

**A Limnological Analysis of Lake Manassas,
With an Updated Baseline Through 2010**

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by

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Abstract

Lake Manassas is an approximate 706 acre man-made lake located in greater Prince William County near the town of Gainesville, Virginia. The lake was created in 1968 on Broad Run to serve as the primary water supply for the City of Manassas and its residents. The Lake Manassas watershed lies within the greater Occoquan River watershed which drains into the Potomac River and Chesapeake Bay. Water within Lake Manassas and its tributaries has been monitored since 1971 and this thesis presents a comprehensive limnological analysis of the Lake with an analysis of water quality impacts over time.

Lake Manassas remains an enriched or eutrophic system, meaning the levels of nutrients and biomass production in lake waters is above desired standards. Nutrient loading occurs via a stream network with the largest contributor being Broad Run which is consistent with previous water quality studies.

The lake serves as the sole water source for nearly 40,000 residents and businesses and ensuring clean and safe water is of significant importance. Close monitoring in conjunction with the implementation of appropriate management practices within the watershed are necessary to prevent water quality from becoming significantly degraded.

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List of Acronyms

BMP	Best Management Practices
BR	Broad Run
CFS	Cubic Feet per Second
CHLA	Chlorophyll <i>a</i>
COND	Specific Conductivity
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
FLO	Flow
HUC	Hydrologic Unit Code
IAD	Washington Dulles International Airport
LIMS	Laboratory Information Management System
LM	Lake Manassas
FW	Fairfax Water
µg/L	Micrograms per Liter
mg/L	Milligrams per Liter
MGD	Millions of Gallons per Day
MSL	Mean Sea Level
NELAC	National Environmental Laboratory Accreditation Conference
NELAP	National Environmental Laboratory Accreditation Program
NH ₃ -N	Ammonia Nitrogen
OP	Orthophosphate Phosphorus
OWML	Occoquan Watershed Monitoring Laboratory
OX-N	Oxidized Nitrogen
QA / QC	Quality Assurance / Quality Control
SD	Secchi Depth
TALK	Total Alkalinity
TDS	Total Dissolved Solids
TEMP	Temperature
THARD	Total Hardness
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USGS	United States Geological Survey
VDEQ	Virginia Department of Environmental Quality
VDGIF	Virginia Department of Game and Inland Fisheries
WRF	Water Reclamation Facility
WTP	Water Treatment Plant

Chapter 1 Introduction

Constructed between 1968 and 1970, Lake Manassas is an artificial impoundment that encompasses approximately 800 acres in western Prince William County, Virginia. The reservoir was constructed to provide drinking water to the City of Manassas and also to supplement the Prince William County Service Authority after rapid urbanization in the area put a significant strain on the existing groundwater supply network (Manassas 2012). Lake Manassas is located within the Broad Run-Catlett's Branch watershed and is part of the larger Occoquan watershed that drains into the Potomac River which is part of the greater Chesapeake Bay drainage.

Data has been collected at Lake Manassas and its tributaries since as early as 1978, with the current network of sampling and gaging stations established in 1984. In 1991, the first water quality characterization report for Lake Manassas was compiled and five-year baseline reports have been prepared since. The purpose of these limnological reports is to identify both short and long term changes to Lake Manassas water quality as it is a primary source of drinking water for the City of Manassas. This report is both a compilation of the data available from 1984 through November 2010, and the establishment of a new baseline for the December 2005 to November 2010 period. The objectives of this study and associated chapters within this report include the following:

- Analyze lake and watershed morphology (Chapter 2)
- Stream water quality characterization (Chapter 5)
- Stream nutrient loading measurement (Chapter 5)
- Lake water quality characterization (Chapter 6)
- Trophic state analysis (Chapter 6)

Selected photographs of the Lake Manassas watershed are included in Appendix A.

Chapter 2 Lake Manassas and its Watershed

Lake History

Constructed between 1968 and 1970, Lake Manassas is an artificial impoundment that encompasses approximately 800 acres in western Prince William County, Virginia. The reservoir was constructed to provide drinking water to the City of Manassas and also to supplement the Prince William County Service Authority after rapid urbanization in the area put a significant strain on the existing groundwater supply network (Manassas 2012).

Figure 2-1 Aerial View of Lake Manassas (August 2010)



Source: 38°46'06.93" N, 77°38'40.84" W. [Google Earth](#). Accessed October 2011.

To develop Lake Manassas, the T. Nelson Elliott Dam was constructed on Broad Run near Glenkirk Road, approximately 10 miles west of the City of Manassas. Under its current configuration, the T. Nelson Elliott Dam is 1,306 feet long and 74 feet high from the dam crest to the stream and consists of both earthen and concrete sections (Manassas 2011). Modifications

to the dam in 1999 included the addition of an inflatable rubber bladder to the spillway that increased the dam height from 285 feet above mean sea level (MSL) to 290 feet MSL (Manassas 2011). Further modifications to the dam were completed in August 2012 that are designed to meet new state requirements for handling a 10,000 year storm event; however, these modifications are to meet structure stability requirements only, and do not impact the spillway elevation or lake capacity (InsideNova 2012).

Historically, Lake Manassas was open to the public for recreational purposes; however, access has been restricted for approximately the last 12 years after a franchise agreement between the city and a marina was ended. There have been several calls from private citizens and conservation groups to reopen the lake; however, there are currently no plans to reopen the lake to the public.

Water Treatment

Located immediately below the T. Nelson Elliott Dam is the City of Manassas Water Treatment Plant (WTP). The WTP, as shown in Figure 2-2, consists of a raw water intake, pre-filtration, coagulation, flocculation, settling, filtration and disinfection processes (Manassas 2012). The WTP was originally designed to operate at a 4 million gallon per day (MGD) capacity which was doubled to 8 MGD in 1987 (Gorrie 2007). The current capacity is 14 MGD (Manassas 2012).

Water is drawn from Lake Manassas at depths ranging from 5 to 55 feet below the lake surface. The raw water is first pre-treated using potassium permanganate, liquid alum, caustic soda, hydrofluorous oleic acid, hexametaphosphate and gaseous chlorine prior to entering settling basins where particulates fall to the bottom (Eggink 2001, Manassas 2012). After settling, the water is then processed through anthracite, gravel and silicate sand filters to remove smaller suspended particles. Finally the filtered water is disinfected with sodium hypochlorite and

stabilized with ammonia and orthophosphate before being pumped into an underground water distribution system (Eggink 2001, Manassas 2012).

Figure 2-2 Aerial View of Lake Manassas Water Treatment Plant (August 2010)



Source: 38°45'42.65" N, 77°37'18.46" W. [Google Earth](#). Accessed October 2011.

Algae within Lake Manassas have caused issues in the water treatment processes in the past, including clogging filters and impacting the taste and odor of the water. Previously, copper sulfate which is an algaecide was applied to the surface of the Lake approximately four times a year. However, the surface applications were ceased in 2000 (Gorrie 2007).

Watershed Identification

Lake Manassas is located within the Broad Run-Catlett's Branch watershed (Figure 2-5) which is a sub-watershed of the greater Broad Run watershed (Figure 2-4) which is located in the Middle-Potomac Anacostia watershed (Figure 2-3). Surface runoff within the Broad Run-Trapp Branch sub-watershed (Figure 2-5) also drains into the Broad Run-Catlett's Branch sub-

watershed (Figure 2-5) where Lake Manassas is located. The Broad Run-Catlett's Branch watershed is identified as hydrologic unit code (HUC) 020700100502. HUCs are established by the United States Geological Survey (USGS) for watersheds and their sub-watersheds. Figures 2-3 through 2-5 depict the watersheds associated with Lake Manassas. The area associated with water entering Lake Manassas encompasses approximately 74.5 square miles (Manassas 2011). Also, for the purposes of this report, Lake Manassas falls within the greater Occoquan River watershed which is monitored by the Occoquan Watershed Monitoring Laboratory (OWML).

Other bodies of water within the Broad Run-Catlett's Branch watershed include Lake Brittle and Buckland Lake which discharge to South Run. Lake Brittle is an approximate 77-acre lake that was constructed with an earthen dam in 1953 for recreational purposes (VDGIF 2012). Lake Brittle is overseen by, and public access is granted by, the Virginia Department of Game and Inland Fisheries (VDGIF). Several other unnamed ponds and tributaries drain into Lake Manassas.

Figure 2-3 Eight Digit HUC - Middle Potomac-Anacostia-Occoquan Watershed

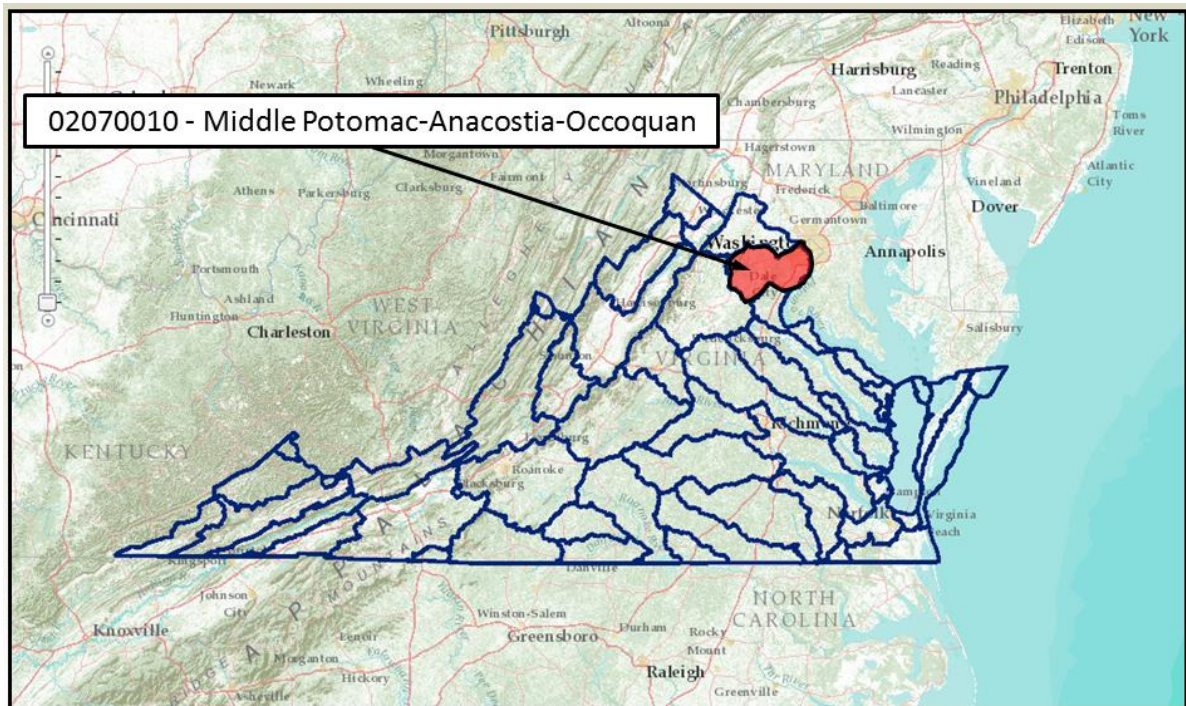


Figure 2-4 Ten Digit HUC - Broad Run Watershed

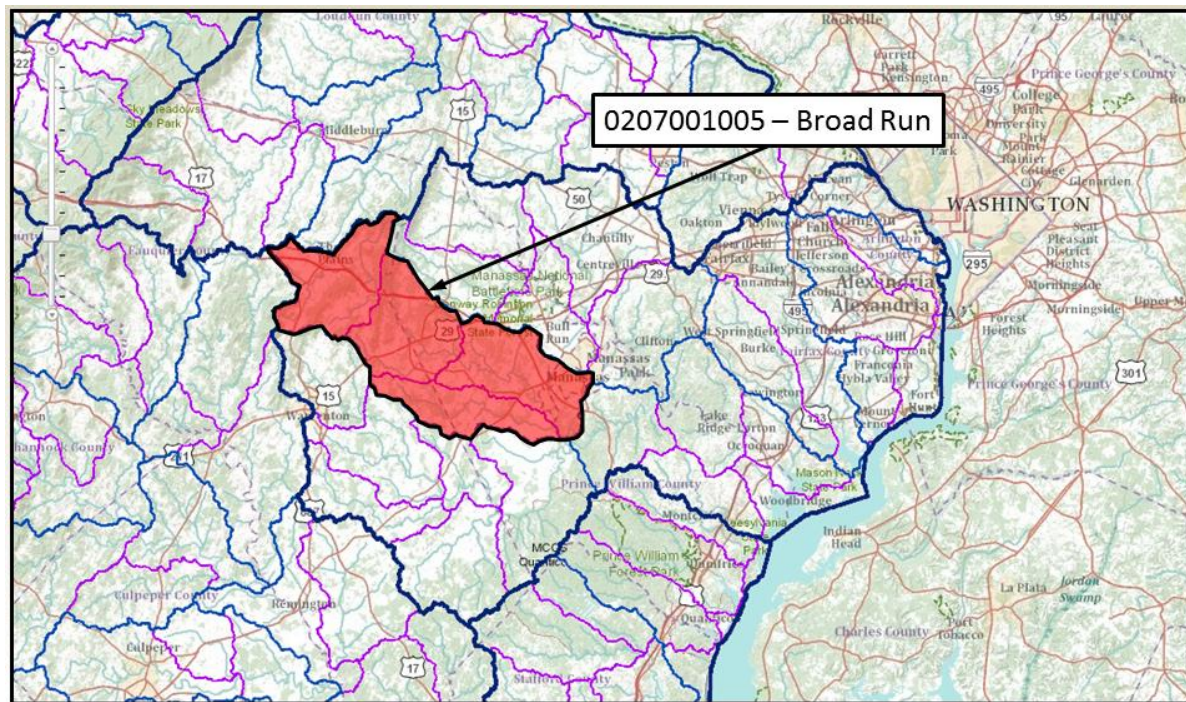
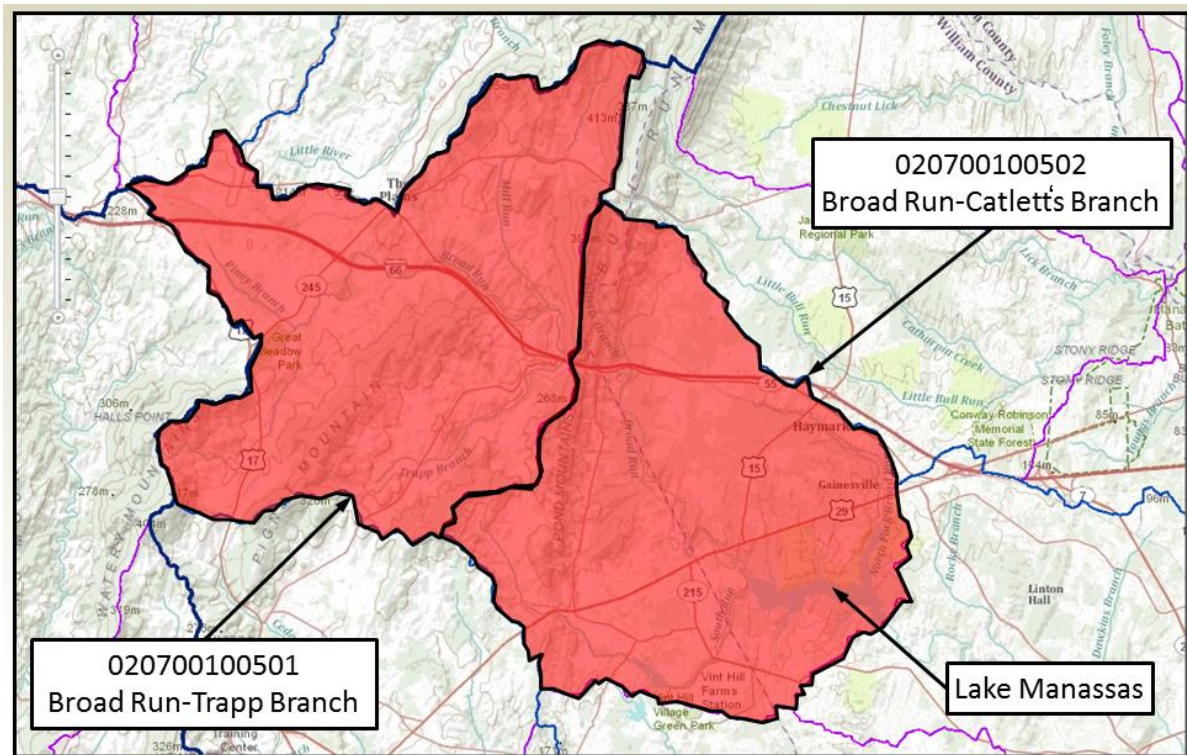


Figure 2-5 Twelve Digit HUC - Broad Run-Trapp Branch and Broad Run-Catlett's Branch Watershed



Watershed Management

Lake Manassas, which discharges to Broad Run, is part of the larger Occoquan River watershed that is monitored by the OWML. Water in Broad Run joins with water in Cedar Run to form the Occoquan Creek near Lake Jackson which was originally constructed for hydroelectric purposes in the 1930s (OWML 2012). The Occoquan Reservoir, which includes the confluence of the Bull Run and Occoquan Creek, serves as a water supply for roughly 1.3 million people in Northern Virginia. Fairfax Water (FW) draws water from both the Occoquan Reservoir and the Potomac River to serve its customers in Northern Virginia (Gorrie 2007).

Excessive pollution within the Occoquan reservoir in the 1970s prompted the state of Virginia to adopt the Occoquan Watershed Policy which mandated high-performance water reclamation

facilities (WRF), establishment of a continued monitoring program and other erosion/sediment control standards (OWML 2012).

It should also be noted that the Vint Hill Farms Wastewater Treatment Plant is located within the boundaries of the Broad Run-Catlett's branch watershed and historically discharged to South Run which drains into Lake Manassas. However, as part of a permit application in 2002 to upgrade the Vint Hill Farms station capacity, discharge water was rerouted to Kettle Run which is still within the greater Potomac-Anacostia-Occoquan Watershed, but no longer discharges to a tributary of Lake Manassas (PWCA 2003).

Land Use Change Over Time

As is discussed throughout the text of this report, the water quality of a lake or reservoir can be directly affected by the flow of nutrients into the water body from runoff. For example nitrogen and phosphorus are commonly found in the runoff from agricultural properties which can in turn result in greater eutrophication of the water quality. One method for protecting water quality is to manage the development within the watershed, so as not to increase the loading within contributing streams and tributaries.

Currently, the property immediately surrounding Lake Manassas is developed with a mix of residential and agricultural use as well as three 18-hole golf courses. Predominantly agricultural land is located to the south and west of Lake Manassas, intermixed with some light small residential developments. The Stonewall, Robert Trent Jones and Virginia Oaks golf course communities are located immediately north of Lake Manassas, and the relatively recent Saranac at Lake Manassas residential community is being constructed to the west of Lake Manassas.

A review of historical aerial photographs made available through Google Earth™ was conducted to consider the changes in land use to the areas immediately surrounding Lake Manassas. This review does not include an analysis of the entire watershed, which can ultimately impact the water quality within Lake Manassas. Selected aerial images are presented below, with development changes identified where appropriate.

Figure 2-6 1989 Aerial Photograph of Lake Manassas



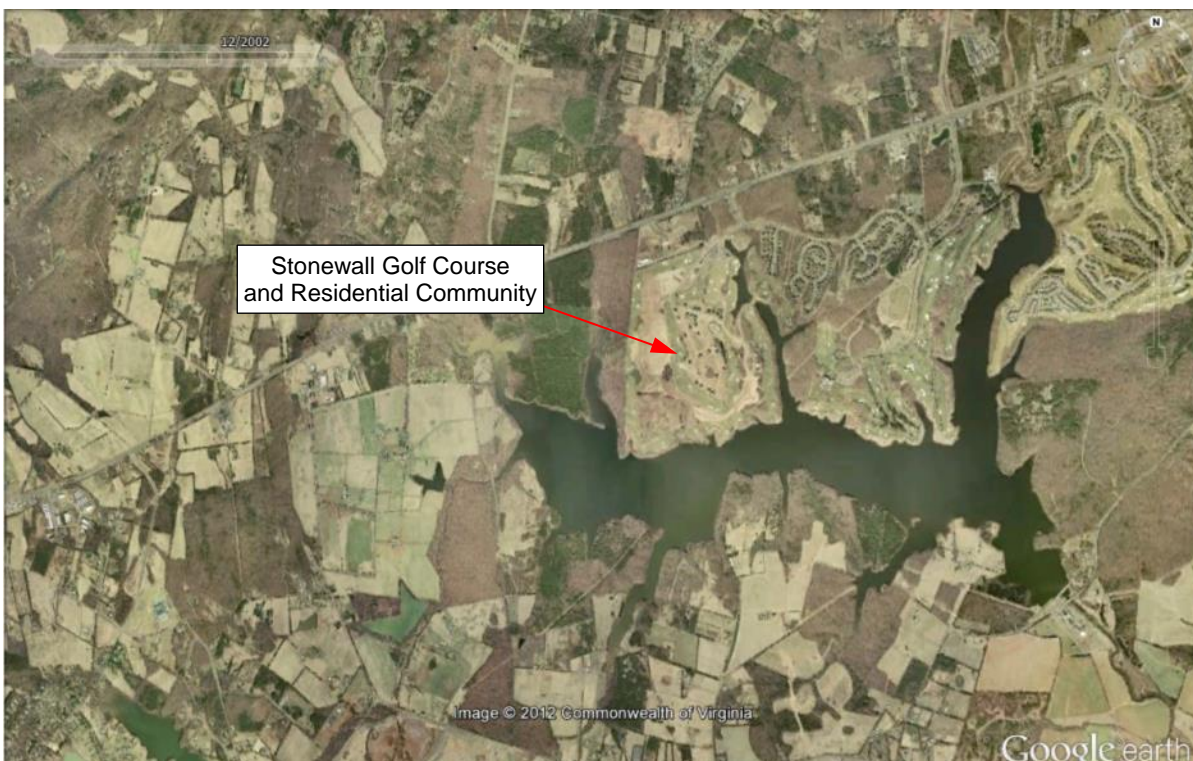
(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-7 1994 Aerial Photograph of Lake Manassas



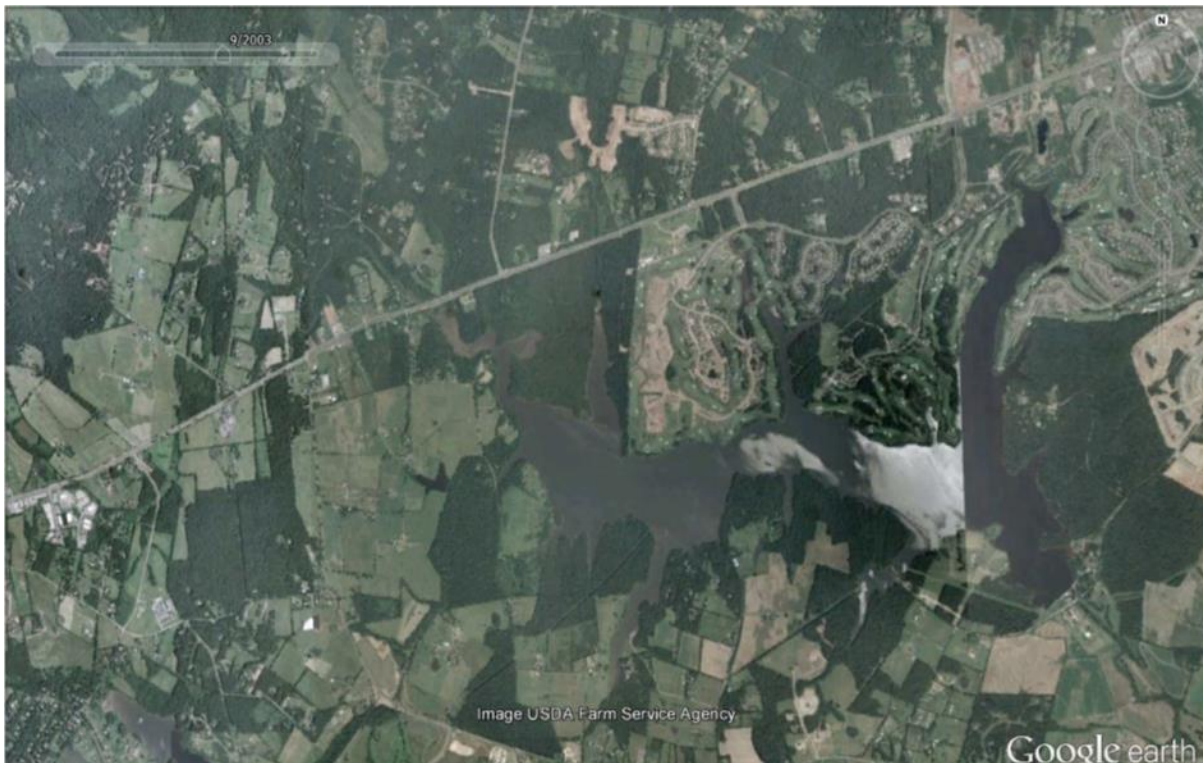
(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-8 2002 Aerial Photograph of Lake Manassas



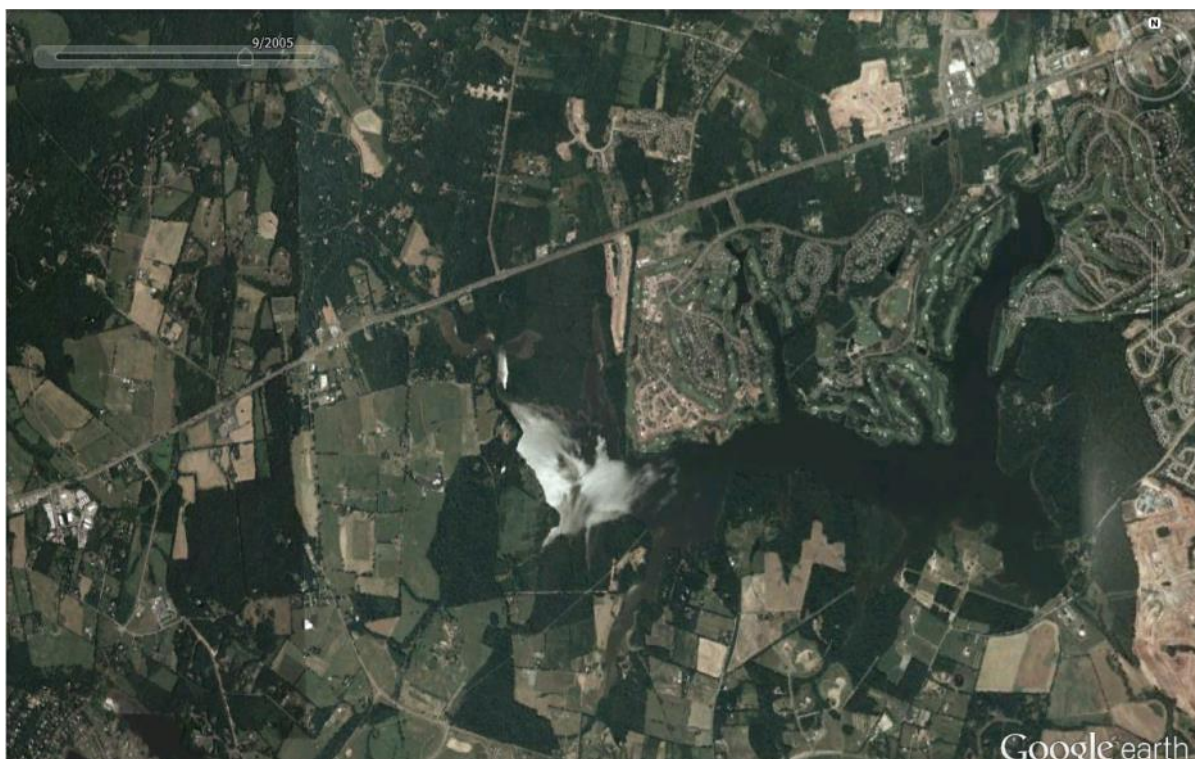
(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-9 2003 Aerial Photograph of Lake Manassas



(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-10 2005 Aerial Photograph of Lake Manassas



