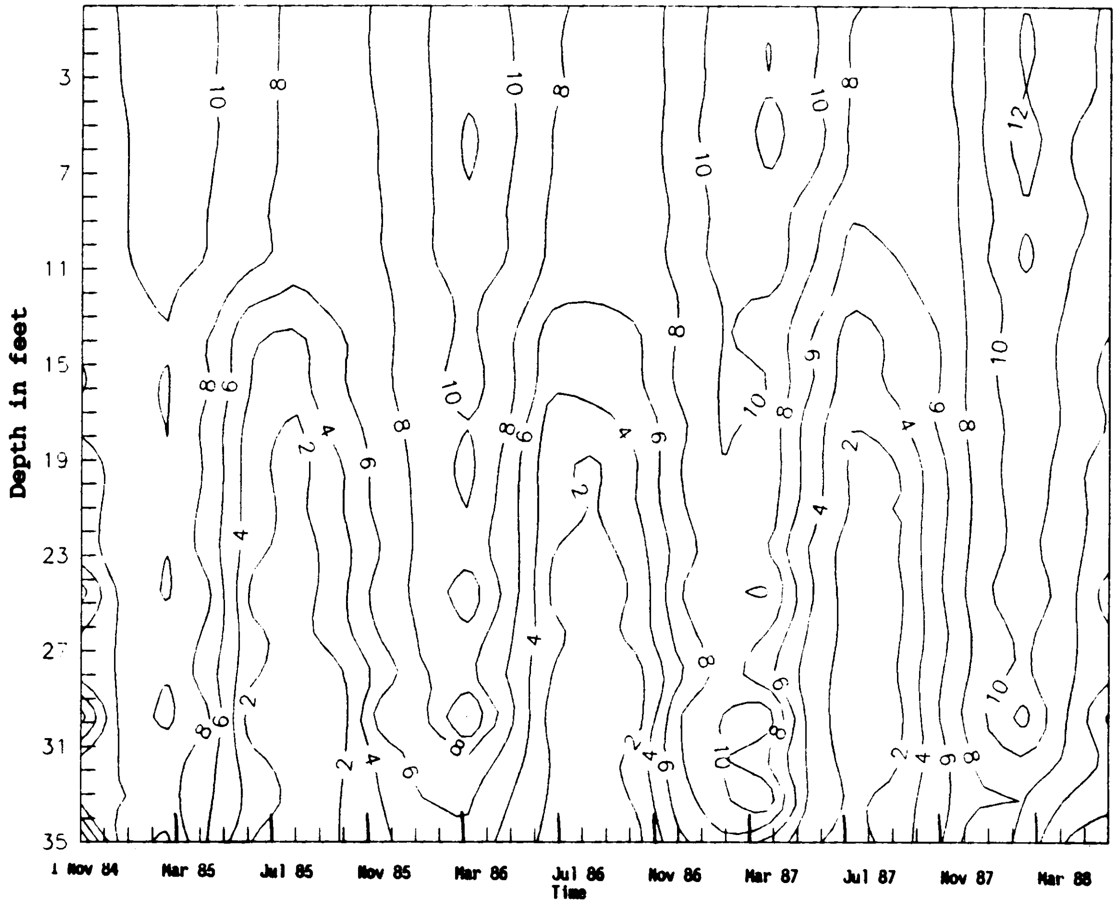

Figure 16 - Dissolved Oxygen Profile at Station LM02

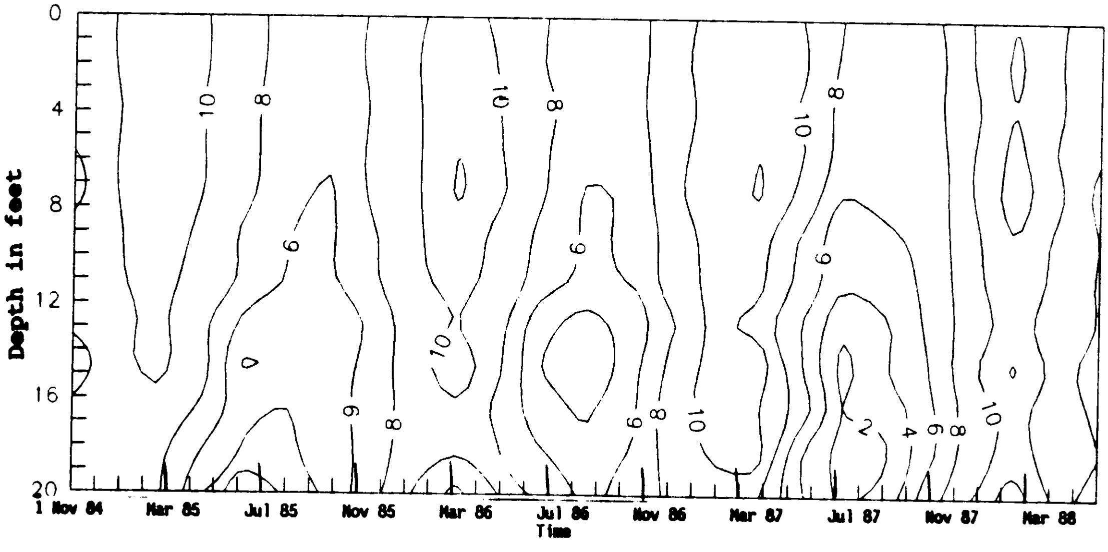

Figure 17 - Dissolved Oxygen Profile at Station LM03

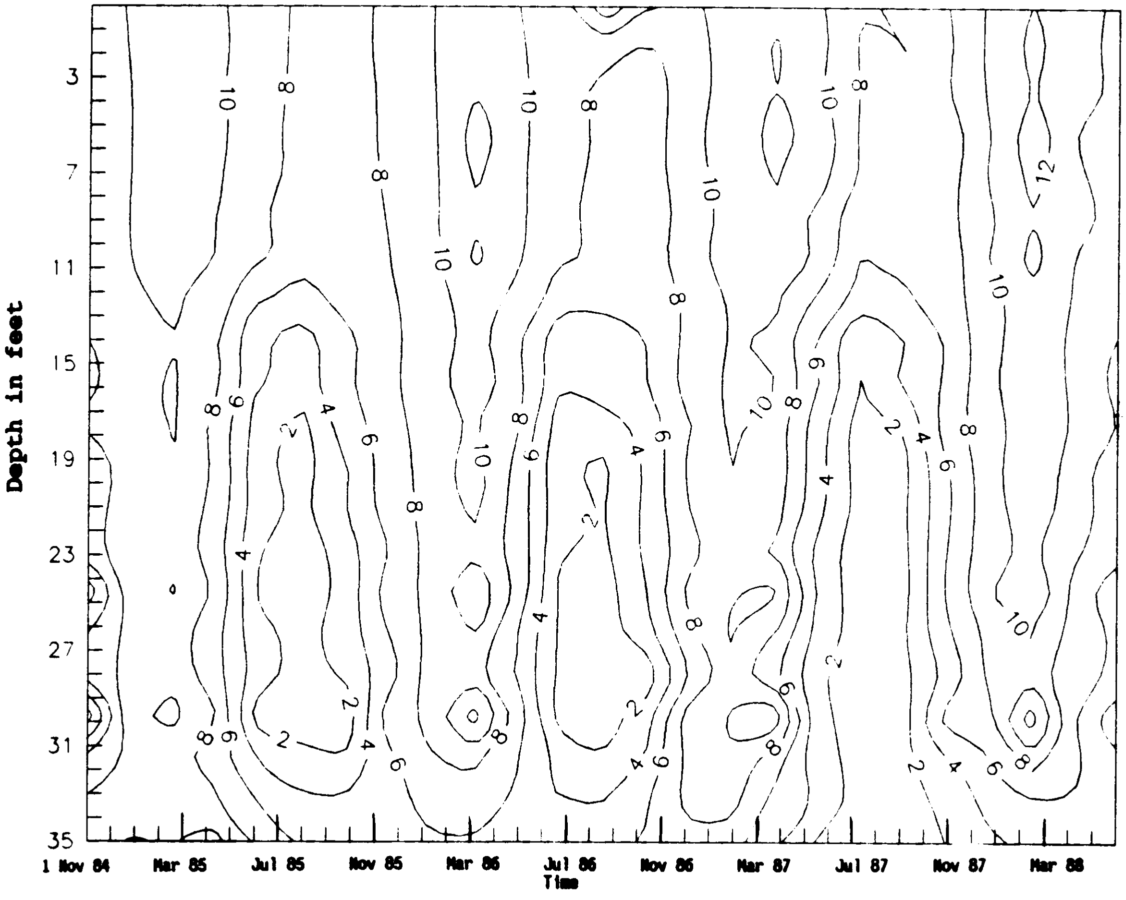

Figure 18 - Dissolved Oxygen Profile at Station LM04

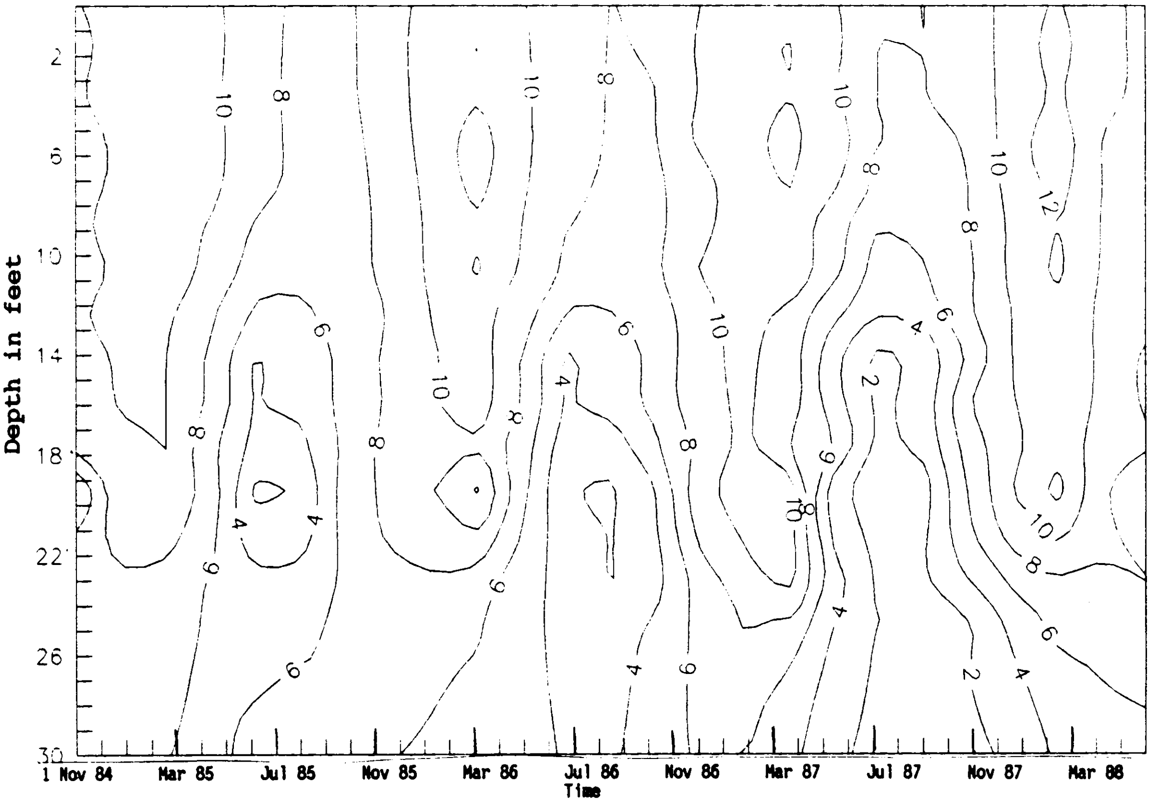

Figure 19 - Dissolved Oxygen Profile at Station LM05

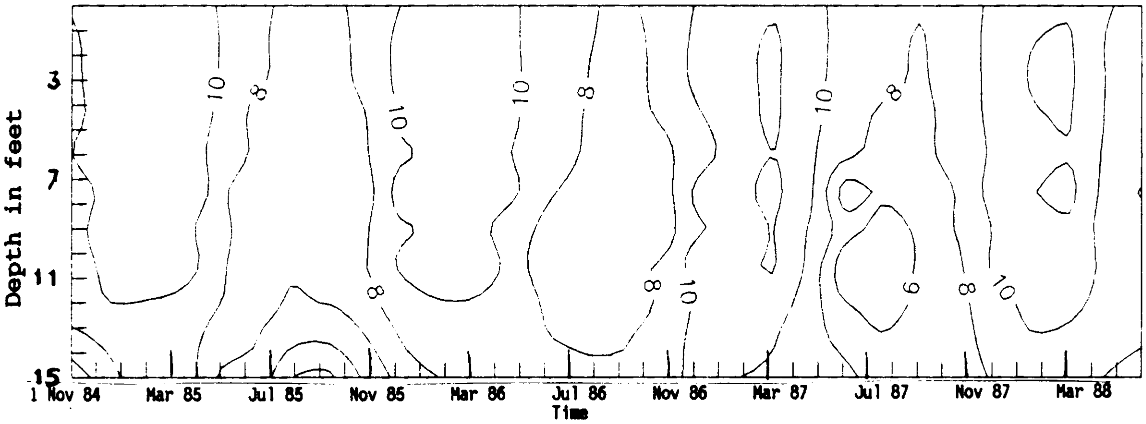

Figure 20 - Dissolved Oxygen Profile at Station LM06

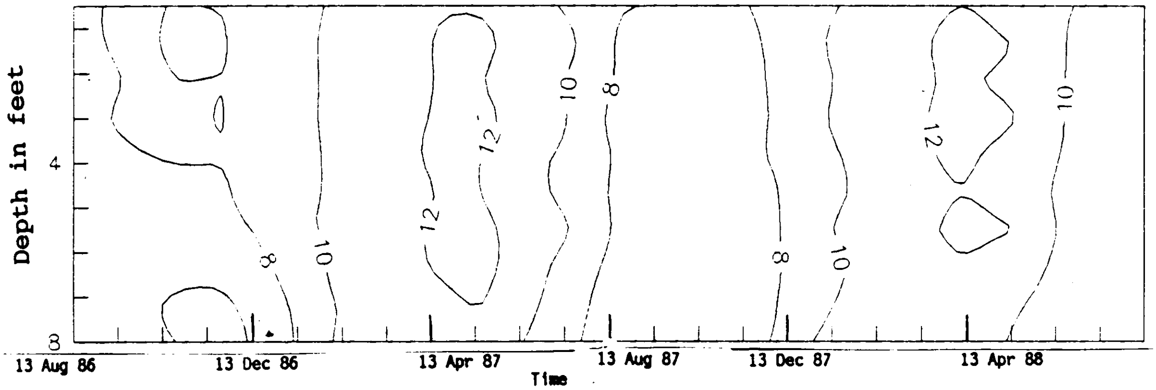

Figure 21 - Dissolved Oxygen Profile at Station LM07

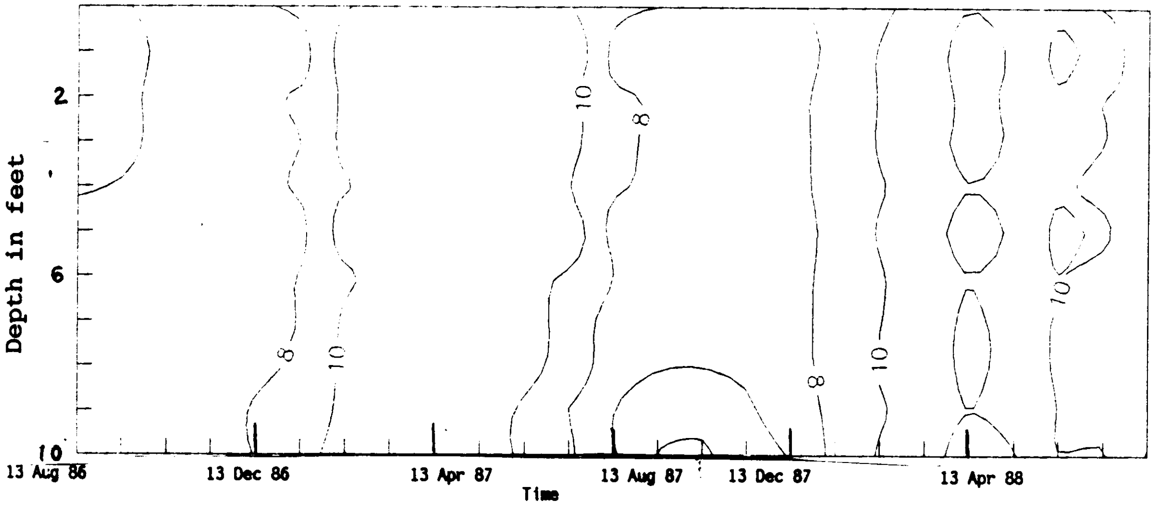

Figure 22 - Dissolved Oxygen Profile at Station LM08

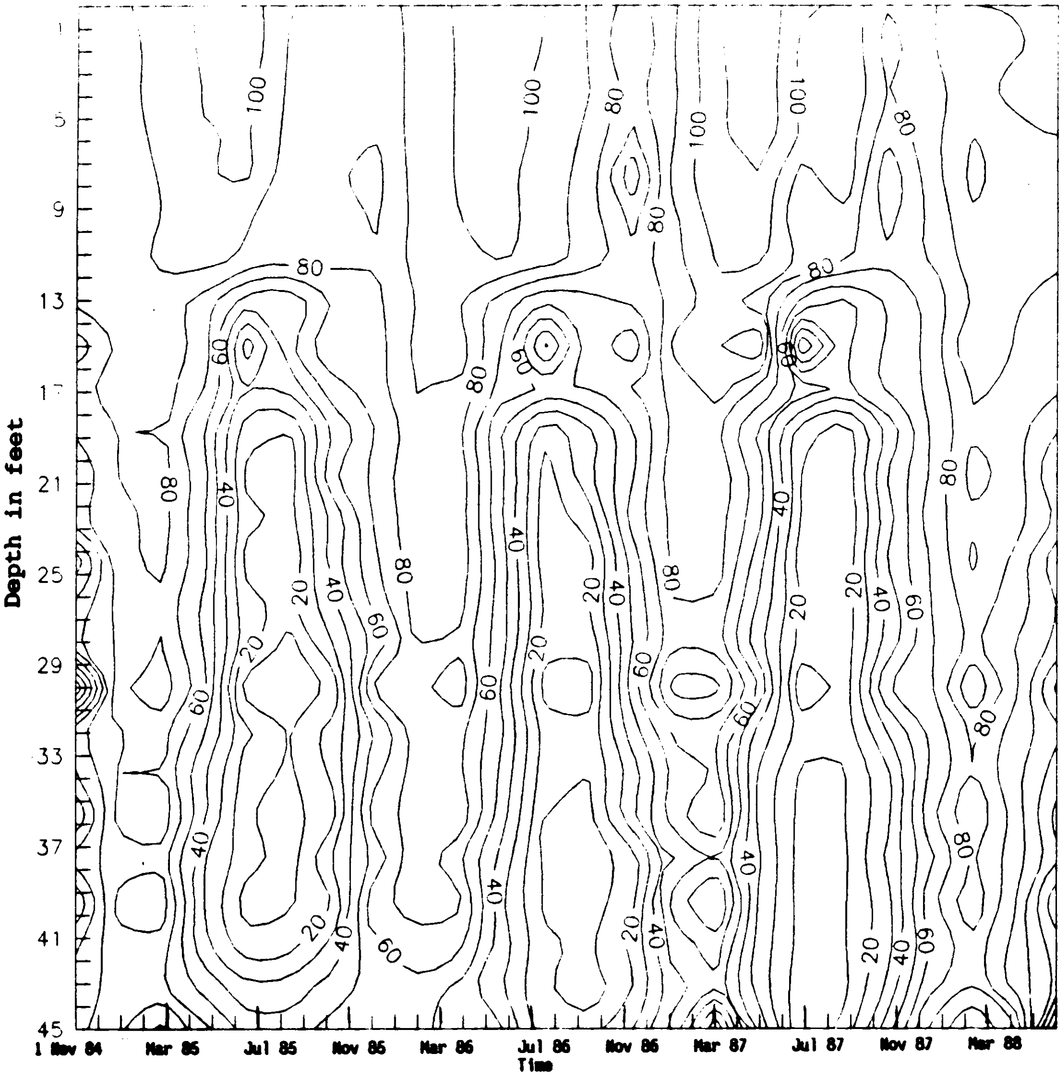

Figure 23 - % Saturation DO Profile at Station LM01

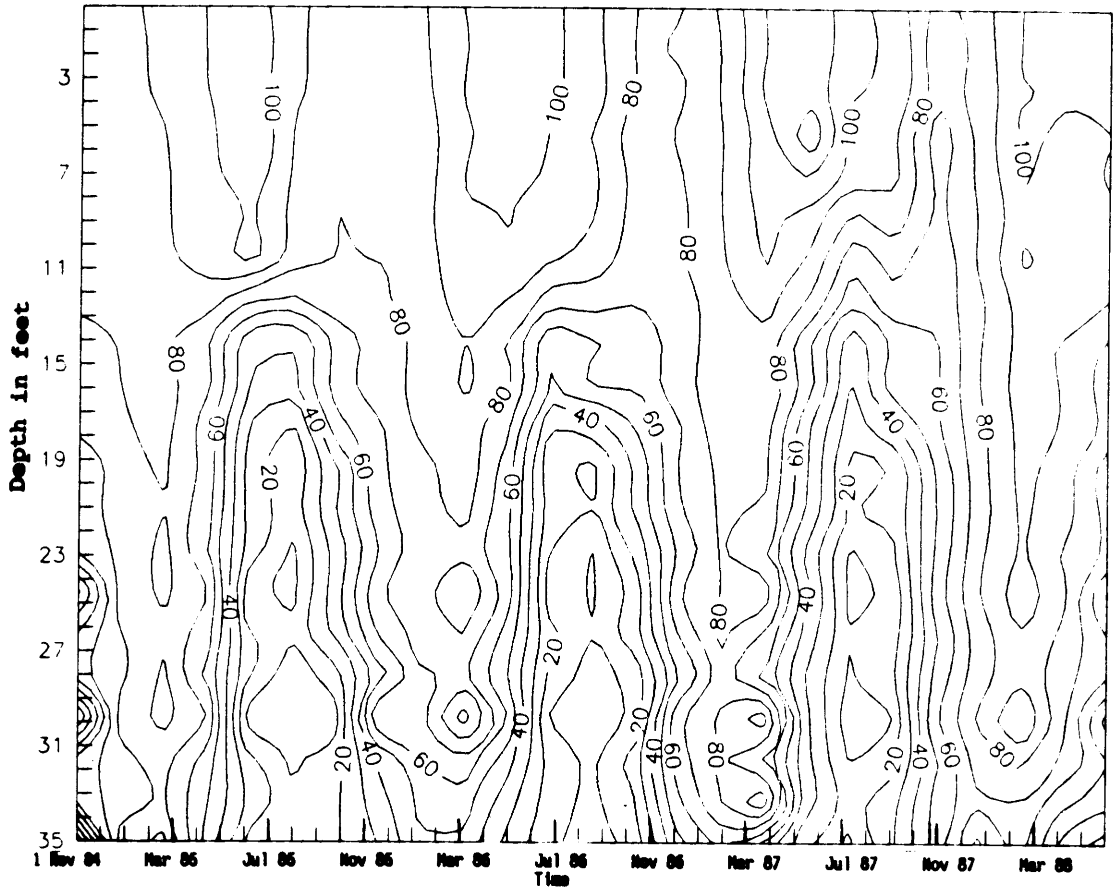

Figure 24 - % Saturation DO Profile at Station LM02

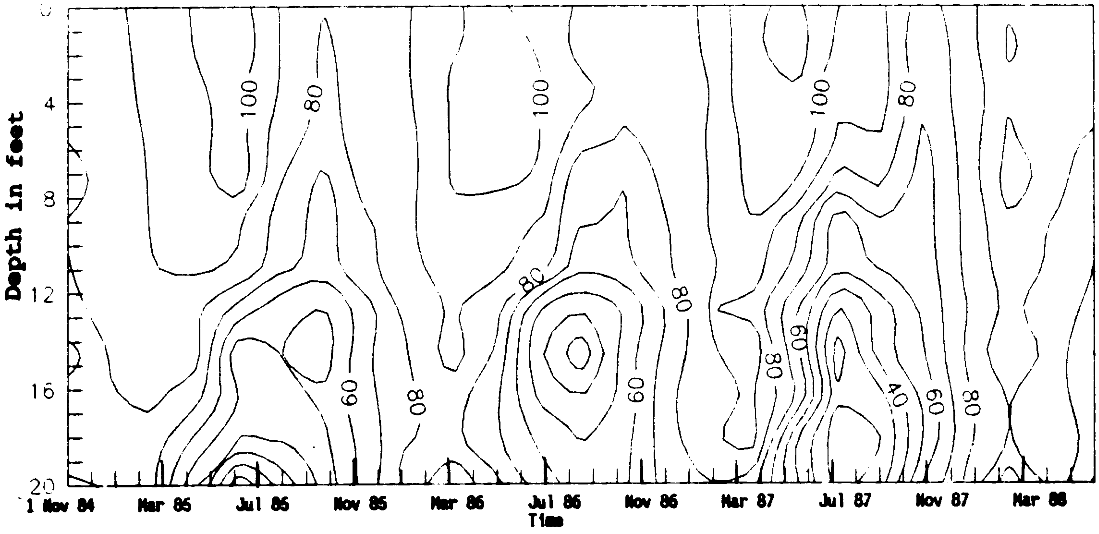

Figure 25 - % Saturation DO Profile at Station LM03

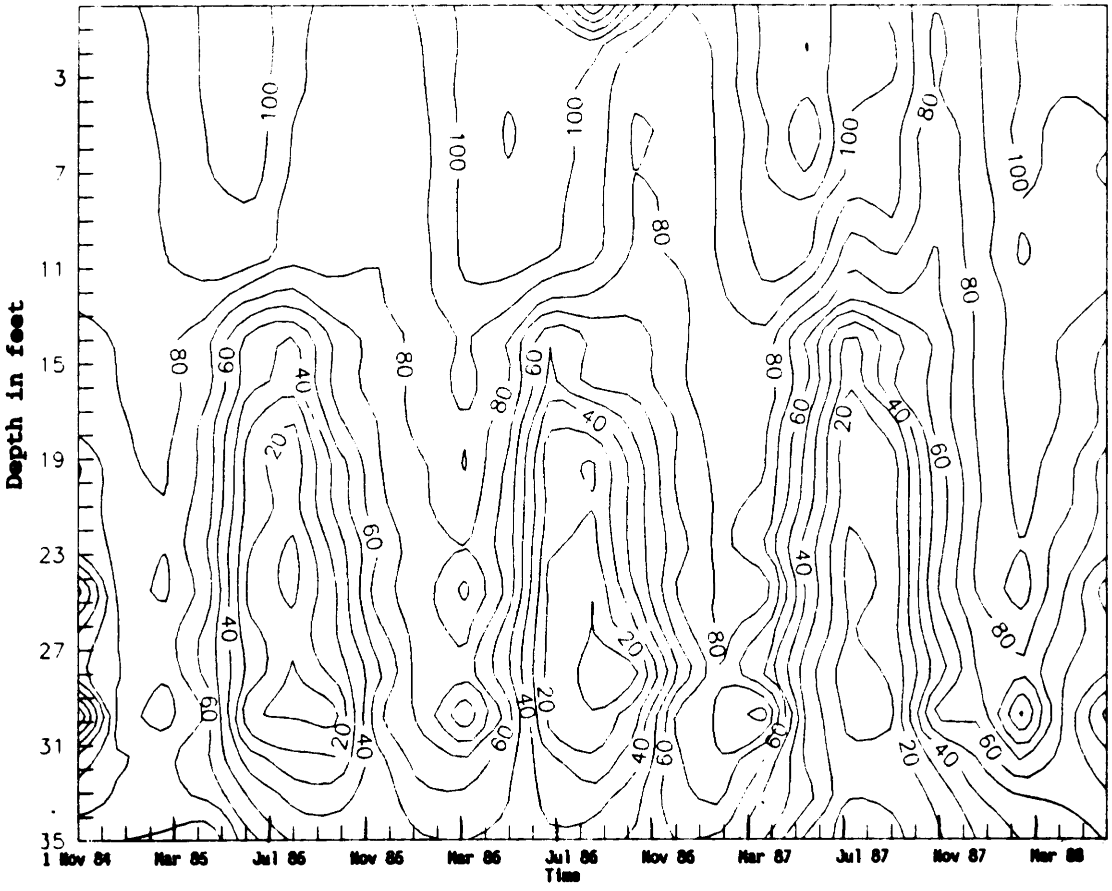

Figure 26 - % Percent Saturation DO Profile at Station LM04

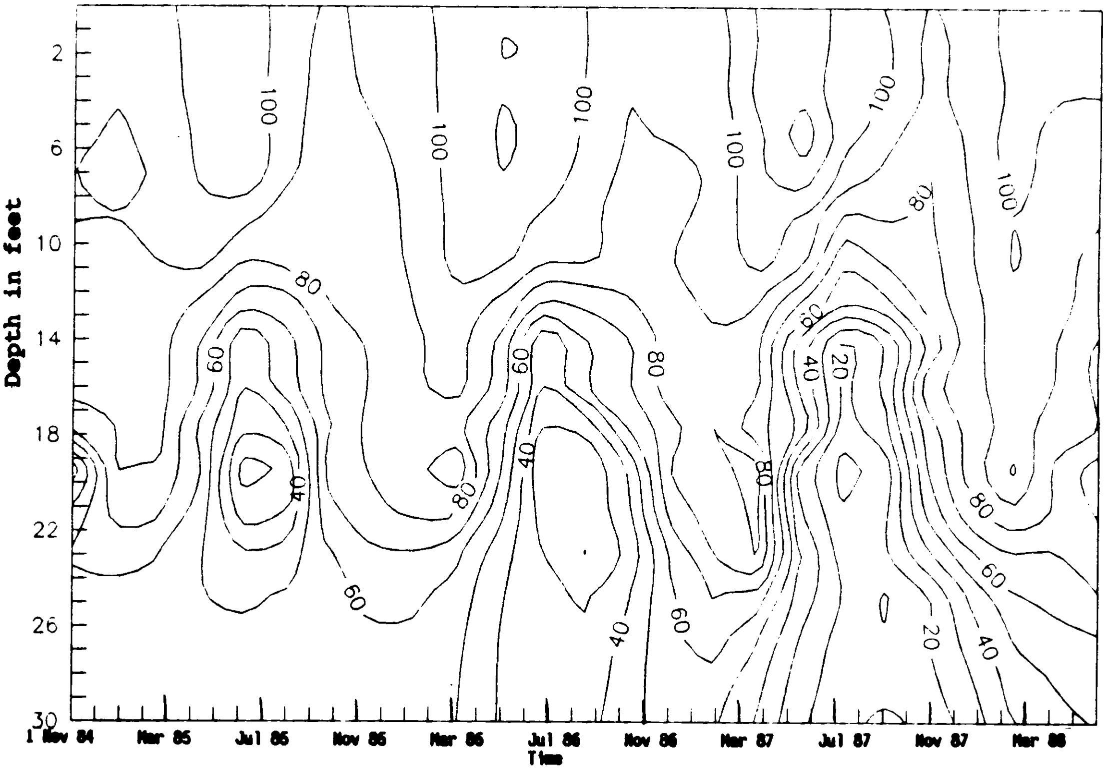

Figure 27 - % Saturation DO Profile at Station LM05

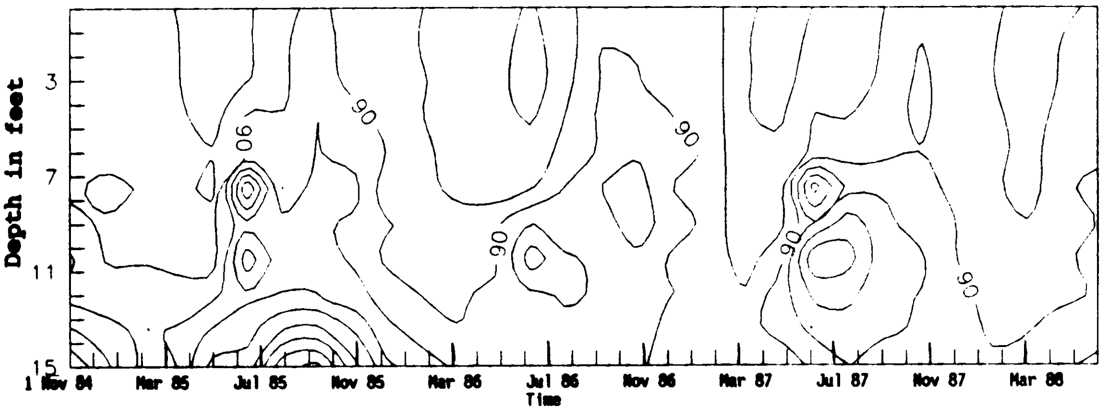

Figure 28 - % Saturation DO Profile at Station LM06

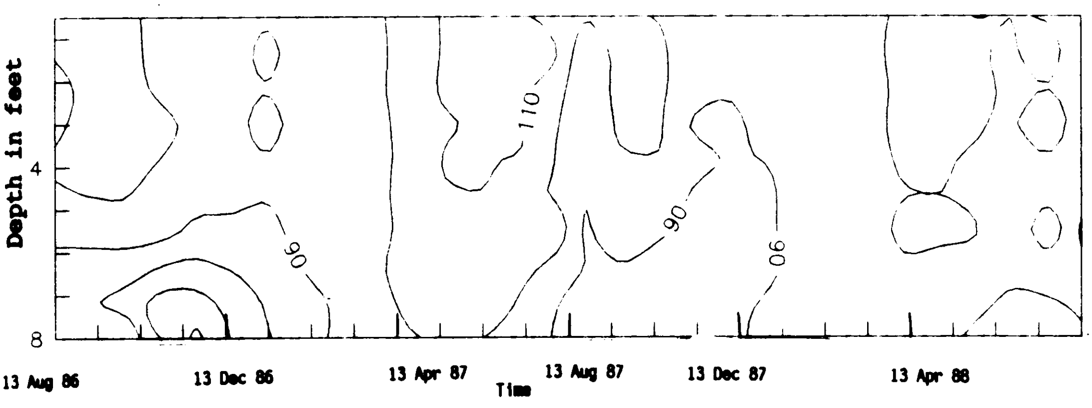

Figure 29 - % Saturation DO Profile at Station LM07

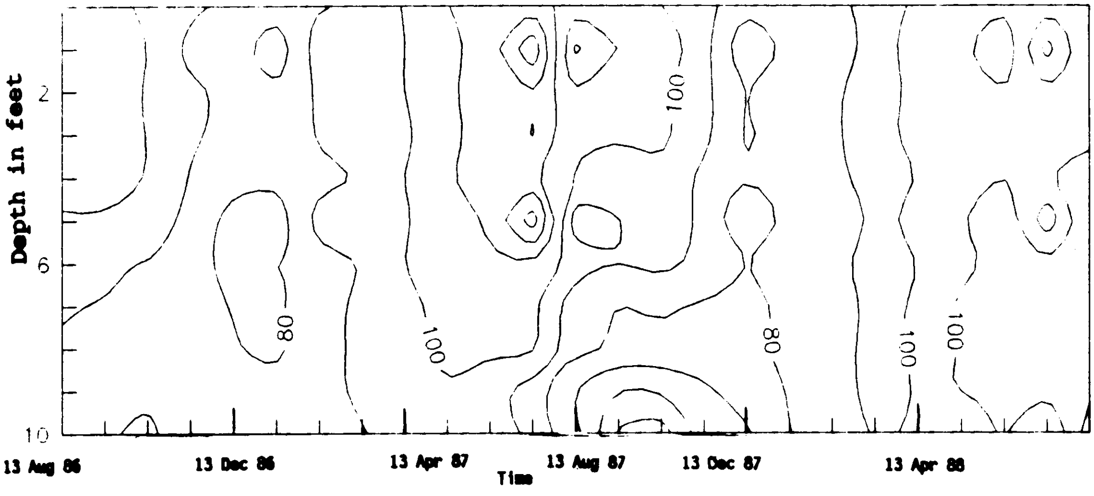

Figure 30 - % Saturation DO Profile at Station LM08

A different presentation technique for the dissolved oxygen data was use in Figures 31 through 34. Figure 31 is the dissolved oxygen data for monitoring station LM01 plotted against time. Two curves are plotted, one curve representing top waters for samples taken at the one foot