AN EXAMINATION OF WATER QUALITY IMPACTS ON LAKE MANASSAS

by

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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 an average rate of 10.5 million gallons per day to the City of Manassas, Virginia. The lake discharges, via the Broad Run, a tributary of the Occoquan Reservoir. The Occoquan Reservoir supplies potable water to over 750,000 people in the Northern Virginia area.

This thesis presents the results of a limnological analysis of Lake Manassas. The 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.

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CHAPTER 1
INTRODUCTION

Lake Manassas is a man-made reservoir located to the west of Manassas, Virginia, in Prince William County. To provide potable water to the city of Manassas and other areas of Prince William County, a dam was constructed over Broad Run between 1968 and 1971. Consequently, a 706 acre reservoir was created in the upper reaches of the Occoquan Watershed. Lake Manassas discharges into the Occoquan Reservoir, which supplies drinking water to a large portion of the Northern Virginia area, making Lake Manassas the subject of many studies.

The first study characterizing the water quality in Lake Manassas was published in 1991, after which an updated analysis was planned every 5 years. It was presumed that each incremental analysis, when compared to the baseline, would illustrate long term trends in the Lake. Water quality data have been collected in the Lake from October, 1984. Principal tributary stream data extends back to July, 1978, while data collection for lesser tributary streams began in August, 1984. Data compiled through December, 2005, were examined in this baseline report update. Therefore, a minimum of 20 years' worth of data for Lake Manassas are included in this updated analysis.

In addition to supplying drinking water to the City of Manassas and portions of Prince William County, Lake Manassas also has a history of recreational use. However, in September, 2003, the Lake was closed to the public, and fishing restricted to the banks of the reservoir. Lake Manassas is also home to recreational facilities along its shoreline. Located on the north shore of the Lake lie three golf courses: Robert Trent Jones International Golf Club, Stonewall Golf Club, and the Virginia Oaks Golf Club. It is crucial for all three golf courses to employ Best Management Practices (BMP) in order to maintain acceptable aesthetic and water quality parameters in the reservoir. Historically, runoff generated from the Robert Trent Jones Golf Course has not been of great concern. Turf management practices on the golf course have prevented undesirable water quality impacts. Analysis of the water quality adjacent to the golf course has produced no discernable impacts.

In the absence of preventative measures, land development generally results in the degradation of a reservoir or lake. In areas where land development is present, runoff contains excess nutrients that, when deposited, cause an increase in the algae population. Algae are known to cause taste and odor problems in drinking water, and can also cause filters to clog at water treatment facilities. Neglecting the presence of algae can increase the productivity of a lake and ultimately lead to the deterioration of the water quality. That is why BMPs are essential to maintaining a quality drinking water source.

The scope of this analysis is to examine the current conditions of Lake Manassas as represented by the past 5 years and to compare these results to the preceding baselines. Data generated in this test period will determine if the current land management practices of the Lake have been successful, or if changes are necessary. It is advantageous to track water quality data of the reservoir over time so that an accurate baseline is established.

There are four main objectives of this study: (1) analyze the morphology of the Lake including dissolved oxygen, nutrient inputs, thermal effects, and Lake productivity; (2) characterize the streams that flow into the reservoir; (3) characterize the loadings into the Lake; and, (4) determine the trophic status of the Lake using analytical models.

CHAPTER 2
LAKE MANASSAS AND ITS WATERSHED

Lake History

In the mid-1960s, an expanding Prince William County population put tremendous strain on the local groundwater supplies. Increasing water demands thrust the aquifer into an overdraft condition. Realizing that increasing population trends would only worsen the situation, the City of Manassas began a study in search of alternative water supplies. The result was a proposed man-made reservoir, Lake Manassas, which was created by building a dam on Broad Run 10 miles west of Manassas. The capacity of the Lake was designed to impound 5.8 billion gallons of water and occupy a surface area of approximately 706 acres. Construction of the dam began in 1968 and was completed in 1970. In conjunction with the dam, a water treatment plant was also built at the base of the dam to supply treated water to the City of Manassas. The City of Manassas Water Treatment Plant began supplying water in 1971 to the City of Manassas through a seven mile long, 24-inch diameter water main (Laufer, 1986).

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 (Laufer, 1986). Currently, the plant is operating at a nominal capacity approximately equal to 11 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 withdrawl of water from Lake Manassas, a small hydroelectric plant at the base of the spillway was completed in 1987. This hydroelectric plant was designed to supplement local peak electricity demand. The hydroelectric plant is therefore only operated intermittently (Harvey, 1989).

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 concrete spillway elevation of the Lake was 285 feet above mean sea level (MSL) (Harvey, 1989). On March 19, 1999 an inflatable rubber bladder was added to the spillway to increase the dam height to 290 feet MSL. All water is typically drawn from the 5-foot level. However, during summer months water is drawn from the 15-foot level and mixed with shallower water in order to reach an acceptable temperature. Deeper waters have shown higher levels of dissolved iron and manganese, elements that cause processing problems, and are typically not used. The treatment plant receives the Lake water via an underground pipeline. During normal Lake levels there is sufficient head to allow for gravity flow, otherwise there are pumps available to pump water from the Lake when water levels are low.

Upon entering the treatment plant, the raw water flows into 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 (Eggink, 2001). Following the mix chamber, water is sent to one of two processing systems. Following the plant expansion that took place in 1987, an identical processing system was commissioned to work parallel with the existing system. As water enters the processing system it flows through a series of settling basins. Rotating flocculators, located prior to the settling basins, enhance flocculation and settling. After settling, water flows into a dual media filter system which consists of granular activated carbon (GAC) layered on top of sand. GAC is typically used to treat taste and odor problems. On a side note, the City of Manassas Water Treatment Plant was the second facility in Virginia to employ GAC as a countermeasure for taste and odor issues. Finished water is held in one of two 205,000 gallon clearwells, which form the structural foundation of the water treatment plant buildings (Harvey, 1989). Water then leaves the clearwells and is pumped into a 24-inch conduit which carries the water to various water tanks throughout the City of Manassas. As part of the disinfection process, gaseous chlorine is added to the water just before it enters the conduit in order to maintain residual chlorine levels throughout the distribution system.

It is important for treatment plant operators to monitor the level at which they disinfect water with chlorine. A by-product of chlorination is the formation of trihalomethanes (THMs). These chemicals are formed when chlorine reacts with naturally occurring organic and inorganic matter in water. THMs are of considerable interest since they are classified as Group B carcinogens (shown to cause cancer in laboratory animals). The EPA requires that drinking water regulations limit the concentration of THMs to less than 80 parts per billion.

Algae from Lake Manassas have consistently created difficulties for treatment plant operators. Processing problems include filter clogging along with taste and odor issues. A management plan to ameliorate these issues included applying copper sulfate, an algicide, to Lake Manassas. Cooper sulfate was administered in powder form via a moving boat typically four times per year, twice in the spring and twice in the fall. However, in February of 2000 copper sulfate applications were terminated by the new plant manager.

Water from Lake Manassas is soft, with an average total hardness of less than 30 milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$) (Eggink, 2001). Soft water is a relative term, but for a water to be soft it must contain low amounts of dissolved calcium and magnesium, which cause water to be hard. Treatment plant operations do not include hardness reduction.

Watershed Management

As previously stated, Lake Manassas and its watershed are contained in the larger Occoquan River watershed. Since the Occoquan reservoir is part of the supply that provides potable water to 1.3 million people and regional businesses, it is considered to be an extremely important water resource in the Northern Virginia area. In 1971, increasing pollution in the Occoquan Reservoir prompted the Commonwealth of Virginia State Water Control Board to issue a policy statement titled "Waste Treatment and Water Quality Management in the Occoquan Watershed" (OWML, 2006). The new policy statement implemented three 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 Occoquan Watershed Policy also mandates that new treatment plants, and the expansion of existing treatment plants located in the watershed, adopt advanced techniques to enhance plant efficiency (OWML, 2006).

Most of the data analyzed in this report were obtained from the Lake Manassas Watershed Monitoring Program. The City of Manassas independently started the Lake Manassas Monitoring Program in 1984, and contracted the Occoquan Watershed Monitoring Laboratory (OWML) to operate the program.

Golf Course Impacts

While golf courses provide many important benefits such as recreational activities and beautiful landscapes, their presence has the potential to degrade surface water quality. With the constant threat of pest insects, weeds, and diseases, golf course superintendents often treat turfgrass areas of golf courses with various insecticides, herbicides, and fungicides. The growing public concern about the possible effects of golf courses on the environment has prompted many superintendents to adopt the concept of Integrated Pest Management (IPM). The philosophy of IPM places less emphasis on chemical control measures and more emphasis on the use of available control measures (e.g., chemical, cultural, biological) in an integrated fashion for effective management of insect, weed, and disease pests (Racke, 2000). Much of the public concern stems from the possibility of pesticides and nutrients ending up in the drinking water supply. There are several interacting processes that will affect the fate of the pesticides and nutrients. These are volatilization, water solubility, sorption, plant uptake, degradation, runoff, and leaching (Beard, 2000). The process with the greatest threat is typically runoff. Nitrogen and phosphorus added to turfgrasses if lost in runoff and subsurface flow can eventually find their way to potable water supplies. Added nutrients, especially phosphorus, can cause eutrophication of surface water, leading to problems with its use for fisheries, recreation, industry, or drinking water due to increases in the growth of undesirable algae and aquatic weeds (Shuman et al. 2000). Research on potential surface runoff of pesticides has resulted in the general finding that limited transport occurs from treated turfgrass areas under most conditions (Racke, 2000). However, high rainfall occurring shortly after application to steep slopes can result in greater quantities of less highly sorbed pesticides being transported. The magnitude of pesticide transport observed in turfgrass environments is much lower as compared with transport observed from bare soil or row crop situations under similar treatment for several reasons. These include the lack of significant sediment erosion that might carry sorbed particles from turfgrass areas, increased sorption by the thatch as compared with soil, and increased infiltration of water and decreased runoff water volumes in turfgrass (Racke, 2000).

In November, 1985, a development company filed a rezoning request with the Prince William County Planning Commission for the purpose of building a golf resort and residential planned unit development on the northern shores of Lake Manassas. The resort was to consist of 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. The preliminary design contemplated the location of the golf courses on the lands directly adjacent to the Lake (Jones-Saunders Associates, 1986). Three golf courses were eventually built: Robert Trent Jones International, Stonewall Golf Club, and Virginia Oaks. The golf course locations are shown in Figure 2-1.

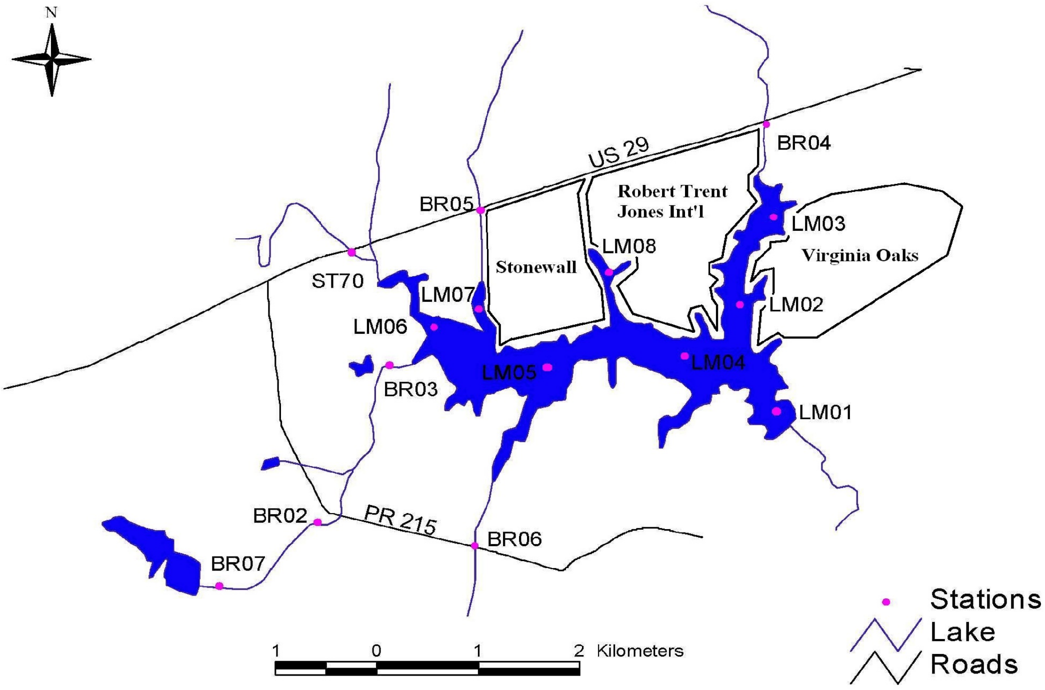


Figure 2-1: Lake Manassas Golf Courses

Water Supply Protection

In an era when technology is improving exponentially, more stringent standards will be applied to drinking water. The use of best available technologies to meet these standards increases the costs involved to create potable water. However, it is important to remain focused on the ultimate goal: protecting a natural resource that is constantly threatened by both natural and man-made processes. One process in particular, land development, plays a crucial role in determining a reservoir's future as a drinking water source. Land development also has the greatest flexibility if properly managed. Lake Manassas lies in a county that is rapidly developing. A proper management program is ultimately the only viable option to maintain balance. The Lake Manassas Watershed Monitoring Program is one component in protecting this valuable resource and preventing potential problems.

CHAPTER 3
LITERATURE REVIEW

Lake Morphology

Lakes and reservoirs, in general, are constantly degrading due to erosion and sedimentation. The study of an impoundment's physical features can lend insight on the eutrophication potential and life expectancy of a lake or reservoir. The majority of our limnological understanding of reservoirs originates from natural lake ecosystems (Wetzel, 2001). In some ways, lakes and reservoirs are assumed to have functional equivalence and will be considered as such in this report for simplification. It is, however, important to note the differences between the two in order to effectively manage and utilize reservoirs (Table 3-1).

Table 3-1: Characteristics of Lakes and Reservoirs (Wetzel, 2001)

Characteristic	Reservoir	Natural Lake
Shape	Narrow or Elongated	Circular or Oval
Sediment Loading	High	Low
Turbidity	High	Low
Water Level Fluctuations	Large, Irregular	Small, Stable
Residence Time	Short	Long
Mean Depth	Shallow to Deep	Moderate to Deep
Outflow	Highly Irregular	Relatively Stable

A reservoir can be segmented into three zones along the longitudinal gradient, each possessing unique characteristics (Wetzel, 2001). They are named in order from the river to the dam: riverine, transitional, and lacustrine zones. The riverine zone is a narrow channelized basin with relatively high flow. This zone exhibits more eutrophic conditions given the high nutrient loads, high suspended solids, and limited light (Ryding and Rast, 1989). The transitional zone is a broader and deeper area with reduced flow. This zone has fewer nutrients, more light penetration, and fewer suspended solids (Cooke et al. 1993). The lacustrine zone is the deeper part of the reservoir that experiences lower velocities. This zone tends to be more oligotrophic and is considered to reflect similar characteristics with lakes due to thermal stratification and morphological interactions (Wetzel, 2001). Lake Manassas is comprised of all three zones riverine, transitional, and lacustrine.

Thermal Stratification

One of the greatest sources of heat to a lake is solar radiation. Much of the heat is directly absorbed by the water with very little being absorbed directly by the sediments (Wetzel, 2001). The geographic location of a lake (latitude and altitude) also determines the amount of solar radiation that reaches the surface waters. Since the majority of the heat is absorbed in the first few meters of water, depth is an important variable when determining the thermal response of a lake (Laufer, 1986). In addition to depth, differences in density directly influence the characteristics of a lake. Water has a maximum density at 4 °C. As the temperature of water increases it becomes less dense with the greater changes in density occurring at higher temperatures. The exception to this rule is that water below 4 °C decreases in density. When water begins to freeze, a hexagonal ice structure begins to form, with voids causing the structure to increase in volume. The void space causes the ice to float on top of the warmer, yet denser, water below.

A stratified lake has three zones of stratification which are shown in Figure 3-1. During the warmer months of summer, the upper portion of a reservoir will be warmer than the bottom. Since the warmer water is less dense then the cooler water beneath it, a natural barrier is formed in the water column causing the top layer to float on top of the bottom layer. The warmer water at the surface is called the epilimnion and the cooler water at the bottom is called the hypolimnion. In between each layer is a region called the metalimnion where the rate of temperature change is the greatest.

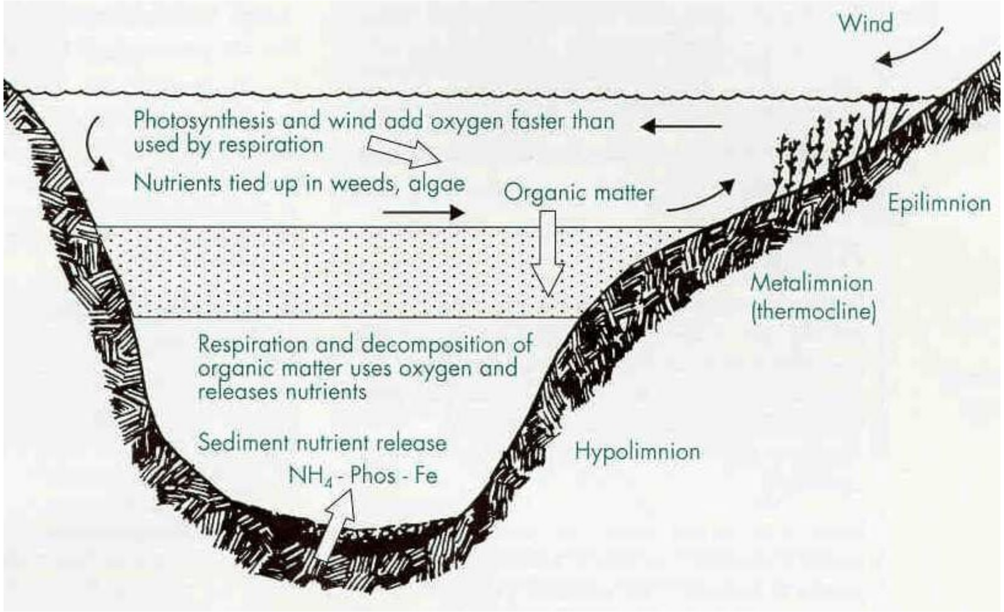


Figure 3-1: Lake Layers Created by Temperature Gradients

As summer turns to fall, solar radiation decreases and the surface waters begin to cool causing the thermal stratification to weaken. The temperature in the water column becomes more uniform and the water layers mix vertically. This process is called the fall turnover. During the spring, increasing solar radiation heats the surface waters and creates a temperature gradient. The increasing temperature in the epilimnion initiates the thermal stratification thereby segregating the hypolimnion from the water column. The duration of the fall turnover is dominated by many factors. In particular, wind energy directed at the surface generates currents which circulate the entire water column (Wetzel, 2001). In late summer, the wind serves as a catalyst for the fall turnover. Once the epilimnion has cooled and the thermal stratification has weakened, only a small amount of wind energy is required to start the fall turnover (Wetzel, 2001).

As stated earlier, geographic location determines the conditions a reservoir will experience. The thermal effects detailed above occur in lakes and reservoirs located in temperate zones. Lake Manassas experiences a single period of mixing termed the fall circulation. This pattern is referred to as monomictic.

Eutrophication

It is important to understand the processes that cause undesirable water quality characteristics in order to properly manage a reservoir. All lakes and reservoirs have a finite life span. This life span may vary from a few years, for shallower lakes, to millions of years, for deeper lakes. Sediment will eventually accumulate causing the lake to fill and slowly become a marsh and ultimately a terrestrial system (Ryding and Rast,1989). This natural aging process is called eutrophication. By definition, eutrophication is the enrichment of lakes and reservoirs with nutrients such as nitrogen and phosphorus. The increased nutrient loads produce large biological populations and can result in detrimental changes in water quality (Ryding and Rast, 1989). The presence of mankind has the potential to accelerate the natural aging of a water body. Cultural eutrophication refers to the increased nutrient loads associated with land development, pollution from sewers, and other human activities.

Nutrient concentrations are one of the many characteristics used to classify a water body. A lake that has low nutrient levels and low plant productivity is termed oligotrophic. Conversely, a lake that exhibits high nutrient levels and large algal populations is termed eutrophic. Lake Manassas has historically been classified as eutrophic. The term mesotrophic refers to the transitional state between eutrophic and oligotrophic conditions.

The supply of nutrients is considered to be one of the most important factors when determining the quantity of plant material in lakes (Harper, 1992). Due to the availability of nutrients in eutrophic lakes, large populations of algae, particularly blue-green algae, can develop quickly. The presence of algae, in turn, controls the amount of oxygen in the water (Harper, 1992). During stratification, the epilimnion encompasses most of the algal populations and the animals which graze on them. Oxygen remains abundant in this layer through biological activities and diffusion from the atmosphere. The hypolimnion experiences decreasing oxygen concentrations during the stratification period. Oxygen is rapidly consumed by bacteria as they decompose organic matter that sinks to the bottom (Ryding and Rast, 1989). Oxygen consumption occurs mostly at the sediment-water interface since the accumulation of organic matter is the greatest

(Wetzel, 2001). Stratification of the water column prevents mixing between the epilimnion and hypolimnion. As a result, the thermocline serves as a barrier preventing oxygen from being replenished in the hypolimnetic waters.

The absence of oxygen in the hypolimnion coincides with a reducing redox potential. The redox potential at the sediment surface determines the release of solutes into the water column (Harper, 1992). Reduced forms of iron, manganese, and sulfides are released from the sediments due to a lack of oxygen (Ryding and Rast, 1989). During the fall turnover, the water column mixes and these solutes are introduced into the epilimnion.

Nutrients

Studies have shown that the most effective measure for the control of eutrophication in lakes and reservoirs is the reduction of external nutrient inputs (Ryding and Rast, 1989). There are many sources that contribute to external nutrient loads within a watershed. These include but are not limited to effluent discharges from sewage treatment plants, land runoff, and deposition from the atmosphere. Internal nutrient loading, such as sediment release and ground water seepage, also exists within a reservoir. It is necessary to identify the most significant nutrient sources as well as understanding their role with respect to the total nutrient input in order to effectively maintain water quality within a lake.

All living organisms require a broad range of elements to sustain life. These elements can be categorized into two groups, macronutrients and micronutrients. The most significant macronutrients include calcium, magnesium, potassium, nitrogen, phosphorus, sulfur, and iron. Elements such as copper, cobalt, molybdenum, manganese, zinc, boron, vanadium, and chlorine are considered to be the most important of the micronutrients.

Algal blooms often cause problems with drinking water quality in lakes and reservoirs. Primary factors for algal growth include light, nutrient supply, and temperature. Increases in biomass can be measured by chlorophyll concentrations or cell volume in algae. The main nutrients that contribute to the growth of algae include nitrogen and phosphorus. Algal growth is said to be nutrient limited if growth is directly dependent upon the supply of a specific nutrient. Many nutrients have the potential to limit algal growth, but nitrogen and phosphorus are the most common limiting nutrients with algal species (Cooke and Carlson, 1989). This concept is shown in Leibig's "Law of the Minimum" (Ryding and Rast, 1989).

In 1840, Justus Leibig discovered that crop growth was limited by whatever essential element was in shortest supply, regardless of whether the total amount required was large or small. Therefore, whichever nutrient is least abundant will control an organism's productivity. Through varies studies, the stoichiometric cellular composition of freshwater algae is given by $C_{68}H_{124}O_{30}N_9P$ (Benefield and Randall, 1985). However, this is only one formula for the cellular composition of freshwater algae. Other studies have produced varying formulas for freshwater algae. Analyzing the molecular formula used by Benefield and Randall, one can deduce that large amounts of carbon, hydrogen, and oxygen are required for the production of cellular biomass. It is also obvious that nutrients such as nitrogen and phosphorus are required to generate biomass. These two nutrients are typically in the shortest supply. By utilizing Leibig's "Law of the Minimum" it is clear that nitrogen and phosphorus have the potential to limit the growth of algae.

Phosphorus is typically the least abundant nutrient and therefore the most limiting species in biological production. Phosphorus exists in both organic and inorganic forms. The most common form being inorganic orthophosphate (PO_4^{3-}), and the only form that can be directly utilized by organisms (Wetzel, 2001). The extremely reactive nature of phosphorus causes it to interact with many cations such as iron and calcium to form insoluble compounds that precipitate. Orthophosphate levels can be limited due to adsorption onto particles. A large portion of phosphorus found in reservoirs is considered to be unusable since it is commonly bound to organic colloids and organisms (Wetzel, 2001). Sedimentation of these particles will subsequently occur and phosphorus will be lost to the sediments. Once deposited, phosphorus will eventually be released back into the water column. Even if only a small amount is released, the impact on the in-lake phosphorus concentration can be significant (Peterson, 1998).

Nitrogen is one of the most abundant macronutrients and is available to freshwater systems in numerous forms. As with phosphorus, nitrogen exists in both organic and inorganic forms. The forms of nitrogen that are available to organisms include dissolved molecular nitrogen (N_2), organic nitrogen, ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-). These forms of nitrogen can enter a lake or reservoir through precipitation, nitrogen fixation both in the water and the sediment, and inputs from surface and groundwater drainage (Wetzel, 2001). Organic nitrogen is typically found in proteins and is continually recycled by plants and animals. These organic forms of nitrogen are converted from nitrogen gas in the atmosphere by microorganisms through a process called nitrogen fixation. Once in the water table, organic nitrogen will be decomposed by heterotrophic bacteria. The end product of this decomposition is ammonia which can be assimilated by plants in shallow waters. Ammonia can also undergo the process of nitrification which occurs naturally in aerobic environments, thus producing nitrite and nitrate. Nitrite is readily oxidized and rarely accumulates (Wetzel, 2001). Nitrate is the common form of inorganic nitrogen usually entering the system through surface waters and precipitation (Wetzel, 2001). The various transformations of nitrogen listed above are part of a biochemical cycle known as the nitrogen cycle.

One method for determining whether phosphorus or nitrogen is the limiting nutrient for plant growth is by using a ratio of total nitrogen to total phosphorus by weight, N:P (Cooke and Carlson, 1989). This concept states that if the N:P ratio is less than 10, nitrogen will be the limiting nutrient, and if the N:P ratio is greater 17, phosphorus will be the limiting nutrient (Cooke and Carlson, 1989). Values that fall between the ratios of 10 and 17 signal an indeterminate zone where it is difficult to tell which nutrient is limiting (Cooke and Carlson, 1989).

Light

As stated earlier, light, in the form of solar radiation, is also necessary for algae to grow. Therefore, light has the potential to be a limiting factor. The primary production of algae using light can be seen in the following equation: $6CO_2 + 6H_2O + \text{light} \rightarrow C_{66}H_{12}O_6 + 6O_2$ (Harper, 1992). Less than half of the solar radiation emitted by the sun reaches the surface of the earth (Wetzel, 2001). Much is lost through scattering, reflection, and absorption by water vapor. Of the percentage of solar radiation that does reach the surface, only light within the visible range (380 to 720 nm) can be used by most algae (Grizzard, 2005). Other factors that contribute to the amount of light readily available to algae are time of day, altitude, and weather (Wetzel, 2001). Light shows a logarithmic reduction along with depth. The optimum position for photosynthesis to take place is 2-3 m below the surface (Harper, 1992). Depths below 2-3 m do not receive enough light and are said to be light limited. Light can also be limited during the winter in northern lakes. Ice and snow covering the water decreases light penetration and severely inhibits algal growth. A buildup of nutrients can subsequently occur as a result of the limited light available. The decreased quantity of light for plant growth is one explanation for better water quality in the winter months (Cooke and Carlson, 1989).

CHAPTER 4
METHODS AND MATERIALS

Sampling Stations

The Occoquan Watershed Monitoring Laboratory (OWML) has been contracted by the City of Manassas to design and administer a monitoring program for Lake Manassas and its tributaries. Sampling of the lake began in October of 1984. Data for some of the tributaries were collected as early as 1975 as part of the greater Occoquan Watershed monitoring program. The OWML's microcomputer database stores all data generated by the monitoring program.

There are eight sampling stations located on Lake Manassas, LM01 to LM08, and eight sampling stations located on the tributaries draining into the lake, BR02 to BR08 and ST70. These stations encompass the Lake Manassas Monitoring Program network and are shown in Figure 4-1. Sample stations with a BR designation are sampled with grab samples, whereas samples from ST70 on Broad Run are both flow weighted composite (storm) and grab samples (baseflow). The sole gaged tributary to the lake is ST70. A gaged monitoring station, ST30, exists five miles downstream from the Lake Manassas dam spillway. Both ST stations are part of the Occoquan Watershed Monitoring Program, and are sampled more intensely.

Field measurements for the LM series sampling stations are obtained at the one-foot, 2.5 foot, and five-foot depths and continue at five-foot increments until the bottom is reached. The sampling frequency is displayed in Table 4-1. Dissolved oxygen, temperature, pH, and

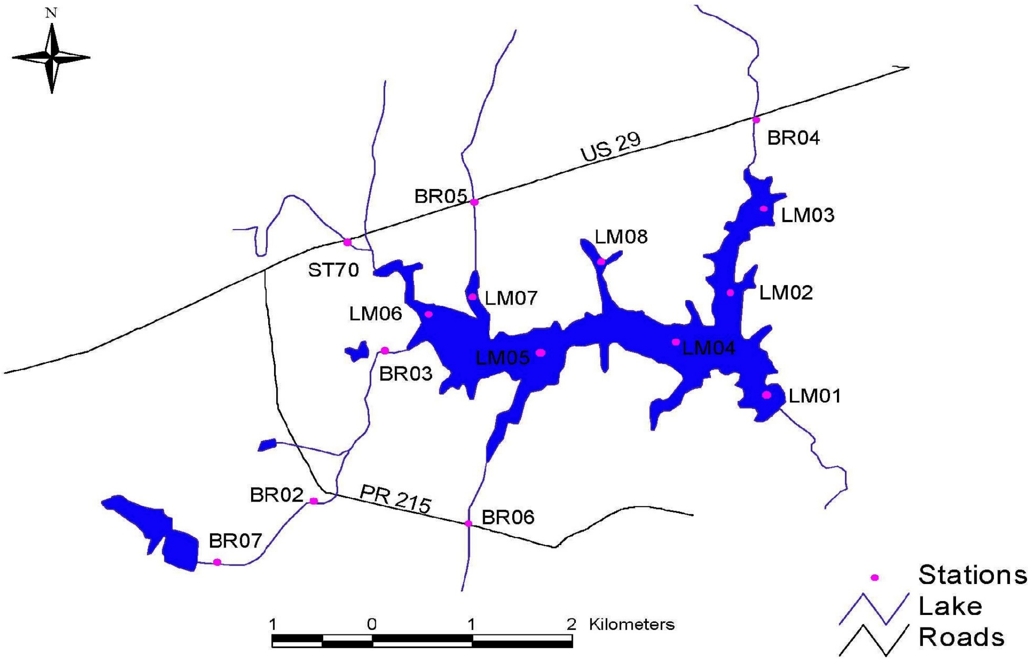


Figure 4-1: Lake Manassas Sampling Stations

Secchi disk readings are among the field measurements obtained from the sampling stations. These analyses include measurements of phosphorus and nitrogen concentrations, solids concentrations, conductivity, chlorophyll *a*, concentrations of select metals, and concentrations of certain synthetic organic compounds (SOCs).

Three monitoring stations are located on the South Run tributary of the Lake. Water from Lake Brittle, a 77 acre impoundment constructed in 1953 as a public fishing lake, is monitored at station BR07. All of the water from Lake Brittle flows through South Run. Station BR03 monitors water flowing in South Run directly before it enters Lake Manassas. Immediately downstream of the Vint Hill Station Wastewater Treatment Plant lies BR02. This station is located to monitor any impacts of discharges from the treatment plant.

Analytical Parameters

The chemical analysis performed on the samples obtained from the Lake Manassas watershed are listed in Table 4-2. The analytical procedure used to analyze this data are subject to the quality assurance/quality control (QA/QC) practices followed at OWML. QA/QC procedures practiced by the OWML include duplicate samples, spiked samples, blanks, and standards in the analysis of samples. Control charts are also used to determine if the analysis falls between the defined boundaries. Additionally, as part of the OWML's commitment to QA/QC practices, routine testing programs administered by the U.S. Geological Survey are conducted on a quarterly basis and submitted to the U.S. Environmental Protection Agency (Daniel, 2006).

Table 4-1: Sampling Frequency (Daniel, 2006)

	Reservoir	Broad Run (ST70)	Tributary
Number of monitoring	8	2	6
Sampling Frequency			
Base Flow - Spring &	Bi-Weekly	Weekly	Bi-Weekly
Base Flow - Fall &	Monthly	Bi-Weekly	Monthly
Runoff	-	All	Seasonal
Routine Analysis			
Dissolved Oxygen	All	Base Flow	All
Temperature	All	Base Flow	All
Conductivity	All	Base Flow	All
Alkalinity	All	Base Flow	All
Ammonium N	All	All	All
Total Kjeldahl N	All	All	All
Oxidized N	All	All	All
Soluble Reactive P	All	All	All
Total P	All	All	All
Total Suspended Solids	All	All	All
Total Dissolved Solids	All	All	All
Phytoplankton	Surface	-	-
Hardness	Quarterly	-	-
Trace Metals	Quarterly	Quarterly	Quarterly
Special Analyses - Water Samples			
Pesticides / Herbicides	4/yr	4/yr	4/yr
Other SOC's	4/yr	4/yr	4/yr
Special Analyses - Lake Sediments			
Pesticides / Herbicides	2/yr	2/yr	2/yr
Nutrients	2/yr	2/yr	2/yr

Table 4-2: Parameters Analyzed in Lake Manassas Watershed Samples (Daniel, 2006)

Abbreviation	Parameter
FLO	Flow
DO	Dissolved Oxygen
TEMP	Temperature
COND	Conductivity
pH	pH
TALK	Alkalinity
PALK	Phenolphthalein Alkalinity
THARD	Total Hardness
SD	Secchi Depth
NH_3-N	Ammonia Nitrogen
TN	Total Nitrogen
OX-N	Oxidized Nitrogen
OP	Orthophosphate Phosphorus
TP	Total Phosphorus
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
CHLA	Chlorophyll *a*
	Selected Trace Metals
SOCs	Selected Synthetic Organic Compounds

Data Reduction Methodology for Stream Stations

Field data collected from Lake Manassas and its tributaries are managed by OWML in an xBase file structure with numerical data stored as characters in order to maintain accuracy and precision information. Prior to analysis, the data stored as characters must be converted to values. The following procedures illustrate the conversions necessary to obtain data in a suitable format for analysis.

1. All field data obtained from sampling stations were extracted from the master database and imported into an Excel spreadsheet.

2. Utilizing macros created at the OWML, all character data representing numeric information were converted to values. Conductivities were corrected for temperature to 25 °C. Negative numbers representing values less than the detection limit were converted to positive numbers at one-half the detection limit. Depths were designated as either top or bottom. Collection dates were correlated to seasons for averaging purposes. Seasons are categorized in the following fashion:

   Winter: December, January, February
   Spring: March, April, May
   Summer: June, July, August
   Fall: September, October, November

3. Included in the master database are both base flow data and storm data. During the analysis of base flow data, all records containing type code “R”, a storm number, or DATE2 - TIME2 values were deleted, leaving only the base flow information.

4. The data were then exported to Microsoft Access where they could be sorted by season and exported to Microsoft Excel for further analysis.

5. Once in Excel, the data were summarized by charts in both tabular and graphical fashions in order to illustrate existing trends.

Similar processes were used for all other types of data, with modifications added where necessary.

Nutrient Loading Rate Calculation Methodologies

The primary source of external loading to Lake Manassas comes from the Broad Run tributary. As a result, the majority of the nutrient loading rate calculations originate from this tributary. Utilizing the Daily Flow-Data Integration (DFDI) Nutrient Load Model created by Johnston, (1999), nutrient loads were calculated for station ST70. Data from this station were extracted between 1984 and 2005. The information stored in the xBase files was converted to a numeric format and sorted by base flow and storm data as previously described. The base flow data were integrated with daily flow values obtained from the stream flow gage at ST30 for the same time period to form a base flow sampling array. Subsequently, chemical concentration values were assigned based on simple linear interpolation. The time period necessary to execute the interpolation of base flow chemistry values considered the time interval both preceding and following the date of a given sample. This procedure provides an estimated chemistry value for each day for the period of record.

Once the daily base flow and estimated chemistry values were established, a sampling array for the storm flow data was generated in the same fashion as the base flow data. Both arrays were combined and inserted at the corresponding date and time and rounded to the nearest minute. Total values for storm flow and chemistry data were used for an entire storm period.

Daily loadings were subsequently calculated by taking the average daily flow rate and multiplying it by the time interval over which it applied. The time interval used was typically 24 hours unless a storm event occurred in which case the time interval was calculated to the nearest minute before and after the storm event. The total nutrient load was determined by summing the daily nutrient loads. The average loading rates were also calculated for the period of concern.

The DFDI Model proved to be a valuable tool for calculating nutrient loads containing both base flow and storm flow data. One aspect of the model that created complications was the requirement for each period of record to contain chemistry and flow data. In certain situations, chemistry or flow data were not available for a particular period of record. This is the result of imperfect data collections due to a variety of field and laboratory factors. Missing data had to be reconstructed in order for the model to operate correctly. Two techniques were used to fill in missing data. Hot-deck infilling replaces missing data by comparing data from a neighboring station. In this case, a linear comparison was made with station ST60, a gauging station in the Occoquan Monitoring Program that has a similar drainage area and is located downstream of the Lake Manassas dam spillway. The other method used to fill in missing data took the arithmetic mean of the data before and after the missing field.

Mann-Kendall Seasonal Analysis

The various sampling stations located on Lake Manassas and its tributaries provide a plethora of chemistry data. It is beneficial to determine if the data provide any statistical trends over time, particularly the rate of change in terms of some central value of the distribution such as mean or median. The Mann-Kendall Seasonal Analysis tests for whether a particular constituent tends to increase or decrease with respect to the different seasons. When the values are compared to a certain level of significance (alpha = 0.05) a trend will be observed no matter how small or large the trend is (Eggink, 2001). The surface and bottom levels of the lake were analyzed with this method, along with the tributaries, over the past twenty years.

CHAPTER 5
STREAM RESULTS

Stream Water Quality

This section presents the results of the analysis performed on the water quality data for the Lake Manassas tributaries. The database contains over 20 years of automated and manual sampling data for the streams flowing into the lake. The period of record analyzed spans from 1984 through 2005.

There are a number of physical and chemical parameters that constitute the database. Thirteen of these parameters are of concern when discussing stream water quality and are listed in Table 5-1. These data offer a comprehensive picture of the stream water quality entering Lake Manassas. Results from the Mann-Kendall analysis for the stream stations are shown in Table 5-2.

Table 5-1: Physical and Chemical Parameters Used in Analysis of Stream Water Quality

Abbreviation	Parameter	Units
DO	Dissolved Oxygen	mg/L
PH	pH	pH units
TEMP	Temperature	°C
COND	Conductivity	µmho/cm (=µS/cm)
TALK	Alkalinity	mg/L as $CaCO_3$
NH_3-N	Ammonia Nitrogen	mg/L as N
TKN	Total Kjeldahl Nitrogen	mg/L as N
OX-N	Oxidized Nitrogen	mg/L as N
OP	Orthophosphate Phosphorus	mg/L as P
TP	Total Phosphorus	mg/L as P
TSS	Total Suspended Solids	mg/L

Table 5-2: Stream Mann-Kendall Analysis

Parameter	BR02	BR03	BR04	BR05	BR06	BR07	ST70
DO	U	–	U	–	–	U	–
PH	–	–	–	–	–	–	–
TEMP	–	U	U	–	–	U	–
COND	L	L	–	–	–	L	U
TALK	L	L	–	–	L	L	L
OP	L	L	L	L	–	–	–
TP	L	L	–	–	U	–	U
NH_3-N	L	–	U	U	U	–	U
TKN	L	–	–		–	L	U
OX-N	L	L	U	–	U	U	–
TSS	L	–	U	U	L	L	U

U = Increasing Trend Present
L = Decreasing Tend Present
– = No Trend Present
Blank = No data in at least the last 5 years

Dissolved Oxygen

Figures 5-1 through 5-7 show the five-year running seasonal averages for DO at the Lake Manassas tributary stations. The DO concentrations for all stations average above 6 mg/L.

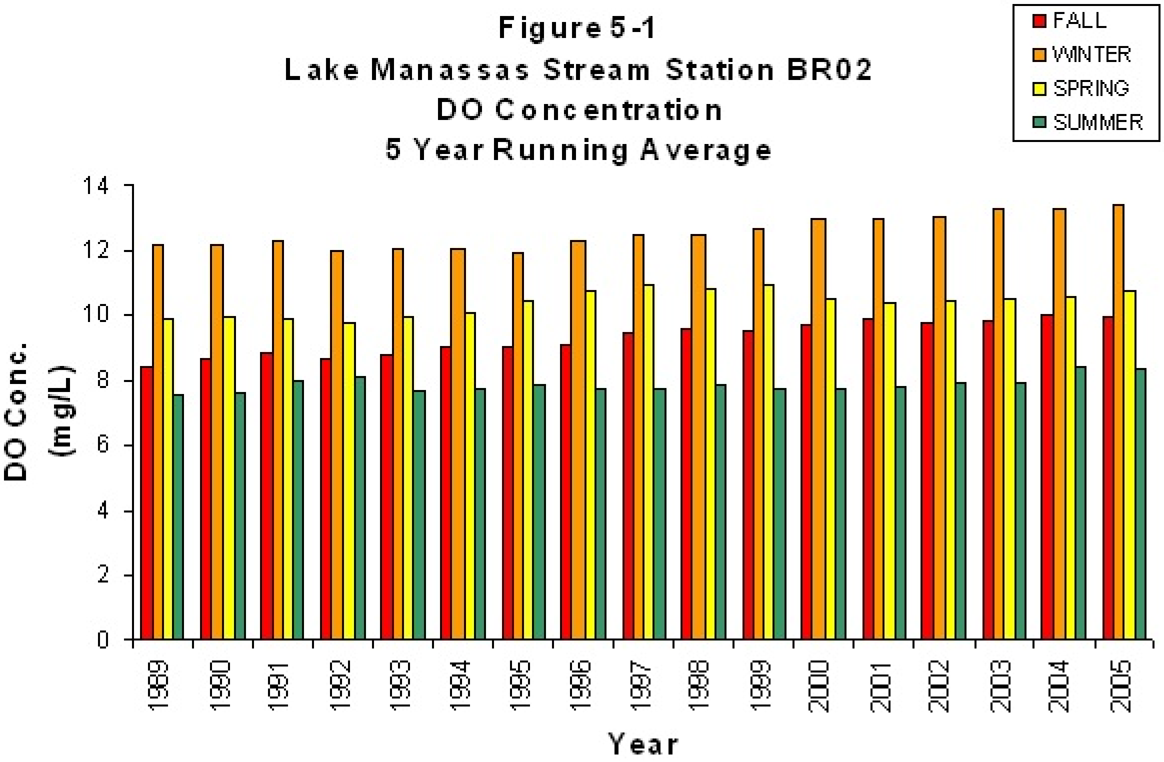


Figure 5-1
Lake Manassas Stream Station BR02
DO Concentration
5 Year Running Average

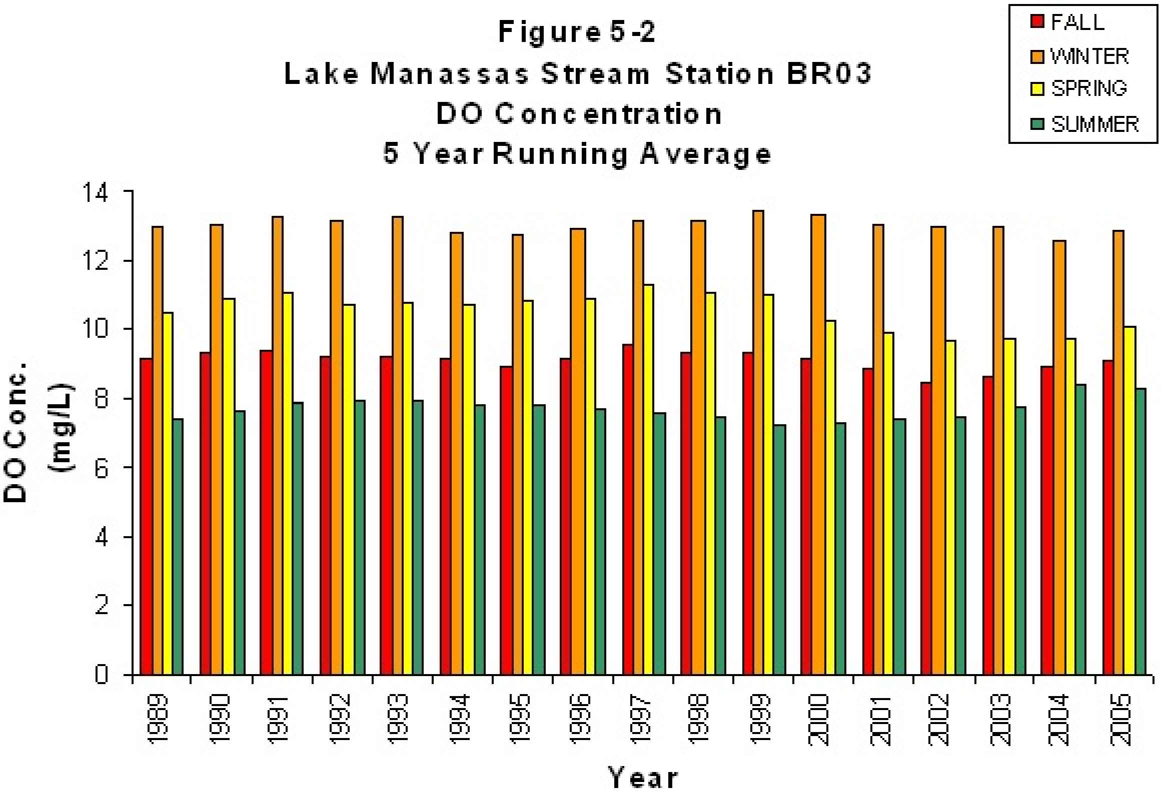


Figure 5-2
Lake Manassas Stream Station BR03
DO Concentration
5 Year Running Average

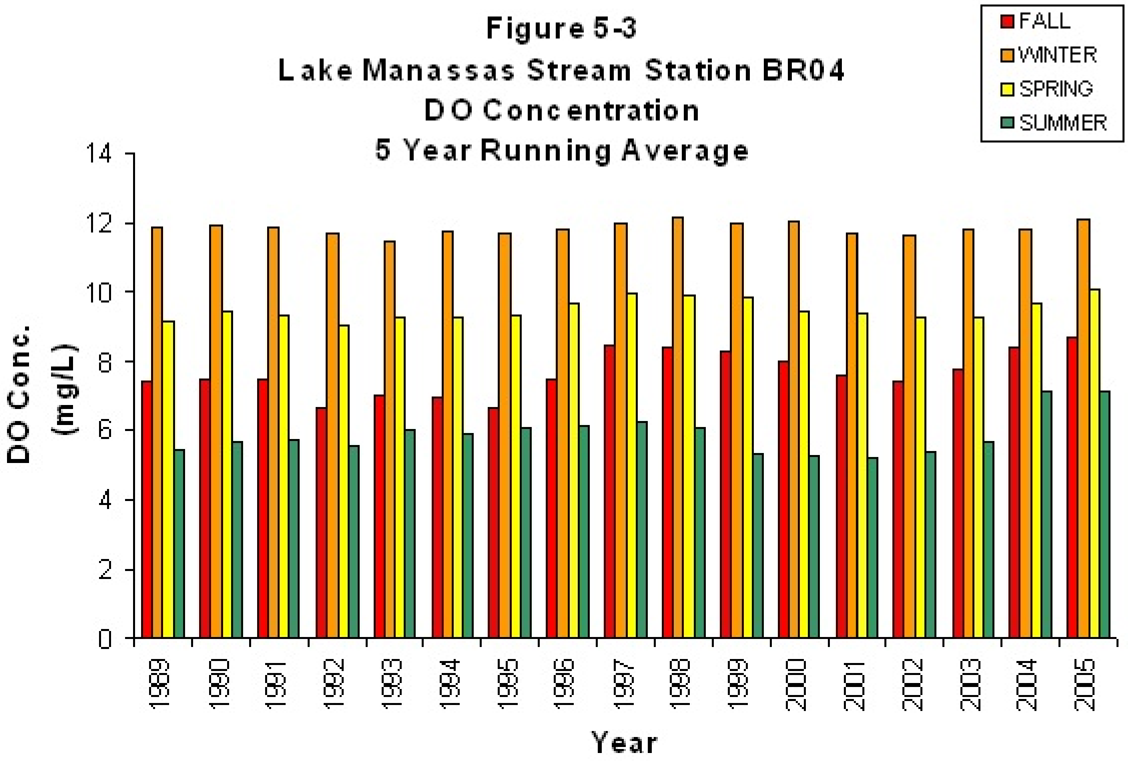


Figure 5-3
Lake Manassas Stream Station BR04
DO Concentration
5 Year Running Average

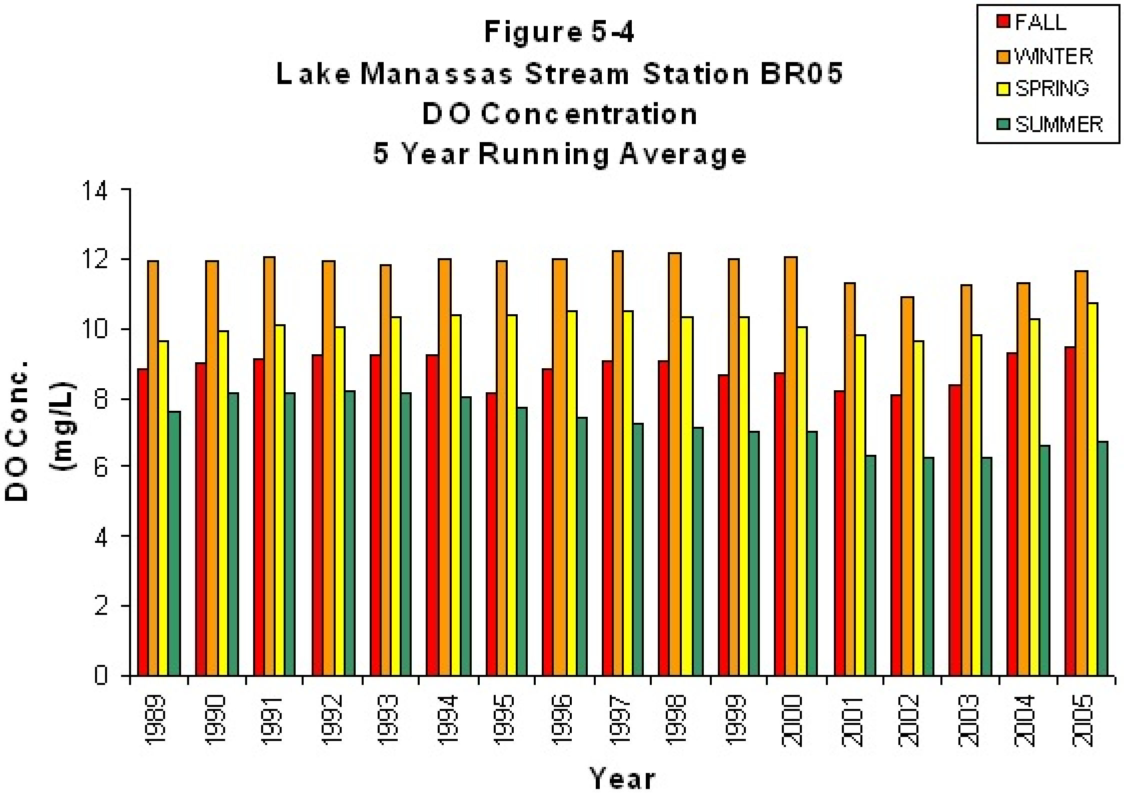


Figure 5-4
Lake Manassas Stream Station BR05
DO Concentration
5 Year Running Average

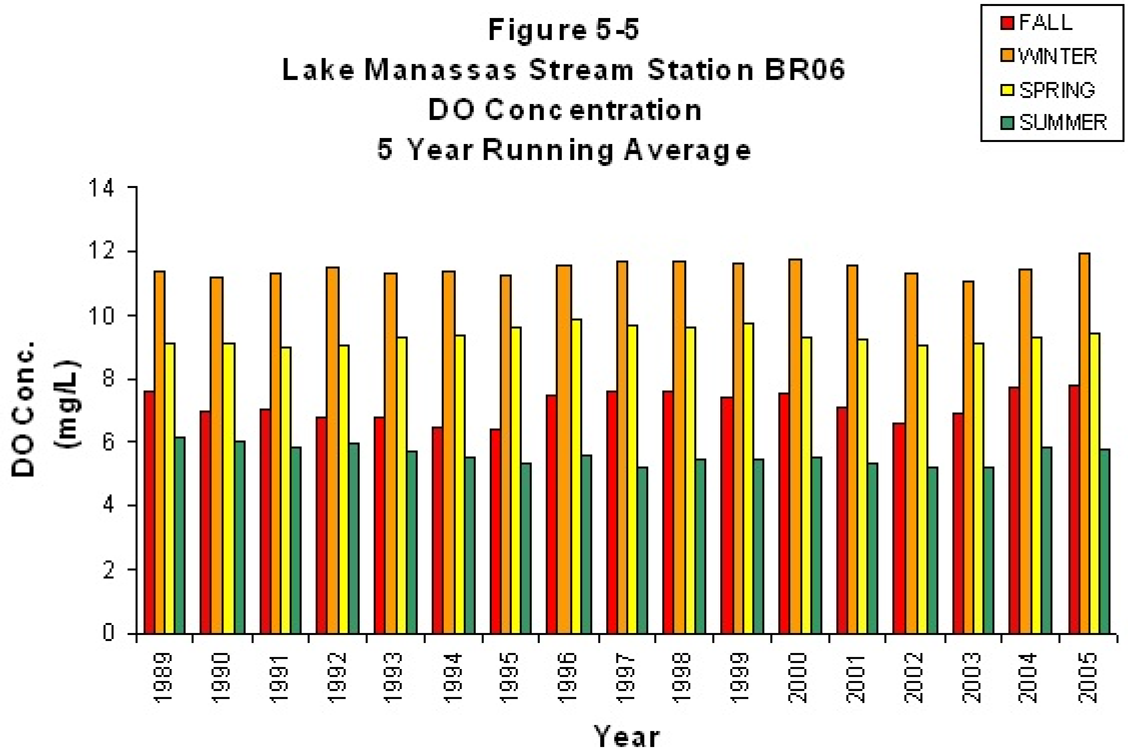


Figure 5-5
Lake Manassas Stream Station BR06
DO Concentration
5 Year Running Average

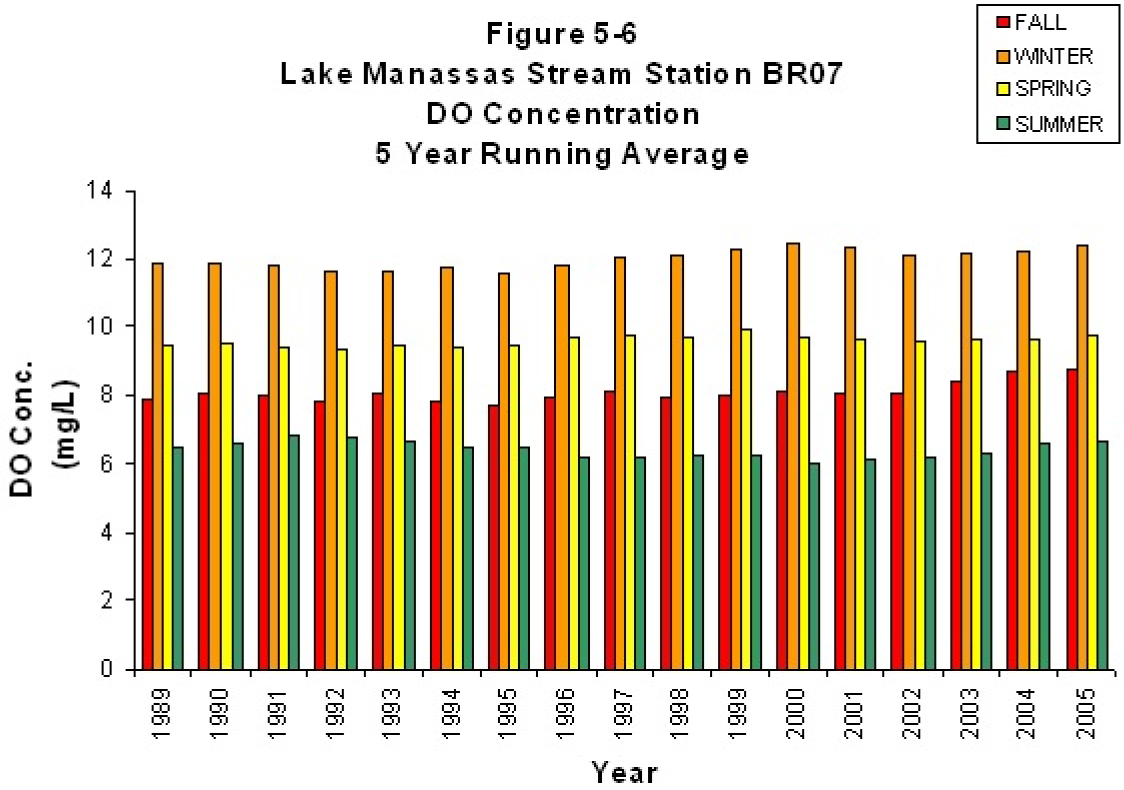


Figure 5-6
Lake Manassas Stream Station BR07
DO Concentration
5 Year Running Average

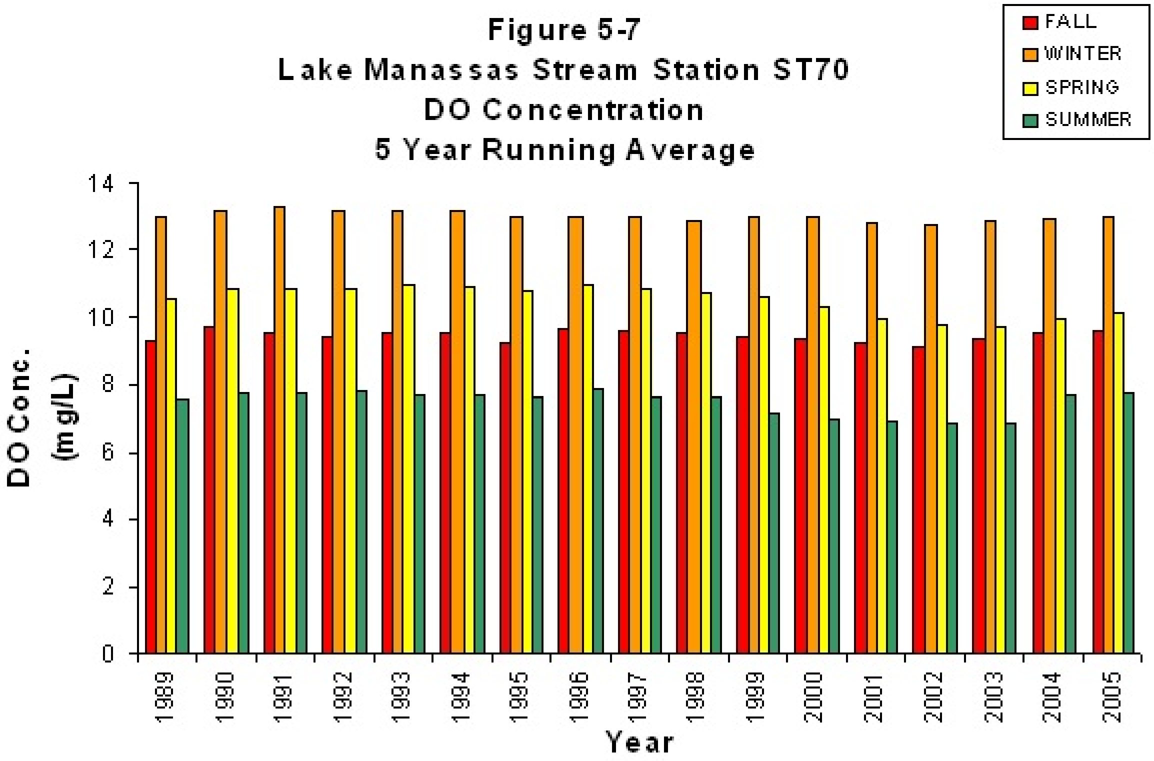


Figure 5-7
Lake Manassas Stream Station ST70
DO Concentration
5 Year Running Average

The maximum DO concentration recorded was 16.86 mg/L. This value occurred in the winter of 2004 at station ST70. There was a violation of the standard, set forth by Virginia's Department of Environmental Quality, at station BR04 in the summer of 1988. The measured DO concentration was 0.8 mg/L, well below the state mandated range (DEQ, 2006). During the winter and spring months all stations exhibited average DO concentrations above 9 mg/L. Most stations during the fall months averaged above 7 mg/L, while stations in the summer months consistently had the lowest values, usually averaging below 7 mg/L. Stations BR04, BR06, and BR07 had the lowest DO concentrations during the summer months. These values should be expected considering that higher temperatures during the summer months bring lower DO concentrations. The summer months also experience low flow conditions in the streams resulting in stagnant conditions that produce low DO concentrations. Furthermore, it should be noted that stations BR04, BR06, and BR07 drain agricultural and pasture lands (Eggink, 2001). Agricultural lands typically have higher BOD runoff rates and consequently produce higher BOD levels in the streams that drain them (Ha and Bae, 2001). Higher BOD levels in turn produce lower DO concentrations due to the BOD utilizing the DO.

Examining the Mann-Kendall Analysis (Table 5-2), increasing trends of DO concentrations are present at stations BR02, BR04, and BR07. Station BR02 is located downstream of the Vint Hill Station Wastewater Treatment Plant. As stated earlier, BR04 and BR07 both drain agricultural lands. The fact that these monitoring stations are witnessing increasing trends of DO is promising since both stations consistently have lower DO concentrations than most other stations.

pH and Alkalinity

The five-year running seasonal averages for pH in the stream samples are shown in figures 5-8 through 5-14. In order to properly calculate these averages, pH values were converted to [H^+], averaged, and converted back to pH. The maximum pH recorded was 9.7 occurring at station BR03 in the spring of 1989. During the winter of 1988 station BR07 experienced the lowest pH of 5.5. The water quality standard range for pH mandated by the state is 6.0 - 8.5. Both the maximum and minimum values fall well outside of this range. However, the yearly averages of pH for all stations fall inside the mandated range. With the exception of one data point, all of the pH values that were outside of the acceptable range occurred in the earlier years, 1985 - 1992. The one exception occurred at station BR06 in the fall of 2002 where the pH was 5.9. This minimum value is only within 0.1 pH unit from the lower acceptable range limit of 6.0. Examining the more recent years, 2000 - 2005, the pH values for all stations look exceptionally well with yearly averages ranging from 6.5, at station BR06, to 7.9 at station BR03.

The results from the Mann-Kendall Analysis show no signs of any trends related to pH in the Lake Manassas tributary stations.

Figure 5-15 shows the seasonal variability of pH at station ST70. With pH values less than 7 the seasonal trend is as follows: $pH_{WINTER} > pH_{SPRING} > pH_{FALL} > pH_{SUMMER}$. The fall and summer pH values are extremely close in this case and sometimes do not follow this trend.

Figure 5-8
Lake Manassas Stream Station BR02
pH
5 Year Running Average

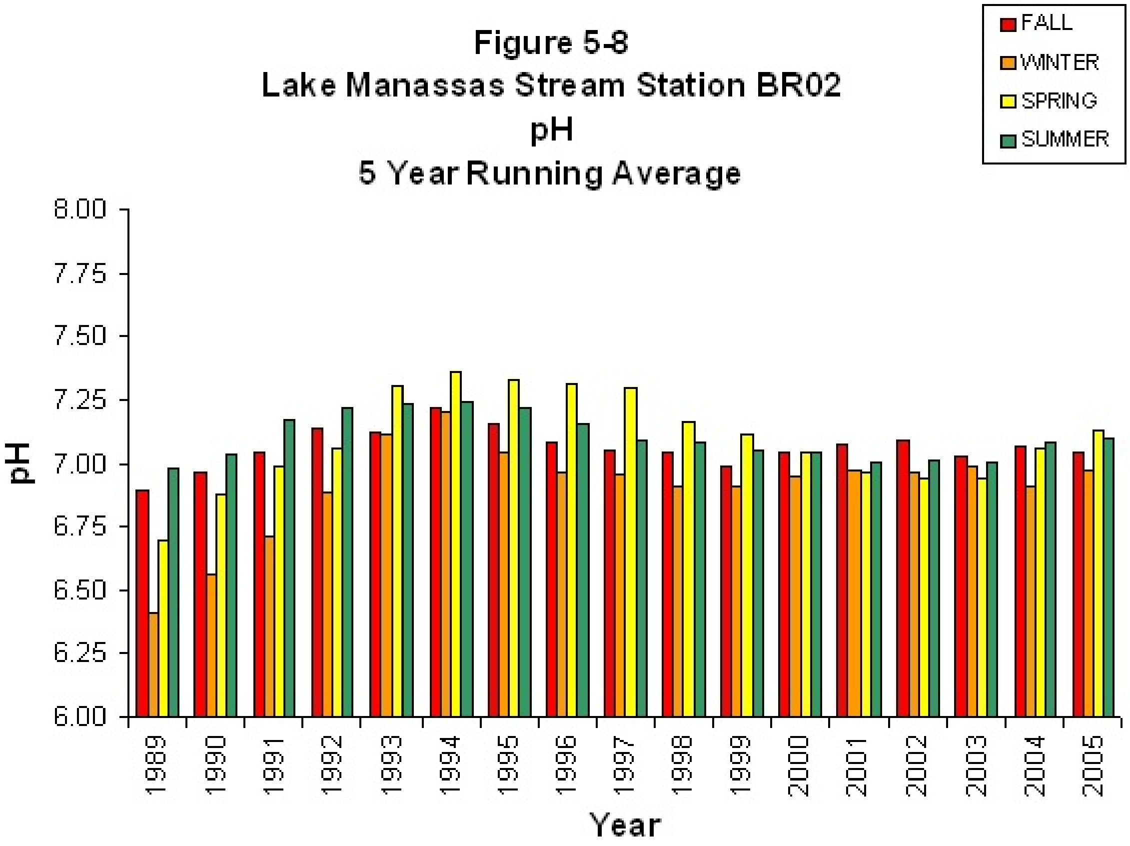
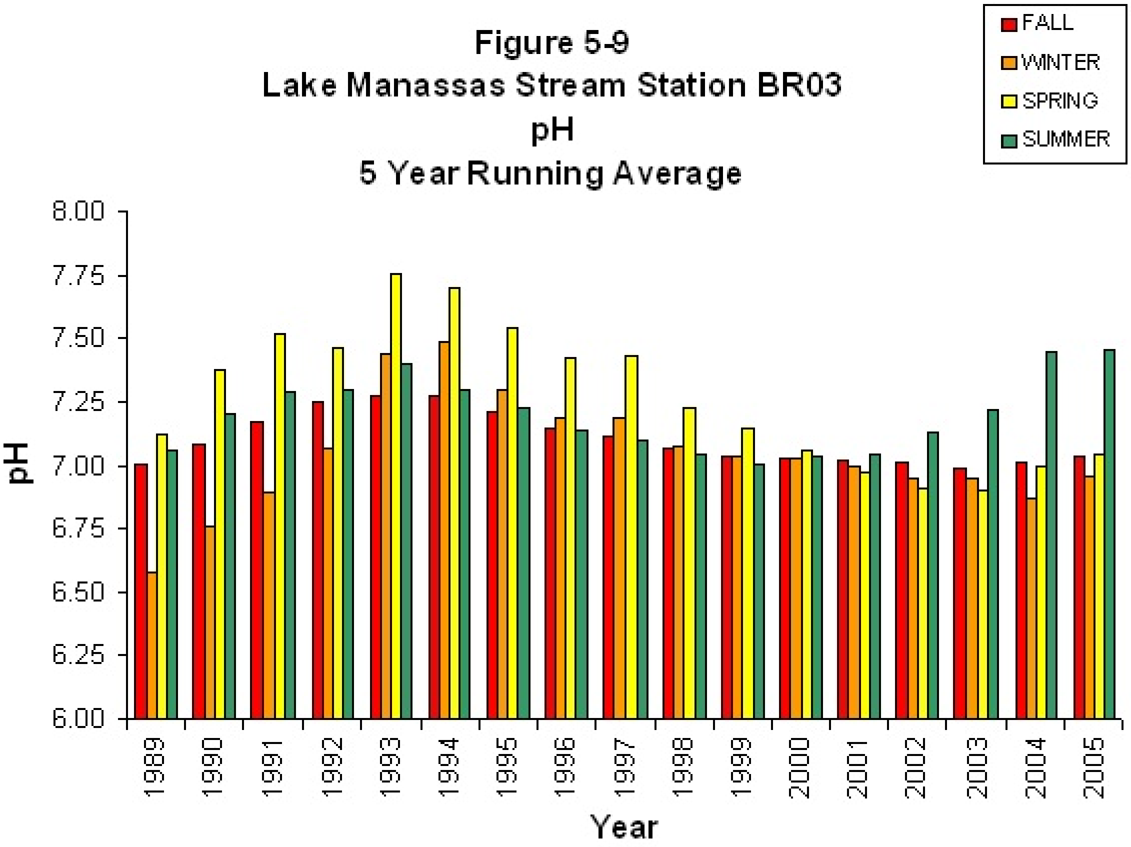


Figure 5-9
Lake Manassas Stream Station BR03
pH
5 Year Running Average



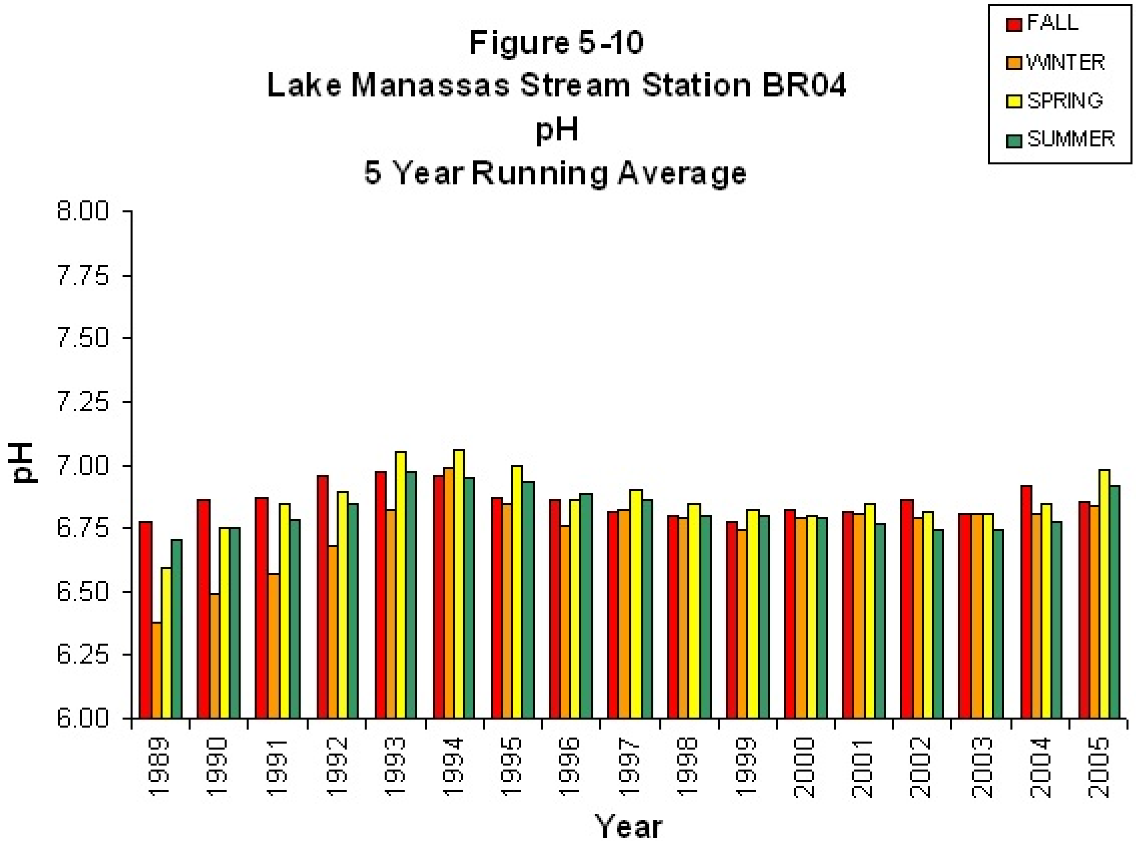


Figure 5-10
Lake Manassas Stream Station BR04
pH
5 Year Running Average

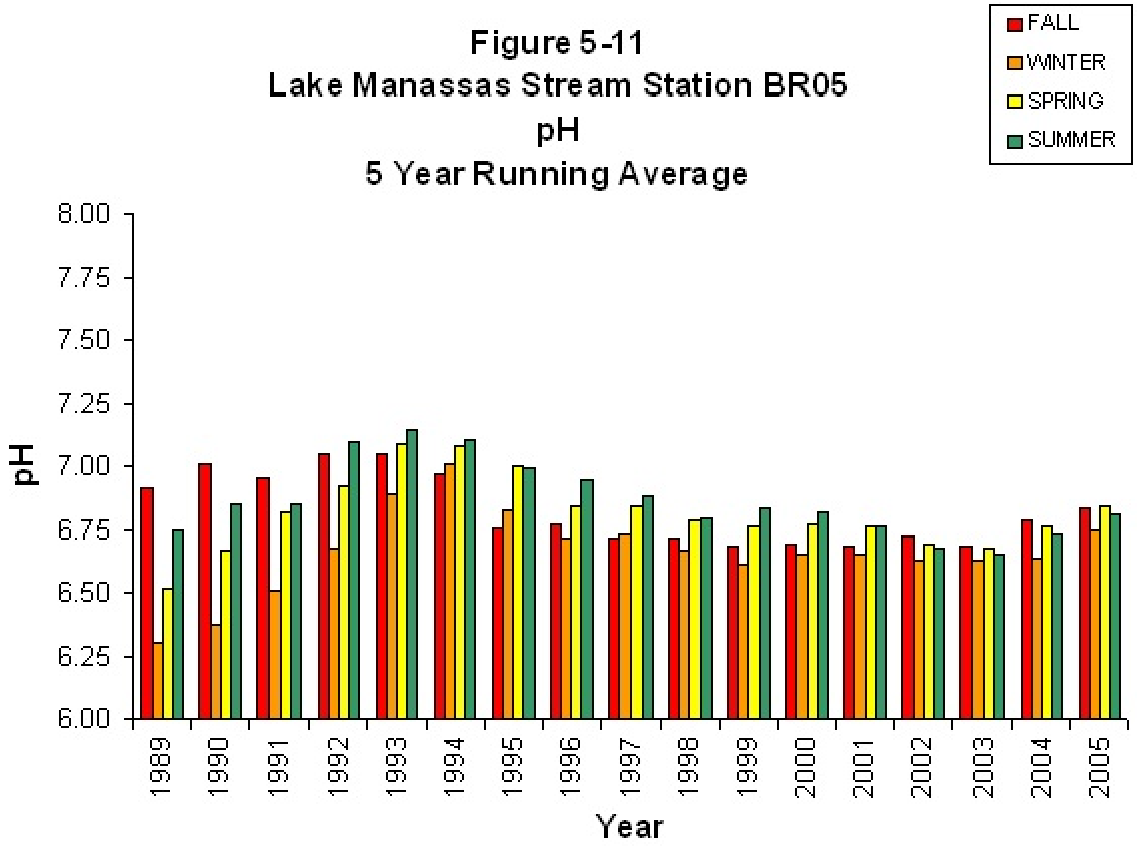


Figure 5-11
Lake Manassas Stream Station BR05
pH
5 Year Running Average

Figure 5-12
Lake Manassas Stream Station BR06
pH
5 Year Running Average

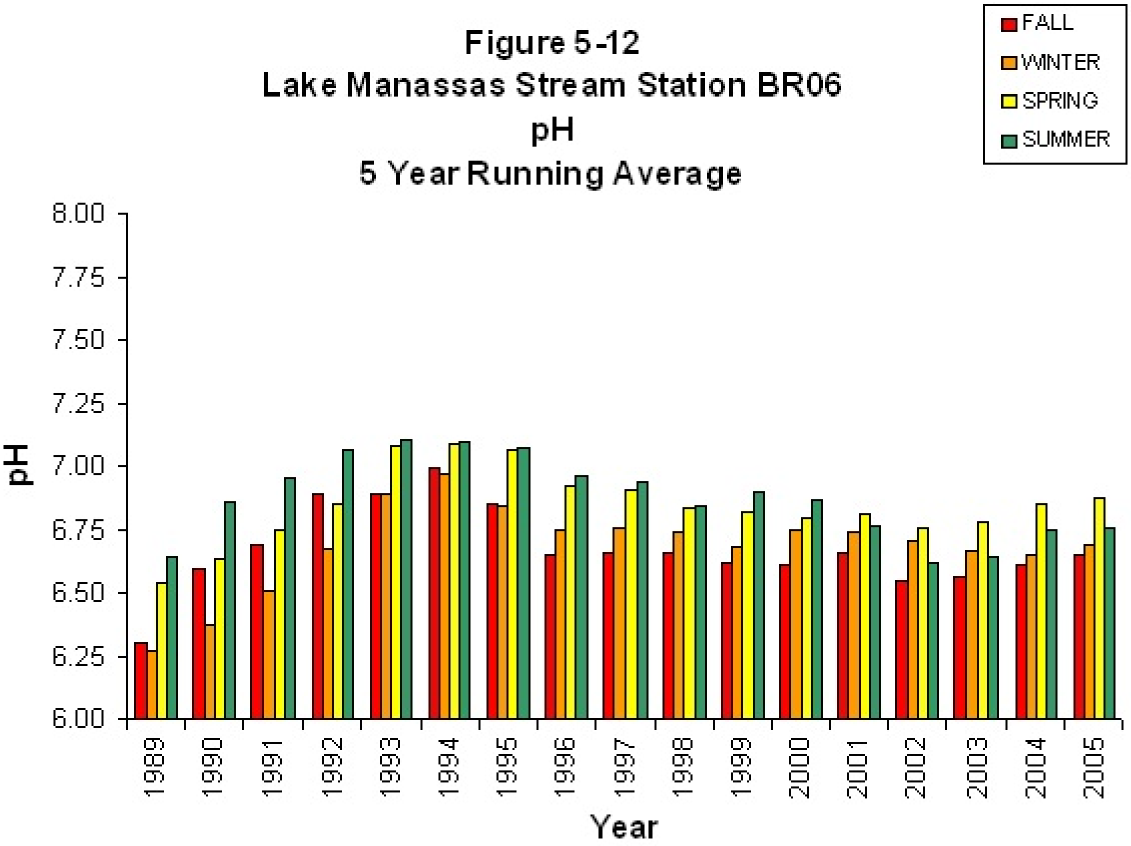
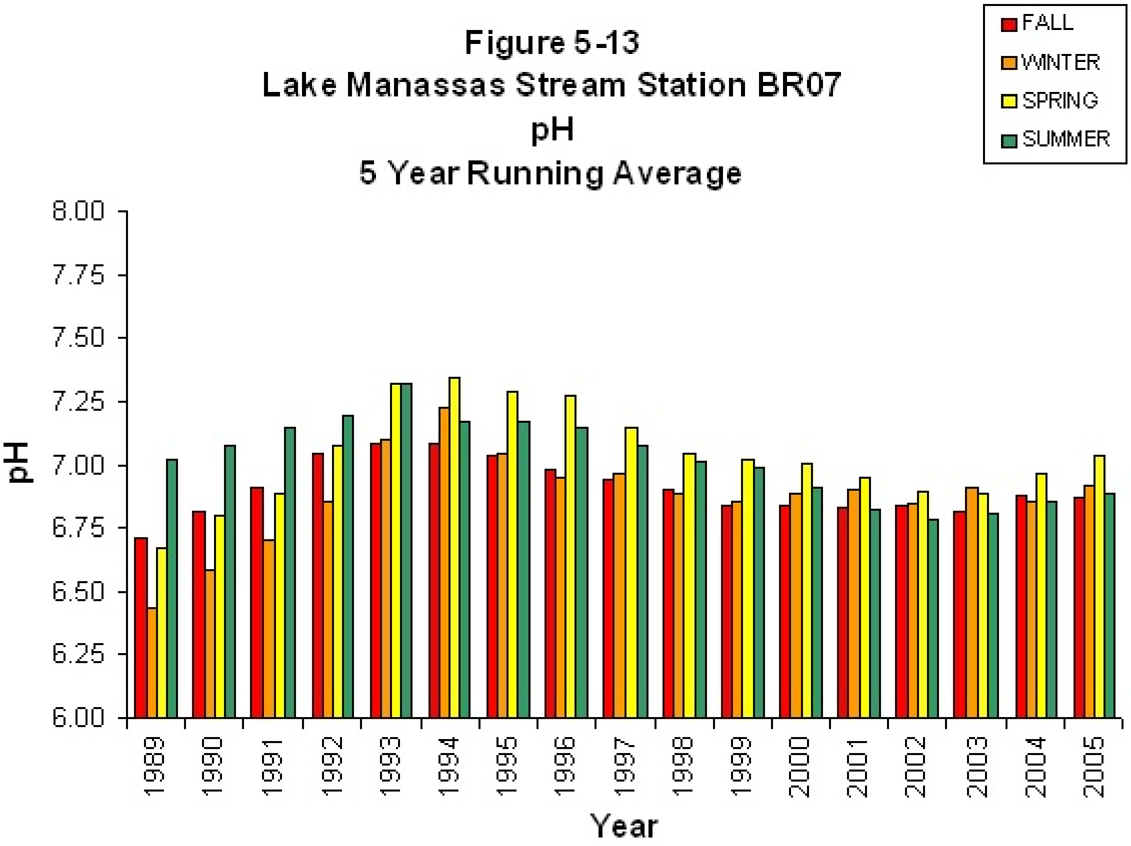


Figure 5-13
Lake Manassas Stream Station BR07
pH
5 Year Running Average



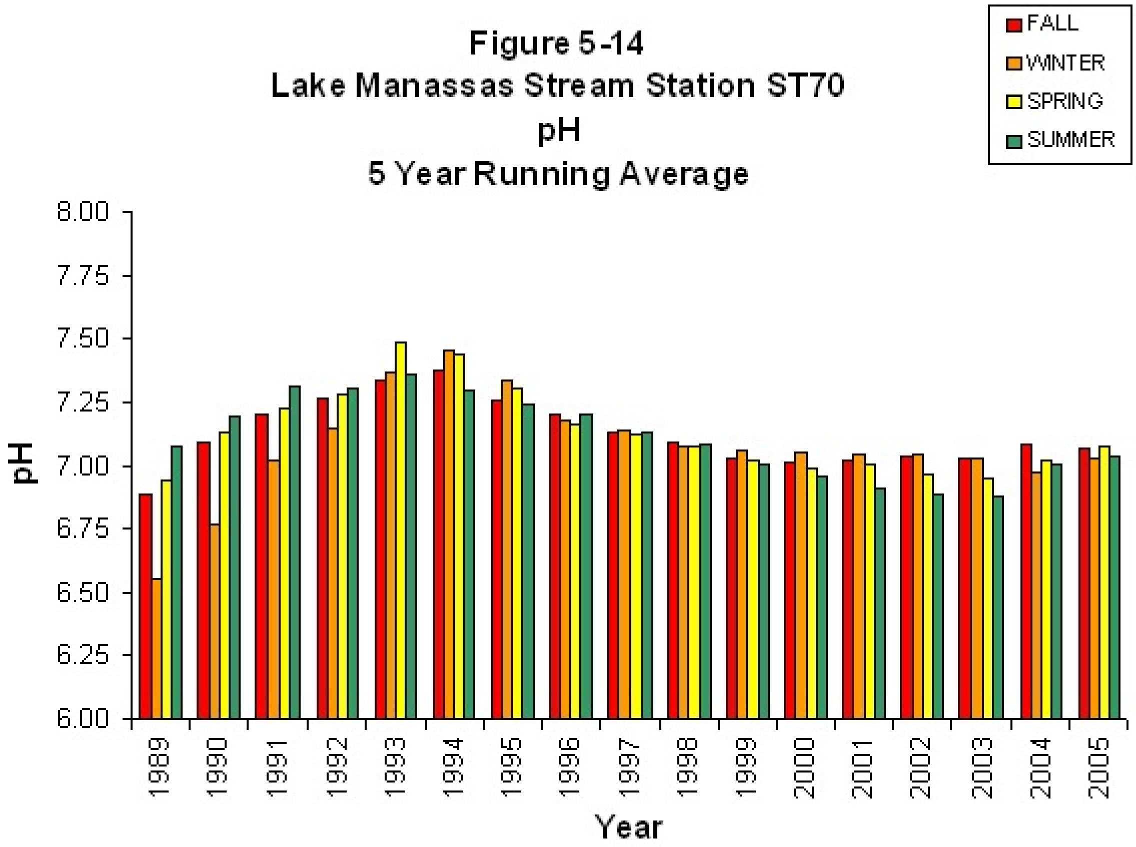


Figure 5-14
Lake Manassas Stream Station ST70
pH
5 Year Running Average

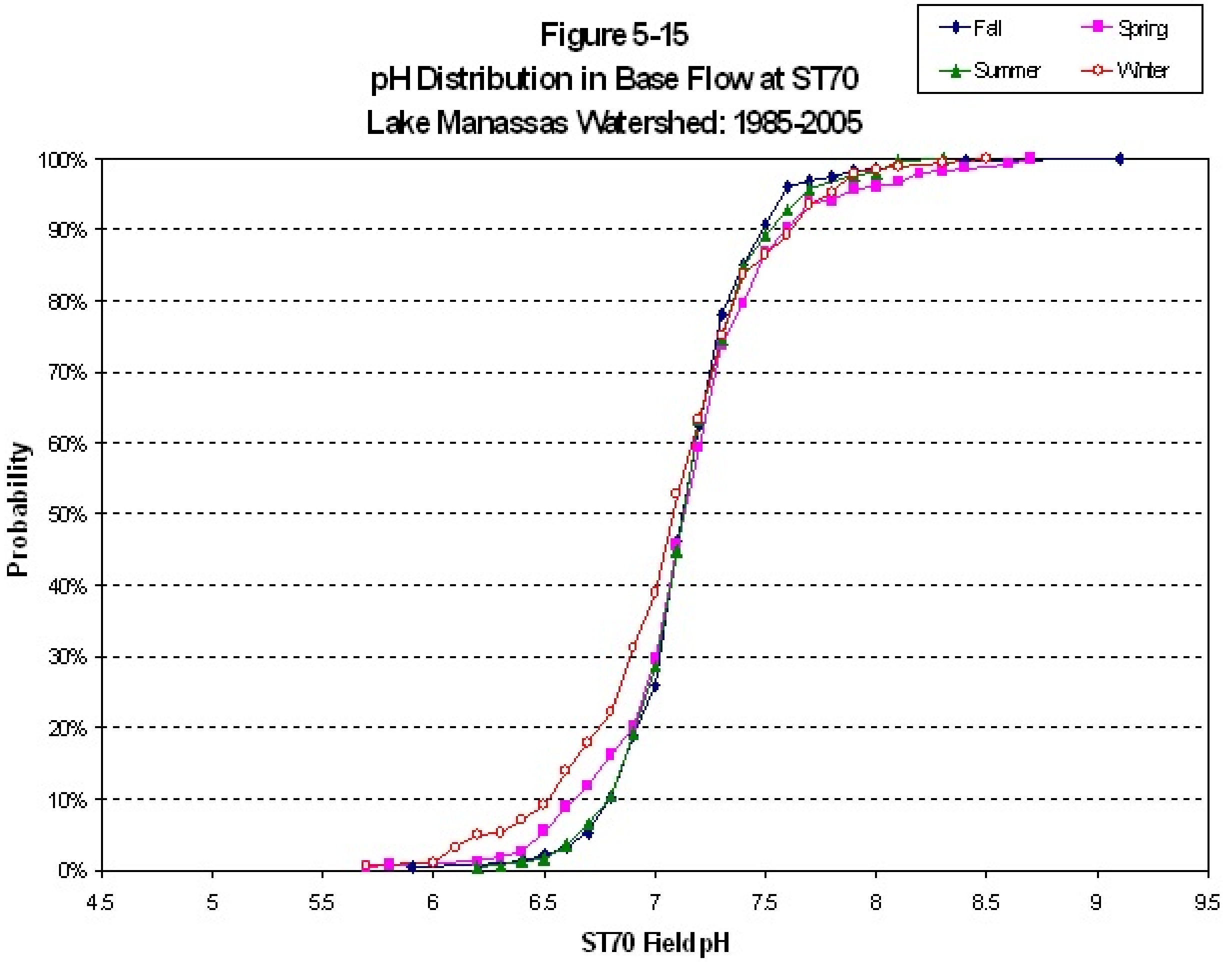


Figure 5-15
pH Distribution in Base Flow at ST70
Lake Manassas Watershed: 1985-2005

When pH values are greater than 7, the following seasonal trend is observed: $pH_{FALL} > pH_{SUMMER} > pH_{WINTER} > pH_{SPRING}$. High pH values during the fall and summer could be the result of algal activity in the water during low flow witnessed during these two seasons. Algae utilize CO_2 in the water for the production of cell mass. The extraction of CO_2 from the water column will subsequently increase the pH. During low flow conditions, this change in pH is readily apparent. As flow characteristics change and runoff into the streams increases, the transport of CO_2 into the streams will also increase. As water flows through the soil it becomes enriched with CO_2 from plant and microbial respiration (Wetzel, 2001). When the streams are dominated by increased flow throughout the winter and spring months, the runoff waters have limited contact with the carbonate-bearing soils thereby lowering pH values (Wetzel, 2001). These periods also experience lower values of alkalinity resulting in the water's decreased ability to resist changes in pH.

Alkalinity values reported as total alkalinity are measured as $CaCO_3$. Figures 5-16 through 5-22 show the five-year running seasonal averages for alkalinity. The maximum value was 215.1 mg/L as $CaCO_3$ recorded at station BR02 in the fall of 1986, while the minimum value was 3.8 mg/L as $CaCO_3$ at station ST70 during the winter of 1987. The Mann-Kendall Analysis (Table 5-2) shows decreasing trends for alkalinity in all stations except BR04 and BR05. The data for these two stations exhibit no trend either upward or downward. The alkalinity for all stations tended to be higher in the summer and fall months. This coincides with an inverse relationship between flow and alkalinity. In most cases, the flow of a stream includes a surface water component and a ground water component. During periods of low flow ground water percolates

Figure 5-16
Lake Manassas Stream Station BR02
Total Alkalinity
5 Year Running Average

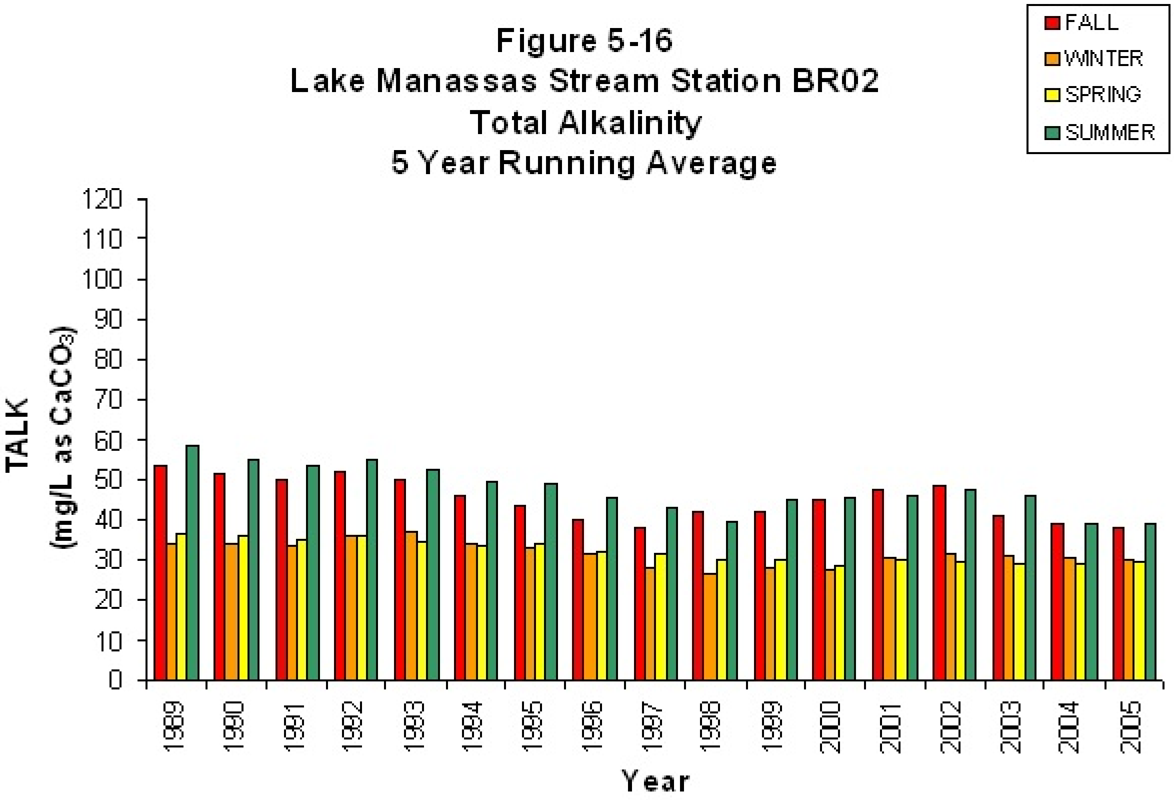
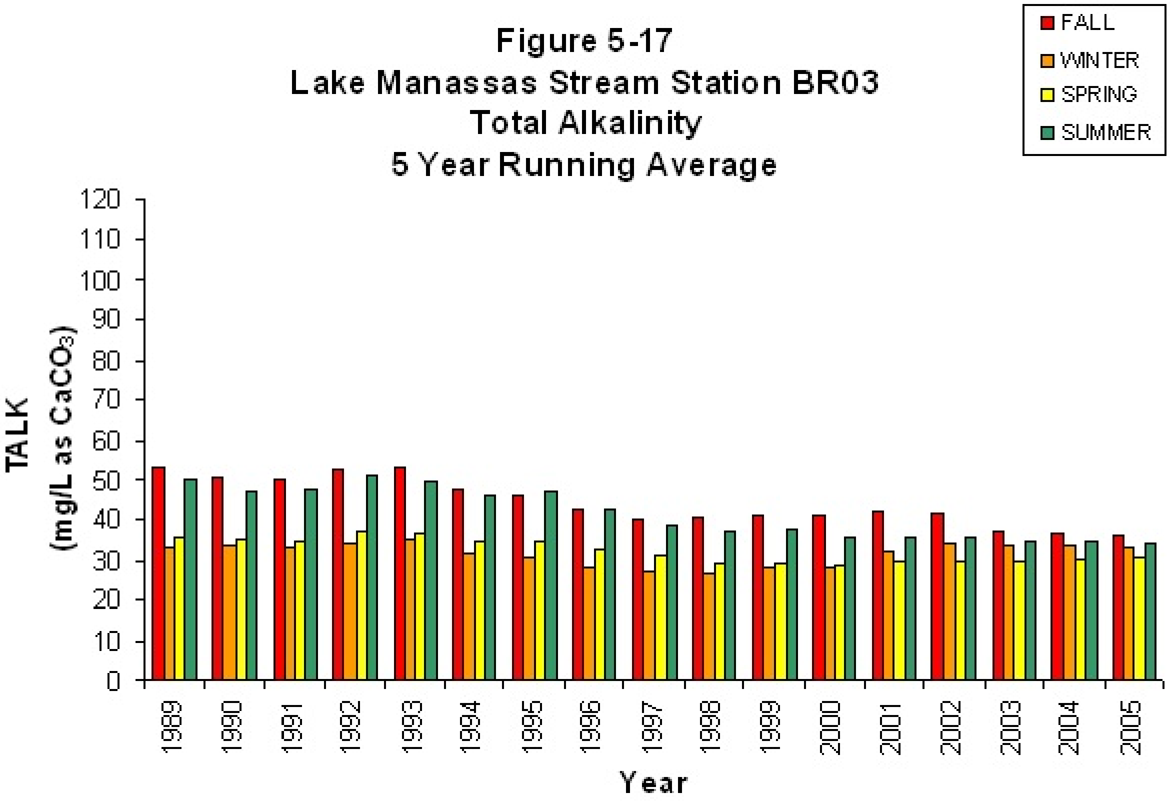


Figure 5-17
Lake Manassas Stream Station BR03
Total Alkalinity
5 Year Running Average



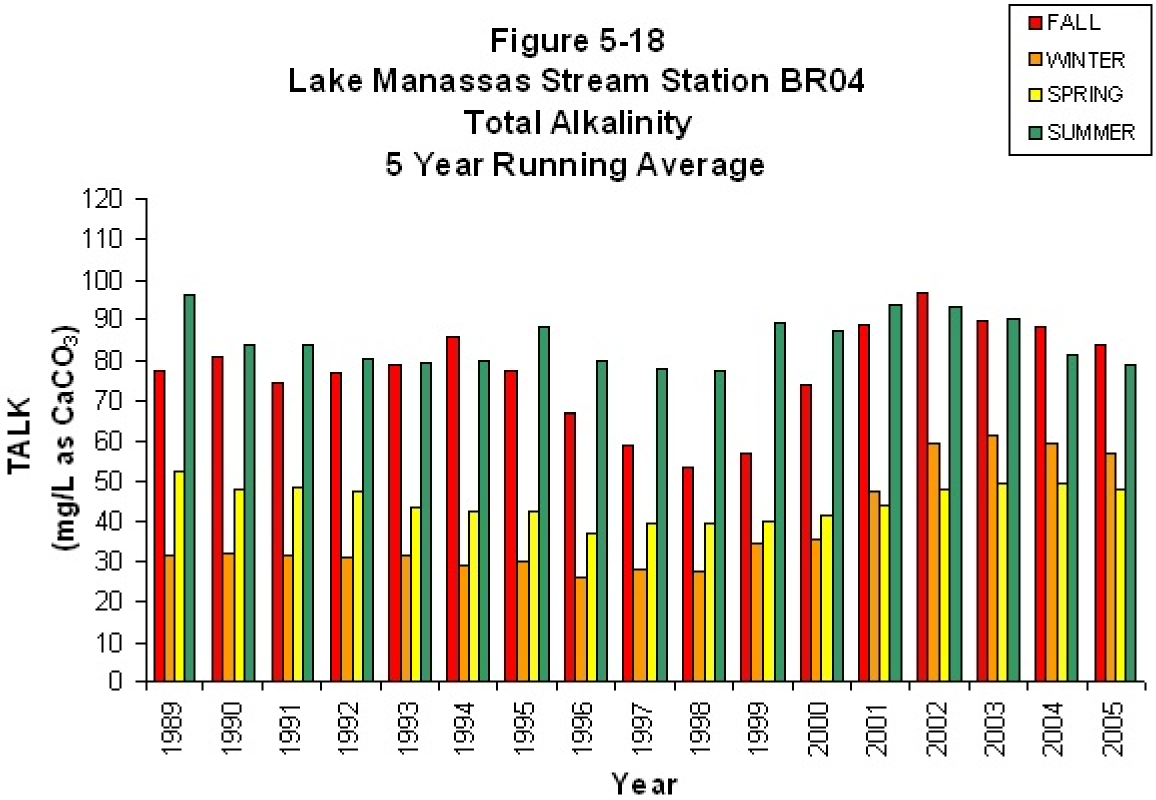


Figure 5-18
Lake Manassas Stream Station BR04
Total Alkalinity
5 Year Running Average

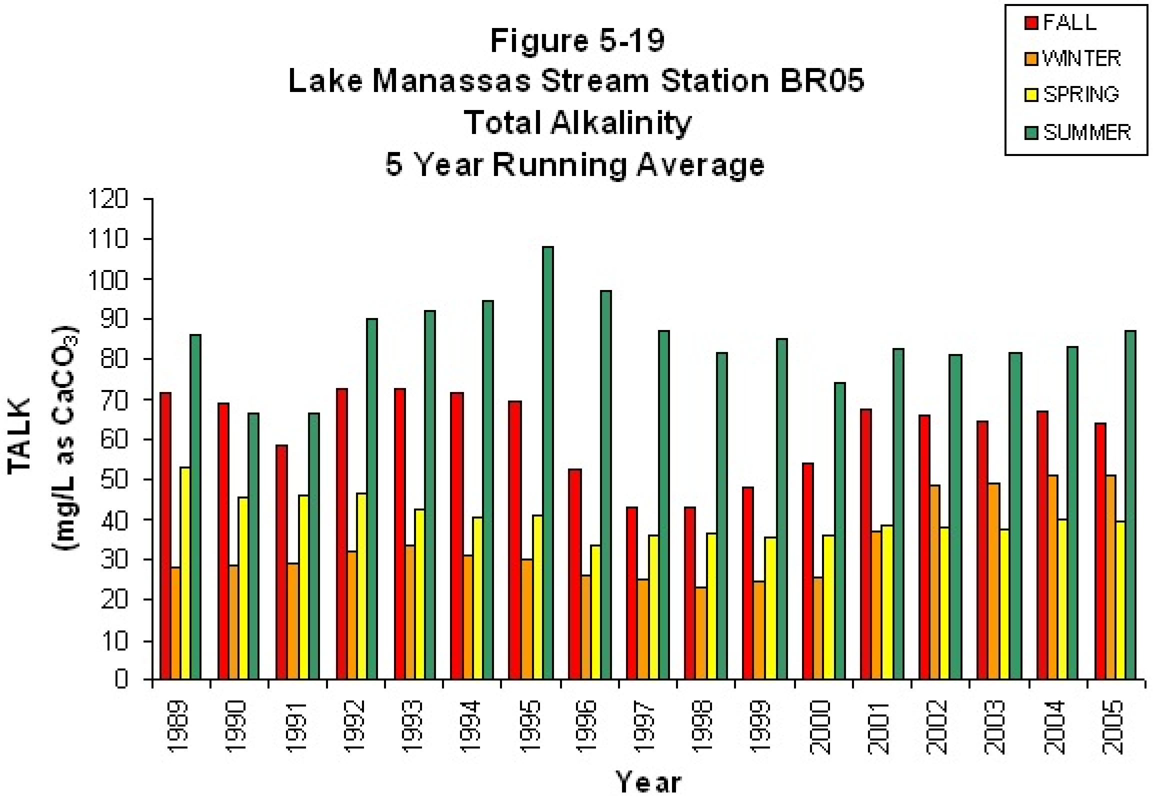


Figure 5-19
Lake Manassas Stream Station BR05
Total Alkalinity
5 Year Running Average

Figure 5-20
Lake Manassas Stream Station BR06
Total Alkalinity
5 Year Running Average

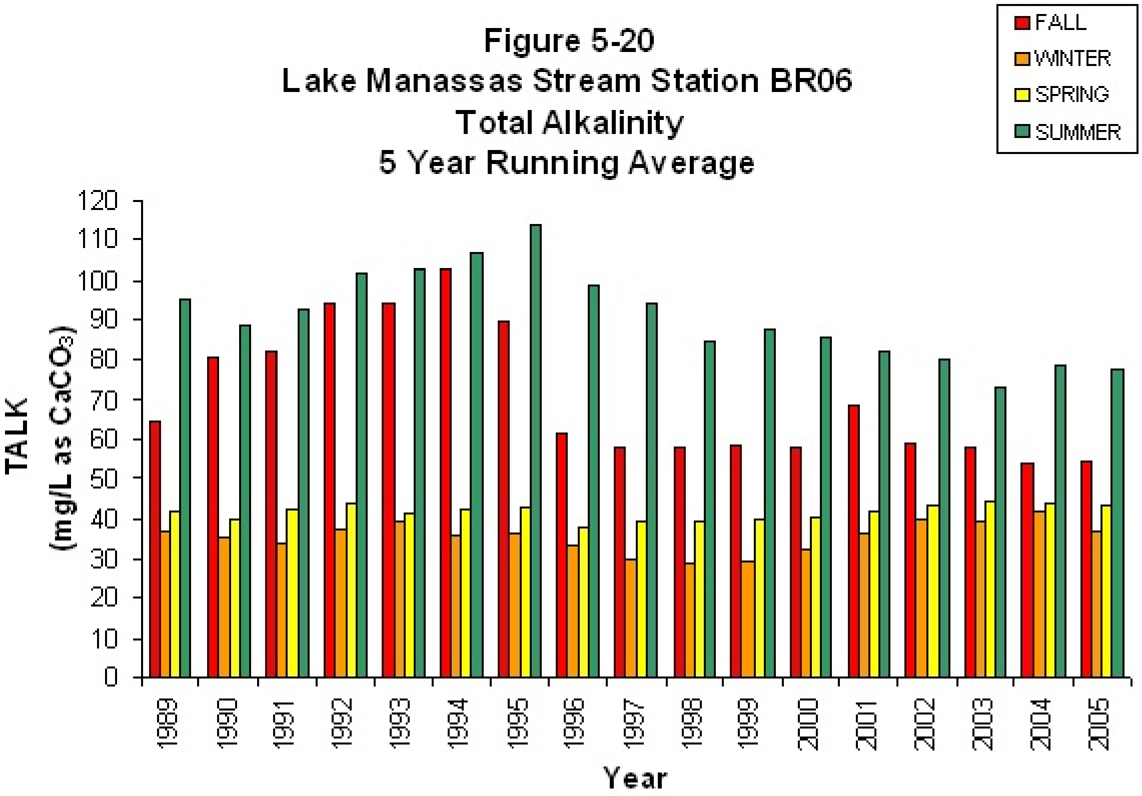
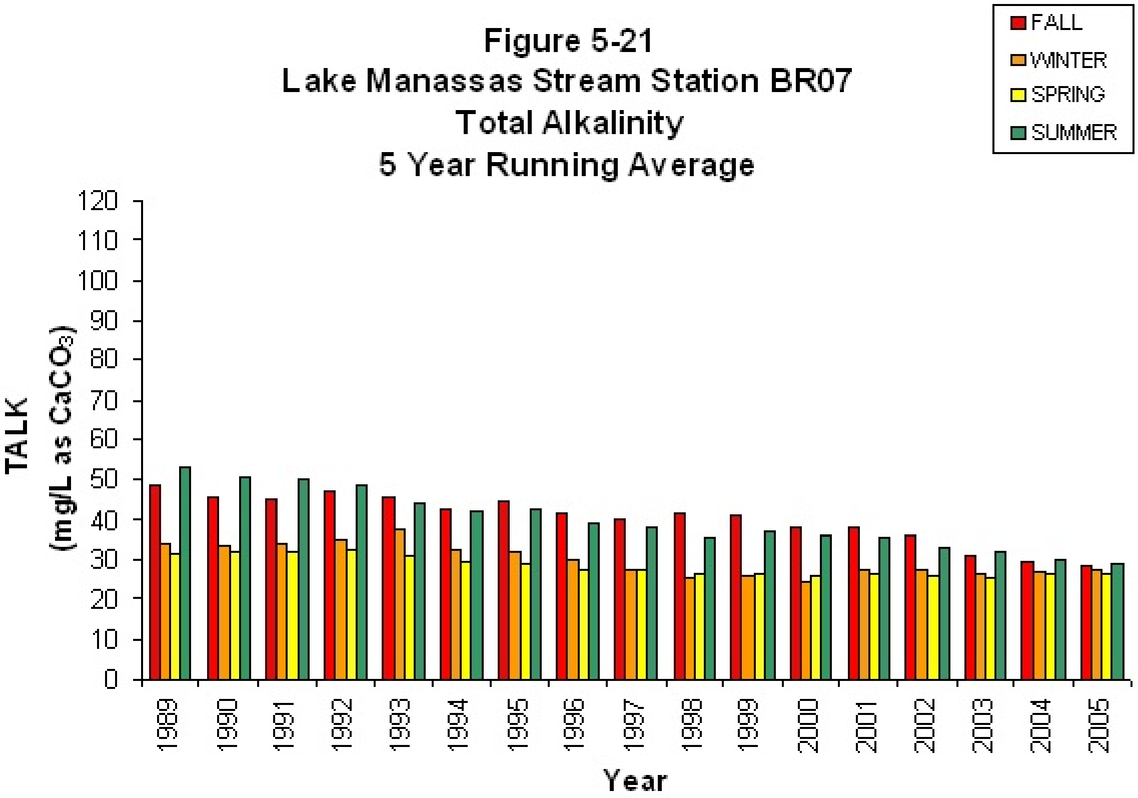


Figure 5-21
Lake Manassas Stream Station BR07
Total Alkalinity
5 Year Running Average



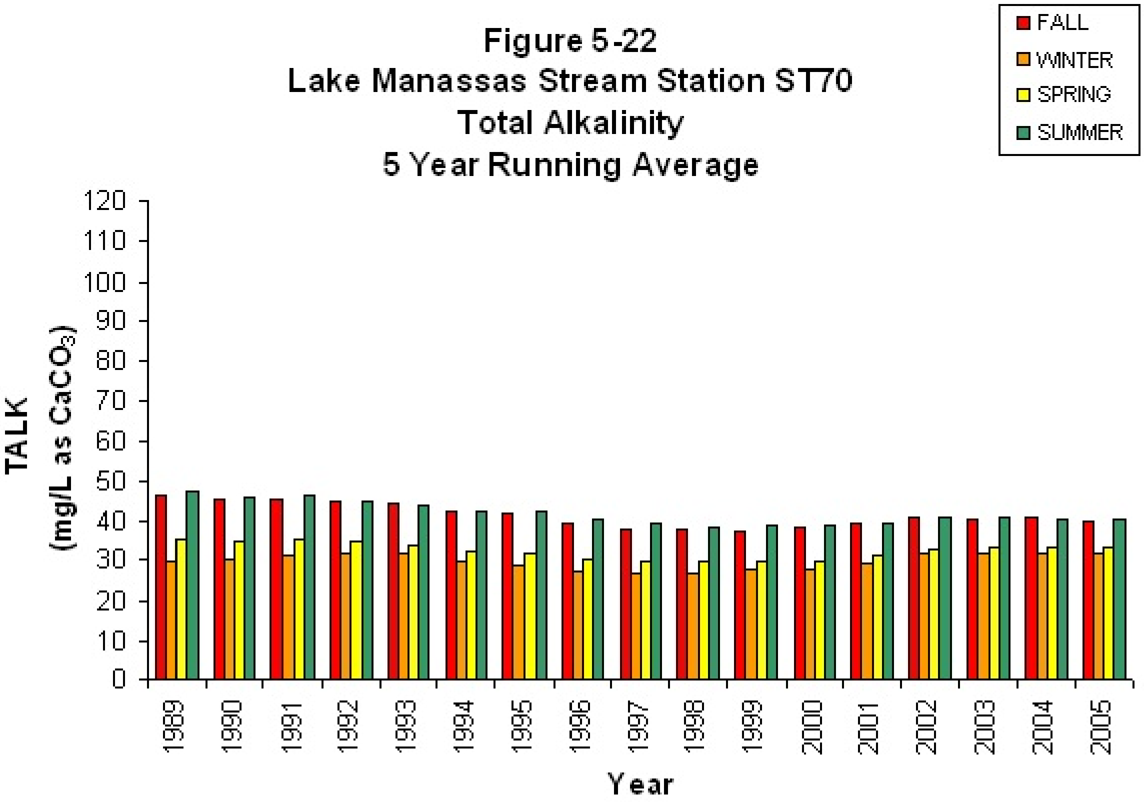


Figure 5-22
Lake Manassas Stream Station ST70
Total Alkalinity
5 Year Running Average

through the stream bed through a process called interflow (Winter et al. 1998). During this process the ground water has prolonged contact with the carbonate bearing soils, resulting in elevated alkalinity values. As stated earlier, when flows are large, runoff waters have limited contact with carbonate-bearing soils. The resulting condition produces lower alkalinity values and a lower ability to resist changes in pH. Despite these conditions, alkalinity values always remained above10 mg/L.