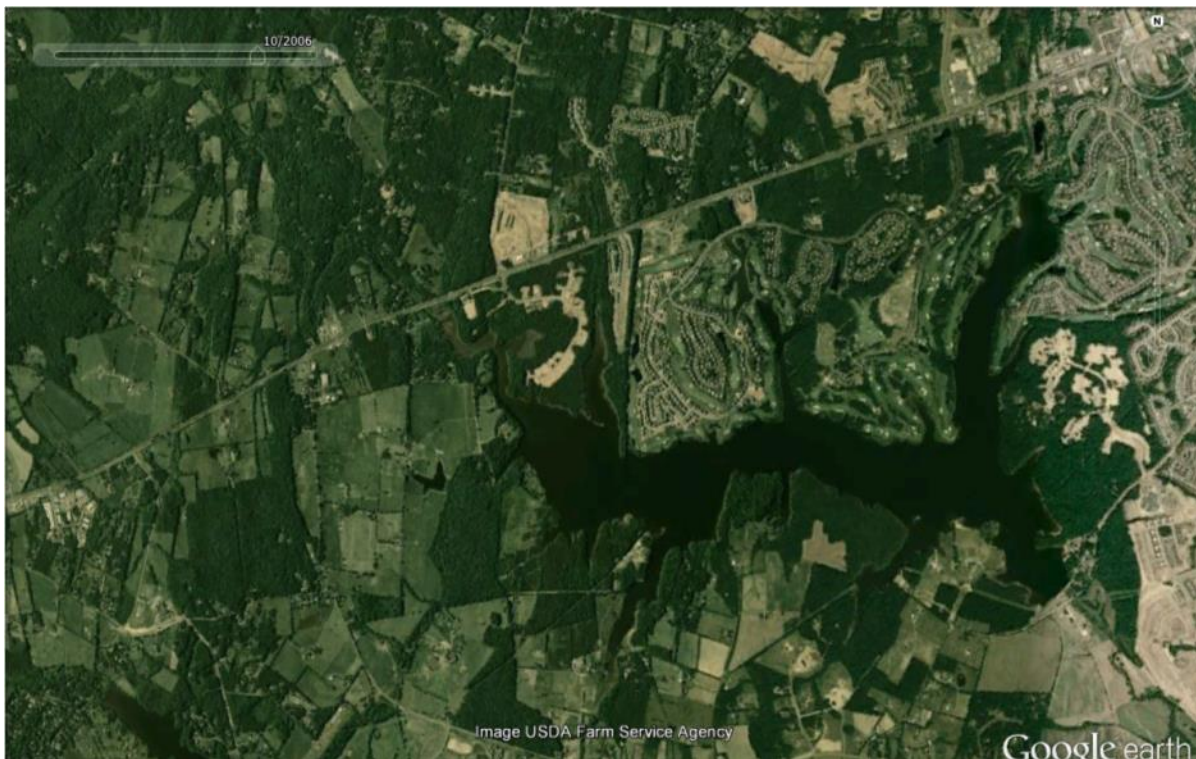
(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-11 2006 (April) Aerial Photograph of Lake Manassas



(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-12 2006 (October) Aerial Photograph of Lake Manassas



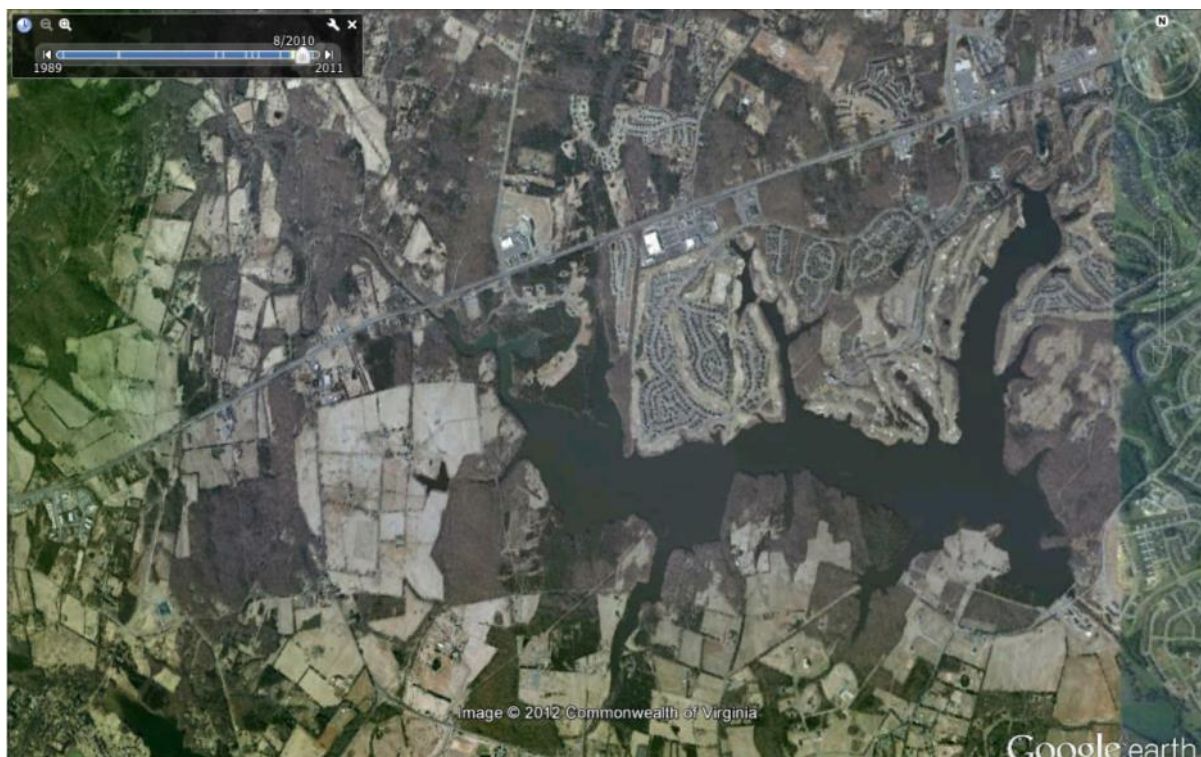
(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-13 2008 Aerial Photograph of Lake Manassas



(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Figure 2-14 2010 Aerial Photograph of Lake Manassas

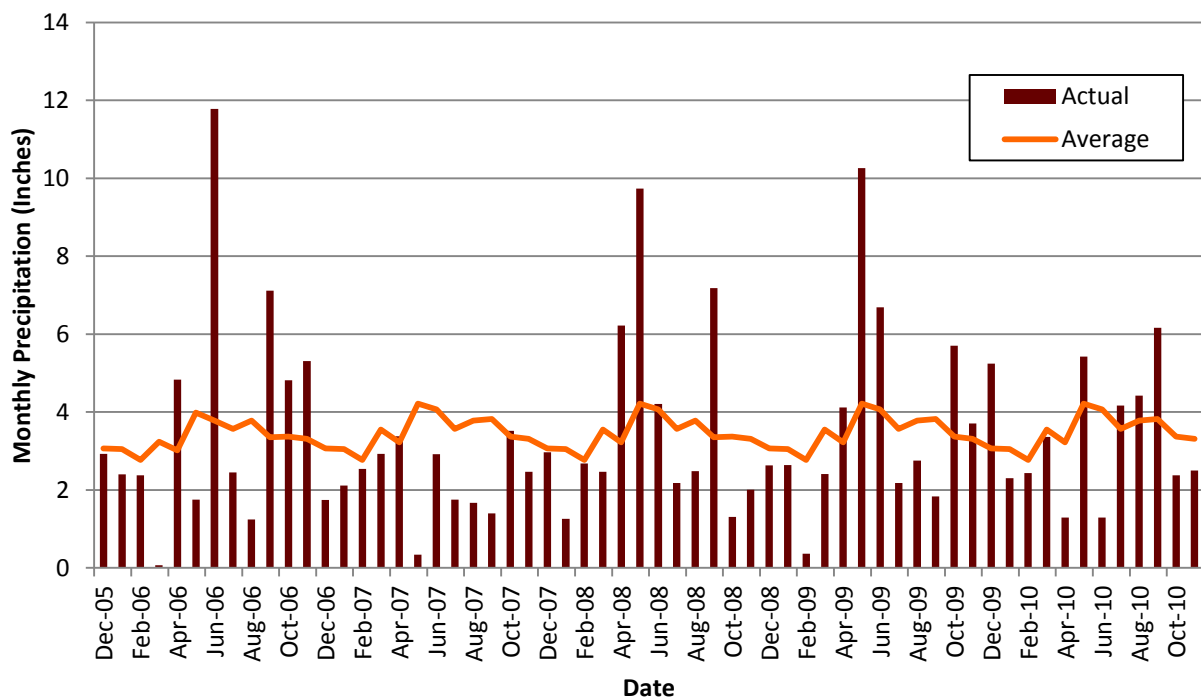


(Source: Google Earth™) (1 inch = Approximately 1.25 miles)

Precipitation Data

As discussed in later chapters of this report, water quality and precipitation are often tied very closely together. For example, low surface water flow may increase interflow to a system from groundwater which often increases minerals associated with hardness. Alternatively, increased precipitation and runoff can increase the flow of nutrients such as nitrogen and phosphorus as well as sediments into a lake or reservoir. Monthly precipitation data were collected from the Washington Dulles International Airport (IAD) weather station for the 2006 to 2010 baseline period and is depicted below in Figure 2-15 (Wunderground 2012).

Figure 2-15 2006 to 2012 Precipitation Data



Both actual and calculated historical averages are presented in Figure 2-15. As shown, approximately 66% of the months considered, have precipitation measurements below the historical average and those months where levels exceeded the average tended to be based on

significant storm events. For example, a single storm event in Jun 2006 accounts for almost six inches of rain (Wunderground 2012).

Chapter 3 Literature Review

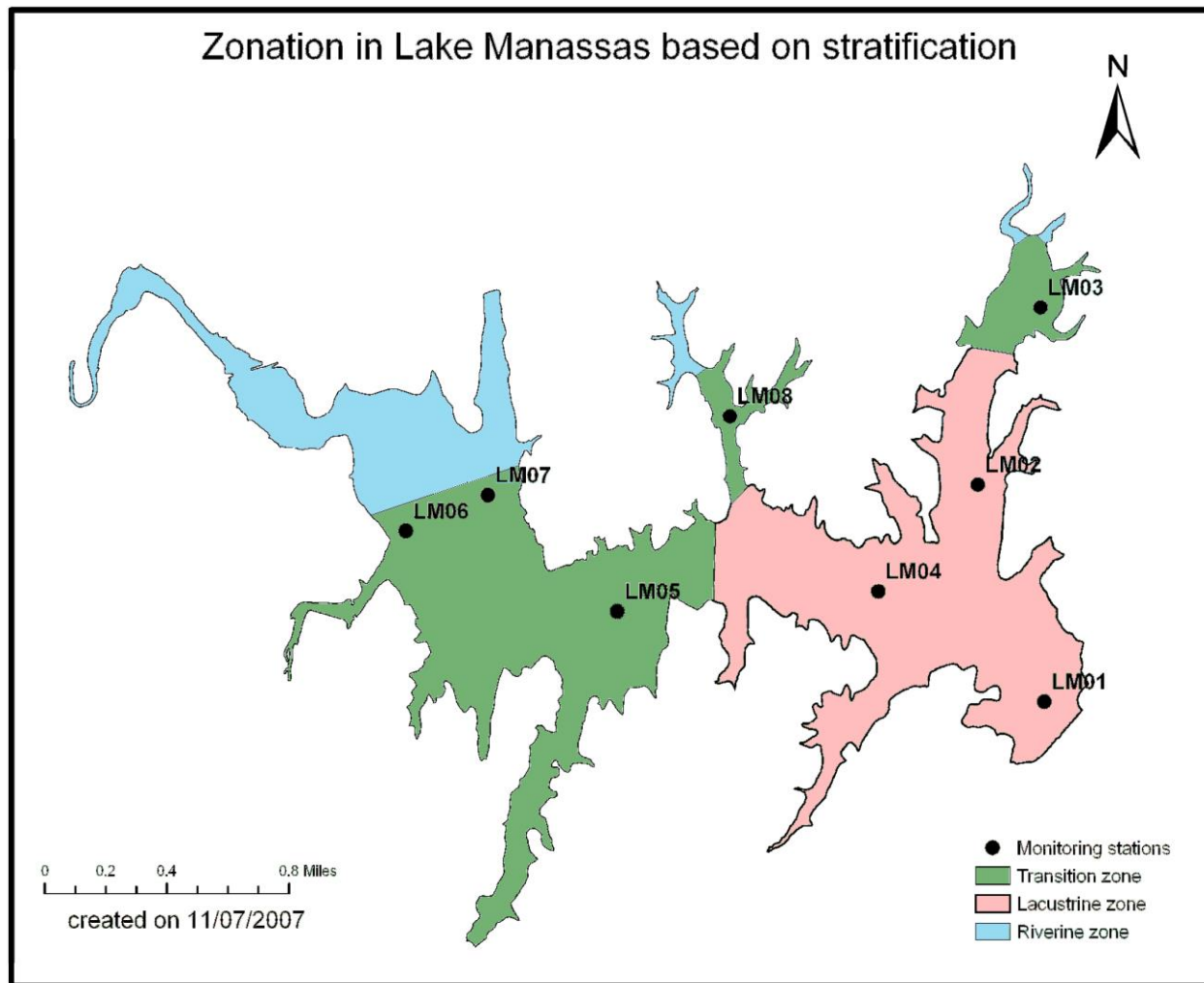
Lake Morphology

Although reservoirs, such as Lake Manassas, are man-made and can vary greatly in size and shape depending on the reservoir's intended purpose, they can, in general, be assumed to have a functional equivalence to natural lake ecosystems. For the purposes of this study, this correlation between natural and man-made lake parameters will be considered true as most of our understanding regarding reservoir morphology originates from studies conducted on natural lake systems (Wetzel 2001). It is important, however, to note several key differences between man-made and natural ecosystems. As reservoirs are commonly constructed near a drainage basin's terminus, they generally tend to be more narrow or elongated in nature, and in some ways act similar to a riverine system. Natural systems are typically more circular or oval in nature and tend to be found centrally located within a drainage area. As a result, the drainage area associated with a reservoir is often much larger than that of a naturally occurring lake. (Wetzel 2001).

By placing a dam near the bottom of a drainage feature, a reservoir can generally be considered as having three distinct zones: lacustrine, transition and riverine. Each distinct zone is defined by unique physical, chemical and biological parameters (Wetzel 2001). Whereas the lacustrine zone of a reservoir is located closest to the dam and has characteristics more typical of a natural lake, the riverine zone is located furthest from the dam along the inflow stream or river and acts more consistent with a natural river system. The transition zone, as its name suggests, is located between the riverine and lacustrine zones and exhibits characteristics of both systems.

Lake Manassas is considered to have all three distinct zones, and for this reason, the water quality analysis presented within this report evaluates the riverine and lacustrine zones individually. Figure 3-1 below, depicts the general zonation boundaries considered for the Lake.

Figure 3-1 Zonation in Lake Manassas Based on Parameter Zonation



Source: (Saji 2008)

As previously discussed, there are several inflow streams into Lake Manassas, and if evaluated individually, each stream can be considered as a riverine zone; however, as the Broad Run stream represents the majority contributor to Lake Manassas, the riverine zone is mainly depicted within this area. Chapter 5 of this report provides details of the riverine zone or stream

analysis of this portion of Lake Manassas, and Chapter 6 details water quality results for the lacustrine or lake portion of Lake Manassas.

When conducting water quality analysis on the distinct systems that occur within a reservoir, it is necessary to consider typical characteristics of each zone as any expectations or goals of a water quality management plan should be realistic and represent the water quality and morphological parameters within each zone contribute to the overall health and quality of the reservoir ecosystem.

Table 3-1 (below) presents typical characteristics of each reservoir zone that may be used for comparative purposes when conducting a water quality analysis. As would be expected, the shallower and faster-flowing riverine zone is capable of carrying larger and heavier sediment loads and therefore greater concentrations of nutrients such as nitrogen and phosphorus. As the inflow water velocity decreases and carrying capacity diminishes, these sediment loads are deposited on the reservoir bottom. During periods of high flow, or significant storm events, these sediments may be picked up and transported farther into the reservoir system, increasing nutrient loads into the lacustrine zone.

Table 3-1 Typical Morphological Characteristics of Lake/Reservoir Zones

Morphological Parameter	Riverine Zone	Transition Zone	Lacustrine Zone
Shape	Long and Narrow	-	Broad and Ovoid to Triangular
Depth	Shallow	Intermediate	Deep
Water Velocity / Turbidity	High	Medium	Low
Suspended Solids	High	Medium	Low
Nutrient Load	High	Medium	Low
Dissolved Oxygen	High	Medium	Low
Light Penetration	Low	Medium	High
Thermal Stratification	Unlikely	Possible	Likely

Source: (Wetzel 2001)

Thermal Stratification

The thermal stratification of a lake is evaluated based on temperature gradients with respect to depth. Solar radiation represents the greatest source of heat to a lake¹ and much of this heat is absorbed directly by the water (Wetzel 2001). Light penetration depends directly on a water body's quality and loading; however, the penetration and resulting heat or radiation always decreases with depth, with the majority of available heat absorbed within the first few meters of water.

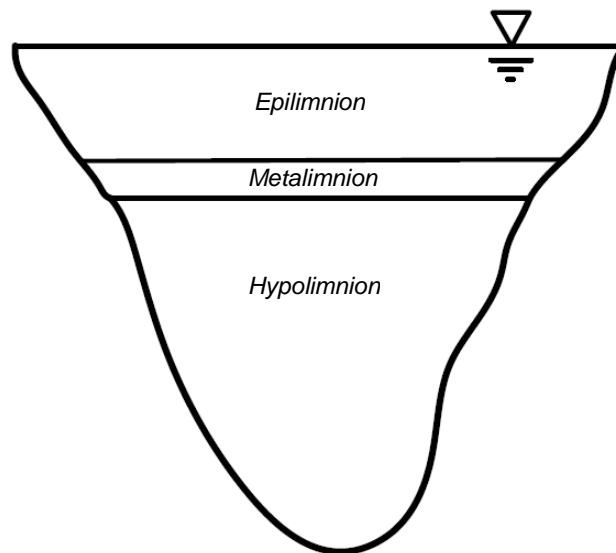
As previously indicated in Table 3-1, the riverine portion of a reservoir system is shallower, and often only a few meters deep. This shallow depth, in conjunction with a higher velocity typically

¹ Geographic location, specifically latitudinal coordination also may determine the amount of solar radiation that reaches surface waters: Wetzel, Robert G. (2001). *Limnology: Lake and River Ecosystems*. Academic Press: An Imprint of Elsevier, San Diego, California. 1006 Pages.

inhibits any significant difference in temperature gradient or thermal stratification. The lacustrine zone of the reservoir however, is the deepest portion of the system and has the lowest water velocities. It is therefore more likely to become thermally stratified.

As one would expect, temperature generally decreases with depth, especially during summer months when solar radiation is at its greatest. As the temperature of water increases, the density decreases and, for this reason², warmer waters will remain at the surface and overlie colder, denser waters. A stratified lake or reservoir is one that, based on these temperature and density gradients, can be defined as having three distinct horizontal zones from the surface down including the epilimnion, metalimnion and the hypolimnion (Wetzel 2001). Figure 3-2 below is a schematic of a thermally stratified lake.

Figure 3-2 Diagram of a Typical Thermally-Stratified Lake/Reservoir



The metalimnion may also be referred to as the *thermocline*, the *sprungschicht* (German) or the

² One important exception to this rule is that water has a maximum density at 4 °C and water below this temperature decreases in density. This exception explains how as water freezes, and ice begins to form, it increases in volume and floats on top of the warmer water below.

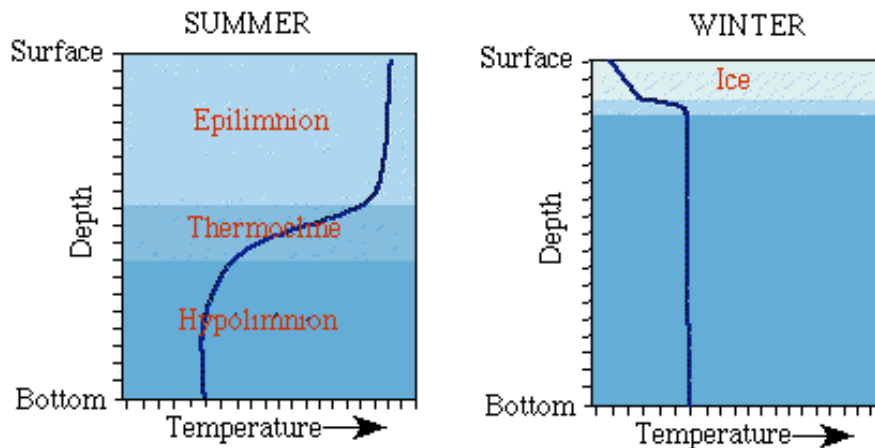
discontinuity layer (Great Britain) (Wetzel 2001). This zone of stratification is defined as the zone exhibiting the greatest or steepest temperature gradient within a water body. This temperature gradient (typically considered as changing a minimum of 1 °C per meter) results in the warmer waters of the epilimnion to essentially “float” above this boundary and may recirculate within the zone, but also prohibits water from transmitting from the epilimnion to the hypolimnion (Wetzel 2001).

Summer stratification may become “overtuned” as the amount of solar radiation decreases due to seasonal climate changes. As surface waters become cooler and denser, the lake’s stability, or work required to mix the entire lake volume, decreases, and with the aid of wind and current convections, results in a complete loss of stratification or a “fall turnover” (Wetzel 2001).

A subsequent winter or “inverse stratification” may occur as temperatures reach 4 °C, the point of maximum density for water. Similar to the fall turnover, a spring turnover may occur as temperatures increase and ice melts. A lake or reservoir that undergoes both spring and fall turnovers is said to be “dimictic” (Wetzel 2001). Lake Manassas, however, experiences only a single period of mixing in the fall and is therefore considered to be “monomictic.” On rare occasions, Lake Manassas has been known to experience a second period of stratification during winter months (OWML 2012). As discussed further in Chapter 6, only single periods of stratification were documented during the updated baseline period (2006 to 2010).

For comparative purposes, Figure 3-3 below, depicts typical thermal stratification depth profiles for lake systems during periods of winter and thermal stratification.

Figure 3-3 Typical Thermal Stratification Profiles



Source: (Maslin 1996)

Eutrophication

Eutrophication is defined as the enrichment of a lake or reservoir body with nutrients including nitrogen and phosphorous. Subsequently, a eutrophic lake may also be referred to as being “enriched.” It is important to note that eutrophication is a natural process that impacts all lake systems. Ultimately, sediment will accumulate and fill in a lake over time and it will eventually become a terrestrial system (Ryding 1989). Although this process is natural, it is necessary for the purposes of properly managing a reservoir to understand that the eutrophication or life span of a system is finite and may vary from a few years for shallower lakes to millions of years for deeper lakes.

On the other hand, cultural eutrophication refers to nutrient loads being increased as a result of human activities such as land development, storm water diversion, waste water discharge, etc. Cultural eutrophication has been observed to greatly increase the rate of natural eutrophication and, as such, minimizing human impacts to nutrient loading plays a key role in properly managing a reservoir.

A lake or reservoir that is considered to not be enriched with nutrients may be referred to as oligotrophic and a nutrient level that lies between oligotrophic and eutrophic is termed as mesotrophic. Additionally, a lake may become extremely enriched and be considered hypereutrophic. Several models have been developed to determine the level of eutrophication within a lake or reservoir and the boundaries between oligotrophic and eutrophic vary slightly with each model. Lake Manassas has been historically classified as enriched and Chapter 6 of this report presents the current trophic state analysis for the reservoir.

Nutrients

As mentioned above, nutrients play a key role in eutrophication of a lake or reservoir. When considering a water quality analysis, nitrogen or phosphorus are considered to be the most likely limiting factor, that is, the factor whose concentration drives or inhibits enrichment within the lake. This is also known as Leibig's "Law of the Minimum" (Ryding 1989). Both nitrogen and phosphorus have multiple forms that are found in a lake or reservoir system. The nitrogen cycle involves the transformation of nitrogen gas, ammonia nitrogen, nitrite and nitrate in both directions through oxidation, nitrification and denitrification. Nitrogen gas can also be absorbed into a lake system through nitrogen fixation by some blue-green algae, particularly heterocyst species (Wetzel 2001). The nitrogen cycle also considers the interactions at both the surface-water and lake-sediment interfaces. The phosphorus cycle involves mostly orthophosphate phosphorus (greater than 90%) (Wetzel 2001).

In addition to considering eutrophication of a lake, nutrients are monitored also because the reduction of external nutrient sources is known to have a positive impact on water quality (Ryding 1989). Nitrogen gas is found in abundance in the atmosphere and can be absorbed by a lake system through natural processes; however, both nitrogen and phosphorus can enter a system through runoff of precipitation. External nutrient sources within a watershed can include

both point and non-point sources such as agricultural runoff, sewage treatment discharge, and sedimentation, among others.

With an understanding of the nutrient balance in a lake or reservoir system, control measures can be implemented to inhibit algal growth if necessary. In many systems, including Lake Manassas, phosphorus is considered to be the most common limiting nutrient. Nitrogen to phosphorus ratios are one method for determining which nutrient is the limiting factor. According to Cook and Carlson, if the N:P ratio is less than 10, nitrogen is the limiting nutrient; if the N:P ratio is greater than 17, phosphorus is the limiting nutrient; and an N:P ratio between 10 and 17 indicates that nitrogen and phosphorus could alternate being the limiting factor (Cooke 1993). Nitrogen to phosphorus ratios for the Lake Manassas system are presented in Chapter 6 of this report. Lake Manassas has always been a phosphorus limited system and the most recent nitrogen to phosphorus ratios for the new baseline period continue this trend and even show increasing ratios at both surface and bottom sampling stations which suggests the lake is becoming a strongly phosphorus limited system.

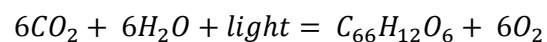
Oxygen

It is difficult to consider dissolved oxygen content independently as algae and animal life control the concentrations within the water column (Harper 1992). For this reason, dissolved oxygen within a lake or reservoir system can be monitored as an indicator potential for organic algal growth within the system. Concentrations of dissolved oxygen vary with depth, season and diurnal cycling (Wetzel 2001).

Light

Light in the form of solar radiation provides a lake or reservoir with the energy necessary for algae to grow and therefore has the potential to be a limiting factor. The amount of radiant energy that reaches a lake or reservoir is dependent on several factors and it is estimated that less than half of the sun's solar radiation reaches the earth's surface, with the majority reflected and absorbed by the upper atmosphere (Wetzel 2001). In addition, other factors including the solar angle and tree or ice cover can reduce the light a system absorbs. The period of time when the sun is visible to a system varies with the seasons. For the Lake Manassas system, the sun is at its lowest angle in winter months and therefore, there is less radiant energy absorbed by the lake during this period. Alternatively, foliage cover and overhang is at its greatest during summer months when the sun is at its greatest angular height which can also impact the amount of absorbed radiant heat.

The light that does reach a lake/reservoir system drives the primary production of algae using the following equation (Harper 1992):



As discussed in greater detail in the following chapters of this report, light has a logarithmic reducing relationship with depth in a lake or reservoir. The optimal depth for algal growth occurs at approximately two to three meters below the lake surface (Harper 1992). Light penetration and water clarity are often considered concurrently and Secchi depth is a measure used by the OWML to monitor water clarity. Secchi depths are presented in Chapter 6 of this report as a factor for evaluating trophic indices.