depth, and the other curve for bottom waters representing the samples taken at the lake bottom for that monitoring station. These plots are called bottom and top plots. Figure 33 is the same as Figure 31 except that the percent saturation dissolved oxygen data are plotted.

Figures 33 and 34 are the same as Figures 31 and 32 except that the data for monitoring station LM08 are used.

It should be noted that the LM01 figures represent approximately four years of environmental monitoring data, whereas the LM08 figures represent approximately two years of environmental monitoring data. Additionally, some of the top and bottom plots indicate that values have approaching zero. The author considers it important to stress those data points that were measured at less than the detection limit for that parameter. By graphing these data points as as half their detectable limit, the data is emphasized. Furthermore, it helps overcome some of the scaling problems associated with graphing data that extends over orders of magnitude.

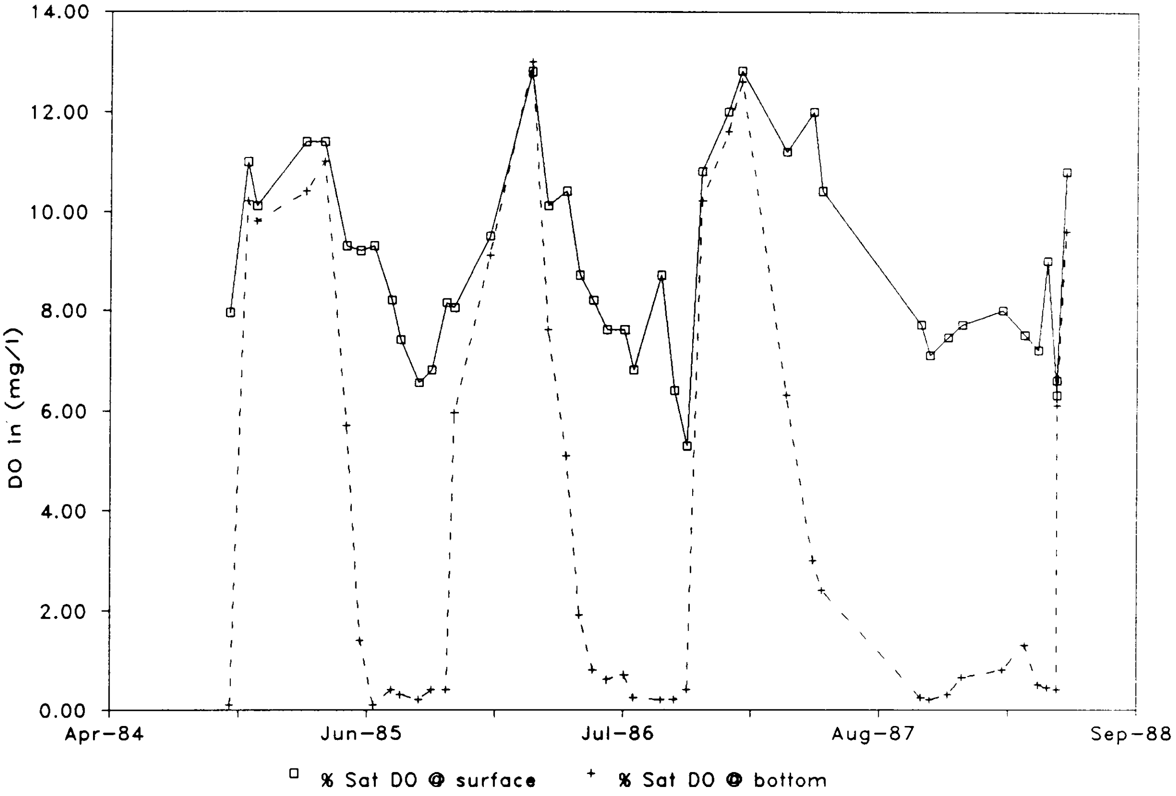

Figure 31 - Top and Bottom DO Profiles at Station LM01

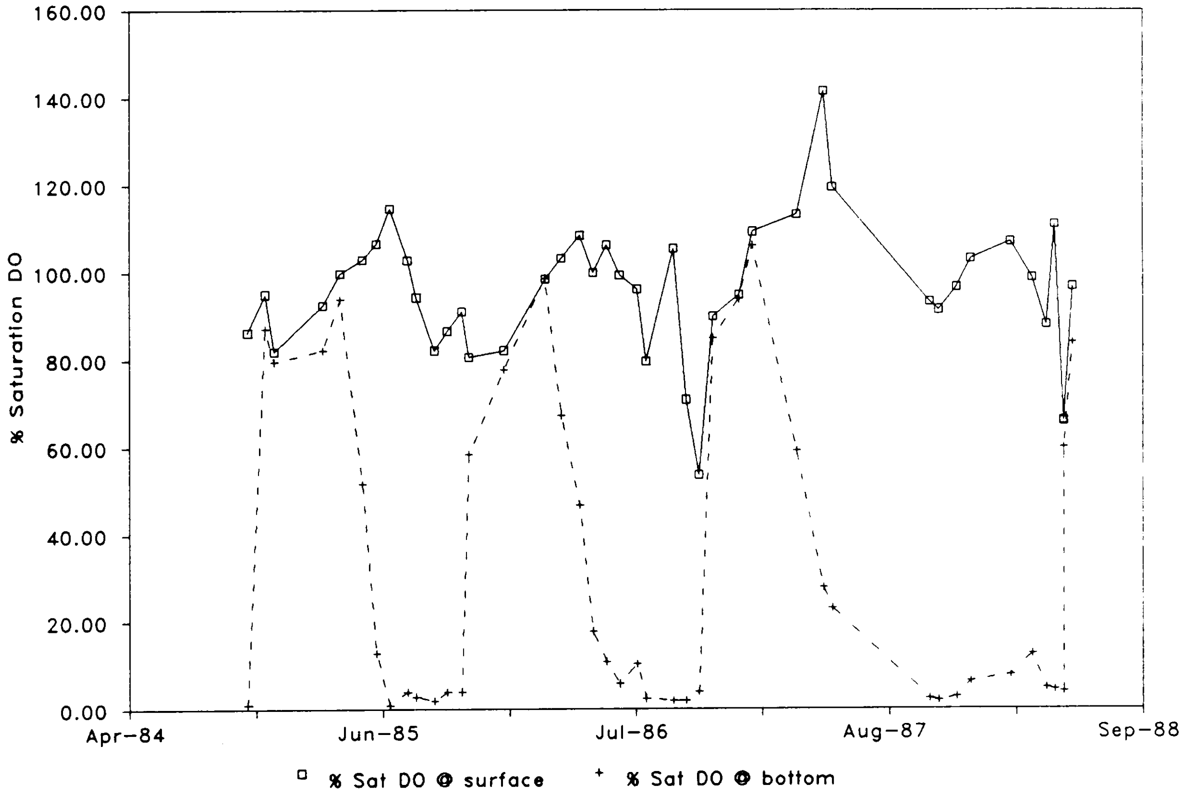

Figure 32 - Top and Bottom % Saturation DO Profiles at Station LM01

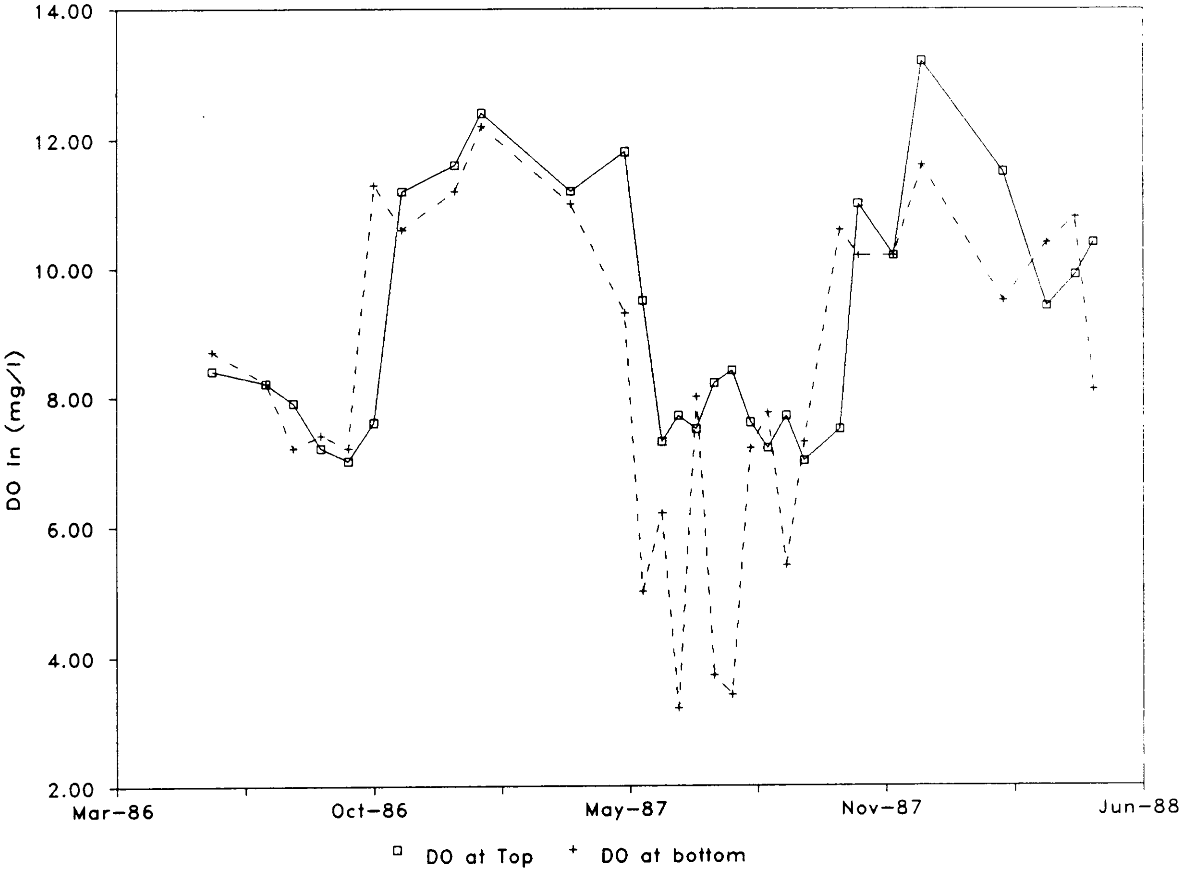

Figure 33 - Top and Bottom DO Profiles at Station LM08

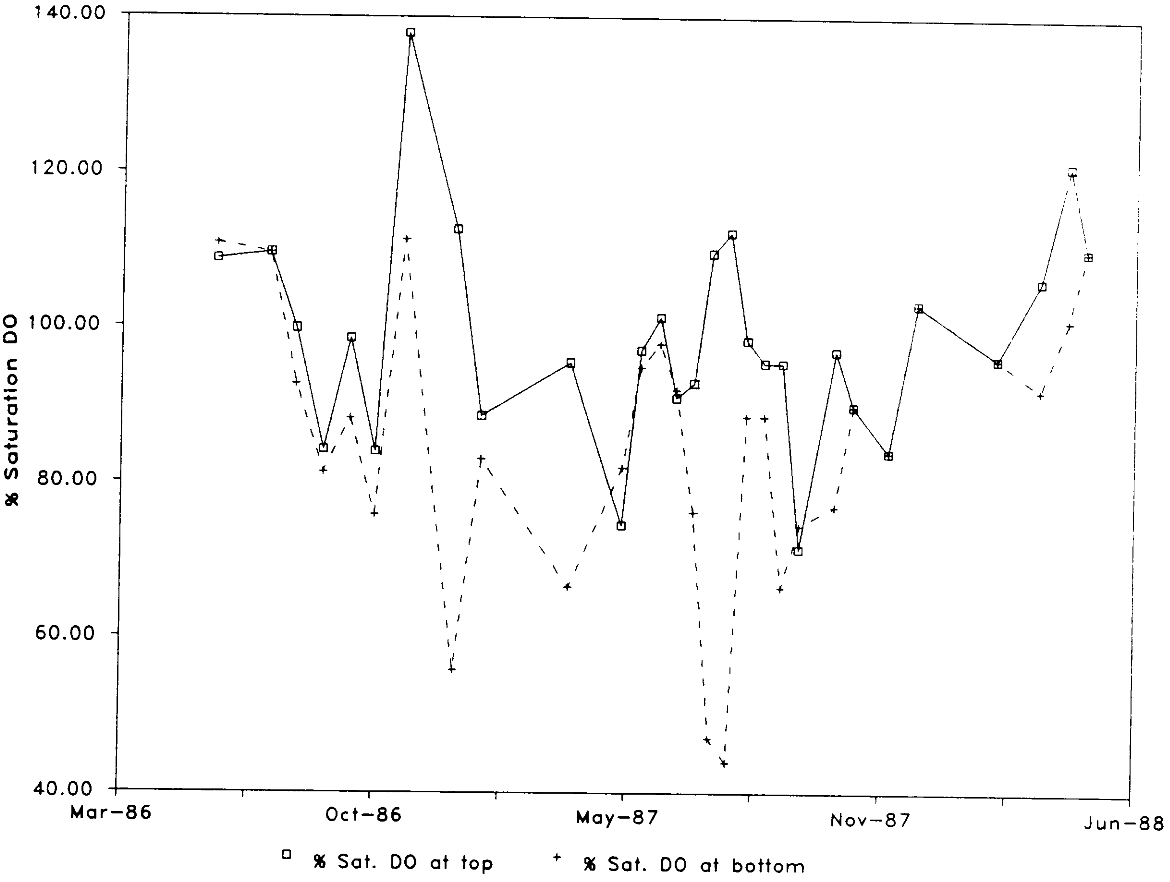

Figure 34 - Top and Bottom % Saturation DO Profiles at Station LM08

Chlorophyll a Profiles

Figures 35 through 42 are plots of the Chlorophyll a concentration at the lake monitoring stations. Contours with depth of Chlorophyll a are not possible because this parameter is not measured at depths other than the surface (one foot depth).

