An Exploration of the Limnological Dynamics of Lake Manassas

by

Judith Eggink

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Approved:

Dr. Adil N. Godrej, Chair
Dr. Daniel L. Gallagher
Dr. Thomas J. Grizzard

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Committee Chair : Dr. Adil N. Godrej

(Abstract)

Lake Manassas, located in the Occoquan Watershed in Virginia is a man-made impoundment of the Broad Run river. This lake surface area is approximately 697 acres, and it drains approximately 46,500 acres. Currently, the reservoir supplies drinking water to the City of Manassas and some areas of Western Prince William County, but if necessary, can help supply drinking water to 750,000 people in the Northern Virginia area.

Since 1984, the Occoquan Watershed Monitoring Laboratory has been sampling seven streams and eight lake stations as part of a program funded by of the City of Manassas. Lake Manassas is an important drinking water resource for the City and the surrounding areas and is used for recreational purposes as well. It is extremely important to continuously monitor the lake closely so that any6 undesirable trends in water quality may be detected and addressed. Currently surrounding the lake are two golf courses, with two more golf courses planned for the future, as well as homes, and recreational areas.

Overall, Lake Manassas is still considered to be eutrophic, which is the same conclusion reached in previous reports. The main nutrient source is Broad Run, but there are other smaller sources as well that are of concern. South Run has decreased nutrient loadings since the last report in 1996. Another conclusion is that the lake is Phosphorus-limited, but at times, the lake comes close to being nitrogen-limited.

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I. INTRODUCTION

Lake Manassas is a man-made impoundment located in Prince William County, Virginia, about 16 miles west of the city of Manassas. The reservoir was created from 1968 through 1971 by placing a dam on the Broad Run. The reservoir has the main purpose of serving as a drinking water supply. The 706-acre reservoir is located on the upper part of the Occoquan Watershed, and has been greatly studied due to the fact that the Occoquan Reservoir is a large potable water source in the northern Virginia area. In 1995, an inflatable dam was added atop the existing dam to create a larger reservoir. Currently the water treatment plant has the ability to produce 8 millions of gallons per day.

Water quality data on the principal tributary stream to the Lake are available beginning in July, 1978; in the lesser tributary streams beginning August, 1984; and in the lake beginning October, 1984. Data collected through December 31, 2000 were considered in this baseline report update. Thus, a minimum of 15 years' of data for the Reservoir is included.

Lake Manassas has also grown in popularity for recreational activities. Currently, on the north shore of the Lake are the Robert Trent Jones International Golf Course and the Virginia Oaks Golf Course. A second Robert Trent Jones International Golf Course is being constructed adjacent to the current one. Maintenance of the lake is important both to keep the aesthetic quality of the lake and to keep the water quality at an acceptable level. The additional golf courses could help or hinder the quality of the water in the lake depending on the management practices employed on the individual sites. To date, the management practice at the Robert Trent Jones International Golf Course has prevented undesirable water quality impacts.

Without appropriate controls, land development typically leads to the deterioration of a reservoir or lake. This is due to the fact that there is an increased flux of nutrients, which in turn may increase the amount of algae in the water system. This, in turn, can lead to taste and odor problems and the clogging of filters. If this continues unabated, the lake will become more and more productive this will eventually lead to deteriorating water quality with implications to water treatment. Specifically designed land-use practices can limit the potential damage done to the reservoir.

It is imperative that the qualities of this reservoir are tracked over time so a baseline can be established and compared to. The objective of this study is to look at the existing conditions of Lake Manassas and compare these results to the previous baselines. These comparisons are useful since they monitor the water quality impacts of current land management practices and development, and will demonstrate if management practices are effective, or if changes are needed.

The specific objectives were (1) to explore the limnological dynamics of Lake Manassas, including morphology, oxygen and thermal effects, lake turnovers, nutrient input, and lake productivity; (2) to characterize streams that flow into the reservoir; (3) to characterize the loadings that occur from the major tributary that runs into the lake; (4) to assess the eutrophic status of the lake using models that have been developed for lakes.

II. LITERATURE REVIEW

History of Lake Manassas

Lake History

In 1962, the Town Council of Manassas requested that the Northern Virginia Soil Conservation District find possible sites for a water reservoir that would replace the increasingly unreliable groundwater supply. The community population was increasing, and the water level in the groundwater would only decrease over time. The survey proposed the development of an impoundment on Broad Run by placing a dam just south of the confluence of Broad Run and the North Fork tributary to Broad Run (Laufer, 1986). The land in this area was purchased, and a dam was constructed using a bond referendum. Construction began in November 1968, and the dam was completed in 1970 (Harvey 1989). Along with construction of the dam, a water treatment plant was constructed at the base of the dam (Harvey 1989). The 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. Currently the plant is operating at a nominal capacity of 8 MGD supplying water to the City of Manassas, and to the Prince William County Service Authority for other areas of Prince William County, Virginia (Laufer 1986). In addition, a small hydroelectric plant at the base of the spillway was completed in 1987 (Harvey 1989). This hydroelectric plant is designed to supplement local peak electricity demand and is therefore only operated intermittently.

Raw water is withdrawn from the lake by an intake system at depths of 5, 15, 25, 35, 45, and

55 feet below full pool (Laufer, 1986). The spillway elevation of the lake is 285 feet above mean sea level (Harvey, 1989). In 1995 an inflatable rubber bladder was added increasing the dam height by potentially 5 feet (Godrej, 2000). Typically, all the water is drawn from the 5-foot level except during the summer when some water is drawn from the 15-foot level and mixed with the shallower water to achieve an acceptable temperature (Laufer, 1986). Deeper water is rarely withdrawn because experience has shown that the higher level of dissolved iron and manganese in the deeper water causes processing problems. The water is then conveyed via an underground pipeline to the treatment plant. Pumps are available to pump water from the lake, but normal lake levels provide sufficient head for gravity flow. The raw water enters the plant in a rapid mix chamber where normally, 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 fluorination purposes, hexametaphosphate for corrosion protection, and some gaseous chlorine for preliminary disinfection (Harvey, 1989).

After the mix chamber, the water is sent to one of two identical processing systems to complete treatment. The plant expansion of 1987 essentially built an identical processing system parallel to the existing system. The water flows through a series of settling basins which contain rotating flocculators to enhance flocculation and settling. The water then flows into dual media filters consisting of a bed of granular activated carbon (GAC) overlying sand. The water from Lake Manassas has had taste and odor problems since the opening of the reservoir. As a historical note, this water treatment plant was the second facility in the State of Virginia to use GAC for taste and odor control. Finished water is held in one of two 205,000 gallon clearwells, which form the structural foundation of the water treatment plant buildings. The water is then withdrawn from the clearwells, and pumped into a 24-inch main which carries the water to water tanks nearer the city. To complete the disinfection process, gaseous chlorine is added just before the water enters the main to provide the necessary chlorine residual for the distribution system.

Treatment plant operators have been experimenting with chemical addition rates to reduce the level of trihalomethanes (THM's) produced by the chlorination process. In general, the THM production level is controlled by the amount of pretreatment chlorination. Some experiments have shown that with minimal pretreatment chlorination, the level of THM's leaving the plant can be maintained below 30 ppb (Laufer 1986). Current drinking water regulations require THM's to be held too less than 80 ppb (EPA Website).

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

The water from Lake Manassas is soft, with an average total hardness of less than 30 milligrams per liter (mg/L) as Calcium Carbonate ($CaCO_3$). Therefore, the treatment plant does not perform any processing for hardness reduction.

Watershed Management

As previously stated, Lake Manassas and its watershed are part of the larger Occoquan Reservoir Watershed. The Occoquan River is impounded by a dam near its outlet into the Potomac

River. The Occoquan Reservoir is a very important water resource in the Northen Virginia area because it is part of a system that supplies potable water to over 1,000,000 people and regional businesses (Godrej, 2001).

In 1971, the Commonwealth of Virginia State Water Control Board issued a policy statement titled "Water Treatment and Water Quality Management in the Occoquan Watershed" (Laufer, 1986). This policy statement was the result of research into the increasing pollution content of the Occoquan Reservoir. In the early 1970's, the major sources of pollution into the watershed were point source discharges from sewage treatment plants. The new policy statement instituted the following major programs:

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

The State Water Control Board revised the Occoquan Watershed Policy in 1980 to include more detailed requirements for the performance of new treatment plants in the watershed. Most of the analytical data used in this document were obtained from the Lake Manassas Watershed Monitoring Program, paid for by the City of Manassas.

Current Watershed Development

In November, 1985, the Robert Trent Jones International golf resort development company requested permission from the Prince- William County, Virginia, Planning Commission to build 2 golf resorts on the northern shores of Lake Manassas. The golf resort plans include golf courses, 800,000 square feet of office space, a 500 unit full service hotel, and a residential community of 400 detached single family homes, 200 condominium homes, and 200 townhouse homes. The placement of this resort is shown in Figure 1, with the golf course nearest to the lake areas. Also shown are other features, including monitoring stations.

Limnological Principles

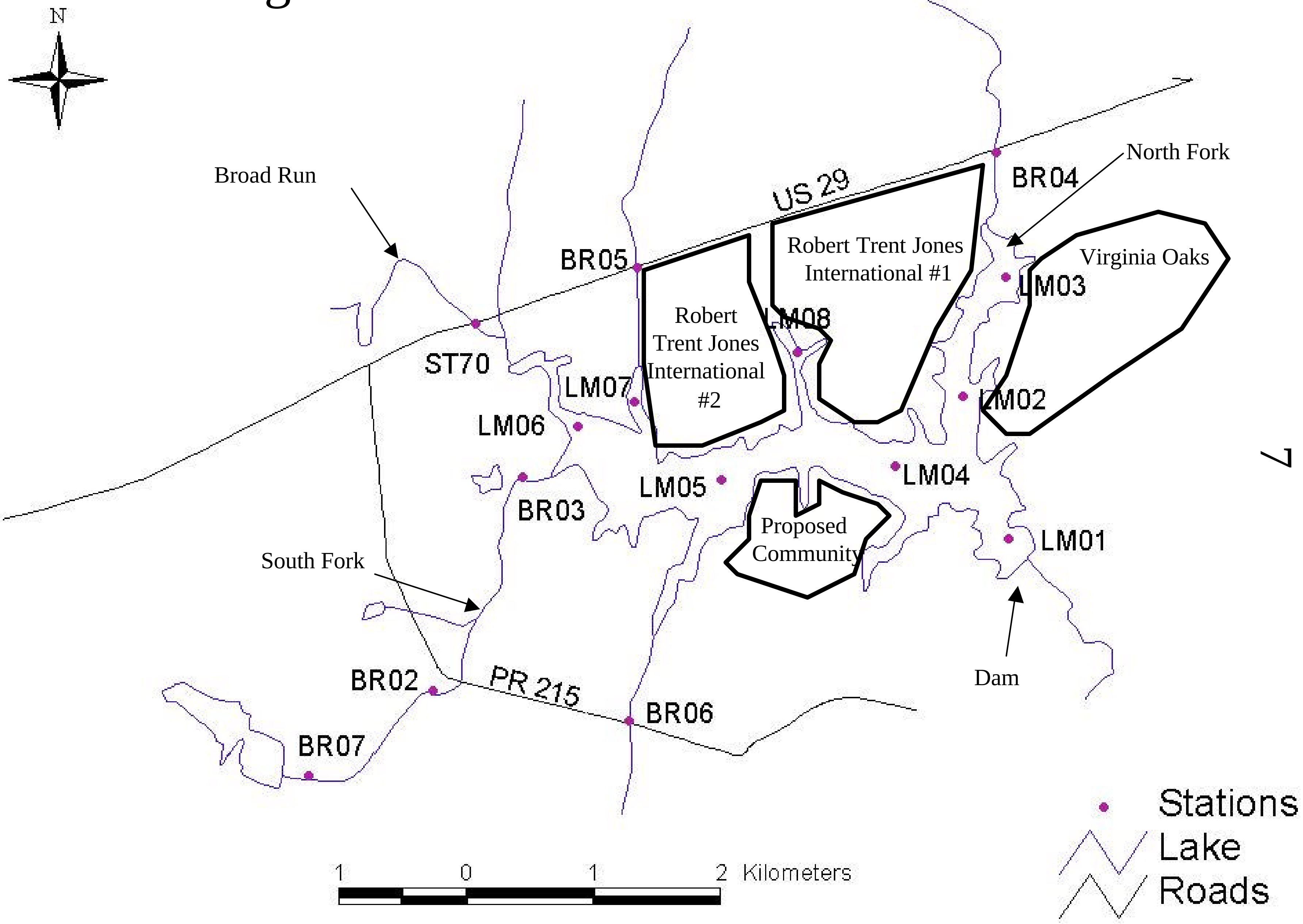
Morphology

Generally, there are some important differences between lakes and reservoirs that can impact any classification made using lake analysis methods. This can make it difficult to obtain the true classification of a reservoir, and consequently, the reservoir may be incorrectly managed (Lind, Terrell, Kimmel, 1993). Understanding these potential errors allow the individual to more correctly implement appropriate reservoir management strategies (Lind, Terrell, Kimmel, 1993). The differences are listed in Table 1.

Table 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

Figure 1 : Lake Manassas Golf Courses



The reservoir can be zoned into three areas with different characteristics. They are called the riverine, transitional, and lacustrine zones (Cooke et al, 1993). The riverine zone is a narrow basin with relatively high flow and is usually the most upstream portion. This zone could be considered more "eutrophic" than the rest of the reservoir due to the fact that there are relatively high nutrients, high turbidity, and limited light (Ryding, Rast, 1989). The transitional zone is a broader, deeper area with a reduced flow. This zone tends to have lower nutrients, turbidity, and more light than the riverine zone (Cooke et al, 1993). The lacustrine zone is the deep part of the reservoir usually near the dam with little flow, more light, little nutrients, and could be considered the more "oligotrophic" section of the reservoir (Wetzel, 2001). Lake Manassas has mostly the riverine and transitional zone features. The areas that have a lacustrine zone are located at stations LM01 and LM04.

Thermal Stratification

Solar radiation is often one of the greatest sources of heat to lakes and reservoirs and most of this heat is directly absorbed by the water (Wetzel, 2001). Some absorption does occur directly to the sediments, but this is minute, especially in moderately deep water, compared to the amount absorbed by the water (Wetzel, 2001). The sediments can also absorb heat in a river or stream, but in this case the amount of heat absorbed is significant. The amount of heat that is absorbed depends greatly on the geographical location (latitude and longitude) of the water body. The heat inputs and outputs of most lakes and reservoirs are largely a surface phenomenon, with most energy being absorbed within the upper few meters (Harper, 1992). During the summer when it is warmer, the upper section of the water body will also become warmer than the bottom. Since this warmer water is less dense than the cooler water on the bottom, the water tends to float (Harper, 1992). As the water surface heats up more and more, a larger temperature difference will occur and stratification takes place (Wetzel, 2001). The top, warm layer is normally called the epilimnion, and the lower, cooler layer is the hypolimnion (Harper, 1992). This stratum creates a barrier, called the metalimnion, in which the epilimnion and the hypolimnion will not mix and remain separate (Cooke et al, 1993). A temperature difference of only a few degrees is all that is necessary to increase the thermal resistance to mixing (Wetzel, 2001). During the progression of summer, the metalimnion will get smaller as the epilimnion heats up more and more.

In the late summer and fall, the solar radiation decreases allowing the loss of heat from the epilimnion. As this water becomes closer in density with the hypolimnion, the more dense water starts to sink (Occoquan Watershed Monitoring Laboratory, 1996). Once the thermal stratification is weak enough, it does not take more than some wind to start fall turnover. This turnover can occur within a few hours if there is a storm or high wind velocity. The circulation continues as the water cools and a uniform temperature occurs from the top to the bottom of the lake or reservoir (Wetzel, 2001).

As the fall progresses into winter, the water gradually cools and reaches a point of maximum density (4°C). In winter, surface ice can form very rapidly. This can create a density gradient between the ice (0°C) and the water (4°C), called an inverse thermal stratification (Wetzel, 2001). This occurs because the colder water, < 4°C, is now lighter and will float. Once frozen, the ice layer effectively seals off the lake or reservoir from the effects of the wind.

As the spring approaches, the air temperature will increase, solar radiation increases, and rain increases. These increases, along with wind, will allow the lake or reservoir to mix (Harper, 1989). The surface to bottom temperature is approximately the same at this point. From this point, the solar radiation will increase and stratification will occur again (Occoquan Watershed Monitoring Laboratory, 1996).

The thermal effects described above are found in lakes and reservoirs in temperate areas. With the two different periods of mixing, this pattern is termed dimictic (Laufer, 1986).

Eutrophication

Eutrophication by definition is "the alteration of the production of a lake along a continuum in the direction of low to high values" (Wetzel, 2001). This process can occur as lake productivity increases and the phosphorus and nitrogen within that lake or reservoir increase (Harper, 1989). This process is a natural aging process that can be accelerated by increasing inputs of nutrients normally associated with human activities (Carpenter et al, 1998). This in turn increases the biological productivity, and decreases the lake or reservoir volume (Ryding, Rast, 1989). As eutrophication occurs, the water body gradually accumulates silt and organic matter, allowing the lake to slowly fill in and become a marsh or swamp (Wetzel, 2001). A water body that is low in nutrients and plant life is termed oligotrophic (Harper, 1992). Between the oligotrophic and eutrophic state of the lake is the mesotrophic state (Wetzel, 2001).

In a eutrophic lake or reservoir, there is a high availability of nutrients which in turn increases the productivity. Algal populations can increase rapidly, particularly blue-green algae, forming mats of growth just under the surface of the water (Occoquan Watershed Monitoring Laboratory, 1996). When photosynthesis of the phytoplankton occurs during the day, they release oxygen in large amounts. This can lead to a supersaturation of dissolved oxygen at the surface of the water (Harper, 1992). Generally, dissolved oxygen numbers greater than 100% at the surface is an indicator that there is algal growth (Harper, 1992).

During the stratification period, the epilimnion does not mix with the hypolimnion. Due to this fact, the oxygen at the surface cannot reach the hypolimnion. The oxygen at this zone is rapidly depleted due to decomposition of organic carbon such as the phytoplankton settling to the bottom (Wetzel, 2001). The dissolved oxygen depth profile during the stratification forms a similar trend as the temperature thermocline (Harper, 1992). Because the dissolved oxygen is extremely low in the hypolimnion, there is no activity of aerobic aquatic species and no presence of fish (Harper, 1992). In the hypolimnion there is the release of reduced forms of iron, manganese and sulfides from the soil into the water column due to the lack of oxygen (Ryding, Rast, 1989). As the fall turnover occurs, these chemical species are released into the epilimnion. All chemical species are necessary for the increase of productivity in the lake or reservoir. This does occur in Lake Manassas, but only at specific deep stations such as LM01 and LM04

Nutrients and Lake Productivity

Nutrient are considered essential elements for the support of living organisms. All organisms have different nutritional requirements, but for the purpose of looking at the nutrients that effect lake productivity, the organism that is of most interest is algae (Harper, 1992). Algae has been know to be a nuisance in lakes that are becoming more eutrophic. These algae can cause problems with water treatment, water quality and aesthetics which in turn can cause economic difficulties. The most important factors in plant growth are light, nutrient supply, and temperature. Primary production of algae are shown with the following equation: $6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$ (Harper, 1992). The increase in biomass can be measured as concentration of chlorophyll or cell volume in algae. At the surface of the lake, the light is above saturation, but has a logarithmic decline with depth. The best position for algae photosynthesis is actually 2-3 m below the surface as inhibition of algae growth occurs right at the surface because of too much light (Harper, 1992). The algae can adapt however to many variations in the quantity of light by changing color.

Most of the algae reactions within the cell are temperature dependant, with $25^{o}C$ to $40^{o}C$ being the optimal photosynthesis range (Harper, 1992). Nutrients are also extremely important in the growth of algae. The specific importance of Nitrogen and Phosphorus is that they have been recognized as critical nutrients that often limit growth. If there were an unlimited supply of nutrient in water body, the algae would keep growing and photosynthesizing. In lakes and reservoirs however, there is not an unending supply of all nutrients. The typical make-up of algae contain approximately the following ratio (Wetzel, 2001)

1P : 7N : 40C per 100 dry weight plant matter or

1P : 7N : 40C per 500 wet weight plant matter

If any of the three elements are limiting and other elements are present in excess of necessary needs, phosphorus can theoretically generate 500 times its weight in living algae, and nitrogen 71 times.(Wetzel, 2001).

As the algae grow, there eventually will be a nutrient restriction and growth will become hampered. This is normally considered to be phosphorus. Nutrient levels are one of the most important determinants of the type of species found in the same lake (Harper, 1992). For instance, green algae will dominate at moderate temperatures when the N:P ratio that is moderate, but blue-green algae dominate when temperatures are high and the N:P ratio is low (Harper, 1992).

Blue-green algae is a specific problem as they can grow under conditions that would kill off most other algae (Smith, 1982). They can grow at low phosphorus levels by storing excess phosphorus, they are very competitive at higher temperatures for low nutrients, more efficient at lower light levels, and prefer to use CO2 as their carbon source (Smith, 1982). Once the blue-green algae have reached a point that they cover the waters surface, they will have detrimental effects on their competitors (Wetzel, 2001).

As the lake moves from an Oligotrophic to Eutrophic state, the nutrient phosphorus increases (Ryding, Rast, 1989). In the Oligotrophic state, the limiting nutrient is usually phosphorus, but as the lake ages, there is a larger input of phosphorus.

Nitrogen is abundant in the environment, but only two percent is available to organisms (Wetzel, 2001). The forms that are available to organisms include dissolved molecular nitrogen (N_2), organic nitrogen, ammonia (NH_3), nitrate (NO_3^-), and nitrite (NO_2^-). The sources of nitrogen include precipitation, nitrogen fixation, and non-point source drainage (Harper, 1992). The dissolved molecular nitrogen normally enters the lake by molecular fixation. Ammonia is normally generated by the bacterial decomposition of organic matter (Wetzel, 2001). Ammonia undergoes a nitrification process in the presence of oxygen from ammonia to nitrite to nitrate (Wetzel, 2001). Nitrate normally is readily oxidizable and rarely accumulates (Petterson, 1998). Nitrite is a very common form of nitrogen and mostly enters the lake or reservoir from precipitation and non-point source discharge (Harper, 1992).

Out of all the other nutrients mentioned above, phosphorus is the least abundant and the most commonly limiting species for biological productivity. The most common form of phosphorus is orthophosphate (PO_4^{-3}), inorganic, and it is also the only form that can be directly used by organisms (Wetzel, 2001). Phosphate though is extremely reactive and can interact with many cations to form insoluble compounds that will precipitate. The availability of orthophosphate is also reduced by the adsorption onto particles. Approximately 90% of the organic phosphorus is bound and unuseable and normally accumulates in the soil (Petterson, 1998). These forms can be measured as total phosphorus (TP) or total soluble phosphorus (TSP) (Ryding, Rast, 1989).

The growth of algae is normally in flux with the availability of the nutrients (Smith, 1982). If there is a large amount of a certain nutrient, the algae will continue to grow and expand until that time that the nutrient becomes limiting (Harper, 1992). The procedure used to determine if a lake or reservoir is limited by either phosphorus or nitrogen is by using a N:P ratio (Barica, 1990). Generally, if the ratio is above 12 then the system is phosphorus limited, and if it is below 12, the system is nitrogen limited (Wetzel, 2001). Overall, the best way to control the eutrophication of a lake or reservoir is to limit the phosphorus that is entering the system. The eutrophication of rivers by man is a more extensive problem that that of lakes (Harper, 1992). Rivers throughout the world have doubled the amount of nutrients (Harper, 1992).

Watershed Management

Golf Course Impact

Golf courses provide beautiful green areas within our urban and suburban landscapes. A typical 18 hole golf course is comprised of 0.8-1.2 ha of putting green area, 0.6-1.2 ha of teeing area, and 10-20 ha of fairway area (Kenna, Snow, 2000). Approximately 20-30% of the golf course is used and maintained to specific criteria (Kenna, Snow, 2000). However, there is public concern about the possible effects of golf courses on the environment (Racke, 2000). Research has been completed on many golf courses to find out if they have any impact on streams, lakes, and reservoirs (Kenns, Snow, 2000). One of the greatest fears of the public is that excess pesticides and nutrients will end up in their drinking water and what the potential effects will be (Kenna, Snow, 2000). 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 greatest threat to drinking water was found to be runoff. Research on potential surface runoff of pesticides has resulted in the general finding that limited transport occurs from treated turfgrass under certain conditions (Beard, 2000). These conditions are usually when a high rainfall occurs within the 24 hours after any pesticides have been added to the turfgrass (Shuman, Smith, Bridges, 2000). Turfgrass, when maintained properly, has the ability to control the amount of soil particles that will enter a lake or reservoir (Shuman, Smith, Bridges, 2000). These soil particles usually have phosphates attached which can contribute to the eutrophication of lakes and reservoirs (Racke, 2000). Also, runoff that occurs from industrial or urban areas usually have many heavy metals, oil, hydrocarbons, and household wastes (Beard, 2000). Turfgrass soils have one of the most biologically active systems for biodegrading organic chemicals and pesticides (Shuman, Smith, Bridges, 2000). Degradation will occur as well as filtration of particulates allowing runoff into the lakes and reservoirs to be much cleaner. Even with these removal mechanisms, detectable but trace amounts of pesticides have been found on golf courses (Malin, Wheeler, 2000). One potential solution is to use a program called Integrated Pest Management (IPM). This philosophy places less emphasis on chemical control measures and more emphasis on the use of all available control methods (i.e., chemical, cultural, biological) in an integrated fashion (Beard, 2000). It is anticipated that continued efforts will be devoted to using IPM given the cost of chemical control methods and issues associated with their use (Beard, 2000).

Water Supply Protection

Over the years, more and more stringent standards have been applied to drinking water. As these standards become more stringent, there will be a higher cost involved to create potable water. The impact of eutrophication on human health can be seen by looking at the lake and the process for treating potable water. Some problems may be the algae is able to penetrate through the water treatment process, chlorination may be impaired by by-products, THM's can form, excessive iron and manganese, or problems with the disinfection system due to ammonia. In addition, algae may cause treatability problems to the drinking water plant by clogging filters and causing taste and odor problems (Harper, 1992).

Lake Manassas is in a rapidly developing area with its water supply and recreational area being important. Any management program would impact the lake, so correct management is extremely important to maintain balance. The Occoquan Basin Nonpoint Pollution Management Program can help protect this valuable resource and prevent potential problems.

III. METHODS AND MATERIALS

Sampling and Analytical Program

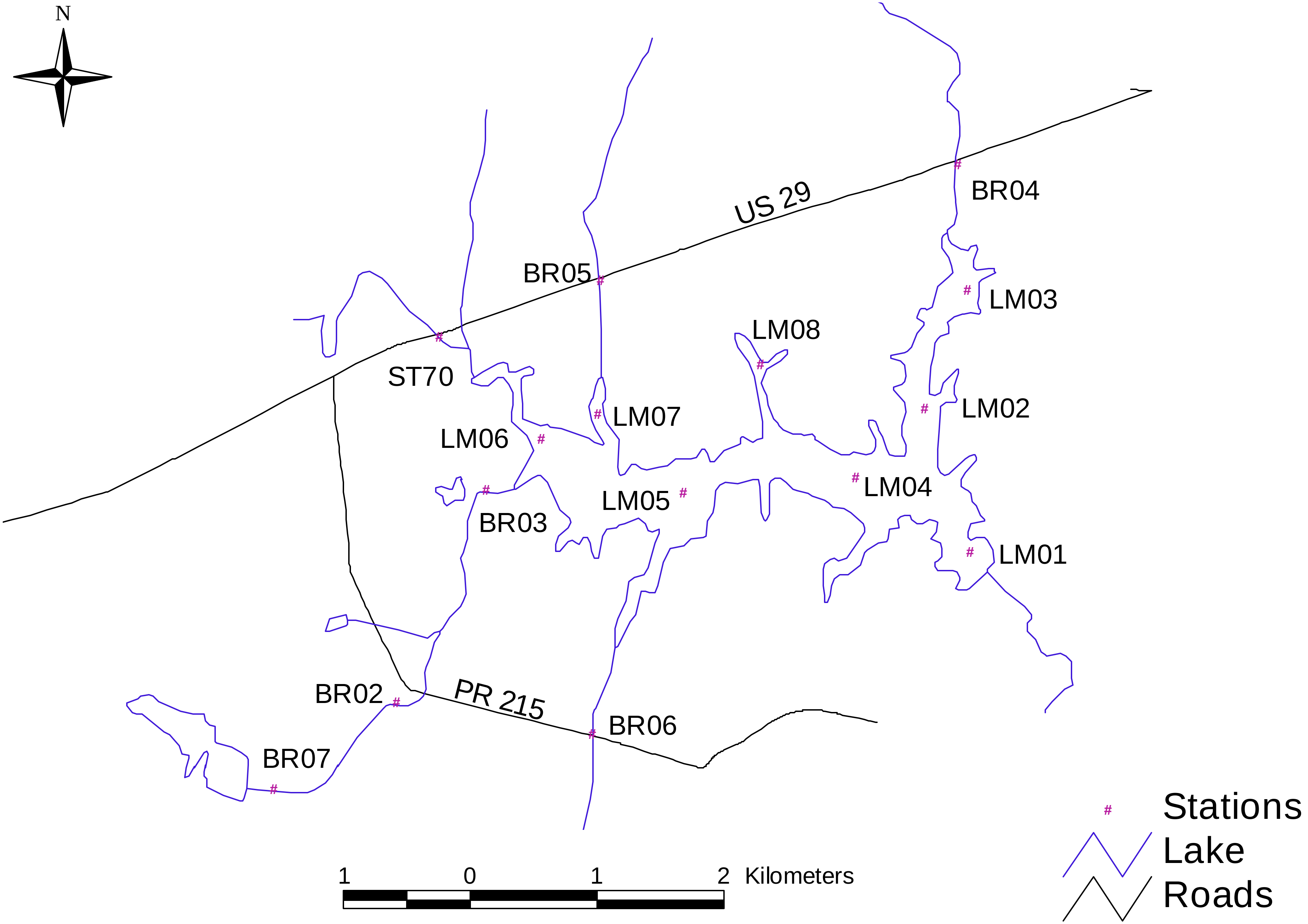
Sampling Stations

The current monitoring for Lake Manassas and its tributaries has been designed and implemented by the Occoquan Watershed Monitoring Laboratory (OWML). The program has been in operation since October 1984, although some tributaries were sampled as early as 1975 under the Occoquan Watershed Monitoring Program. All data generated by the monitoring programs are stored in OWML's microcomputer database.

The Lake Manassas Monitoring Program sampling network consists of eight sampling locations on the lake, designated as LM01 to LM08 (Figure 2, Table 2). Sampling sites are also located on the tributaries draining into the lake, and are designated as BR02 through BR08 and ST70. All samples obtained at the BR sites are grab samples. Samples from ST70 on Broad Run are both flow weighted composite (storm) and grab samples (baseflow). ST70 is the only tributary to the Lake that is gaged. Five miles downstream from the Lake Manassas dam spillway is a gaged monitoring station, ST30.

At the LM series Lake sampling stations, field measurements are obtained at the one-foot, two-and-a-half-foot, and five-foot depths, and then at five-foot increments until the bottom is reached. The sampling frequency can be found in Table 3. Field measurements include dissolved oxygen, temperature, pH, and Secchi disk reading. Samples obtained from the one-foot depth and the bottom are returned to the laboratory for further analysis. Laboratory analyses include measurements

Figure 2 : Lake Manassas Sampling Stations



concentrations of phosphorus and nitrogen forms, solids concentrations, conductivity, chlorophyll *a*, concentration of selected metals, and selected synthetic organic compounds.

Table 2: Stream Monitoring Station Locations (OWML, 2001)

Station Number	**Station Name**
BR02	South Run at Route 215 (Vint Hill Rd.)
BR03	South Run at Route 684
BR04	North Fork at Route 29-211
BR05	Unnamed tributary to Lake Manassas, located at Route 29-211 between Routes 15 and 703
BR06	Unnamed tributary to Lake Manassas, located at Route 215 west of Greenwich
BR07	South Run at Route 793 immediately below Lake Brittle (above Vint Hill Farms Station)
BR08	Unnamed tributary to Route 684
ST70	Broad Run at Buckland (upstream).
ST30	Broad Run at Linton Hall (downstream).

Table 3: Summary of Analytical Program (OWML, 2001)

	Reservoir	Broad Run (ST70)	Tributary
Number of monitoring stations	8	2	2
Sampling Frequency			
Base Flow - Spring & Summer	Bi-Weekly	Weekly	Bi-Weekly
Base Flow - Fall & Winter	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 (NO2–N+NO3–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 Pigments	Surface	-	-
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

Grab samples from the BR stations on the tributaries are analyzed for the same parameters as the Lake samples. The flow-weighted composite samples and grab samples from the ST30 and ST70 stations are also analyzed.

The South Run tributary of the Lake is monitored at three stations. The water from Lake Brittle, a state-owned impoundment, used as a fishing reservoir, is monitored at location BR07. Just before it enters Lake Manassas, South Run is monitored at BR03. The Vint Hill Station Wastewater Treatment Plant is currently running above stations BR02 and BR03 and is potentially considering an expansion.

Analytical Parameters

The chemical analysis performed on samples collected in the Lake Manassas watershed are listed in Table 4. These analyses are subjected to the quality assurance / quality control (QA/QC) practices followed as OWML. QA/QC practices at OWML include duplicate samples, spiked samples, blanks, and standards in the analysis of samples. OWML also uses control charts to determine if the analysis is within prescribed bounds. Regular participation in round-robin testing programs administered by the U.S. Geological Survey on a quarterly basis, and performance evaluation samples submitted to the U.S. Environmental Protection Agency, is also part of OWML's commitment to QA/QC (OWML Laboratory Procedure Manual, 2000).

Table 4: Parameters Analyzed in Lake Manassas Watershed Samples

Abbreviation	Parameter
FLO	Flow
DO	Dissolved Oxygen
TEMP	Temperature
COND	Conductivity
ALK	Alkalinity
NH3-N	Ammonia Nitrogen
TKN	Total Kjeldahl 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
	Selected Synthetic Organic Compounds (SOCs)

Data Reduction Methodology for Stream Stations

Sample data for Lake Manassas and its tributaries are maintained by OWML in an xBase file with numerical data stored as character strings to ensure data accuracy and precision. Prior to analysis, the data must be converted to values. The following procedures were used to reduce the character data in the xBase files to a format suitable for analysis.

1. All sample data for individual stream sampling stations were extracted from the master database, imported into a spreadsheet, and placed into individually tabbed sheets in Excel.

2. Using macros developed at the OWML, all character data representing numeric information were converted to values; conductivities were corrected for temperature to 25°C; and negative numbers indicating values less than the detection limit were converted to positive numbers at one-half the detection limit. Sample collection dates were then correlated to seasons for averaging of sample data as follows:

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

3. The master data base contained both base flow data and storm data. For the analysis of base flow data, all records with type code “R” , or a storm number, or having DATE2 - TIME2 values assigned were deleted, leaving only the base flow information.

4. The data were then exported to Microsoft Access. Data were sorted by season and exported into Microsoft Excel as needed using queries.

5. Summary Charts, both tabular and graphical, were prepared to assist in reviewing and analyzing the base flow data.

A similar process, with appropriate modifications, was used for all other types of data.

Nutrient Loading Rate Calculation Methodologies

Loading rates to Lake Manassas from the Broad Run tributary were calculated as follows:

1. ST70 chemistry data were extracted for the period 1980 - 2000. Numeric information was changed from character data to numeric format and sorted by base flow and storm data as previously described.

2. The base flow chemistry data were merged with the daily flow record from the stream flow gage at ST70 for the same period.

3. For the daily time period between base flow chemistry samples, chemistry data were copied from the date of the sample to the mid-point of the time interval between successive samples both preceding and following the date of a given sample. This provided an estimated chemistry value for each day for the period of record.

4. With daily base flow and estimated chemistry values established, storm flow data were inserted

at the specified date and time to the nearest minute. Total storm flow and chemistry, as determined by the automated sampling station, were used for the entire storm period.

5. Daily loadings were then calculated by multiplying the average daily flow rate by the actual chemistry for that day and by the time interval over which it applied (normally 24 hours unless a storm event was inserted in which case it was calculated to the nearest minute before and after the storm event).

6. Daily nutrient loadings were then added cumulatively to determine the total nutrient load, as well as the average loading rates for the period of record.

Mann Kendal Seasonal Analysis

This analysis was completed to locate any trends occurring in the lake over the last fifteen years. This analysis takes into account the different seasons and looks statistically at all the numbers on the same basis. The numbers are then compared at a certain significance level (alpha=0.05) and if a trend is present, the data will show it, be it a small or large trend. Both the surface and bottom sections of the lake were looked at separately while the streams were looked at separately.

IV. RESULTS AND DISCUSSION

Stream Water Quality

Introduction

The database for base flow stream monitoring for Lake Manassas covers the period of August 1984 through December 2000. It currently represents over 20 years of automated and manual sampling for Broad Run, the main tributary supplying Lake Manassas. Additionally, there are over 15 years of manual sampling data for four additional streams emptying into the lake. This increased data, combined with refined techniques for estimating daily flows and calculating nutrient loadings, offers an extensive and detailed picture of the stream water quality supplying Lake Manassas.

Stream samples are analyzed for a significant number of physical and chemical parameters. Thirteen of these parameters are of primary concern when discussing stream water quality and are listed in Table 5. Base flow samples were analyzed for the period August 1984 to December 2000 for all streams. The location of the sampling stations in relationship to Lake Manassas and its tributaries is shown in Figure 2.

Table 5: 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	^{o}C
COND	Conductivity	µmho/cm (=µS/cm)
TALK	Total Alkalinity	mg/L as $CaCO_3$
OP	Orthophosphate Phosphorus	mg/L as P
TSP	Total Soluble Phosphorus	mg/L as P
TP	Total Phosphorus	mg/L as P
NH3-N	Ammonia Nitrogen	mg/L as N
SKN	Soluble Kjeldahl Nitrogen	mg/L as N
TKN	Total Kjeldahl Nitrogen	mg/L as N
OX-N	Oxidized Nitrogen	mg/L as N
TSS	Total Suspended Solids	mg/L

Analysis of Base Flow Data

Base Flow data were analyzed using numerous methods. These involve the Mann Kendal Seasonal Analysis to look for trends over the years, and plotting averages and cumulative percentages of the data. Data in the previous reports (Occoquan Watershed Monitoring Laboratory Reports, 1991, 1996), have been displayed as the change in individual parameters from the previous baseline. This has been changed to five-year running averages which are used to portray the changes in the Lake in a more visually pleasing manner. When looking at all plots of five-year running average data, the year represented on the x-axis is the last year in the five-year average. For example if the five-year average was from 1984 - 1989, then the year is considered 1989 for plotting purposes. In conjunction, the Mann Kendal Seasonal Analysis tells us if there is a trend within a certain level of significance (alpha = 0.05). An alpha of 0.05 indicates that there is a 95% confidence of a trend within the numbers. Table 5 shows the results of the Mann Kendal Seasonal Analysis for all stations and all parameters.

Dissolved Oxygen

Figures 3 and 4 show the five-year running average for DO for each season. Overall, seasonal averages for dissolved oxygen are usually above 7.0 mg/L. The maximum for the 5-year running average ending in 1996 was 20.3 mg/L, at station BR03 in the summer, while a minimum of 2.3 mg/L was found at station BR06 in the summer of 1994. During the winter and spring all stations remained above 7 mg/L. During the fall, most stations exceeded 7.0 mg/L, yet in the Summer, stations BR04, BR06, and BR07 had D.O. levels less than 7.0 mg/L. This is normal though due to high temperatures

Table 6 - Mann Kendall Analysis

Parameter	BR02	BR03	BR04	BR05	BR06	BR07	ST70
DO	**U**	-	-	-	-	-	-
PH	-	-	-	-	-	-	-
TEMP	-	-	**U**	-	-	-	-
COND	**L**	**L**	-	-	-	-	**U**
TALK	**L**	**L**	-	**L**	-	**L**	**L**
OP	**L**	**L**	**L**	-	-	-	**U**
TSP							**U**
TP	**L**	**L**	**L**	-	-	-	**U**
NH3-N	**L**	-	-	-	-	-	**U**
SKN							-
TKN	**L**	**L**	**L**	-	**L**	**L**	-
OX-N	**L**	**L**	**U**	-	**U**	**U**	-
TSS	-	-	-	-	**L**	-	**U**

Definitions:

U = Increasing Trend Present

L = Decreasing Trend Present

- = No Trend Present

Blank = No data in at least the last 5 years

Figure 3
Lake Manassas Stream Stations
DO Concentration
5 Year Running Average

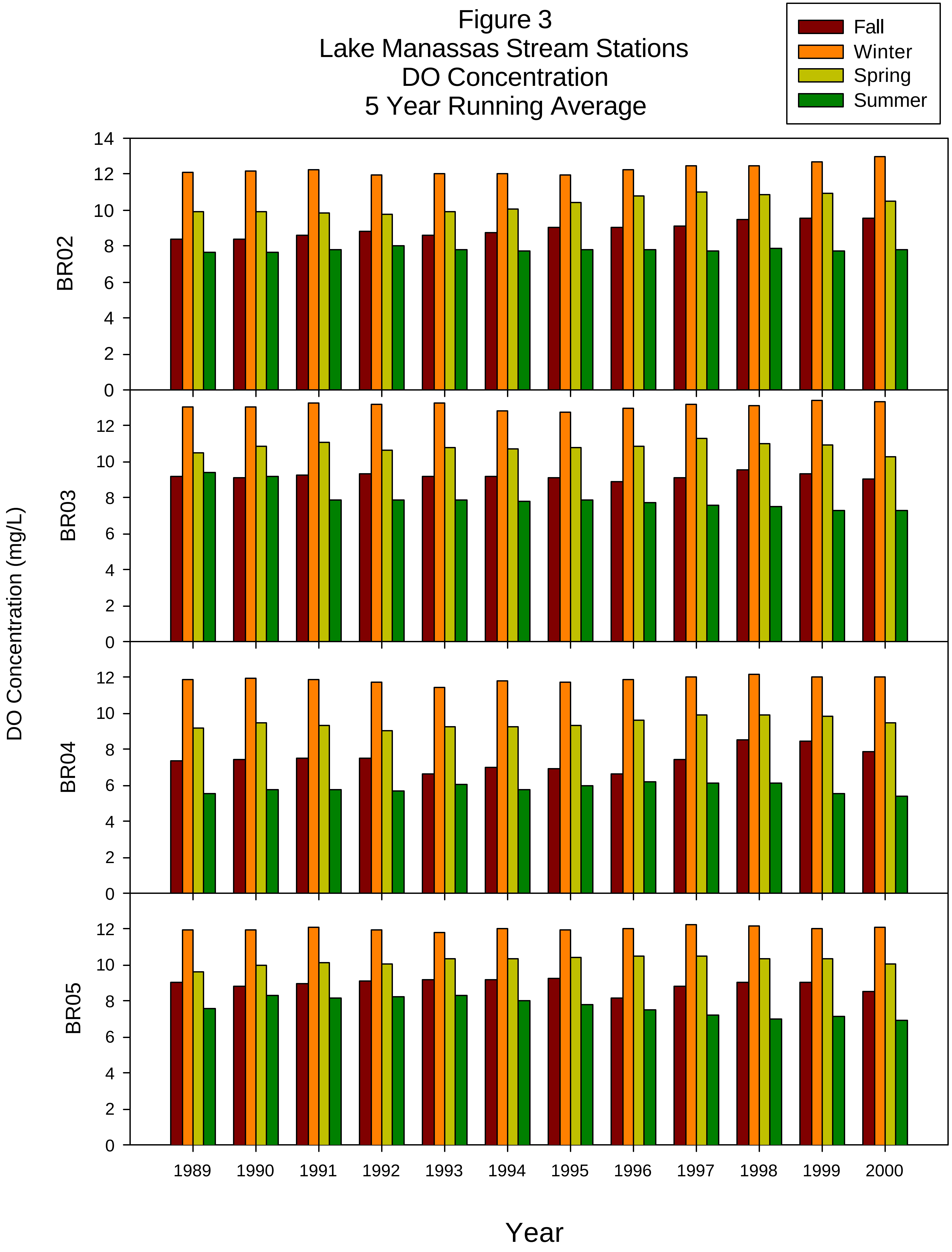
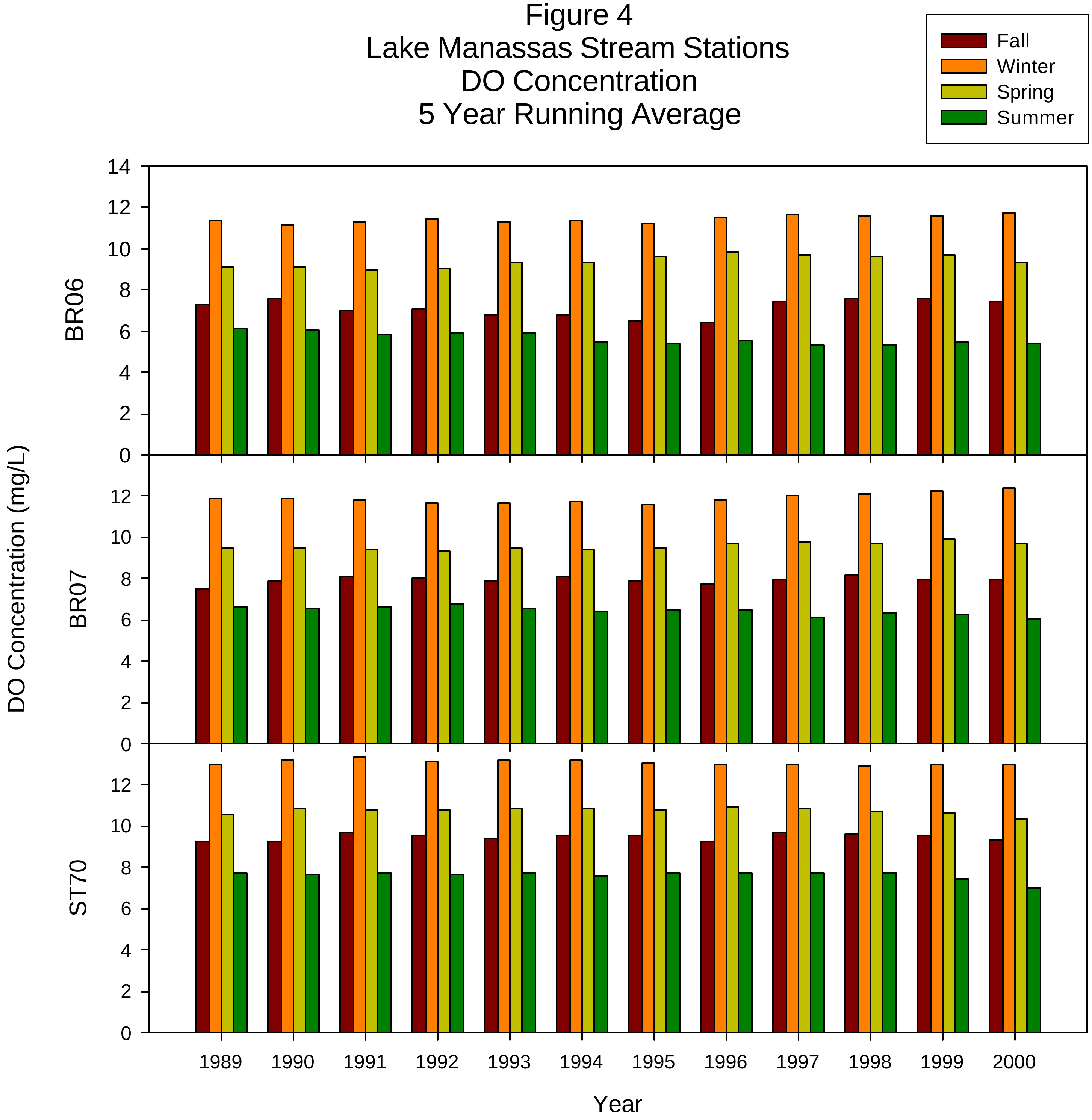


Figure 4
Lake Manassas Stream Stations
DO Concentration
5 Year Running Average



and low flow conditions and remained consistent with the previous baseline reports.

Stations BR04, located on the North Fork, and BR06, located on the southern tributary, consistently had the lowest DO concentrations of all the stations during the fall and summer months. These streams drain agricultural and pasture lands, which could result in a higher BOD (Biological Oxygen Demand) concentration due to runoff. The higher the BOD concentration in the stream, the lower the DO concentration due to the BOD utilizing the DO.

Using the Mann Kendal Seasonal Analysis (Table 6), it was found that station BR02 has an increasing trend of DO over time. Station BR02 is located on South Run, downstream of the Vint Hill Wastewater Treatment Plant. This could potentially be due to the fact that the Vint Hill Water Wastewater Treatment Plant is controlling its effluent better. There were no other trends found in any of the other stations with respect to DO

Along the length of South Run starting at Lake Brittle and moving toward Lake Manassas are stations BR07, BR02, and BR03. The lowest DO concentration occurred at BR07 and increased as the stream reached station BR03. This occurred during all seasons with the most pronounced season being summer and the least being the spring.

Hydrogen Ion Activity and Alkalinity

During the five year running average years ending in 1990, the maximum value for pH was 8.2 at station ST70 in the spring, and the minimum value was 5.9 at station BR03 in 1981 during the winter. The minimum pH for each of the stations and seasons was relatively constant between 6.1 and 6.7. The maximum pH for each of the stations and seasons was usually between 7 and 8. The Mann Kendall Seasonal Analysis showed no trends for pH, either upward or downward.

Figure 5 shows the seasonal distribution of pH for station ST70. The winter overall had a lower pH than all other seasons. A possible reason for the pH increase in the summer and fall is that the streams are at a low flow condition. Algae will extract CO_2 from the water, thereby increasing pH and since there is less water, this change is readily noticeable. There is also more interaction of the water with the soil, which in turn increases the alkalinity and increases the buffering capacity of the water. The water pH will then increase and become basic. In the winter and spring when the water flow increases, there will be much more runoff to the streams. Runoff is very low in O_2, but very high in CO_2 due to bacterial respiration (Wetzel, 2001). This empties into the streams, increasing the CO_2 content which is already high because decomposition dominates over in-channel photosynthetic production. Some CO_2 is lost to the environment but the bacterial respiration within the stream is much greater so the CO_2 continues to increase. Since there is also a decrease in the alkalinity or buffering capacity of the water, the water has a tendency to become more acidic.