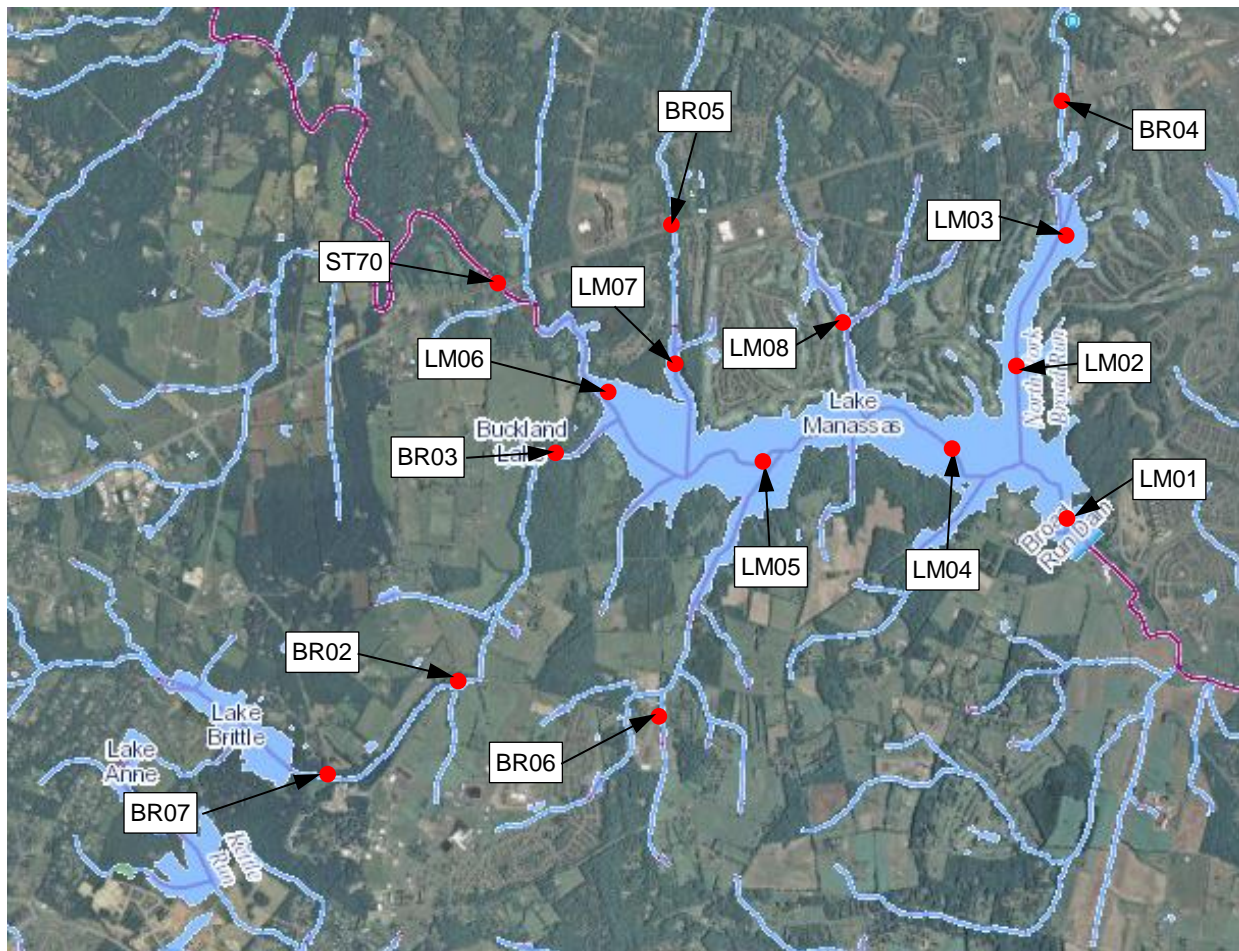
Chapter 4 Methods and Materials

Sampling Stations

Under contract with the City of Manassas, the Occoquan Watershed Monitoring Laboratory (OWML) has overseen the sampling program at Lake Manassas since October 1984, with some data collected as early as 1975 as part of the greater Occoquan Watershed monitoring program. The analysis of Lake Manassas is conducted using a network of 16 monitoring/sampling stations. Eight sampling stations are located on Lake Manassas itself and are designated with the LM abbreviation (Stations LM01, LM02, LM03, LM04, LM05, LM06, LM07 and LM08). An additional eight sampling stations are located on the tributaries to Lake Manassas, including BR02, BR03, BR04, BR05, BR06, BR07, BR08 and ST70. Sampling station ST70 also represents the sole gauging station for the Lake Manassas monitoring network. Stream sampling stations with the BR prefix are sampled using grab sampling techniques (i.e., a snapshot-in-time sample), whereas stream sampling station ST70 includes both flow weighted composite (i.e., storm) samples and grab samples (i.e., base flow).

The location of each lake and stream sampling station is depicted in Figure 4-1 below and Table 4-1 includes location information for each sampling station. Stream sampling station BR08 is not depicted in Figure 4-1 below; however, it is located upstream (north-northwest) of Station ST70.

Figure 4-1 Map of Lake Manassas Sampling Stations



Source:(USGS 2013), Accessed November 2012; (OWML 2012). (1 inch = Approximately 1.1 Miles)

Table 4-1 Sampling Stations

Stream Sampling Stations	
Station Number	Station Name / Location
BR02	South Run at Route 215 (Vint Hill Road)
BR03	South Run at Route 684 (Buckland Mill Road)
BR04	North Fork at Route 29 (Lee Highway)
BR05	Unnamed tributary to Lake Manassas, located at Route 29 (Lee Highway) between Route 15 (James Madison Highway) and Route 703 (Old Carolina Road)
BR06	Unnamed tributary to Lake Manassas, located at Route 215 (Vint Hill Road) west of Greenwich
BR07	South Run at Route 793 (Shepherdstown Road) immediately below Lake Brittle and above Vint Hill Farms Station
BR08	Broad Run north of Route 29-15 (Lee Highway) (Upstream)
ST70	Broad Run at Route 29-15 (Lee Highway) near Buckland (Upstream)
ST30	Broad Run at Route 619 (Linton Hall Road) (Downstream)

Lake Sampling Stations	
Station Number	Station Name / Location
LM01	Lake Manassas: Closest to the dam
LM02	Lake Manassas: Southern portion of North Fork branch
LM03	Lake Manassas: Northern portion of North Fork branch
LM04	Lake Manassas: Eastern portion
LM05	Lake Manassas: Western portion
LM06	Lake Manassas: Near confluence with Broad Run and South Run
LM07	Lake Manassas: Unnamed tributary branch
LM08	Lake Manassas: Unnamed tributary branch

Source: (OWML 2012).

Table 4-2 describes the OWML’s sampling frequency for lake and stream sampling stations.

Table 4-2 Sampling Frequency

	Reservoir (lake)	Broad Run (ST70)	Tributary (stream)
Number of Sampling Stations	8	2	6
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
Ammonia Nitrogen (NH ₃ -N)	All	All	All
Total Kjeldahl Nitrogen (TKN)	All	All	All
Oxidized Nitrogen (Ox-N)	All	All	All
Soluble Reactive Phosphorus	All	All	All
Total Phosphorus	All	All	All
Total Suspended Solids	All	All	All
Total Dissolved Solids	All	All	All
Phytoplankton	Surface	-	-
Hardness	Quarterly	-	-
Trace Metals	Quarterly	Quarterly	Quarterly
Special Analyses – Water Samples			
Pesticides / Herbicides	4 / year	4 / year	4 / year
Other Semi-Volatile Organic Compounds (SVOCs)	4 / year	4 / year	4 / year
Special Analyses – Lake Sediments			
Pesticides / Herbicides	2 / year	2 / year	2 / year
Nutrients	2 / year	2 / year	2 / year

Source: (Gorrie 2007).

Analytical Parameters

The lake sampling stations are measured in the field at depth intervals of: 1 foot, 2.5 feet, 5 feet, and at 5-foot intervals until the lake bottom is encountered. In addition, Secchi disk measurements are collected at each sampling station during a sampling event. Secchi disk readings, dissolved oxygen (DO), temperature and pH are measured in the field. Additional

sampling parameters are evaluated in the OWML, including nutrients, select metals and other organics.

A summary of the analytical parameters evaluated during sampling events is presented below in Table 4-3. The data collected and analytical results are subject to quality assurance / quality control (QA/QC) protocols established by the OWML, consistent with industry best practices. QA/QC practices include the evaluation of blank, duplicate, spike and standard samples. OWML is now a certified lab under NELAP (National Environmental Laboratory Accreditation Program) (OWML 2012, NELAC 2013).

Table 4-3 Sampling Parameters

Abbreviation	Parameter
FLO	Flow
DO	Dissolved Oxygen
TEMP	Temperature
COND	Conductivity
pH	pH
TALK	Total Alkalinity
PALK	Phenolphthalein Alkalinity
THARD	Total Hardness
SD	Secchi Depth
NH3-N	Ammonia Nitrogen
TN	Total Nitrogen
OX-N	Oxidized Nitrogen
OP	Orthophosphate Phosphorus
TP	Total Phosphorus
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
CHLA	Chlorophyll <i>a</i>
SOCs	Selected Synthetic Organic Compounds
	Selected Trace Metals

Data Reduction Methodology

The OWML collects water quality and flow data from the Lake Manassas reservoir systems. Because of the voluminous amount of data recorded from the sampling stations, the OWML maintains a specific quality control procedure for downloading, extracting and applying the data for analytical purposes. All lab data are stored in a LIMS (Laboratory Information Management System), and are tracked under the accreditation rules. From the LIMS database, data are periodically transferred to an xBase-format file with numerical data stored as characters as a method for enhancing precision in values. All analysis begins with a conversion from characters to numerical values via OWML-created macro controls. Data can then be exported to a Microsoft Excel file for additional analysis. In addition to the basic procedure outlined above, specific data corrections and sorting are performed in accordance with the OWML data quality procedures, and include the following:

- Negative values represent detection limits when the concentration measured was below the detection limit. These “negative” values are then, in turn, converted to a ½ the original detection limit value, so as not to artificially reduce the overall trend in concentrations. For example, a stored value of –1.0 for a given parameter indicates that no concentration above 1.0 had been detected in that sample. The value is then converted to 0.5, or ½ of the original detection limit.
- Specific conductivity values are influenced by temperature values, and using a correction formula, are converted to a reference temperature of 25 °C.

$$\text{Conductivity (25 °C)} = \frac{\text{Conductivity (Measured)}}{1 + 0.191(\text{Temperature (Actual)} - 25)}$$

- Sampling depths for lake sampling stations are assigned a value of either “surface” or “bottom” (i.e., top and bottom). As mentioned above, the lake sampling stations are measured in the field at depth intervals of: 1 foot, 2.5 feet, 5 feet, and continuously in 5 foot intervals until the lake bottom is encountered. The sample collected at 1 foot is

designated as the surface sample. The bottom sample is typically collected about 1 foot above the bottom sediment layer at that location.

- Data are also categorized based on seasons for many of the data analyses. The OWML groups data based on the seasonal calendar (northern hemisphere) as described below:
 - Winter: December, January, February
 - Spring: March, April, May
 - Summer: June, July, August
 - Fall: September, October, November

Because the seasonal year does not directly correspond to calendar year, samples collected in December are considered as part of the next calendar year. For example, a December 2, 2006, sample is considered to be part of the 2007 sampling year. This is the reason why data in this report include data to November 2010.

Nutrient Loading Calculation Methods

The OWML estimates loading values for Lake Manassas using the *Daily Flow, Data Integration (DFDI) Model* developed in 1999 (Johnston 1999). The DFDI model incorporates daily flow and station chemical databases, and considers baseflow loading and stormflow loading simultaneously. A brief summary of this method and its application for this analysis of Lake Manassas is presented below:

- The daily flow and station chemical databases are manipulated so that the data can be incorporated into DFDI Model calculation spreadsheet. Manipulations are done using OWML developed macros similar to the ones described in the Data Reduction Methodology section.
- For the analysis of Lake Manassas, loading rates were calculated using data collected from sampling station ST70 as it is located on Broad Run, near the entrance to Lake Manassas. Additionally, Broad Run represents largest flow contributor to the reservoir,

and for estimating purposes can be expected to represent the total system loading.

- In some instances, daily flow values for sampling station ST70 were missing, either due to equipment malfunctions or downtime for maintenance. Specifically, a significant period in 2008 had very little calculated flow data to use for analysis. Daily flow values from sampling station ST60, which is located on Bull Run and has a similar drainage area to ST70, were used in these instances to create a linear correlation between the flow values of the two stations, to “fill” the missing data values for ST70. In a few cases, arithmetic means were calculated from flow data to fill missing values when sampling station ST60 also contained missing values for a given time period.
- Daily base flow and chemical concentration data were assigned based on linear interpolations, considering the date and time in which a sample was collected. Storm flow data were used in conjunction with chemical concentration data to calculate loading values for an entire storm period. Daily base loadings were calculated based on the appropriate time period over which it was sampled (typically 24 hours), unless a storm event occurred during that time period.
- A second loading analysis was conducting using the same methodology as described above; however, the daily flow rates were scaled up ($FLO / 0.7$) as the gauging station where measurements were collected is located on Broad Run, which represents only 70 percent of the water draining into Lake Manassas. These calculations are for comparative purposes only, as consideration was not given to the nutrient loads associated with each tributary where data are collected.

Mann-Kendall Seasonal Analysis

A Mann-Kendall trend test was conducted using the available data to determine any significant or minor trends in the water quality of Lake Manassas. Specifically, the Mann-Kendall trend test is a nonparametric statistical method for determining ranking correlations, or testing

randomness against a trend (Hirsch 1982). Mann-Kendall Seasonal analyses were conducted using the five-year running averages for stream station data parameters in addition to five-year running averages for surface (1 foot) and bottom (depths vary, but typically collected about 1 foot above the bottom sediment layer at that location) lake sampling station parameters. All analyses were conducted using five-year running averages over the same five year period (2006 through 2010) and additional discussion regarding the results of the Mann-Kendall seasonal analysis for stream and lake sampling stations is provided in Chapters 5 and 6, respectively. A 95-percent level of confidence was used during each analysis. It should also be noted that the Mann-Kendall Seasonal Analysis by nature considers only increasing or decreasing trends. In some instances however, there appears to be a divergent trend with respect to seasonality. For example, in Figure 5-1, the five-year running averages for dissolved oxygen and stream station BR02 appear to show a slight increasing trend during winter months and a stronger decreasing trend during summer and fall months. These polarizations are indicated as no trend when conducting a Mann-Kendall Seasonal Analysis, and therefore may not be indicative of actual trends. Again, these observations will be discussed further in Chapters 5 and 6 of this report, where appropriate.

Chapter 5 Stream Results

Stream Water Quality

This section includes a summary of the analyses performed on the water quality of the Lake Manassas tributaries. Data analyzed as part of this report includes sampling conducted from 1984 through 2010. Table 5-1 includes a list of the parameters analyzed for as part of the stream water quality analysis.

Table 5-1 Physical/Chemical Parameters Used in Stream Water Quality Analysis

Abbreviation	Parameter	Units
DO	Dissolved Oxygen	mg/L
PH	pH	pH units
TEMP	Temperature	°C
COND	Conductivity	µmho/cm (µS/cm)
TALK	Total Alkalinity	mg/L as CaCO ₃
NH ₃ -N	Ammonia Nitrogen	mg/L as N
TKN	Total Kjeldahl Nitrogen	mg/L as N
OX-N	Oxidized Nitrogen	mg/L as N
OP	Orthophosphate Phosphorus	mg/L as P
TP	Total Phosphorus	mg/L as P
TSS	Total Suspended Solids	mg/L

Table 5-2, below lists the statistical trends calculated based on the data collected from the Lake Manassas stream stations for the new baseline period beginning in Winter 2006 and continuing through Fall 2010. The Mann-Kendall Seasonal analysis was conducted on a four season (winter, spring, summer, fall) correlation for five-year running averages and any overall increasing or decreasing trends are indicated below (95 percent confidence).

Table 5-2 Mann-Kendall Seasonal Analysis – Stream Stations

Parameter	BR02	BR03	BR04	BR05	BR06	BR07	ST70
Dissolved Oxygen (DO)	-	-	-	-	-	-	-
pH	-	-	-	U	-	-	-
Temperature	-	L	-	-	-	-	-
Specific Conductivity	U	U	U	U	U	U	U
Total Alkalinity (Alk)	U	U	U	U	-	U	-
Orthophosphate Phosphorus (OP)	-	-	-	-	-	U	L
Total Phosphorus (TP)	-	U	L	L	-	-	L
Ammonia Nitrogen (NH ₃ -N)	-	-	-	-	-	-	-
Total Kjeldahl Nitrogen (TKN)	-	-	L	-	-	-	L
Oxidized Nitrogen (Ox-N)	-	-	U	U	-	-	L
Total Nitrogen (TN)	-	-	L	U	-	L	L
Total Suspended Solids (TSS)	-	-	L	-	U	-	L

Notes:

U – Increasing Trend

L – Decreasing Trend

- – No Trend Observed

The following sections include a summary of the findings for the analyte values evaluated for the new baseline period. Each section includes summary statistics that present average and maximum concentrations for both the 1984 to 2010 and 2006 to 2010 periods. If a statistical trend has been identified it is discussed in further detail within these sections of the report.

Dissolved Oxygen

Five-year running averages for dissolved oxygen (DO) concentrations for each stream sampling station are depicted in Figures 5-1 through 5-7.

- DO concentrations for the 1984 to 2010 period range from 0.8 mg/L to 17.3 mg/L, with the highest concentration of 17.3 mg/L detected at sampling station BR02 on 17-FEB-2009. The average DO concentration for all sampling stations during this period was calculated to be 9.3 mg/L.
- DO concentrations for the 2006 to 2010 period range from 1.5 mg/L to 17.3 mg/L, with the highest concentration of 17.3 mg/L detected at sampling station BR02 on 17-FEB-

2009. The average DO concentration for all sampling stations during this period was calculated to be 7.54 mg/L.

- The Mann-Kendall Seasonal Analysis for DO concentrations shows no increasing or decreasing trends for the 2006 to 2010 period. This is in contrast to the 2005 updated baseline report in which increasing trends were observed at sampling stations BR02, BR04 and BR07.
- The seasonal trend for DO concentrations at all sampling stations generally shows Summer-DO < Fall-DO < Spring-DO < Winter-DO.

The Virginia Department of Environmental Quality (VDEQ) has published a minimum dissolved oxygen concentration value of 4.0 mg/L and a daily average value of 5.0 mg/L for nontidal waters (i.e., Coastal and Piedmont zones). The VDEQ “recognizes that the natural quality of these waters may fluctuate” and these water quality standards are established to consider potential human impact to natural systems (VDEQ 2010). There have been a total of 53 occurrences with DO concentrations measured below 4.0 mg/L in Lake Manassas stream sampling stations. These standard violations represent less than 1.3 percent of all stream station sampling events where a dissolved oxygen concentration was measured.

It should also be noted that the majority of these occurrences where DO concentrations below 4.0 mg/L were detected occurred at stream sampling stations BR04, BR06 and BR07 which are known to include runoff from agricultural lands (Eggink 2001). Agricultural lands are known to typically have higher biochemical oxygen demand (BOD) in surface runoff which in turn can increase BOD rates in surficial stream water (Ha 2001). Increased BOD, in turn, reduces dissolved oxygen concentrations.

Although no statistically significant trends were detected as part of the Mann-Kendall seasonal analysis, there are apparent trends in some instances. As depicted in Figure 5-1, there is an apparent decrease in dissolved oxygen concentrations from 2005 to 2010 during the summer and fall seasons at stream sampling station BR02 while spring and winter seasons appear to not be following this trend. These trends are also apparent at stations BR04 and BR06, suggesting a greater consumption of dissolved oxygen during warmer months. However, because these trends are not statistically significant and only representative of the last five years of data averaging, additional monitoring of future concentrations is necessary to determine if the observed trend is statistically significant or not.