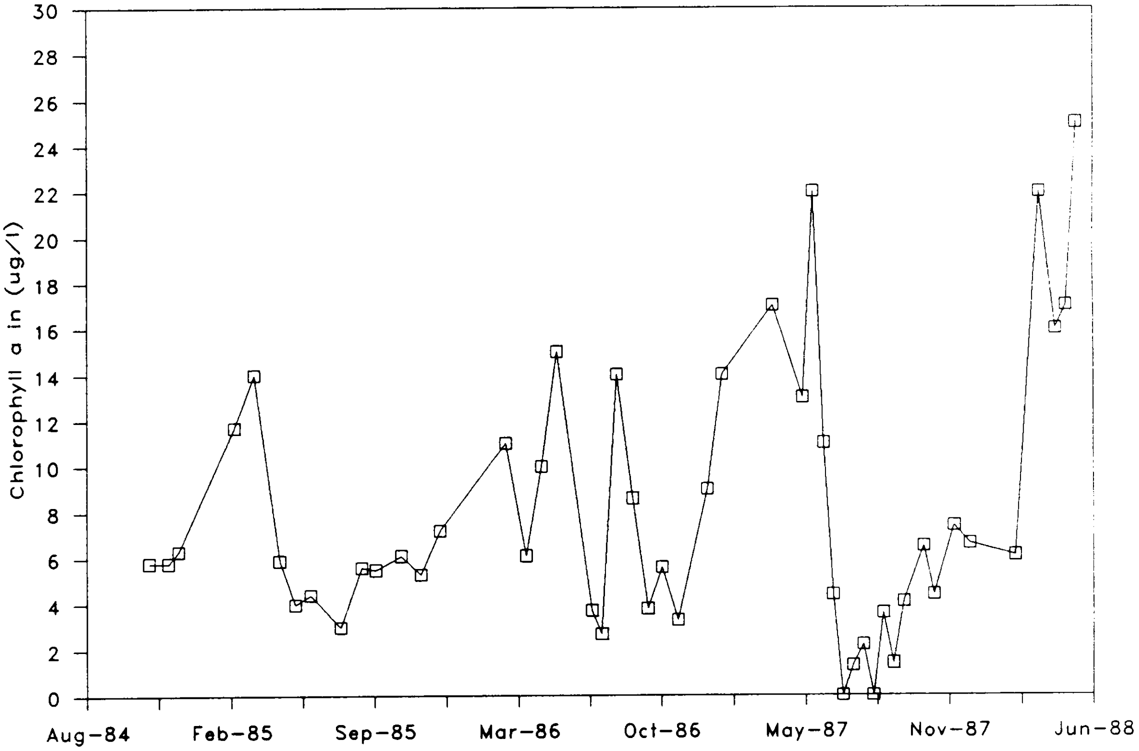

Figure 35 - Chlorophyll a Profile at LM01

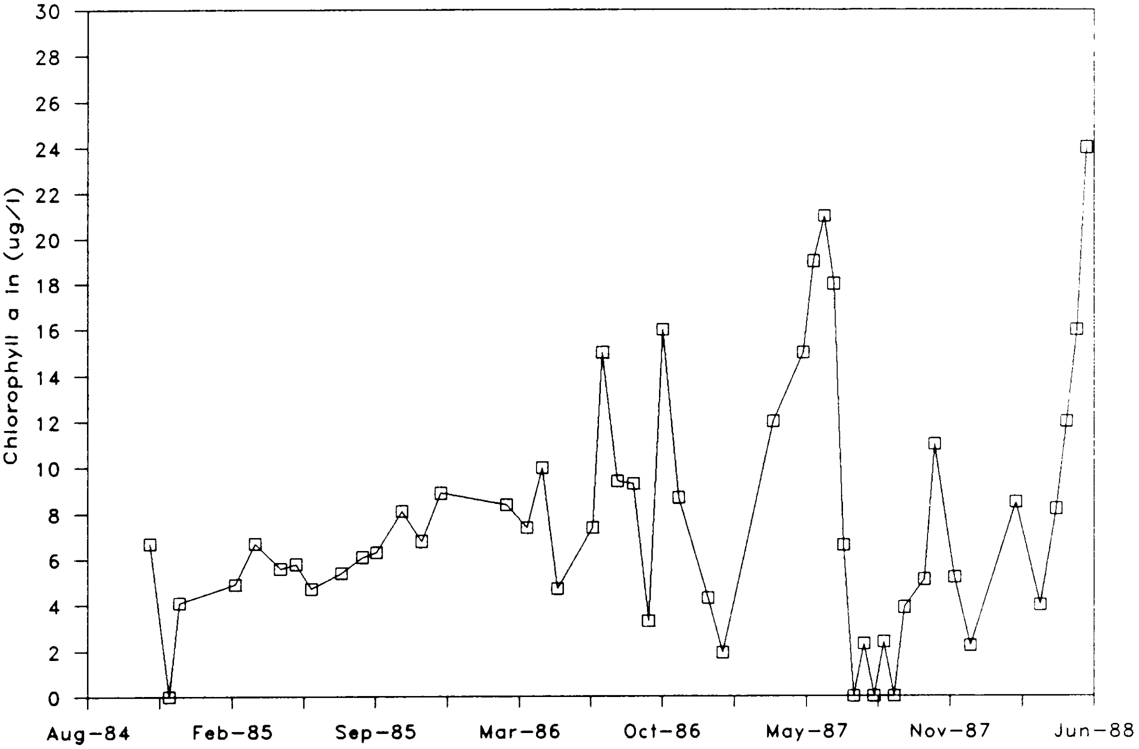

Figure 36 - Chlorophyll a Profile at LM02

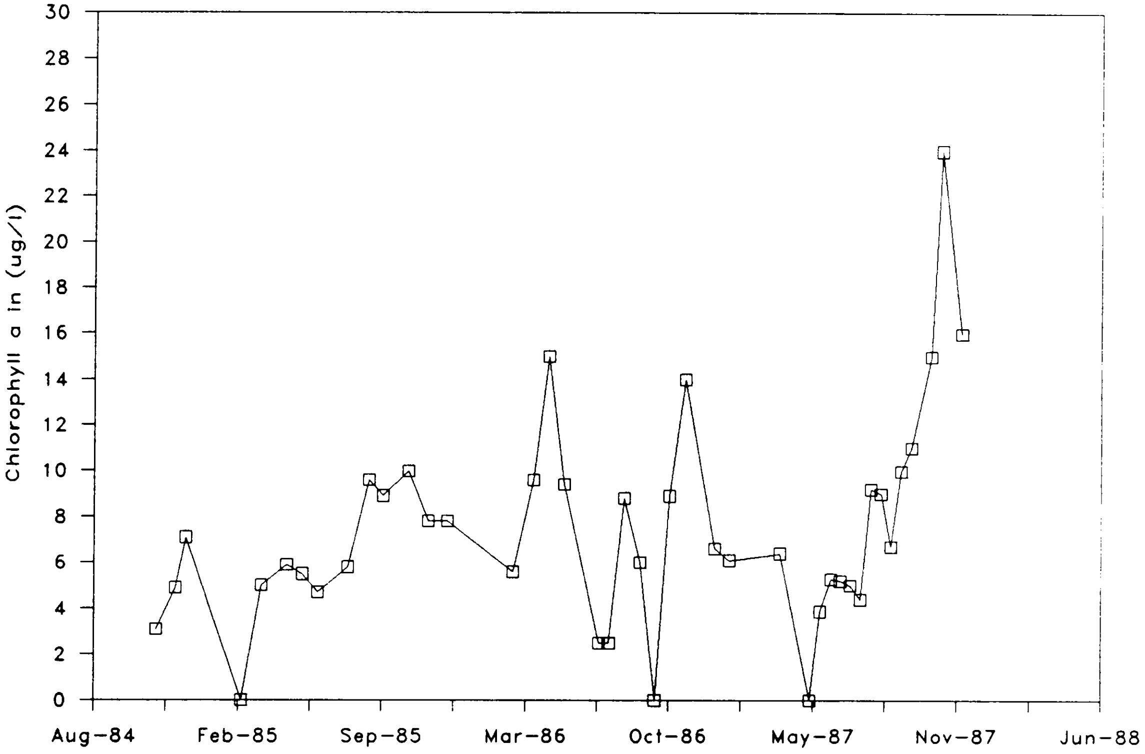

Figure 37 - Chlorophyll a Profile at LM03

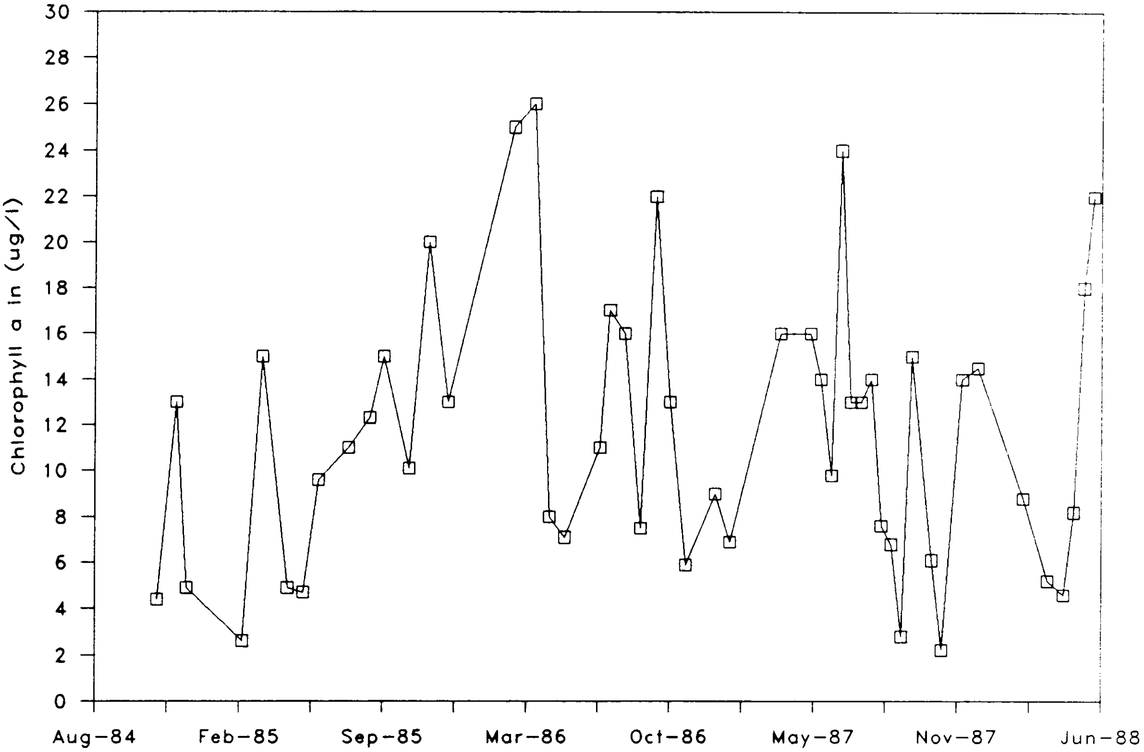

Figure 38 - Chlorophyll a Profile at LM06

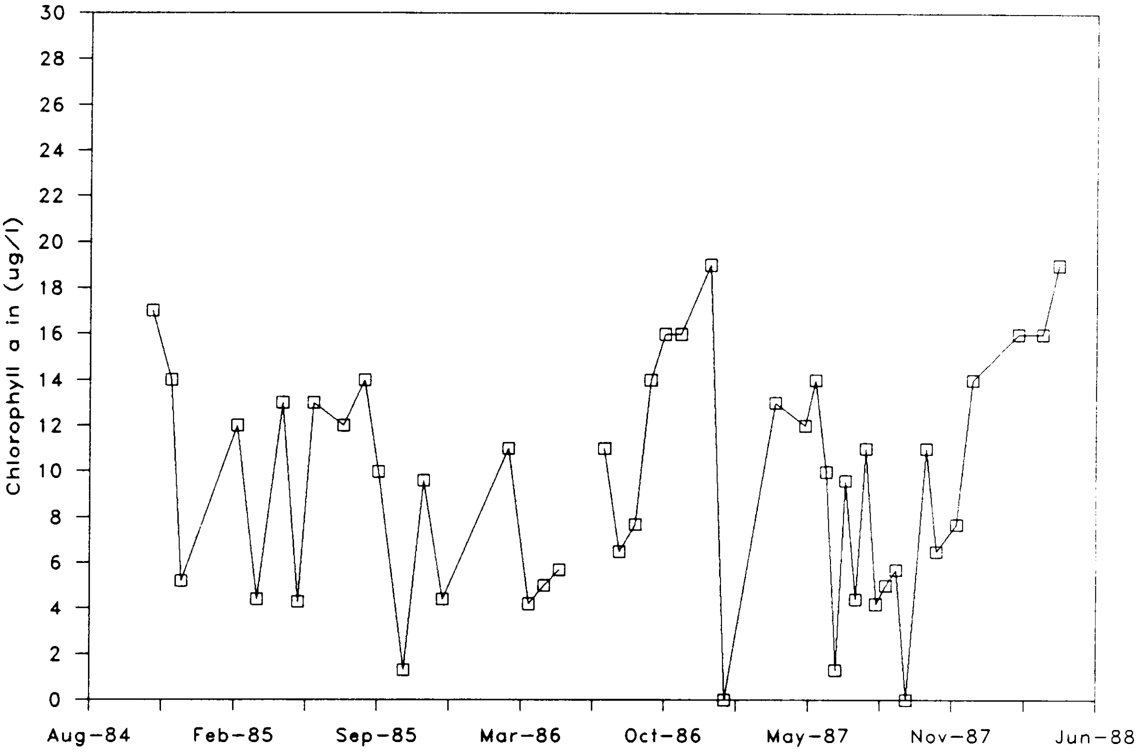

Figure 39 - Chlorophyll a Profile at LM07

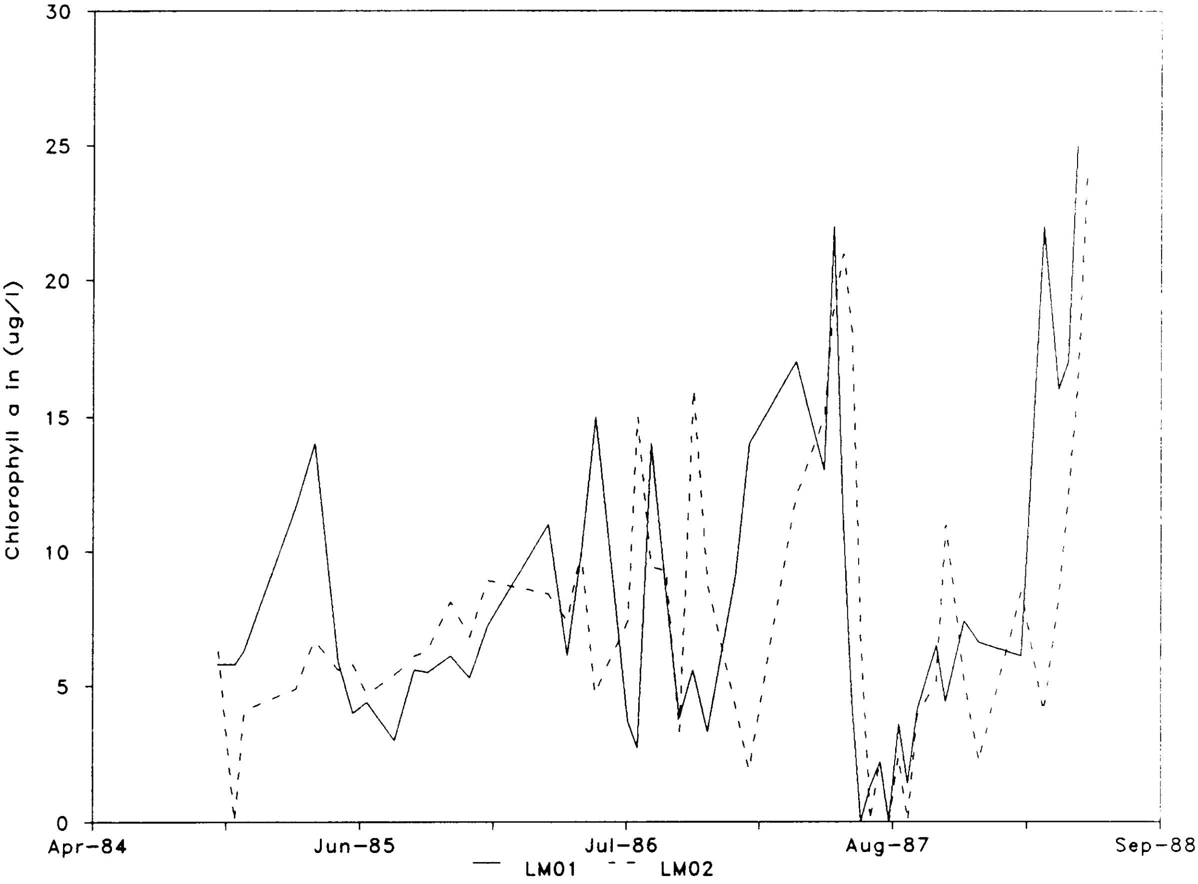

Figure 40 - Chlorophyll a Profile at LM01 and LM02

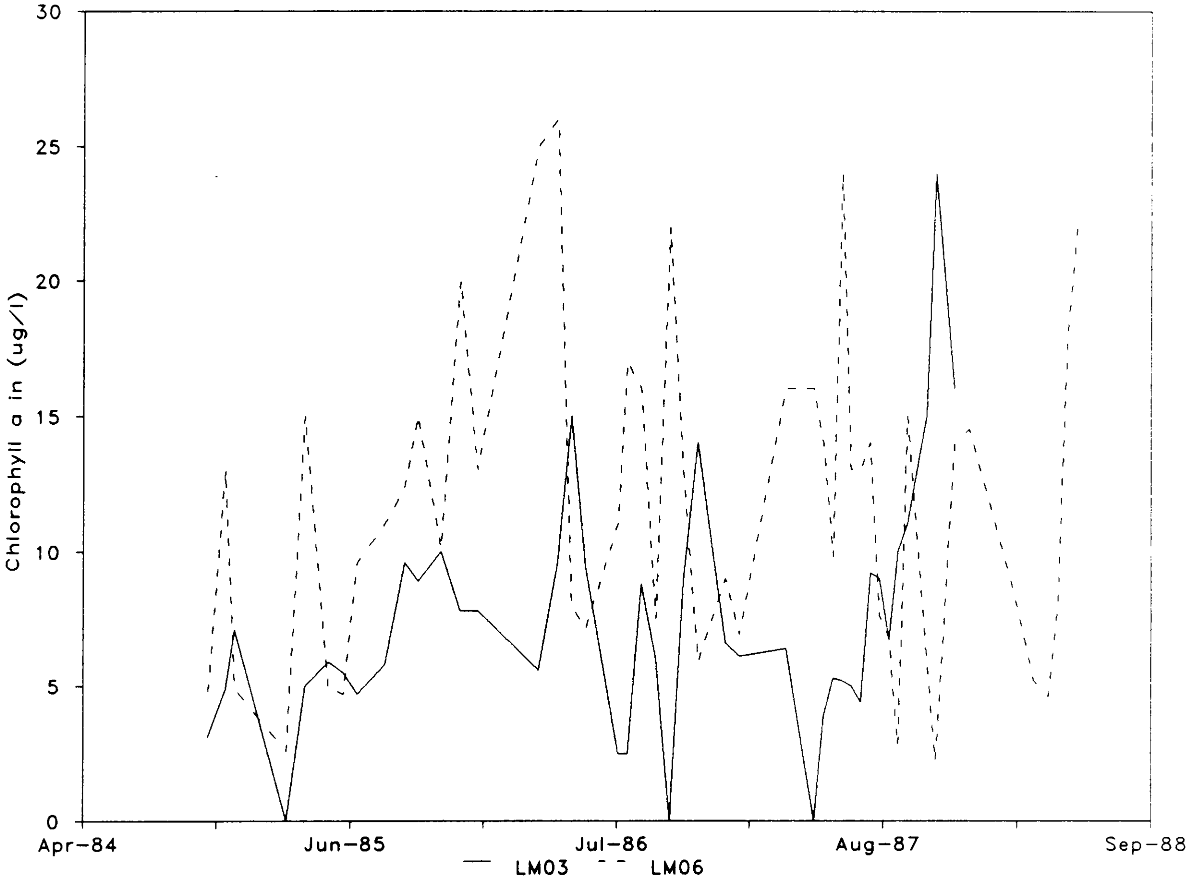

Figure 41 - Chlorophyll a Profile at LM03 and LM06

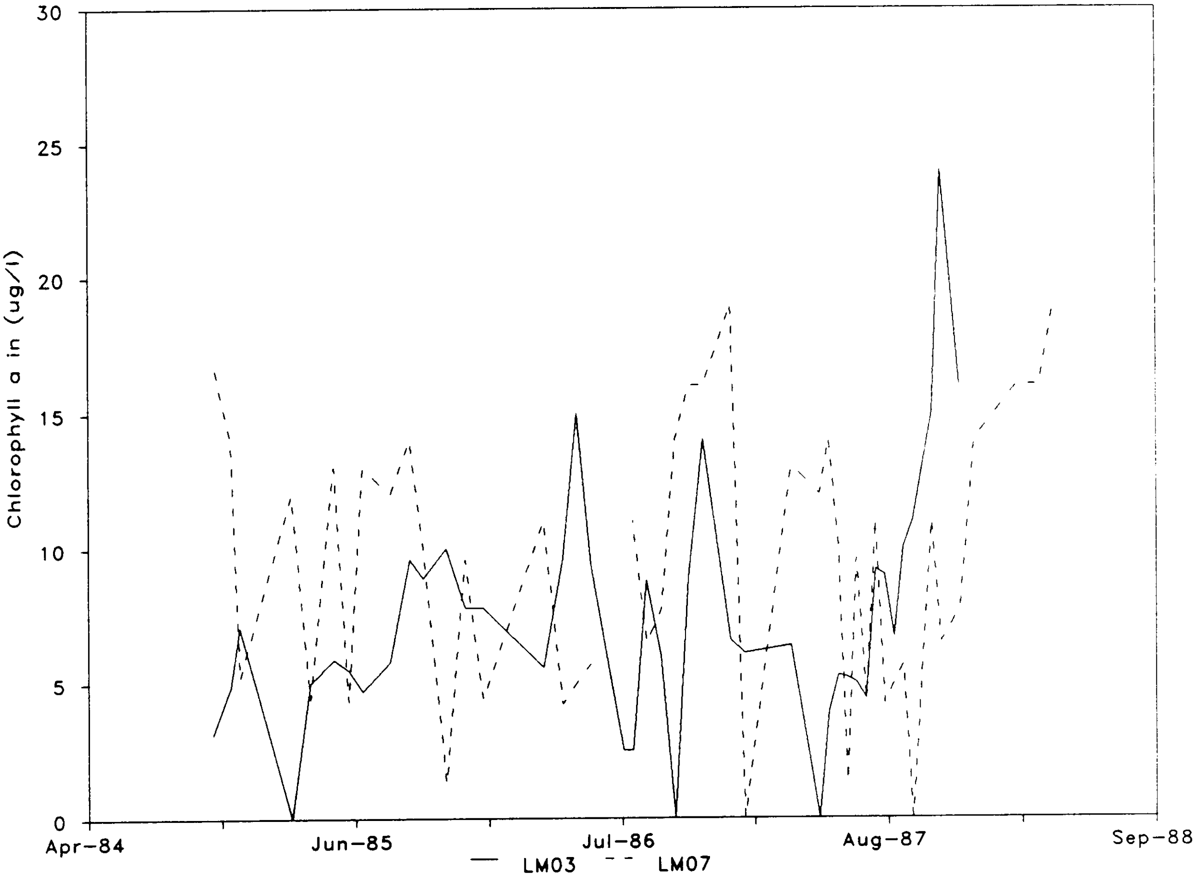

Figure 42 - Chlorophyll a Profile at LM03 and LM07

Figures 43, 44, and 45 are additional comparative plots of chlorophyll a concentration at different locations in the lake. On Figure 45, the data for station LM07 do not span the entire range of the abscissa