Temperature

Figures 5-23 through 5-29 show the five-year running seasonal averages for temperature at the stream stations. During the summer of 1988, the maximum temperature was recorded as 32.5 °C at station ST70. A minimum temperature of -1 °C was recorded at multiple stations during multiple years. The majority of the low temperatures occurred during the winter of 1985. During this time period the minimum temperature was recorded at stations BR04, BR05, and ST70. The minimum temperature was also measured at stations BR03 and ST70 during the winter of 1990 and the winter of 1996, respectively. An upward trend in stream temperature was discovered at stations BR03, BR04, and BR07 through the Mann-Kendall Analysis (Table 5-2). Despite the upward trend witnessed at these three stations, the maximum allowable temperature (32 °C) set by Virginia's DEQ was never surpassed. The only time a record exceeded the water quality limit was during the summer of 1988 at station ST70, where the measured temperature was 32.5 °C. No trends were witnessed at any other stations.

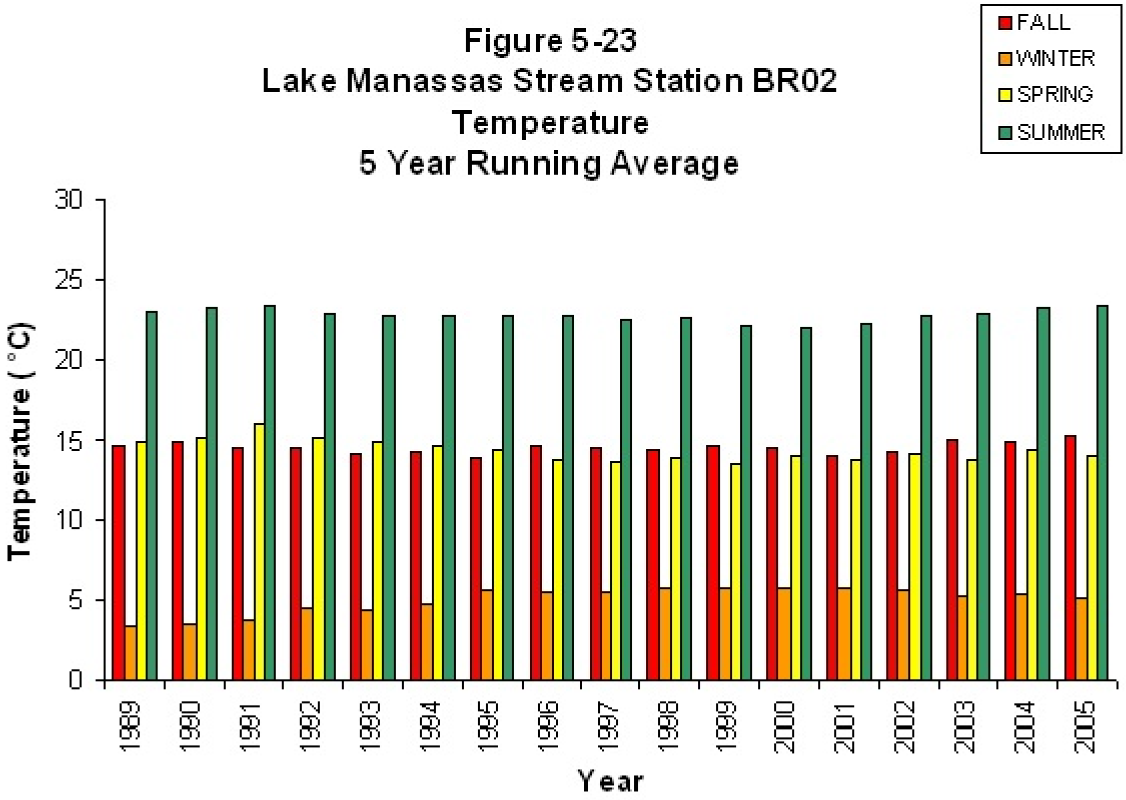


Figure 5-23
Lake Manassas Stream Station BR02
Temperature
5 Year Running Average

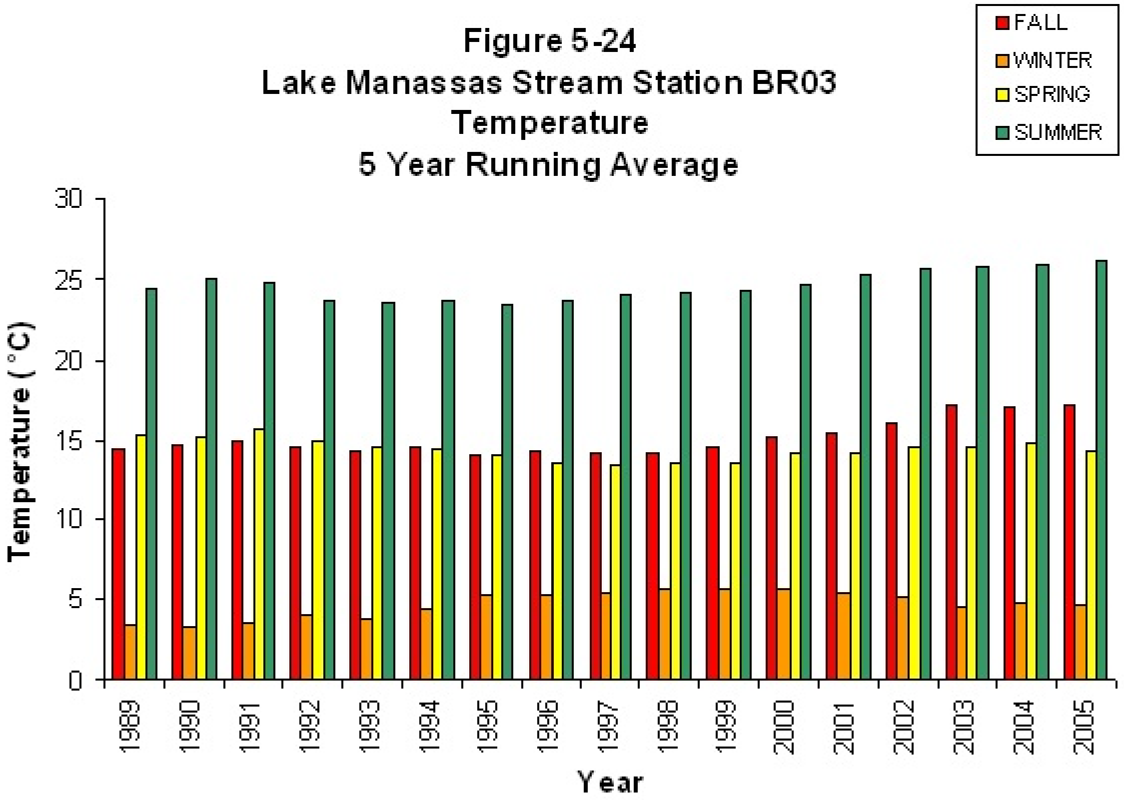


Figure 5-24
Lake Manassas Stream Station BR03
Temperature
5 Year Running Average

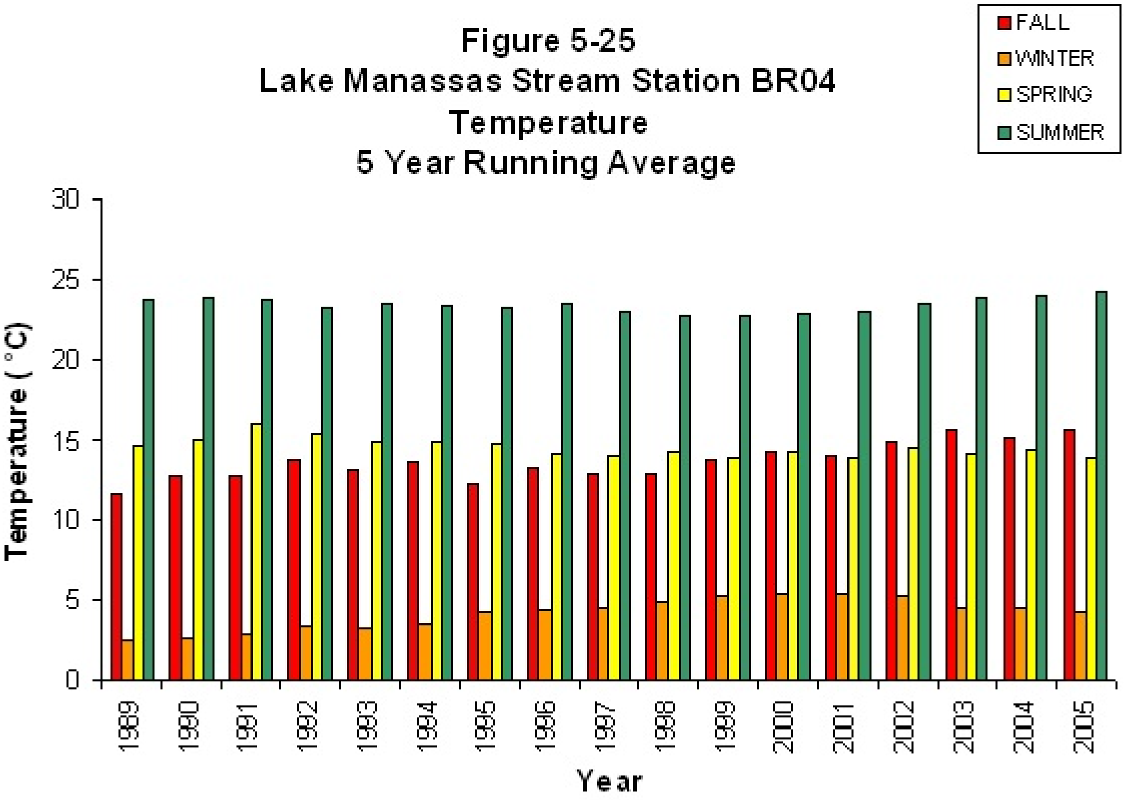


Figure 5-25
Lake Manassas Stream Station BR04
Temperature
5 Year Running Average

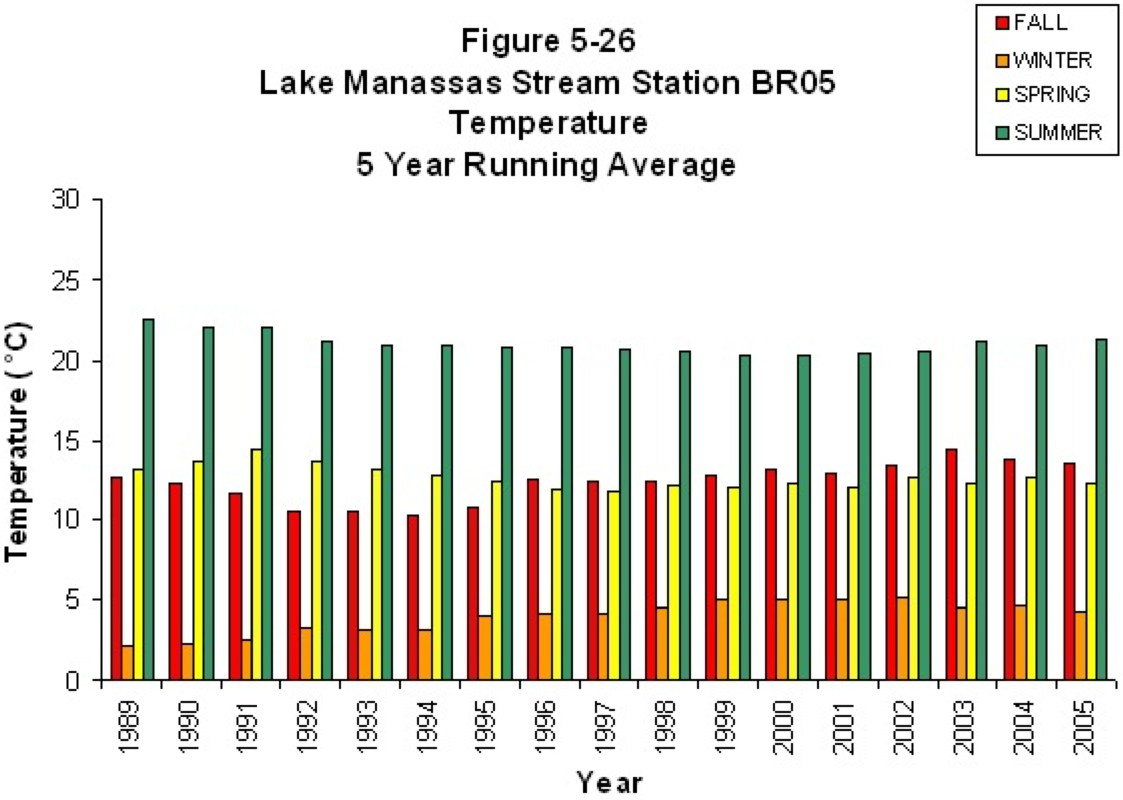


Figure 5-26
Lake Manassas Stream Station BR05
Temperature
5 Year Running Average

Figure 5-27
Lake Manassas Stream Station BR06
Temperature
5 Year Running Average

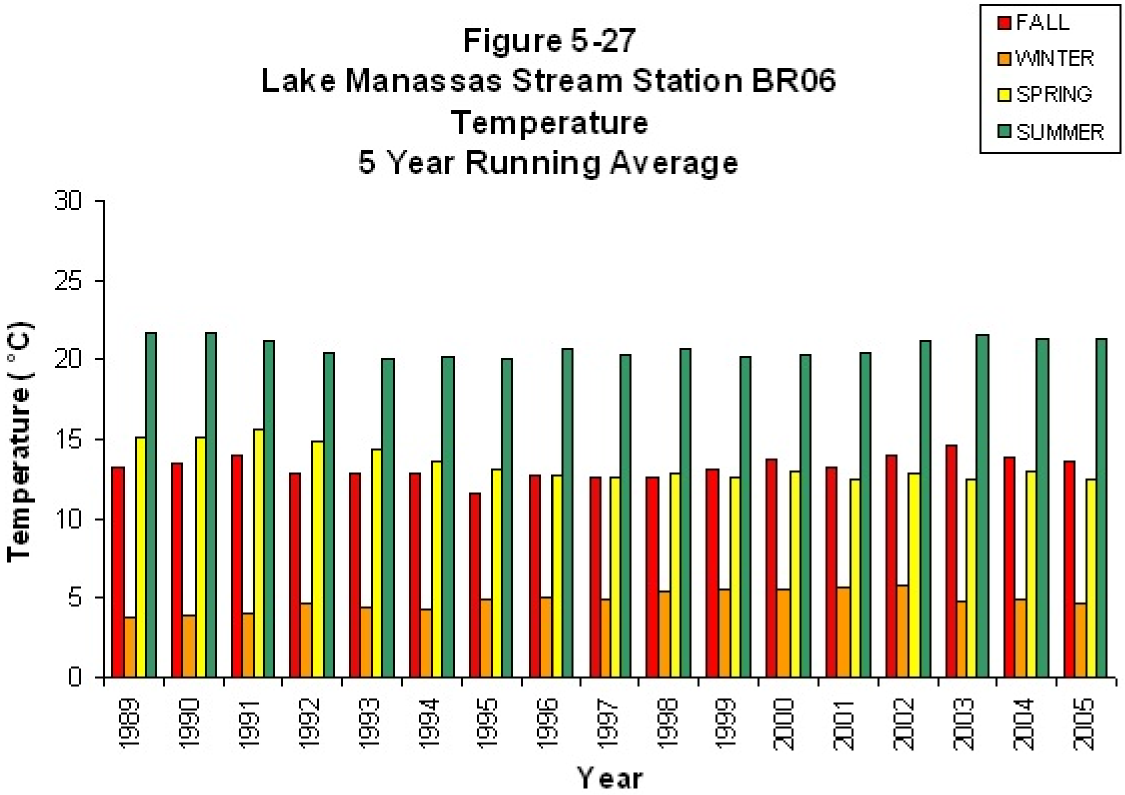
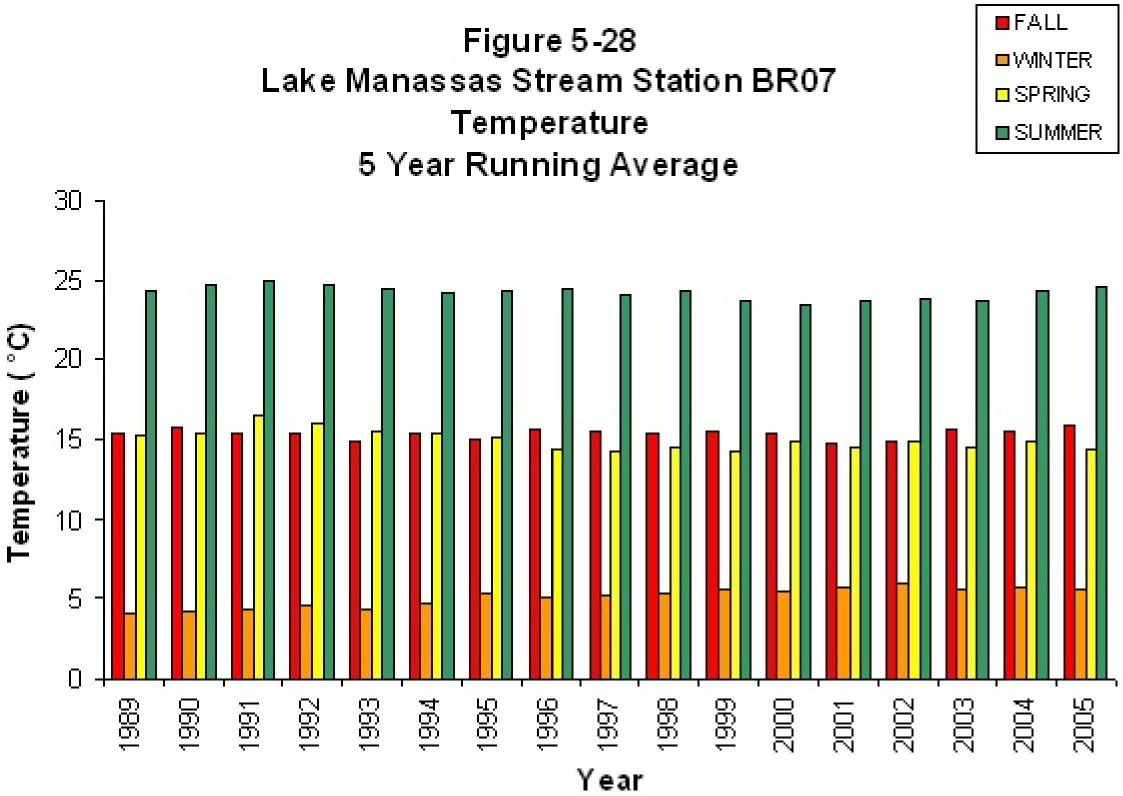


Figure 5-28
Lake Manassas Stream Station BR07
Temperature
5 Year Running Average



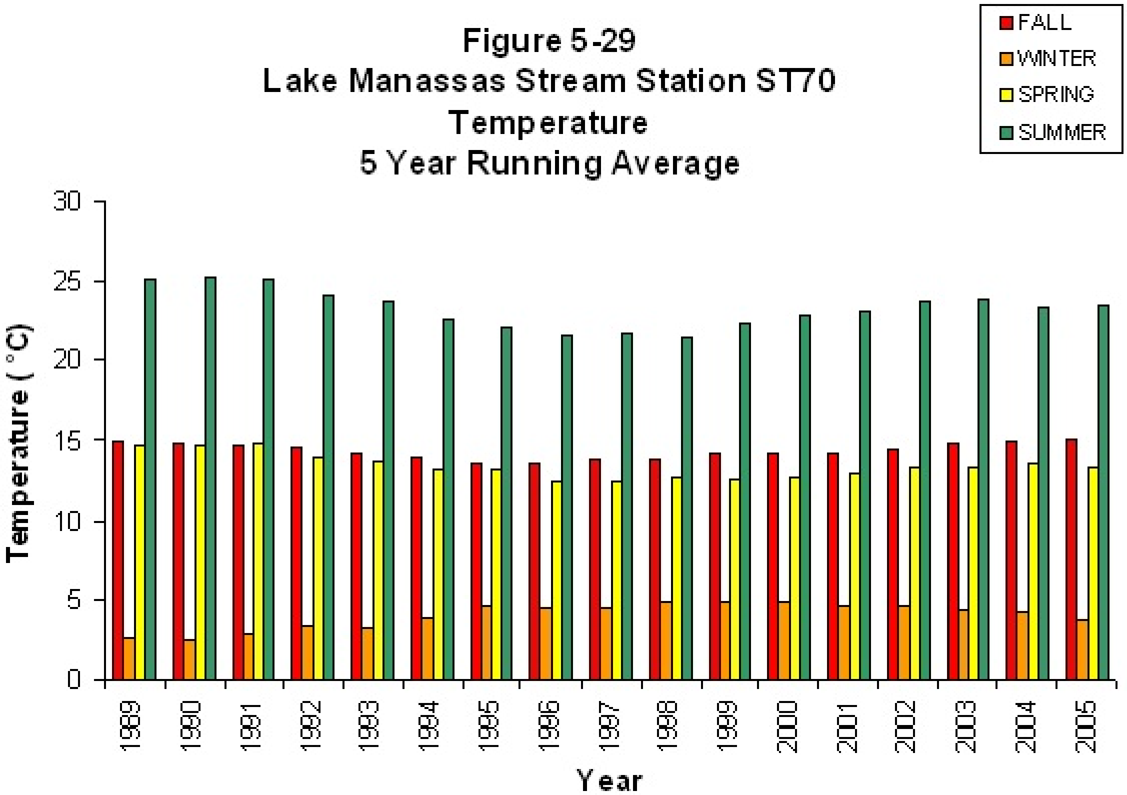


Figure 5-29
Lake Manassas Stream Station ST70
Temperature
5 Year Running Average

Conductivity

Conductivity is a measure of the ability of water to pass an electric current. The presence of inorganic dissolved solids can affect the conductivity in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. To relate the conductivity to a standard condition, the values for conductivity have been corrected to a temperature of 25 °C. The five-year running seasonal averages for conductivity are displayed in Figures 5-30 through 5-36. The maximum recorded value was 1,725 μS/cm at station BR05 in the winter of 2002. The minimum value observed was 1 μS/cm and occurred at stations BR03, BR04, BR05, and ST70 over multiple years. During the winter of 2000 the minimum value was recorded at station BR03, while during the summer of 1995 and the spring of 2003 the minimum value was measured at stations BR04 and BR05, respectively. The minimum recorded value was also observed twice at station ST70, during the spring of 1995 and the summer of 2005.

The Mann-Kendall Analysis (Table 5-2) produced decreasing trends for conductivity at stations BR02, BR03, and BR07, while an increasing trend was observed at station ST70. Taking note of Figures 5-30 through 5-36, it is evident that conductivity was greater in the fall and summer. This would indicate that conductivity has an inverse relationship with flow since fall and summer exhibited lower flows. However, this relationship does not uniformly apply to normalized values. In more recent years, the conductivity during the winter has shown a dramatic increase. This phenomena is present at stations BR04, BR05, and BR06. A possible explanation for the increased concentrations could be attributed to de-icing operations conducted during winter months. A concern of previous baseline reports was that the discharge from the Vint Hill Station Wastewater Treatment Plant was producing increased conductivity in the

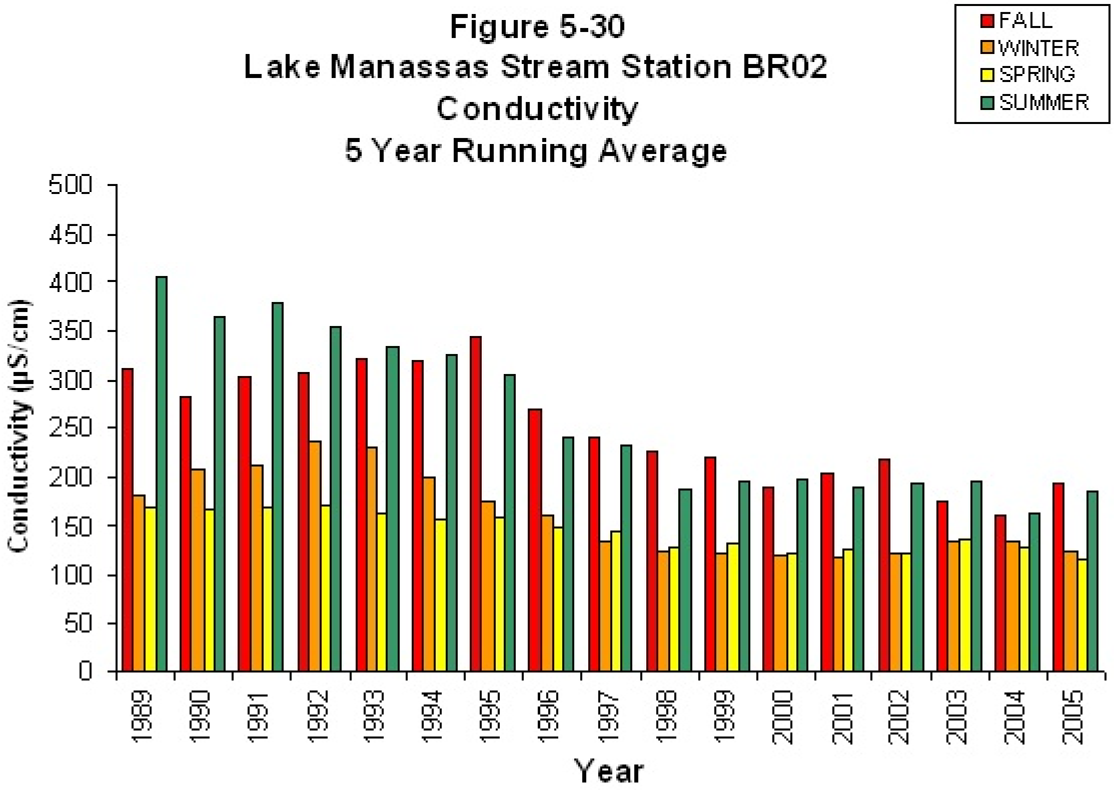


Figure 5-30
Lake Manassas Stream Station BR02
Conductivity
5 Year Running Average

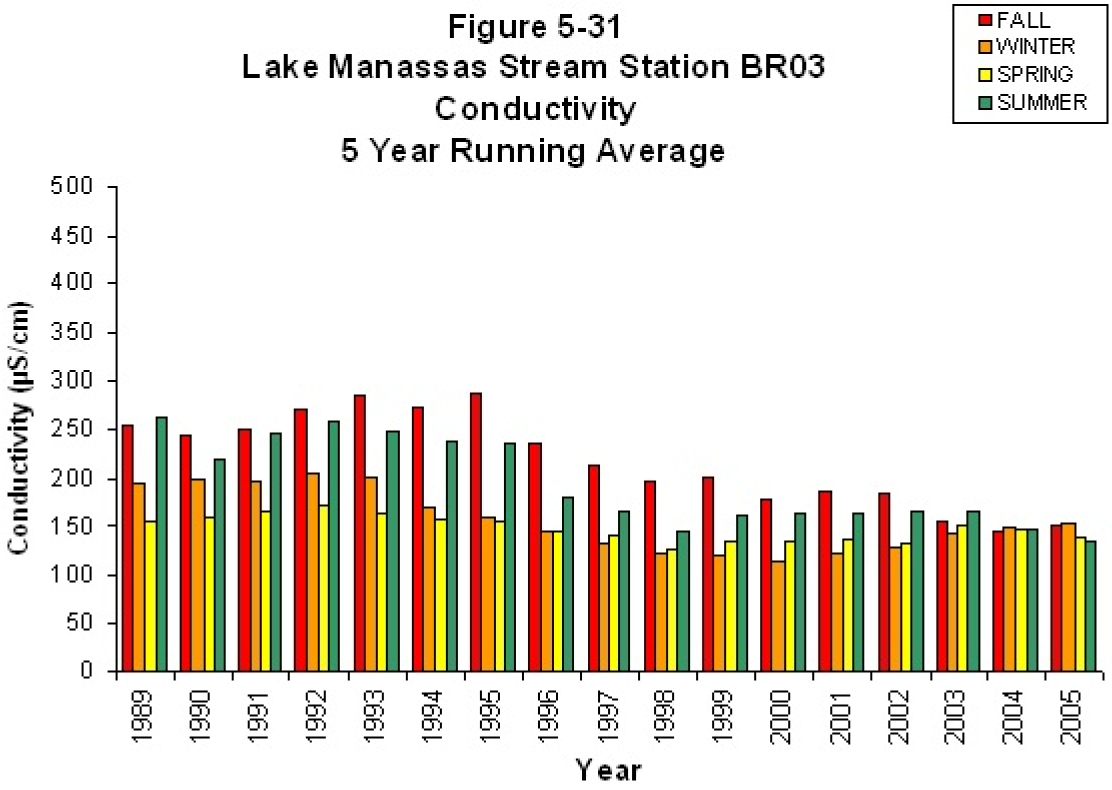


Figure 5-31
Lake Manassas Stream Station BR03
Conductivity
5 Year Running Average

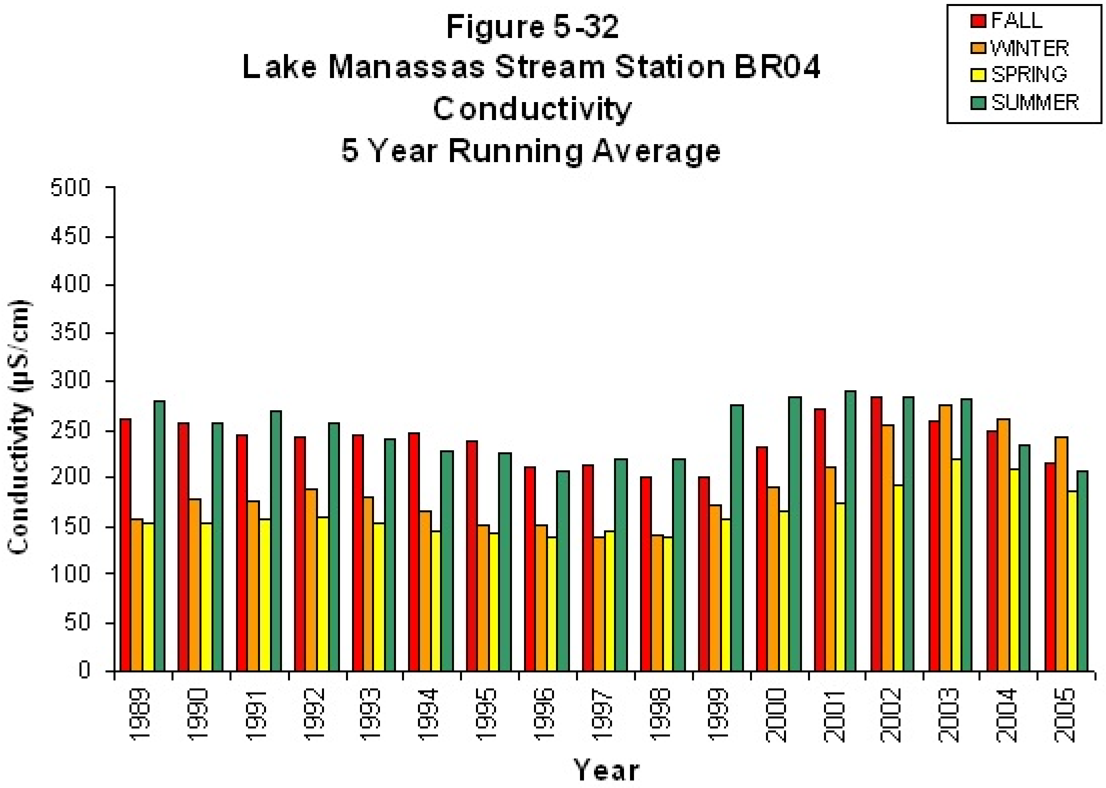


Figure 5-32
Lake Manassas Stream Station BR04
Conductivity
5 Year Running Average

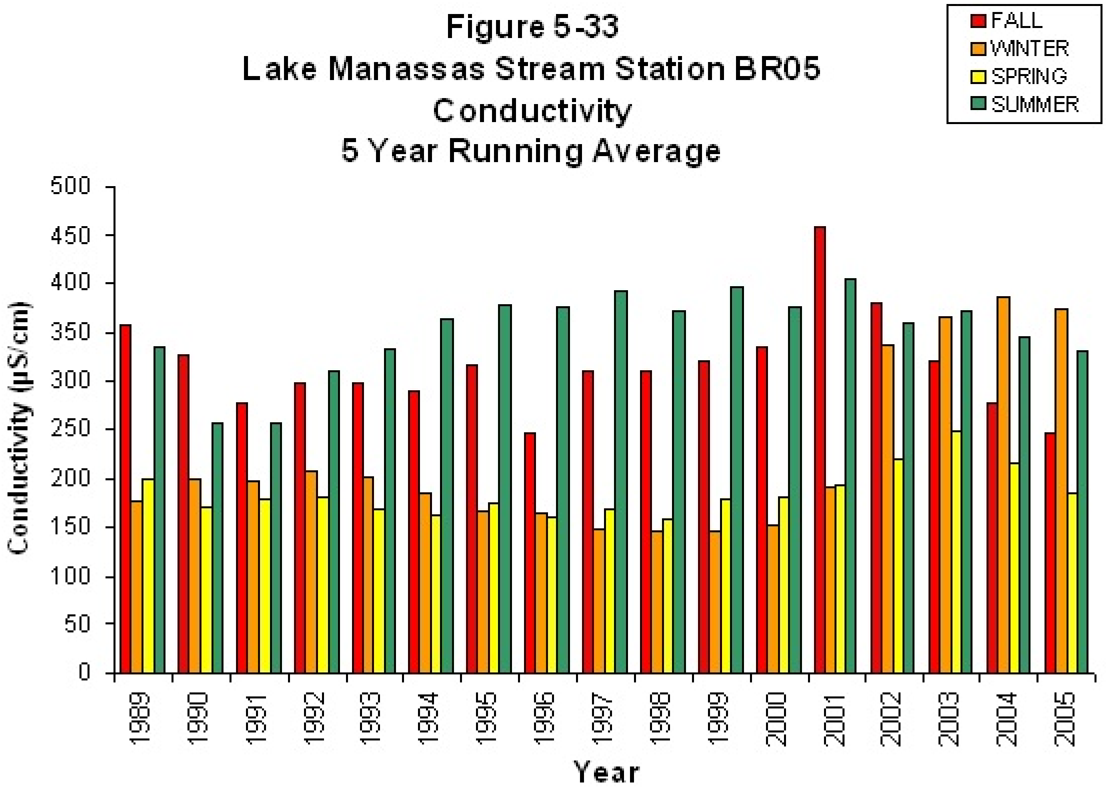


Figure 5-33
Lake Manassas Stream Station BR05
Conductivity
5 Year Running Average

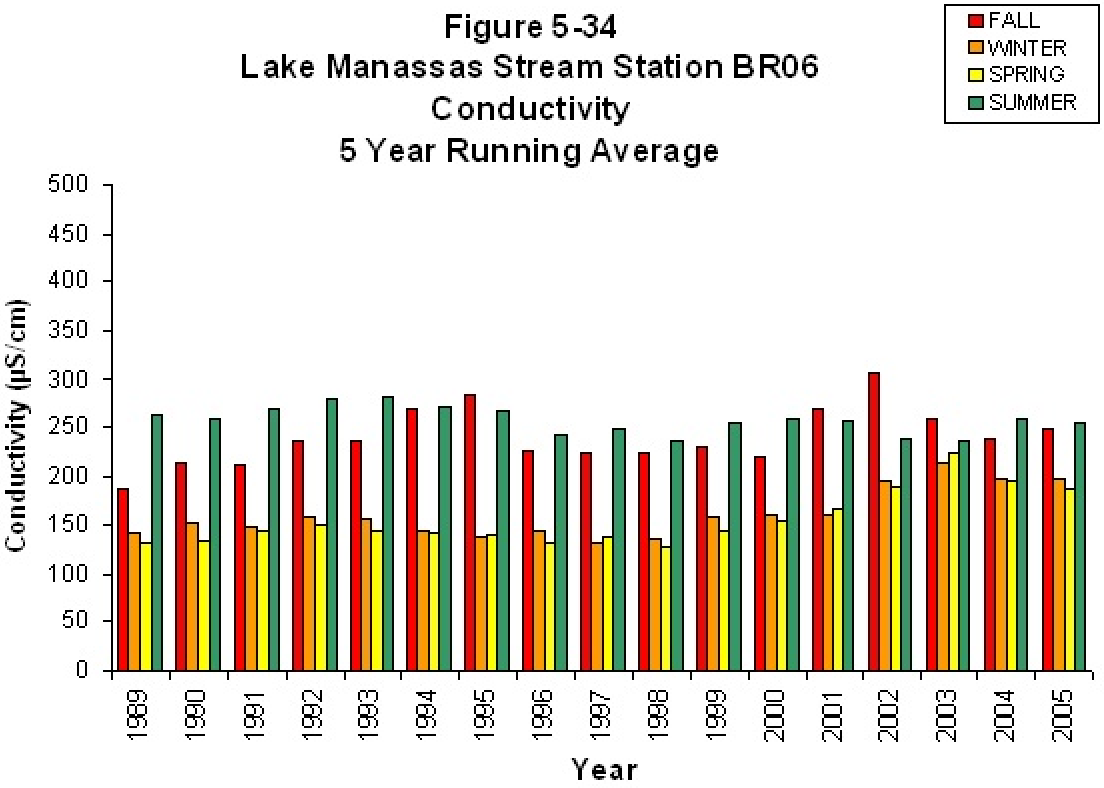


Figure 5-34
Lake Manassas Stream Station BR06
Conductivity
5 Year Running Average
FALL
WINTER
SPRING
SUMMER
Conductivity (µS/cm)
0
50
100
150
200
250
300
350
400
450
500
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
Year

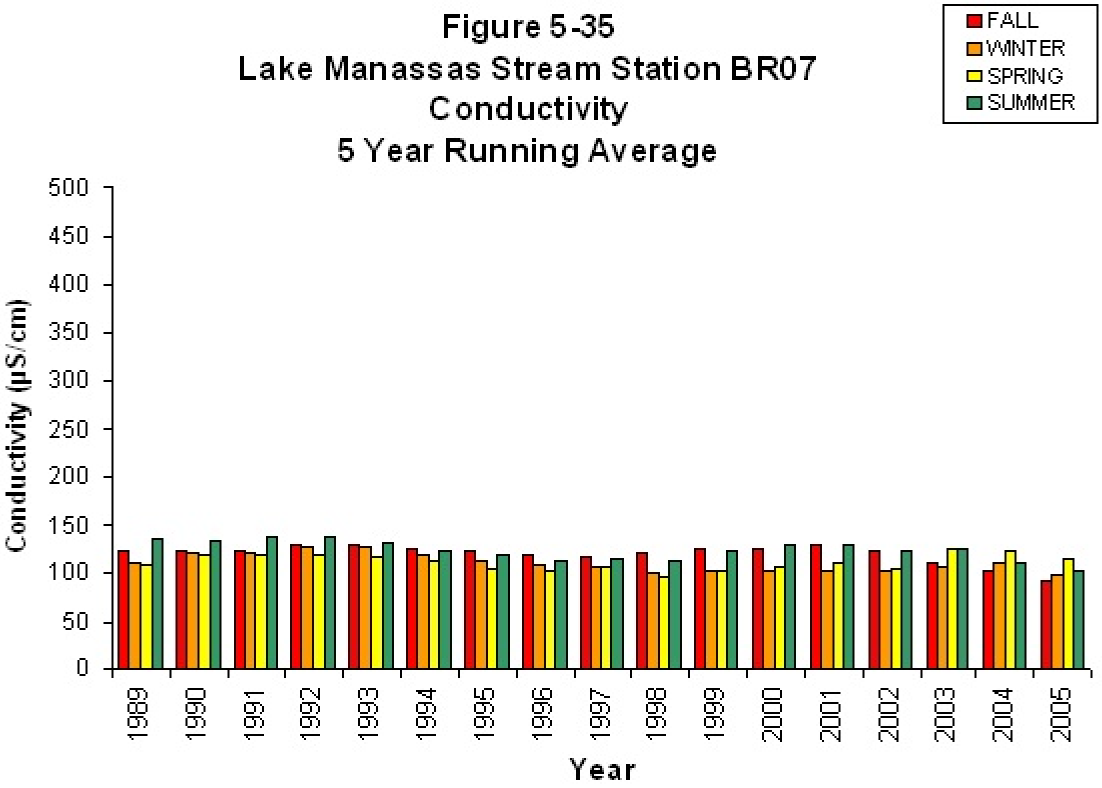


Figure 5-35
Lake Manassas Stream Station BR07
Conductivity
5 Year Running Average
FALL
WINTER
SPRING
SUMMER
Conductivity (µS/cm)
0
50
100
150
200
250
300
350
400
450
500
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
Year

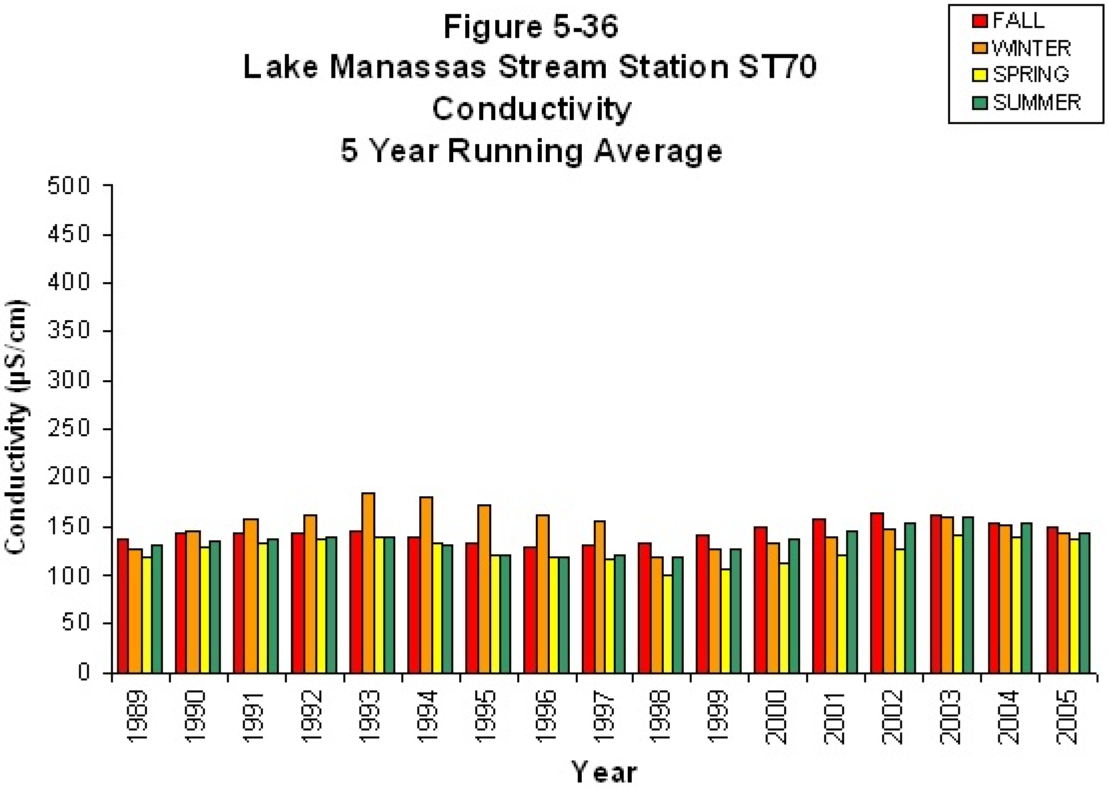


Figure 5-36
Lake Manassas Stream Station ST70
Conductivity
5 Year Running Average

water. This concern is no longer an issue given that at all stations along South Run have decreasing trends of conductivity as shown in the Mann-Kendall Analysis (Table 5-2).

Total Suspended Solids

Five-year running seasonal averages for TSS are displayed in Figures 5-37 through 5-43. The concentration of suspended solids is important to both stream and lake ecosystems. Inorganic suspended solids attenuate light, through scattering and absorption. High concentrations of suspended solids degrade water transparency thereby decreasing light available to support photosynthesis (Cooke et al. 1993). Under runoff conditions, Broad Run (ST70) exhibited the highest TSS values. This is to be expected since Broad Run contributes the majority of flow to Lake Manassas. An increasing trend of TSS concentrations was measured at this station determined by the Mann-Kendall Analysis (Table 5-2). Upward trends were also detected at stations BR04 and BR05. Decreasing trends were encountered at stations BR02, BR06, and BR07 with regard to TSS concentrations. No trend was present at station BR03.

In general, large increases in suspended solids are observed during runoff events. This often results in a large portion of TSS concentrations being delivered during short intervals of high flow. Examining the more recent years (2000 - 2005) at station ST70, yearly averages of TSS concentrations have typically been highest during the winter and spring months. There was one exception to this observation which occurred as a result of one high reading in the summer of

Figure 5-37
Lake Manassas Stream Station BR02
Total Suspended Solids Concentration
5 Year Running Average

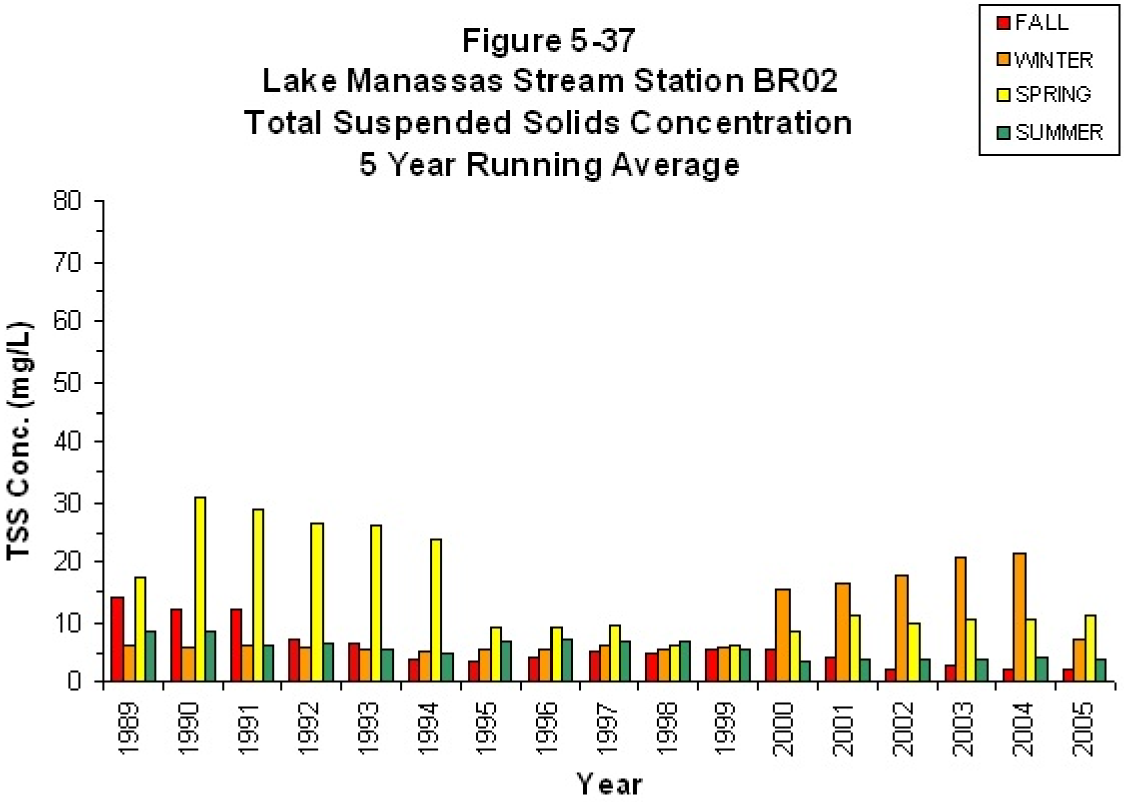
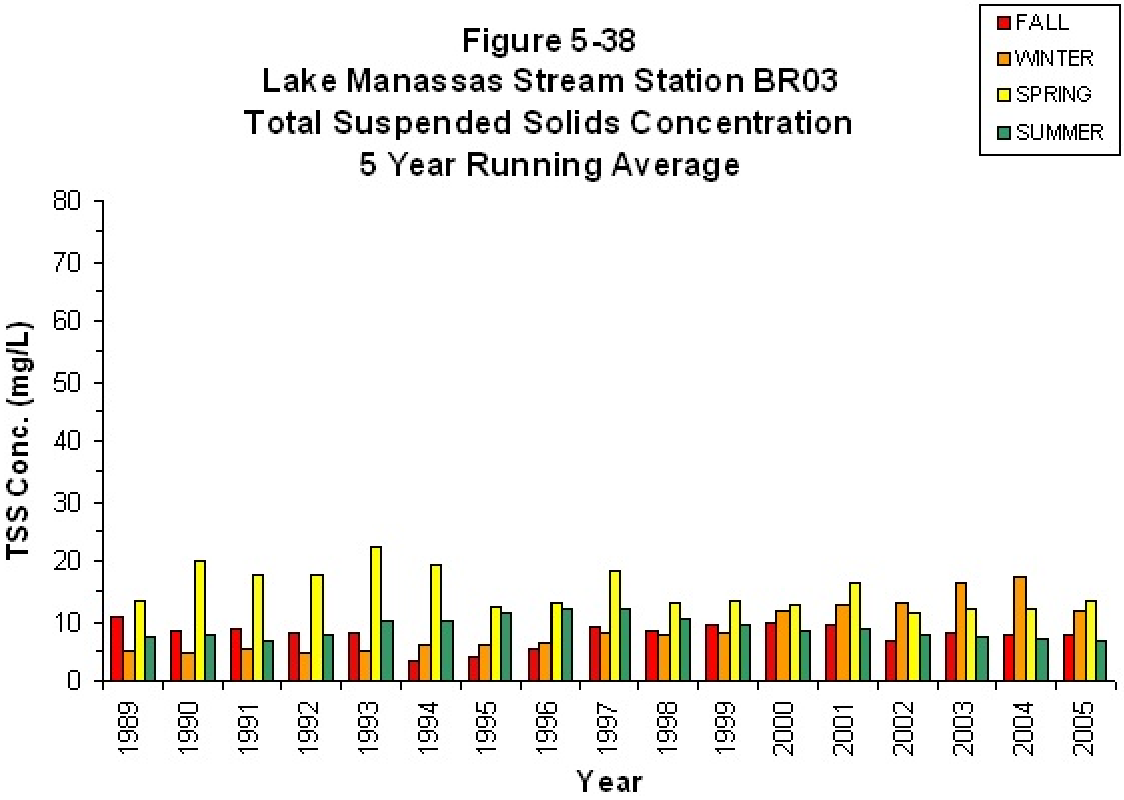


Figure 5-38
Lake Manassas Stream Station BR03
Total Suspended Solids Concentration
5 Year Running Average



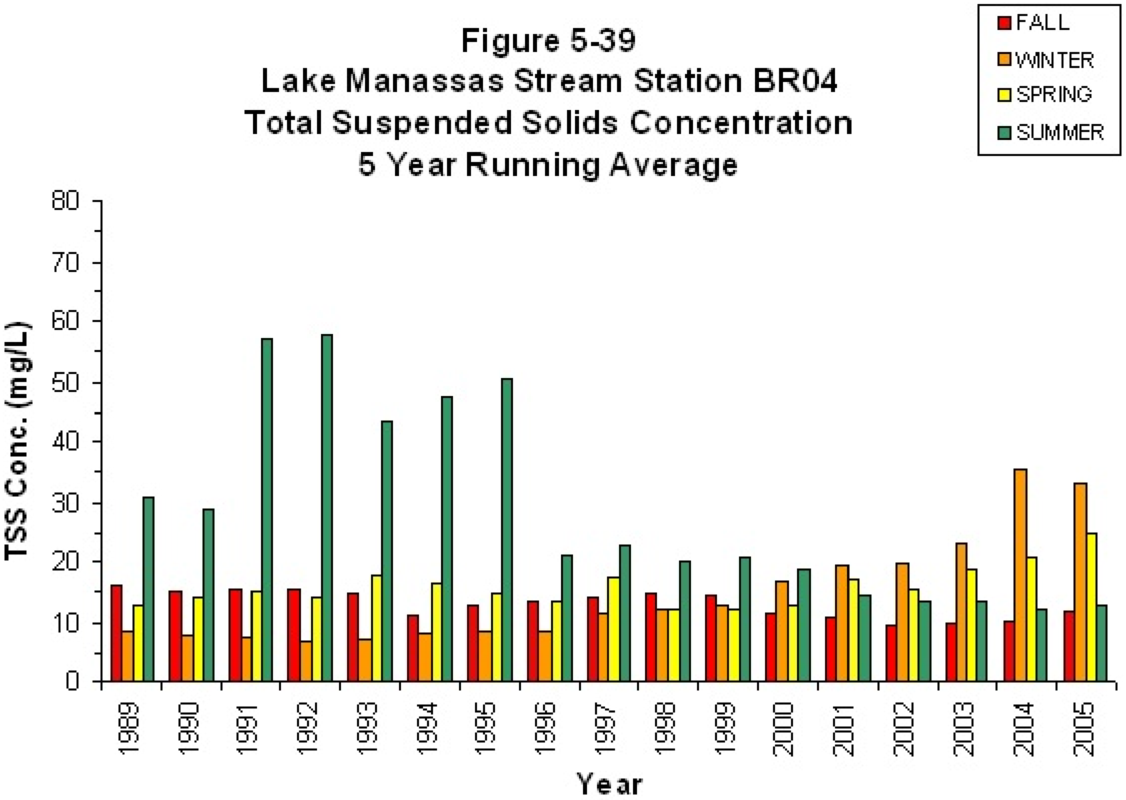


Figure 5-39
Lake Manassas Stream Station BR04
Total Suspended Solids Concentration
5 Year Running Average

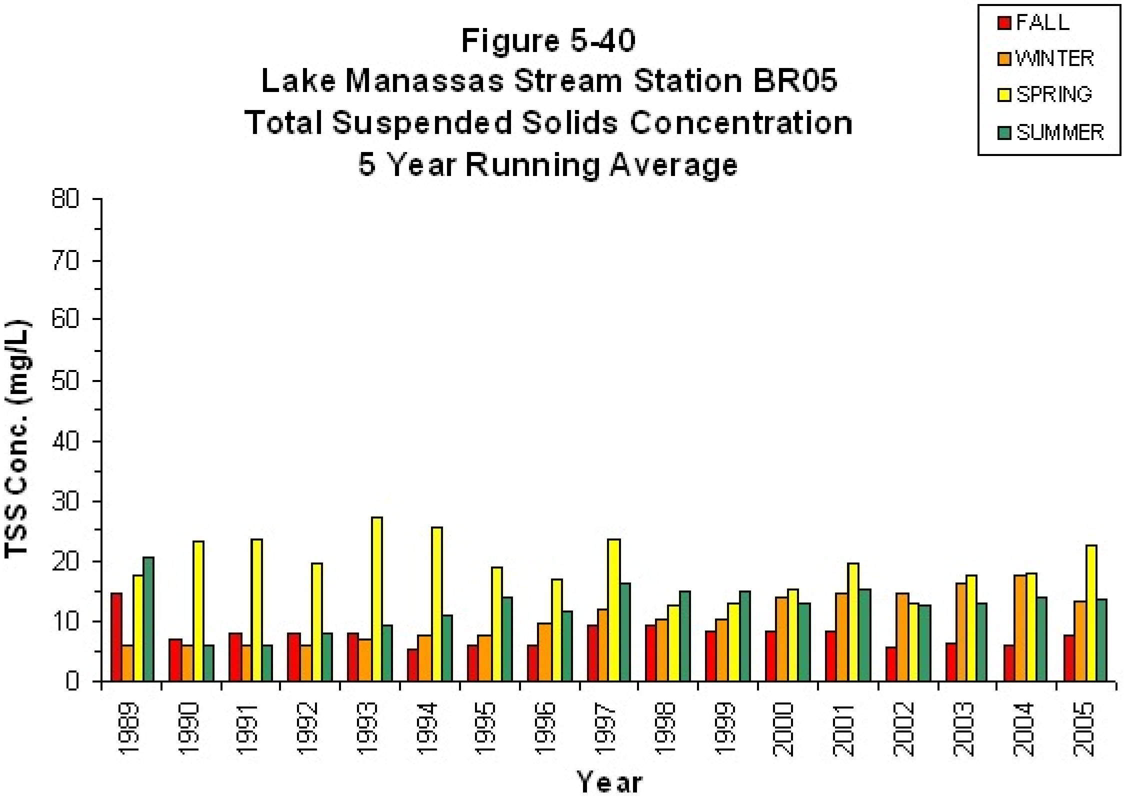


Figure 5-40
Lake Manassas Stream Station BR05
Total Suspended Solids Concentration
5 Year Running Average

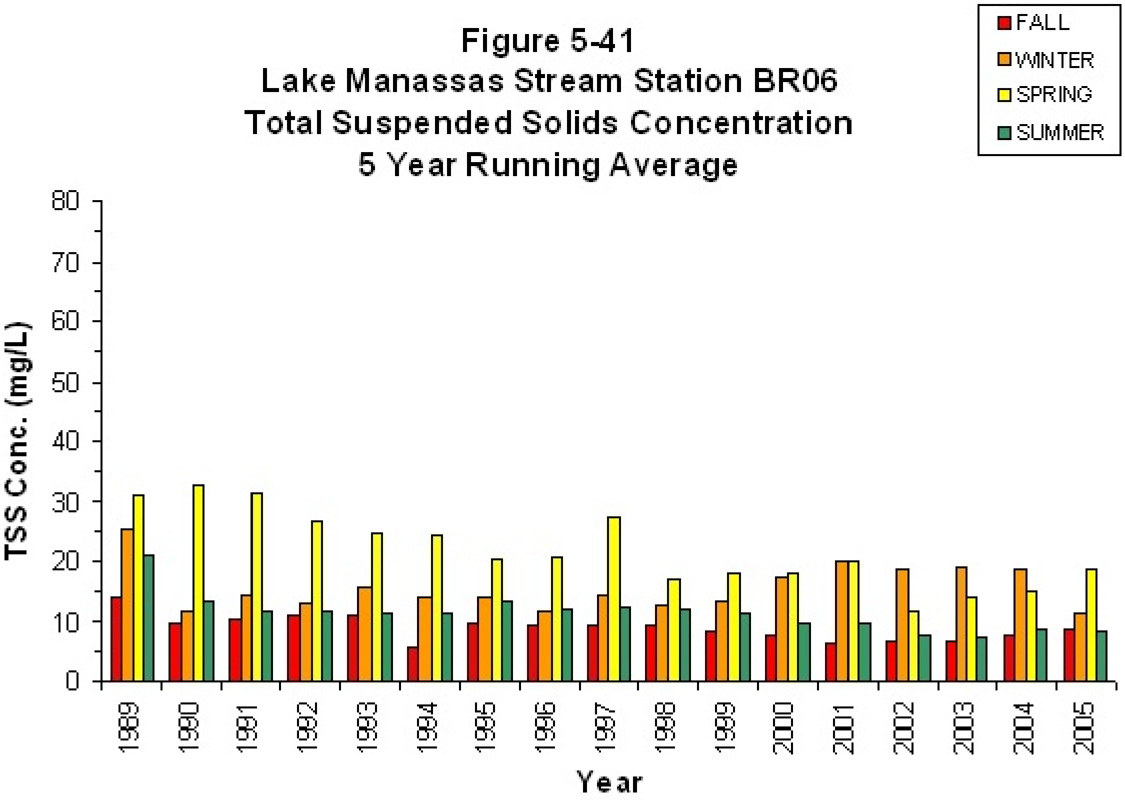


Figure 5-41
Lake Manassas Stream Station BR06
Total Suspended Solids Concentration
5 Year Running Average

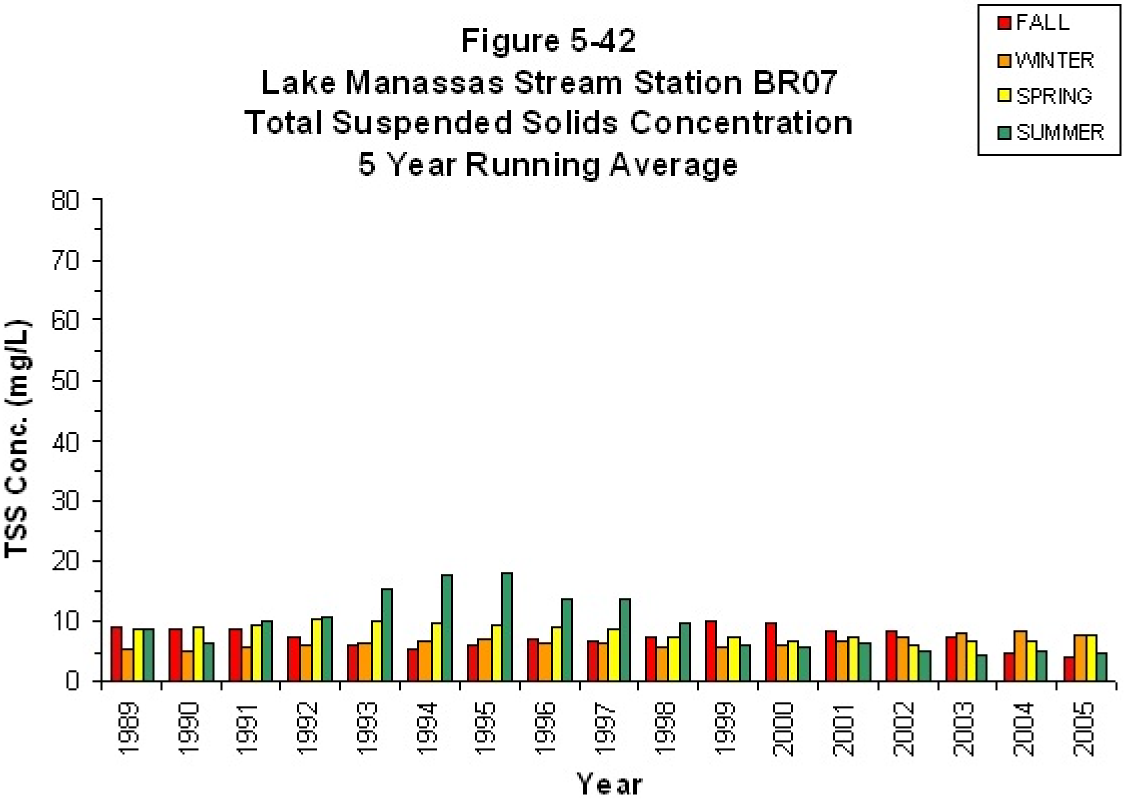


Figure 5-42
Lake Manassas Stream Station BR07
Total Suspended Solids Concentration
5 Year Running Average

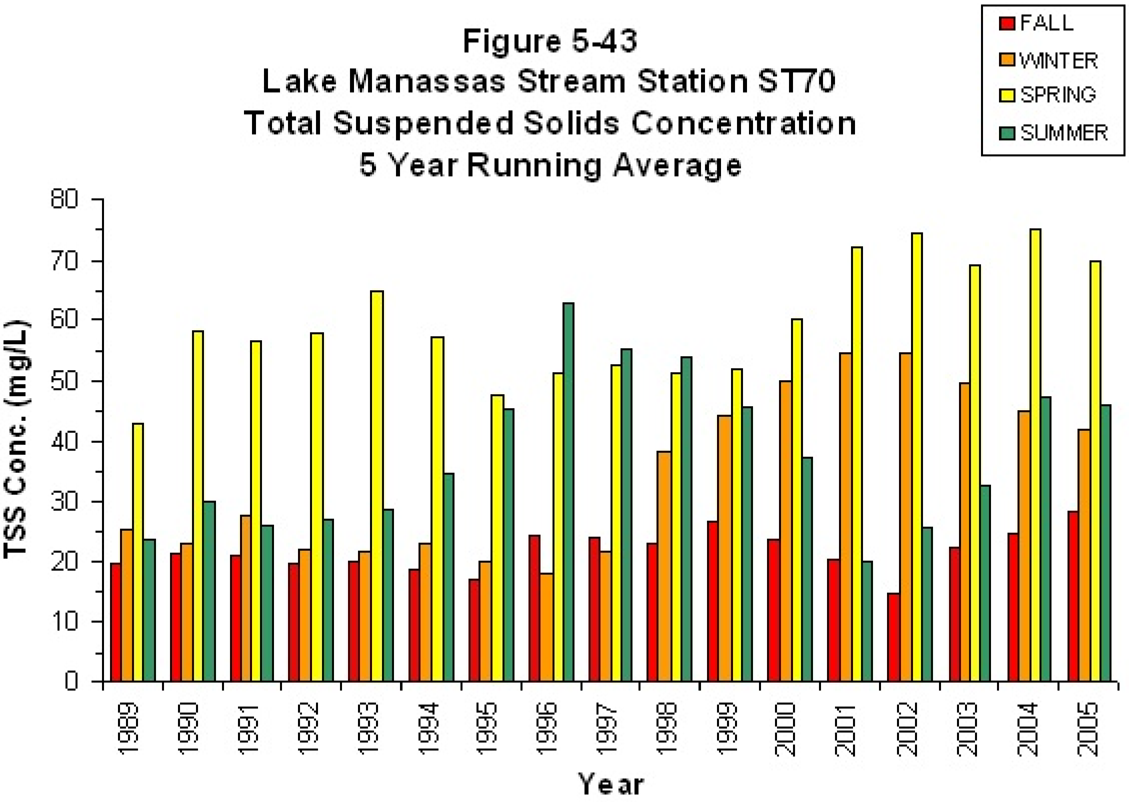


Figure 5-43
Lake Manassas Stream Station ST70
Total Suspended Solids Concentration
5 Year Running Average

1994 where the TSS concentration was 710 mg/L. The high concentrations recorded during the winter and spring months were most likely the result of high flows occurring during these months.

Nitrogen

The major source of nitrogen loading in streams originates from either surface runoff or ground water discharge. Additionally, small contributions from the atmosphere and plants should also be considered. The nitrogen cycle that takes place in streams and rivers is similar to that of lakes and is dominated by bacterial, fungal, and other microbial metabolism (Wetzel, 2001). Nitrogen is used frequently as it progresses downstream. The rate at which an atom of nitrogen is utilized and released is contingent upon the type and amount of microbiota attached to the stream bed (Wetzel, 2001). Increased microbiota populations will result in longer detention times of nitrogen in the streams. This analysis will consider three types of nitrogen: oxidized nitrogen (OX-N), ammonia nitrogen (NH_3-N), and total Kjeldahl nitrogen (TKN).

Five year running averages for all three types of nitrogen concentrations in the Lake Manassas stream stations are shown in Figures 5-44 through 5-64. All Mann-Kendall Seasonal trends referred to below can be found in Table 5-2. The most significant trend can be observed at station BR02 where a decreasing trend is present for all three types of nitrogen. A decreasing trend of TKN and an increasing trend of Ox-N were detected at station BR07.

Figure 5-44
Lake Manassas Stream Station BR02
Oxidized Nitrogen Concentration
5 Year Running Average

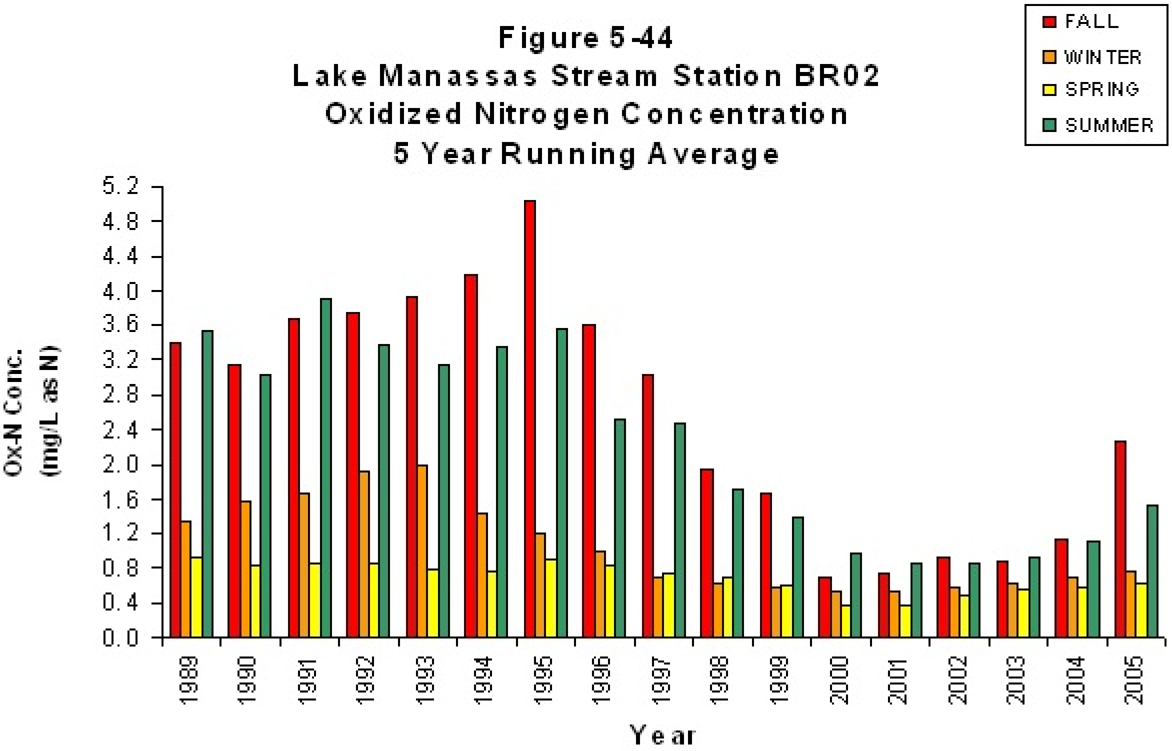
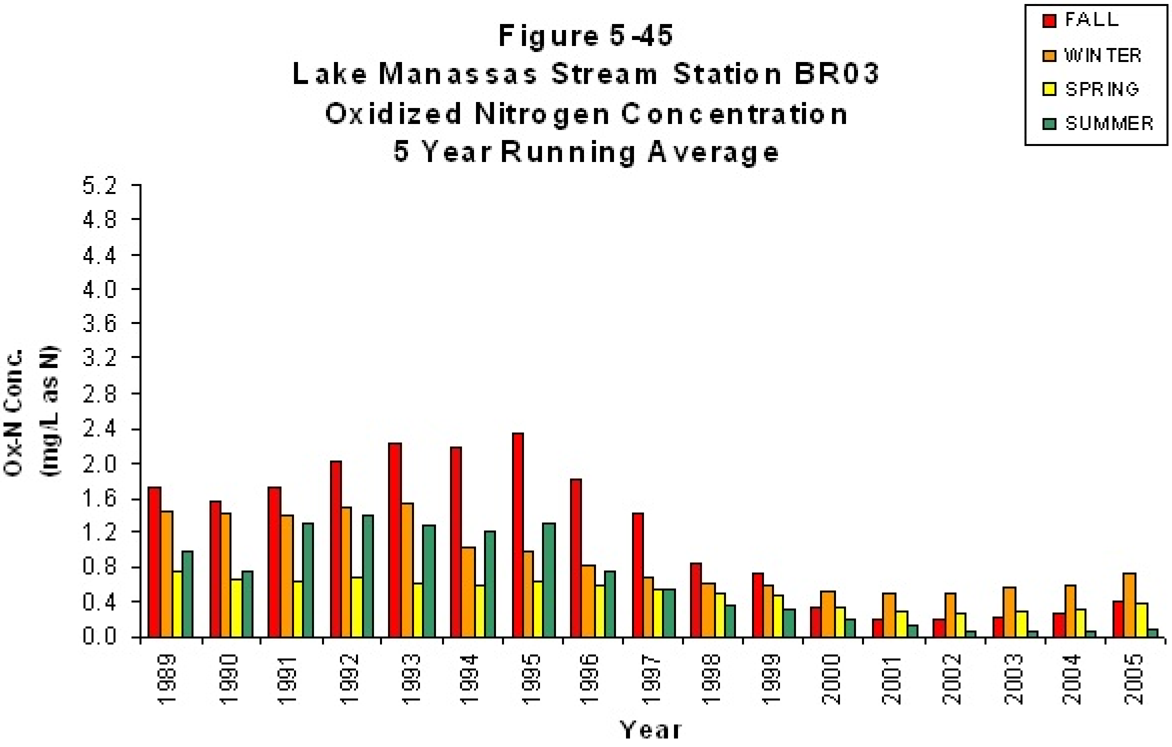


Figure 5-45
Lake Manassas Stream Station BR03
Oxidized Nitrogen Concentration
5 Year Running Average



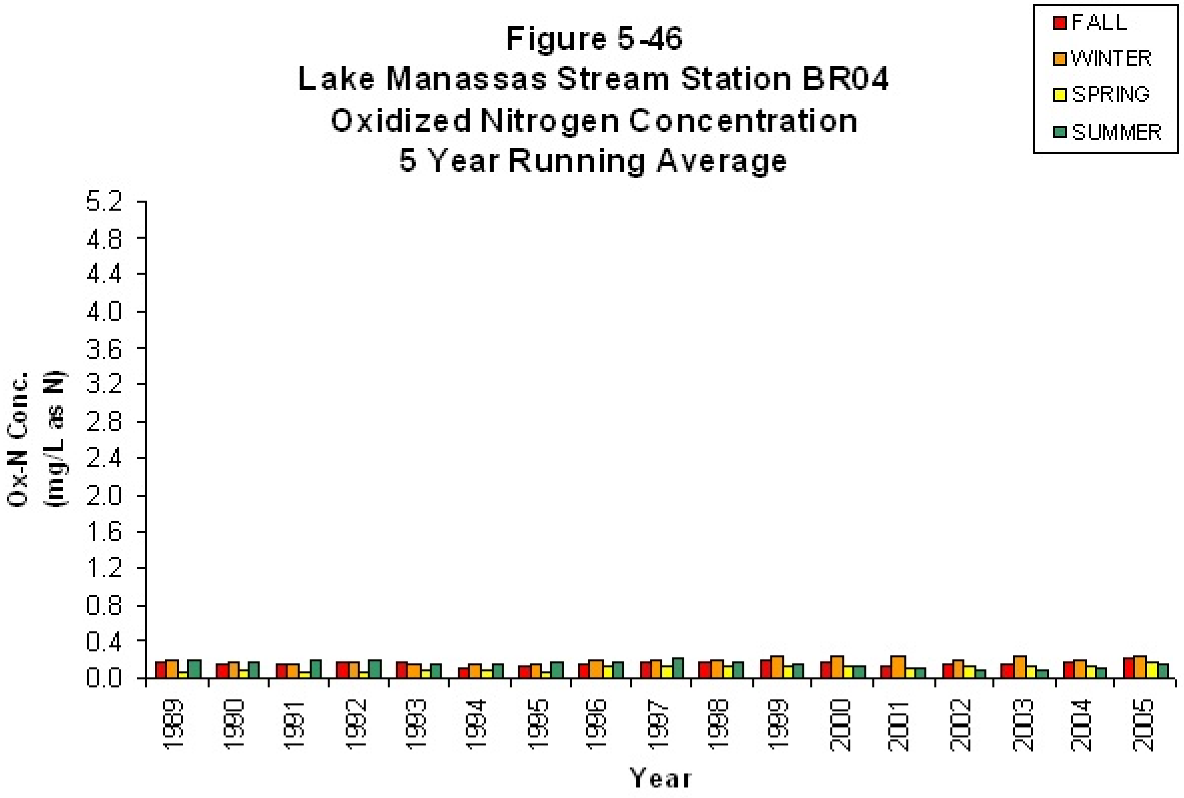


Figure 5-46
Lake Manassas Stream Station BR04
Oxidized Nitrogen Concentration
5 Year Running Average

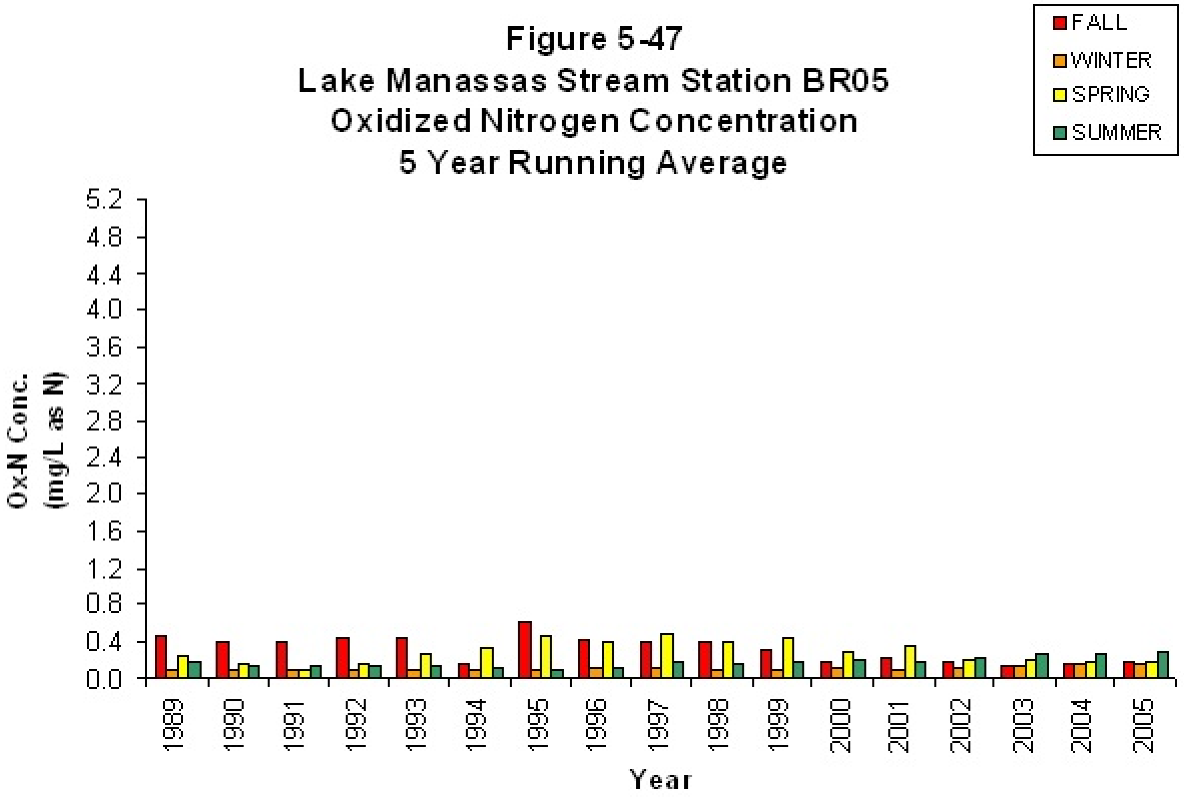


Figure 5-47
Lake Manassas Stream Station BR05
Oxidized Nitrogen Concentration
5 Year Running Average

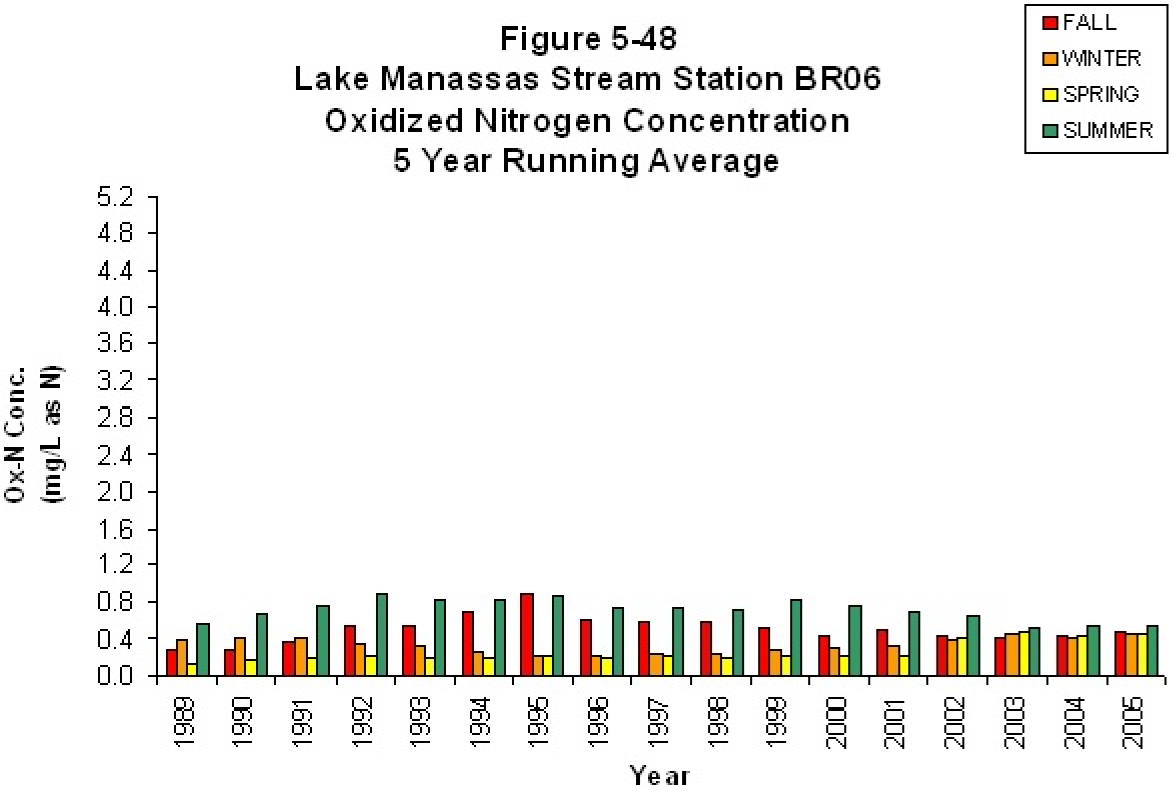


Figure 5-48
Lake Manassas Stream Station BR06
Oxidized Nitrogen Concentration
5 Year Running Average

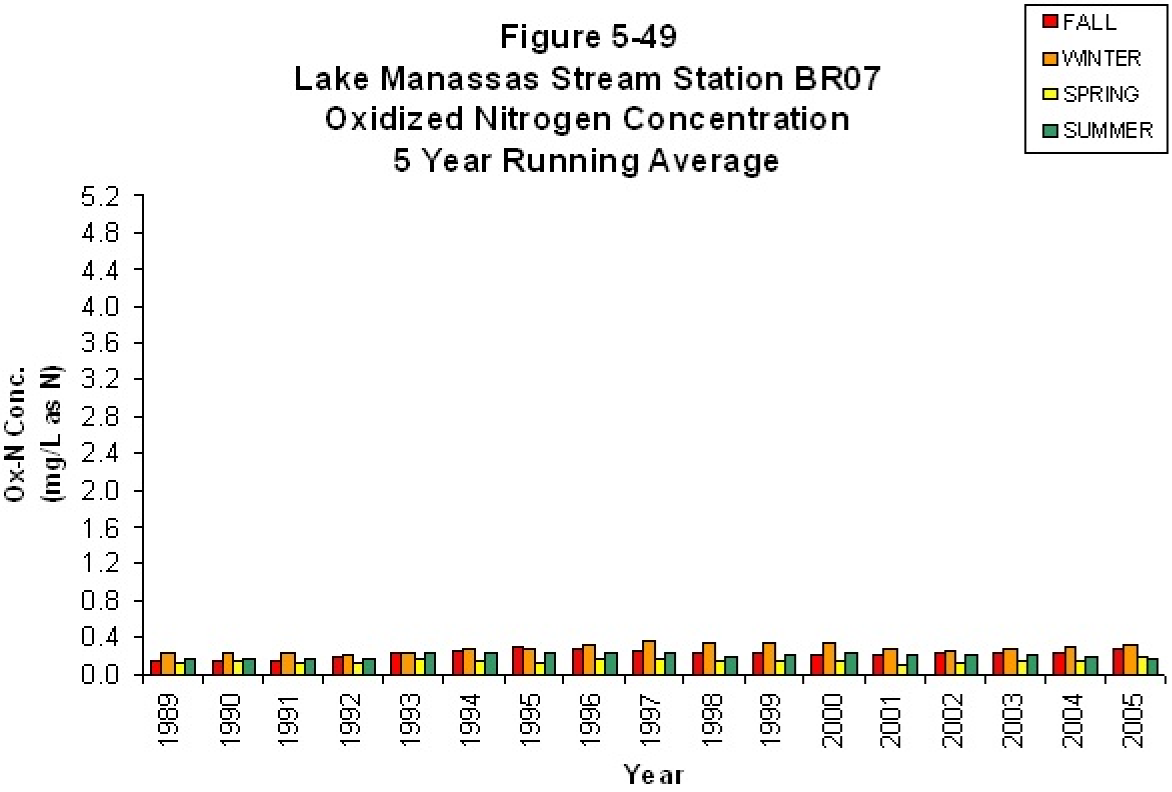


Figure 5-49
Lake Manassas Stream Station BR07
Oxidized Nitrogen Concentration
5 Year Running Average

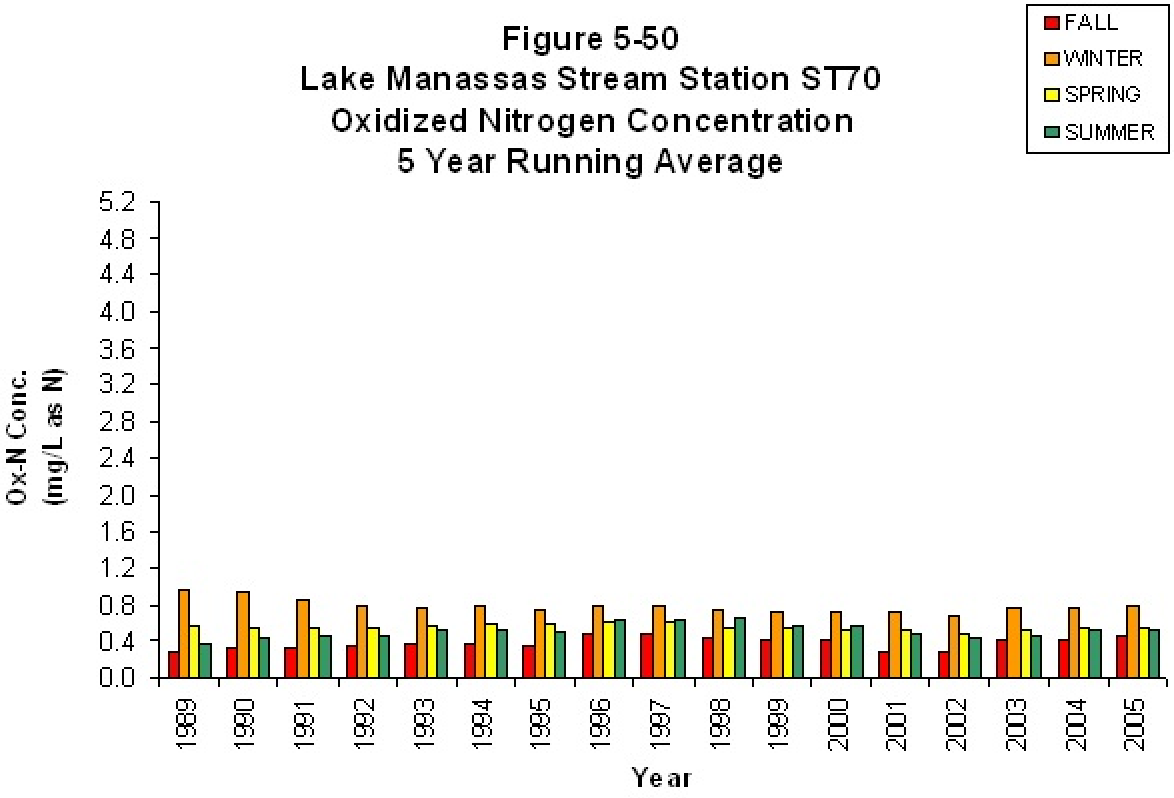


Figure 5-50
Lake Manassas Stream Station ST70
Oxidized Nitrogen Concentration
5 Year Running Average

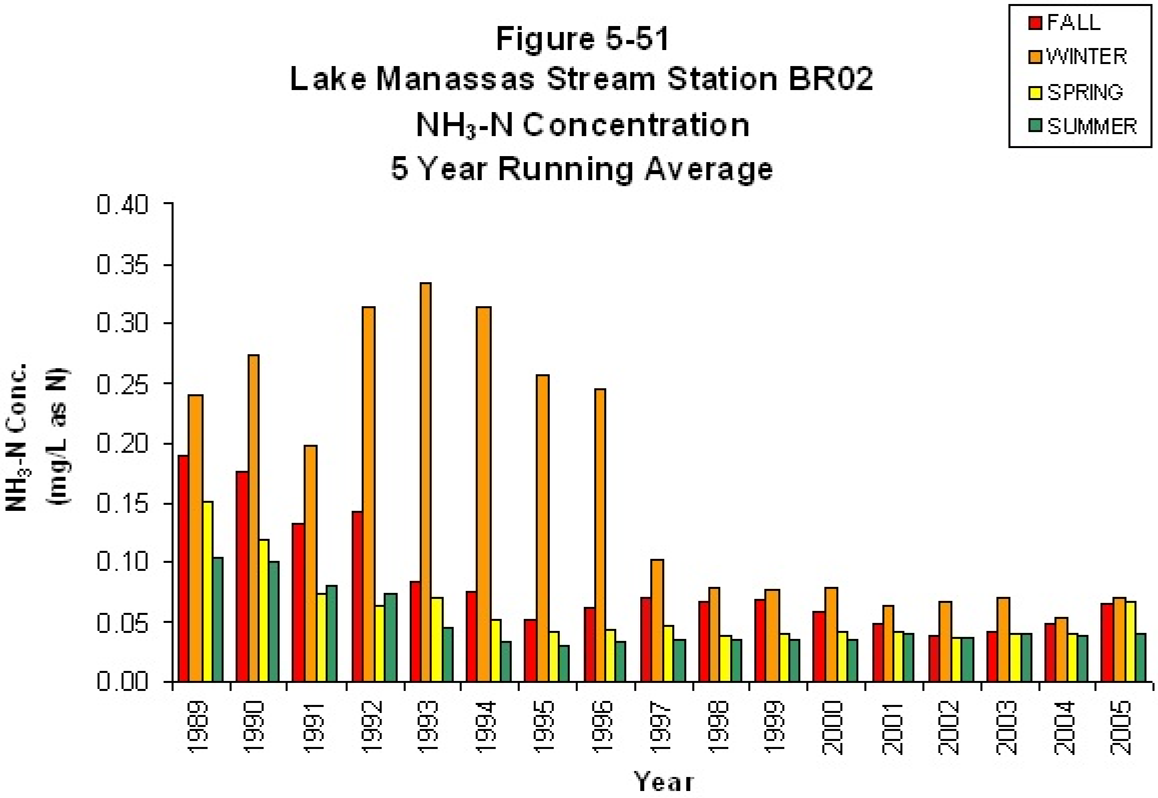


Figure 5-51
Lake Manassas Stream Station BR02
NH_3-N Concentration
5 Year Running Average

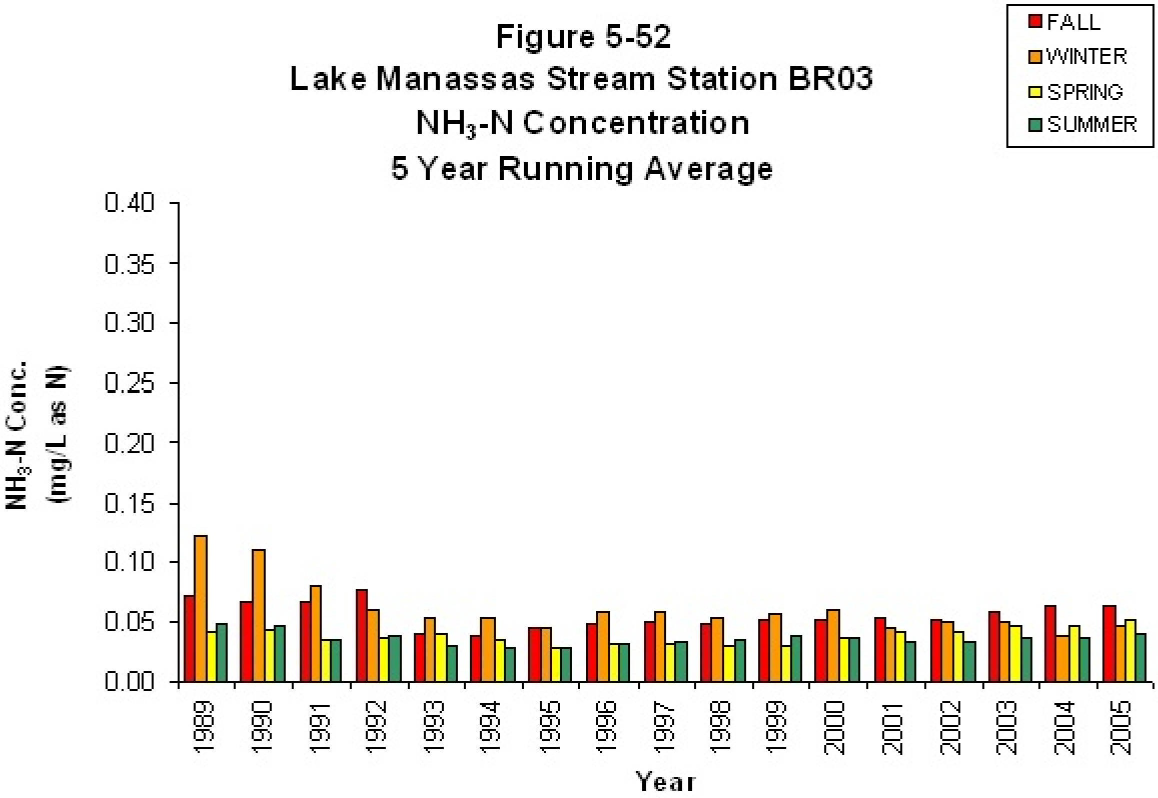


Figure 5-52
Lake Manassas Stream Station BR03
NH_3-N Concentration
5 Year Running Average

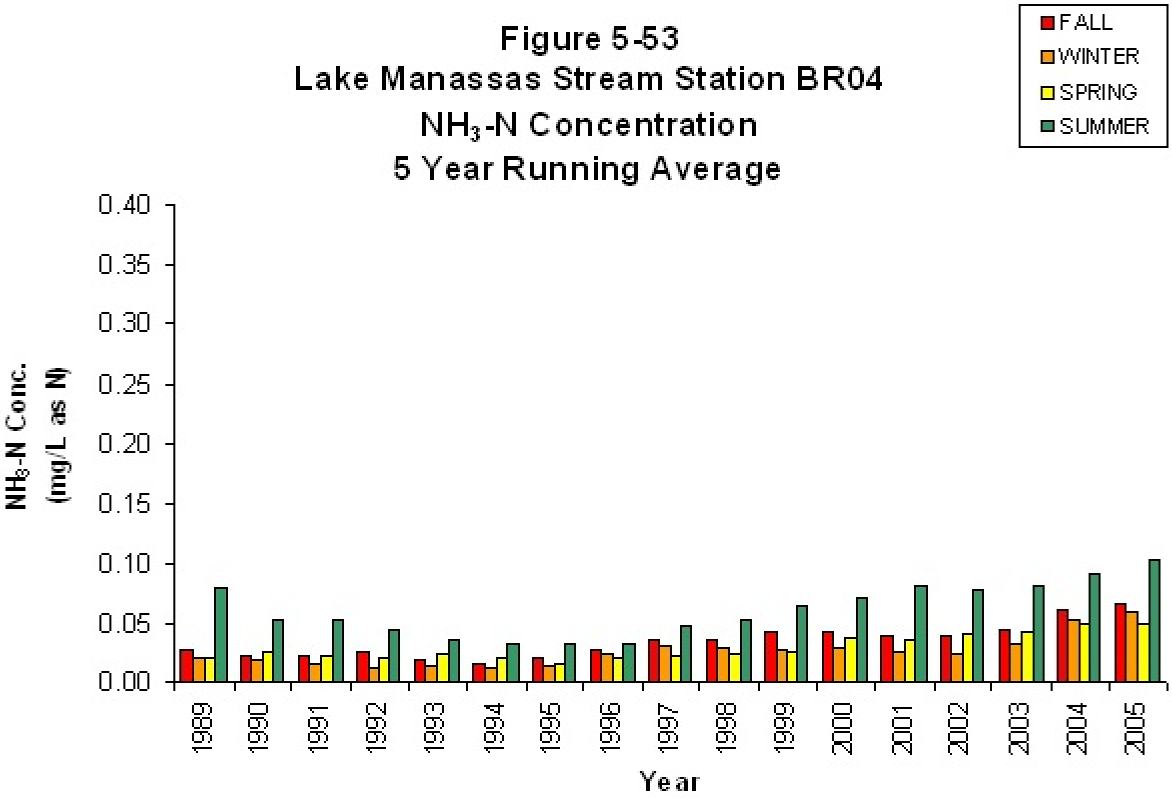


Figure 5-53
Lake Manassas Stream Station BR04
NH_3-N Concentration
5 Year Running Average