Total Alkalinity has decreased overall in the water entering Lake Manassas (Figure 6) and there is actually a trend toward lower alkalinity occurring in stations BR02, BR03, BR05, BR07 and ST70 indicated by the Mann Kendal Seasonal Analysis. Figures 7 and 8 shows the five-year running

Figure 5
pH Distribution in Base Flow at ST70
Lake Manassas Watershed: 1978-2000

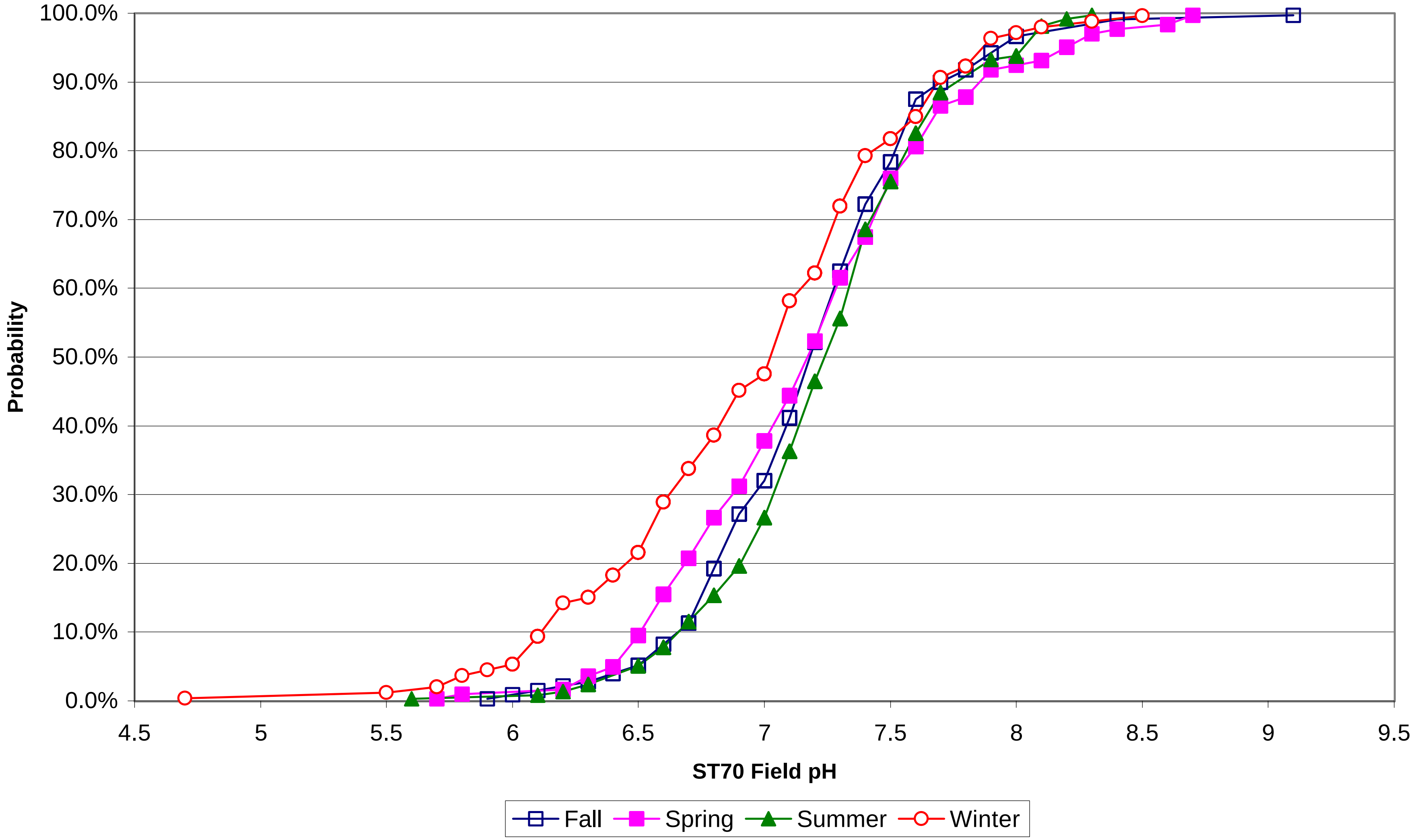


Figure 6
Mean Total Alkalinity at ST70 as Function of FLow
Lake Manassas: 1978-2000

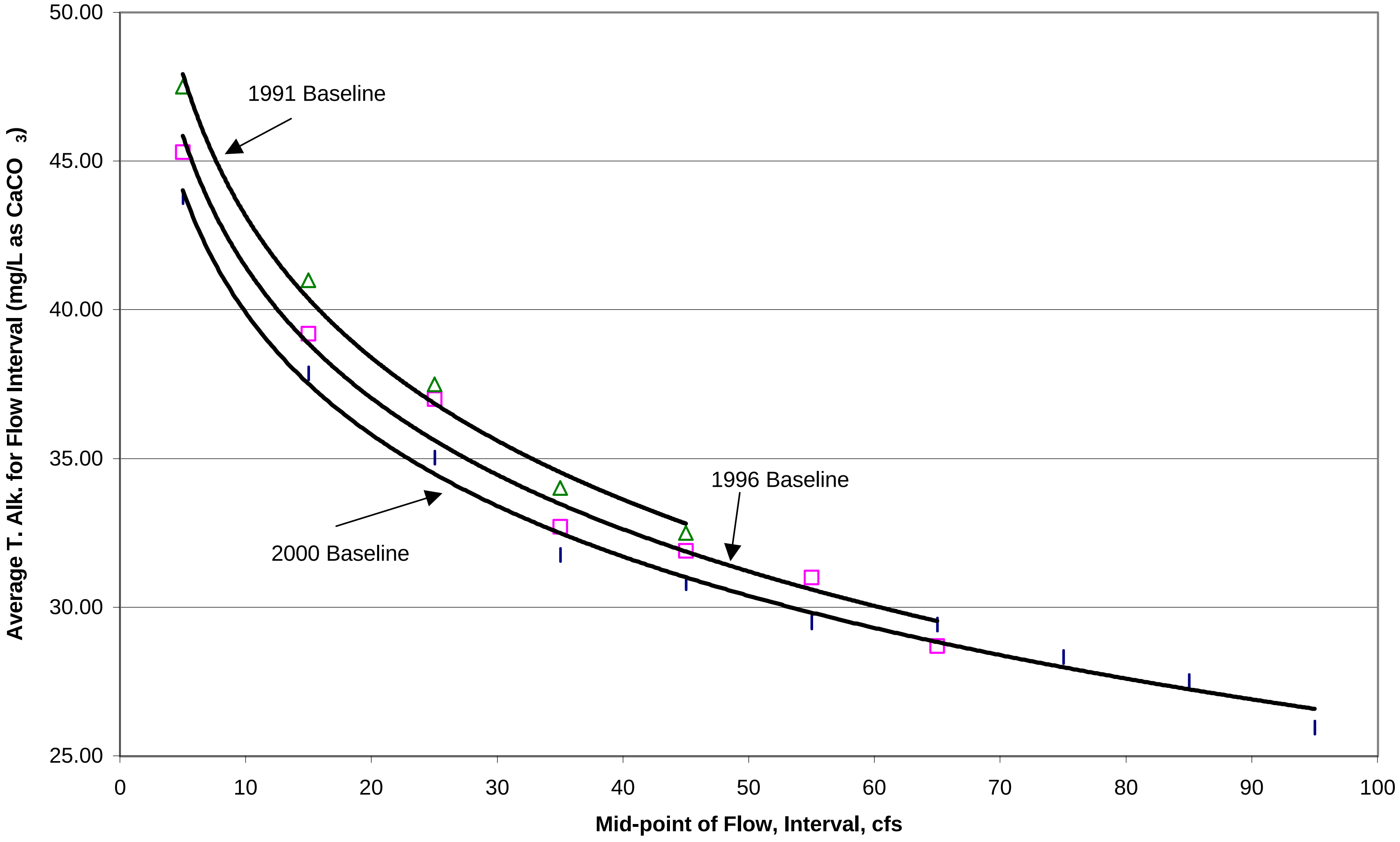


Figure 7
Lake Manassas Stream Stations
Total Alkalinity
5 Year Running Average

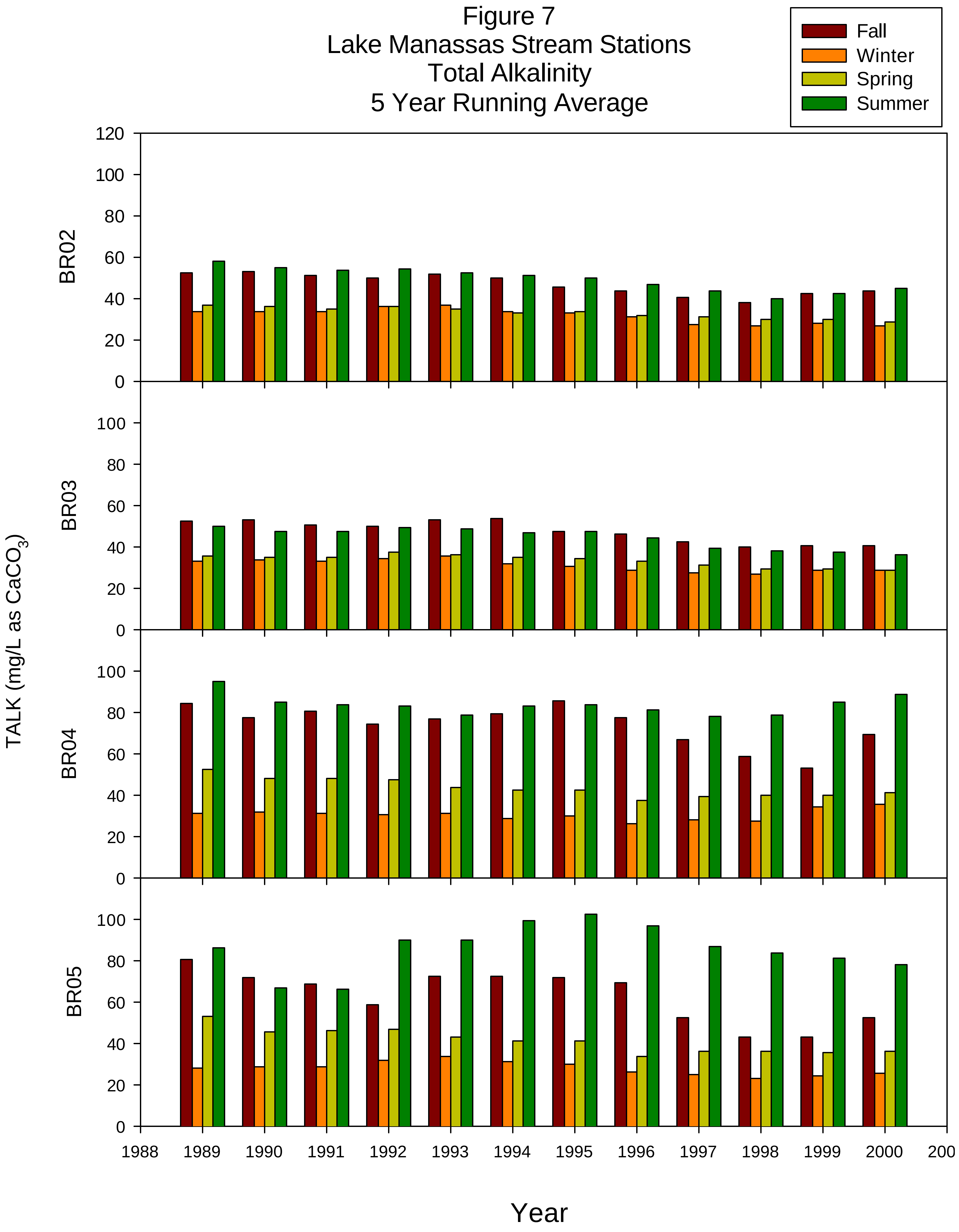
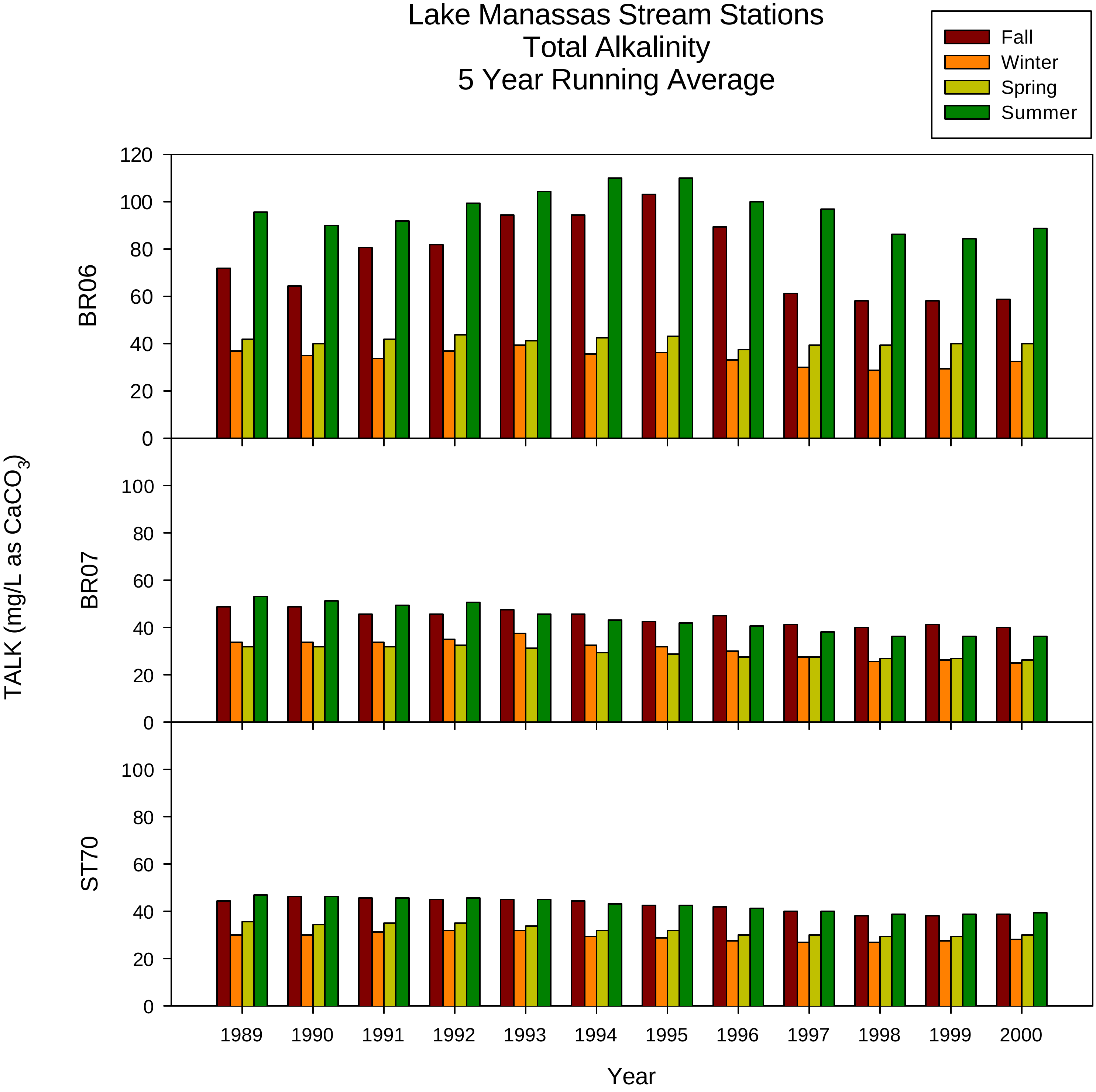


Figure 8
Lake Manassas Stream Stations
Total Alkalinity
5 Year Running Average



average for each station from 1984 to 2000. The minimum alkalinity level for the five year running average ending in 1991 was 16.6 mg/L as $CaCO_3$ at station BR06 in the summer and the maximum level was 215 mg/L as $CaCO_3$ at BR04 in 1987 during the fall.

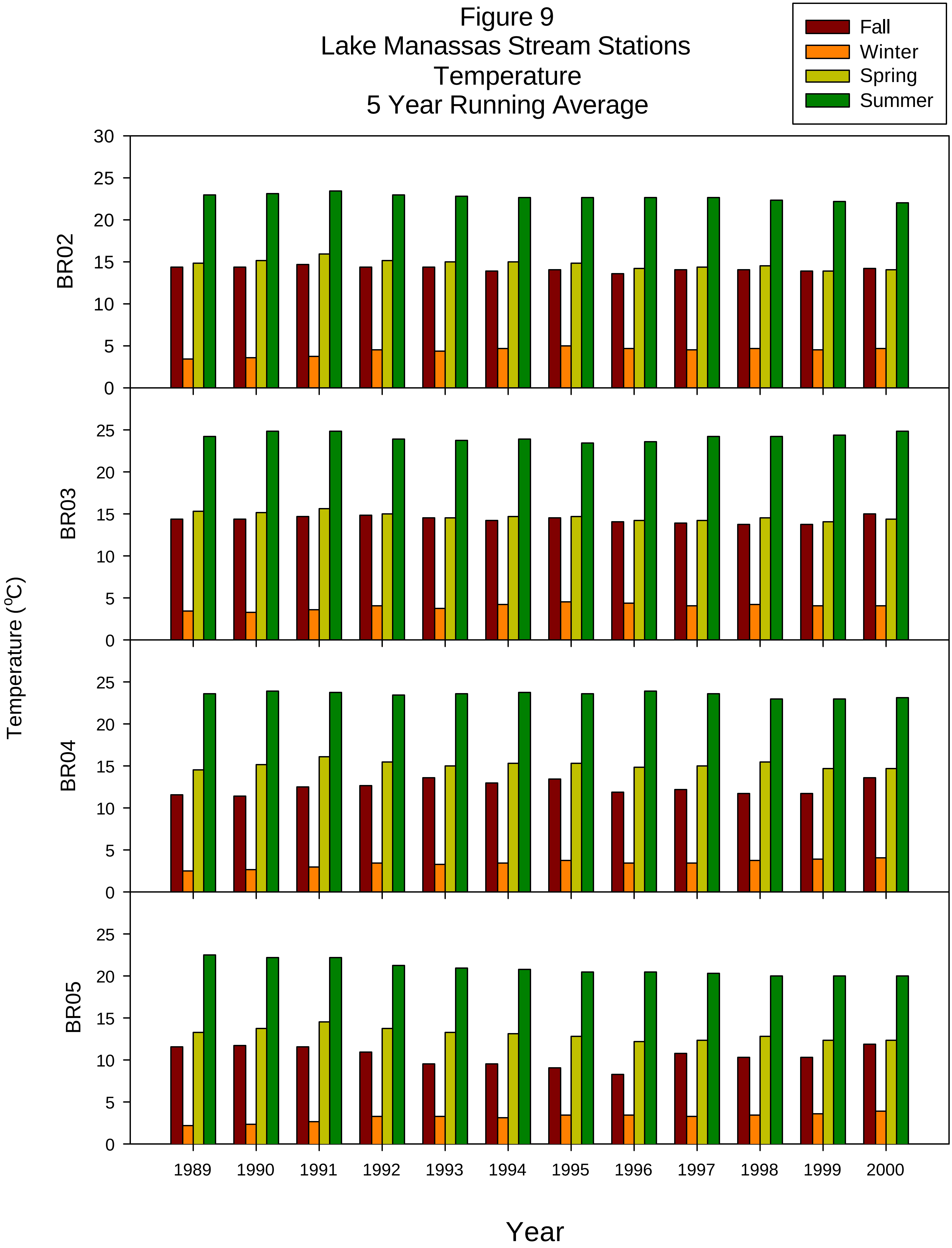
Temperature

Figures 9 and 10 show the five-year temperature running averages for each station over fifteen years. During the five-year running average period ending in 2000, the maximum temperature measured was 26.3 ^{o}C at station BR03 in the Summer, and the minimum 5 year averaged value was 1.3^{o}C at station BR05 in the winter of 1989 Overall, there was not much variability between stations for any particular season or from averaged 5 year increments of data.

Conductivity

Figures 11 and 12 show the five- year running average conductivity bar charts for all sampling stations. The conductivity value that is shown has been corrected for temperature to 25 ^{o}C. The maximum conductivity value for the five year running average ending in 1999 was 2190 µmho/cm at station BR05 in the winter, and the minimum value was 72.7 µmho/cm at station BR07 in the spring of 1998. The Mann Kendall Seasonal Analysis revealed that there is a declining trend for stations BR02 and BR03 and an increasing trend for ST70. Both ST70 and BR07 have had consistently lower values than the other stations over the fifteen years, and stations BR02 and BR03 appear to be developing the same pattern. This may be due to a reduction in agricultural runoff as there are more particulates and higher TSS in the waters. Stations BR02, BR05 and BR06 all showed marked increases in conductivity in the fall and summer.

Figure 9
Lake Manassas Stream Stations
Temperature
5 Year Running Average



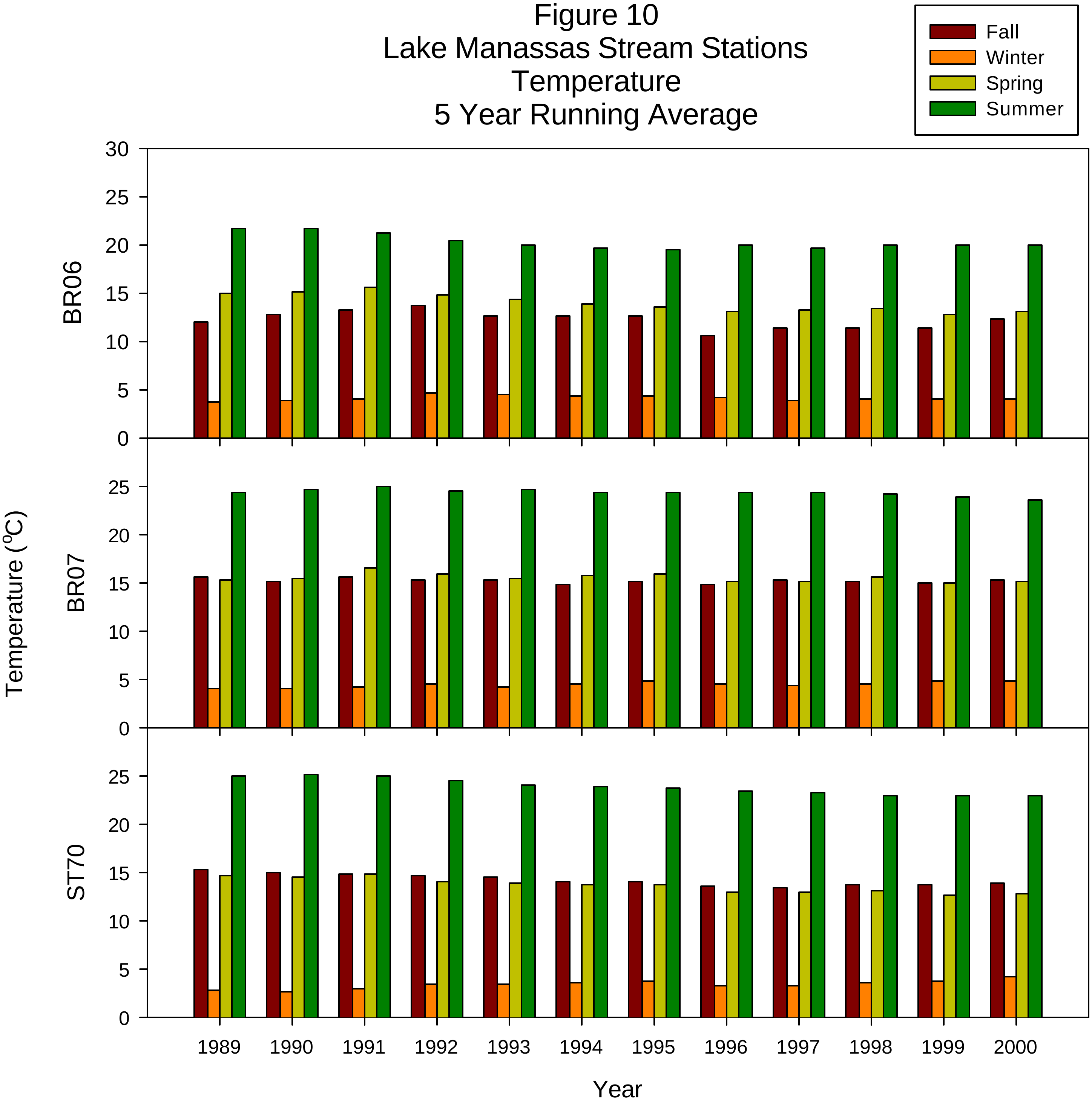


Figure 10
Lake Manassas Stream Stations
Temperature
5 Year Running Average

Figure 11
Lake Manassas Stream Stations
Conductivity
5 Year Running Average

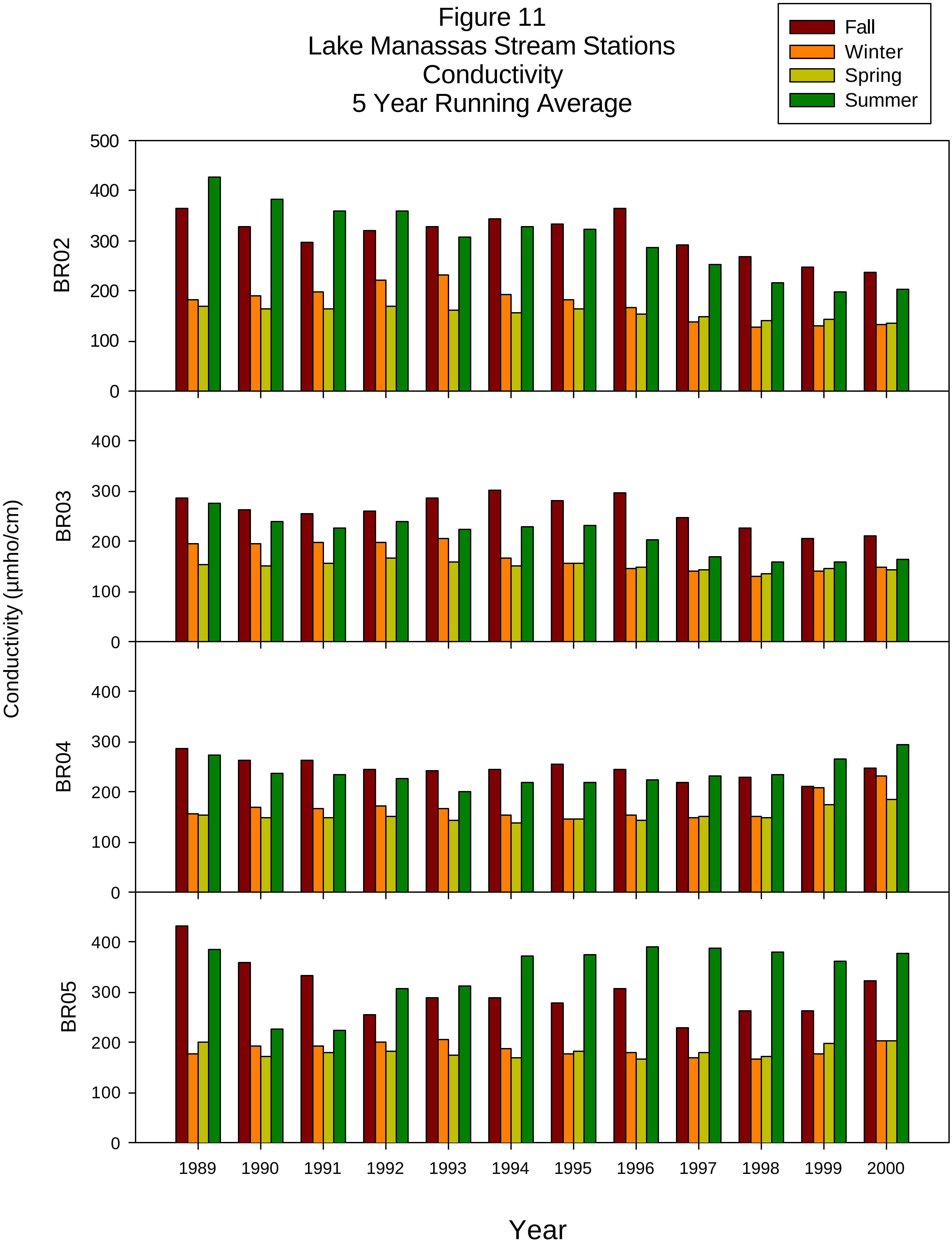
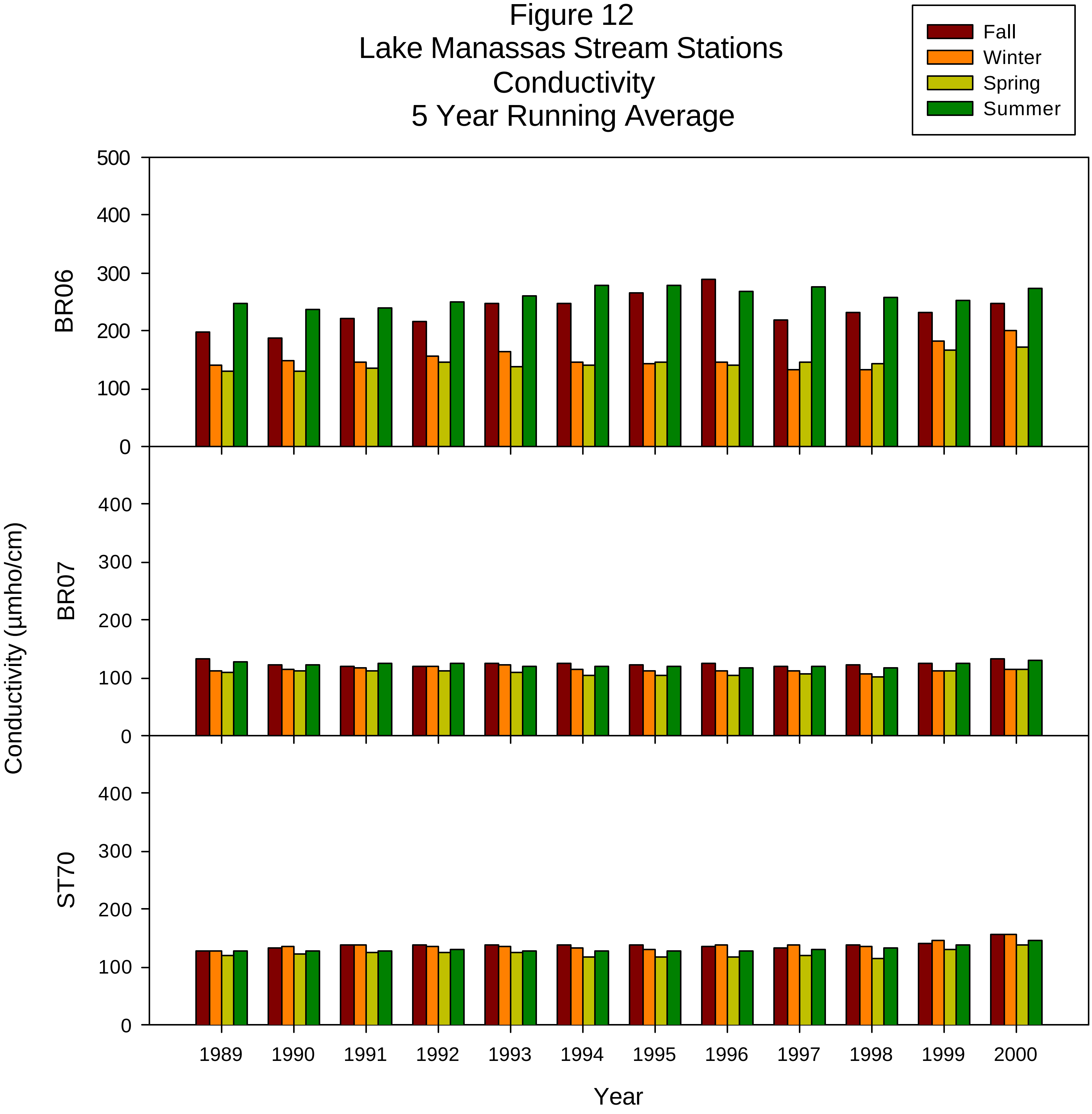


Figure 12
Lake Manassas Stream Stations
Conductivity
5 Year Running Average



There was a marked decrease in conductivity at stations BR02 and BR03 which are now close to the value of BR07, which is an upstream station. BR05 and BR06 still show high conductivities in the summer and fall which could be due to agricultural runoff.

Total Suspended Solids (TSS)

Figures 13 and 14 showed the five-year running average of TSS over the period of 15 years. The high summer values obtained during the earlier years at station BR04 are because of one high TSS reading of 347mg/L (Occoquan Watershed Monitoring Laboratory, 1996). From the Mann Kendal Seasonal Analysis (Table 6) station BR06 showed a declining trend while ST70 shows an increasing trend. Station ST70 showed most of its increase in TSS during the summer and winter months. Station BR05 has shown an interesting change in that the spring season used to have the highest TSS average values, and then in 1993 to 1994 the average values changed and the summer then increased and currently showed the higher value.

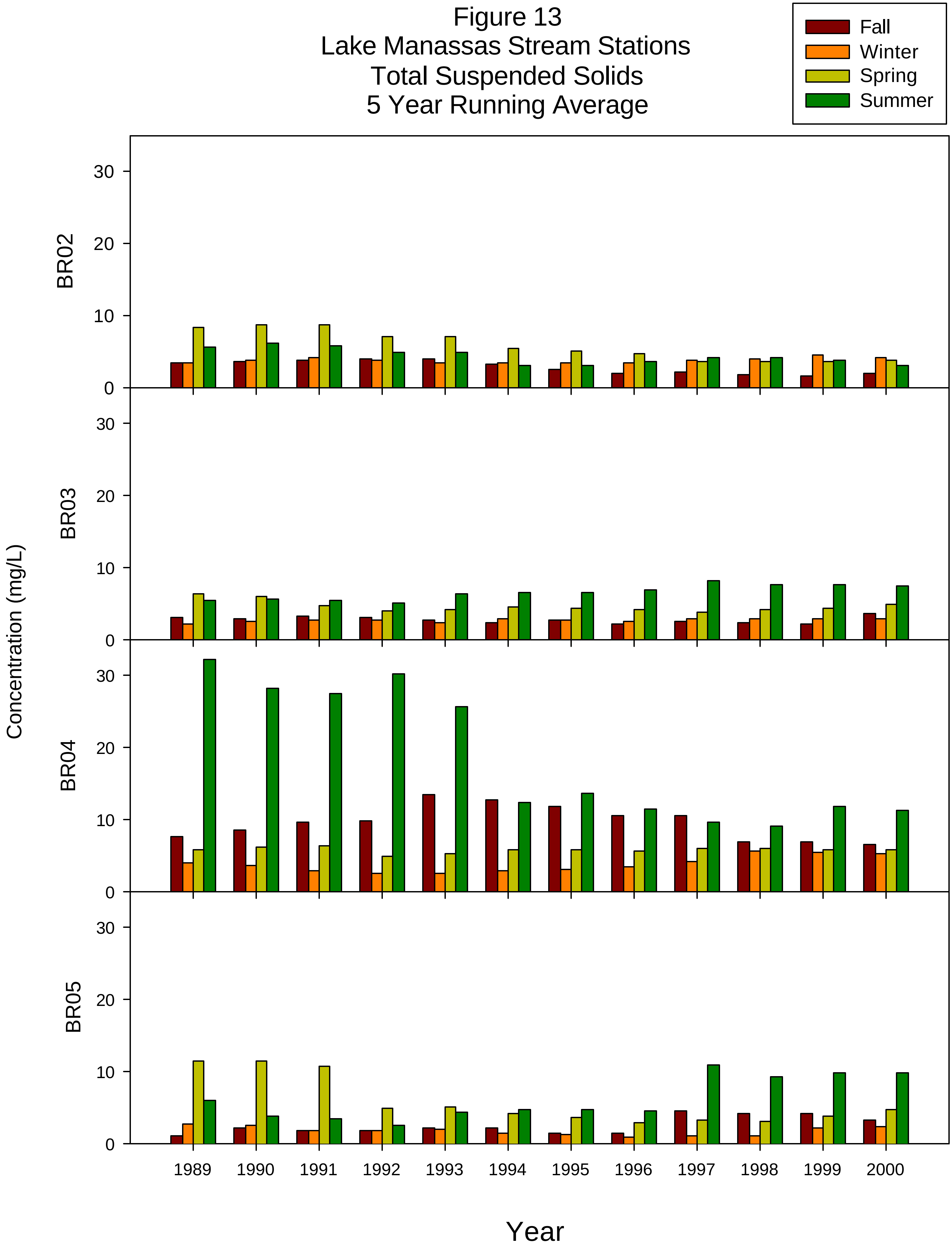
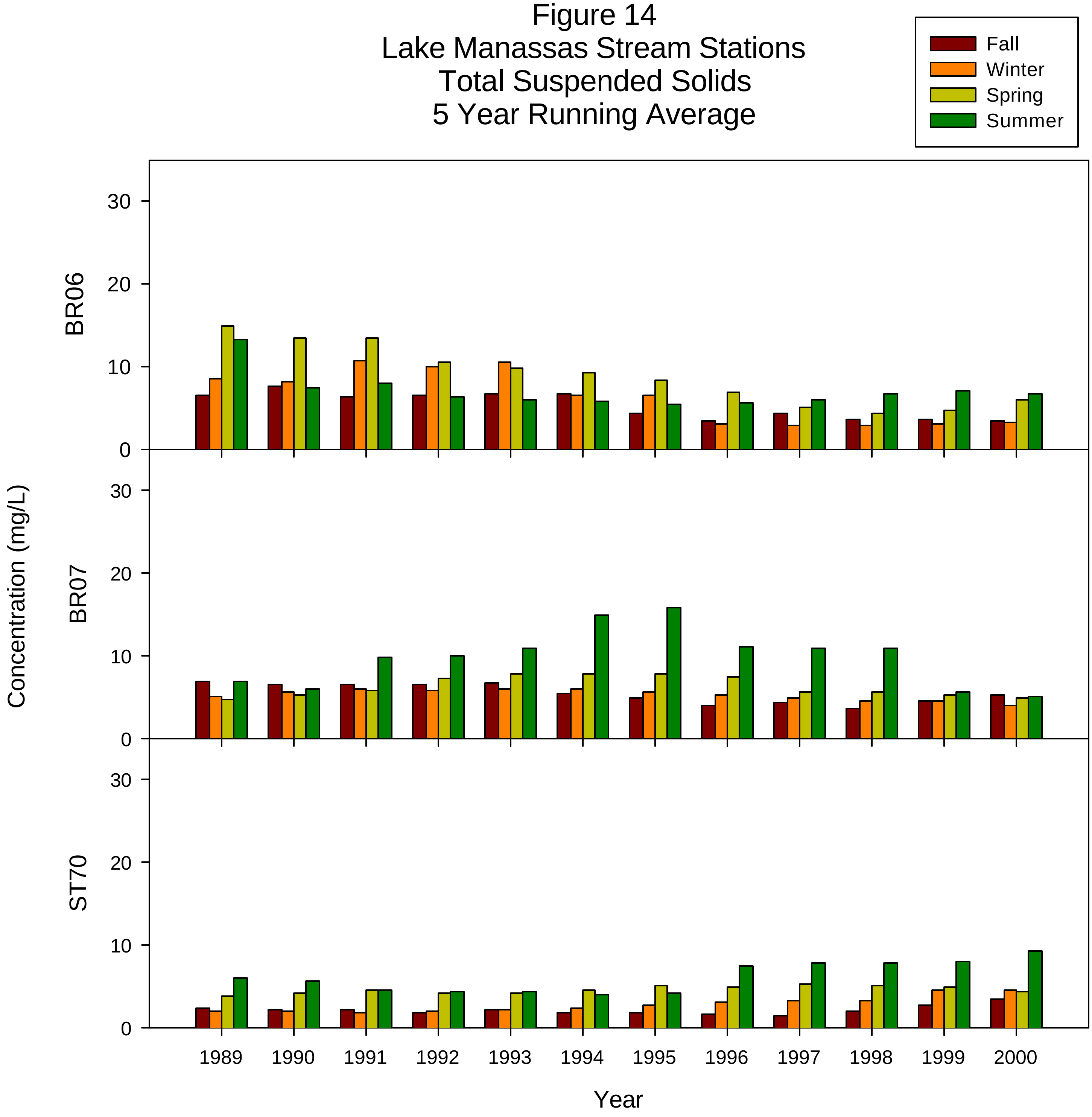


Figure 13
Lake Manassas Stream Stations
Total Suspended Solids
5 Year Running Average

Figure 14
Lake Manassas Stream Stations
Total Suspended Solids
5 Year Running Average



Nutrients

The productivity of Lake Manassas is determined in large part by the concentrations of nutrients that are available for biological uptake. The nutrient supply is regulated to a great extent by tributary flows to the reservoir.

Nitrogen

A large portion of the nitrogen load in streams is from surface runoff or groundwater discharge, with small contributions from air deposition or plants. The nitrogen cycling that occurs in the streams is similar to that of lakes and is largely influenced by bacterial, fungal, and other microbial metabolism (Wetzel, 2001). The nitrogen is used repeatedly as it continues downstream. The amount of time it takes for an atom of Nitrogen to make it all the way downstream depends on the type and amount of microbiota attached to the stream bed. The more microbiota in the stream, the longer it takes for that atom of Nitrogen to make it downstream.

Five-year running averages of nitrogen concentrations at Lake Manassas stream stations are shown in Figures 15 through 22. The four types of nitrogen shown are oxidized nitrogen (OX-N), ammonia (NH3-N), soluble Kjeldahl nitrogen (SKN), and total Kjeldahl nitrogen (TKN). All trends referred to below can be found in Table 5 (results of the Mann Kendal Seasonal Analysis). The most noticeable trend is that BR02 has a decreasing trend for all types of nitrogen excluding SKN. There are no data for SKN except on station ST70 for the last five years. The decrease at BR02 could be due to the fact that the Vint Hill Wastewater Plant maybe treating its effluent to higher standards. BR03 has

Figure 15
Lake Manassas Stream Stations
Ox-N Concentration
5 Year Running Average

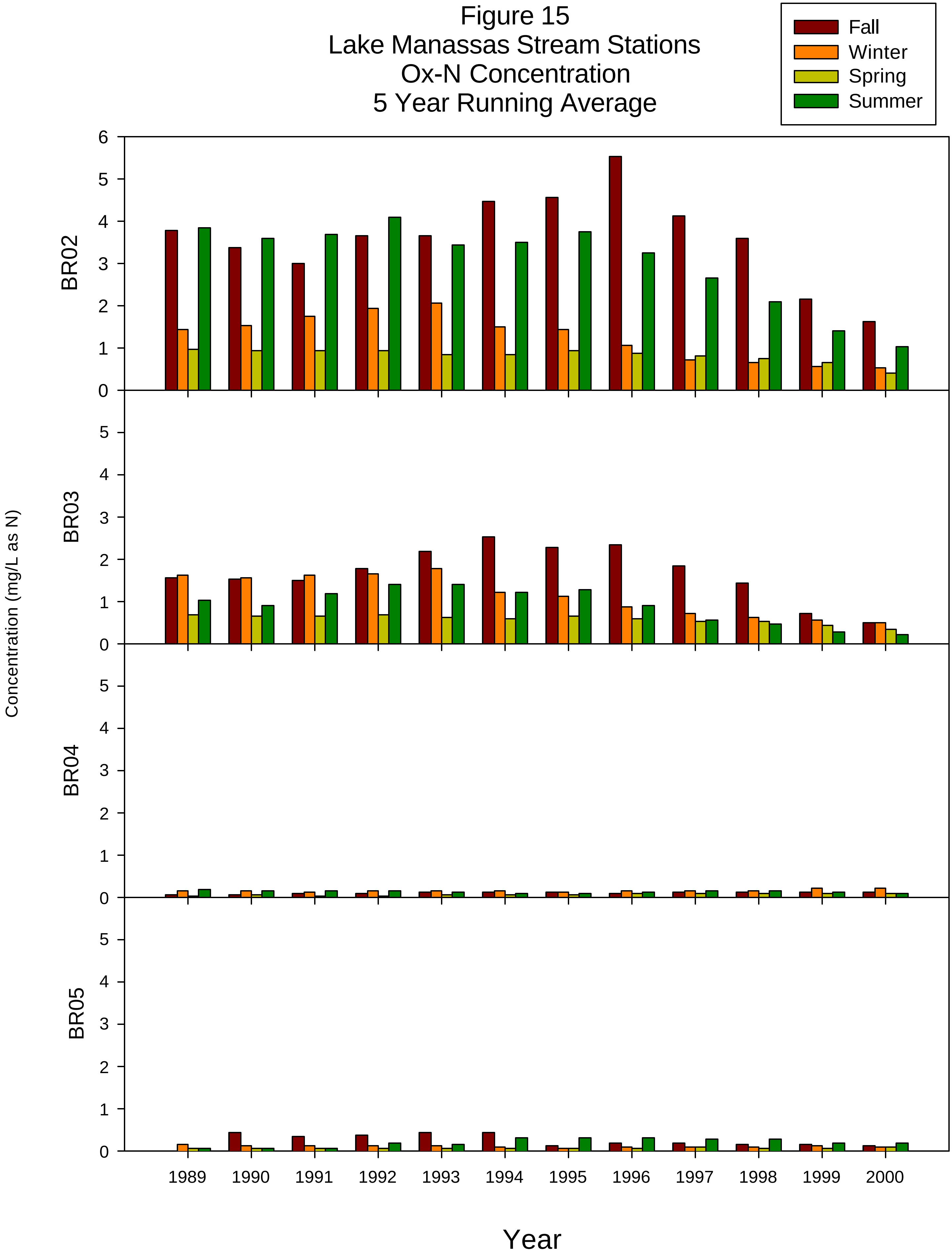


Figure 16
Lake Manassas Stream Stations
Ox-N Concentration
5 Year Running Average

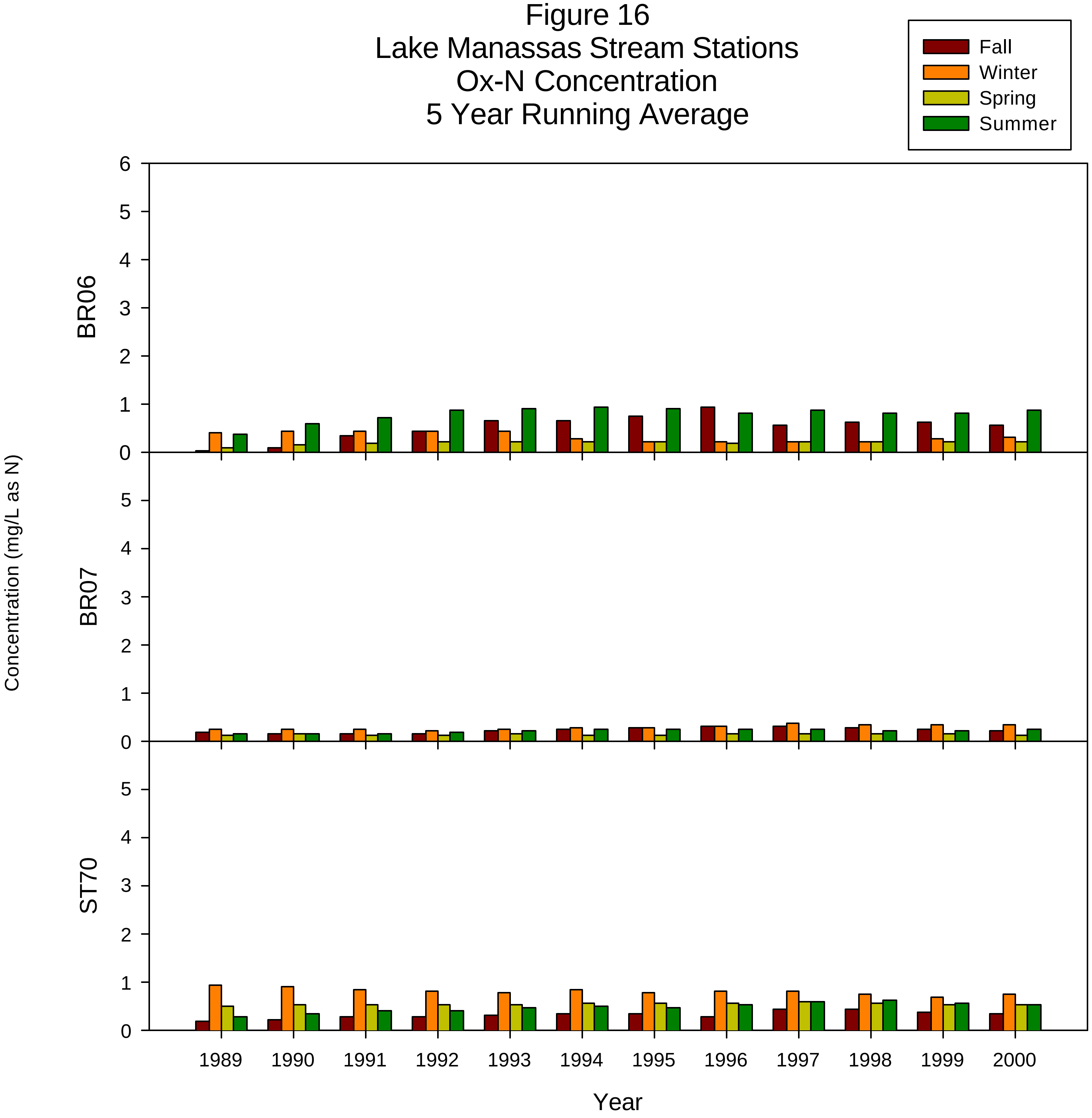
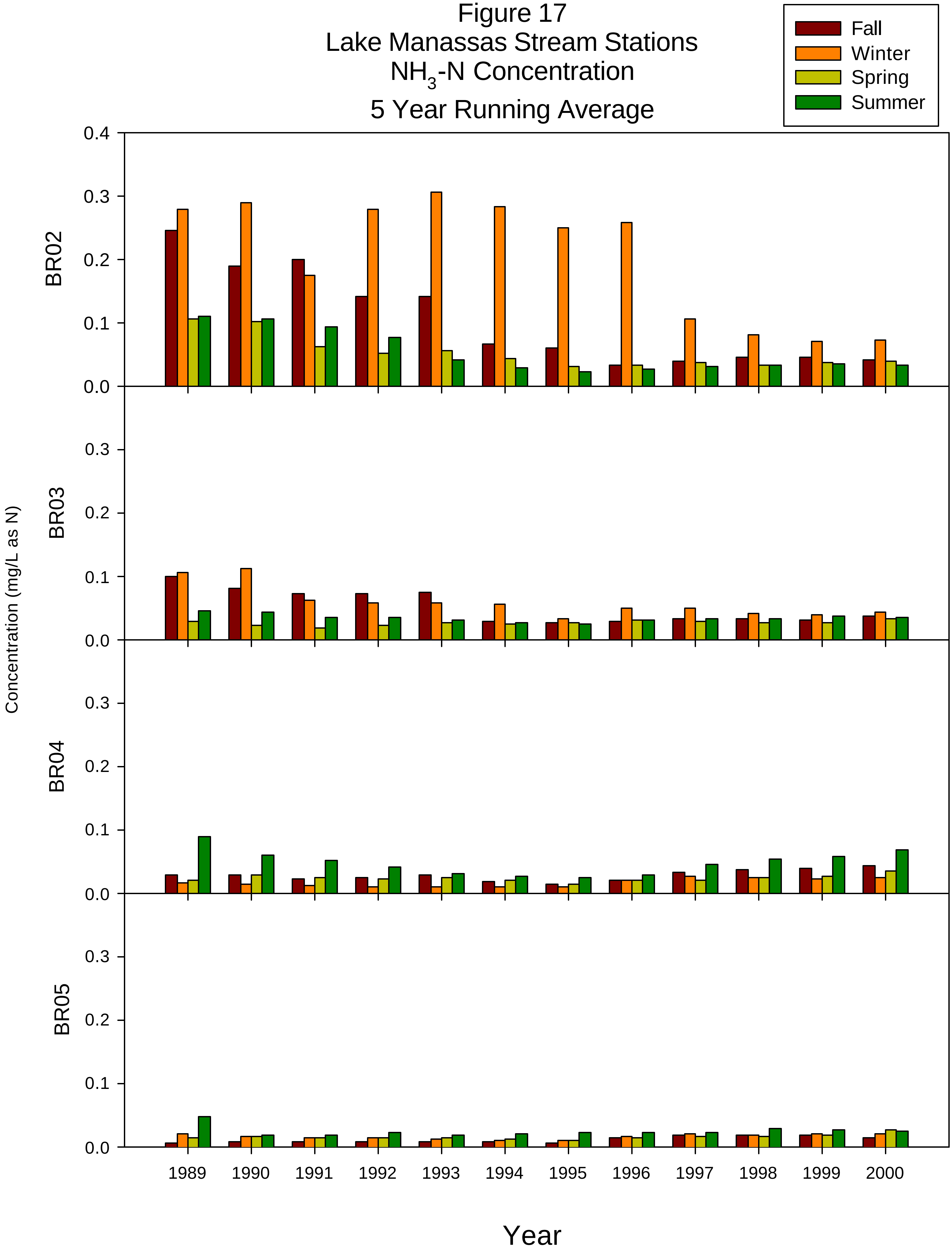


Figure 17
Lake Manassas Stream Stations
NH_3-N Concentration
5 Year Running Average



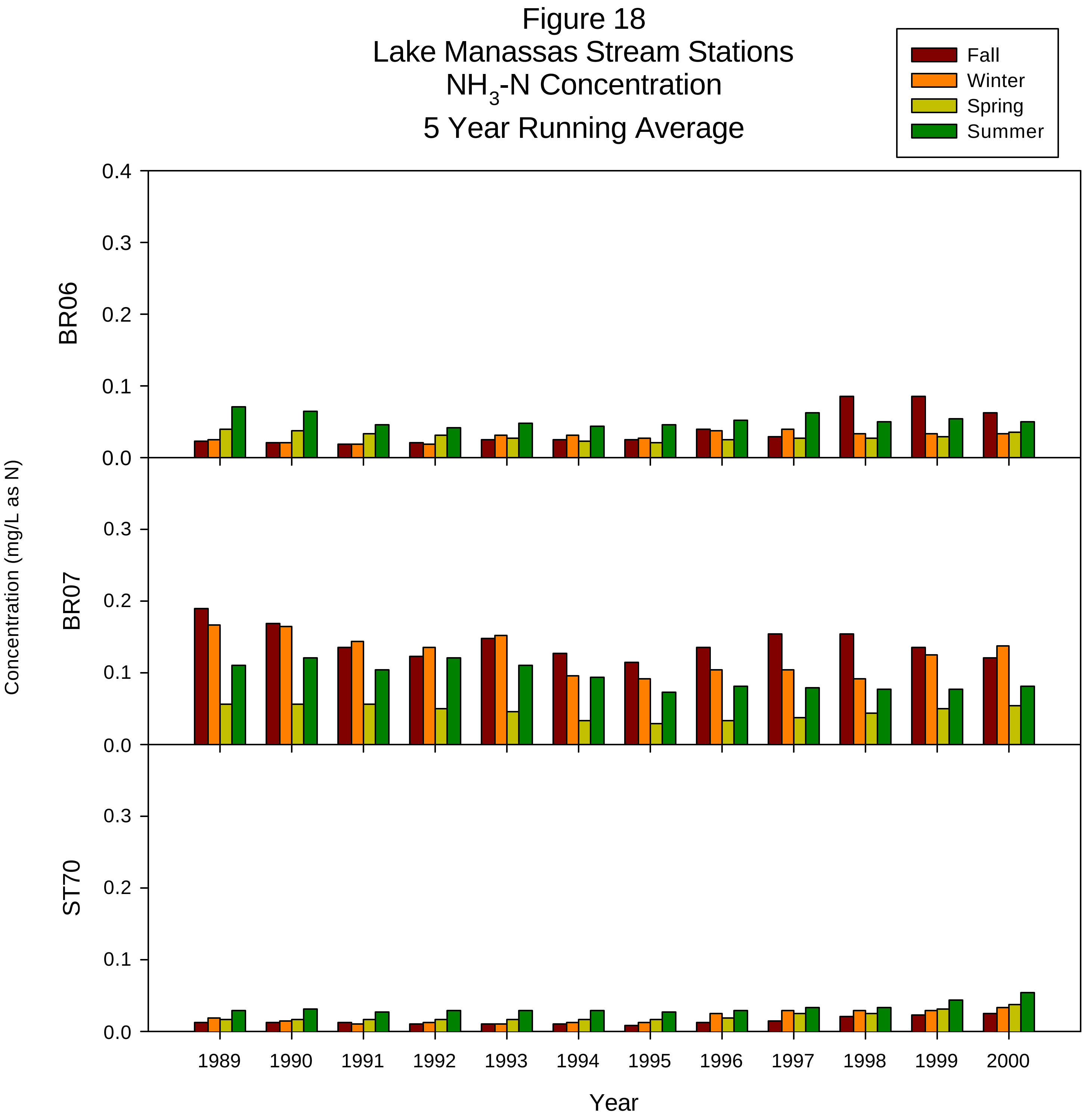


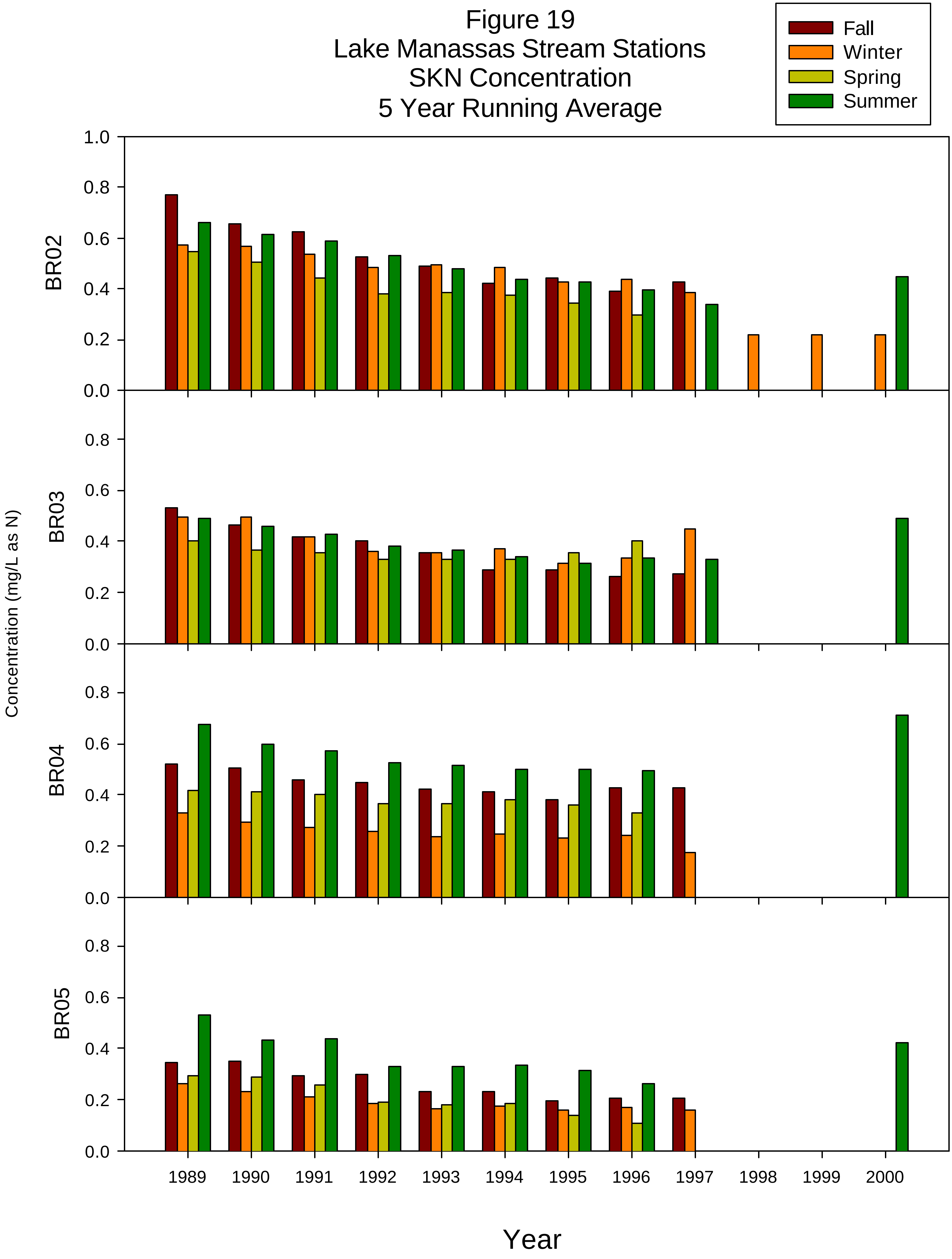
Figure 18

Lake Manassas Stream Stations

NH_3-N Concentration

5 Year Running Average

Figure 19
Lake Manassas Stream Stations
SKN Concentration
5 Year Running Average



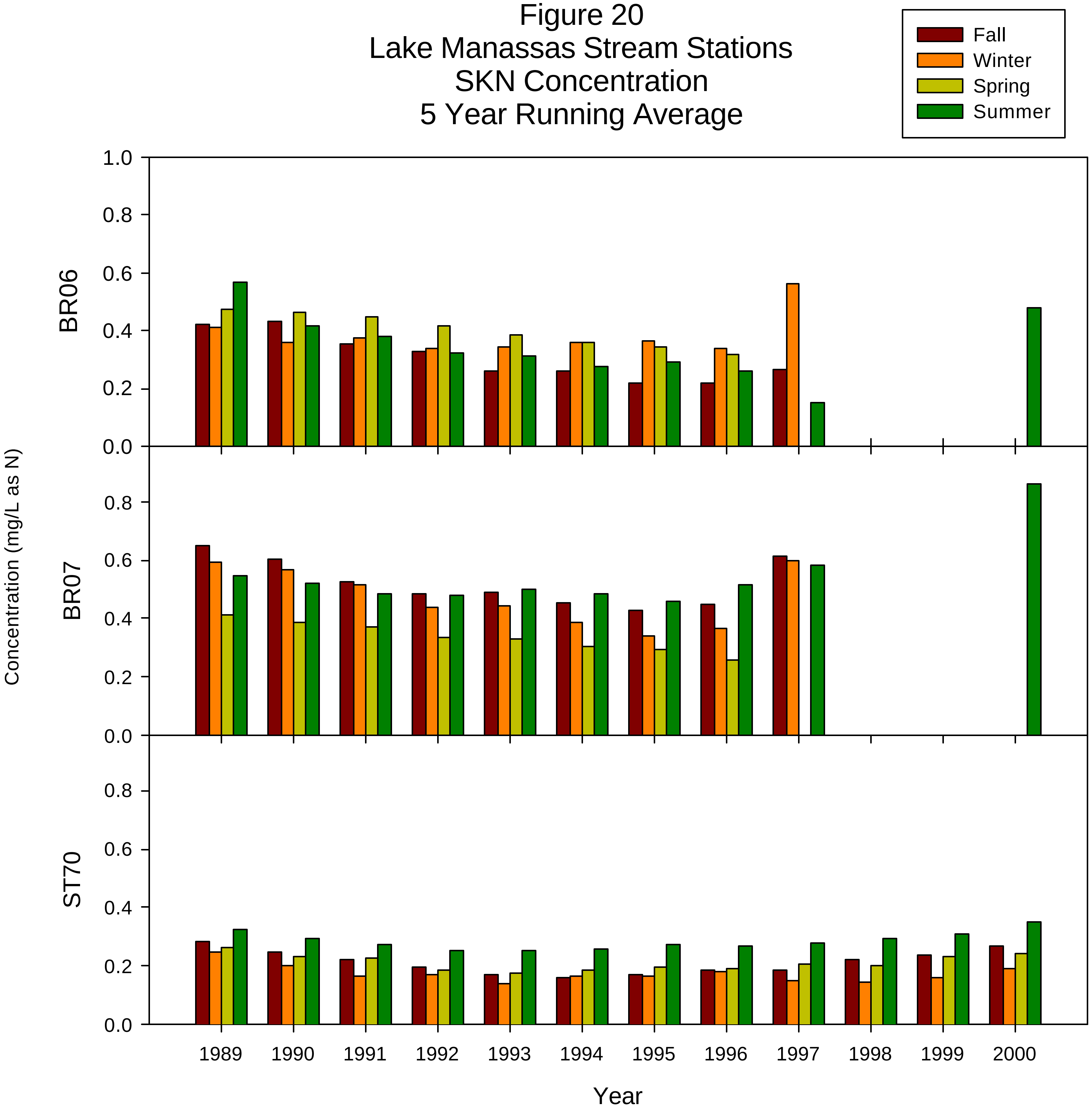
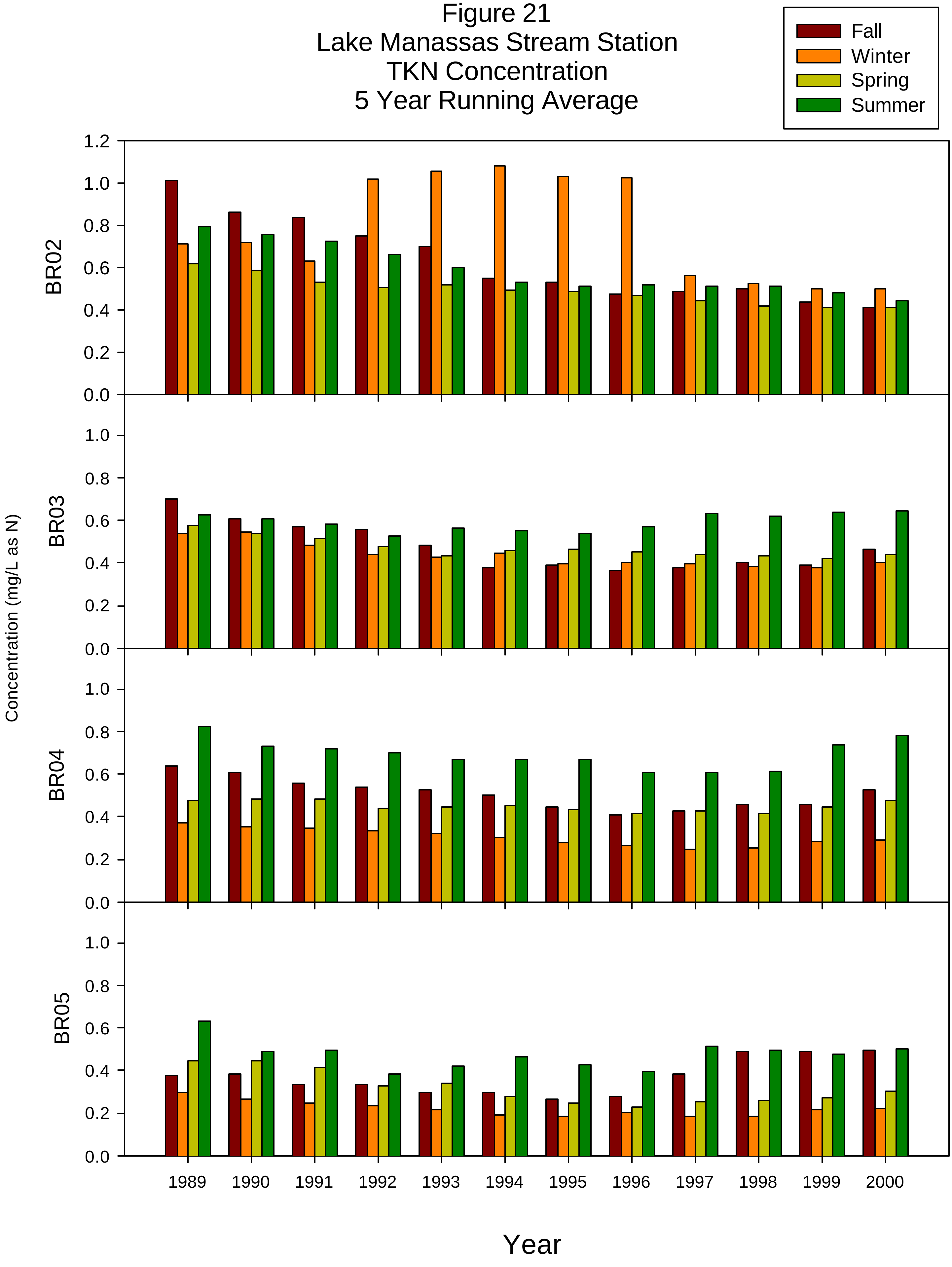