Figure 5-1 Five Year Running Average of DO for Station BR02

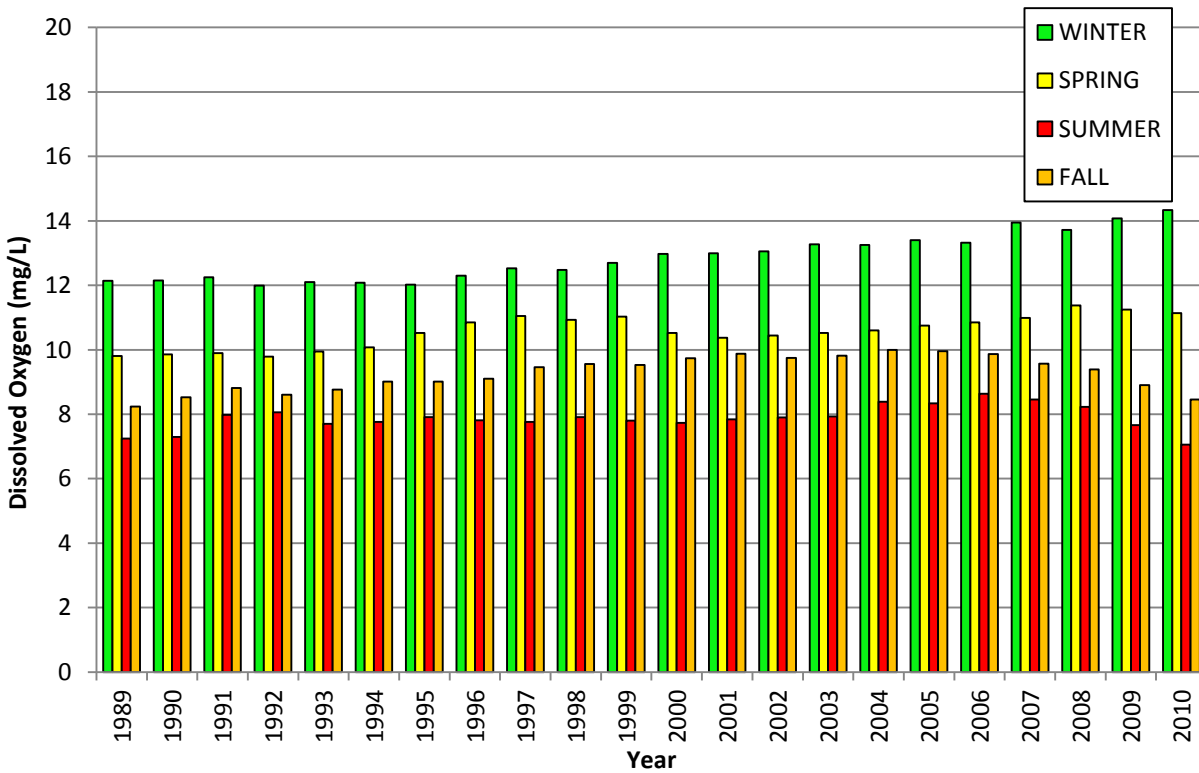


Figure 5-2 Five Year Running Average of DO for Station BR03

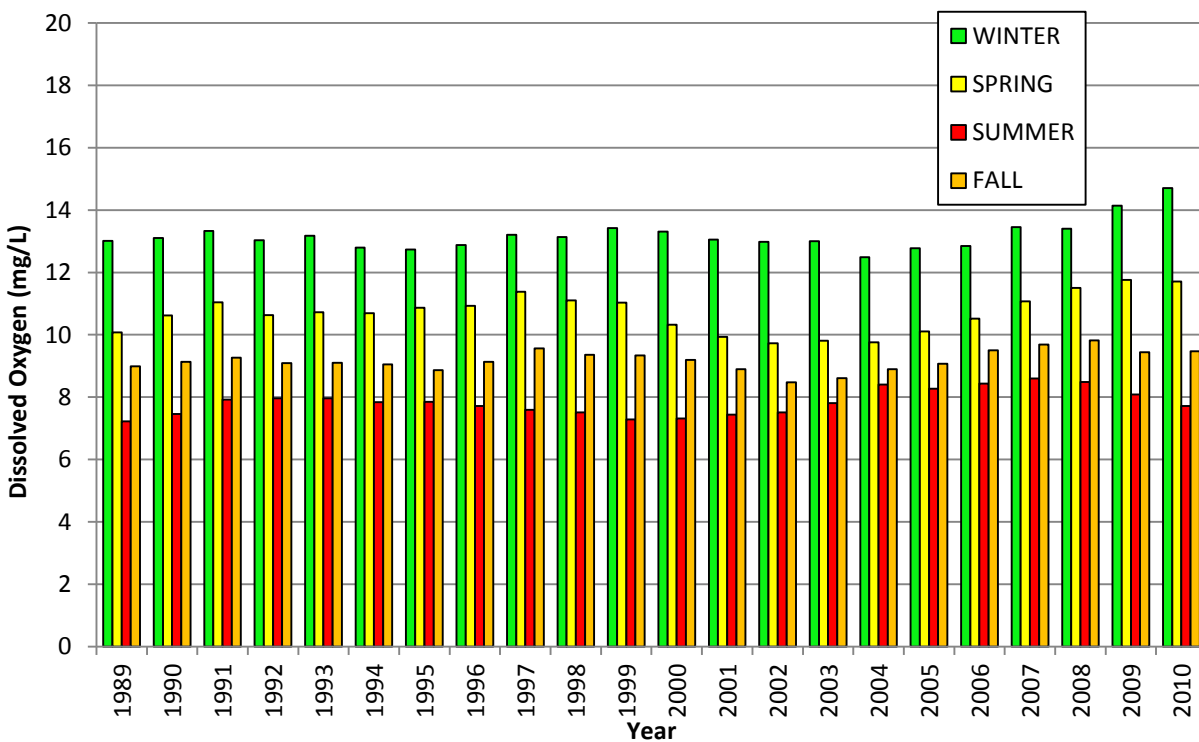


Figure 5-3 Five Year Running Average of DO for Station BR04

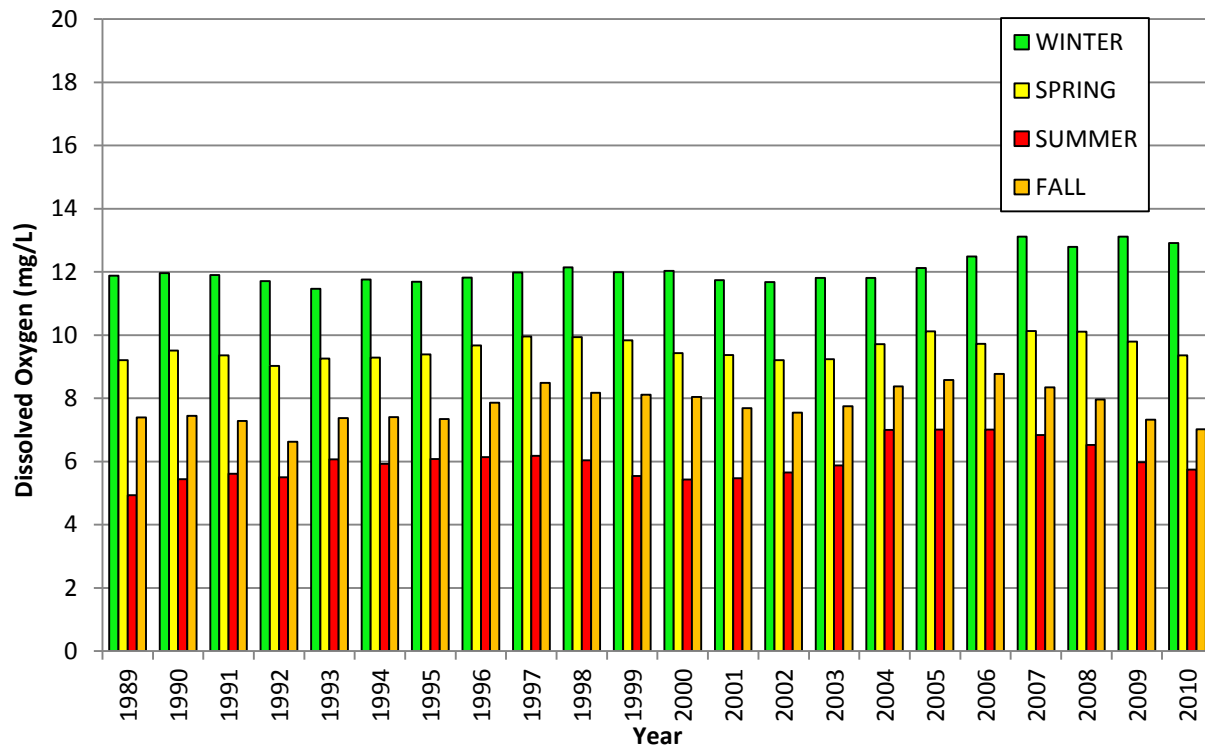


Figure 5-4 Five Year Running Average of DO for Station BR05

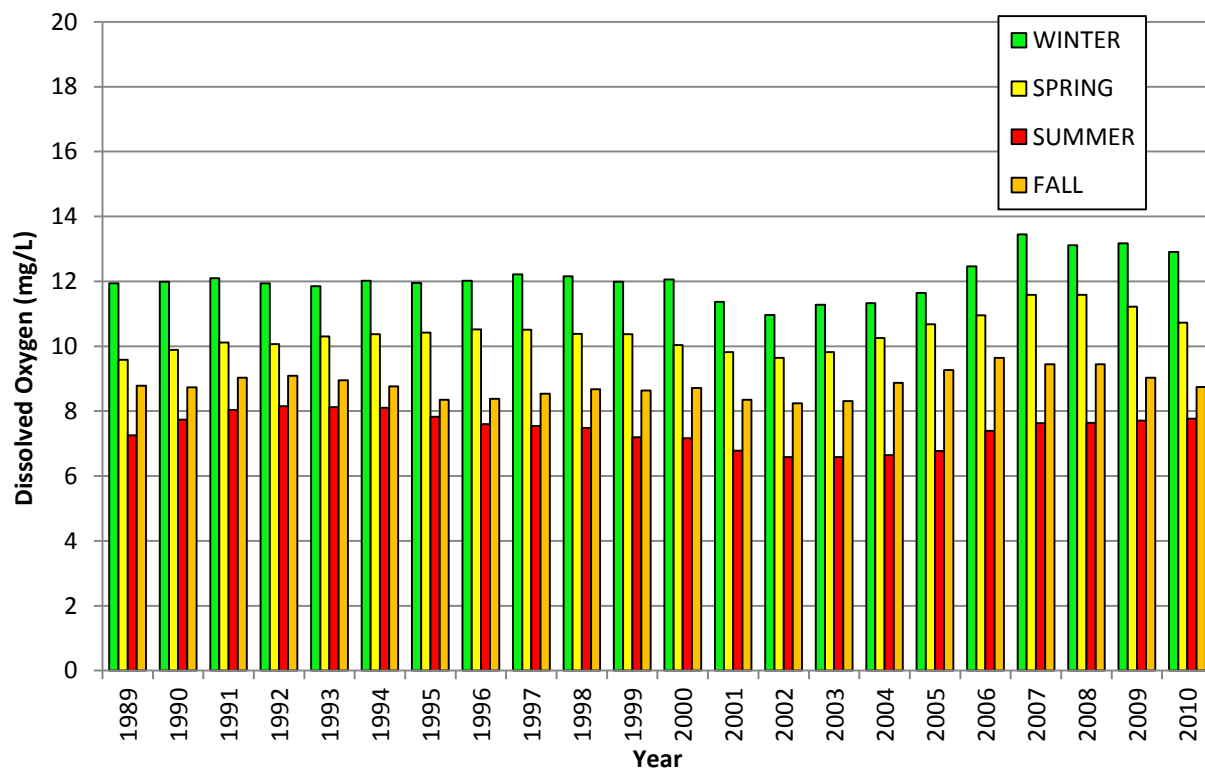


Figure 5-5 Five Year Running Average of DO for Station BR06

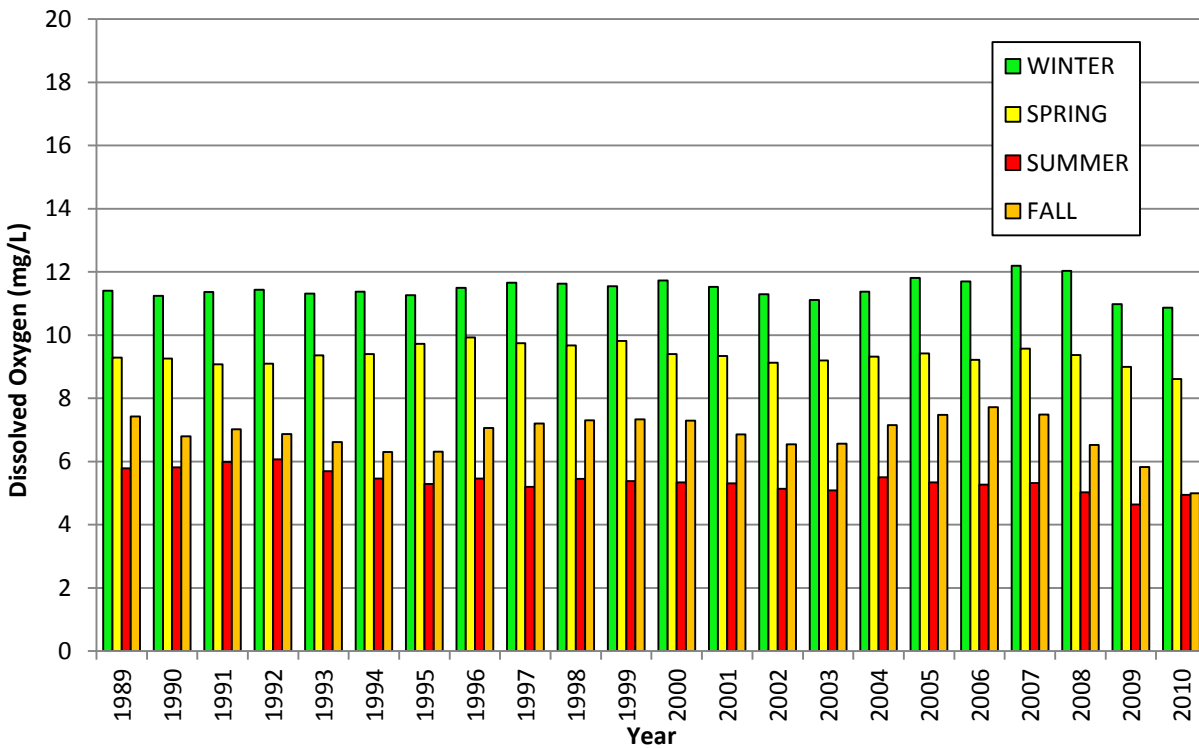


Figure 5-6 Five Year Running Average of DO for Station BR07

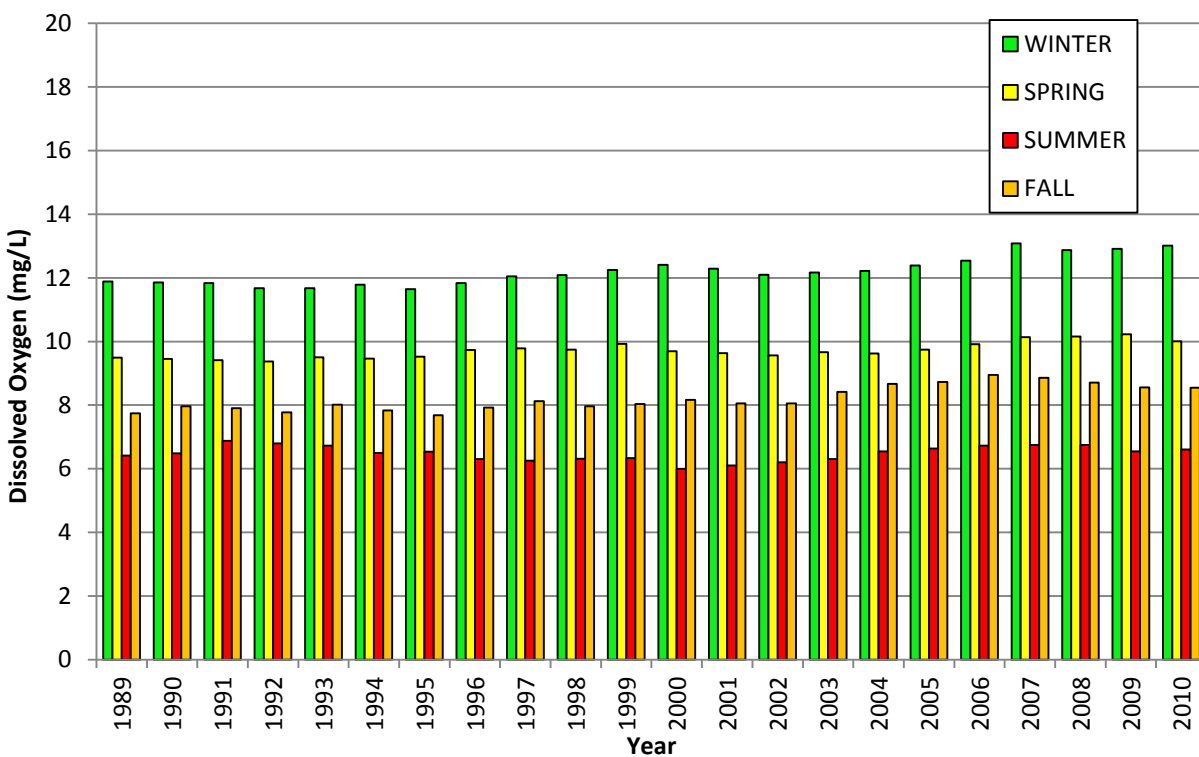
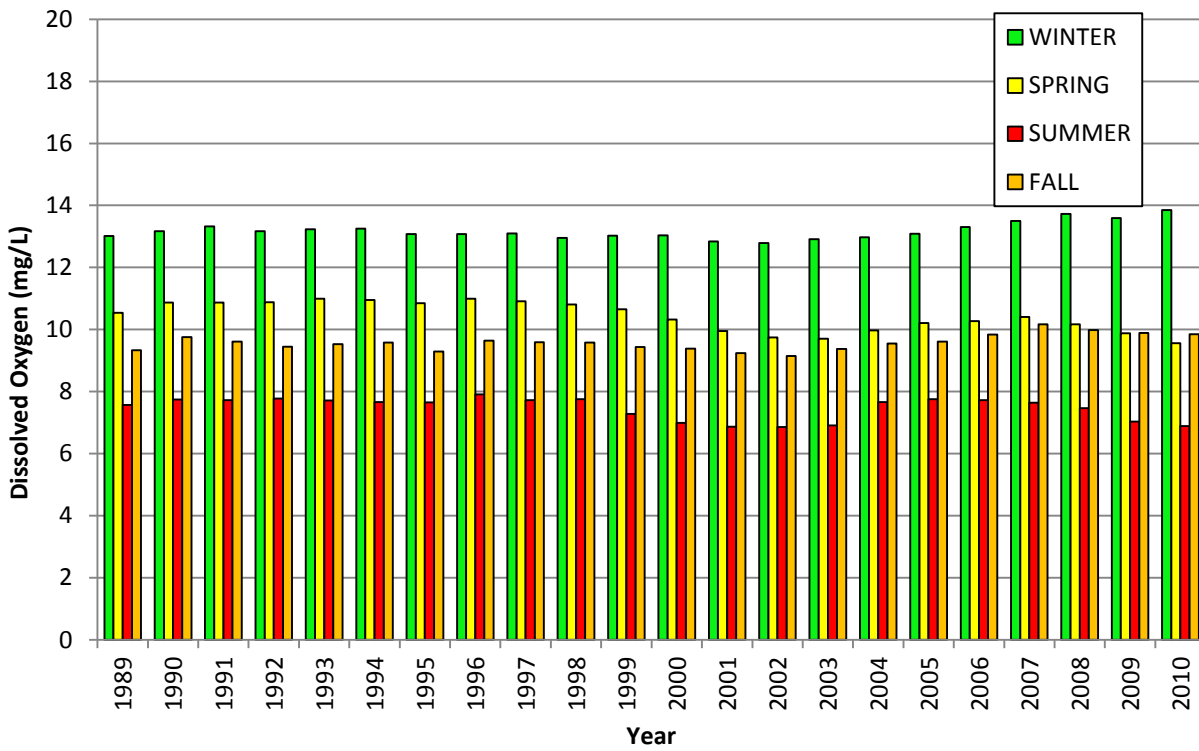


Figure 5-7 Five Year Running Average of DO for Station ST70



pH and Alkalinity

Five-year running averages for pH for each stream sampling station are depicted in Figures 5-8 through 5-14.

- pH measurements for the 1984 to 2010 period range from 4.7 to 9.7, with the highest field measurement of 9.7 detected at sampling station BR03 on 18-APR-1989 and the lowest measurement of 4.7 detected at sampling station ST70 on 27-JAN-1981. The overall average pH measurement for all sampling stations during this period was calculated to be 7.0.
- pH measurements for the 2006 to 2010 period range from 6.0 to 8.8, with the highest measurement of 8.8 detected at sampling station BR03 on 23-APR-2007. The overall average pH measurement for all sampling stations during this period was calculated to be 6.7.
- The Mann-Kendall Seasonal Analysis for pH measurements shows an increasing trend for sampling station BR05 and no other significant trends at other sampling stations for the 2006 to 2010 period.

The distribution of pH in base flow, as measured from sampling station ST70, is depicted in Figure 5-15 for the period 1985 through 2010.

- The seasonal variability in pH at sampling station ST70 indicates a seasonal trend of Summer-pH < Fall-pH < Spring-pH < Winter-pH, for pH values less than 7.0 with summer and fall pH values very close and not always following this trend.
- For pH values greater than 7.0, measurements collected during summer, fall and winter months track very closely and are, in general, all greater than those collected during spring months.

An increase in pH can generally be attributed to an increase in algae production within a reservoir. The production of algal mass consumes carbon dioxide and in turn increases a water's pH. This increase tends to be most evident in streams during low flow periods when algae has an opportunity to grow (Wetzel 2001). Alternatively, a decrease in pH may be attributed to an increase in flow rates. Higher surficial flow as a result of increased precipitation may bring carbon dioxide rich waters to a water body as runoff passes quickly over carbonate soil materials (Wetzel 2001).

The VDEQ has published an acceptable pH range of 6.0 to 9.0 for nontidal waters (Coastal and Piedmont zones). As stated previously, the VDEQ "recognizes that the natural quality of these waters may fluctuate" and these water quality standards are established to consider potential human impact to natural systems (VDEQ 2010). There have been a total of 24 occurrences of pH measurements below 6.0 and 6 occurrences of pH measurements above 9.0 in Lake Manassas stream sampling stations. These standard violations represent less than 0.65 percent of all stream station sampling events where a pH measurement was recorded. No measurements outside of the VDEQ acceptable range were detected during the 2006 to 2010 baseline period.

A statistically significant increasing trend is apparent at sampling station BR05; however, the maximum pH measurement detected was 7.9 on 22-OCT-2007 which is well within the VDEQ acceptable range. Additional monitoring will be required to determine if this increasing trend will continue and whether or not it will impact the water quality within Lake Manassas.

Five-year running averages for total alkalinity (ALK) concentrations for each stream sampling station are depicted in Figures 5-16 through 5-22.

- Total alkalinity concentrations for the 1984 to 2010 period range from 3.8 to 353.8 mg/L

as CaCO₃, with the highest concentration of 353.8 mg/L as CaCO₃ detected at sampling station BR05 on 21-AUG-2006. The average total alkalinity concentration for all sampling stations during this period was calculated to be 46.9 mg/L as CaCO₃.

- Total alkalinity concentrations for the 2006 to 2010 period range up to 353.8 mg/L as CaCO₃, with the highest concentration of 353.8 mg/L as CaCO₃ detected at sampling station BR05 on 21-AUG-2006. The average total alkalinity concentration for all sampling stations during this period was calculated to be 51.6 mg/L as CaCO₃.
- The Mann-Kendall Seasonal Analysis for total alkalinity concentrations shows increasing trends for all sampling stations, with the exception of stations BR06 and ST70 for the 2006 to 2010 period trends for which are decreasing and unchanging, respectively.

Alkalinity, as a measure of calcium carbonate (CaCO₃) has a generally inverse relationship with surficial flow. During periods of low precipitation, a stream that is in contact with groundwater can receive a proportionally larger volume of water through interflow. Unlike runoff, groundwater is generally in contact with carbonate soil materials for a much longer period of time and this contribution to surface water can increase a water body's alkalinity (Winter 1998).

The most significant increase is apparent in stream sampling station BR05 as depicted in Figure 5-19. This increasing trend is consistent with the findings of increasing pH values described above. Both an increase in pH and alkalinity can be attributed to low flow in a stream when groundwater contributes a significantly larger portion of system recharge. An additional discussion regarding the increasing trends in pH and alkalinity at sampling station BR05 and the potential impact changes in land use may be having on the water quality is provided later in this chapter.