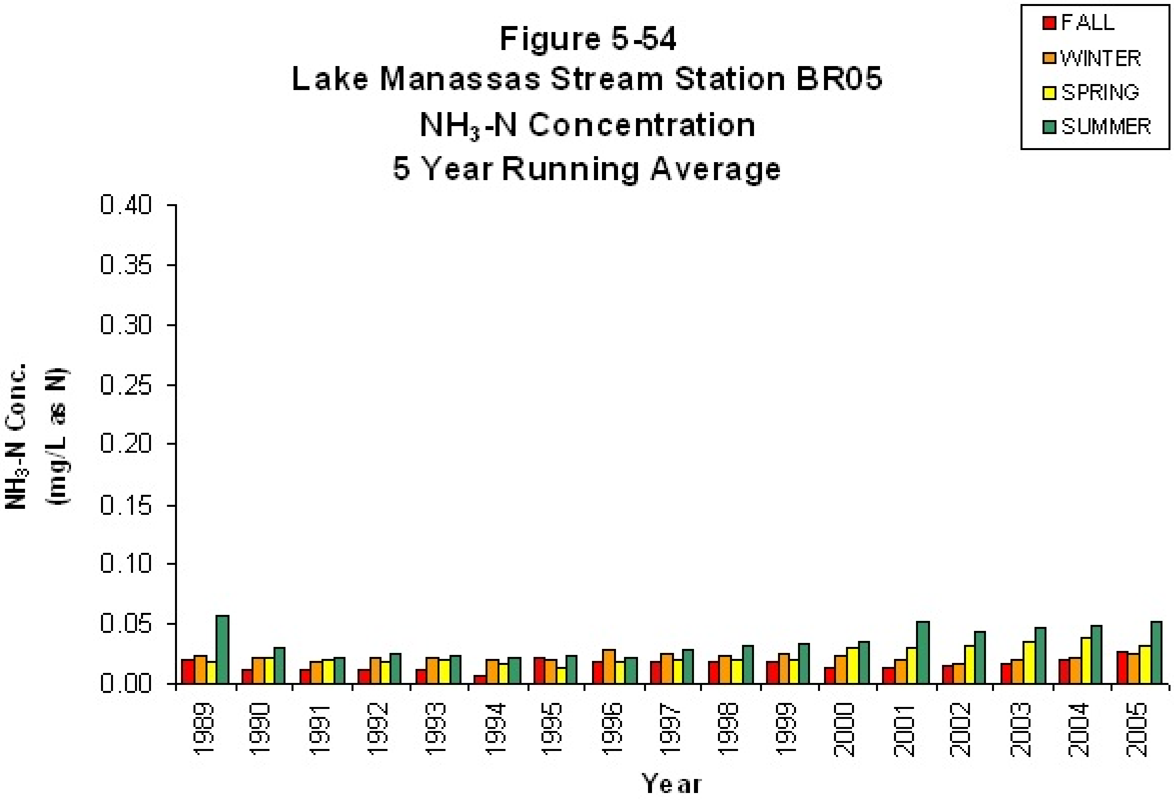


Figure 5-54
Lake Manassas Stream Station BR05
NH_3-N Concentration
5 Year Running Average

Figure 5-55
Lake Manassas Stream Station BR06
NH_3-N Concentration
5 Year Running Average

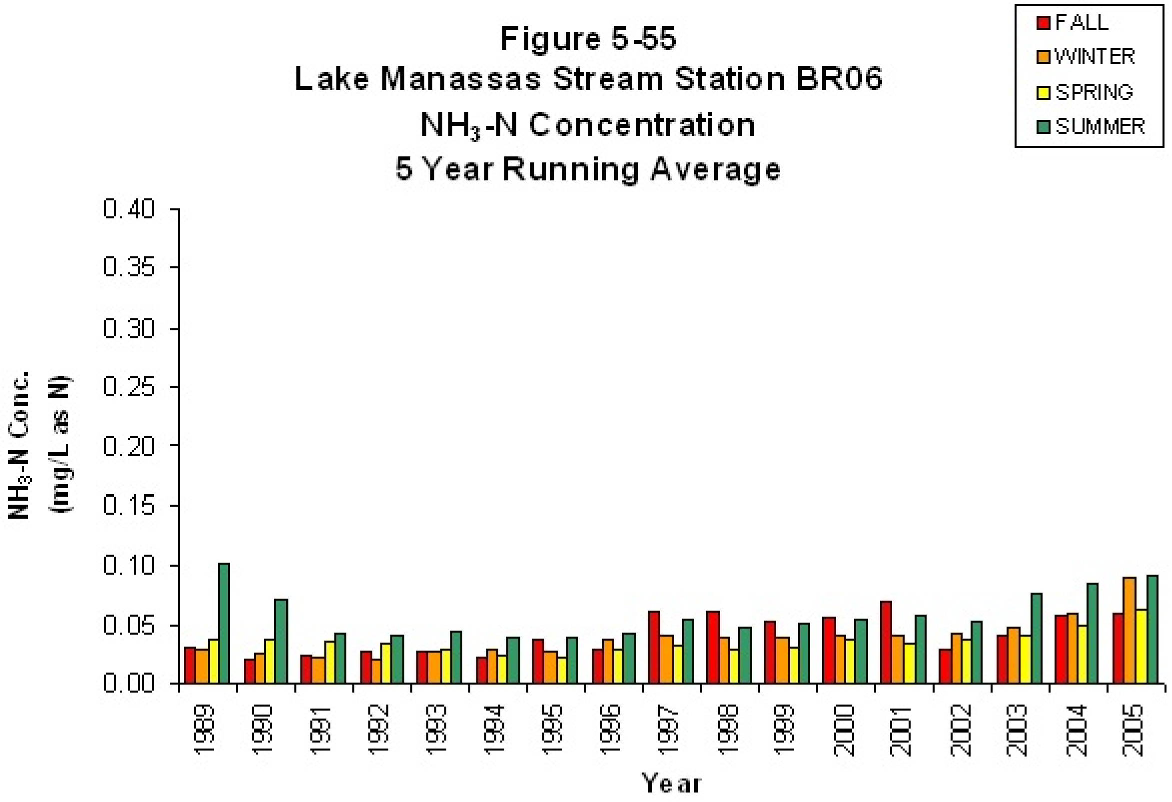
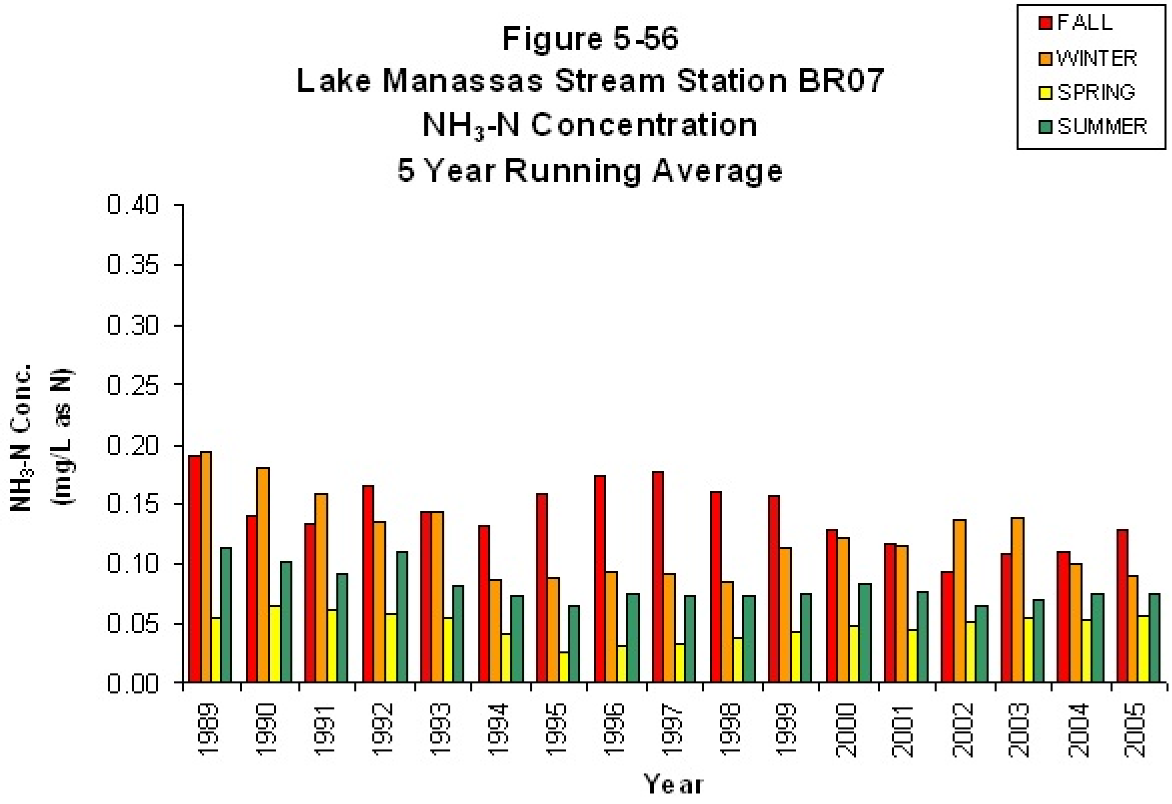


Figure 5-56
Lake Manassas Stream Station BR07
NH_3-N Concentration
5 Year Running Average



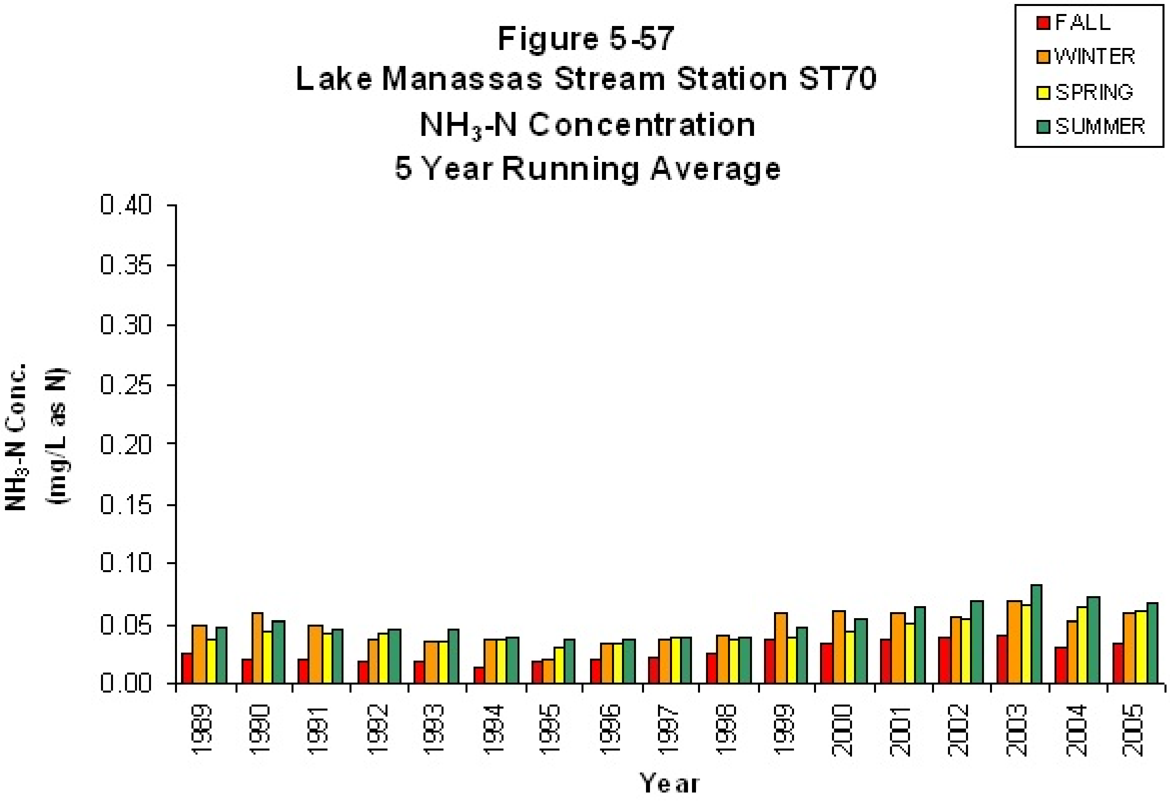


Figure 5-57
Lake Manassas Stream Station ST70
NH_3-N Concentration
5 Year Running Average

Figure 5-58
Lake Manassas Stream Station BR02
Total Kjeldahl Nitrogen Concentration
5 Year Running Average

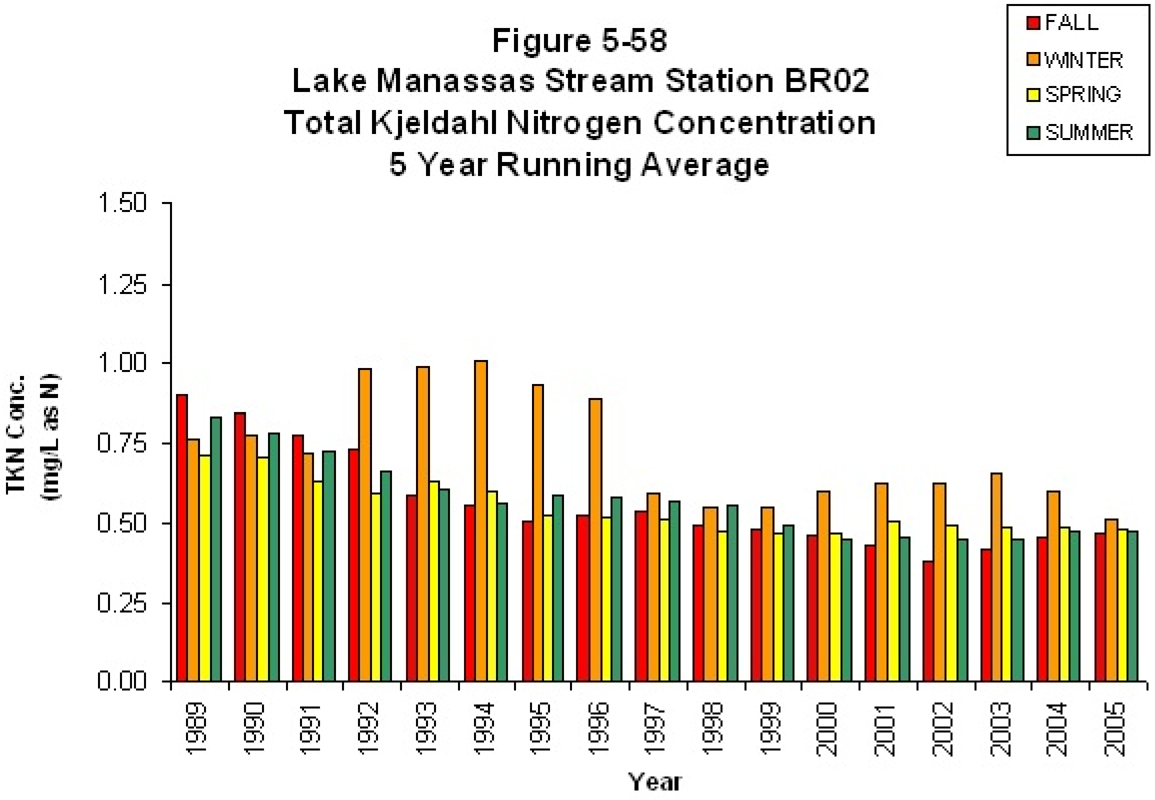


Figure 5-59
Lake Manassas Stream Station BR03
Total Kjeldahl Nitrogen Concentration
5 Year Running Average

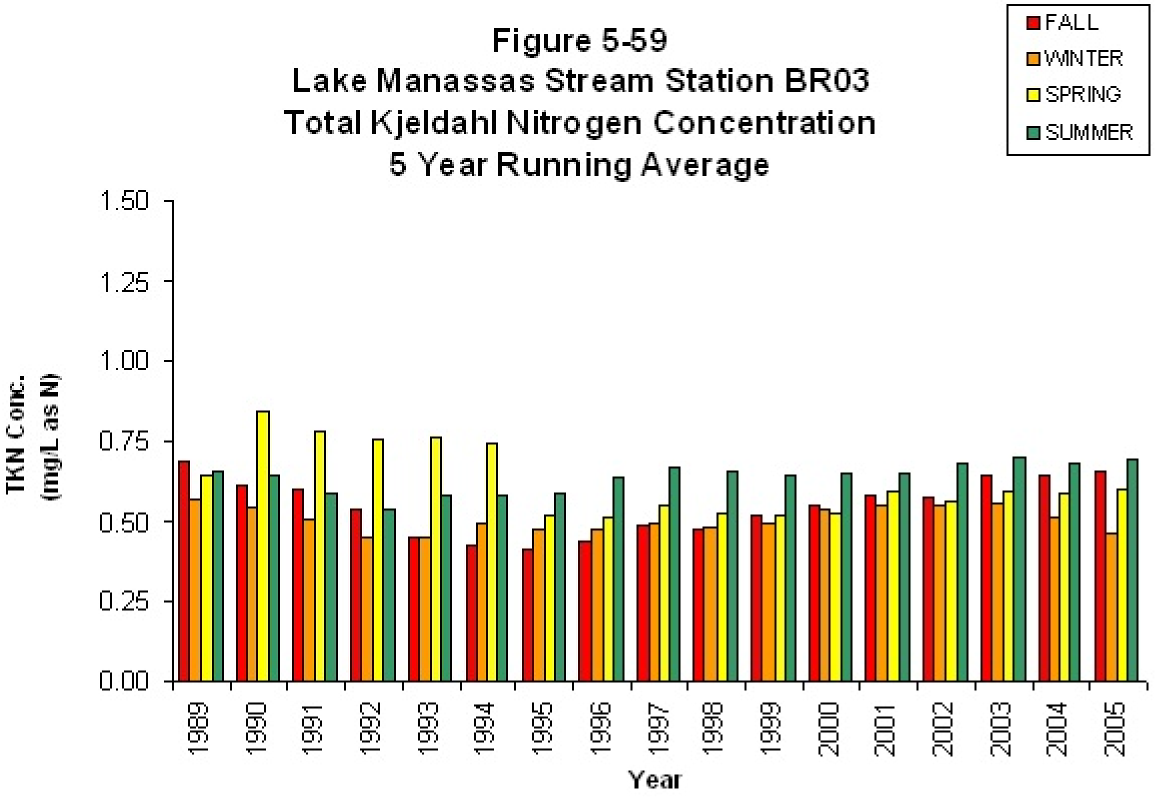


Figure 5-60
Lake Manassas Stream Station BR04
Total Kjeldahl Nitrogen Concentration
5 Year Running Average

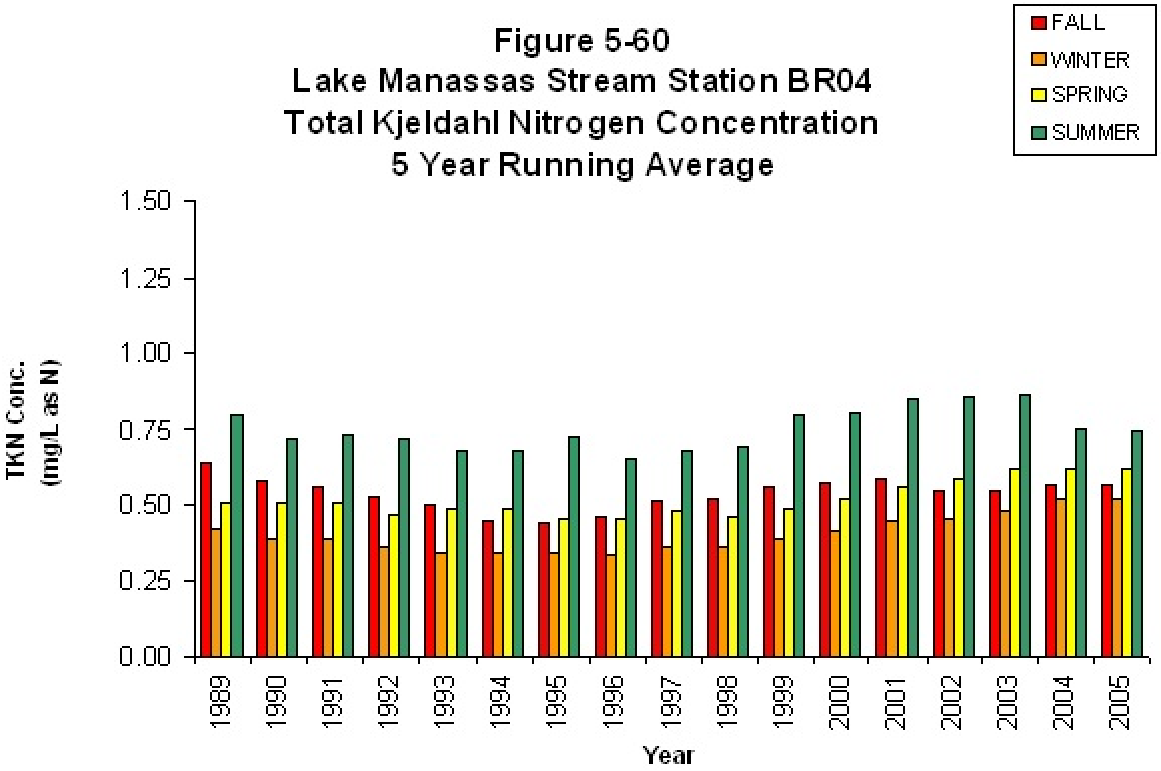
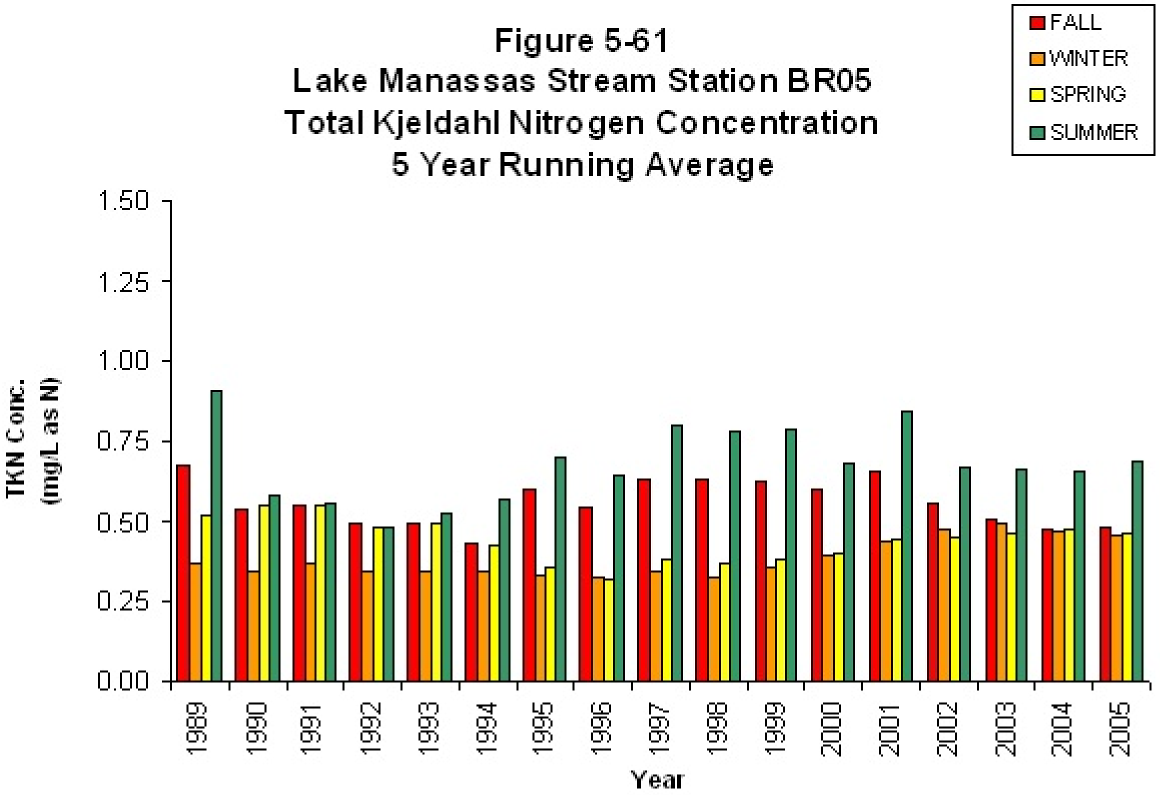


Figure 5-61
Lake Manassas Stream Station BR05
Total Kjeldahl Nitrogen Concentration
5 Year Running Average



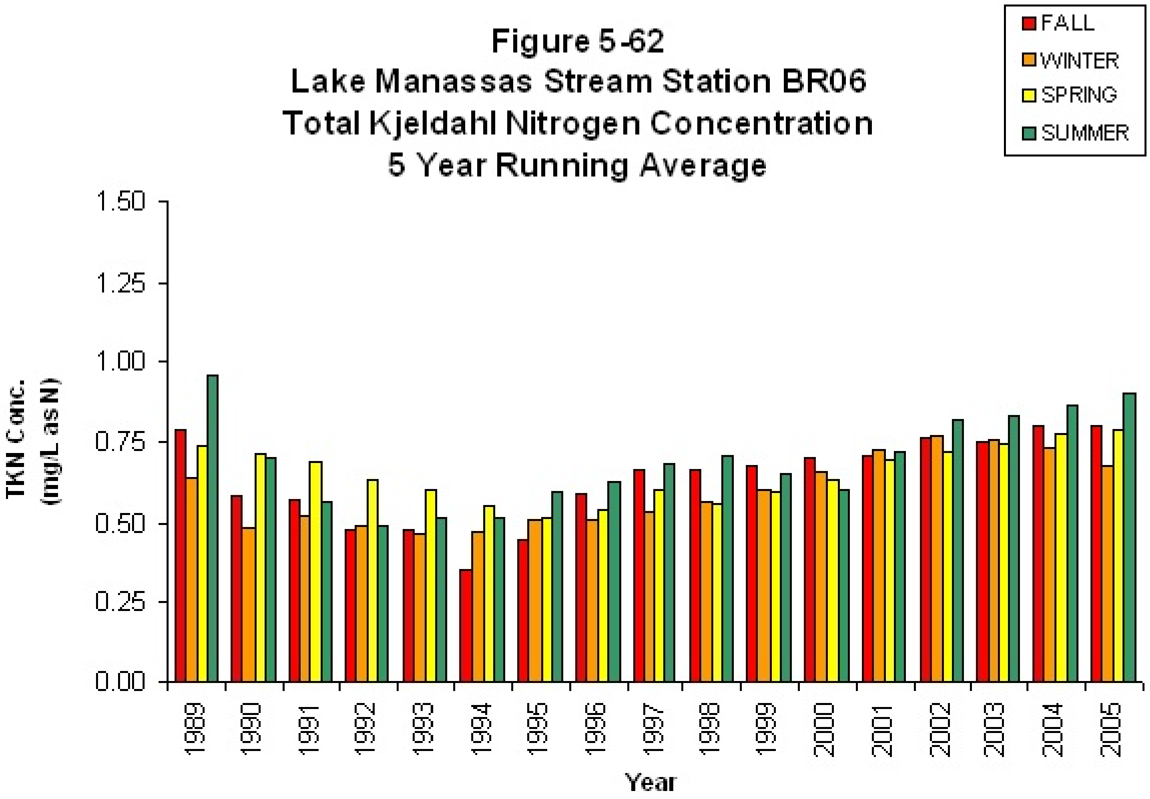


Figure 5-62
Lake Manassas Stream Station BR06
Total Kjeldahl Nitrogen Concentration
5 Year Running Average

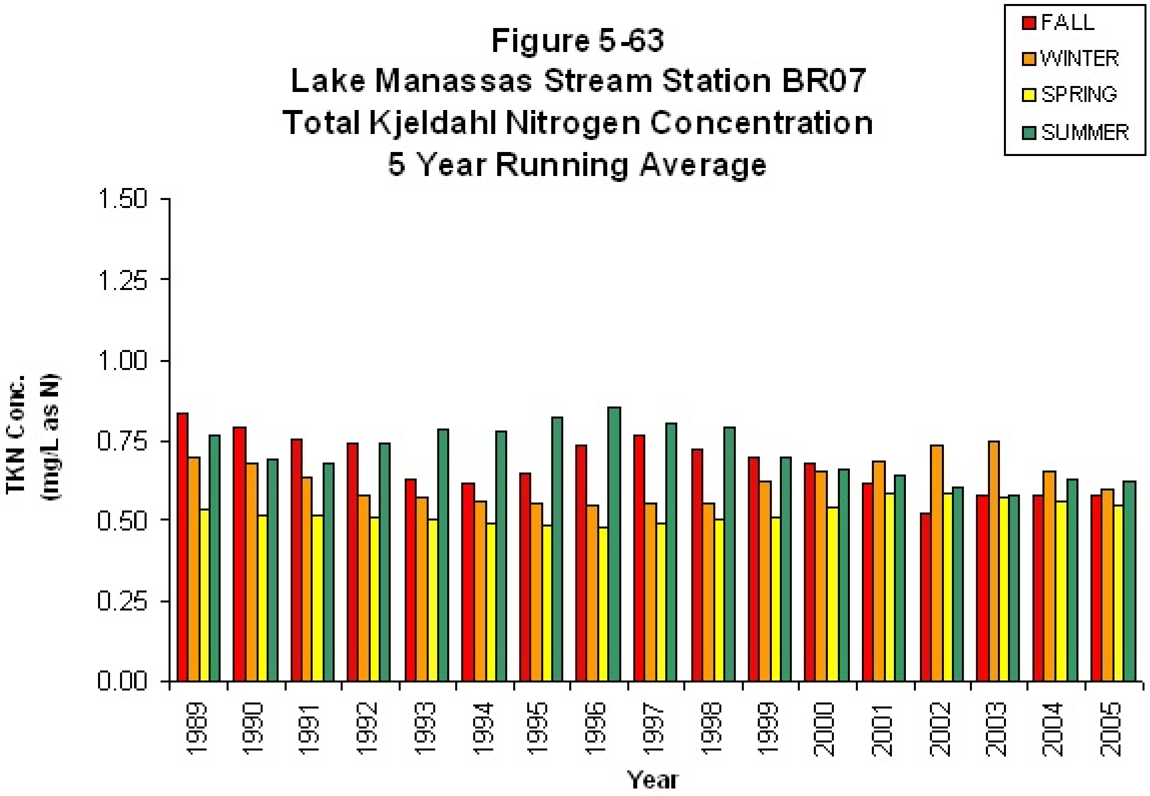


Figure 5-63
Lake Manassas Stream Station BR07
Total Kjeldahl Nitrogen Concentration
5 Year Running Average

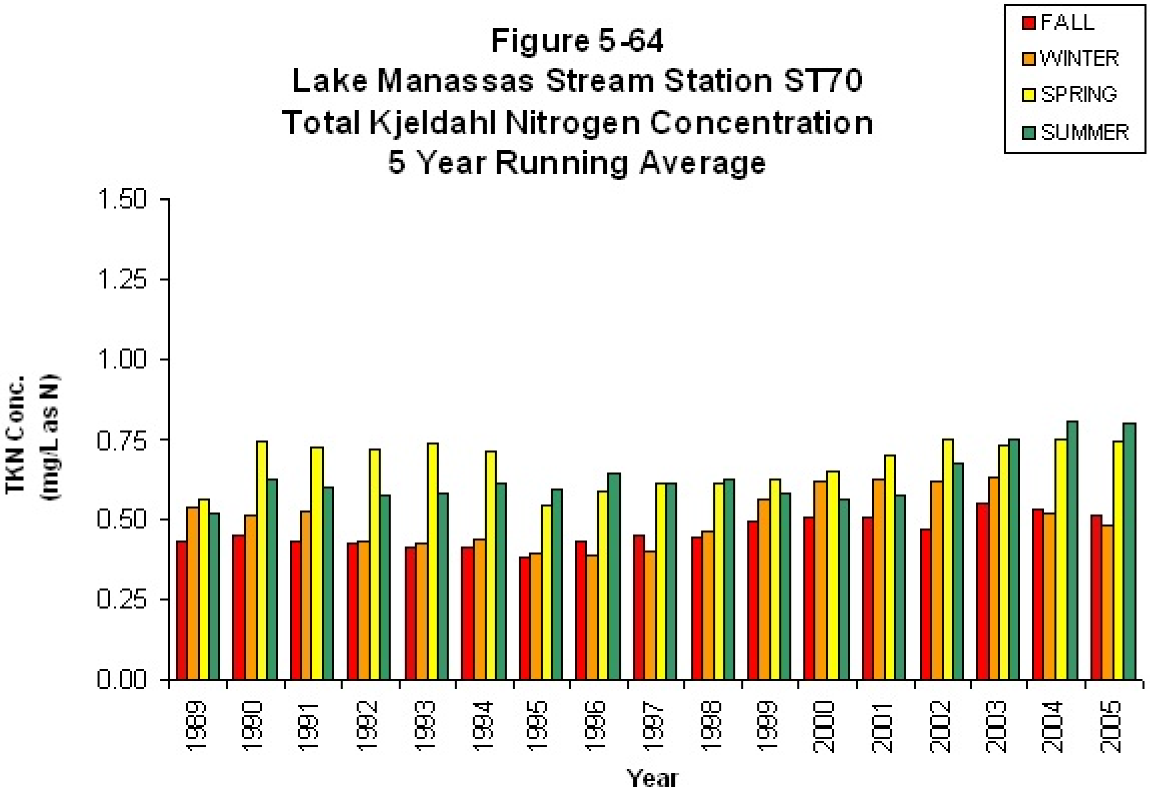


Figure 5-64
Lake Manassas Stream Station ST70
Total Kjeldahl Nitrogen Concentration
5 Year Running Average

The increasing trend of Ox-N should not be of great concern because this station is located above the Vint Hill Wastewater Treatment Plant. A decreasing trend of Ox-N was observed at station BR03. The data for this station did not support trends for any other types of nitrogen. Increasing trends of NH_3-N were observed at stations BR04, BR05, and BR06. Additionally, increasing trends of Ox-N were present at stations BR04 and BR06. No other trends, with respect to nitrogen forms, were observed at these three stations. As stated earlier, stations BR04, BR05, and BR06 drain agricultural lands. The increasing trends of NH_3-N and Ox-N could be attributed to increasing nutrient runoff from these lands. Station ST70 experienced increasing trends of NH_3-N and TKN. This station is located on Broad Run which is the main source of nutrient loading to Lake Manassas.

During the fall of 1988 the greatest value of NH_3-N and Ox-N equal to 2.17 and 20.9 mg/L as nitrogen, respectively, were measured at station BR02. The maximum value of TKN, equal to 2.09 mg/L as N, was recorded at station BR02 during the winter of 1992.

There is no one particular season that consistently has higher concentrations of nitrogen forms than another. However, during the last five years the fall has typically had the lowest concentrations. Given that the fall months ordinarily experience low flow conditions, the resulting nutrient loading into the streams would therefore be reduced.

Phosphorus

Phosphorus plays an integral role in biological metabolism (Wetzel, 2001). When compared to other nutrients, phosphorus is typically the least abundant. This commonly results in phosphorus limiting biological productivity. Phosphorus exists in both dissolved and suspended forms in water. Dissolved phosphorus is generally more abundant in rivers than in lakes and shows marked increases following rainfall events. Dissolved phosphorus can be further broken down into organic and inorganic forms. The organic version of dissolved phosphorus is utilized slower than inorganic dissolved phosphorus (Wetzel, 2001). The slower rates of utilization produce an accumulation of phosphorus compounds in the water column. These compounds are then exported downstream for subsequent utilization. The only directly utilizable form of soluble inorganic phosphorus is orthophosphate (PO_4^{3-}). Under oxidizing conditions, phosphate reacts with many cations (e.g., Fe^{2+}, Fe^{3+}, and Ca^{2+}) to form insoluble compounds that precipitate out of the water. The presence of phosphate can also be affected by adsorption to inorganic colloids such as clays, carbonates, and hydroxides.

The two different types of phosphorus that will be examined are Orthophosphate Phosphorus (OP) and Total Phosphorus (TP). Five year running averages for these forms of phosphorus are shown in Figures 5-65 through 5-78. The Mann-Kendall seasonal analysis for all forms of phosphorus can be found in Table 5-2. Examining the stations along the South Fork, decreasing trends of OP were observed at stations BR02 and BR03. No trends were reported at station BR07.

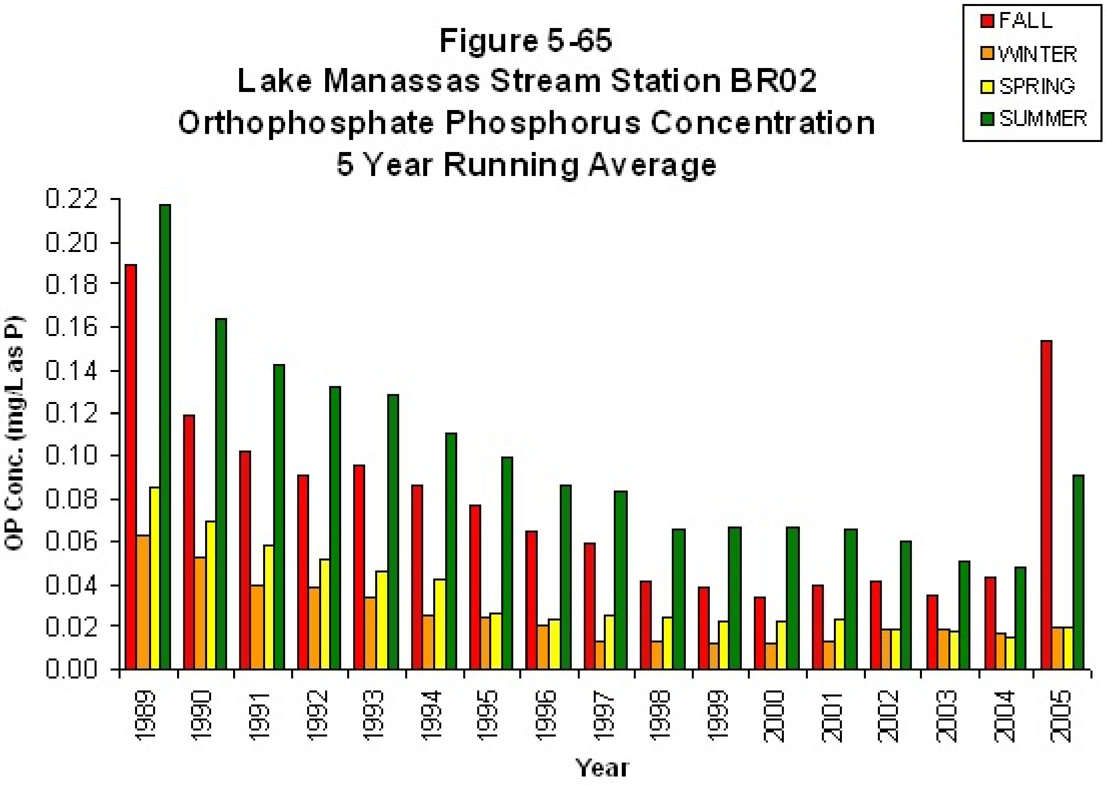


Figure 5-65
Lake Manassas Stream Station BR02
Orthophosphate Phosphorus Concentration
5 Year Running Average

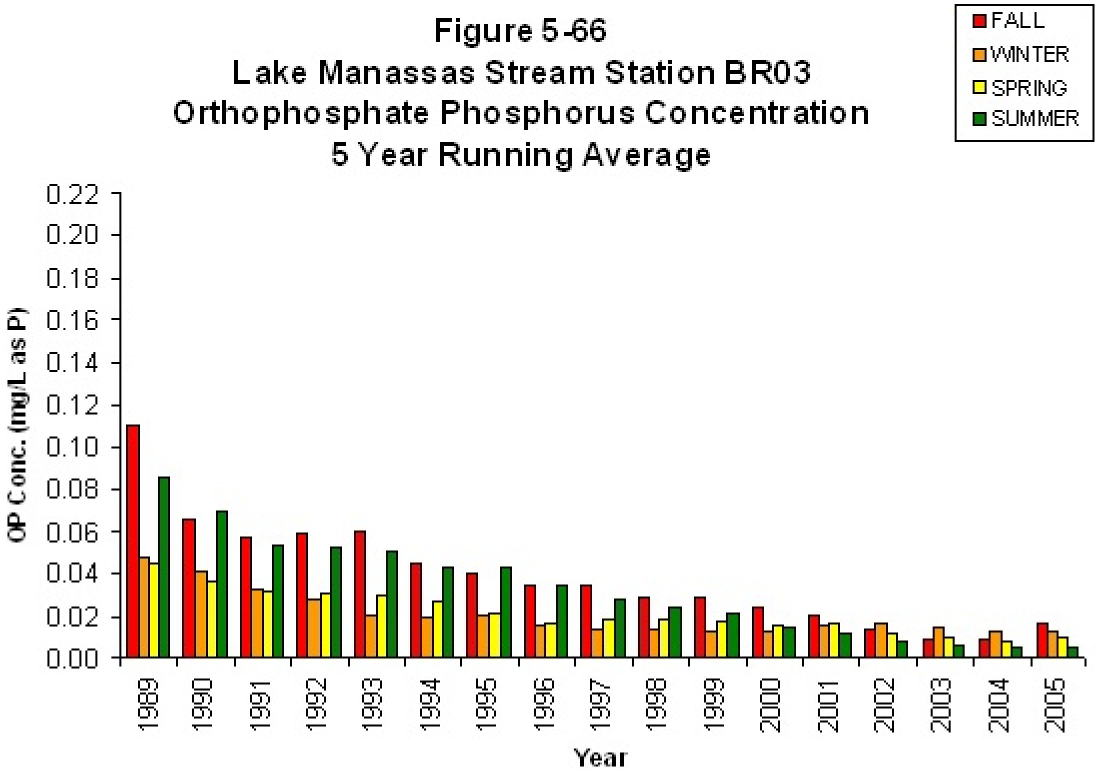


Figure 5-66
Lake Manassas Stream Station BR03
Orthophosphate Phosphorus Concentration
5 Year Running Average

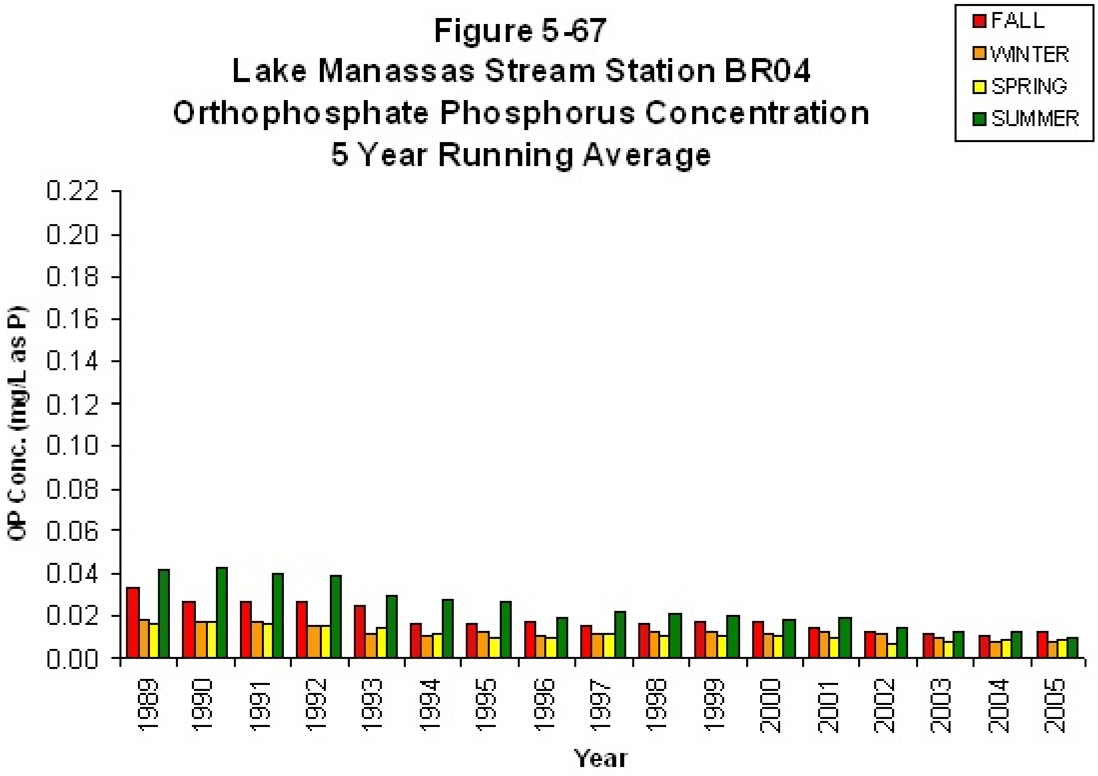


Figure 5-67
Lake Manassas Stream Station BR04
Orthophosphate Phosphorus Concentration
5 Year Running Average

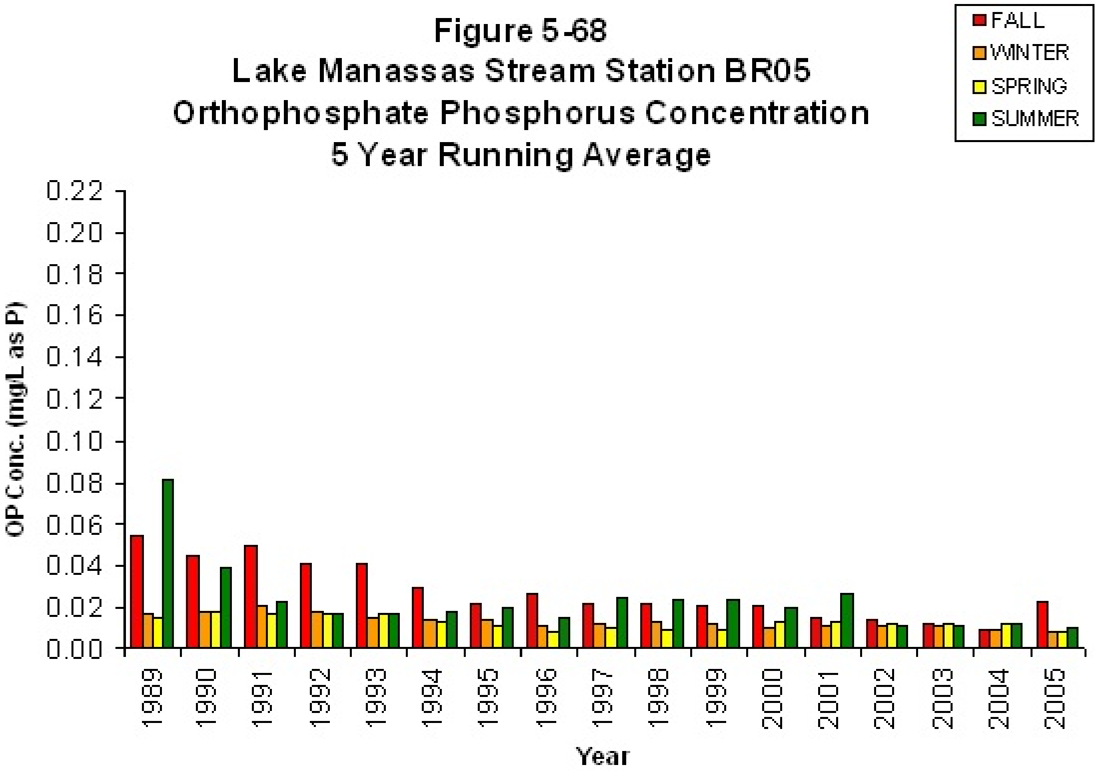


Figure 5-68
Lake Manassas Stream Station BR05
Orthophosphate Phosphorus Concentration
5 Year Running Average

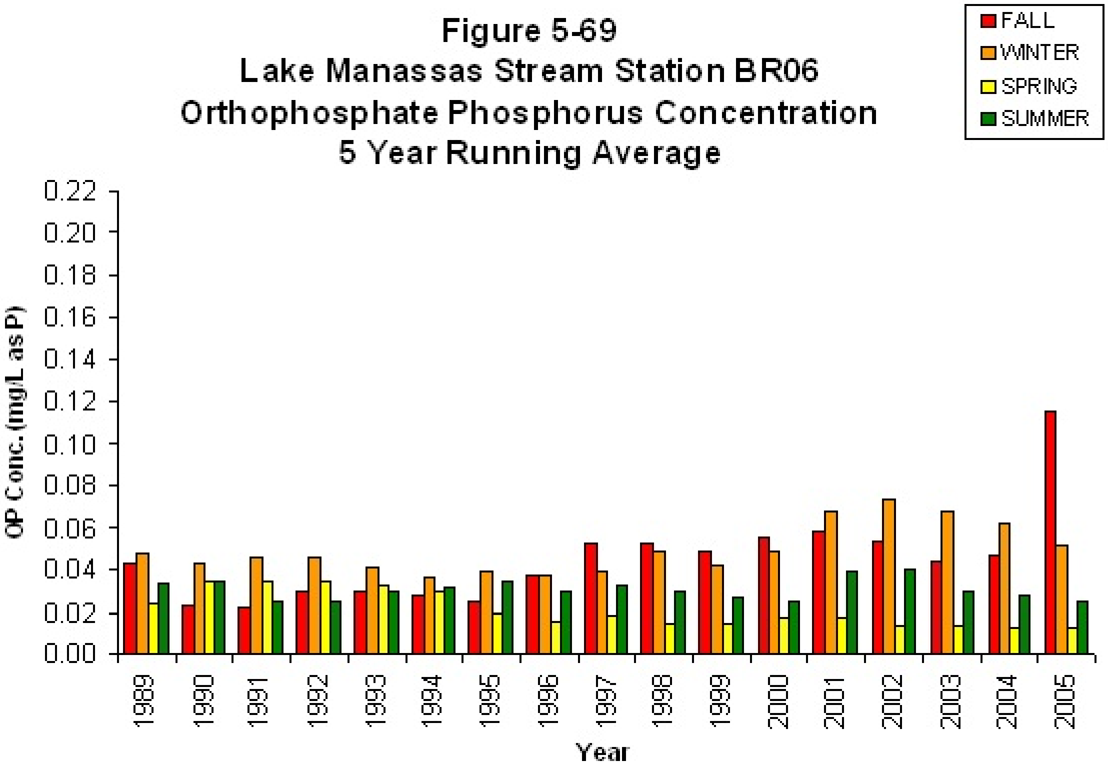


Figure 5-69
Lake Manassas Stream Station BR06
Orthophosphate Phosphorus Concentration
5 Year Running Average

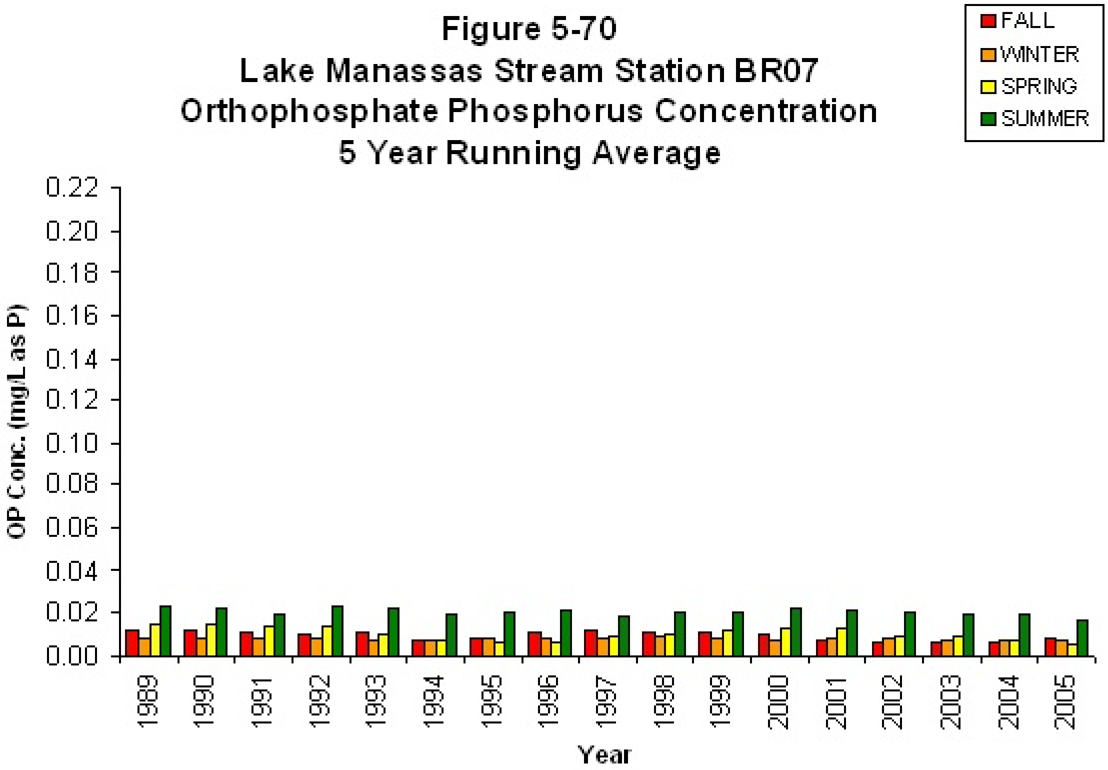


Figure 5-70
Lake Manassas Stream Station BR07
Orthophosphate Phosphorus Concentration
5 Year Running Average

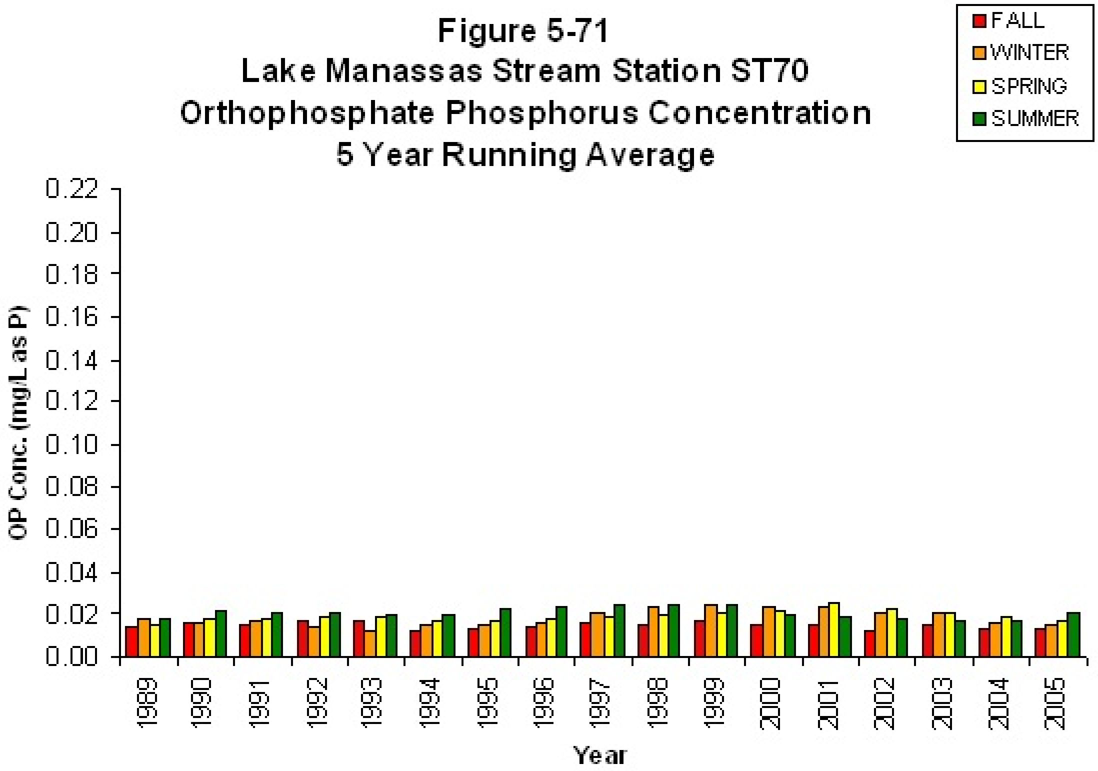


Figure 5-71
Lake Manassas Stream Station ST70
Orthophosphate Phosphorus Concentration
5 Year Running Average

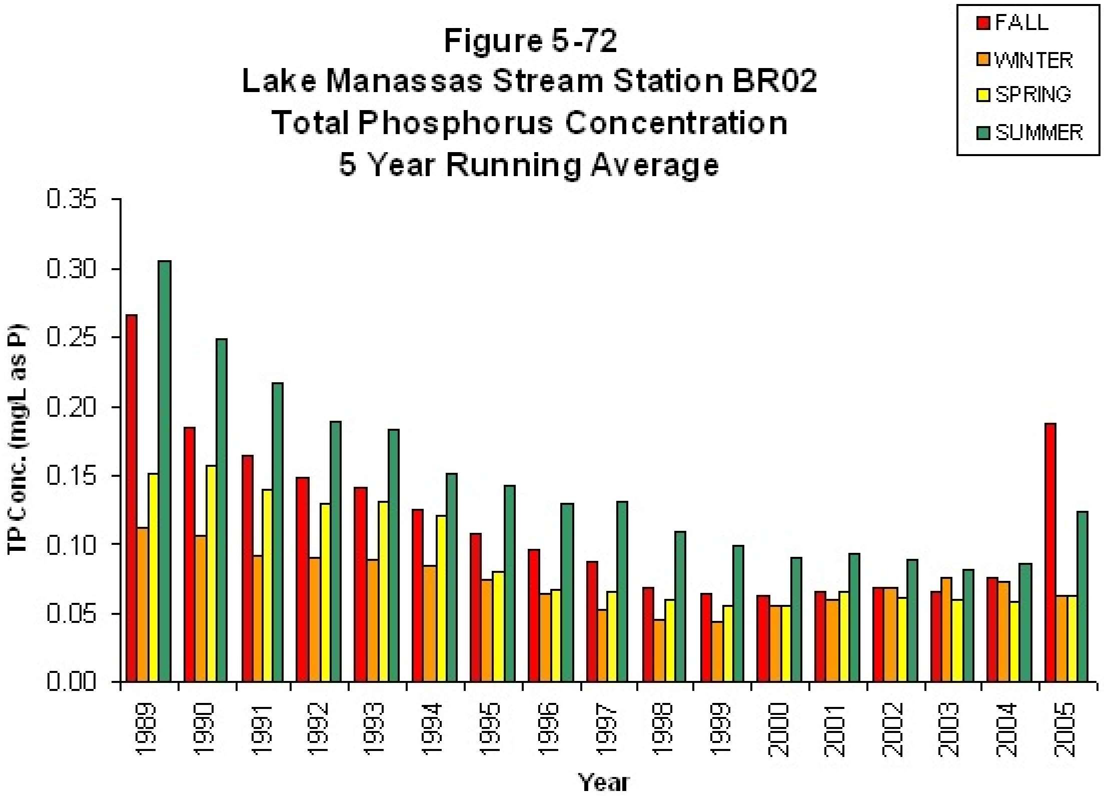


Figure 5-72
Lake Manassas Stream Station BR02
Total Phosphorus Concentration
5 Year Running Average

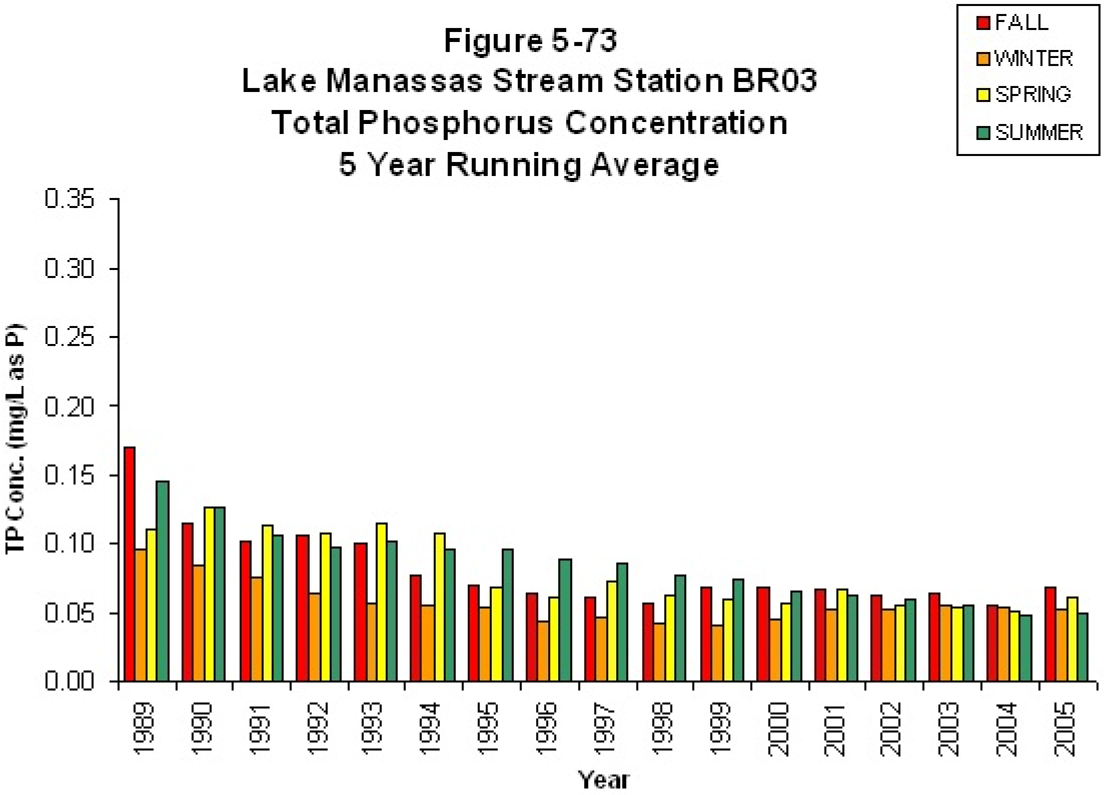


Figure 5-73
Lake Manassas Stream Station BR03
Total Phosphorus Concentration
5 Year Running Average

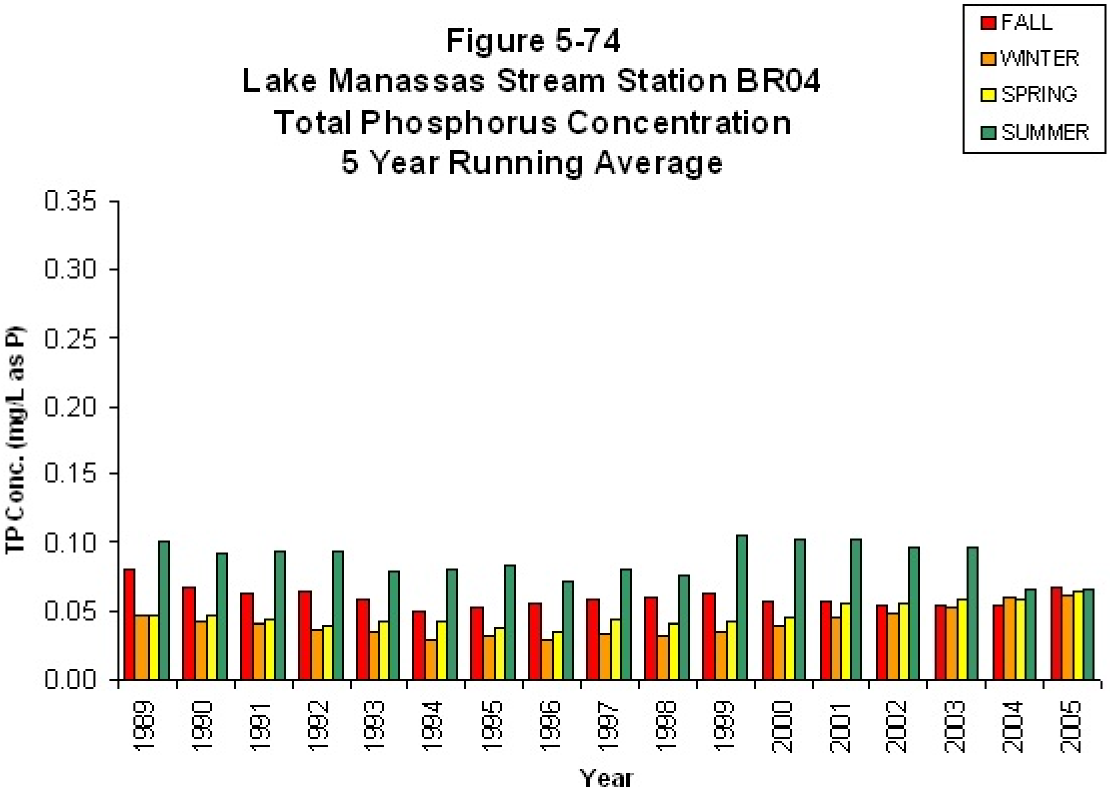


Figure 5-74
Lake Manassas Stream Station BR04
Total Phosphorus Concentration
5 Year Running Average

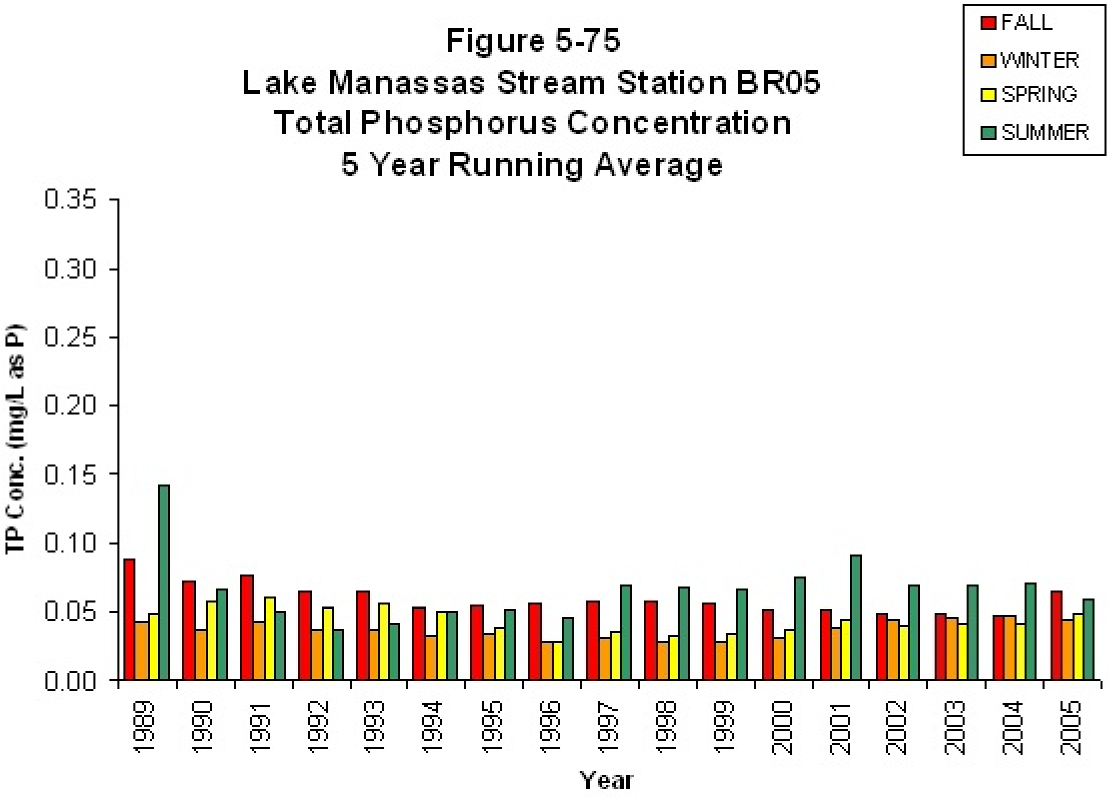


Figure 5-75
Lake Manassas Stream Station BR05
Total Phosphorus Concentration
5 Year Running Average

Figure 5-76
Lake Manassas Stream Station BR06
Total Phosphorus Concentration
5 Year Running Average

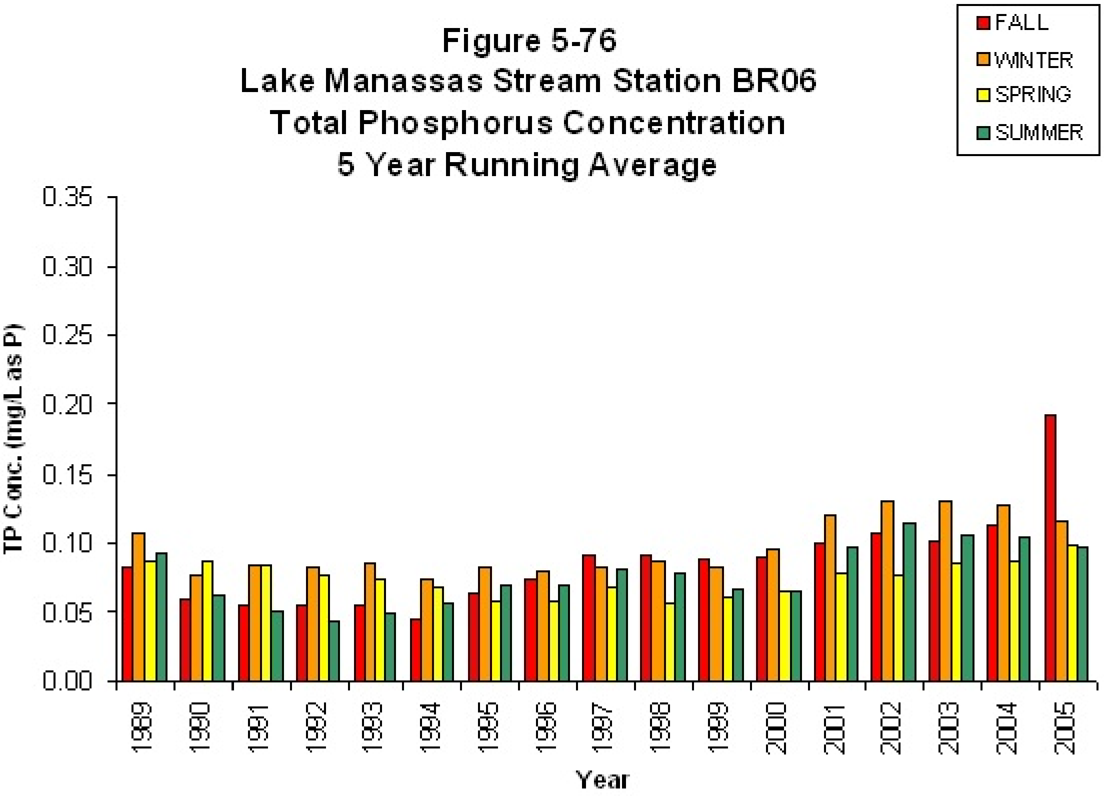
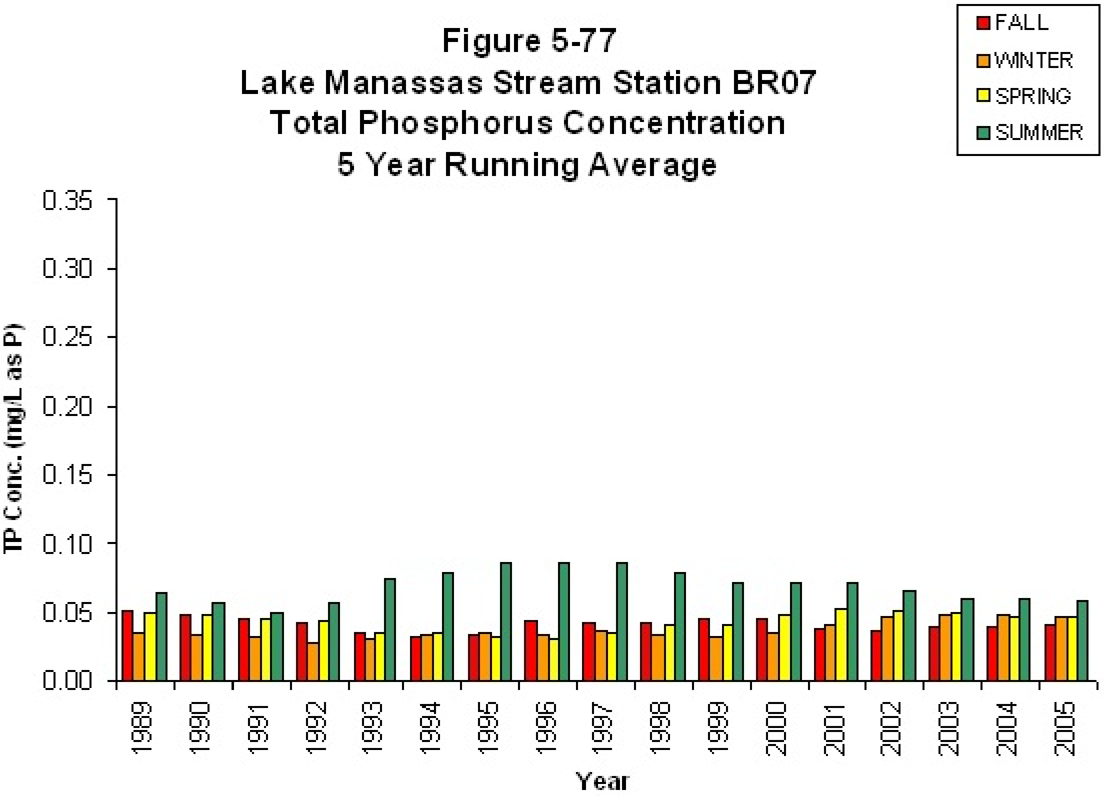


Figure 5-77
Lake Manassas Stream Station BR07
Total Phosphorus Concentration
5 Year Running Average



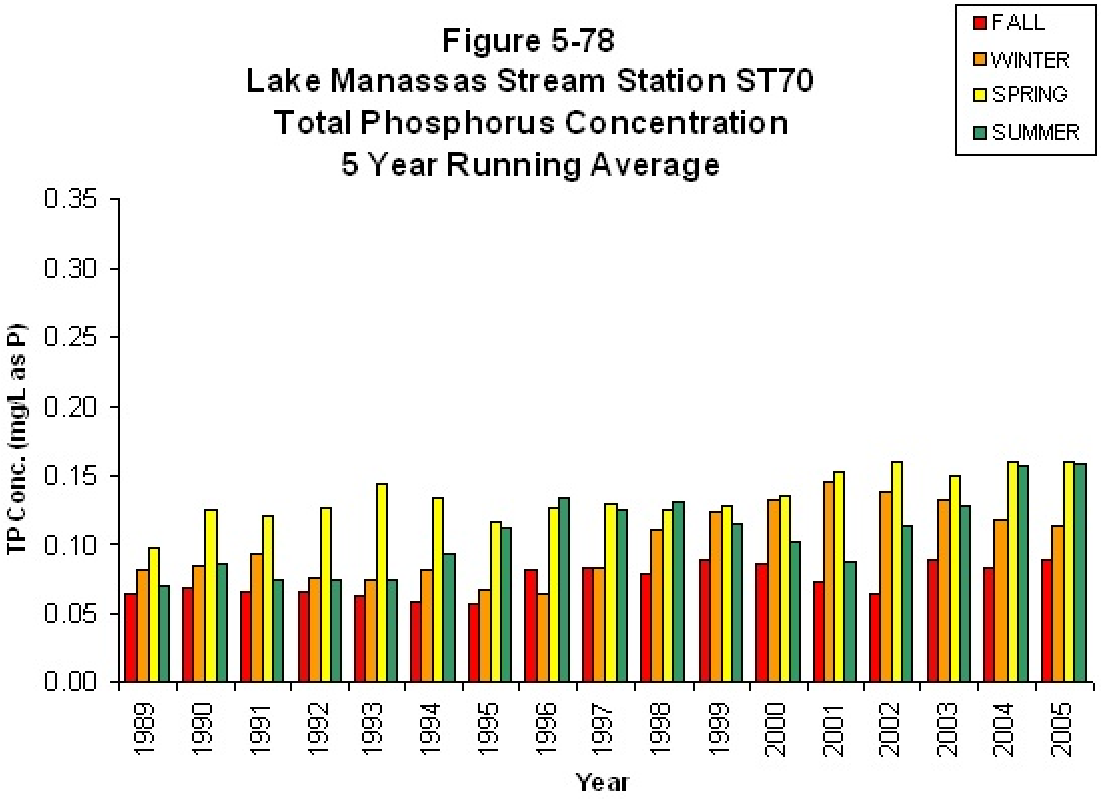


Figure 5-78
Lake Manassas Stream Station ST70
Total Phosphorus Concentration
5 Year Running Average

Decreasing trends of OP were reported at stations BR04 and BR05, while an increasing trend of OP was detected at station BR06. Increased nutrient runoff from agricultural lands is a possible explanation for the increase in OP at this station. Along Broad Run, increasing trends of TP were measured at station ST70. No other trends with respect to phosphorus forms were observed.

During the fall of 2005, witnessed the maximum values of OP and TP at station BR06 were 1.55 and 2.03 mg/L as phosphorus, respectively.

For the most part, the fall tends to have the lowest values of phosphorus forms at station ST70. The remaining stations report varying seasons as having the greatest or least phosphorus concentrations.

Nutrient Loading Rates to Lake Manassas from Broad Run

Nutrient inputs into the lake from both external and internal sources are directly related to the productivity of Lake Manassas. Broad Run is the primary source for the nutrient inputs, representing 70% of the entire Lake Manassas watershed. An automated sampling station, ST70, located on Broad Run, records hydrologic and chemistry data necessary for nutrient loading calculations. The data collected at this station have made it possible to compute nitrogen and phosphorus loading rates for the period 1984 to 2005. The calculated loading rates provide insights on nitrogen to phosphorus ratios as well as the reservoir trophic status based on nutrient loading from reservoir tributaries.

Flow weighted nutrient curves have been generated for station ST70 and are shown in Figures 5-79 through 5-83. The cumulative average nutrient loading rates are displayed in Table 5-3. These averages were calculated by integrating under the nutrient loading curve.

Table 5-3: Average Nutrient Loading Rates in Broad Run (ST70)

Period	Nutrient (lb/day)				
	Ox-N	NH_3-N	TKN	OP	TP
1981 - 1985	215.8	16.7	205.2	7.4	39.2
1986 - 1990	125.6	8.5	143.5	3.7	26.2
1991 - 1995	180.3	6.3	113.8	4.4	24.3
1996 - 2000	112.9	9.4	134.4	4.2	34.4
2001 - 2005	188.7	13.1	171.4	4.5	38.2
1981 - 2000	190.0	11.7	171.4	5.5	35.6
1981 - 2005	195.7	12.5	178.7	5.6	38.1

Figure 5-79
Lake Manassas
Cumulative Oxidized Nitrogen Loading at ST70
1981 - 2005

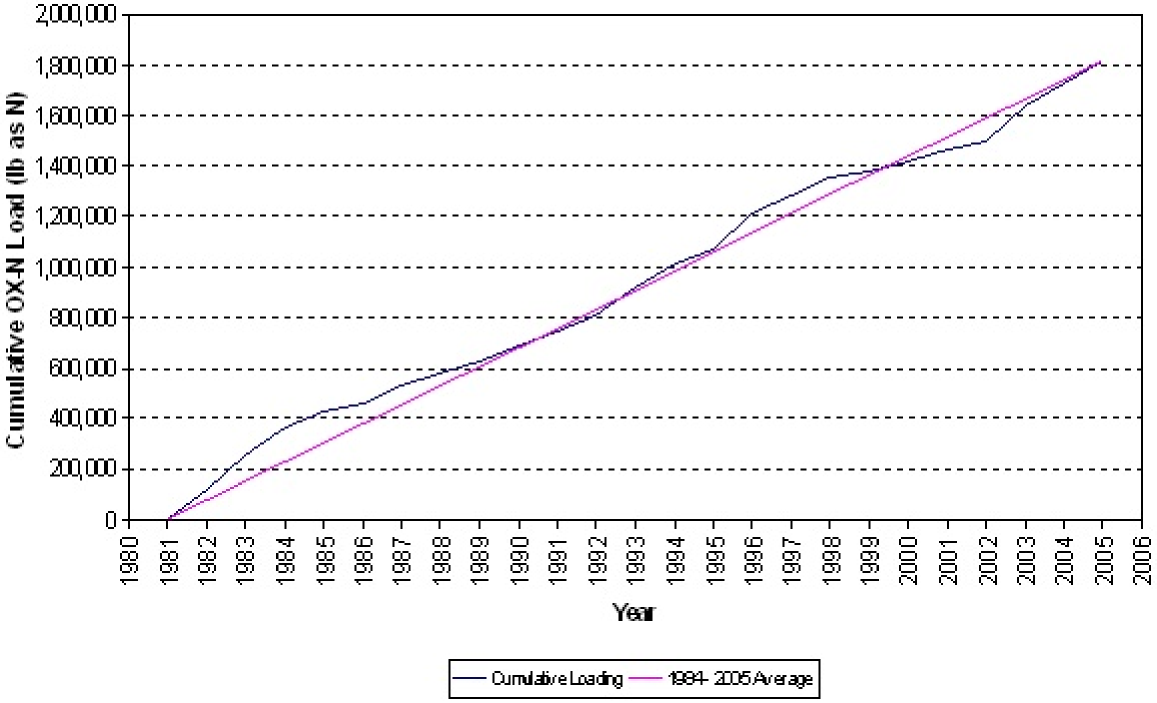


Figure 5-80
Lake Manassas
Cumulative NH_3-N Loading at ST70
1981 - 2005

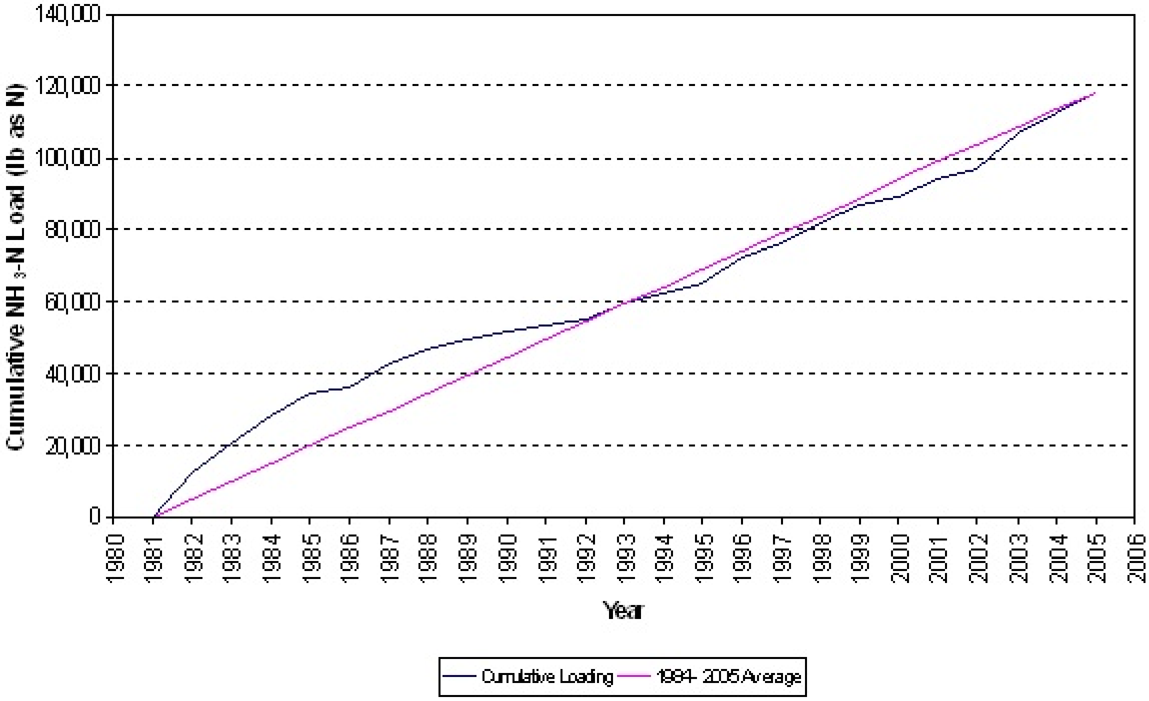


Figure 5-81
Lake Manassas
Cumulative Total Kejldahl Nitrogen Loading at ST70
1981 - 2005

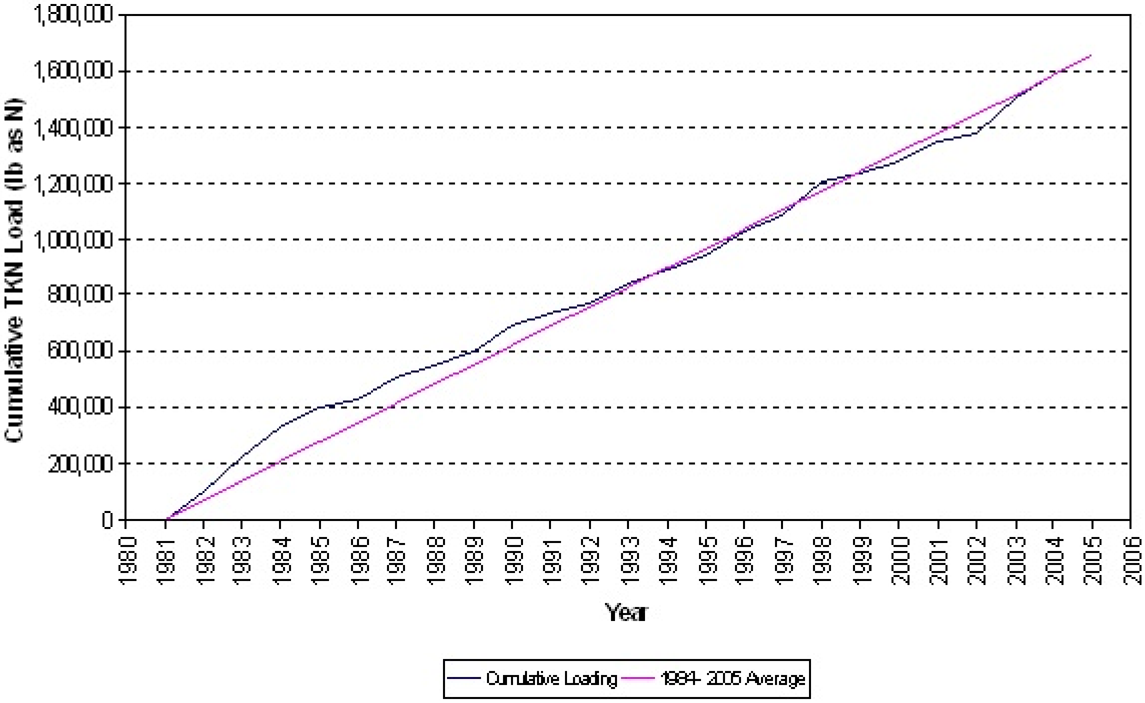


Figure 5-82
Lake Manassas
Cumulative Orthophosphate Loading at ST70
1981 - 2005

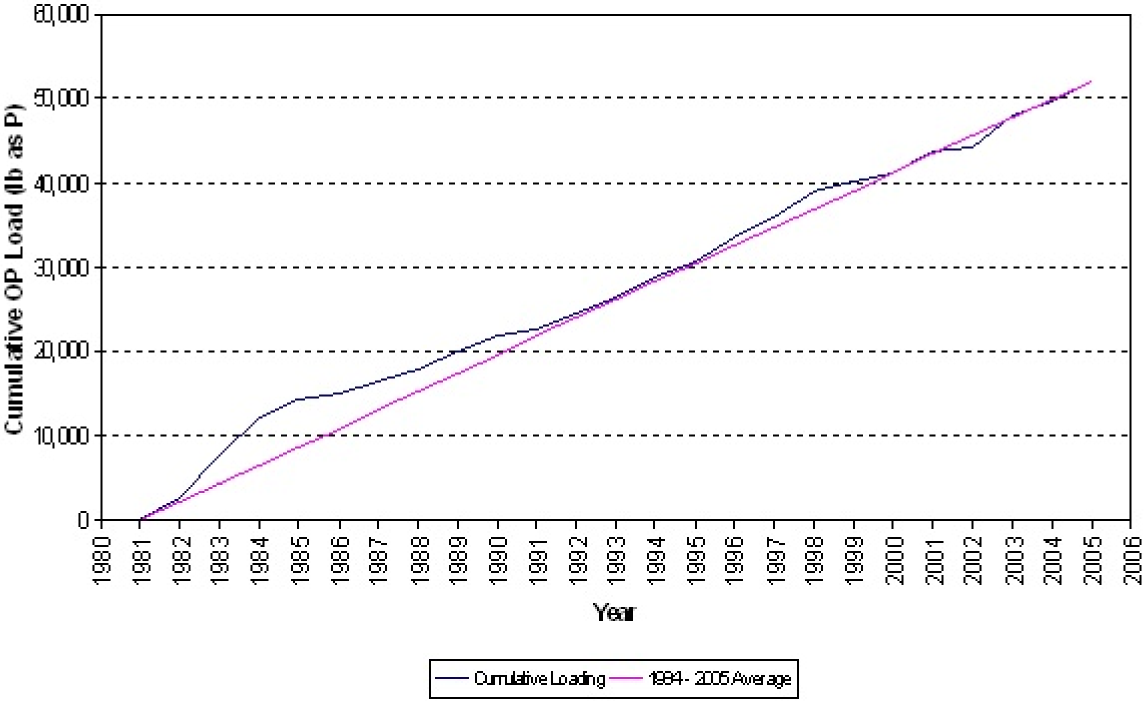


Figure 5-83
Lake Manassas
Cumulative Total Phosphorus Loading at ST70
1981 - 2005

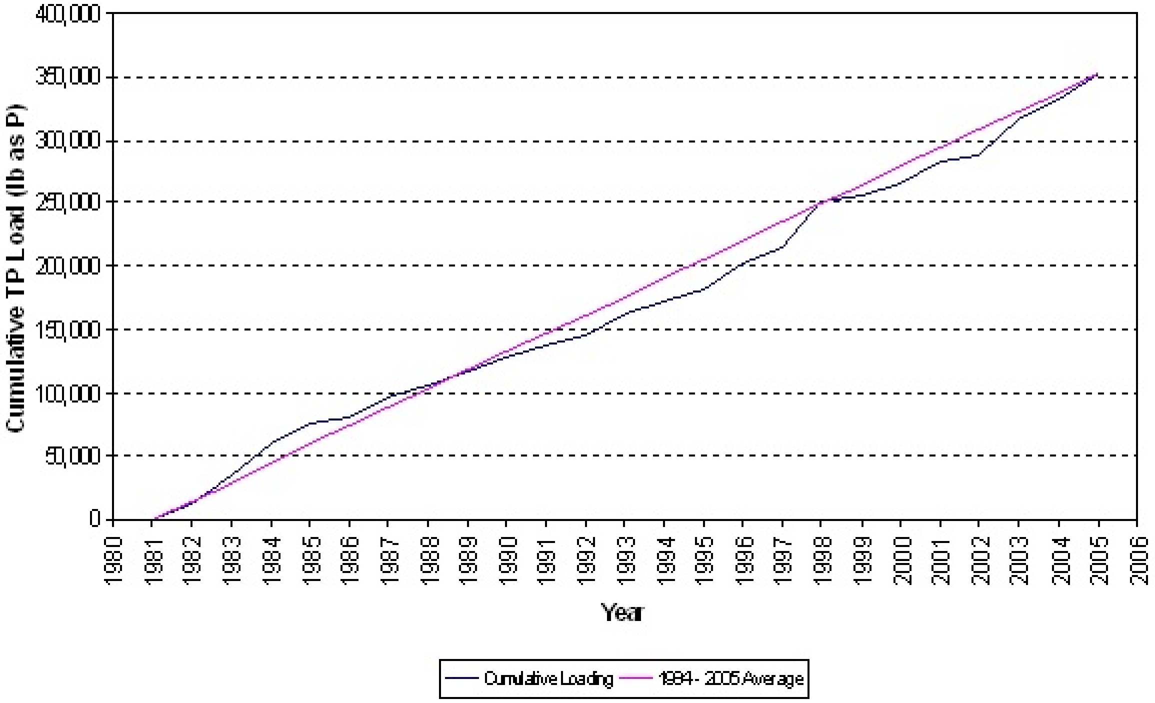


Table 5-4 shows the percent increase or decrease between the two time intervals shown in the first column. The results displayed in this table show dramatic increases of Ox-N and NH3-N during the most recent five year intervals. The loading rates found in Table 5-4 confirm the results of the Mann-Kendall analysis when comparing the 20 to 25 year averages. These numbers corroborate that there are increasing trends of NH_3-N, TKN, and TP. When the five year averages are compared, the nutrient loading rates for NH_3-N, TKN, and TP fall from 1981 to 1995 and then rise again over the next 10 years. The remaining constituents have varying trends in the first 20 years, however, the last five years all show increasing trends. The increasing trends of nutrients should be of concern for Lake Manassas. As nutrients inputs increase, the lake becomes more eutrophic which can cause problems with drinking water treatment.

Table 5-4: Percent Change in Broad Run (ST70) Nutrient Loading Rates

Time Period	Ox-N	NH_3-N	TKN	OP	TP
1981 - 1985 & 1986 - 1990	-41.8%	-48.7%	-30.1%	-49.6%	-33.2%
1986 - 1990 & 1991 - 1995	+43.6%	-26.3%	-20.7%	+17.1%	-7.0%
1991 - 1995 & 1996 - 2000	-37.4%	+48.8%	+18.1%	-4.7%	+41.4%
1996 - 2000 & 2001 - 2005	+67.2%	+39.8%	+27.5%	+7.7%	+11.2%

CHAPTER 6
LAKE RESULTS

Lake Water Quality

The water quality of a lake or reservoir may be characterized by traditional parameters such as: dissolved oxygen, temperature, nitrogen, phosphorus, and chlorophyll *a* concentrations. Additionally, models such as those created by Carlson and Vollenweider are defined mathematically and can provide insight towards the water quality of an impoundment. The results presented in this section describe the water quality condition of Lake Manassas based on parameters measured at eight monitoring stations between 1985 and 2005. Furthermore, five year running averages are included to identify any long term trends present in the lake.

Monitoring stations LM06, LM05, LM04, and LM01 are located along the main axis of the lake. LM06 is the farthest upstream and LM01 is closest to the dam (Figure 4-1). The principal body of water storage is represented by these stations. Station LM01 is the deepest site on the lake with a full pool depth of 50 feet with the bladder addition. Stations LM08, LM07, LM03, and LM02 are located along the north shore of the lake, and are flanked by the Robert Trent Jones International, Stonewall, and Virginia Oaks Golf Courses. Station LM02 is the deepest station along the north shore with a full pool depth of 40 feet. The remaining stations along the north shore have full pool depths of 15 - 25 feet. The impacts of the golf courses, if any, will be made apparent because of the reduced storage volume at these monitoring stations.

A Mann-Kendall Seasonal Analysis was completed on the data collected at the eight monitoring stations along Lake Manassas. The analysis was performed to locate any trends occurring in the lake over the last twenty years. All four seasons were examined statistically and compared with a certain level of significance (alpha = 0.05). Both the surface and bottom sections of the lake were investigated separately. Tables 6-1 and 6-2 show the results of this analysis and will be referred to throughout this section.

Table 6-1: Mann-Kendall Analysis for Lake Surface Samples

Parameter	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
DO	-	U	-	U	U	U	U	U
pH	U	U	U	U	U	U	U	U
TEMP	-	-	-	-	-	-	-	-
COND	U	U	U	U	U	U	U	U
TALK	-	-	U	-	-	-	-	-
OP	L	L	L	L	-	-	L	-
TP	U	U	U	U	U	U	U	U
NH_3-N	-	U	U	U	U	U	U	U
TKN	U	U	U	U	U	-	U	U
OX-N	-	-	-	-	-	-	-	-
TSS	-	-	-	-	-	-	L	-
CHLa	U	U	U	U	U	U	U	U

U = Increasing Trend Present
L = Decreasing Tend Present
– = No Trend Present
Blank = No data in at least the last 5 years

Table 6-2: Mann-Kendall Analysis for Lake Bottom Samples

Parameter	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
DO	-	-	L	-	-	-	L	L
pH	U	U	U	U	U	U	U	U
TEMP	-	-	-	-	-	L	-	-
COND	U	U	U	U	U	U	-	U
TALK	-	-	U	-	-	-	-	-
OP	L	L	-	-	-	-	L	L
TP	-	L	-	-	-	-	-	-
NH_3-N	-	-	U	U	-	U	U	U
TKN	-	-	U	U	-	-	U	U
OX-N	-	-	-	-	-	-	-	U
TSS	L	L	L	L	L	L	L	L

U = Increasing Trend Present
L = Decreasing Tend Present
– = No Trend Present
Blank = No data in at least the last 5 years

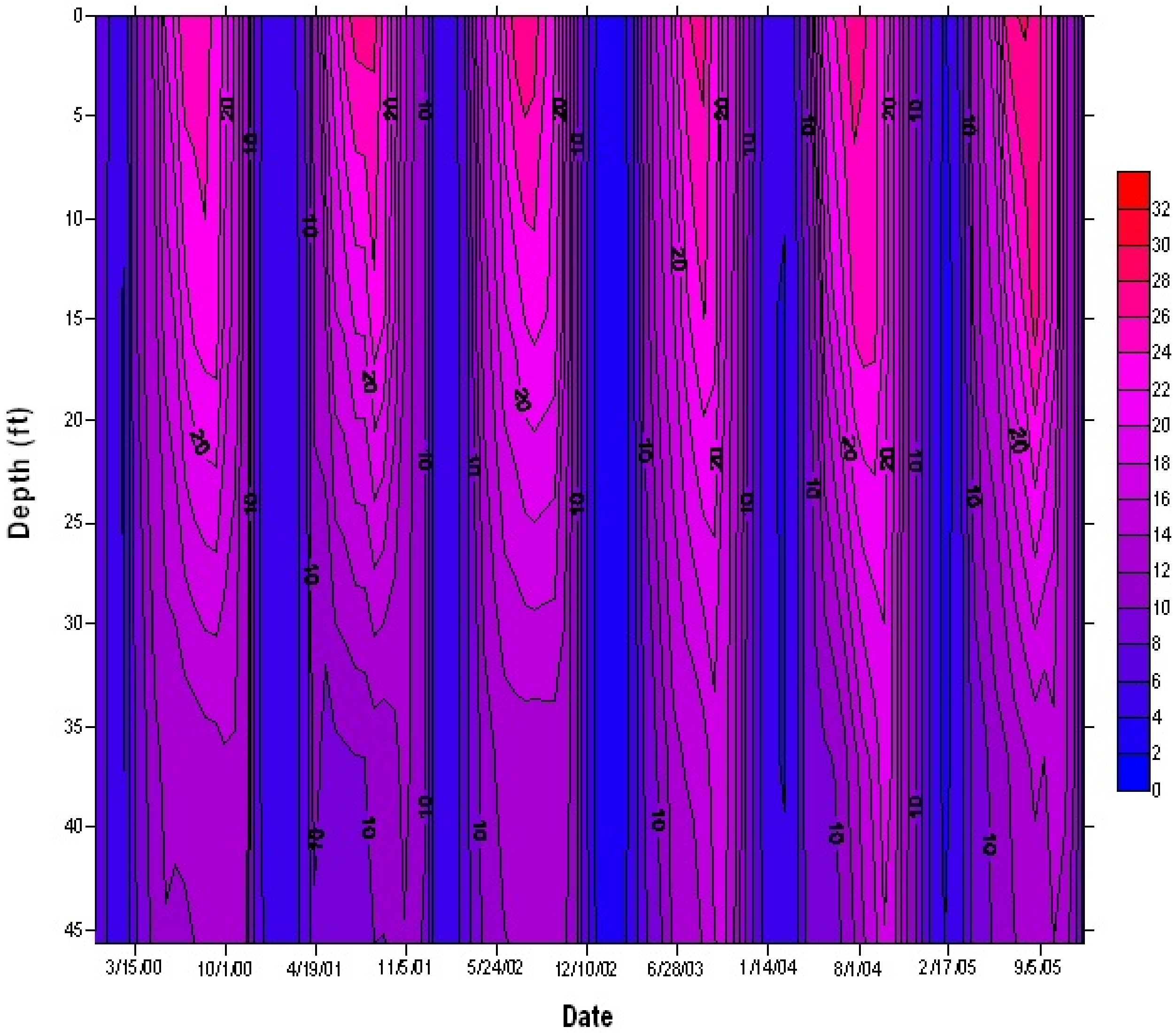
Thermal Effects

As described earlier, during the spring and early summer months, solar radiation coupled with wind currents induce the warming of the upper portion of a lake water column (epilimnion). The temperature gradient generated by increasing temperatures in the epilimnion cause the lake to stratify into layers of water with different temperatures and densities. During stratification, the epilimnion, a warmer and less dense layer of water, floats on a cooler, more dense layer of water (hypolimnion). A subsequent barrier is generated by the varying densities in each layer of water preventing the migration of dissolved gases and ionic species between layers. As summer turns to fall, the epilimnion cools to a point where the difference in density between the epilimnion and the hypolimnion is insignificant. This process is called the fall turnover, in which winds can produce mixing in the lake. The mixing action generated by the turnover cause the dissolved materials in the hypolimnion to mix with the rest of the lake. The transition from a stratified condition to a mixed condition can occur over the course of a few hours if sufficient wind currents are present.

Figure 6-1 shows the temperature isopleths for station LM01 during the period 2000 - 2005. This is the deepest station in the lake thereby giving it the greatest tendency to stratify since there is less chance of mixing. Stratification is clearly shown between early spring and late fall at this station.