Figure 20
Lake Manassas Stream Stations
SKN Concentration
5 Year Running Average

Figure 21
Lake Manassas Stream Station
TKN Concentration
5 Year Running Average



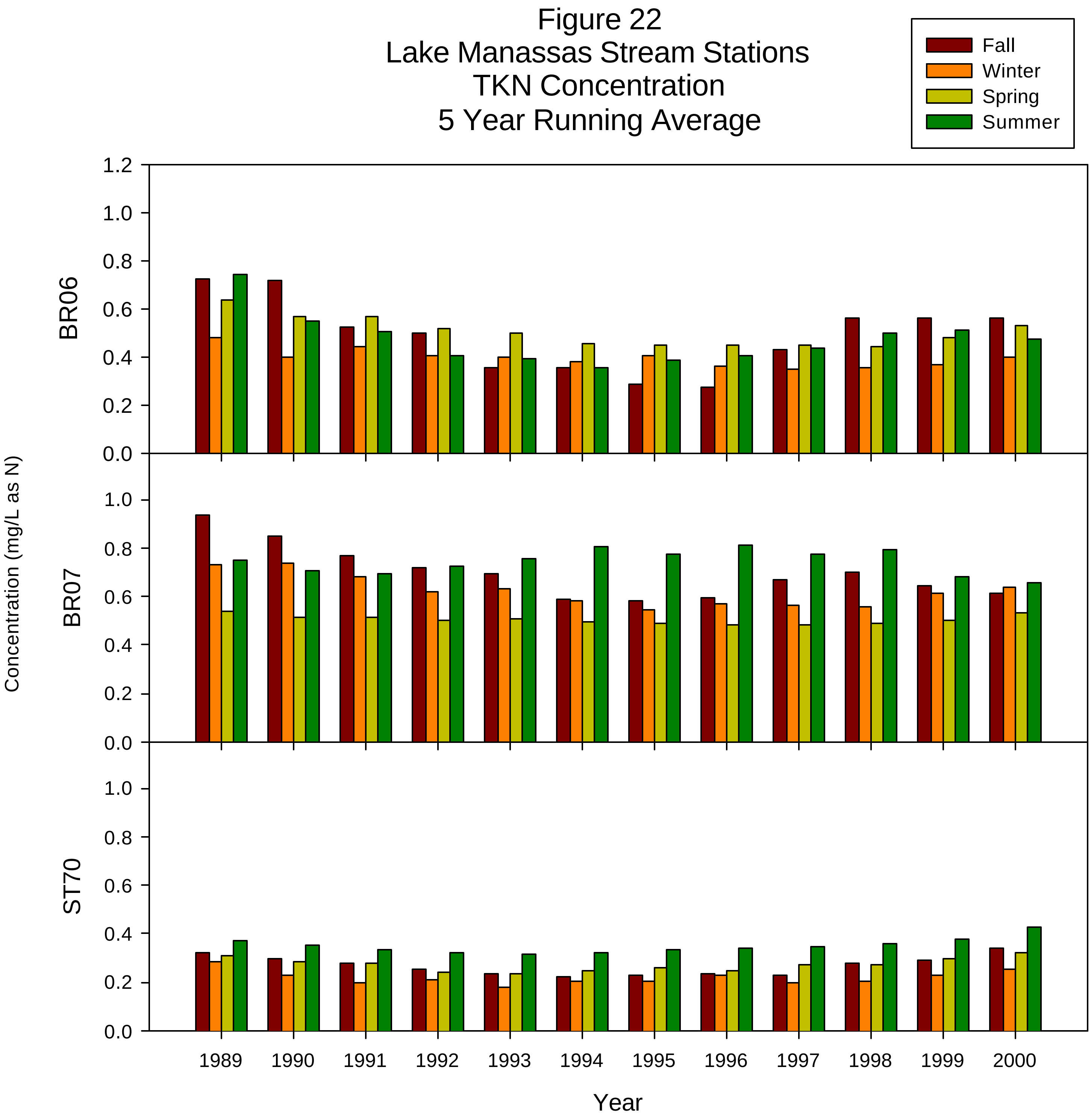


Figure 22
Lake Manassas Stream Stations
TKN Concentration
5 Year Running Average

decreasing trends for TKN and OX-N. BR04, BR06, BR07 have decreasing trends in TKN, but increasing in OX-N. The only trend observed at ST70 for nitrogen was an increase in NH3-N. Most of these increases and decreases are relatively minor though, except for stations BR02 and BR03. This would help reduce the nitrogen entering the reservoir and help maintain a nitrogen limiting system.

There does not seem to be any one season that has more nitrogen than another, although the spring tends to have the lowest amount. This could be because of high flow conditions and dilution. There is still a slight decrease in the fall and summer between stations BR02 and BR03. The most likely reason for this is dilution of the stream at BR03 in the summer and fall. The small pond above BR03 could be influencing this station or the lake water is encroaching into the mouth of the stream, right where BR03 is located. This has been noticed happening when there is a full pool and low flow in the streams. Station LM06 (data analyzed later) has a low average OX-N concentration (0.05-0.4 mg/L depending on the season), so if this mixes with station BR03, there will be a decrease in the OX-N.

Phosphorus

Phosphorus plays a major role in biological metabolism (Wetzel, 2001). Phosphorus is usually the least abundant for most organisms, and most often is the limiting-nutrient. Orthophosphate is the only directly useable form of soluble inorganic phosphorus. It is also found that dissolved phosphorus is usually higher in streams than lakes. This could be due to the higher soil surface area to water creating a larger surface area for the phosphorus to dissolve out of the sediments into the water. In streams phosphorus can be limiting but when the nutrient increases so does the microbial activity.

Five year running averages are shown in Figures 23 through 28. The three different types of phosphorus that will be examined are Total Phosphorus (TP), Orthophosphate phosphorus (OP) and Total Soluble Phosphorus (TSP). Unfortunately, there are no data for the last five years on any station except ST70 for TSP, so it will not be discussed except for that specific station. All trends come from Table 6, Mann Kendall Seasonal Analysis. Stations BR02, BR03 and BR04 have decreasing trends in OP and TP. Stations BR05, BR06 and BR07 showed no trends at all while ST70 showed an increasing trend in all three types of phosphorus.

Overall, the fall and summer values are higher than the spring and summer values. LM06 used to have the winter and spring values higher than the fall and spring, but this turned around in 1995 and now the fall and summer values are the highest. The reason for this change is not known.

BR02 and BR03 show the same correlation as with nitrogen, BR03 values are less than BR02 for TP and OP. This could be due to dilution as mentioned above, and / or due to algal activity between the two stations. Levels at BR03 are now approximately the same as the other streams and BR06 now has the highest average of the streams directly entering the lake. Station BR06 does have a farm pond upstream that may be adding to the phosphorus loading.

Figure 23

Lake Manassas Stream Stations
Total Phosphorus
5 year running average

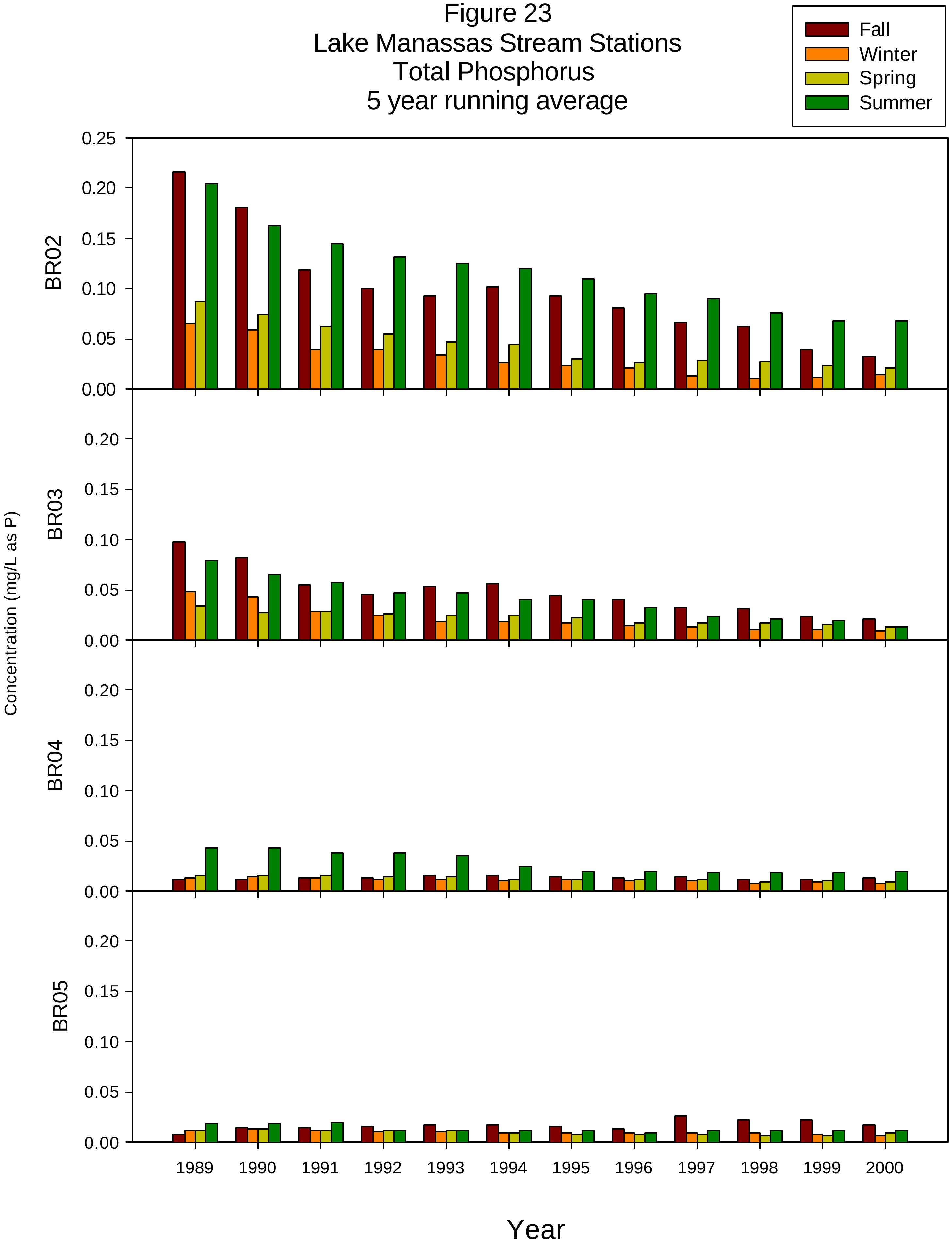


Figure 24
Lake Manassas Stream Stations
Total Phosphorus
5 year running average

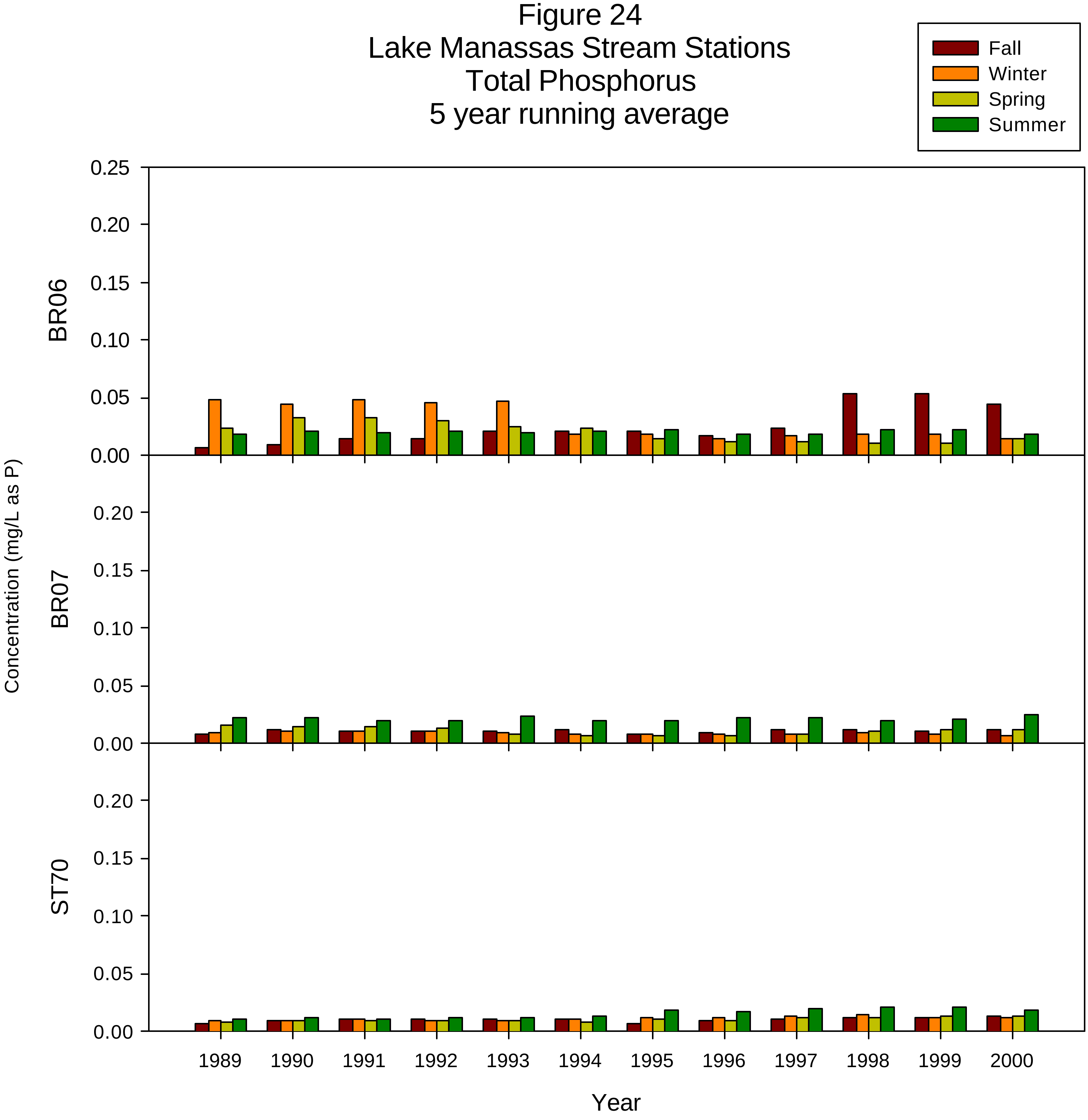


Figure 25
Lake Manassas Stream Stations
OP Concentration
5 Year Running Average

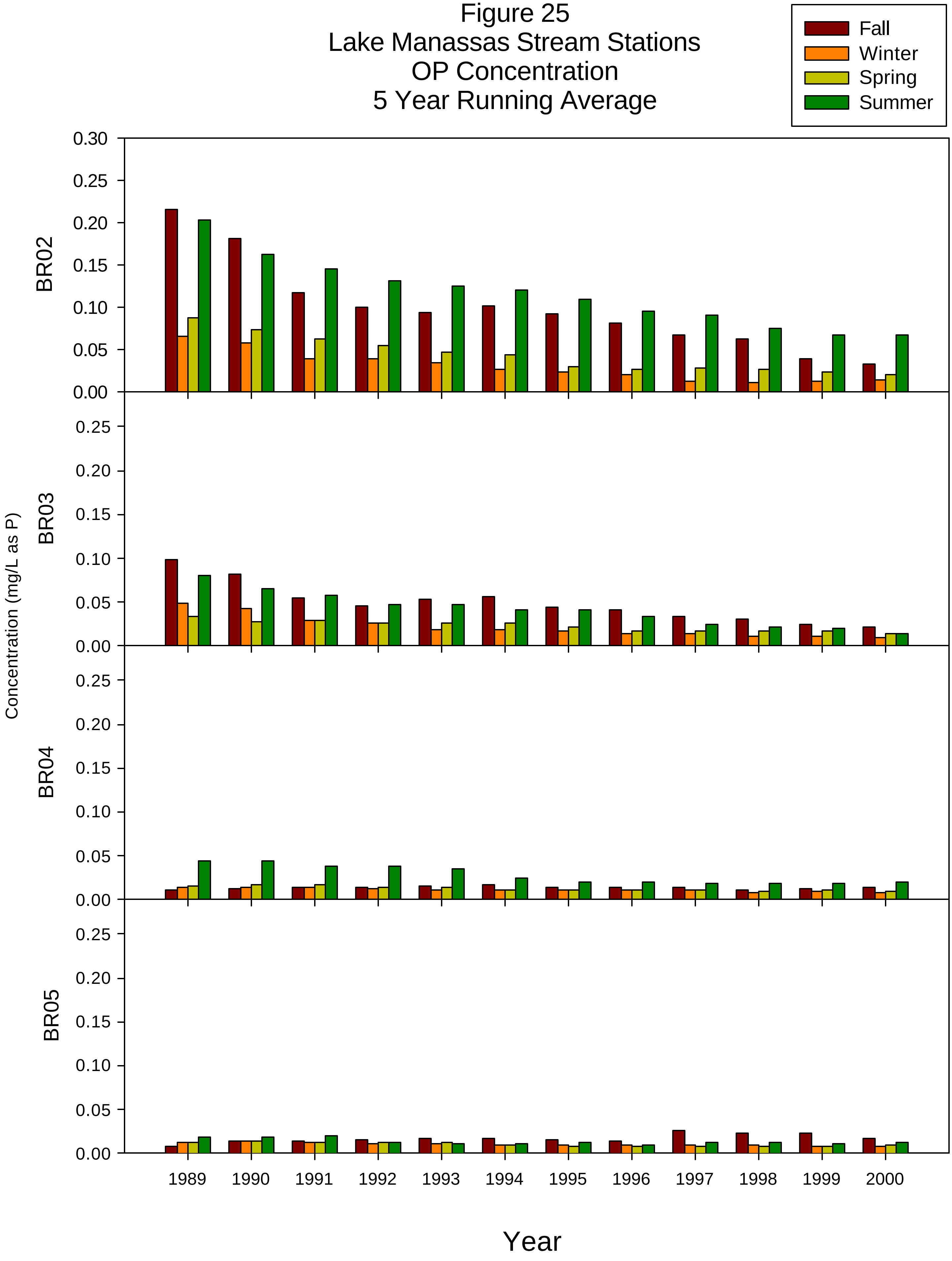


Figure 26
Lake Manassas Sampling Stations
OP Concentration
5 Year Running Average

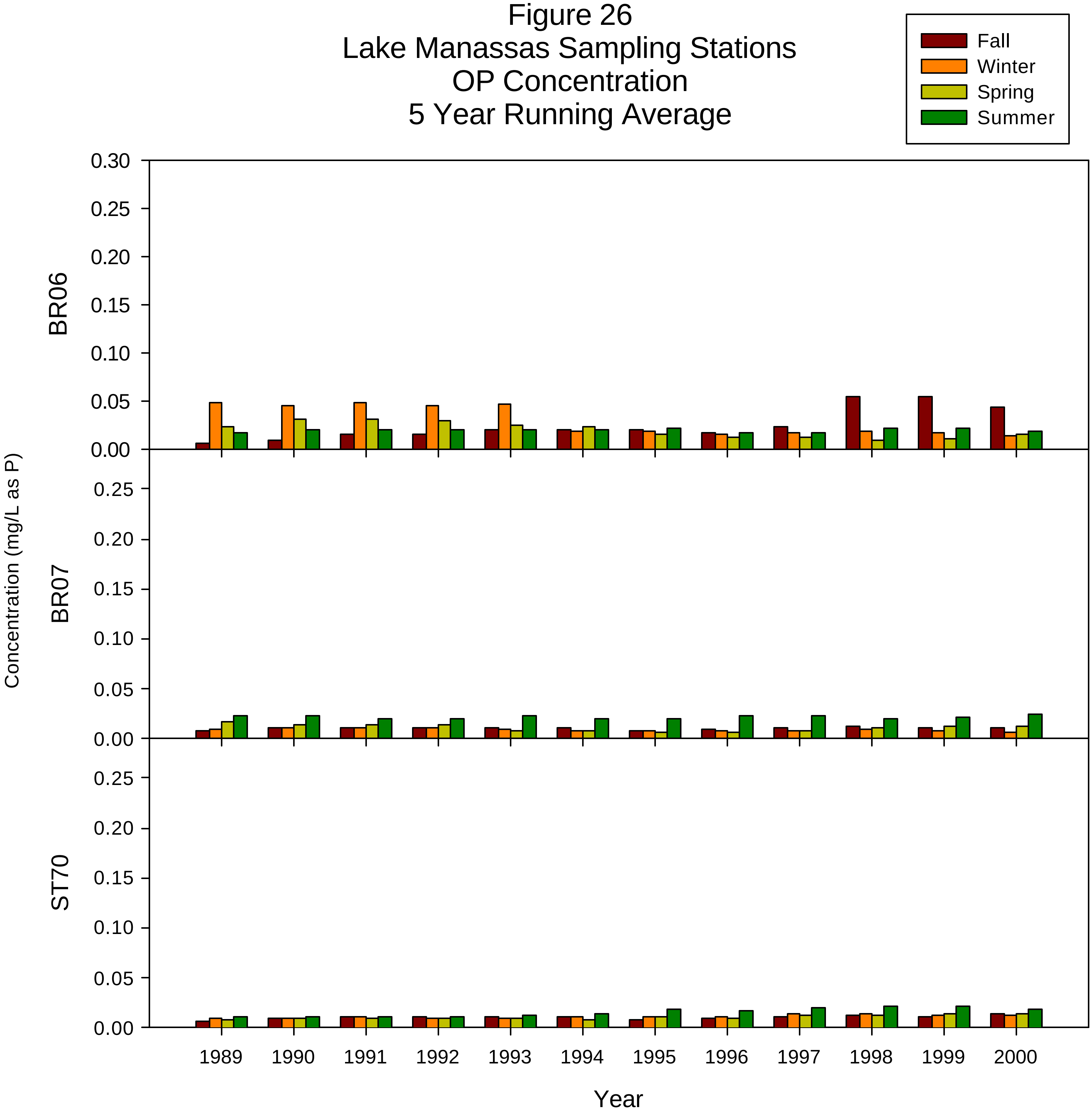
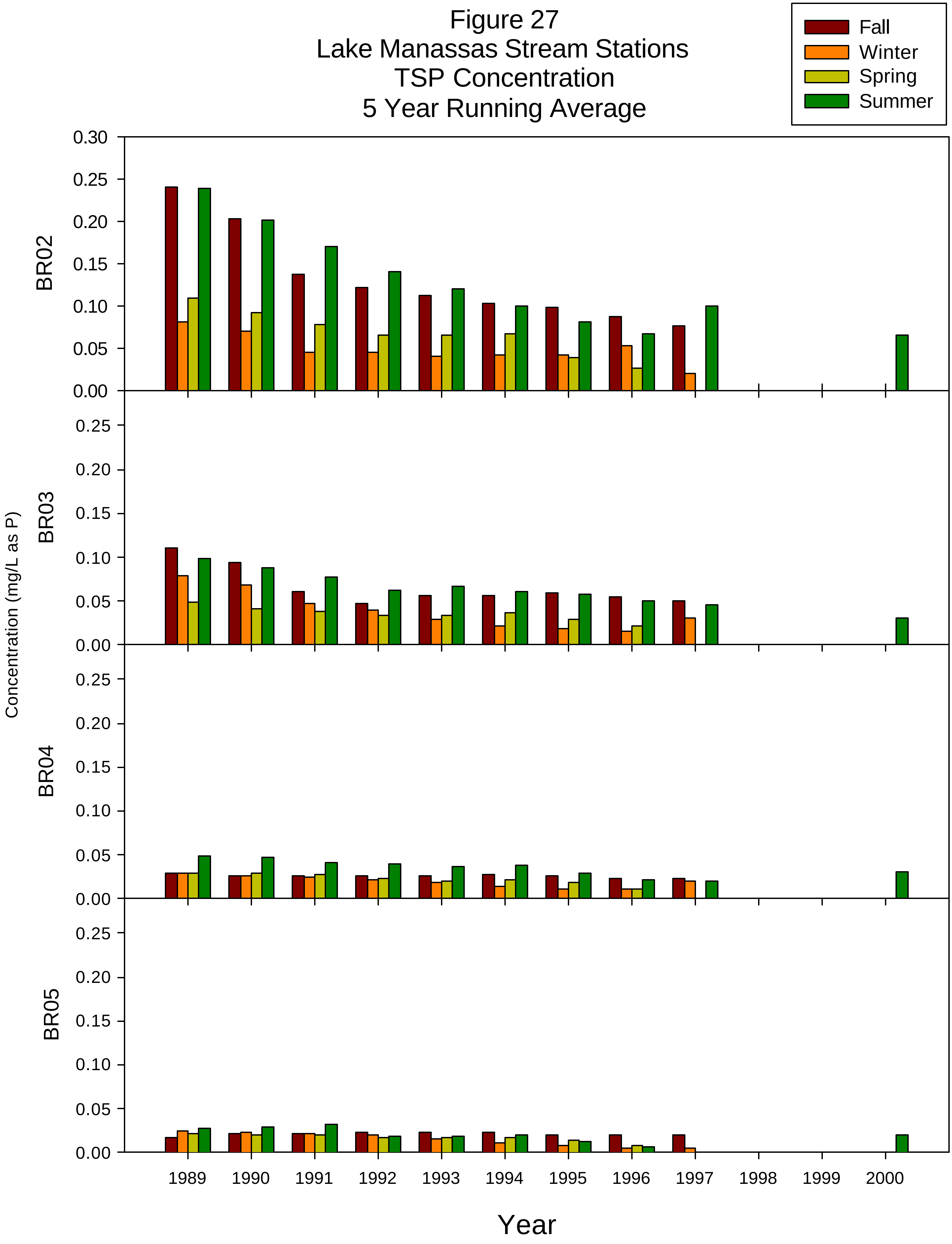


Figure 27
Lake Manassas Stream Stations
TSP Concentration
5 Year Running Average



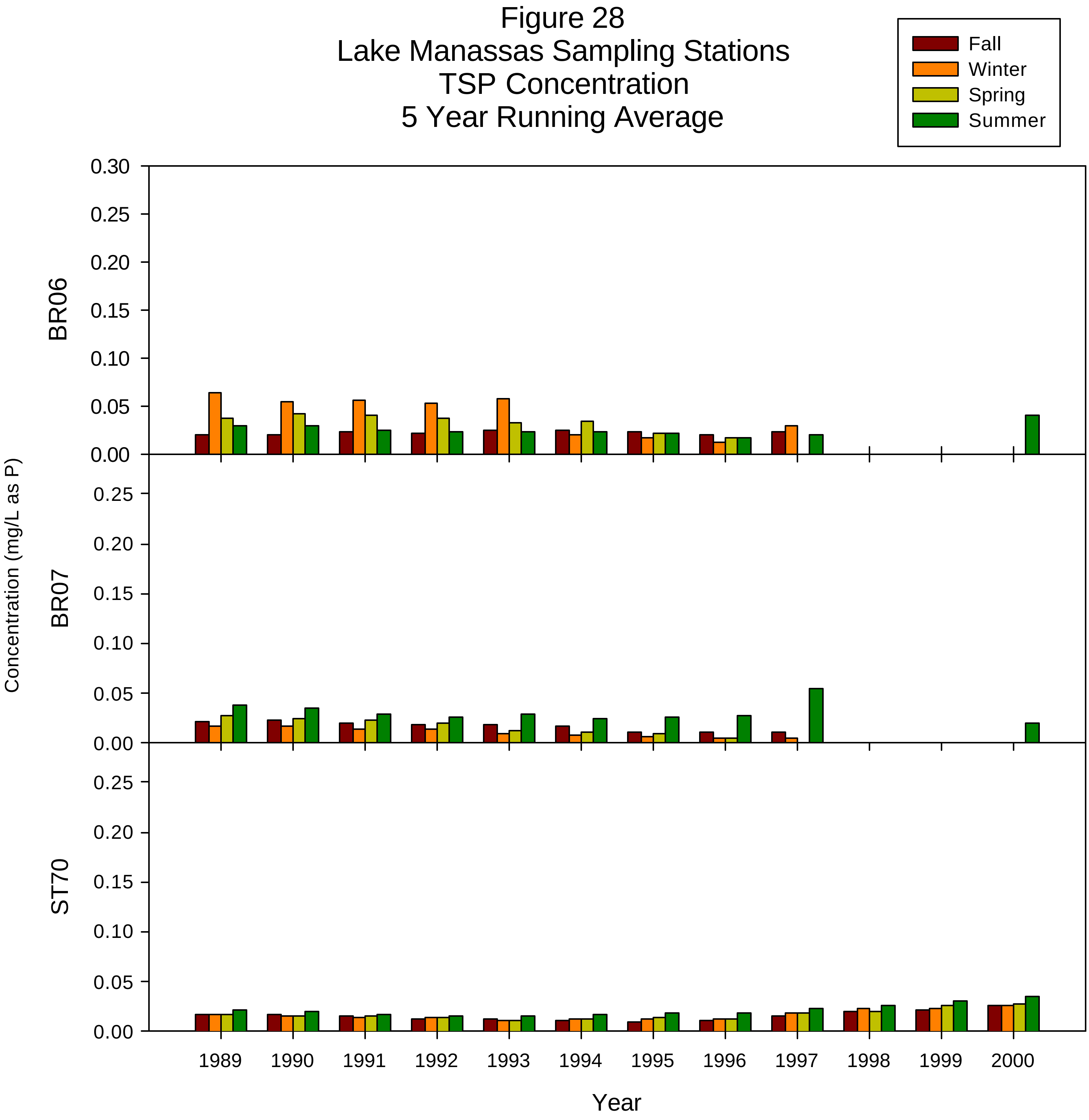


Figure 28
Lake Manassas Sampling Stations
TSP Concentration
5 Year Running Average

Nutrient Loading Rates to Lake Manassas From Broad Run

Introduction

Lake productivity is primarily a function of nutrient inputs to a lake from both external and internal sources. For Lake Manassas, the Broad Run drainage represents 70% of the entire Lake Manassas watershed, and, as a result, it is the primary source of external loading to the reservoir. An automated stream flow gage and sampling station exists on Broad Run and provides an extensive hydrologic and chemistry database for making nutrient loading calculations. From this data, nitrogen and phosphorus loading rates have been determined for the period 1980 to 2000. These loading rates have in turn allowed determination of nitrogen to phosphorus ratios as well as the reservoir trophic status based on nutrient loading from the reservoir tributaries.

Nutrient Loading Rate Calculation Results

Flow weighted nutrient curves have been generated for station ST70 on Broad Run for the period of October 23, 1980 through December 31, 2000. The curves can be seen in Figures 29 - 35. The cumulative average nutrient loading rates are shown in Table 7. These were calculated by summing the nutrients and dividing by the length of time that the data were summed over.

Figure 29
Lake Manassas
Cumulative OP Loading at ST70
October 28, 1980 to December 31, 2000

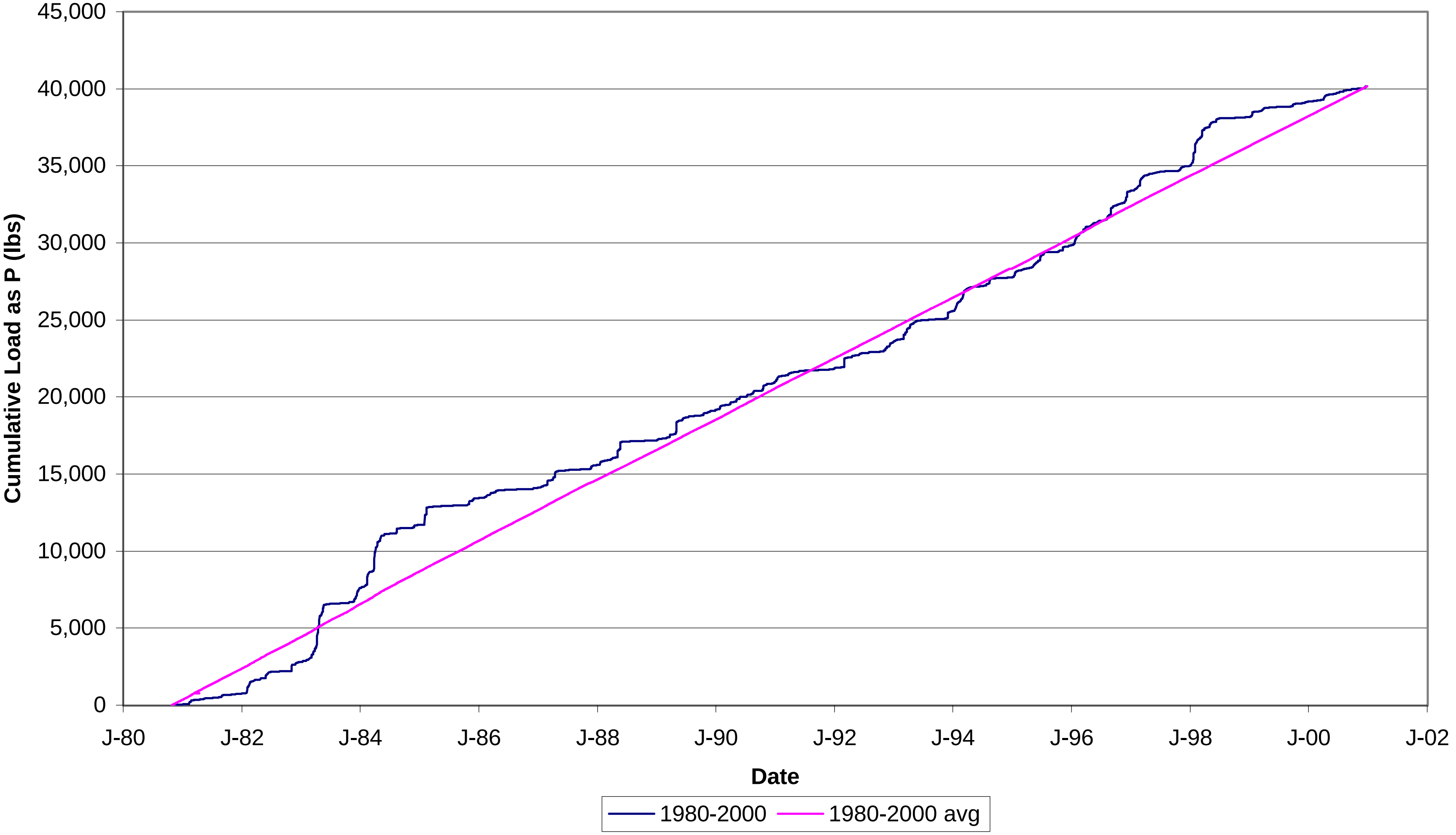


Figure 30
Lake Manassas
Cumulative TSP Loading at ST70
October 28, 1980 to December 31, 2000

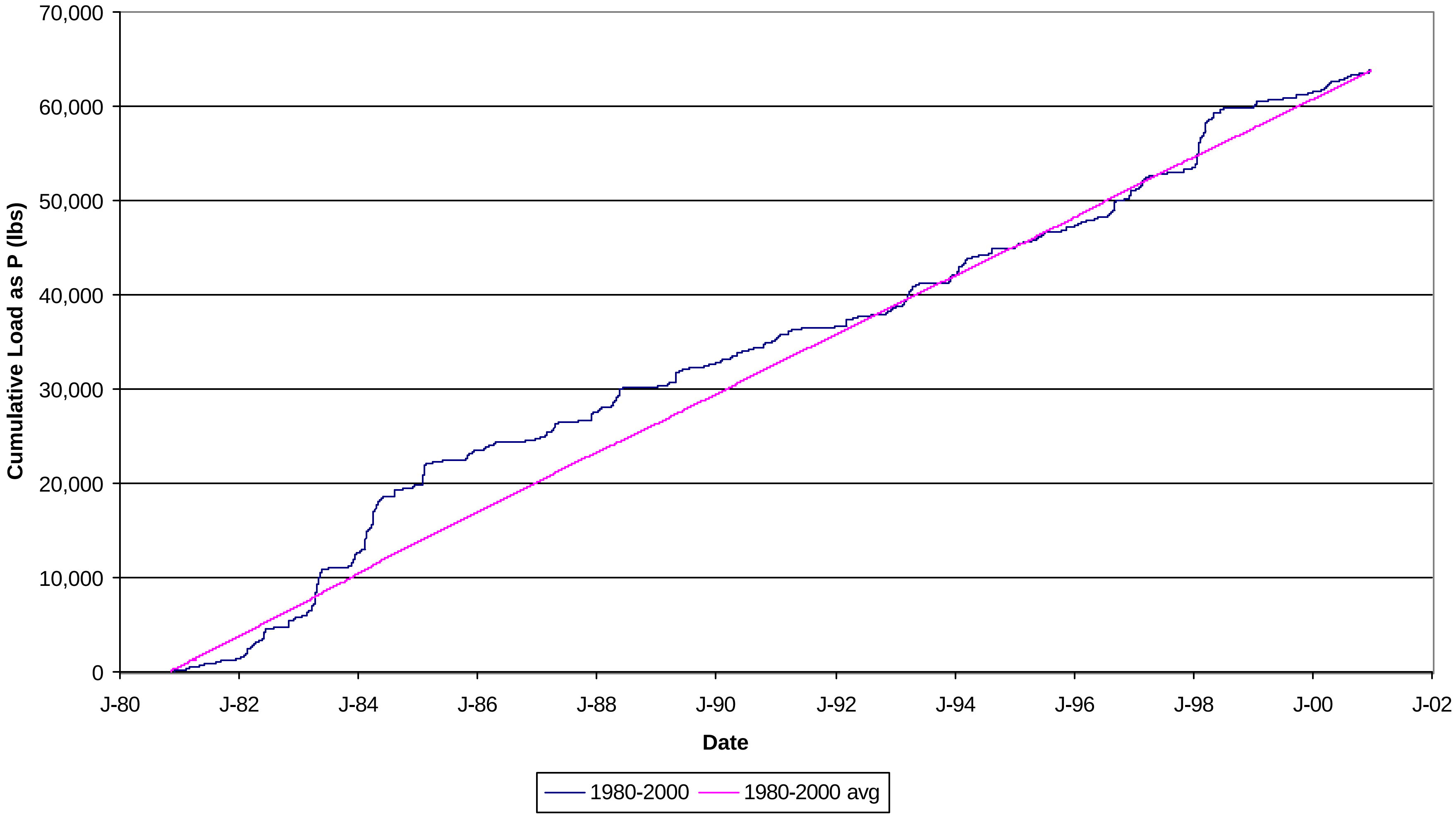


Figure 31
Lake Manassas
Cumulative TP Loading at ST70
October 28, 1980 to December 31, 2000

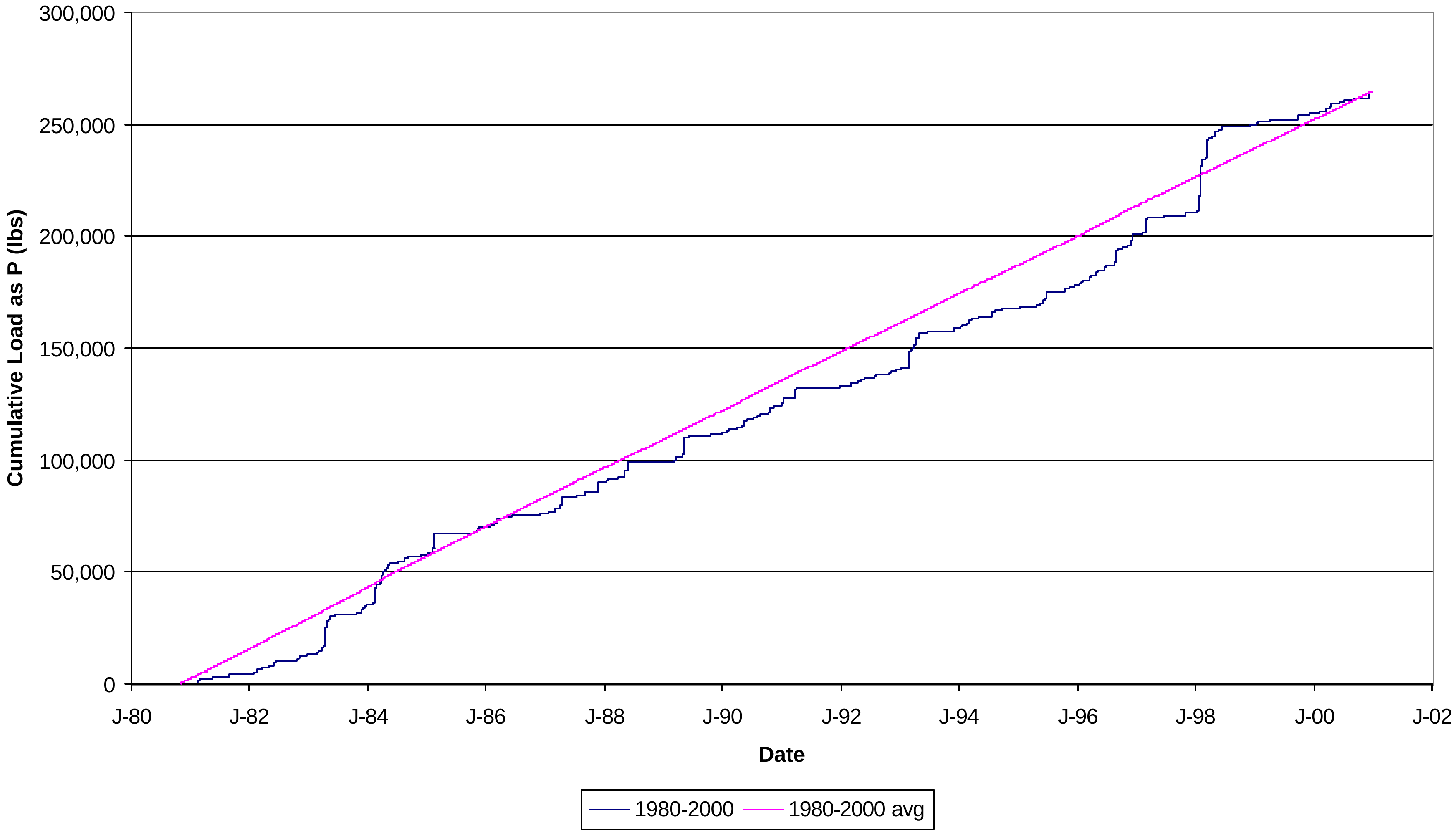


Figure 32
Lake Manassas
Cumulative OX-N Loading at ST70
October 28, 1980 - December 31, 2000

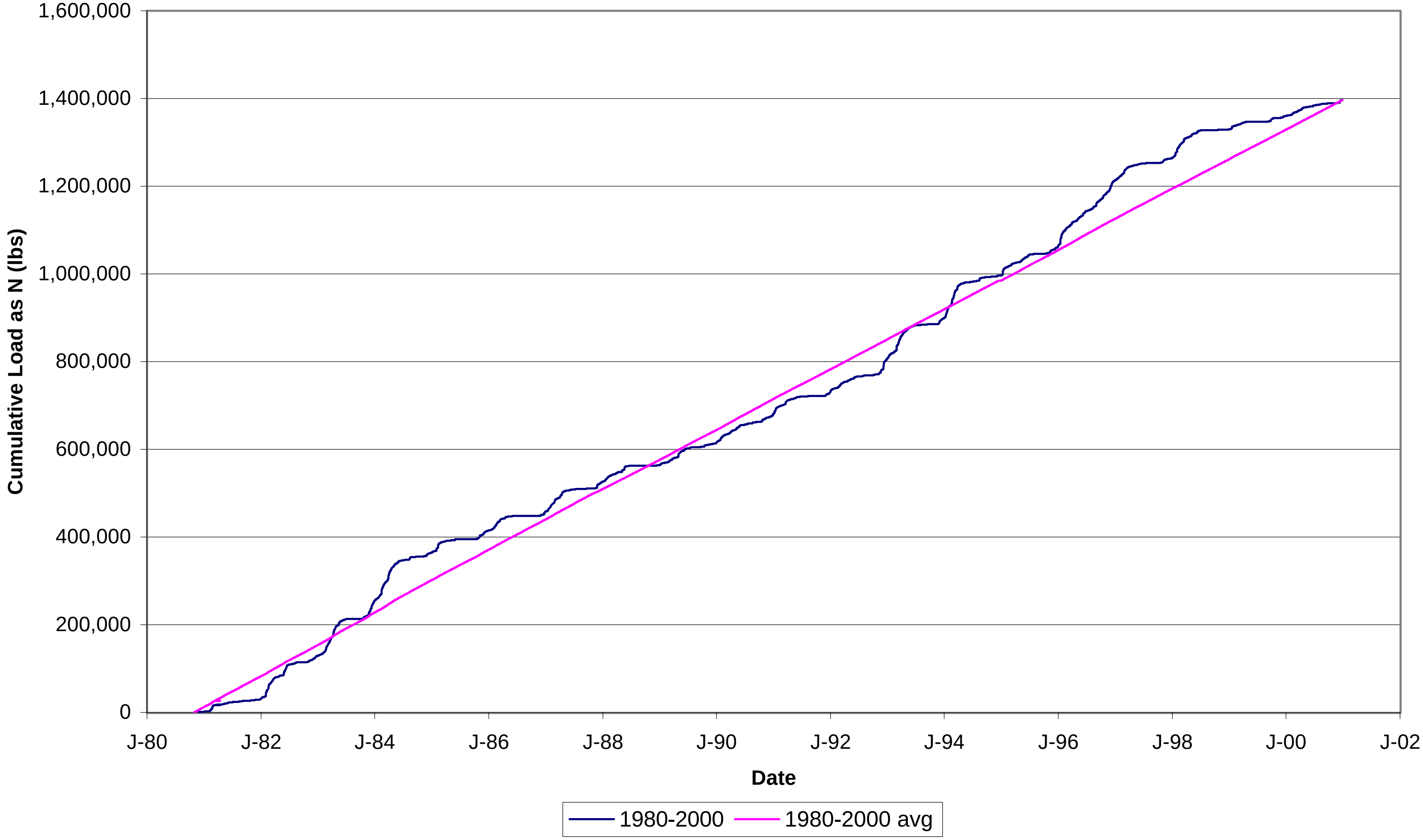


Figure 33
Lake Manassas
Cumulative TKN Loading at ST70
October 28, 1990 to December 31, 2000

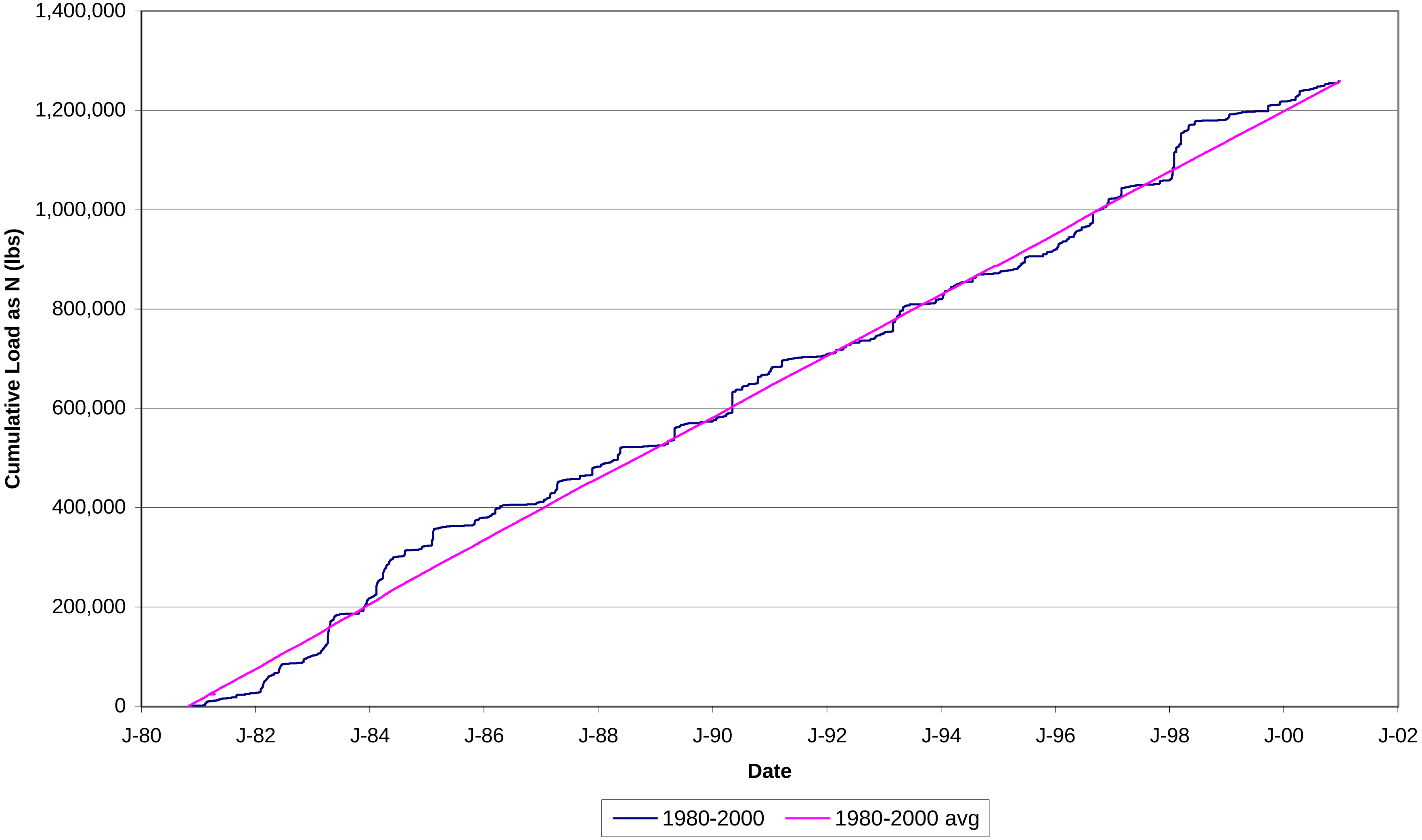


Figure 34
Lake Manassas
SKN Loading at ST70
October 28, 1980 to December 31, 2000

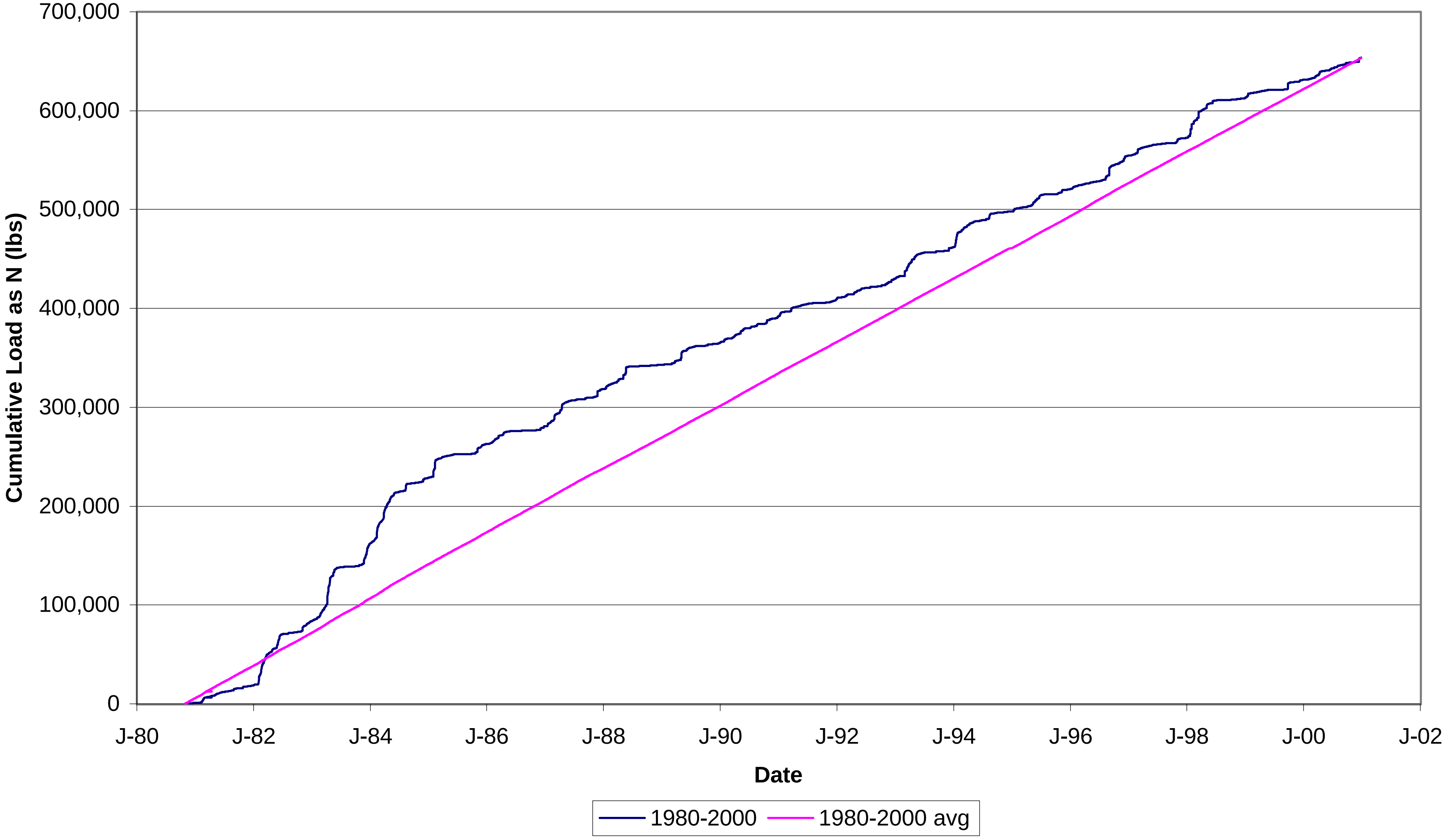


Figure 35
Lake Manassas
Cumulative NH_3-N Loading at ST70
October 28, 1980 - December 31, 2000

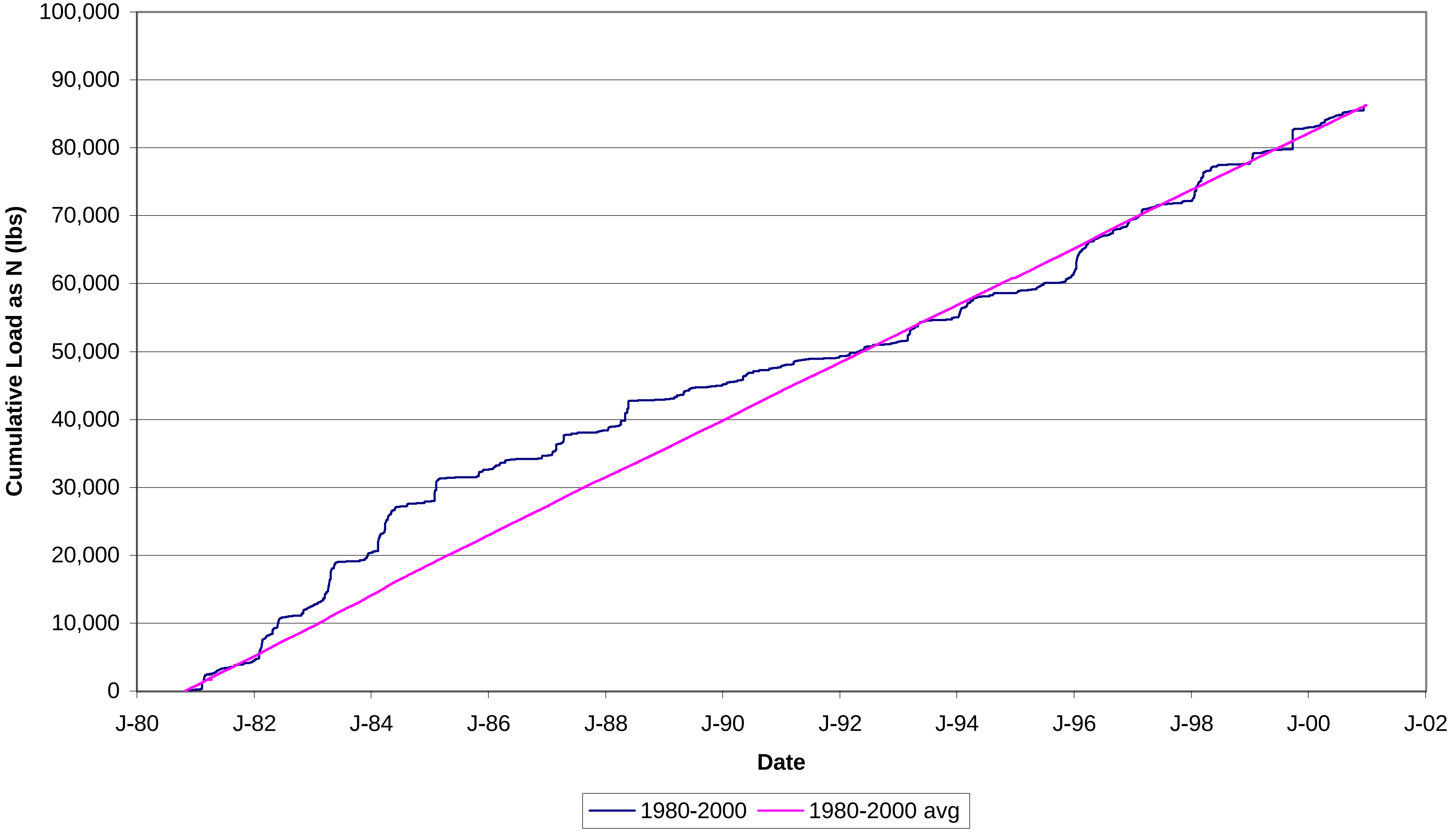


Table 7 - Nutrient Loading Rates in Broad Run (Occoquan Watershed Monitoring Laboratory, 1996)

Nutrient (lb/day)	**OP**	**TSP**	**TP**	**OX-N**	**TKN**	**SKN**	**NH_3-N**
10/80 - 05/88	6.2	10.8	35.6	202.4	188.0	122.9	15.4
06/88 - 12/94	4.5	6.2	28.8	192.9	168.8	96.4	11.3
12/94 - 12/00	5.6	8.6	44.1	181.7	175.6	70.5	12.6
10/80 - 12/94	5.4	8.7	32.4	181.9	146.6	65.7	6.6
10/80 - 12/00	5.5	8.7	35.9	189.5	170.8	88.7	11.7

The numbers confirm the results of the Mann Kendal Seasonal Analysis. The loading rate analysis showed that OP, TSP, TP, and NH_3-N all had an upward trend when comparing the 15 to 20 year average. Comparing the 5 year averages, the nutrient loading rates for the most part decrease from 1980 to 1994, and then start to increase again. From the data, the TP value is now above the first calculation done on the stream. Overall, this could be cause for concern for Lake Manassas. As the nutrients increase, the lake will become more Eutrophic and less productive for drinking water.