Figure 5-8 Five Year Running Average of pH for Station BR02

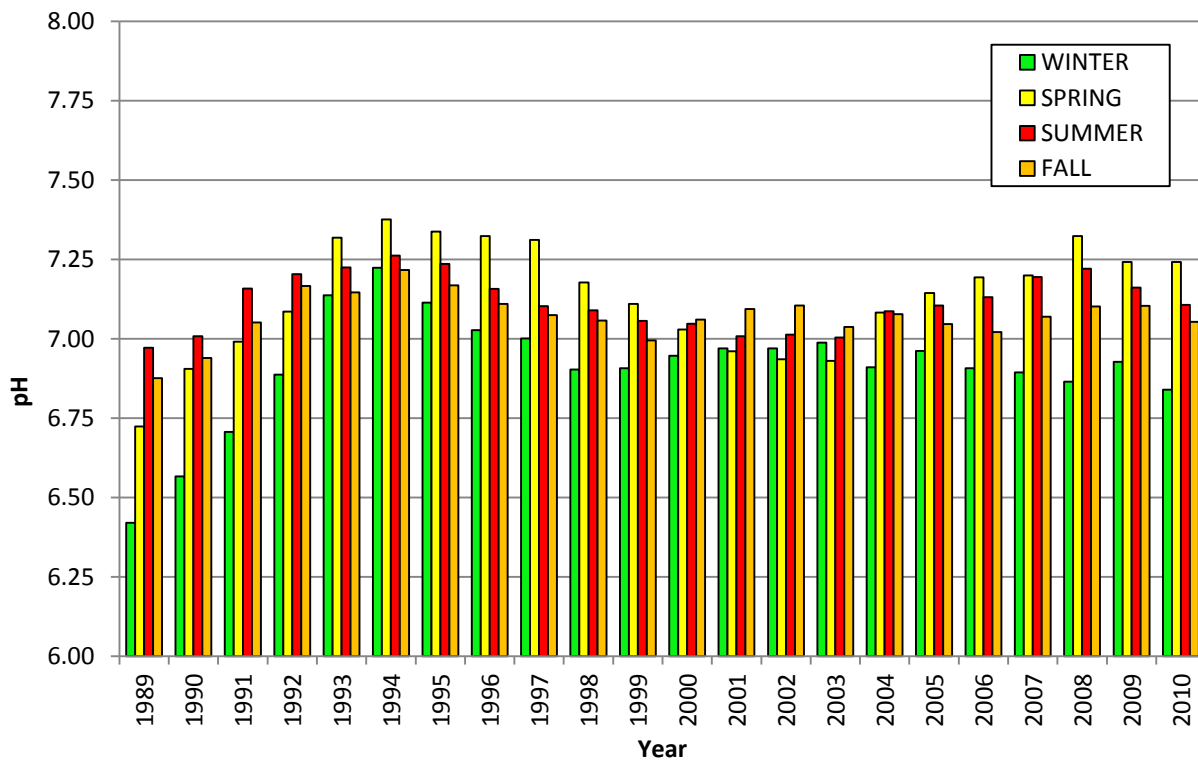


Figure 5-9 Five Year Running Average of pH for Station BR03

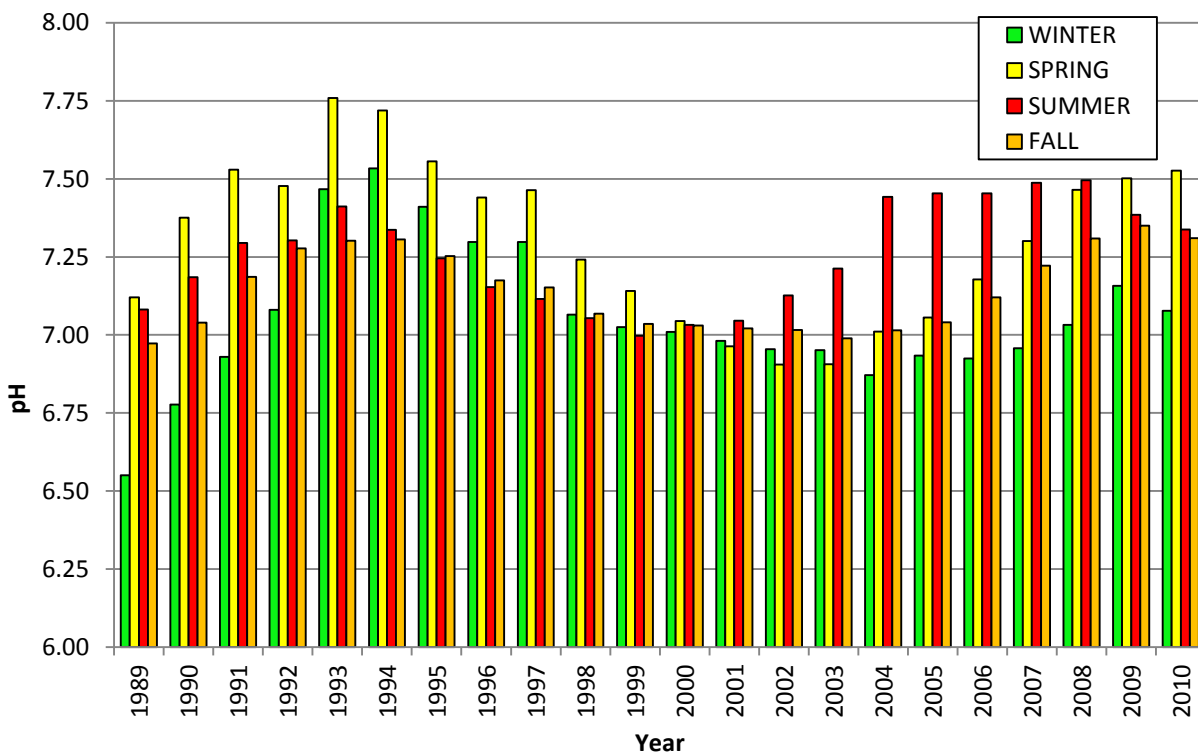


Figure 5-10 Five Year Running Average of pH for Station BR04

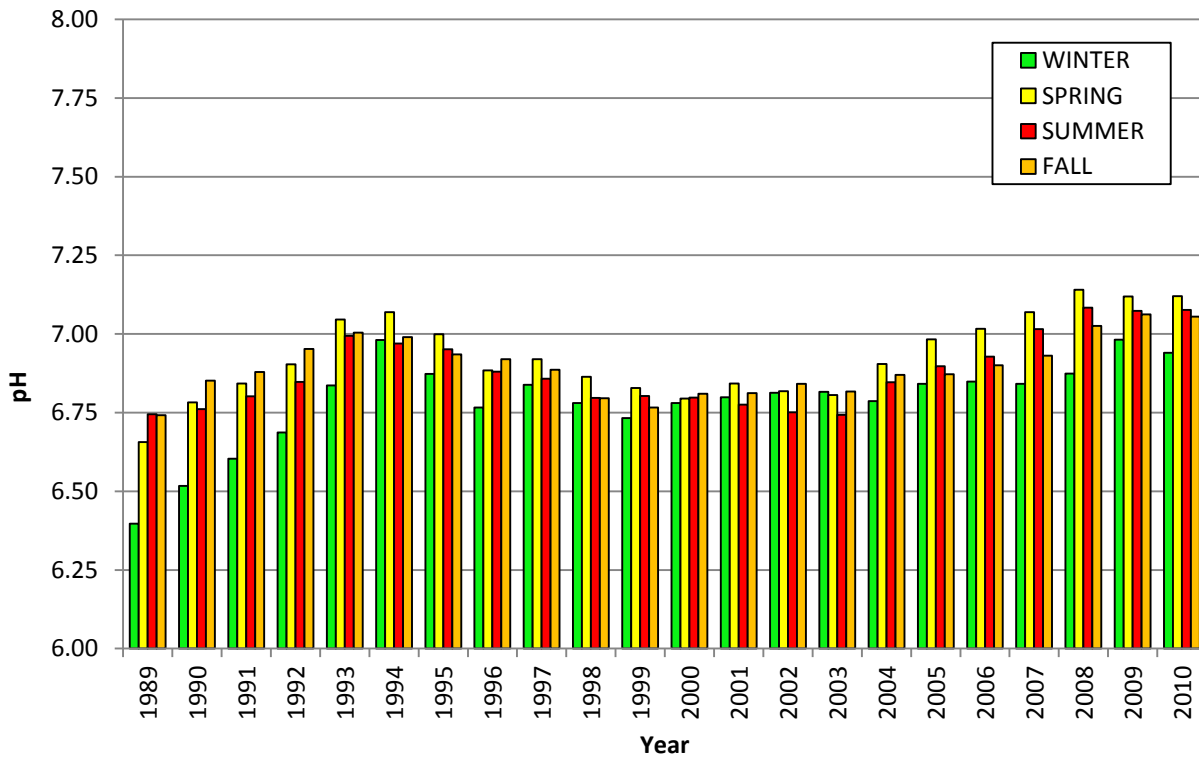


Figure 5-11 Five Year Running Average of pH for Station BR05

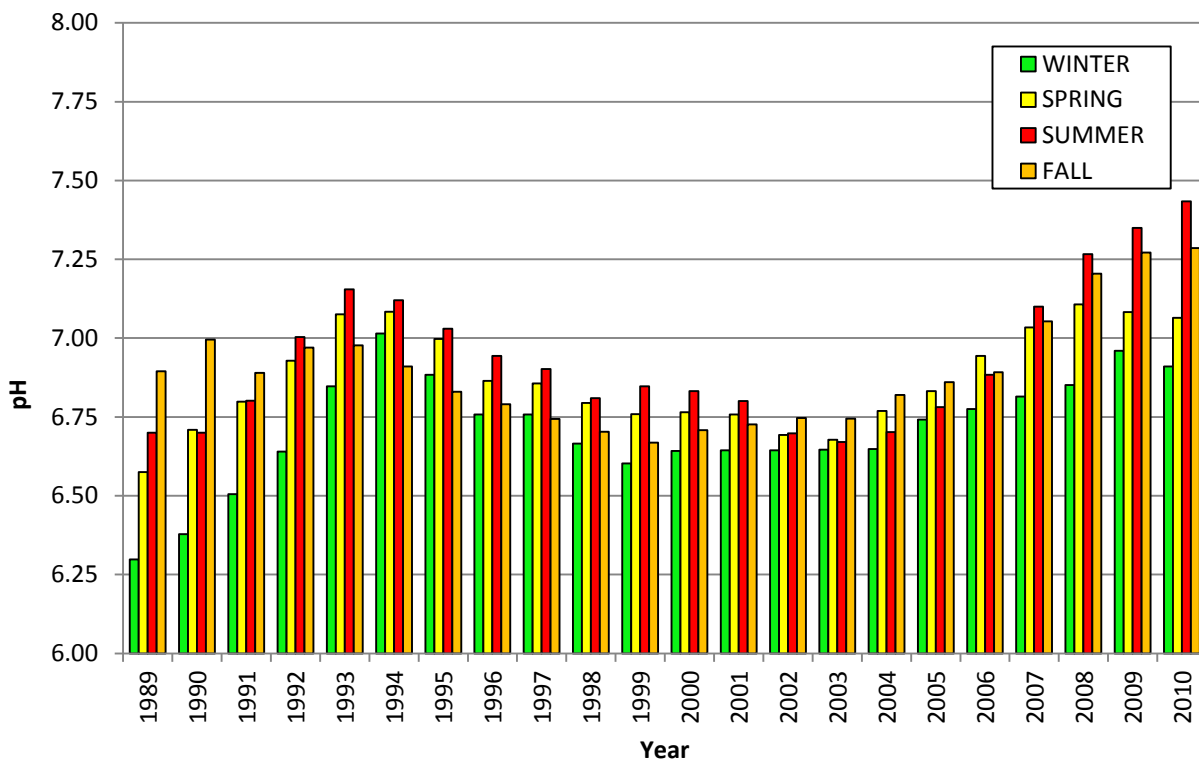


Figure 5-12 Five Year Running Average of pH for Station BR06

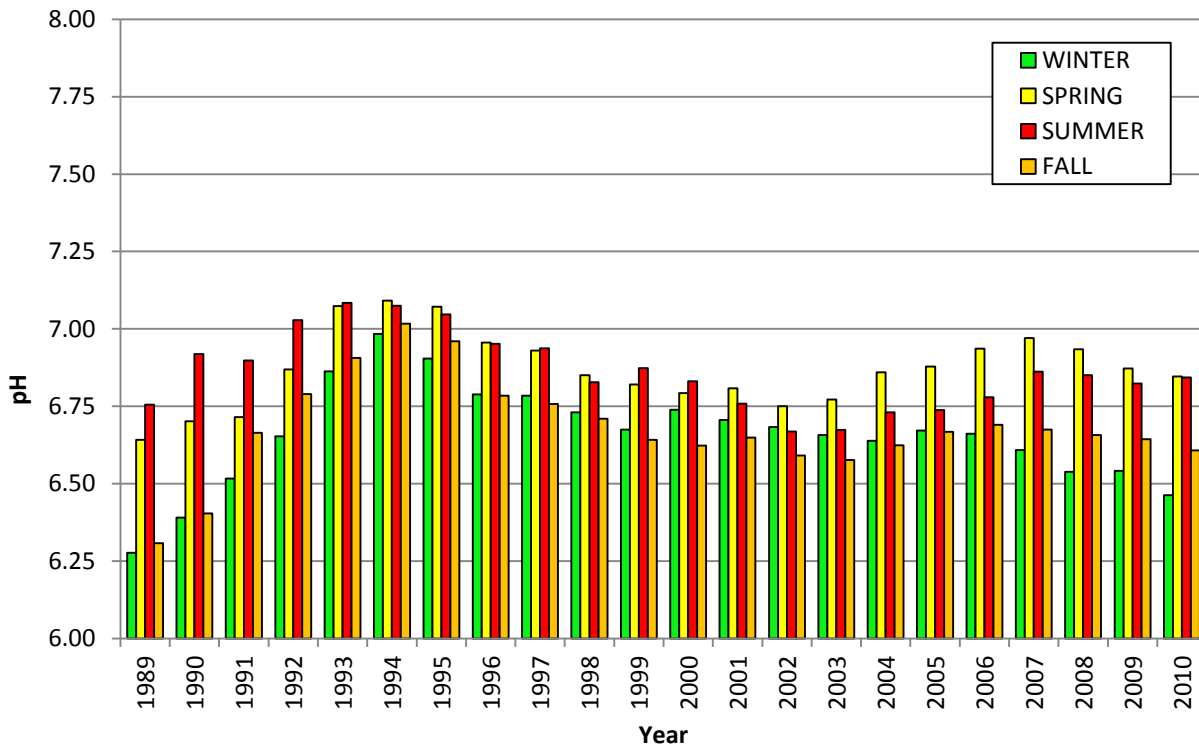


Figure 5-13 Five Year Running Average of pH for Station BR07

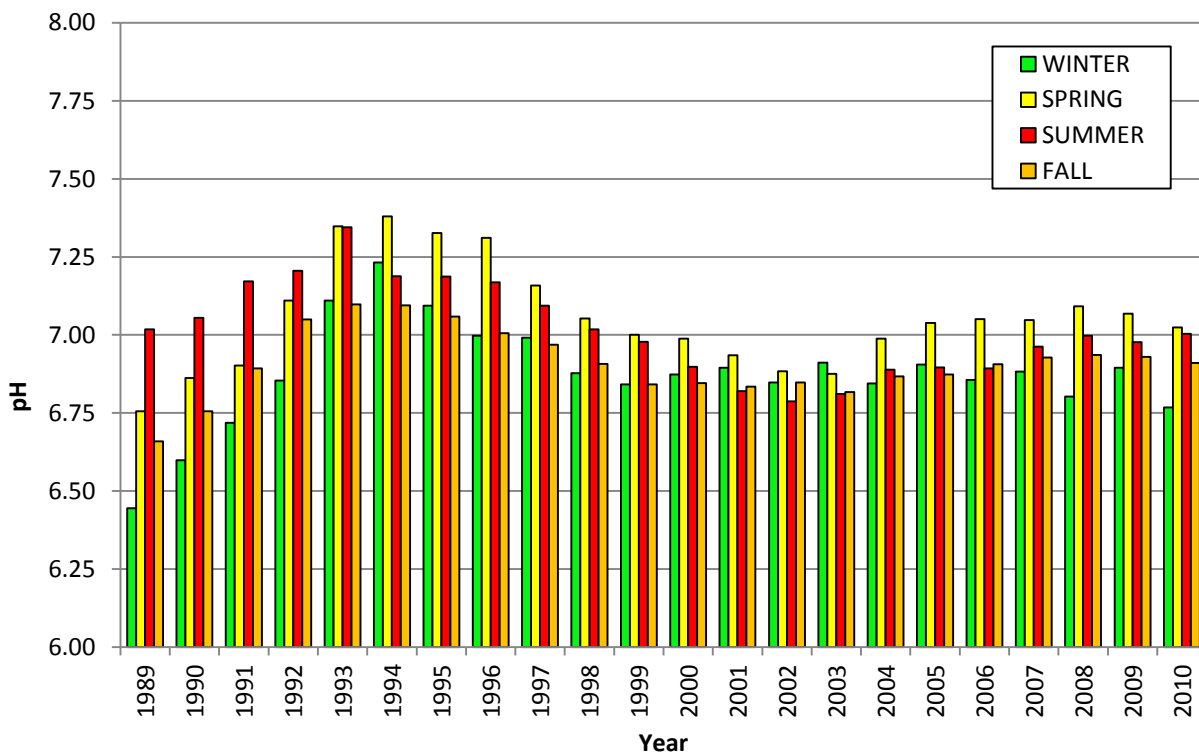


Figure 5-14 Five Year Running Average of pH for Station ST70

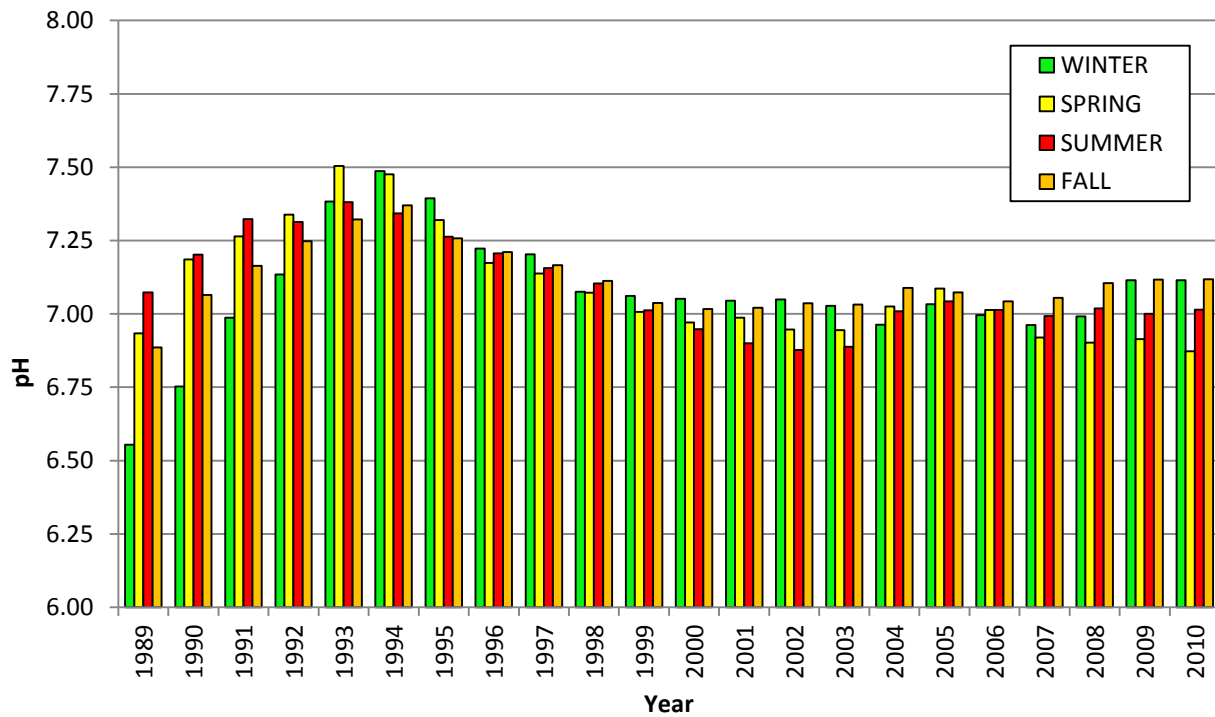


Figure 5-15 pH Distribution in Base Flow at Station ST70 (1985-2010)

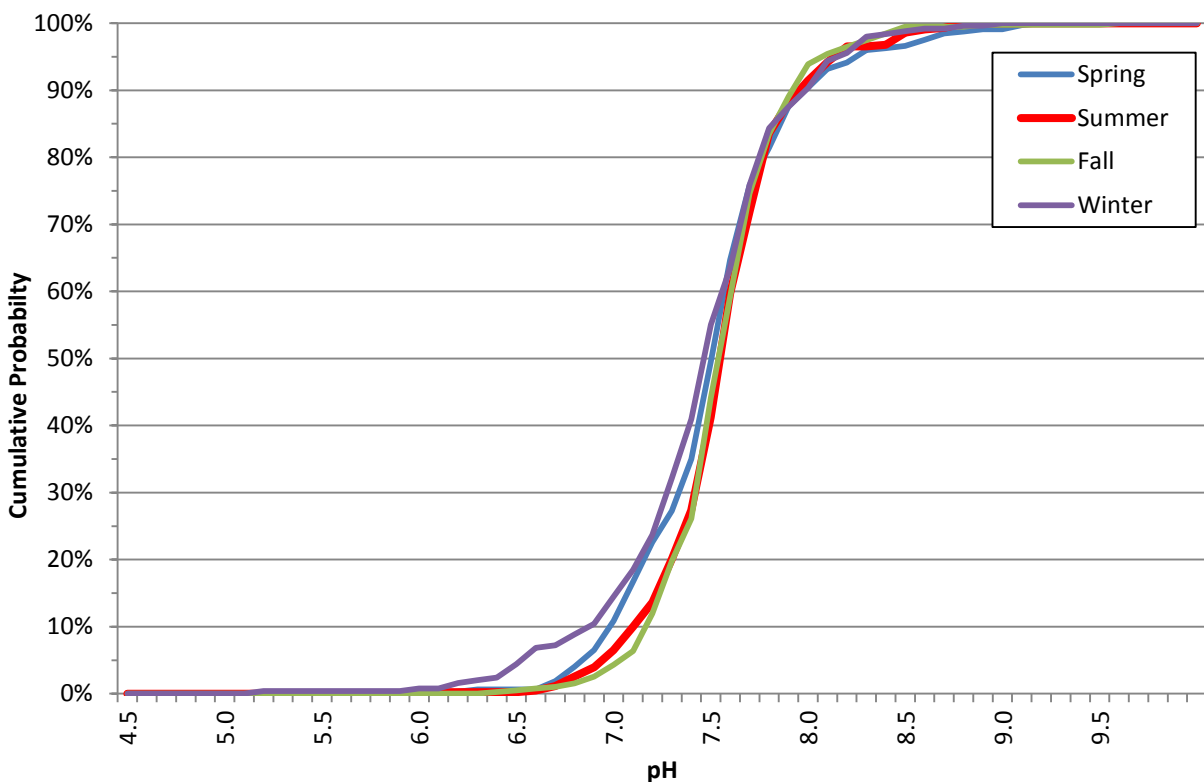


Figure 5-16 Five Year Running Average of Total Alkalinity for Station BR02

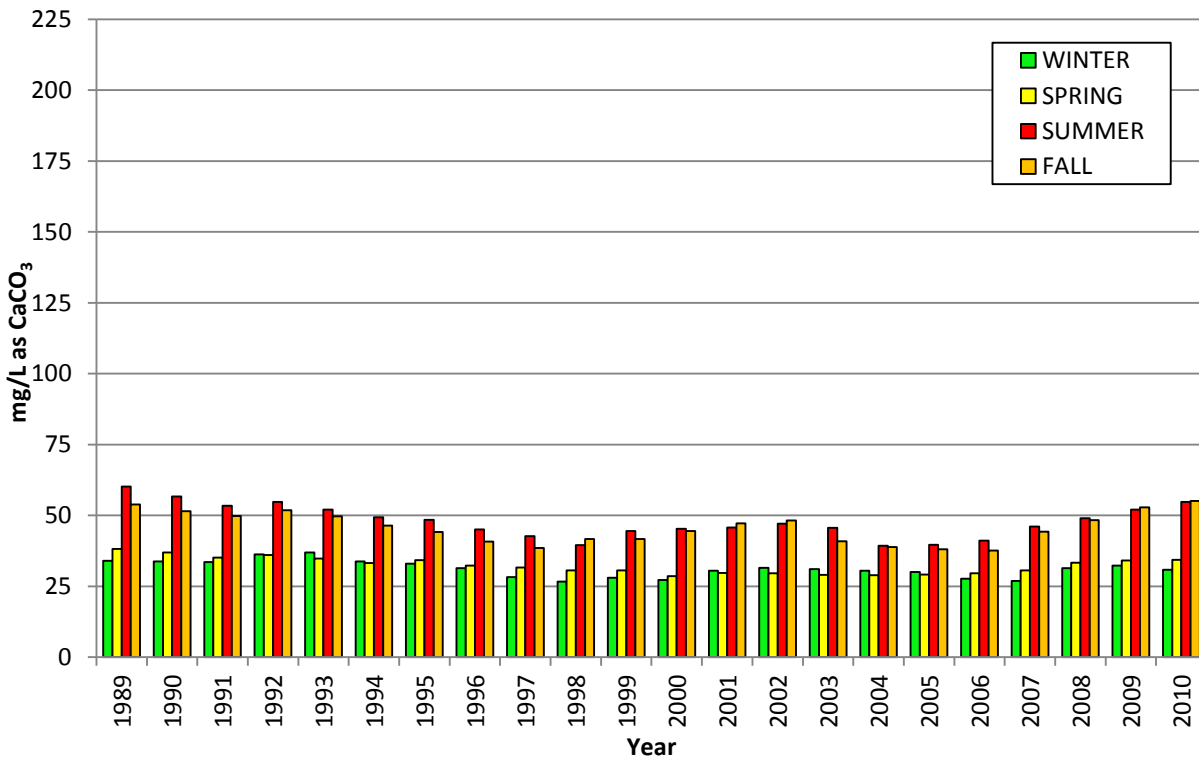


Figure 5-17 Five Year Running Average of Total Alkalinity for Station BR03

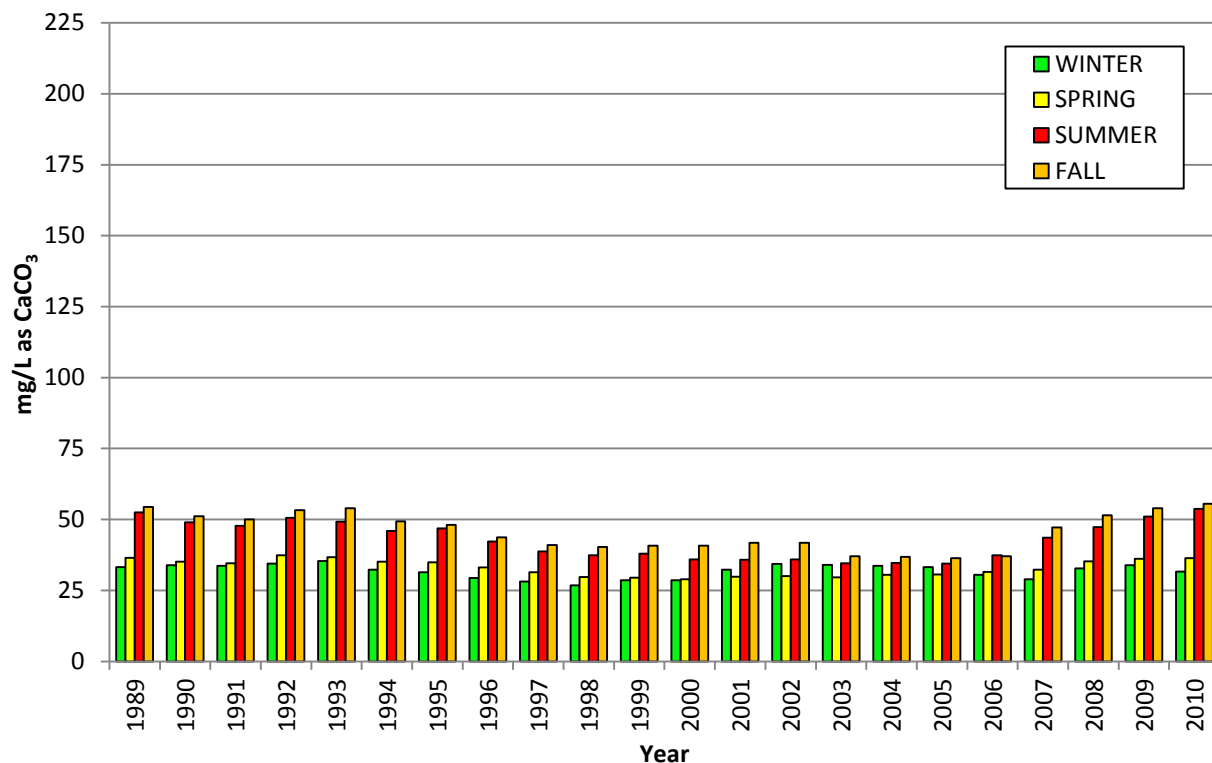


Figure 5-18 Five Year Running Average of Total Alkalinity for Station BR04

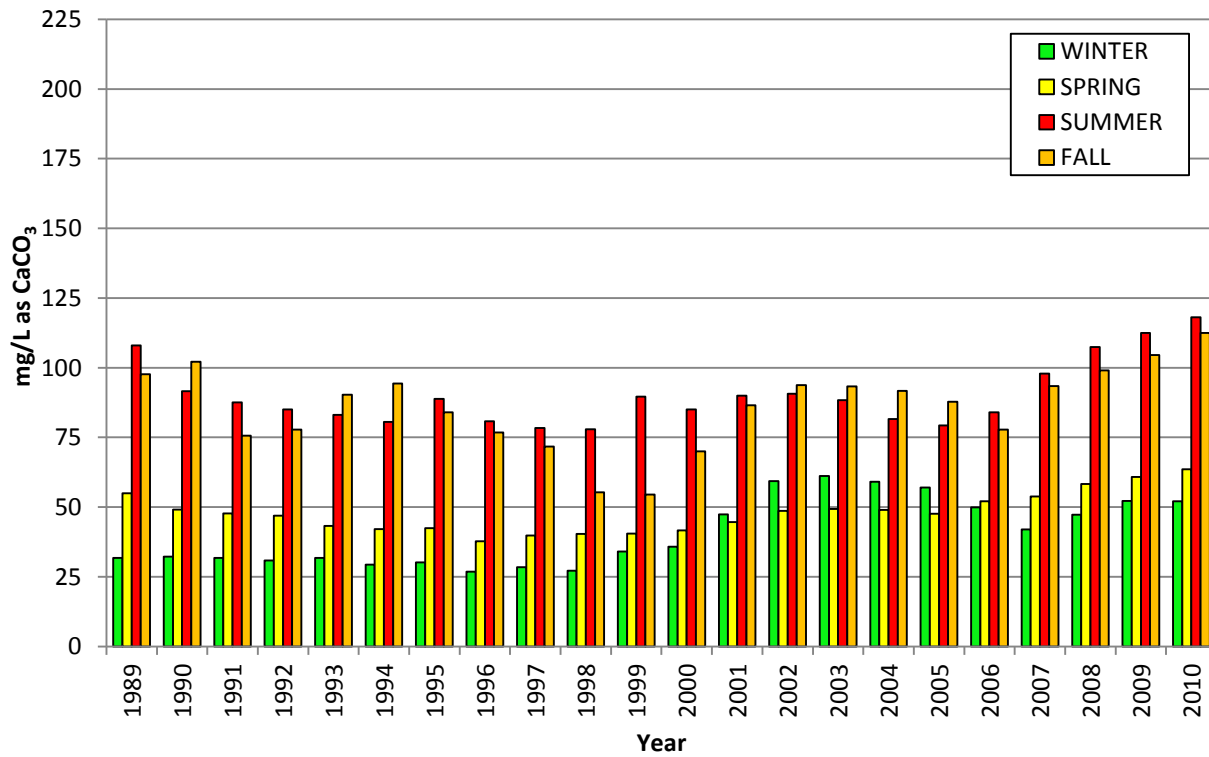


Figure 5-19 Five Year Running Average of Total Alkalinity for Station BR05

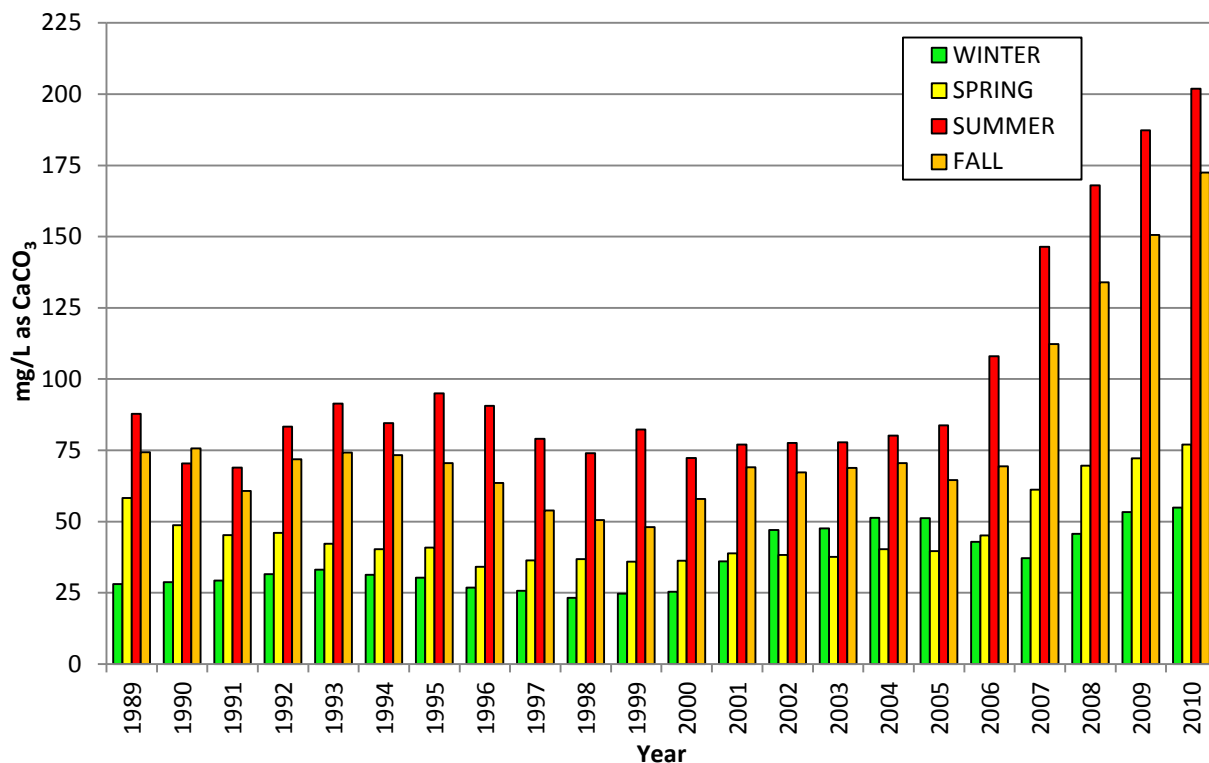


Figure 5-20 Five Year Running Average of Total Alkalinity for Station BR06

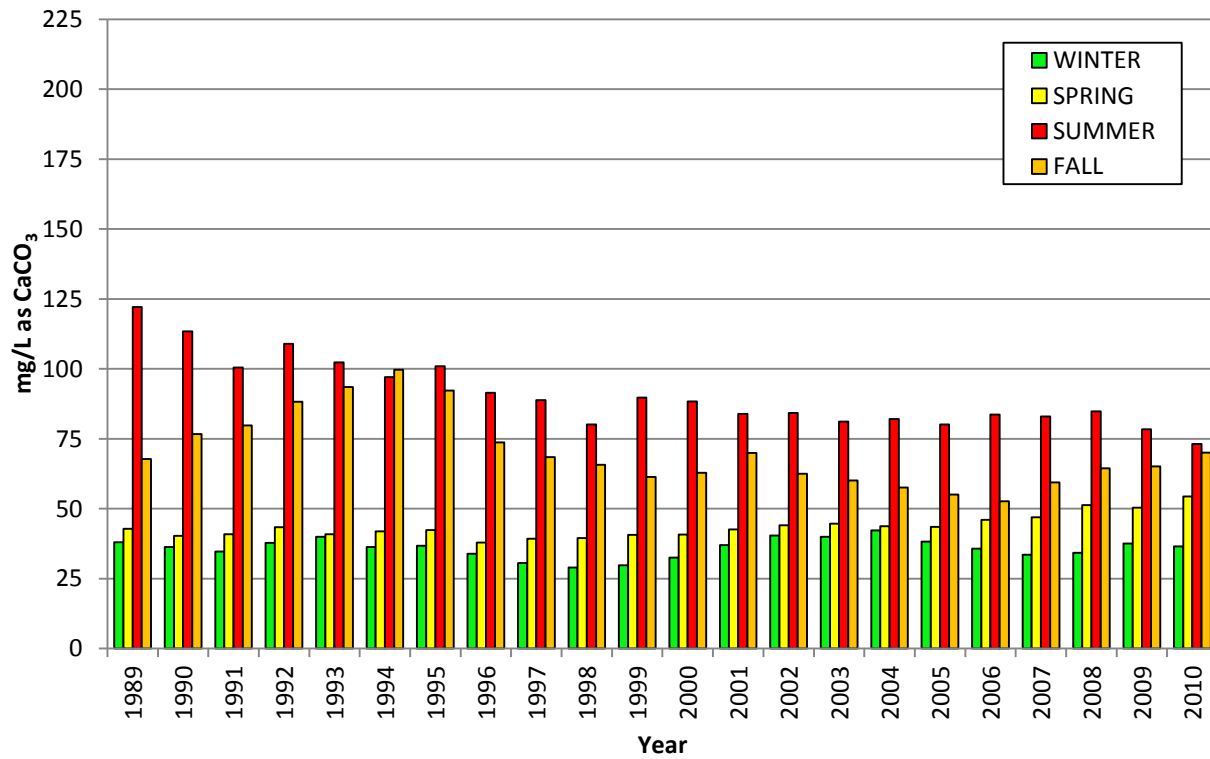


Figure 5-21 Five Year Running Average of Total Alkalinity for Station BR07

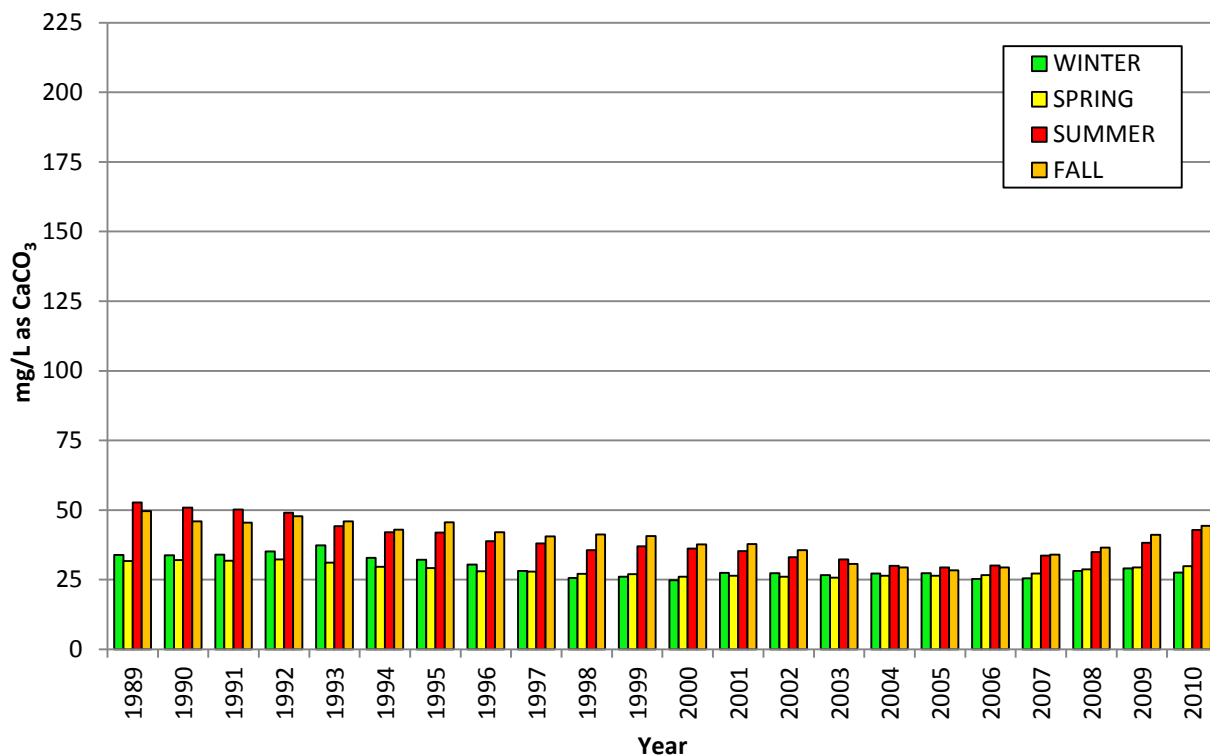
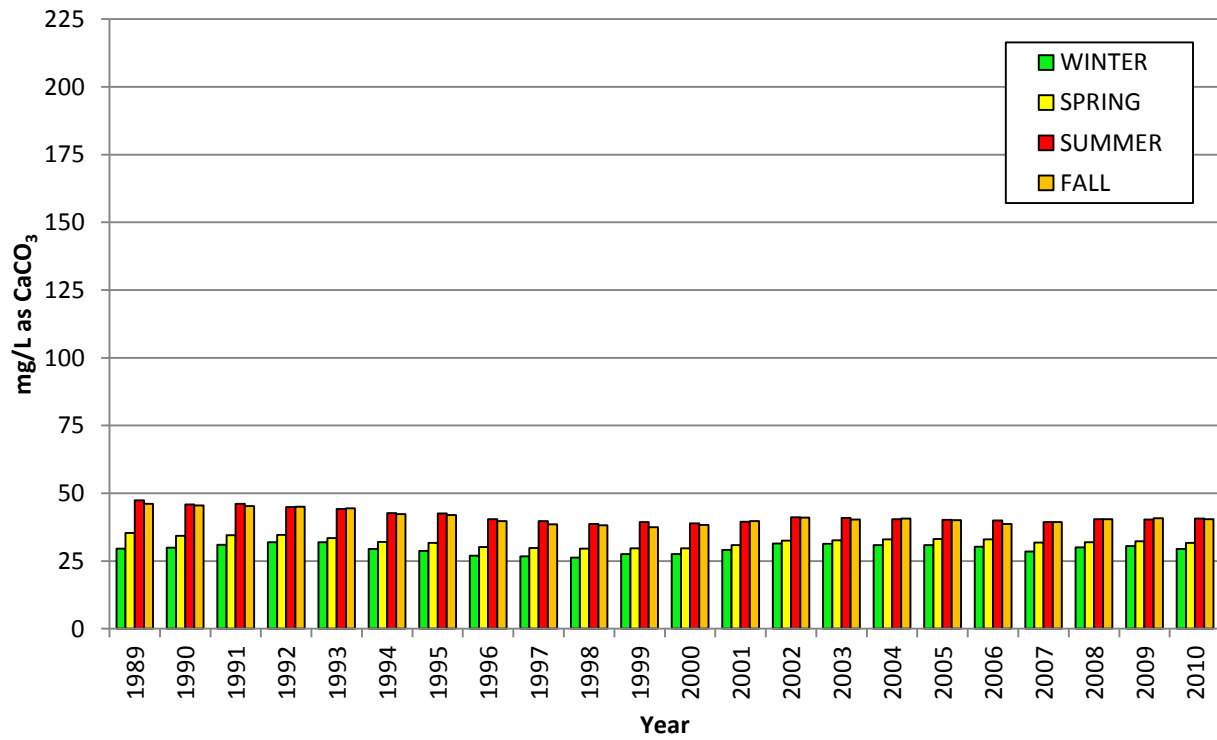


Figure 5-22 Five Year Running Average of Total Alkalinity for Station ST70



Temperature

Five-year running averages for temperature (TEMP) for each stream sampling station are depicted in Figures 5-23 through 5-29.