Figures 6-2 through 6-17 show the five-year running averages from the surface and the bottom of the lake for all stations. Surface temperatures remained consistent over the years for each

Figure: 6-1
Station LM01 Temperature Isopleths
2000 - 2005



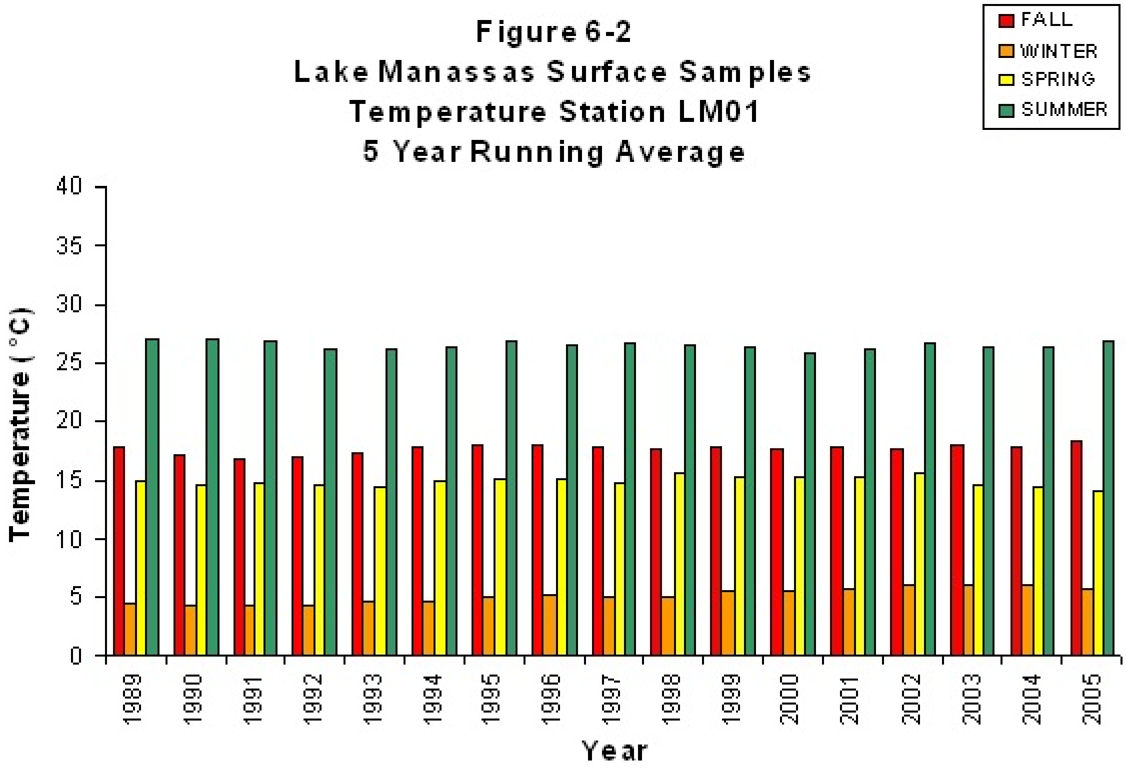


Figure 6-2
Lake Manassas Surface Samples
Temperature Station LM01
5 Year Running Average

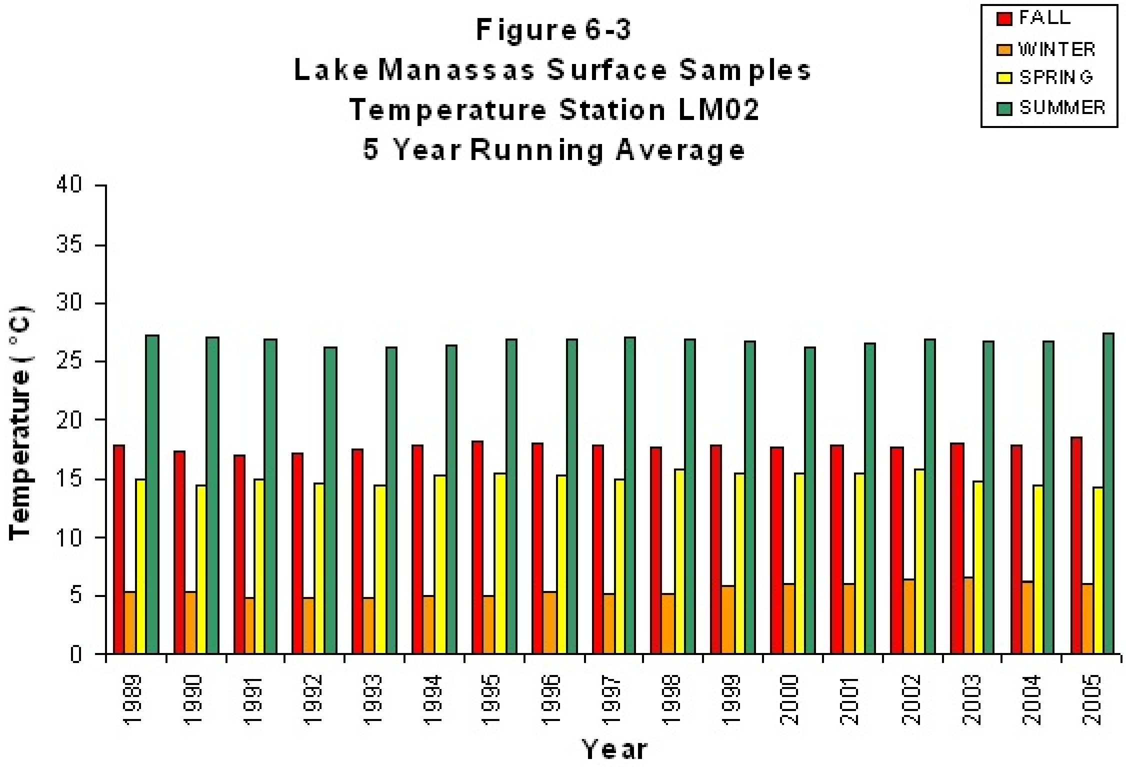


Figure 6-3
Lake Manassas Surface Samples
Temperature Station LM02
5 Year Running Average

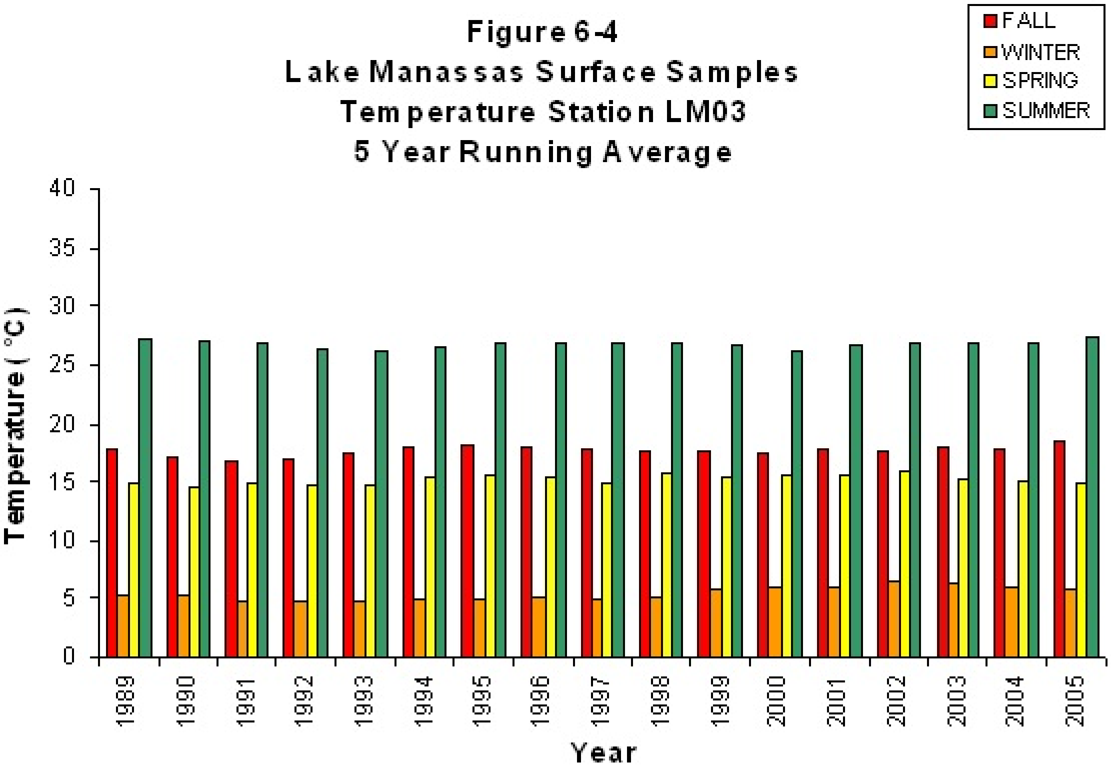


Figure 6-4
Lake Manassas Surface Samples
Temperature Station LM03
5 Year Running Average

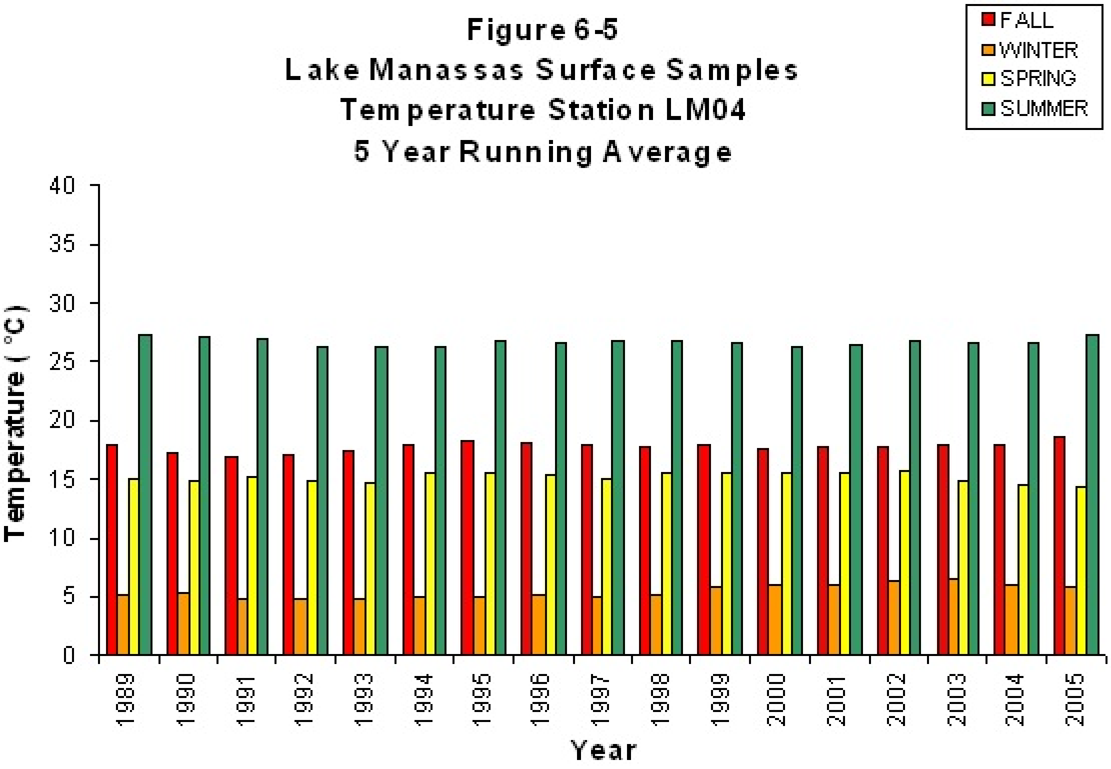


Figure 6-5
Lake Manassas Surface Samples
Temperature Station LM04
5 Year Running Average

Figure 6-6
Lake Manassas Surface Samples
Temperature Station LM05
5 Year Running Average

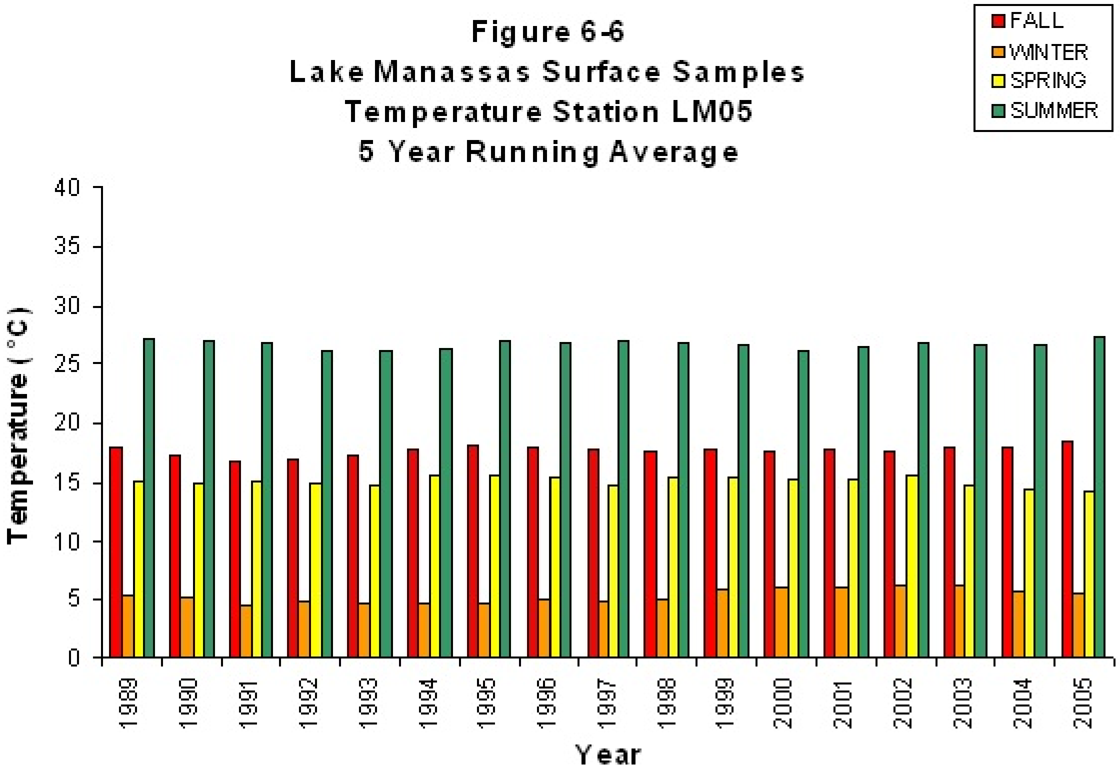
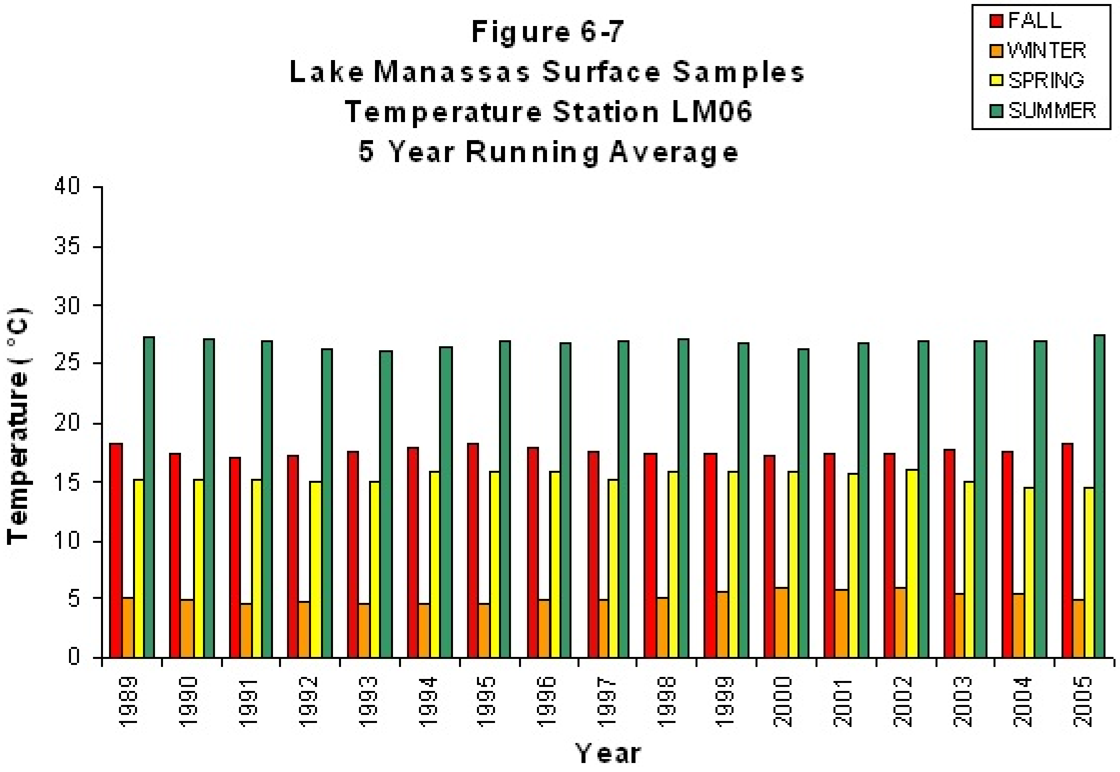


Figure 6-7
Lake Manassas Surface Samples
Temperature Station LM06
5 Year Running Average



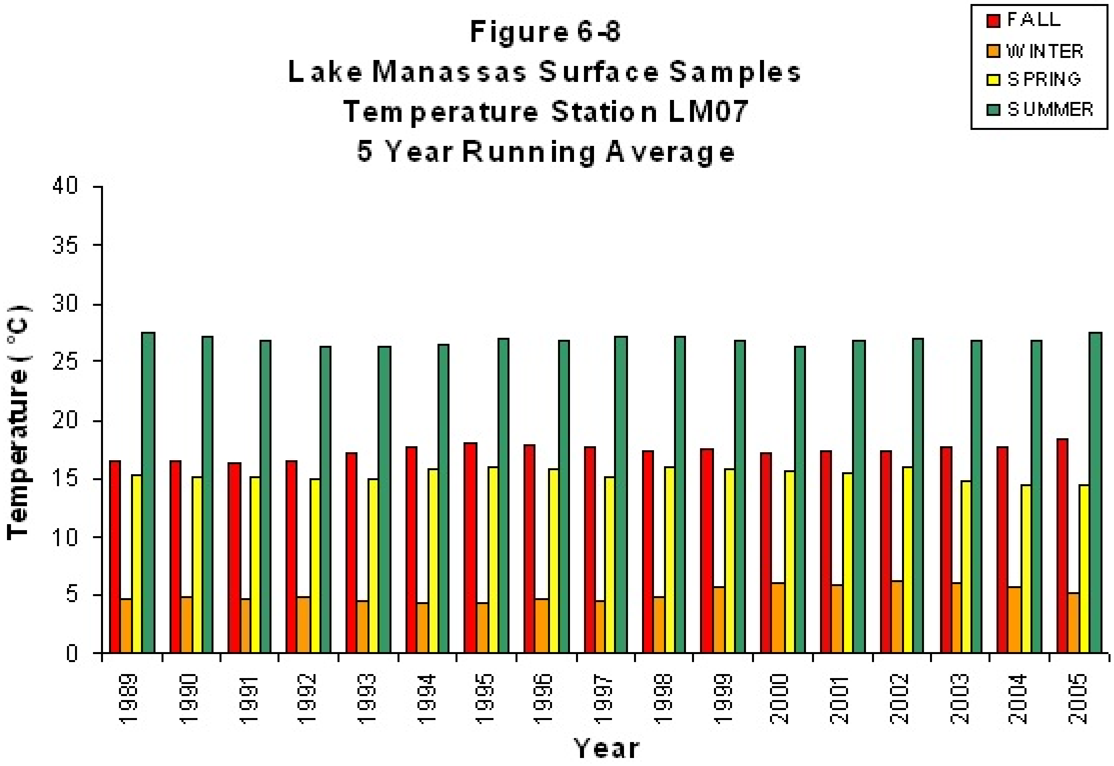


Figure 6-8
Lake Manassas Surface Samples
Temperature Station LM07
5 Year Running Average

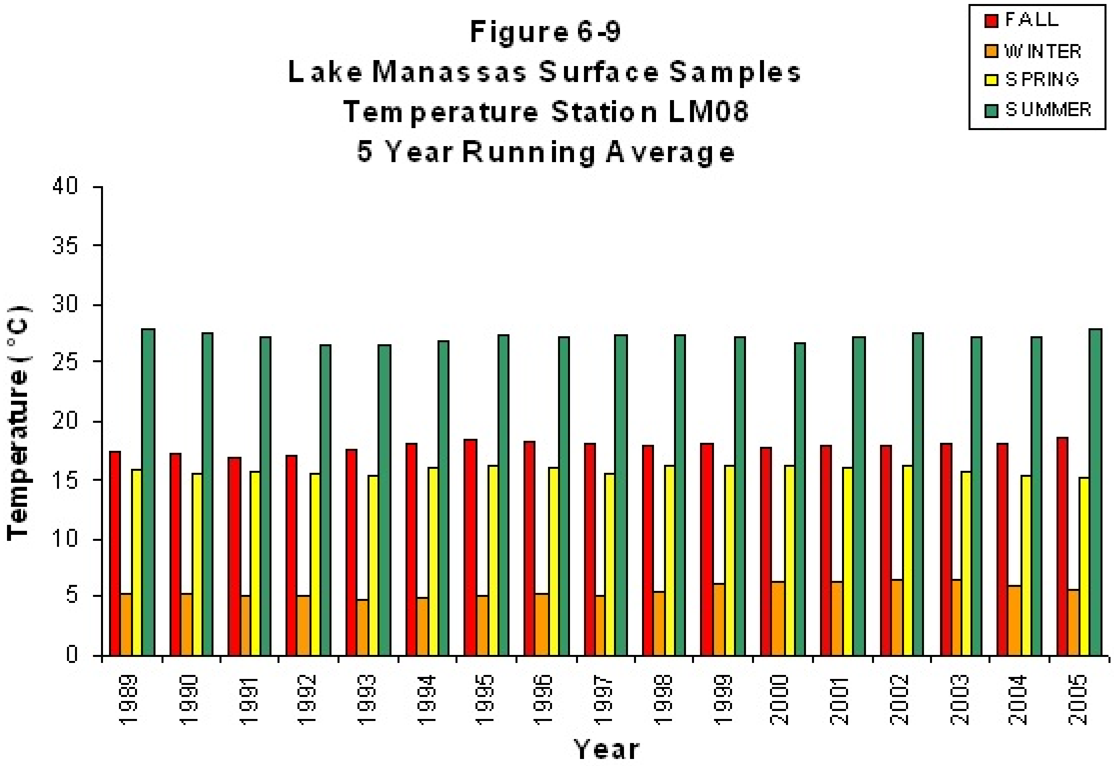


Figure 6-9
Lake Manassas Surface Samples
Temperature Station LM08
5 Year Running Average

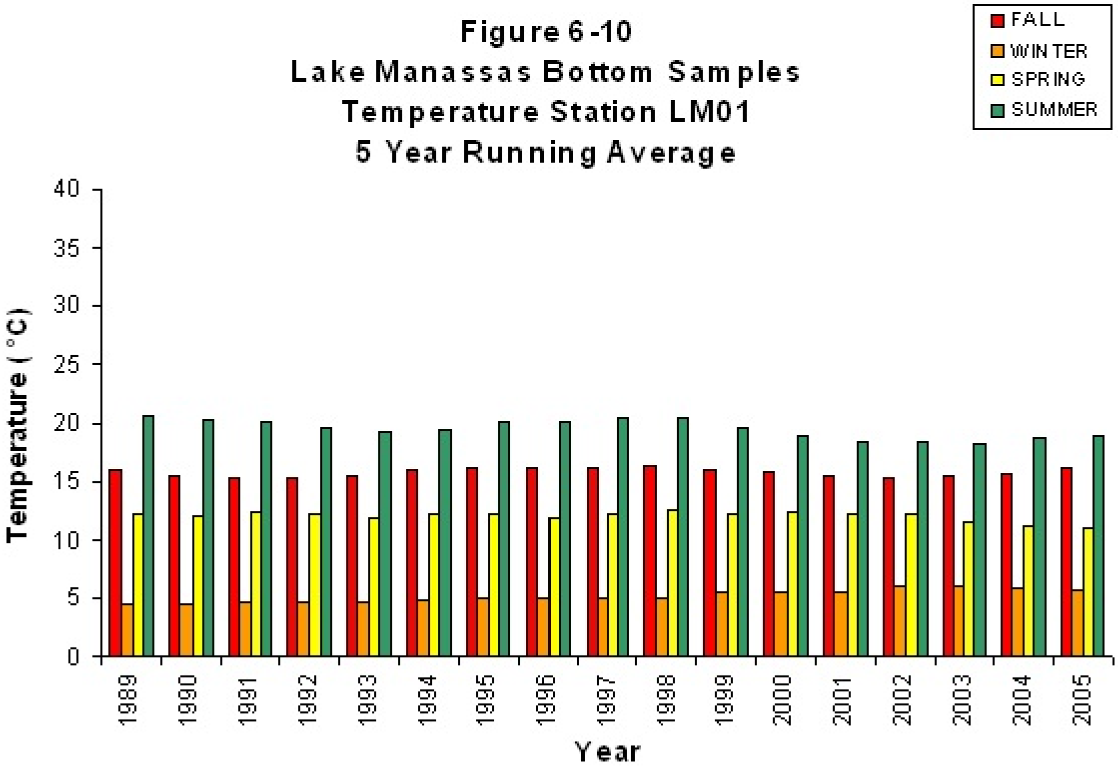


Figure 6-10
Lake Manassas Bottom Samples
Temperature Station LM01
5 Year Running Average

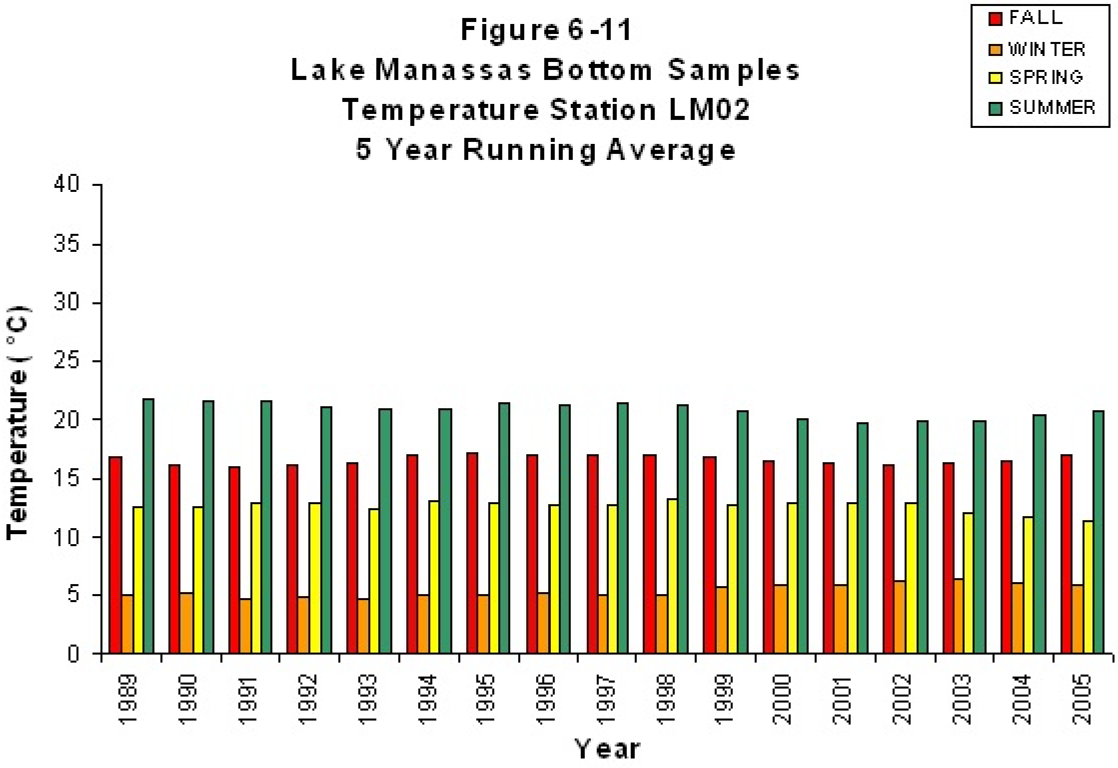


Figure 6-11
Lake Manassas Bottom Samples
Temperature Station LM02
5 Year Running Average

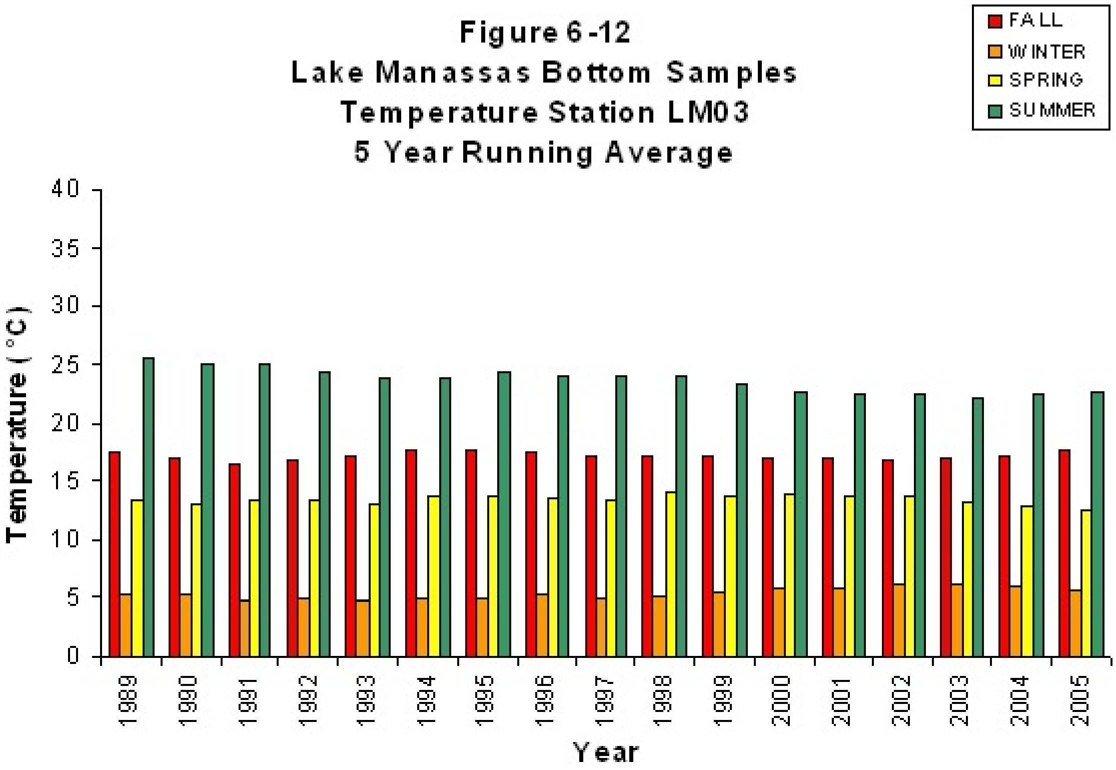


Figure 6-12
Lake Manassas Bottom Samples
Temperature Station LM03
5 Year Running Average

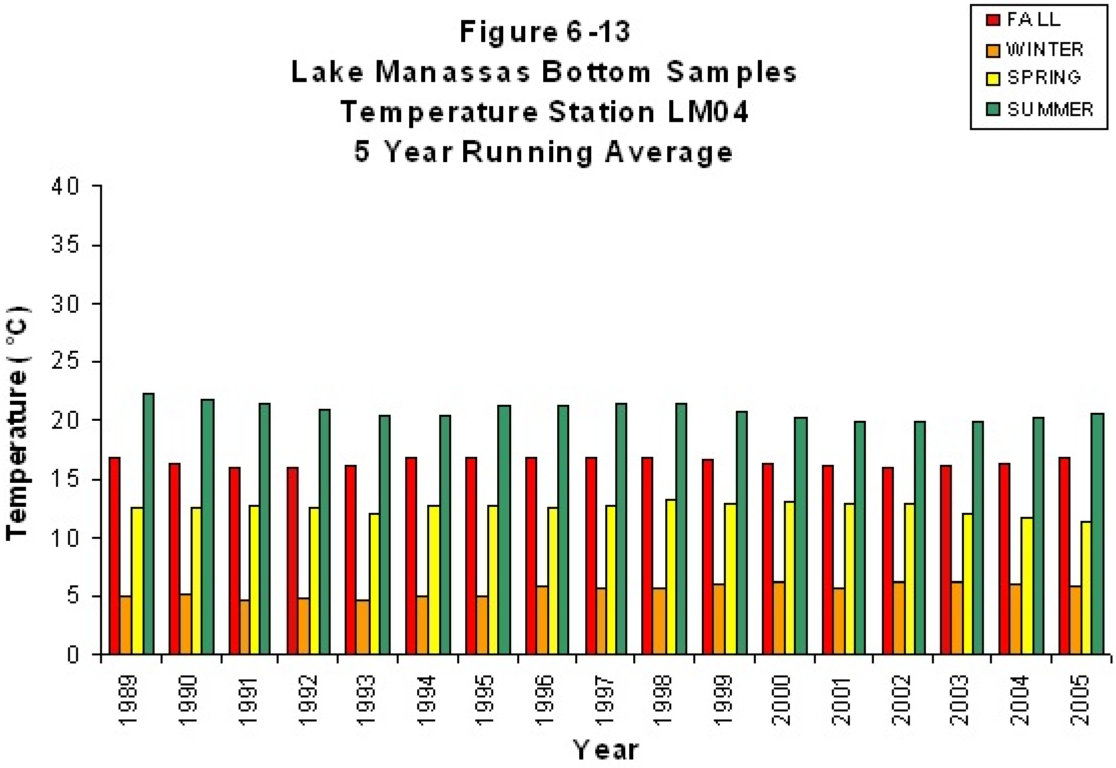


Figure 6-13
Lake Manassas Bottom Samples
Temperature Station LM04
5 Year Running Average

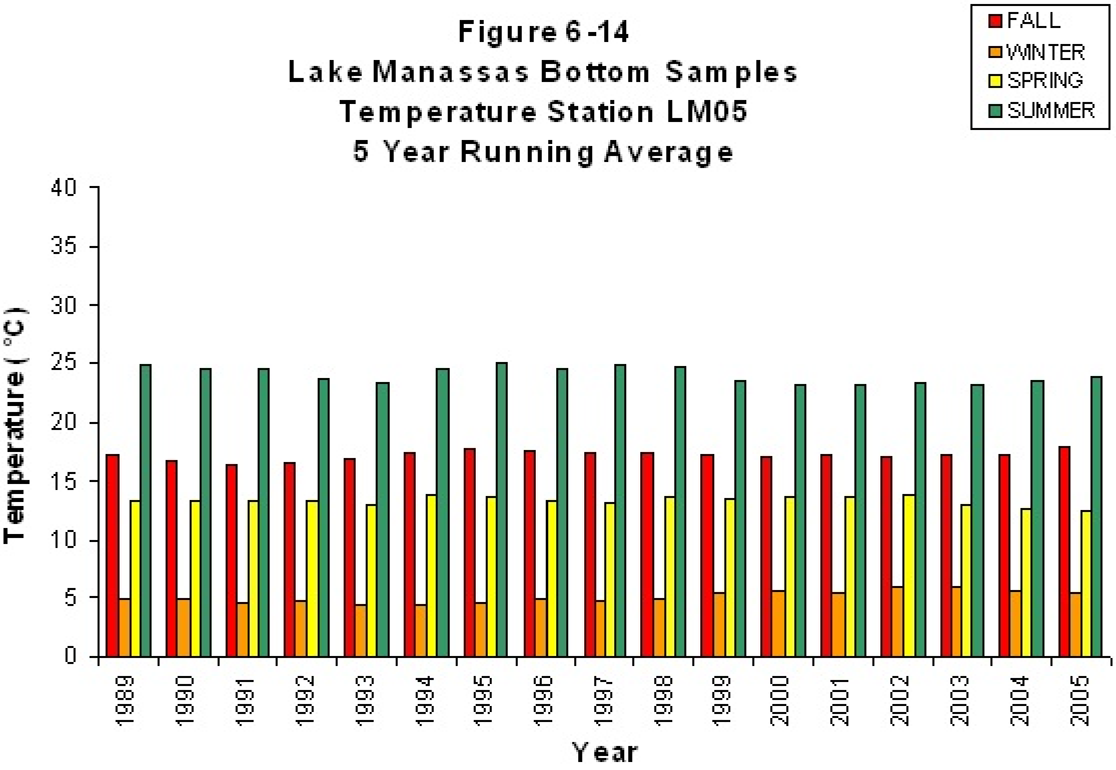


Figure 6 -14
Lake Manassas Bottom Samples
Temperature Station LM05
5 Year Running Average

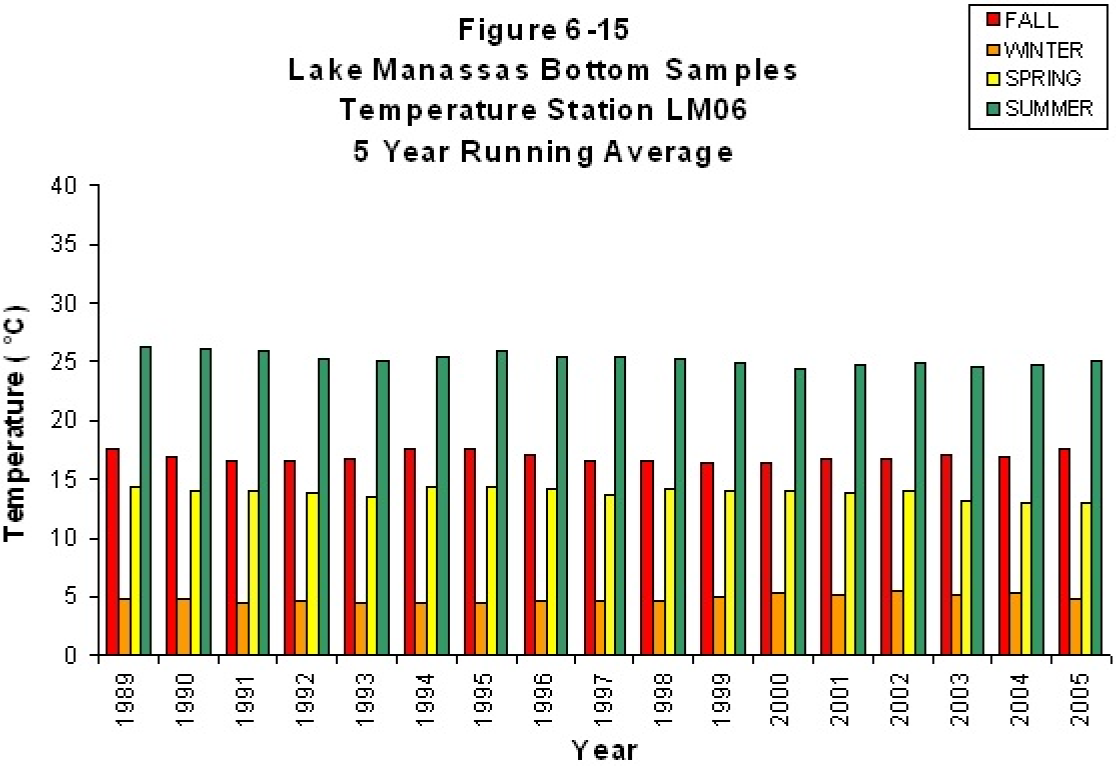


Figure 6 -15
Lake Manassas Bottom Samples
Temperature Station LM06
5 Year Running Average

Figure 6-16
Lake Manassas Bottom Samples
Temperature Station LM07
5 Year Running Average

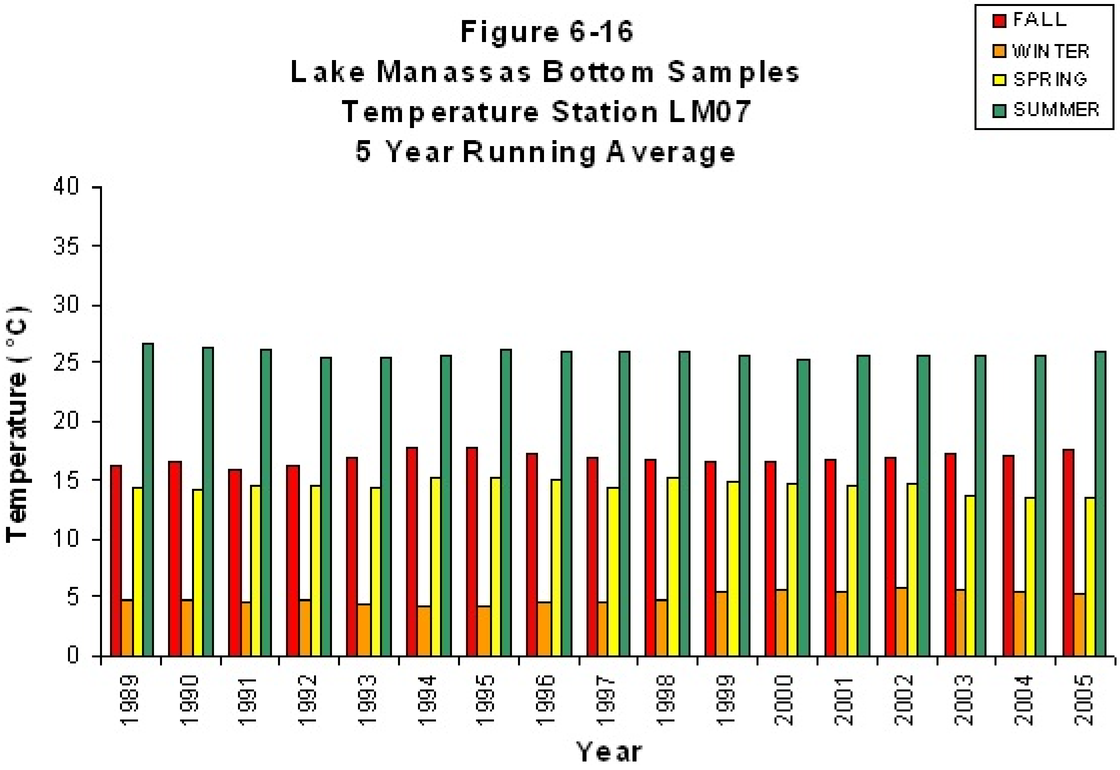
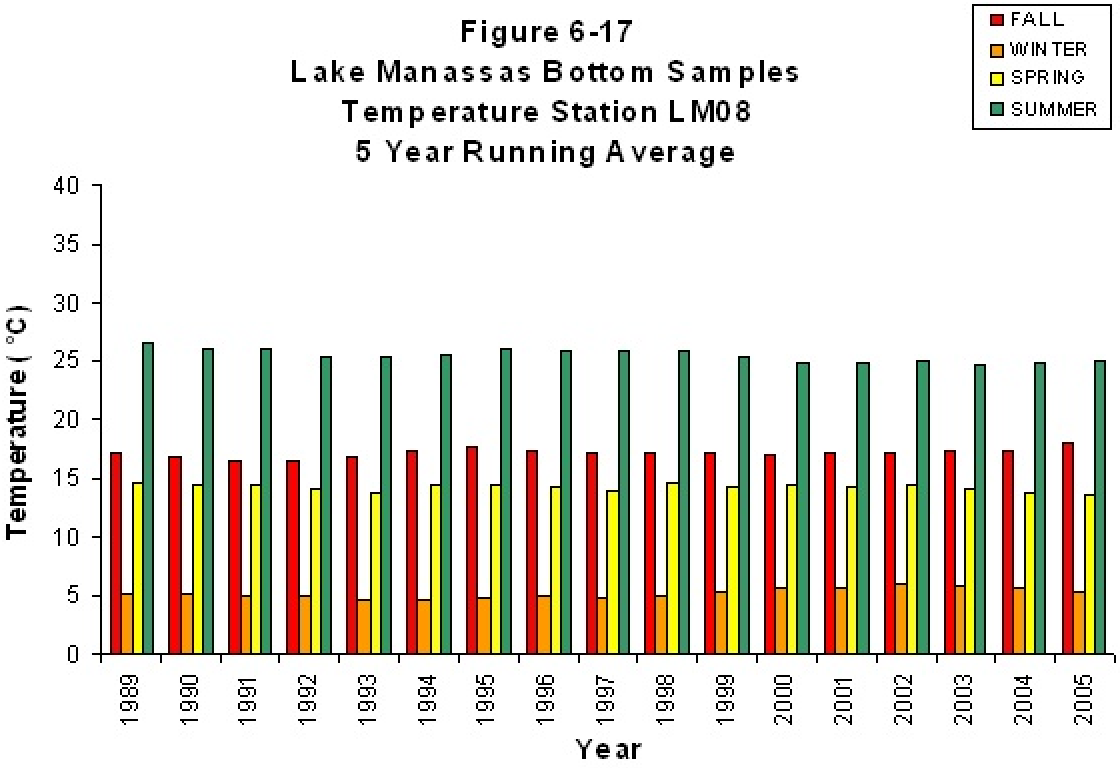


Figure 6-17
Lake Manassas Bottom Samples
Temperature Station LM08
5 Year Running Average



individual station. The Mann-Kendall analysis for the surface waters (Table 6-1) showed no signs of any trend, either upward or downward. The graphs representing the bottom samples for temperature show that stations LM01, LM02, LM03 have the lowest temperatures (Figures 6-10 through 6-17). This indicates that these stations potentially have the strongest stratification. Stations LM06, LM07, and LM08 rank among the shallowest of stations and therefore exhibit the warmest temperatures in the bottom sections of the water column (Figures 6-10 through 6-17). The Mann-Kendall analysis for the bottom waters (Table 6-2) shows a decreasing trend for temperature at station LM06. This is a sign that the stratification at station LM06 is gaining strength. Increasing water depths resulting from the addition of the inflatable bladder is most likely cause for the stratification at station LM06 gaining strength. No other trends were present in the bottom waters. Despite the location of stations LM04 and LM05 in the middle of the lake, temperatures were moderate when compared to the remaining stations. As a result, stratification of average strength could be expected at these two stations.

The average temperature between the surface and bottom waters of the lake is shown in Figure 6-18. A one-to-one line is drawn to illustrate the difference in temperatures of the epilimnion and hypolimnion. The data points shown on the graph represent average temperatures for individual seasons at each station. For the most part, the average temperatures fall along the one-to-one line with the exception of the summer data.

Figure 6-18
Surface Temperature vs. Bottom Temperature - Lake Manassas
All Lake Stations (2001 - 2005)

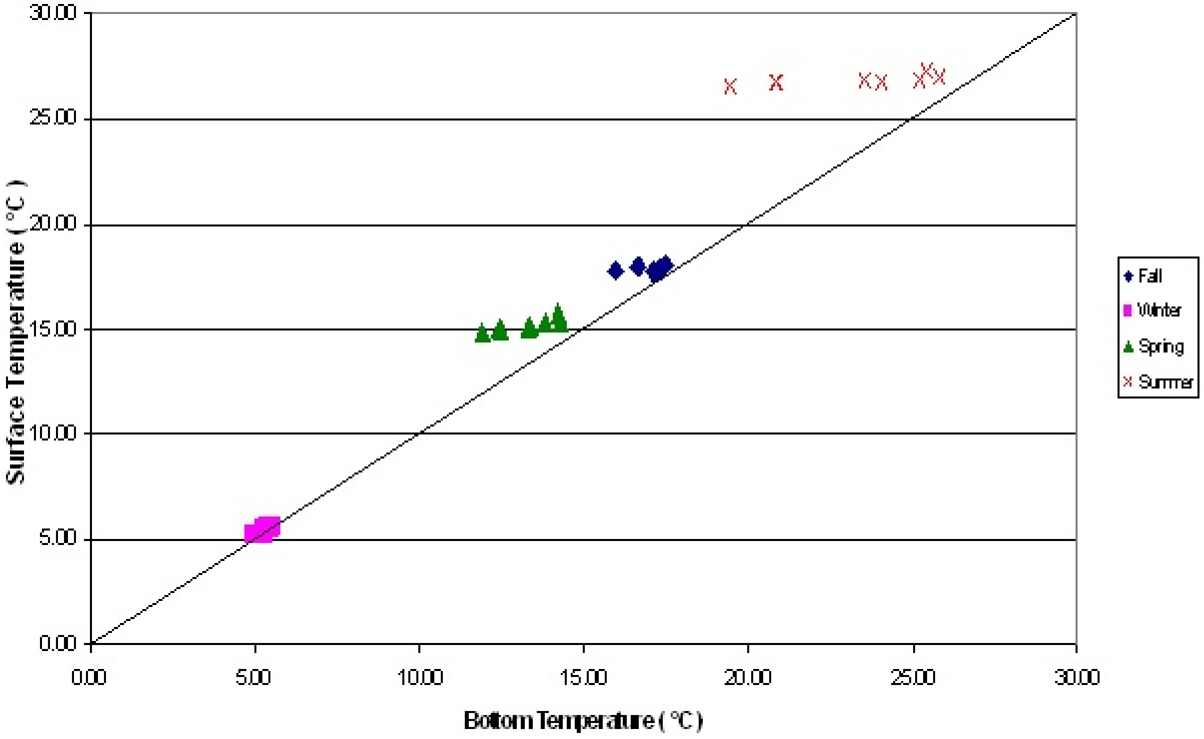


Figure 6-19
Lake Manassas-Station LM01, 2002
Temperature Profile

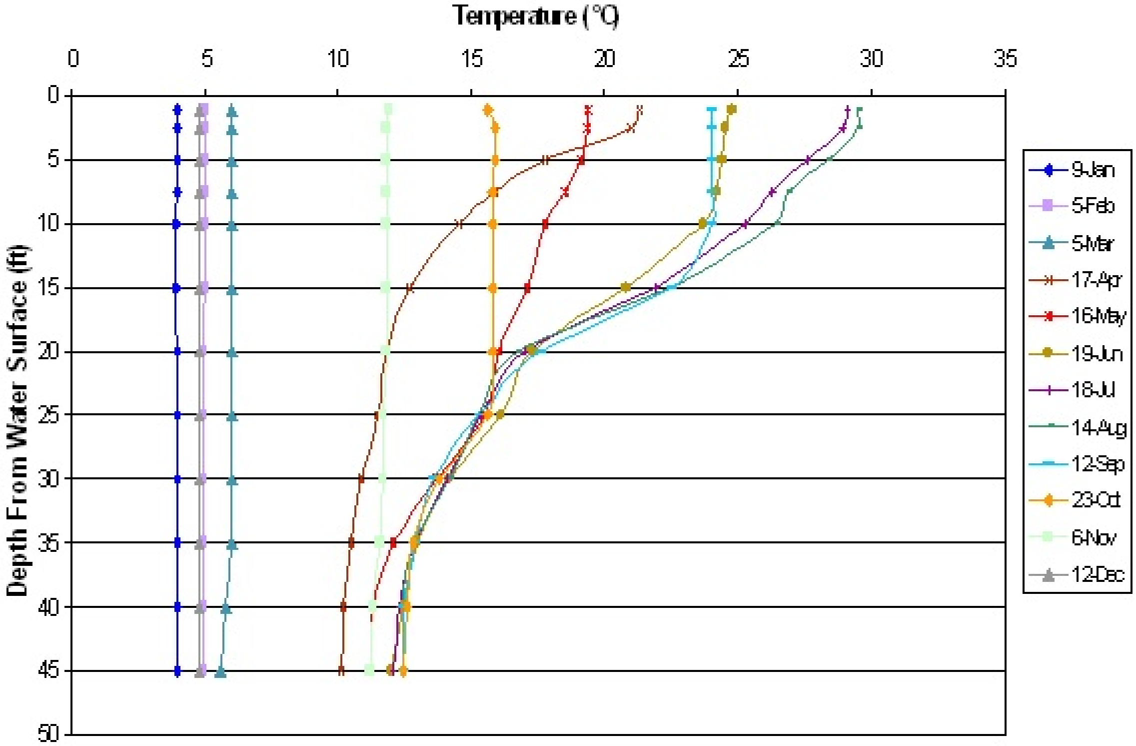
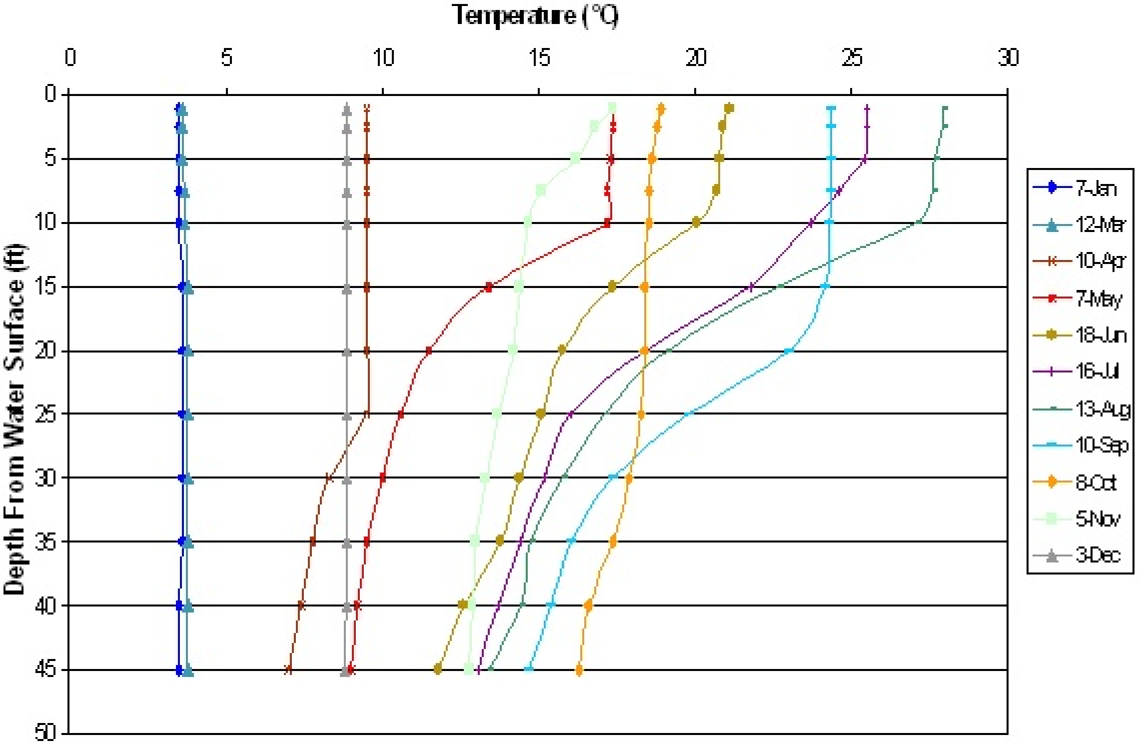


Figure 6-20

Lake Manassas-Station LMD1, 2003

Temperature Profile



These data points stray from the 1:1 line because of stratification. During stratification, the temperature in the hypolimnion is low and the temperature in the epilimnion is high. As a result, the data points are further away from the 1:1 line. When stratification weakens, the temperatures in the hypolimnion and the epilimnion approach the same value. This causes the data points to lie along the 1:1 line.

In order to demonstrate the typical yearly stratification experienced by the lake, Figures 6-19 and 6-20 were developed to show temperature versus depth over the course of 2002 and 2003, respectively, at station LM01. Stratification began in mid-April during 2002, while in 2003 stratification began in early May. A possible reason for the varying dates of stratification between these two years is that 2002 received considerably less rain than 2003 (Appendix A). Another possible reason for the earlier stratification in 2002 is that surface temperatures during the spring of 2002 increased earlier than in the spring of 2003. Additionally, as seen from the plots, the transition between the epilimnion and the hypolimnion occurs at a depth of 3 - 20 feet depending on strength of stratification.

Dissolved Oxygen

Dissolved oxygen (DO) is the most fundamental parameter in any body of water and is essential to the metabolism of all aerobic aquatic organisms. The dynamics of DO reflect an equilibrium between oxygen-producing processes (photosynthesis) and oxygen-consuming processes such as respiration, nitrification, and chemical oxidation. The consumption and production of DO are influenced by plant and algal biomass, light intensity, and temperature. The thermal stratification that results from increasing temperatures creates a barrier that prevents the migration of chemical species such as DO between the epilimnion and hypolimnion. During stratification the epilimnion is in contact with the atmosphere and the concentration of DO is repeatedly replenished through diffusion across the air-water interface.

Dynamics of DO differ in the hypolimnion. When organic matter dies, it sinks to the bottom of a lake and decomposes along the way. The decomposition of organic matter (respiration) in the hypolimnion depletes DO concentrations to a point where a significant deficit can be observed. The effective barrier created by thermal stratification prevents the recharge of DO in the hypolimnion and subsequently causes the deficit to continue throughout the summer and early fall months.

Figures 6-21 and 6-22 show the DO and percent DO isopleths for station LM01. Values for percent saturation DO were calculated using a non-linear equation (Lindeburg, 2005) that took into account temperature and dissolved oxygen concentrations (Eq. 6-1). Corrections for pressure and ionic strength were not considered because the effects of these parameters on the solubility of oxygen are small when compared to the effect of temperature.

Equation 6-1: Percent Saturation Dissolved Oxygen (Lindeburg, 2005)

$$\%\,\text{Saturation DO} = \left[\frac{\text{Measured DO (mg / L)}}{\text{DO Saturation Level (mg / L)}}\right] \times 100$$

The five-year running averages of DO in the surface waters of Lake Manassas are shown in Figures 6-23 through 6-30. Overall, the surface levels of DO have remained relatively constant over the last twenty years. Examining the Mann-Kendall Analysis (Table 6-1), increasing trends of DO are present at stations LM02, LM04, LM05, LM06, LM07, and LM08. This evidence could likely be attributed to increased algal growth at these stations during the summer months.

Figure: 6-21
Station LM01 Dissolved Oxygen Isopleths
2000 - 2005

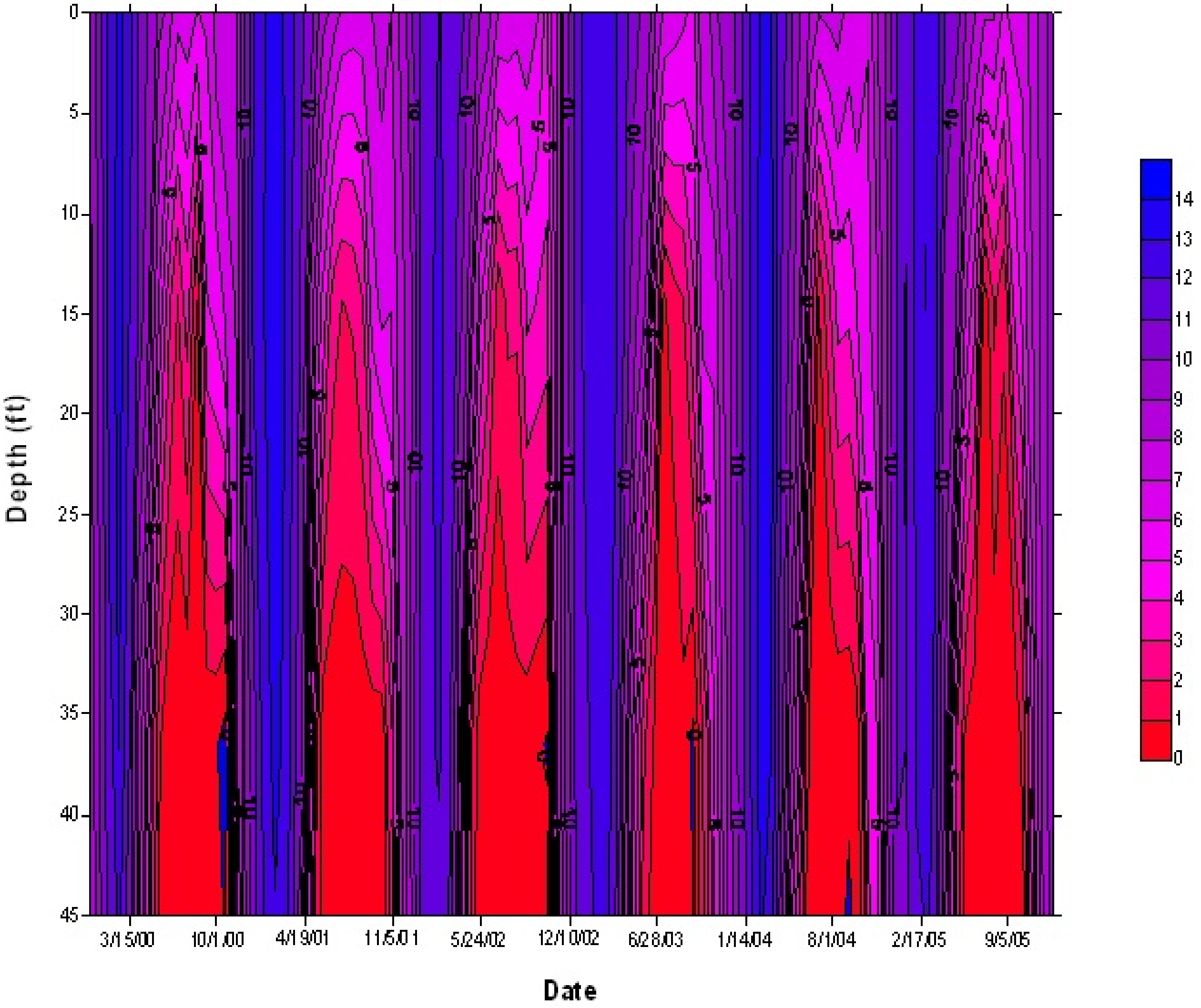
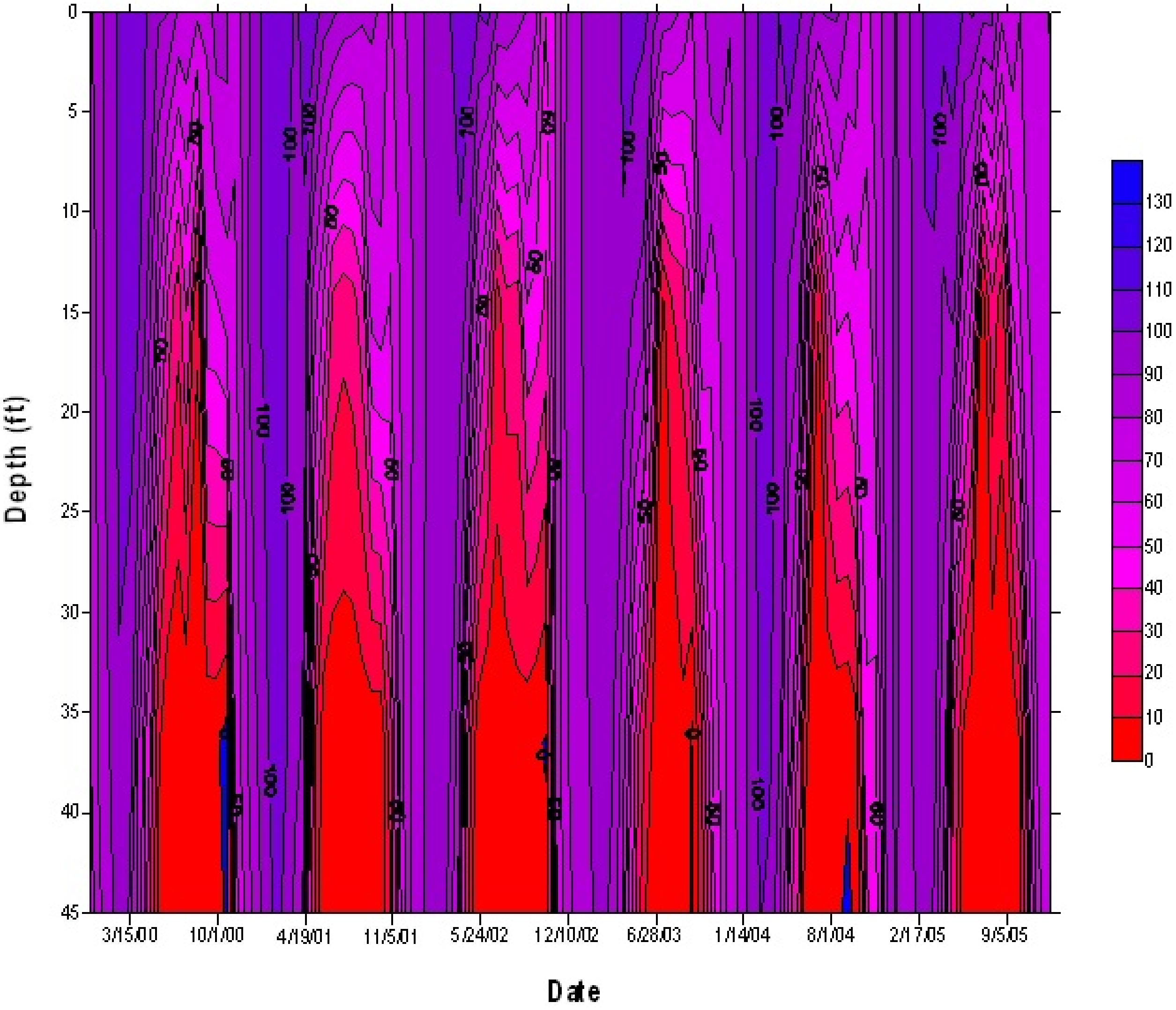


Figure: 6-22
Station LM01 Percent DO Saturation Isopleths
2000 - 2005



Figures 6-31 through 6-38 illustrate the five-year running averages of DO in the bottom waters of Lake Manassas. As stated earlier with respect to temperature, stations LM01, LM02, and LM03 exhibit signs of strong stratification due to low temperatures in the hypolimnion. As a result, we would expect to see low concentrations of DO (< 1 mg/L) in the hypolimnion during the summer. This phenomena holds true for these three stations. In fact, stations LM04 and LM05 also have DO concentrations < 1 mg/L during the summer. This could be evidence that these two stations are beginning to experience stronger stratification during the summer months. The inflatable bladder could be attributed to the strengthening stratification at these two stations due to the elevated water levels. The Mann-Kendall Anaylsis (Table 6-2) indicates that decreasing trends of DO in the hypolimnion are present at stations LM03, LM07, and LM08. These three stations are located on the north shore of the lake and are adjacent to the three existing golf courses.

The percent saturation of DO over time at station LM01 for both the surface and bottom layers is displayed in Figure 6-39. DO concentrations on the surface have an inverse relationship with DO concentrations in the bottom waters. As DO increases on the surface, the DO level on the bottom decreases. The stratification at this particular station is considered to be the strongest when the DO concentrations at the bottom of the lake are at a minimum. Increasing DO levels at the surface are due to algal productivity, while decreasing DO levels in the hypolimnion are the result of thermal stratification. Figure 6-40 shows the percent saturation of DO over time for station LM06. Again, the surface and bottom waters are displayed in this figure. As with station LM01, an inverse relationship of DO with respect to the surface and bottom waters was

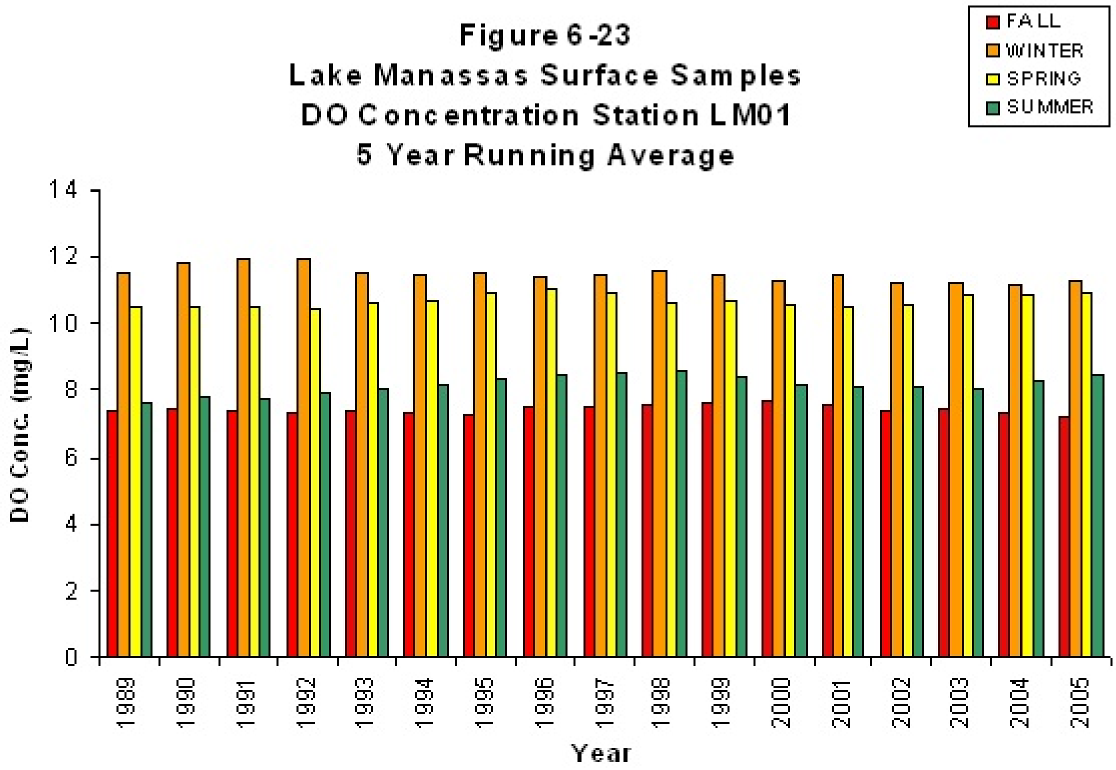


Figure 6-23
Lake Manassas Surface Samples
DO Concentration Station LM01
5 Year Running Average

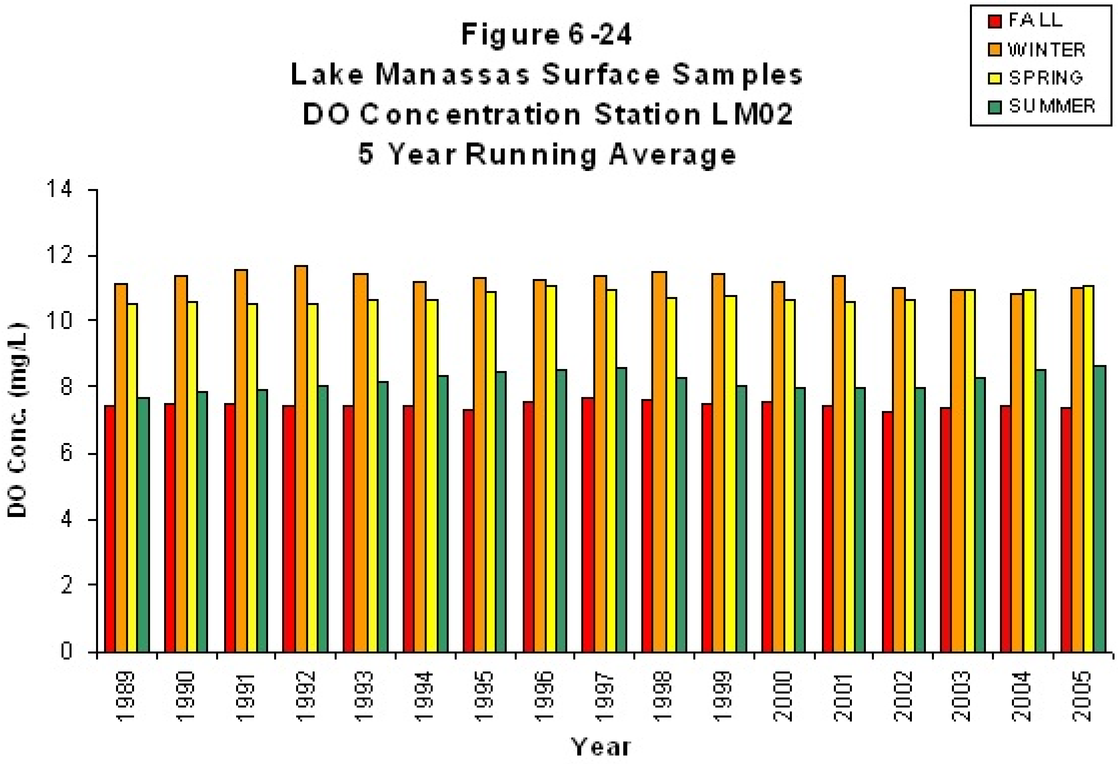


Figure 6-24
Lake Manassas Surface Samples
DO Concentration Station LM02
5 Year Running Average

Figure 6-25
Lake Manassas Surface Samples
DO Concentration Station LM03
5 Year Running Average

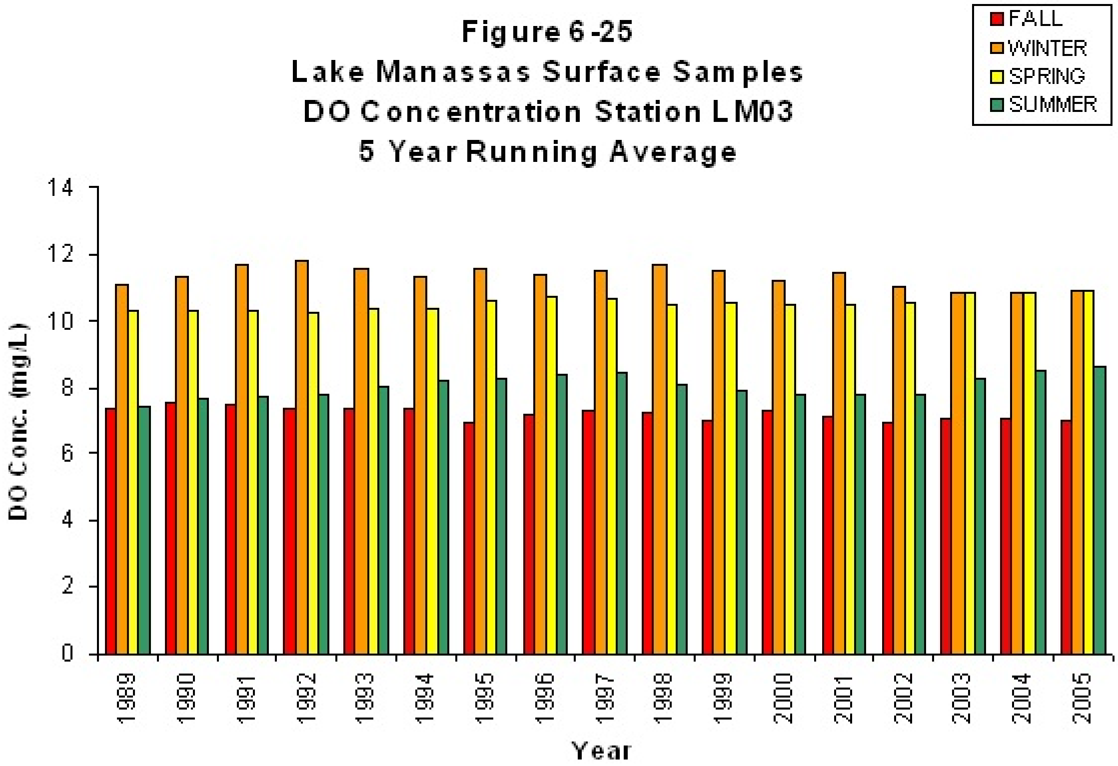
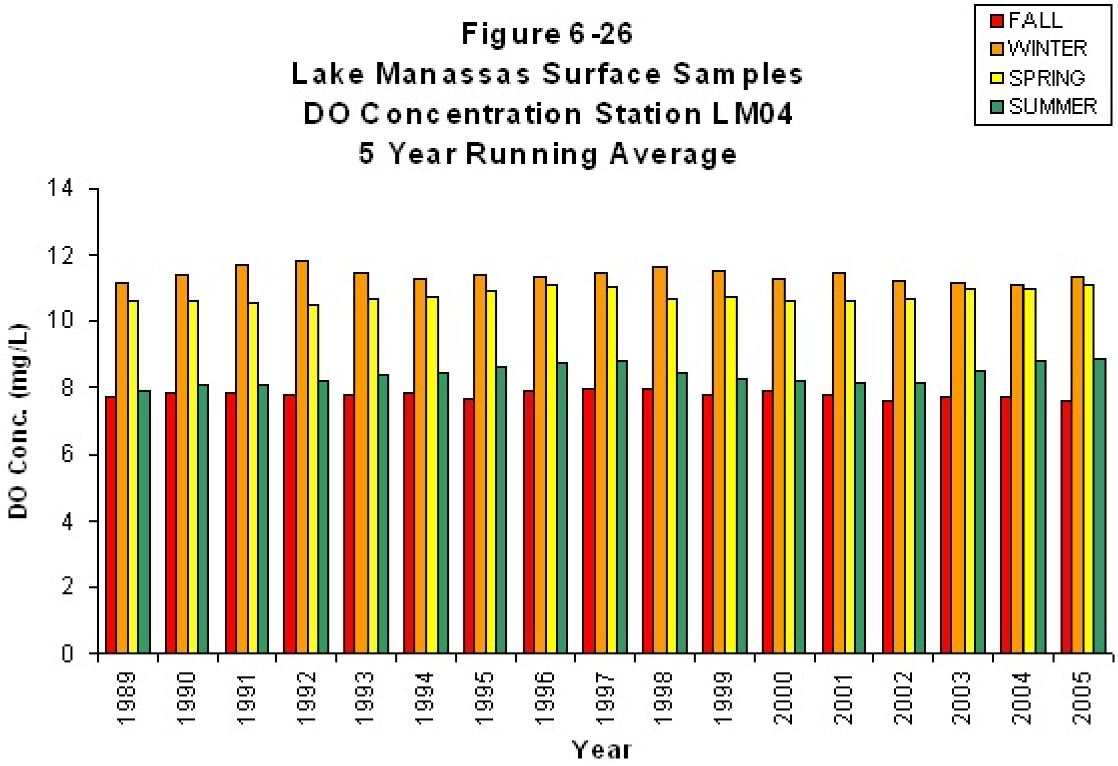


Figure 6-26
Lake Manassas Surface Samples
DO Concentration Station LM04
5 Year Running Average



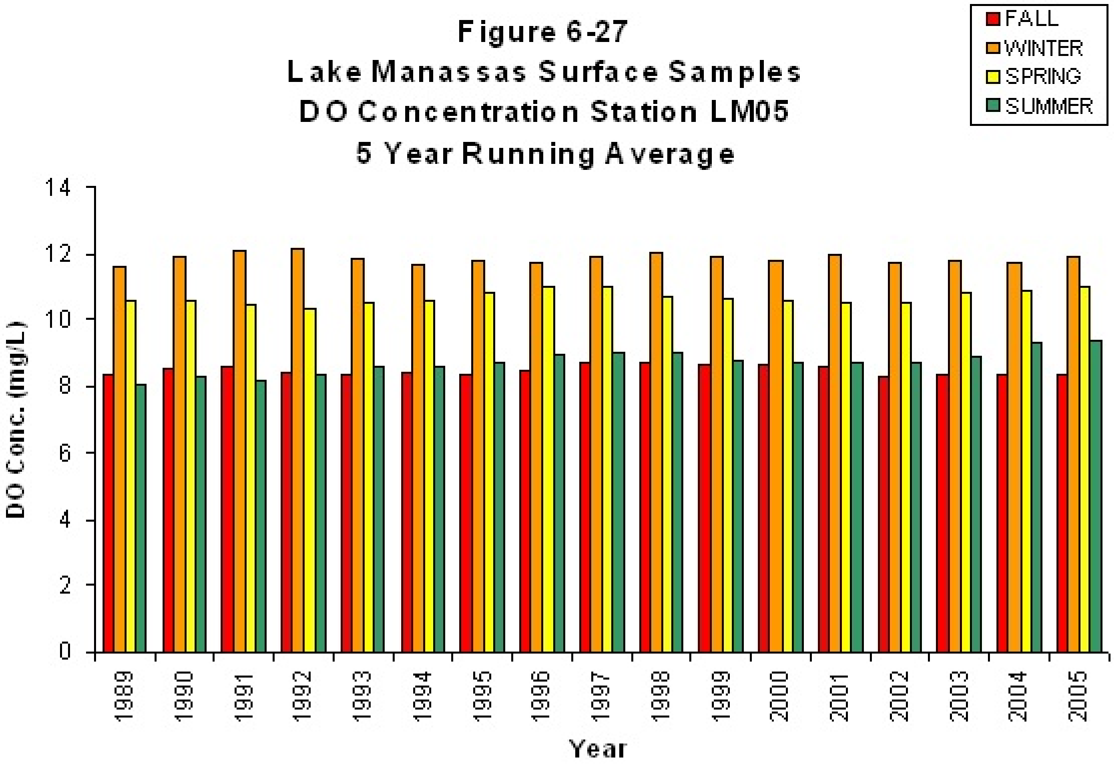


Figure 6-27
Lake Manassas Surface Samples
DO Concentration Station LM05
5 Year Running Average

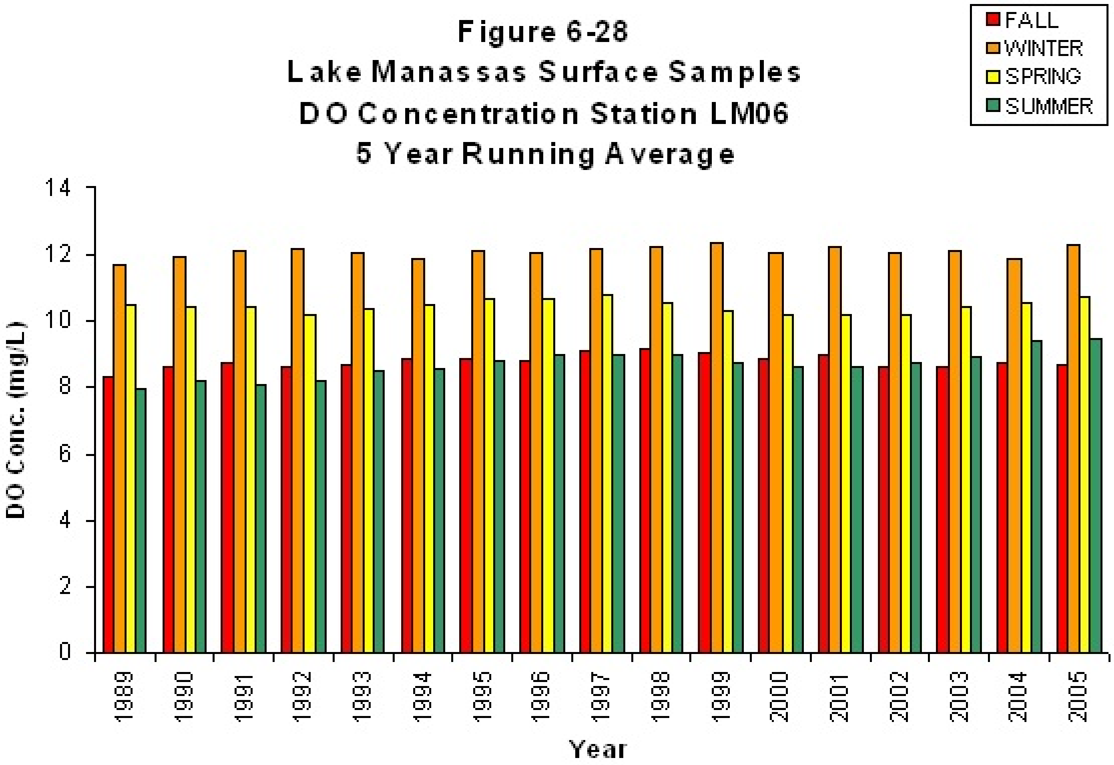


Figure 6-28
Lake Manassas Surface Samples
DO Concentration Station LM06
5 Year Running Average

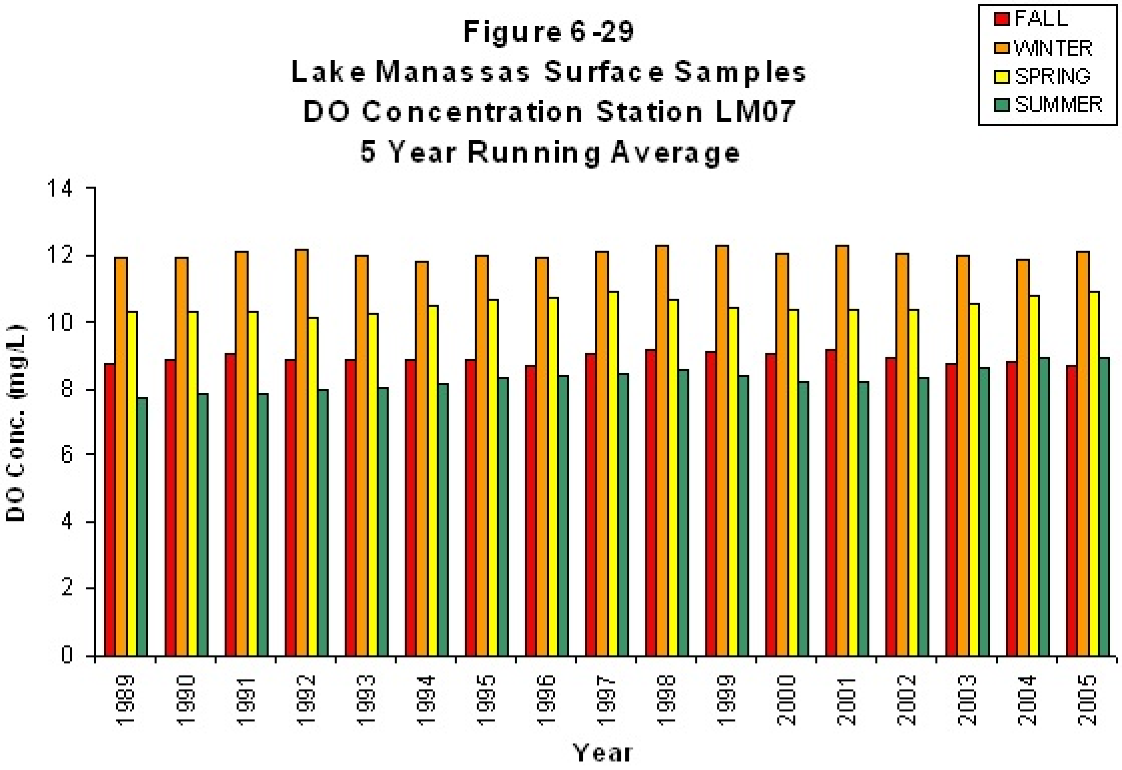


Figure 6-29
Lake Manassas Surface Samples
DO Concentration Station LM07
5 Year Running Average

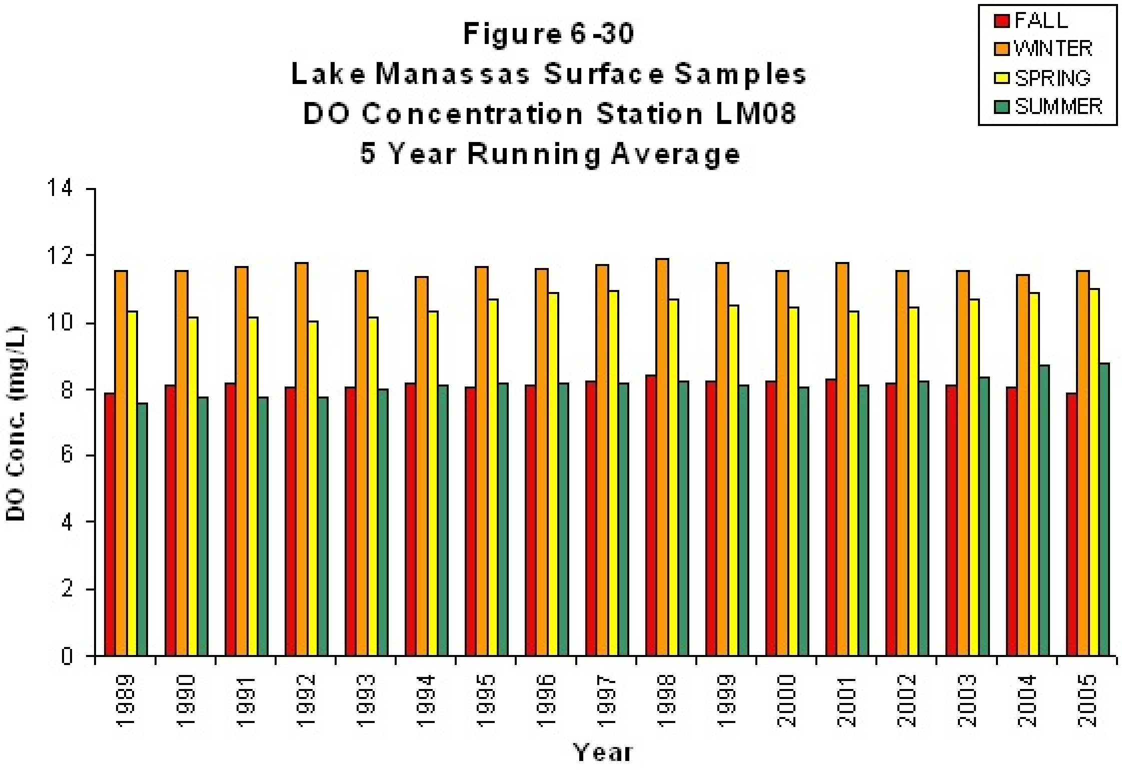


Figure 6-30
Lake Manassas Surface Samples
DO Concentration Station LM08
5 Year Running Average

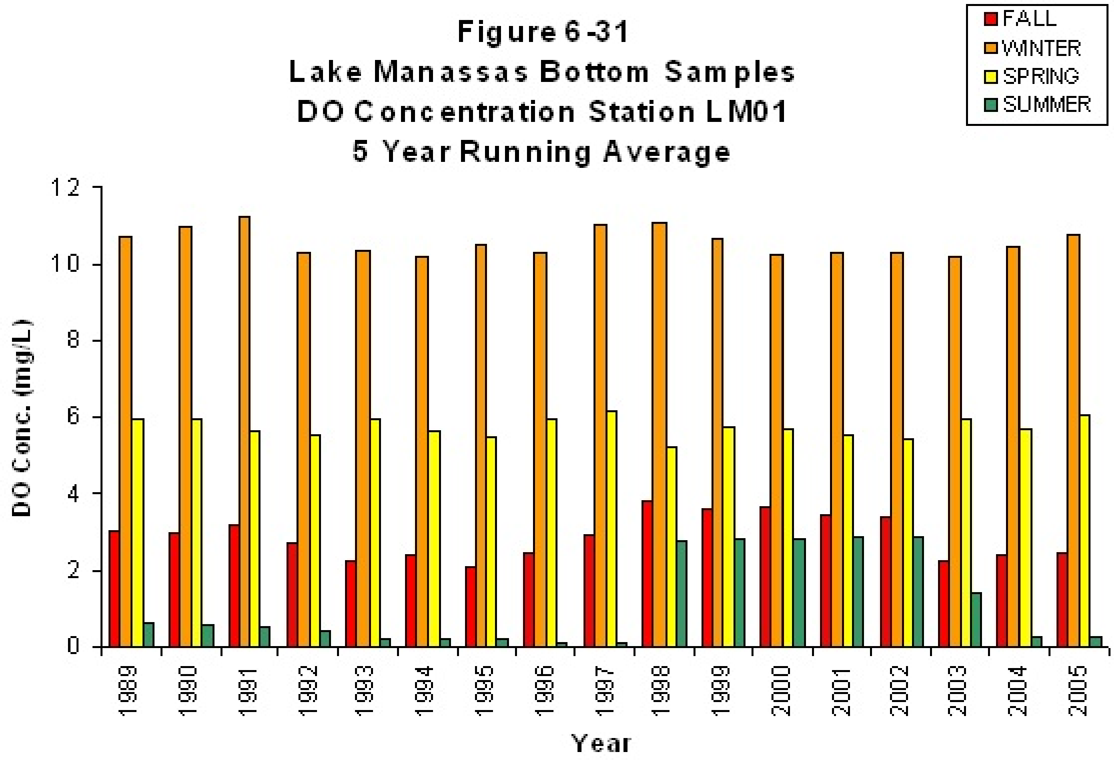


Figure 6-31
Lake Manassas Bottom Samples
DO Concentration Station LM01
5 Year Running Average

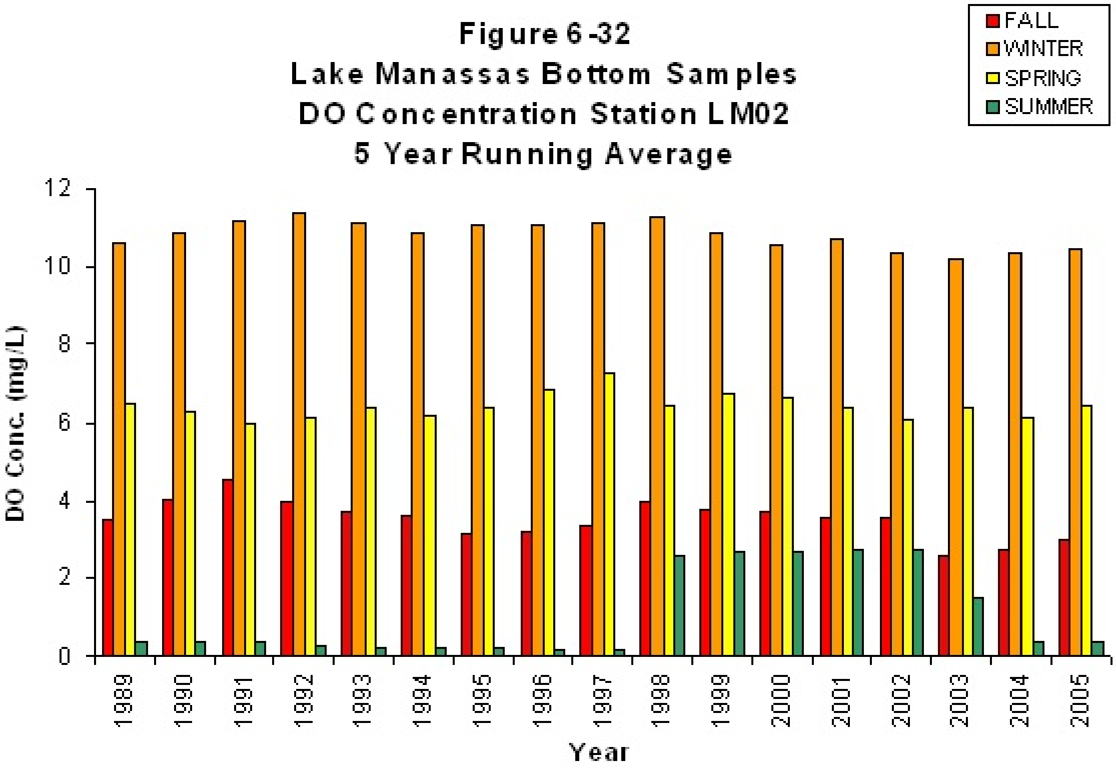


Figure 6-32
Lake Manassas Bottom Samples
DO Concentration Station LM02
5 Year Running Average

Figure 6-33
Lake Manassas Bottom Samples
DO Concentration Station LM03
5 Year Running Average

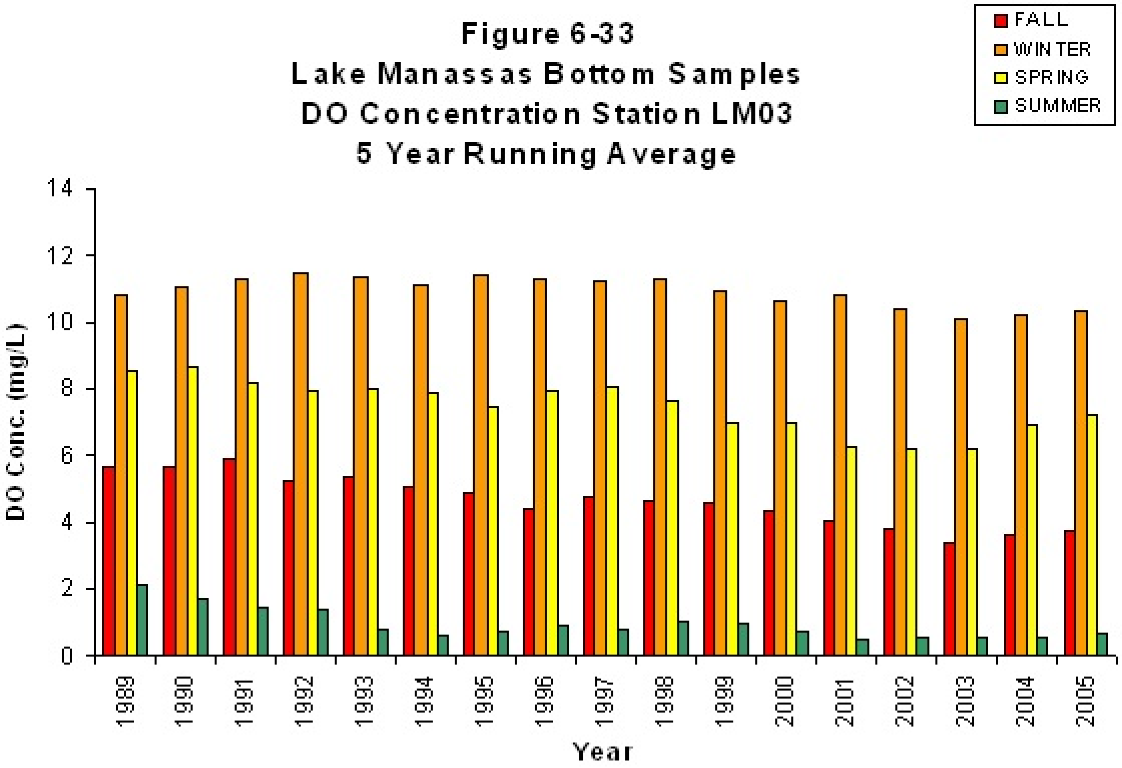
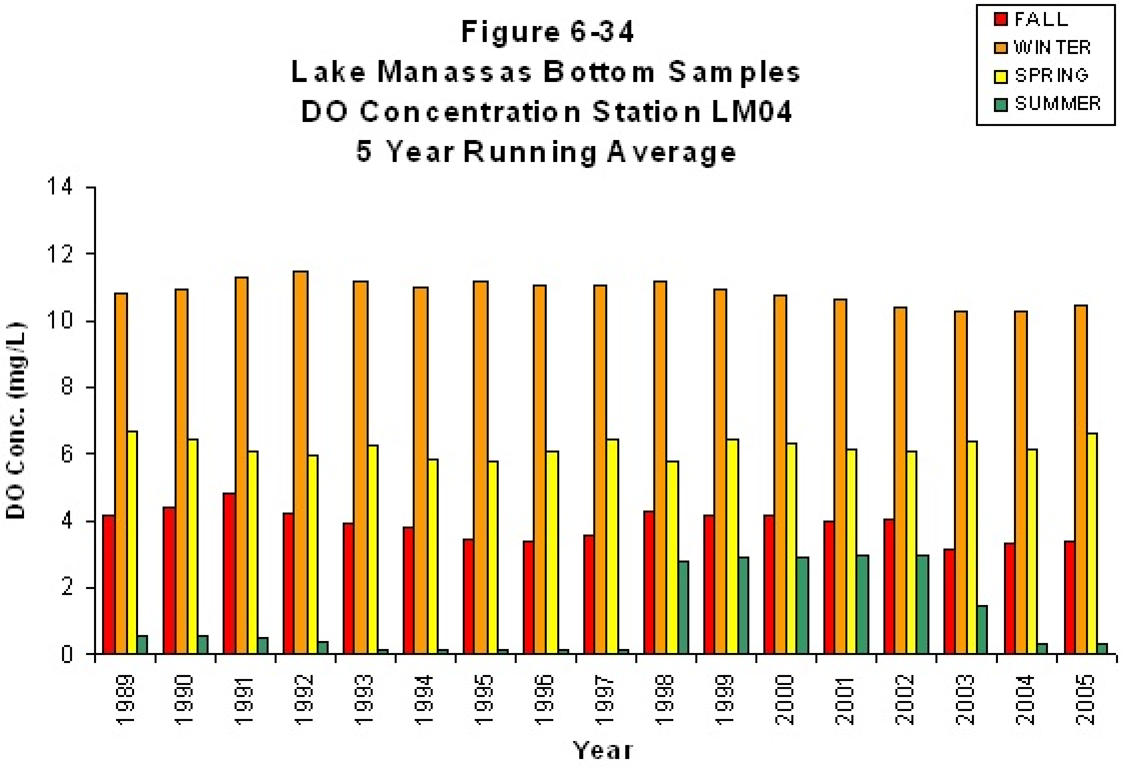


Figure 6-34
Lake Manassas Bottom Samples
DO Concentration Station LM04
5 Year Running Average



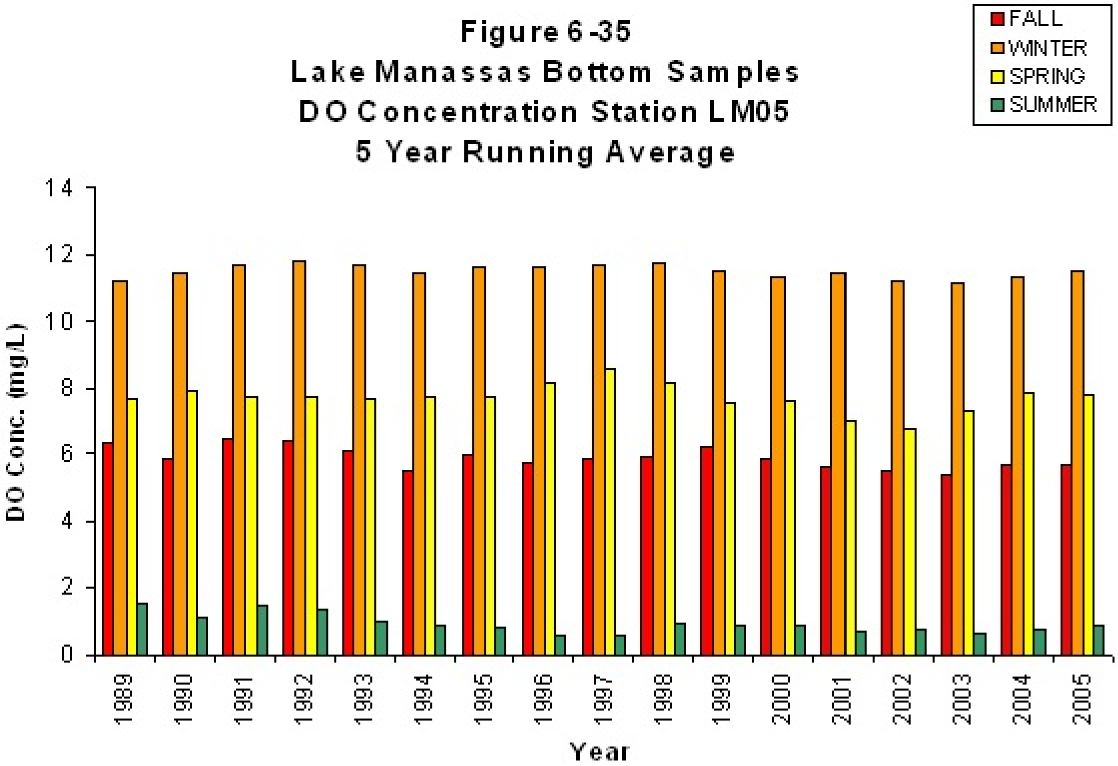


Figure 6-35
Lake Manassas Bottom Samples
DO Concentration Station LM05
5 Year Running Average

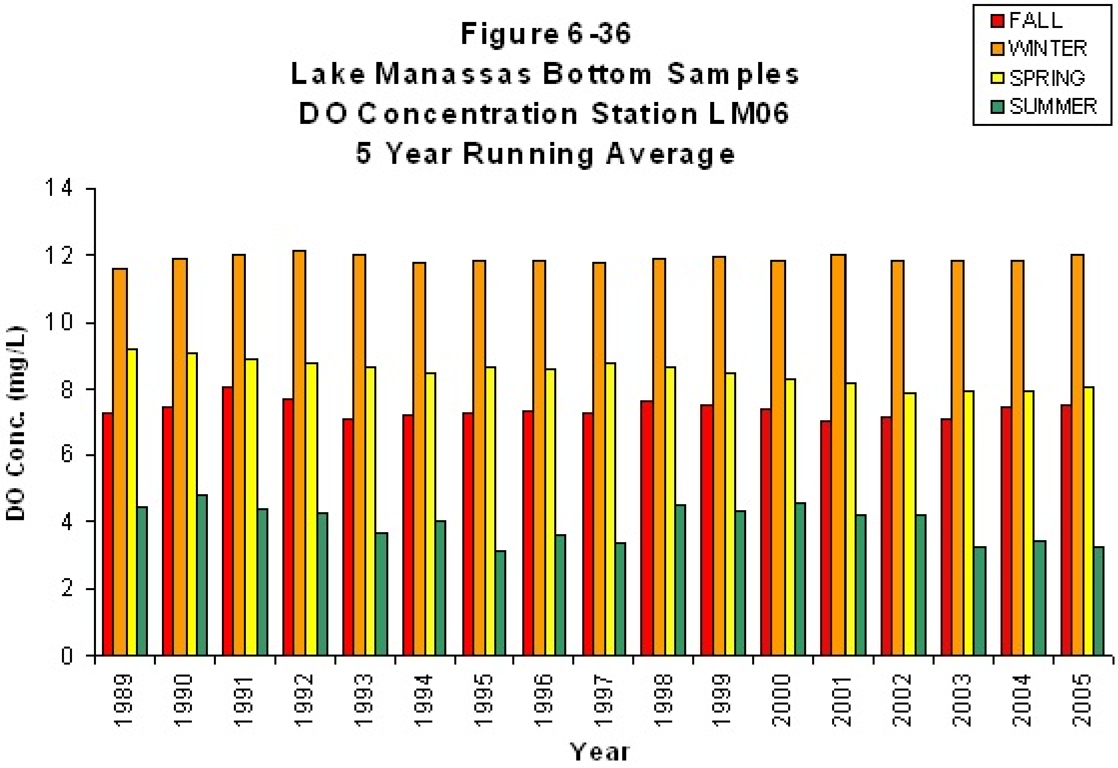


Figure 6-36
Lake Manassas Bottom Samples
DO Concentration Station LM06
5 Year Running Average

Figure 6-37
Lake Manassas Bottom Samples
DO Concentration Station LM07
5 Year Running Average

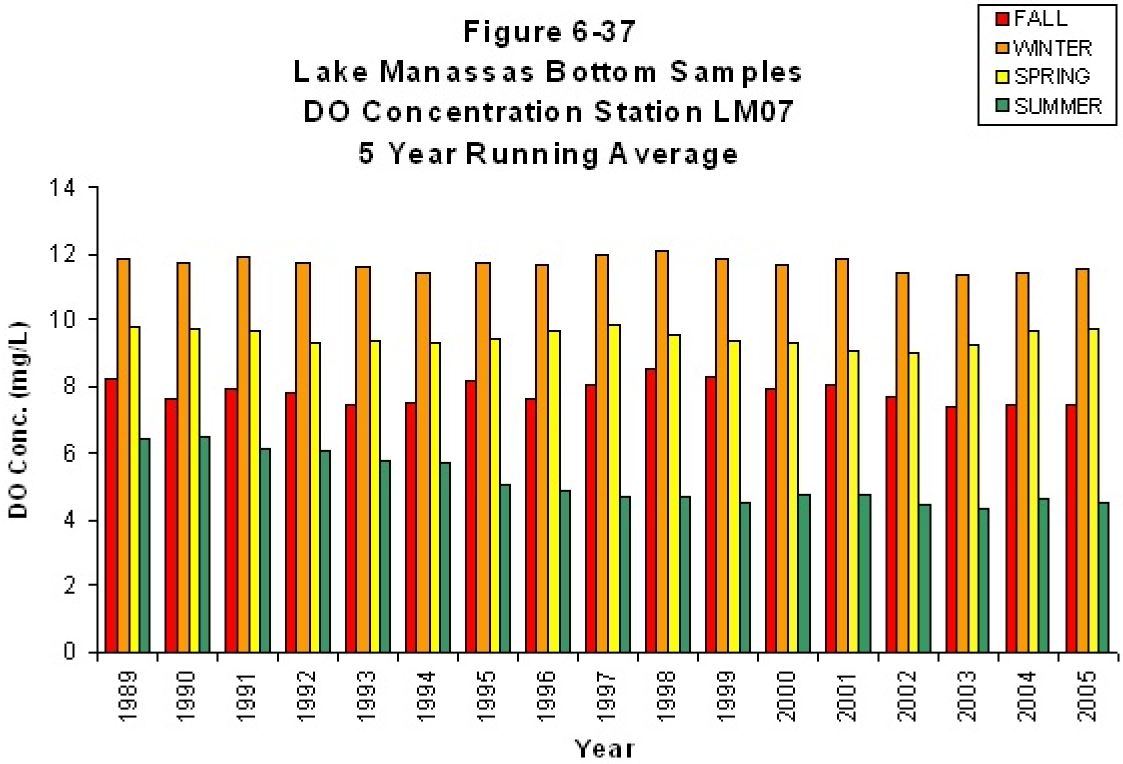
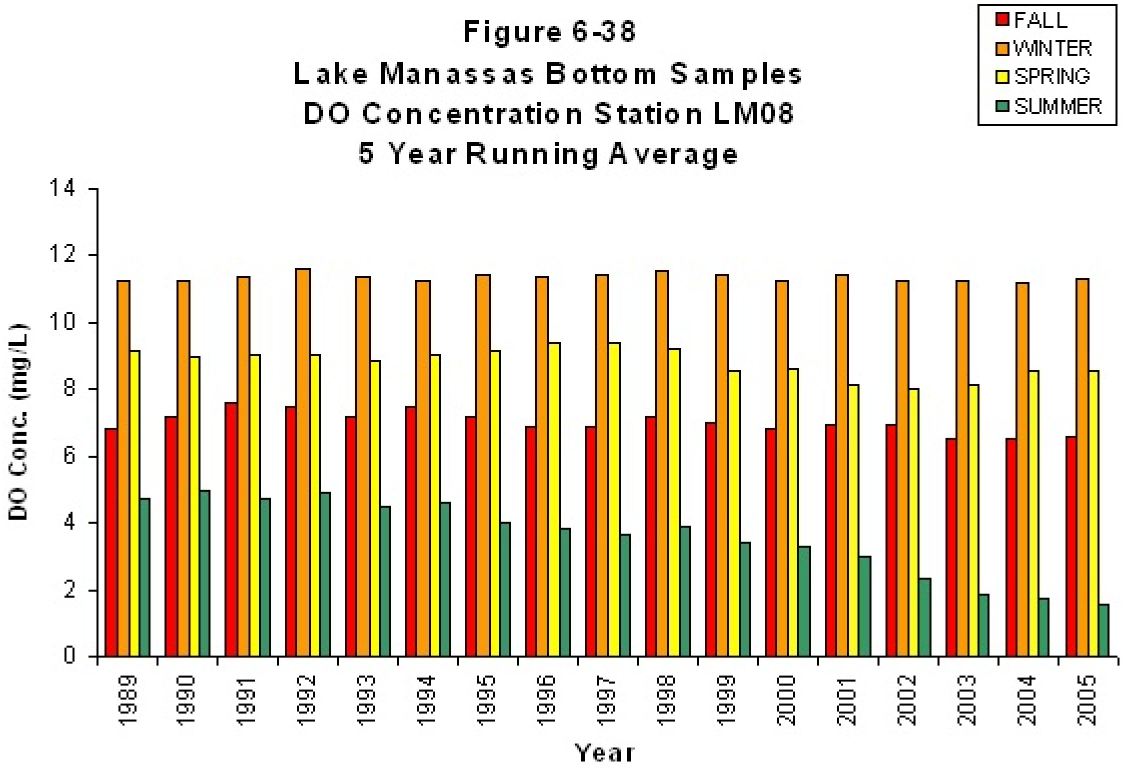


Figure 6-38
Lake Manassas Bottom Samples
DO Concentration Station LM08
5 Year Running Average



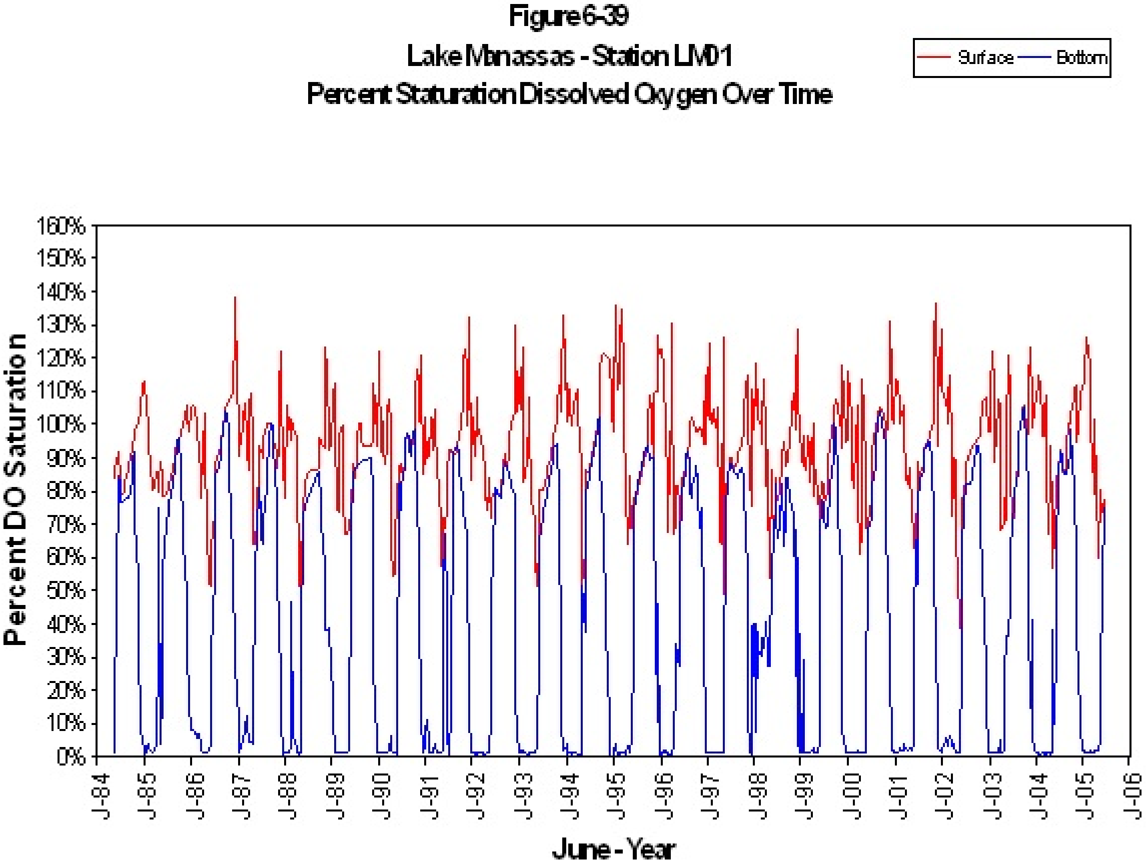
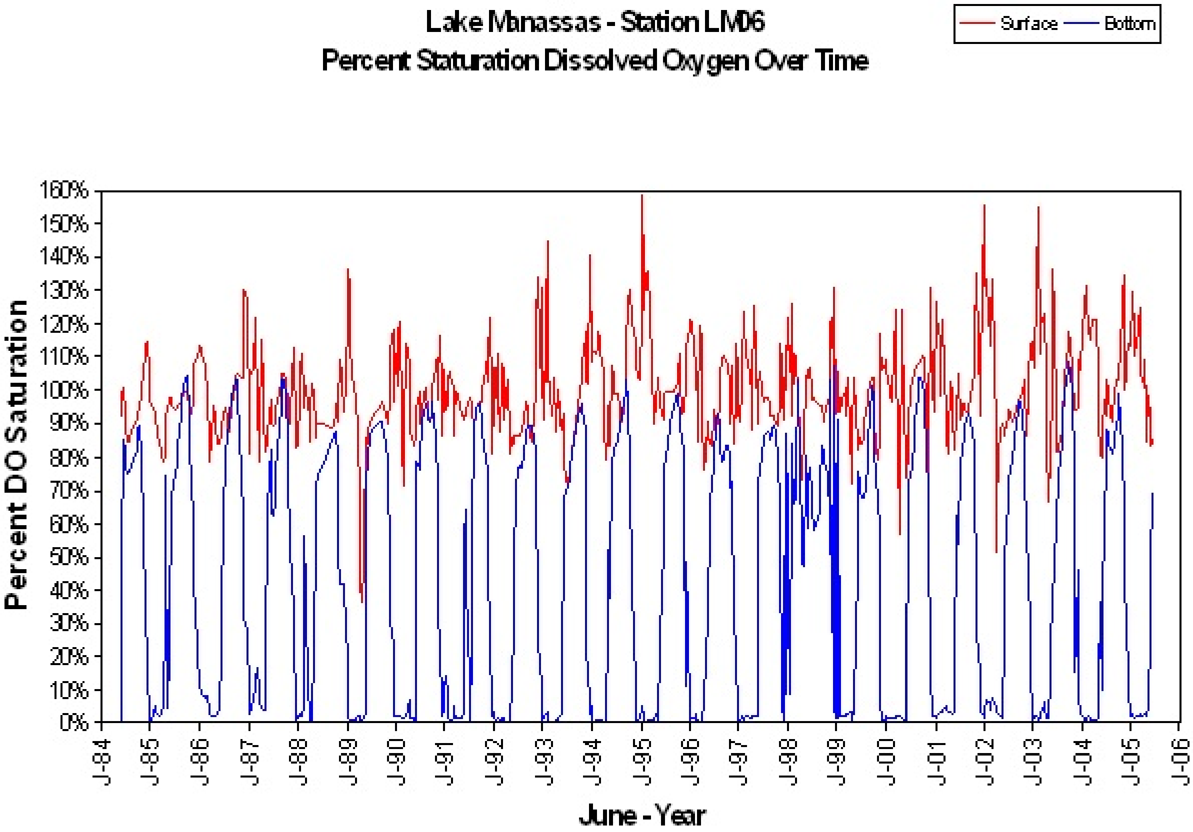


Figure 6-39
Lake Manassas - Station LM01
Percent Staturation Dissolved Oxygen Over Time

Figure 6-40
Lake Manassas - Station LM06
Percent Staturation Dissolved Oxygen Over Time



detected at station LM06. However, increased DO levels at the surface were measured at station LM06. Increased algal productivity is a likely explanation for the elevated DO levels at this station. Later sections in this document will show that the chlorophyll *a* concentrations have increased at this station.