Table 8 - Percent Decrease (dec.) or Increase (inc.) in Loading Rates Between Different Time Periods

Time Period	OP	TSP	TP	OX-N	TKN	SKN	NH_3-N
1980 - 1988 and 1994 - 2000	- 9.6%	-20.40%	23.9%	-10.2%	-6.6%	-42.6%	-18.2%
1988 - 1994 and 1994 - 2000	24.4%	38.7%	53.1%	-5.8%	4.0%	-26.9%	11.5%

The percent of increase or decrease between the five year intervals is calculated (Table 8). Both SKN and OX-N have decreased over the last 20 years. A period in the time frame of 1998 to 1999 shows an increase in the cumulative loading of all nutrients except for NH3-N. This is most likely due to an active storm period during those years.

Reservoir Water Quality

Introduction

The water quality of a lake or reservoir can be characterized based on commonly-measured parameters including temperature, dissolved oxygen, nitrogen, phosphorus, and chlorophyll *a* concentrations. Additionally the trophic status of a lake or reservoir can be defined using mathematical models and statistical analyses. This section describes the baseline water quality condition of Lake Manassas based on parameters measured at eight monitoring stations between October 1984 and December 2000, and through the use of the Vollenweider, EPA, and Carlson Trophic State Index models. Included is a five-year running average in order to identify long term trends in the lake.

Monitoring stations LM06, LM05, LM04 and LM01 are located along the main axis of the lake, with LM06 farthest upstream and LM01 closest to the dam (Figure 2). These stations represent the body of principal water storage. Station LM01 is the deepest site on the lake with a full pool depth of 45 feet with the bladder addition. Station LM04 is the second-deepest site with a full pool depth of 35 to 40 feet. Monitoring stations, LM08, LM07, LM03, and LM02 are located along the north shore of the lake, and near the Robert Trent Jones International Golf Course. Station LM02 is similar in depth to Station LM04, with a full pool depth of 35-40 feet. The remaining stations along the north shore have full pool depths of only 10 - 25 feet. Because these stations have relatively less storage volume than the stations located along the main axis of the lake, water quality impacts of the Robert Trent Jones International Golf Course, if any, are likely to be detected here.

Mann Kendall Seasonal Analysis

This analysis was completed to locate any trends occurring in the lake over the last fifteen years. This analysis takes into account the different seasons and looks statistically at all the numbers on the same basis. The numbers are then compared at a certain significance level (alpha=0.05) and if a trend is present, the data will show it, be it a small or large trend. Both the surface and bottom sections of the lake were looked at separately. Tables 9 and 10 show the results of this analysis and will be referred to often in discussing the water quality of Lake Manassas.

Thermal Effects

In the spring and early summer, the combination of solar heating and a reduction in windy conditions brings about the warming of the upper portion of a lake water column and the stratification of many lakes and reservoirs into layers of water with different temperatures and densities. During this period, a warmer, less dense layer of water (the epilimnion) floats on a cooler, more dense layer of water (hypolimnion) creating an effective barrier to the exchange of dissolved gases and ionic species. With the change in seasons from summer to fall, the epilimnion cools to a point where its density is no longer significantly different from that of the hypolimnion. When this occurs, wind can cause sufficient mixing action to create a condition known as turnover. The hypolimnion and its dissolved materials mix with the rest of the lake to create chemical conditions which are more uniformly distributed throughout the depth of the lake. The transition from the stratified to a mixed condition may occur over a period of a few hours, particularly if wind speeds are significant.

Table 9 - Mann Kendall Seasonal Analysis of Lake Manassas Surface Samples

Parameter	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
DO	-	-	-	-	U	U	U	-
PH	U	U	U	U	U	U	U	U
TEMP	-	-	-	-	-	-	-	-
COND	U	U	U	U	U	U	-	U
TALK	-	-	-	-	-	-	-	-
OP	-	-	-	-	-	-	-	-
TSP								
TP	-	-	-	-	-	-	-	-
NH3-N	-	-	-	-	N *L	-	-	-
SKN								
TKN	-	-	-	U	-	-	U	U
OX-N	-	-	-	-	-	-	-	-
TSS	-	-	-	-	-	-	L	-
CHLa	-	U	U	U	U	-	-	-

Definitions:

U = Upper Trend Present (Increasing)

L = Lower Trend Present (Decreasing)

- = No Trend Present

Blank = No data in at least the last 5 years

N *L = Borderline between no trend and lower trend (i.e., Zcompute = -1.63 and Z = -1.64)

Table 10 - Mann Kendall Seasonal Analysis of Lake Manassas Bottom Samples

Table 10 - Mann Kendall Seasonal Analysis of Lake Manassas 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	U	U	L	-	-	L	-	L
COND	U	U	U	U	U	U	ø	U
TALK	-	-	U	-	-	-	-	-
OP	-	-	-	-	-	-	-	-
TSP								
TP	-	-	-	-	-	-	-	-
NH3-N	-	-	U	-	-	-	-	-
SKN								
TKN	-	-	U	-	-	-	U	U
OX-N	L	L	-	L	-	-	-	-
TSS	L	L	-	L	L	-	-	-

Definitions:

U = Upper Trend Present (Increasing)

L = Lower Trend Present (Decreasing)

- = No Trend Present

Blank = No data in at least the last 5 years

Figure 36 shows temperature isopleths for the period from October 1984 to December 2000 for station LM01. This station is the deepest in the lake and has a greater tendency to show strong stratification since there is less chance of mixing. As shown in Figure 36, stratification does occur from late spring until the early fall.

Figures 37 through 40 show the five-year running averages from the surface and the bottom of the lake for all stations. The surface temperatures are consistent over the years for each individual season. There are no increasing or decreasing trends for any of the stations. The bottom graph shows that stations LM01, LM02, LM03, and LM04 have the lowest temperatures, which would indicate the strongest stratification. At the bottom of the lake there are some trends to be found: stations LM01 and LM02 are increasing in temperature, while stations LM03, LM06, and LM08 are all decreasing in temperature. This shows that the stratification at station LM01 and LM02 may be less strong while it may be increasing at the other three stations. Stations LM05 and LM06 both have higher hypolimnion temperatures in the summer, indicating weaker stratification. Occasionally, if the wind is strong enough, the waters at Station LM06 will destratify.

Figure 41 shows the average surface temperature versus the average bottom temperature of the lake. A one-to-one line is drawn-in and the data compared. Each season is represented by a different color and symbol, and each point represents a different station. For the most part, the temperatures fall along the one-to-one line with the summer being the exception because of stratification. When strong stratification occurs, the temperature of the hypolimnion will be low and that of the epilimnion will be

Figure 36
Station LM01 Temperature Isopleths
1995 - 2000

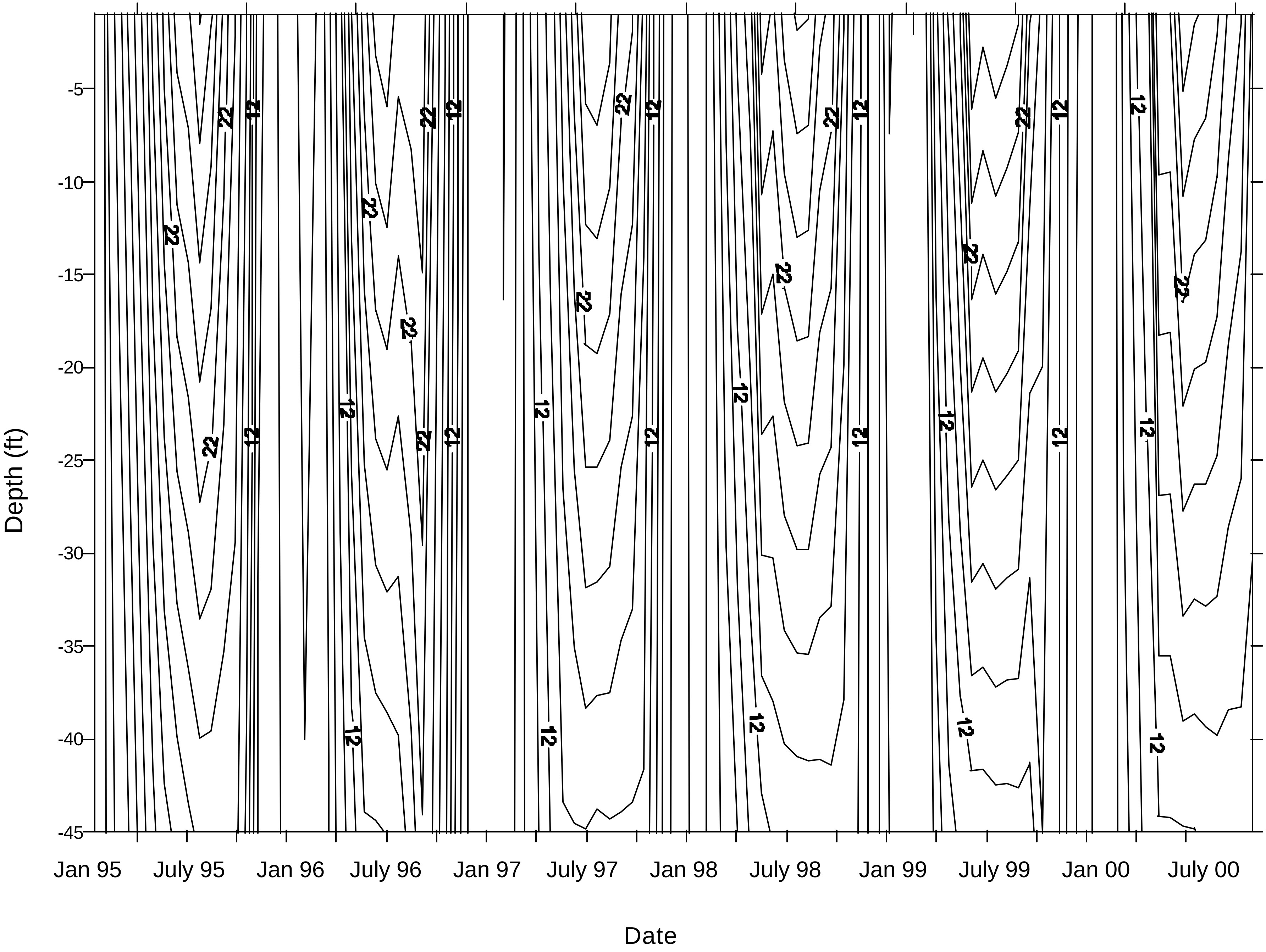


Figure 37
Lake Manassas (Surface)
Seasonal 5 year Running Average
Temperature,1984-2000

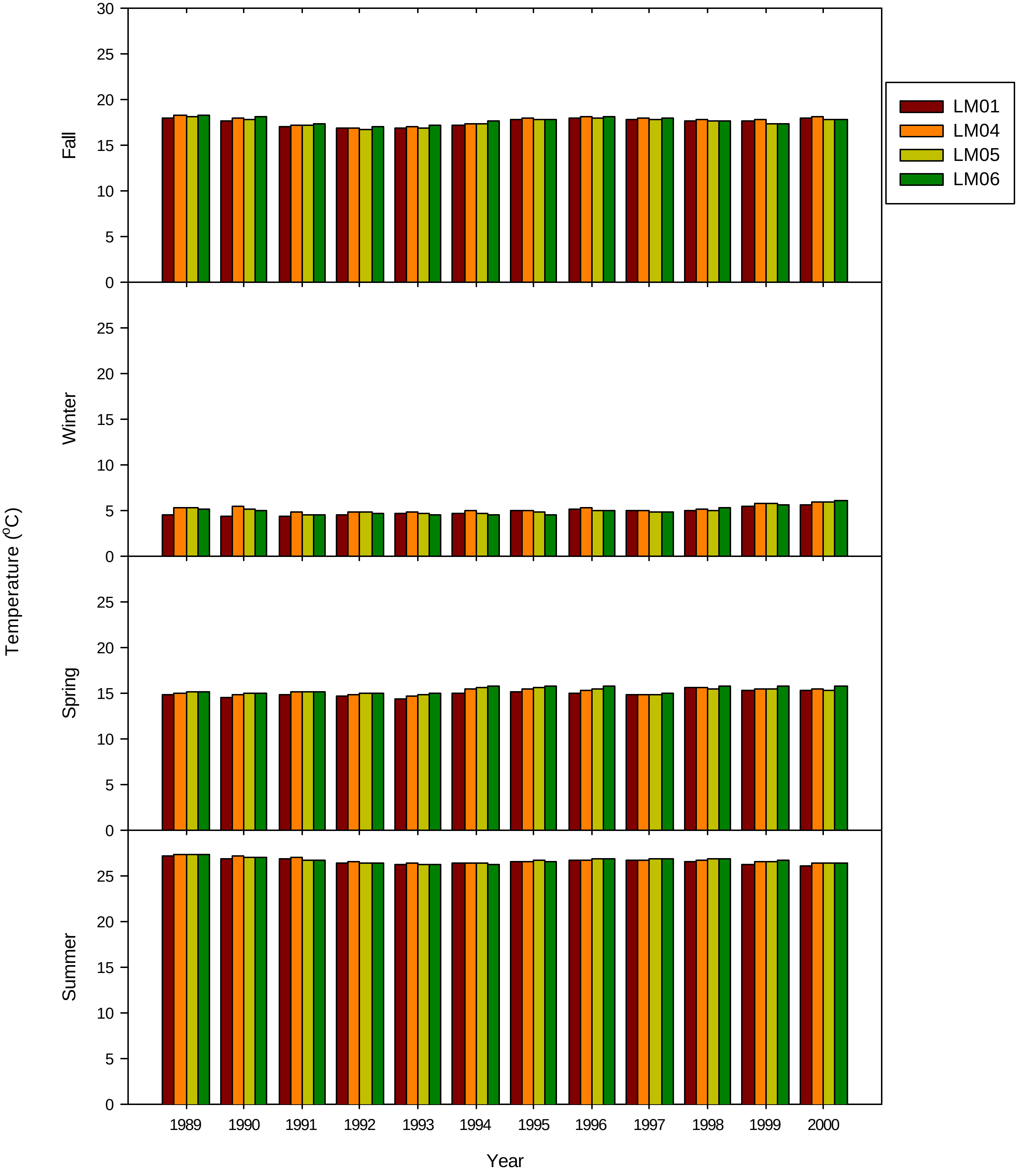


Figure 38
Lake Manassas (Surface)
Seasonal 5 year Running Average
Temperature,1984-2000

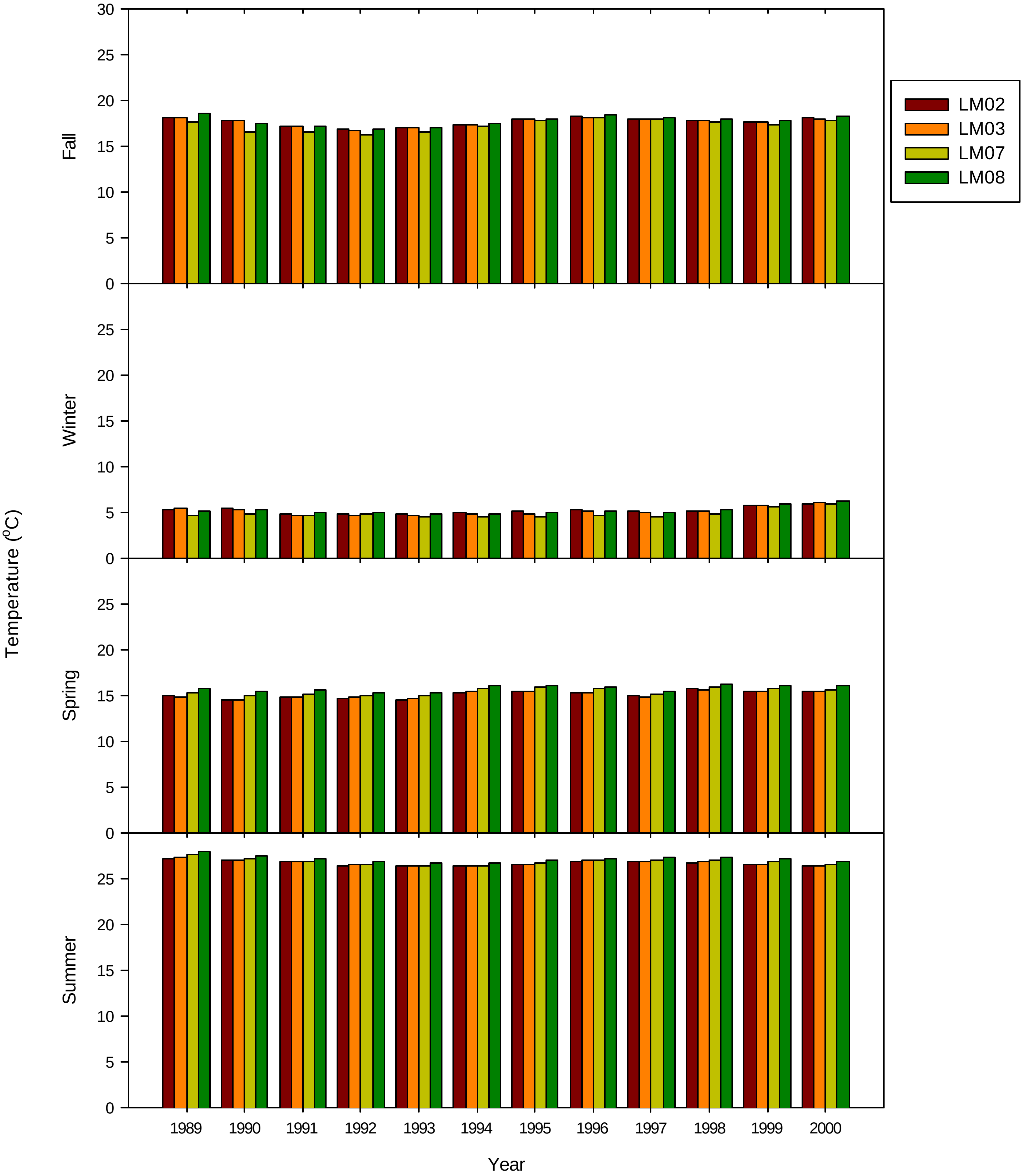


Figure 39
Lake Manassas (Bottom)
Seasonal 5 year Running Average
Temperature, 1984-2000

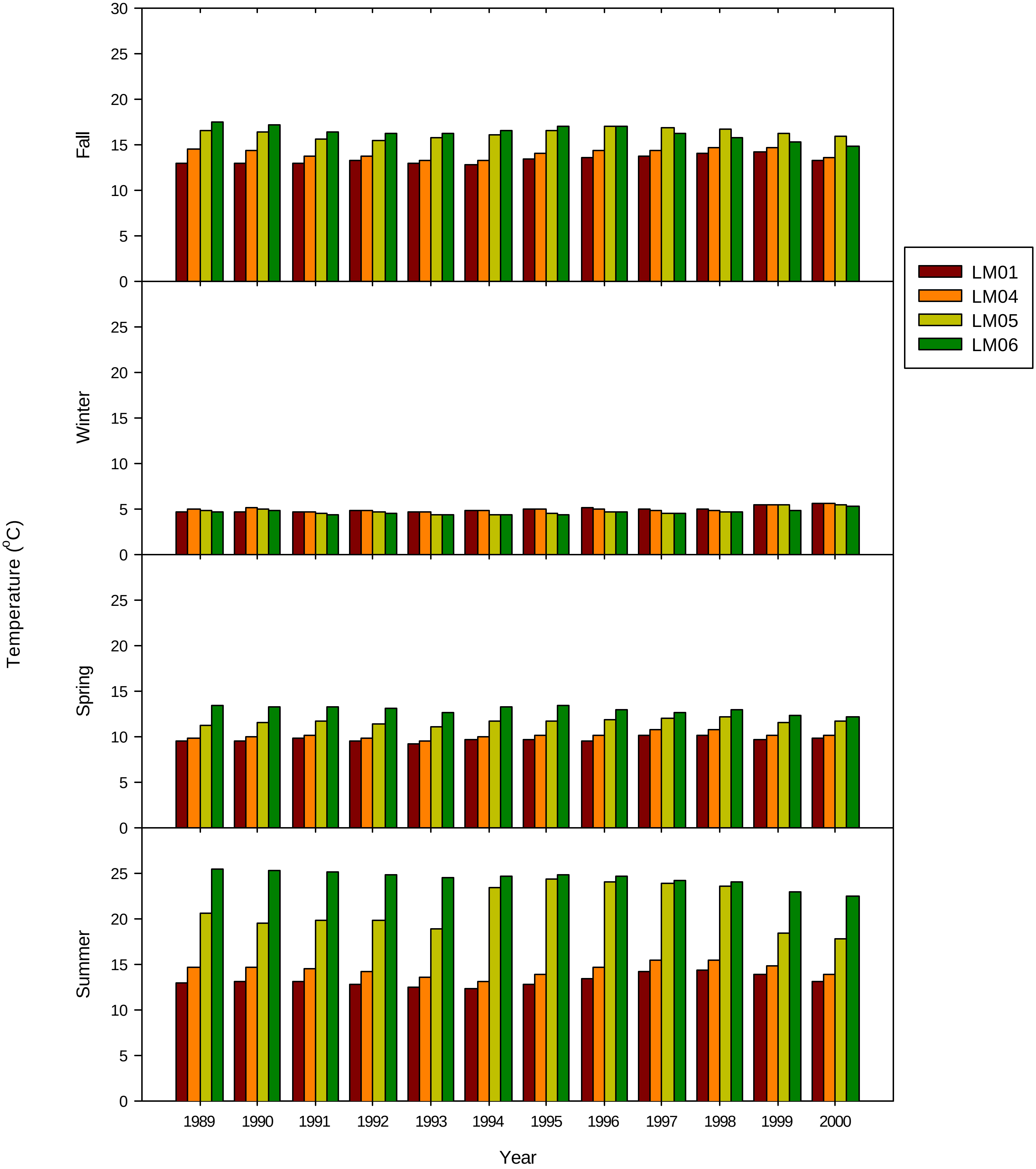


Figure 40
Lake Manassas (Bottom)
Seasonal 5 year Running Average
Temperature, 1984-2000

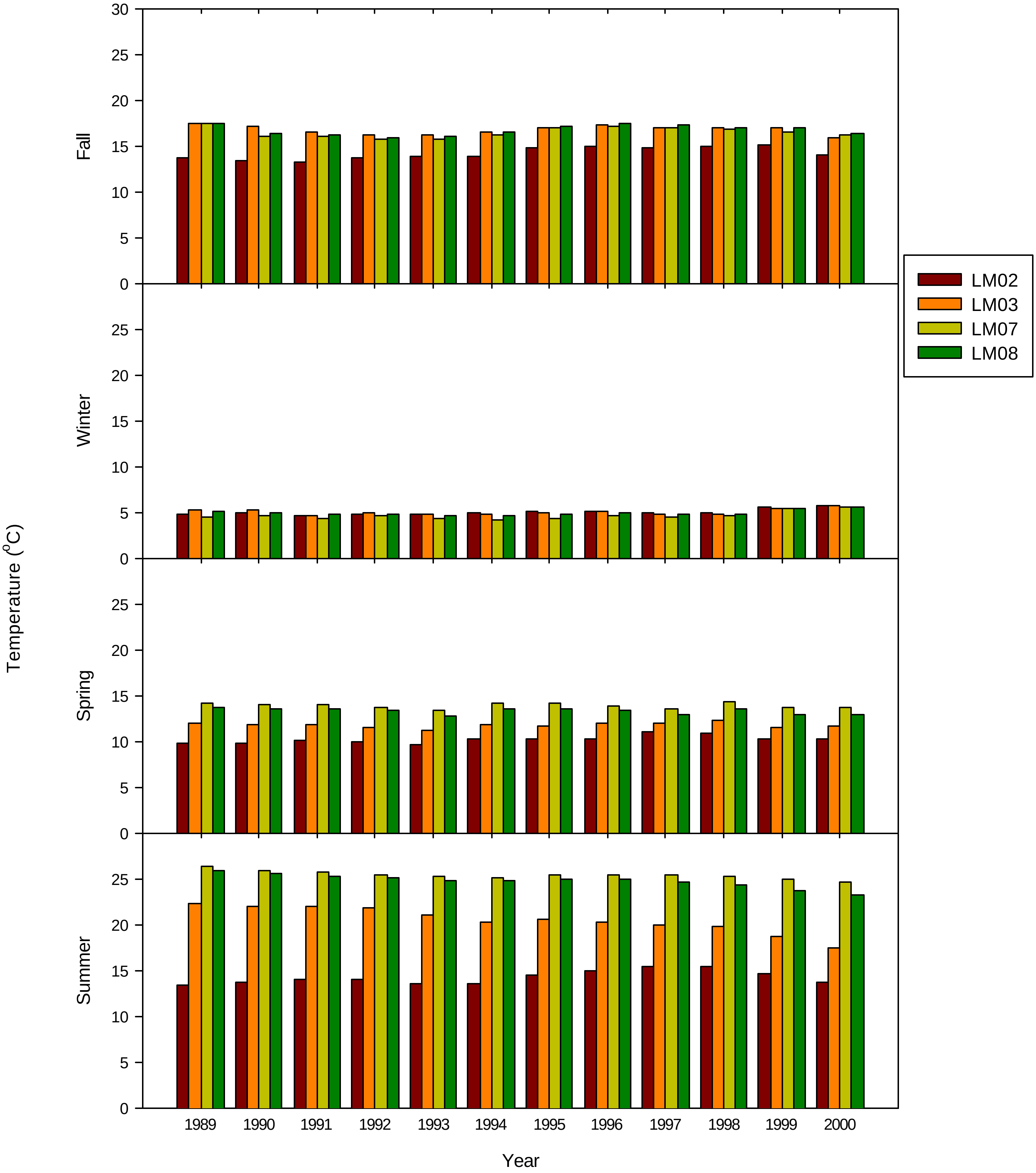
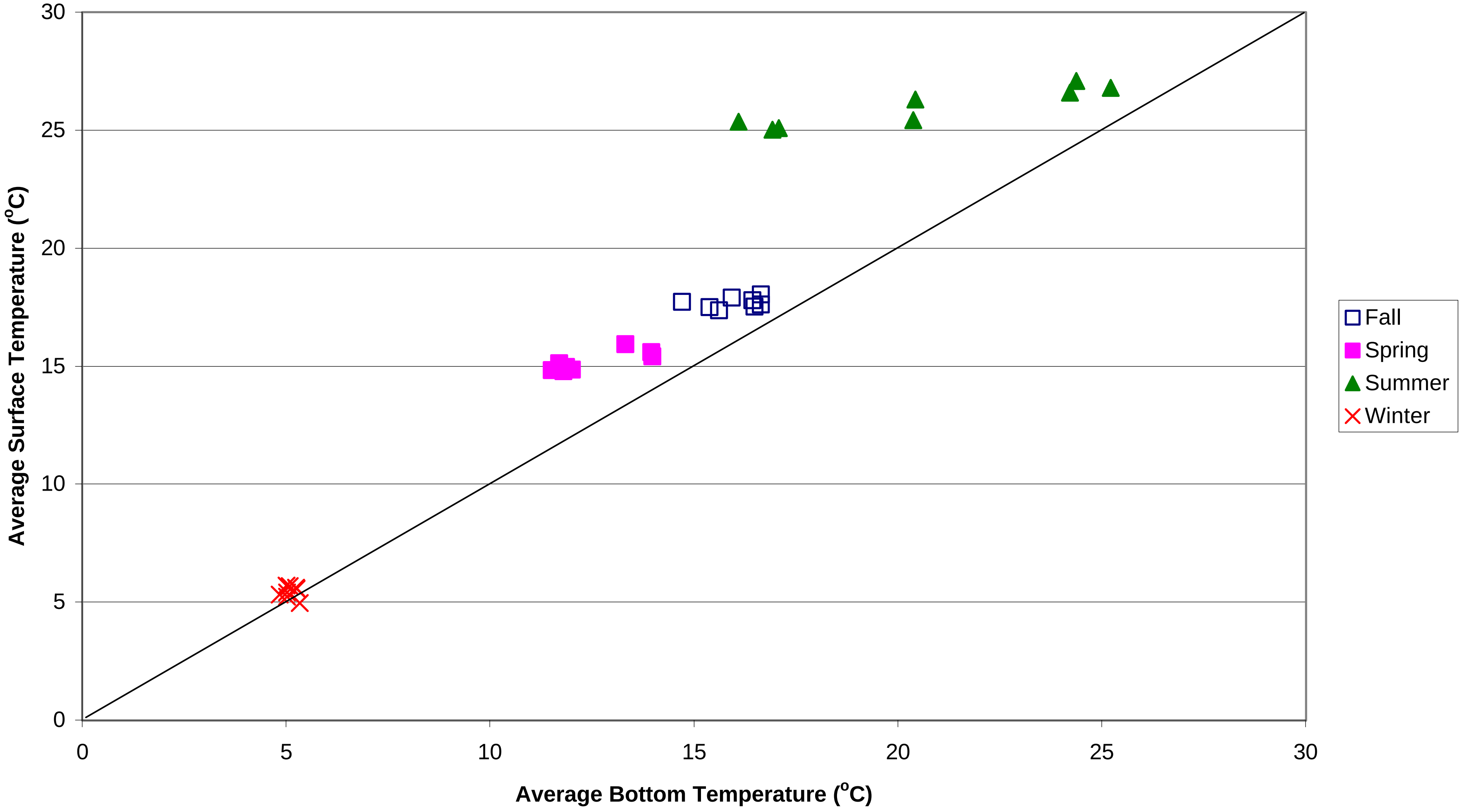


Figure 41
Lake Manassas
Average Surface and Bottom Temperature Comparison



high. This would result in the points being farther away from the 1:1 line. As the stratification weakens, the hypolimnion and epilimnion temperatures will come closer together, causing the data points to lie on the 1:1 line.

As an example of the typical yearly stratification experienced by the lake, Figures 42 and 43 show the temperature over the depth of the lake for 1997 and 1998, respectively. In 1998 the stratification is complete earlier than in 1997. This could be due to the fact that there were fewer storms and less rain during that year. As can be seen from the plots, the transition between the epilimnion and the hypolimnion occurs 10 - 25 feet below the surface.

Dissolved Oxygen

Dissolved Oxygen (DO) is an important component of any body of water. Many organisms utilize oxygen, and the solubility and availability of nutrients is affected by the lack, or excess of, DO. This ultimately will affect the productivity and nature of a lake or reservoir. During the late spring stratification of the reservoir starts, and by early summer the lake is completely stratified. During stratification there is a distinct difference in the processes occurring with respect to DO in both the epilimnion and the hypolimnion. The epilimnion is in direct contact with the atmosphere so any DO that is depleted due to biological activity will be replaced. On the other hand, the hypolimnion does not have direct contact with the atmosphere because the temperature gradient prevents mixing. The main depletion of DO results from dead organisms sinking into the hypolimnion, where they are decomposed by bacteria both in the water column and the sediments. Oxygen is depleted as a result of respiration

Figure 42
Lake Manassas, Station LM01, 1997
Temperature Profile

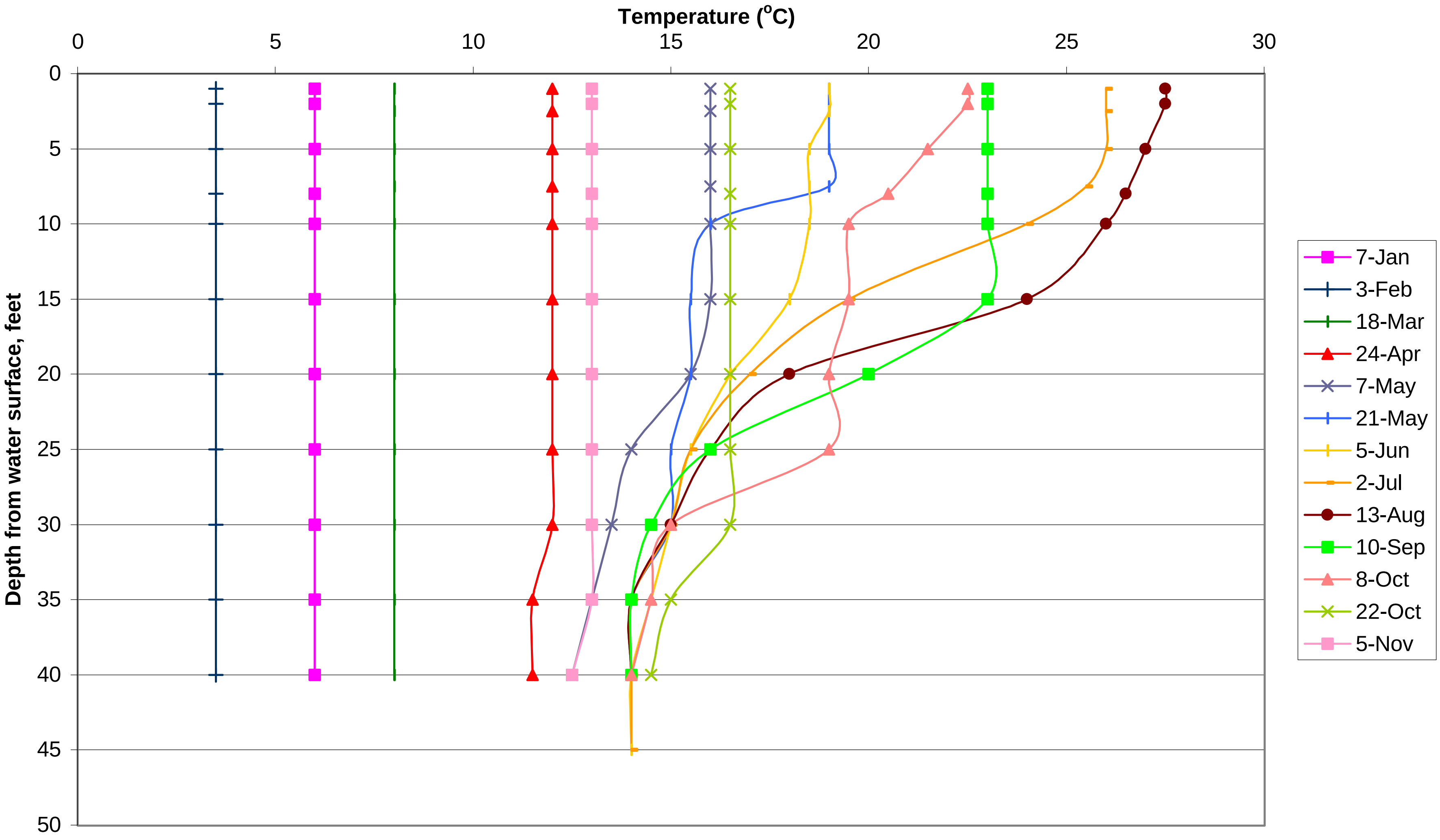
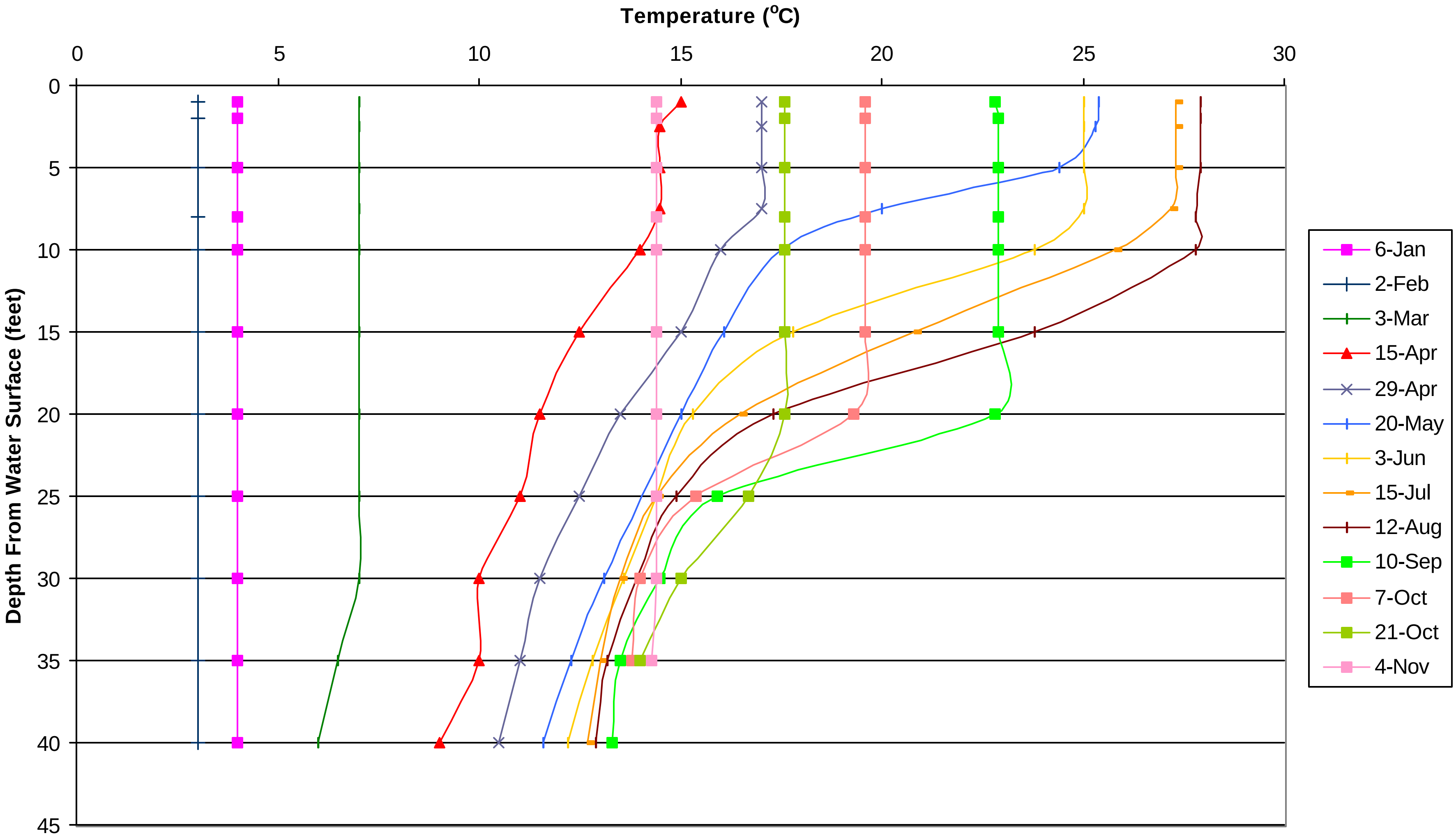


Figure 43
Lake Manassas, Station LM01, 1998
Temperature Profile



and the absence of replenishment from the surface.

Figures 44 and 45 show the DO and percent DO isopleths at station LM01for the period from January 1995 to December 2000. Figures 46 through 49 show the five-year running average of DO for both the surface and the bottom of the lake at all stations. Percent dissolved oxygen numbers were calculated by using a nonlinear equation and the temperature, dissolved oxygen, and depth. No corrections were made for pressure or ionic strength at different depths because the effects of these parameters on the solubility of oxygen in water are quite small compared to the effect of temperature.

Overall, in Figures 46 through 49 the surface levels of DO are quite constant over the last fifteen years. From the Mann Kendall Analysis, LM05, LM06, and LM07 have rising levels of DO on the surface of the lake. This could possibly be evidence of increasing algal growth at those stations in the summer. These three stations are all located on the west side of the lake.

Figures 48 and 49 show the DO levels on the bottom of the lake. The most strongly stratified stations are LM01, LM02, LM03 and LM04 with the average summertime DO levels being <1 mg/L. Station LM05 also stratifies during the summer with DO concentrations being around 2 mg/L. From the Mann Kendall Analysis, stations LM01, LM03, and LM04 all have their DO concentrations decreasing over time at the bottom of the lake. These stations are all located on the east side of the lake.

Figure 50 shows the % DO at station LM01 at both the surface and the bottom of the lake. As the DO

Figure 44
Station LM01 Dissolved Oxygen Isopleths
1995 - 2000

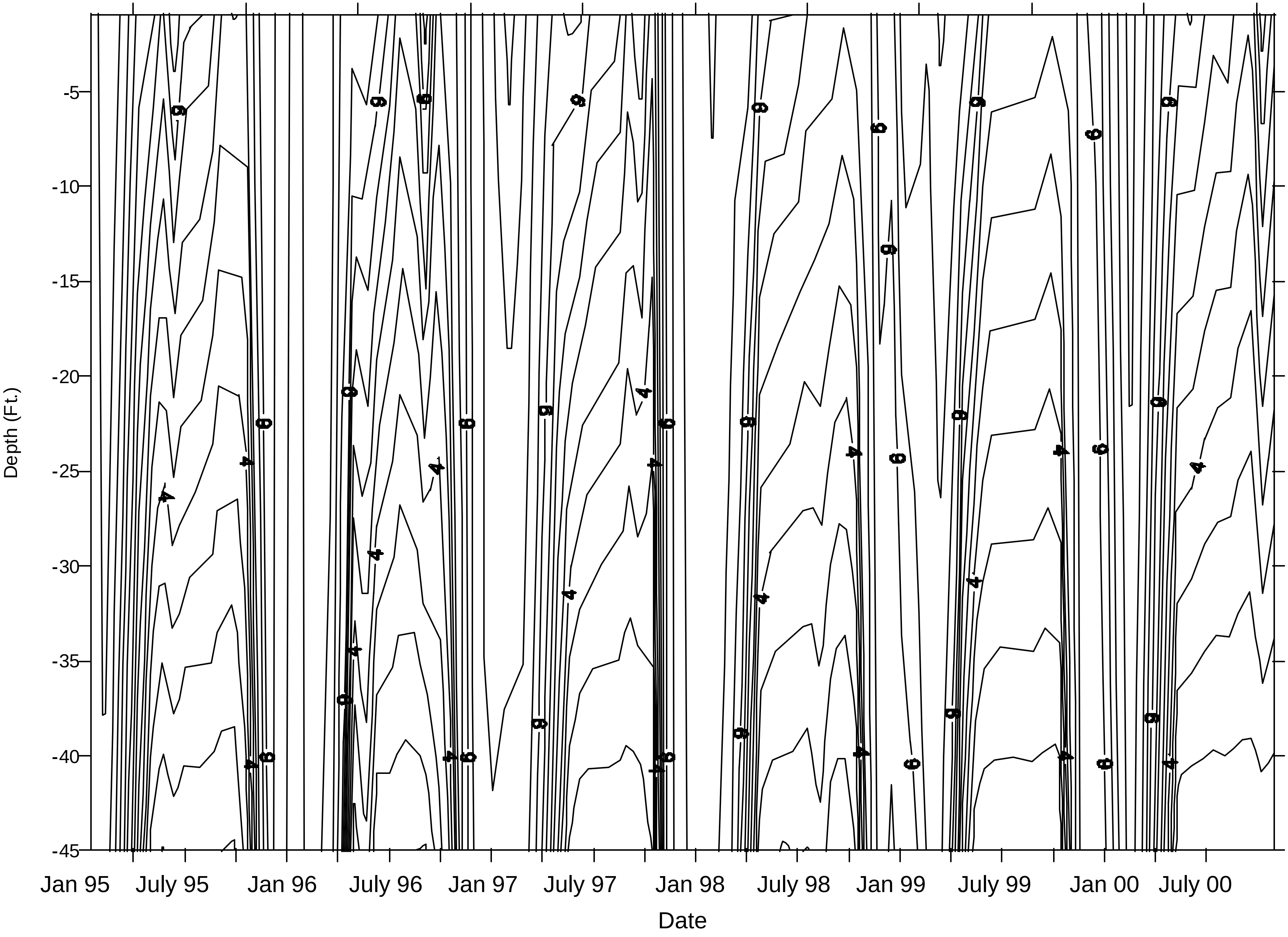


Figure 45
Station LM01 % DO Saturation Isopleths
1995 - 2000

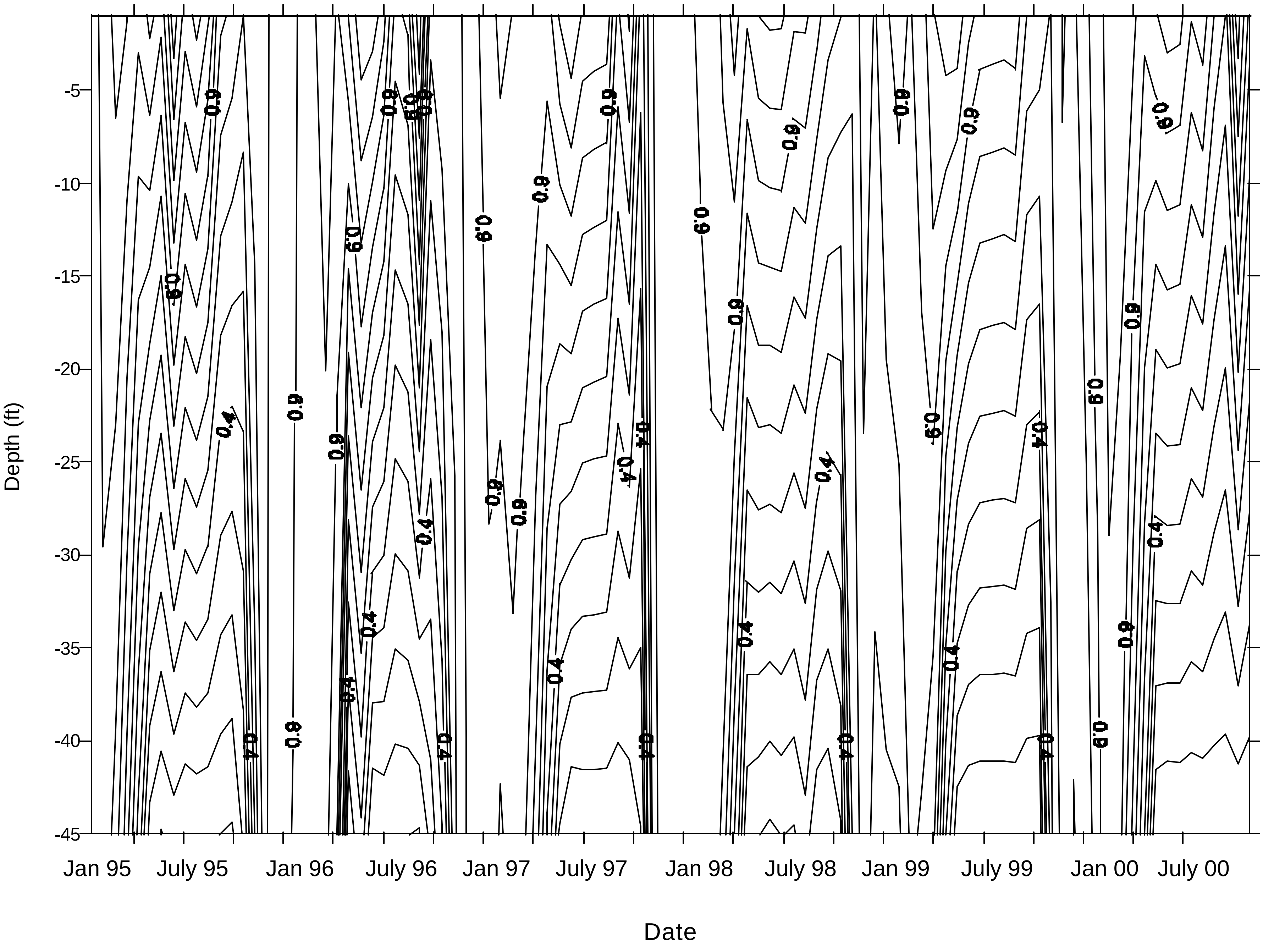


Figure 46
Lake Manassas (Surface)
Seasonal 5 year Running Average
Dissolved Oxygen,1984-2000

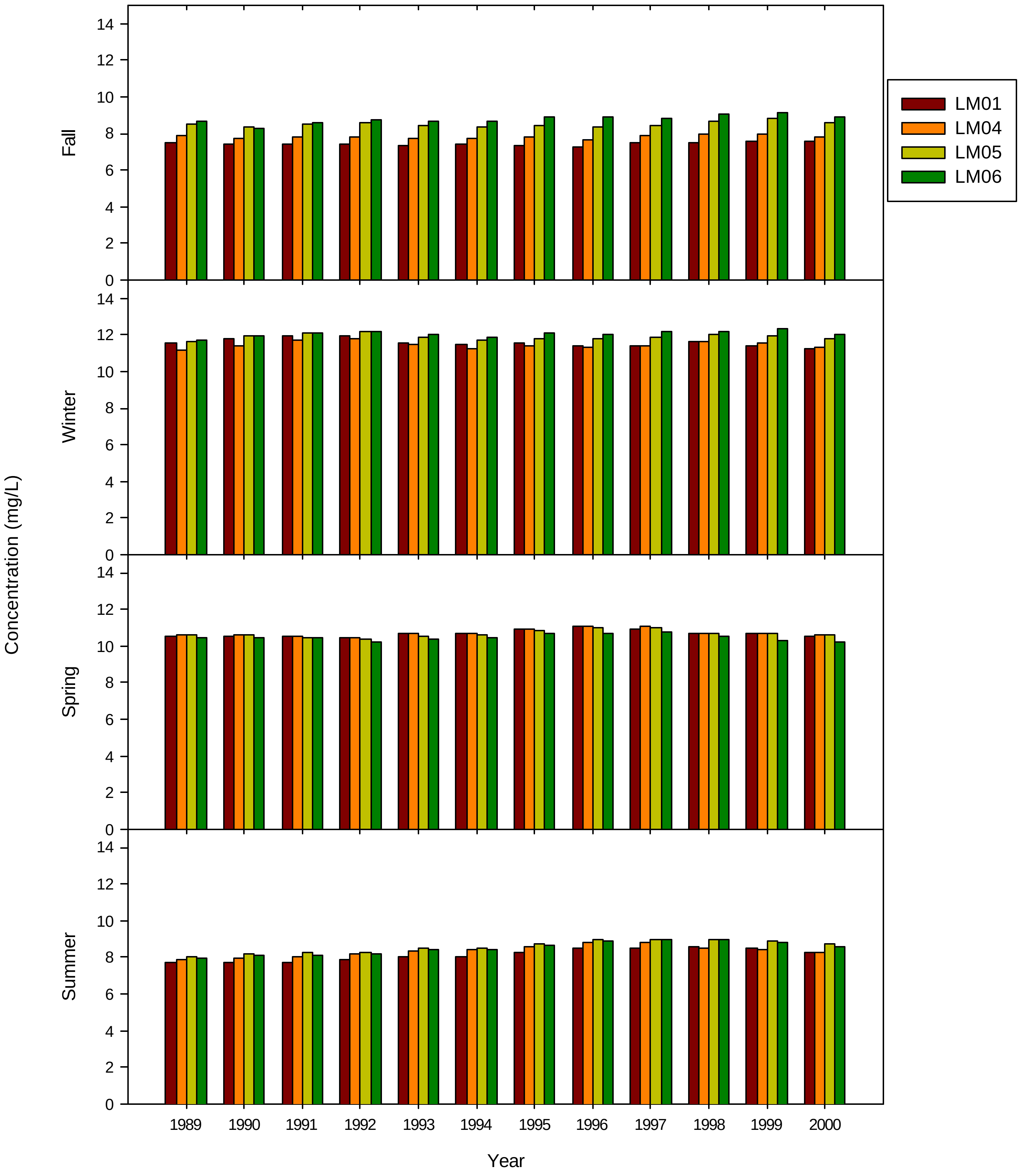


Figure 47
Lake Manassas (Surface)
Seasonal 5 year Running Average
Dissolved Oxygen,1984-2000