- Temperature measurements for the 1984 to 2010 period range from -1 °C to 32.5 °C, with the highest field measurement of 32.5 °C detected at gaging station ST70 on 15-AUG-1988. The average temperature measurement for all sampling stations during this period was calculated to be 14.9 °C.
- Temperature measurements for the 2006 to 2010 period range from 0 °C to 28.2 °C, with the highest measurement of 28.2 °C detected at gaging station ST70 on 21-JUL-2008. The average temperature measurement for all sampling stations during this period was calculated to be 13.9 °C.
- The Mann-Kendall Seasonal Analysis for temperature measurements shows a slight decreasing trend at sampling station BR03 and no other significant trends at the remaining stations for the 2006 to 2010 period.
- The seasonal trend for temperature measurements at all sampling stations generally indicates Winter-TEMP < Spring-TEMP < Fall-TEMP < Summer-TEMP.

The VDEQ has published a maximum acceptable temperature of 32 °C for nontidal waters (Coastal and Piedmont zones). As stated previously, the VDEQ “recognizes that the natural quality of these waters may fluctuate” and these water quality standards are established to consider potential human impact to natural systems (VDEQ 2010). There has only been one occurrence of temperature measurements exceeding the VDEQ standard. On 16-AUG-1988, a temperature of 32.5 °C was recorded at sampling station ST70. No measurements above the VDEQ acceptable maximum were detected during the 2006 to 2010 baseline period.

Figure 5-23 Five Year Running Average of Temperature for Station BR02

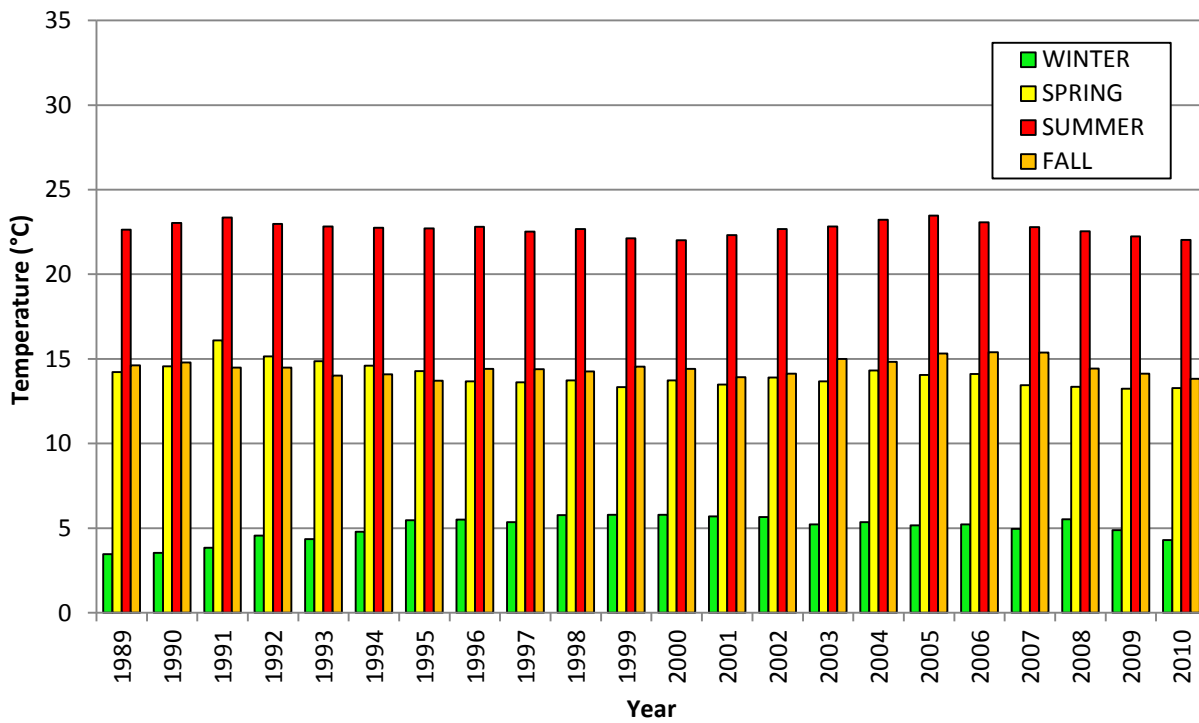


Figure 5-24 Five Year Running Average of Temperature for Station BR03

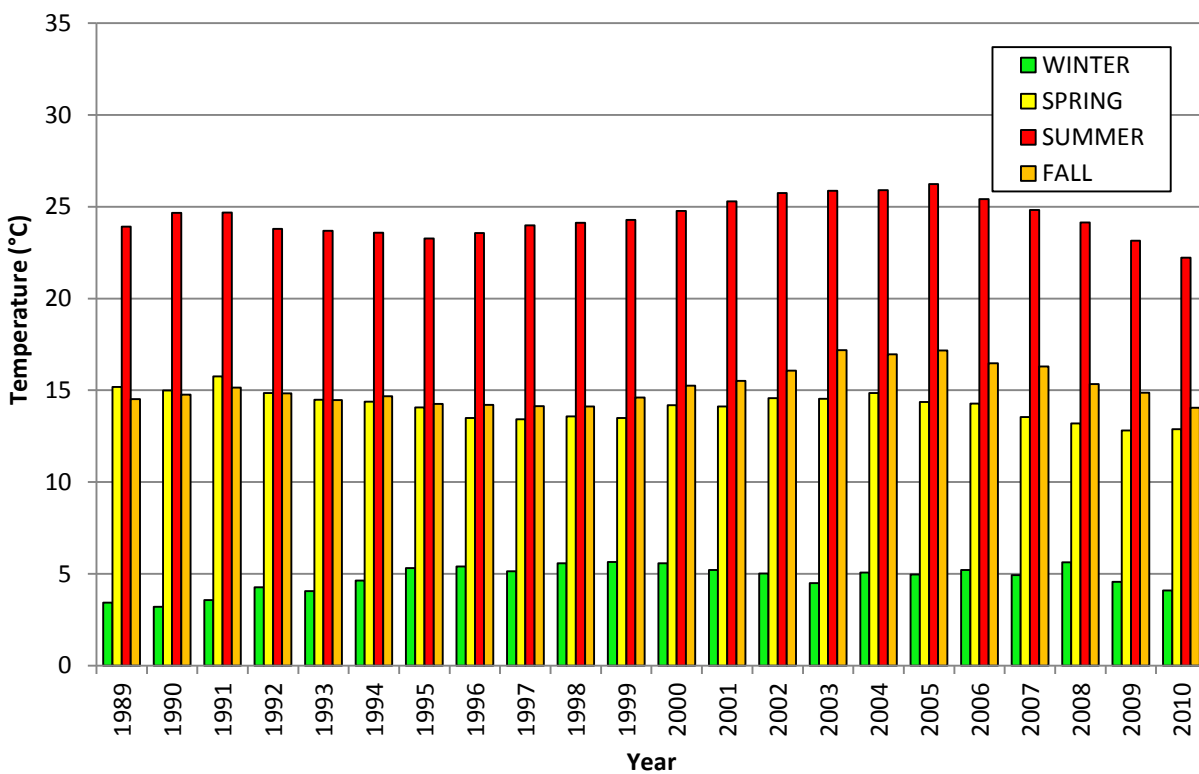


Figure 5-25 Five Year Running Average of Temperature for Station BR04

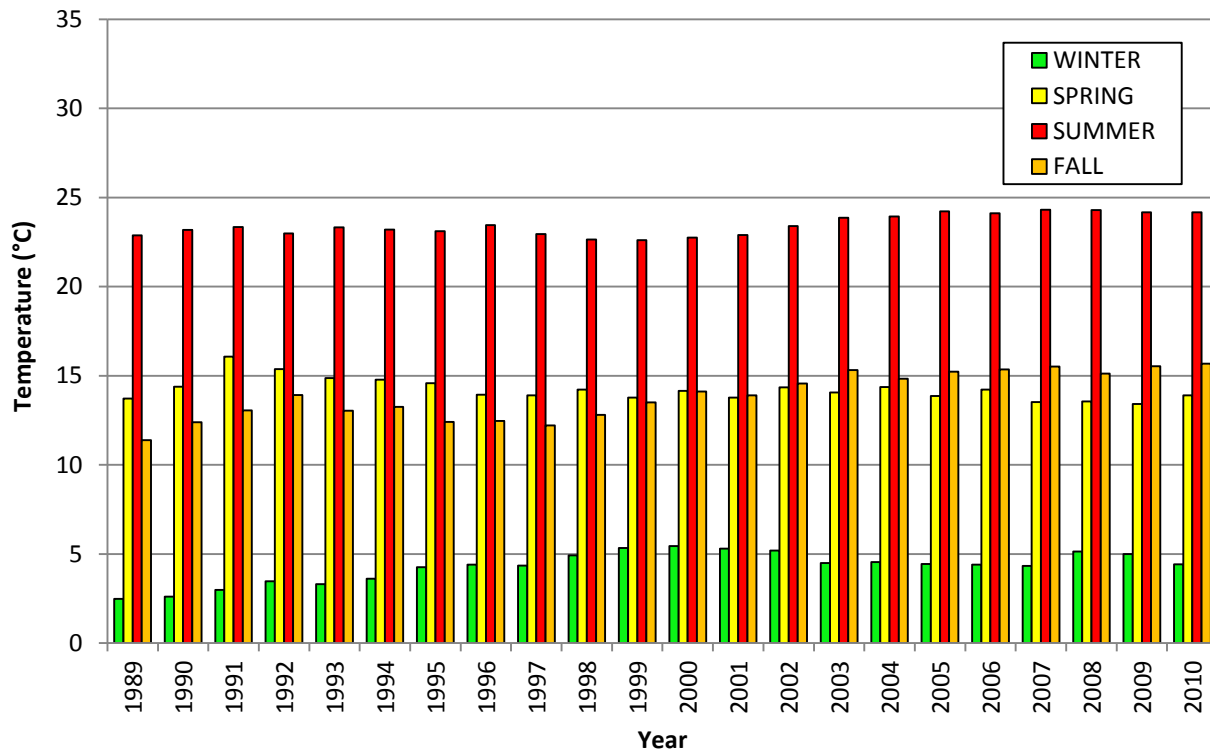


Figure 5-26 Five Year Running Average of Temperature for Station BR05

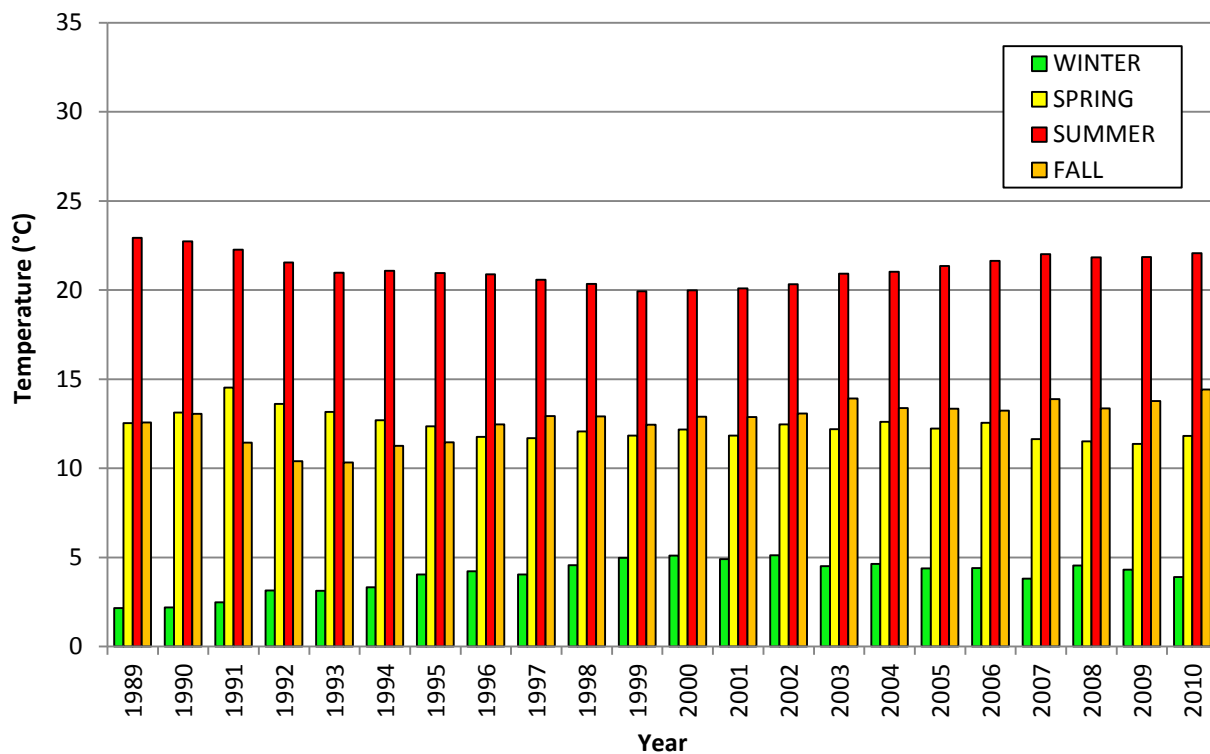


Figure 5-27 Five Year Running Average of Temperature for Station BR06

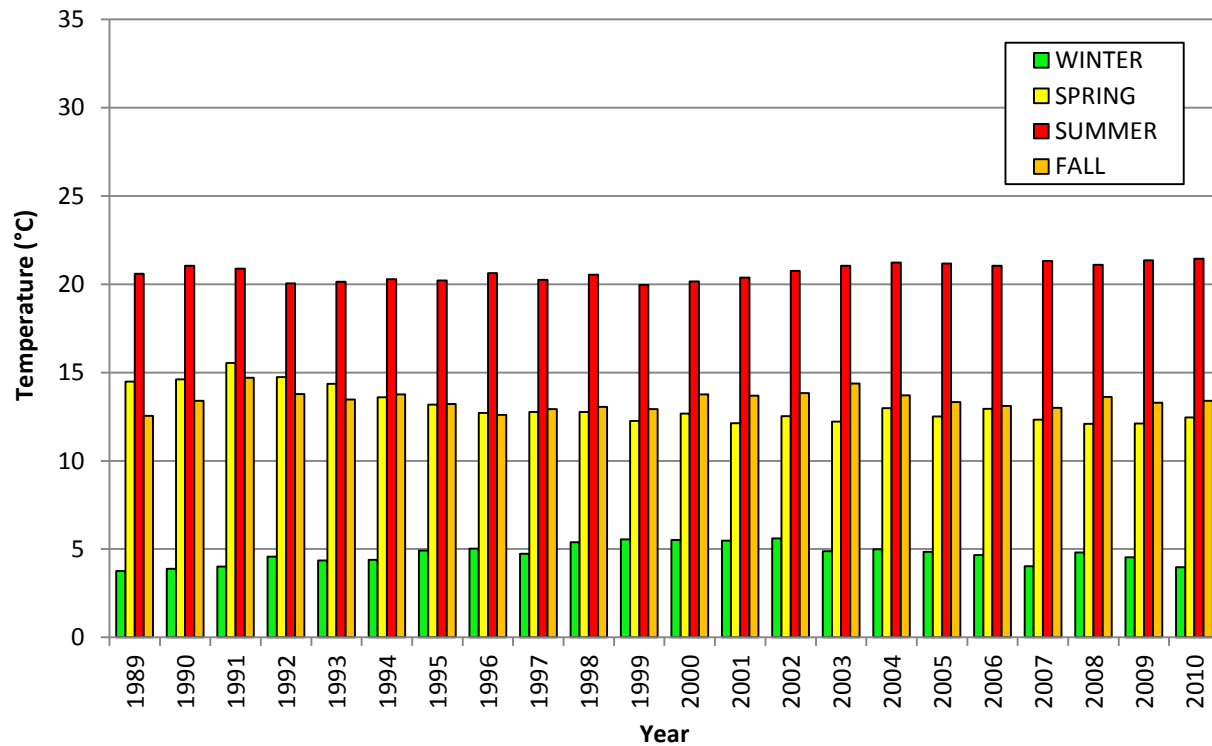


Figure 5-28 Five Year Running Average of Temperature for Station BR07

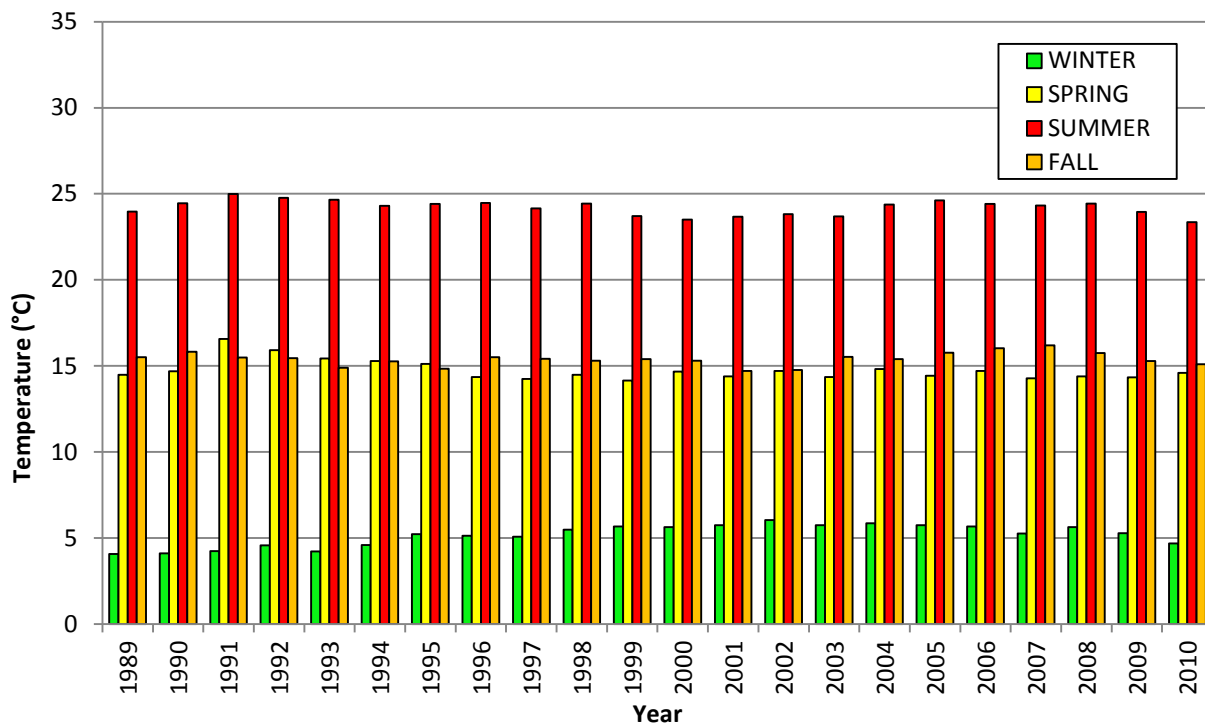
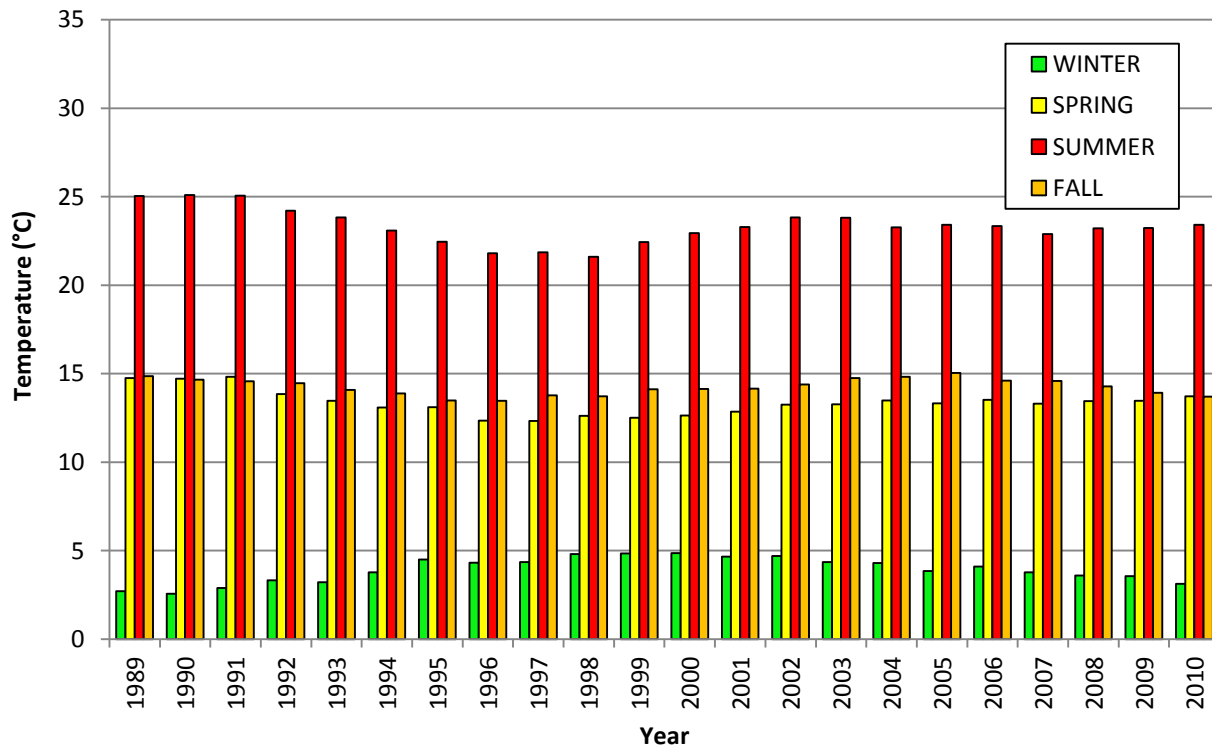


Figure 5-29 Five Year Running Average of Temperature for Station ST70



Conductivity

Five-year running averages for conductivity (COND) for each stream sampling station are depicted in Figures 5-30 through 5-36.

- Conductivity measurements for the 1984 to 2010 period range from 2.5 $\mu\text{S}/\text{cm}$ to 1,724 $\mu\text{S}/\text{cm}$, with the highest measurement of 1,724 $\mu\text{S}/\text{cm}$ detected at sampling station BR02 on 7-JAN-2002. The average conductivity measurement for all sampling stations during this period was calculated to be approximately 192 $\mu\text{S}/\text{cm}$.
- Conductivity measurements for the 2006 to 2010 period range up to 919 $\mu\text{S}/\text{cm}$, with the highest measurement of 919 $\mu\text{S}/\text{cm}$ detected at sampling station BR05 on 12-JUL-2010. The average conductivity measurement for all sampling stations during this period was calculated to be approximately 246 $\mu\text{S}/\text{cm}$.
- The Mann-Kendall Seasonal Analysis for conductivity measurements shows increasing trends at all sampling stations for the 2006 to 2010 period.

Conductivity, or specific conductance, is a measure of resistance to electrical flow within a solution. This resistance in a typical lake or reservoir is generally proportional to the presence of inorganic ions within the water column (Wetzel 2001). Temperature also plays a large role in conductivity fluctuations and for the purposes of this report, conductivity measurements were converted, using the international chemical standard reference of 25 °C. This conversion is done using the following equation:

$$\text{Conductivity (25 }^\circ\text{C)} = \frac{\text{Conductivity (Measured)}}{1 + 0.191(\text{Temperature (Actual)} - 25)}$$

Although the Mann-Kendall seasonal analysis shows increasing trends at all stream sampling stations, the increases are generally minimal with the exception of station BR05, where the increase is most apparent. As shown in Figure 5-33, the highest measurements of conductivity

are collected during summer and fall months when stream flow rates tend to be lower, as opposed to winter and spring months when flow rates tend to be greater. This inverse relationship with flow rates is likely responsible for the significant increases in conductivity measurements.