Figure 6-41 plots the average DO concentration at the bottom of the lake with the average DO concentration at the surface for the time period 2001 - 2005. In order to determine possible relationships between the surface and bottom DO values, a 1:1 line was drawn on the graph. The data points shown on the graph represent average DO concentrations for individual seasons at each station. DO concentrations were typically the highest and similar in the winter months both for the epilimnion and the hypolimnion. The resulting data points plot along the 1:1 line. Similar surface values to those in the winter are found in the spring. However, the bottom values are quite different. This is the result of stratification occurring in deeper sections first and subsequently in shallower sections, which is shown by the data points plotting away from the 1:1 line. The summer and fall also experience this pattern. However the stratification in the summer is the strongest. Figure 6-42 plots a similar figure, though percent saturated DO is plotted instead. Again, the winter months plot close to the 1:1 line indicating that the percent saturated DO concentrations are similar in both the epilimnion and hypolimnion. The summer, fall, and spring months plot data points that move away from the 1:1 line illustrating as with the previous plot the difference in percent saturated DO between the epilimnion and the hypolimnion. Also visible in this plot is the strength of stratification during the summer. Data points that plot farther away from the 1:1 line exemplify a very strong stratification in the lake.

Figure 6-41
Surface vs. Bottom Seasonal DO Concentration - Lake Manassas
All Lake Stations (2001 - 2005)

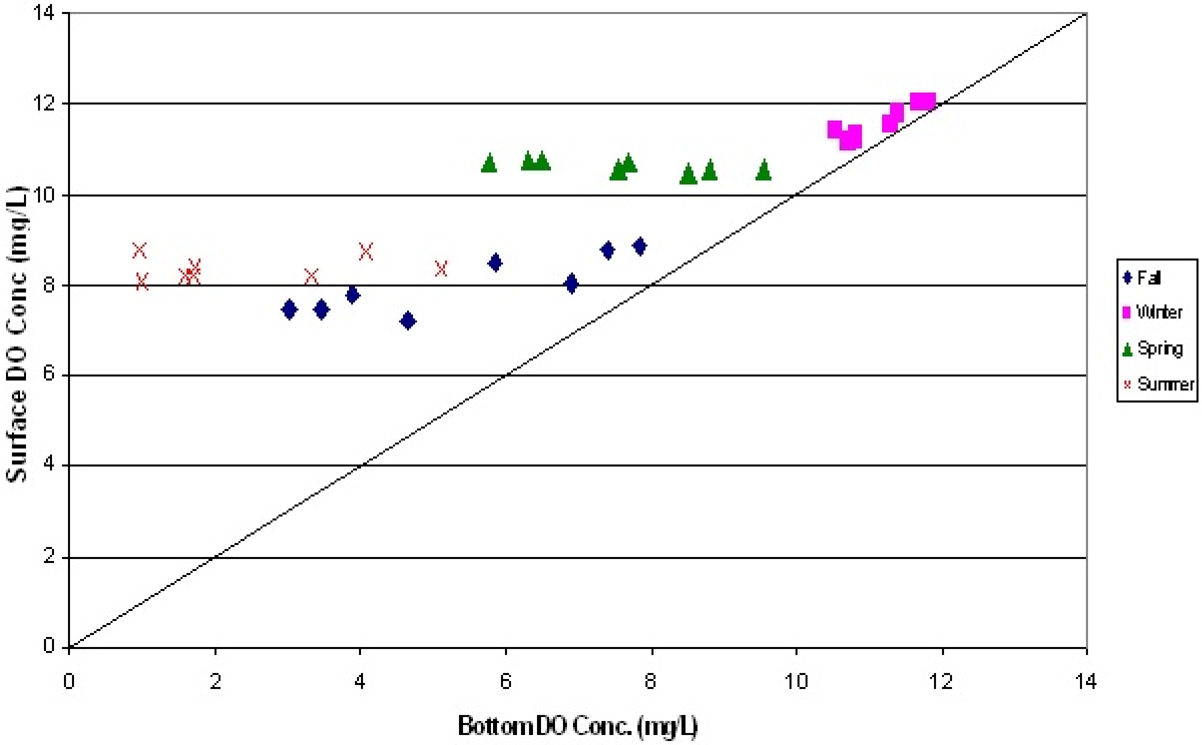
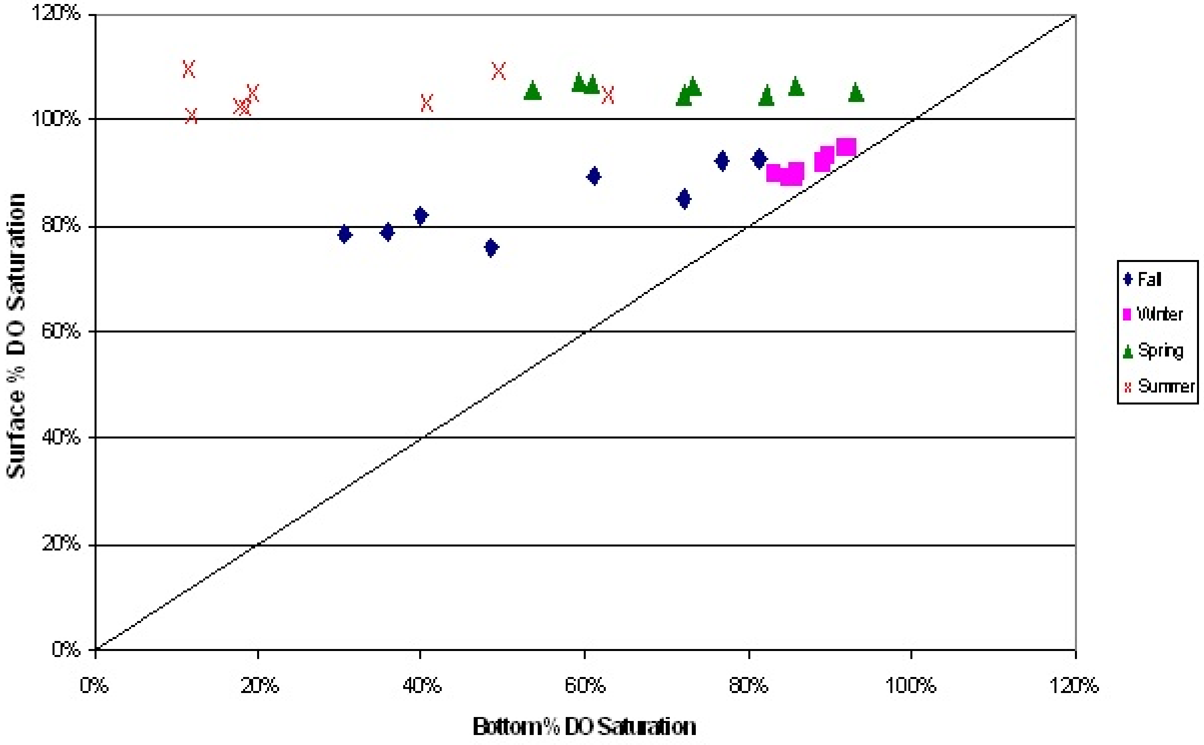


Figure 6-42
Surface vs. Bottom Seasonal Percent DO Sat. Concentration - Lake Manassas
All Lake Stations (2001 - 2005)



Profiles of DO and percent saturated DO can be found in Figures 6-43 and 6-45, respectively. Both figures plot profiles at station LM01 during 2002. The highest DO concentration of the year was measured during April at 13.47 mg/L. After this point, the DO concentration decreased, and stratification began between April and May. June experiences the strongest stratification visible by lowest concentration of DO in the hypolimnion and the largest change in DO values between the epilimnion and hypolimnion. The month of October shows signs of the fall turnover growing near with the epilimnion increasing in depth to 20 feet from 10 feet in September. November marks the month when the lake is completely mixed illustrated by the similar DO concentrations throughout the water column. The profile of percent saturated DO provides similar results. The summer months all show saturated DO values above 100%. This indicates the growth and presence of algae. In the event the saturated DO values drop below 100%, algae growth would most likely cease due to a decreasing phosphorus supply limiting any further algal growth. As more phosphorus enters the system, algal growth would resume and the saturated DO values would rise above 100%.

Figures 6-44 and 6-46, again, display profiles of DO and percent saturated DO, but are for 2003. Both years, 2002 and 2003 were chosen to profile because each year received varying amounts of rainfall. The average annual rainfall for 2002 was 34.27 inches, while the average annual rainfall for 2003 was 58.65 inches. These values accurately represent dry and semi-wet precipitation conditions when compared to the average annual rainfall for the Occoquan Reservoir basin during the same years; 34.77 inches and 57.52 inches, respectively. When the profiles of DO concentrations are compared between 2002 and 2003 an interesting observation

Figure 6-43
Lake Manassas-Station LMD1, 2002
Dissolved Oxygen Profile

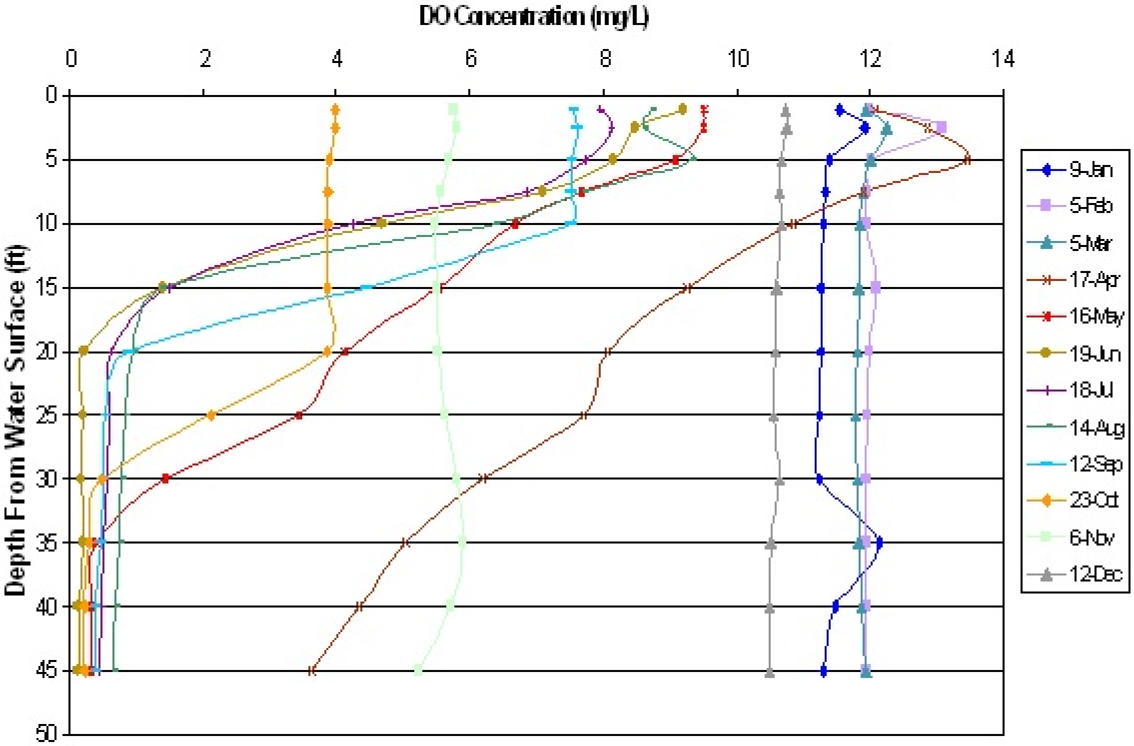


Figure 6-44
Lake Manassas-Station LMD1, 2003
Dissolved Oxygen Profile

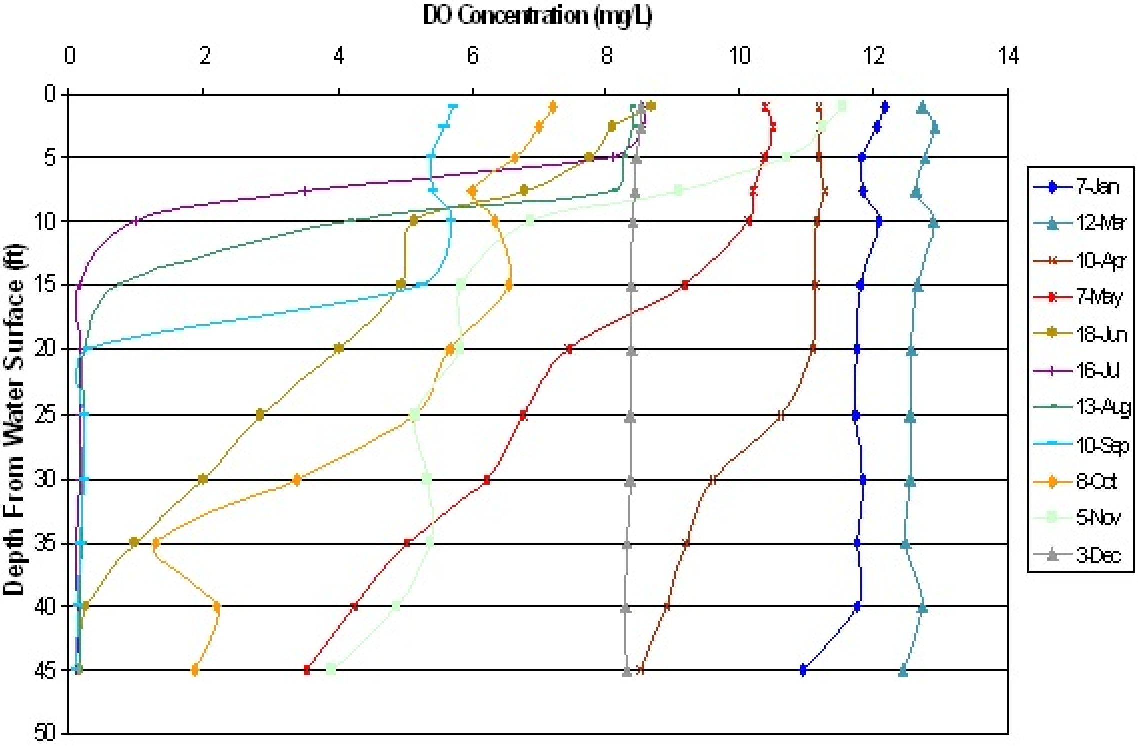


Figure 6-45
Lake Manassas-Station LMD1, 2002
Profile of Percent Saturation DO

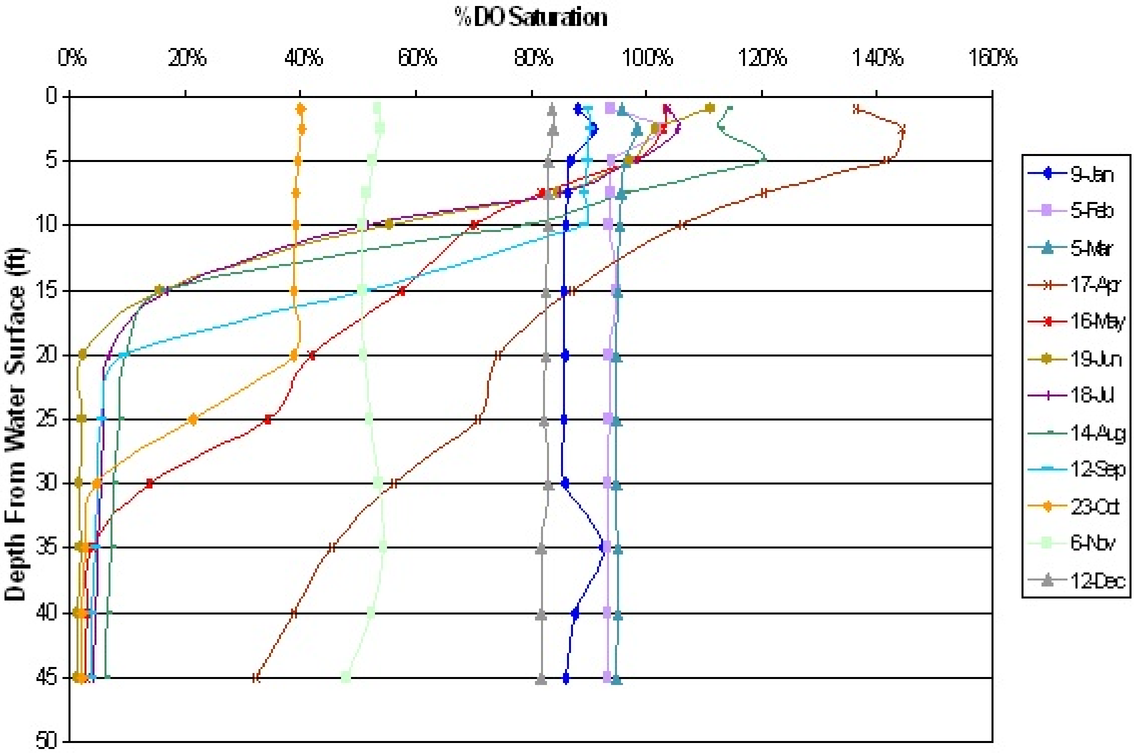
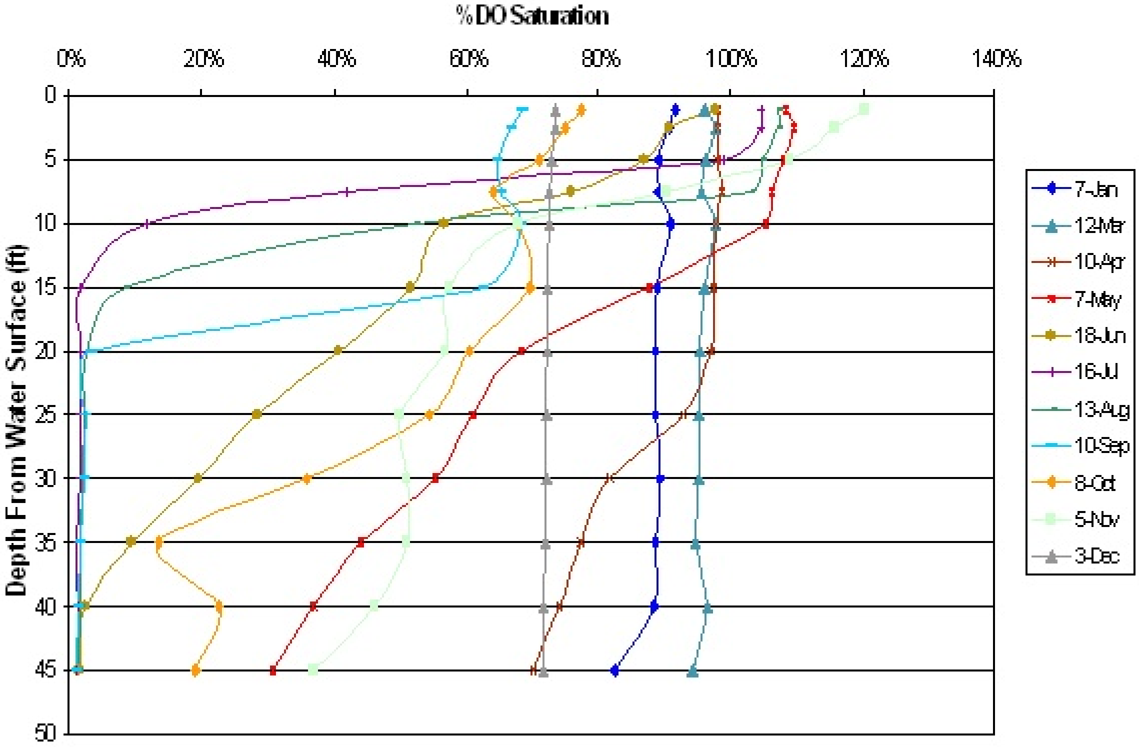


Figure 6-46
Lake Manassas-Station LM01, 2003
Profile of Percent Saturation DO



is made. As stated previously, stratification in 2002 began between April and May. During 2003, signs of stratification are visible in June, however, this stratification is weak and the water column does not become fully stratified until July. The fall turnover occurs in relatively the same month in 2003 as it did in 2002. However, in 2003 the hypolimnion has about 2 mg/L more DO than 2002 during the month of October. Another interesting note is that during periods of strong stratification, the thermocline existed between 5 and 20 feet in 2002 during July. The thermocline in 2003 during the month of July exists between 5 and 15 feet. Overall, 2002 had a longer period of stratification than 2003. Additionally, the thermocline in 2002 was 5 feet greater in depth than in 2003. A possible explanation for these observations is that the additional rainfall experienced during 2003 (Appendix A) created additional turbulence in the water column causing a mixing action.

Nutrients

The mass of nutrients contained in an aquatic ecosystem drives the productivity and trophic status of a lake. The nutrients that largely control the growth of algae are nitrogen and phosphorus. All of the nutrients that enter the lake are not necessarily available for biological production. Nitrogen can be lost through sedimentation, denitrification, and flushing from the system. In Lake Manassas, phosphorus is the least abundant and therefore limits biological activity. Phosphorus can exit the system through precipitation and adsorption to particulate matter in the water column, therefore further reducing its concentration in the lake and limiting the production of algae.

Nitrogen

The first form of nitrogen analyzed is Total Kjeldahl Nitrogen (TKN) which is a measure of the total reduced forms of nitrogen in the lake including organic nitrogen and ammonium (NH_4^+). Figures 6-47 through 6-62 show the five-year running averages of TKN for both the surface and bottom sections of the lake. As shown in Table 6-1, all stations, with the exception of LM06, report increasing trends of TKN at the surface. As algae die and begin to sink, heterotrophic bacteria consume the decaying organic matter while producing NH_4^+ as an end product of the decomposition (Wetzel, 2001). The elevated algal population in the lake could be a possible reason for the increasing trend of TKN at most stations. The Mann-Kendall Analysis for TKN in the bottom waters of the lake are shown in Table 6-2. Stations LM03, LM04, LM07, and LM08 reported increasing trends of TKN. During the summer when the lake is stratified, the hypolimnion becomes depleted of oxygen and the sediments subsequently release NH_4^+ (Wetzel, 2001). The TKN concentrations in the hypolimnion increase as a result. This phenomena is a possible explanation for the increasing trend of TKN at the four stations.

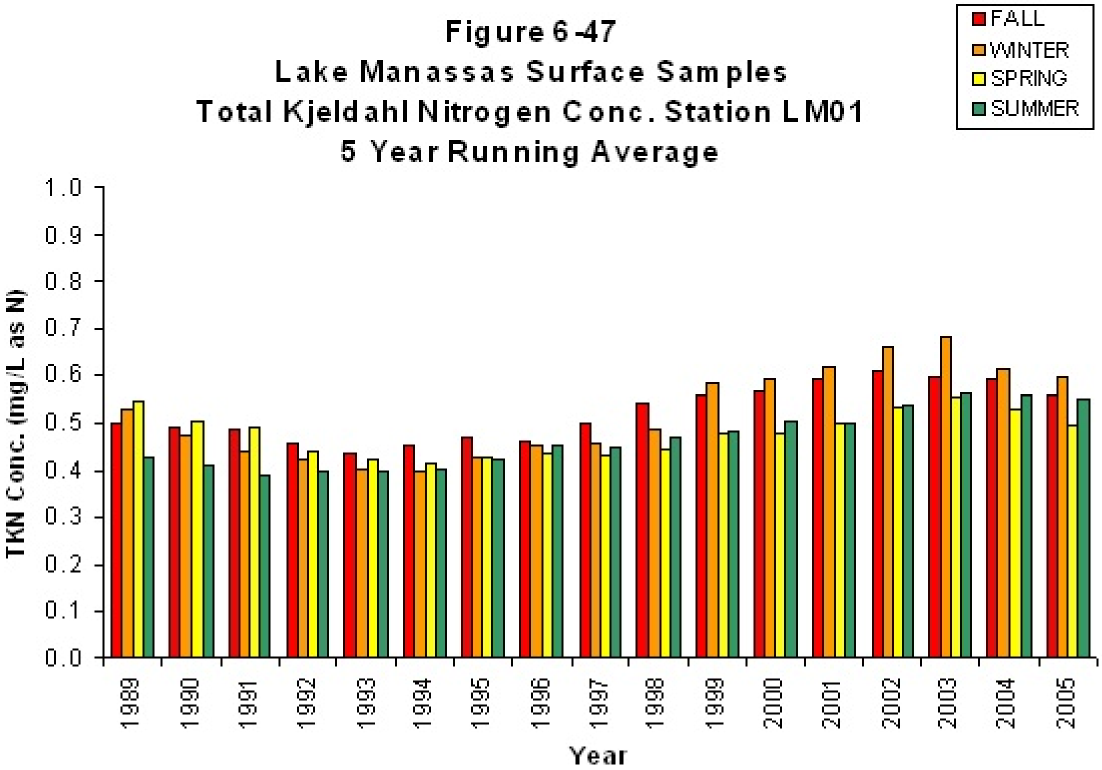


Figure 6-47
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM01
5 Year Running Average

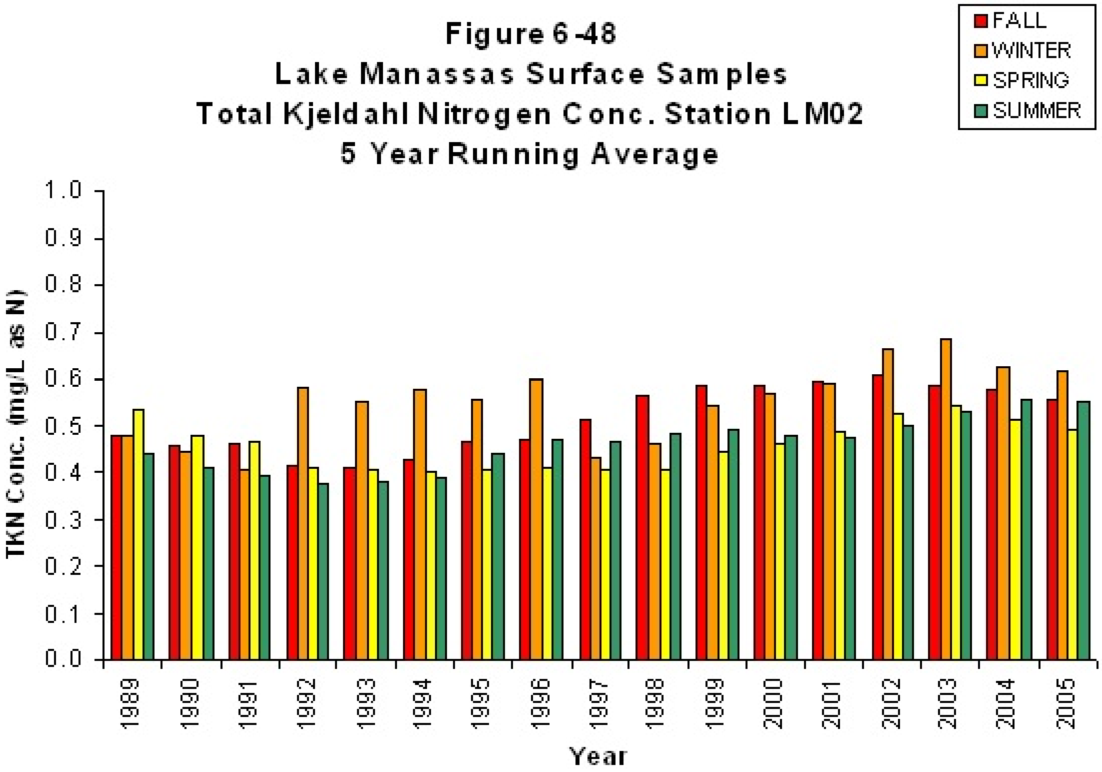


Figure 6-48
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM02
5 Year Running Average

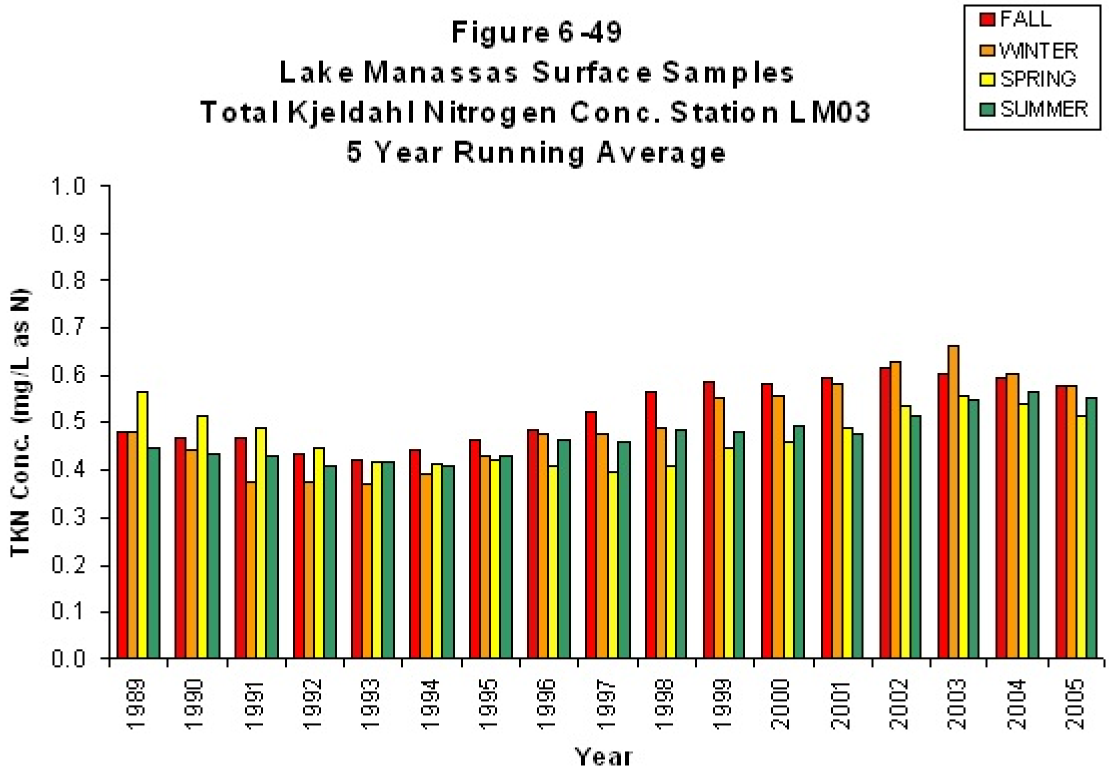


Figure 6-49
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM03
5 Year Running Average

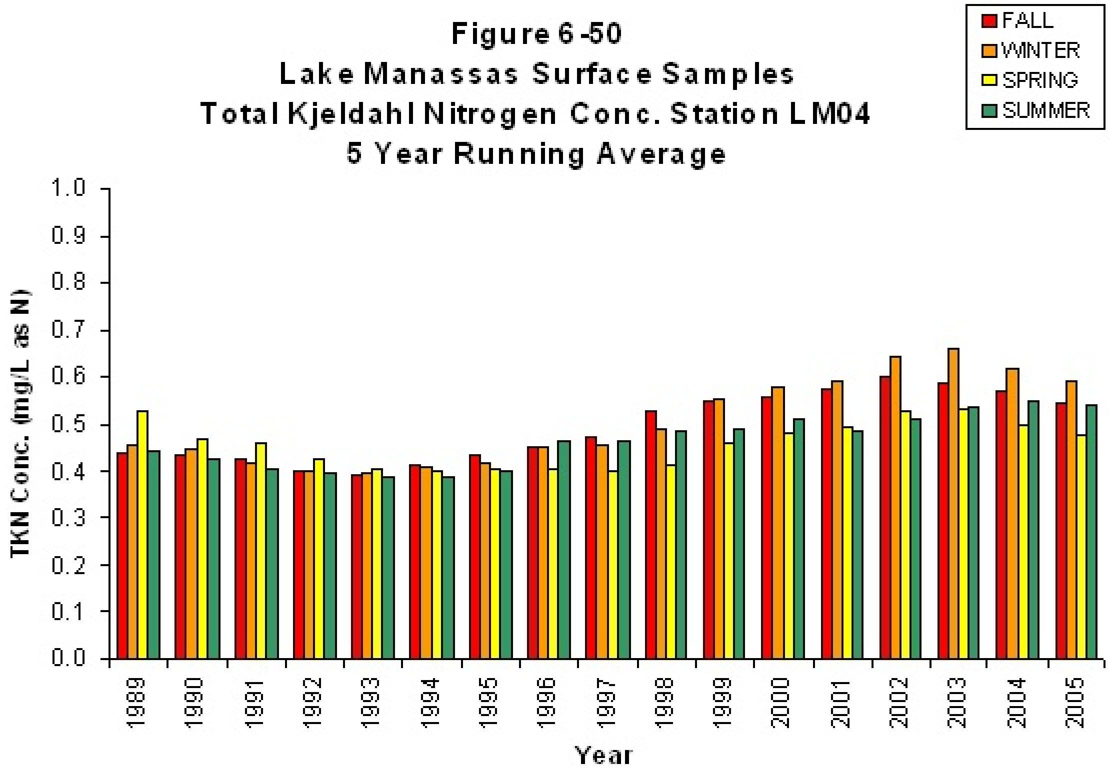


Figure 6-50
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM04
5 Year Running Average

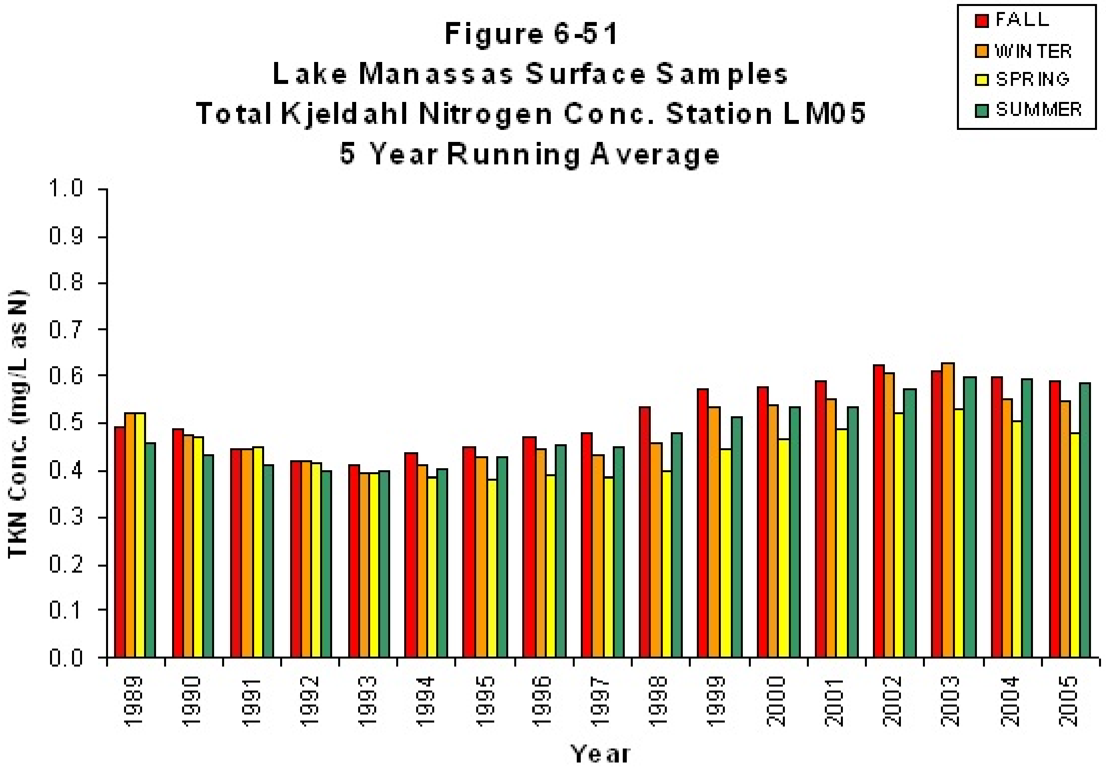


Figure 6-51
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM05
5 Year Running Average

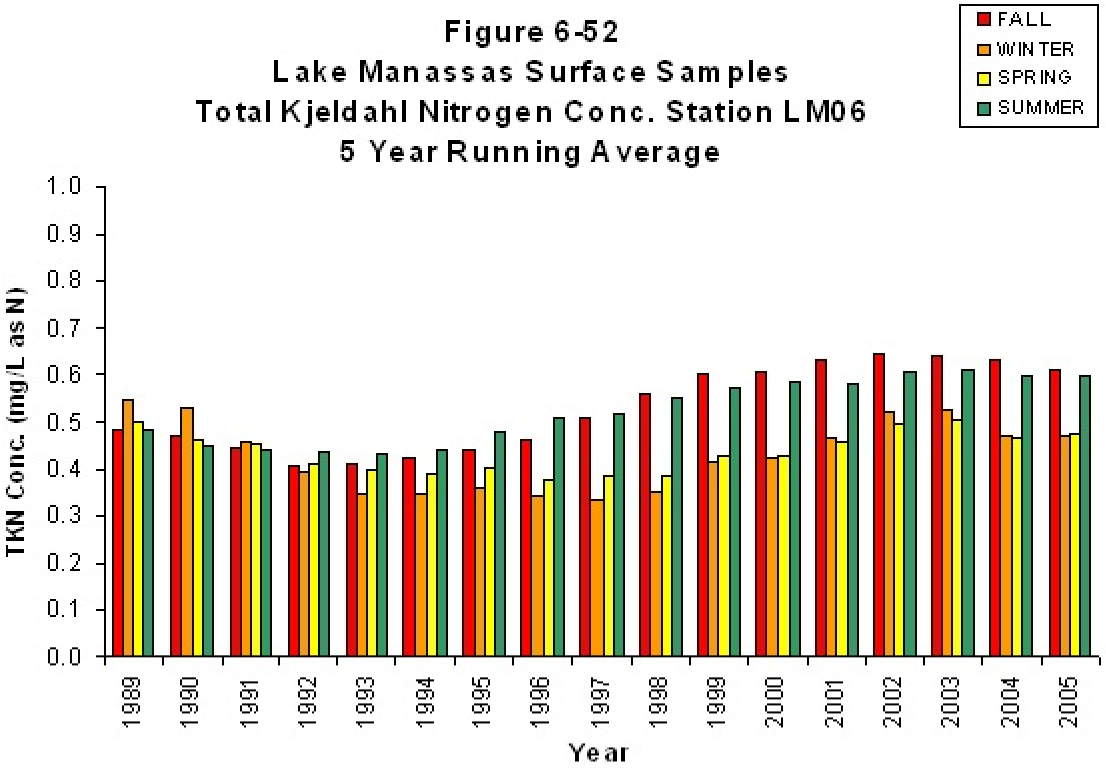


Figure 6-52
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM06
5 Year Running Average

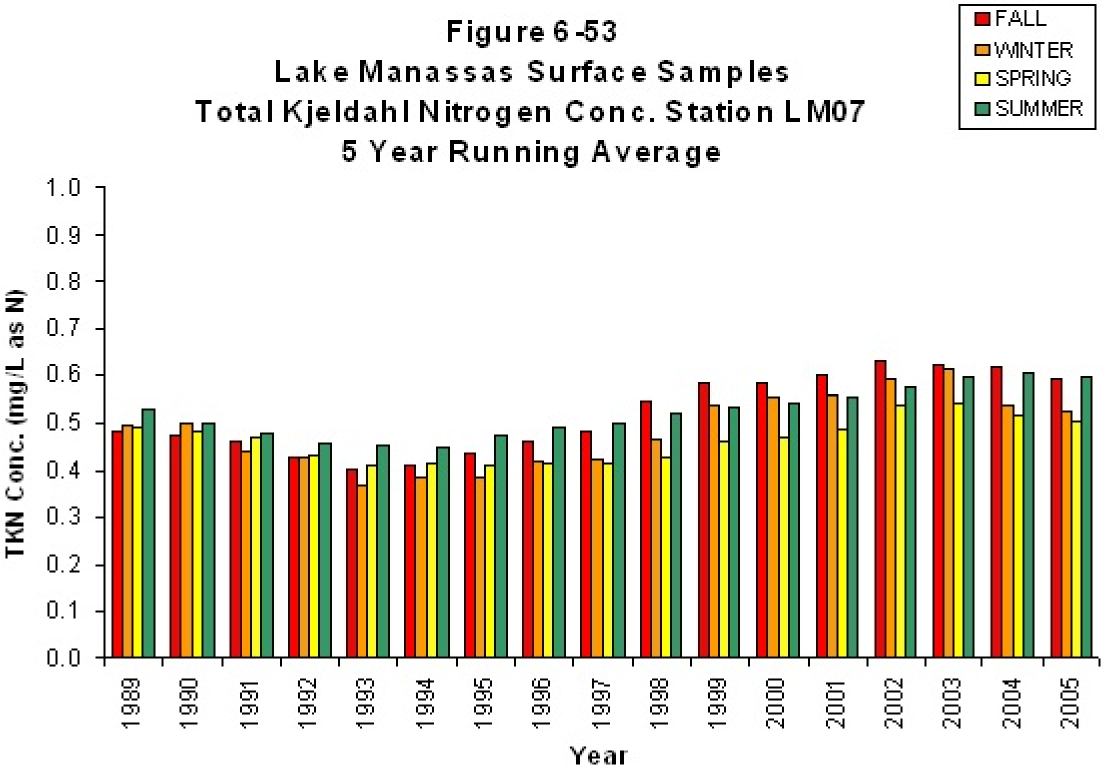


Figure 6-53
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM07
5 Year Running Average

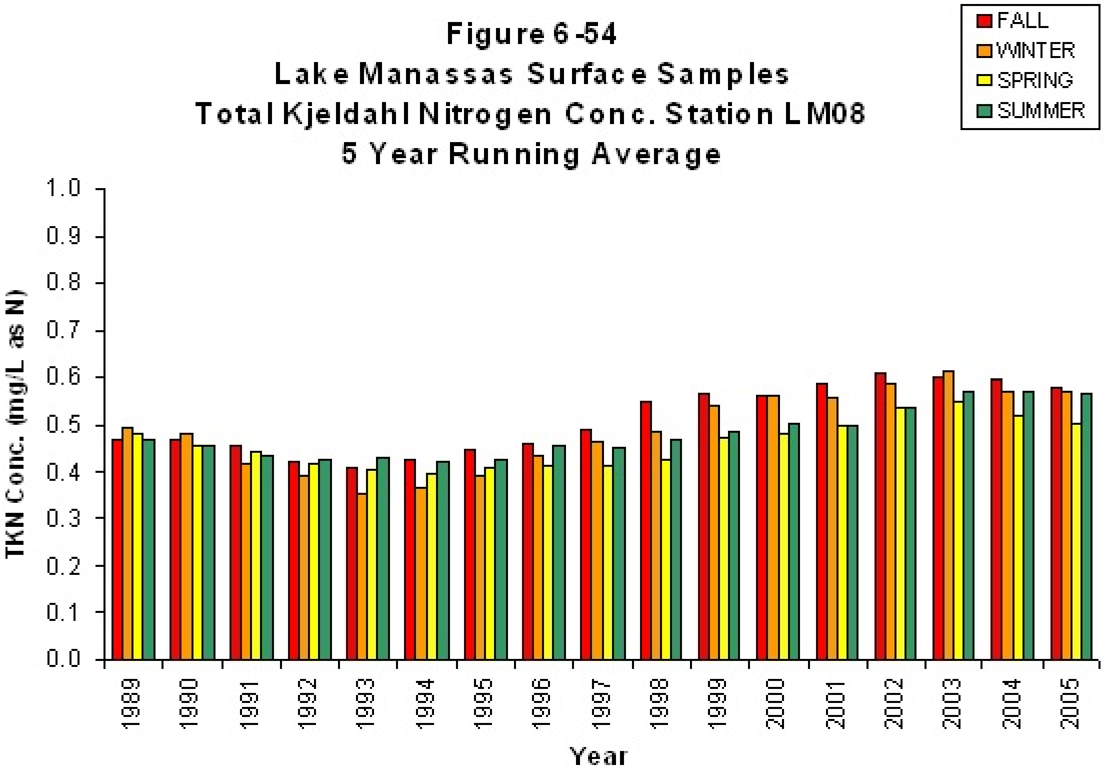


Figure 6-54
Lake Manassas Surface Samples
Total Kjeldahl Nitrogen Conc. Station LM08
5 Year Running Average

Figure 6-55
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM01
5 Year Running Average

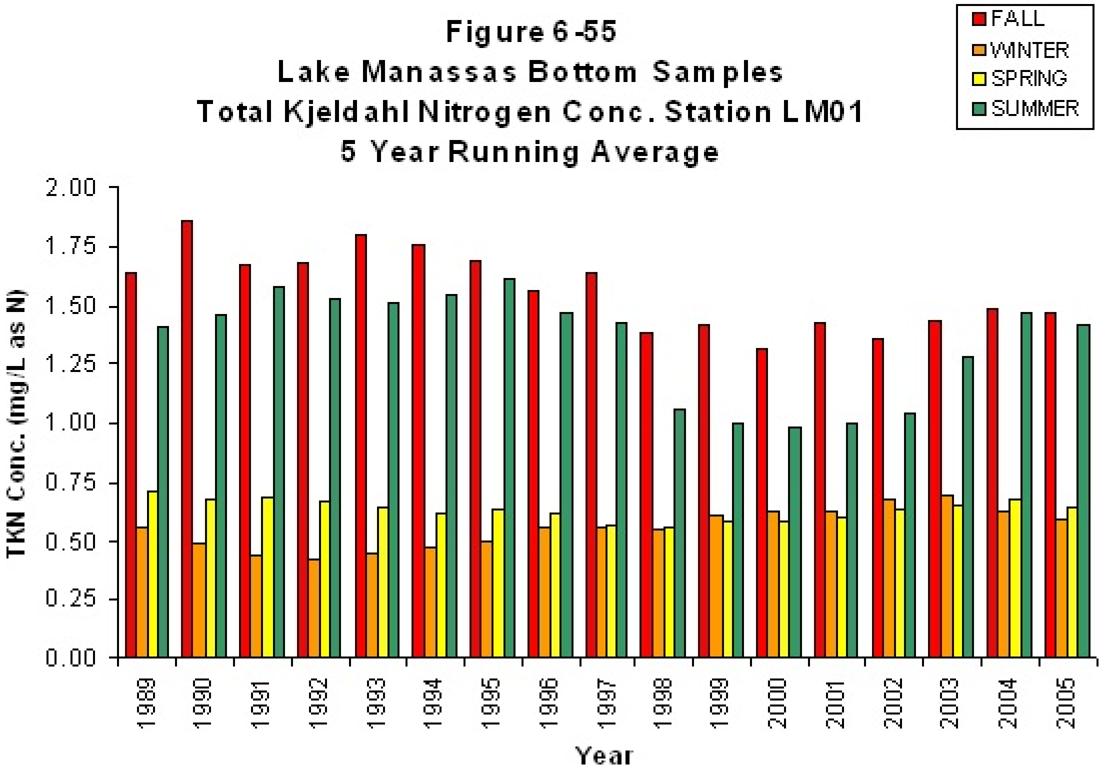


Figure 6-56
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM02
5 Year Running Average

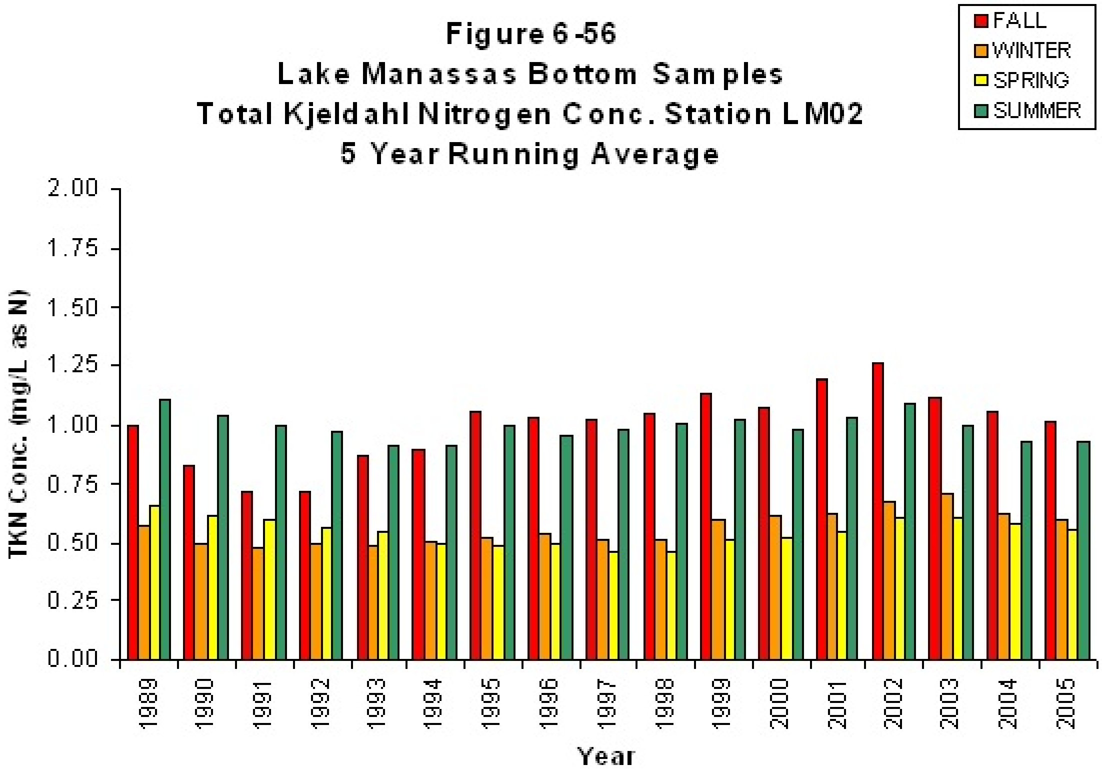


Figure 6-57
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM03
5 Year Running Average

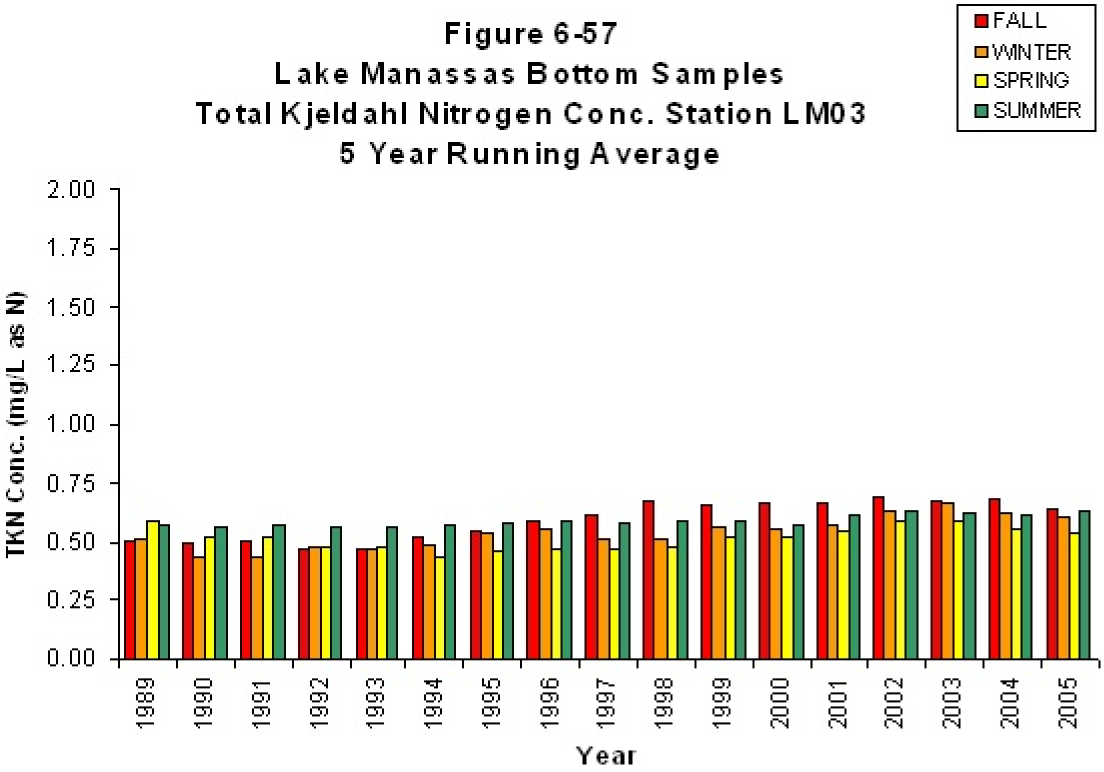


Figure 6-58
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM04
5 Year Running Average

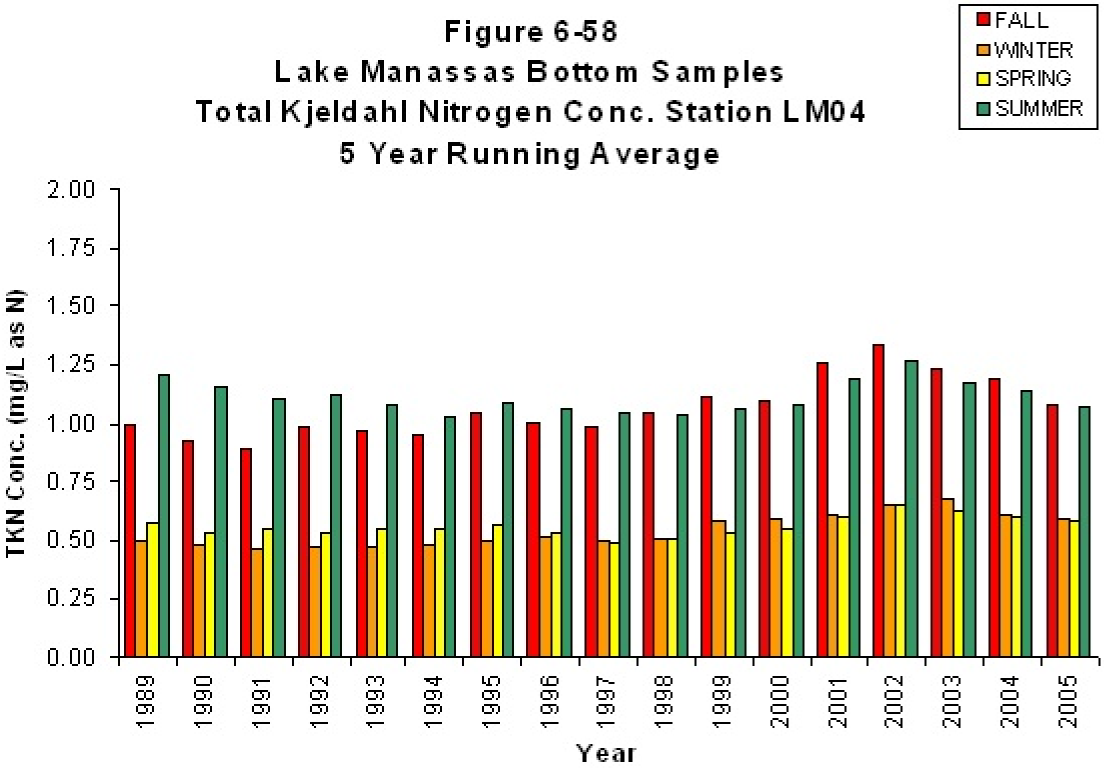


Figure 6-59
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM05
5 Year Running Average

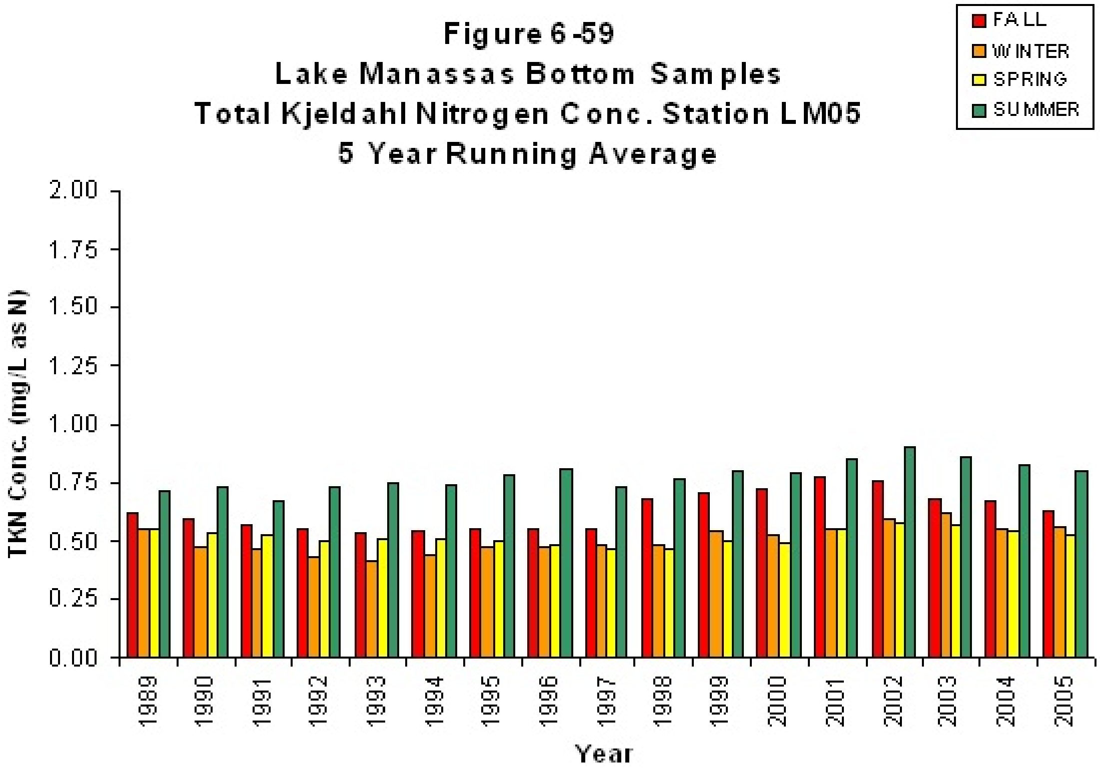


Figure 6-60
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM06
5 Year Running Average

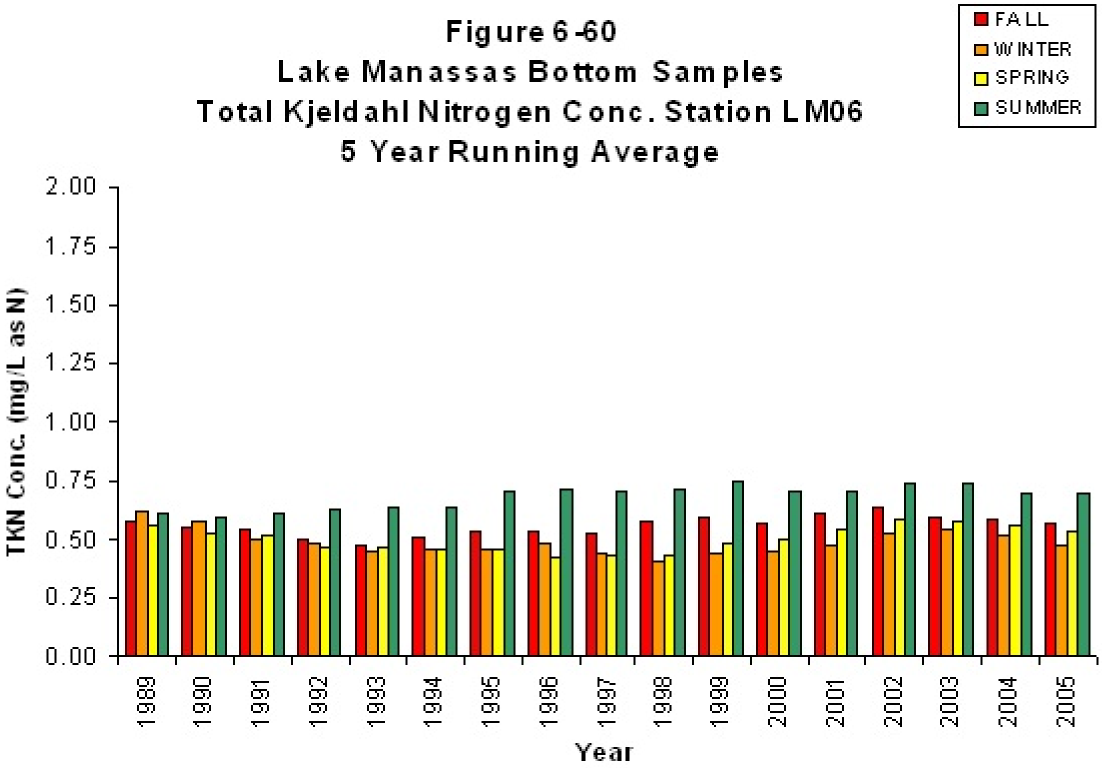


Figure 6-61
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM07
5 Year Running Average

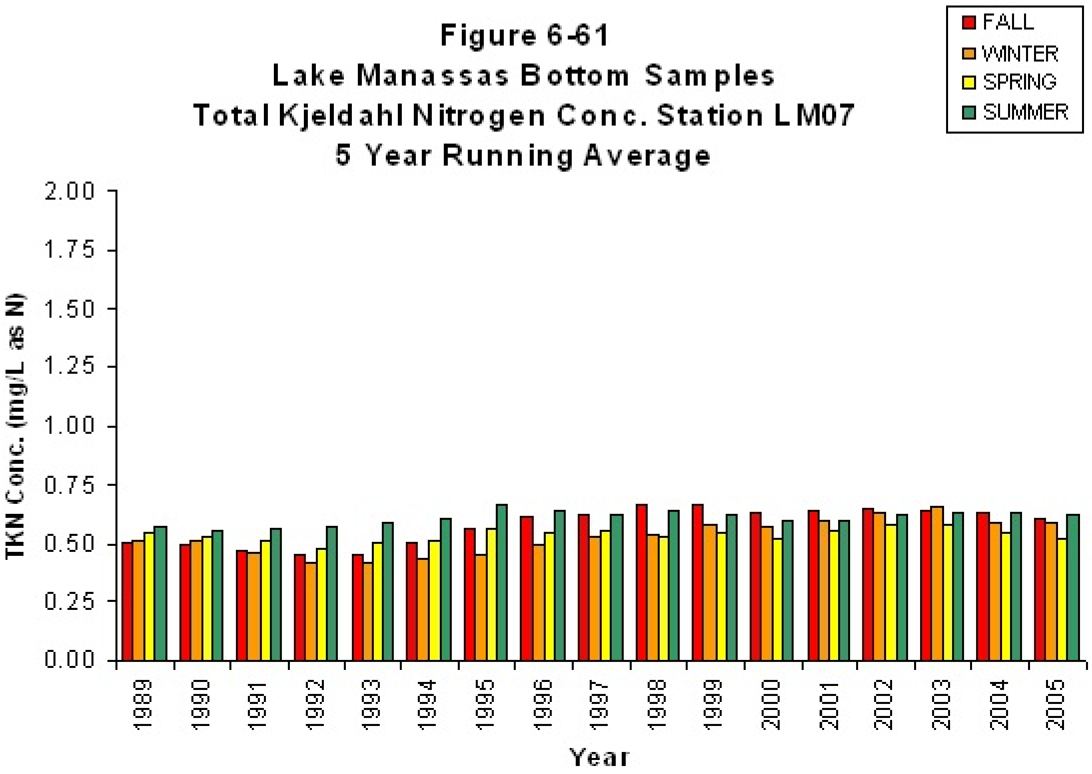


Figure 6-62
Lake Manassas Bottom Samples
Total Kjeldahl Nitrogen Conc. Station LM08
5 Year Running Average

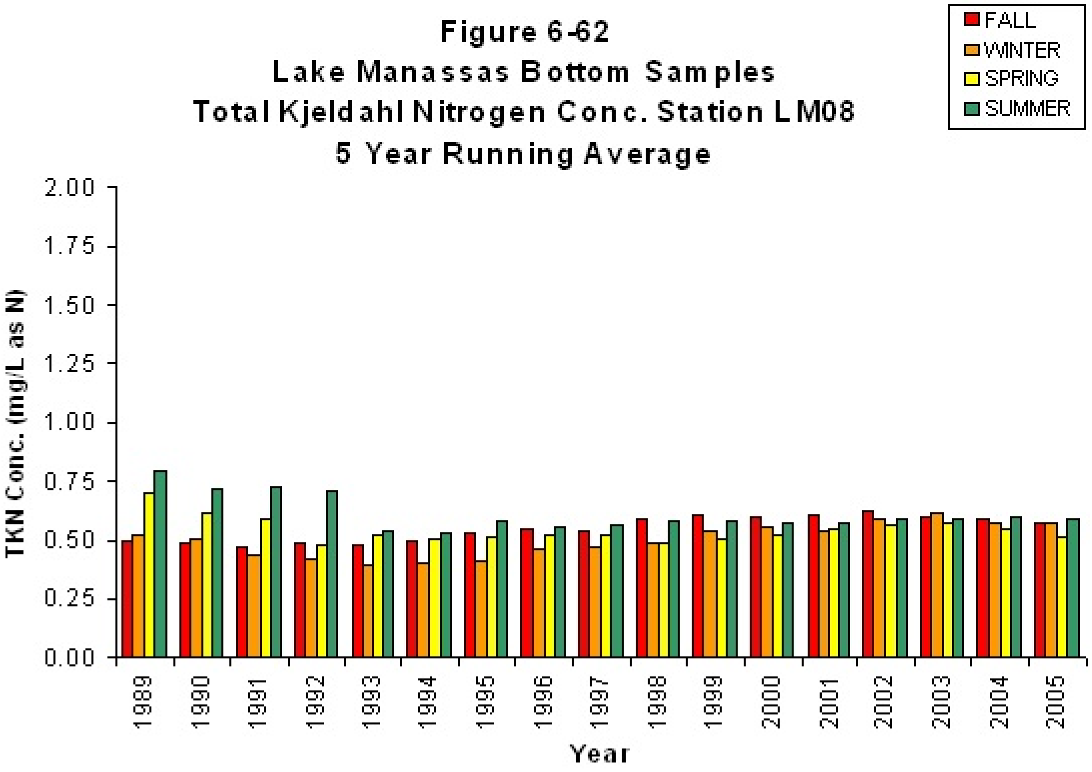
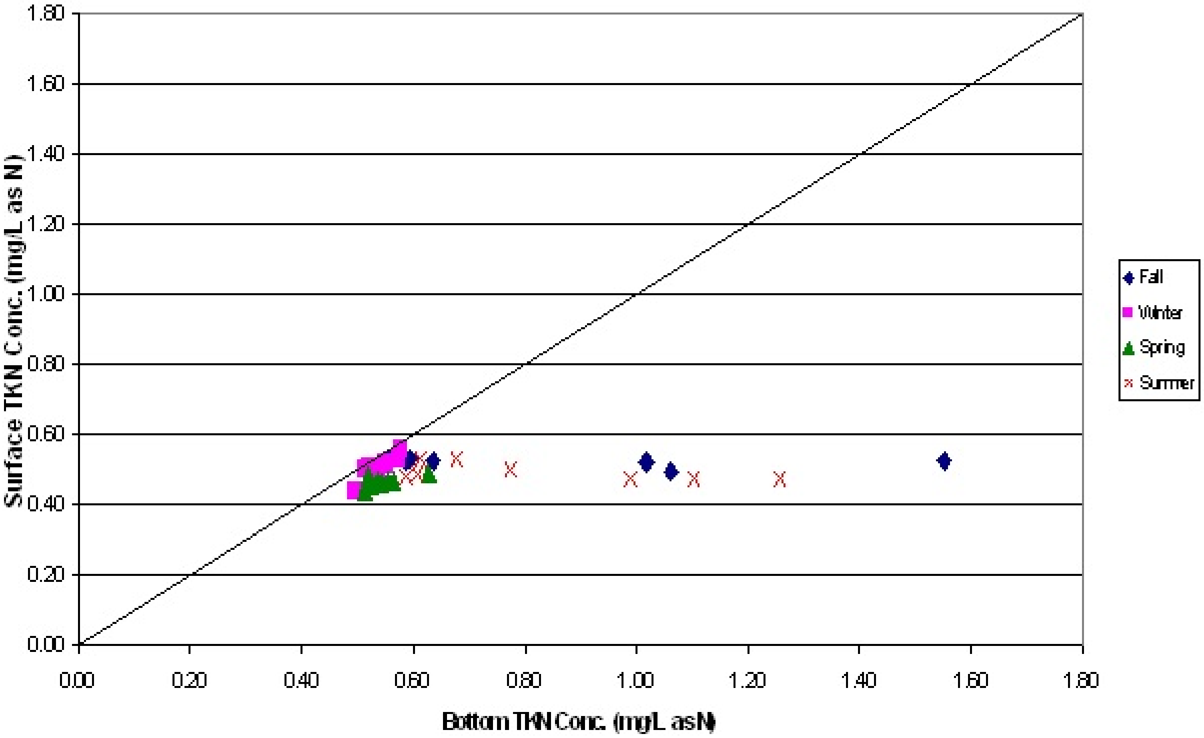


Figure 6-63 is a plot of the surface TKN concentrations compared to the bottom concentrations for all seasons. Each data point represents a monitoring station for a particular season. A 1:1 line is then drawn and compared to the data. For the most part, the data points cluster together in an area close to and below the 1:1 line, indicating that the majority of the TKN concentrations are greater in the hypolimnion. A few stations during the summer and fall months plotted away from and below the 1:1 line. This is a result of TKN values being much greater in the hypolimnion than in the epilimnion, which is further evidence that the sediments are releasing NH_4^+ during the summer and fall stratification.

Oxidized Nitrogen (Ox-N) is a measure of nitrite (NO_2-N) and nitrate (NO_3-N). The utilization of Ox-N varies throughout the water column. In the surface waters of lakes, algal productivity has the potential to reduce Ox-N concentrations. During the summer months, algae utilize Ox-N for the production of amino acids and proteins. In the bottom waters of a lake or reservoir, the depletion of dissolved oxygen brought on by summer stratification can influence Ox-N concentrations. When oxygen is no longer available in the hypolimnion, Ox-N undergoes a process known as dissimilatory denitrification where nitrate serves as the electron acceptor in energy metabolism. Nitrifying bacteria will only utilize Ox-N when DO is depleted from the

Figure 663
Surface vs. Bottom Seasonal TKN Concentration - Lake Manassas
All Lake Stations (2001 - 2005)



system. This process is not instantaneous and can take days following the summer stratification to occur. The onset of the fall turnover can produce dramatic increases in Ox-N concentrations in the hypolimnion.

The five-year running averages for Ox-N in the surface and bottom waters of Lake Manassas are shown in Figures 6-64 through 6-79. The winter months consistently have the most Ox-N while summer has the least. In the more recent years, stations LM01, LM02, LM03, and LM04 have reported the spring as having more Ox-N than in the winter, particularly in the bottom waters. Station LM06, located where Broad Run discharges into the lake, typically has higher concentrations of Ox-N than any other station. The surface and bottom water concentrations reduce dramatically during the summer and fall at this station. This is most likely due to algal growth. Tables 6-1 and 6-2 show the Mann-Kendall Analysis for Ox-N in the surface and bottom waters, respectively. Station LM08 reported an increasing trend of Ox-N in the bottom waters, indicating that stratification is weak at this station and that DO is not completely diminished. No other trends were reported with respect to Ox-N.

Figure 6-80 shows the bottom Ox-N concentration plotted against the surface Ox-N concentration. Each data point represents a monitoring station for a particular season. A 1:1 line is drawn which is compared to the data. Most of the data points lie close to the line and below it illustrating that the bottom values of Ox-N are either similar or greater than the surface Ox-N values. Overall, the summer values plot closest to the line.

Figure 6-64
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM01
5 Year Running Average

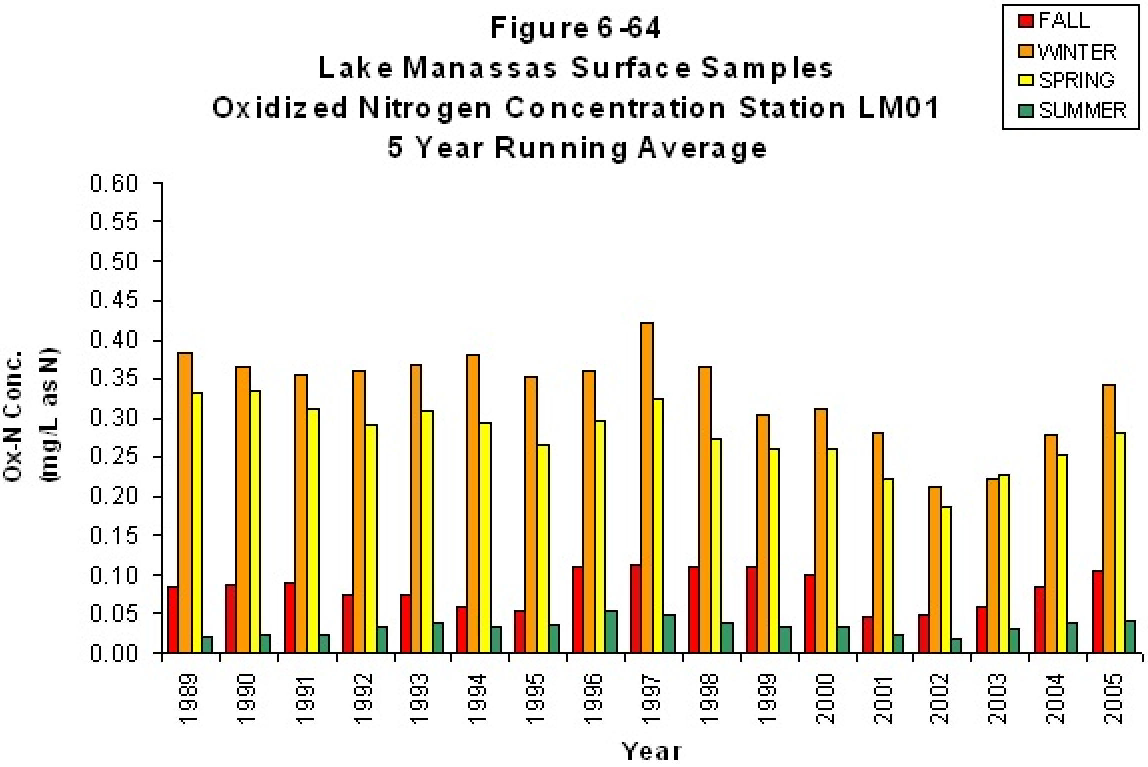
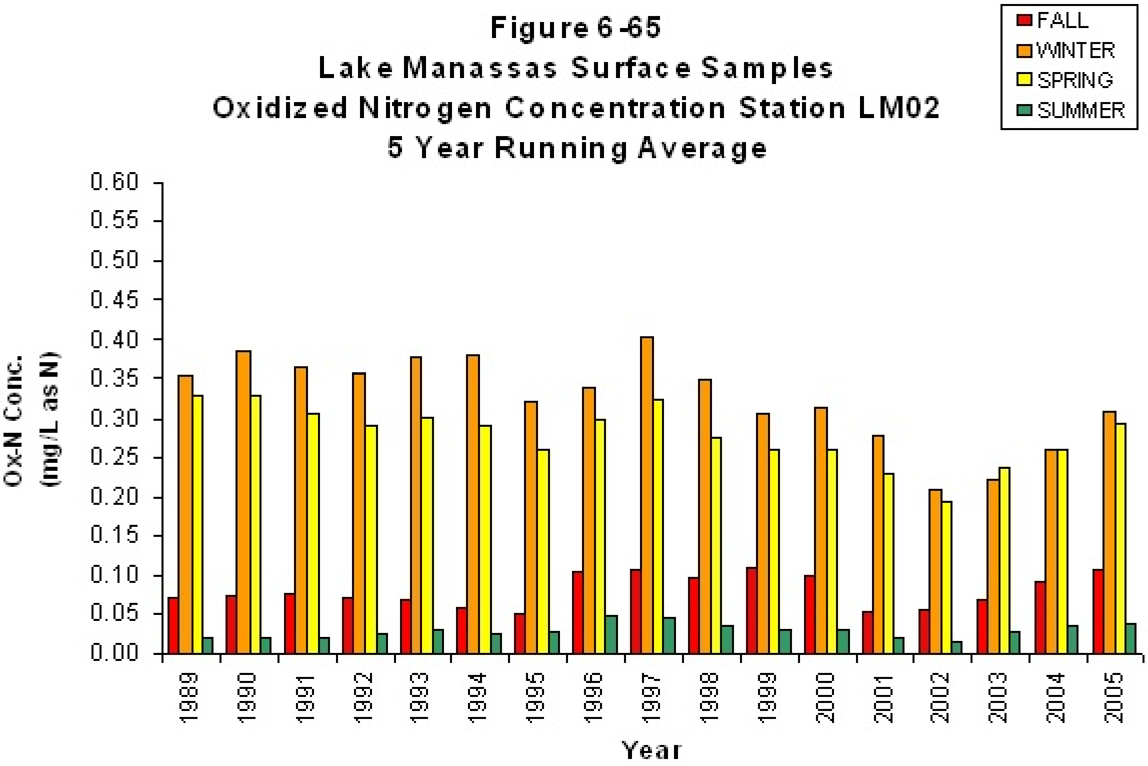


Figure 6-65
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM02
5 Year Running Average



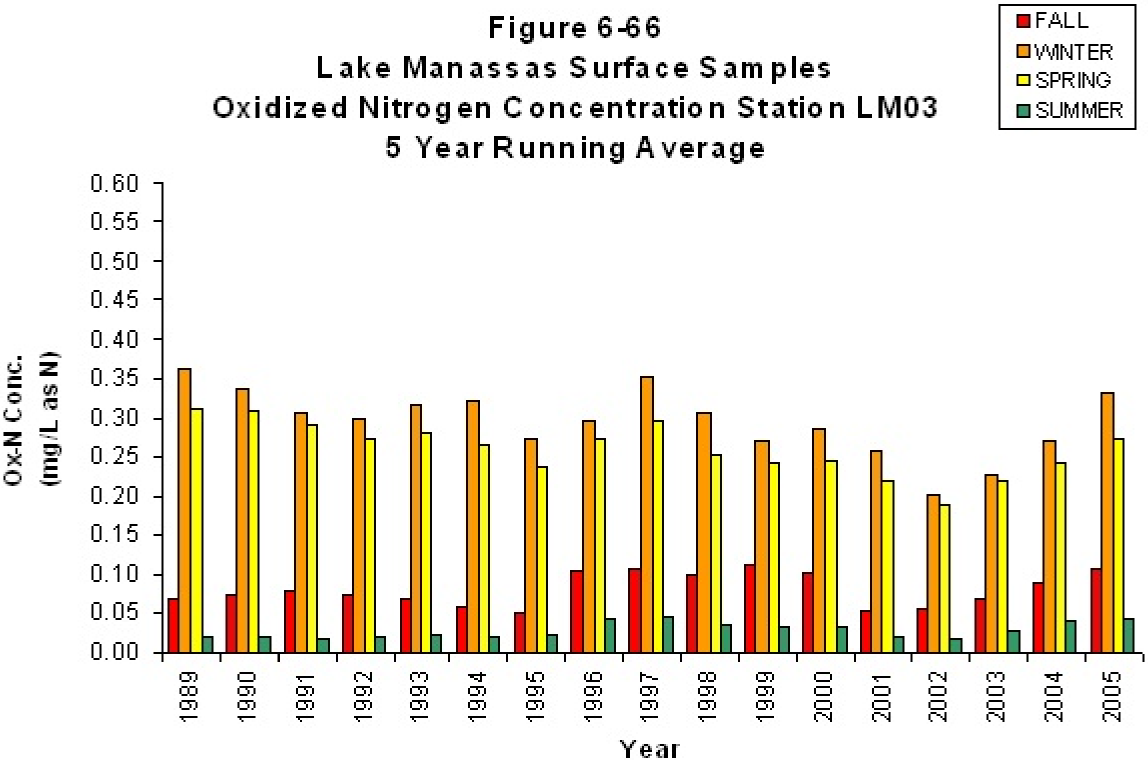


Figure 6-66
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM03
5 Year Running Average

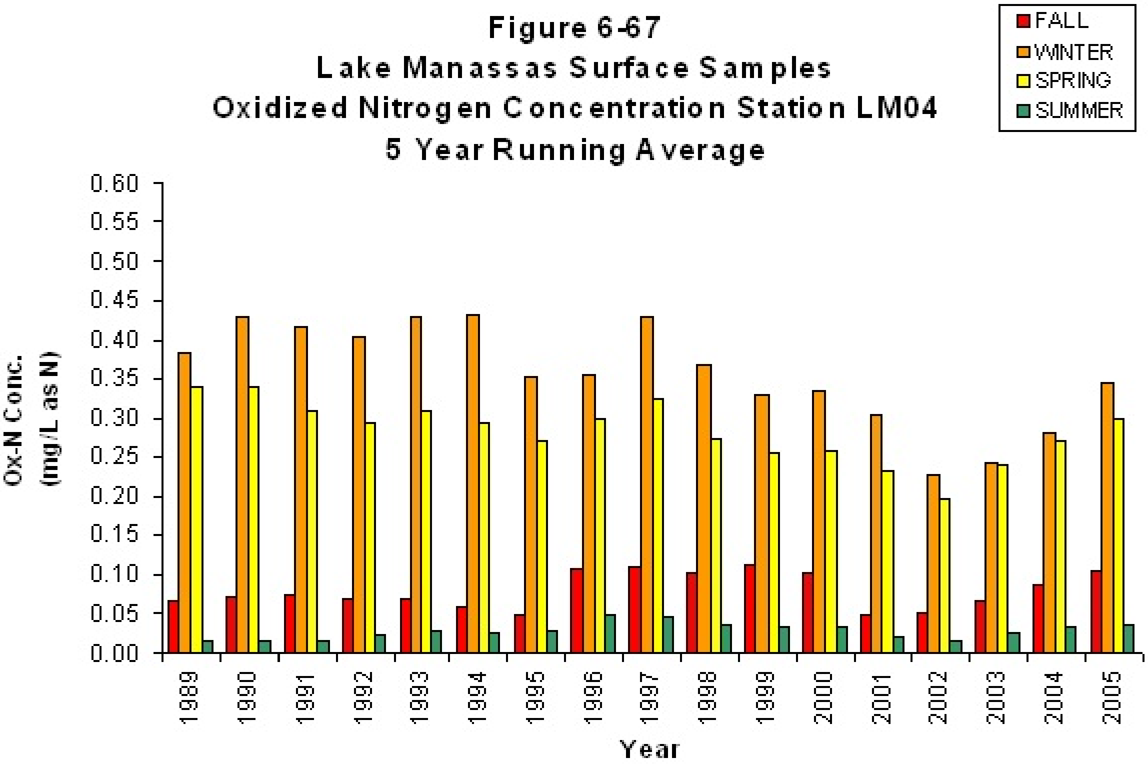


Figure 6-67
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM04
5 Year Running Average

Figure 6-68
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM05
5 Year Running Average

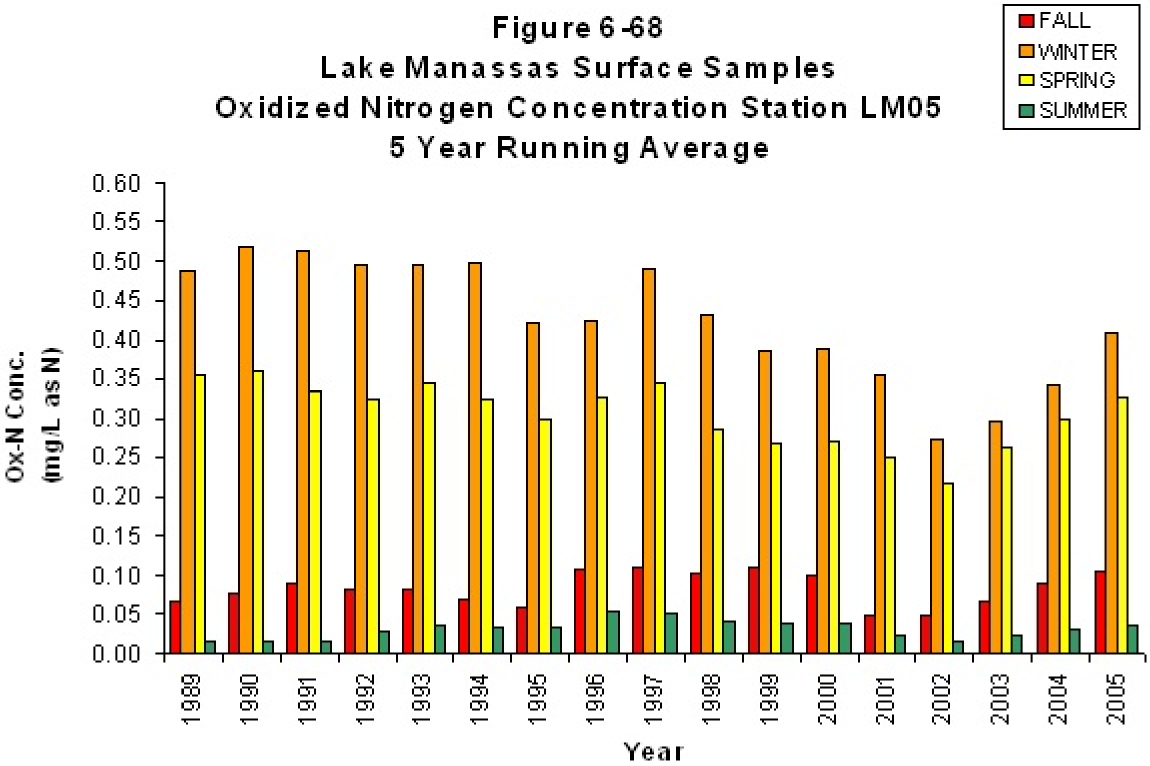
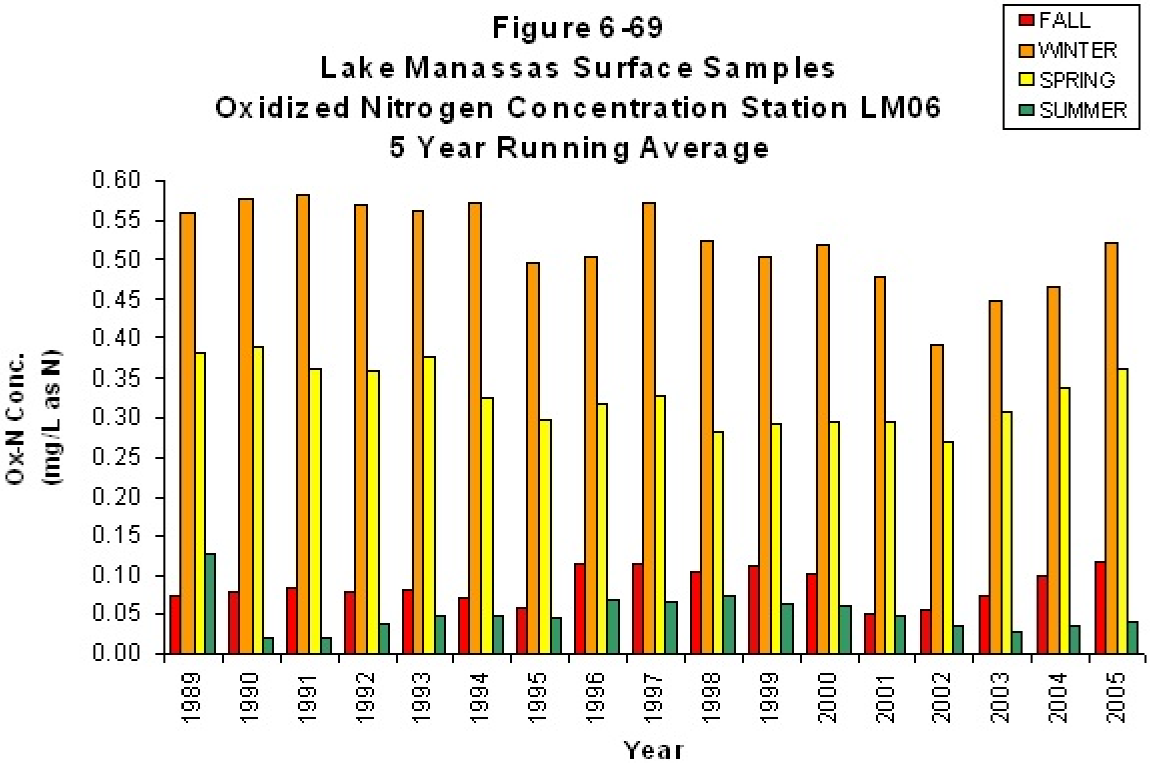


Figure 6-69
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM06
5 Year Running Average



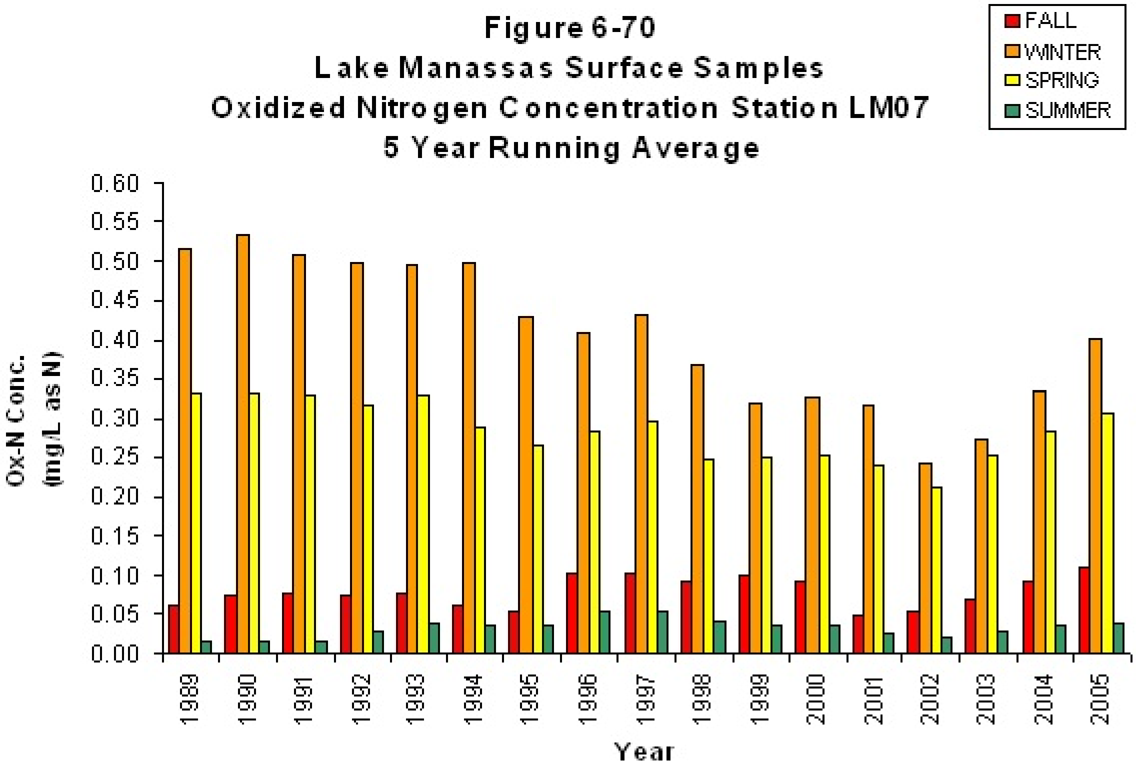


Figure 6-70
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM07
5 Year Running Average

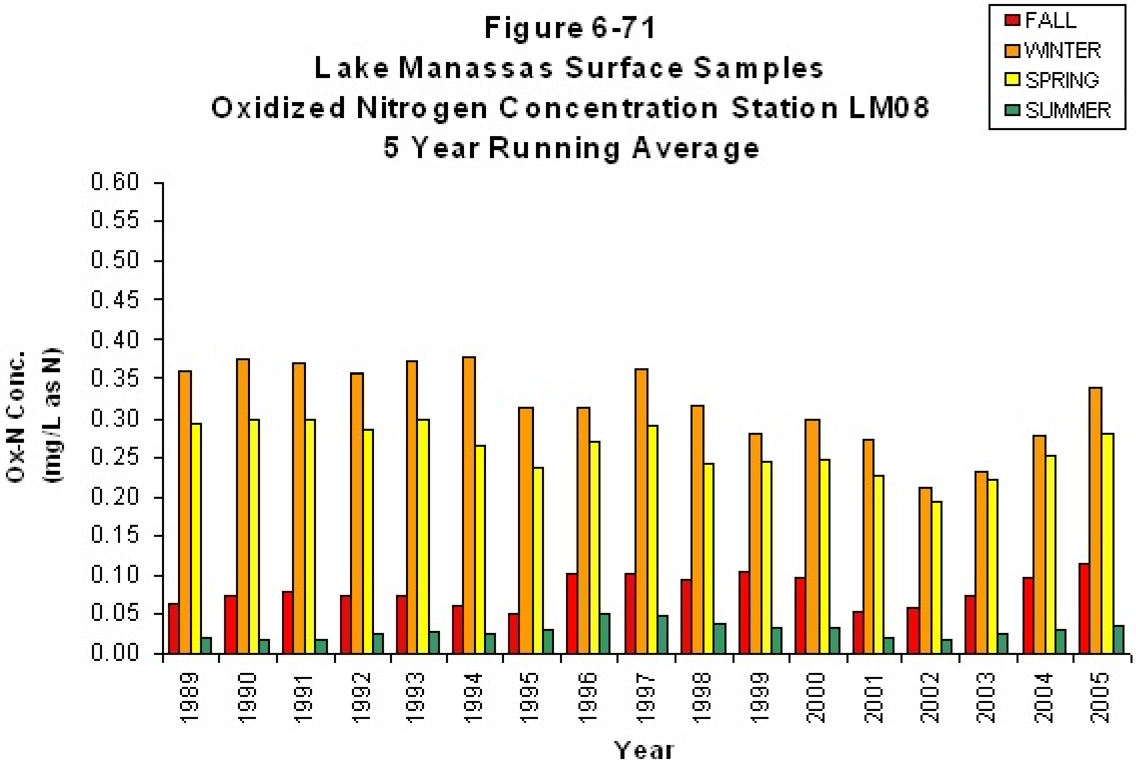


Figure 6-71
Lake Manassas Surface Samples
Oxidized Nitrogen Concentration Station LM08
5 Year Running Average