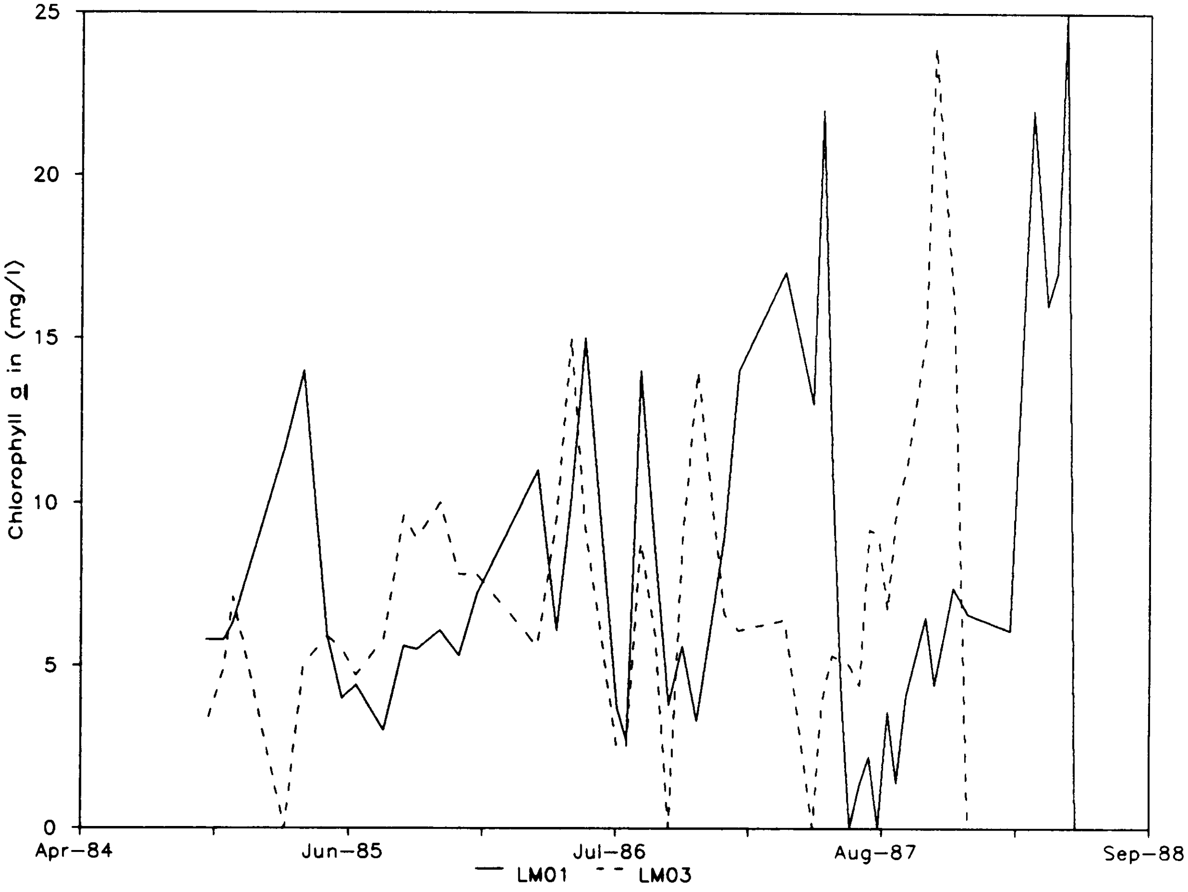

Figure 43 - Chlorophyll a Profile at LM01 and LM03

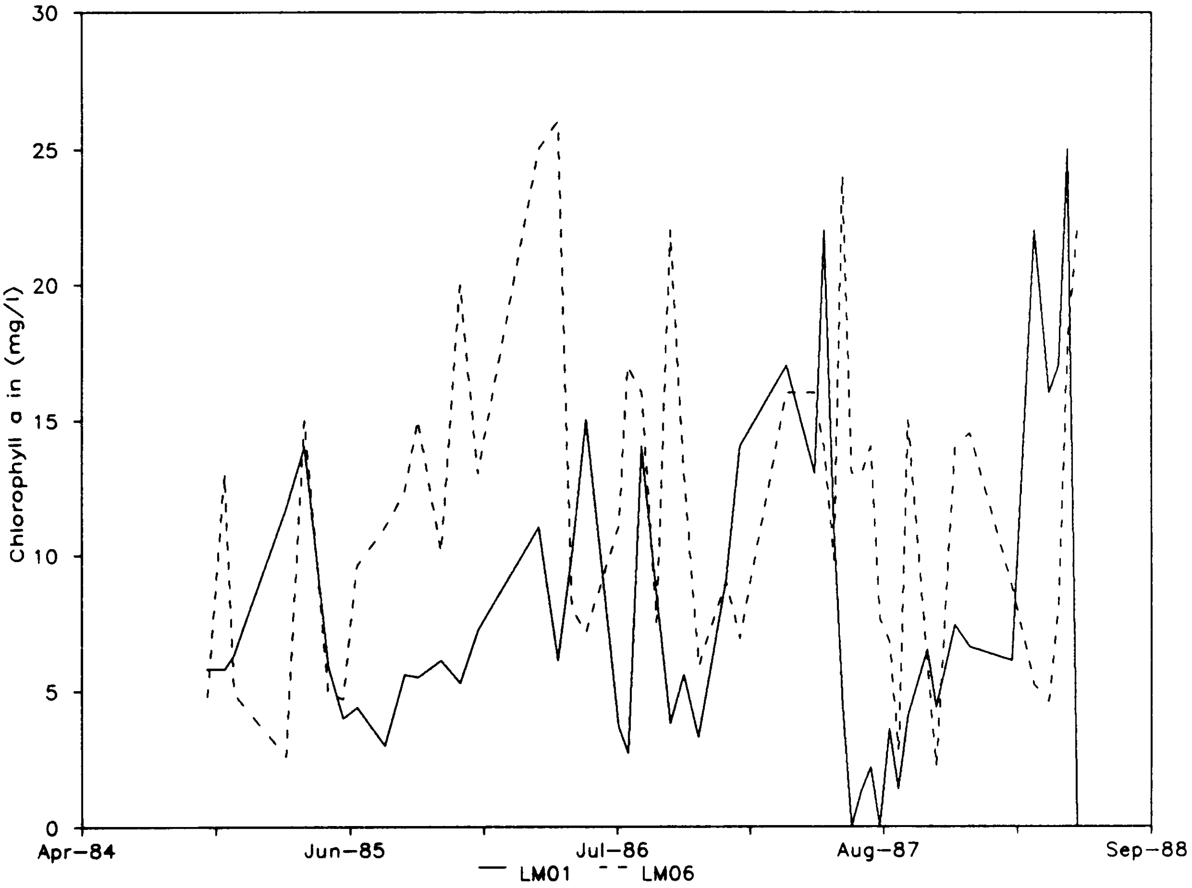

Figure 44 - Chlorophyll a Profile at LM01 and LM06

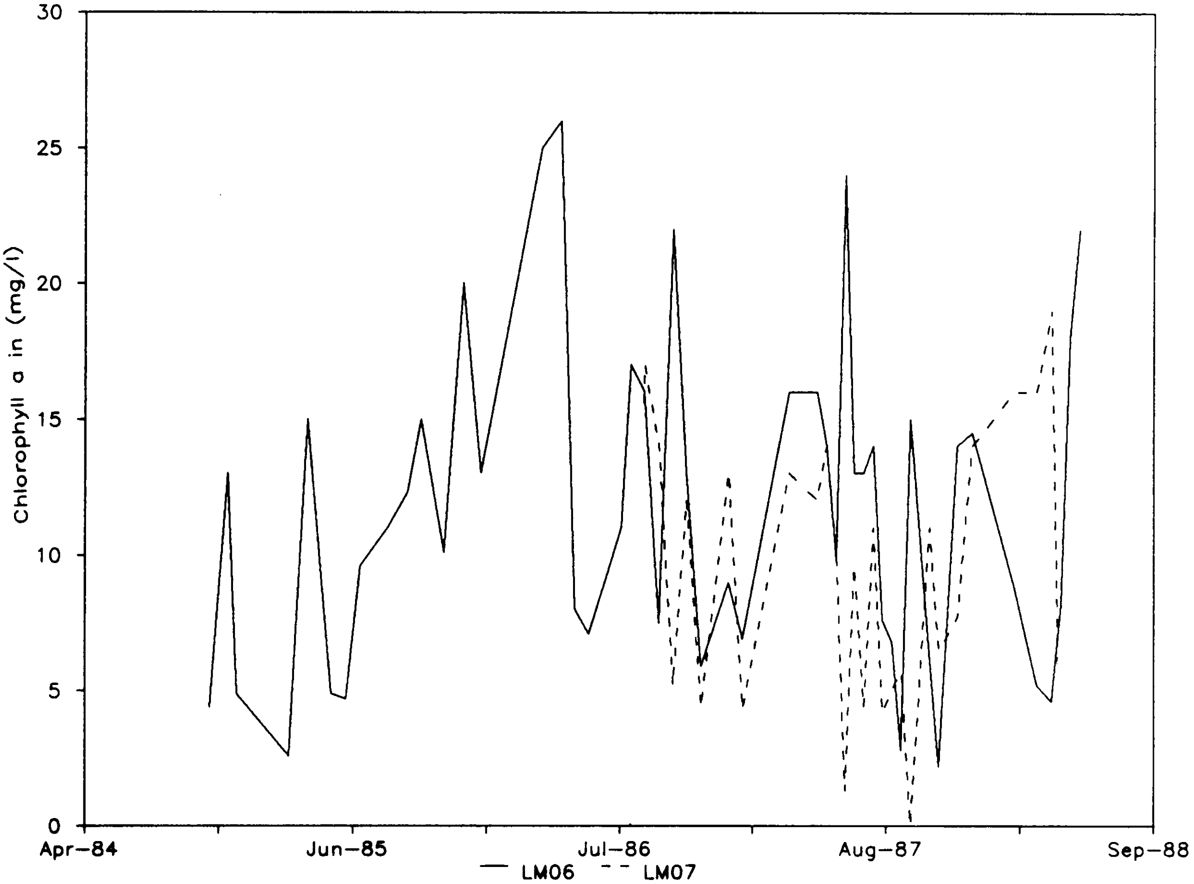

Figure 45 - Chlorophyll a Profile at LM01 and LM07

Lake Manassas Nitrogen and Phosphorus

Figures 46, 47, and 48 are plots of ammonia and oxidized nitrogen in the bottom waters at LM01, LM06, and LM07.

Figure 49 is a plot of the oxidized nitrogen in the top and bottom waters at LM01.

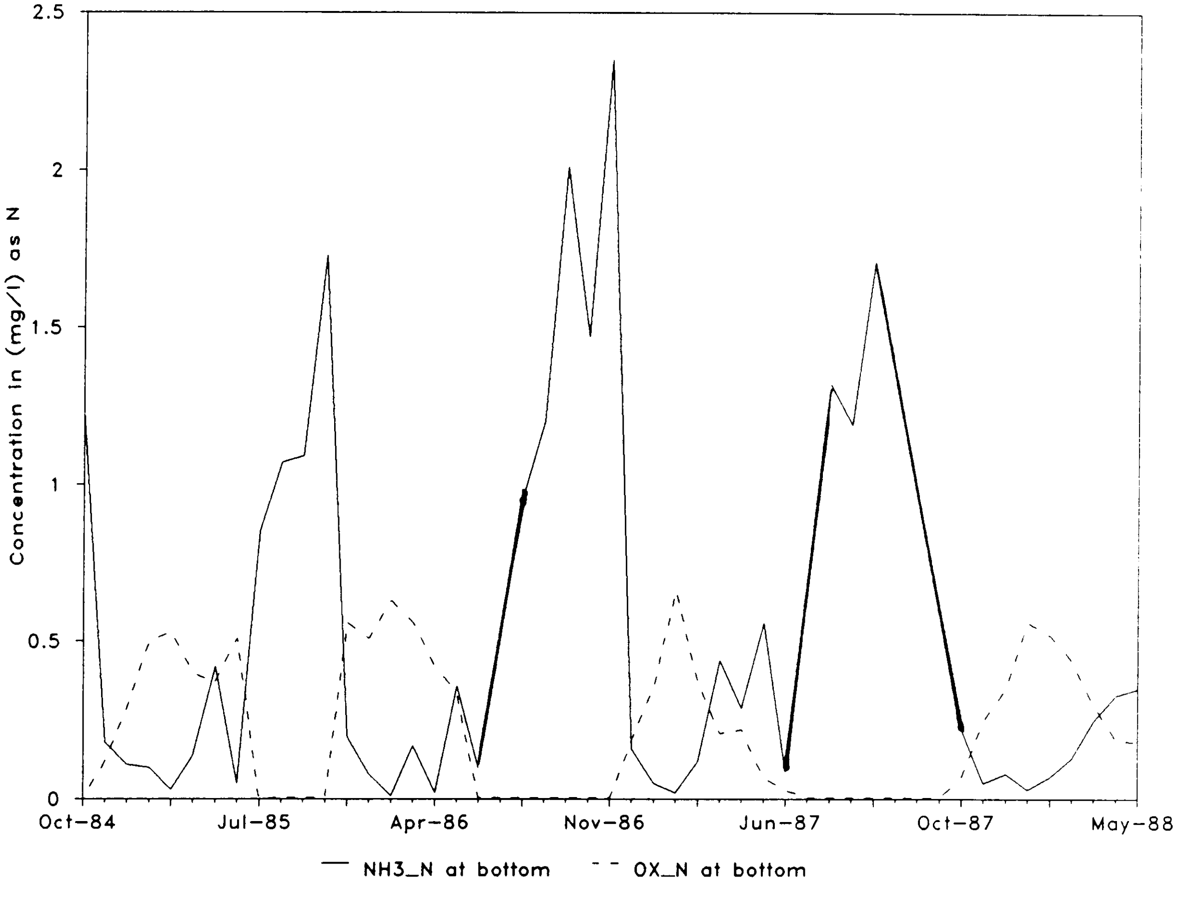

Figure 46 - Nitrogen in the Bottom Waters at LM01

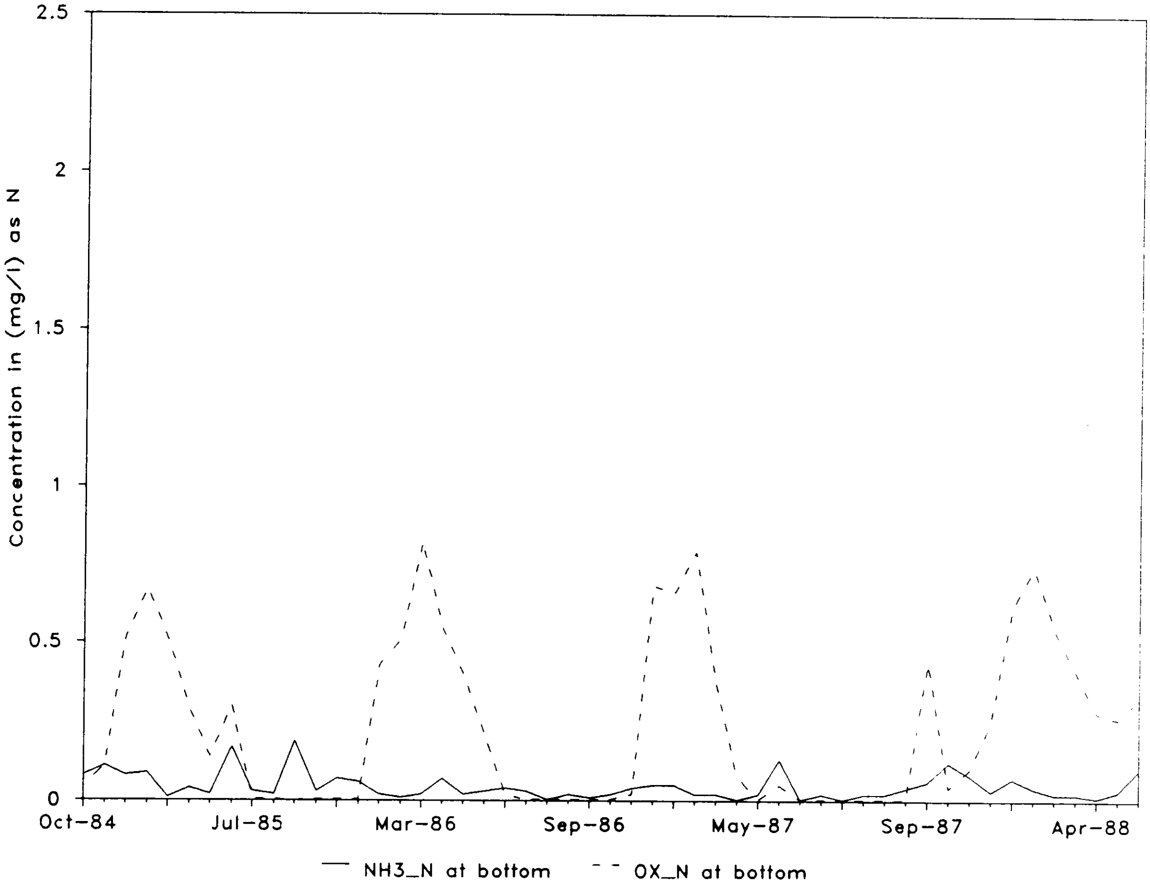

Figure 47 - Nitrogen in the Bottom Waters at LM06

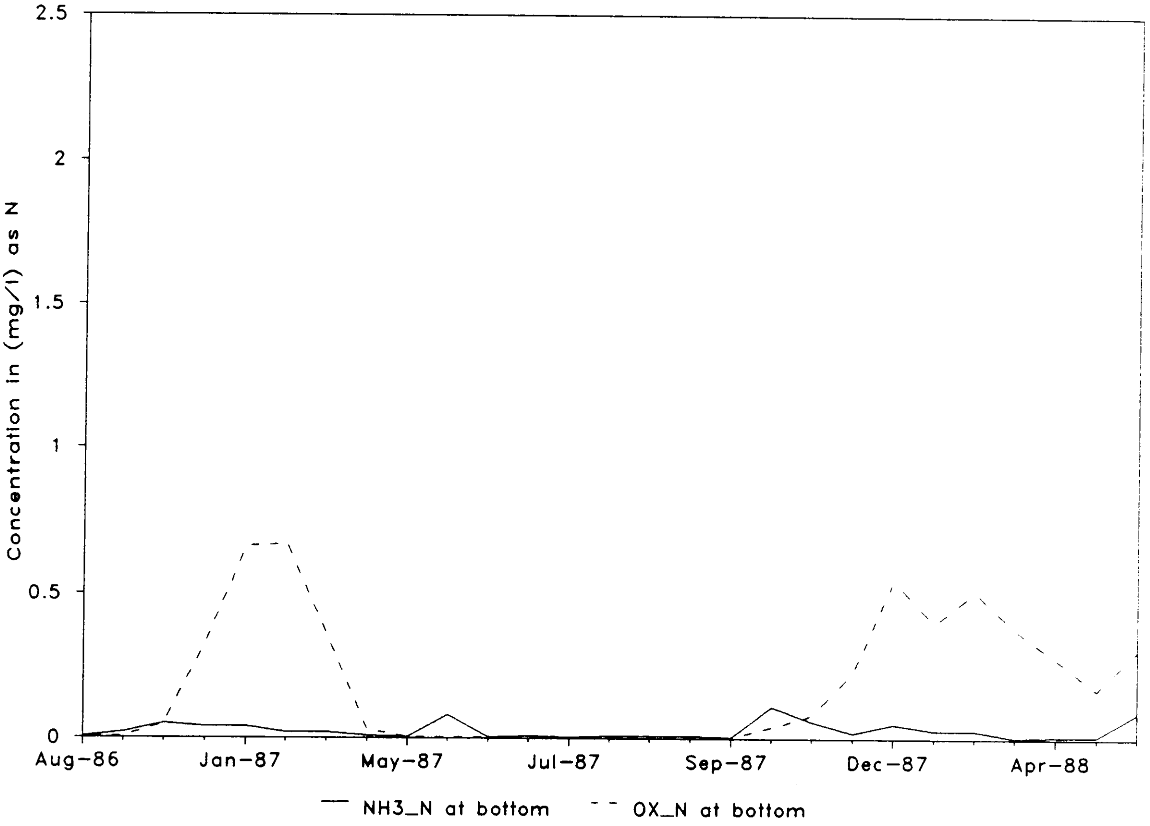

Figure 48 - Nitrogen in the Bottom Waters at LM07

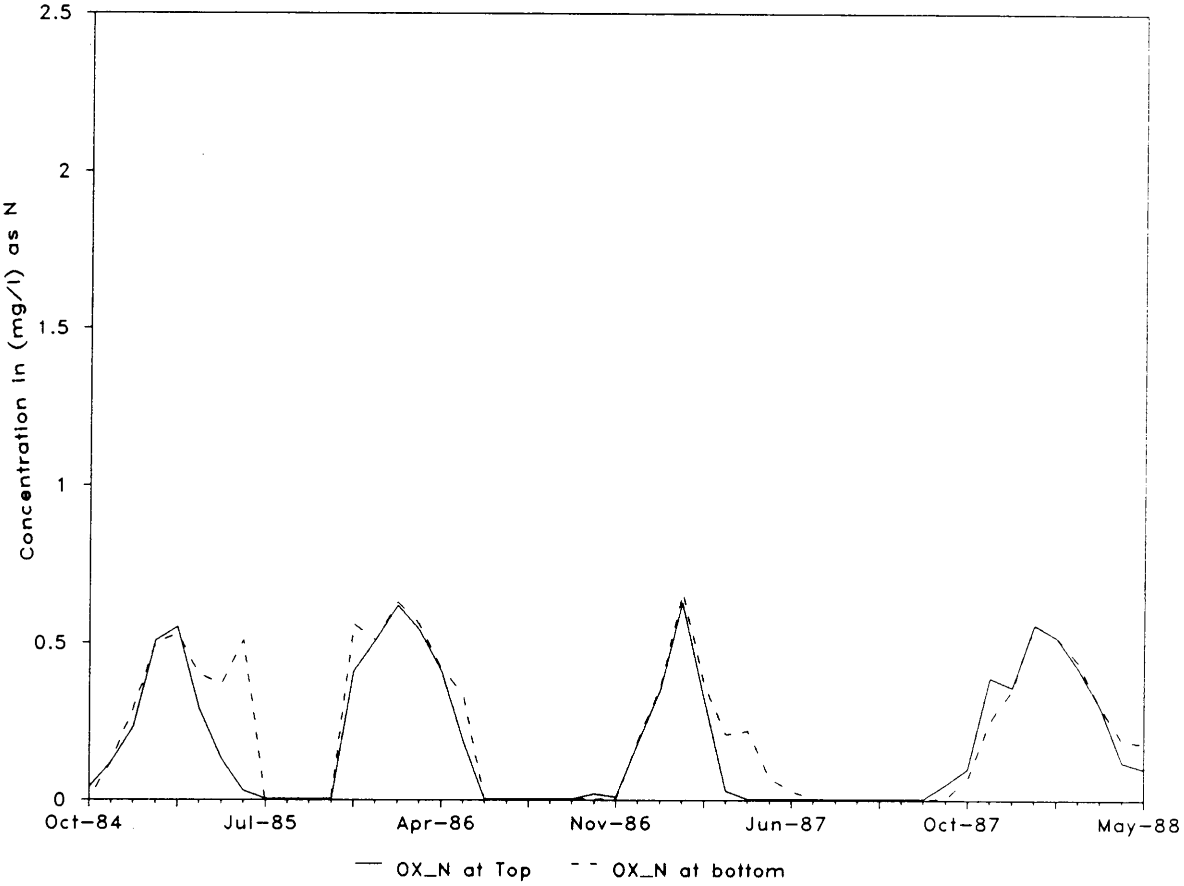

Figure 49 - Oxidized Nitrogen at the Top and Bottom at LM01

Figures 50 and 51 are plots of the total nitrogen and total phosphorus in bottom waters at LM01 and LM06.