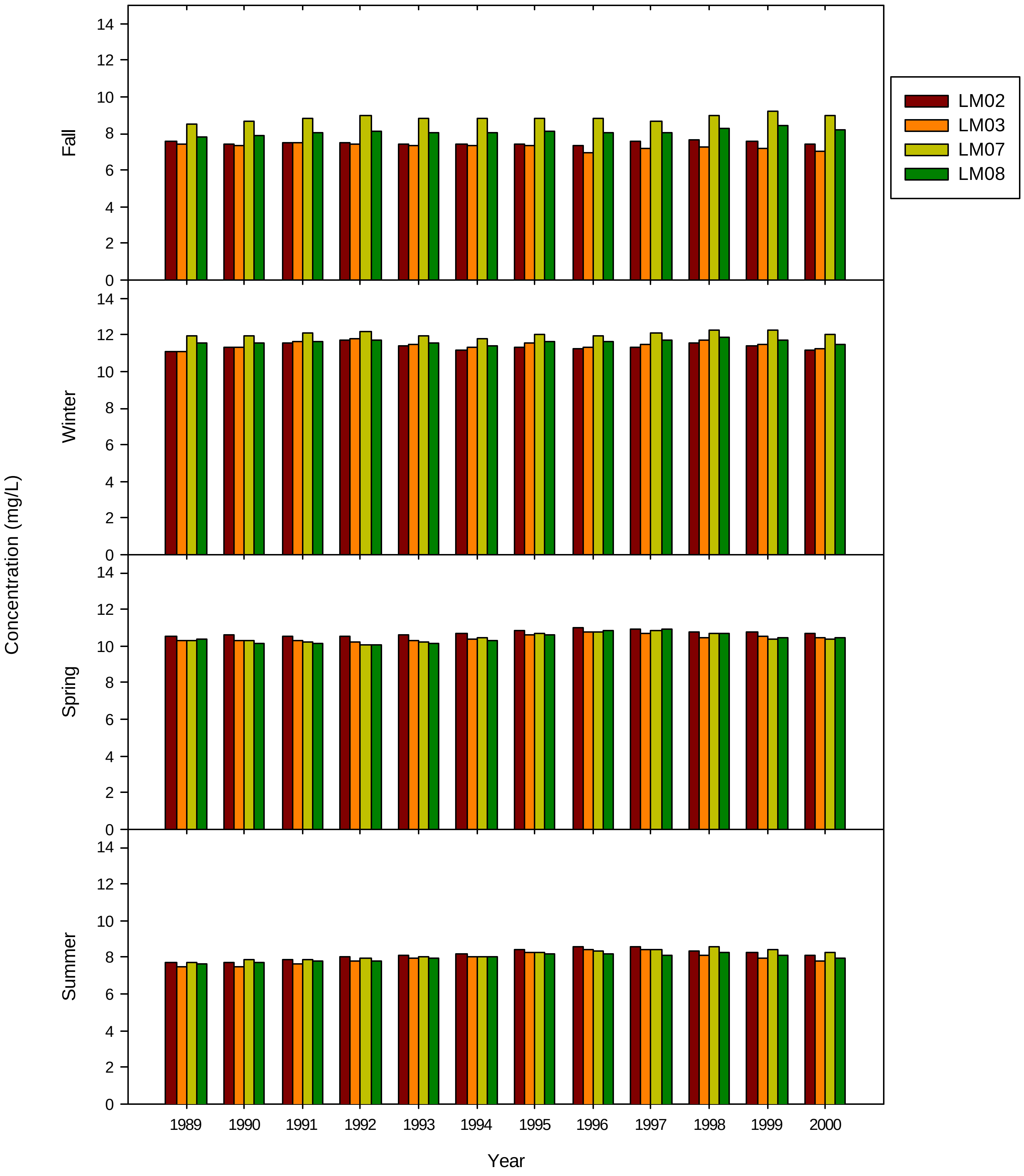


Figure 48
Lake Manassas (Bottom)
Seasonal 5 year Running Average
Dissolved Oxygen, 1984-2000

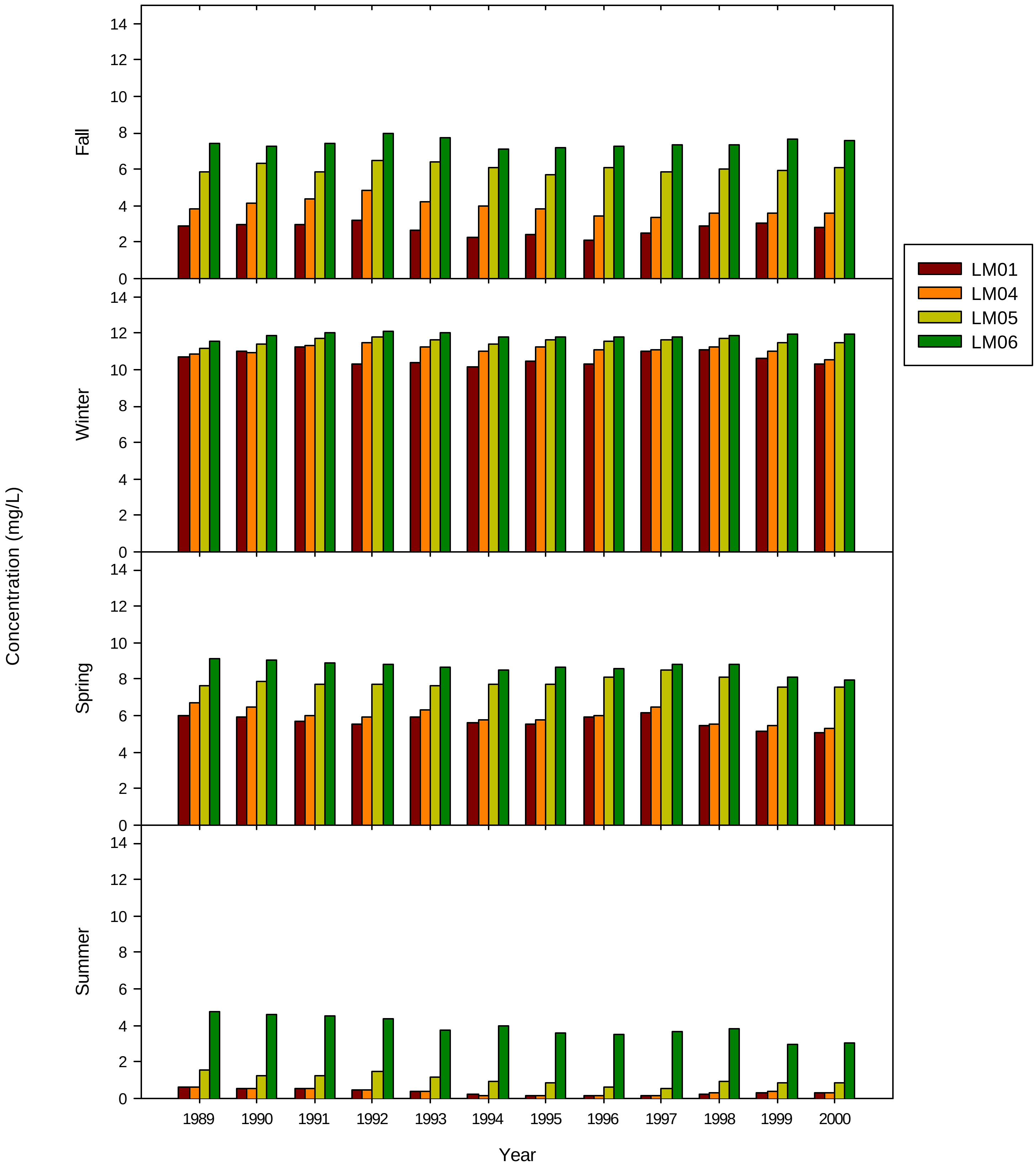


Figure 49
Lake Manassas (Bottom)
Seasonal 5 year Running Average
Dissolved Oxygen, 1984-2000

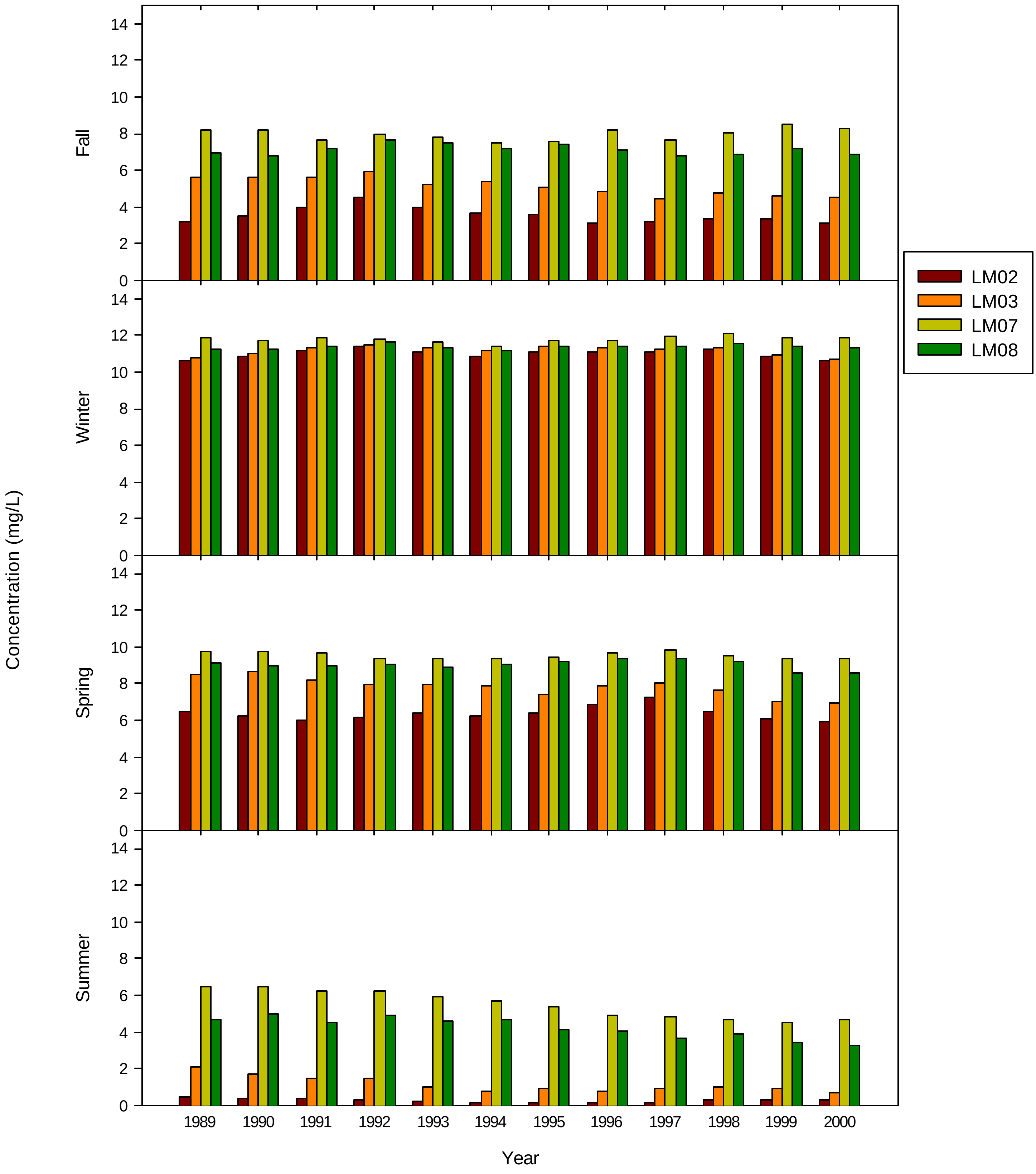
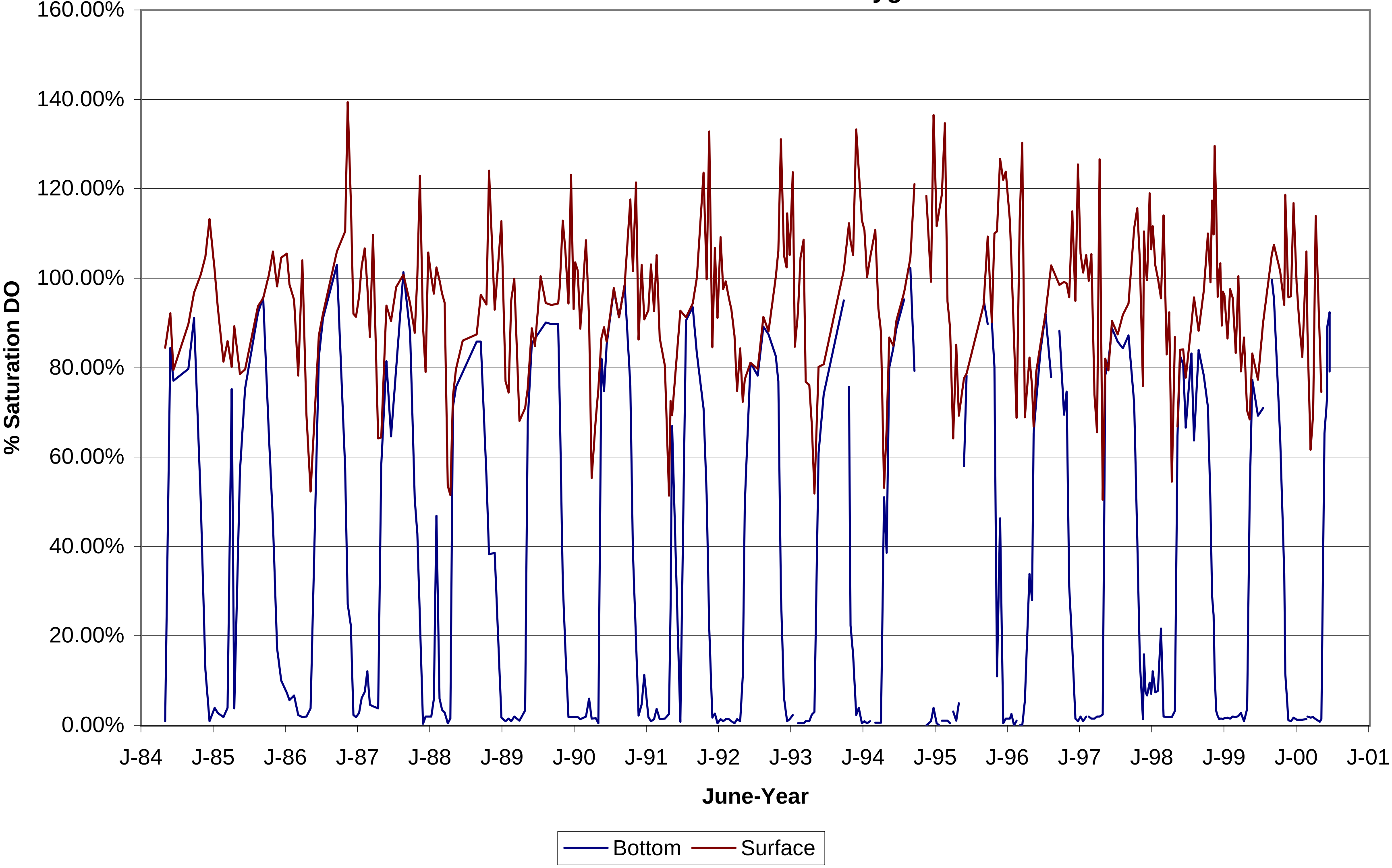


Figure 50
Lake Manassas - Station LM01
Percent Saturation Dissolved Oxygen



concentration on the surface rises, the DO level at the bottom of the lake decreases, the lowest level of 0.5% being achieved when stratification is strongest. The water is supersaturated, with respect to DO, at the surface of the lake due to the presence of algae. The bottom water is depleted of oxygen because it is isolated in the hypolimnion and biological activity depletes oxygen. It remains depleted of oxygen until fall turnover occurs.

Figure 51 shows % DO at station LM06. As the DO level on the surface rise, the DO at the bottom of the lake decreases. This is the same phenomenon that occurs at station LM01 except for the fact that the DO levels at the bottom of the lake fluctuate a bit more. This is because this station does not stratify as strongly as station LM01 and will occasionally mix during the summer if there is a storm.

Figure 52 plots the average bottom DO of the lake against the average surface DO. A 1:1 line is then drawn across the graph to see how the data lie. Each color represents a different season with each point representing a different station, eight in total per season. The winter months tend to have the highest overall DO concentration at both the surface and bottom of the lake, which is shown by the data plotting along the one-to-one line. The spring tends to have very similar surface values, but the bottom values are quite different. This is because in spring stratification starts earlier at deeper stations and later at the shallower stations. Both the summer, when the stratification is strongest, and fall also exhibit this pattern. Figure 53 shows the same type of graph, but % DO sat. is plotted instead. The winter months still cluster around the one-to-one line, but it is easy to see that in the spring and summer the %DO levels rise above 100% on the surface, and the low %DO levels are on the bottom of the

Figure 51
Lake Manassas - Station LM06
Percent Saturation Dissolved Oxygen

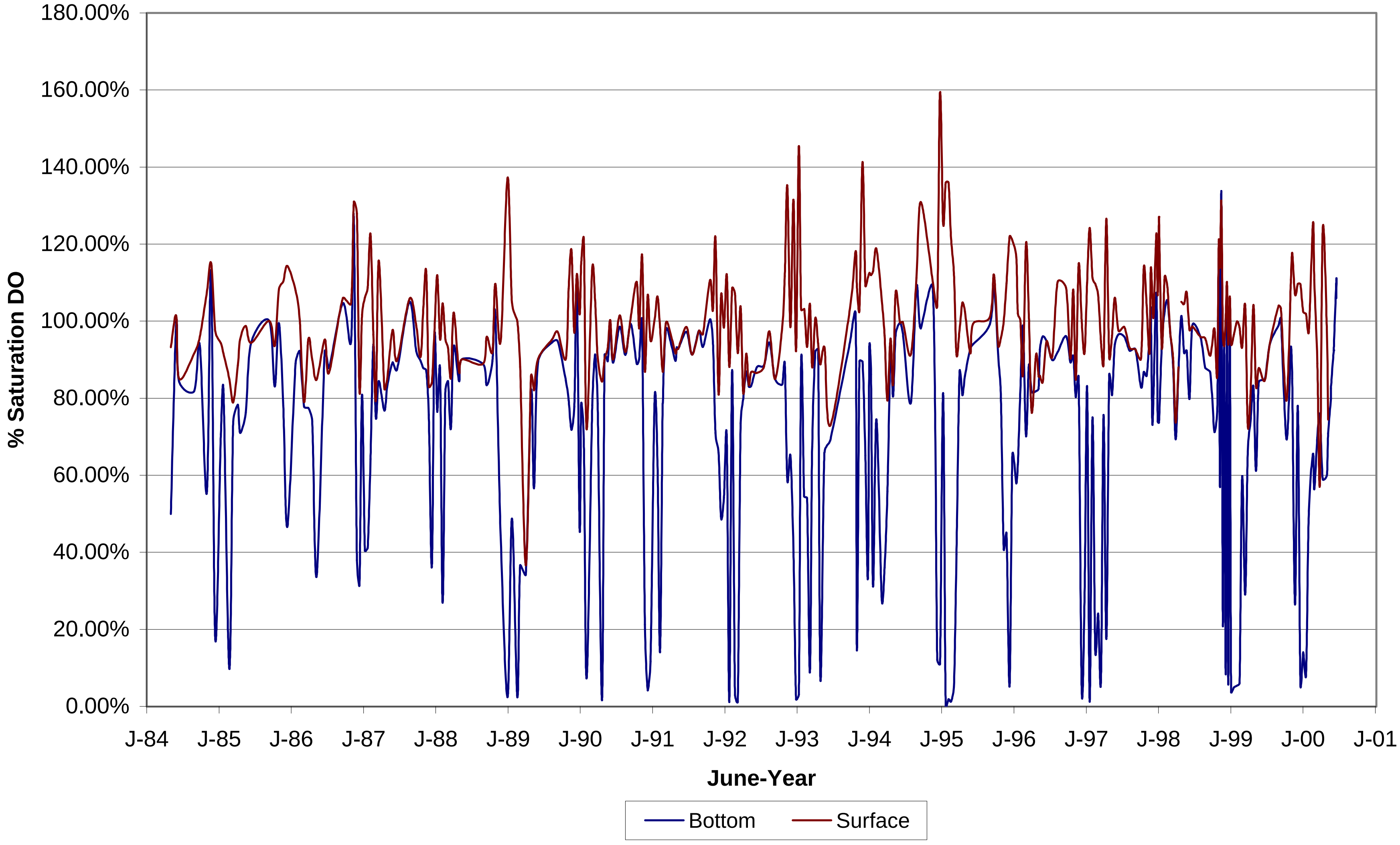


Figure 52
Lake Manassas
Average Surface and Bottom DO Concentrations Compared

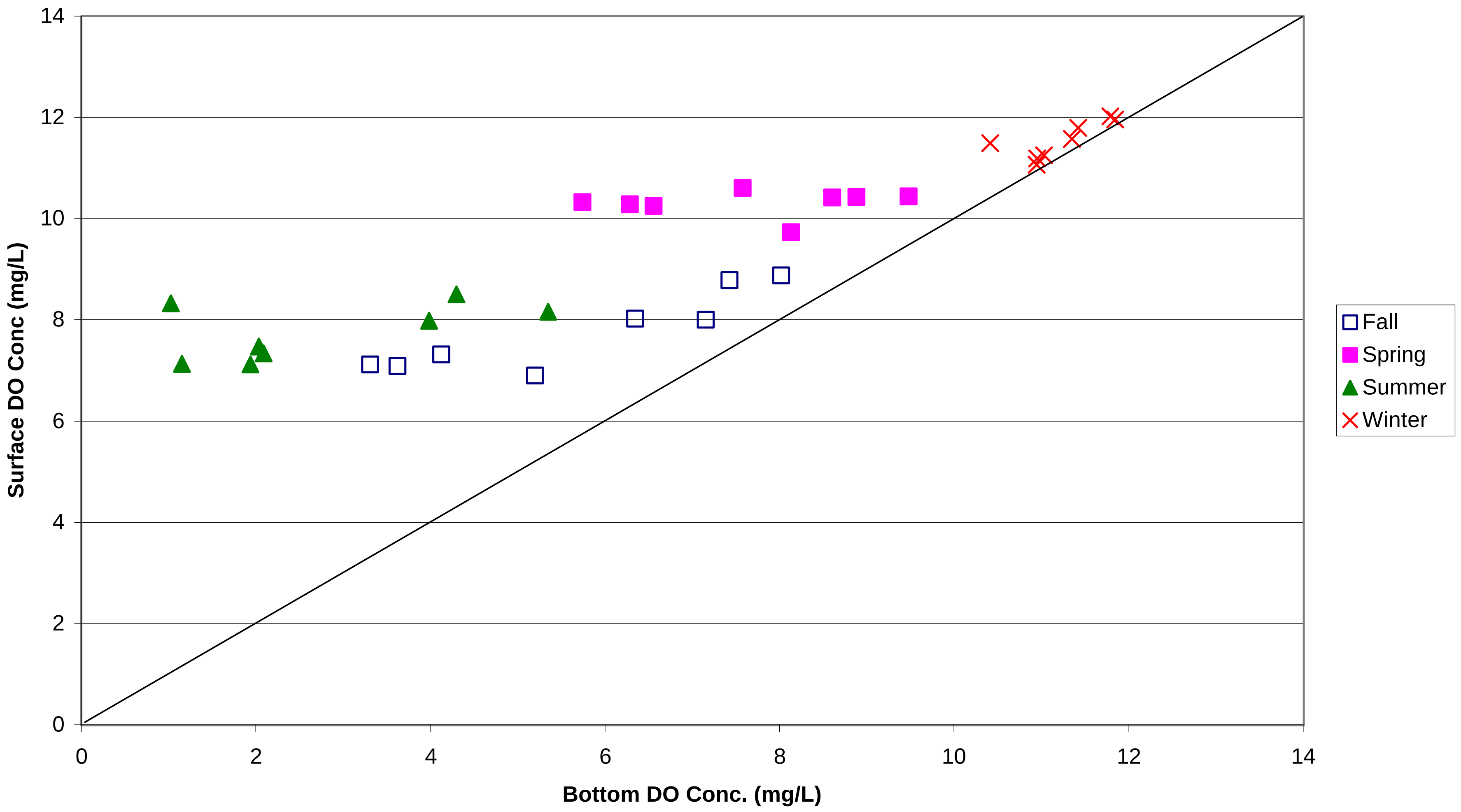


Figure 53
Lake Manassas
Average Surface and Bottom DO sat Concentrations Compared

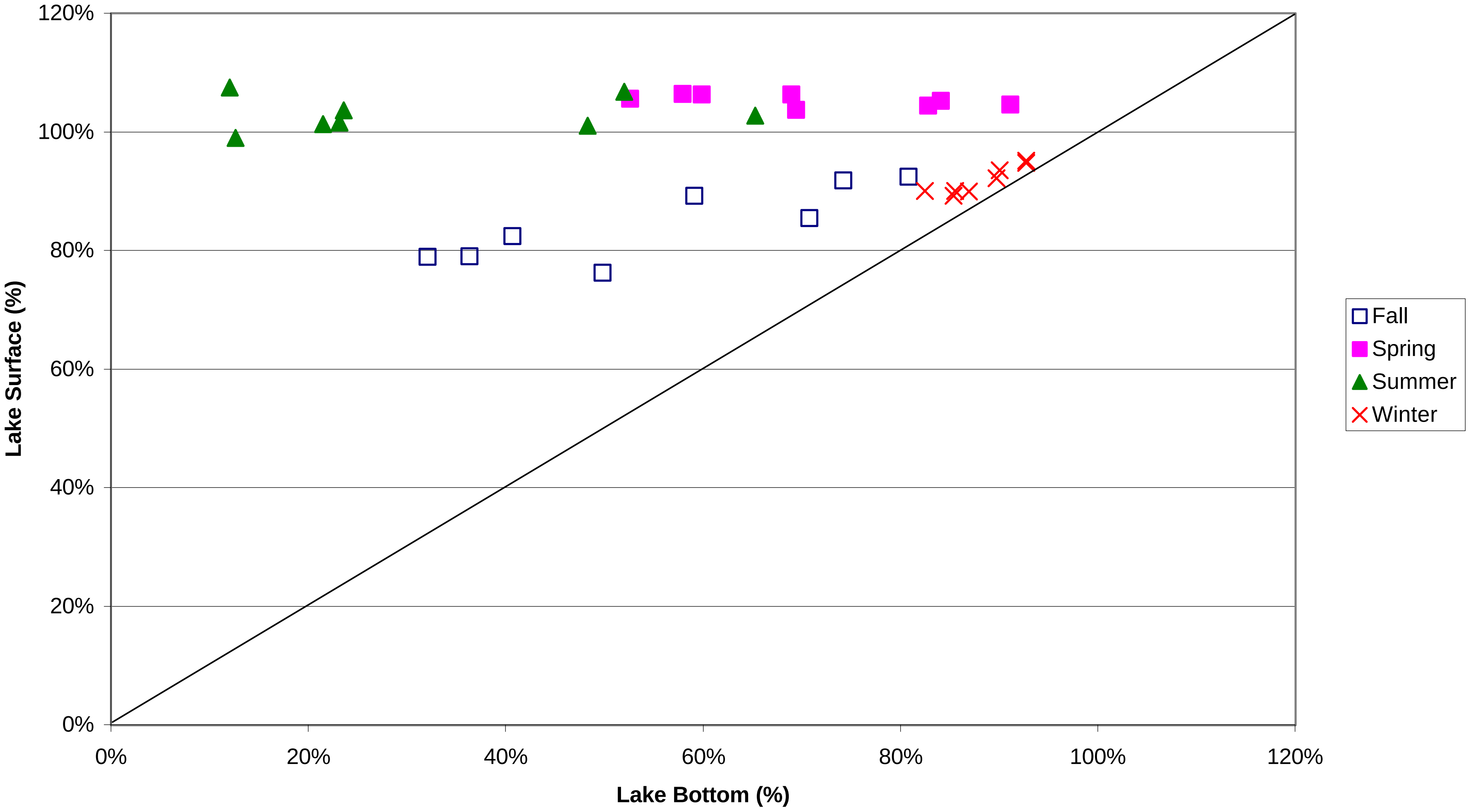


Figure 54
Lake Manassas, Station LM01, 1997
Dissolved Oxygen Profile

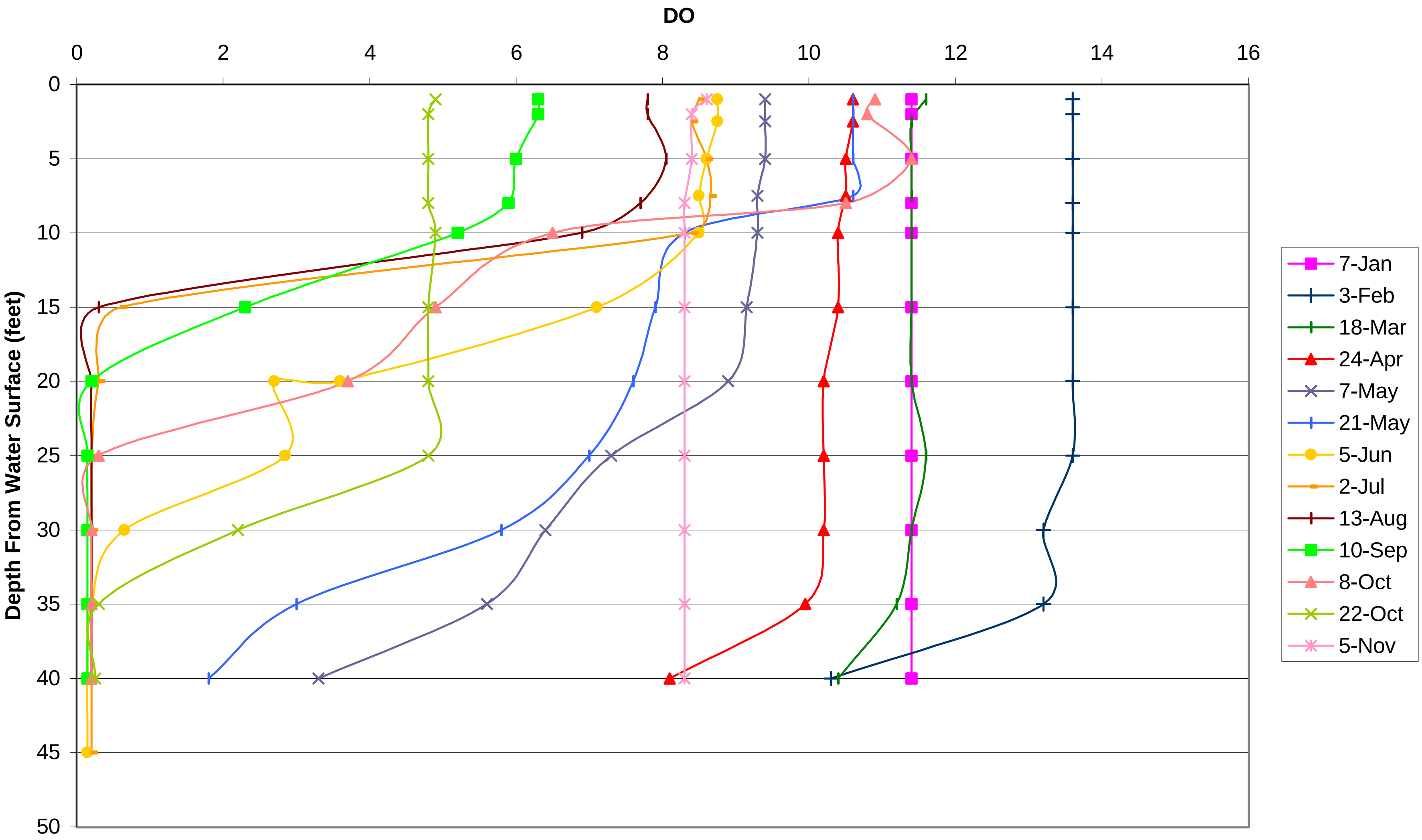
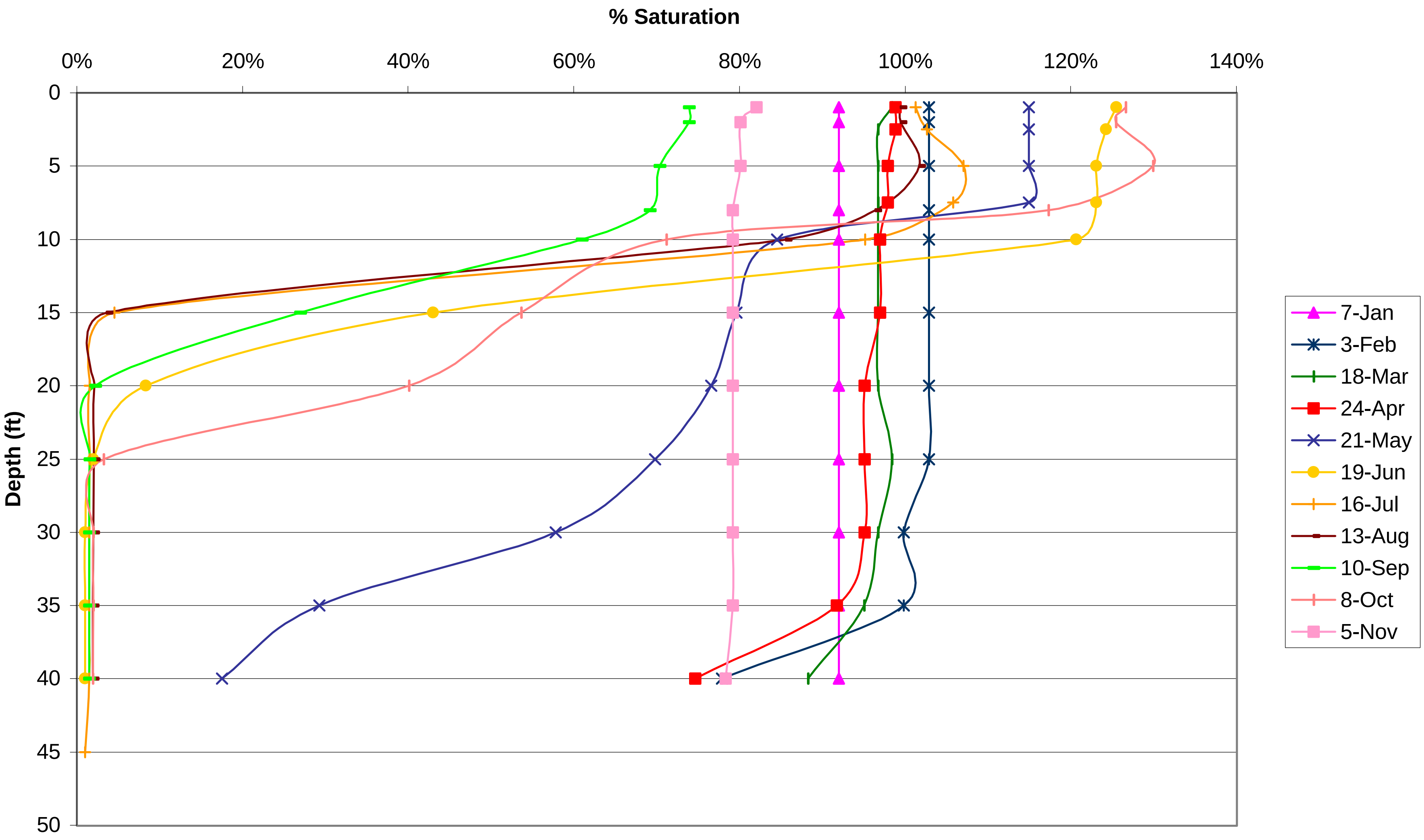


Figure 55
Lake Manassas, Station LM01, 1997
Profile of Percent Saturation DO



lake.

Figure 54 and 55 show the profiles of DO and % DO sat in 1997 over the full year at station LM01. During the month of February, the DO is at the highest concentration of the year. From this point the DO decreases and the lake starts to stratify between April and May. The highest degree of stratification at this station is acheived around the end of June to the beginning of July. The beginning of October shows the start of the fall turnover and it is complete by the beginning of November. The profile of %DO sat. shows the same thing, but an interesting item shows up on this graph. On May 21, the %DO sat. is above 100%, then decreases below 100% on June 5th, but then by June 19th, the %DO sat. is back above 100%. When the %DO sat. is above 100%, it indicates the growth and presence of algae. It is possible that the algae became limited by phosphorus and the growth stopped. This would cause the %DO sat. to decrease below 100%. It is thought that as more phosphorus enters the lake the algae start to grow again and the %DO sat. increases again to above 100%.

Figures 56 and 57 are the same type as described above, but are for 1998. Both 1997 and 1998 had different amounts of rainfall, and will in turn have different periods and / or strength of stratification. The year 1997 had a total of 33 inches of rainfall while 1998 had 41 inches. There were also differences between each season for 1997 and 1998. The year 1997 had high rainfall in the Fall while 1998 had a higher rainfall for the rest of the seasons. The stratification in 1998 started in the middle of April, and is fully complete in May. An interesting note is that during August the DO concentration increased slightly at the very bottom of the lake. The fall turnover then occurred between October and November.

Figure 56
Lake Manassas, Station LM01, 1998
Dissolved Oxygen Profile

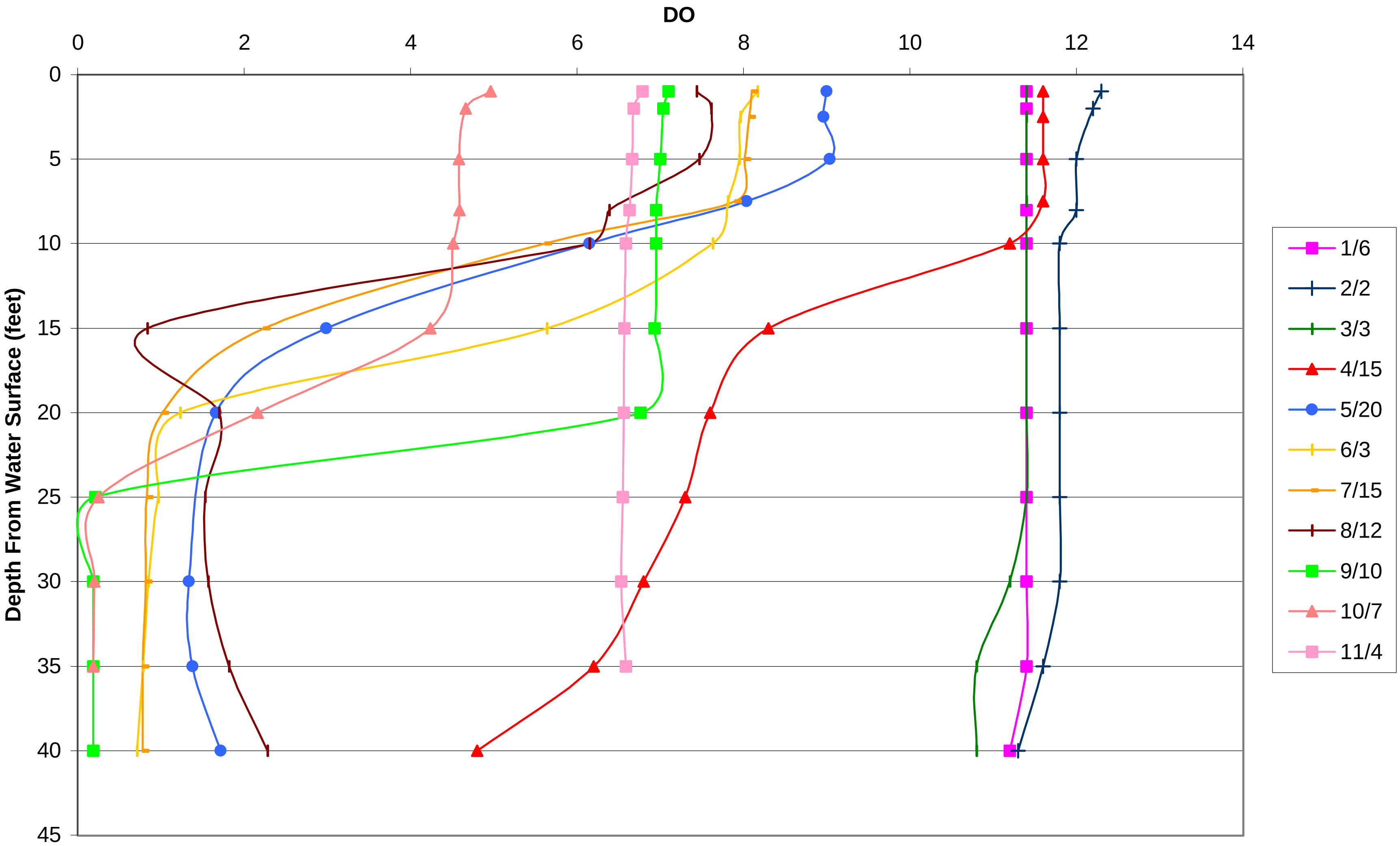
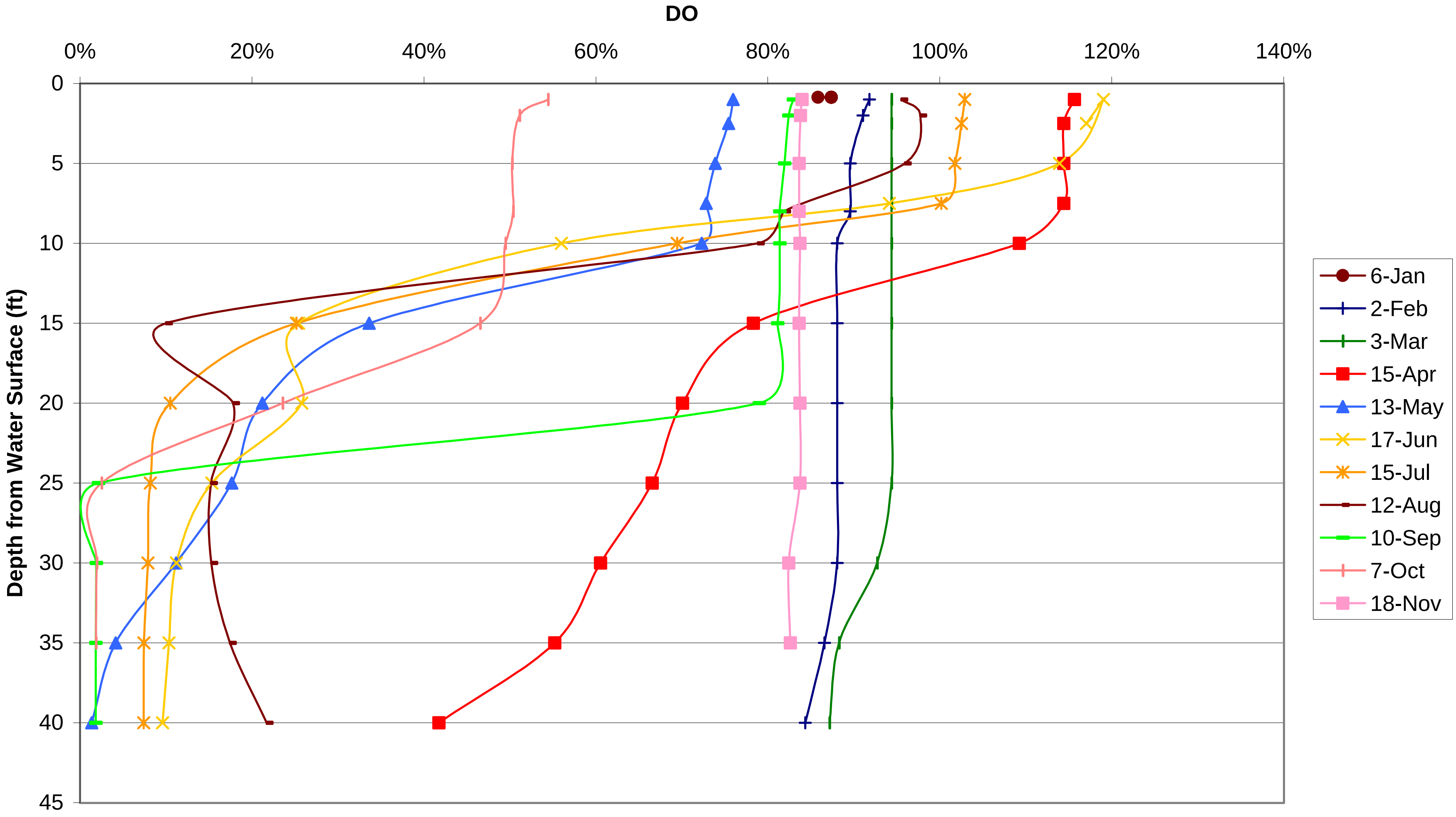


Figure 57
Lake Manassas - StationLM01, 1998
Profile of Percent Saturation DO



Another item of interest is that during the summer the thermocline was nearer the surface of the lake at 10 ft. and in September the thermocline moved down to a depth of 20 ft. This could be due to the fact that as the temperature of the epilimnion decreases, the water becomes more dense and will start to sink. Overall 1998 tended to have a longer stratification period than 1997. This could be because 1998 had less rain than 1997, and therefore less disturbance of the water column.

Nutrients

The productivity of a lake, and its trophic status, is largely determined by the amount of nutrients in the system. These nutrients are nitrogen and phosphorus, and these often control the growth of algae. Not all of the nutrients that are brought into the lake are available to microorganisms and algae. Nitrogen can be lost through sedimentation, outflow, and reduction by bacterial denitrification. Phosphorus is the least abundant and tends to limit biological activity. Phosphorus can precipitate out of water, and adsorb to colloids and particulates, thus making it unavailable for biological activity.

Nitrogen

Reduced Nitrogen

Total Kjeldahl nitrogen (TKN) is a measure of the total reduced forms of Nitrogen in the Lake and includes organic nitrogen and ammonium (NH_4^+). Figures 58 through 61 show the seasonal five-year running averages for both the surface and the bottom of the lake for TKN.

The surface values are relatively consistent over the fifteen years with little change over station or

Figure 58
Lake Manassas (Surface)
Seasonal 5 year Running Average
TKN,1984-2000

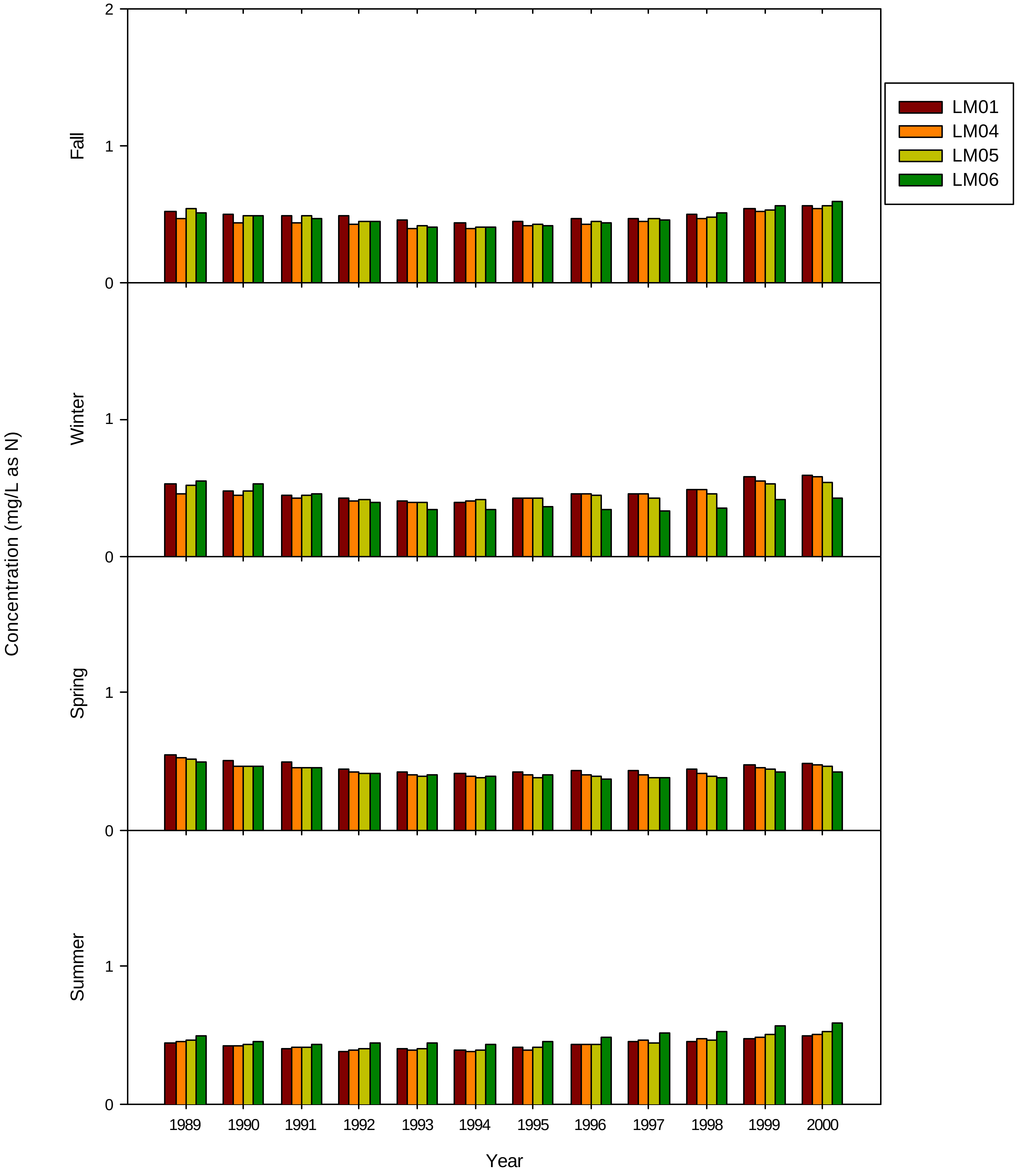


Figure 59
Lake Manassas (Surface)
Seasonal 5 year Running Average
TKN,1984-2000

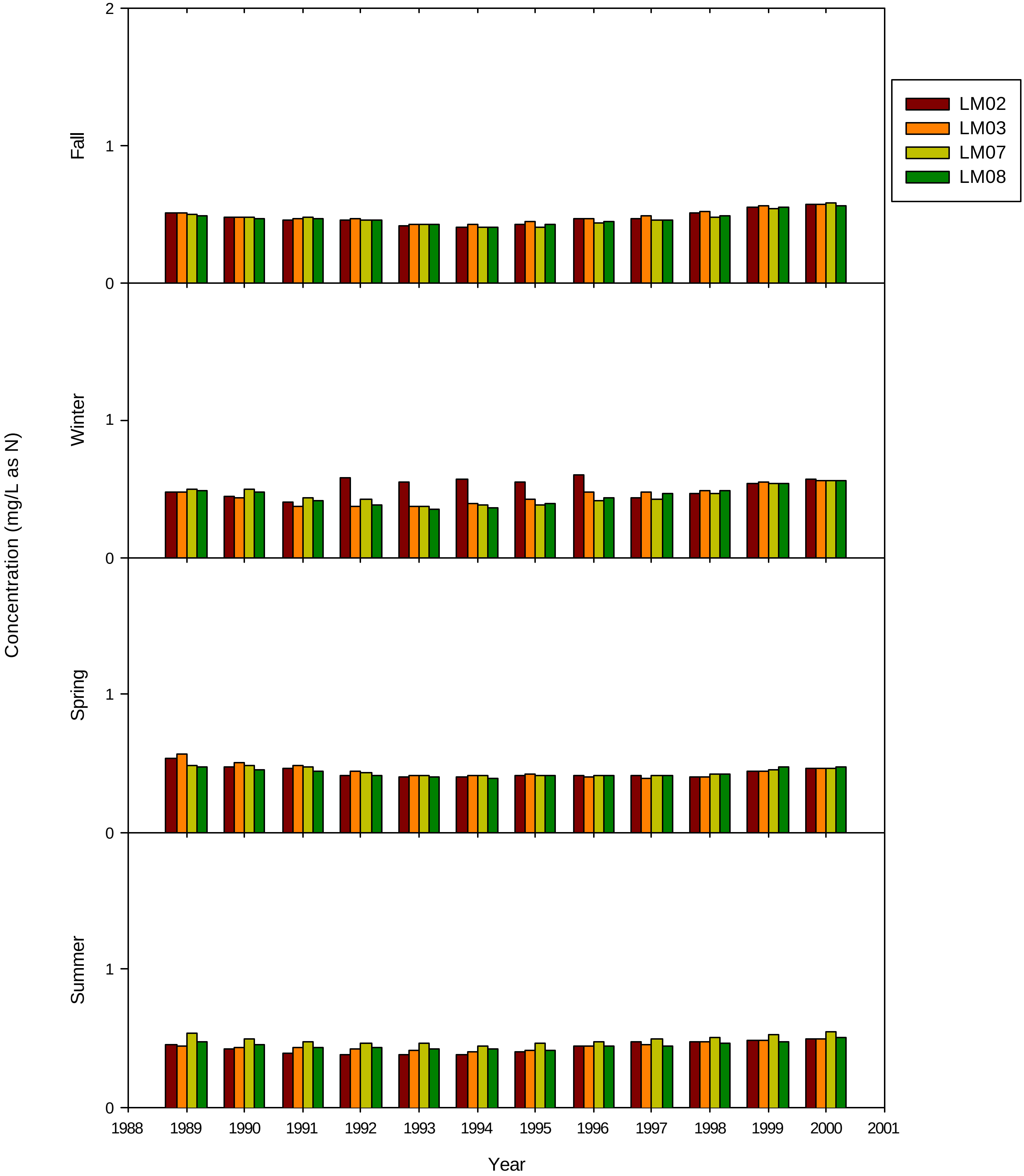


Figure 60
Lake Manassas (Bottom)
Seasonal 5 year Running Average
TKN, 1984-2000

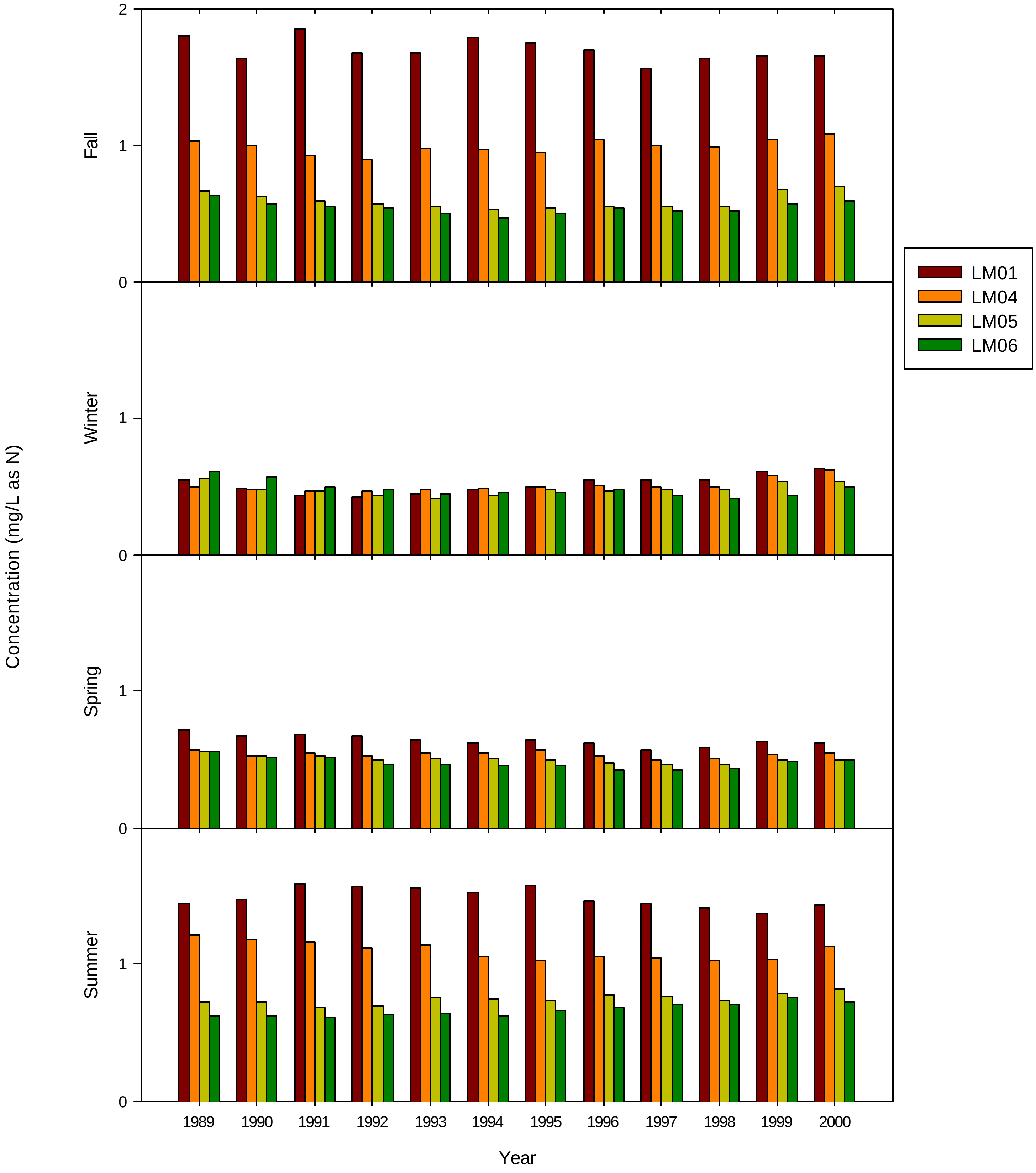
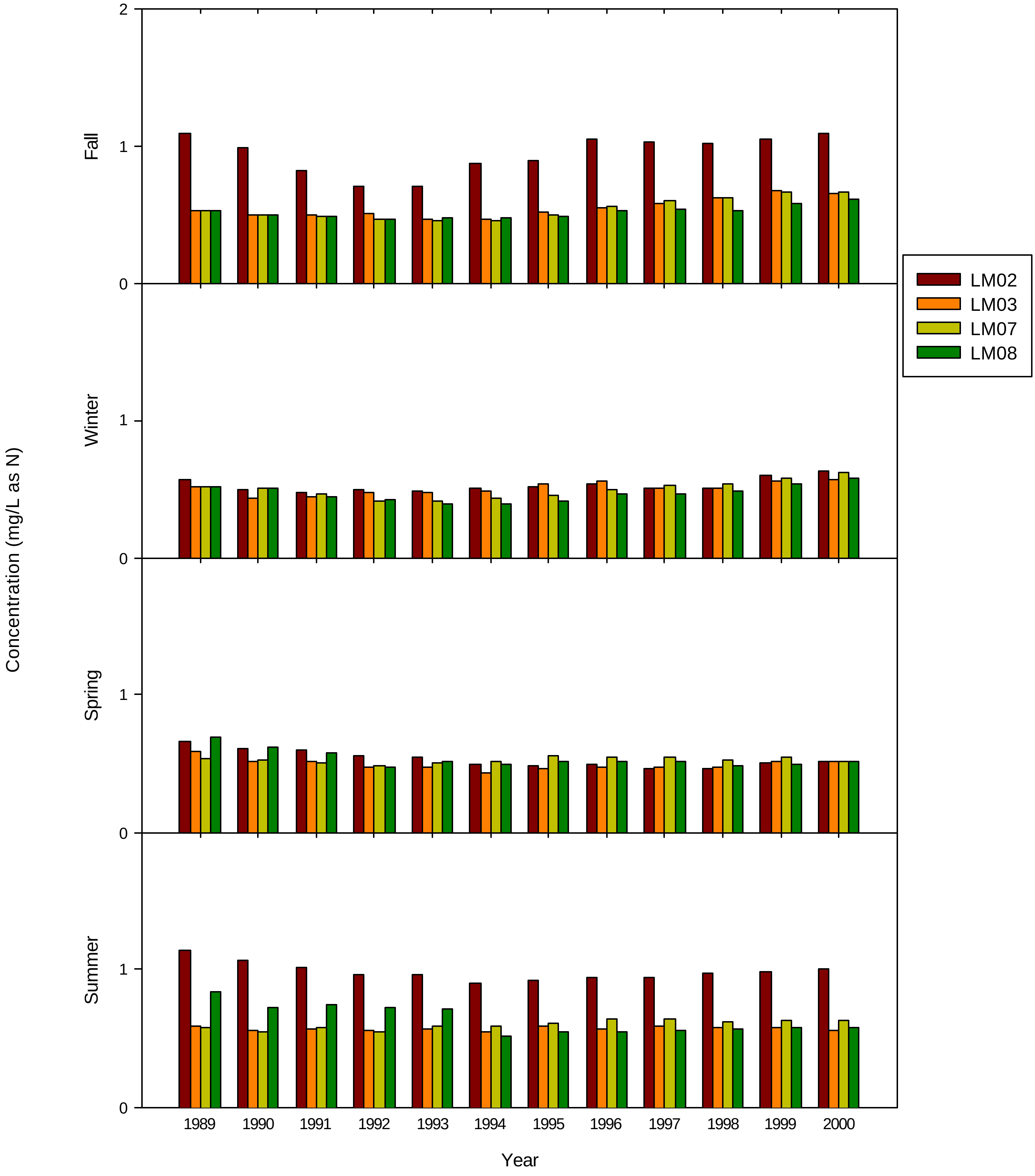


Figure 61
Lake Manassas (Bottom)
Seasonal 5 year Running Average
TKN, 1984-2000



season. Stations LM04, LM07, and LM08 show an increasing trend of TKN at the surface. Stations LM07 and LM08 are located on the northern side of the lake in individual branches, while LM04 is located on the eastern end near the middle of the lake. LM04 and LM08 are located near the Robert Trent Jones International golf course and this could possibly be a factor. The bottom values of the lake show a different picture. There is a large increase in the amount of TKN at the bottom of the lake for stations LM01, LM02, and LM04 during the summer and fall. This is due to the fact that stratification occurs at this time. In the hypolimnion, ammonia is probably released from the sediment. There also is the decomposition of organic matter. The nitrogen is trapped and lingers in the hypolimnion until fall turnover. Station LM03, LM07, and LM08 show an increase over time of TKN at the bottom of the lake. Overall, stations LM07 and LM08 have an increasing trend for TKN.