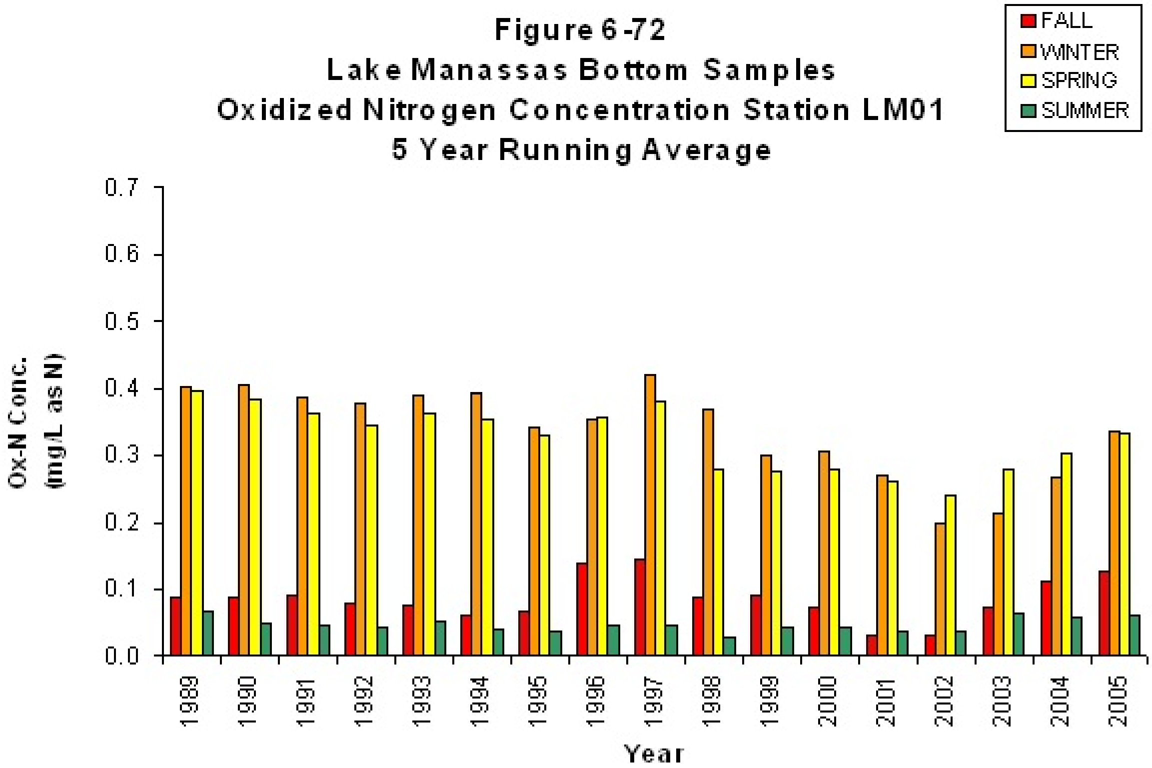


Figure 6-72
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM01
5 Year Running Average

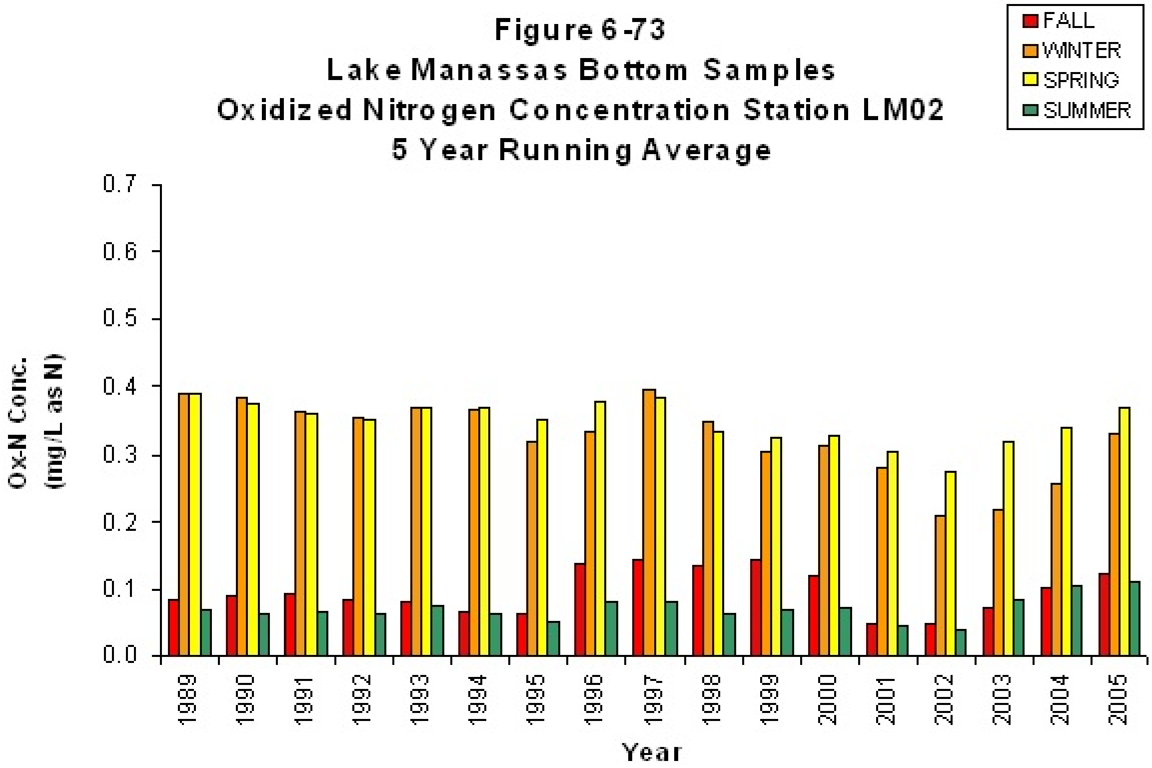


Figure 6-73
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM02
5 Year Running Average

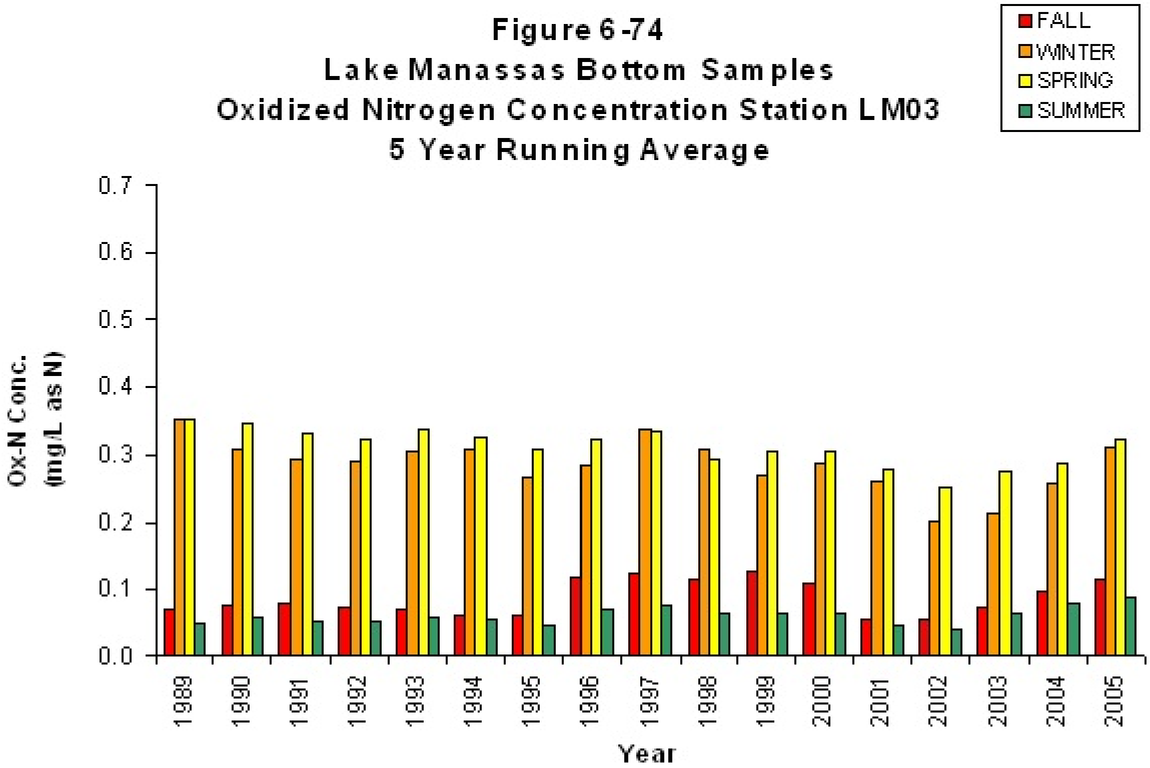


Figure 6-74
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM03
5 Year Running Average

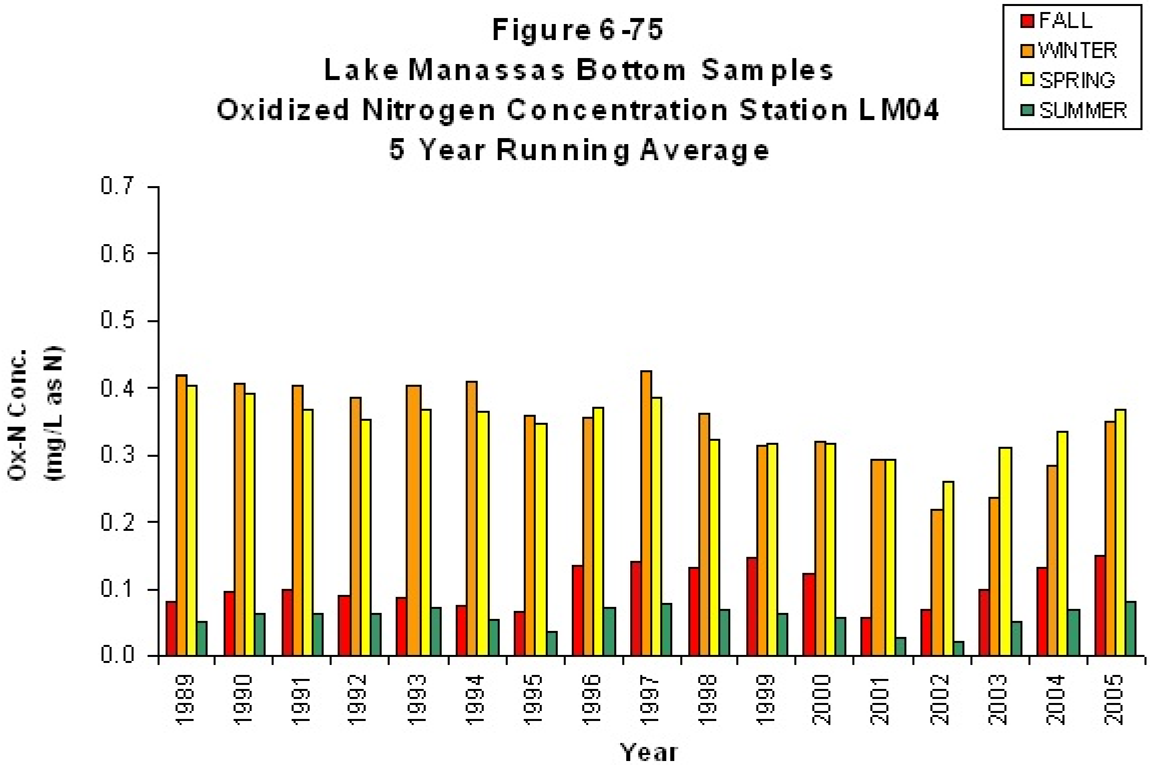


Figure 6-75
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM04
5 Year Running Average

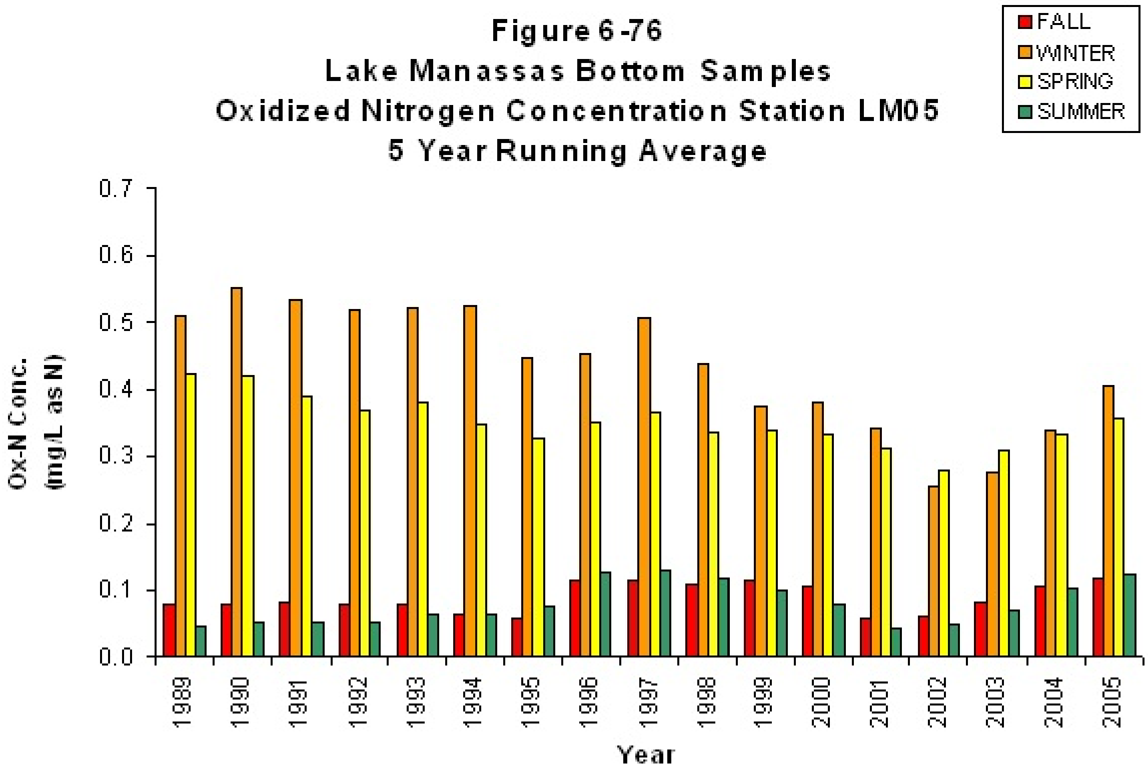


Figure 6-76
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM05
5 Year Running Average

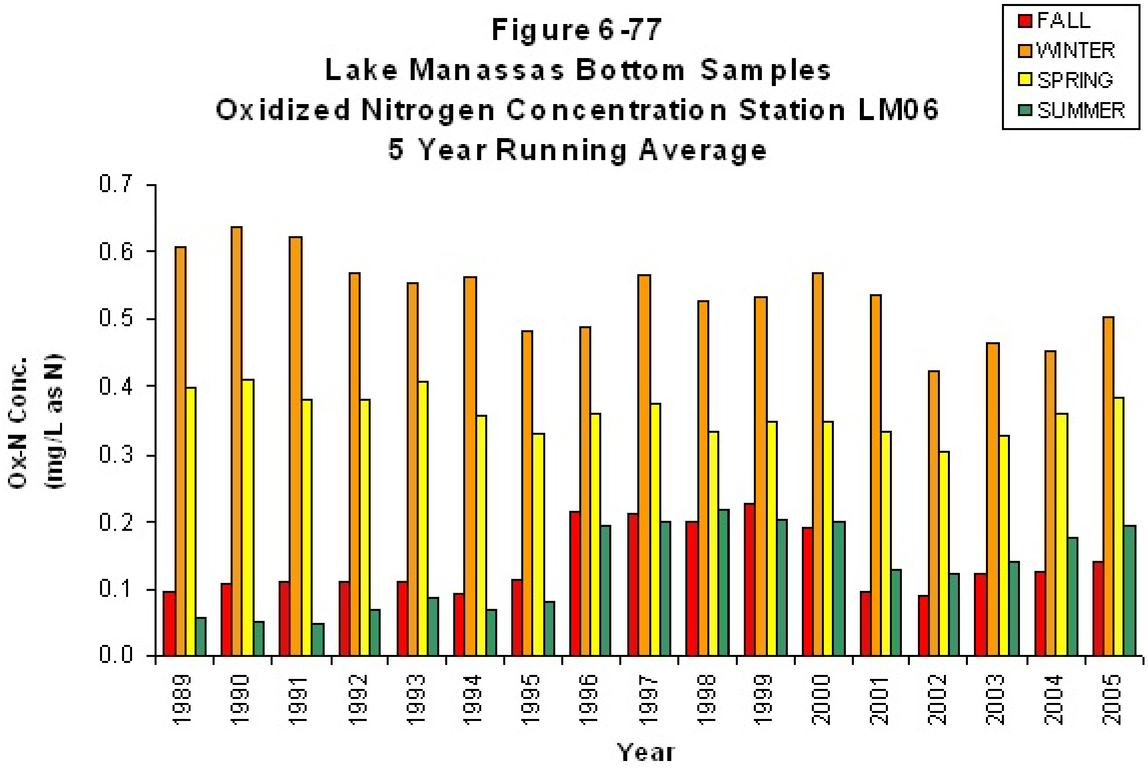


Figure 6-77
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM06
5 Year Running Average

Figure 6-78
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM07
5 Year Running Average

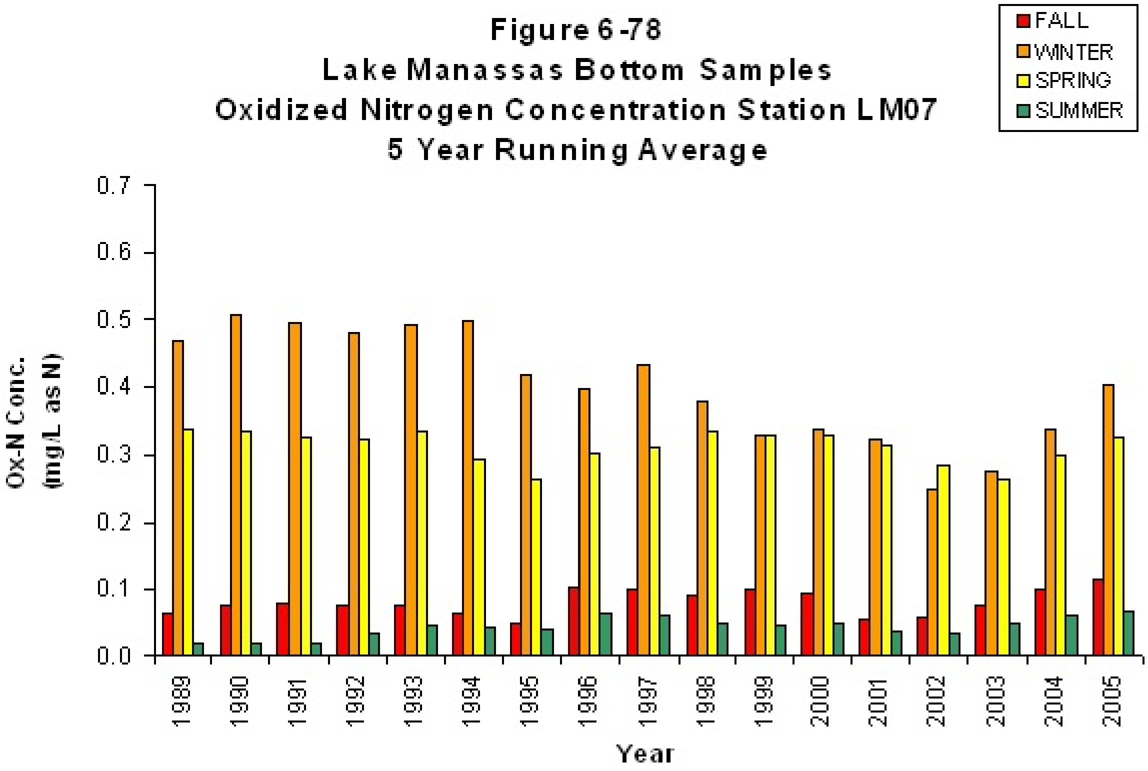


Figure 6-79
Lake Manassas Bottom Samples
Oxidized Nitrogen Concentration Station LM08
5 Year Running Average

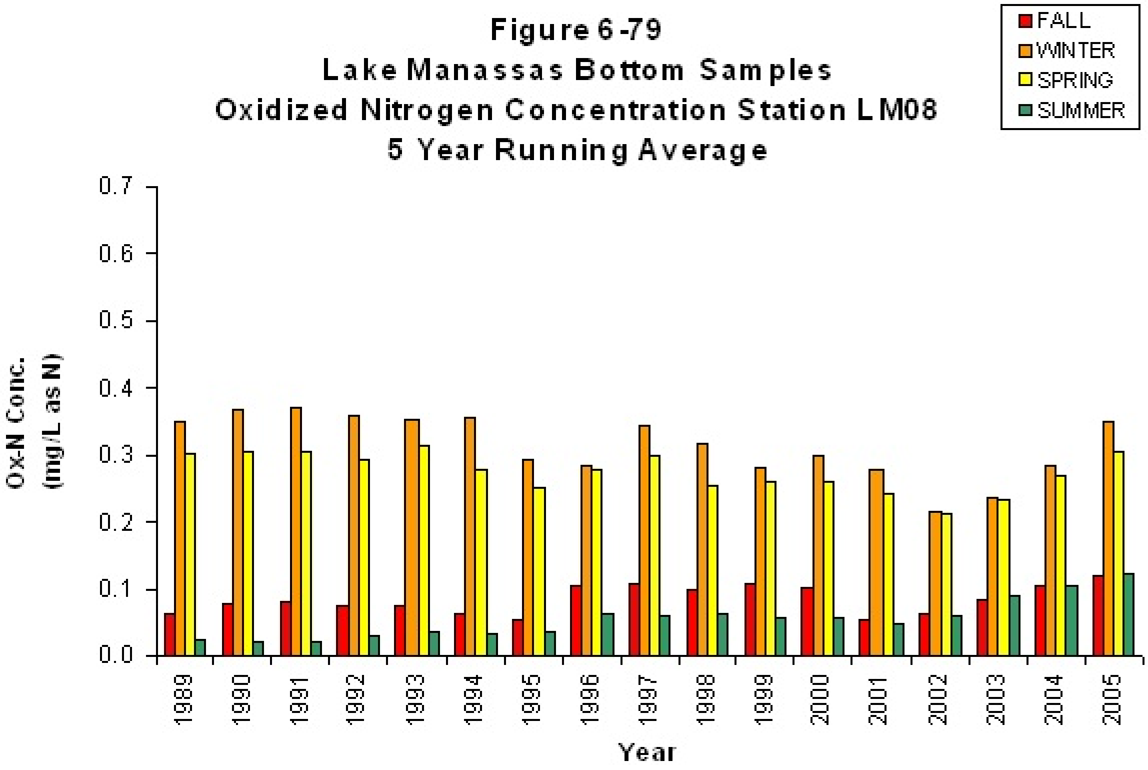
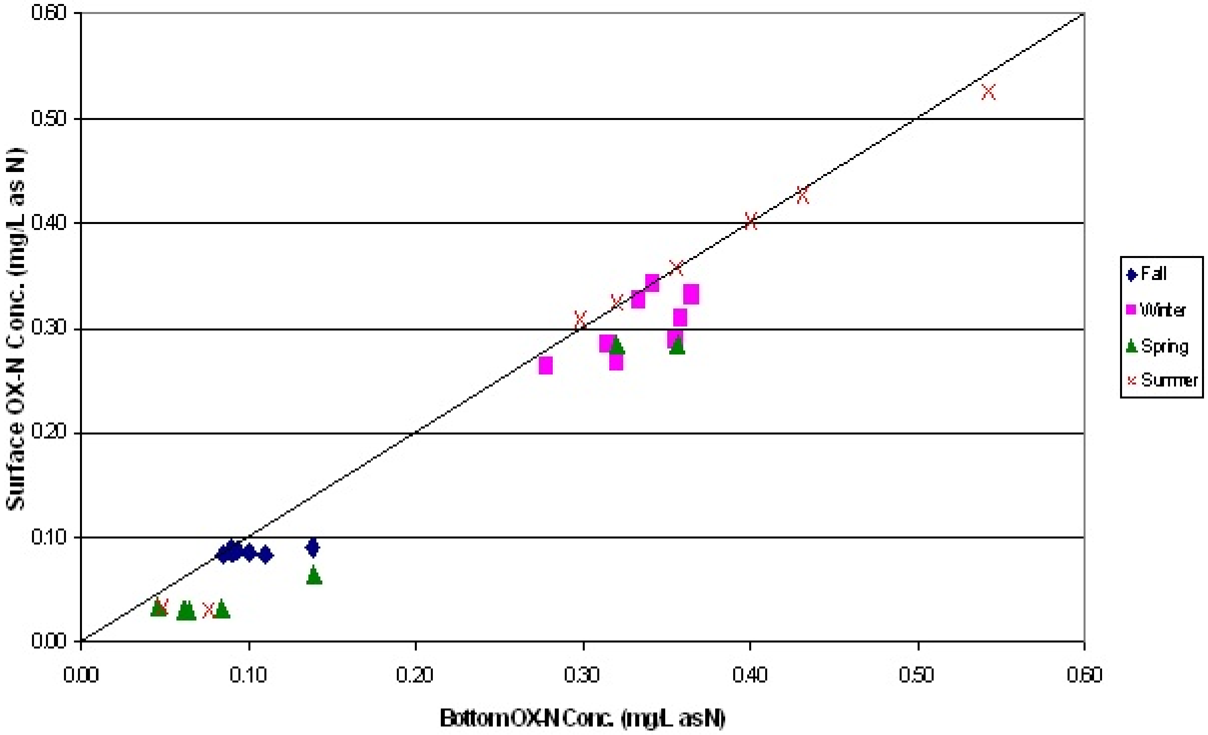


Figure 6-80
Surface vs Bottom Seasonal Ox-N Concentration - Lake Manassas
All Lake Stations (2001 - 2005)



Phosphorus

Phosphorus is an essential element for biological life, however, too much can accelerate eutrophication. When compared to other micronutrients, phosphorus tends to be the least abundant and the first to limit biological production. The thermal stratification experienced by lakes and reservoirs influences the distribution of total phosphorus in the epilimnion and hypolimnion. In the epilimnion, algae and bacteria consume phosphorus for cell metabolism. In the hypolimnion, once the supply of DO and other inorganic electron acceptors has been exhausted from the system, biological activity continues in the creation of a chemically reducing environment. This is exposed by a decline in the oxidation-reduction potential (ORP). ORP is the measurement (in mV) of the tendency or strength that indicates whether a solution is oxidizing or reducing. A higher value indicates an oxidizing environment, while a lower value signifies a reducing environment. Once the ORP has been significantly reduced, iron and manganese may be released from the sediments. During this situation, ferric iron (Fe^{3+}) is reduced to ferrous iron (Fe^{2+}), which is more soluble at ranges of pH experienced by most fresh water ecosystems. Along with Fe^{3+}, much of the inorganic phosphorus precipitates out of the lake sediments. Upon the reduction of Fe^{3+} to Fe^{2+}, phosphorus is released into the hypolimnion. The resulting phosphorus concentrations in the hypolimnion increase during periods of intense stratification. Once the barrier between the epilimnion and hypolimnion weakens during the fall turnover, the increased phosphorus concentrations become available to algae and other microbial species at the surface. The potential for algal blooms to develop during this period increase dramatically.

Figures 6-81 through 6-96 show the five-year running average for TP at the surface and bottom of the lake. All of the stations report increasing trends of TP at the surface as shown in the Mann-Kendall Analysis (Table 6-1). Stations LM06 and LM07 consistently have the largest concentrations of TP at the surface. These stations are located in the northwest section of the lake and near the discharge point of Broad Run. No one particular season has more TP than another at any station.

The TP concentrations in the bottom waters exhibit a different scenario. As given in Table 6-2, the Mann-Kendall Analysis shows a decreasing trend of TP in bottom waters at station LM02. No other trends were present at the remaining stations. The summer and fall months clearly show elevated levels of TP at all stations, supporting the idea of phosphorus release from lake sediments. LM01, LM02, LM04, and LM06 tend to show higher levels of TP than any other stations. These stations are deeper than the other stations and exhibit strong stratification. As a result, the phosphorus release from the sediments will be greater at these stations.

Figure 6-97 is a plot of the surface TP concentrations compared to the bottom concentrations for all seasons. As before, each data point represents a station for a particular season. A 1:1 line is drawn and the data compared. As shown in the figure, all of the data points plot below the 1:1 line, indicating that the hypolimnion contains higher levels of TP than in the epilimnion. The spring and winter months plot near the 1:1 line, and the summer and fall months plot farther away from the 1:1 line.

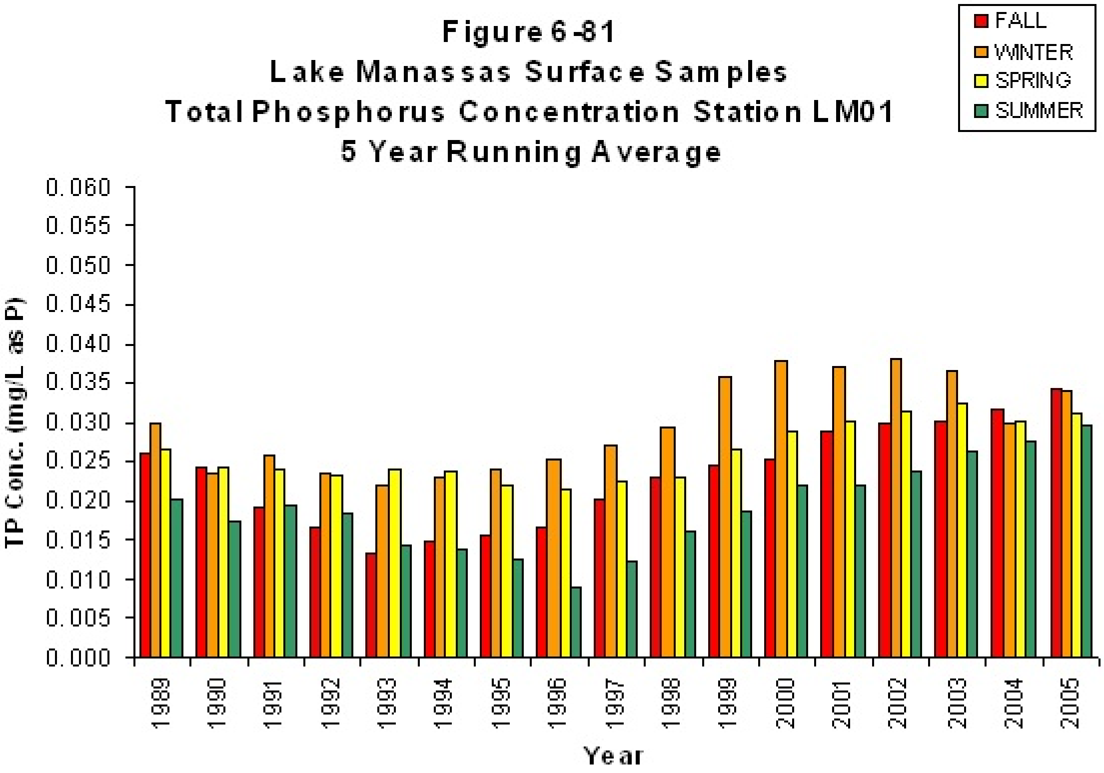


Figure 6-81
Lake Manassas Surface Samples
Total Phosphorus Concentration Station LM01
5 Year Running Average

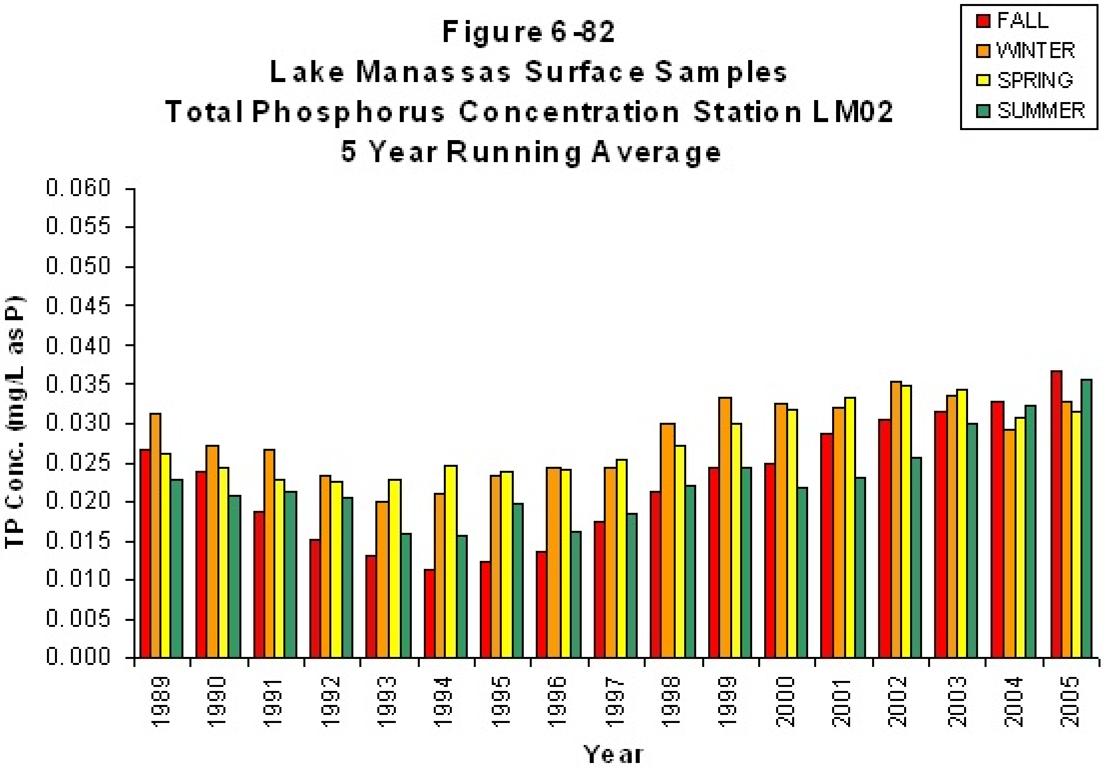


Figure 6-82
Lake Manassas Surface Samples
Total Phosphorus Concentration Station LM02
5 Year Running Average

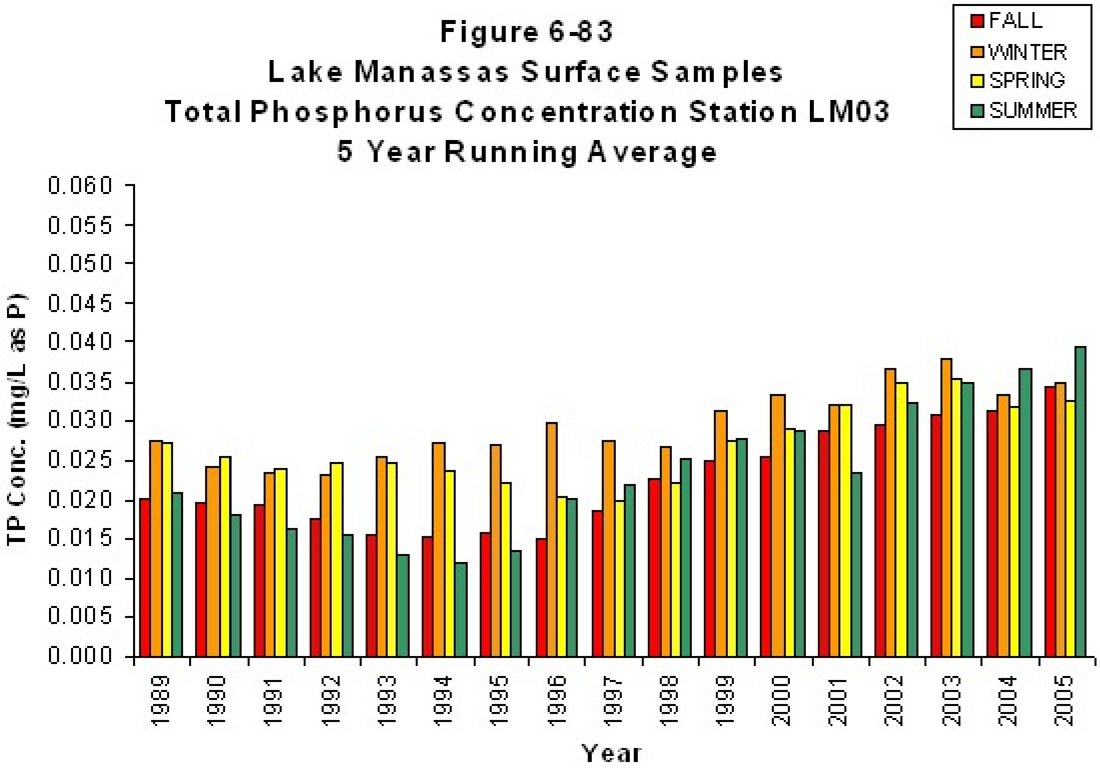


Figure 6-83
Lake Manassas Surface Samples
Total Phosphorus Concentration Station LM03
5 Year Running Average

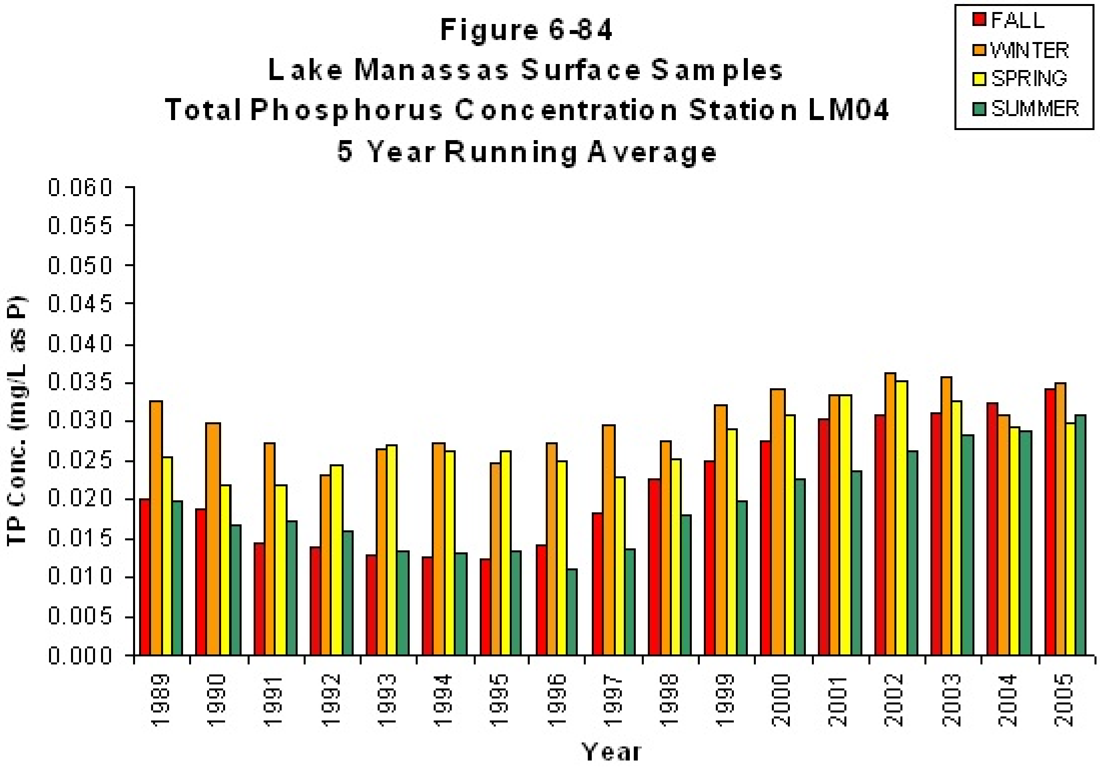


Figure 6-84
Lake Manassas Surface Samples
Total Phosphorus Concentration Station LM04
5 Year Running Average

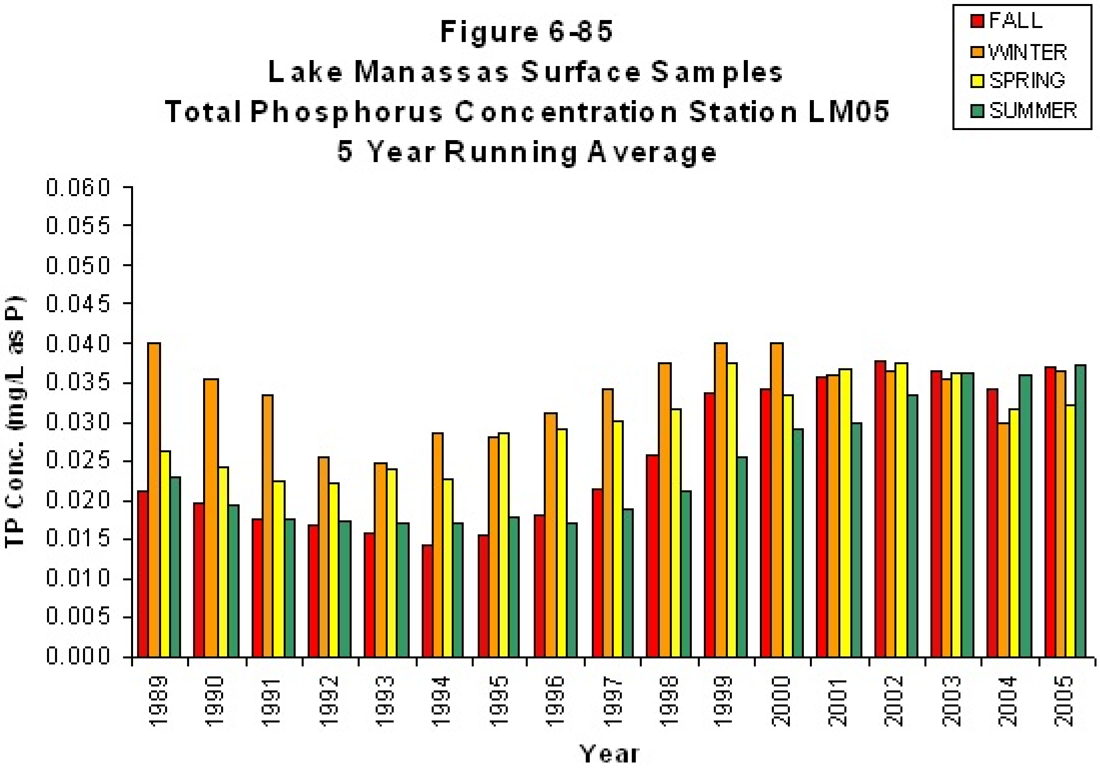


Figure 6-85
Lake Manassas Surface Samples
Total Phosphorus Concentration Station LM05
5 Year Running Average

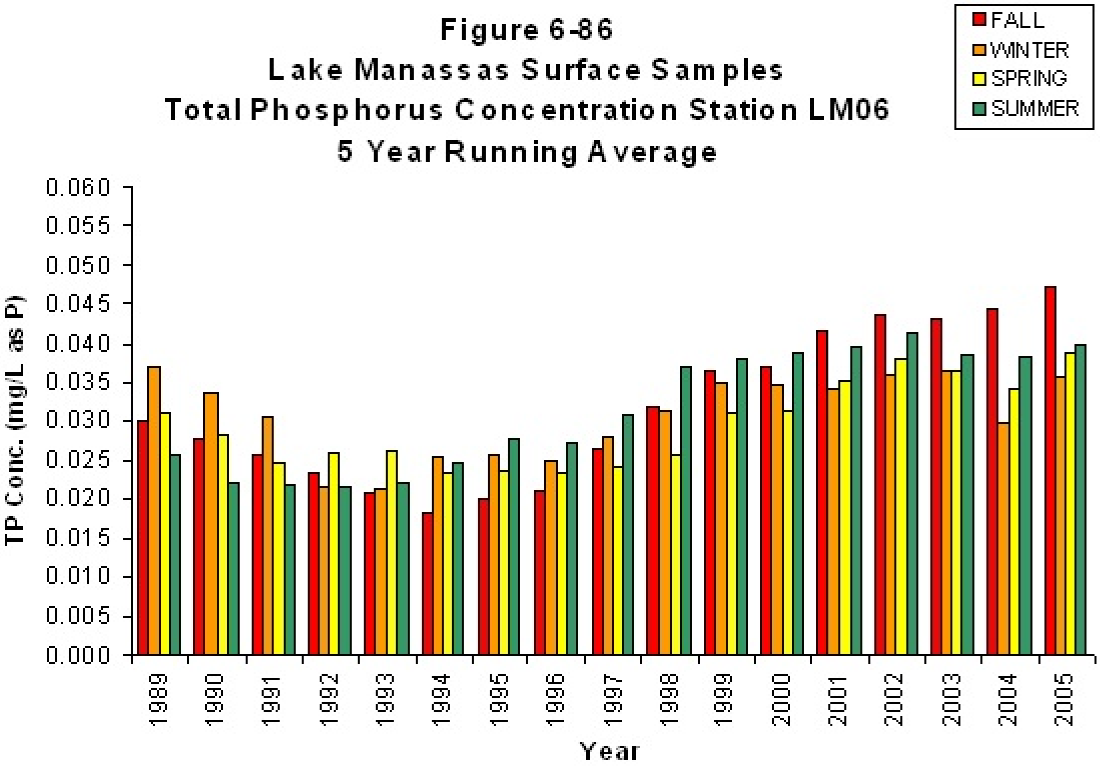


Figure 6-86
Lake Manassas Surface Samples
Total Phosphorus Concentration Station LM06
5 Year Running Average

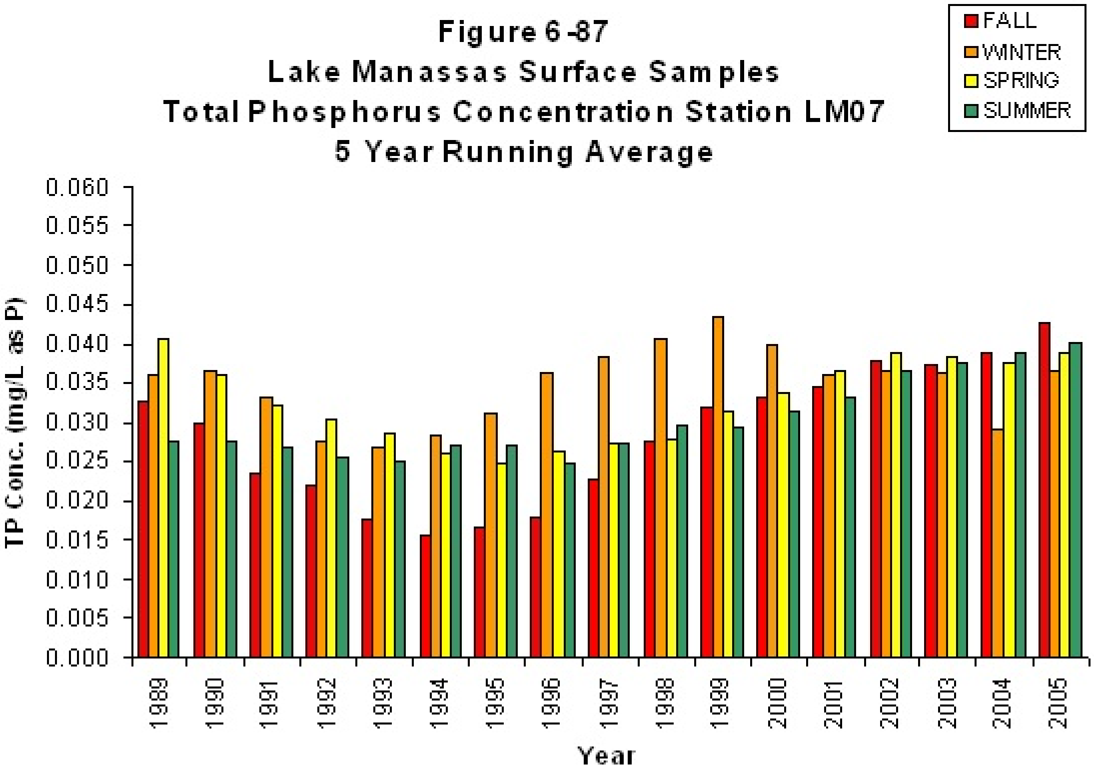


Figure 6-87

Lake Manassas Surface Samples

Total Phosphorus Concentration Station LM07

5 Year Running Average

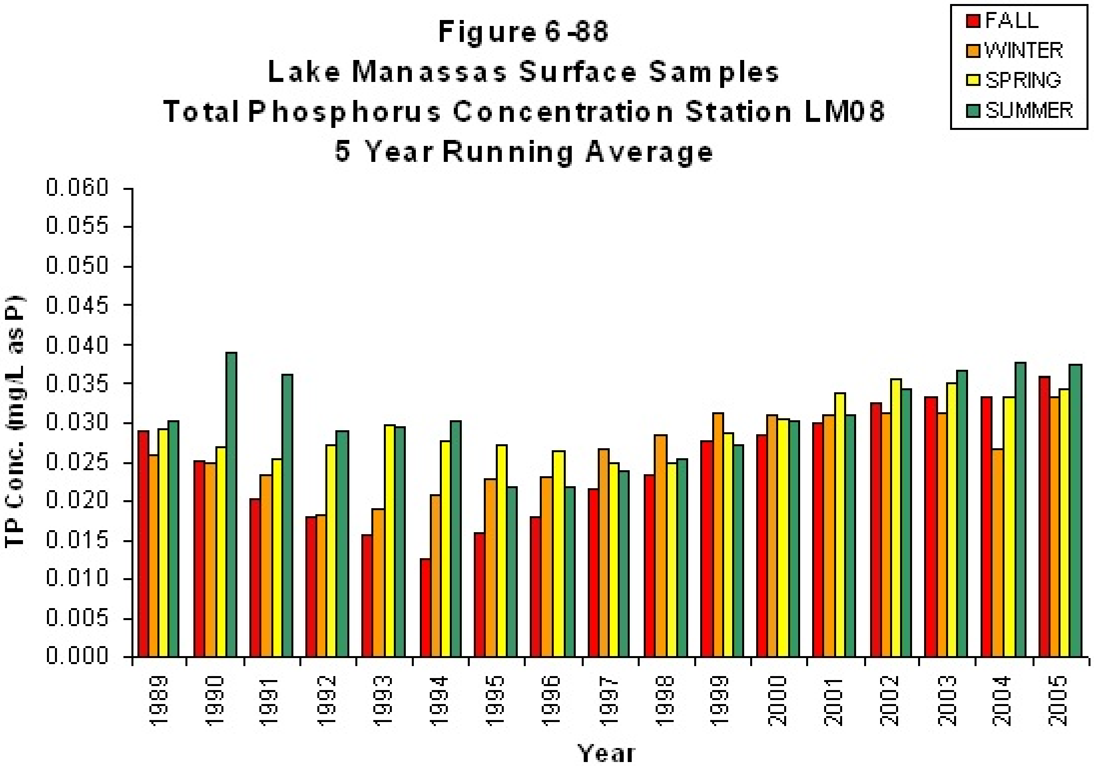


Figure 6-88

Lake Manassas Surface Samples

Total Phosphorus Concentration Station LM08

5 Year Running Average

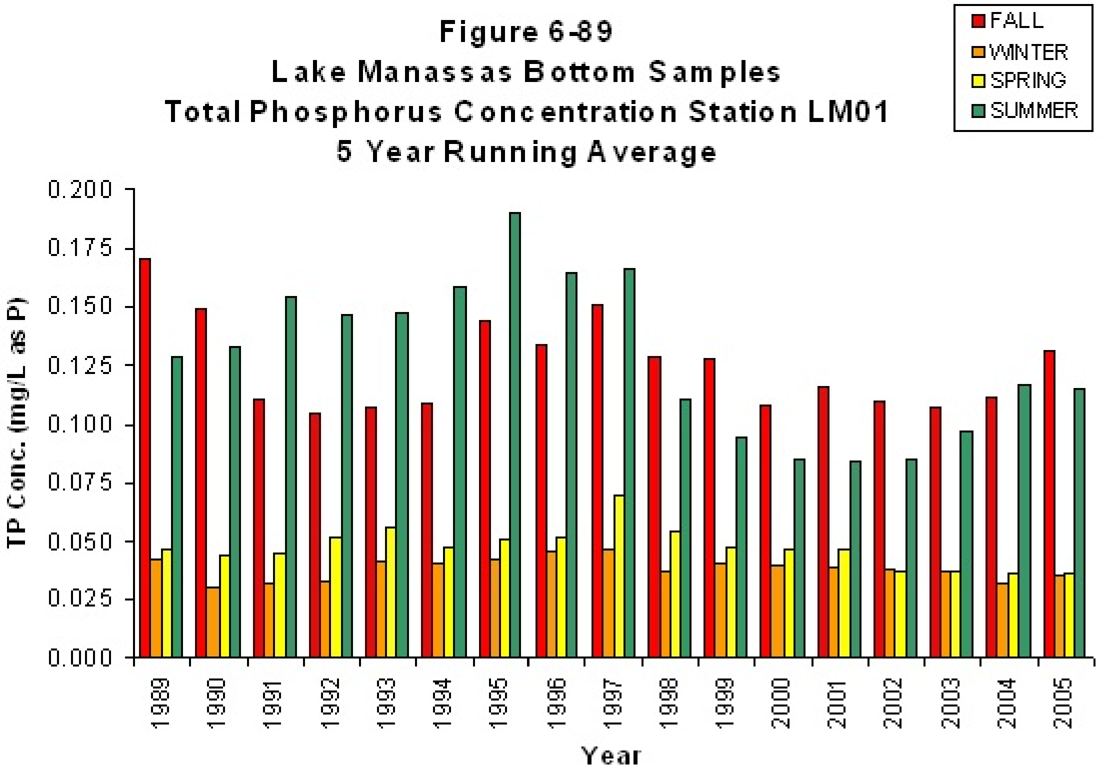


Figure 6-89
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM01
5 Year Running Average

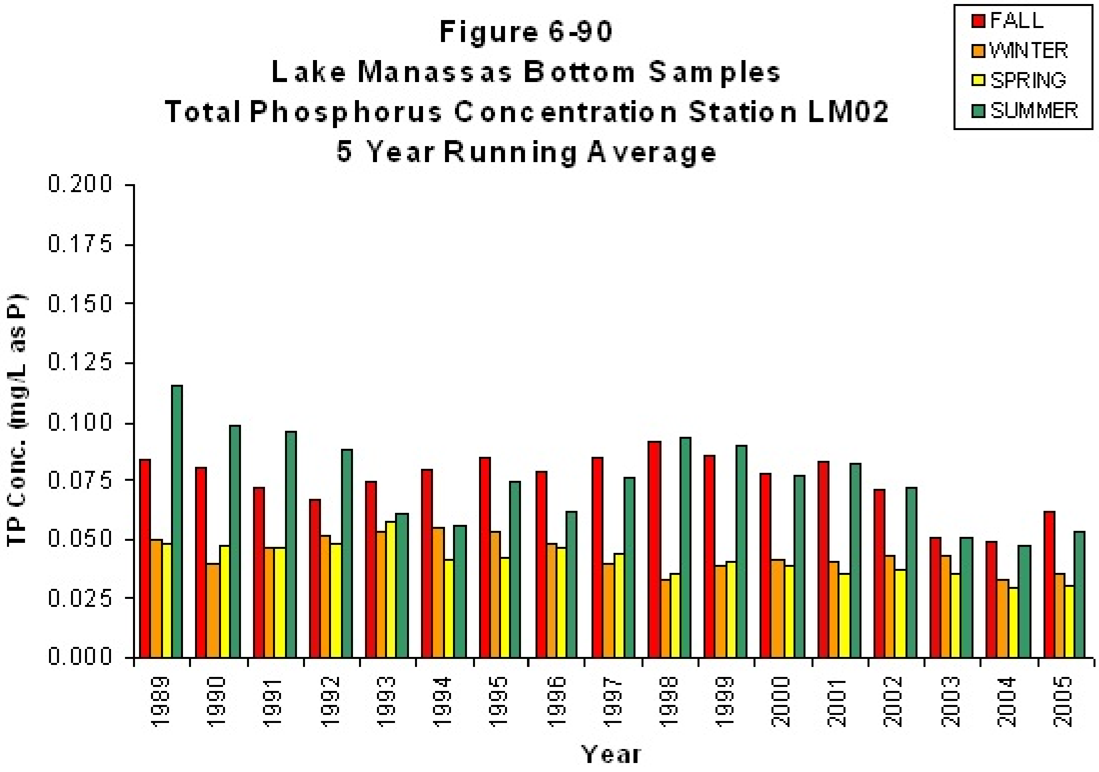


Figure 6-90
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM02
5 Year Running Average

Figure 6-91
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM03
5 Year Running Average

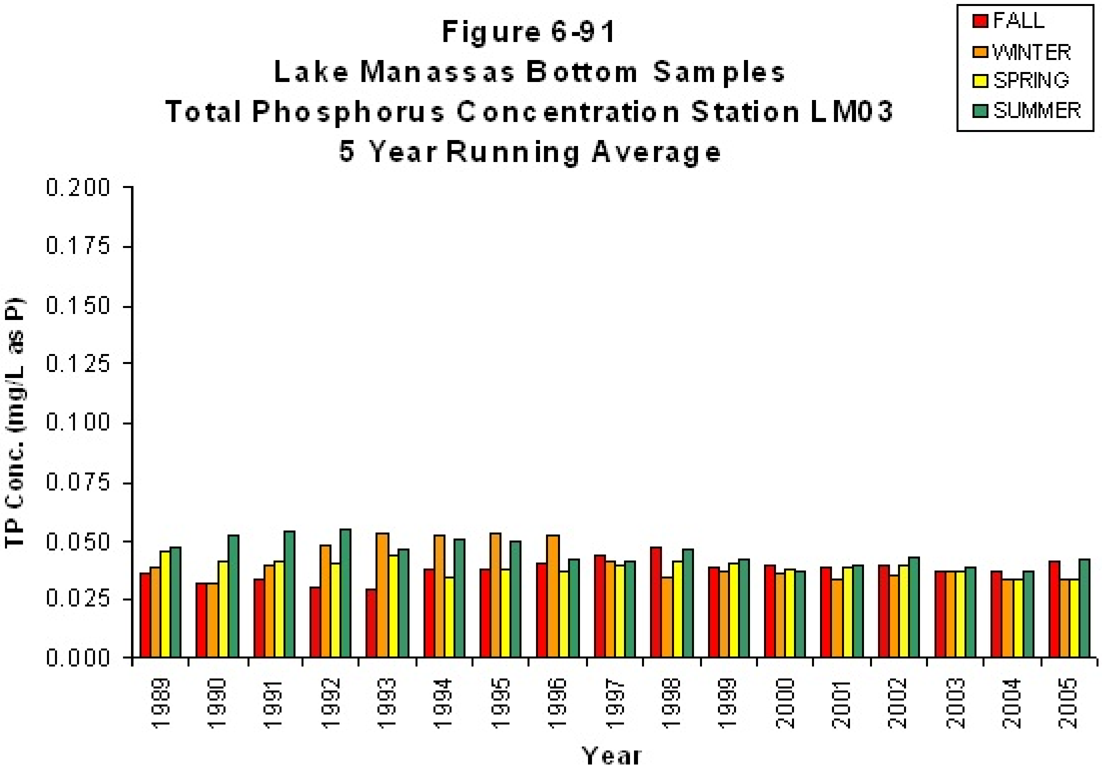
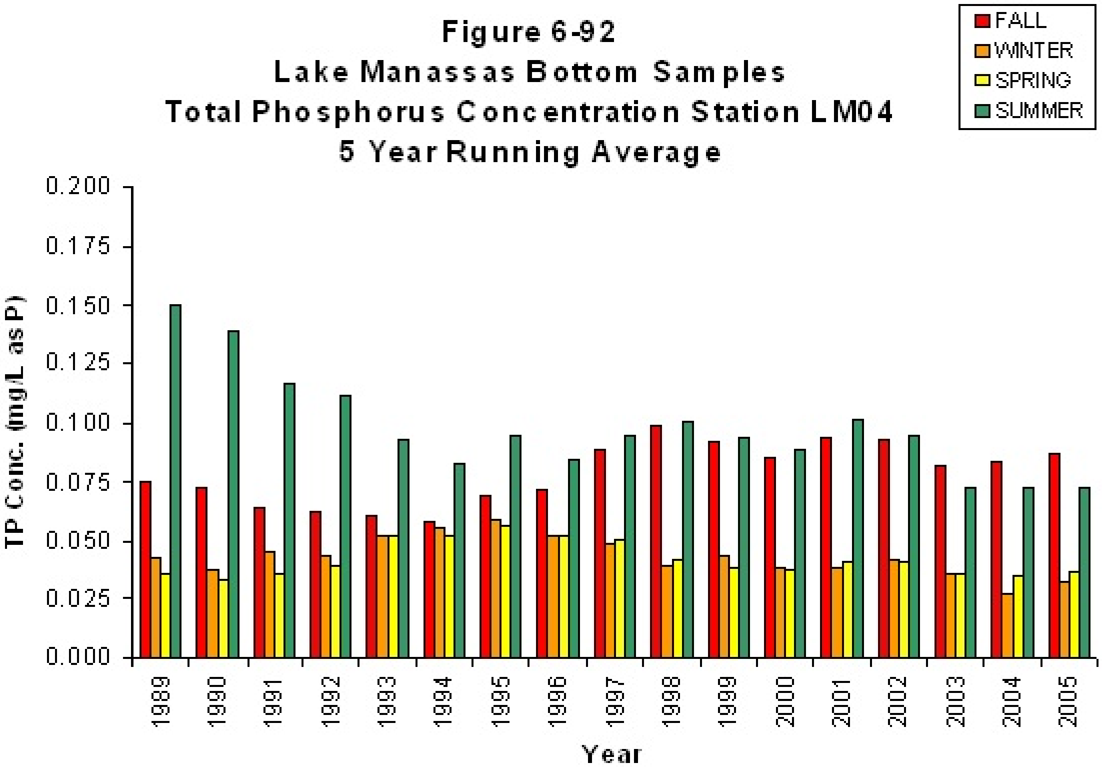


Figure 6-92
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM04
5 Year Running Average



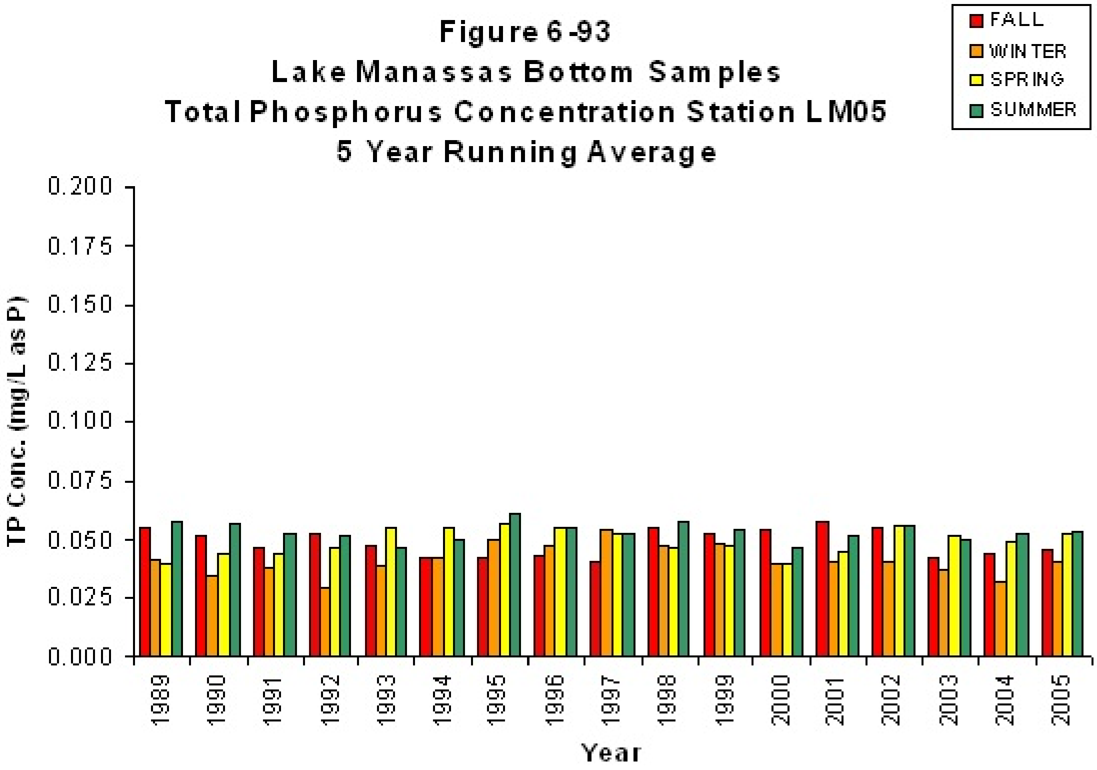


Figure 6-93
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM05
5 Year Running Average

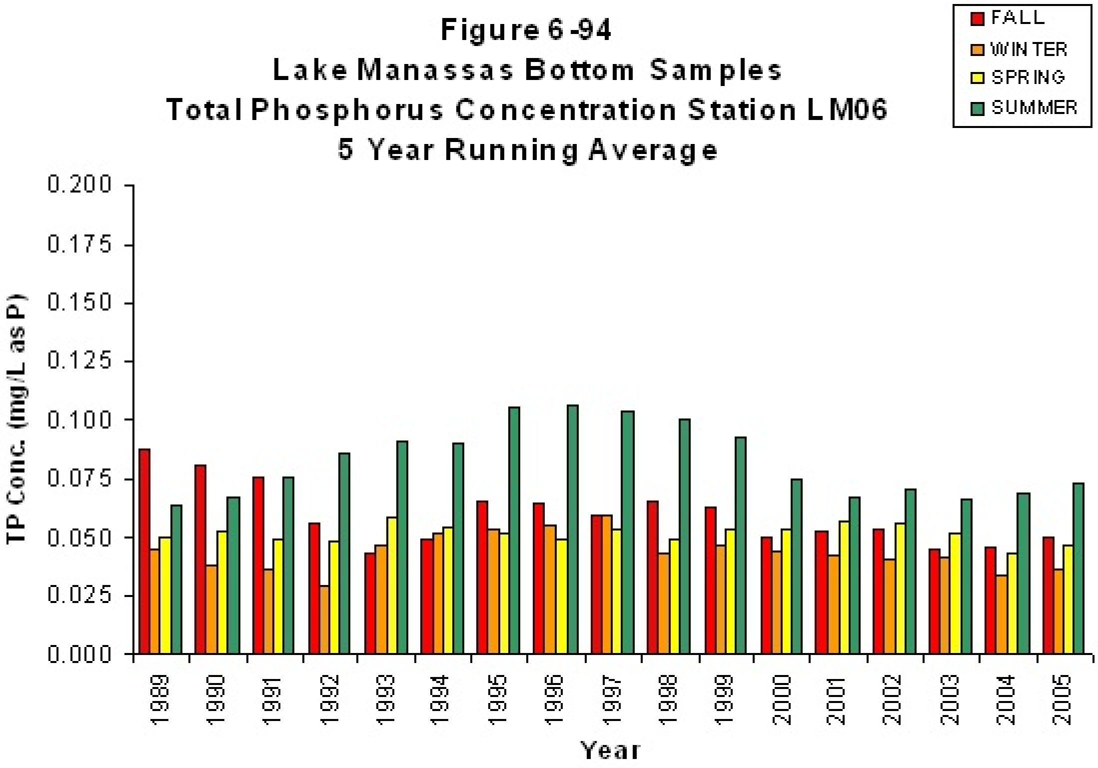


Figure 6-94
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM06
5 Year Running Average

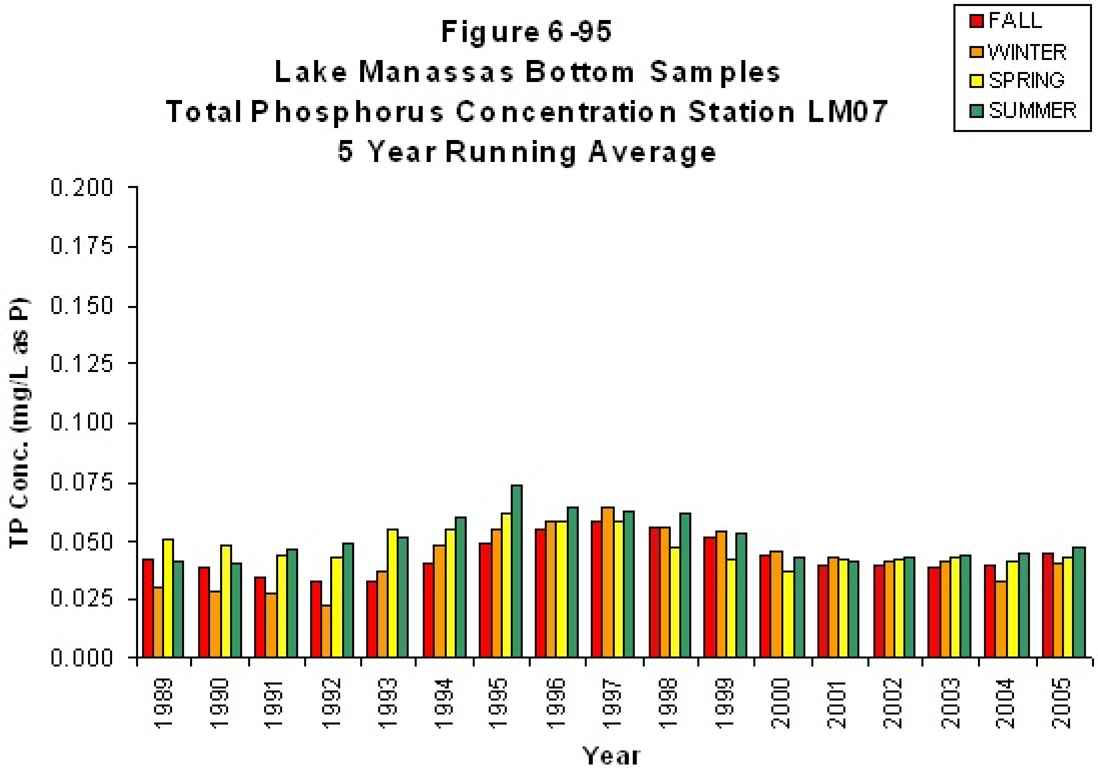


Figure 6-95
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM07
5 Year Running Average

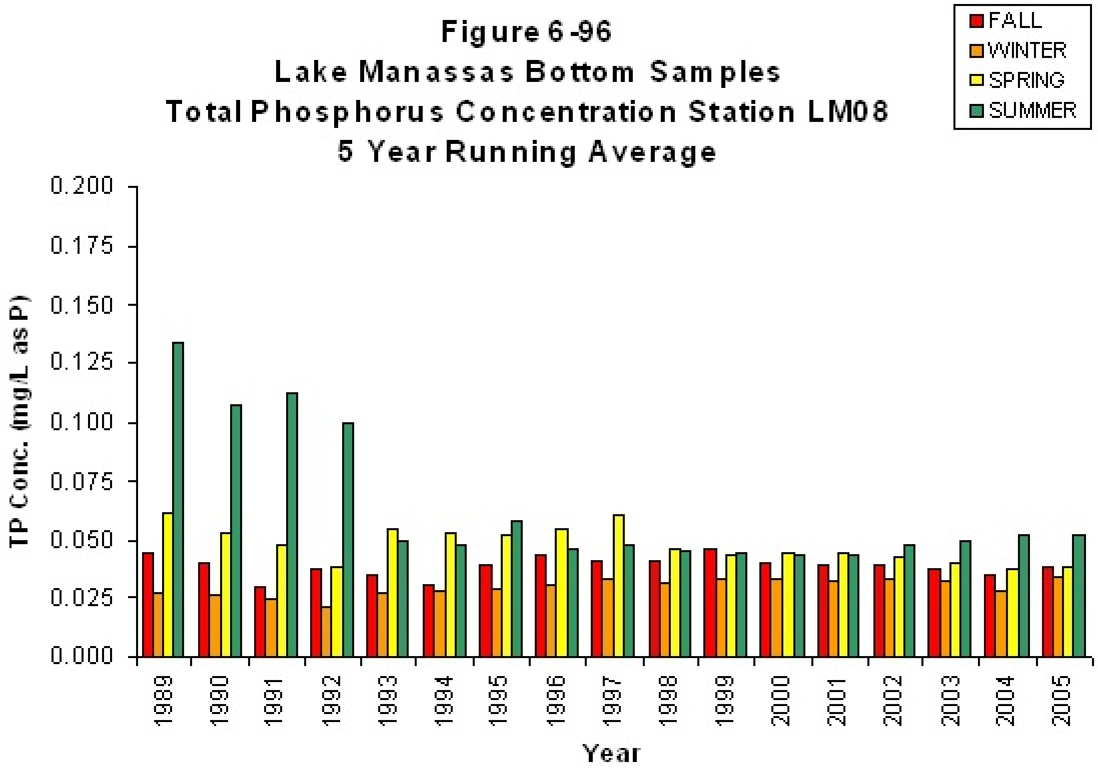
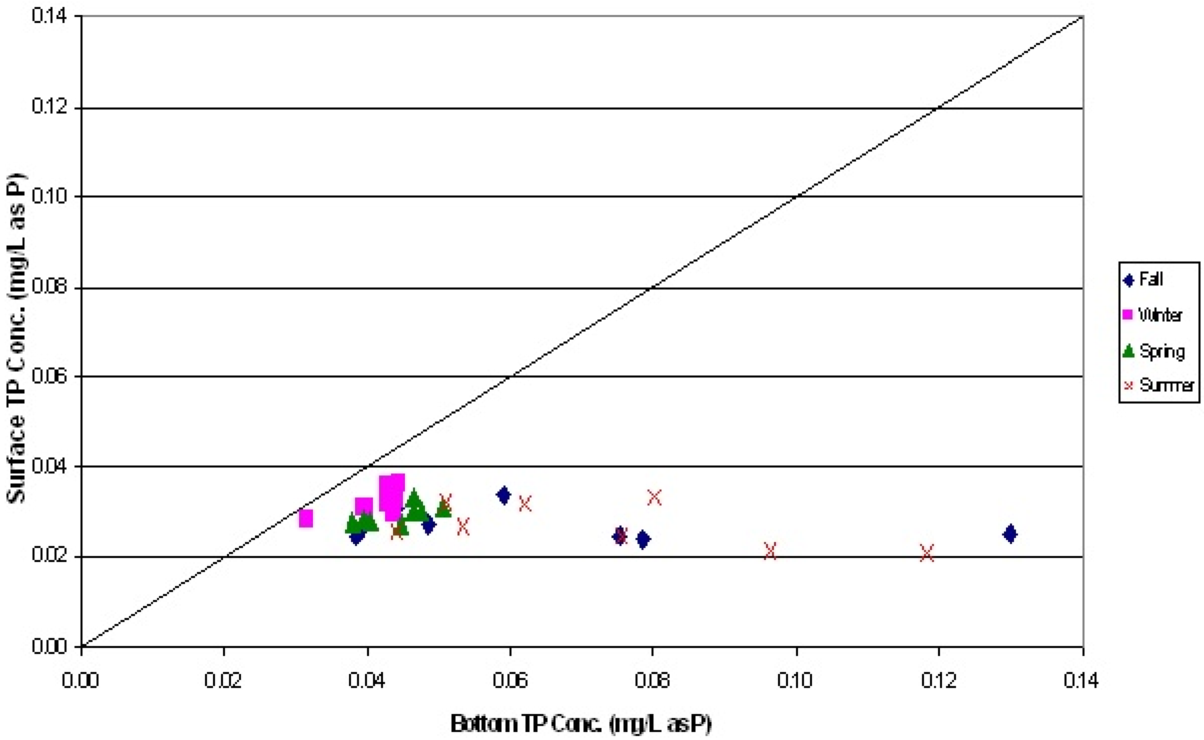


Figure 6-96
Lake Manassas Bottom Samples
Total Phosphorus Concentration Station LM08
5 Year Running Average

Figure 6-97
Surface vs Bottom Seasonal TP Concentration - Lake Manassas
All Lake Stations (2001 - 2005)



This is further evidence that phosphorus release from the sediments exists during the summer and fall stratification, thereby increasing the bottom TP concentrations in those seasons.

Orthophosphate phosphorus (OP) is a soluble reactive form of phosphorus that is readily available for biological uptake. Concerns exist with dissolved orthophosphorus because it is readily available to algae and under certain conditions can stimulate excess algal growth leading to subsequent depletion of dissolved oxygen. Figures 6-98 through 6-113 show the five-year running seasonal averages for OP at the surface and bottom of the lake. Overall, the surface concentrations of OP remain relatively constant, while the bottom concentrations show some fluctuations. Stations LM01, LM02, and LM04 have the highest concentrations in the hypolimnion. Each of these stations show elevated levels of OP during the summer and fall months. The depth at these stations is greater than others in the lake and consequently they endure longer periods of intense stratification. Tables 6-1 and 6-2 presents the results of the Mann-Kendall Analysis with respect to the surface and bottom concentrations of OP, respectively. Decreasing trends of OP were measured in the surface waters at stations LM01, LM02, LM03, LM04, and LM07. Additionally, decreasing trends of OP were detected in the bottom waters at stations LM01, LM02, LM07, and LM08. OP values at station LM06 did not exhibit the increased trends TP values experienced, implying that a higher percentage of inorganic phosphorus is present at station LM06. Station LM06 is located near the discharge of Broad Run into Lake Manassas, and is thus influenced by inorganic phosphorus concentrations associated with large runoff events.

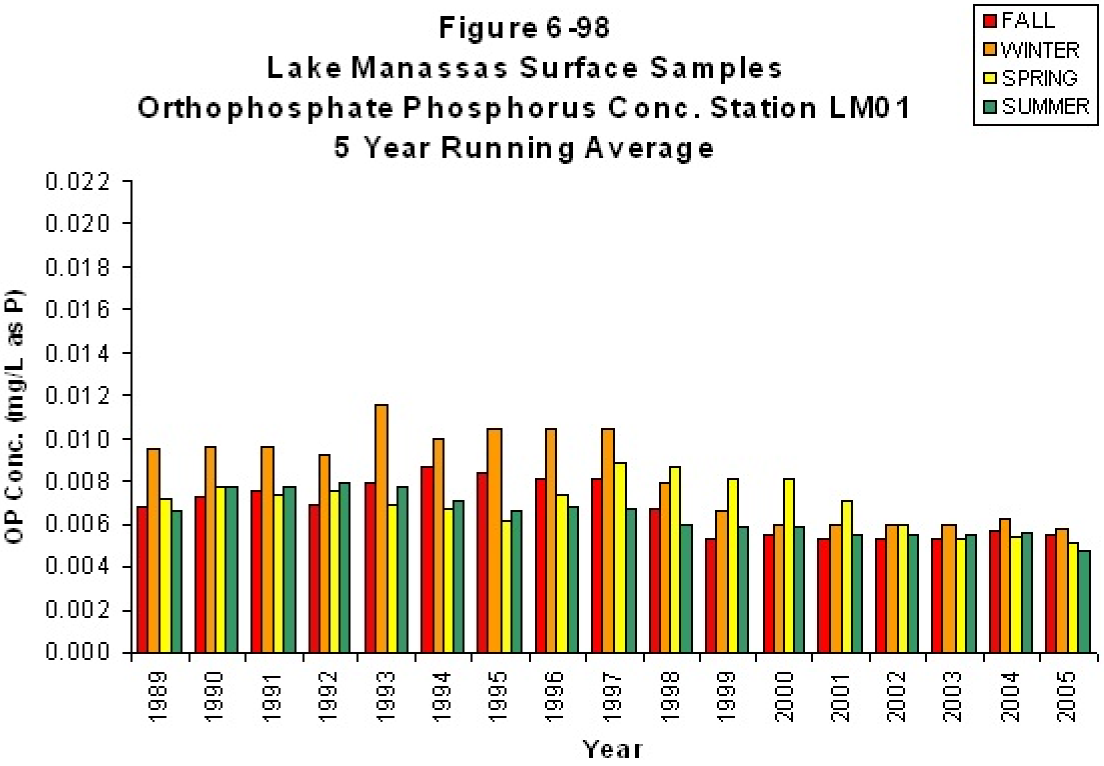


Figure 6-98
Lake Manassas Surface Samples
Orthophosphate Phosphorus Conc. Station LM01
5 Year Running Average

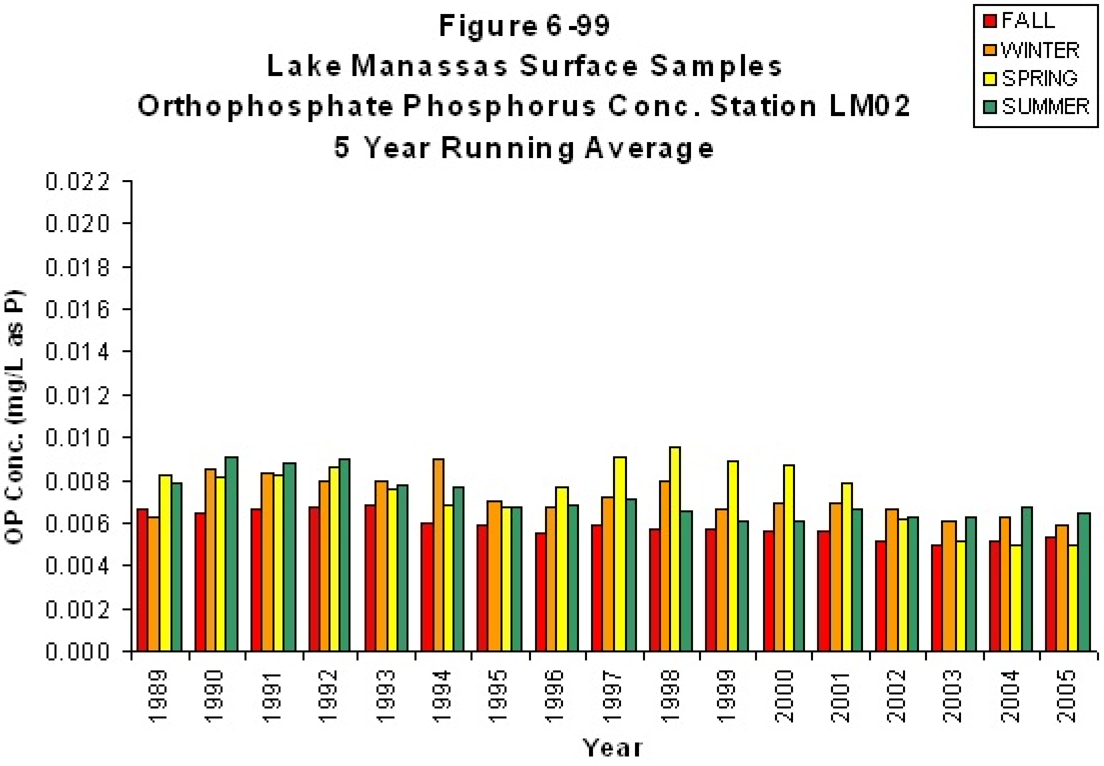


Figure 6-99
Lake Manassas Surface Samples
Orthophosphate Phosphorus Conc. Station LM02
5 Year Running Average

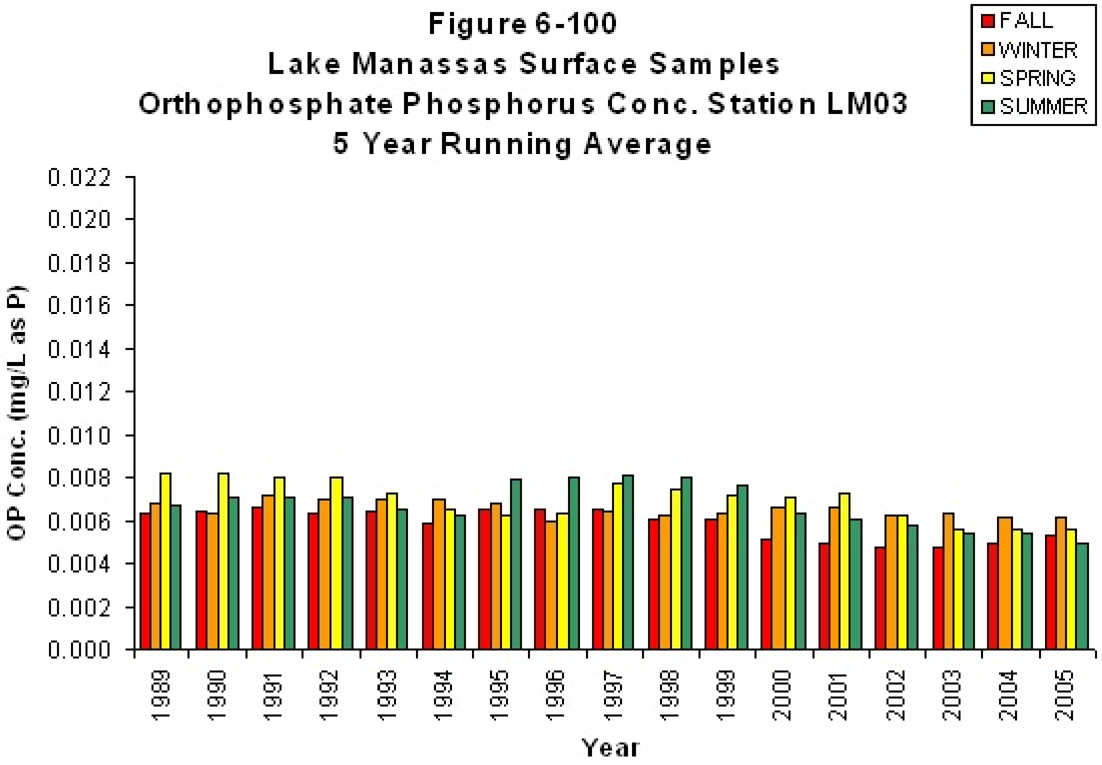


Figure 6-100

Lake Manassas Surface Samples

Orthophosphate Phosphorus Conc. Station LM03

5 Year Running Average

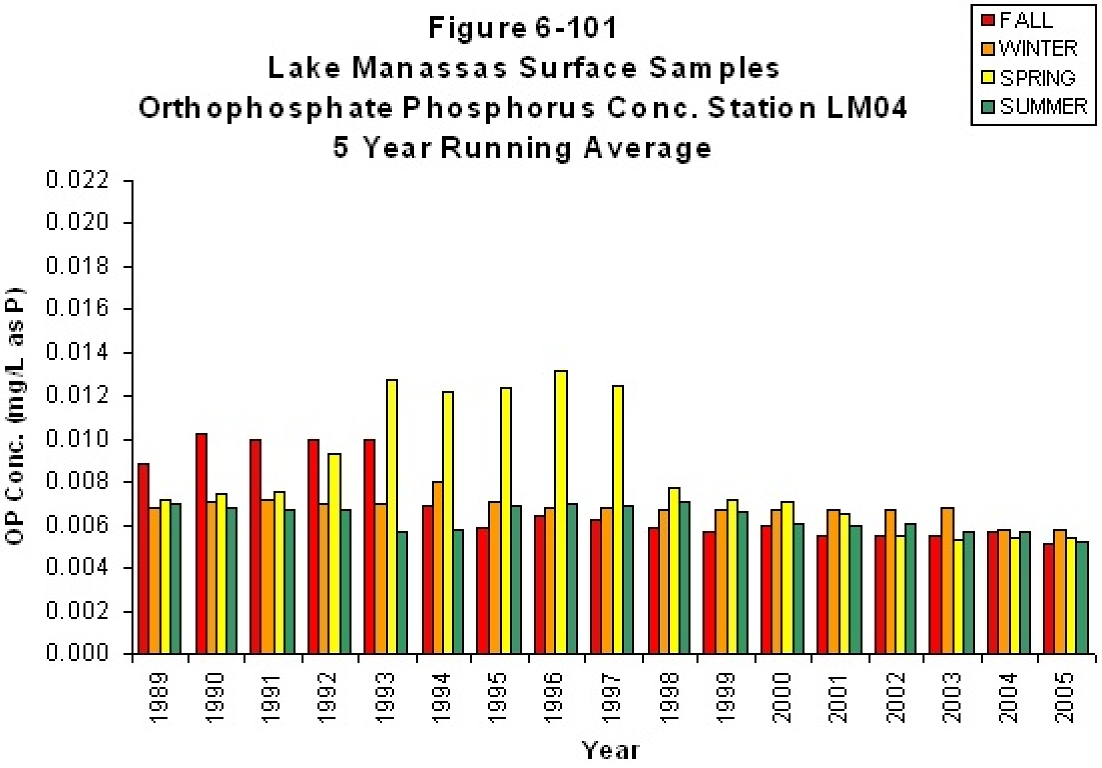


Figure 6-101

Lake Manassas Surface Samples

Orthophosphate Phosphorus Conc. Station LM04

5 Year Running Average

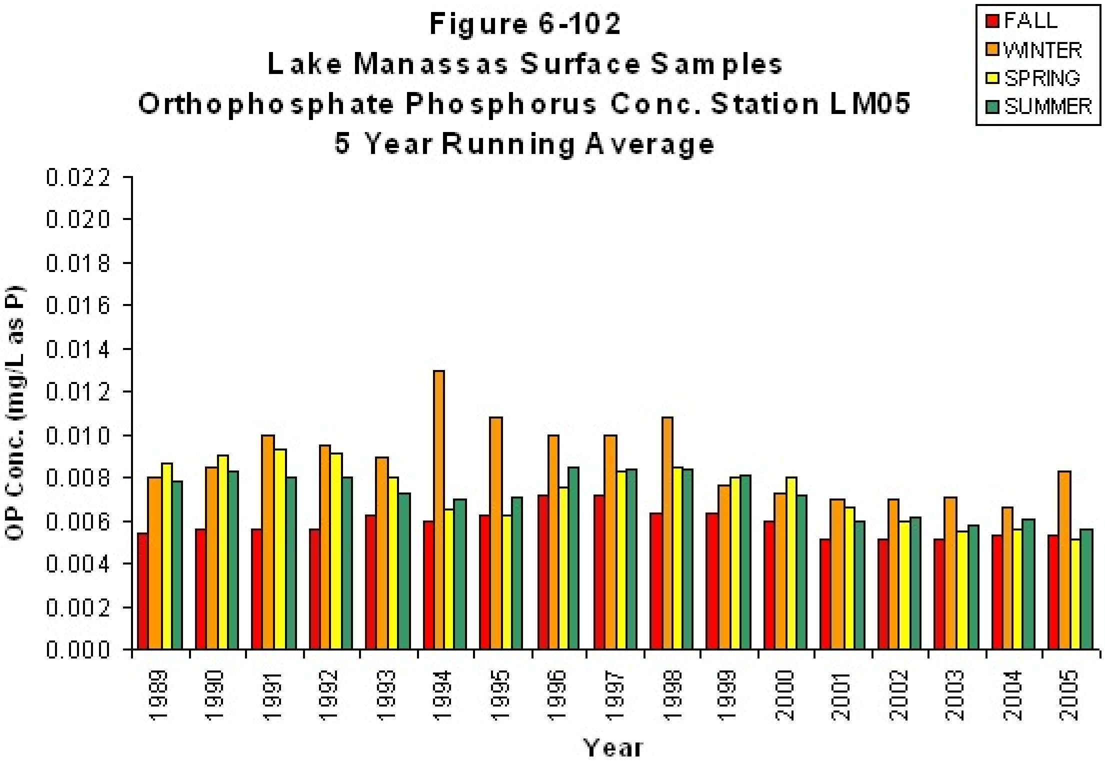


Figure 6-102
Lake Manassas Surface Samples
Orthophosphate Phosphorus Conc. Station LM05
5 Year Running Average

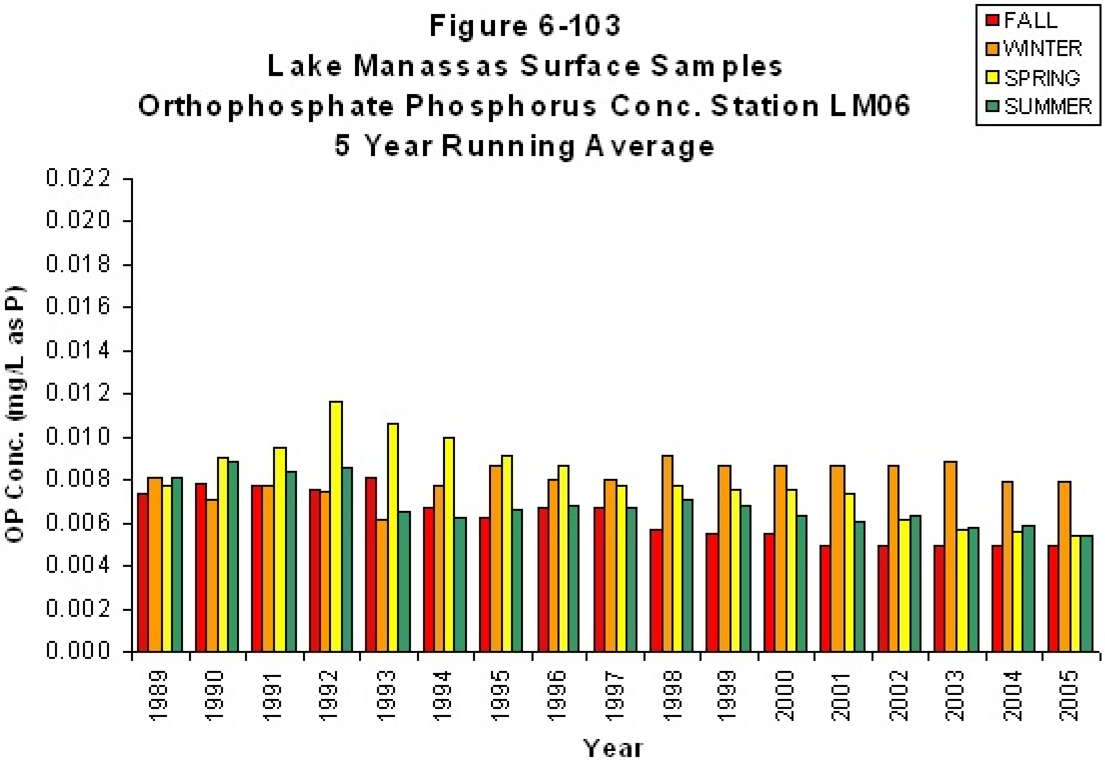


Figure 6-103
Lake Manassas Surface Samples
Orthophosphate Phosphorus Conc. Station LM06
5 Year Running Average

Figure 6-104
Lake Manassas Surface Samples
Orthophosphate Phosphorus Conc. Station LM07
5 Year Running Average

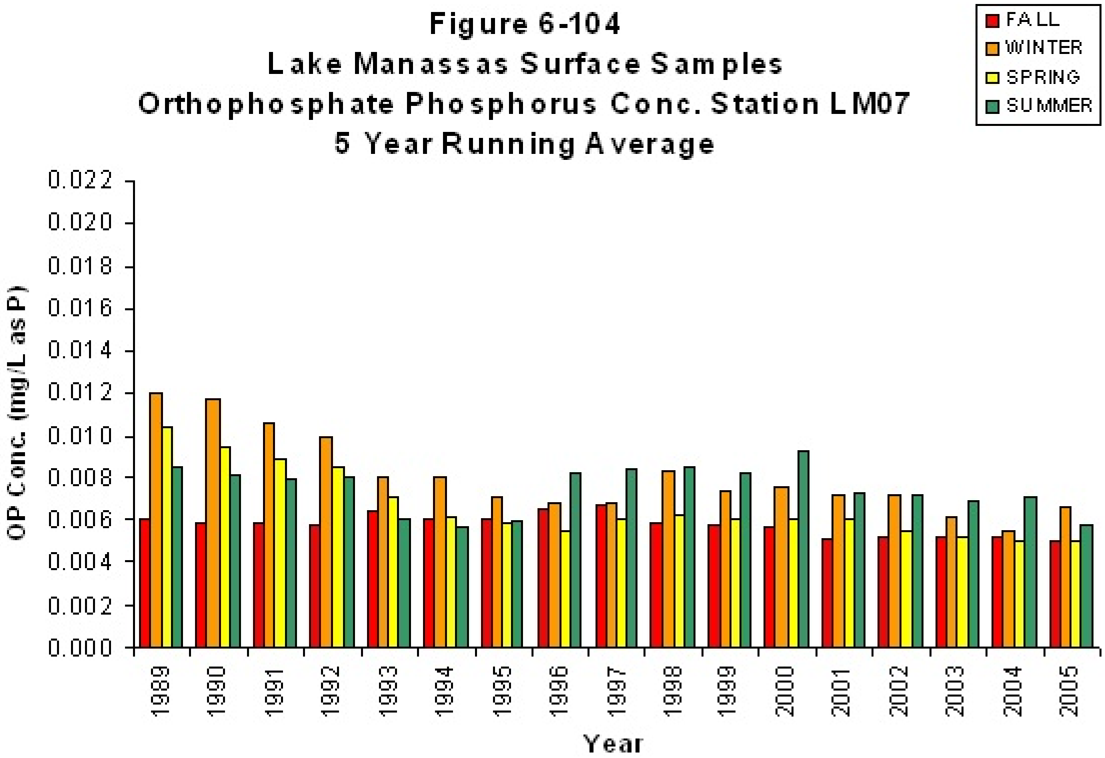


Figure 6-105
Lake Manassas Surface Samples
Orthophosphate Phosphorus Conc. Station LM08
5 Year Running Average

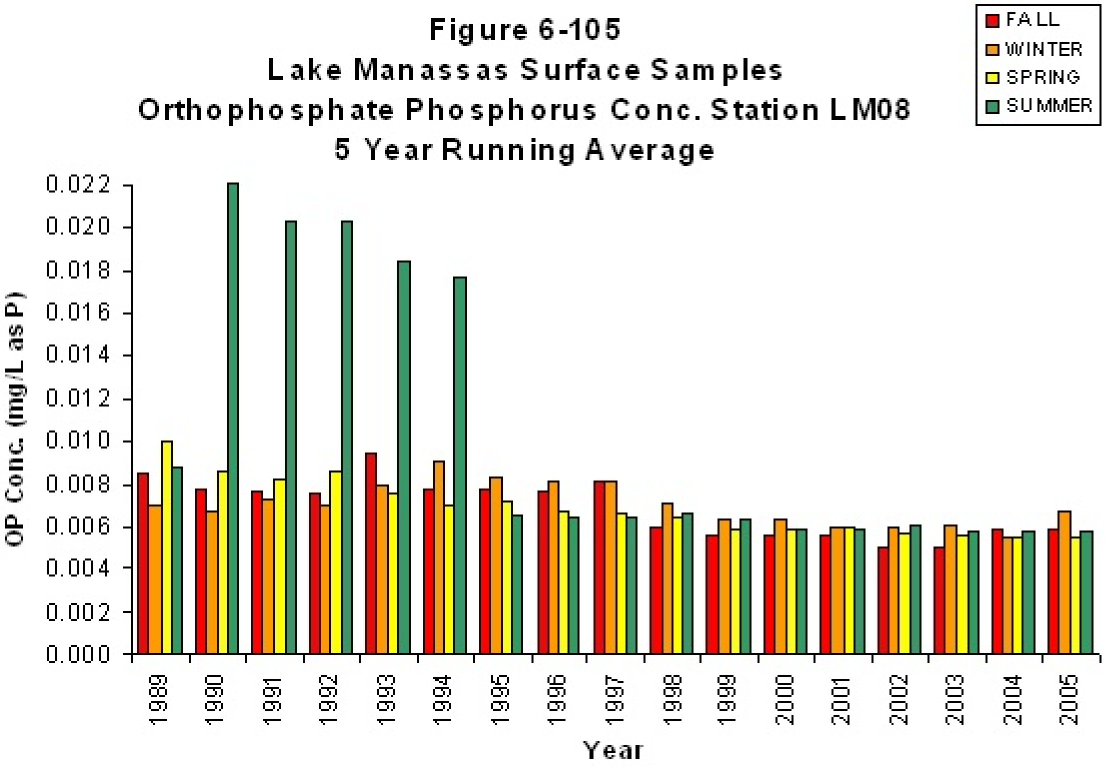


Figure 6-106
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM01
5 Year Running Average

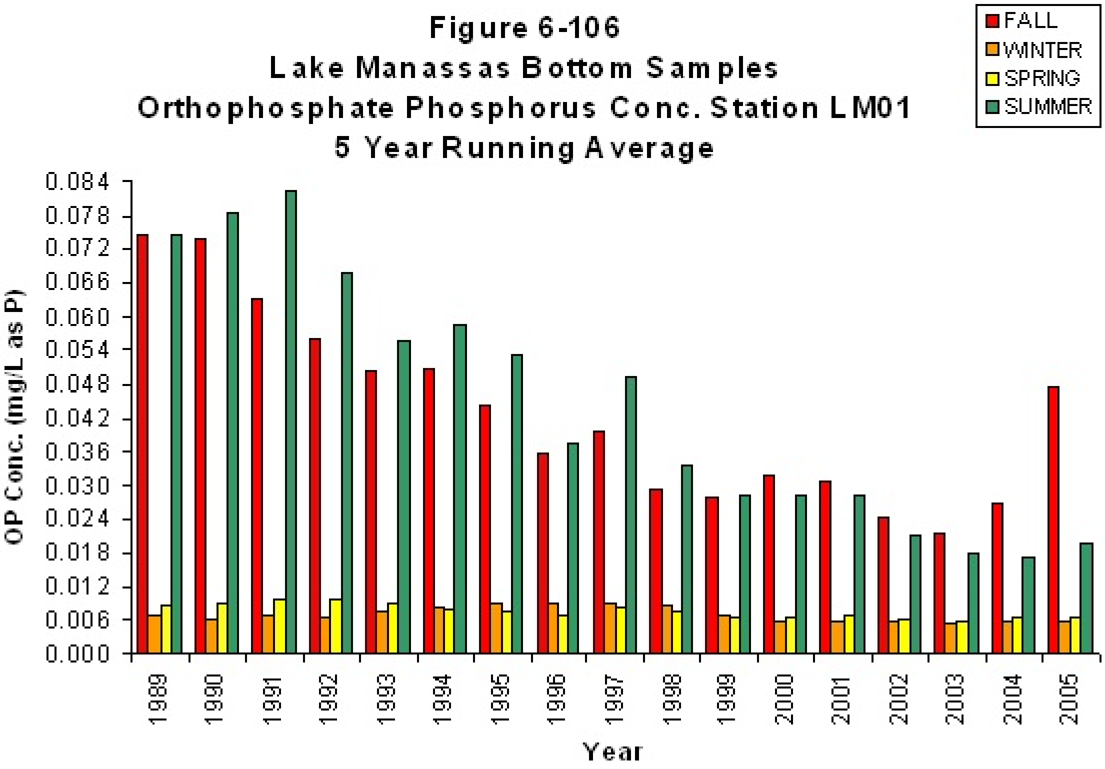
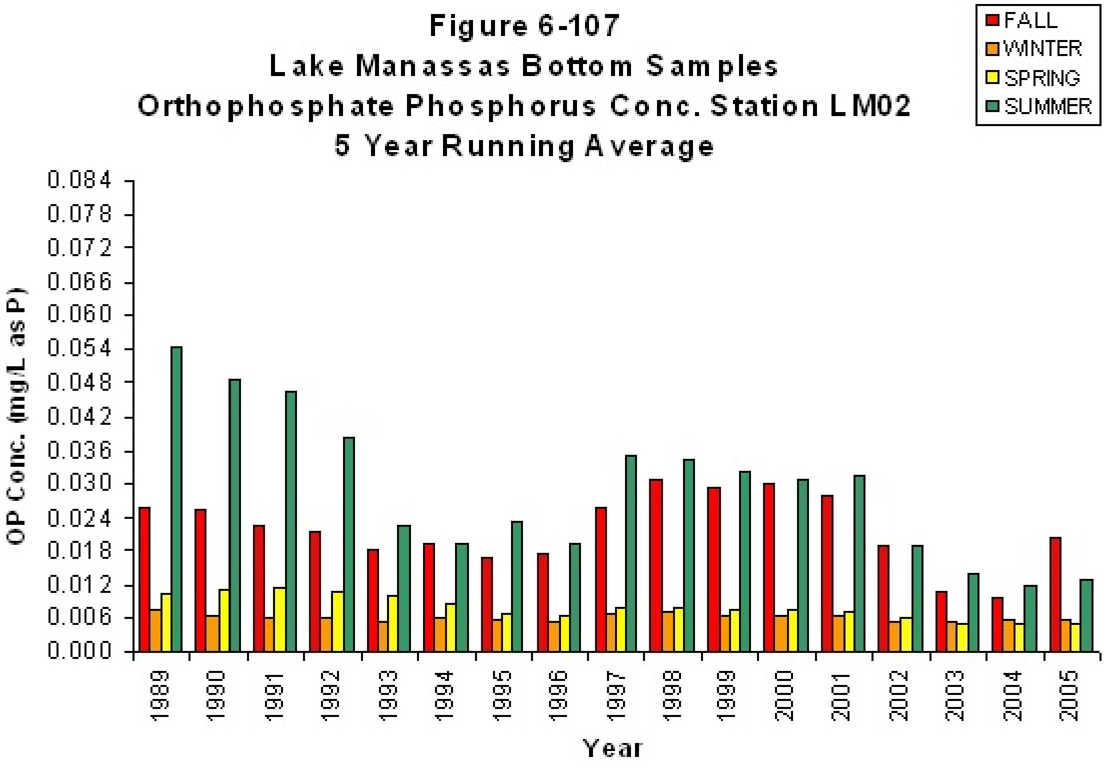