Figures 52 and 53 are plots of the phosphorus concentrations in the bottom waters at LM01 and LM06.

Figure 54 is the plot of total phosphorus in the surface waters at three monitoring stations, LM01, LM03, and LM06.

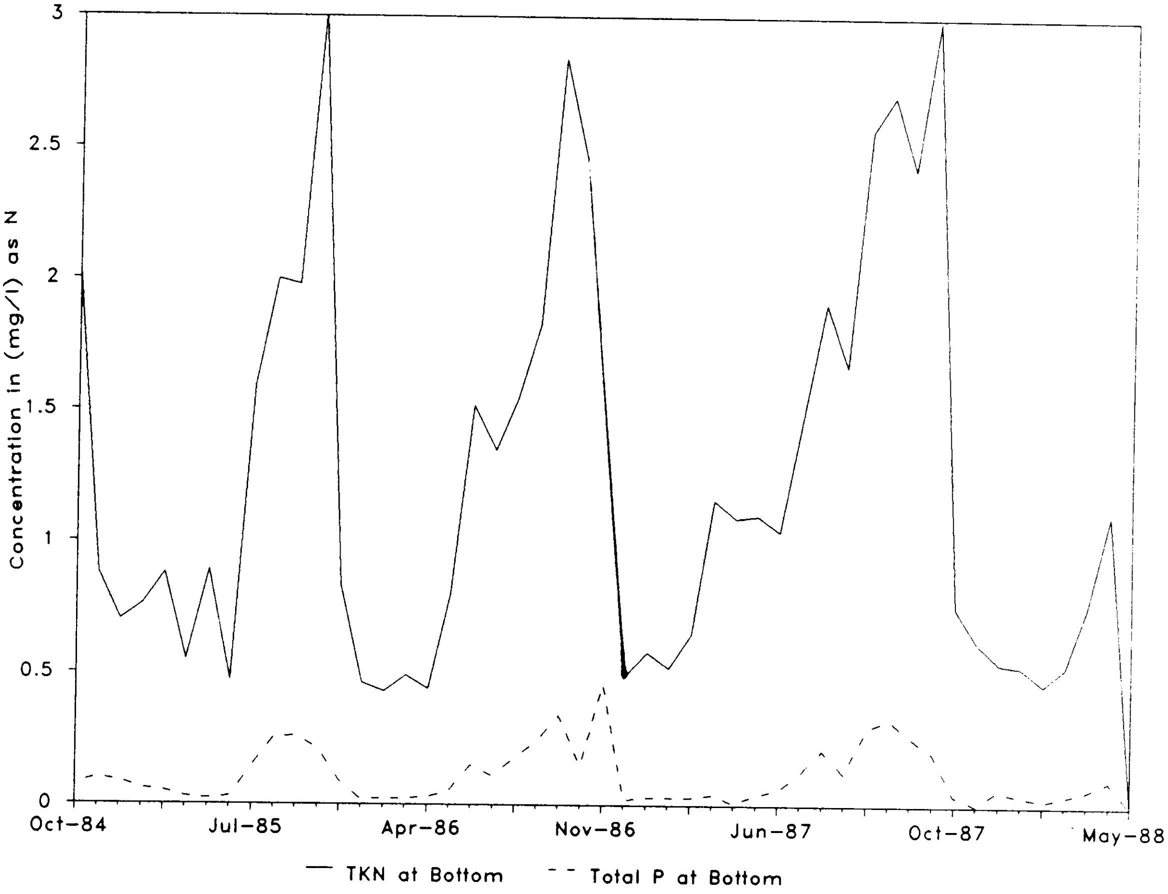

Figure 50 - Nitrogen and Phosphorus at the Bottom of LM01

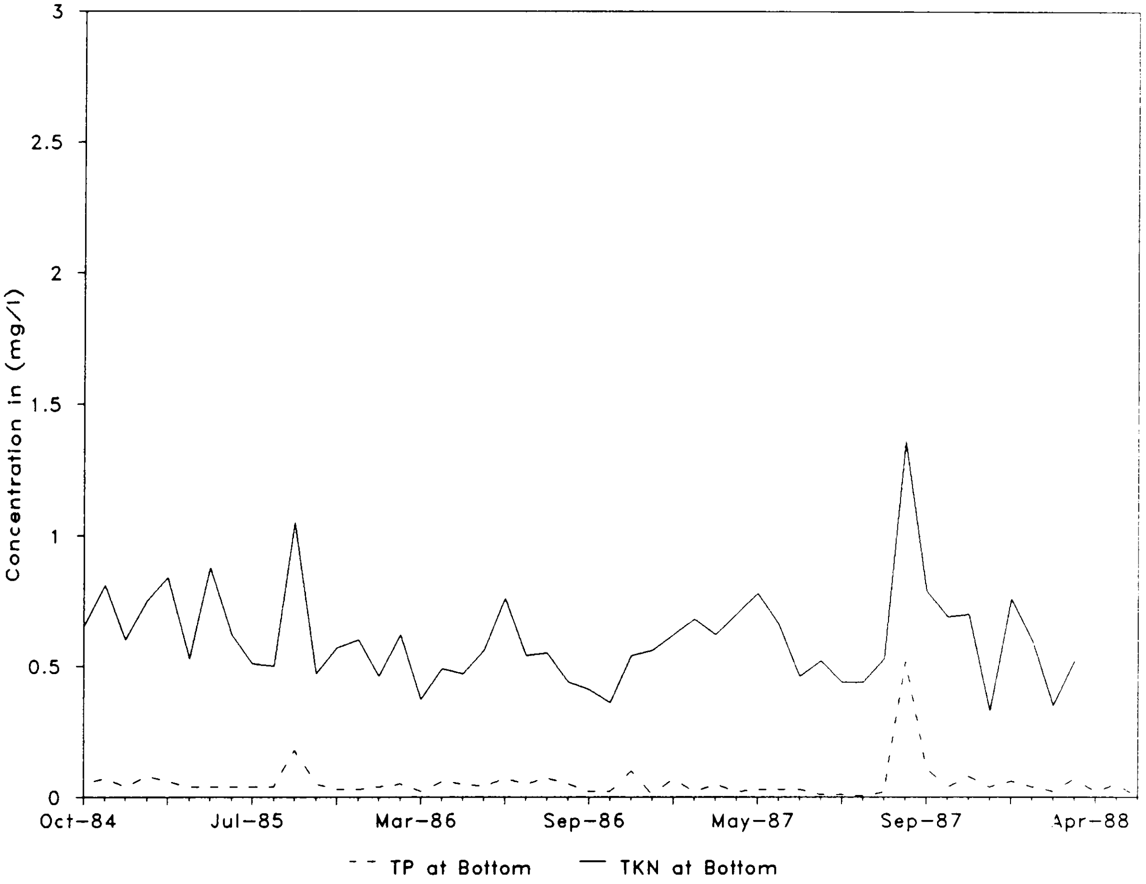

Figure 51 - Nitrogen and Phosphorus in the Bottom at LM06

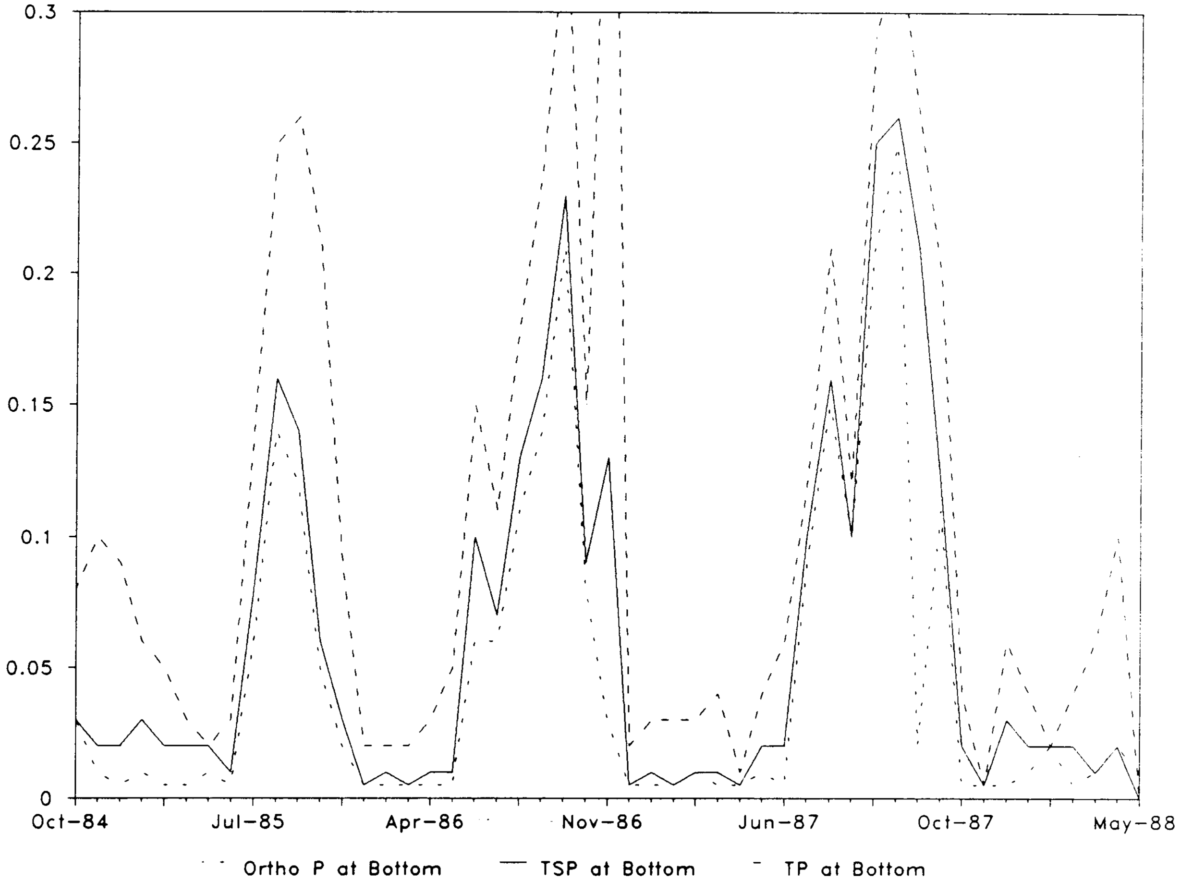

Figure 52 - Phosphorus in the Bottom at LM01

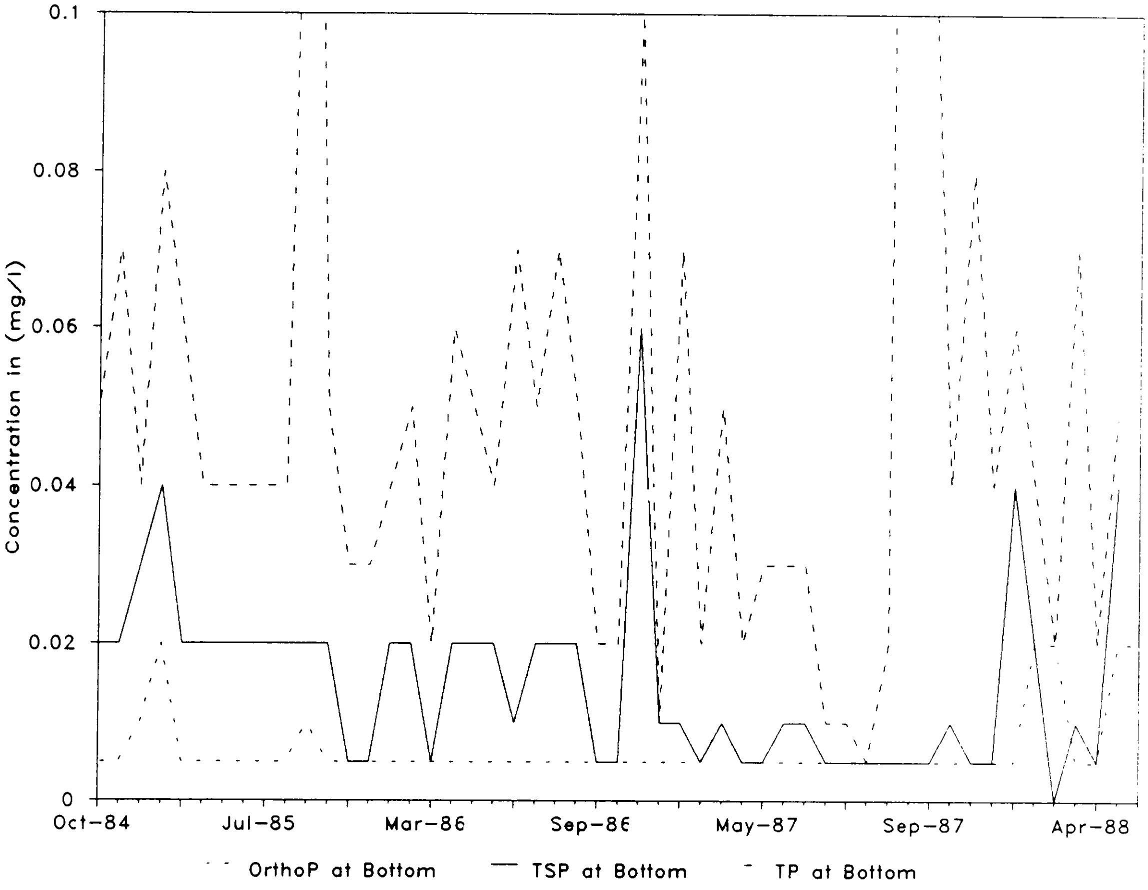

Figure 53 - Phosphorus in the Bottom at LM06

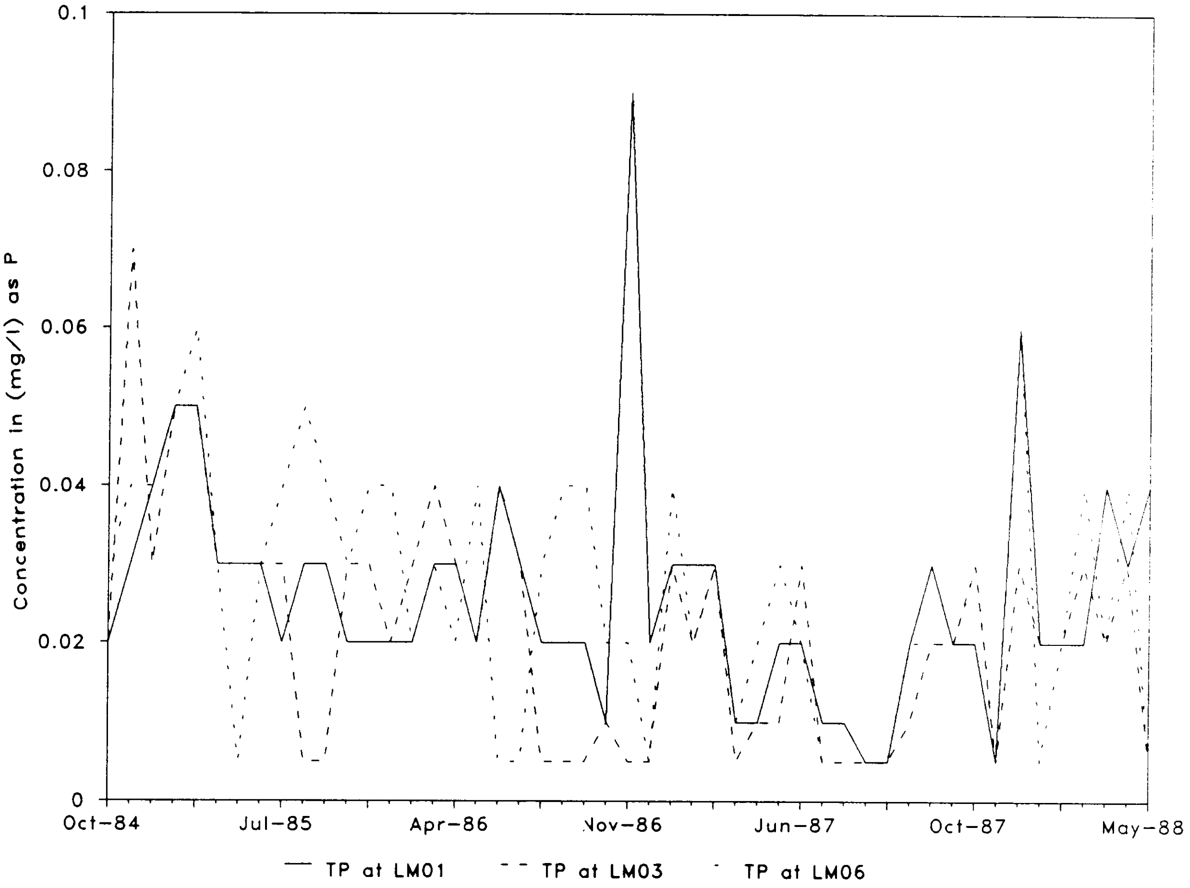

Figure 54 - Total Phosphorus in the Top

at LM01, LM03, and LM06

Lake Manassas Watershed Properties

Table 8 gives the data for the five basins used for this thesis. Figures 1 and 5 show the relative location of the basins.

Figure 55 is a plot of rainfall in the Lake Manassas watershed on a yearly basis.

Figure 56 is a plot of the Percent of Runoff for the ST70 basin as a function of rainfall. In Figure 56, the points represent actual data and the straight line is a regression fit of that data.