Figure 5-30 Five Year Running Average of Conductivity for Station BR02

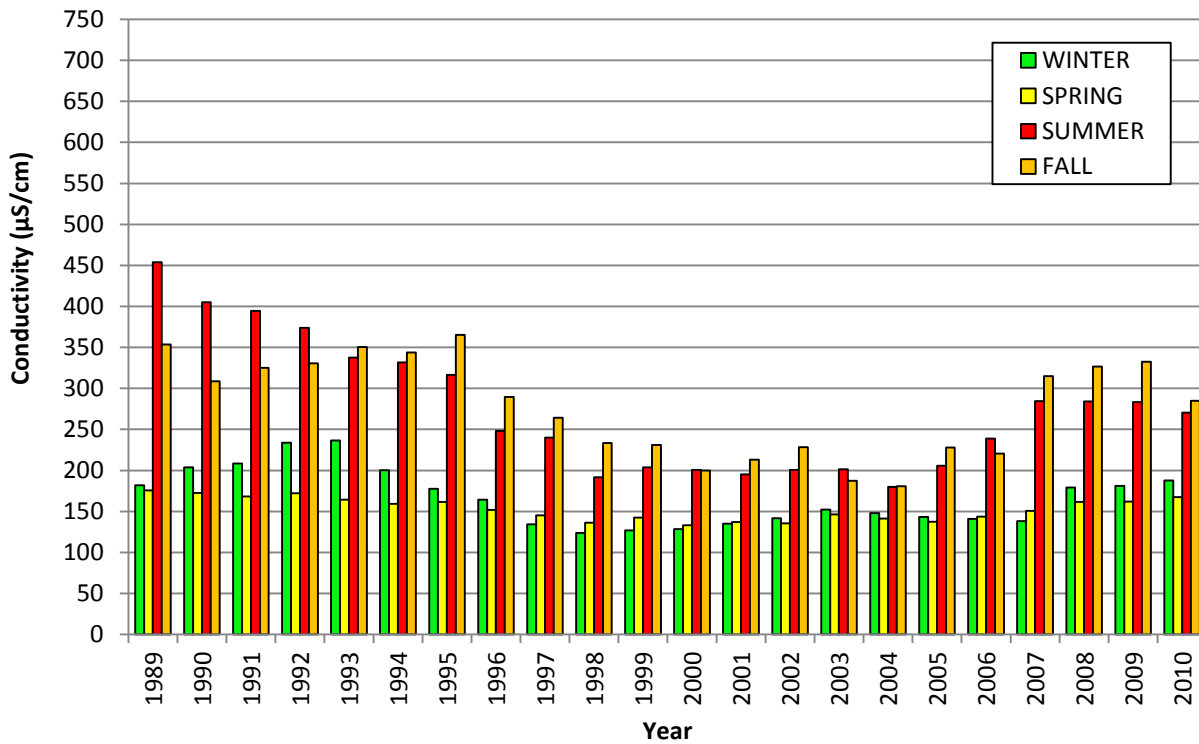


Figure 5-31 Five Year Running Average of Conductivity for Station BR03

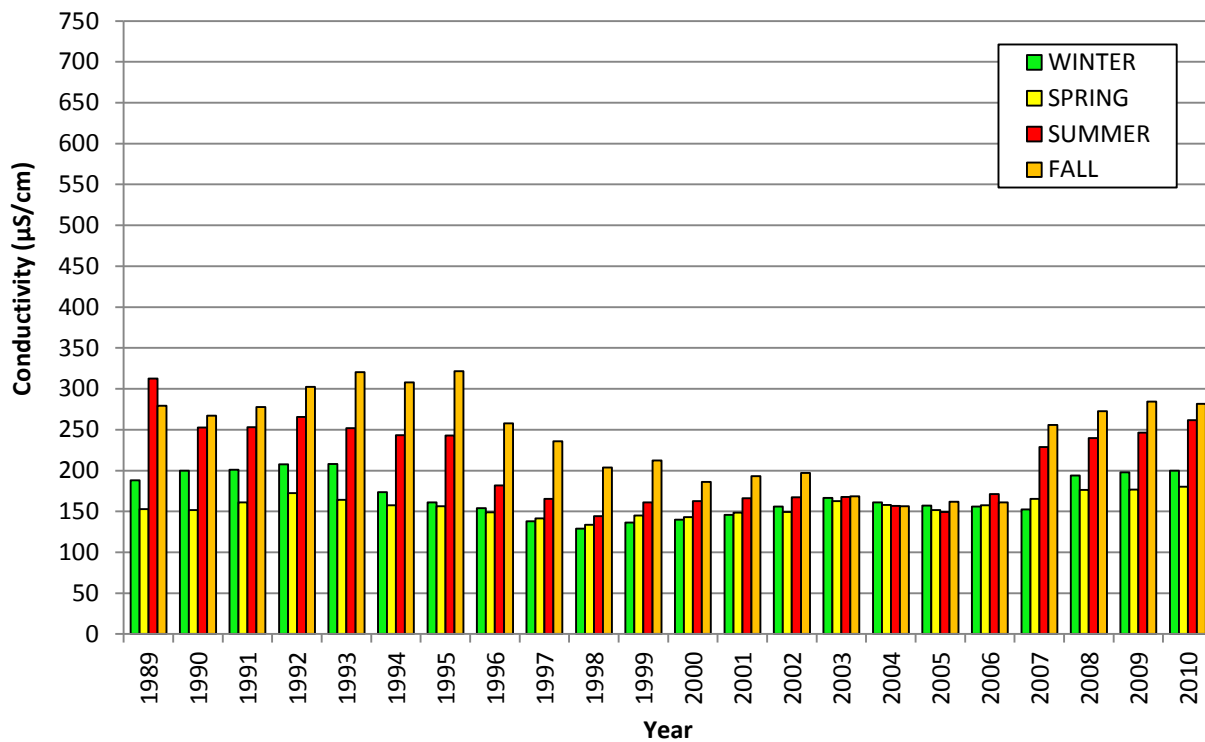


Figure 5-32 Five Year Running Average of Conductivity for Station BR04

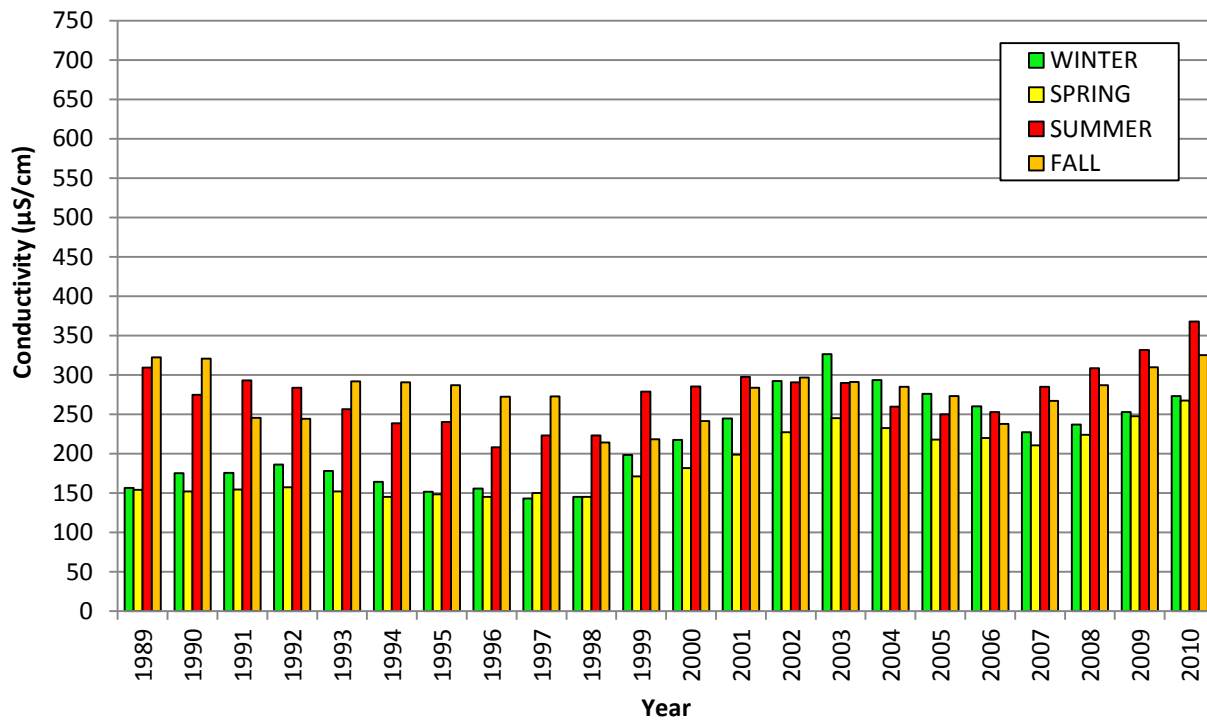


Figure 5-33 Five Year Running Average of Conductivity for Station BR05

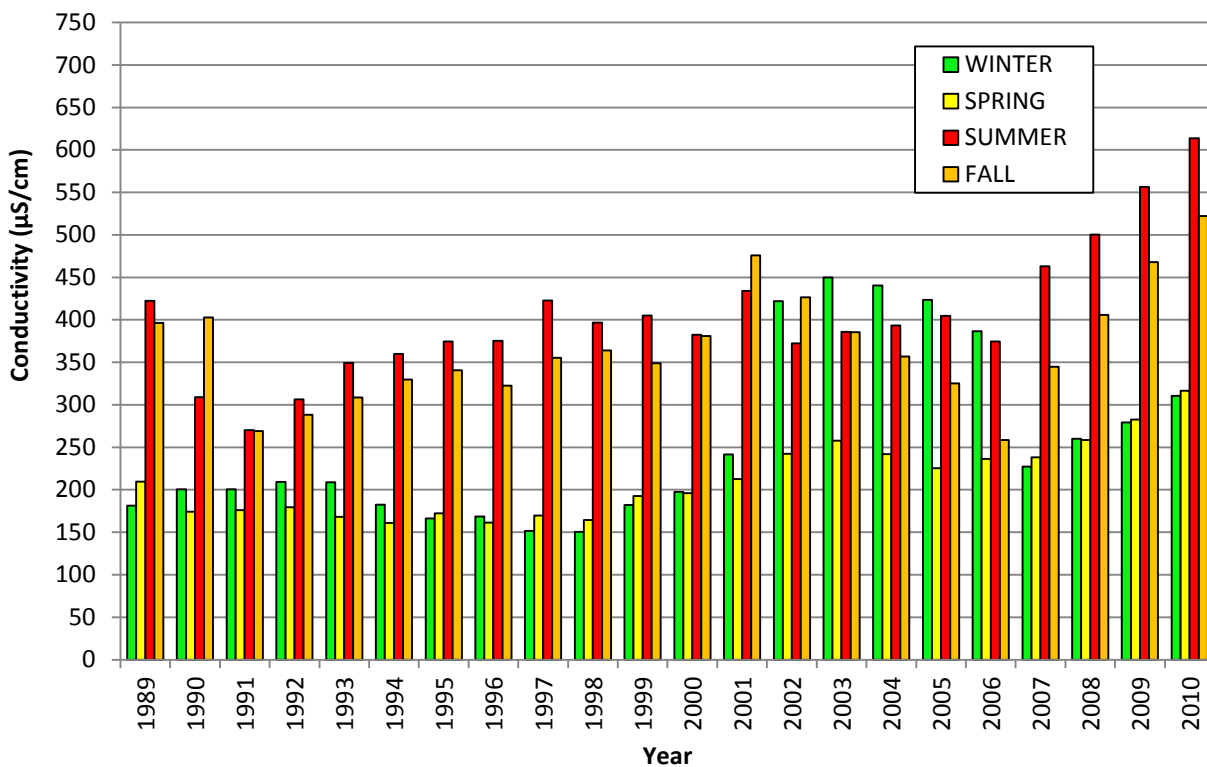


Figure 5-34 Five Year Running Average of Conductivity for Station BR06

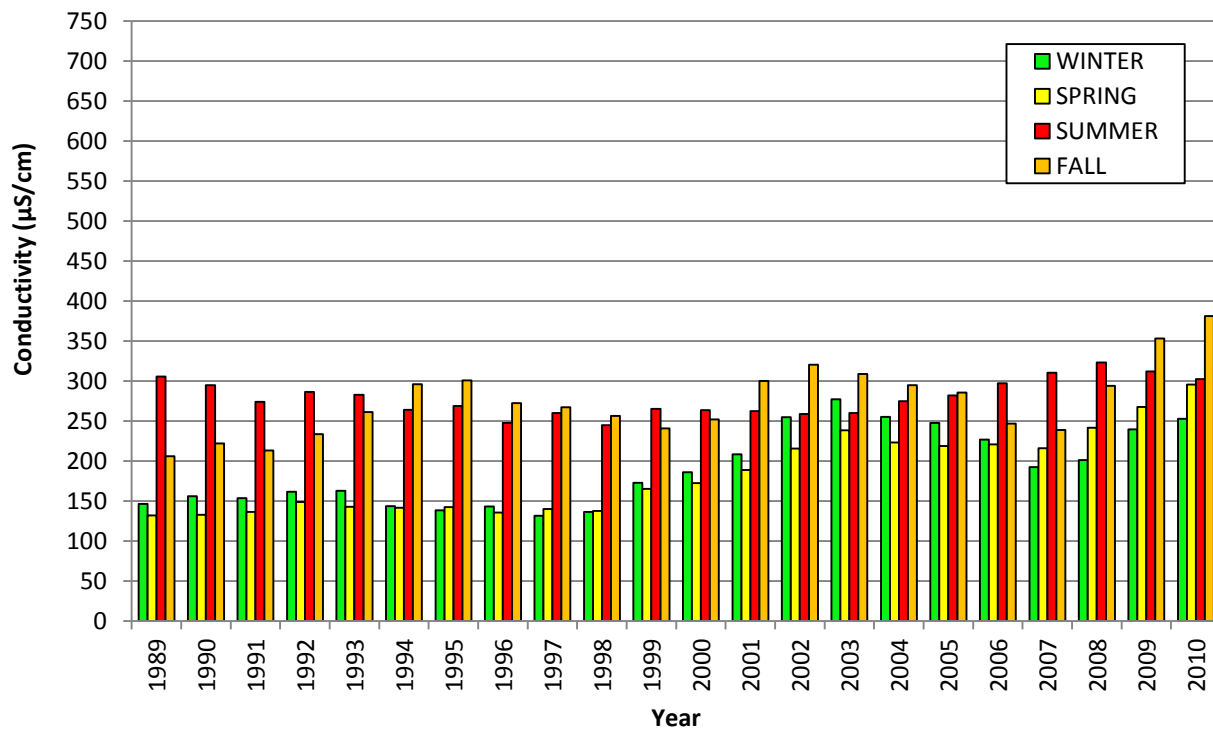


Figure 5-35 Five Year Running Average of Conductivity for Station BR07

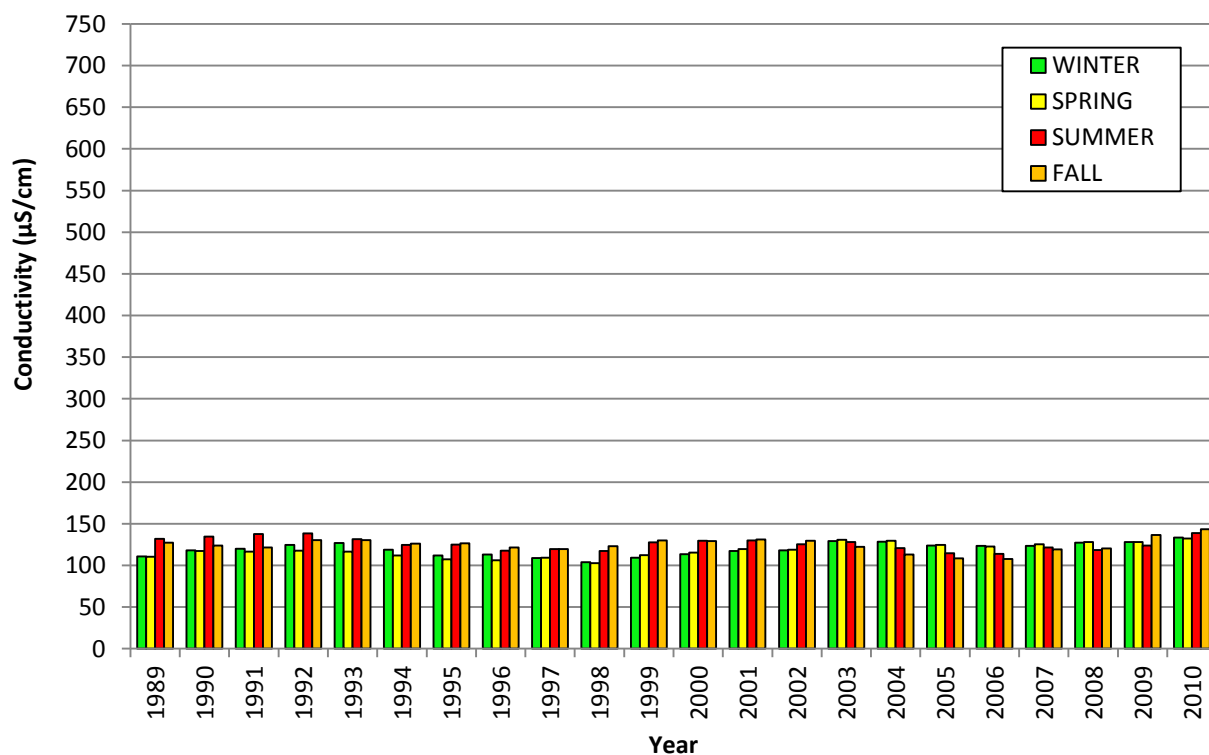
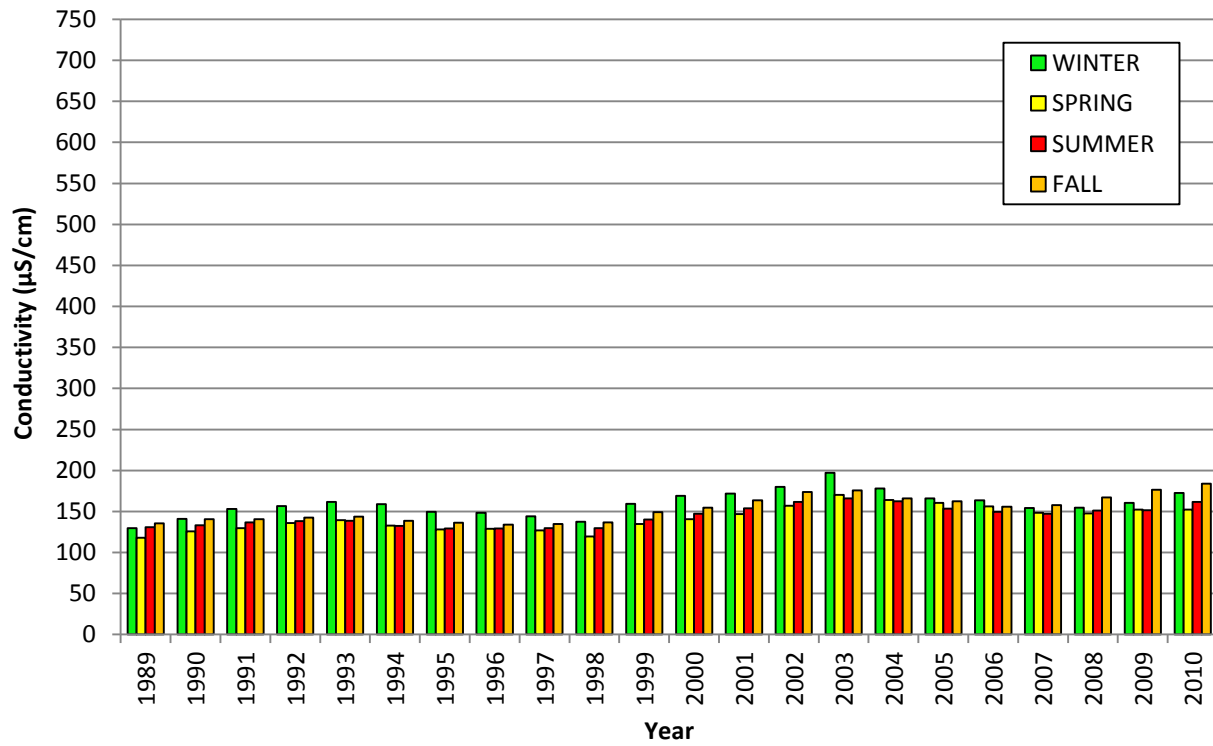


Figure 5-36 Five Year Running Average of Conductivity for Station ST70



Total Suspended Solids

Five-year running averages for total suspended solids (TSS) concentrations for each stream sampling station are depicted in Figures 5-37 through 5-43.

- Total suspended solids concentrations for the 1984 to 2010 period range from 2.5 mg/L to 793 mg/L, with the highest concentration of 793 mg/L detected at sampling station BR04 on 29-JUL-1991. The average total suspended solids concentration for all sampling stations during this period was calculated to be 19.5 mg/L.
- Total suspended solids concentrations for the 2006 to 2010 period range from 0.5 mg/L to 444 mg/L, with the highest concentration of 444 mg/L detected at gaging station ST70 on 9-JUN-2009. The average total suspended solids concentration for all sampling stations during this period was calculated to be 13.5 mg/L.
- The Mann-Kendall Seasonal Analysis for total suspended solids concentrations shows an increasing trend at sampling station BR06 and decreasing trends at stations BR04 and ST70, with no other significant trends detected at the remaining sampling stations for the 2006 to 2010 period.

Total suspended solids are a measure of particulate material that general remains in suspension within the water column and does not settle out. The OWML samples for TSS by measuring those particulates that pass through a 0.45-micron filter (OWML 2012). These particulates typically include fine solids such as clay and silts as well as organic plankton, algae and debris matter.

Total suspended solids can generally be correlated with surficial flow rates. Increased precipitation results in runoff into a stream body and those runoff waters can pick up and carry solids along the way (EPA 2012). As would be expected, during low flow periods, TSS measurements tend to decrease as is seen in the Mann-Kendall seasonal analysis for stream

sampling stations BR04 and ST70. However, an increasing trend is apparent at station BR06. As shown in Figure 5-41, there appears to be a strong increase in TSS, particularly in summer months. Because increased flow rates are not generally associated with summer seasons, this increase may be a result of external runoff or land development applications. Additional investigation may be warranted within the vicinity of stream station BR06 to determine if the measured increase can be attributed to any point sources.

As shown in Figure 5-37 there is an apparent significant increase in TSS concentrations at sampling station BR02 during the 1990 to 1994 (spring) and 2000 to 2004 (winter) periods. However, these increases appear to be a result of significantly elevated concentrations being measured during a single sampling event. These occurrences in general do not represent typical measurements. The increase associated with spring five year running averages from 1990 to 1994 is a result of two sampling events with elevated TSS concentrations: 440 mg/L on 10-MAY-1990 and 132 mg/L on 4-MAR-1993.

In addition, an increase is apparent on Figure 5-39 for sampling station BR04 between 1989 and 1992 (summer). This increase is a result of a single sampling event with an elevated TSS concentration: 793 on 29-JUL-1991.

The VDEQ does not have a published standard for maximum total suspended solid concentrations; however, the VDEQ, in cooperation with the U.S. EPA, is developing Total Maximum Daily Load (TMDL) reports for water bodies within the greater Chesapeake Bay watershed. Although a TMDL for total suspended solids has not been established or proposed for Broad Run, Lake Manassas, or the Occoquan watershed, TSS is considered a TMDL contaminant, and measures should be taken to limit concentrations where possible. Total suspended solids are known to decrease water transparency and the amount of light available

to support photosynthesis, which plays a significant role in stream and lake ecosystems (Cooke 1993).