Figure 6-107
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM02
5 Year Running Average



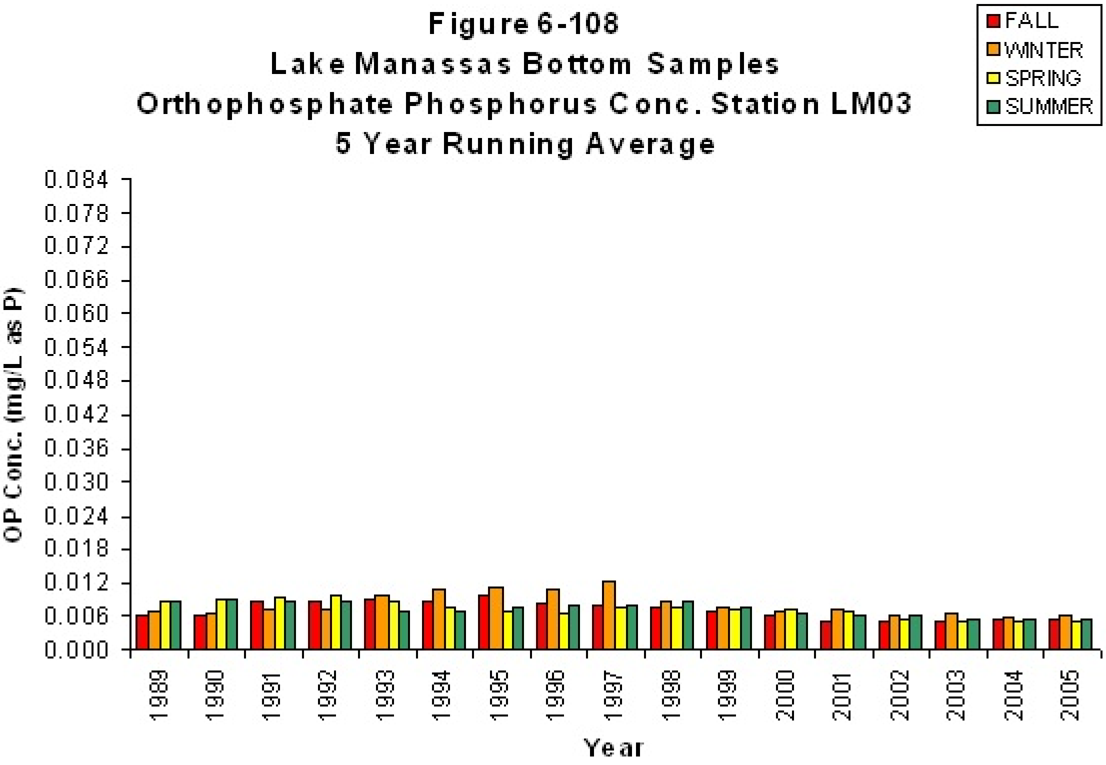


Figure 6-108
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM03
5 Year Running Average

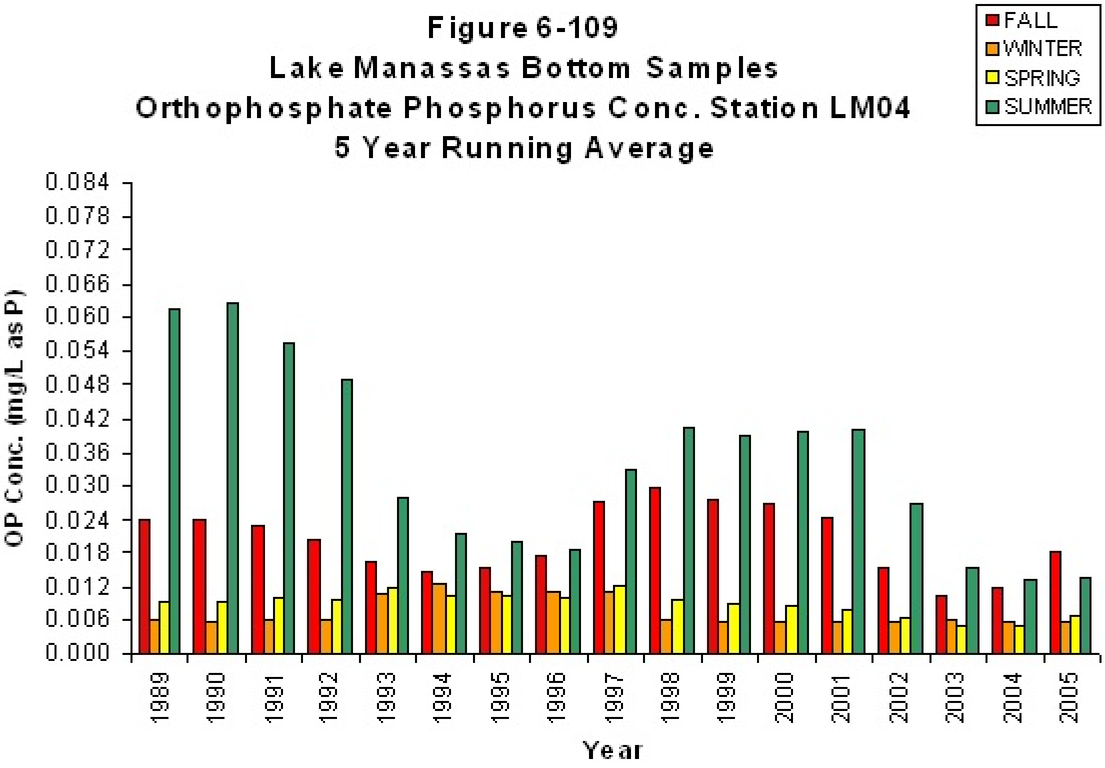


Figure 6-109
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM04
5 Year Running Average

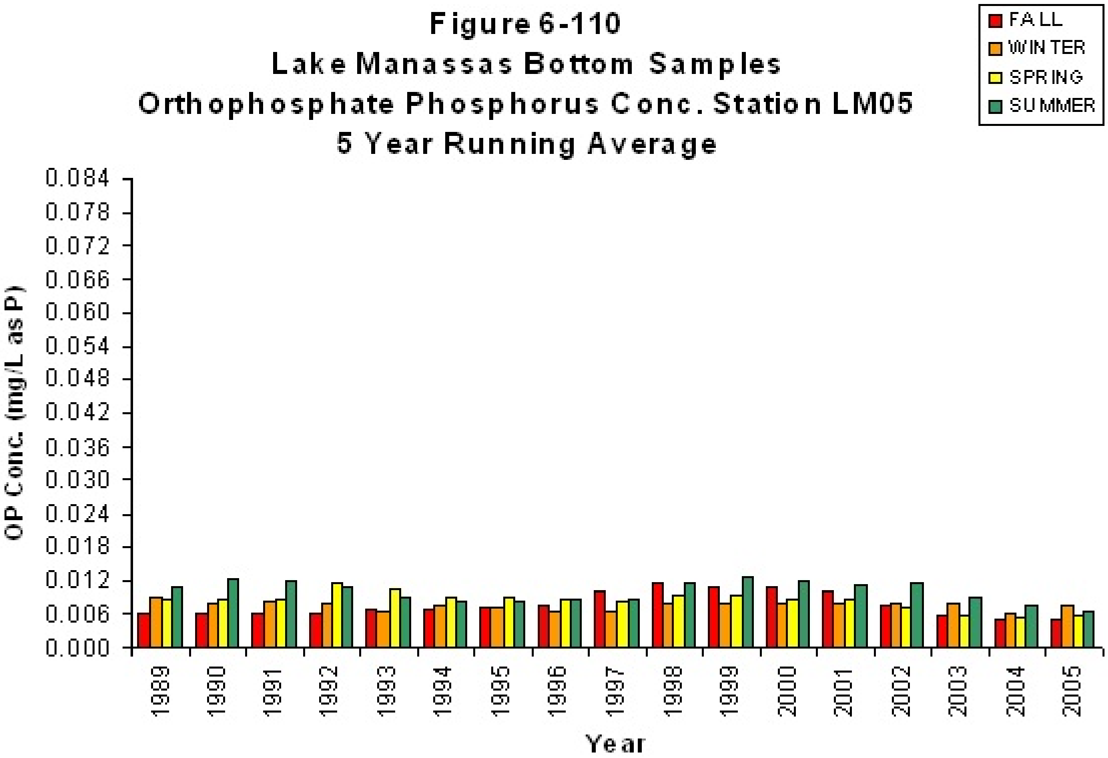


Figure 6-110
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM05
5 Year Running Average

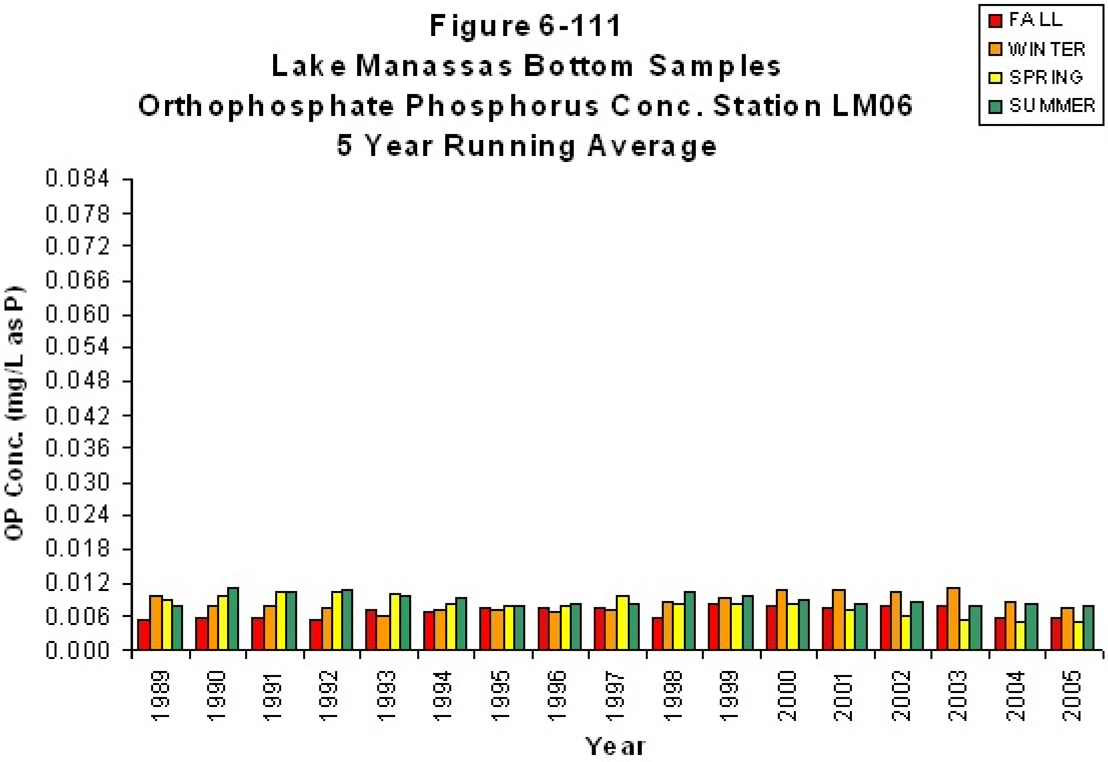


Figure 6-111
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM06
5 Year Running Average

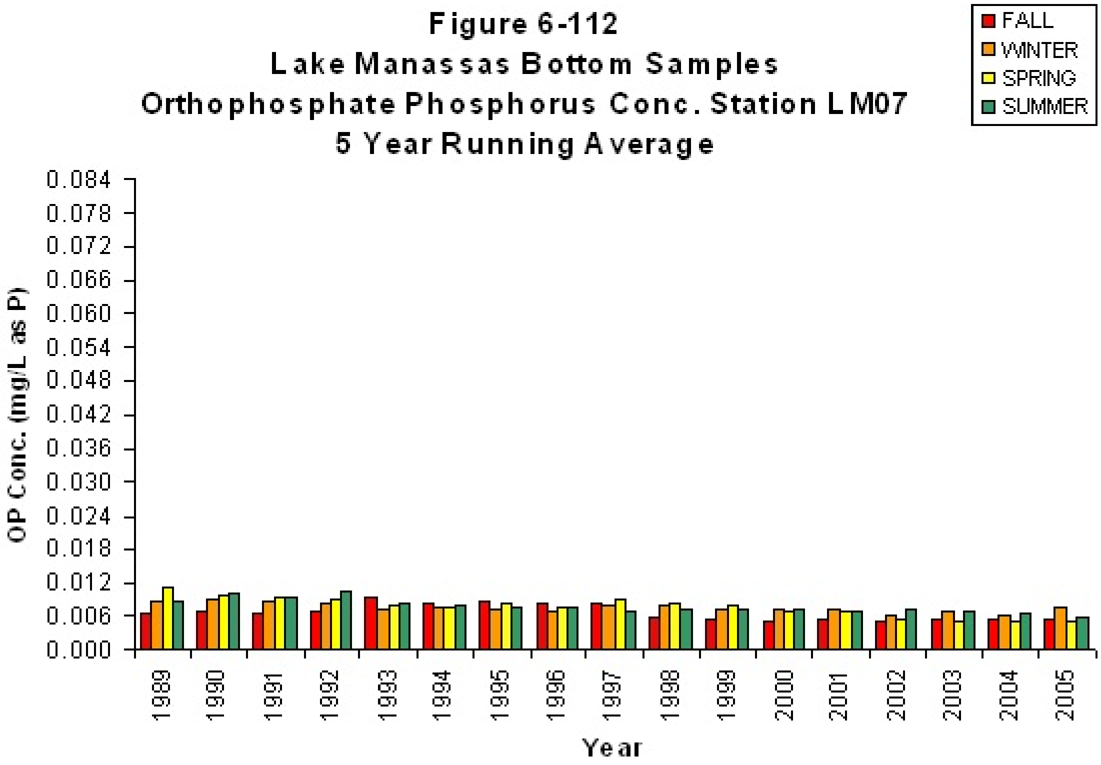


Figure 6-112
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM07
5 Year Running Average

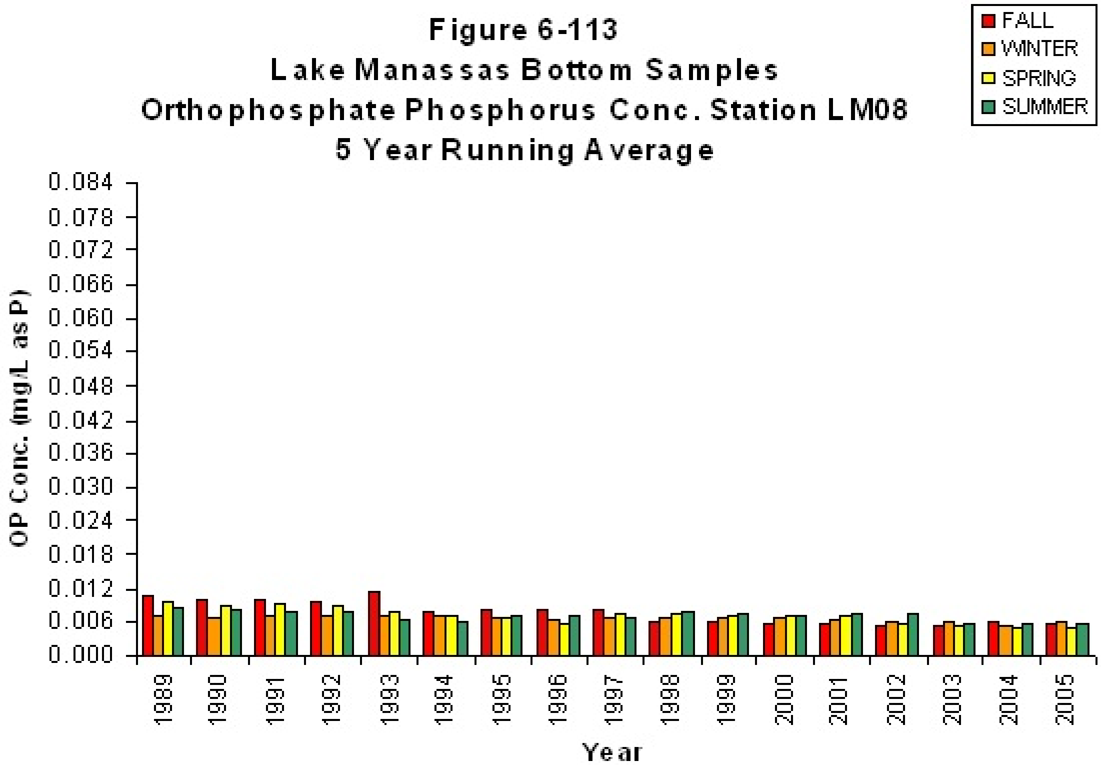


Figure 6-113
Lake Manassas Bottom Samples
Orthophosphate Phosphorus Conc. Station LM08
5 Year Running Average

Nutrient Summary

A distinct pattern exists between the flow of nutrients and changes in seasons. Figure 6-114 shows the cycle of nutrients at the bottom of station LM01 over the period from 1984 to 2005. During the transition from spring to summer, the DO and Ox-N concentrations begin to fall. When the DO concentration falls below 4 mg/L, the values of NH_3-N begin to rise. Once the DO and Ox-N concentrations have been exhausted, the TP concentrations will begin to rise. The absence of DO in the hypolimnion causes the redox potential to decrease and subsequently the sediments will release phosphorus into the water column. The Ox-N will only be depleted once the DO has been completely consumed since Ox-N is used as an alternate electron acceptor in the absence of DO. Following the fall turnover, Ox-N and DO concentrations increase in the hypolimnion, as a result of mixing in the water column. The fall turnover marks a sudden decrease in NH_3-N and TP, while the DO values rise. The increase in DO is concurrent with an increase in Ox-N concentrations, as the Ox-N is no longer required as an electron acceptor. Also, the ORP increases with the presence of DO and rebinds the phosphorus to the sediments.

The changes in concentrations at the surface are quite different from the bottom. Figure 6-115 shows the relationship of TP, Ox-N and DO at the surface of station LM01 over the period from 1984 to 2005. Since the surface is in constant contact with the atmosphere, the DO concentrations never fall below 4 mg/L. As a result, the oxidation-reduction potential does not fall to a point that induces the release of TP or NH_3-N.

Figure 6-114
Lake Manassas (Bottom)
Station LM01, 1984-2005

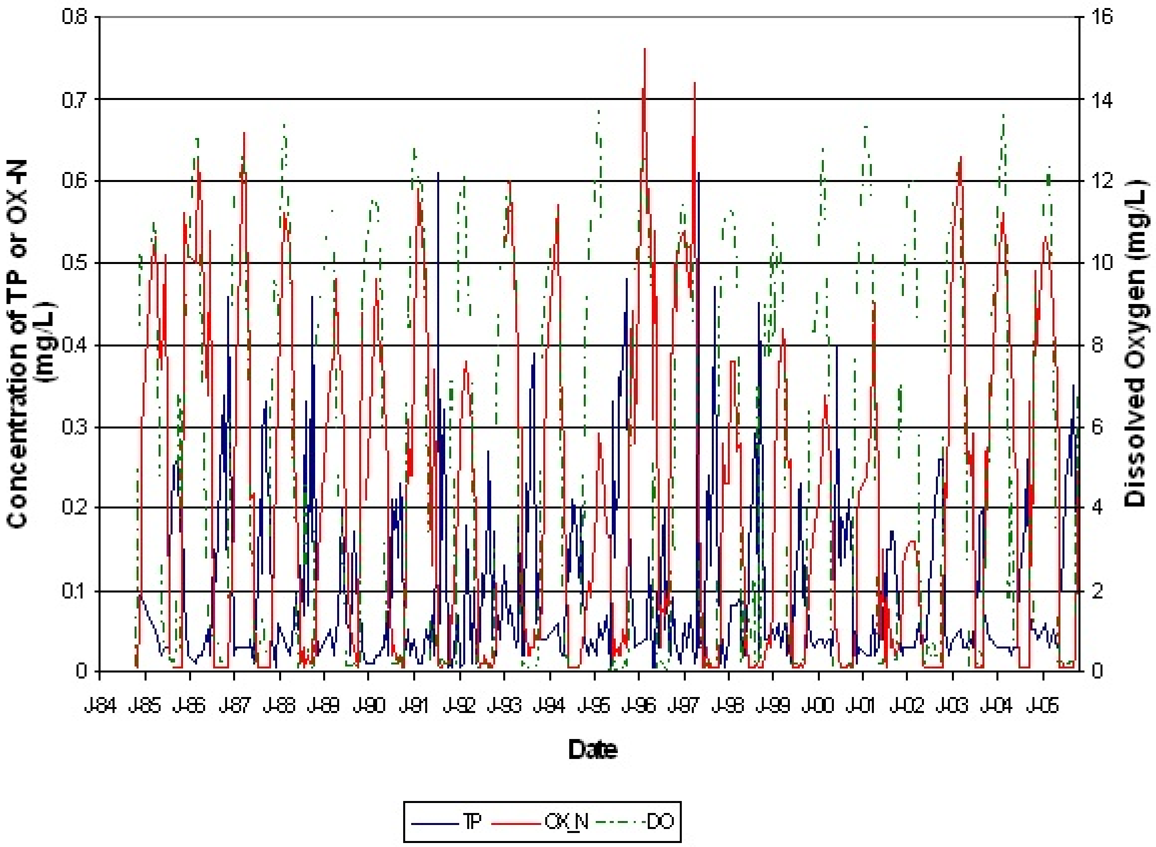
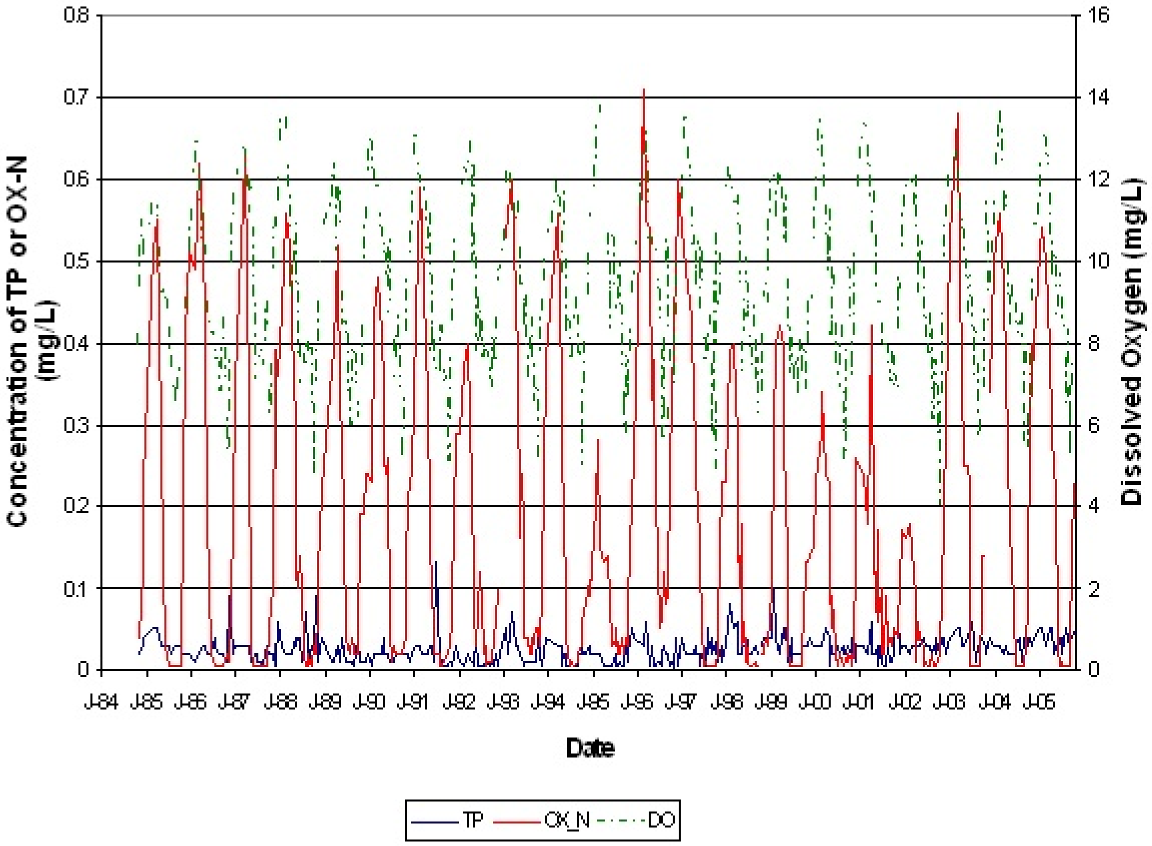


Figure 6-115
Lake Manassas (Surface)
Station LM01, 1984-2005



The surface of the lake typically experiences constant levels of TP with fluctuations resulting from large runoff events. The Ox-N concentrations change from season to season and generally follow trends of DO. The highest concentrations of Ox-N occur in the winter.

Examining the bottom of the lake, Ox-N concentrations reach a maximum during the winter and spring, when DO is present and Ox-N is not used as an alternate electron acceptor. The summer and fall months mark increases in TP following decreases in DO and Ox-N.

Nitrogen to Phosphorus Ratios

The prevalence of algal species is largely affected by the ratio of total nitrogen to total phosphorus. N:P ratios greater than 20:1 indicate phosphorus-limited systems, while N:P ratios equal to or less than 5:1 are associated with nitrogen-limited systems (Wetzel, 2001). An N:P ratio of 10:1 marks the lower limit of a transition from a phosphorus- to a nitrogen-limited system. Cyanobacteria (blue-green algae) posses the capacity to out-compete other algal species in a nitrogen-limited system because of their ability to fix atmospheric nitrogen. Blue-green algae can cause significant problems with water treatment such as taste, odor, and filter clogging. From the standpoint of drinking water quality, it is generally beneficial to maintain a phosphorus-limited system.

Figures 6-116 through 6-123 show the yearly averages for TN:TP ratios in the surface and bottom waters of Lake Manassas. Each bar represents the TN:TP ratio average for a single year.

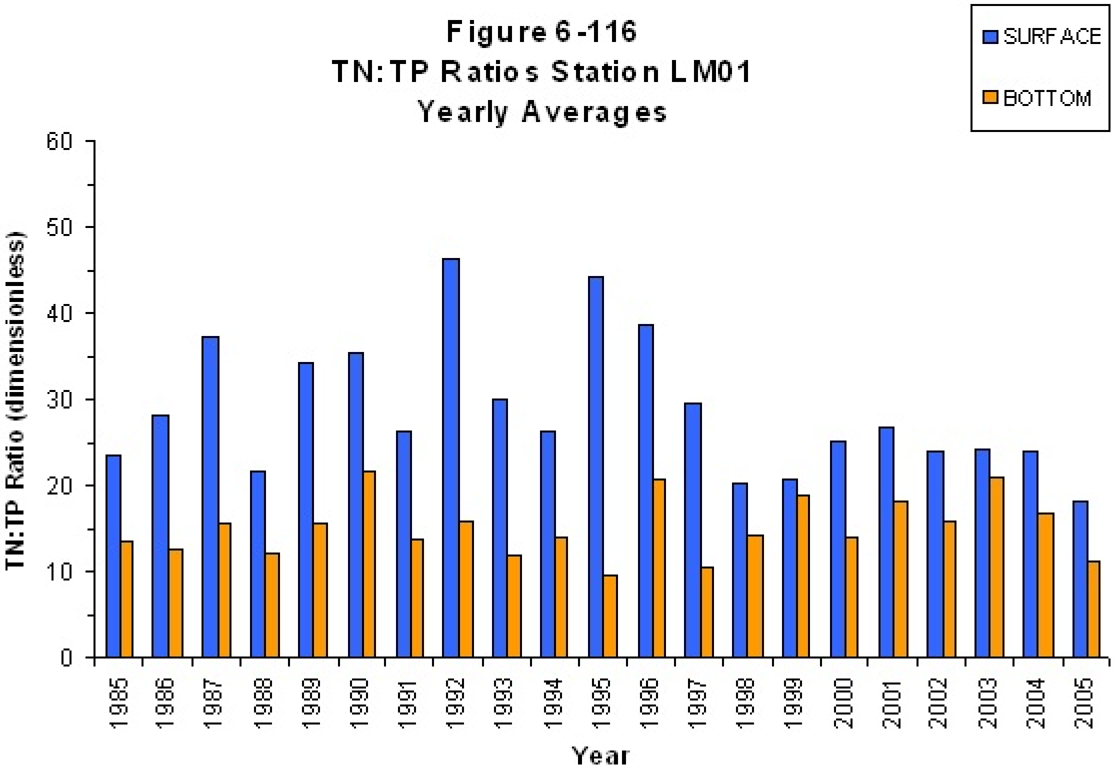


Figure 6-116
TN:TP Ratios Station LM01
Yearly Averages

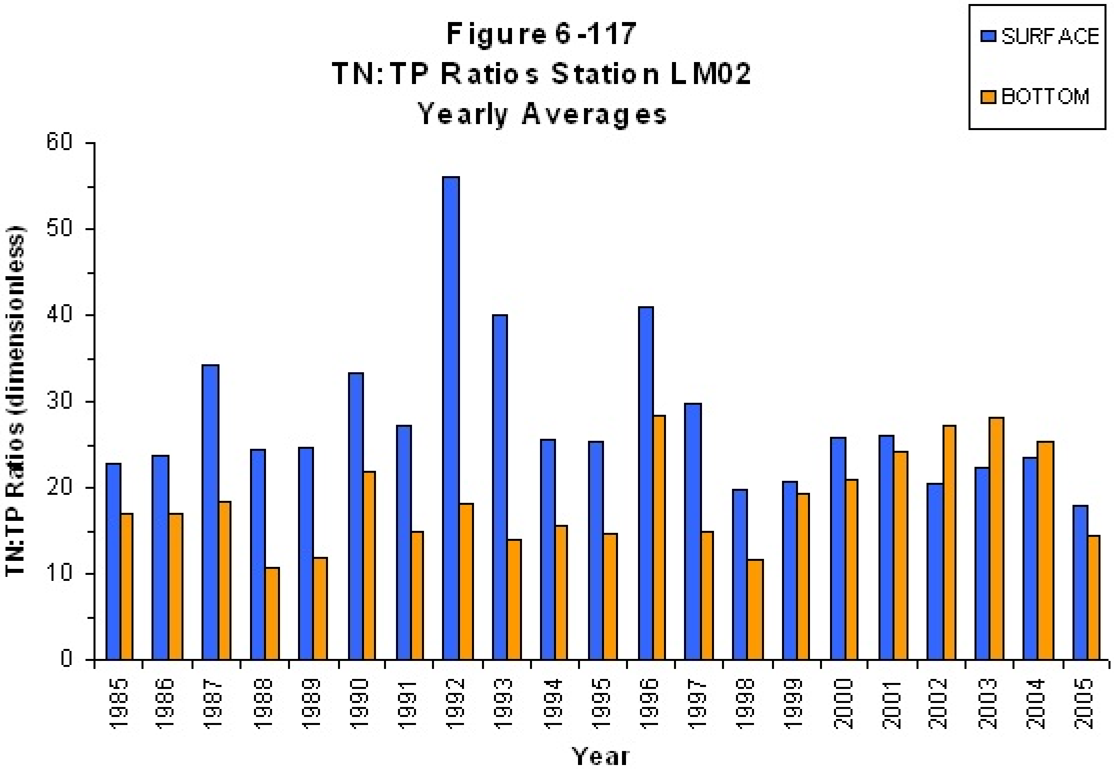


Figure 6-117
TN:TP Ratios Station LM02
Yearly Averages

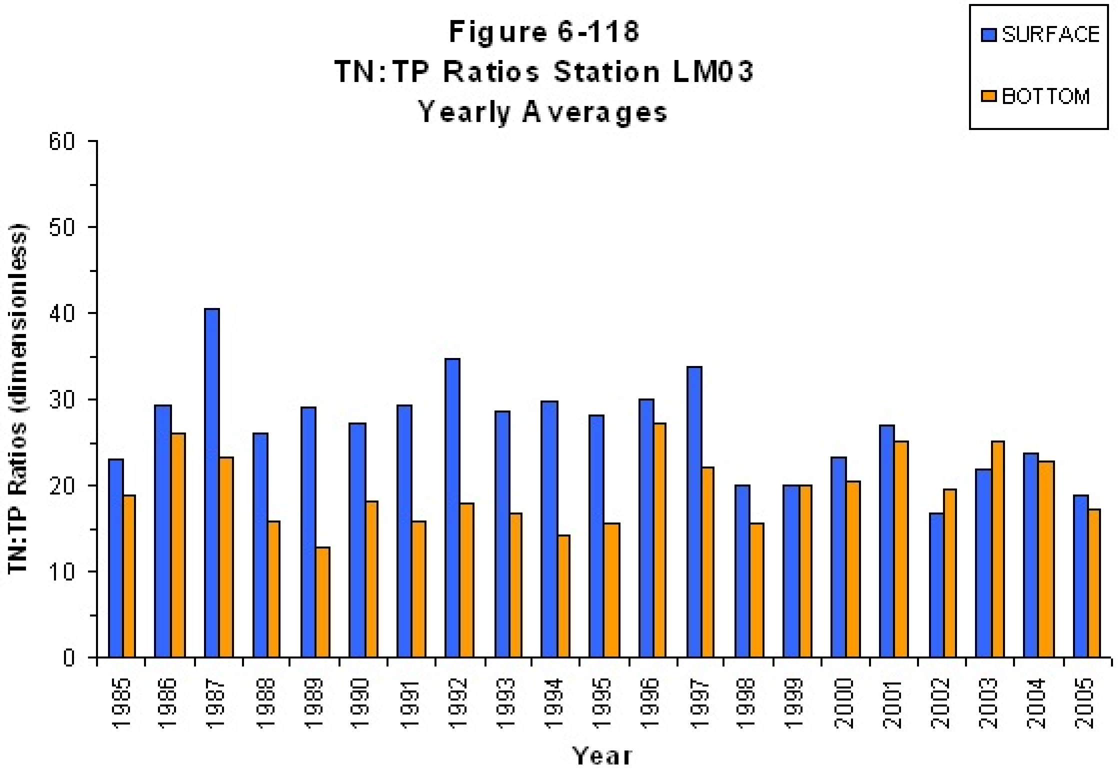


Figure 6-118
TN:TP Ratios Station LM03
Yearly Averages

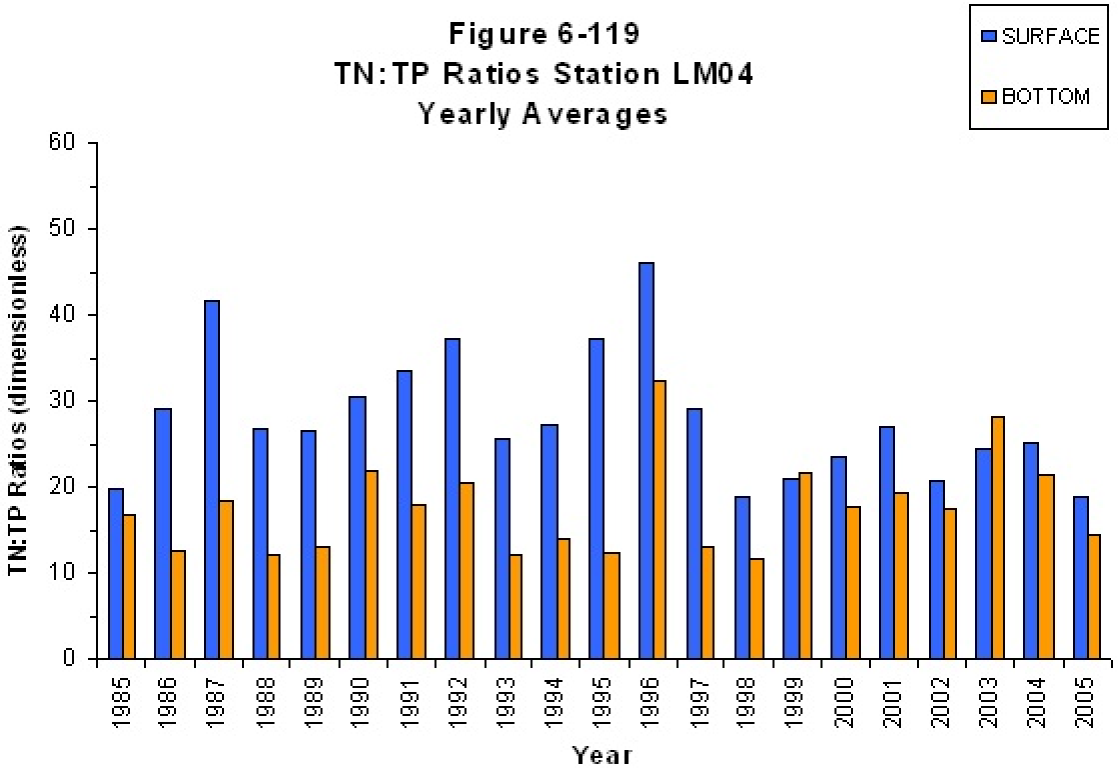


Figure 6-119
TN:TP Ratios Station LM04
Yearly Averages

Figure 6-120
TN:TP Ratios Station LM05
Yearly Averages

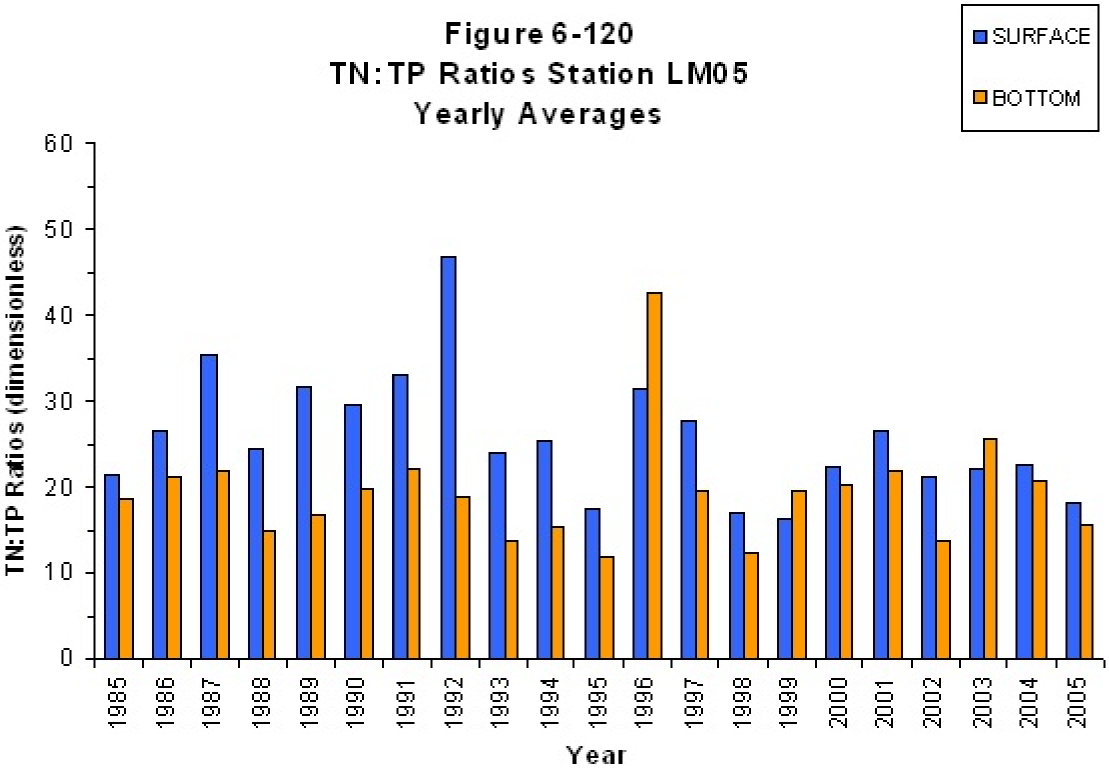


Figure 6-121
TN:TP Ratios Station LM06
Yearly Averages

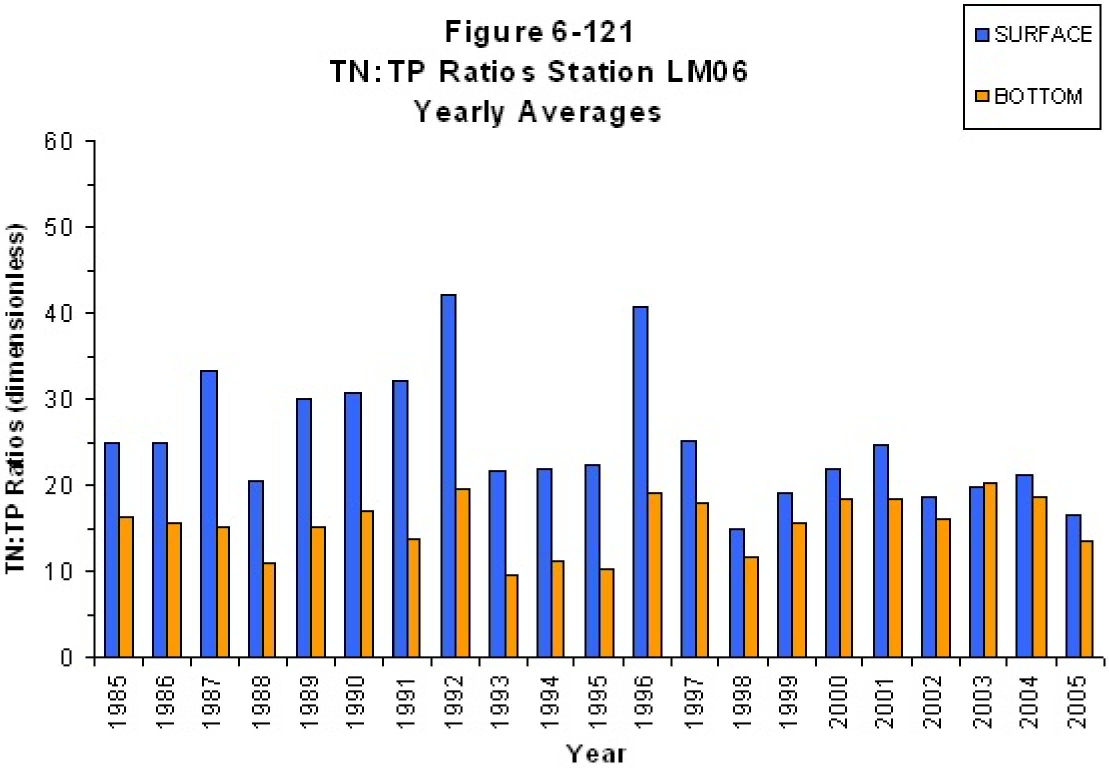


Figure 6-122
TN:TP Ratios Station LM07
Yearly Averages

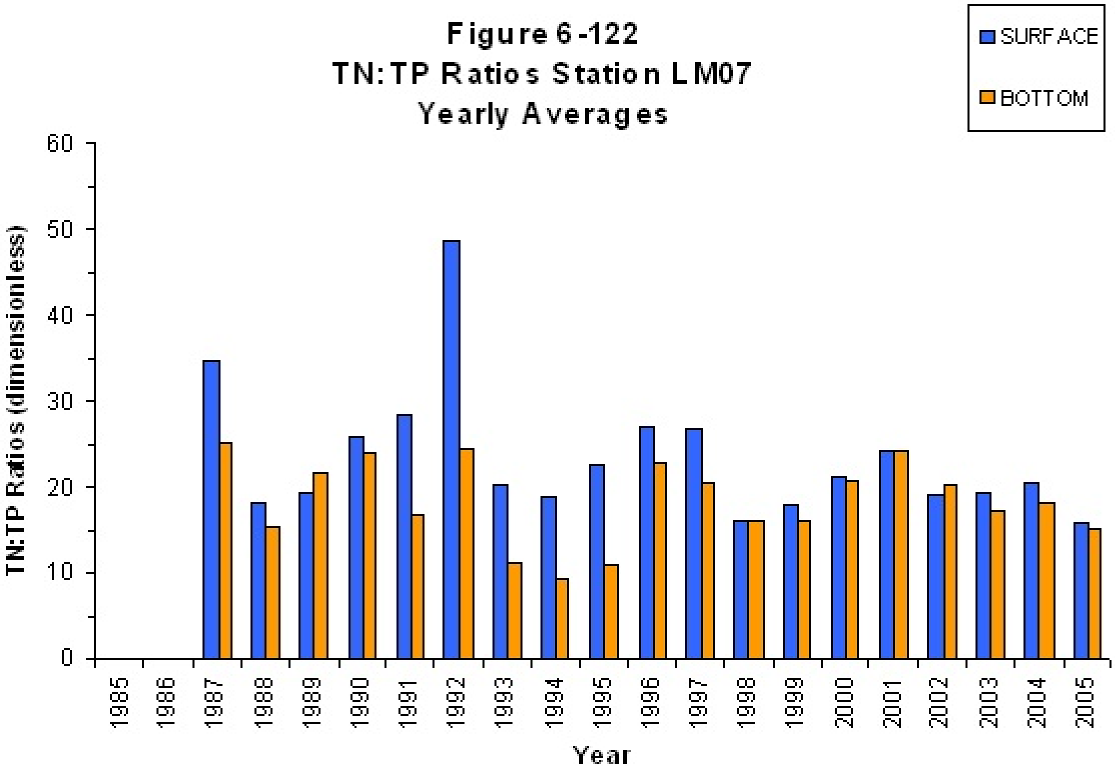
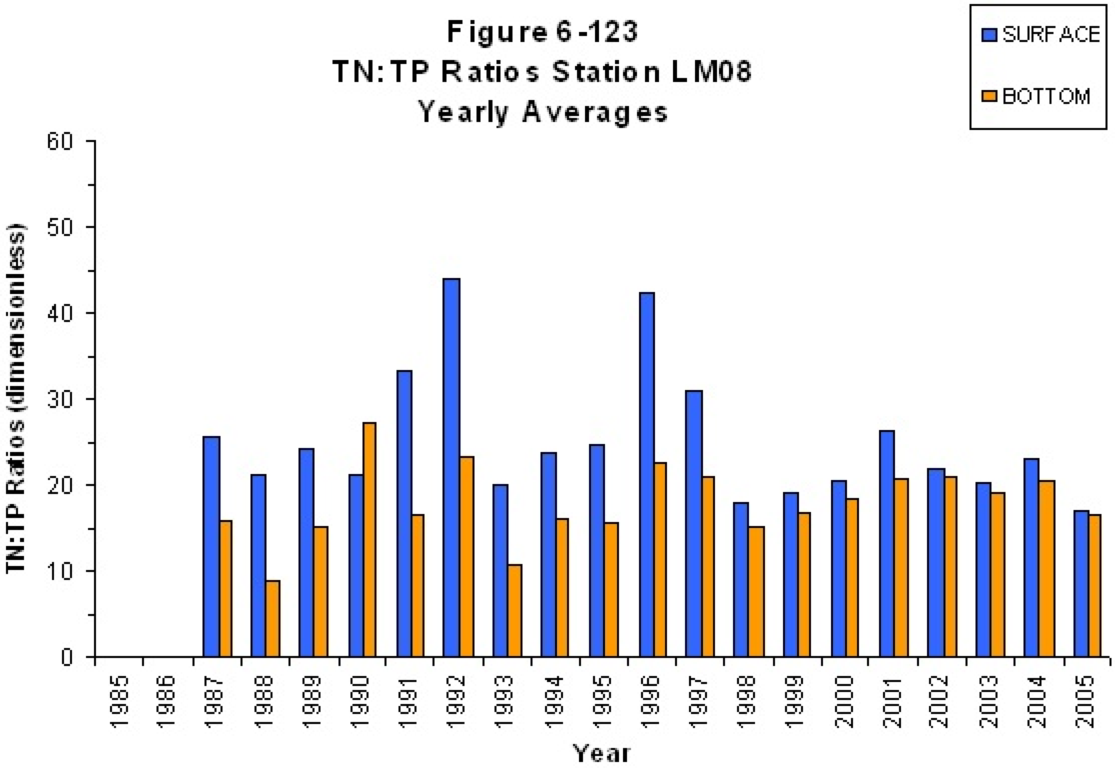


Figure 6-123
TN:TP Ratios Station LM08
Yearly Averages



The ratio is between 20:1 and 55:1 at the surface which can be considered average-to-strongly phosphorus-limited. The ratio at the bottom is between 10:1 and 40:1. Algal growth is typically limited to the epilimnion so TN:TP ratios in the hypolimnion are not of great concern.

Figures 6-124 through 6-139 display the seasonal five-year running averages for TN:TP ratios at the surface and bottom of Lake Manassas. The past five years have seen decreasing ratios at all stations during the summer, however, these ratios have maintained levels above 15:1. Despite the decreasing ratios, Lake Manassas remains phosphorus-limited. The fall months have seen rather consistent levels, while the winter and spring months have seen increasing levels. The bottom of the lake experiences ratios between 10:1 and 30:1. The winter and spring months typically have larger ratios than the summer and fall months. When the summer and fall ratios drop to 10:1, the potential of a switch to a nitrogen limited system dramatically increases. The lake is usually stratified during these months and this would not affect the surface waters.

Chlorophyll *a*

Chlorophyll *a* is the primary photosynthetic pigment found in most plants, algae, and cyanobacteria. Measuring chlorophyll *a* is relatively easy and proves to be a critical tool in predicting algal biomass in aquatic systems. High concentrations of chlorophyll *a* are symptomatic of algal blooms and potentially eutrophic conditions. Chlorophyll *a* measurements are generally taken at the surface, where algae are expected to be found.

The five-year running seasonal averages of chlorophyll *a* in the surface waters of Lake Manassas are shown in Figures 6-140 through 6-147. The largest values of chlorophyll *a* were measured at stations LM01, LM02, LM03, LM04, and LM08 during the winter months, while large concentrations were measured during the fall at stations LM05, LM06, and LM07. The largest values of chlorophyll *a* were detected at station LM06. Copper sulfate was historically applied to combat algal growth. However, these treatments were terminated in February 2000. The effects of removing algicide treatments from the reservoir management plan were initially positive, and are illustrated in a sudden drop in chlorophyll *a* concentrations at most stations during 2000. However, the past five years have seen increasing trends of chlorophyll *a* at all stations as seen in the Mann-Kendall Analysis, Table 6-1. The increasing phosphorus concentrations in the lake are contributing to the problems associated with increasing chlorophyll *a* concentrations. As more phosphorus enters the lake, the potential for algal growth escalates.

Figure 6-124
Lake Manassas Surface Samples
TN:TP Ratios Station LM01
5 Year Running Average

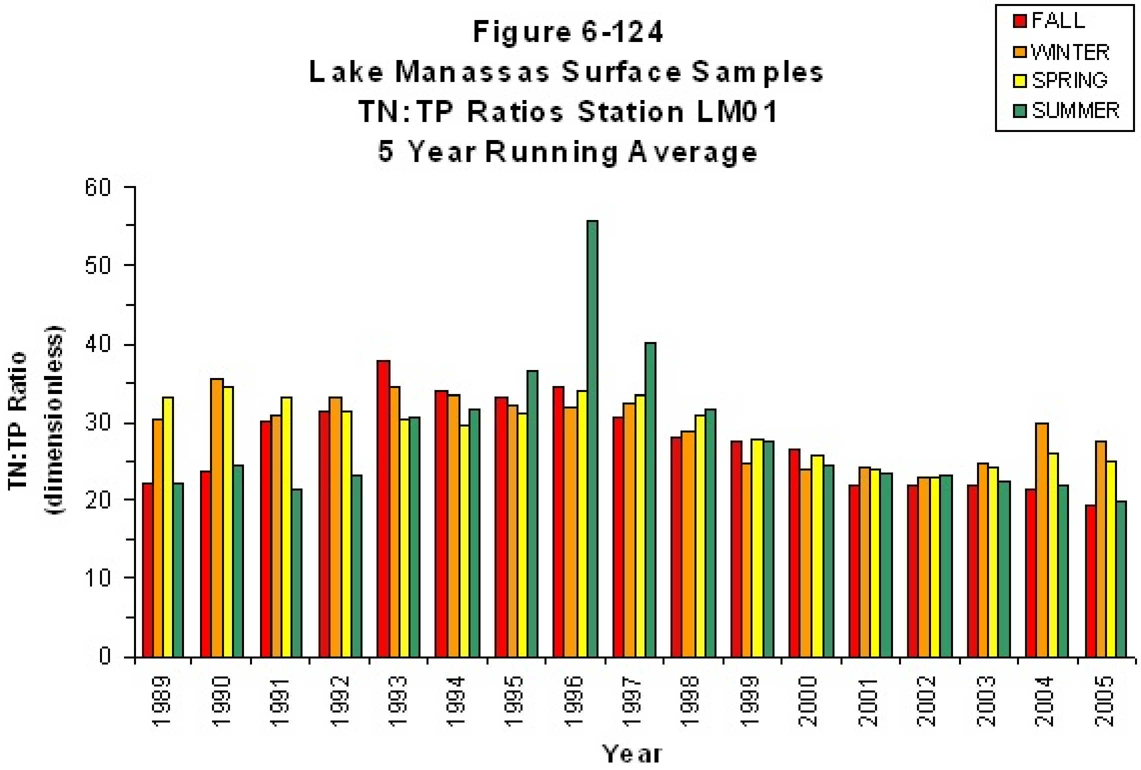
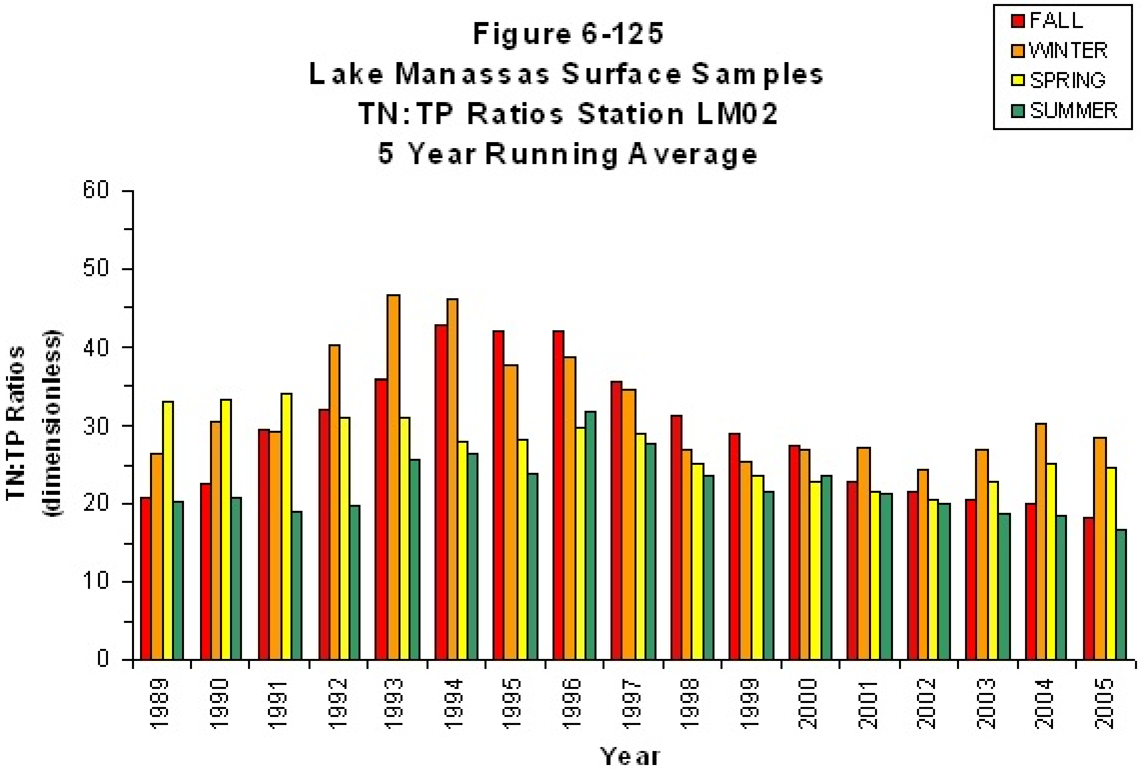


Figure 6-125
Lake Manassas Surface Samples
TN:TP Ratios Station LM02
5 Year Running Average



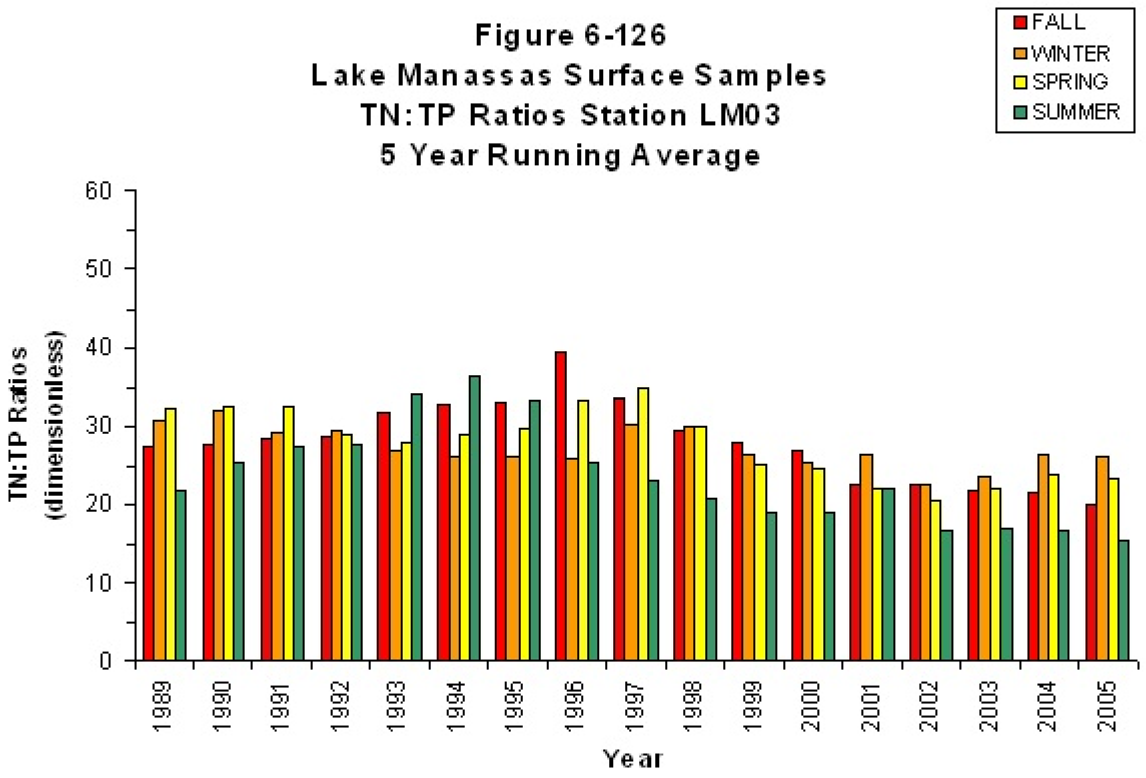


Figure 6-126
Lake Manassas Surface Samples
TN:TP Ratios Station LM03
5 Year Running Average

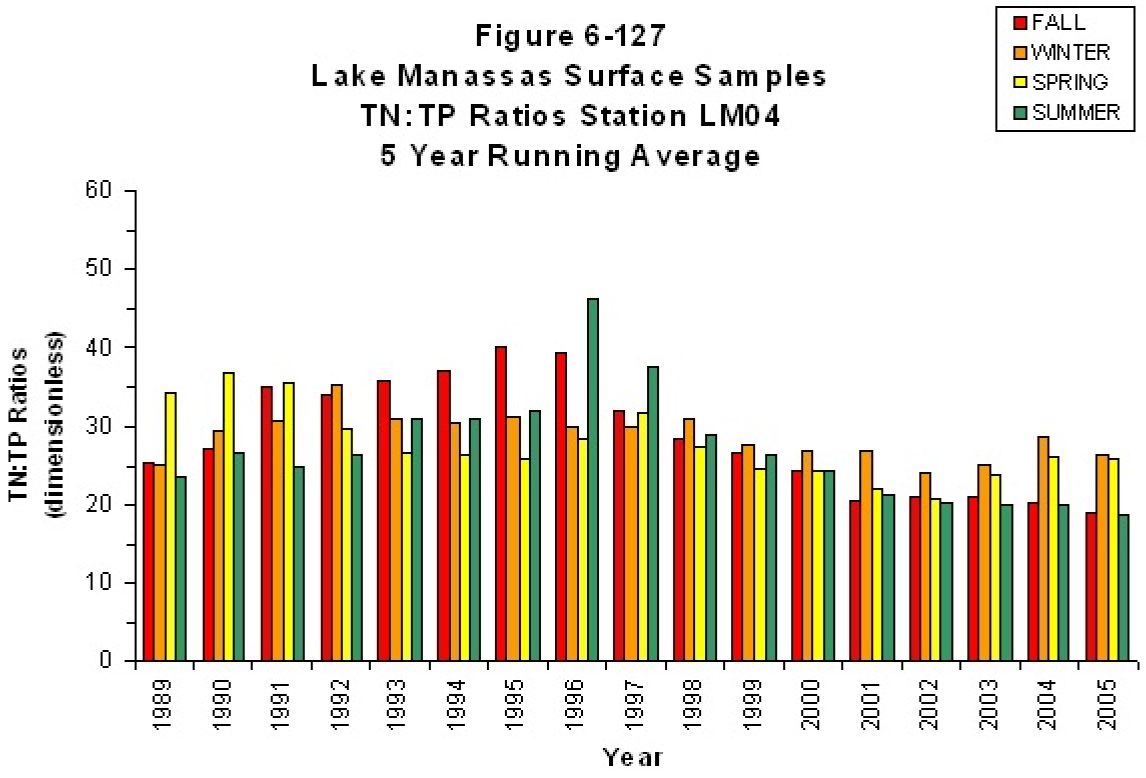


Figure 6-127
Lake Manassas Surface Samples
TN:TP Ratios Station LM04
5 Year Running Average

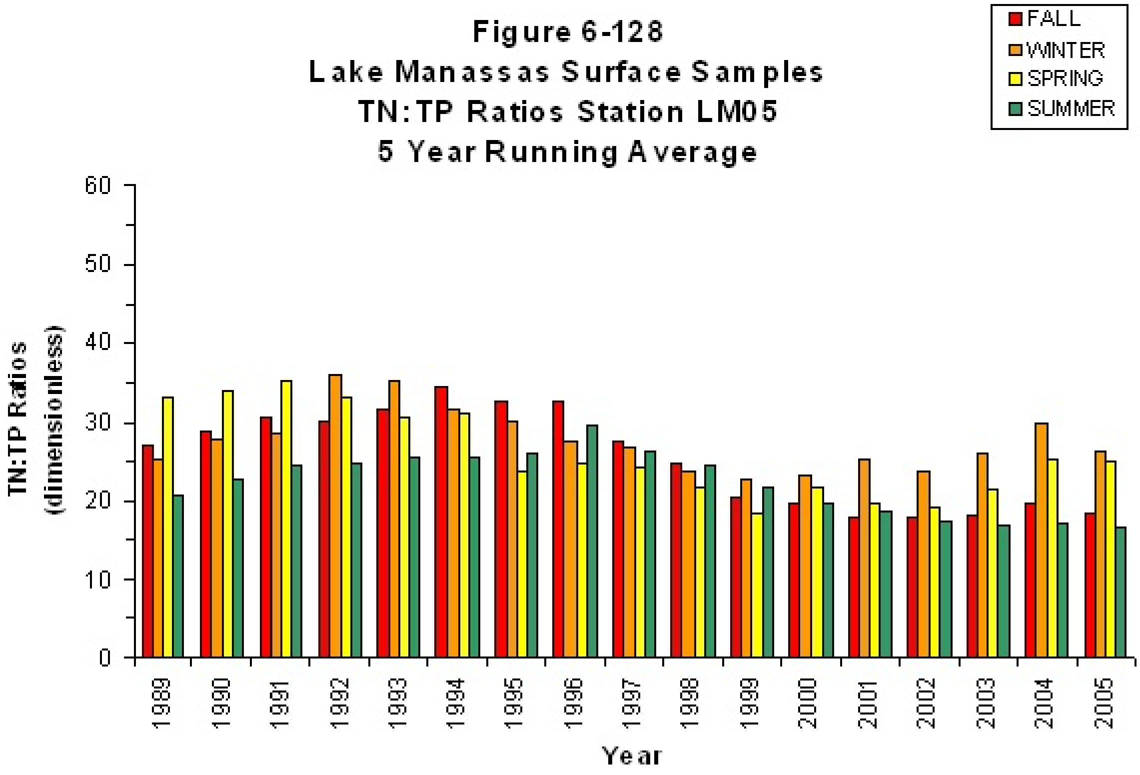


Figure 6-128
Lake Manassas Surface Samples
TN:TP Ratios Station LM05
5 Year Running Average

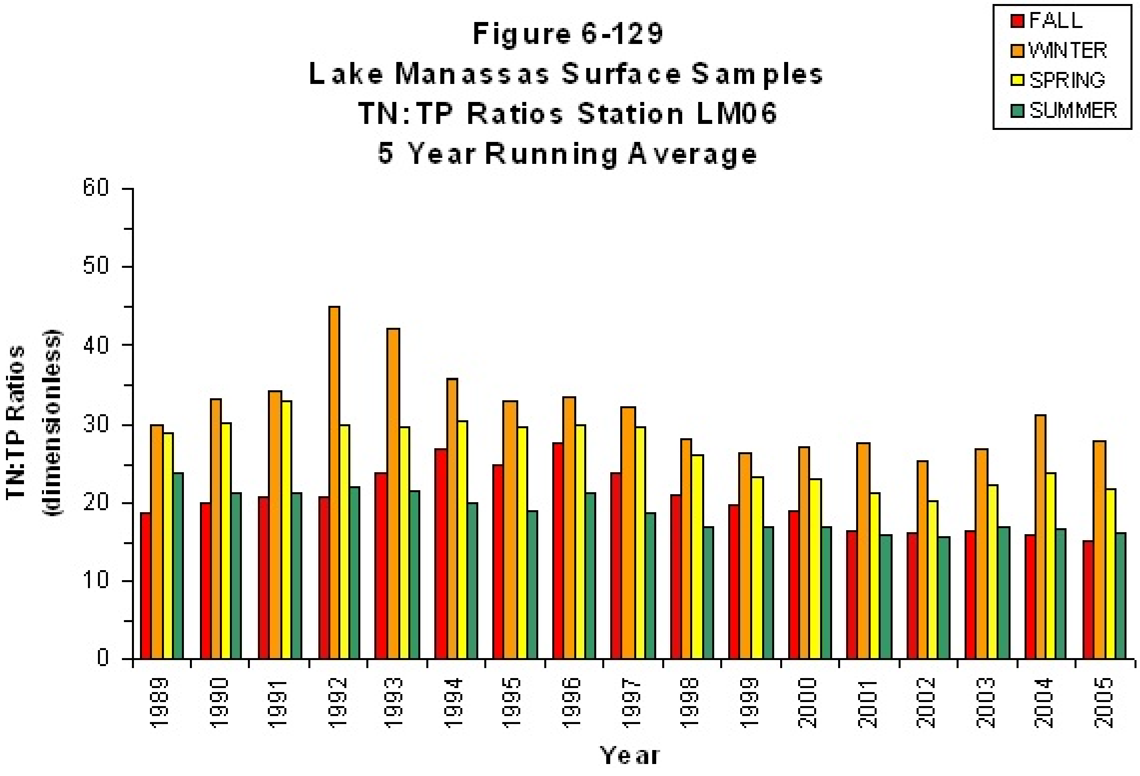


Figure 6-129
Lake Manassas Surface Samples
TN:TP Ratios Station LM06
5 Year Running Average

Figure 6-130
Lake Manassas Surface Samples
TN:TP Ratios Station LM07
5 Year Running Average

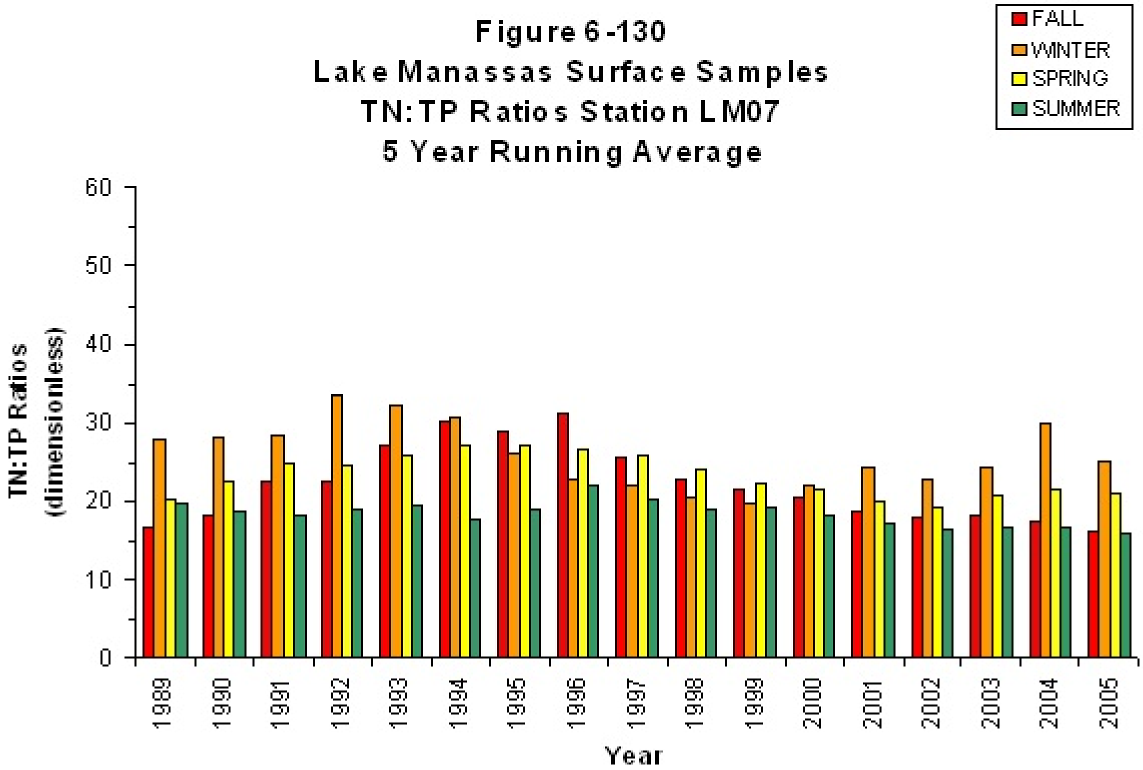
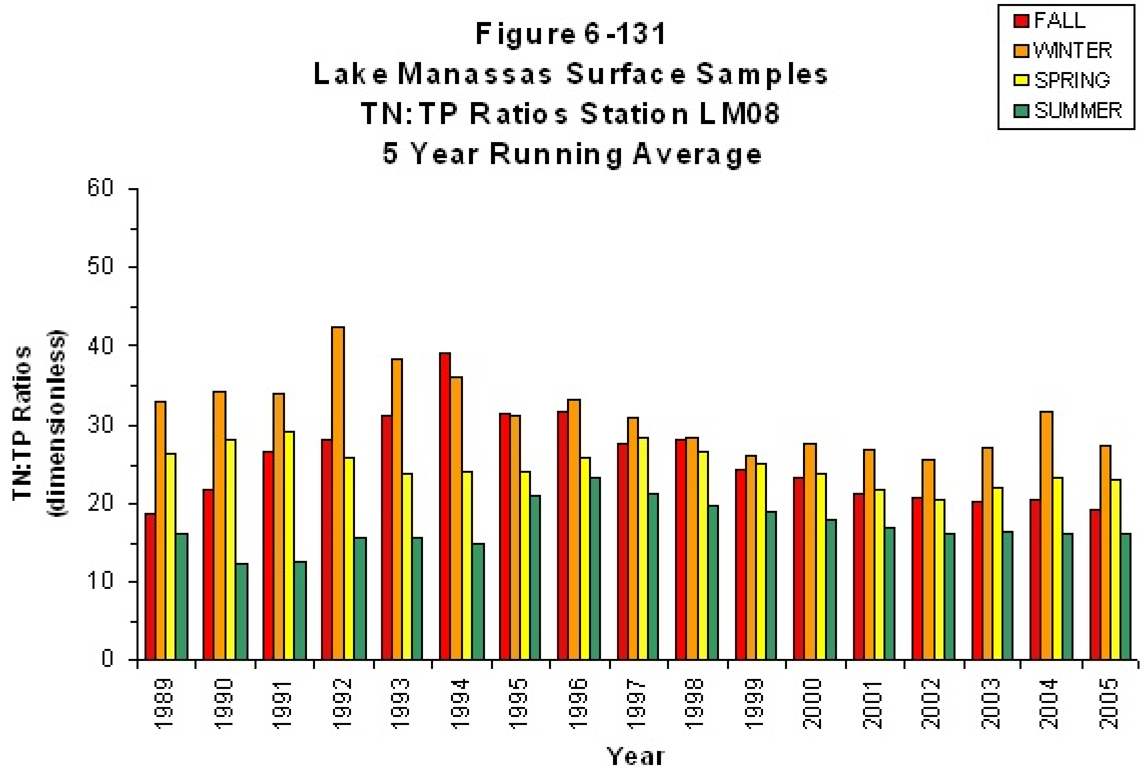


Figure 6-131
Lake Manassas Surface Samples
TN:TP Ratios Station LM08
5 Year Running Average



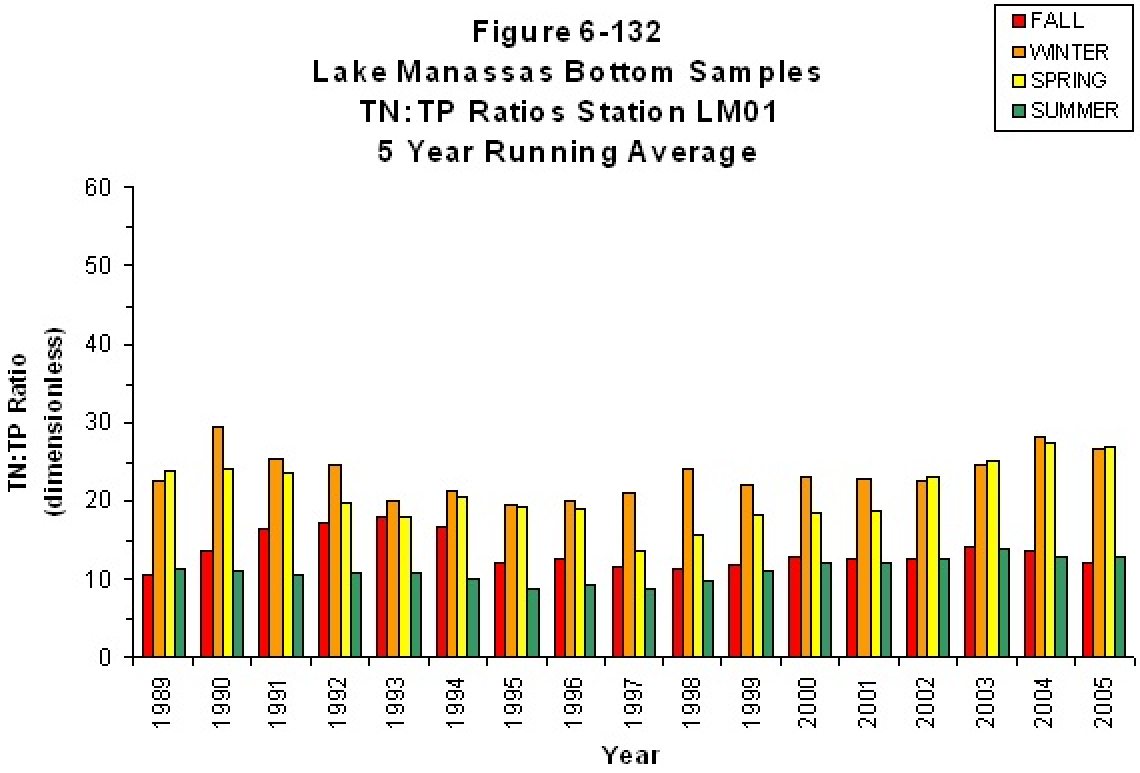


Figure 6-132
Lake Manassas Bottom Samples
TN:TP Ratios Station LM01
5 Year Running Average

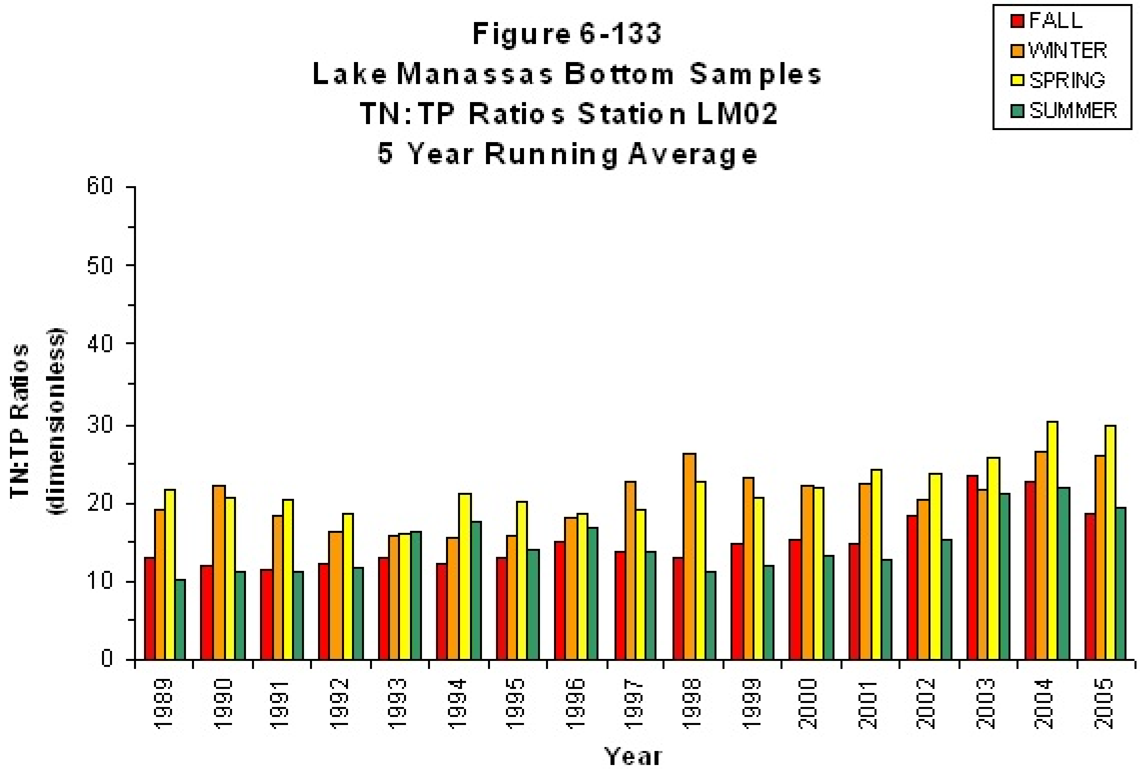


Figure 6-133
Lake Manassas Bottom Samples
TN:TP Ratios Station LM02
5 Year Running Average

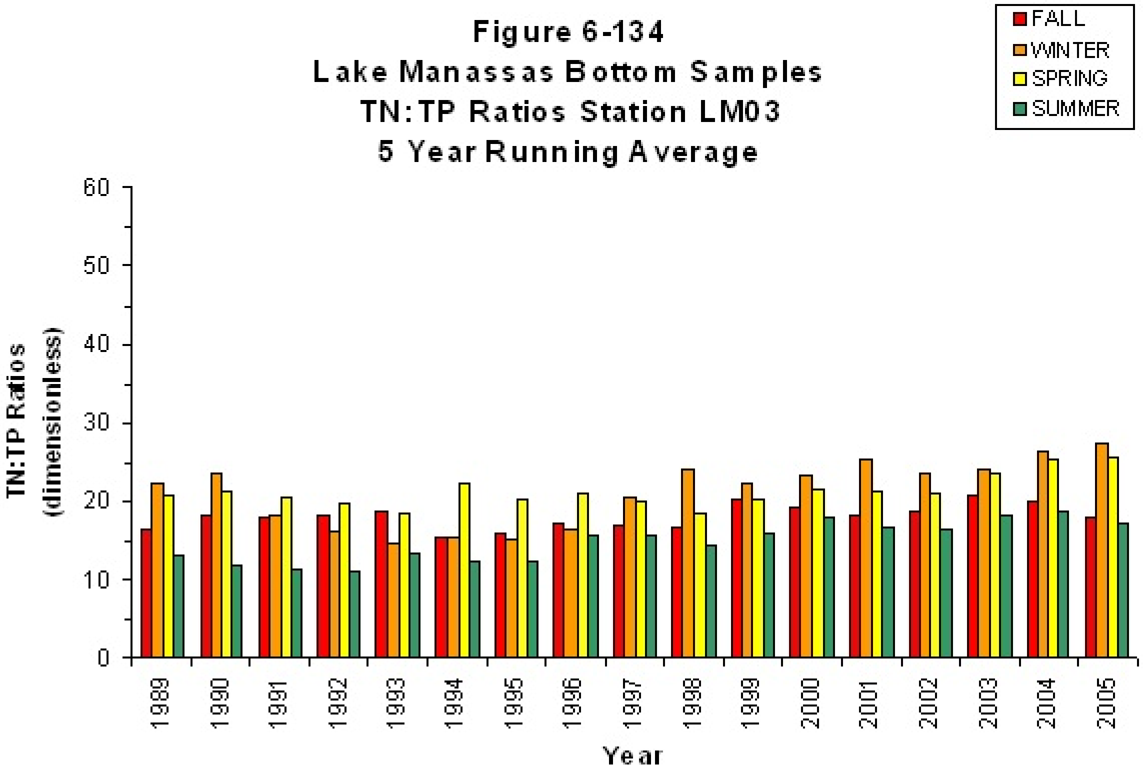


Figure 6-134
Lake Manassas Bottom Samples
TN:TP Ratios Station LM03
5 Year Running Average

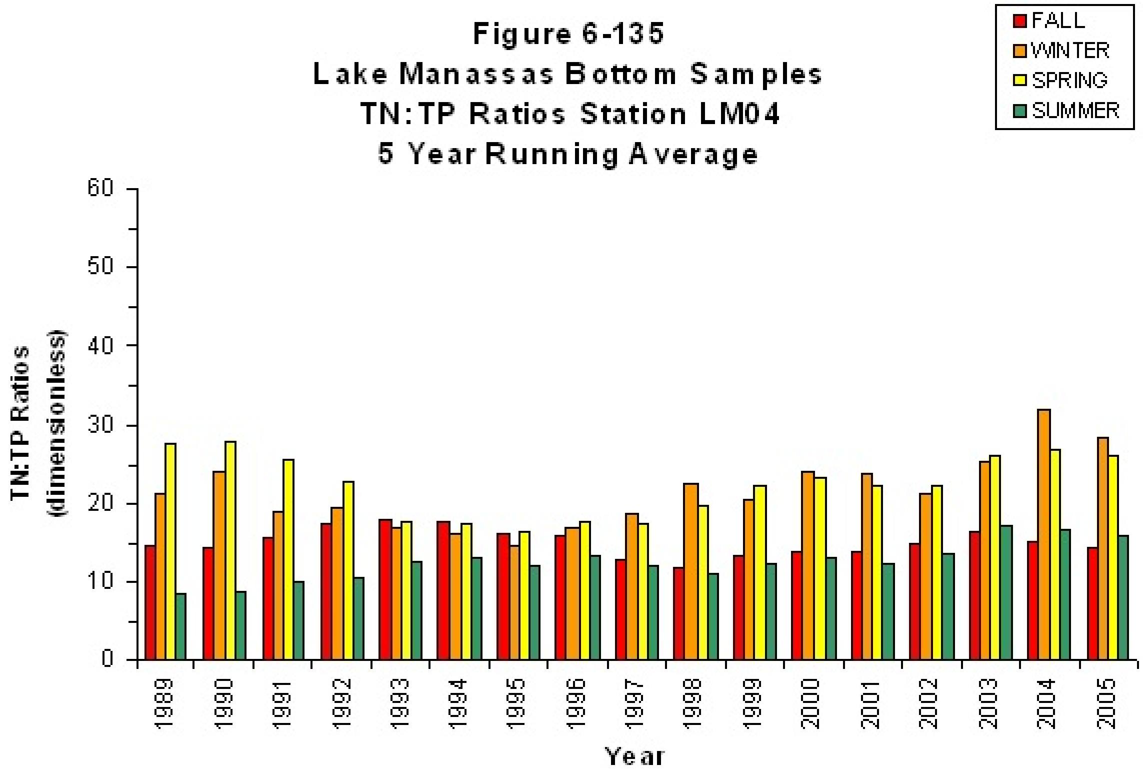


Figure 6-135
Lake Manassas Bottom Samples
TN:TP Ratios Station LM04
5 Year Running Average

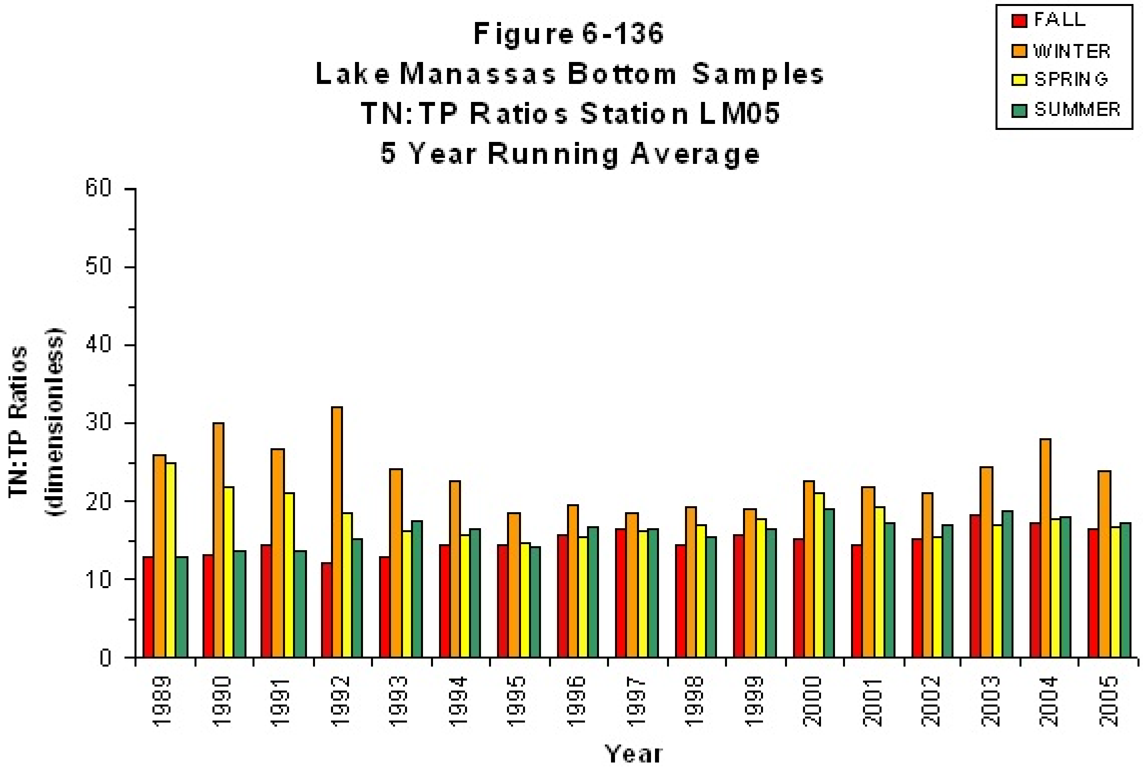


Figure 6-136
Lake Manassas Bottom Samples
TN:TP Ratios Station LM05
5 Year Running Average

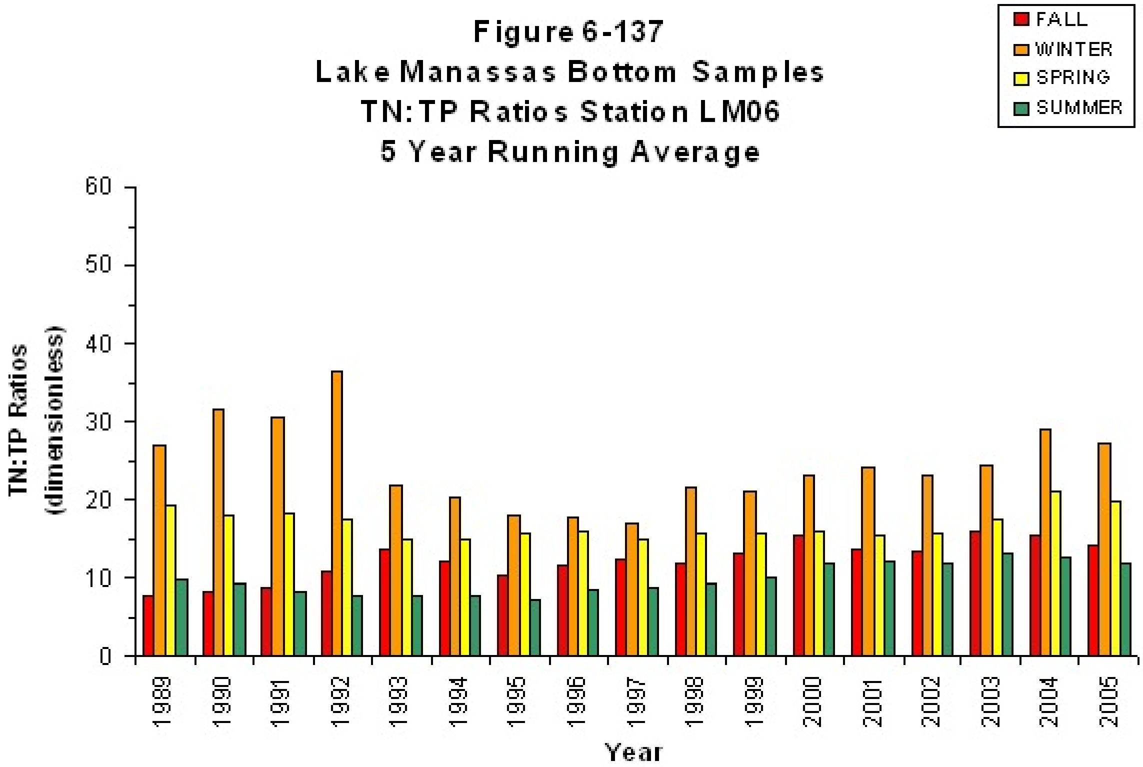


Figure 6-137
Lake Manassas Bottom Samples
TN:TP Ratios Station LM06
5 Year Running Average

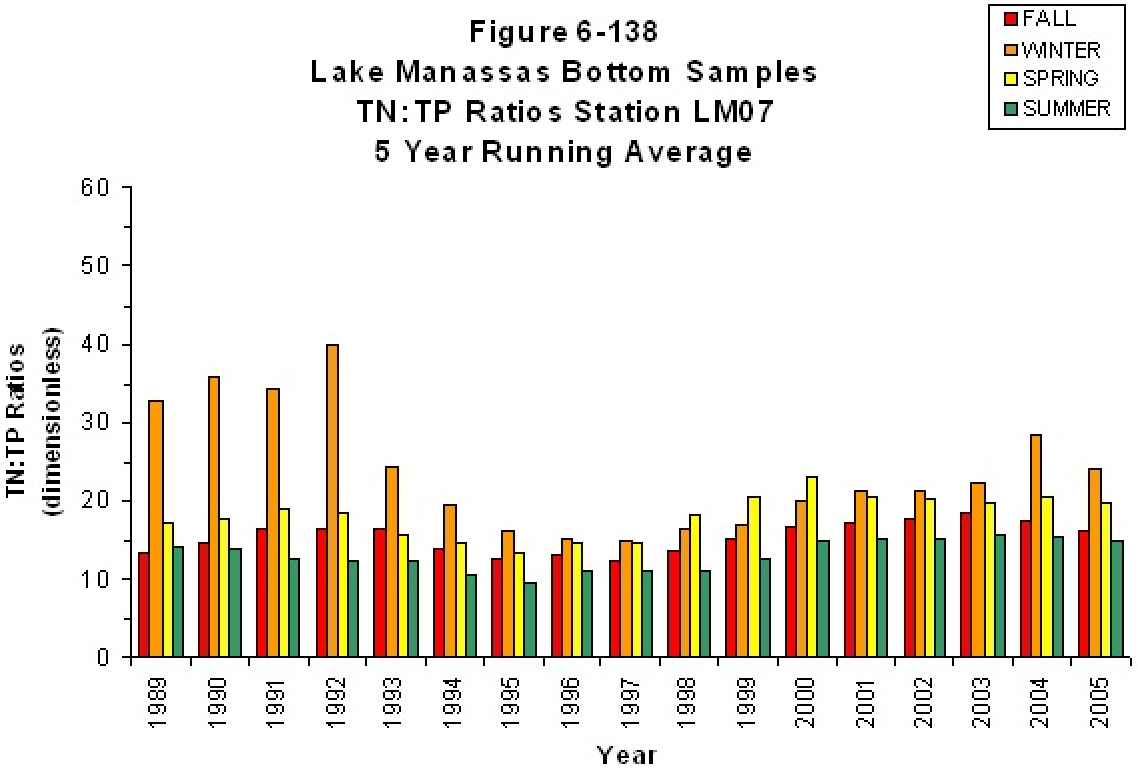


Figure 6-138
Lake Manassas Bottom Samples
TN:TP Ratios Station LM07
5 Year Running Average

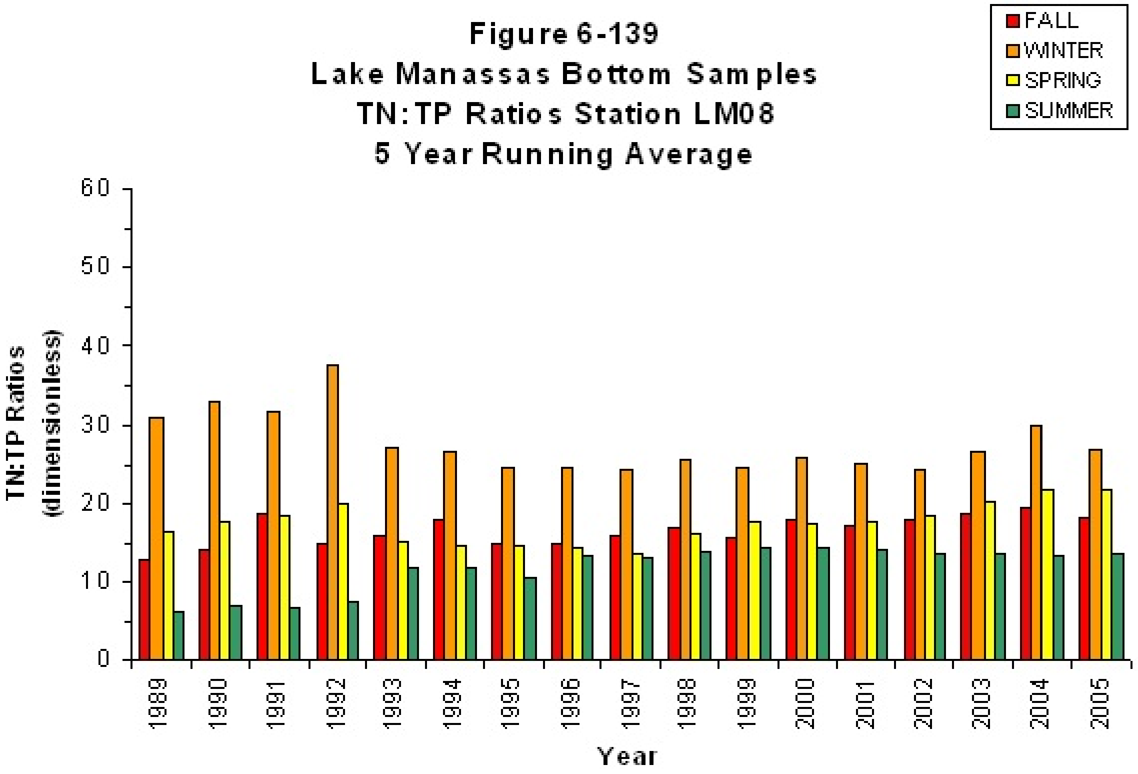


Figure 6-139
Lake Manassas Bottom Samples
TN:TP Ratios Station LM08
5 Year Running Average

Figure 6-140
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM01
5 Year Running Average

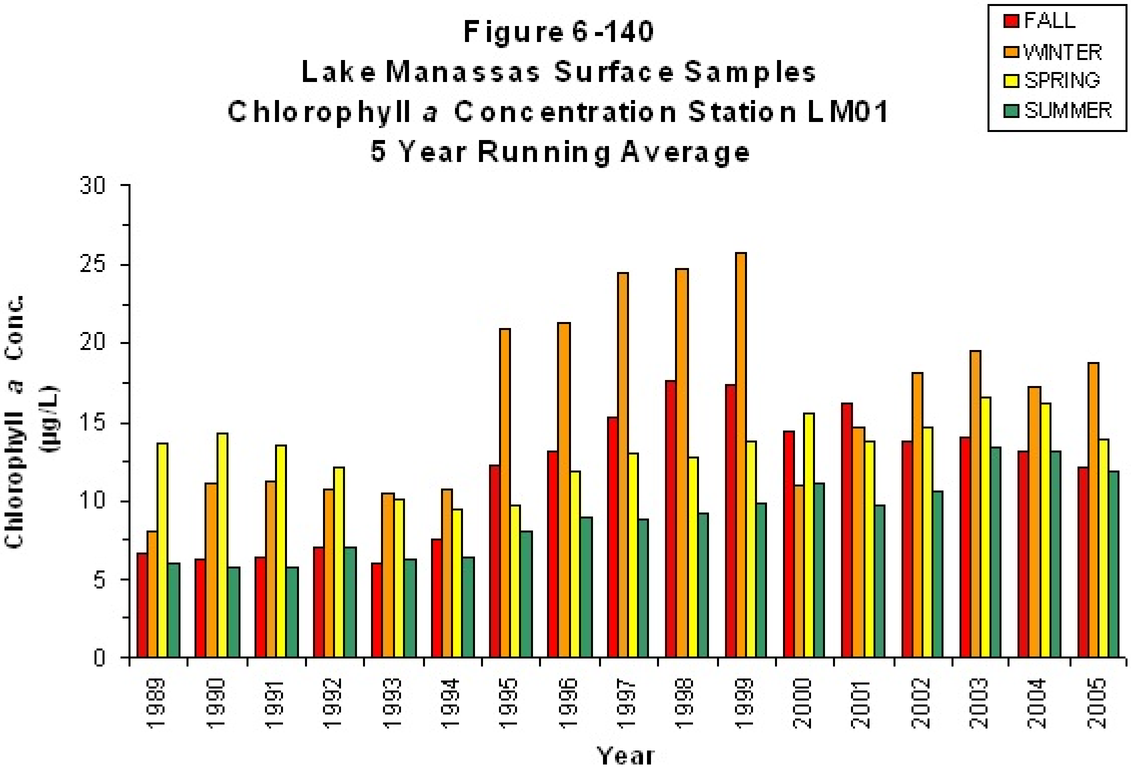
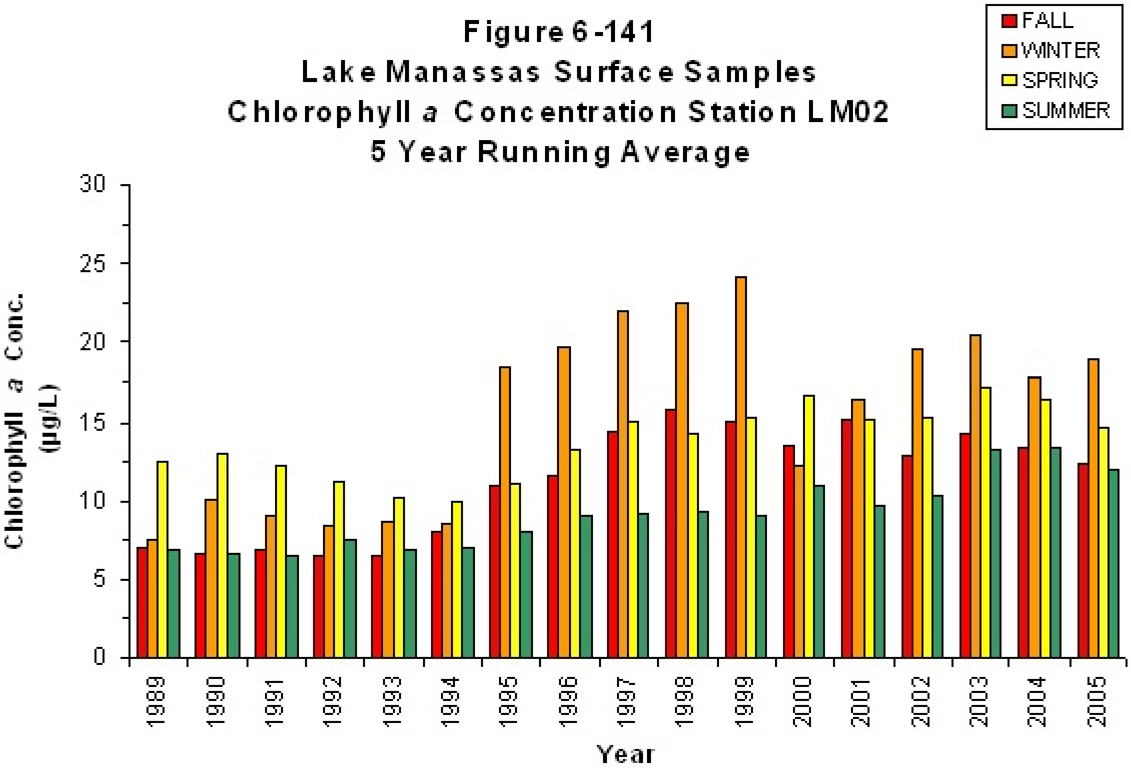


Figure 6-141
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM02
5 Year Running Average



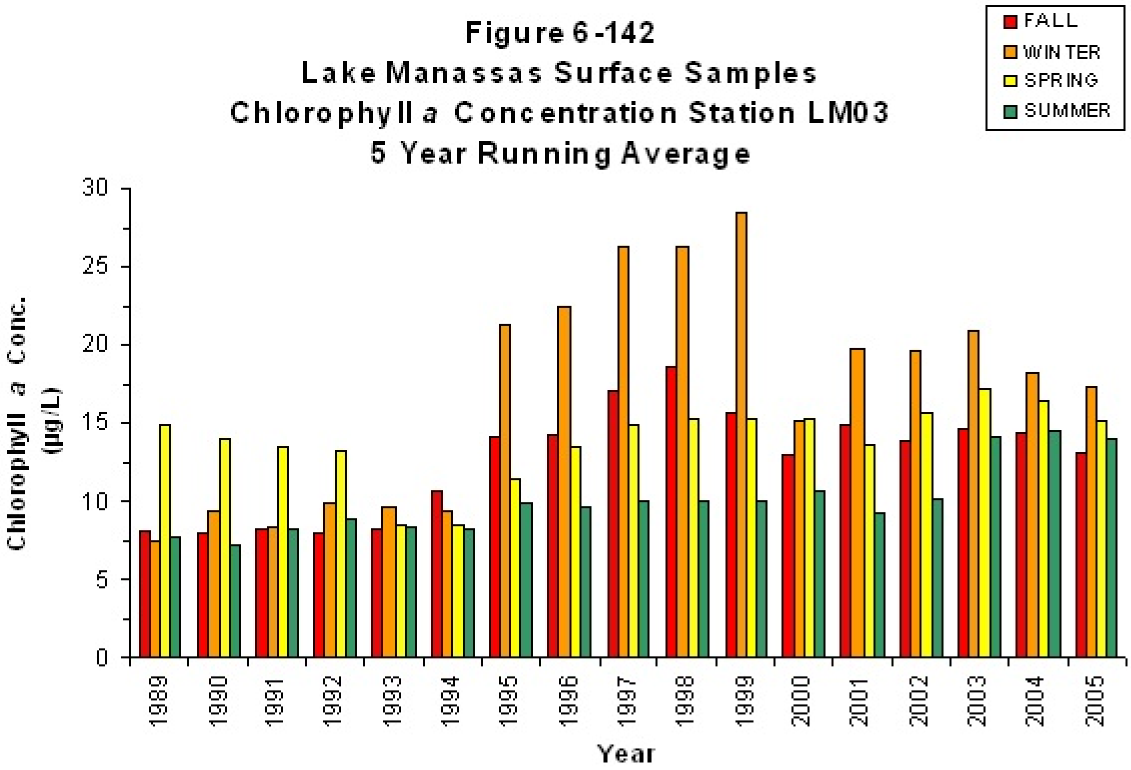


Figure 6-142
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM03
5 Year Running Average

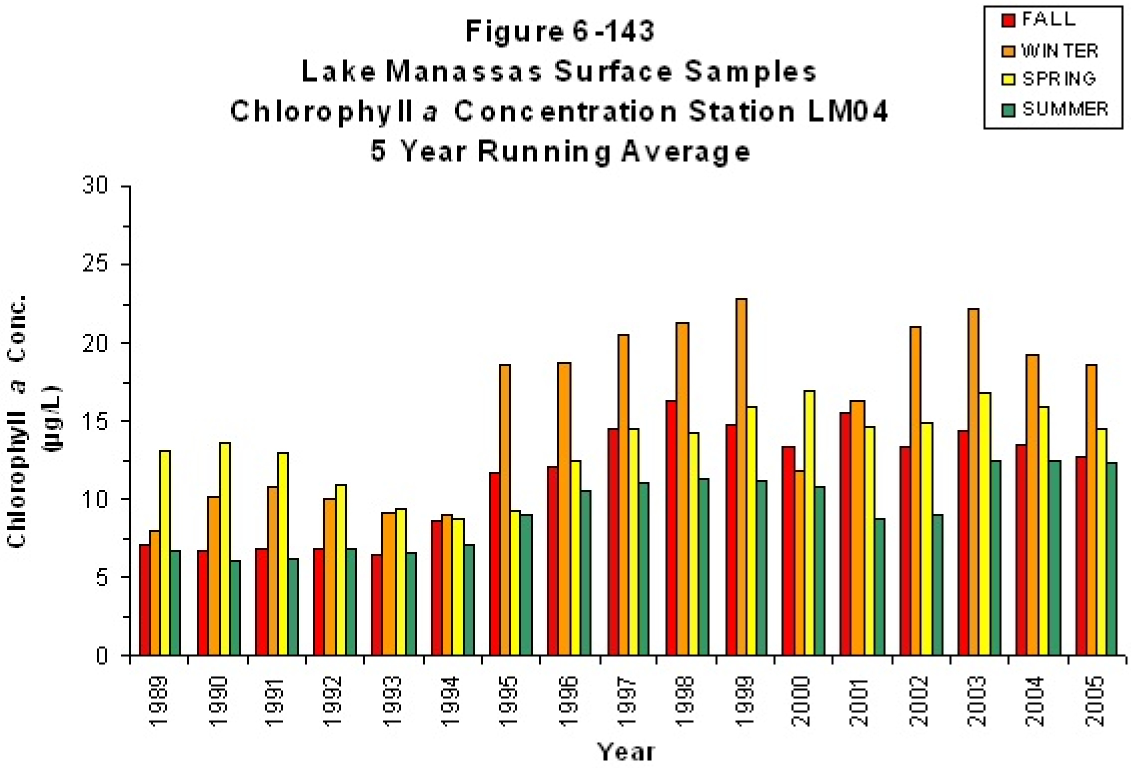


Figure 6-143
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM04
5 Year Running Average

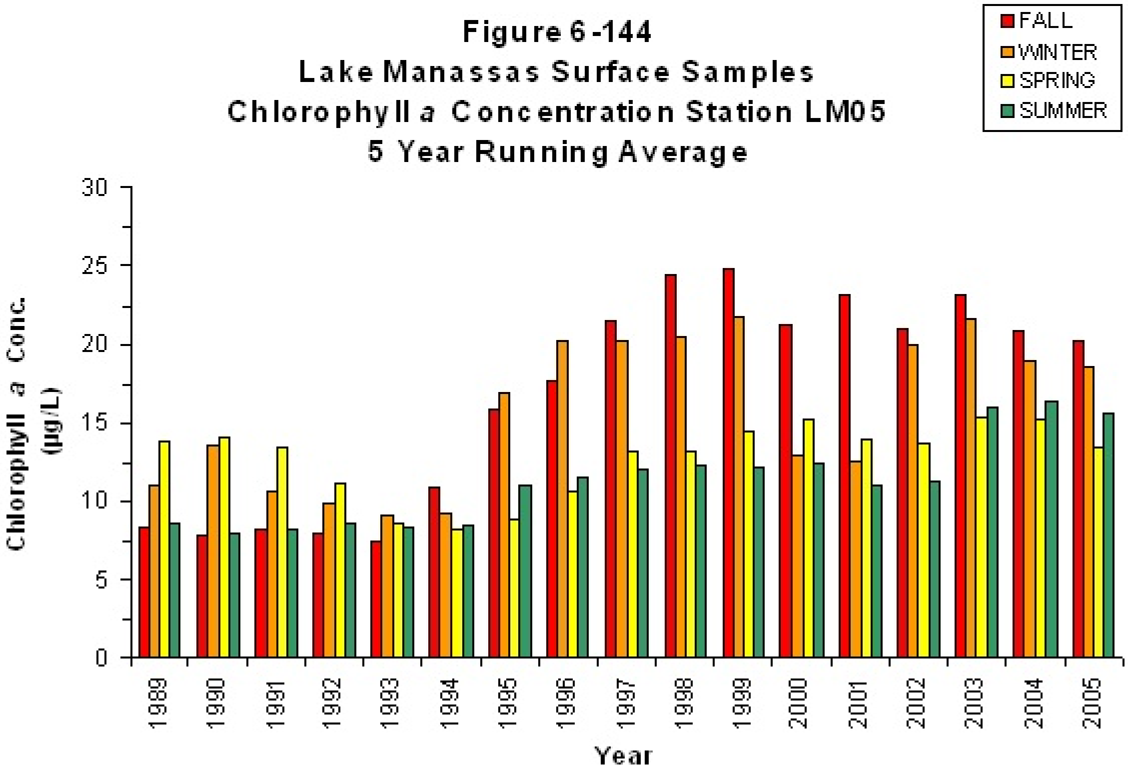


Figure 6-144
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM05
5 Year Running Average

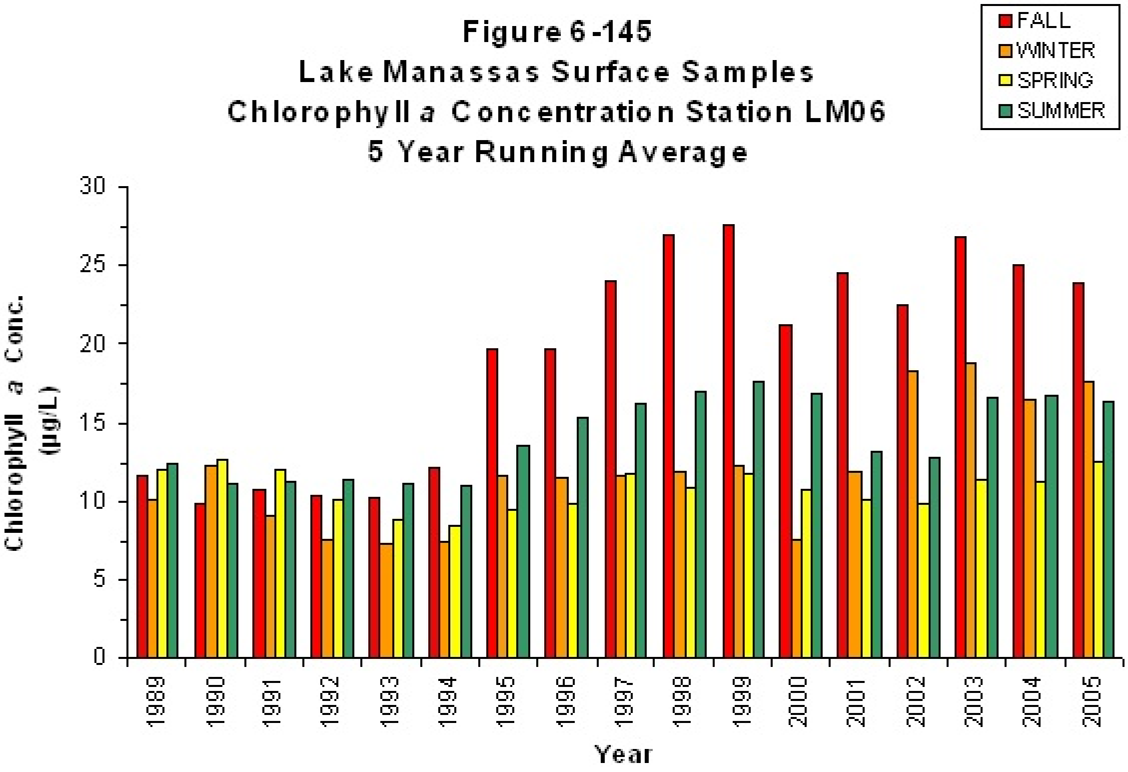


Figure 6-145
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM06
5 Year Running Average

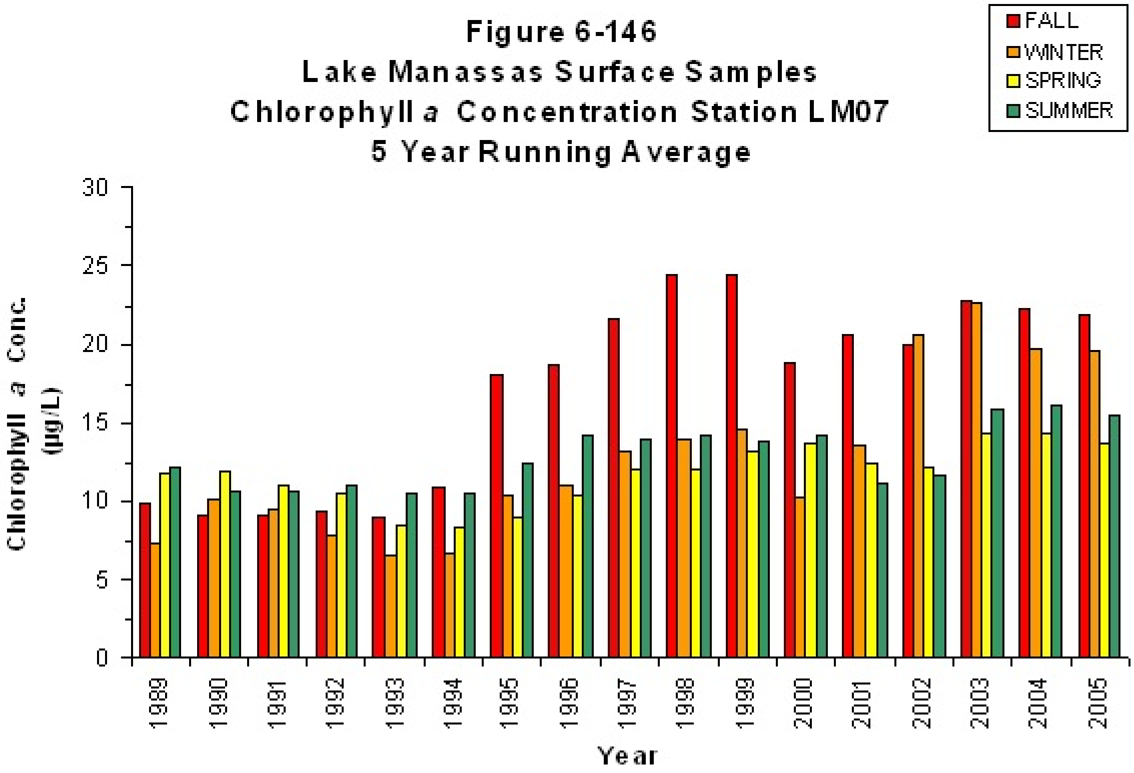


Figure 6-146
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM07
5 Year Running Average

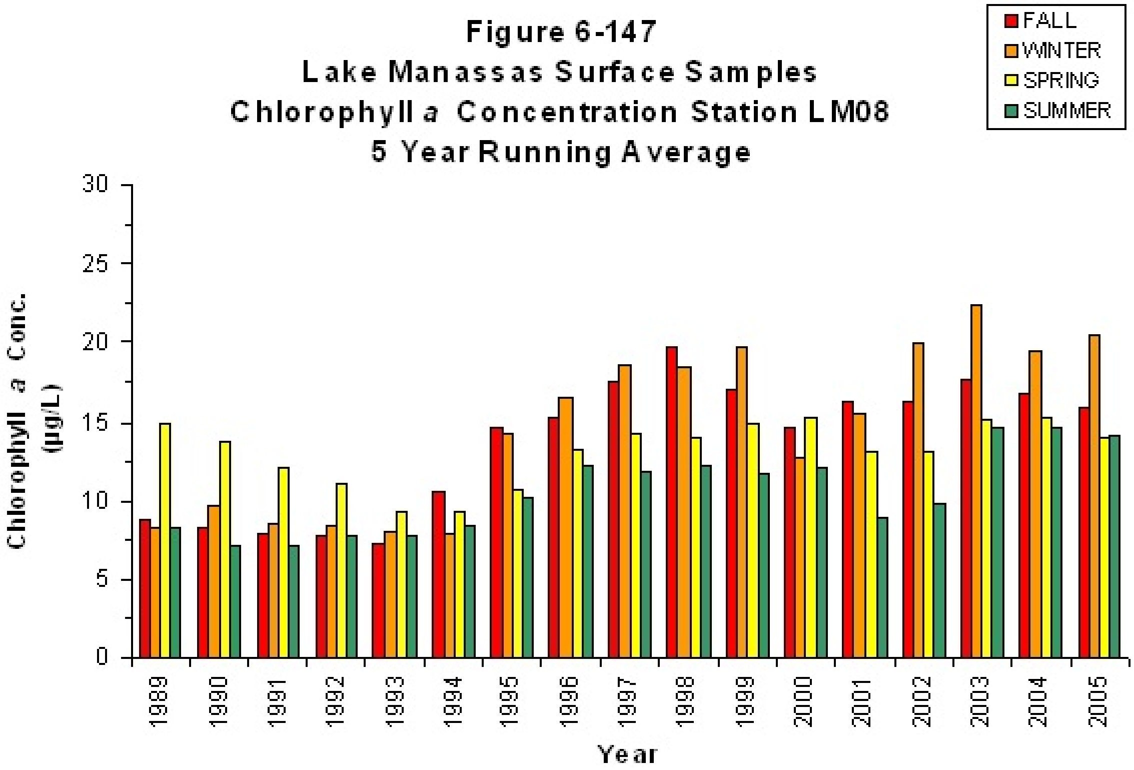


Figure 6-147
Lake Manassas Surface Samples
Chlorophyll *a* Concentration Station LM08
5 Year Running Average

Trophic State

The ability to quantify and predict the trophic status of a lake or reservoir is useful when the productive status has to be monitored, controlled, or corrected (Falkenborg et al. 1974). The term trophic state refers to the measure of a lake's biological productivity. A number of mathematical models have been developed over the years to characterize the trophic state of lakes and reservoirs. These models analyze measured parameters and incorporate them into empirically developed relationships. This section considers two models to characterize the trophic state of lakes: the Vollenweider Model, which emphasizes nutrient inputs as the primary criteria for lake classification and the Carlson Trophic State Index which independently estimates algal biomass through chlorophyll *a* concentrations, transparency, and total phosphorus concentrations (Wetzel, 2001). Because the development of these models is through empirical data, their results must be used with appropriate professional judgement (Wetzel, 2001).