Table 8 - Properties of Lake Manassas Watershed Basins

Tributary Name	Basin Area (sq. miles)	Percent of Total Area
BR03 - South Run	7.47	10.2
BR04 - North Fork	8.32	11.4
BR05 - Northern Arms	3.11	4.3
BR06 - Southern Arms	2.67	3.6
ST70 - Broad Run	40.43	70.5

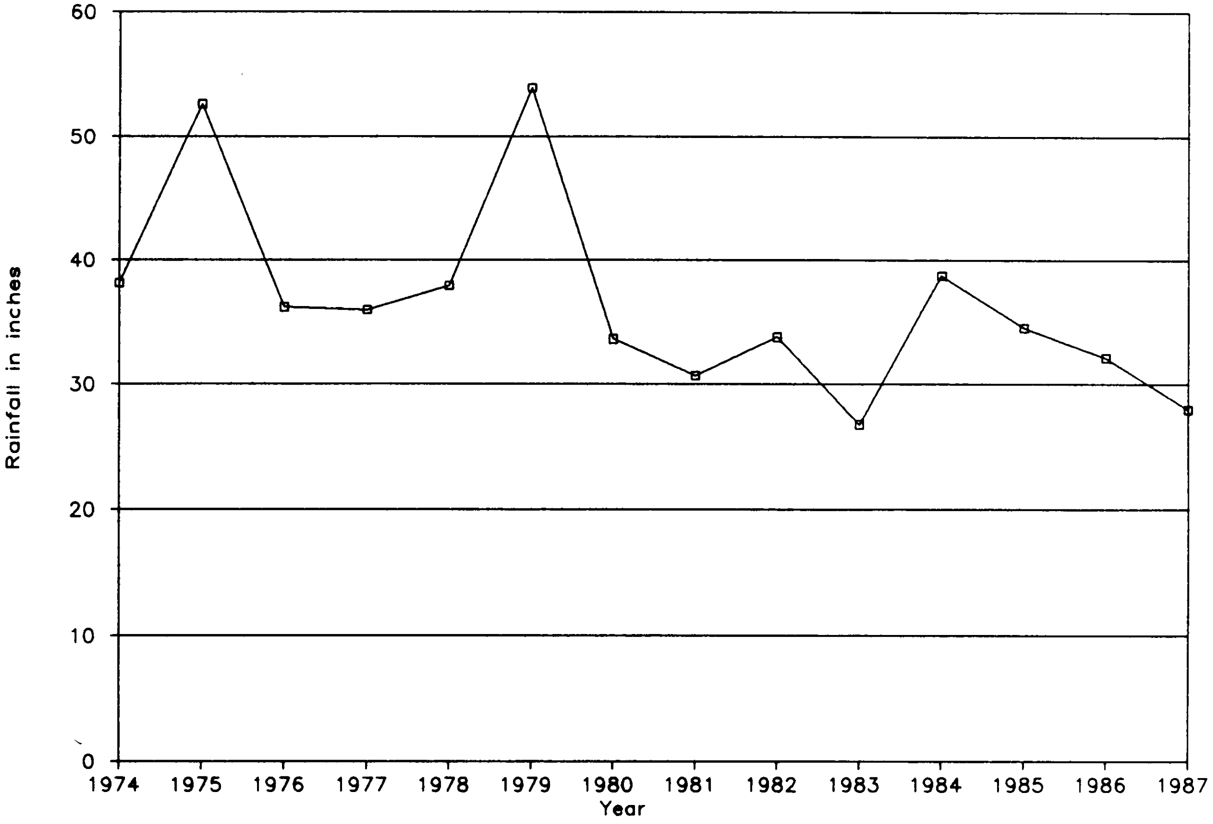

Figure 55 - Rainfall in Lake Manassas watershed

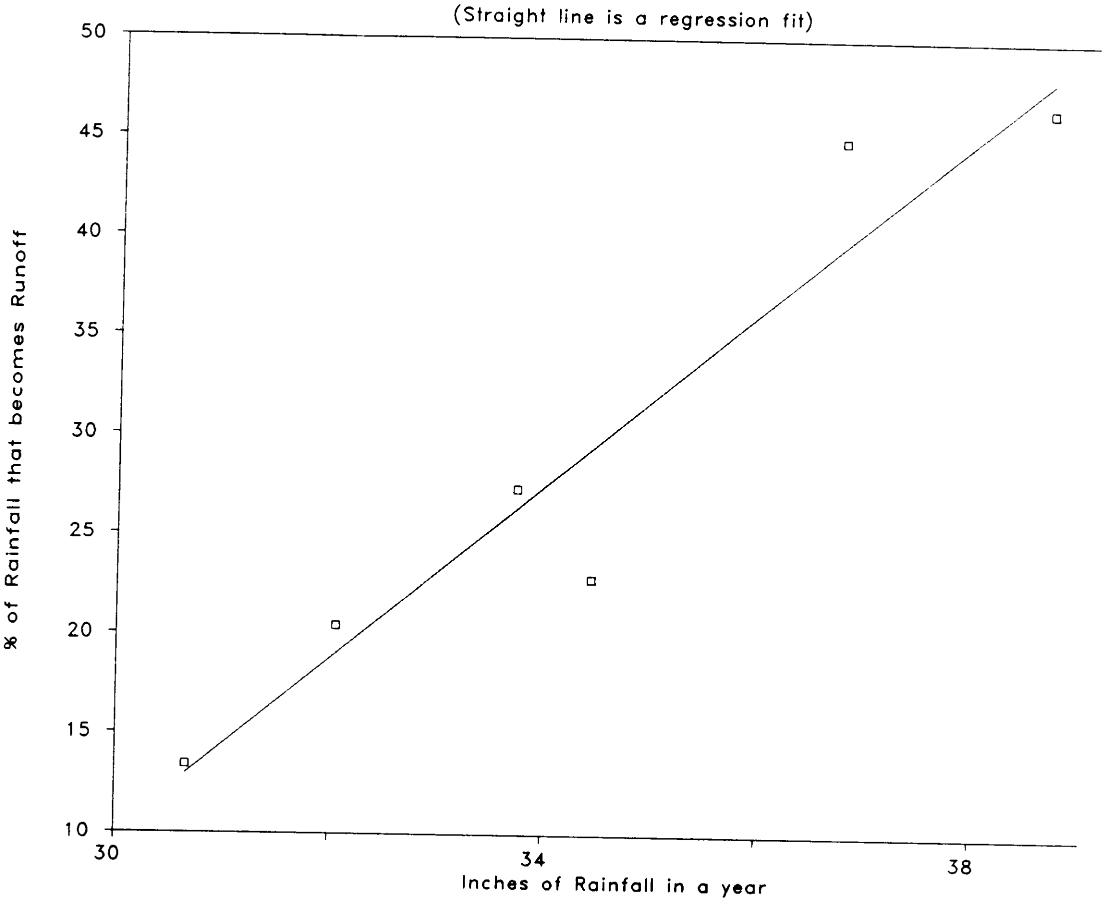

Figure 56 - % Runoff into Broad Run versus Yearly Rainfall

Lake Manassas Watershed Environmental Monitoring Data

Table 9 is a summary of the database for the sampling of the drainages into Lake Manassas. The table contains the maximum, minimum, average, median, and the standard deviation values for the listed parameters. For sampling station ST70 a flow weighted average value is also listed because flow data existed for this station. When the database was analyzed, if a given constituent was less than its detectable limit, it was evaluated at half the value of the detectable limit. This way a parameter value of zero was not "averaged into" the analysis. In most cases, if this was not done, over half of the data in the database would have been evaluated at zero, and underestimated the predicted values. It should be noted that this is slightly different than the data presentation technique of the top and bottom plots where these values were plotted as negative values.

Table 10 is the summary of data for the monitoring of pollutant metals in the streams. The format for Table 10 is similar to that of Table 9.

Table 9 - Summary of Environmental Monitoring Data for Drainages into Lake Manassas (all measurements in mg/L)

Monitoring Station number BR03

BR03		DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	!	9.70	105.00	42.16	0.09	0.11	0.15	0.07	0.54	0.67	1.10	8.37	6.9
Maximum	!	14.00	177.00	86.10	0.42	0.42	0.47	0.54	0.94	1.61	4.04	38.00	8.4
Median	!	9.90	98.00	38.00	<0.01	0.05	0.09	0.02	0.51	0.61	0.61	8.00	7.1
Minimum	!	5.00	17.00	25.90	0.01	0.01	0.03	0.01	0.27	0.29	0.38	0.00	5.3
St. Dev.	!	2.45	22.00	14.40	0.09	0.10	0.10	0.09	0.16	0.23	0.88	13.31	0.5

Monitoring Station number BR04

BR04	!	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	!	9.05	83.00	50.20	0.02	0.04	0.07	0.03	0.51	0.60	0.12	11.45	6.4
Maximum	!	13.40	119.00	215.10	0.11	0.17	0.30	0.46	1.20	1.45	0.48	84.00	7.3
Median	!	10.20	80.00	42.00	0.02	0.02	0.04	0.02	0.64	0.58	<0.01	5.00	6.6
Minimum	!	2.50	28.00	19.80	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.50	6.0
St. Dev.	!	2.71	17.60	47.60	0.02	0.03	0.05	0.06	0.20	0.26	0.13	14.93	1.0

Monitoring Station number BR05

BR05	!	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	!	9.98	89.10	39.02	0.03	0.05	0.07	0.03	0.45	0.56	0.18	14.60	6.5
Maximum	!	13.00	107.21	186.00	0.59	0.65	1.09	0.26	1.52	3.69	1.19	177.00	7.5
Median	!	11.20	88.00	48.00	<0.01	0.02	0.02	<0.01	0.30	0.34	<0.01	2.00	6.4
Minimum	!	3.55	44.50	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1.50	5.7
St. Dev.	!	2.10	11.20	43.30	0.08	0.09	0.14	0.04	0.27	0.52	0.24	31.60	0.4

Monitoring Station number BR06

BR05	!	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	!	9.10	83.00	39.40	0.03	0.04	0.09	0.04	0.54	0.77	0.24	27.20	6.4
Maximum	!	13.20	110.80	190.10	0.20	0.22	0.50	0.38	1.77	2.42	2.56	383.00	7.4
Median	!	9.40	93.00	50.00	<0.01	0.02	0.03	0.02	0.61	0.66	<0.01	7.00	6.1
Minimum	!	4.00	30.30	20.80	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1.00	5.9
St. Dev.	!	2.80	18.80	37.20	0.04	0.04	0.09	0.06	0.27	0.50	0.40	63.19	0.4

Table 9 - continued

Monitoring Station number ST70

ST70	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
FlowWtAvg	7.30	--	22.1	<0.01	0.03	0.10	0.04	0.39	0.59	0.74	37.43	--
Average	9.70	95.4	40.3	0.02	0.03	0.07	0.04	0.38	0.54	0.51	26.3	6.7
Maximum	15.4	132	60.8	0.08	0.18	0.64	0.39	1.09	2.1	1.52	371	7.9
Median	10.6	100	50	<0.01	0.02	0.02	<0.01	0.3	0.41	<0.01	4	6.8
Minimum	4.7	56	3.8	<0.01	<0.01	<0.01	0.01	0.08	0.11	<0.01	0.2	5.7
St. Dev.	2.5	12.5	9.6	0.02	0.03	0.12	0.04	0.38	0.54	0.51	26.3	0.8

Monitoring Station number BR03
(repeated for comparison with BR02 and BR07)

BR03	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	9.70	105.00	42.16	0.09	0.11	0.15	0.07	0.54	0.67	1.10	3.37	6.9
Maximum	14.00	177.00	86.10	0.42	0.42	0.47	0.54	0.94	1.61	4.04	88.00	8.4
Median	9.90	98.00	38.00	<0.01	0.05	0.09	0.02	0.51	0.61	0.61	3.00	7.1
Minimum	5.00	17.00	25.90	0.01	0.01	0.03	0.01	0.27	0.29	0.08	0.00	5.8
St. Dev.	2.45	22.00	14.40	0.09	0.10	0.10	0.09	0.16	0.23	0.88	13.31	0.5

Monitoring Station number BR02

BR02	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	9.30	90.10	43.37	0.16	0.19	0.23	0.17	0.70	0.83	1.93	12.57	6.7
Maximum	13.20	123.00	87.60	0.77	0.79	0.82	1.31	2.16	2.16	11.19	180.00	7.7
Median	8.60	84.00	29.80	0.06	0.10	0.12	0.02	0.70	0.68	0.58	2.00	6.5
Minimum	4.00	45.00	26.70	<0.01	0.02	0.04	<0.01	0.31	0.36	0.16	0.50	5.9
St. Dev.	2.34	15.90	14.32	0.16	0.17	0.17	0.27	0.30	0.35	2.39	28.80	0.4

Monitoring Station number BR07

BR07	DO	%DO SAT	TALK	OP	TSP	TP	NH3_N	SKN	TKN	OX_N	TSS	PH
Average	8.94	87.40	38.68	0.01	0.03	0.05	0.13	0.54	0.71	0.20	8.94	6.6
Maximum	13.20	111.30	71.40	0.13	0.16	0.23	0.69	1.01	1.99	0.61	80.00	7.5
Median	7.60	90.00	36.00	<0.01	0.02	0.03	0.06	0.46	0.66	<0.01	4.00	6.5
Minimum	4.60	45.50	24.00	<0.01	<0.01	<0.01	<0.01	0.24	0.34	<0.01	0.00	5.5
St. Dev.	2.47	15.60	12.50	0.02	0.03	0.04	0.12	0.19	0.28	0.13	11.47	0.5

Table 10 - Summary of Metal Content of
Drainages to Lake Manassas
(all measurements are ug/l

Monitoring Station # BR03

BR03	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	4	3	4	9	11	13	11	15	11	11	4	3	8	12	2	4	15	11	13	12
# < MDL	3	3	3	9	11	11	11	7	11	0	2	2	0	1	2	4	9	11	3	7
Average	3.9		0.6			1		21		228	0.4	10.5	176	46			11.3		18.8	11.3
Maximum						1		120		580	0.5		795	210			17.4		99	20
Minimum						1		3		22	0.3		13	3			4.4		3	7

Monitoring Station # BR04

BR04	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	2	-	2	6	9	8	9	13	9	9	2	-	6	9	-	3	13	9	13	9
# < MDL	2	-	2	5	8	6	9	4	9	0	2	-	0	1	-	3	6	9	2	3
Average				7	7	1		11.8		488			255	144			18.8		14.4	9.2
Maximum								44		890			1050	884			68.9		38	22
Minimum								2		271			49	6			4.4		3	5

Monitoring Station # BR05

BR05	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	2	-	2	7	9	9	9	14	9	9	2	-	7	10	2	3	14	9	13	10
# < MDL	2	-	2	7	9	8	9	4	9	0	1	-	0	2	1	3	7	9	2	3
Average						1		7		483	1.4		75	19.4	23		17.6		21.4	10.1
Maximum								32		1120			312	29			29.7		30	24
Minimum								2		195			15	9			6.4		2	5

Monitoring Station # BR06

BR06	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	2	-	2	7	8	10	8	15	8	8	2	-	7	8	1	3	14	8	12	9
# < MDL	2	-	1	6	8	8	8	3	8	0	1	-	0	0	1	3	7	8	0	4
Average			0.6	6		1.5		6.75		628	0.8		166	78.8			8.9		21.5	8
Maximum						2		16		995			305	264			18.5		118	14
Minimum						1		2		240			11	21			2.3		6	5

Table 10 - continued

Monitoring Station # BR03

BR03	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	4	3	4	9	11	13	11	15	11	11	4	3	8	12	2	4	15	11	13	12
# < MDL	3	3	3	9	11	11	11	7	11	0	2	2	0	1	2	4	9	11	3	7
Average	3.9		0.6			1		21		228	0.4	10.5	176	46			11.3		16.8	11.8
Maximum						1		120		580	0.5		795	210			17.4		99	20
Minimum						1		3		22	0.3		13	3			4.4		3	7

Monitoring Station # BR02

BR02	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	5	3	5	9	11	14	11	15	11	11	5	3	8	12	3	4	16	11	16	12
# < MDL	4	3	3	9	11	14	11	6	11	0	3	2	0	2	2	4	9	11	2	7
Average	3.6		0.3					7.7		270	1.7	1.6	246	58	27		11.5		27	32
Maximum			0.4					13		780	2.2		1131	160			20.6		130	114
Minimum			0.2					1		35	1.2		36	22			4.4		1	5

Monitoring Station # BR07

BR07	TAG	EAG	TCD	ECD	SCD	ECR	SCR	ECU	SCU	SFE	THG	EHG	EMN	SMN	ENI	SNI	EPB	SPB	EZN	SZN
# samples	4	3	45	11	11	14	11	18	11	11	4	3	10	12	2	4	16	11	16	11
# < MDL	4	3	1	10	11	13	10	10	11	0	2	2	0	0	2	4	10	11	5	9
Average			0.3	6		1	205	4		430	1.9	2.2	348	171			8		22	7.5
Maximum			0.4					8		592			975	540			18.6		106	10
Minimum			0.1					1		50			61	32			4.4		2	5

In order to further characterize the Lake Manassas watershed, the data from station ST70 were used to develop cumulative loading curves for various nutrients. Figures 57 through 63 are the nutrient cumulative loading curves for the Broad Run drainage into Lake Manassas. The straight lines represent the linear regression fits to the data plotted. The loading data is plotted versus time in months. The regression lines were calculated forcing them through the origin.