Figure 62 shows the average TKN concentration for all seasons with the bottom values plotted against the surface values. Each data point represents a station, eight in all. A one-to-one line is then plotted and compared to the data. Overall the data are clustered in one area near the one-to-one line, but the summer months and some stations in the fall show that the bottom TKN increases. This is due to the increase in TKN in the hypolimnion are a result of anoxic conditions.

During 1998 a series of measurements was made of nutrients at different depths at station LM01. Figure 63 is a plot of this. This plot shows that the surface TKN concentrations remain constant while the bottom values have an increasing trend. This increase starts to take place at about 20 to 25 feet depth. During this year the thermocline was located at the 20-25 foot depth and below that the

Figure 62
Lake Manassas
Average Surface and Bottom TKN Comparison

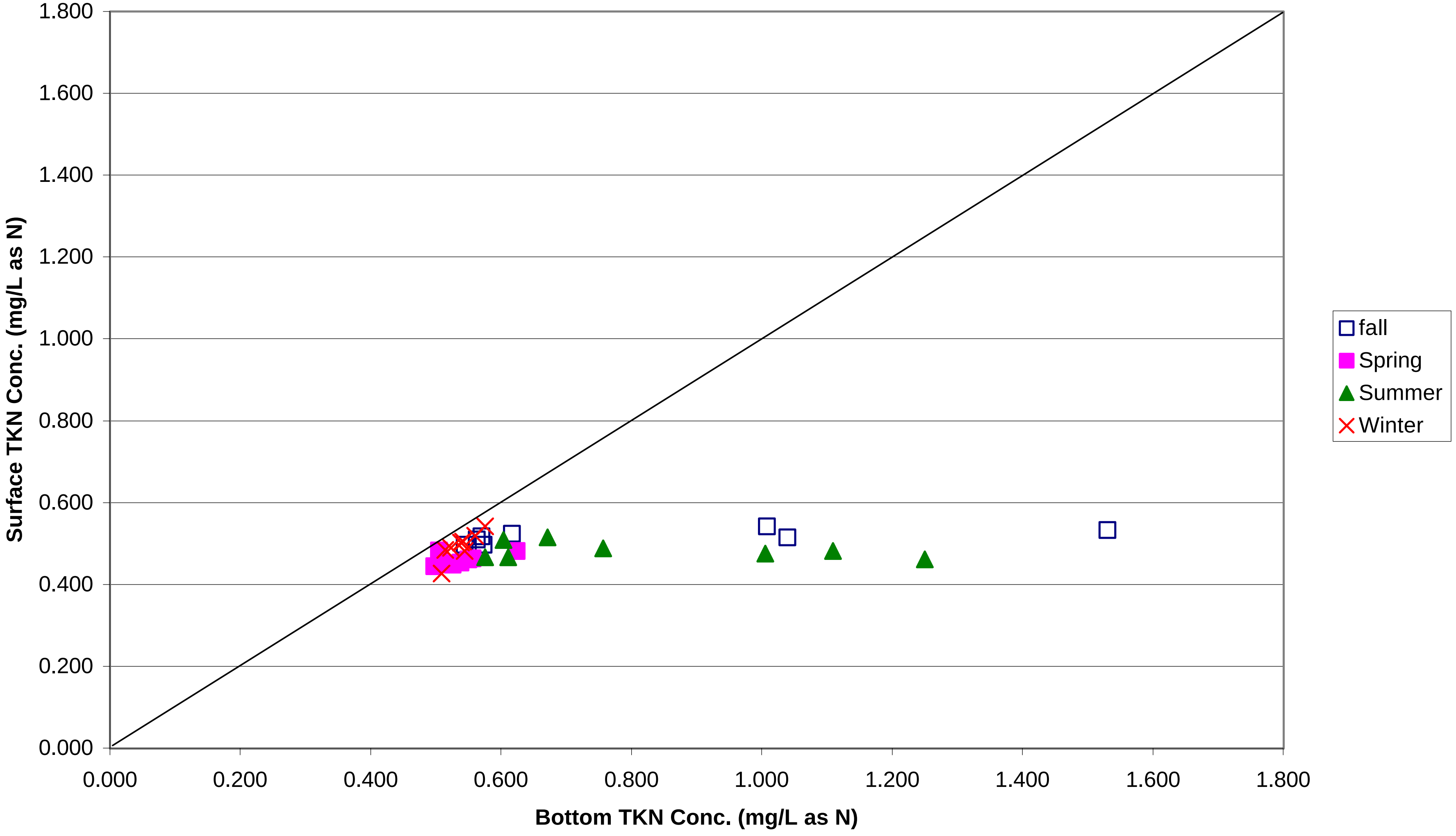
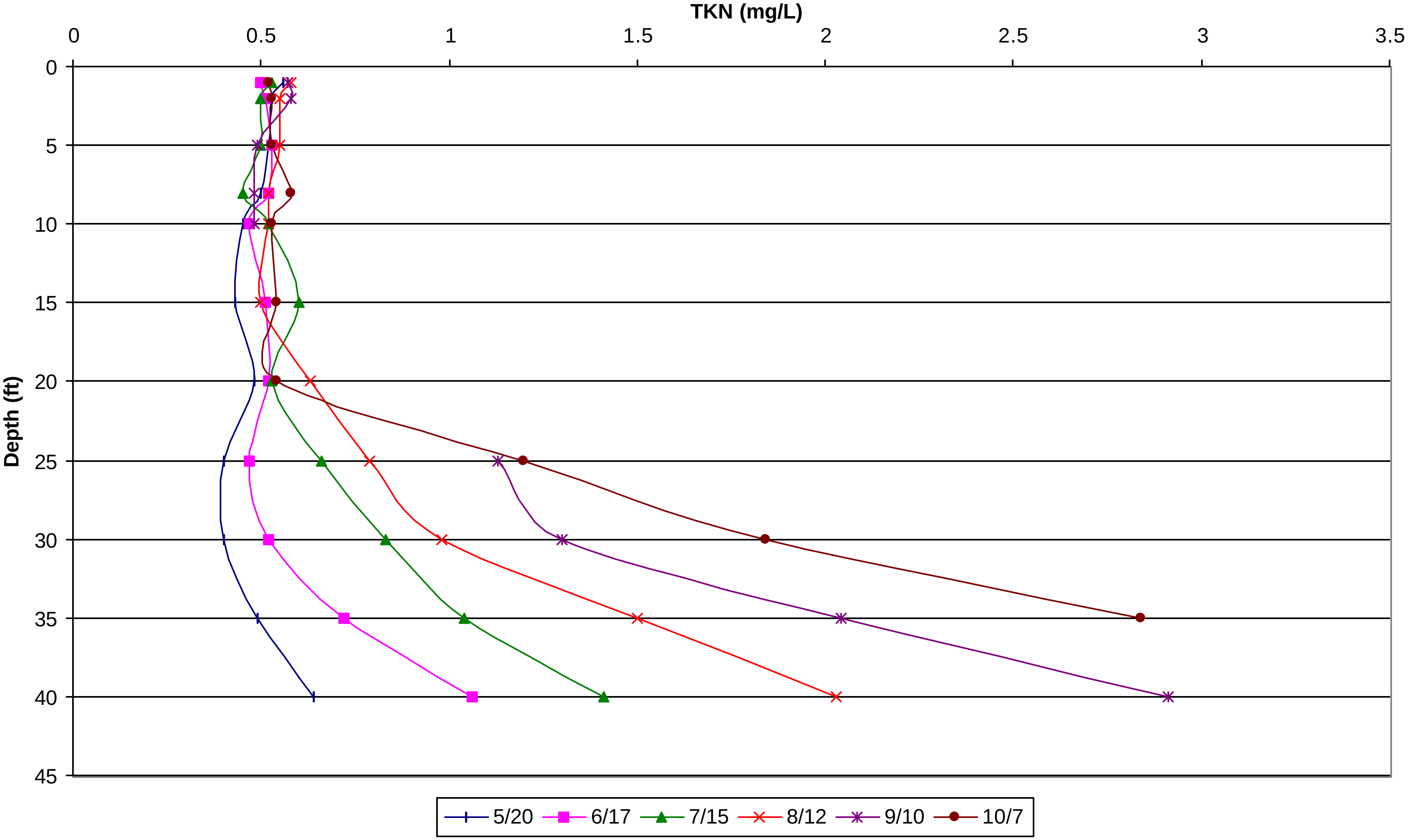


Figure 63
Lake Manassas - Station LM01, 1998
Profile of TKN



dissolved oxygen was quite low, in the hypolimnion. The TKN concentration was highest at the 40-foot depth.

Oxidized Nitrogen

Oxidized Nitrogen is a measure of NO2-N and NO3-N. Oxidized Nitrogen may be influenced by the growth of algae on the surface of the lake since algae use OX-N in the production of amino acid and proteins. As the algae are the most productive in the summer, that would indicate low levels of OX-N during that season. On the bottom of the lake when it is stratified, or the hypolimnion, there is a decrease in the amount of DO present. Microorganisms will use OX-N, an alternate electron acceptor, when there is no DO available. This would imply that the decrease of OX-N at the bottom of the lake would lag behind the depletion of DO from the hypolimnion since the DO takes time to be completely utilized. During fall turnover, the oxidized nitrogen will increase on the bottom of the lake because of higher surface concentrations mixing with the bottom waters.

Figures 64 through 67 show the five-year seasonal running averages of OX-N for the surface and the bottom of the lake. The winter months have the most OX-N while the summer has the least. Station LM06 has the tendency to have more OX-N than the other stations, especially during the winter. Both the surface and bottom concentrations in the summer decrease significantly at LM06, with the surface values being lower. This is most likely due to the growth of algae. This growth is most likely not present in the hypolimnion. The small amount of time that the microorganisms have to use up the OX-N, in the absence of DO would imply that the bottom concentrations would remain higher than those at

Figure 64
Lake Manassas (Surface)
Seasonal 5 year Running Average
OX-N,1984-2000

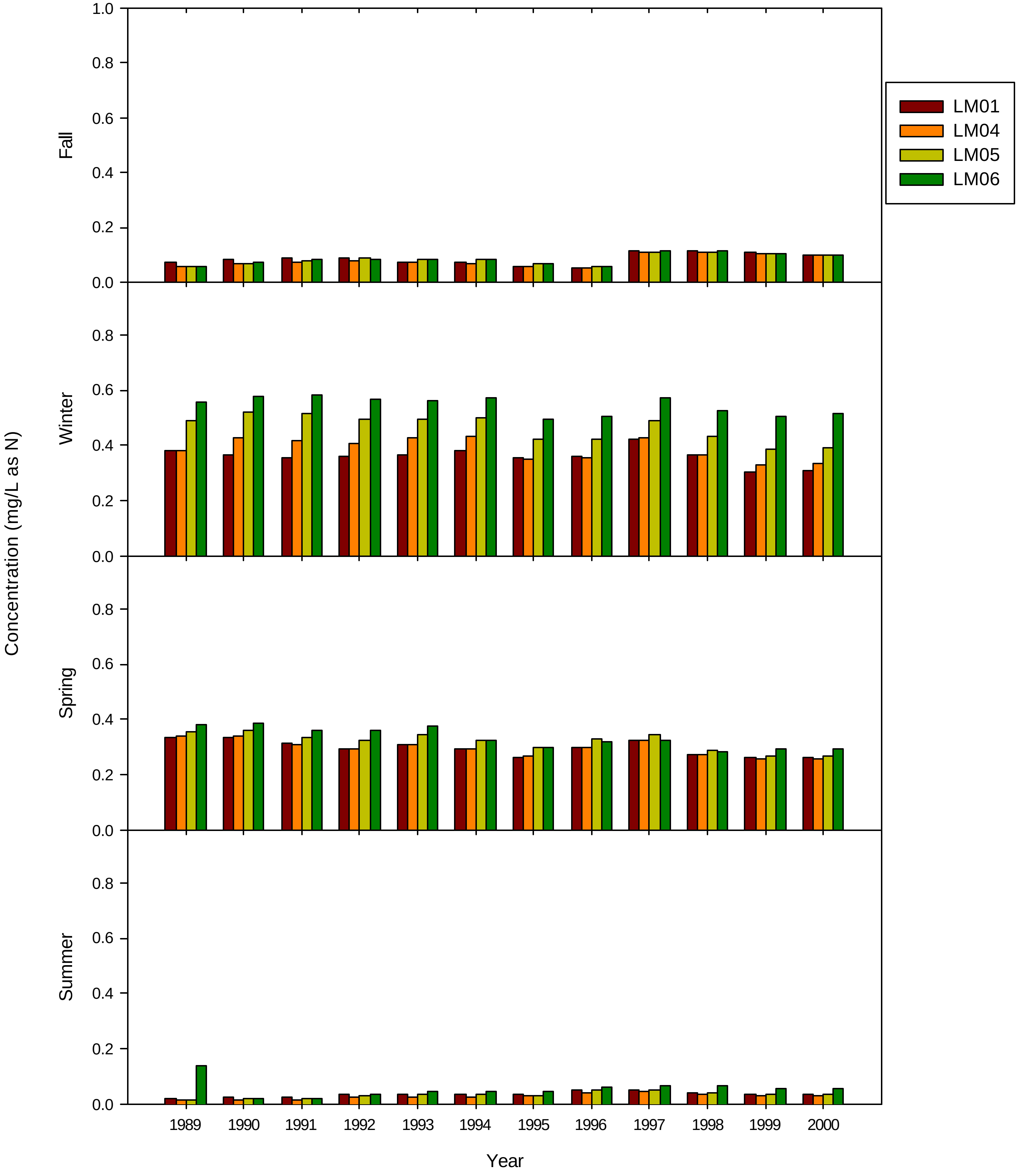


Figure 65
Lake Manassas (Surface)
Seasonal 5 year Running Average
OX-N,1984-2000

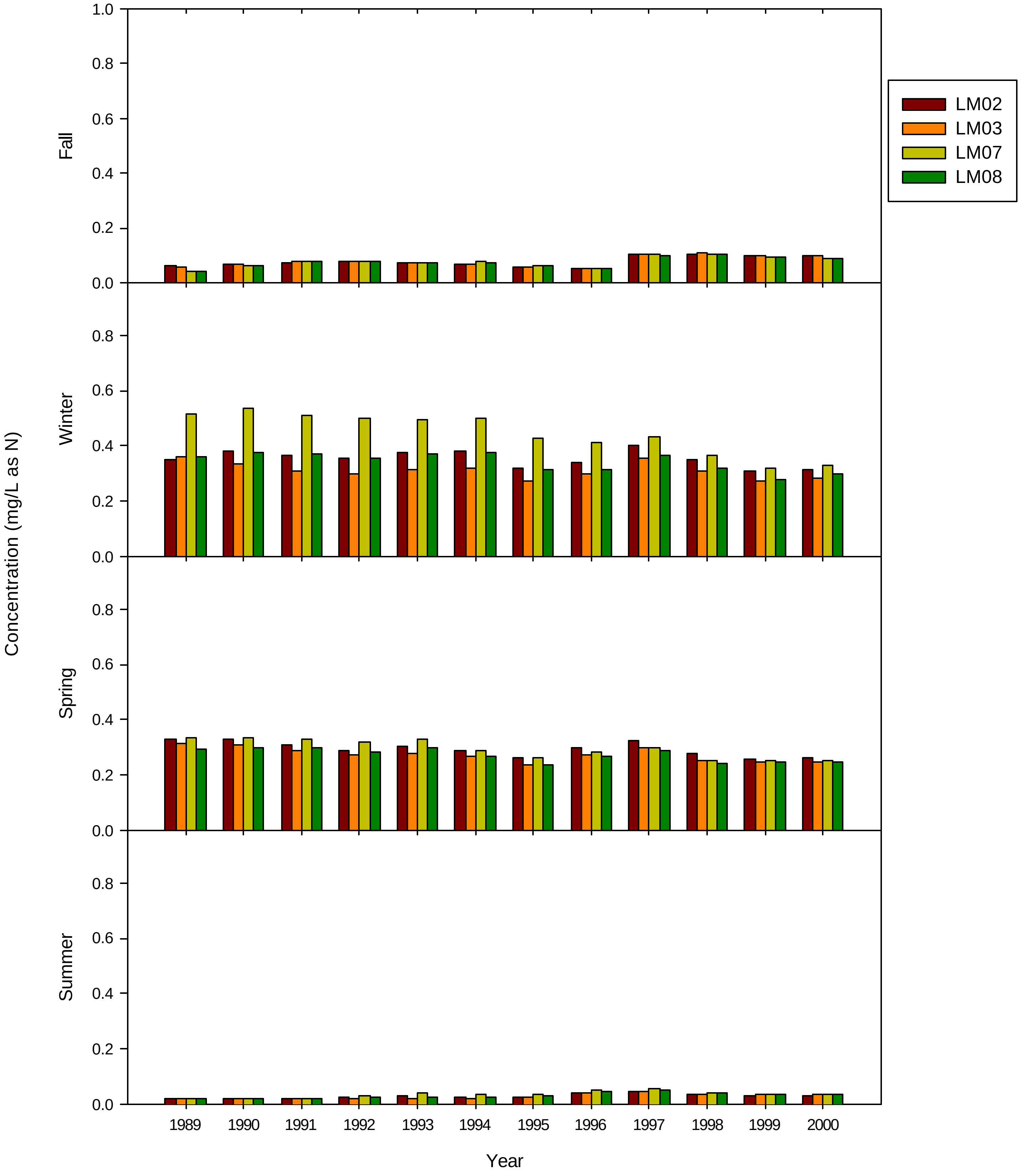


Figure 66
Lake Manassas (Bottom)
Seasonal 5 year Running Average
OX-N, 1984-2000

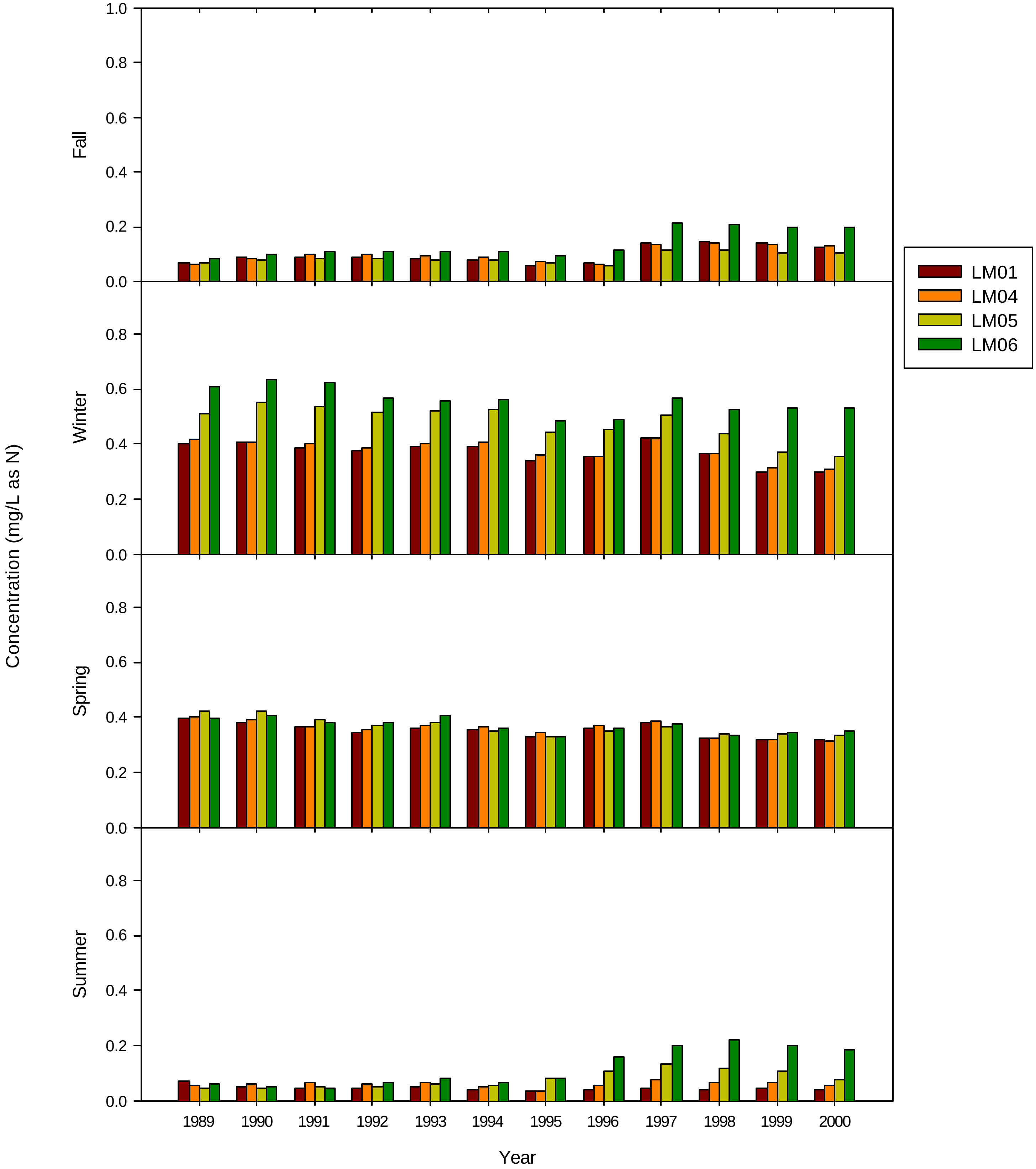
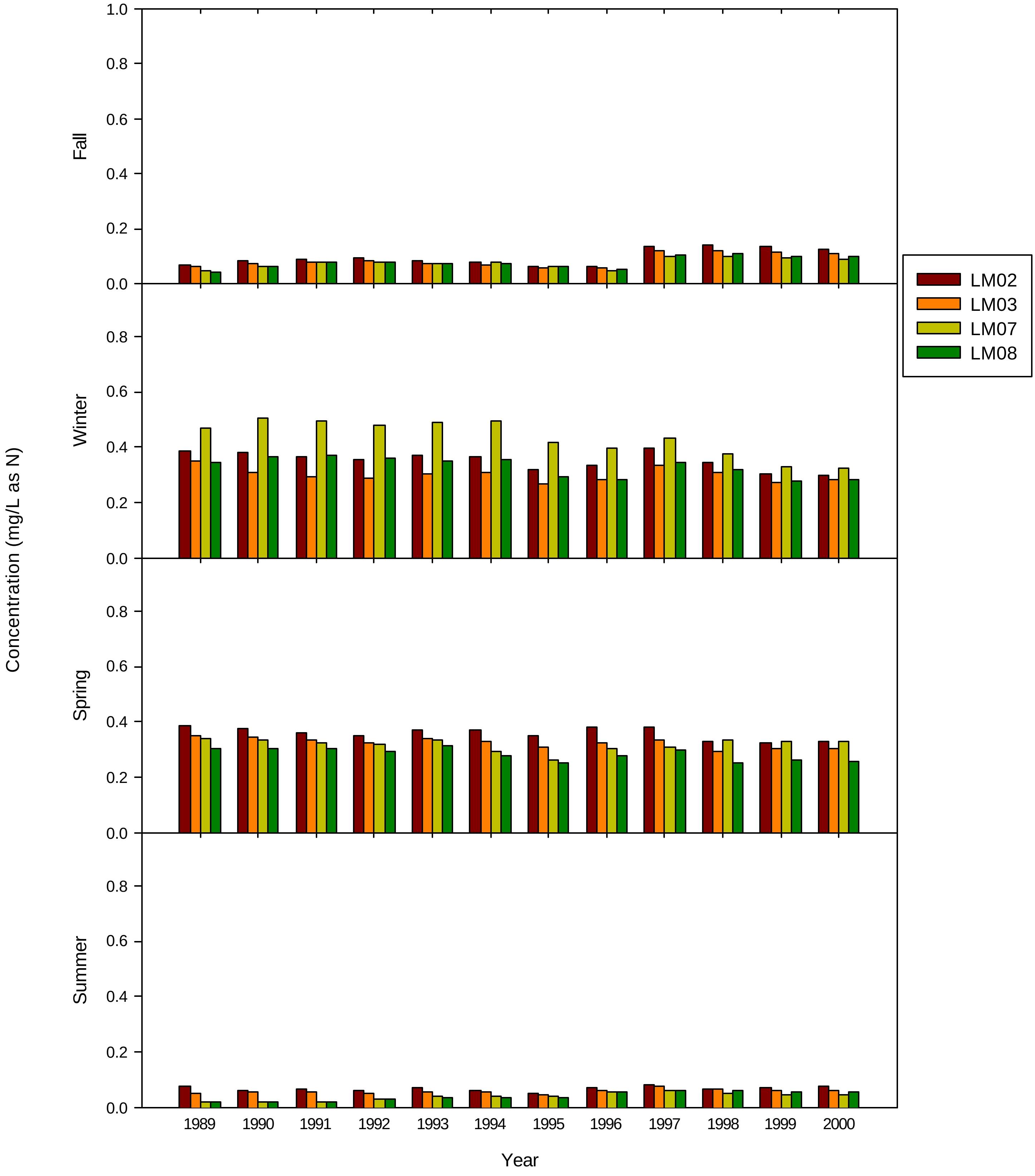


Figure 67
Lake Manassas (Bottom)
Seasonal 5 year Running Average
OX-N, 1984-2000



the surface. During the fall lake concentrations increase slightly due to the decrease in algae and the fall turnover. The graph shows the average over the full fall season, and would incorporate highs and lows during the season. There are no trends at the surface of the lake but the lake bottom shows decreasing trends at stations LM01, LM02 and LM04. All three of these stations are located on the east side of the lake and are quite deep. The probable reason for this decrease is that the stratification may be lasting longer, with a consequently longer duration of reduced DO, thus allowing the microorganisms to use more of the oxidized nitrogen. The trends for LM01 and LM04 show that there is a decreasing trend of dissolved oxygen at the bottom of the lake. A look at the temperature and dissolved oxygen profiles of 1997 and 1998 (see figures 42, 43, XX and XX) shows that 1998 had a longer stratification period.

Figure 68 shows the bottom OX-N concentration of the lake plotted against the surface OX-N concentration. The four seasons are represented in various colors and shapes and each datapoint represents a station, eight in all. There is a one-to-one line drawn in the graph which the data are compared to. Most of the points have a tendency to lie close to the line, showing that the concentrations are about the same in the surface and the bottom. During the summer though, the bottom has a higher concentration since there is no algal synthesis.

In 1998 nutrient depth profile measurements were taken over several months at station LM01. Figure 69 shows this data in graph form. The month of May shows a high value for OX-N, which then becomes lower in June and then not detectable until October. The concentration of OX-N decreases

Figure 68
Lake Manassas
Average Surface and Bottom OX-N Concentration Comparison

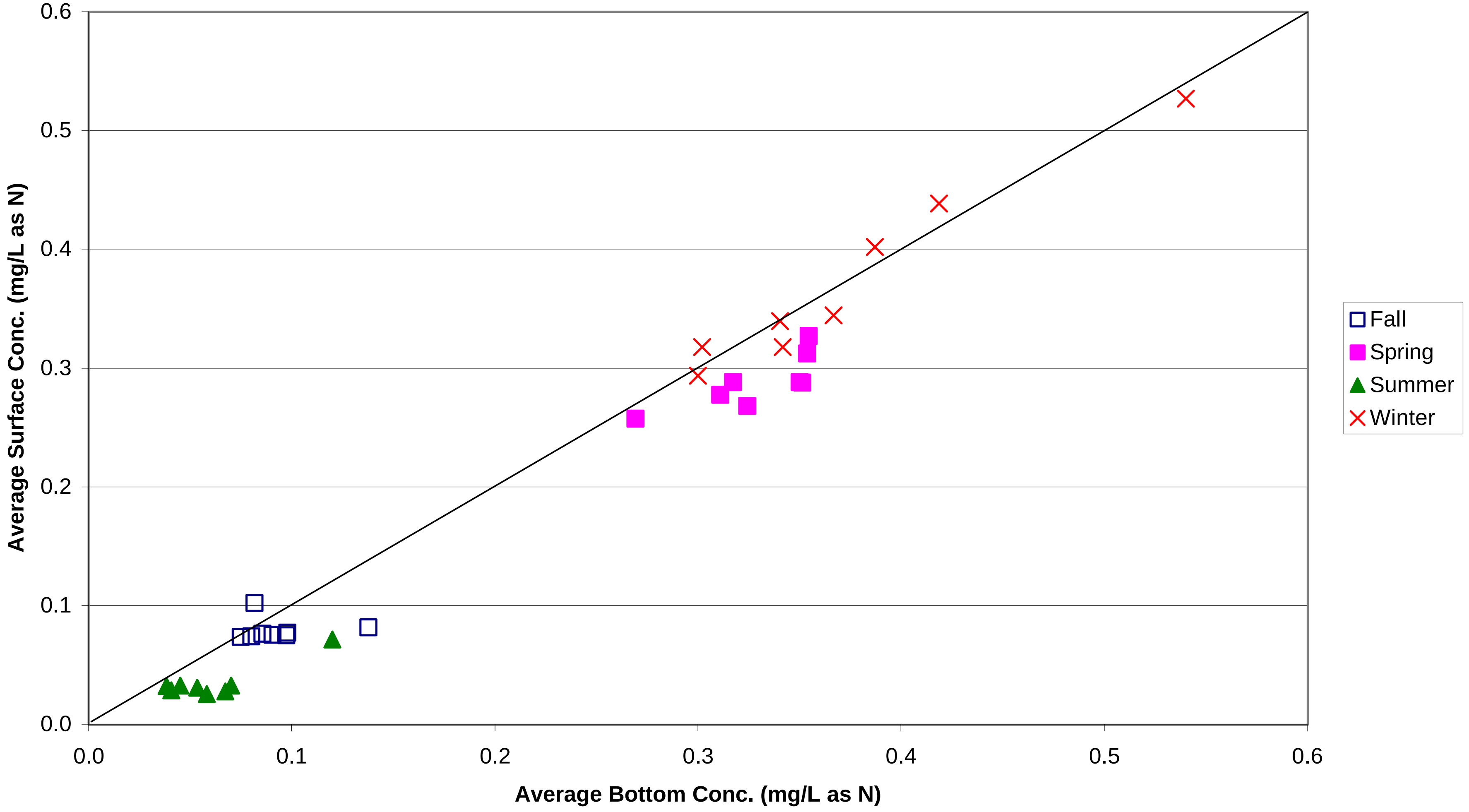
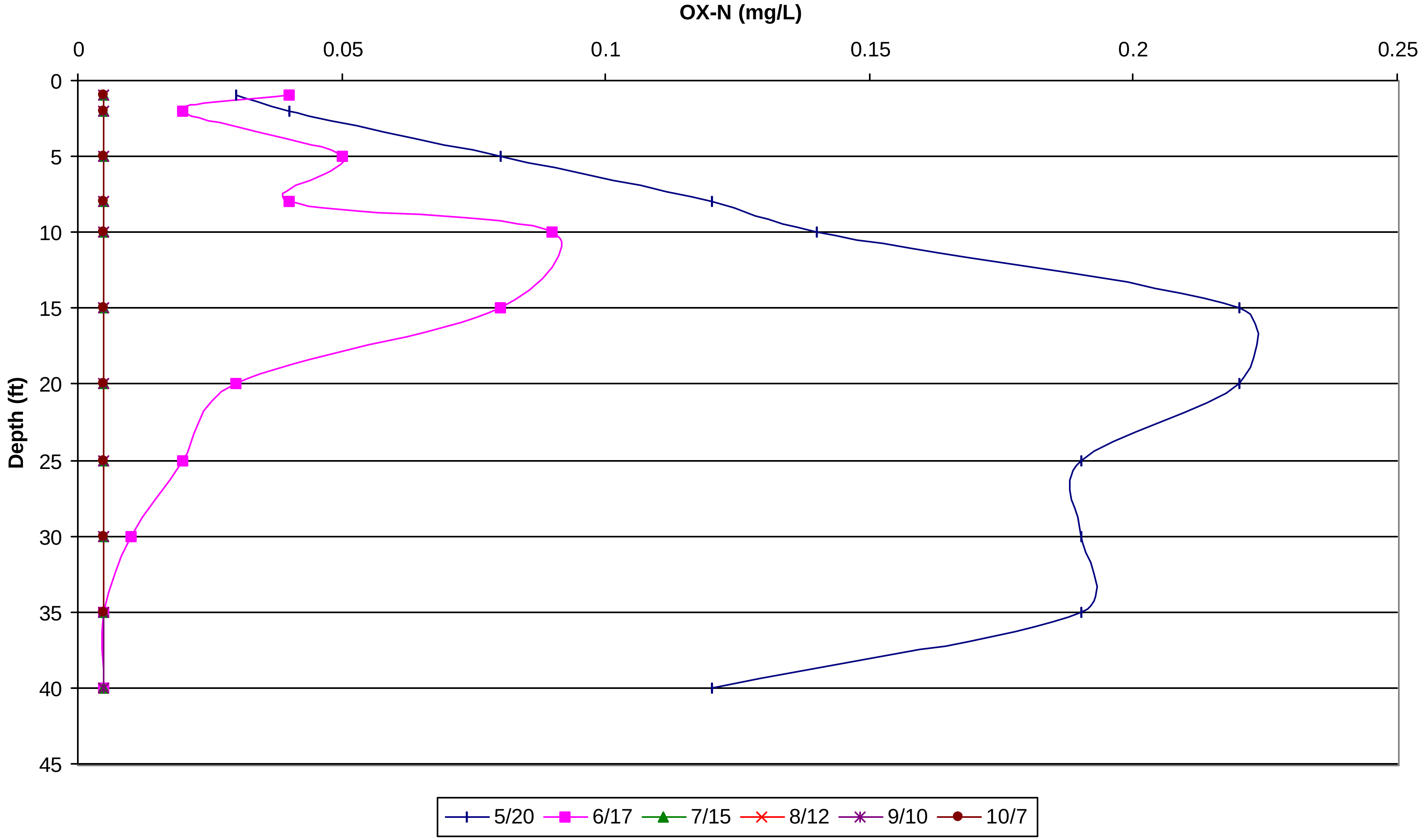


Figure 69
Lake Manassas, Station LM01, 1998
Profile of Oxidized Nitrogen



because during the months of stratification, is it is used as an alternate electron acceptor in the absence of DO.

Phosphorus

Phosphorus is the least abundant nutrient and tends to limit biological activity since it plays a major role in biological metabolisms. During the stratification period in a lake, a difference usually arises in the concentration of phosphorus in the hypolimnion and the epilimnion. In the epilimnion, phosphorus is rapidly incorporated into algae and bacteria. In the hypolimnion, once the DO and other inorganic electron acceptors decrease, biological activity then continues in the creation of a chemically reducing environment. This is shown by a reduction in the oxidation - reduction potential. Once this value is low enough, iron and manganese are released from the sediment. Iron in the Fe^{3+} form is reduced to Fe^{2+}, which is much more soluble in the pH range of most natural waters. Most of the inorganic phosphorus is normally precipitated out along with Fe^{3+}, but once the reduction of the iron occurs, the phosphorus is then released into the hypolimnion, causing the phosphorus concentrations to increase. Another more indirect and efficient release of phosphorus is through the complexation of iron sulfides by sulfate-reducing bacteria. Iron sulfides decrease the amount of iron in the system, thereby allowing the release of phosphorus. This indirect form depends on the concentration of sulfate found in waters. As the amount of sulfate increases, the amount of phosphorus released can be significantly higher. During fall turnover, this phosphorus is then released into the epilimnion (Wetzel, 2001).

Figures 70 through 73 show the five-year running average for TP at surface and the bottom of the lake.

Figure 70
Lake Manassas (Surface)
Seasonal 5 year Running Average
TP,1984-2000

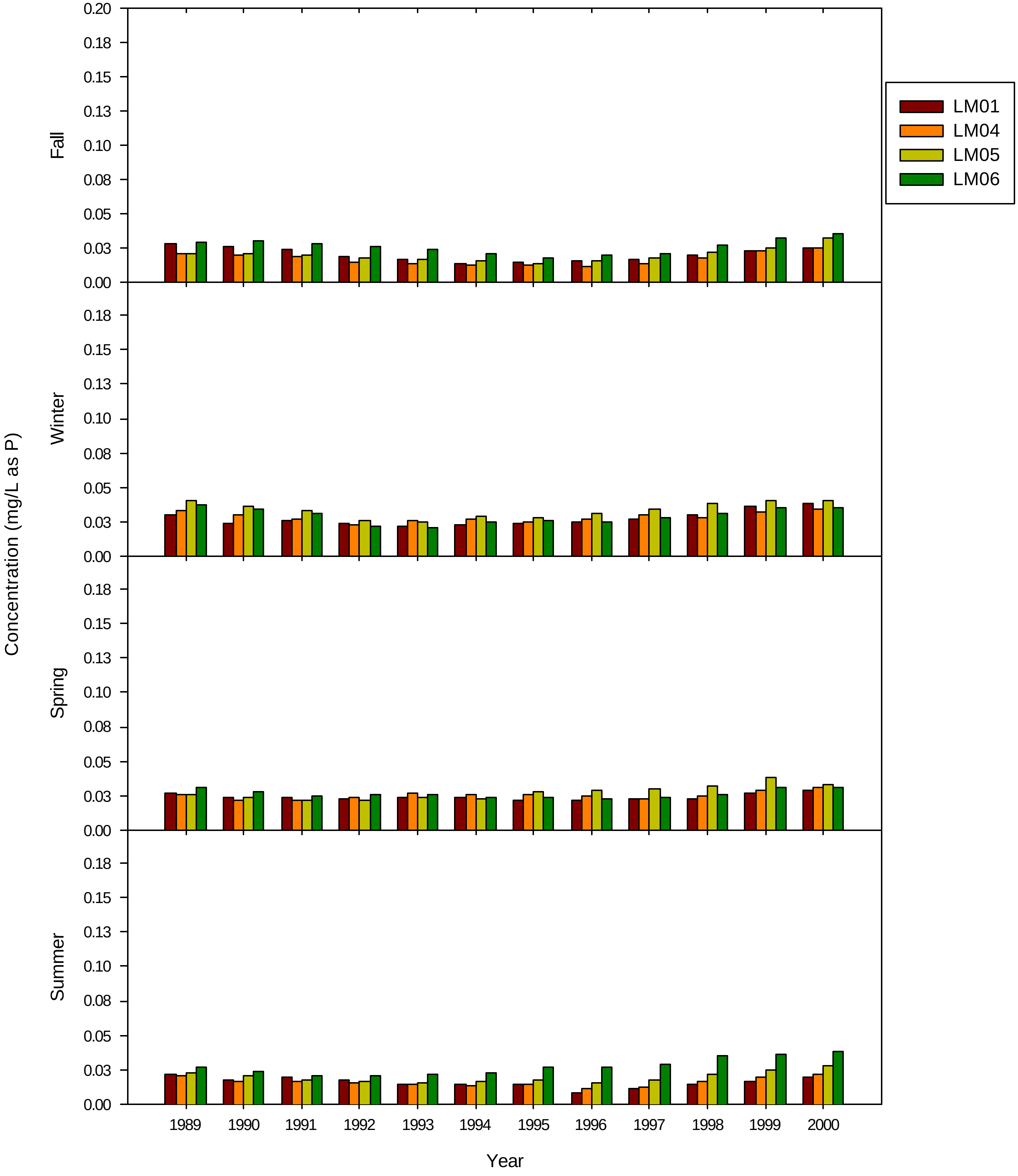


Figure 71
Lake Manassas (Surface)
Seasonal 5 year Running Average
TP,1984-2000

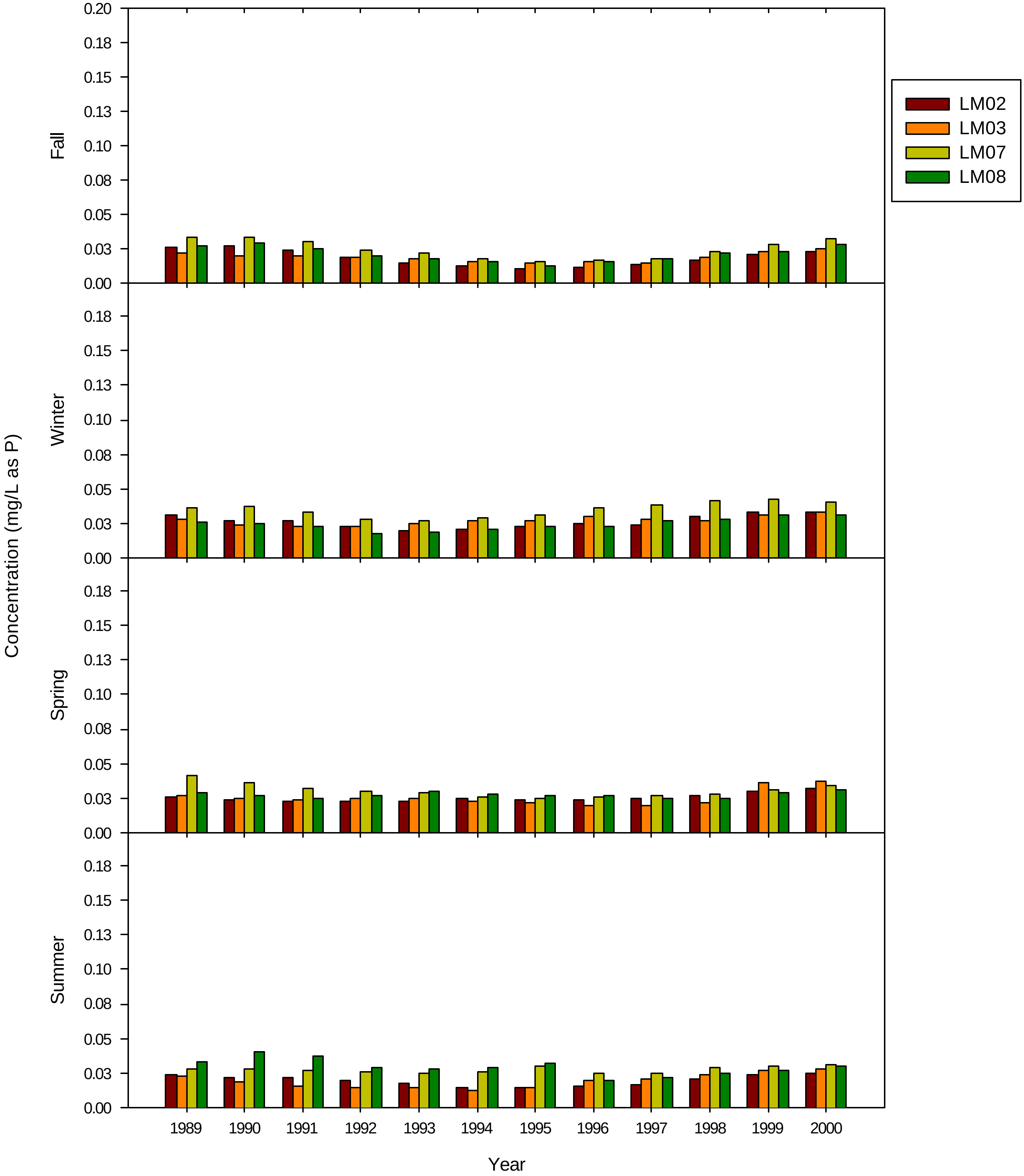


Figure 72
Lake Manassas (Bottom)
Seasonal 5 year Running Average
TP, 1984-2000

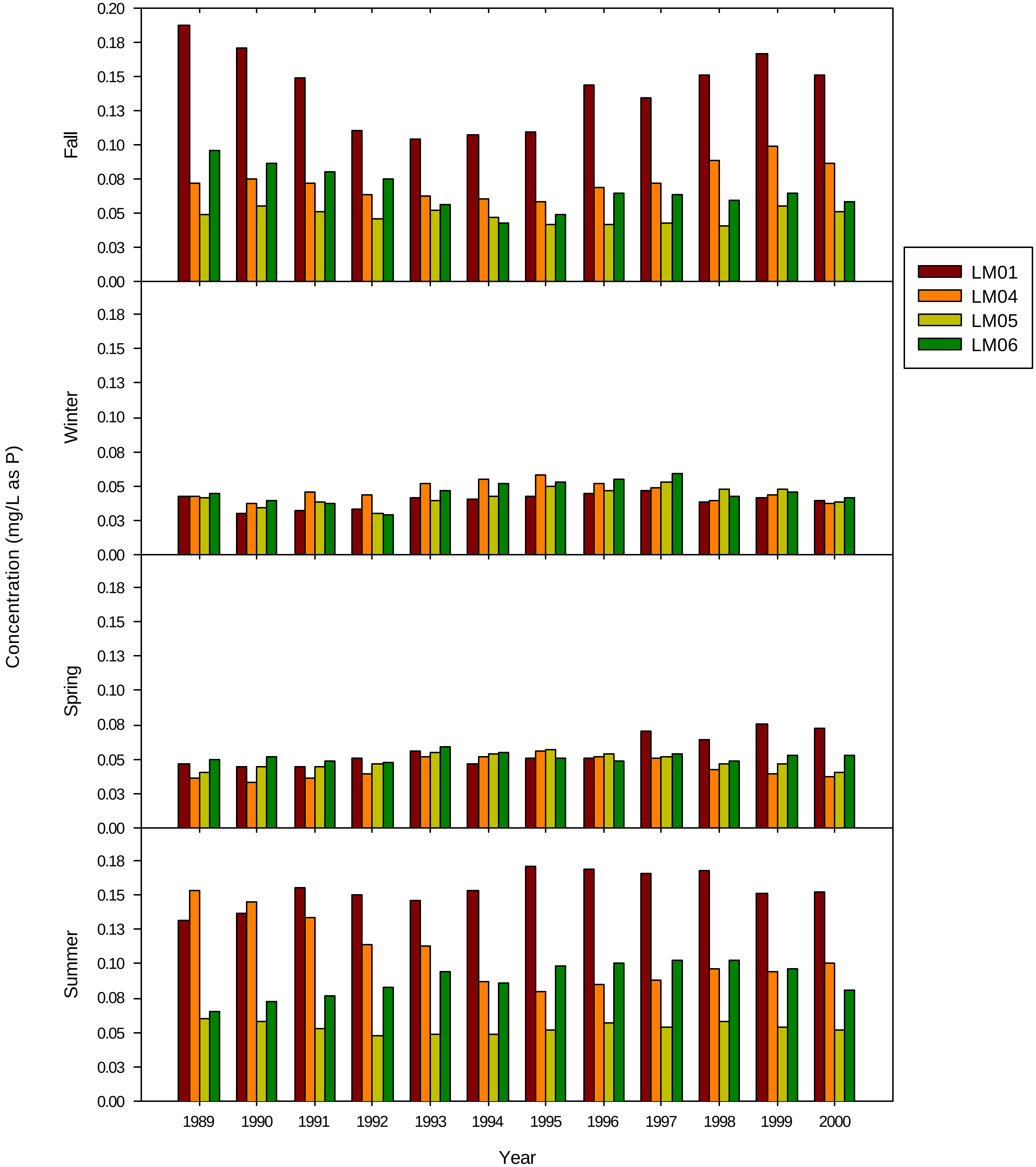
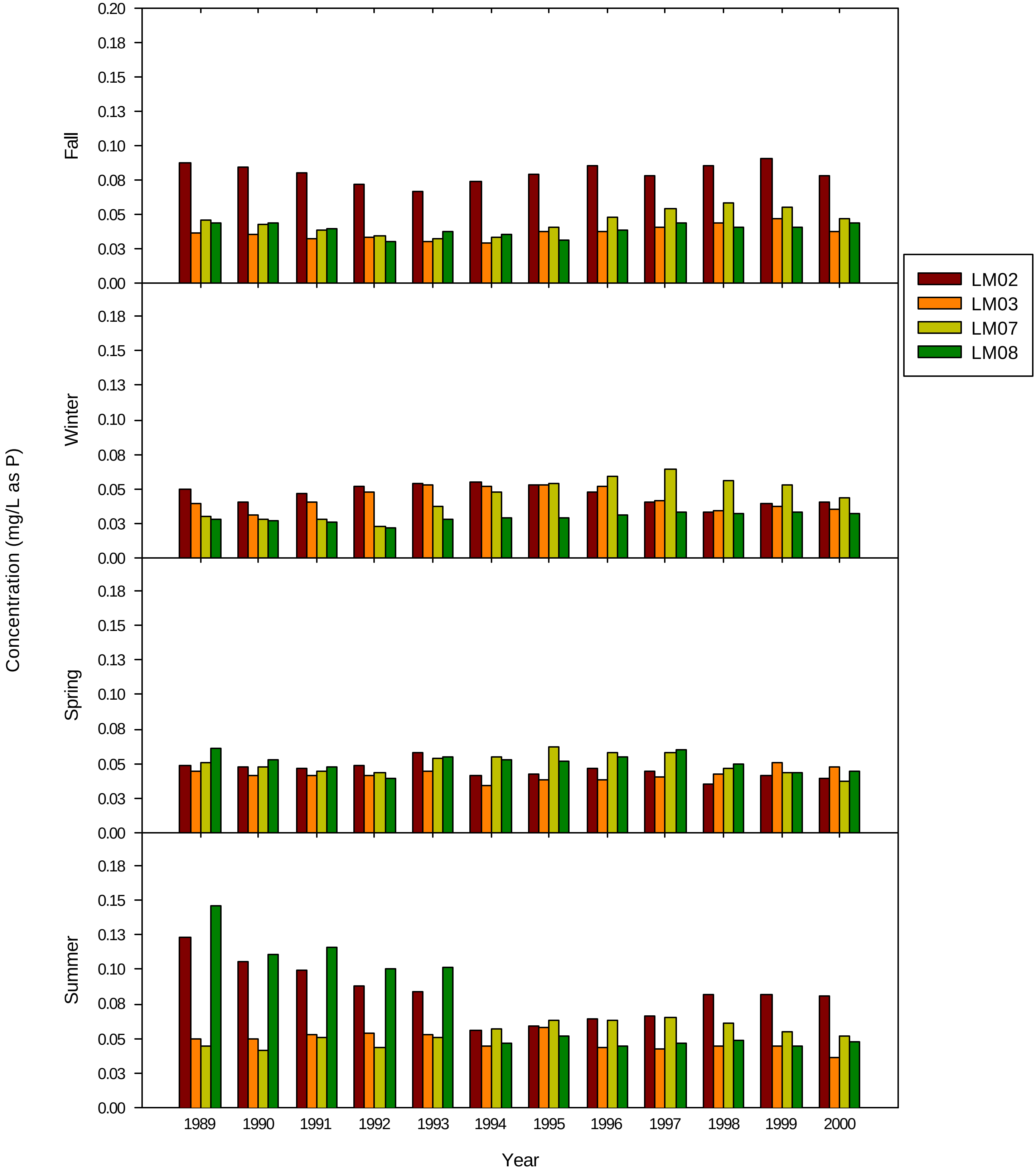


Figure 73
Lake Manassas (Bottom)
Seasonal 5 year Running Average
TP, 1984-2000



All stations in the lake are shown seasonally. Overall, the surface concentrations are constant, with no trends discerned. The bottom of the lake shows another picture. The winter and spring seasons are still constant but the fall and summer months have fluctuations depending on which station is being looked at. Stations LM01, LM02, LM04, and LM06 tend to show a higher TP concentration than any of the other stations. The reason for this is that these stations are deeper, causing a more intense stratification to occur, thus causing a greater release of phosphorus from the sediments. This accumulates in the hypolimnion during the summer, and is mixed throughout the lake at fall turnover. Station LM04 at the surface has seen fluctuation in its TP levels over the past fifteen years. It started out being higher than most stations and has been reduced to approximately the same concentration as LM06. Overall there are no trends in the bottom TP concentration of the lake.

Figure 74 demonstrates the same phenomenon as above, but in a different manner. The date for both the spring and winter seasons are somewhat clustered and near the one-to-one line. Summer and fall data show differences, because the bottom TP levels are higher for the stations that stratify more strongly, thereby showing data spread out along the abscissa.