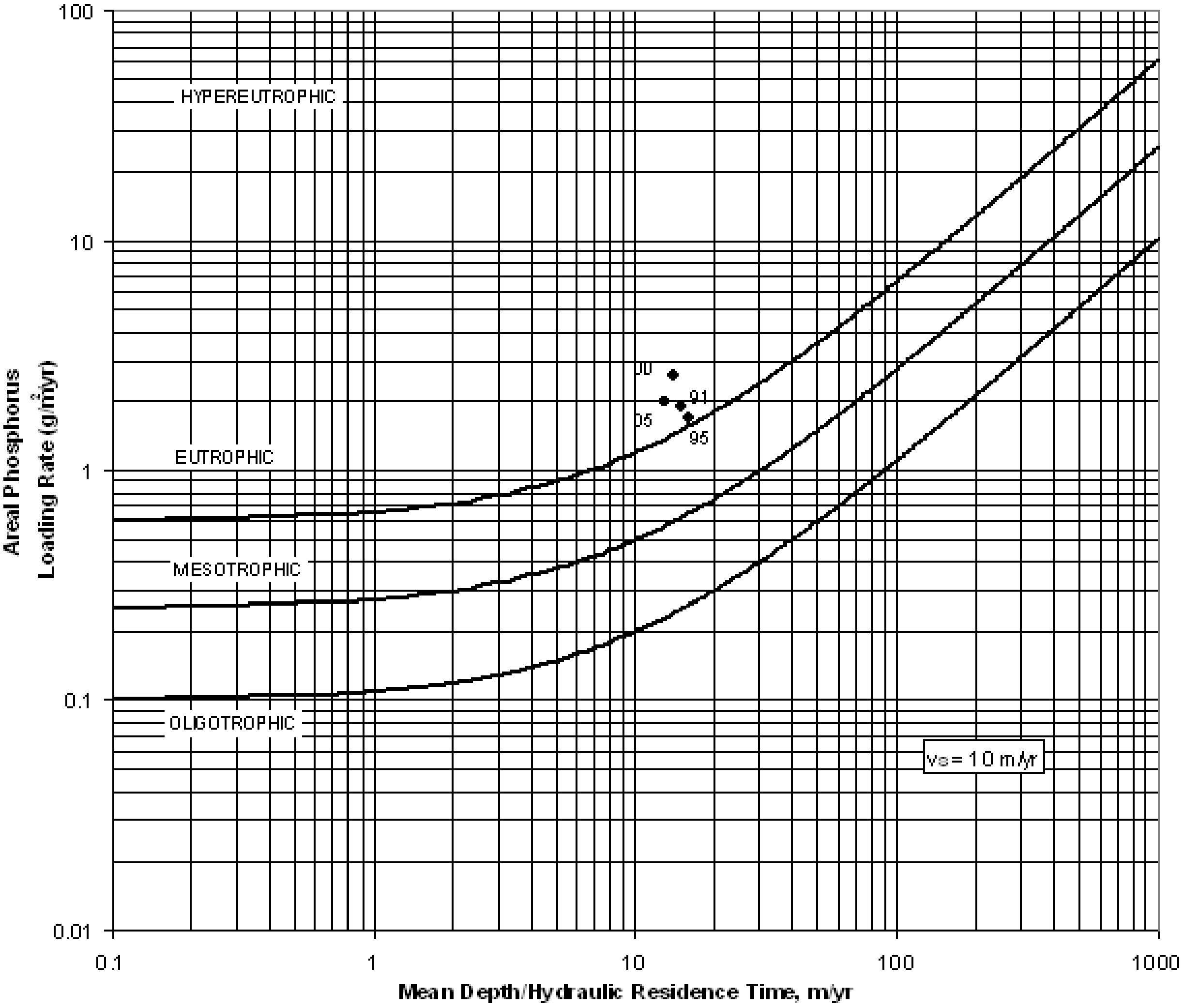
Vollenweider Model

The Vollenweider Model predicts the degree of eutrophication based on the quantity of phosphorus entering the system. A mass balance approach is used to calculate the change in total phosphorus being equal to the influent loading of phosphorus minus the sum of the outflow and sedimentation of phosphorus. The empirical relationship between phosphorus loading, flushing rate, and trophic state is shown in Figure 6-148. The ordinate represents the loading rate per unit area of lake surface and is calculated by dividing the annual phosphorus loading by the surface area of the lake. The abscissa is defined as the mean depth of the lake divided by the mean residence time. This value relates the rate at which the water moves through the system to the amount of algae that can be produced due to light penetration.

There are four assumptions which must be made in order to use the Vollenweider Model:

1. The lake is well mixed, thus ignoring stratification effects,
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.

Figure 6-148
Lake Manassas
Vollenweider Input-Output Phosphorus Loading Model (Wetzel, 2001)



Despite these assumptions, this model proves to be useful when detailed flow rate and phosphorus loading data are available. Station ST70 on Broad Run is the sole stream station associated with Lake Manassas that collects nutrient loading and daily flow data. The annual loading rate is calculated through load spreadsheets developed at the OWML. This rate is provided in pounds per day and must be converted to grams per year and then divided by the surface area of the lake at full pool conditions in order to obtain the y-coordinate for the Vollenweider Loading Model. The mean residence time is calculated by dividing the lake volume at full pool conditions by the mean daily flow calculated at station ST70. The abscissa value is finally calculated when the mean depth is divided by the mean residence time.

A summary of the data used in the Vollenweider graph calculations are shown in Table 6-3. The table additionally shows data from the previous three reports (Eggink, 2001). The calculated points are plotted on the Vollenweider graph for comparison (Fig. 6-148). The equation used to find the phosphorus loading rate is found in equation 6-2 (Wetzel, 2001). With the addition of the inflatable bladder over the dam spillway the lake volume has increased causing the detention time to increase and the flushing rate to decrease. However, the increased volume did not have a big enough impact to change the trophic state.

Equation 6-2: Vollenweider Equation, Phosphorus Loading Rate (Wetzel, 2001)

$$\text{Phosphorus Loading} = \frac{P}{\left(\frac{\bar{z}}{T_w}\right)\left(1 + T_w\right)}$$

P = Phosphorus conc. $\left(\frac{mg}{L}\right)$
$\bar{z}$ = mean depth (ft)
T_w = hydraulic detention time (yr)

Table 6-3: Vollenweider Model Parameters

Parameter	1991 Baseline	1995 Baseline	2000 Baseline	2005 Baseline
TP (lbs/day)	32.4	28.8	44.1	55
Flow Rate (cfs)	47.5	51.3	44.3	65.52
Lake Volume (gal)	4.20×10^9	4.20×10^9	4.08×10^9	8.34×10^9
Mean Depth (m)	5.6	5.6	7.01	6.97
Lake Surface (ac)	694	694	697	1119
Phosphorus Loading ($g/m^2/yr$)	1.9	1.7	2.6	2.01
Mean Depth/Mean Residence Time (z/t), (m/yr)	15	16.1	14.03	12.96

Carlson Trophic State Indices

Trophic state is defined as the total weight of living biological material (biomass) at a specific location and time. The trophic state index developed by Carlson in 1977 independently estimates algal biomass through Secchi depth, total phosphorus and chlorophyll *a* concentrations. The equations used to develop these relationships are shown in Table 6-4 (Carlson, 1977). A TSI is a useful tool for comparing lakes in similar regions, and for predicting algal productivity. The scale used in Carlson's index is similar to the Vollenweider model in that they both assume a phosphorus-limited system. Carlson discovered that man-made impoundments exhibit different relationships than did natural waters. One difference that Carlson noted was that reservoirs, typically have a shorter residence time than lakes. This characteristic can increase the turbidity in a reservoir, thereby affecting the Secchi disk results. As with any analytical model, the results produced by Carlson's TSI should be used with caution. Certain factors, such as changing seasons and highly turbid waters, have the ability to disrupt the accuracy of Carlson’s model.

Table 6-4: Carlson’s Trophic State Index (Carlson, 1977)

TSI*	**Secchi Disk Depth (m)**	**Surface Total Phosphorus (µg/L)**	**Surface Chlorophyll *a* (µg/L)**
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	56
70	0.5	96	154
90	0.12	384	427
100	0.062	768	1183

*Note: $\text{TSI Secchi (SD)} = 10 \times \left(6 - \left(\ln\left(\frac{SD}{2}\right)\right)\right)$

$$\text{TSI Total Phosphorus (TP)} = 10 \times \left(6 - \left(\frac{\ln\left(\frac{48}{TP}\right)}{2}\right)\right)$$

$$\text{TSI Chlorophyll}\,a\,\text{(CHLa)} = 10 \times \left(6 - \left(\frac{2.04 - (0.68 * \ln(\text{CHLa}))}{\ln(2)}\right)\right)$$

Table 6-5 provides water quality definitions associated with TSI value means. The range of Carlson's index ranges from approximately 0 to 100, although the index theoretically has no lower or upper bounds. The three index variables are interrelated by linear regression models and should produce a similar index value. Theoretically, any of the three TSI variables could be used to classify an impoundment. For the purpose of classification, priority is given to chlorophyll *a* concentrations because that variable is the most accurate in predicting algal biomass. Lower TSI values typically indicate better water quality from a nutrient enrichment standpoint.

Table 6-5: Water Quality as Reflected by the Carlson Trophic State Index in Lakes (Carlson, 1977).

TSI Value	Interpretation
< 30	Classic Oligotrophy. Clear water, oxygen throughout the year in the hypolimnion, salmonis fisheries in deep lakes.
30 - 40	Deeper lakes still exhibit classical Oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.
40 - 50	Water moderately clear, but increasing probability of anoxia in hypolimnion during the summer. Iron and Manganese problems begin to develop during the summer. Raw water begins to have noticeable odor. THM precursors in raw water will begin to exceed 0.1 mg/L.
50 - 60	Lower boundary of classic eutrophy: decreased transparency, anoxic hypolimnia during the summer, macrophyte problems may be evident, warm-water fisheries only. Iron and Manganese and taste and odor problems continue to worsen.
60 - 70	Blue-green algae dominant during the summer, algal scums probable, extensive macrophyte problems possible.
70 - 80	Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Reservoir becomes hypertrophic (light limited).
> 80	Algal scums, summer fish kills, few macrophytes, dominance of rough fish

The Mann-Kendall Analysis (Table 6-6) shows that there is an increasing trend for the TSI value of chlorophyll *a* and TP at all stations while there is a decreasing trend for the TSI value of Secchi disk transparency at all stations except LM04. This analysis further confirms that increased phosphorus concentrations are entering the lake and contributing to algal growth which in turn decreases transparency in the lake.

Table 6-6: Mann-Kendall Analysis for Carlson's TSI values

	LM01	**LM02**	**LM03**	**LM04**	**LM05**	**LM06**	**LM07**	**LM08**
TSI - CHLa	**U**	**U**	**U**	**U**	**U**	**U**	**U**	**U**
TSI - TP	**U**	**U**	**U**	**U**	**U**	**U**	**U**	**U**
TSI - SD	**L**	**L**	**L**	**-**	**L**	**L**	**L**	**L**

U = Increasing Trend Present
L = Decreasing Tend Present
) = No Trend Present
Blank = No data in at least the last 5 years

Figures 6-149 through 6-172 show the five-year running seasonal averages for the TSI values of chlorophyll *a*, total phosphorus, and Secchi depth at all Lake stations. In order to provide a generalized trophic state of Lake Manassas, averages for each TSI variable were computed for all eight monitoring stations between 2000 and 2005. Figure 6-173 shows the results of the TSI averages for the lake including the standard deviation for each TSI variable. All three TSI parameters indicate that the lake is at the lower boundary of eutrophic conditions.

Figure 6-149
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM01
5 Year Running Average

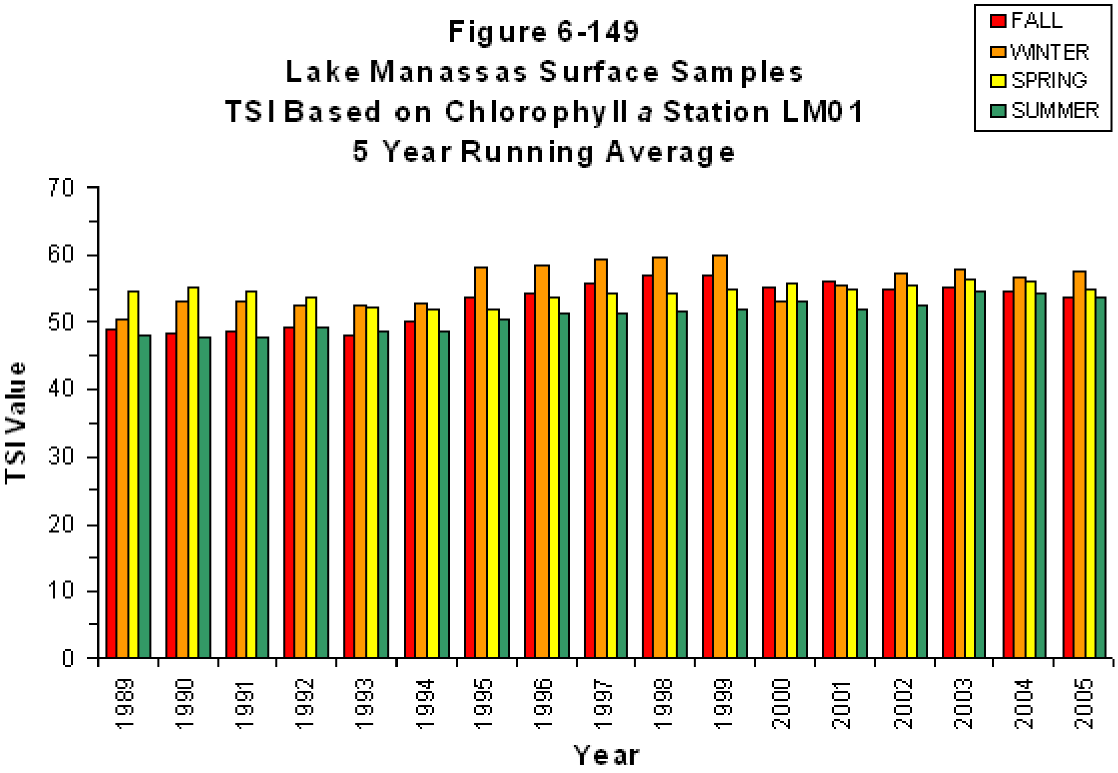


Figure 6-150
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM02
5 Year Running Average

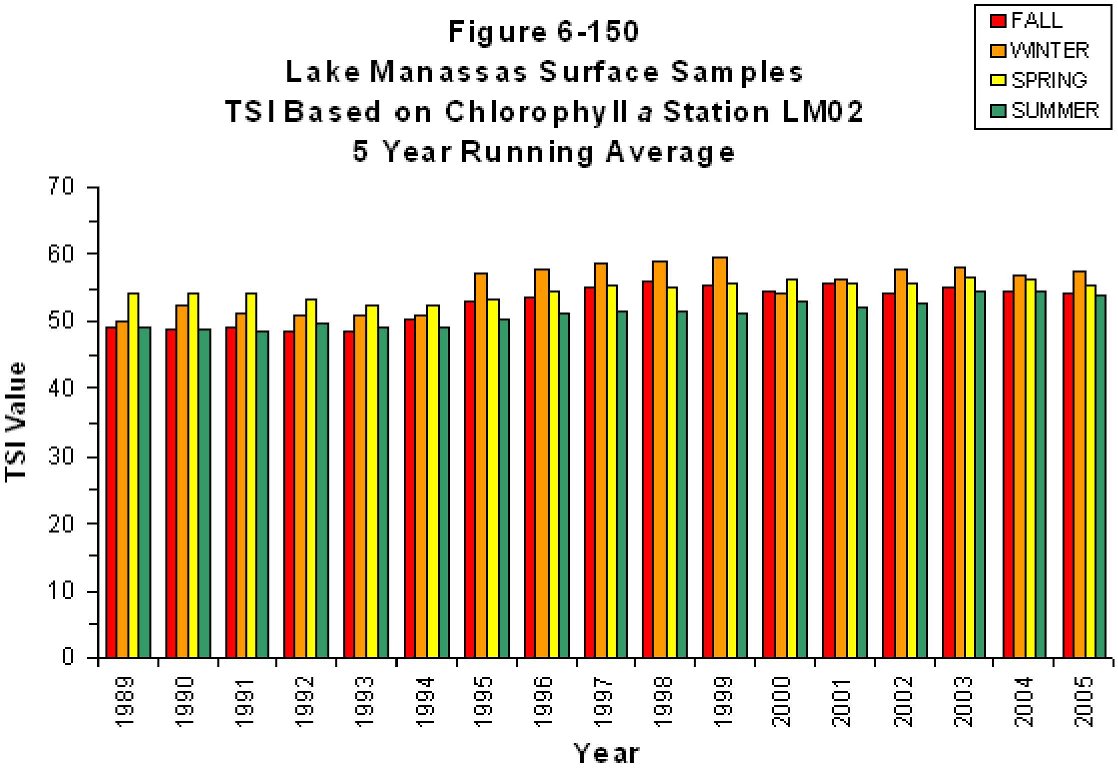


Figure 6-151
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM03
5 Year Running Average

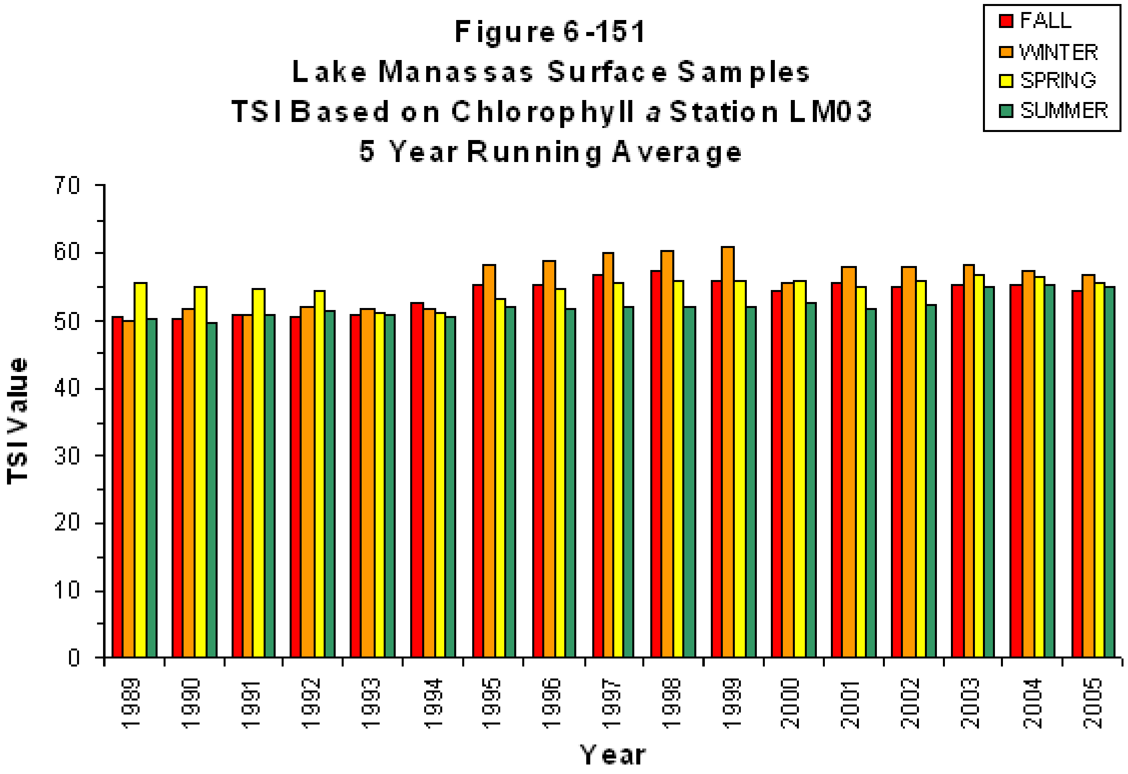


Figure 6-152
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM04
5 Year Running Average

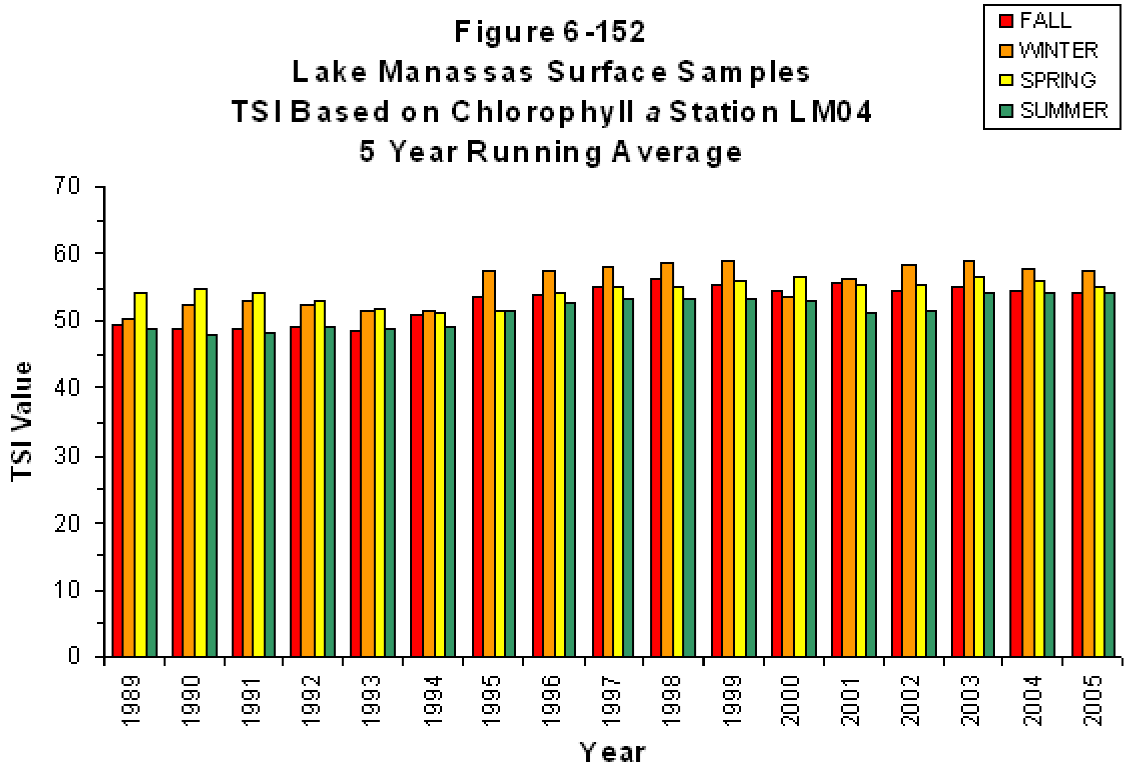


Figure 6-153
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM05
5 Year Running Average

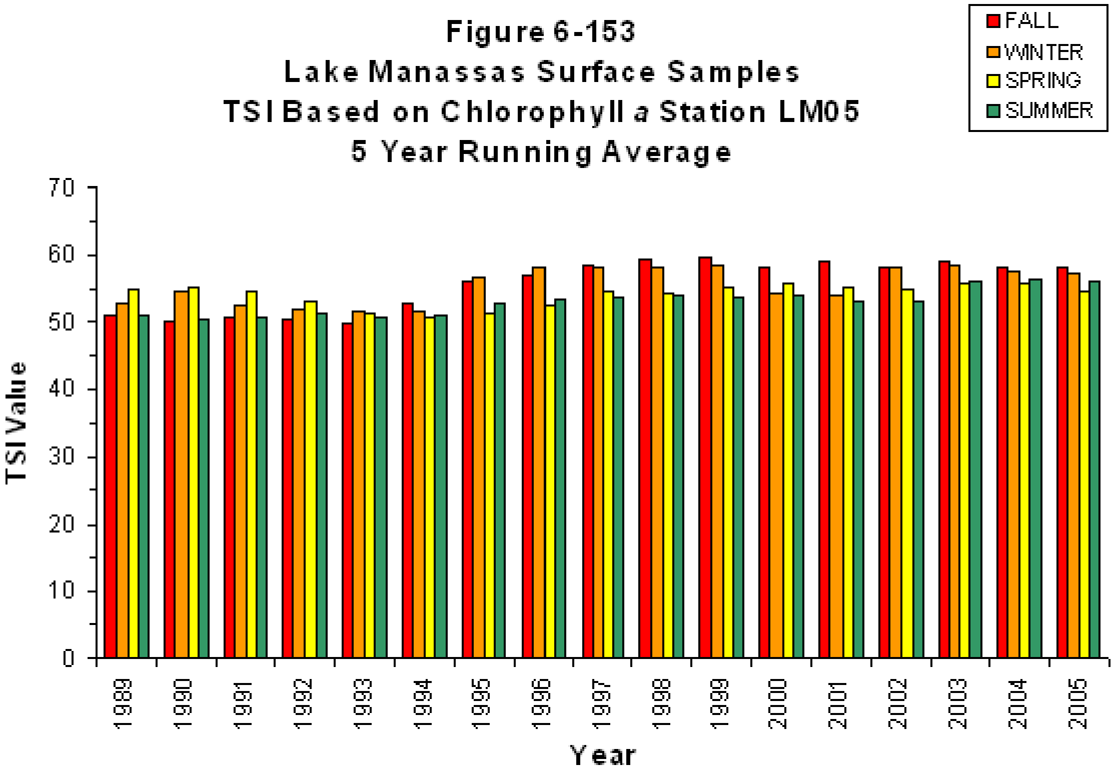


Figure 6-154
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM06
5 Year Running Average

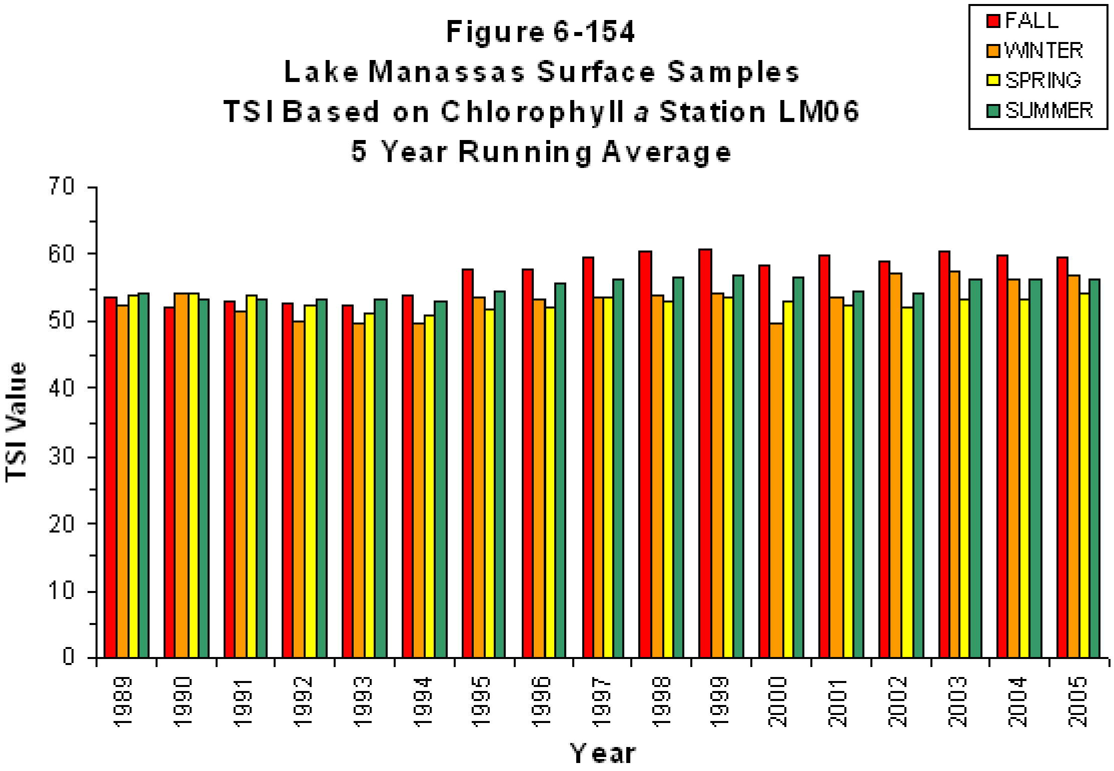


Figure 6-155
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM07
5 Year Running Average

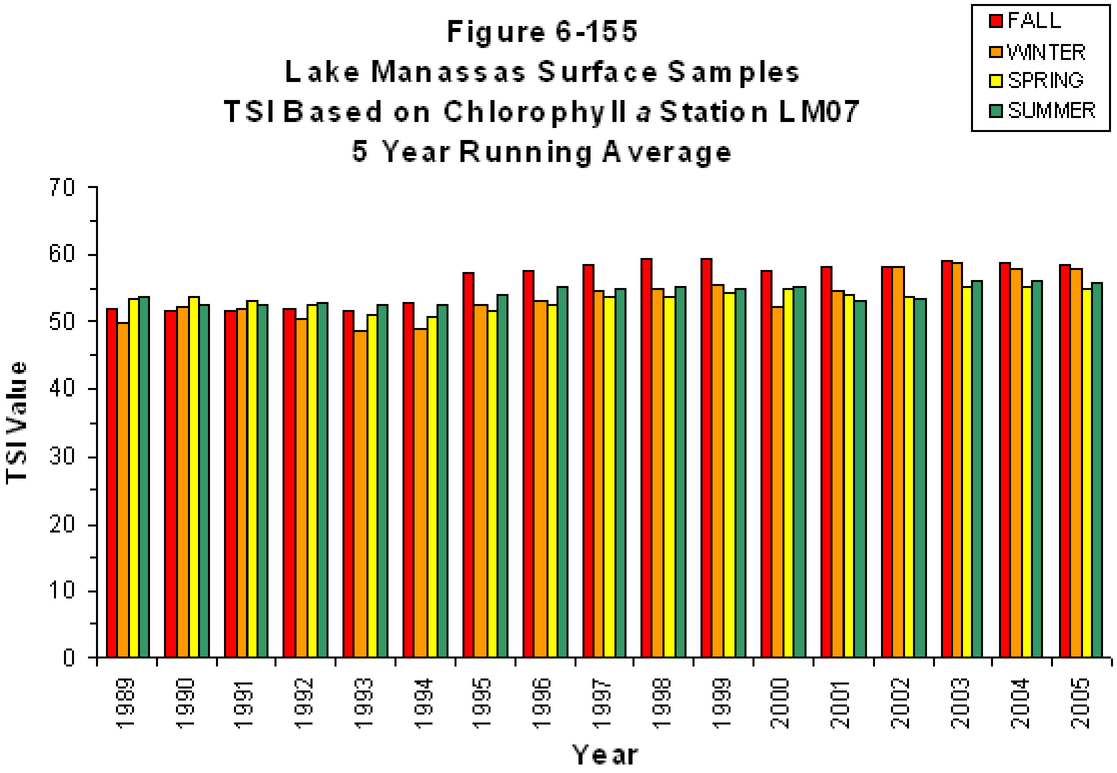
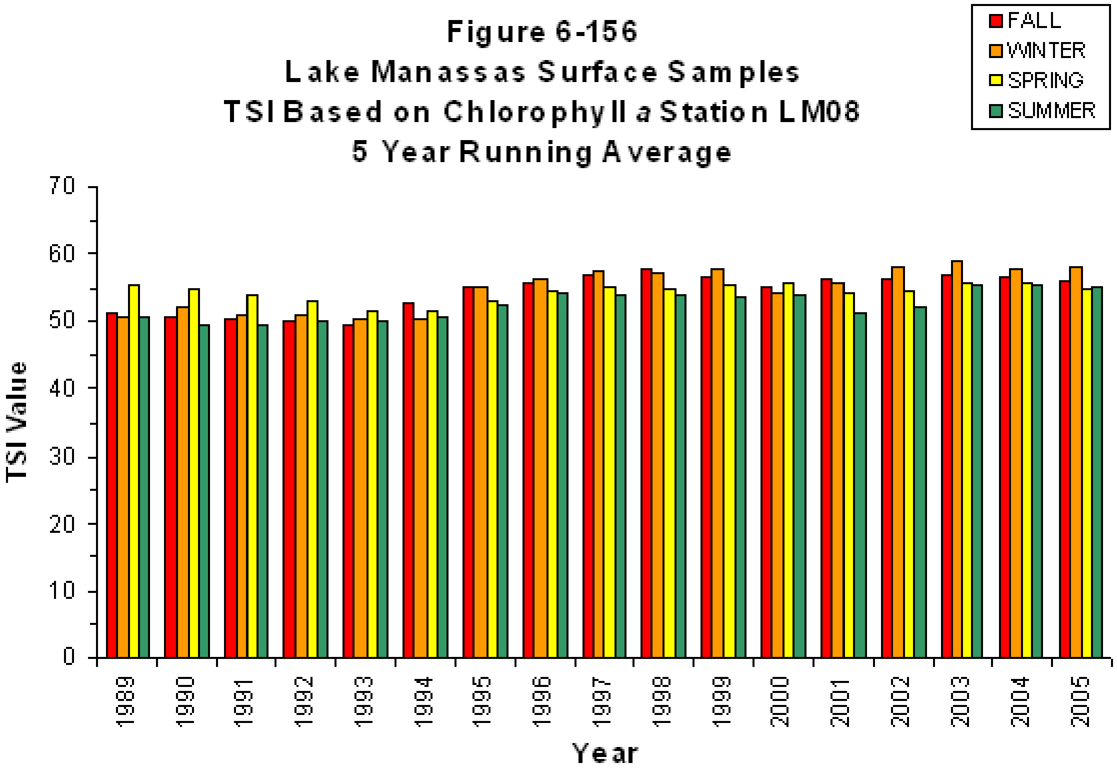


Figure 6-156
Lake Manassas Surface Samples
TSI Based on Chlorophyll *a* Station LM08
5 Year Running Average



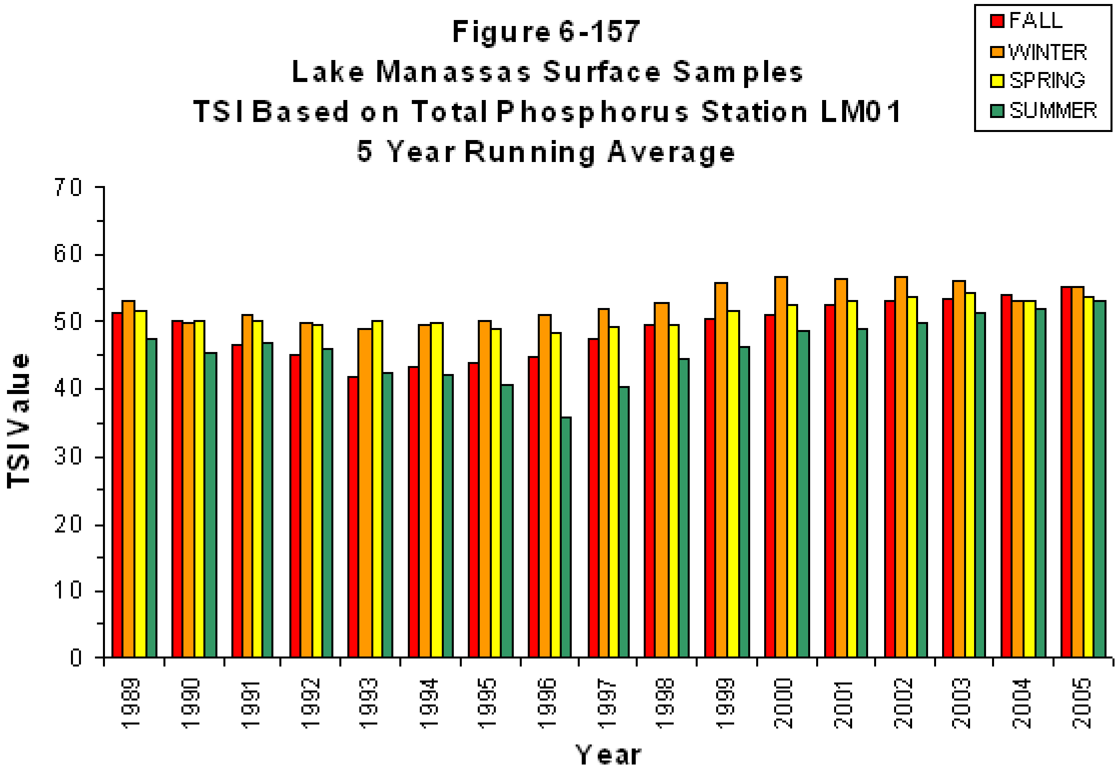


Figure 6-157
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM01
5 Year Running Average

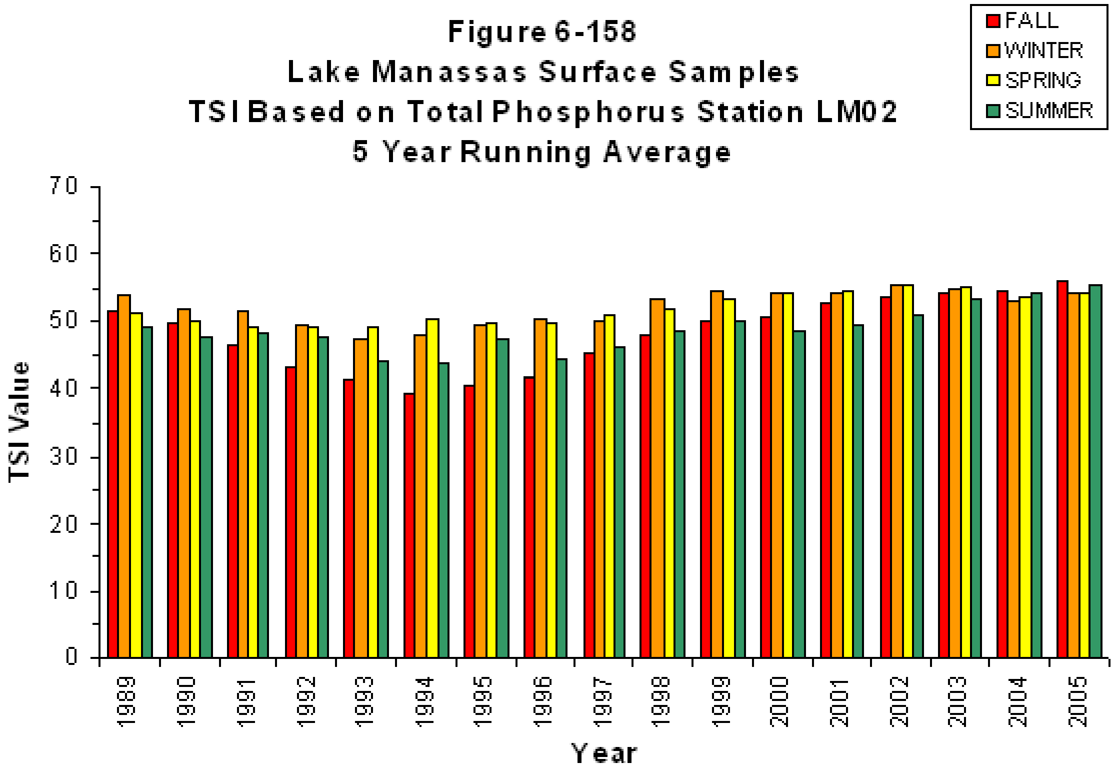


Figure 6-158
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM02
5 Year Running Average

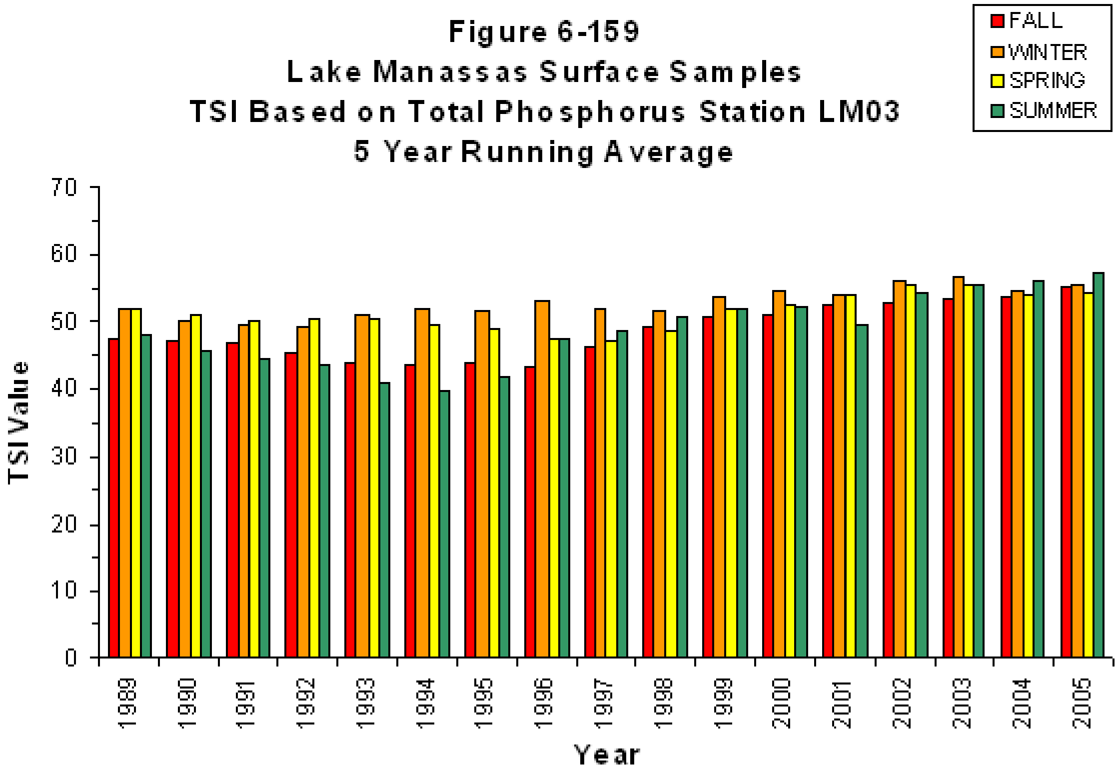


Figure 6-159
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM03
5 Year Running Average

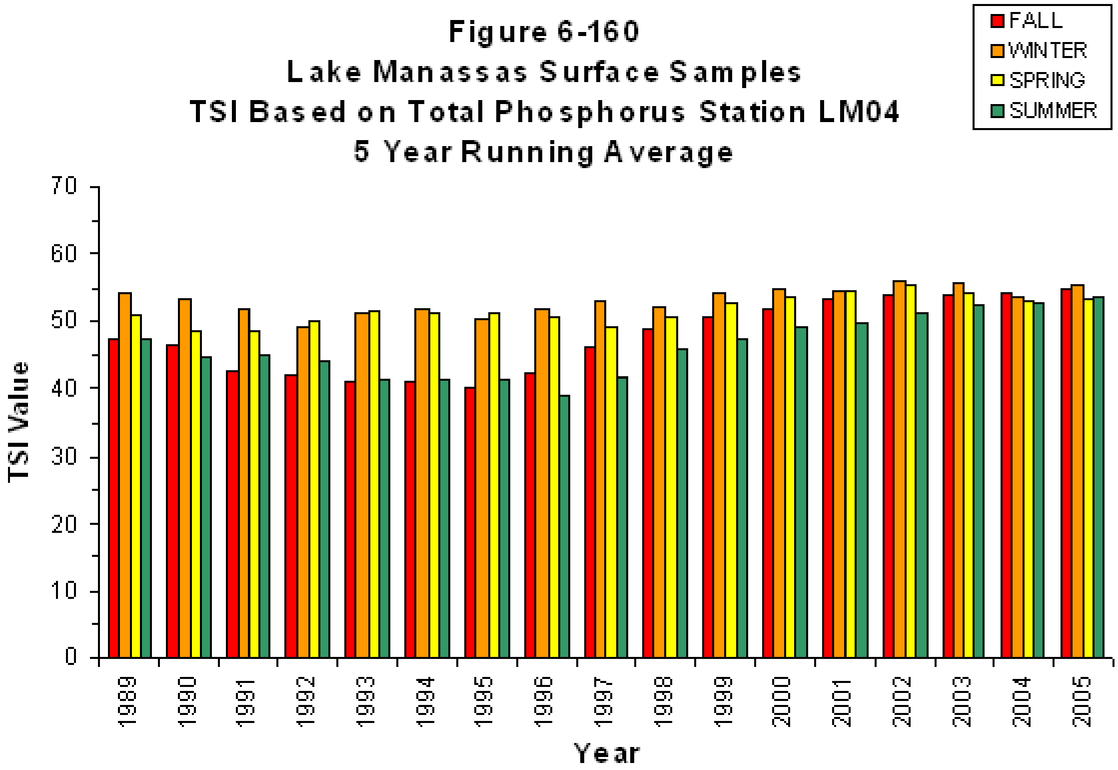


Figure 6-160
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM04
5 Year Running Average

Figure 6-161
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM05
5 Year Running Average

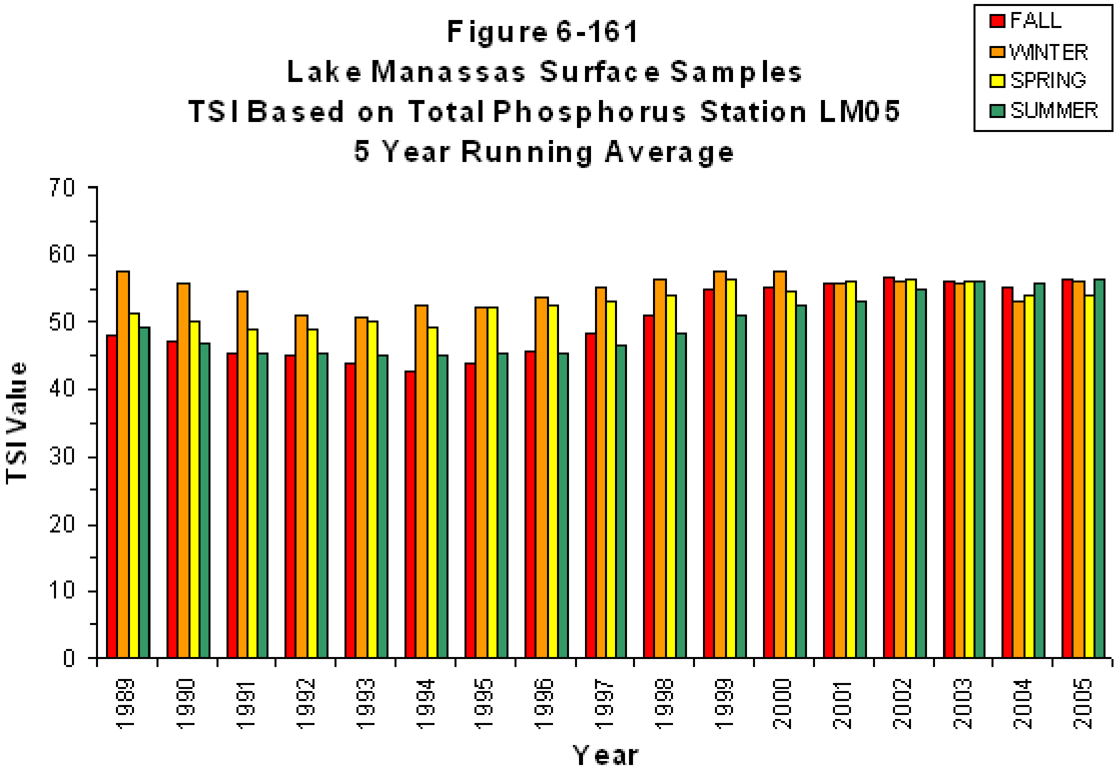
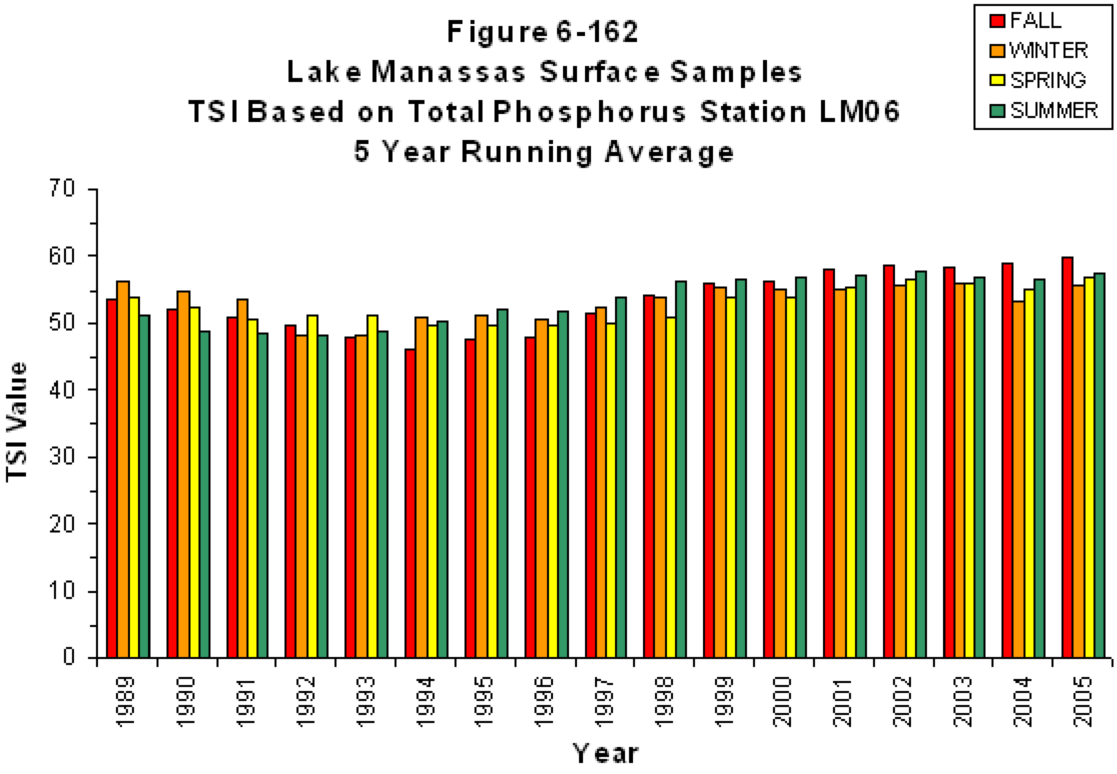


Figure 6-162
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM06
5 Year Running Average



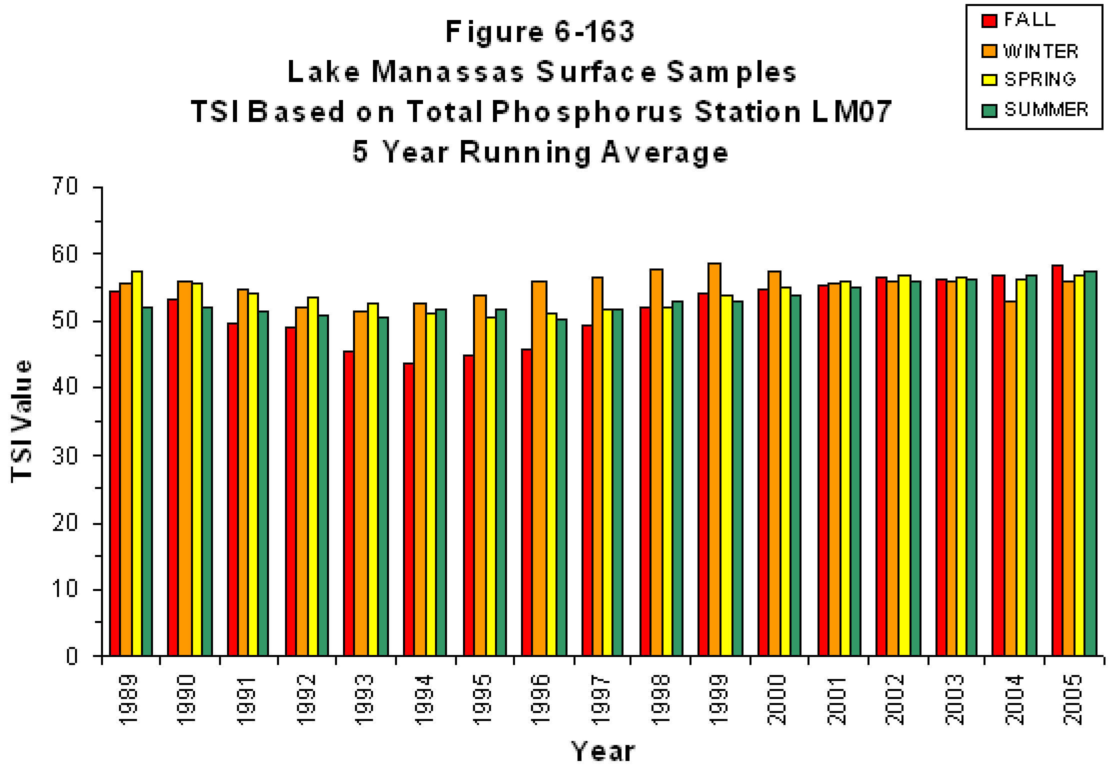


Figure 6-163
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM07
5 Year Running Average

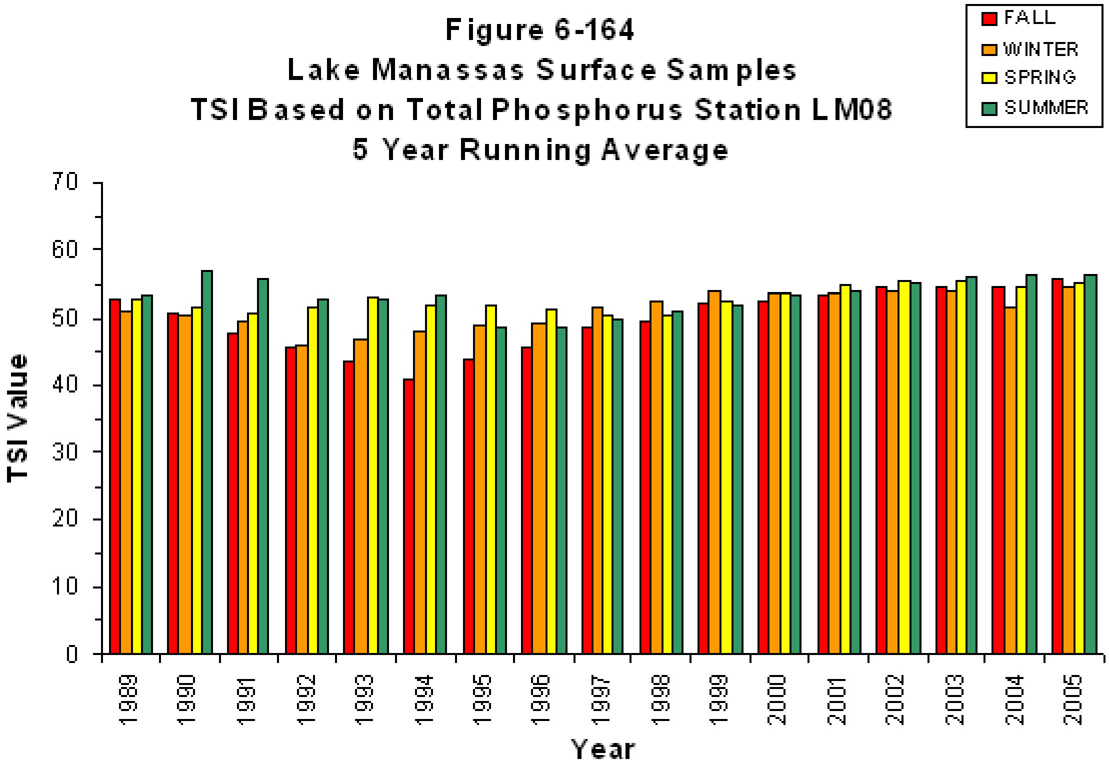


Figure 6-164
Lake Manassas Surface Samples
TSI Based on Total Phosphorus Station LM08
5 Year Running Average

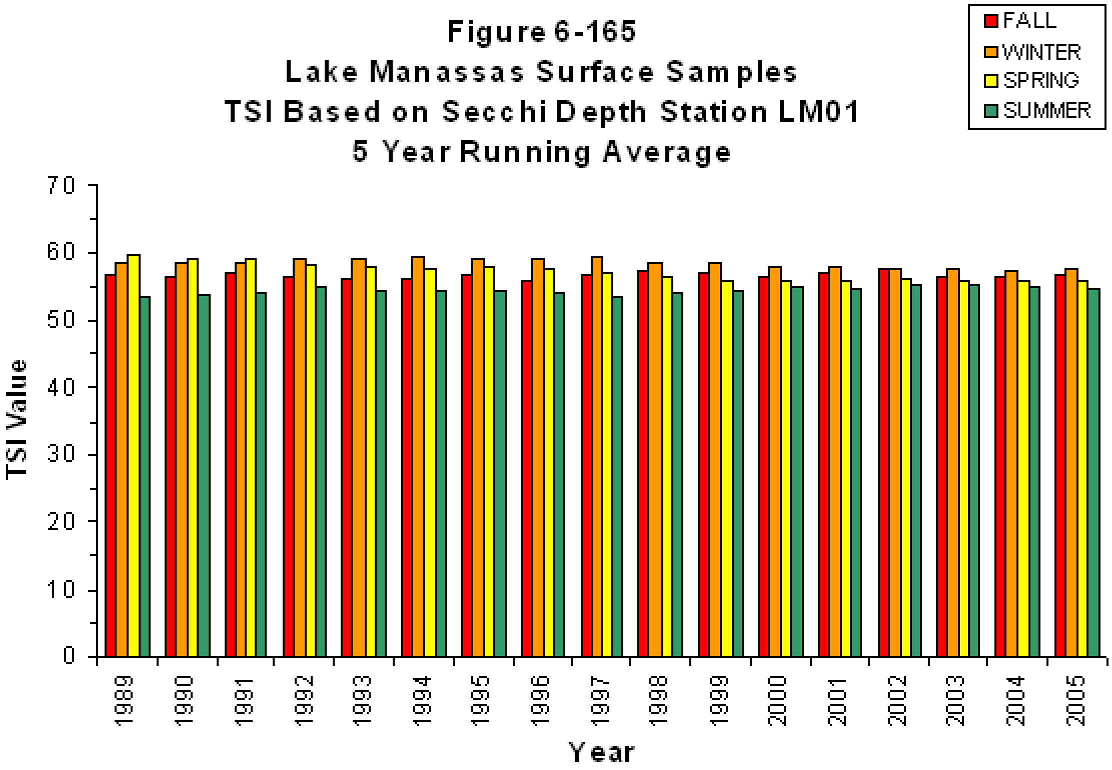


Figure 6-165
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM01
5 Year Running Average

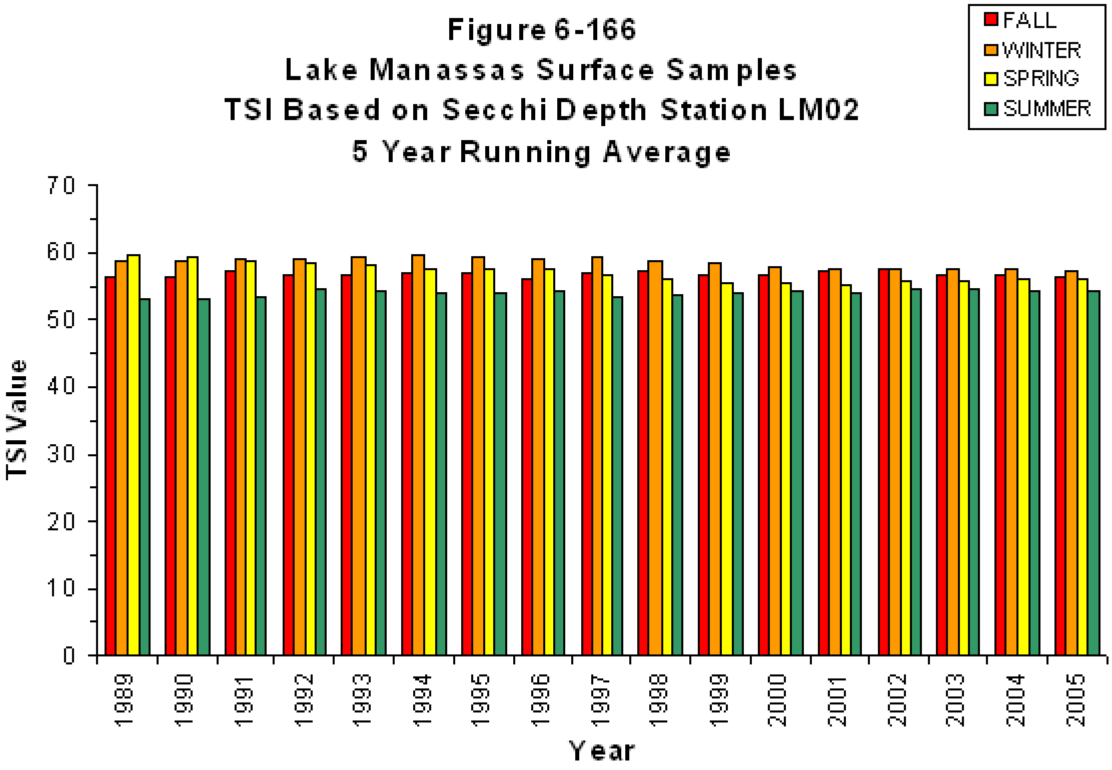


Figure 6-166
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM02
5 Year Running Average

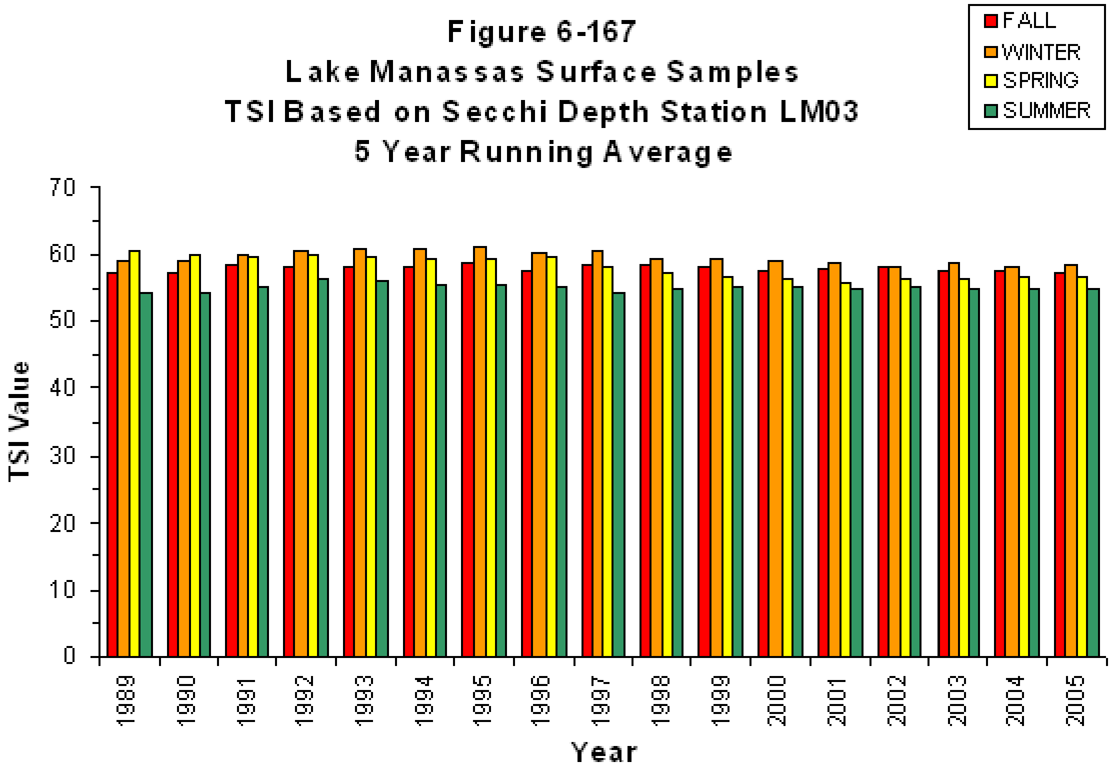


Figure 6-167
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM03
5 Year Running Average

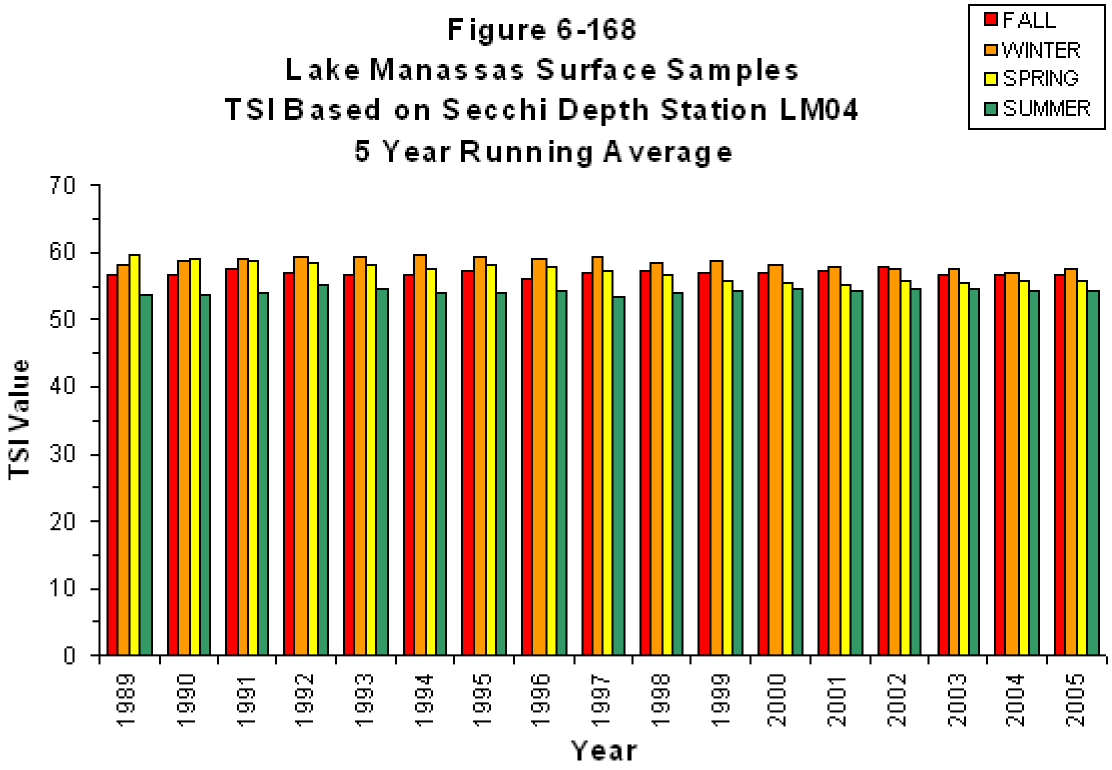


Figure 6-168
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM04
5 Year Running Average

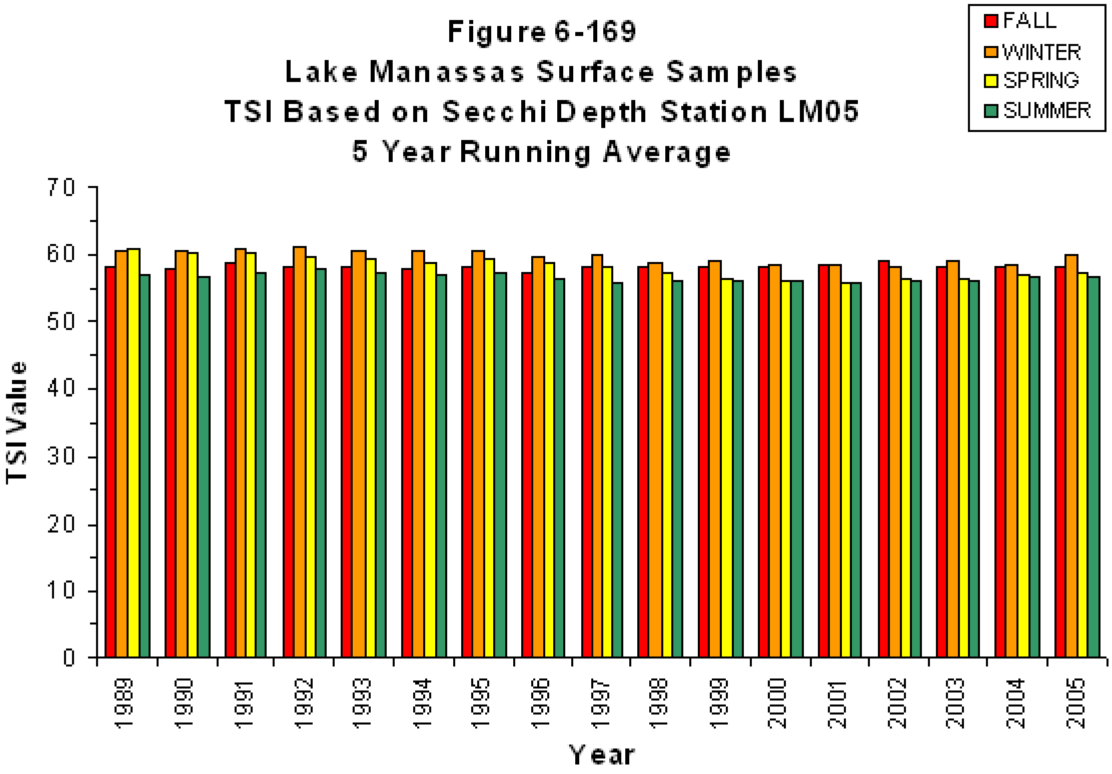


Figure 6-169
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM05
5 Year Running Average

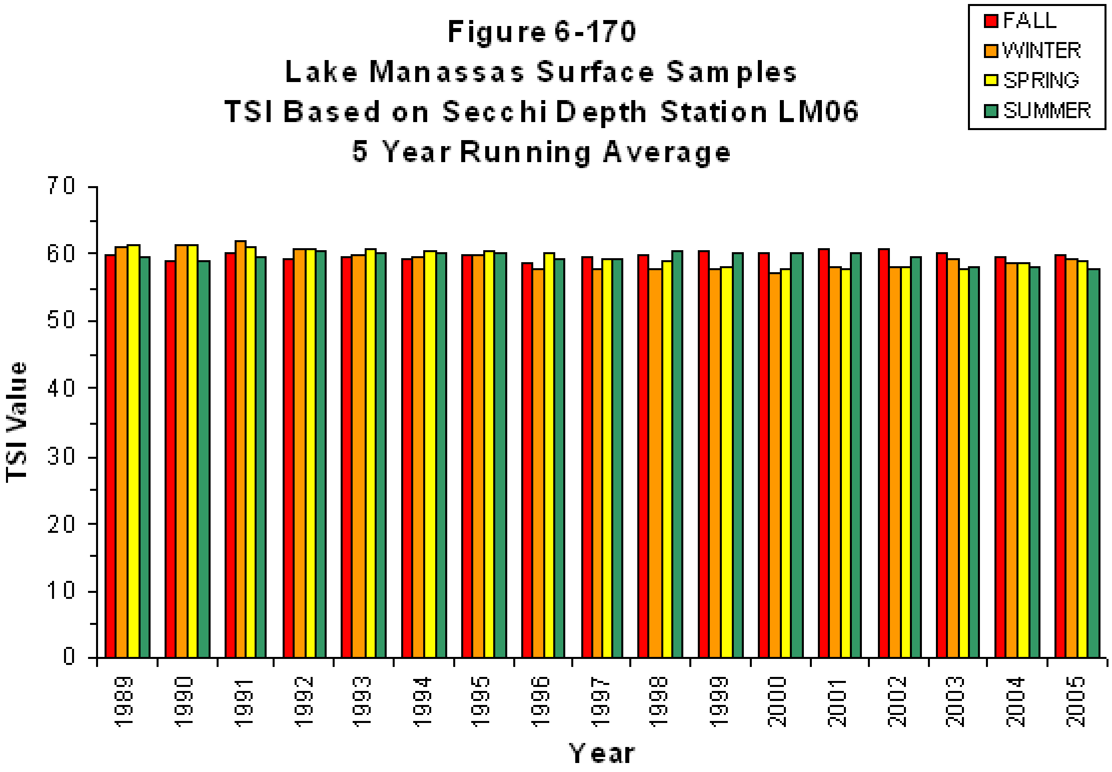


Figure 6-170
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM06
5 Year Running Average

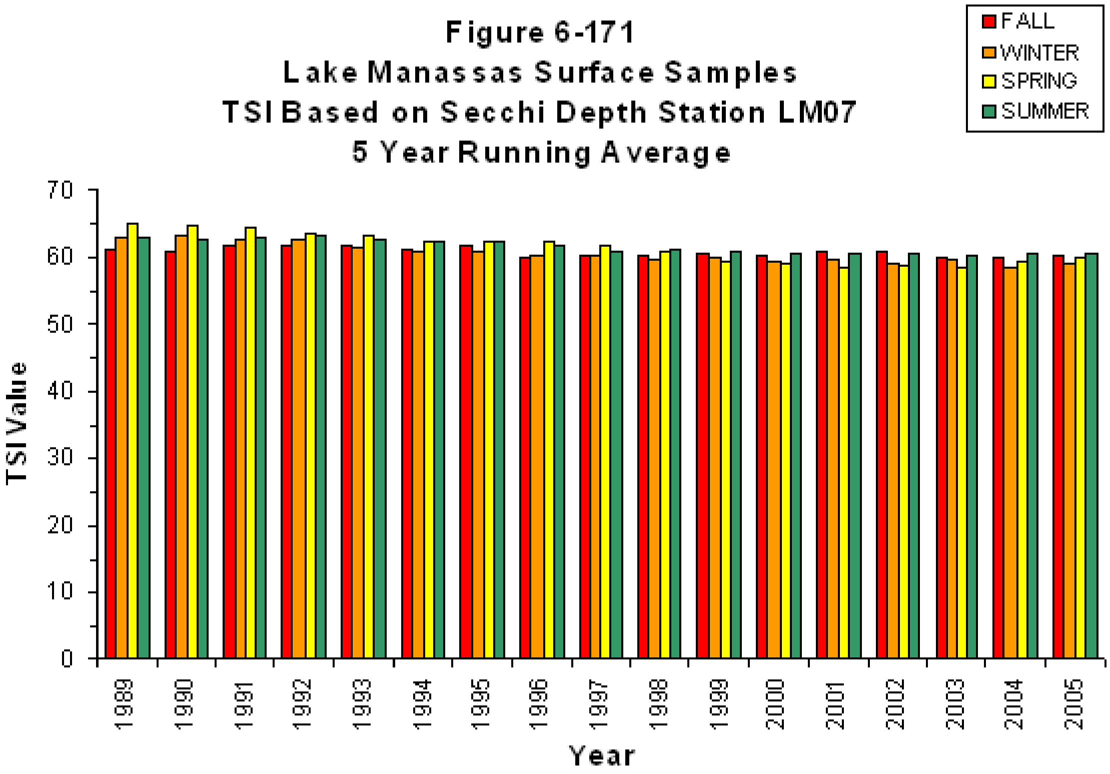


Figure 6-171
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM07
5 Year Running Average

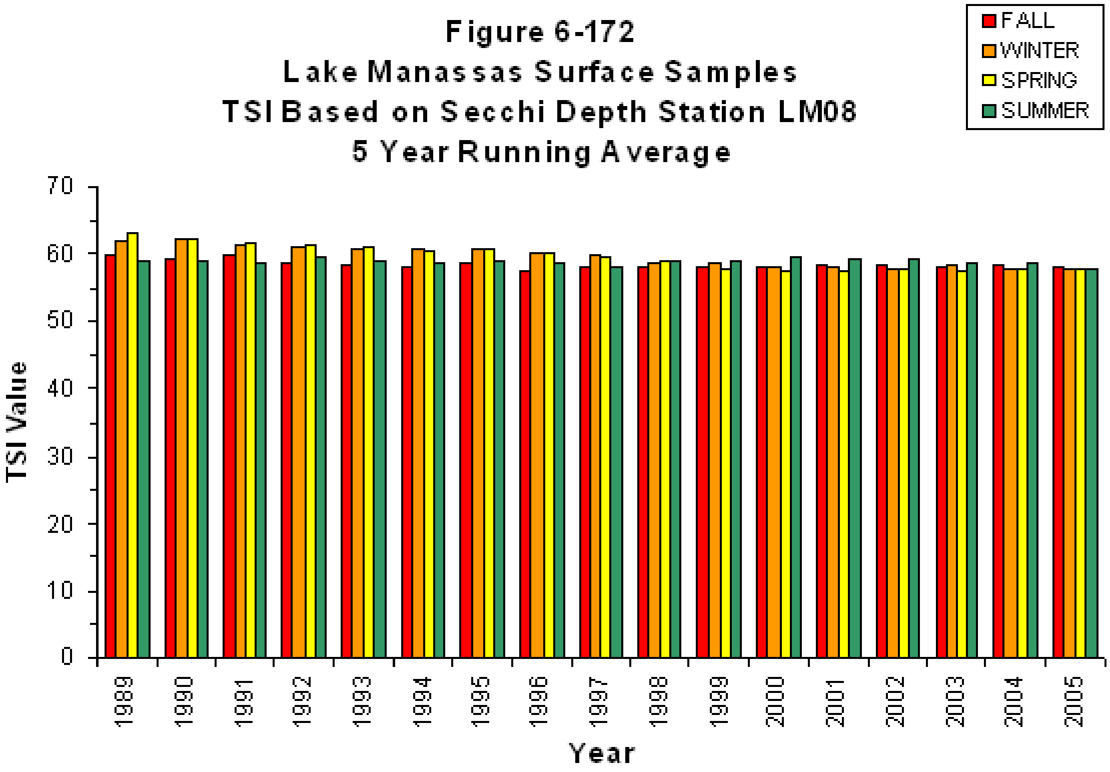
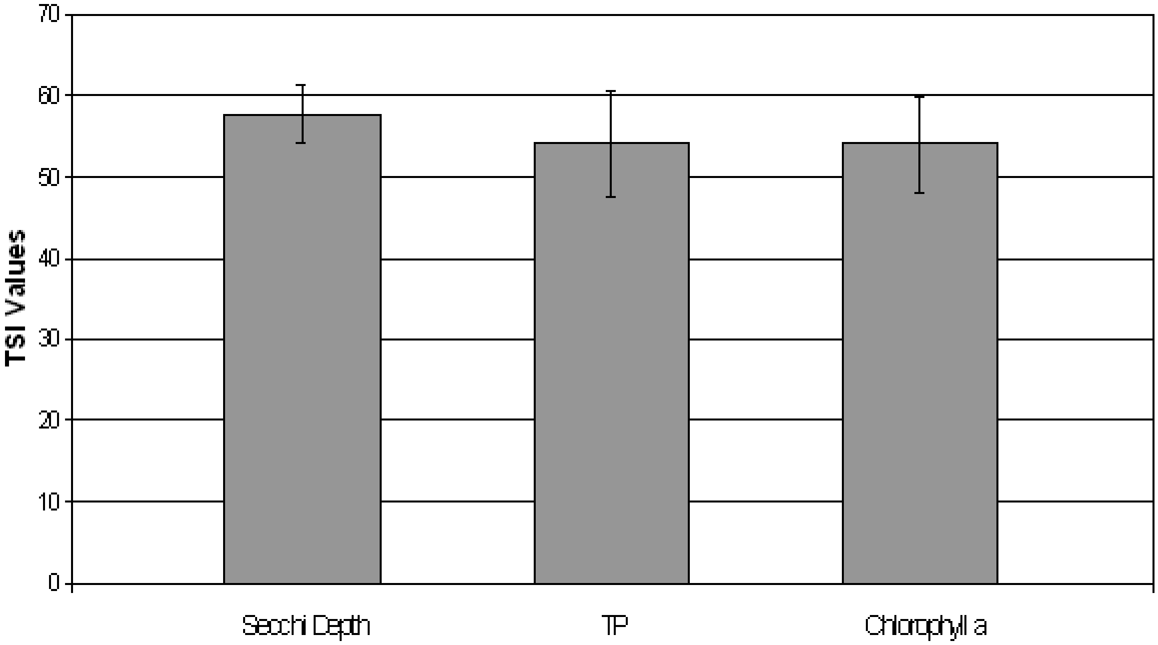


Figure 6-172
Lake Manassas Surface Samples
TSI Based on Secchi Depth Station LM08
5 Year Running Average

Figure 6-173
Lake Manassas
2000 - 2005 Average of Carlson Trophic State Index Values



The EPA provides an additional analysis that uses the same three parameters as Carlson (Secchi depth, TP, and chlorophyll *a*), but averages the raw numbers instead of applying linear regression. Table 6-7 provides the ranges for the EPA classification. For Lake Manassas, the average Secchi depth was 1.2 m, while the averages for TP and chlorophyll *a* were 34.95 µg/L and 15.49 µg/L, respectively.   The results of the EPA analysis agree with those provided by Carlson's indices: the lake is eutrophic.

Table 6-7: EPA Trophic State Index System
(Occoquan Watershed Monitoring Laboratory, 2006)

Trophic Condition	Chlorophyll *a* (µg/L)	Total Phosphorus (µg/L)	Secchi Disk Depth (m)
Oligotrophic	< 7	< 10	> 3.7
Mesotrophic	7 to 12	10 to 20	2 to 3.7
Eutrophic	> 12	> 20	< 2.0

Model Results

Based on the results of the Vollenweider, Carlson TSI, and EPA models the trophic status of Lake Manassas has not changed significantly since the previous baseline report. The Vollenweider model suggests a slight improvement in trophic state of the lake with decrease in phosphorus loading from the 2000 baseline. Carlson's model produces similar TSI values for Secchi depth, but TSI values for chlorophyll *a* and TP have increased. In summary, the following observations are consistent with the previous baseline report:

1. The lake is in the eutrophic range of the Vollenweider model, but is close to the mesotrophic range.
2. The lake is at the "Lower Boundary of Classic Eutrophy" according to Carlson's Trophic State Indices.
3. The lake is eutrophic with respect to the EPA model.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

The Lake Manassas Monitoring Program has been in operation since 1984. Over that period, a plethora of data has been collected to assist in management decisions associated with the water quality of the lake. The periodic baseline reports are essential to the monitoring program because they provide insight towards the evolving characteristics of the reservoir over time. Most of the conclusions from the previous baseline report resonate in this report with some updated information. The conclusions from this report are listed below, followed by recommendations based on the findings of this document.

Conclusions

1. Lake Manassas continues to be a eutrophic lake with little divergence from the previous baseline conditions. The trophic status of the lake has not significantly changed. The Vollenweider model shows that the lake status remains eutrophic but close to the mesotrophic range.

2. The amount of phosphorus entering the lake remains high, with increasing trends of total phosphorus occurring at stations ST70 and BR06. The increasing trends observed at station ST70 are of concern because Broad Run is the principal tributary entering the lake.

3. The addition of the inflatable bladder during 1995 has the capability to add 5 feet of elevation to the lake full pool which can double the lake volume. An increase in the lake’s surface area resulting from this has created additional wetlands upstream which has the potential to alternate the existing chemistry in those areas. However, the increase in lake volume has not affected the trophic status of the lake. As expected, an increase in lake volume has resulted in increased detention times and a decrease in flushing rates.

4. Impacts from the three golf courses along the north shore are minimal and pose little threat to the water quality of the Lake. Turf and stormwater management practices implemented by the Robert Trent Jones International Golf Course are likely the cause of a nominal foot print.

5. As with the previous baseline, conductivity levels have increased at all of the lake stations and station ST70. Increasing nutrients and other dissolved solids entering the lake are likely the cause for the rise in conductivity levels.

6. All lake stations have shown increases in pH which is a change from the previous baseline in which only a few lake stations showed increasing pH levels. Increased algae production in the lake can produce elevated pH levels. Algae will extract CO_2 from the water as they multiply, thereby increasing the pH.

7. The lake remains a phosphorus-limited system. The TN:TP ratios have slightly decreased during the three years. The ratio at the surface of the lake is typically higher than the bottom and remains above 15:1. This situation should be monitored given that a TN:TP ratio of 10:1 signifies the beginning of a shift to a nitrogen-limited system.

8. With the exception of the South Fork tributary, the remaining streams have shown increasing nutrient levels entering the lake. This is cause for concern because increased nutrient loading can accelerate the eutrophication process, which in turn degrades the overall water quality of the lake.

9. The rise in nutrient loading coupled with the elimination of copper sulfate treatments has increased algal productivity in the lake. Increasing trends of chlorophyll *a* were observed at all eight lake stations. If this situation is not addressed, significant problems associated with water treatment, such as filter clogging, taste, and odor issues, have the potential to worsen at the Lake Manassas Plant. This may affect the water quality distributed to the Manassas City residents.

Recommendations

1. The Lake Manassas Monitoring Program should continue so that changes in the water quality of the lake can be detected. Future data collected will assist in the evaluation of development impacts within the watershed.

2. Due to the continuing eutrophied nature of the Lake, the reimplementation of algal control technologies will help in control of algal growth. A study could be performed to investigate the algal kill rates and residence times of potential algicides in order to determine the appropriate one to use.

3. Further investigation ascertaining the cause of the increased nutrient loading entering the lake should be conducted. The first step in reducing nutrient loads into the lake is identifying the source. A reduction in nutrient inputs would also assist in controlling the rising algae populations.

4. Best Management Practices (BMPs) should be employed to any new development in the Lake Manassas watershed to ensure the quality of water in the reservoir.

5. It may be useful to examine the wetlands created upstream of the lake as a result of the inflatable bladder system. New ecosystems develop in these wetlands and have a profound effect on the internal water chemistry associated with those locations. These effects resonate downstream and potentially affect the water quality in the lake.

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APPENDIX A

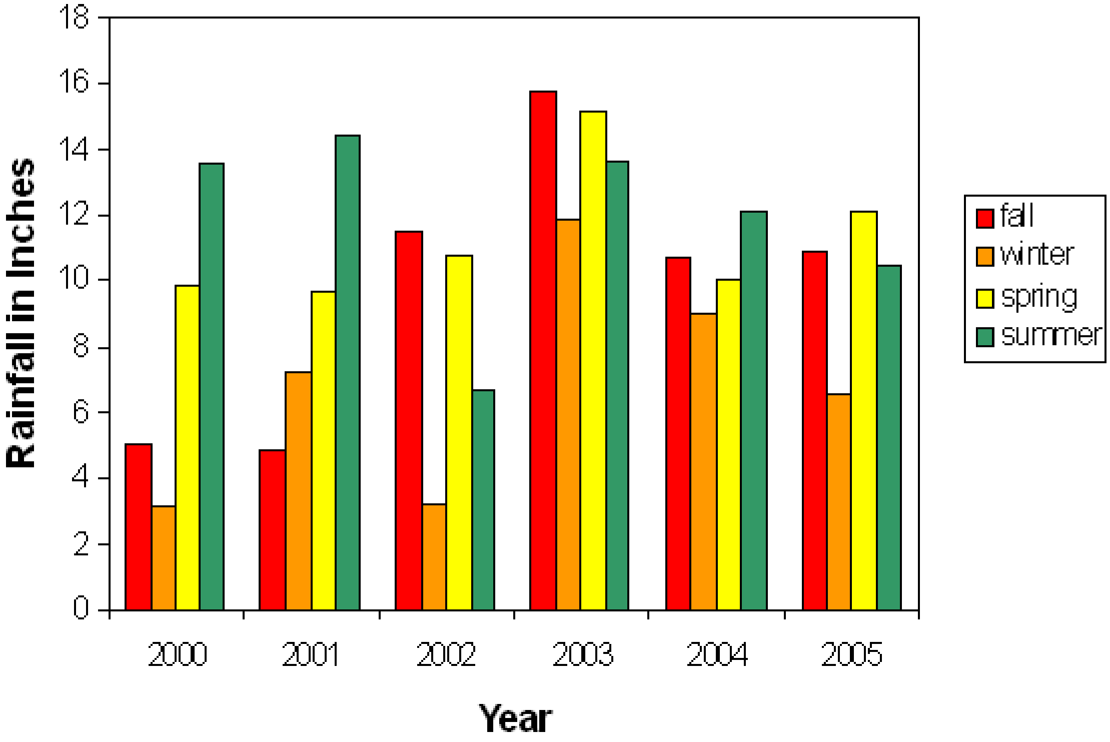
Rainfall data for the Lake Manassas watershed are displayed in Table A-1 and Figure A-1. All data were obtained from the precipitation gage atop the roof of the Lake Manassas Water Treatment Plant just downstream of the dam spillway.

Comparing data between 2002 and 2003, it is clear that the Lake Manassas Watershed received considerably more rainfall in 2003 than in 2002. During 2003, the Lake received approximately 12 inches of rainfall during the winter months, more than double received during the winter of 2002. Excessive rainfall during the winter months can delay stratification in a lake, especially when a large portion of the annual rainfall occurs before the onset of spring.

Table A-1: Lake Manassas Yearly Rainfall

Year	Yearly Rainfall Average (in/yr)
2000	35.57
2001	33.69
2002	34.27
2003	58.65
2004	38.42
2005	39.93

Figure A-1
Seasonal Rainfall for Lake Manassas



VITA

Jason Gorrie was born on June 29, 1978 in Heidelberg, Germany. He grew up in many interesting places located on the eastern seaboard of the United States and various cities in Germany. After graduating High School from Montgomery Catholic High School located in Montgomery, Alabama Mr. Gorrie attended Auburn University in pursuit of a Bachelor of Science degree in Civil Engineering. After graduating in the winter of 2000, Mr. Gorrie went to work for Dewberry and Davis, LLC as a transportation engineer. During this time Mr. Gorrie realized the importance of environmental issues and decided to further his education in Environmental Engineering. While employed with Dewberry and Davis, Mr. Gorrie began taking night classes at the Virginia Tech National Capital Region campus in the hopes of earning a Masters degree in Environmental Engineering.

Mr. Gorrie is expected to graduate from Virginia Polytechnic and State University with a Master of Science degree in Environmental Engineering in the Spring of 2007. Upon graduation, he will move to Charlotte, North Carolina to begin work with his new employer, Stantec.