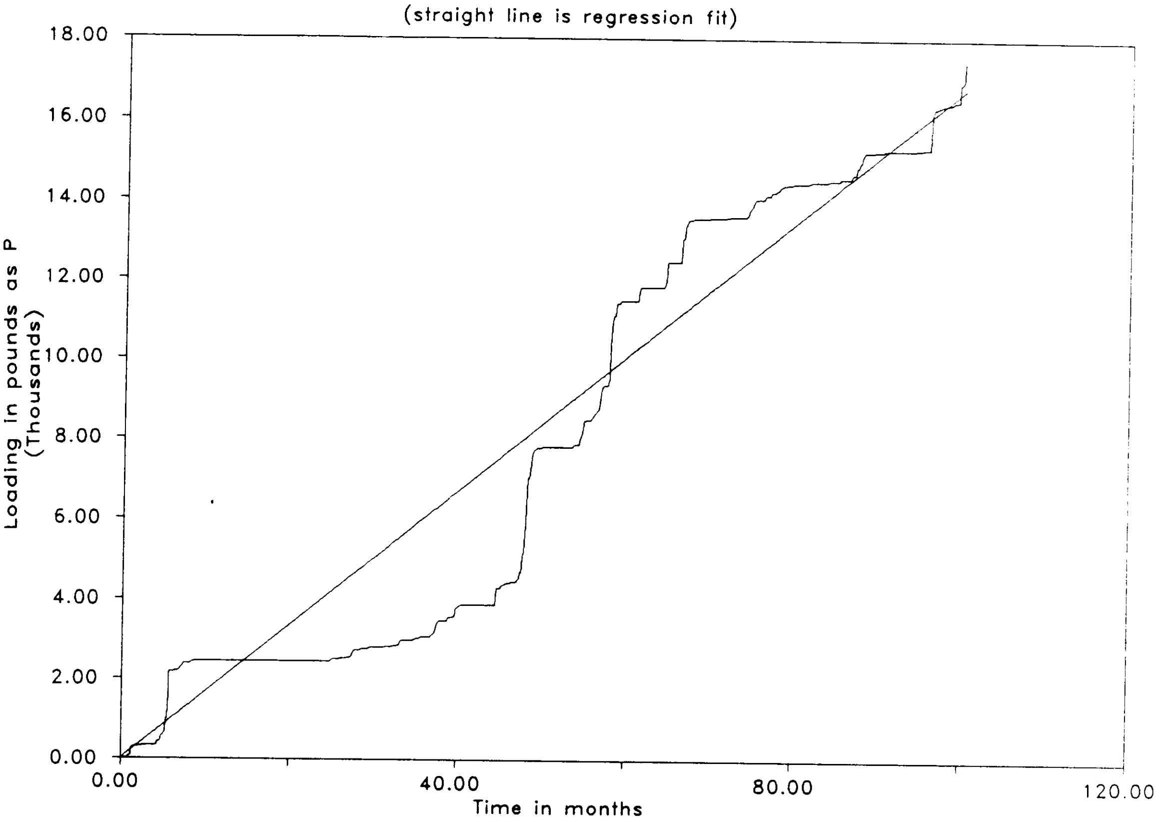

Figure 57 - ST70 loading of Orthophosphorus

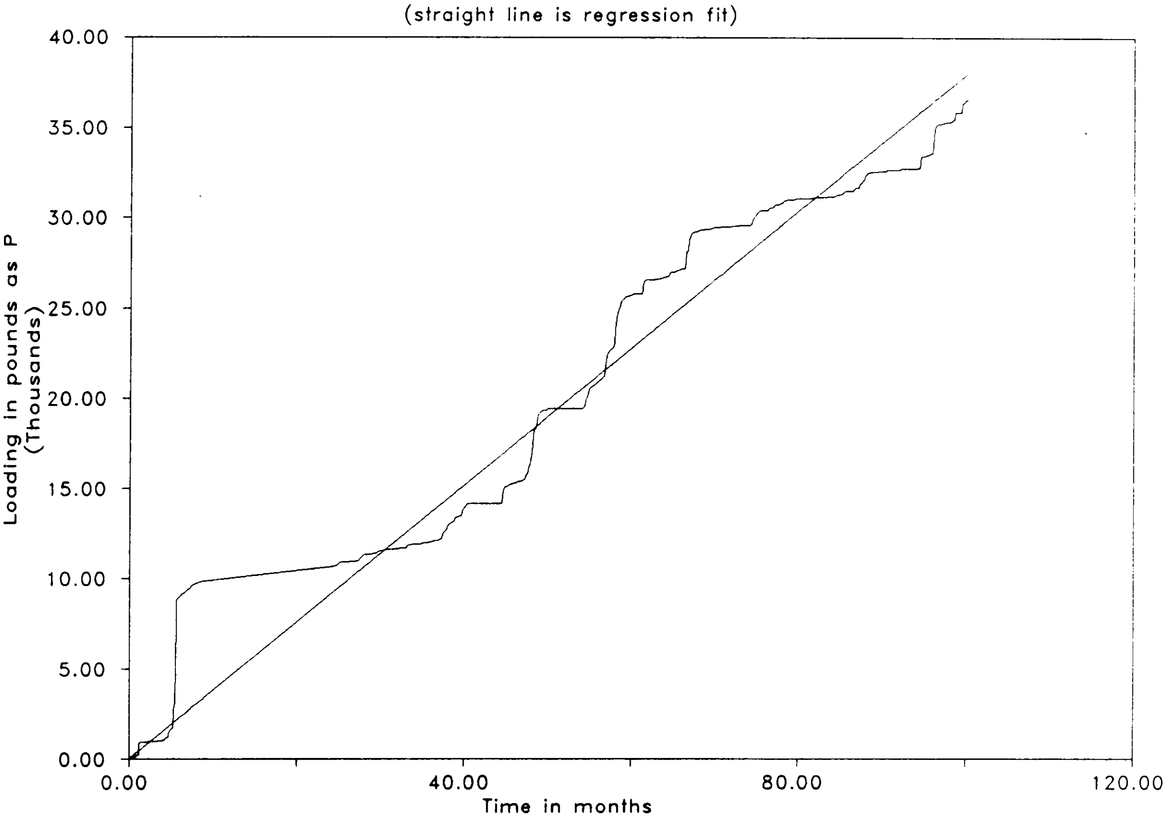

Figure 58 - ST70 Loading of Total Soluble Phosphorus

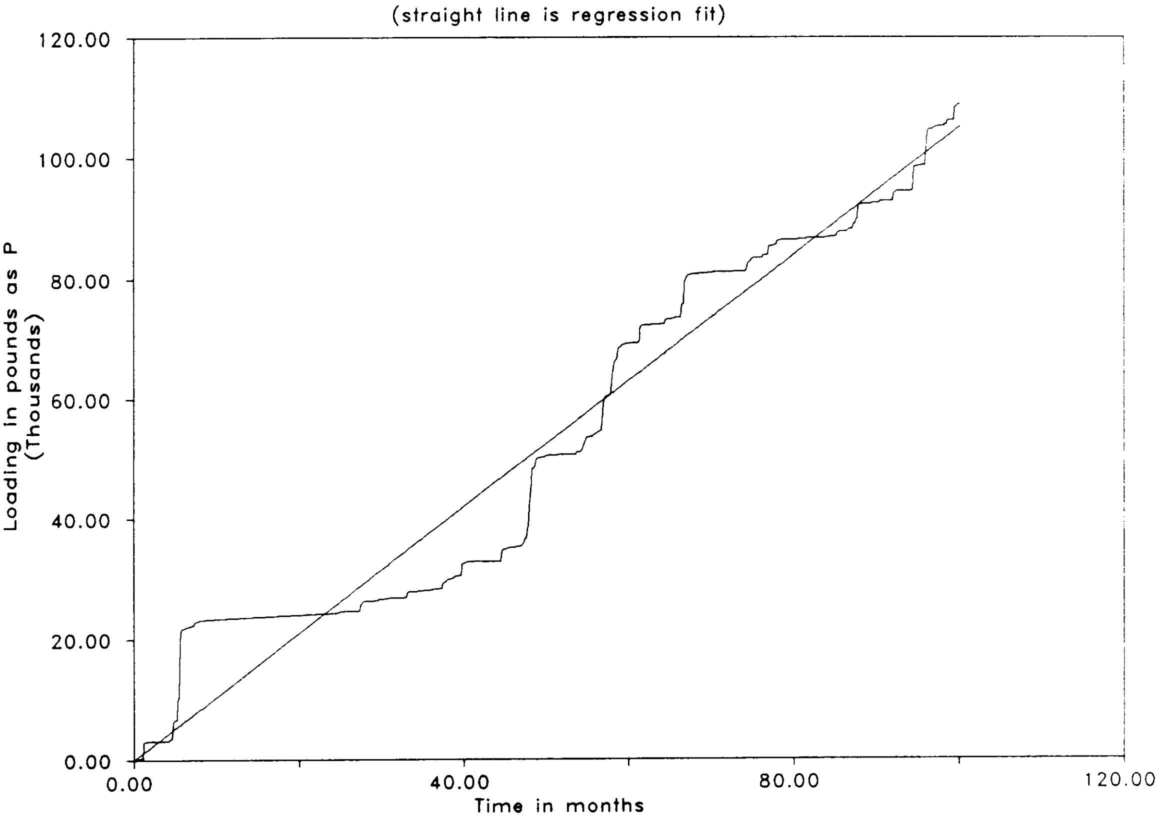

Figure 59 - ST70 Loading of Total Phosphorus

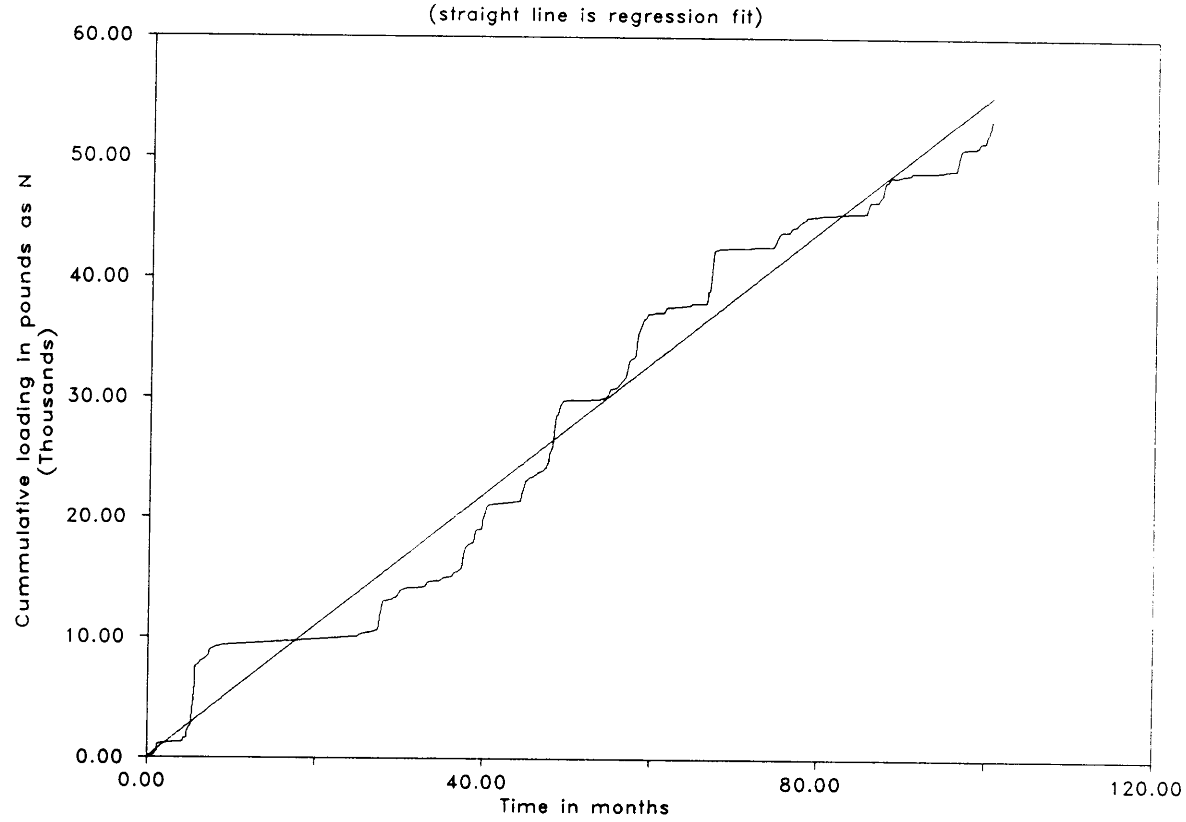

Figure 60 - ST70 Loading of Ammonia Nitrogen

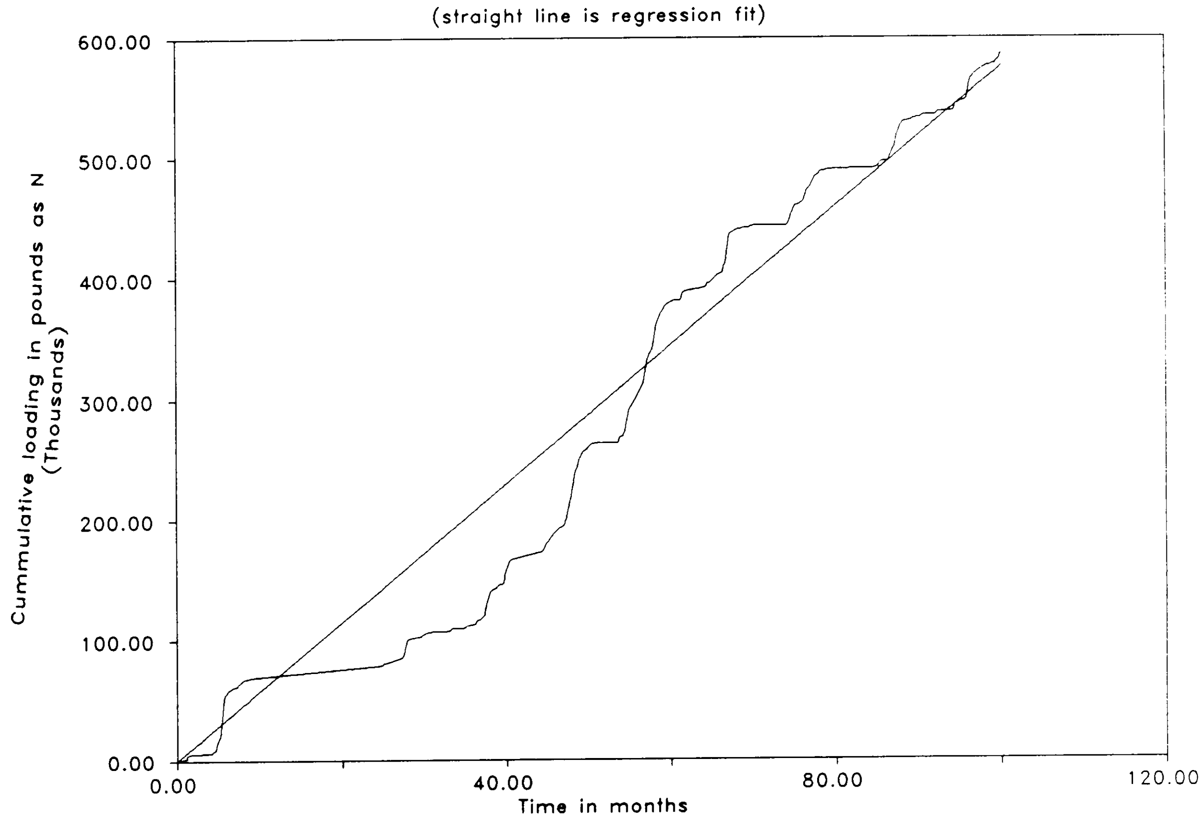

Figure 61 - ST70 Loading of Oxidized Nitrogen

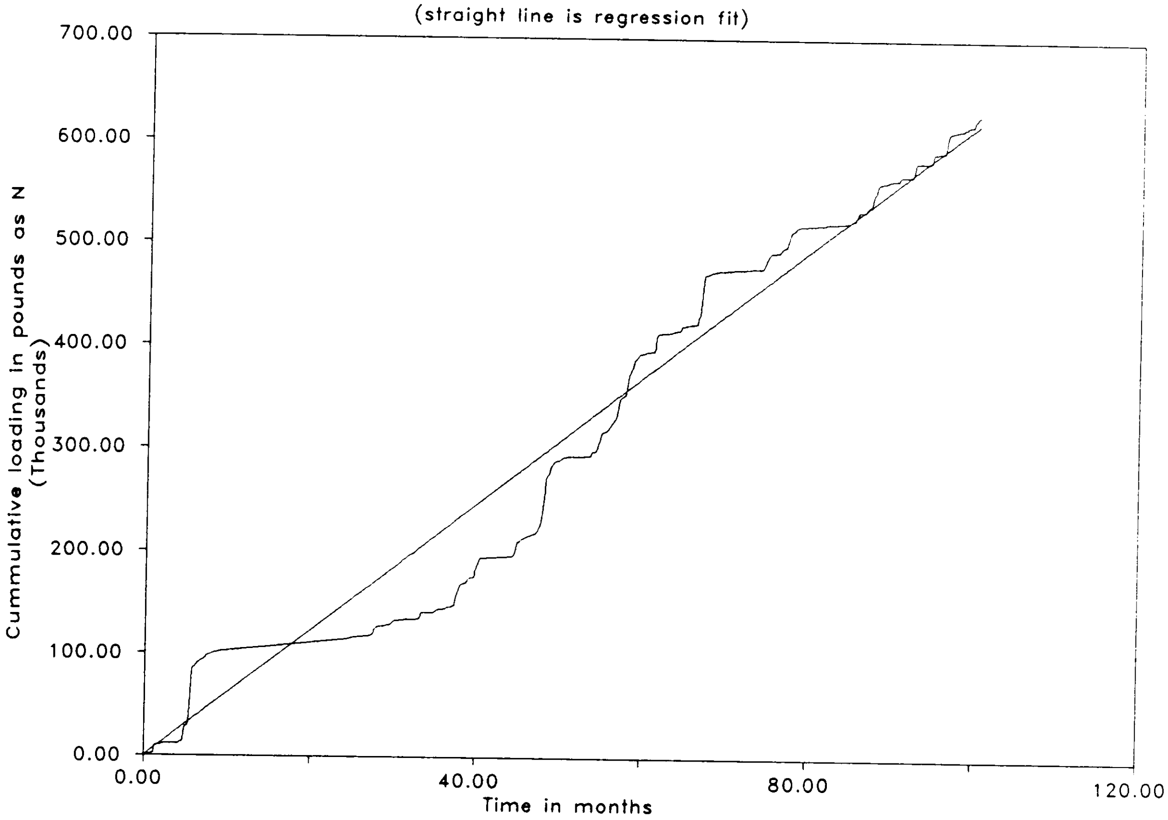

Figure 62 - ST70 Loading of TKN

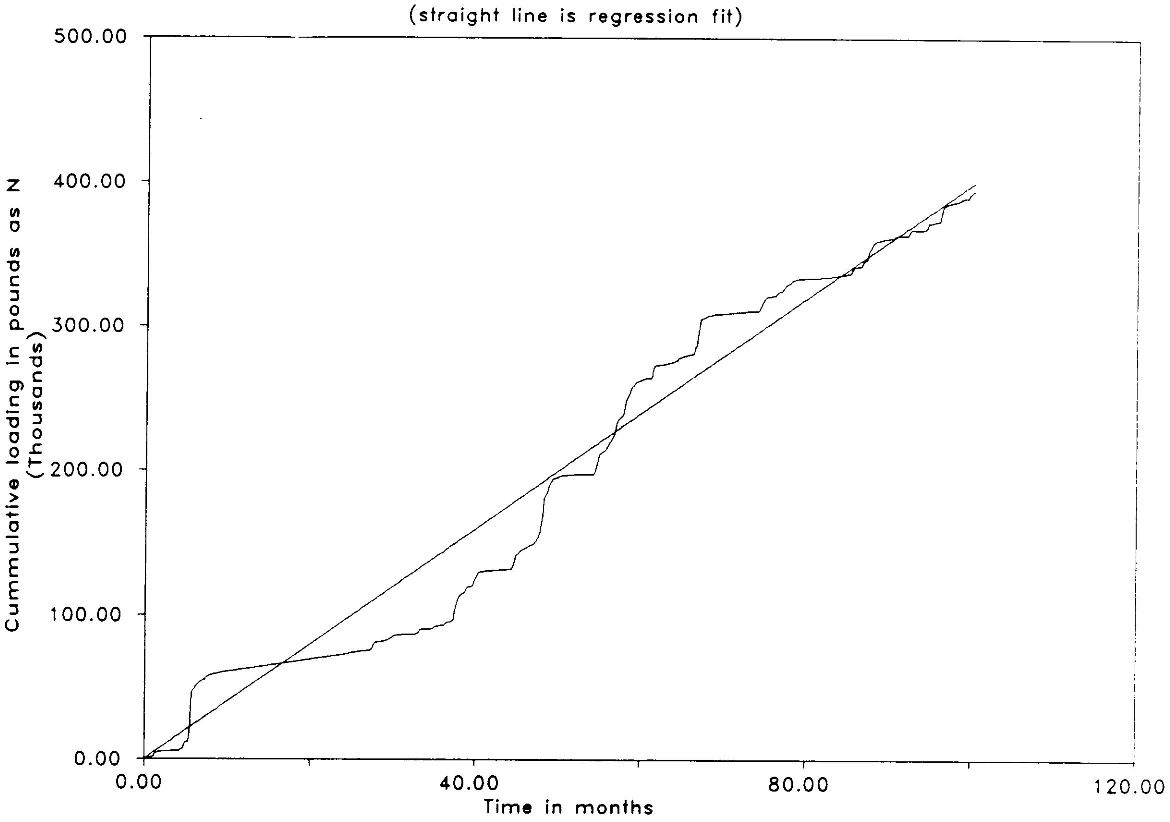

Figure 63 - ST70 Loading of SKN

Prediction of the Eutrophic Status of Lake Manassas

As discussed in Chapter III, application of the Vollenweider analysis for this project involved development of a computer "spreadsheet model" of Lake Manassas.

The spreadsheet model is shown in Figure 64. The numbers shown in Figure 64 represent the results for a given "run" of the modeling program. The program automatically records the results for each run for subsequent statistical analysis.

Figures 65 and 66 represent the summary statistical analysis for the current total phosphorus loading to the lake using both median and average distributions. Figures 67 and 68 represent the graphical equivalents to the data contained in Figures 65 and 66.

The output data for the total phosphorus loadings and the z/tau hydraulic parameter for the lake are combined to produce an "operating box" on the normal Vollenweider plot. Figure 69 shows the "operating box" for the model output of the currently predicted eutrophic conditions in Lake Manassas. The box of Figure 69 represents the area of the Vollenweider curve which, with a probability of approximately 90%, is the current eutrophic condition of Lake Manassas. The box is clearly well above the "Dangerous" loading curve established by Vollenweider.

```
                                                       Lake Area            Lake Volume
                                                       in acres =      694  in gallons= 4.2E+09

This spreadsheet uses the Lotus modeling               Yearly Rainfall      Lake Mean Depth (z)
program called @RISK.                                  in inches =  37.0900 in meters =    3.51
------------------------------------------------------ -------------------- --------------------
Version 2    5/8/89                                                AVERAGE  AVERAGE   MEDIAN    MEDIAN
          Basins to  Stream  Basin Area  Percent  Yearly Flow  Total P  P Loading  Total P  P Loading
            Lake      Code     (ft2)     of Area     (ft3)      (mg/L)  (gm/m2/yr) (mg/L)  (gm/m2/yr)
          ---------- -------- ---------- -------- ----------- -------- ---------- -------- ----------
          Broad Run   ST70     1.44E+09     70.5   1.83E+09  0.094364      1.736 0.036946      0.681
          North Fork  BR04     2.32E+08     11.4   2.94E+08  0.068509      0.203 0.039780      0.118
          North Arms  BR05     8.68E+07      4.3   1.10E+08  0.070992      0.079 0.040457      0.045
          South Arms  BR06     7.45E+07      3.6   9.44E+07  0.086562      0.082 0.038049      0.036
          South Run   BR07     2.08E+08     10.2   2.64E+08  0.048557      0.129 0.031068      0.083
          Vint Hill   BR02       N\A        N\A    1.31E+07  2.543067      0.336 2.543067      0.336
          ---------- -------- ---------- -------- ----------- -------- ---------- -------- ----------
                                                   2.60E+09           2.57E+00  =  Load =  1.30E+00
          Lake Inflow/Lake Volume (tau) =  4.631  z/tau = 0.758
                                                               AVERAGE  AVERAGE   MEDIAN    MEDIAN
                                                               Total P  P Loading Total P  P Loading
                                                               (mg/L)  (gm/m2/yr) (mg/L)  (gm/m2/yr)
                                                               ------------------ ------------------
                                                                0.0944     1.740 0.036946     0.681
                                                                0.0685     0.203 0.039780     0.118
                                                                0.2499     0.278 0.070992     0.079
                                                                0.0866     0.083 0.038049     0.036
                                                                0.0486     0.129 0.031068     0.083
                                                                2.5431     0.336 2.543067     0.336
                                                               ------------------ ------------------
                                                                         2.77E+00  =  Load =  1.33E+00

                                                                  200% Increase in the Northern Arms
                                                                 Total P Concentration

                                                               AVERAGE  AVERAGE   MEDIAN    MEDIAN
                                                               Total P  P Loading Total P  P Loading
                                                               (mg/L)  (gm/m2/yr) (mg/L)  (gm/m2/yr)
                                                               ------------------ ------------------
                                                               0.094364     1.740 0.036946     0.681
                                                               0.068509     0.203 0.039780     0.118
                                                               0.070992     0.079 0.040457     0.045
                                                               0.086562     0.083 0.038049     0.036
                                                               0.048557     0.129 0.031068     0.083
                                                                  N/A        N/A      N/A       N/A
                                                               ------------------ ------------------
                                                                         2.23E+00  =  Load =  9.63E-01
                                                                         ----------           ----------

                                                                Eliminate Vint Hill Total P content
```

Figure 64 - Spreadsheet Statistical Model for Lake Manassas

Figure 65 - Current Average Phosphorus Loading

```
                    CURAVGLOAD @RISK Risk Analysis 08-May-1989

Expected/Mean Result = 2.625  Maximum Result = 17.05  Minimum Result = .387

Range of Possible Results = 16.666 Probability of Positive Result = 100%

Probability of Negative Result = 0% Standard Deviation = 2.149  Skewness = 2.477  Kurtosis = 11.439

Variance = 4.620

Probability of Result > 0      = 100%
                      > 2      = 50.7%
                      > 4      = 16.2%
                      > 6      = 7.6%
                      > 8      = 2.9%
                      > 10     = 1.8%
                      > 12     = .8%
                      > 14     = .3%
                      > 16     = .2%
                      > 18     = 0%

Probability of Result <= 0     = 0%

Percentile Probabilities: (Chance of Result < Shown Value)
                       < .387    = 0%
                       < .7005   = 5%
                       < .8637   = 10%
                       < .9972   = 15%
                       < 1.1463 = 20%
                       < 1.2609 = 25%
                       < 1.3819 = 30%
                       < 1.5154 = 35%
                       < 1.6509 = 40%
                       < 1.8254 = 45%
                       < 2.0286 = 50%
                       < 2.196   = 55%
                       < 2.3703 = 60%
                       < 2.5494 = 65%
                       < 2.7891 = 70%
                       < 3.13    = 75%
                       < 3.5893 = 80%
                       < 4.2797 = 85%
                       < 5.2896 = 90%
                       < 6.7701 = 95%
                       < 17.0532= 100%
```

Figure 66 - Current Median Phosphorus Loading

```
                         CURMEDLOAD  @RISK Risk Analysis  08-May-1989

Expected/Mean Result = 1.345  Maximum Result = 20.629  Minimum Result = .351

Range of Possible Results = 20.278 Probability of Positive Result = 100%

Probability of Negative Result = 0% Standard Deviation = 1.486  Skewness = 6.041  Kurtosis = 58.255

Variance = 2.209

Probability of Result > 0      = 100%
                      > 2.25   = 10.3%
                      > 4.5    = 2.9%
                      > 6.75   = 1.5%
                      > 9      = .7%
                      > 11.25  = .3%
                      > 13.5   = .2%
                      > 15.75  = .2%
                      > 18     = .2%
                      > 20.25  = .1%
                      > 22.5   = 0%

Probability of Result <= 0     = 0%

Percentile Probabilities:  < .3513   = 0%
                           < .4652   = 5%
                           < .5175   = 10%
                           < .5686   = 15%
                           < .6169   = 20%
                           < .6648   = 25%
                           < .7113   = 30%
                           < .7579   = 35%
                           < .8113   = 40%
                           < .8665   = 45%
                           < .935    = 50%
                           < 1.0197 = 55%
                           < 1.1146 = 60%
                           < 1.204   = 65%
                           < 1.3068 = 70%
                           < 1.4605 = 75%
                           < 1.644   = 80%
                           < 1.9643 = 85%
                           < 2.2777 = 90%
                           < 3.3592 = 95%
                           < 20.6293= 100%
```