Figure 75 shows a depth profile for TP at station LM01 during 1998. Above 20 ft, most of the concentrations are the same. Below this depth TP increases over time and depth, with the highest values being located near the sediment-water interface at the bottom. This is a confirmation of the fact that once the DO concentrations are below 2 mg/L, there will generally be a release of phosphorus from the sediments. As the DO concentrations fall, the phosphorus release will increase (Harper,

Figure 74
Lake Manassas
Average Surface and Bottom TP Concentration Comparison

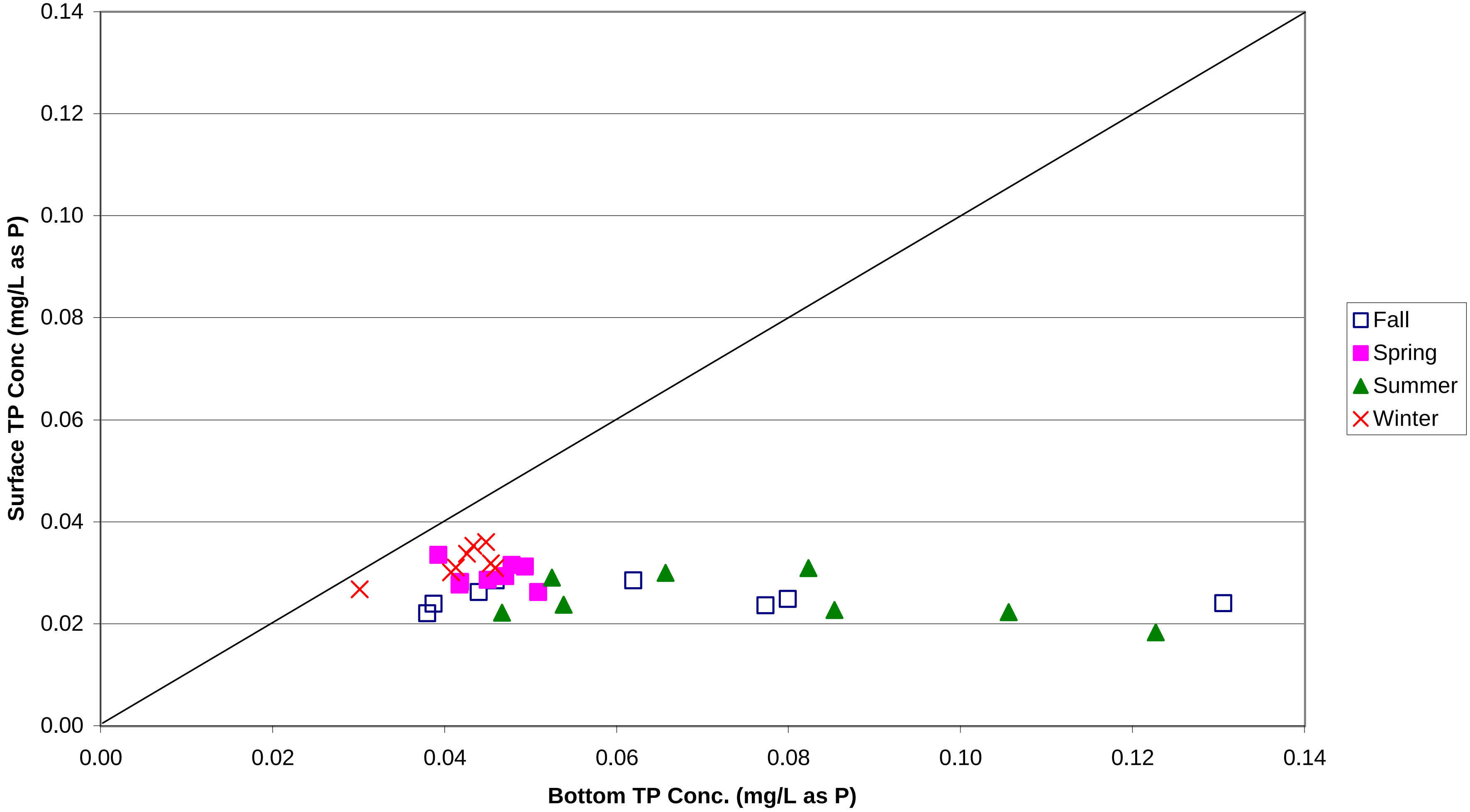
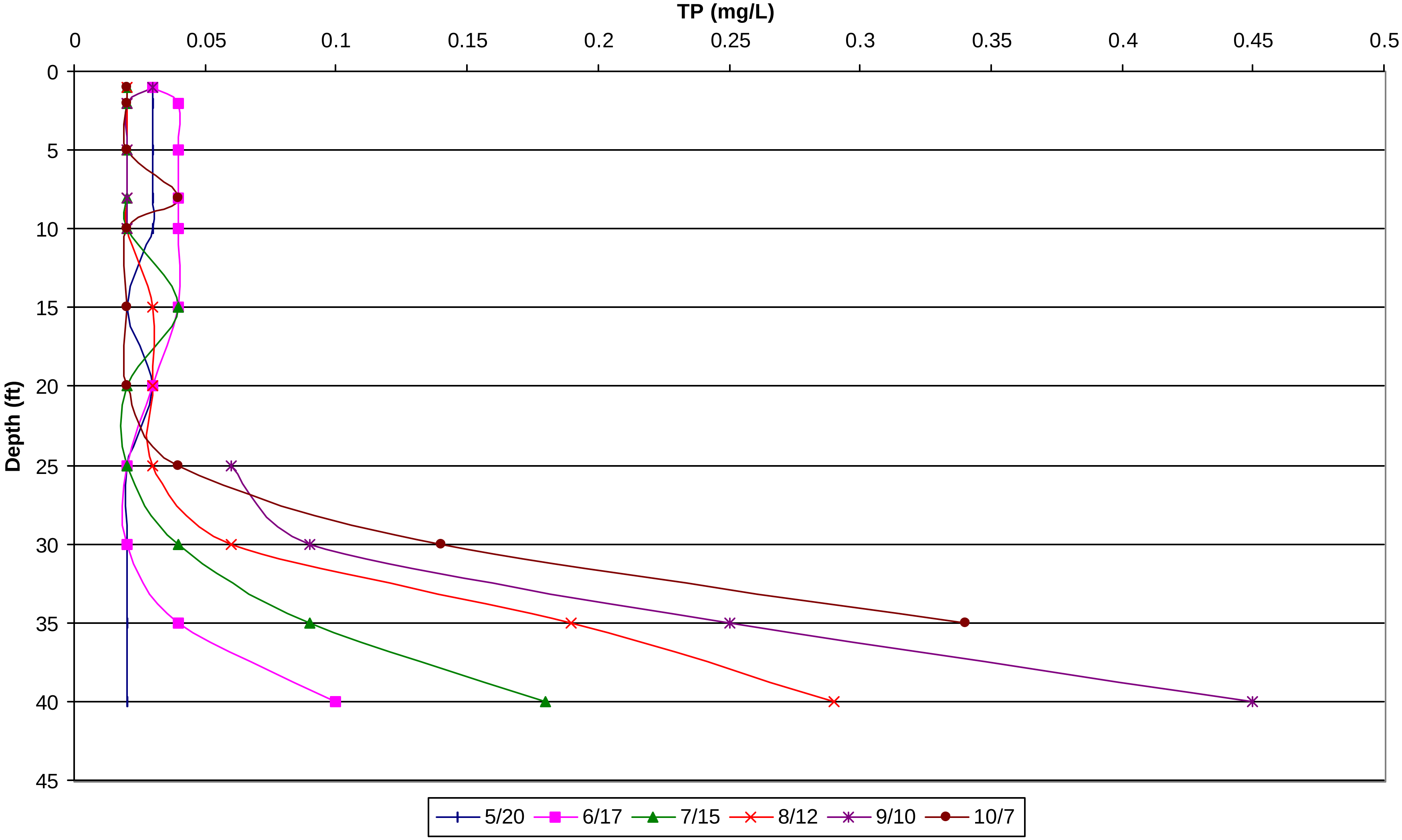


Figure 75
Lake Manassas, Station LM01, 1998
Profile of Total Phosphorus



1992) and the highest concentrations of TP will be at the sediment-water interface.

Orthophosphorous

Figures 76 through 79 show the five-year running average of orthophosphate phosphorus for the surface and bottom of the lake. Overall the surface concentrations are fairly constant, while the bottom concentrations show some fluctuations. Stations LM01, LM02, and LM04 tend to have higher concentrations. These are the deeper stations and tend to have longer and stronger stratification periods. Station LM06 OP values do not show the higher trends as they did for the TP values, thus indicating a higher fraction of inorganic phosphorus present in LM06 waters. This could be due to LM06 being close to ST70 and thus being influenced more strongly during storms, with their sediment-associated phosphorus.

Figure 80 shows the depth profile of OP during 1998 at station LM01. The concentrations were approximately the same above 25 feet. May, June, and July showed an increasing trend in the bottom waters, and in August the concentrations went down. This could be due to the fact that the DO levels increased slightly at that time to above 2 mg/L. This could be enough oxygen to slow down the reduction of iron because the oxidation-reduction potential is higher. After August, the concentrations went up again with the highest values being at the sediment-water interface.

Nutrient Summary

There is a distinct pattern that the nutrients follow season after season. Figure 81 shows the trends of

Figure 76
Lake Manassas (Surface)
Seasonal 5 year Running Average
OP,1984-2000

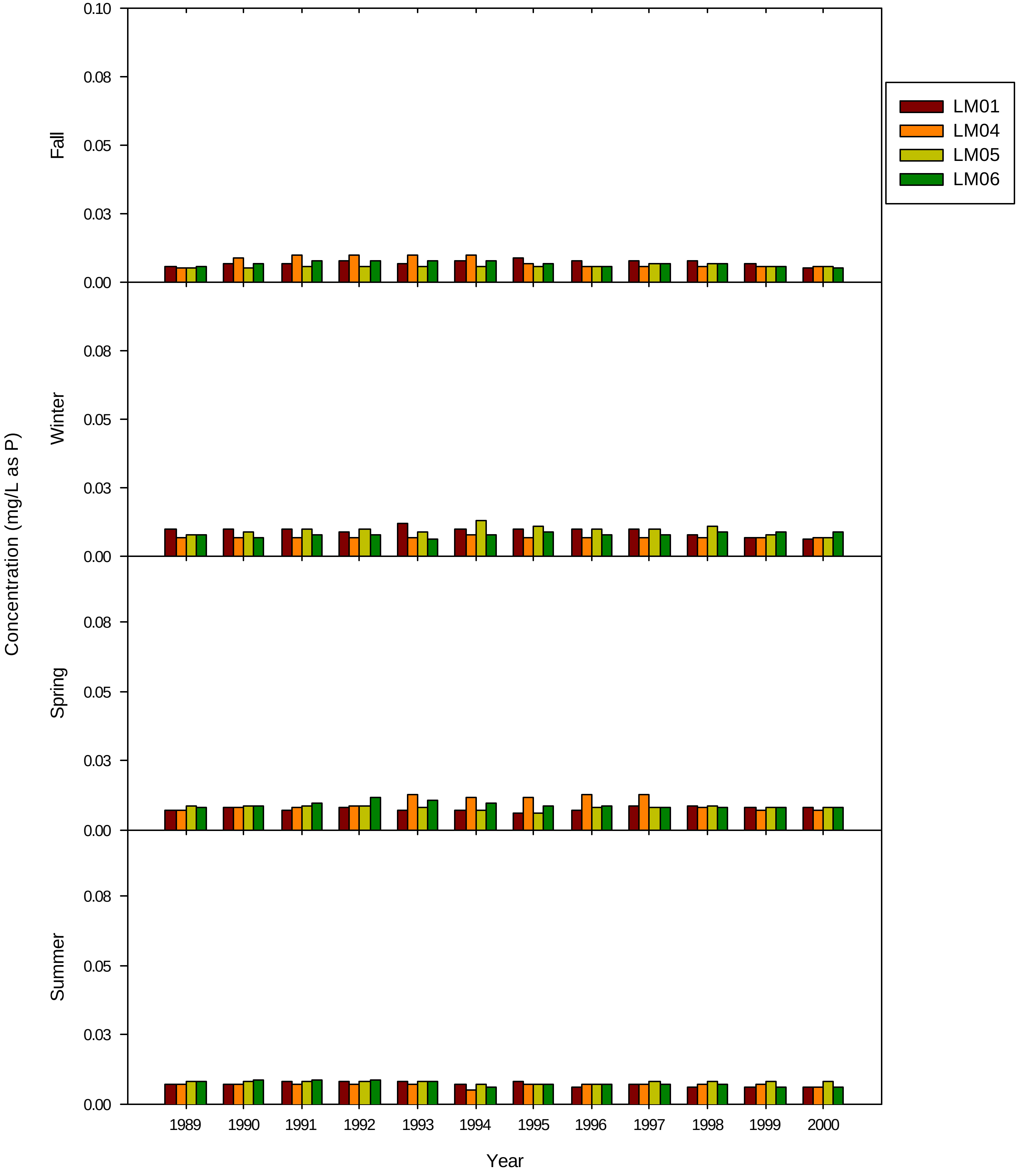


Figure 77

Lake Manassas (Surface)

Seasonal 5 year Running Average

OP,1984-2000

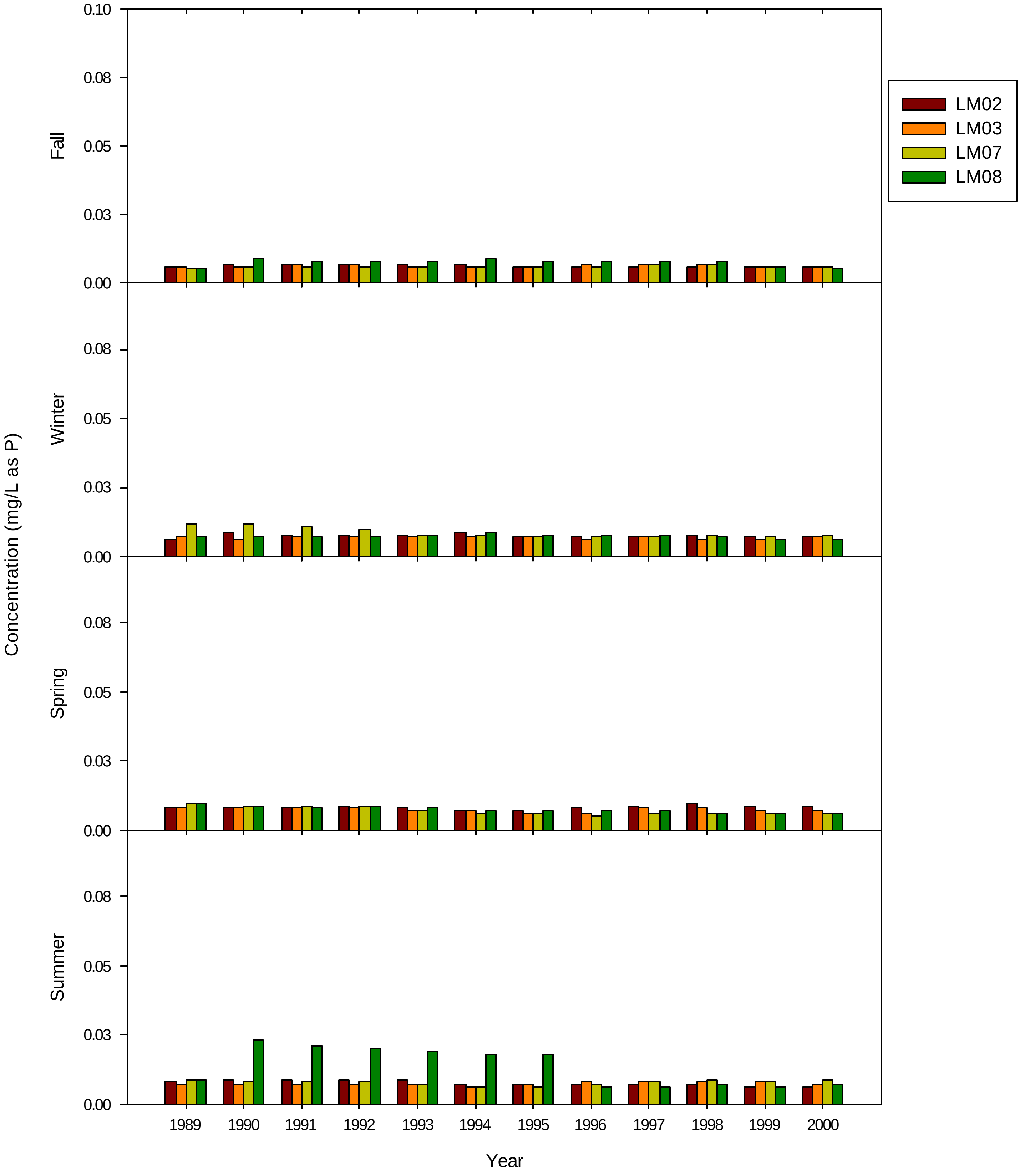


Figure 78
Lake Manassas (Bottom)
Seasonal 5 year Running Average
OP, 1984-2000

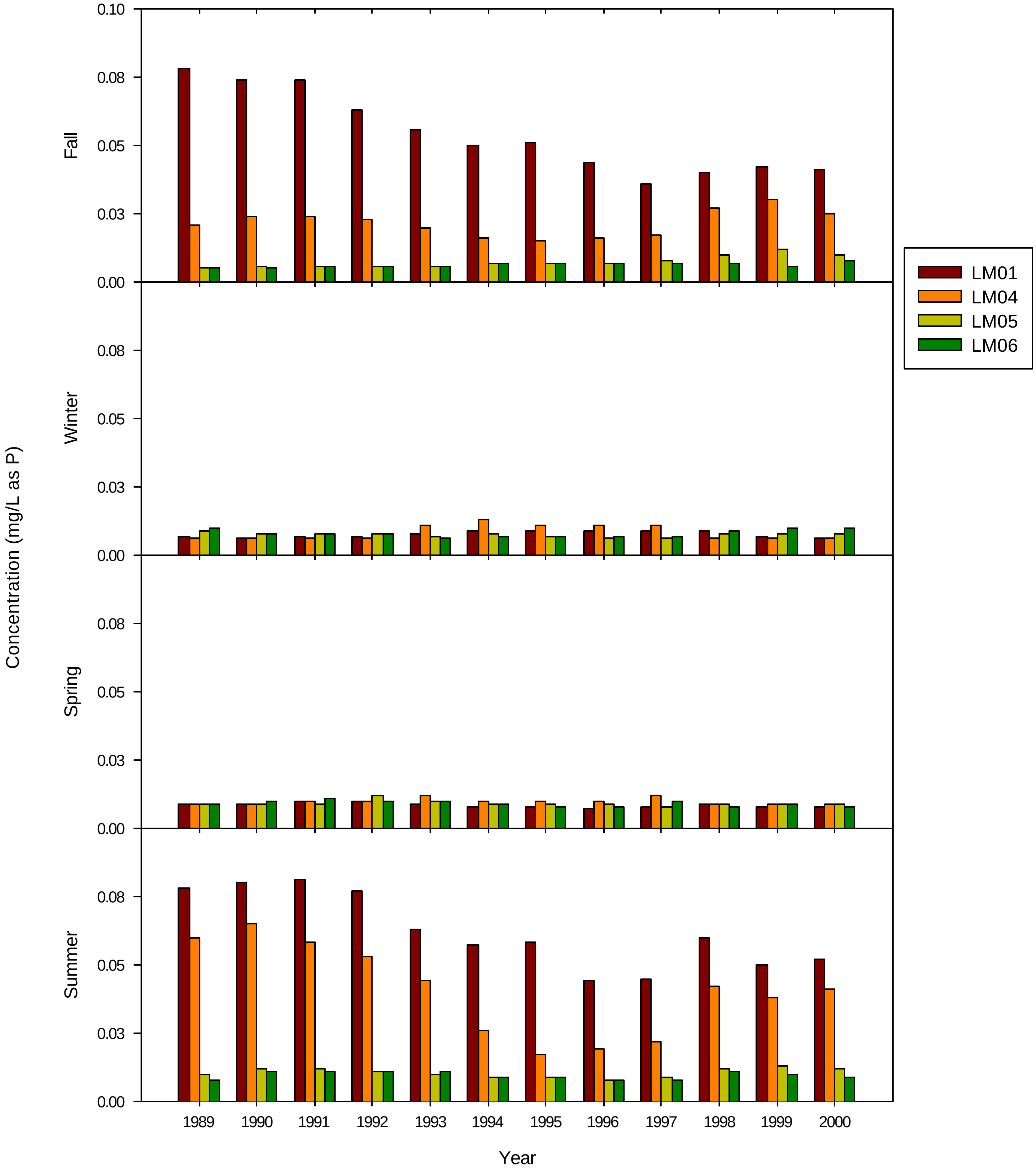


Figure 79
Lake Manassas (Bottom)
Seasonal 5 year Running Average
OP, 1984-2000

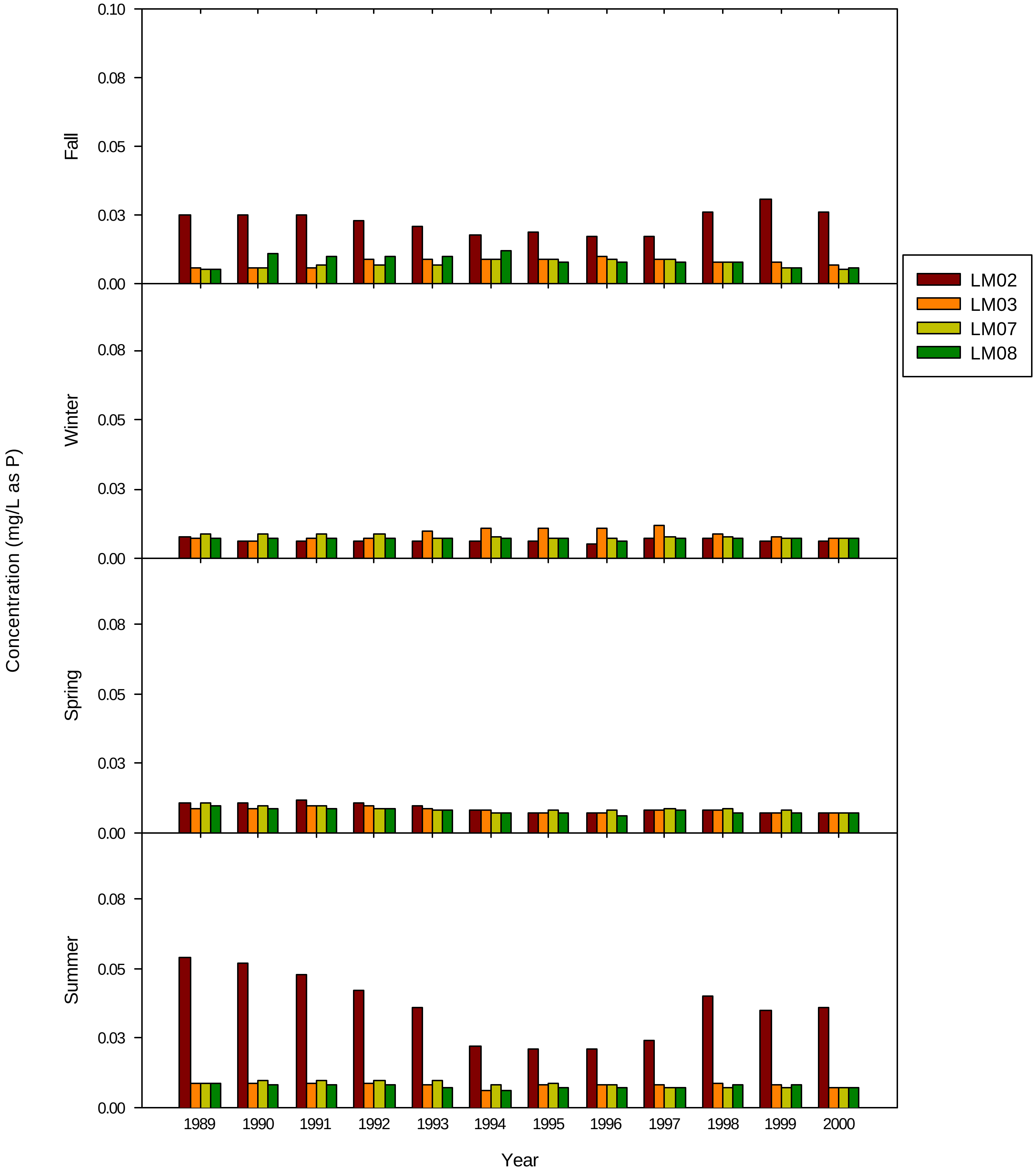


Figure 80

Lake Manassas - Station LM01, 1998

Profile of Orthophosphate phosphorus

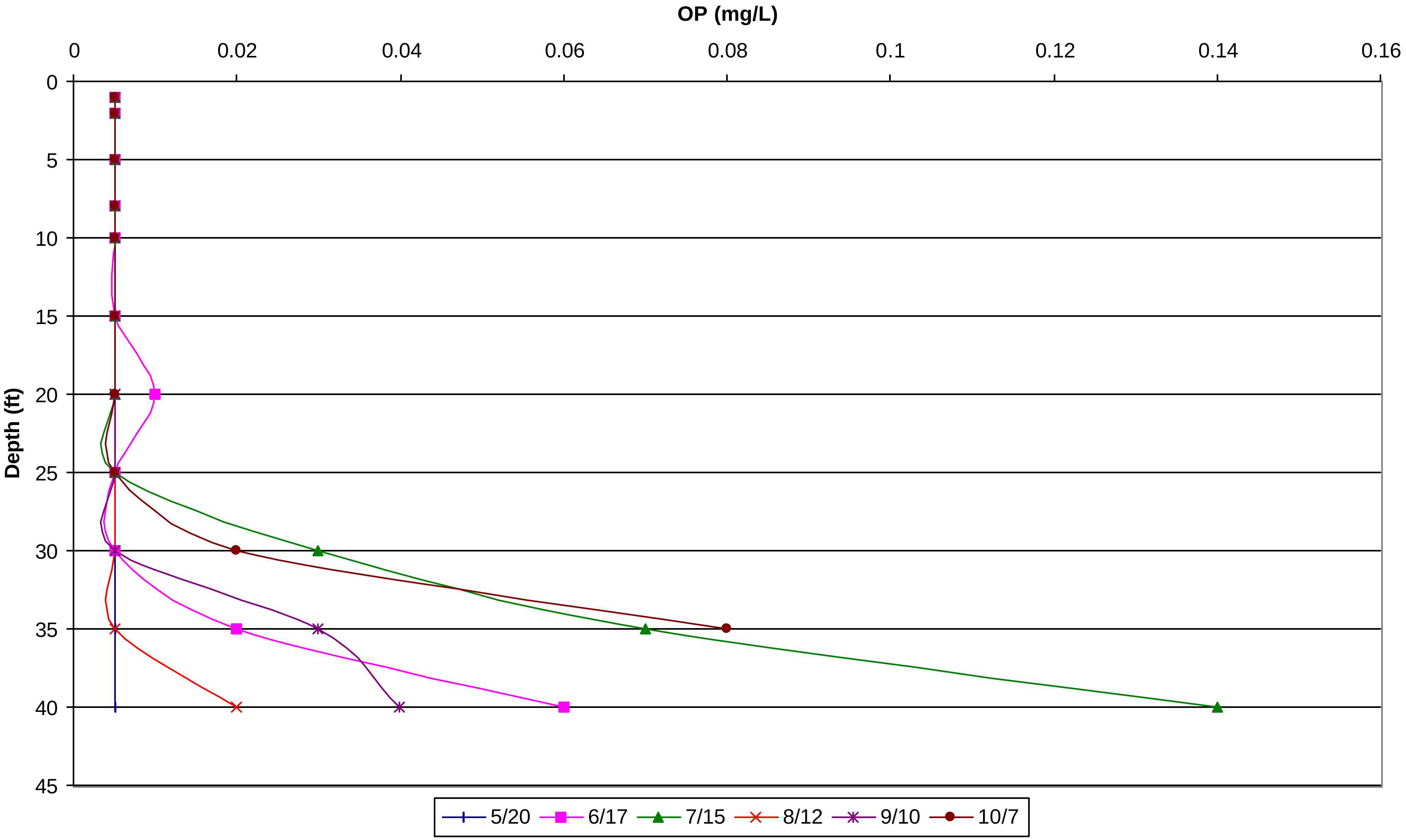
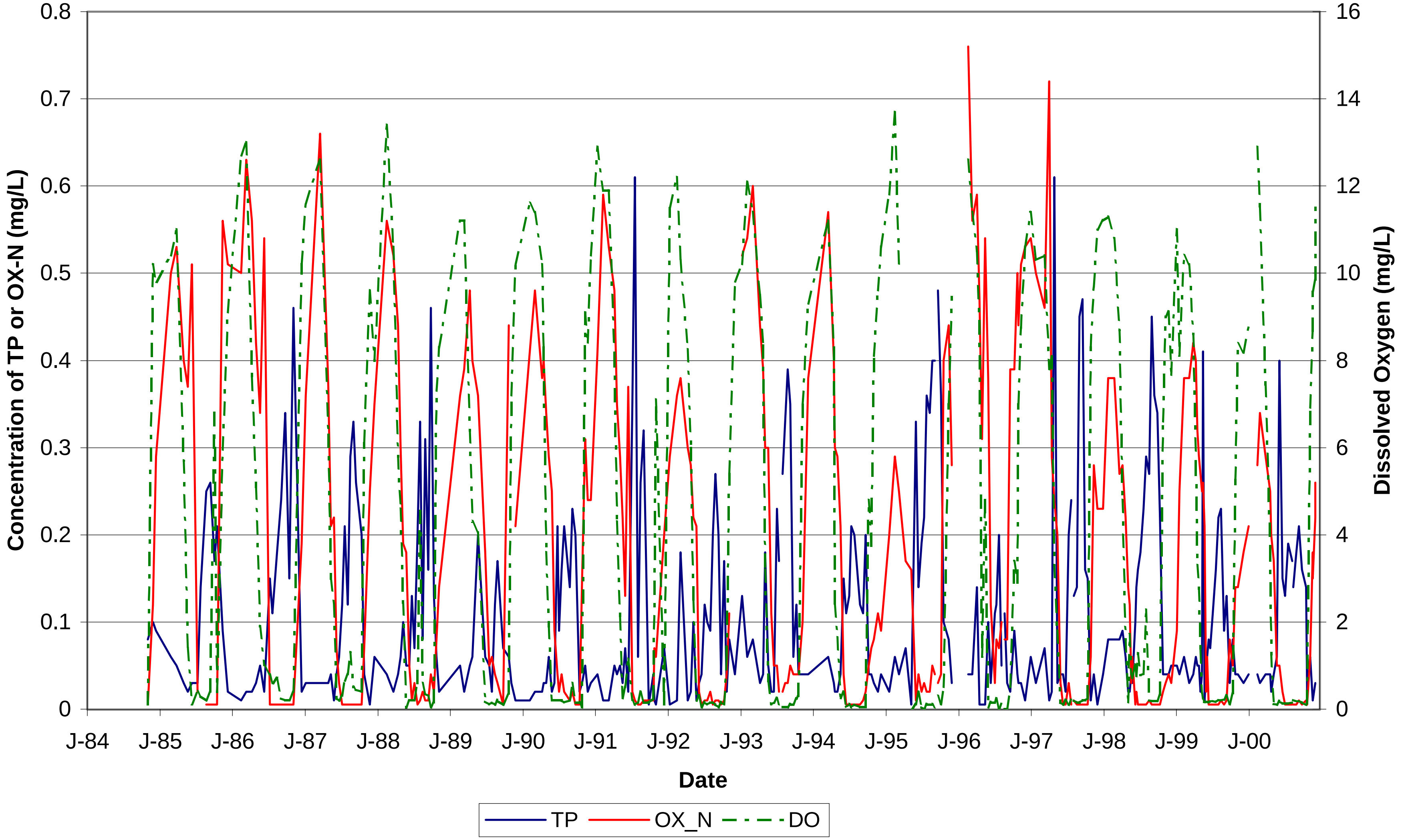


Figure 81
Lake Manassas (Bottom)
Station LM01, 1984-2000



the nutrients, over the period from 1984 to 2000, for the bottom of the lake. As the DO decreases from April to June, the oxidized nitrogen falls as well. When the DO level falls below approximately 4 mg/L, the NH3-N starts rising while the OP remains low until all the DO and OX-N have been depleted. The OX-N usually will only be depleted after the DO is completely gone as it is used as an alternate electron acceptor in the absence of DO in the hypolimnion waters. When this happens, the NH3-N and OP, or TP, rise substantially. The increase in these constituents has been explained above. In October the lake turns over and there is a sudden decrease in NH3-N and phosphates, while the DO concentrations rises. Concurrent with this is a rise in the OX-N concentration, as it is no longer needed as an alternate electron acceptor in the presence of oxygen.

Concentration changes at the surface of the lake show different characteristics. Since no thermal stratification occurs, the DO concentration does not go below 5 mg/L. This in turn does not allow the oxidation-reduction potential to fall, and subvert the release of OP or NH_3-N. OX-N increases as the DO concentrations increase but this only occurs after the fall turnover. This can also be seen in Figures 82 and 83. On the surface of the lake, TP is relatively constant while the OX-N changes relative to season, with the winter having the highest concentration of OX-N. On the bottom of the lake, the winter and spring still have the highest OX-N values. Looking at the summer and fall season shows a different pattern. With the low DO concentrations in the hypolimnion, there will be an increase in TP.

Figure 82
Lake Manassas (Surface)
Comparison of OX-N vs. TP

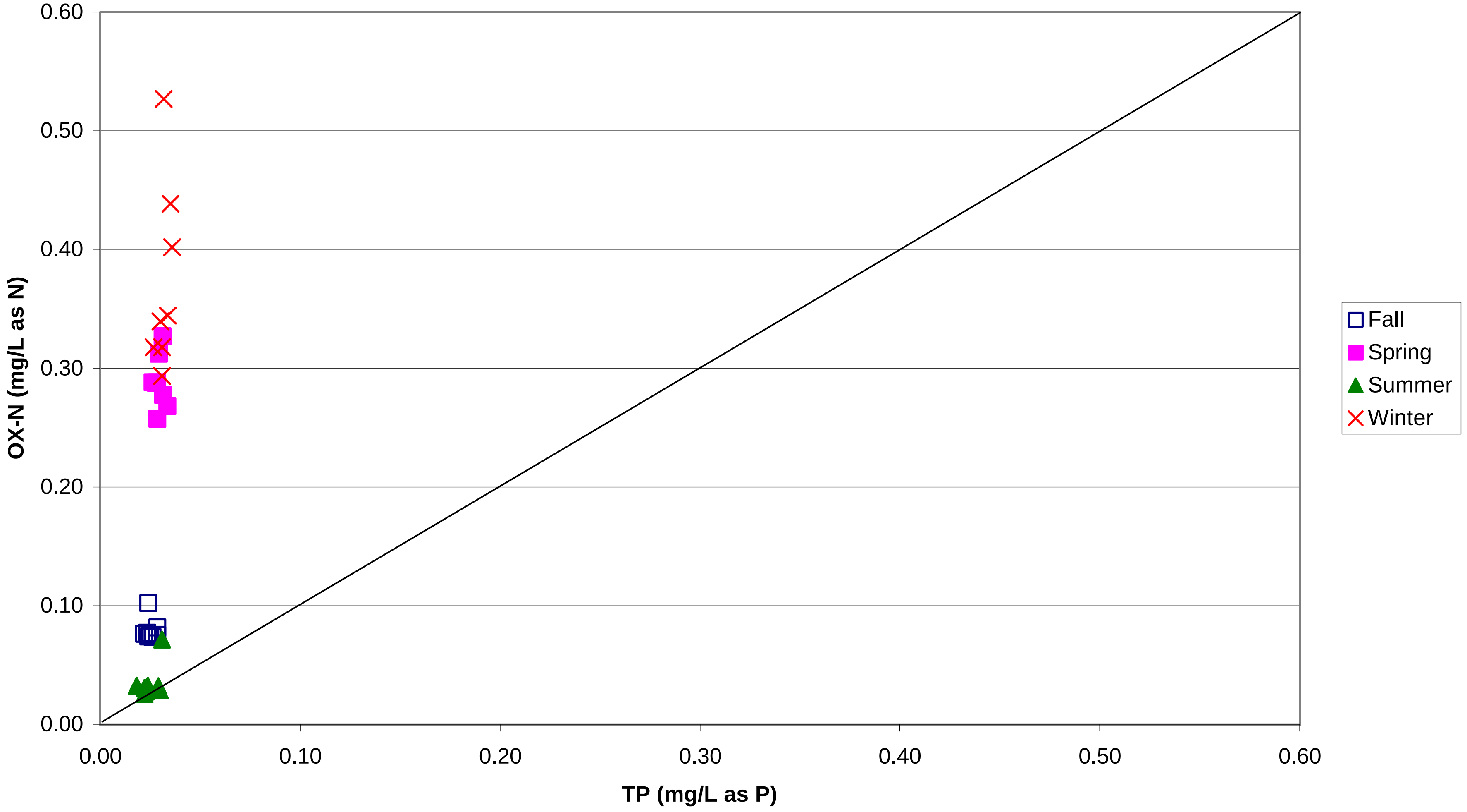
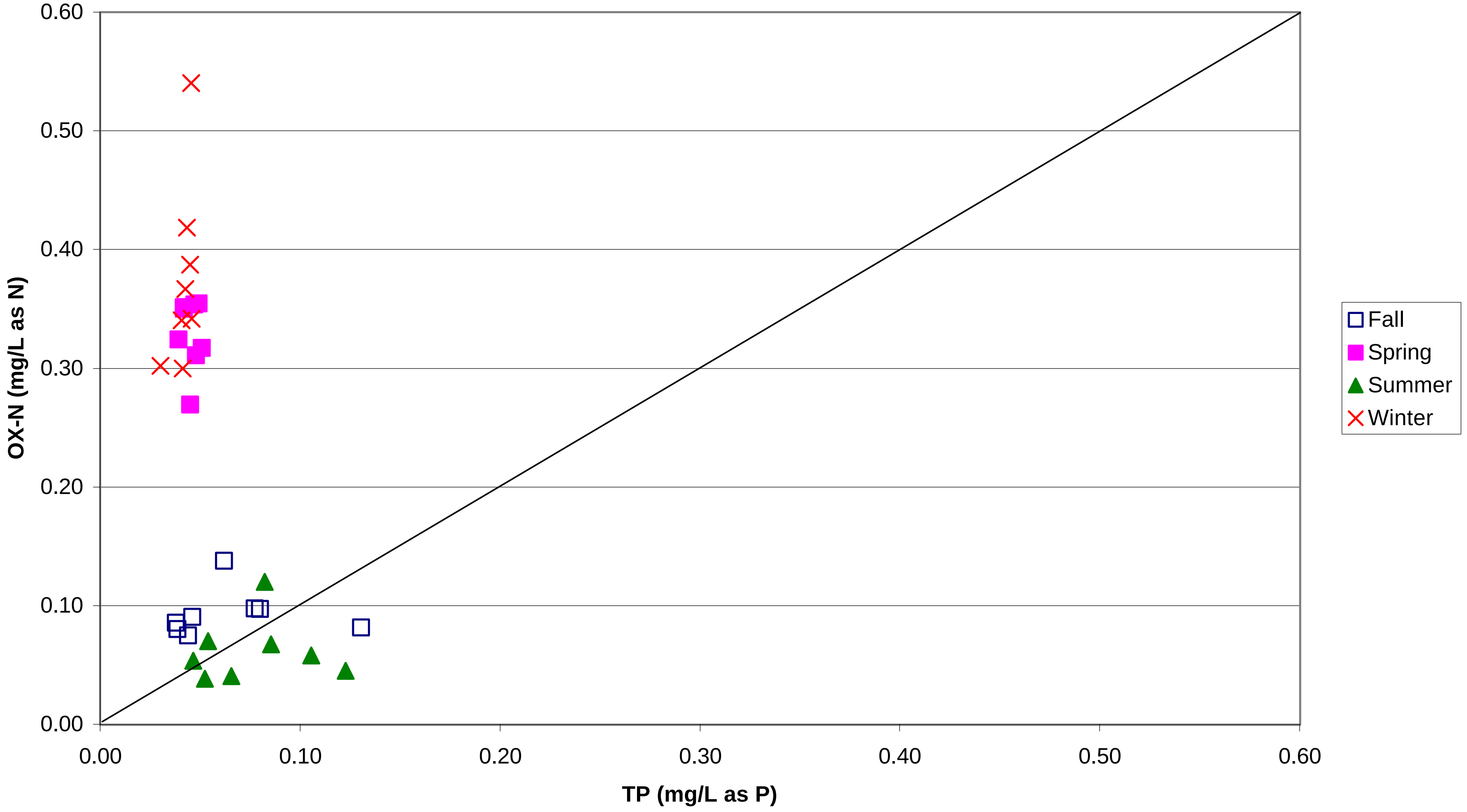


Figure 83
Lake Manassas (Bottom)
Comparison of OX-N vs TP



Nitrogen to Phosphorus Ratios

The ratio of total nitrogen to total phosphorus strongly affects the predominance of algal species in a given body of water. N:P ratios greater than 20:1 are associated with phosphorus limited systems, while ratios of 5:1 are associated with nitrogen limiting systems (Wetzel, 2001). An N:P ratio of 10:1 is commonly used as the lower value at which the shift from phosphorus to nitrogen limitation is likely to occur. The shift of a nitrogen limited system is cause for concern because cyanobacteria (blue-green algae) will dominate in a nitrogen limited system causing potential taste, odor and clogging problems in water treatment systems. Blue-green algae dominate in a nitrogen limiting system as they have the ability to store excess phosphorus for use when the phosphorus concentrations are low and have the ability to out-compete other organisms for low levels of nutrients. For drinking water purposes, it is better to maintain a phosphorus-limited system.

Figures 84 and 85 show the average five-year rolling average of TN:TP ratios for each season. Each bar is an average of all 8 stations. The ratio is between 20:1 and 40:1 for the surface. This can be considered phosphorus-limited. At the bottom of the lake the ratio is between 10:1 and 30:1 with the lowest values occurring in the summer.

Figures 86 through 89 show the individual five-year running average numbers. Overall, for the surface in the last five years, the ratio has usually been above 20:1, with the exception of LM06, LM07, and LM08, where it sometimes drops below 20:1. At the bottom of the lake though, the summer and fall months show that the ratio is normally around 10:1 and sometimes a little lower. This would then

Figure 84
Lake Manassas (Surface)
Seasonal 5 year Rolling Average of all Stations
TN:TP ratios, 1984-2000

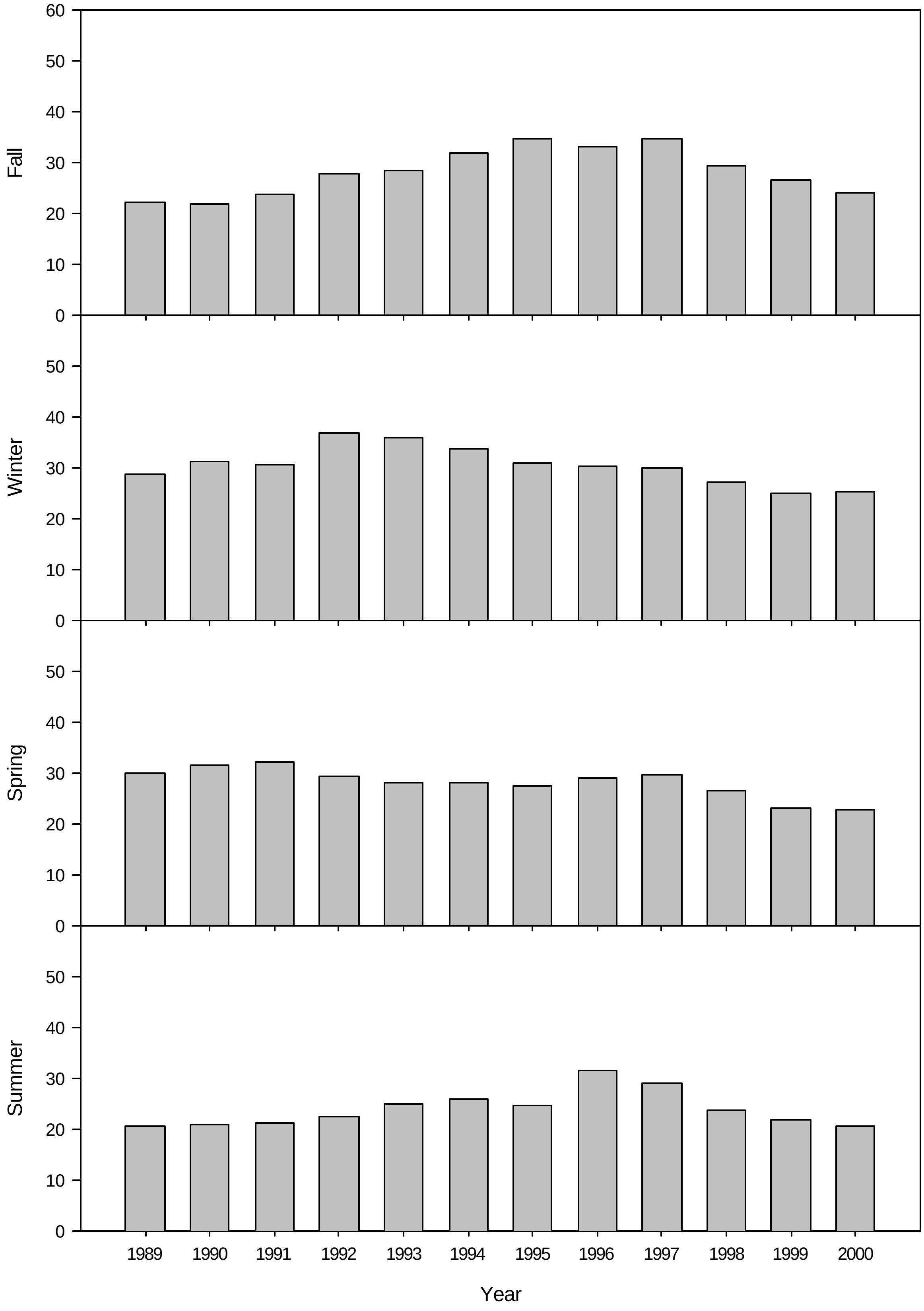


Figure 85
Lake Manassas (Bottom)
Seasonal 5 year Rolling Average of all Stations
TN:TP ratios, 1984-2000

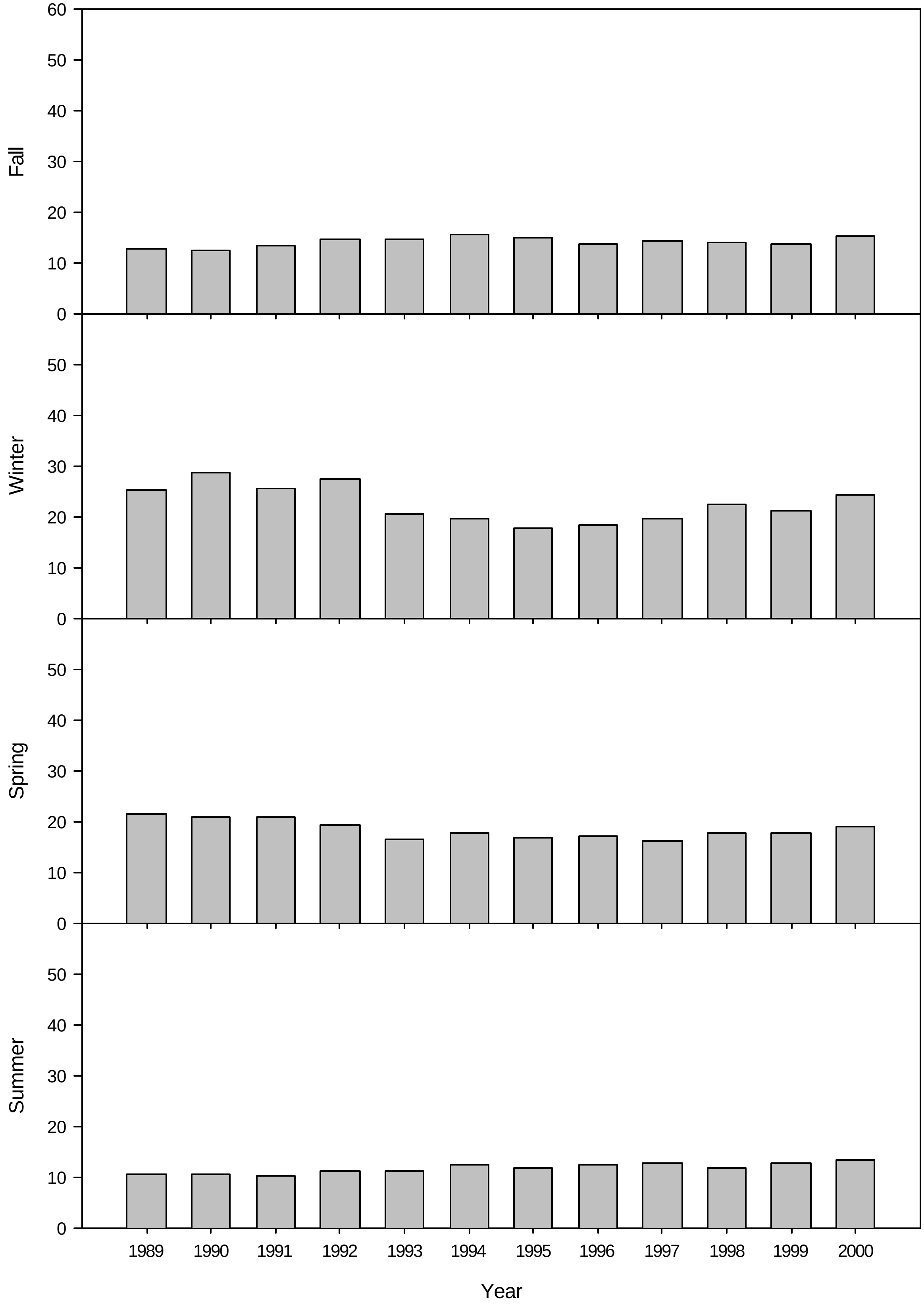


Figure 86
Lake Manassas (Surface)
Seasonal 5 year Rolling Average
TN:TP Ratios, 1984-2000

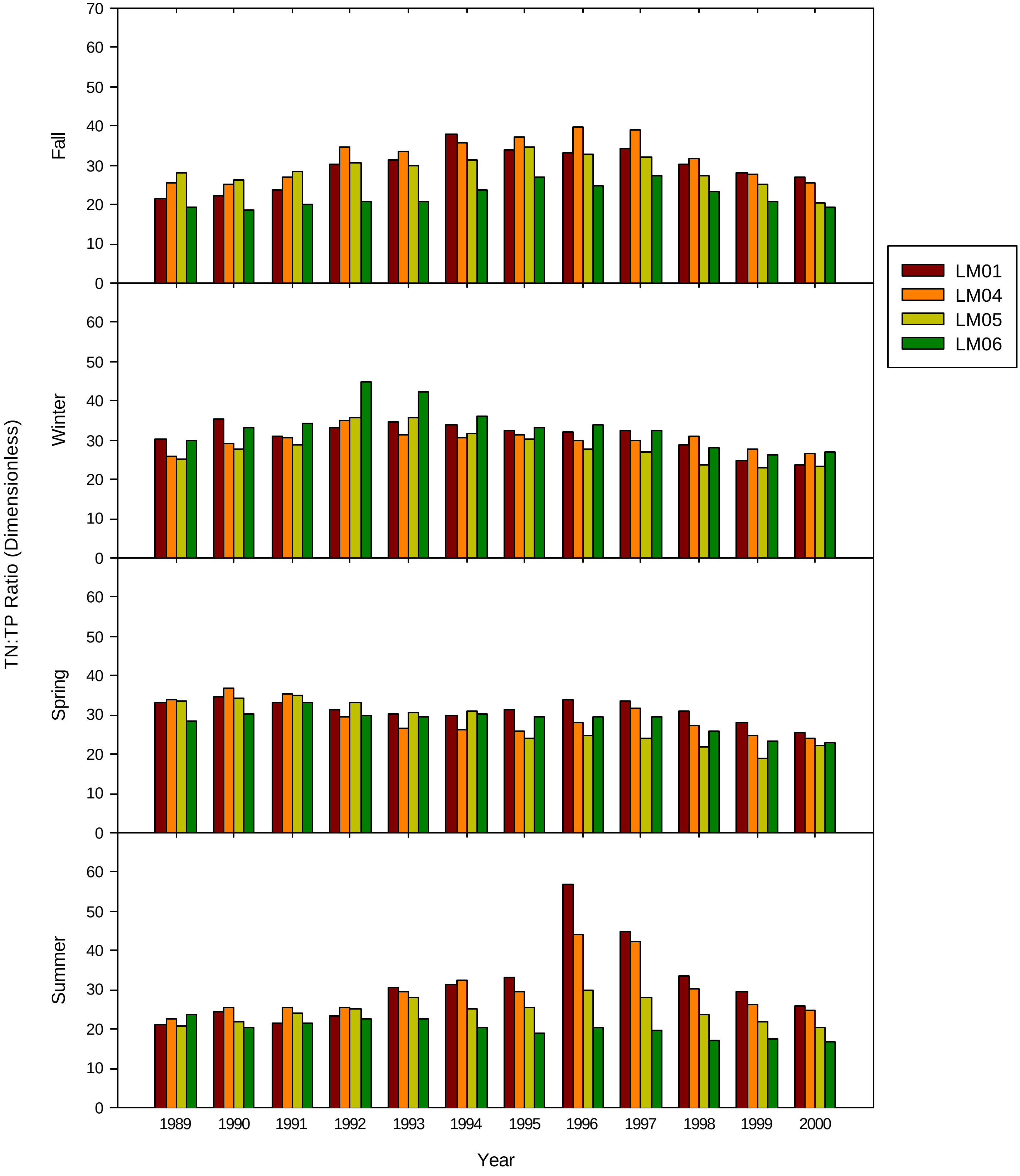


Figure 87
Lake Manassas (Surface)
Seasonal 5 year Rolling Average
TN:TP Ratios, 1984-2000

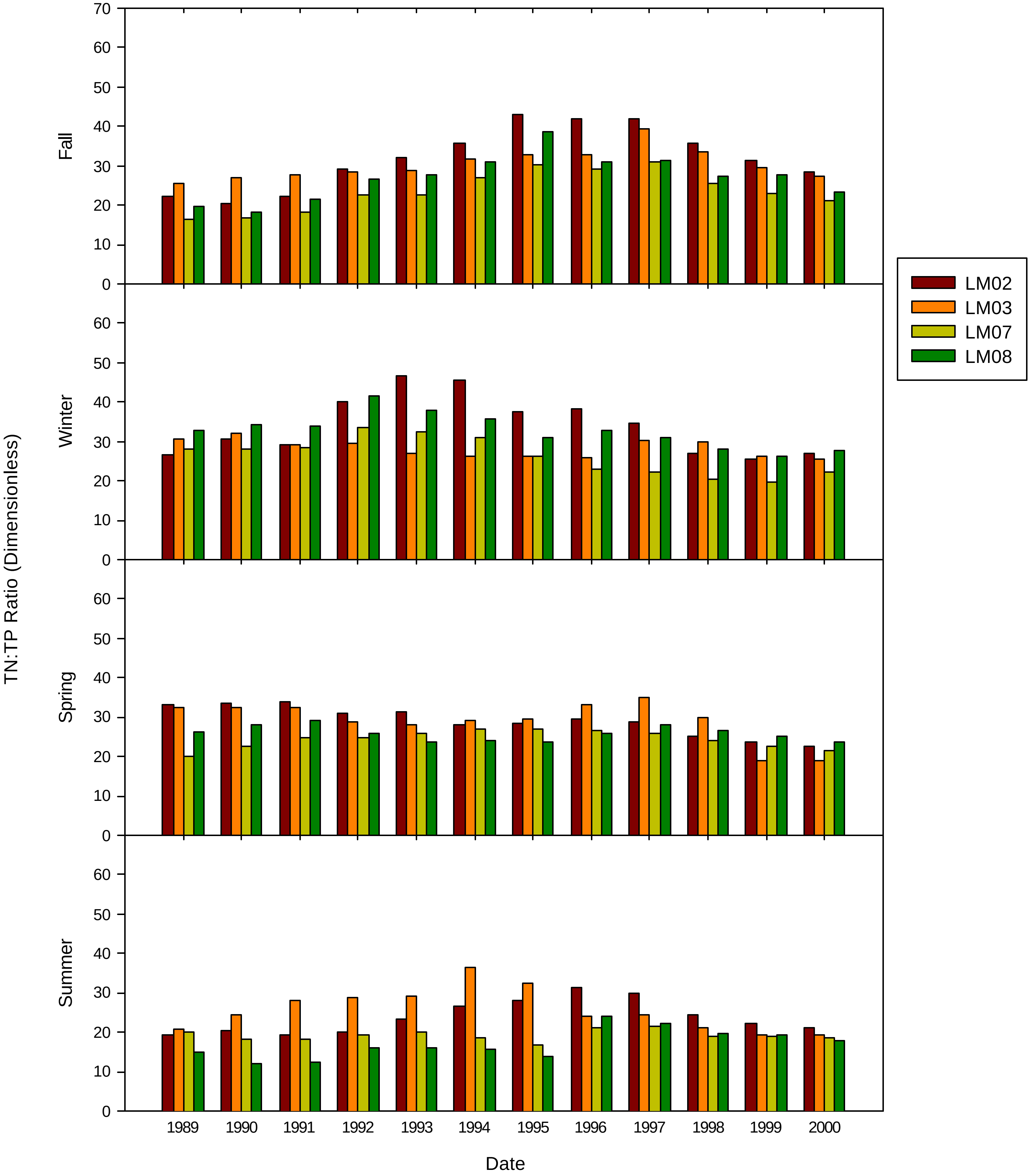


Figure 88
Lake Manassas (Bottom)
Seasonal 5 year Rolling Average
TN:TP Ratios, 1984-2000

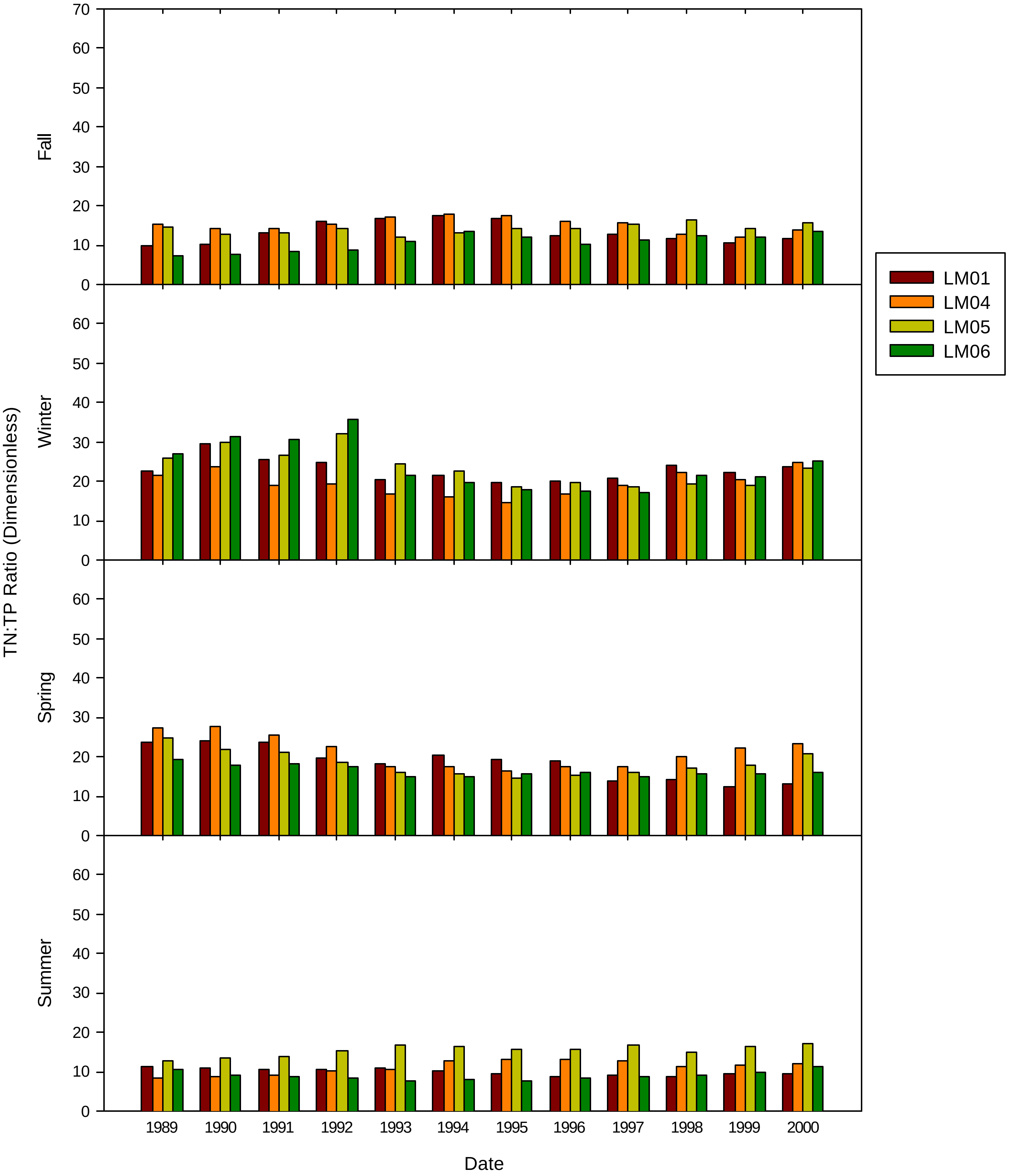
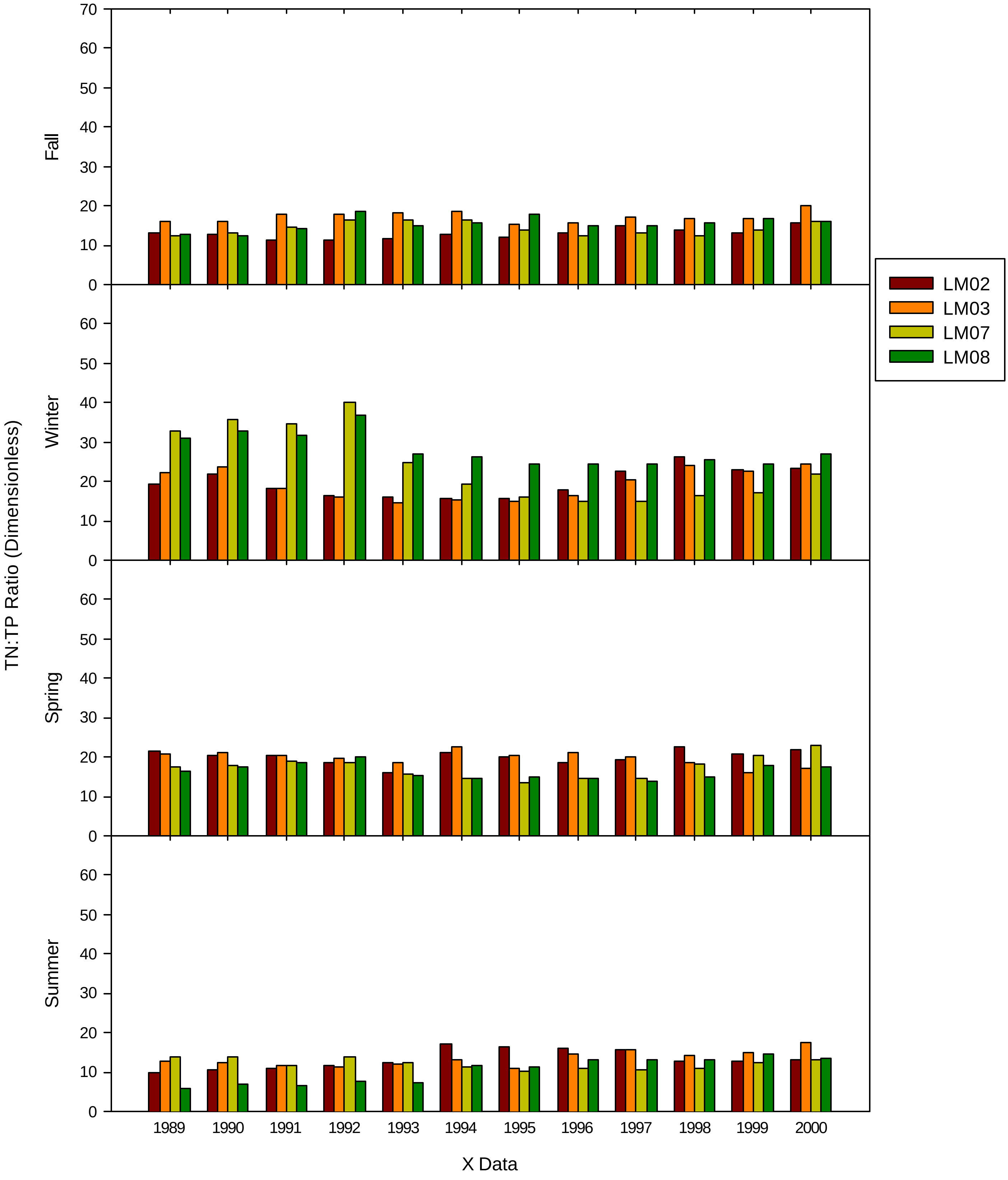


Figure 89
Lake Manassas (Bottom)
Seasonal 5 year Rolling Average
TN:TP Ratios, 1984-2000



potentially be a nitrogen limiting area. During this period the lake is stratified, however, and this would not affect the upper area of the lake.