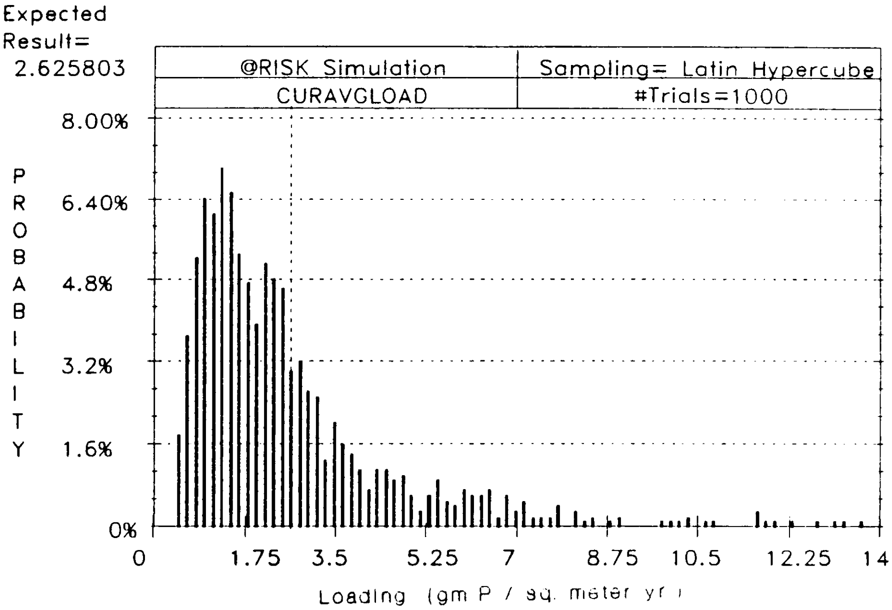

Figure 67 - CURAVGLOAD Output Distribution Graph

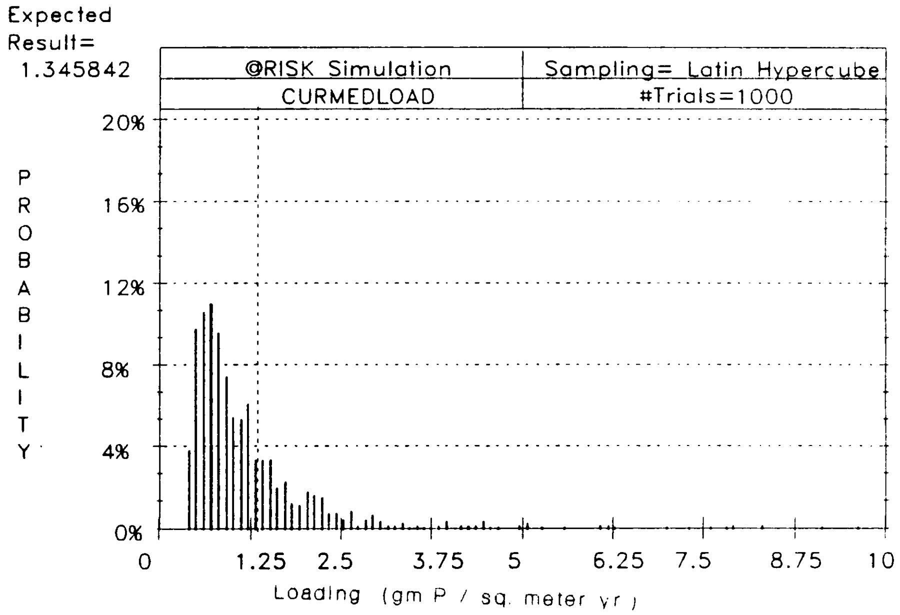

Figure 68 - CURMEDLOAD Output Distribution Graph

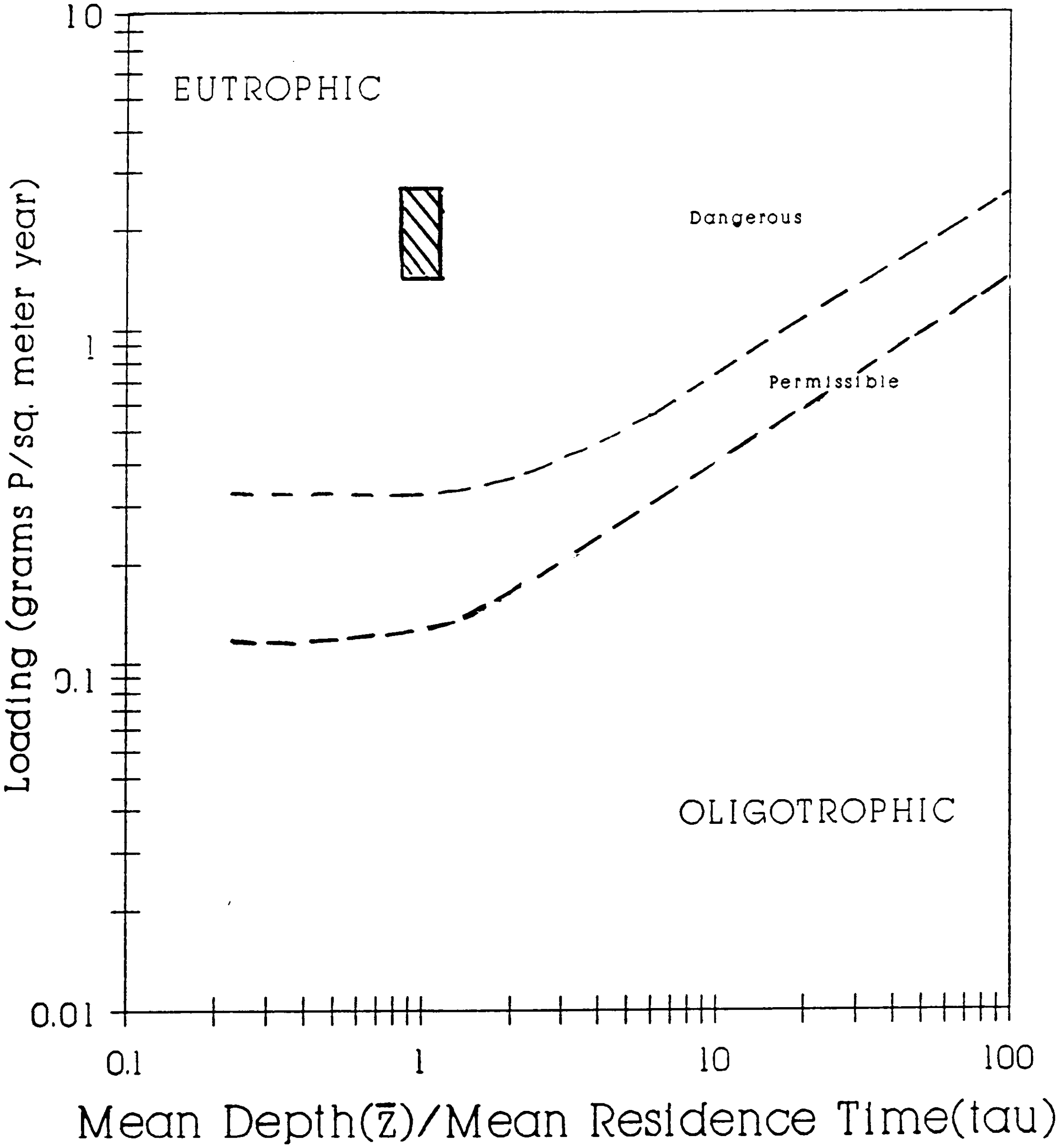

Figure 69 - Vollenweider Plot of Current Conditions in Lake Manassas

Two other cases were analyzed by the model; a case for increased concentration in the total phosphorus in runoff from the Northern Arms area (the area for proposed development as a resort area), and a case for the elimination of the sewage treatment plant input from the Vint Hill Army Station.

Table 11 summarizes the predicted total phosphorus loadings for the lake in all three cases. Inspection shows that for the case of a 200% increase in the Northern Arms total phosphorus contamination, the total phosphorus loading to the entire lake does not change substantially. This is because the flow contribution from the Northern Arms watershed is a small fraction of the total lake watershed flow (approximately 4.3%). Graphically the difference between these two cases is very small and Figure 69 would not change perceptibly.

The elimination of the Vint Hills sewage treatment plant point source from the lake phosphorus input sources results in an improvement in the predicted eutrophic status. Not only are the predicted loadings lower, but the "box" grows in size. This increase in box size is due mainly to the logarithmic nature of the graph. Figure 70 shows the operating boxes for both the case of eliminating the Vint Hill point source.

Table 11 - Summary of Results from Spreadsheet Model of Lake Manassas

Case Assumptions	Net Loading (gm/m2/yr) Average Values	Median Values
#1 - Current Conditions	2.54	1.35
#2 - Increase Northern Arms by 200 % in Total P	2.63	1.38
#3 - Eliminate Vint Hill Point Source discharge	2.29	1.00

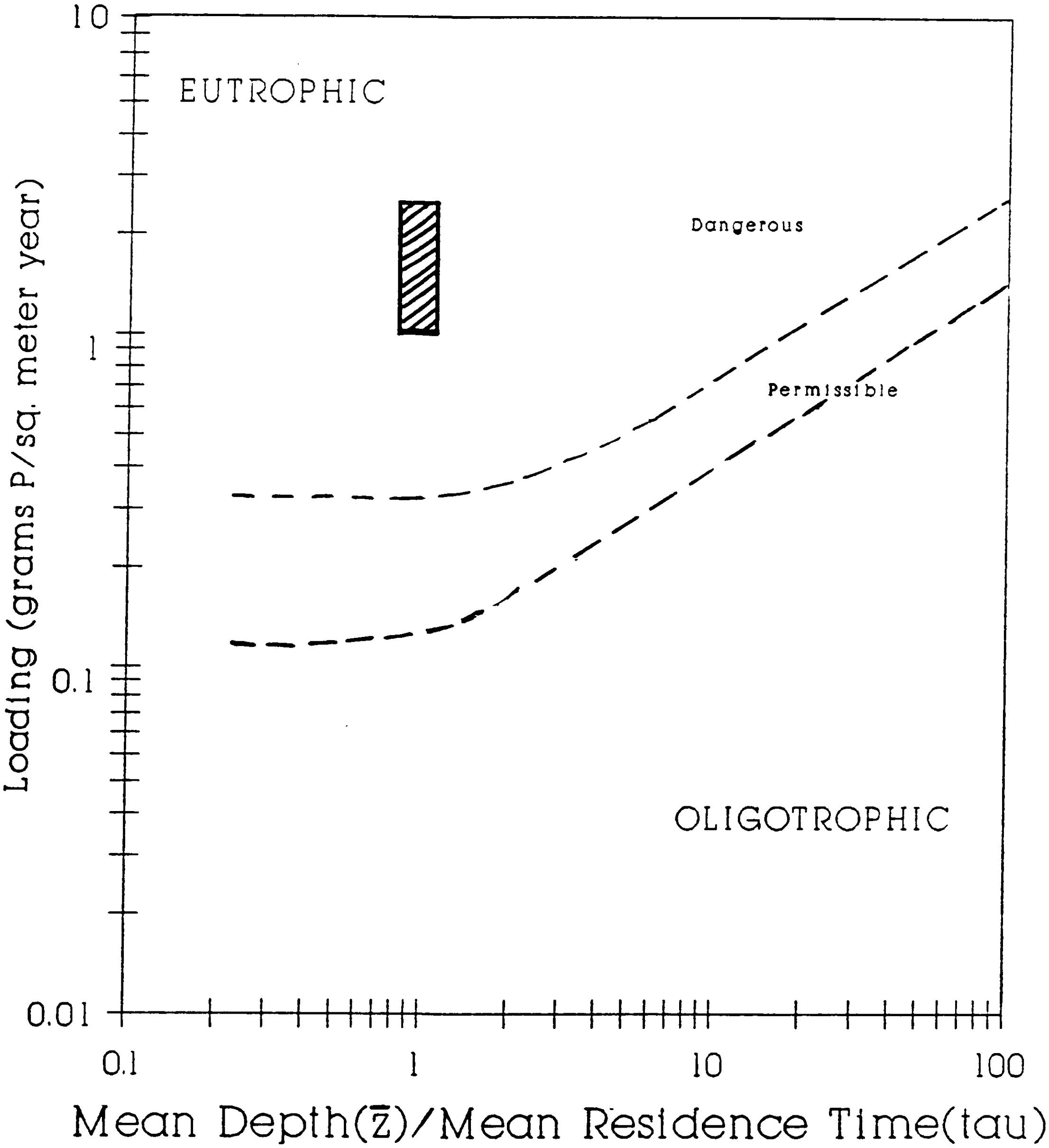

Figure 70 - Vollenweider Plot of Lake Manassas after eliminating the Vint Hill point source discharge

Table 12 represents the results of applying the other eutrophic models discussed in Chapter III.

Table 12 - Summary of Other Trophic Models

		Secchi Dish (meters)	Surface TP (ug/l)	Surface Chla (ug/l)	TSI(S)	TSI(TP)	TSI(Cha)
LM01	avg	1.34	24.79	8.6	56.58	50.16	58.85
	std	0.47	16.45	5.5	4.6	6.66	6.12
LM02	avg	1.31	23.13	7.6	56.7	51.9	58.85
	std	0.52	17.57	5.86	4.88	5.28	5.93
LM03	avg	1.22	24.17	7.33	57.81	51.55	58.84
	std	0.41	17.54	4.65	4.46	6.61	4.75
LM06	avg	0.99	26.04	11.4	60.34	53.69	62.08
	std	0.32	18.34	5.9	4.20	5.39	5.76
LM07	avg	0.89	32.29	9.7	62.00	53.61	60.68
	std	0.24	32.16	4.6	3.58	9.84	6.07

Based on Table 4 - These data show the lake to be Eutrophic for Average Total Phosphorus and Secchi Dish reading and Mesotrophic for Average Chlorophyll a

Based on Table 3 - These data show the lake to be at the high end of the mesotrophic and into the low end of the eutrophic range.

Chapter V

DISCUSSION

Discussion of Monitoring Program Results for Lake Manassas

Table 7 lists the morphological characteristics of Lake Manassas as measured for this thesis. The volume of 4.2 billion gallons agrees well with some previous studies (1). The lake was originally designed for a volume of approximately 5.8 billion gallons. However, the original engineering company which designed the lake has recently performed another study to measure the lake's volume. Although the results of that study were not available at the time this thesis was written, unofficial results confirm that the lake's volume is closer to a figure of 4.2 billion gallons (2).

The temperature profile data, Figures 7 through 14, show that Lake Manassas is a monomictic lake, with typical fall turnovers. The summer stratification is very evident, especially in the deeper portions of the lake. There is no quantifiable winter stratification, however when ice is present, sampling is not performed. This unavailable data makes it difficult to make conclusive statements regarding winter stratification.

Figures 8, 9, 11, and 12 show that at depths of over 30 feet (the hypolimnion) the temperature rarely, if ever, rises above 10°C. These figures also show that during periods of turnover, the entire water column reaches a temperature of 10°C.

Figures 9, 12, 13, and 14 are useful for characterizing the epilimnion of Lake Manassas. These figures show that the epilimnion extends to a depth of 12 to 15 feet during the summer months. Figure 12 shows that at Station LM06, there is almost no stratification to a depth of 15 feet in the summer months. Figure 9 shows that at Station LM03 there is an approximately 3°C layer at 15 feet. This difference may be due to the location of the two stations. Station LM03 is at the end of a narrow arm of the lake, whereas Station LM06 is in the center of a relatively broad section of the lake and is significantly further from land. Therefore, wind forces on the lake at LM06 may induce better mixing conditions than at LM03. Given the small thermal gradient present between the surface and 15 feet, this small difference in wind mixing force would probably be enough to account for the difference between LM06 and LM03.

The DO contour figures further confirm these conclusions, and provide further insight into Lake Manassas dynamics. Figures 15 through 22 provide the DO contours, and Figures 23 through 30 the percent of DO saturation contours. Figures 15, 16, and 18 clearly show the stratification of DO in the water column of the lake. DO levels in the epilimnion during summer months typically exceed 10 mg/L. Figures 23, 24, and 26 confirm that these DO levels are at or above the saturation level of DO, corrected for actual temperature at that location. This pattern of DO content indicates that oxygen producing, photosynthetic organisms are prolific during the summer months. Therefore, the addition of copper sulfate to the lake during the spring and fall may help reduce the magnitude of the spring and fall algal blooms, it does not strongly affect the warm season algal crop.

The transition from epilimnion to hypolimnion is more dramatic on the %DO saturation contour figures. Figures 23, 24, and 26 show that at a depth of 11 to 12 feet, the % DO saturation begins to change rapidly with depth.

Referring to Figure 6, a depth of 12 feet corresponds to an elevation of 273 feet above mean sea level, or a lake volume of 2.0 billion gallons. Therefore, the epilimnion volume is estimated at (4.2 - 2.0) or 2.2 billion gallons, and comprises approximately 52% of the lake volume.

Figures 31 through 34 also clearly depict the hypolimnion DO conditions. Figure 31 clearly shows that DO at the lake bottom of station LM01 essentially goes to zero. This means that anaerobic conditions are quite prevalent for the 4 to 5 month summer period. Figures 31 through 34 also clearly show the mixing periods of lake turnover.

Figures 33 and 34 are the top and bottom DO curves for station LM08. For the two year monitoring period contained in the database, the top and bottom DO concentrations at LM08 showed little difference except for a 6 month period in the summer of 1986, when some stratification did occur. However, the conditions were not as severe as in deeper portions of the lake. The lowest DO concentration reached was 3.3 mg/L which corresponded to a 40% DO saturation level.

Figures 35 through 42 present the data for chlorophyll a in the surface waters at the sampling points. The data clearly show the presence of chlorophyll a at all locations in the lake. The peaks do not always concur at the same time of year or at the same date from location to location. This time disparity may be due to the addition of copper sulfate to the lake, the difference in time between sampling and the copper sulfate addition, and the nonuniformity of the copper sulfate addition.

Figures 43 through 45 are a different presentation technique for the chlorophyll a data. Figure 43 shows that the chlorophyll a concentration at stations LM01 and LM03 behave very similarly. The maximum peaks are very similar in magnitude. The time at which the maximum occurs is, however, different. Figure 44 is a comparison of the chlorophyll a at stations LM01 and LM06. The chlorophyll a at LM06 has slightly higher peaks, but, more predominantly, a higher average concentration. This is most likely due to the better availability of nutrients in the area around LM06 from South Run. Figure 45 is a comparison of chlorophyll a at LM06 and LM07. This figure shows that LM06 is a more productive region for chlorophyll a than is LM07. This may not be expected because LM07 is a shallow area, and the better light penetration should help produce more littoral communities at LM07. However, the better availability of nutrients at LM06 has a stronger affect on the net productivity.

Figures 46, 47, and 48 are plots of the ammonia and oxidized nitrogen in the bottom waters of LM01, LM06 and LM07. The pattern of the data is quite evident. The oxidized nitrogen follows a cyclical pattern, with the ammonia nitrogen cycle being in an exactly opposite phase pattern. However, there is a distinct difference between the data from LM01, and that from LM06 and LM07. At LM06 and LM07, the oxidized nitrogen peaks are substantially higher than expected for the amount of ammonia present. At LM01, the ammonia peaks correspond with fall turnover, and the oxidized nitrogen level which follows does not correspond to the peak value expected. The major difference between LM01 and the other stations is depth. Note that when corrected for scale differences, the peak values of oxidized nitrogen at all three stations is very similar. Therefore, it appears that either the sediment releases oxidized nitrogen at LM01, or, at the shallow depths of LM06 and LM07, the ammonia adsorption to sediment and the nitrification reaction may be great enough to keep the ammonia concentration very low.

Figure 49 is a top and bottom plot of oxidized nitrogen at station LM01. The plot shows a clear agreement between oxidized nitrogen in the top and bottom waters of LM01. There is a cyclical pattern, with peaks in the spring and early summer, and lows in late summer and fall. There is no apparent difference in magnitude or periodicity between the top and bottom waters.

Figures 50 and 51 are plots of the bottom concentrations of total nitrogen and total phosphorus at stations LM01 and LM06. The plots show periodicity agreement between the nitrogen and phosphorus in the bottom waters at these locations. The relative magnitudes are different, which is as expected because the two parameters are not related.

Figures 52 and 53 are plots of the various phosphorus parameters in the bottom waters of LM01 and LM06. The plots show that the total phosphorus is about twice the value of the total soluble phosphorus.

Figure 54 is a plot of the total phosphorus in the surface waters of LM01, LM03, and LM06. This graph shows no apparent difference between the peak concentrations at LM01, LM03, and LM06. However, the average concentration at LM06 does appear to be higher than the other two locations. This corresponds with the chlorophyll a data of Figures 43 and 44. Also, there appears to be a trend in the data towards a lower average phosphorus concentration at all the sample locations over the monitoring period analyzed. This trend follows Figure 55 which shows a decreasing rainfall rate over the same monitoring period analyzed.

Inspection of Figure 55 clearly shows that as yearly rainfall increases, the amount of runoff increases. This observation makes sense because consistently wet conditions indicate the soil will be saturated more often, encouraging runoff. Figures 54, 55 and 56 indicate a strong connection between the rainfall rate and the amount of phosphorus present in the lake. This confirms the connection between the lake and its watershed: it is unlikely that there are other substantial sources of nutrients into the lake.

Figure 56 shows that as rainfall rate increases, so does the amount of runoff. As stated previously, this observation is also fundamental. The predicted values for percent runoff agree well with the long term runoff rate of 35%, measured by the U.S. Geological Survey in the region.(30)

Discussion of Monitoring Program Results for the Lake Manassas Watershed

Table 9 summarizes the conventional and nutrient monitoring data for the various surface water drainages into Lake Manassas. The first observation is the adverse impact of the Vint Hill treatment plant discharge on the quality of the water in South Run. South Run at station BR02 contains significant quantities of both phosphorus and oxidized nitrogen. There is not a substantial increase in ammonia nitrogen. Therefore, the Vint Hill treatment plant does appear to have an efficient nitrification system.

Some general conclusions for the lake's drainages can be made:

1. The pH values of the drainages are at or slightly below neutrality. None of the drainages differ significantly in the parameter.

2. The average and median total suspended solids concentration values appear to be low; some high values do appear, but are generally associated with storm events. Typical average values between 8 and 20 mg/L and typical median values of 7 mg/L. Maximum values ranged from 80 mg/L to 383 mg/L.

3. The dissolved oxygen content of all the streams is near saturation, with typical median and average values above 87% saturation. Station BR03 had the highest maximum at 177% saturation. This data indicates that (a) the biological oxygen demand in the streams is not large enough to produce an oxygen deficit, and (b) photosynthesis is occurring in the streams.

4. The conventional nutrient concentrations in all the streams are similar, except in South Run. Average and median total phosphorus concentrations correspond closely between the streams with values from 0.05 to .10 mg/L. In contrast BR02, the Vint Hill discharge, has an average and median value between 0.10 and 0.20 mg/L. The maximum observed total phosphorus

at BR02 was 0.82 mg/L, over twice the maximum observed in any other stream. However, oxidized nitrogen at the BR02 station is the most significant nutrient. Oxidized nitrogen at BR02 has an average of 1.93 mg/L and median value of 0.58 mg/L. These values are between a factor of 5 and 10 times higher than the other stations. Ammonia nitrogen is not significantly higher in BR02 than other stations with an average and median value of 0.17 and 0.02 mg/L respectfully.

Table 10 summarizes the metal pollutant monitoring data for the various surface water drainages into Lake Manassas. In general, inspection of the data shows no significant metal pollution in any of the drainages into Lake Manassas. Only iron, copper, manganese, and zinc appear consistently at concentrations well above detection limits, however, these metals are found commonly in soil (15). The high levels of these metals correspond with periods of high total suspended solids, indicating the connection between the metal content and the sediment entrained in the stream flow. Most of the other metals were not detected above their respective detectable limits. One exception is lead, which was detected in about half of the samples for which it was analyzed, with an average value of

20 ug/L. Most of the detectable lead concentations occurred in the early dates of the sample period. The lack of lead being detectable in the later samples may be an indication of the effectiveness of unleaded gasolines.

Figures 57 through 63 represent the cumulative loadings curves for the conventional nutrients from Broad Run (ST70). The curves show some cyclic behavior, related to the rainfall patterns. However, in general the plots show that the loading curves follow a straight line quite closely. This indicates that the magnitude of the nutrient input from the Broad Run watershed did not change over the monitoring period.

Discussion of the Modeling Results Predicting the Eutrophic Status of Lake Manassas

Application of the Vollenweider model to Lake Manassas shows that the lake is eutrophic, with the yearly phosphorus loading rate well above the "dangerous" curve as defined by Vollenweider. The computer model developed for Lake Manassas predicts a small effect on the overall quality of the water in the lake if the runoff from the Northern Arms area of the lake changes substantially. The predicted changes in the lake's eutrophic status would probably not be detectable in the lake, but monitoring the runoff into the lake should detect any adverse effects. There could be a localized increase in the algae growth of the Northern Arm, similar to the behavior of LM06 versus the rest of the lake. Elimination of the major point source to the lake, the Vint Hill sewage treatment plant, would have a more pronounced effect, but it would not lower the predicted phosphorus loading rate below the "dangerous" curve.

Application of the other eutrophic index models shows the lake to be either very high in the mesotrophic range or well into the eutrophic range, depending on which parameter is used for indexing. Most of the parameters indicate that the lake is eutrophic. In particular, the Carlson TSI method shows the lake does tend toward the eutrophic region, based on the historical data.

Chapter VI

CONCLUSIONS

1. Lake Manassas is a eutrophic lake. Some established eutrophic prediction models show the lake to be "seriously" eutrophic, others show it higher than average, tending toward being eutrophic. The Vollenweider model shows the lake is well above the "dangerous" loading curve. Monitoring results show that the watershed nutrient properties have been relatively constant over approximately the last ten years. Therefore, the eutrophic condition of the lake is not rapidly degrading.

2. Current eutrophic conditions in the lake indicate that there is no "quick fix" alternative. Morphological characteristics such as shoreline ratio and flushing time are such that substantial improvements (approximately an order of magnitude) in watershed water quality would be required to improve the overall eutrophic status.

3. The development of the Northern Arms watershed, and the associated potential for an increased nutrient loading (i.e. phosphorus) to the lake, should not result in a significant change in the eutrophic status of the lake. However, any additional nutrient loading to the lake would be an undesirable situation.

4. The addition of copper sulfate to the lake may help minimize the peak values of spring and fall algae blooms. However, this chemical addition does not have a substantial affect on the overall net biomass production.

5. The current monitoring program established for Lake Manassas and its watershed is sufficient for tracking the lake's status. The monitoring program adequately monitors both the significant point and non-point sources to the lake.

Chapter VII

RECOMMENDATIONS

1. The computer model developed for predicting the eutrophic status of Lake Manassas could be improved by incorporating the effects of the withdrawal-refill cycle normally associated with reservoirs. The existing environmental monitoring database contains a field for pool elevation in the lake. Recording the value of this parameter during environmental sampling would enable this improvement to the computer model to be made.

2. In order to better understand the absolute affects of the copper sulfate addition, it may be desirable to devise an experiment where one of the smaller arms of the lake actually not be treated with the other arms of the lake. The chlorophyll a concentration in the untreated arm could then be compared to the treated arms. If this type of experiment is considered to be too risky, perhaps a sliding scale of copper sulfate dose could be developed with commensurate chlorophyll a monitoring. This type of experiment could help to better quantify the benefits of copper sulfate addition.

3. The policies of nutrient control within the Lake Manassas watershed (as part of the greater Occoquan

Watershed) should continue to be observed and enforced. Further degradation of the watershed water quality will only magnify an existing unsatisfactory situation.

4. Further research into sediment-water interactions may help develop a methodology to minimize nutrient release from the sediments in the lake.

Chapter VIII

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