Chlorophyll *a*

Chlorophyll *a* is the primary photosynthetic pigment of all oxygen producing organisms and is usually present in algae, especially in blue-green algae. Measuring the amount of Chlorophyll *a* in a lake or reservoir is relatively easy. The higher the concentration, the more algae in the system, and the higher the potential for a more eutrophic system.

The 5 year seasonal running average of chlorophyll *a* at all 8 stations is plotted in figures 90 and 91. The highest levels of chlorophyll *a* can be found in the fall and winter. During the fall and winter season, stations LM06, and LM07 tend to have higher values, while LM01, LM02, LM03, LM04, and LM05 tend to have lower values. The potential reason for the chlorophyll *a* levels not being high in the summer is due to the fact that copper sulfate is added to the lake to prevent the growth of algae. Because this algaecide is added to the lake, it is difficult to make significant conclusions with respect to algal growth.

From the Mann Kendall analysis in Table 9, some trends can be found. Stations LM01 through LM05 have an increasing trend for chlorophyll *a*. This could mean that there is an increase of algae in the deeper sections of the lake. This could be due to an increase in the influx of phosphorus from ST70, the main inflow. As more phosphorus enters the system, there is the potential for more algal growth,

Figure 90
Lake Manassas (Surface)
Seasonal 5 year Running Average
Chlorophyll *a*, 1984-2000

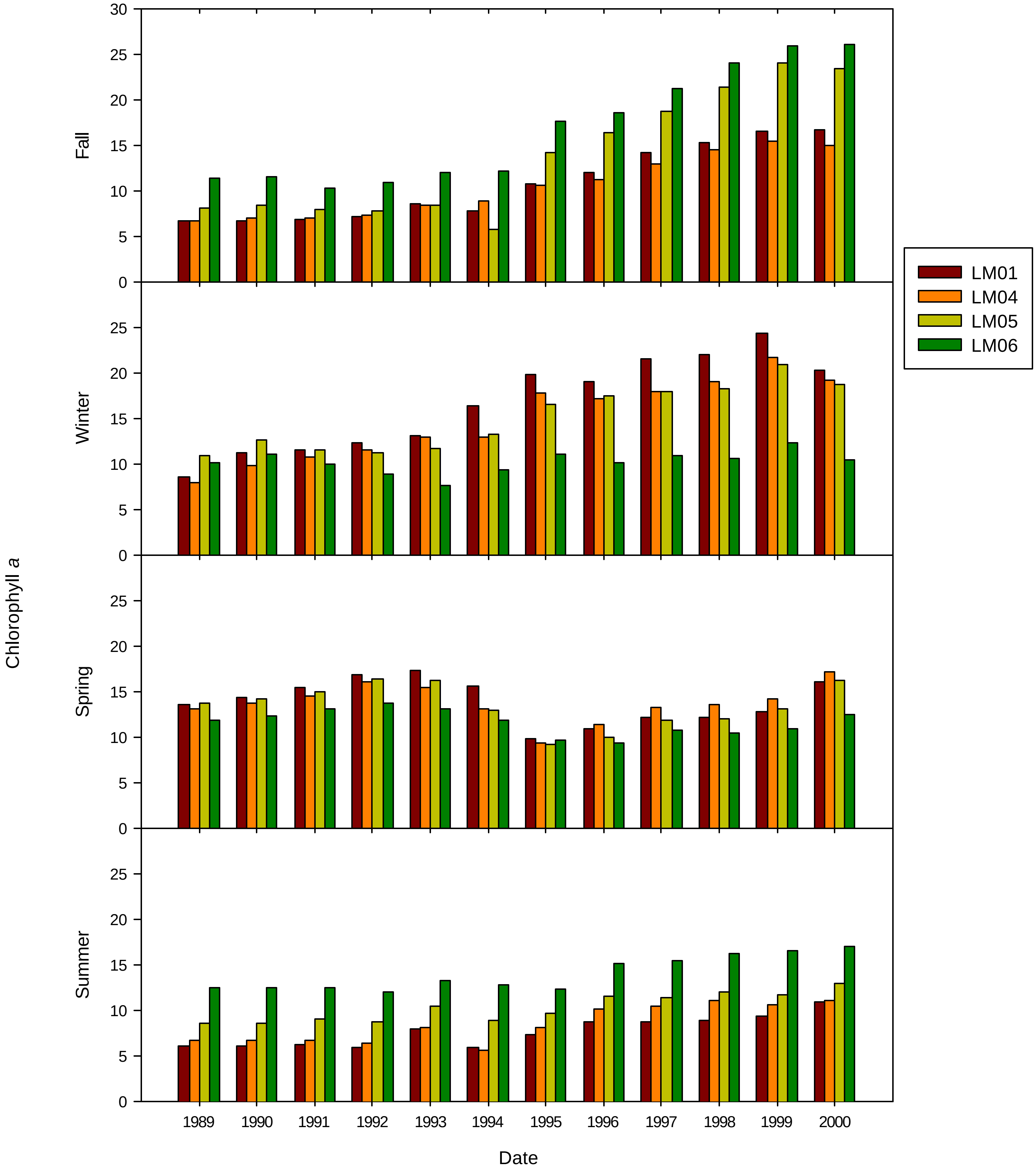
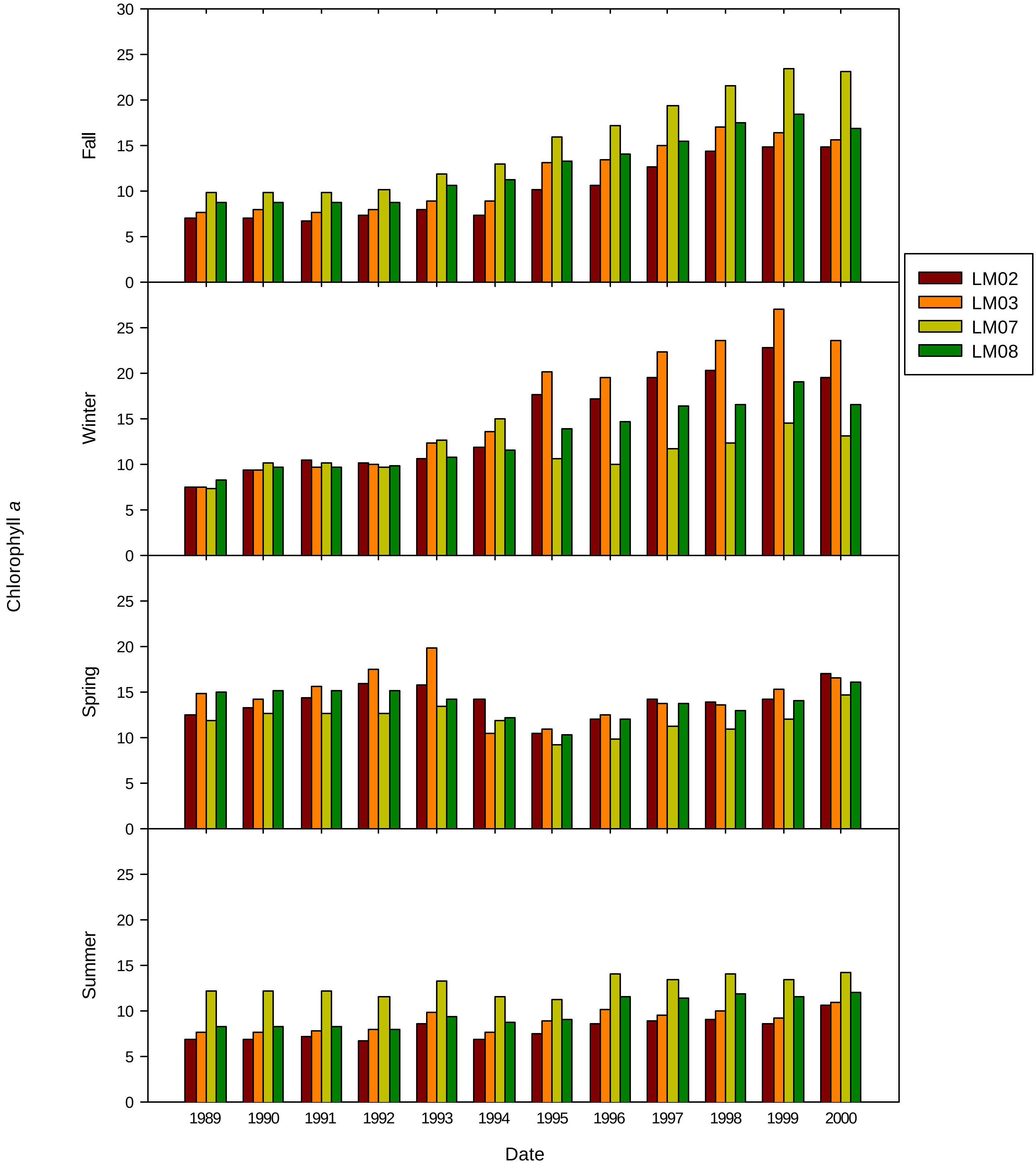


Figure 91
Lake Manassas (Surface)
Seasonal 5 year Running Average
Chlorophyll *a*, 1984-2000



and this in turn could increase the chlorophyll *a* level.

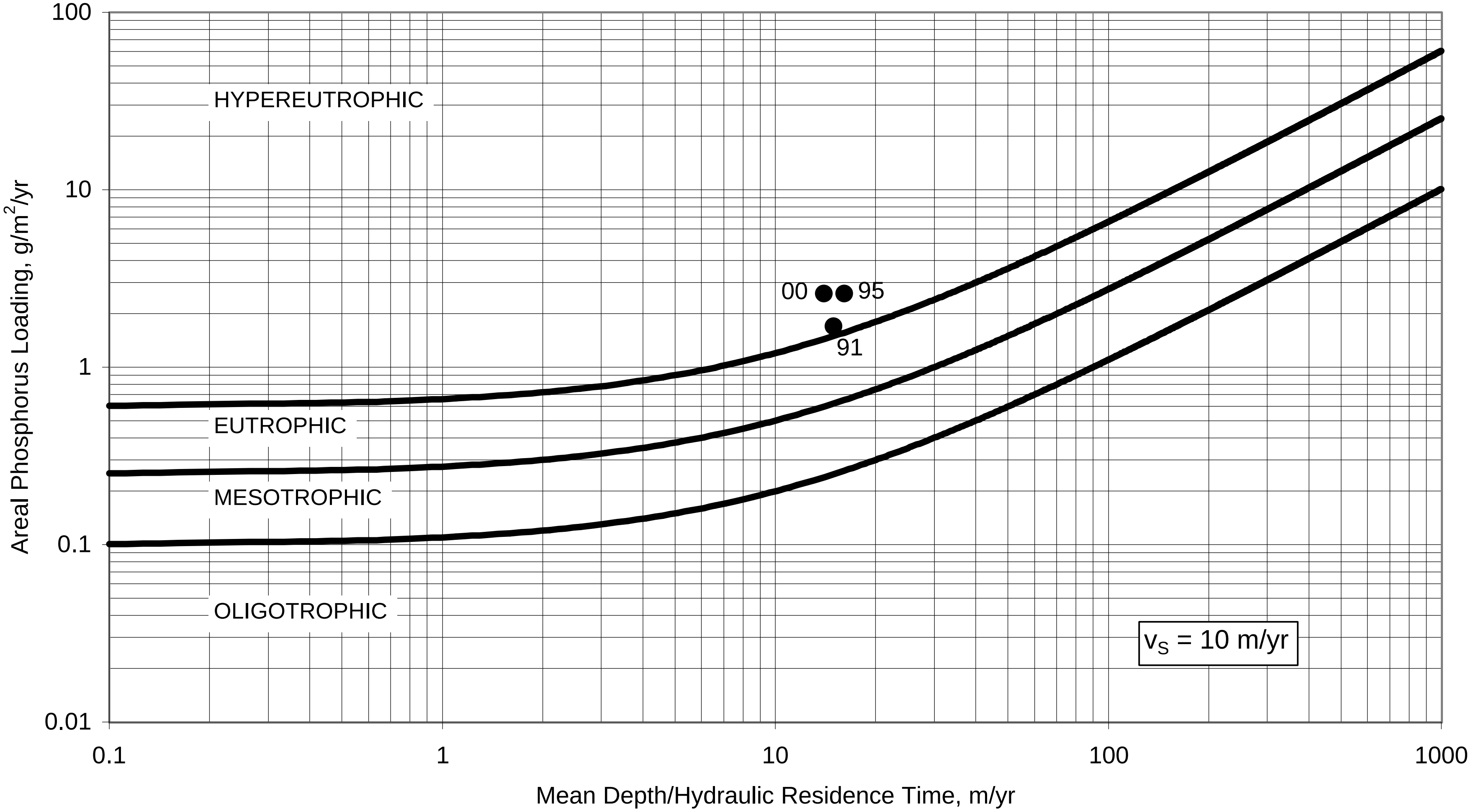
Trophic Status of Lake Manassas

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 ; Rohlich, 1969). A variety of mathematical models have been developed to characterize the trophic status of lakes and reservoirs by incorporating measured parameters into empirically developed relationships. In this section, two models used to characterize lakes will be considered: the Vollenweider Model, which assumes phosphorus-limiting conditions and predicts lake trophic status by calculating phosphorus loading into the lake, and the Carlson Trophic State Index which utilizes in-lake water quality data (Wetxel, 2001). Because these models are empirically developed, their results must be tempered with appropriate professional judgement (Wetzel, 2001)

Vollenweider Model

The Vollenweider model uses a mass balance of phosphorus to determine lake trophic status. The change in total phosphorus in the lake is equal to the influent loading of phosphorus minus the sum of the outflow of phosphorus and the sedimentation of phosphorus (Occoquan Watershed Monitoring Laboratory, 1996). The general relationships between phosphorus loading, lake flushing and trophic status are shown graphically in Figure 92. The annual phosphorus loading rate divided by the surface area of the lake is plotted on the ordinate and represents the loading rate per unit area of lake surface. The mean depth of the lake divided by the mean residence time is plotted on the abscissa. This value

Figure 92
Lake Manassas
Vollenweider Input-Output Phosphorus Loading Model .



relates the rate at which water is changed in the lake to the amount of the lake which can produce algae due to light penetration.

There are four assumptions which must be made when using 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.

This model is even useful when detailed phosphorus loading and flow rate data are available. Station ST70 on Broad Run has provided a long term record of nutrient loadings and daily flow data. The slope of the average loading curve for total phosphorus in Figure 35 provides the annual loading rate. This rate, in pounds per day, is converted to grams per year and divided by the surface area of the lake at full pool conditions. The mean residence time is calculated by dividing the lake volume at full pool conditions by the mean daily flow as recorded at ST70. The lake mean depth is then divided by the mean residence time after conversion to appropriate units. Table 11 summarizes the data used in the calculations for the Vollenweider graph.

The previous data from the last two reports are shown, as well as the difference between this report and the previous reports. The calculated points were then plotted the Vollenweider diagram for the year 1991, 1996 and 2000 for this report. Since the elevation of the dam spillway was increased, the volume of the lake increased. This new volume was used to calculate a 2000 value and graphed along with the other two values. The value shows a slight move into the more hypereutrophic zone.

Table 11: Vollenweider Model Parameters

Parameter	Data Source	1991 Baseline	1995 Baseline	2000 Baseline
TP (lbs/day)	ST70	32.4	28.8	44.1
Flow Rate (cfs)	ST70	47.5	51.3	44.3
Lake Volume (gallons)	Survey (OWML 00)	4.2×10^9	4.2×10^9	4.08×10^9
Mean Depth (m)	Survey (OWML 00)	5.6	5.6	17.97
Lake Surface Area (acres)	Survey (OWML 00)	694	694	697
Phosphorus Loading ($g/m^2/yr$)	Calculated	1.9	1.7	2.6
M. Depth/M. Res. Time (z/t), (m/yr)	Calculated	15.0	16.1	14.03

Carlson Trophic State Indices

In 1977, Carlson published a scheme to classify lakes based on average surface water Secchi disk readings, phosphorus and chlorophyll *a* concentrations using the equations given in Table 12 (Carlson, 1977). Carlson emphasized that a trophic state index (TSI) is not a water quality index, but that the TSI can be useful for comparing lakes within regions, and as a management tool for predicting the productivity changes when used in conjunction with loading concepts. Like the Vollenweider model, Carlson's scale is based on the assumption that the lake is phosphorus limited. Many factors can affect the ability of Carlson's model to accurately predict the trophic state index of a lake, including seasonal changes and highly colored or turbid waters. Carlson found that the man-made impoundments showed different relationships than did natural waters. One difference from a lake is that the reservoir has a shorter residence time, which would increase the turbidity, and thereby affect the Secchi disk results.

Table 12 shows the equations used to calculate the TSI as well as some sample calculations while Table 13 shows the definition of what each TSI value means. The model generally yields a TSI value between 0 and 100. In addition, each of these equations is designed to so that each parameter will give approximately the same TSI value. If the parameters yield a different value, then the results of the tests may be inaccurate or there are other factors within the lake causing this deviation. Lower TSI numbers generally means better water quality from the standpoint of nutrient enrichment.

Table 12 - Calson's Trophic State Indices (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	0.34
30	8	6.0	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

Analytical equations to generate the table given above are:

TSI Secchi = 10*(6-(ln(S)/ln(2)))

TSI Total Phosphorus (TP) = 10*(6-(ln(48/TP)/ln(2))

TSI Chlorophyll a (Chla) = 10*(6-((2.04-0.68*ln(Chla))/ln(2))

Table 13 - 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 Kendal Analysis (Table 14) shows that there is an increasing trend for the TSI value of Chlorophyll *a* and a somewhat downward trend in a few stations for Secchi Depth. There are no trends present for the TSI value for Total Phosphorus.

Table 14- Mann Kendall Analysis for TSI values for Carlson's Trophic State Analysis

	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
TSI - Chla	**U**	**U**	**U**	**U**	**U**	**U**	**-**	**U**
TSI - TP	-	-	-	-	-	-	-	-
TSI - Secchi	-	-	-	-	-	**L**	**L**	**L**

Definitions:

U = Upper Trend Present (Increasing)

L = Lower Trend Present (Decreasing)

- = No Trend Present

Plots 93 through 98 shows the 5-year running average for the TSI values for Chlorophyll *a*, Total Phosphorus, and Secchi Depth. Figure 100 shows the average and standard deviation of each of the three TSI values from 1995 to 2000. The TSI value for Chlorophyll *a* shows a Eutrophic to Mesotrophic State, while the Secchi Depth shows a Eutrophic state and the Total Phosphorus shows anywhere from an Oligotrophic to Eutrophic state. The EPA analysis, which is an analysis that looks at the same three values as the TSI index, but looks at raw averaged numbers, shows that the Chlorophyll *a* is in the eutrophic to mesotrophic state while both Secchi Depth and Total Phosphorous were in the Eutrophic state. These results agree with the information stated about the differences in applying the indices to lakes and reservoirs. Literature stated that the trophic state of the reservoir depended on what species was chosen.

Figure 93
Lake Manassas (Surface)
Seasonal 5 year Running Average
Carlson's TSI Based on Chlorophyll *a*, 1984-2000

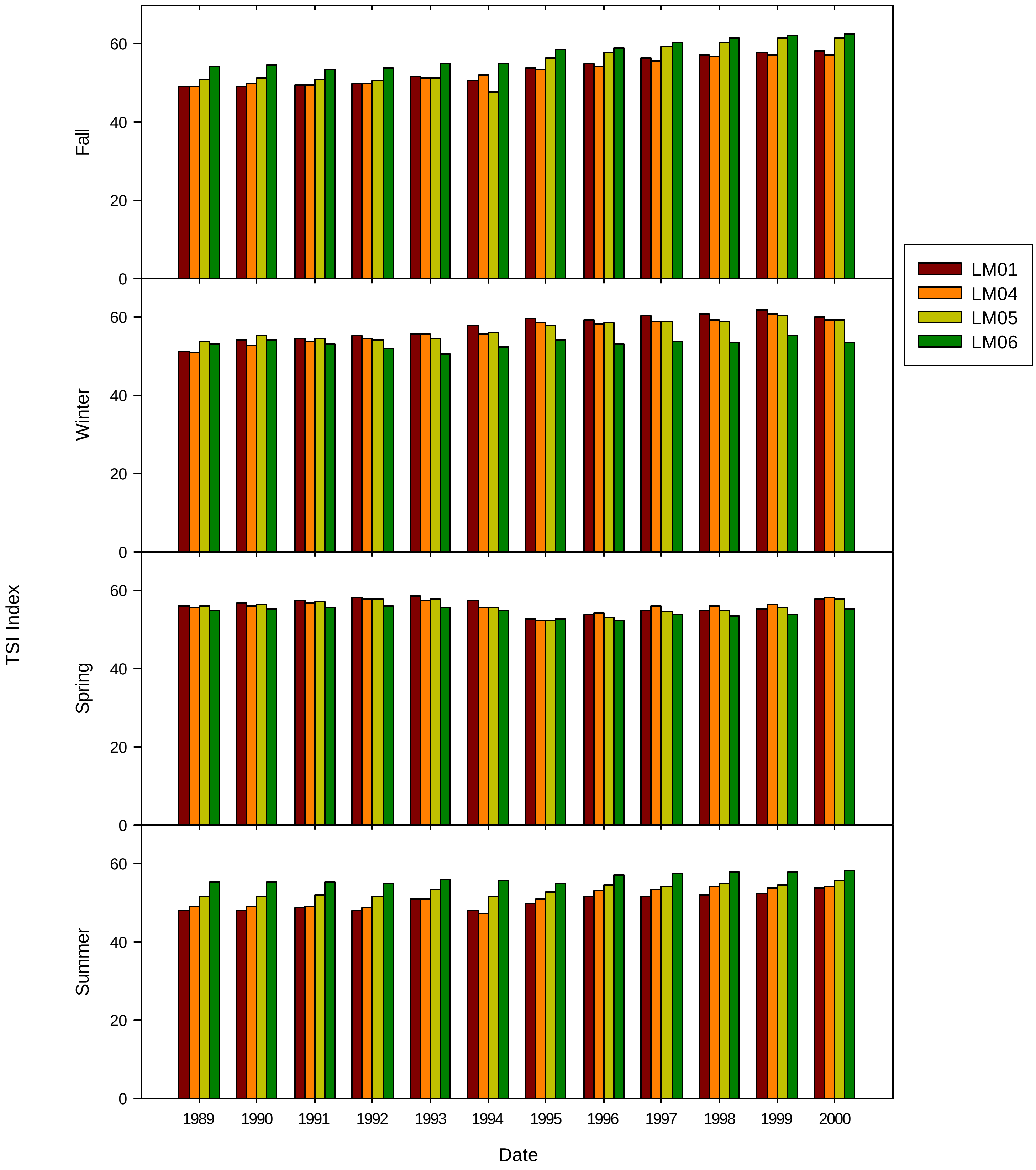


Figure 94
Lake Manassas (Surface)
Seasonal 5 year Running Average
Carlson's TSI Based on Chlorophyll *a*, 1984-2000

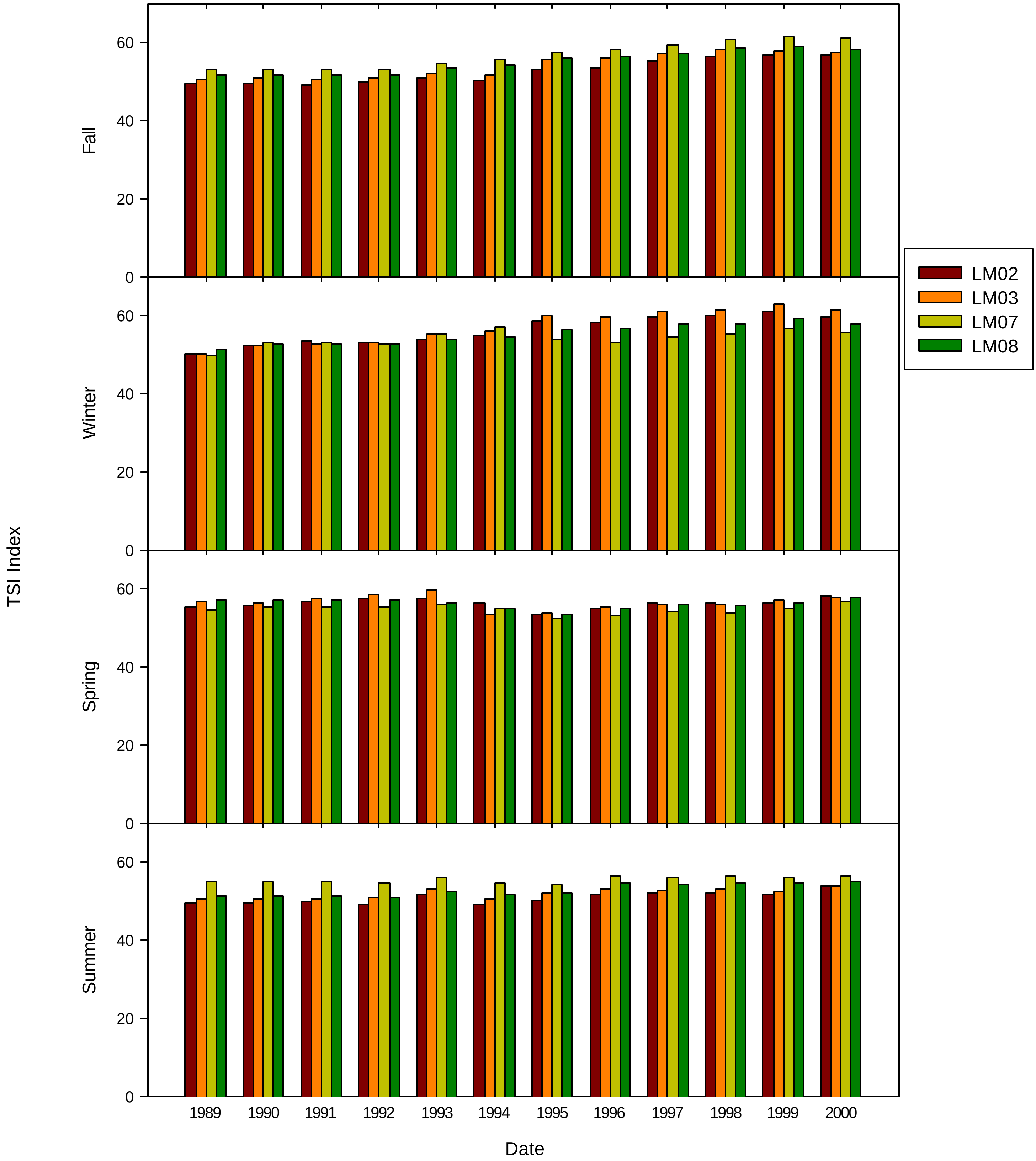


Figure 95
Lake Manassas (Surface)
Seasonal 5 year Running Average
Carlson's TSI Based on Total Phosphorus, 1984-2000

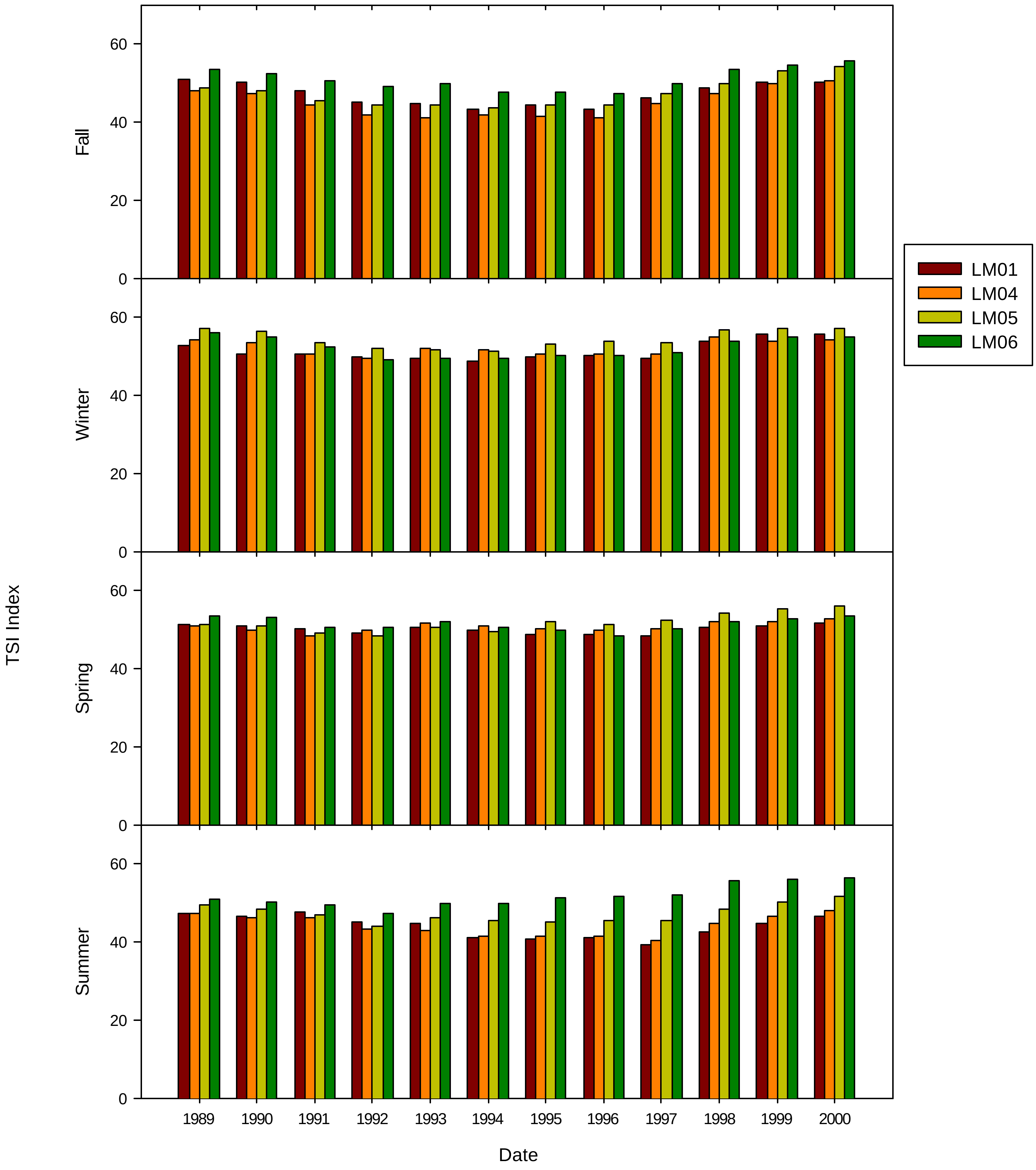


Figure 96
Lake Manassas (Surface)
Seasonal 5 year Running Average
Carlson's TSI Based on Total Phosphorus, 1984-2000

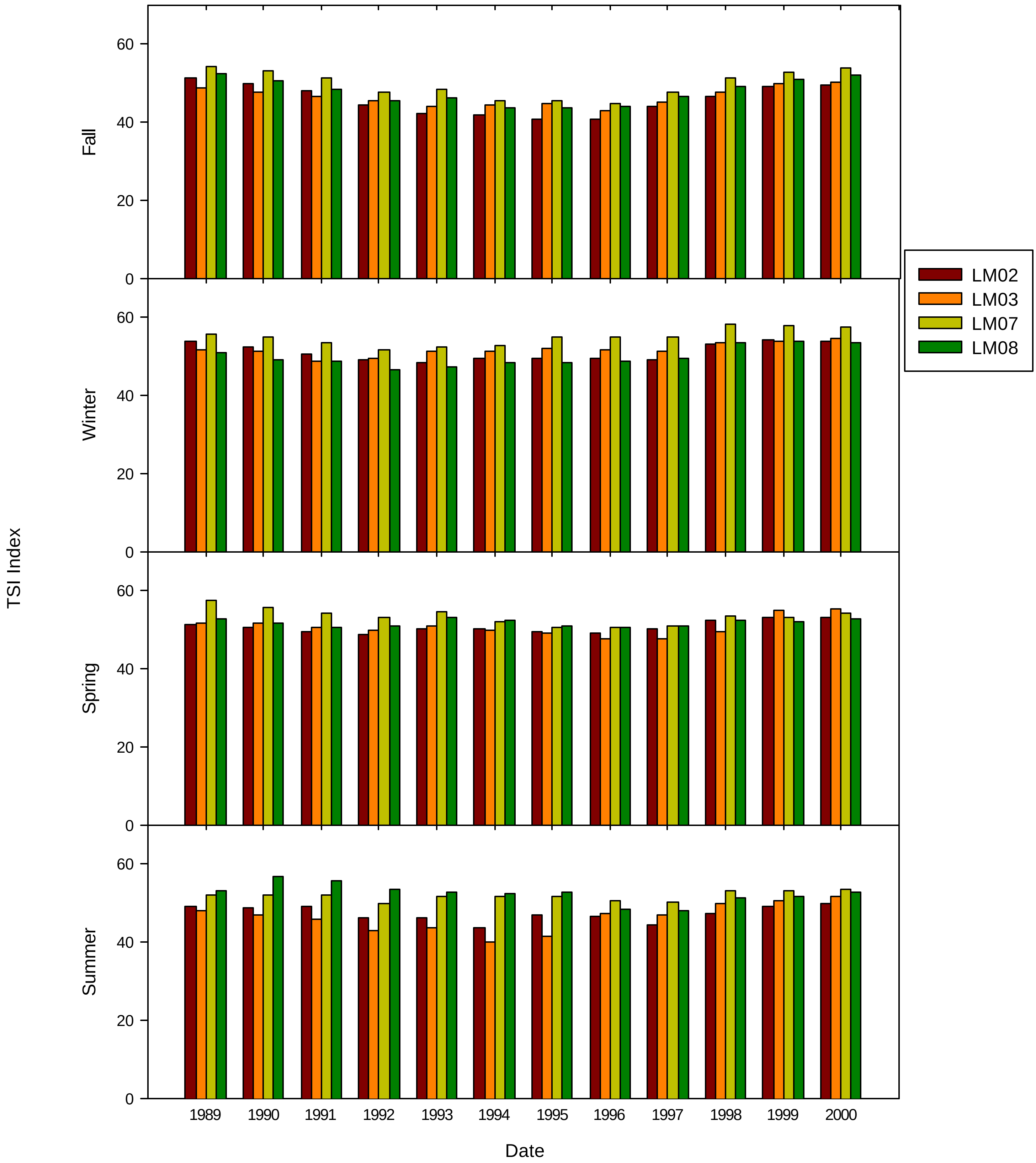


Figure 97
Lake Manassas (Surface)
Seasonal 5 year Running Average
Carlson's TSI Based on Secchi Depth, 1984-2000

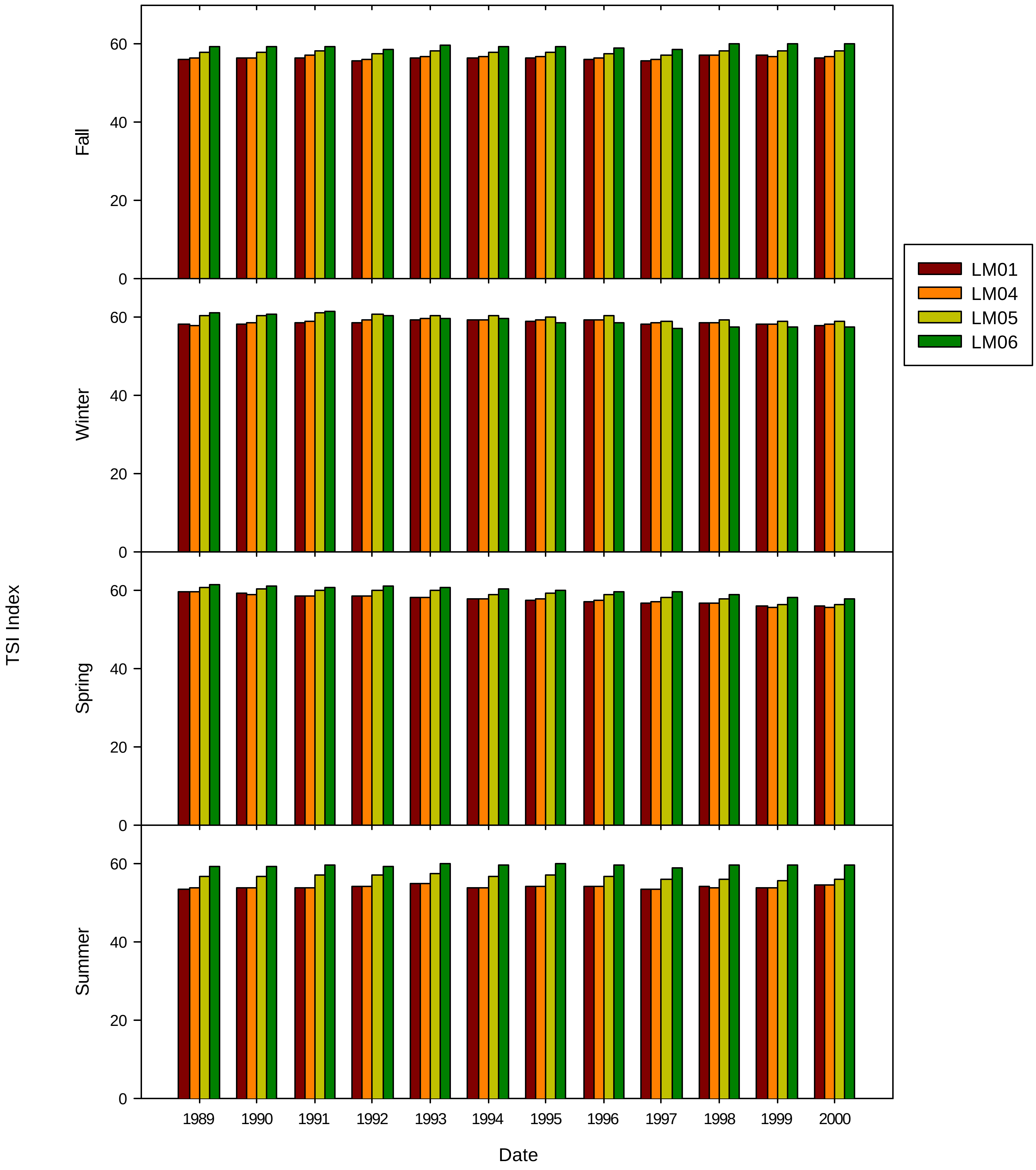
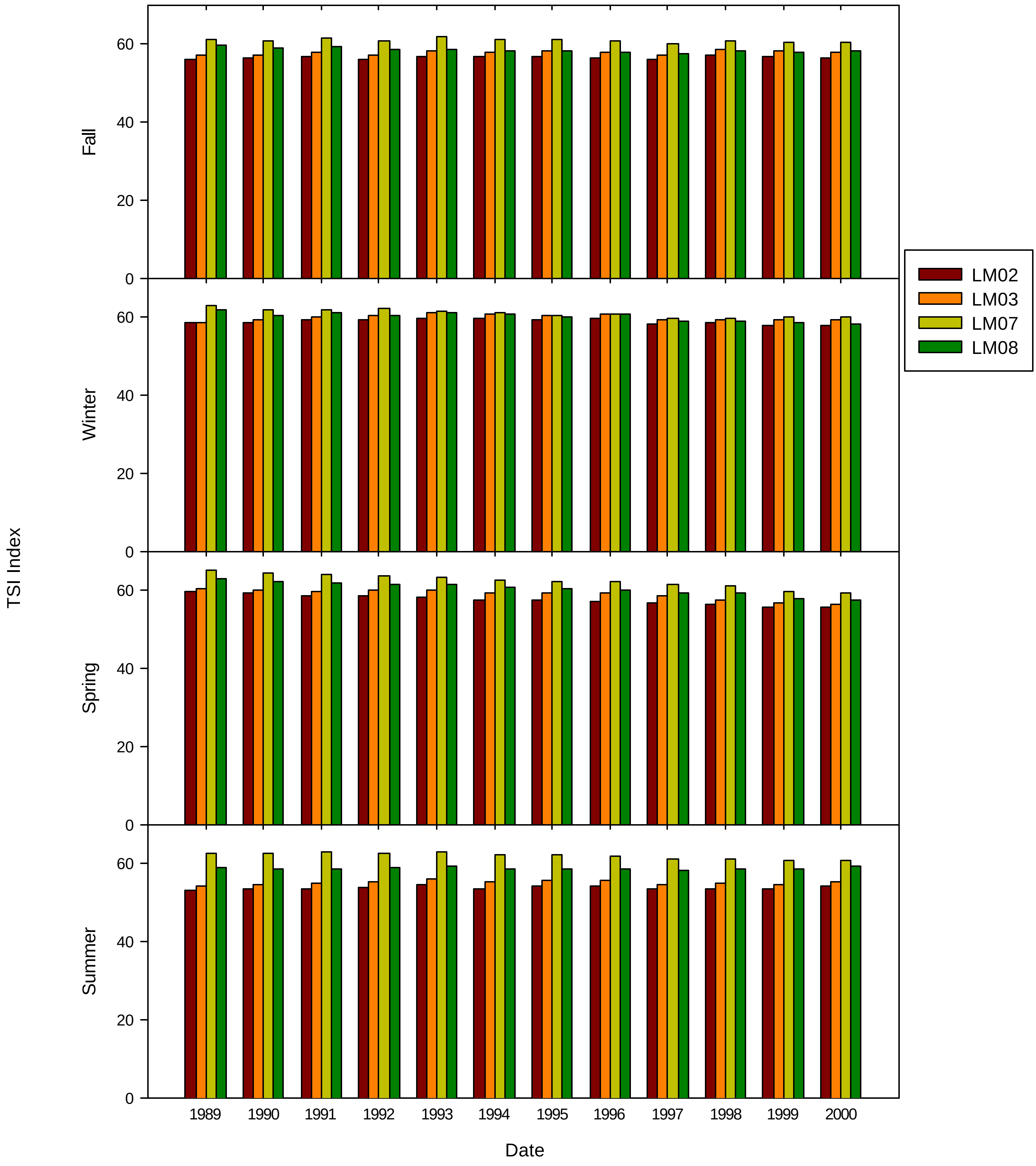


Figure 98
Lake Manassas (Surface)
Seasonal 5 year Running Average
Carlson's TSI Based on Secchi Depth, 1984-2000



Model Results

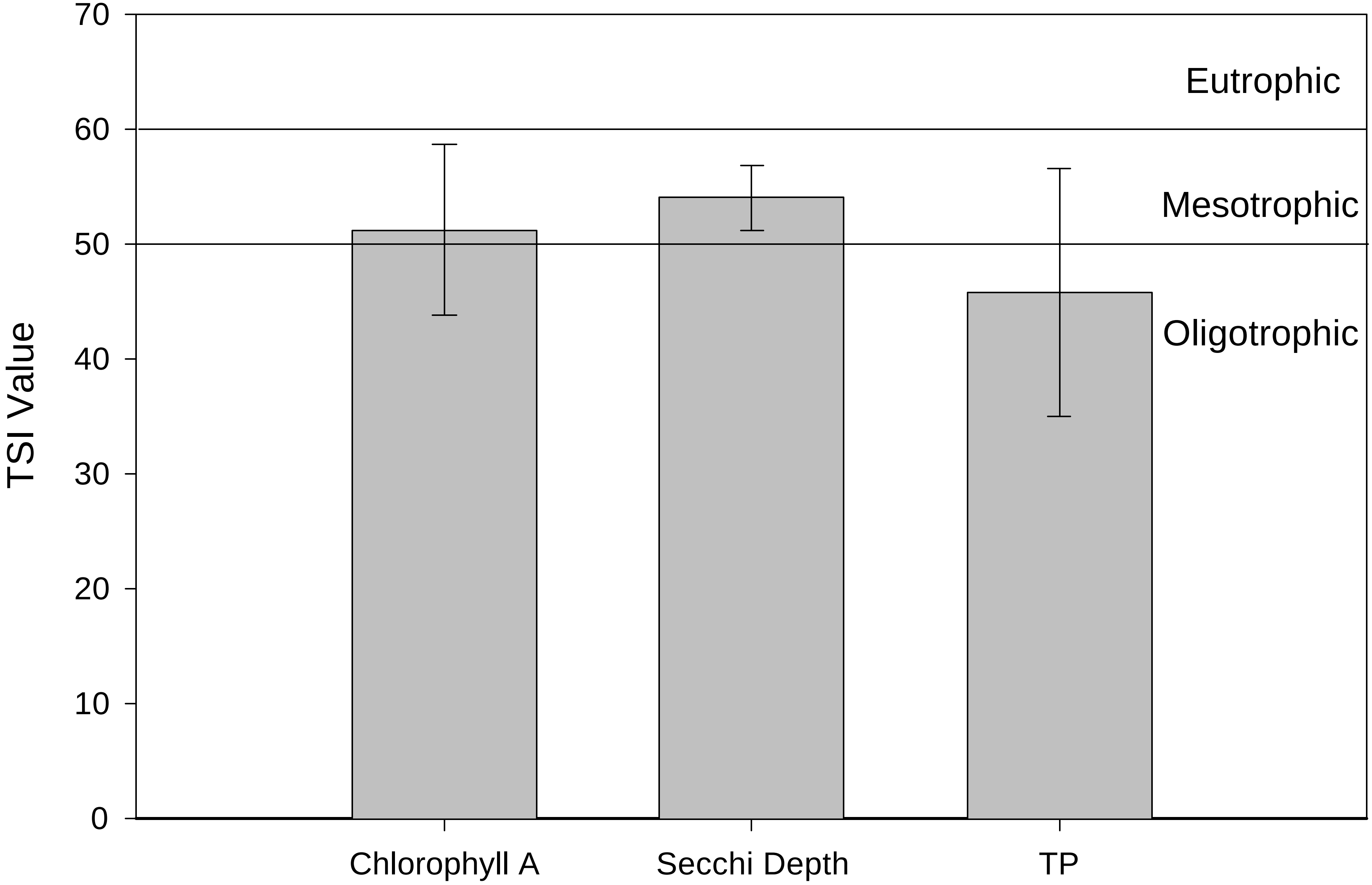
Based on the results from the Vollenweider, EPA (Table 15) and Carlson Trophic State Index models, the lake has changed only slightly, becoming more eutrophic. The Vollenweider model generally shows that with the increased lake volume is a decrease in the quality of the water. The EPA model shows that the lake is Mesotrophic to Eutrophic while the Carlson State Trophic Index (Figure 99) shows that the lake is anywhere between Oligotrophic and Eutrophic depending on the parameter used. To summarize

1. The lake is in the eutrophic range for the Vollenweider Model.
2. The lake is in the lower areas of the eutrophic range for Carlson's TSI values.
3. The lake is mostly in the eutrophic zone for the EPA model.

Table 15 - EPA Trophic State Index System (Occoquan Watershed Monitoring Laboratory, 1996)

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

Figure 99
Lake Manassas
1995 - 2000 Average of Carlson Trophic State Index in Lakes



V. CONCLUSIONS AND RECOMMENDATIONS

The Lake Manassas Monitoring Program has been in operation since 1984. The data collected has proven to be extremely helpful, and often times necessary for making management decisions for trying to maintain the water quality of the Lake Manassas reservoir. There have been previous reports completed on Lake Manassas and this allows for an evolving picture of what is happening over time in the Lake. The conclusions that have been reached for this document are given below, followed by recommendations based on the findings of this document

Conclusion

1. Lake Manassas is still eutrophic with little change from previous baselines. The amount of phosphorus that enters the lake is still high, but this has remained relatively constant except for Station ST70, which has an increasing concentration of phosphorus. This later fact may be of concern because ST70 is the principal tributary to the lake.

2. An inflatable bladder / dam was added to the lake in 1995 and this added up to an additional 5 ft elevation in the lake full pool from the concrete dam. This addition, while increasing the amount of water in the reservoir, had no effect on the eutrophic status of the lake.

3. The Robert Trent Jones International golf course has not impacted the quality of the lake in any discernable adverse manner. This is probably due to integrated stormwater and turfgrass management practices on the course. With the knowledge of what this golf course has done, hopefully other golf course developers can follow in the footsteps of the Robert Trent Jones International golf course.

4. There are increasing conductivity levels throughout the lake. The only stream that also has increasing conductivities is station ST70. This is probably due to the fact that there is an increase in the amount of nutrients and other dissolved solids entering the lake. Again, as ST70 is on the principal tributary entering the lake, this indicates a need to track the upstream development.

5. Most lake stations have an increase in pH values, while more of the stream stations show this increase. This is probably due to the growth of algae, as they extract the CO_2 from the water, thereby increasing the pH.

6. The lake remains a phosphorus limited system. Overall the TN:TP ratios have slightly decreased. If this trend continues without management, there may be periodic changes during seasonal periods to a nitrogen limited system.

8. The stations below the Vint Hill wastewater treatment facility show decreasing concentrations of nutrients. This may be due to the facility either providing improved treatment or less discharge in relation to natural flow.

.Recommendations

1. The basic Lake Manassas Water Quality Monitoring Program should continue so that water quality data from future years may be used to evaluate development impacts.

2. To gain a better understanding of the consequences of copper sulfate in lake Manassas, it is suggested that experiments be performed to assess algae kill rates and duration, residence time in the water column, and other implications the copper may have the lake. Also, other potential powders or chemicals could be looked at as a replacement for copper sulfate.

3. Monitoring of the Virginia Oaks golf course, especially for the first few years, will provide information about the export of nutrients from it to the lake.

4. It may be helpful to start looking at benthic organisms in the water and soil. As the water quality of the reservoir changes, so will the amount and type of species found in the water and soil. Also, there are new predictors (models) of the trophic status of lakes and reservoirs that incorporate this information.

5. Any new developments in the watershed should follow the newest policies and regulations including the incorporation of appropriate second-generation BMP's.

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VII. VITA

Judith Eggink was born on June 28, 1972 in Scheidam, The Netherlands. She grew up in many diverse locations around the world, but spent her high school years in Buffalo, NY. She has received a Bachelor of Science degree from the University at Buffalo in Chemical Engineering in 1997. She then received a position with Corning, Inc. working in the Specialty Materials Division as a process engineer. In this position, she worked in the microlithography industry as well as high purity fused silica development. Approximately three years later, the author left Corning in pursuit of a Master degree.

In the spring of 2000, she was accepted to the Virginia Polytechnic Institute and State University starting in the Fall of 2000, for Environmental Engineering. In June of 2001 this author moved to Charlotte, NC to take a position at Brown and Caldwell in Environmental Engineering and continued to work on this thesis.