Figure 5-37 Five Year Running Average of TSS for Station BR02

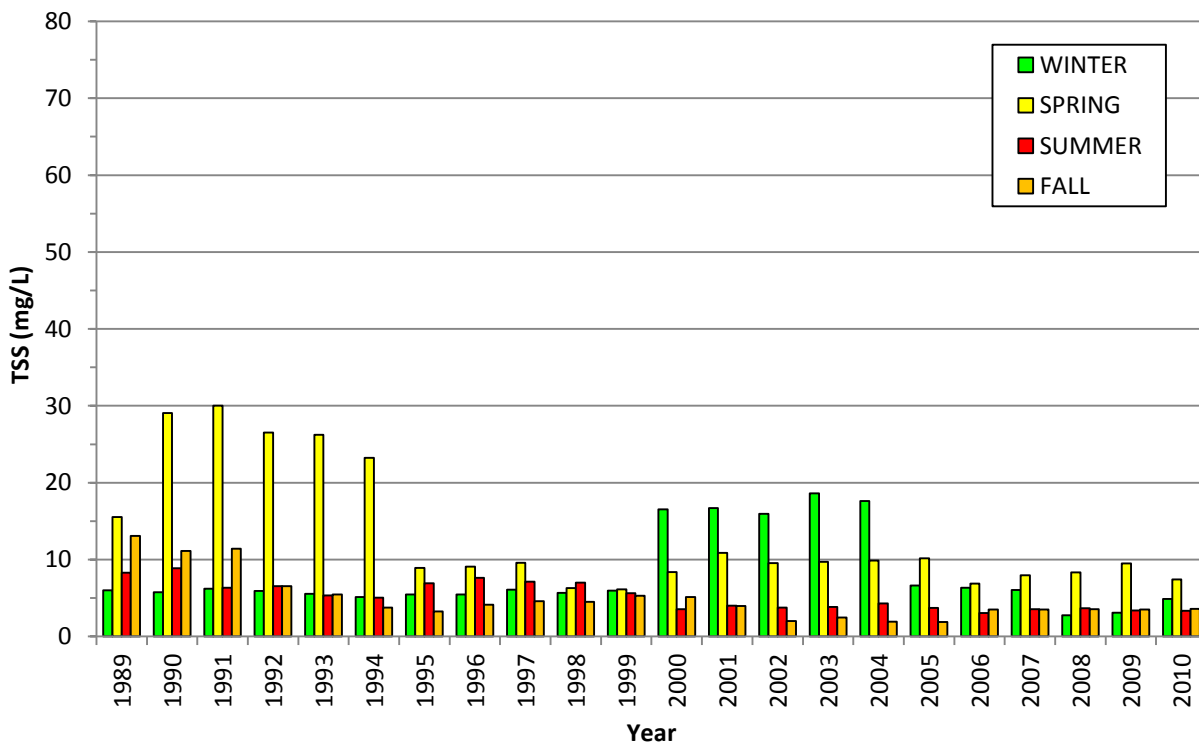


Figure 5-38 Five Year Running Average of TSS for Station BR03

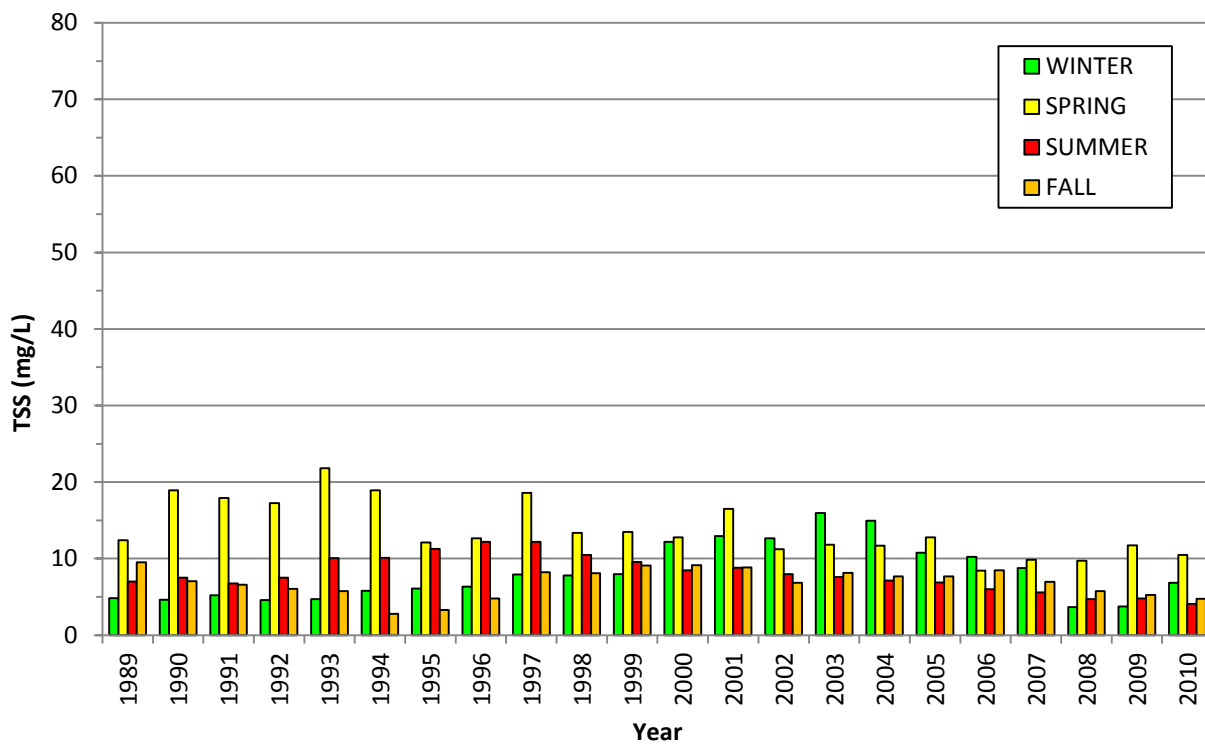


Figure 5-39 Five Year Running Average of TSS for Station BR04

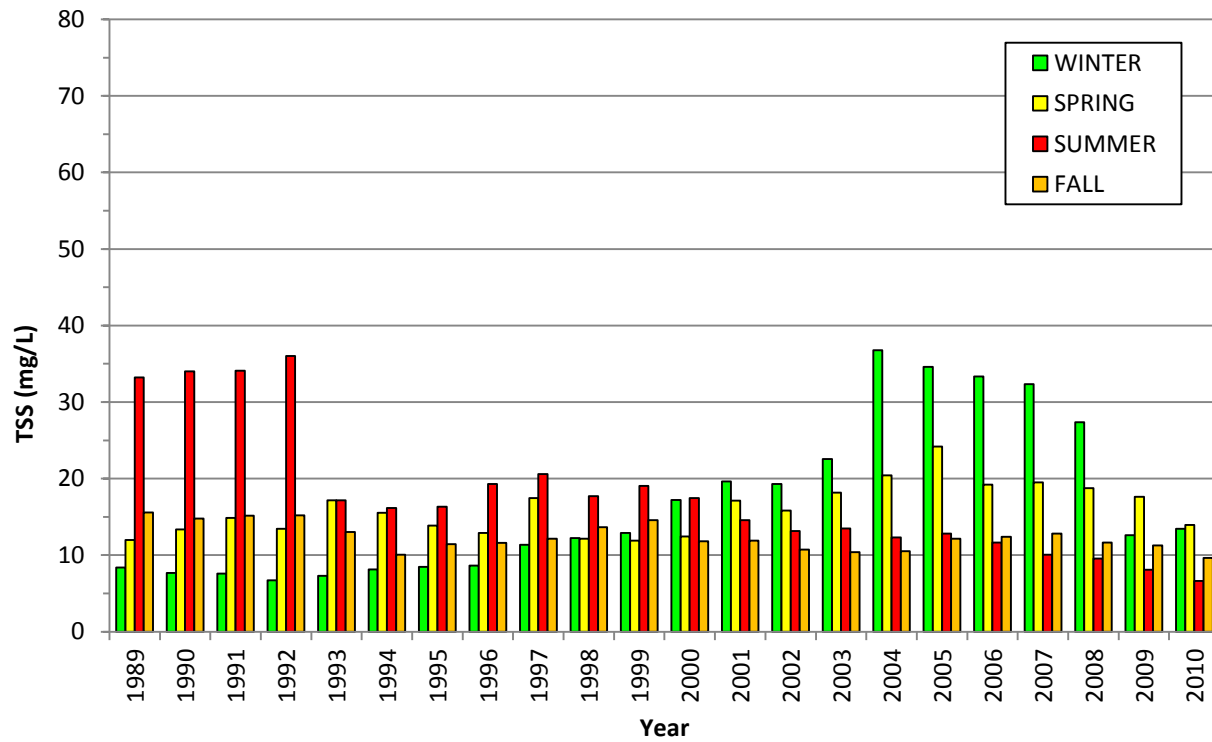


Figure 5-40 Five Year Running Average of TSS for Station BR05

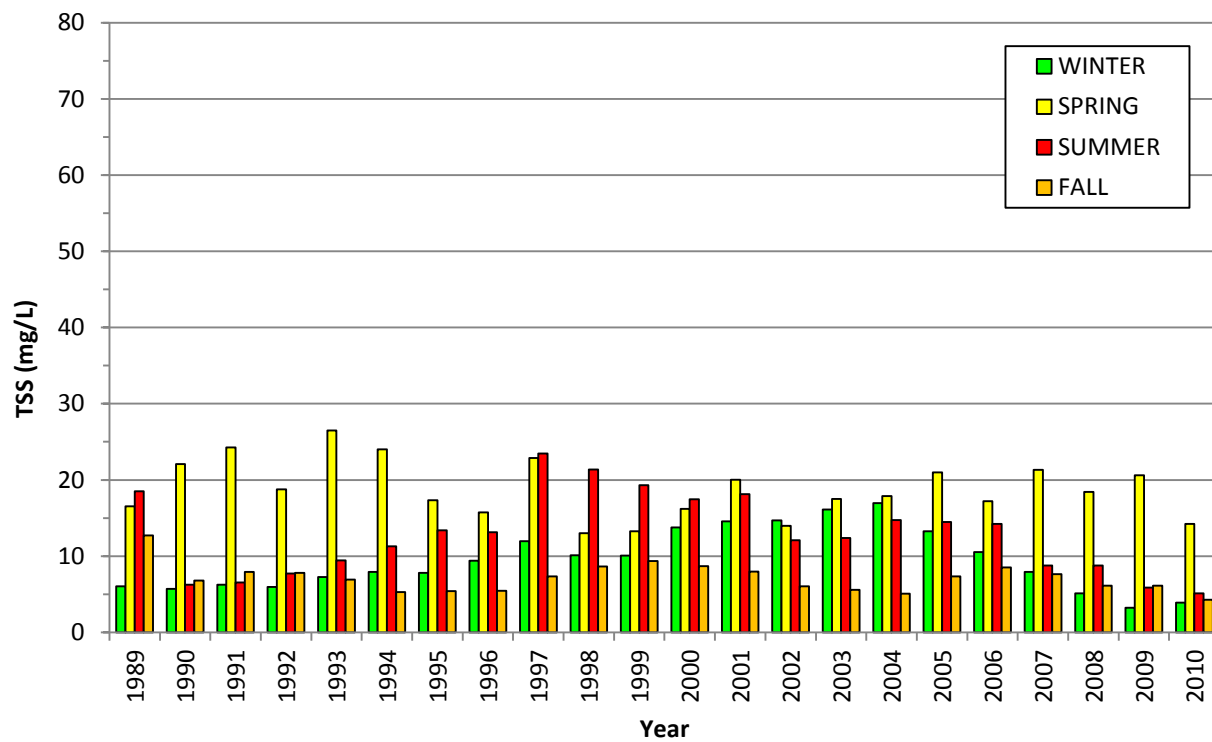


Figure 5-41 Five Year Running Average of TSS for Station BR06

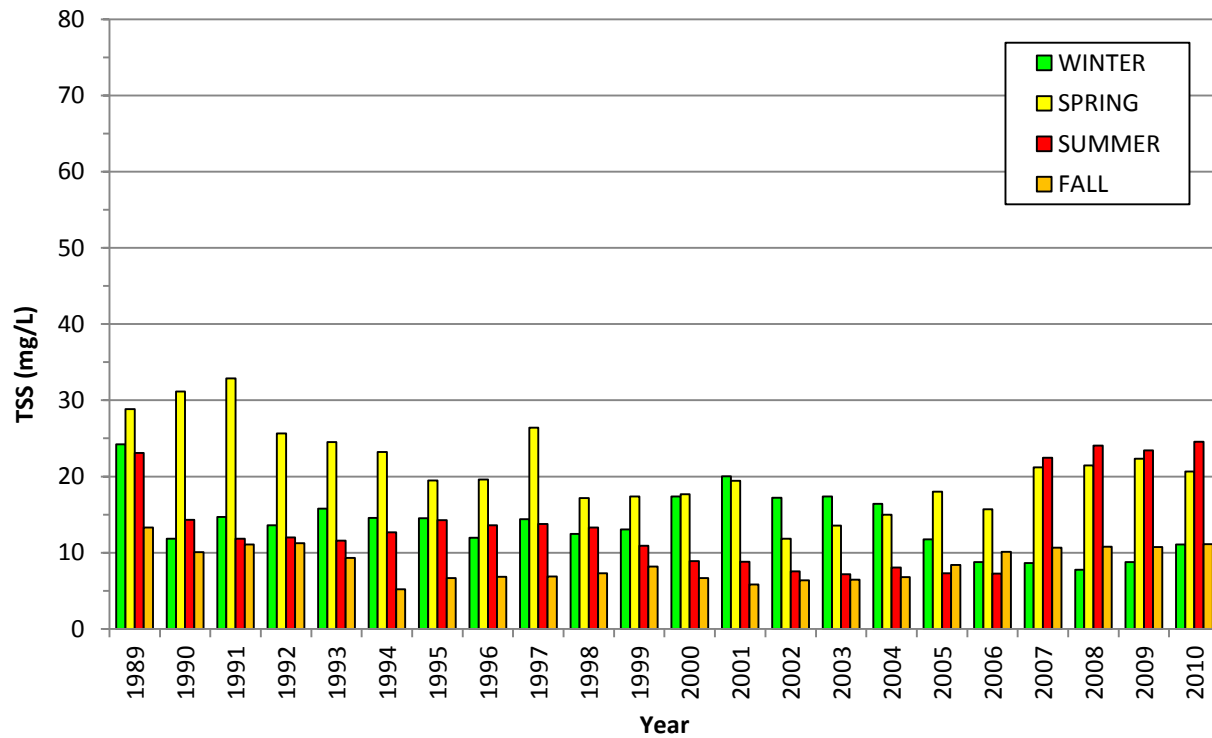


Figure 5-42 Five Year Running Average of TSS for Station BR07

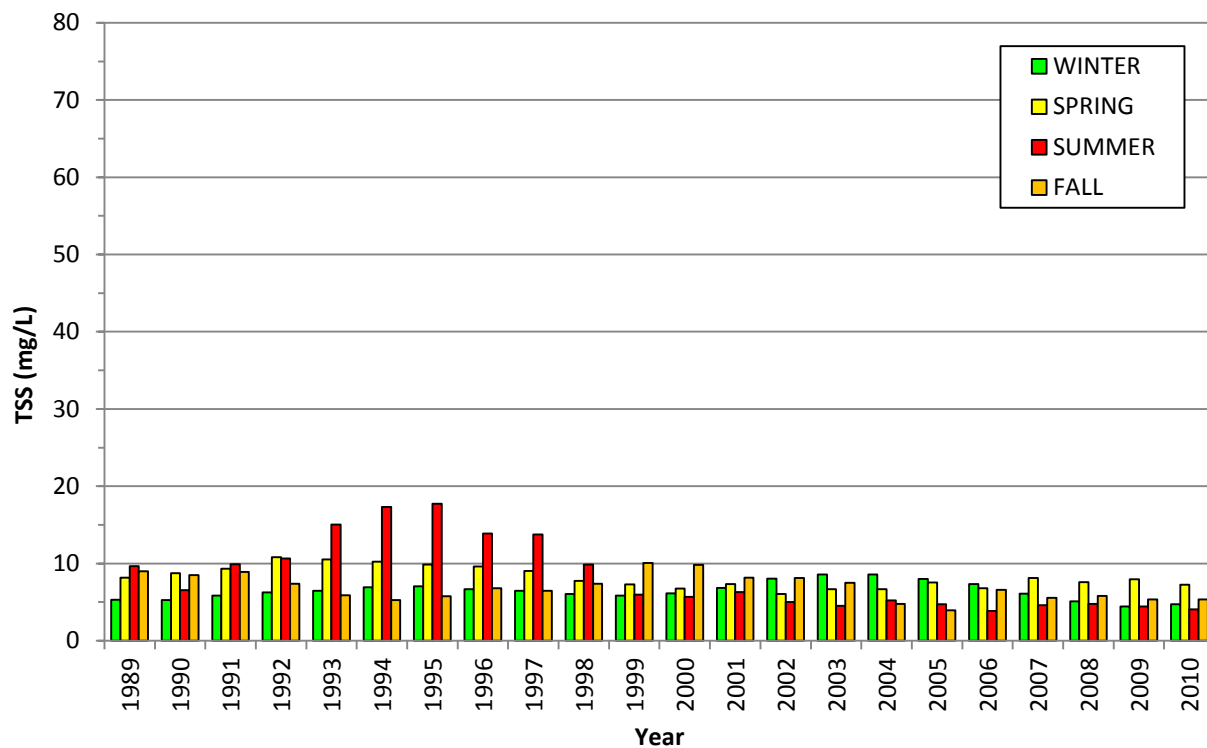
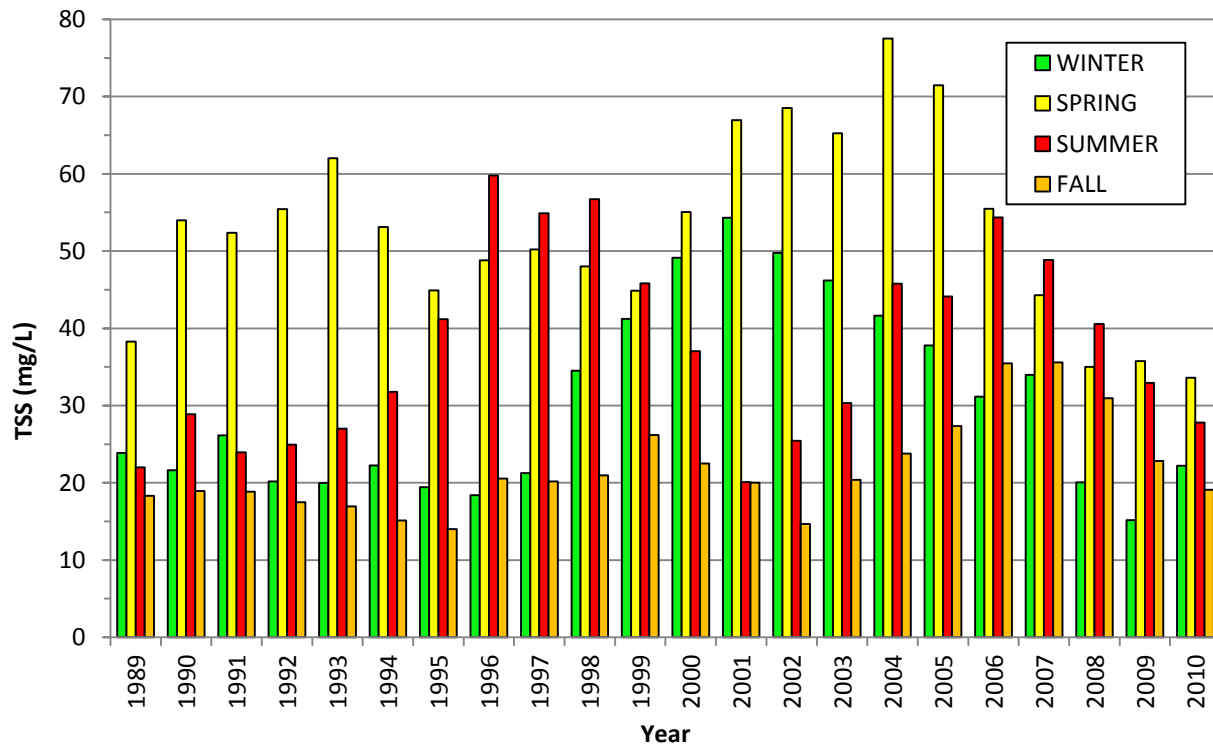


Figure 5-43 Five Year Running Average of TSS for Station ST70



Nitrogen

The OWML collects samples from stream sampling stations and measures for three forms of nitrogen: oxidized nitrogen, ammonia nitrogen and total Kjeldahl nitrogen. The nitrogen cycle, or transformation from one form to another through various processes, occurs within a watershed. Like many other constituents discussed in this report, the major source of nitrogen to a watershed is from surface runoff and in some cases groundwater discharge to a stream. In addition, atmospheric nitrogen fixation contributions from plants plays a role in the nitrogen cycle and should be considered (Wetzel 2001).

Five-year running averages for oxidized nitrogen (OX-N) concentrations for each stream sampling station are depicted in Figures 5-44 through 5-50.

- Oxidized nitrogen concentrations for the 1984 to 2010 period range from 0.01 mg/L as N to 20.9 mg/L as N, with the highest concentration of 20.9 mg/L as N detected at sampling station BR02 on 1-NOV-1988. The average oxidized nitrogen concentration for all sampling stations during this period was calculated to be 0.6 mg/L as N.
- Oxidized nitrogen concentrations for the 2006 to 2010 period range from 0.01 mg/L as N to 8.39 mg/L as N, with the highest concentration of 8.39 mg/L as N detected at sampling station BR02 on 15-NOV-2007. The average oxidized nitrogen concentration for all sampling stations during this period was calculated to be 0.57 mg/L as N.
- The Mann-Kendall Seasonal Analysis for oxidized nitrogen concentrations shows increasing trends at sampling stations BBR04 and BR05, a decreasing trend at gaging station ST70, and no other significant trends detected at the remaining sampling stations for the 2006 to 2010 period.

Five-year running averages for ammonia nitrogen (NH₃-N) concentrations for each stream sampling station are depicted in Figures 5-51 through 5-57.

- Ammonia nitrogen concentrations for the 1984 to 2010 period range from 0.1mg/L as N to 2.17 mg/L as N, with the highest concentration of 2.17 mg/L as N detected at sampling station BR02 on 15-NOV-1988. The average ammonia nitrogen concentration for all sampling stations during this period was calculated to be 0.06 mg/L as N.
- Ammonia nitrogen concentrations for the 2006 to 2010 period range from 0.01 mg/L as N to 0.67 mg/L as N, with the highest concentration of 0.67 mg/L as N detected at sampling station BR02 on 6-OCT-1988. The average ammonia nitrogen concentration for all sampling stations during this period was calculated to be 0.06 mg/L as N.
- The Mann-Kendall Seasonal Analysis for ammonia nitrogen concentrations shows no significant trends for the 2006 to 2010 period.

Five-year running averages for total Kjeldahl nitrogen (TKN) concentrations for each stream sampling station are depicted in Figures 5-58 through 5-64.

- Total Kjeldahl nitrogen concentrations for the 1984 to 2010 period range from 0.15 mg/L as N to 19.2 mg/L as N, with the highest concentration of 19.2 mg/L as N detected at sampling station BR06 on 5-JAN-1993. The average total Kjeldahl nitrogen concentration for all sampling stations during this period was calculated to be 0.59 mg/L as N.
- Total Kjeldahl nitrogen concentrations for the 2006 to 2010 period range from 0.15 mg/L as N to 2.4 mg/L as N, with the highest concentration of 2.4 mg/L as N detected at sampling station BR06 on 4-JUN-2007. The average total Kjeldahl nitrogen concentration for all sampling stations during this period was calculated to be 0.53 mg/L as N.

- The Mann-Kendall Seasonal Analysis for total Kjeldahl nitrogen concentrations shows decreasing trends at stations BR04 and ST70 and no other significant trends detected at the remaining sampling stations for the 2006 to 2010 period.

As shown in Figure 5-62 there is an apparent significant increase in TKN concentrations at sampling station BR06 during the 1993 to 1997 (summer) period. However, this increase appears to be a result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with summer five year running averages from 1993 to 1997 is a result of a single sampling event with elevated TKN concentrations: 2.24 mg/L as N on 12-JUN-1995.

Five-year running averages for total nitrogen (TN) concentrations for each stream sampling station are depicted in Figures 5-65 through 5-71.

- Total nitrogen concentrations for the 1984 to 2010 period range from below detection limits to 21.86 mg/L as N, with the highest concentration of 21.86 mg/L as N detected at sampling station BR02 on 1-NOV-1988. The average total Kjeldahl nitrogen concentration for all sampling stations during this period was calculated to be 1.21 mg/L as N.
- Total nitrogen concentrations for the 2006 to 2010 period range from below detection limits to 9.38 mg/L as N, with the highest concentration of 9.38 mg/L as N detected at sampling station BR02 on 24-SEP-2007. The average total Kjeldahl nitrogen concentration for all sampling stations during this period was calculated to be 1.16 mg/L as N.

- The Mann-Kendall Seasonal Analysis for total nitrogen concentrations shows decreasing trends at stations BR04, BR07 and ST70 and an increasing trend at station BR05 for the 2006 to 2010 period.

Figure 5-44 Five Year Running Average of Oxidized Nitrogen for Station BR02

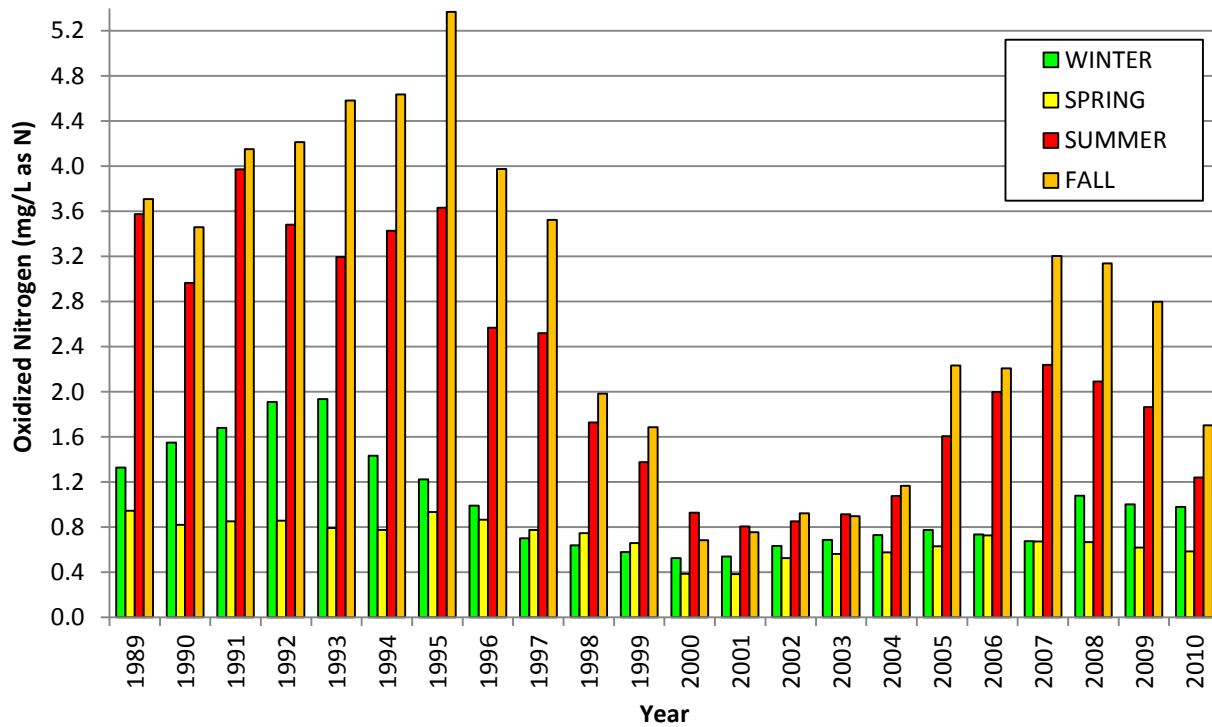


Figure 5-45 Five Year Running Average of Oxidized Nitrogen for Station BR03

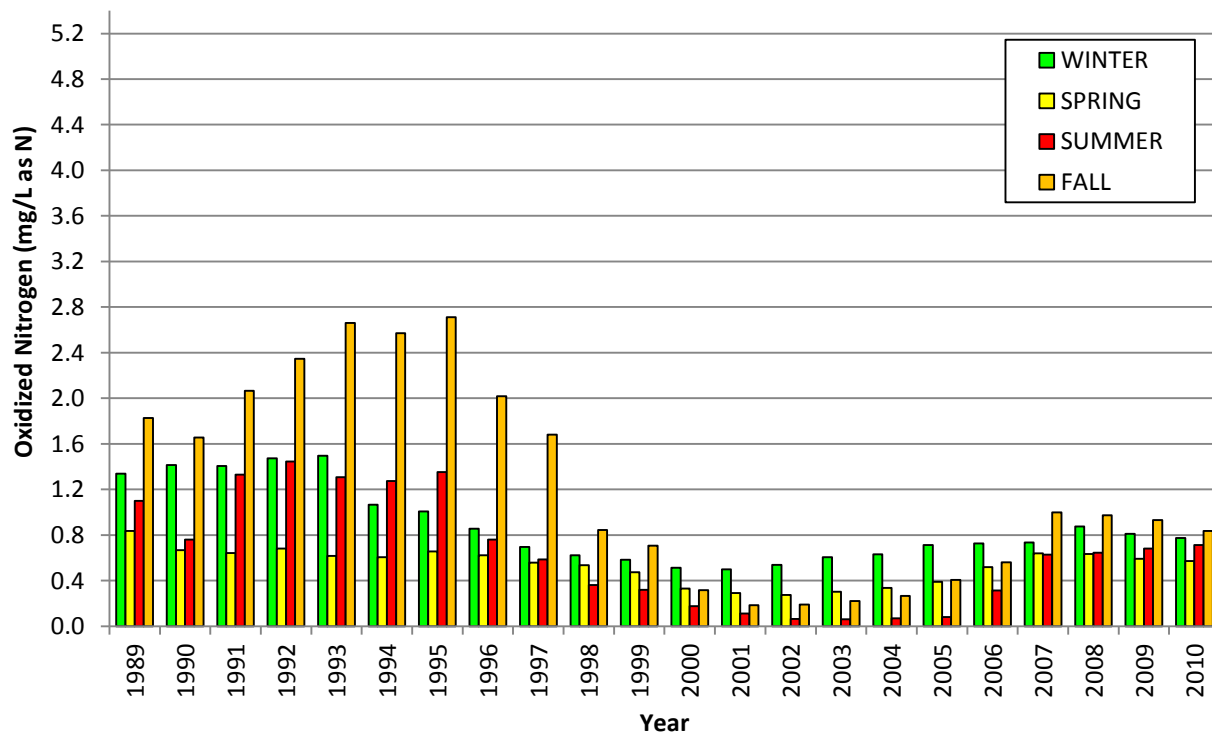


Figure 5-46 Five Year Running Average of Oxidized Nitrogen for Station BR04

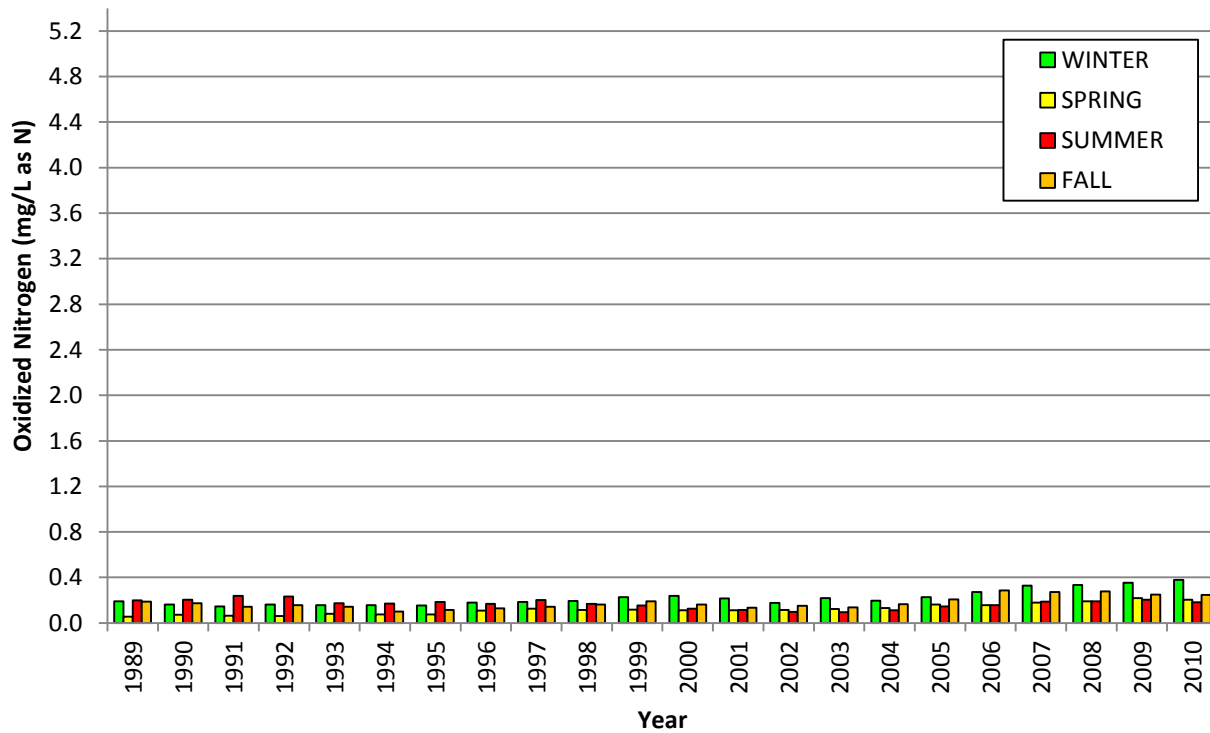


Figure 5-47 Five Year Running Average of Oxidized Nitrogen for Station BR05

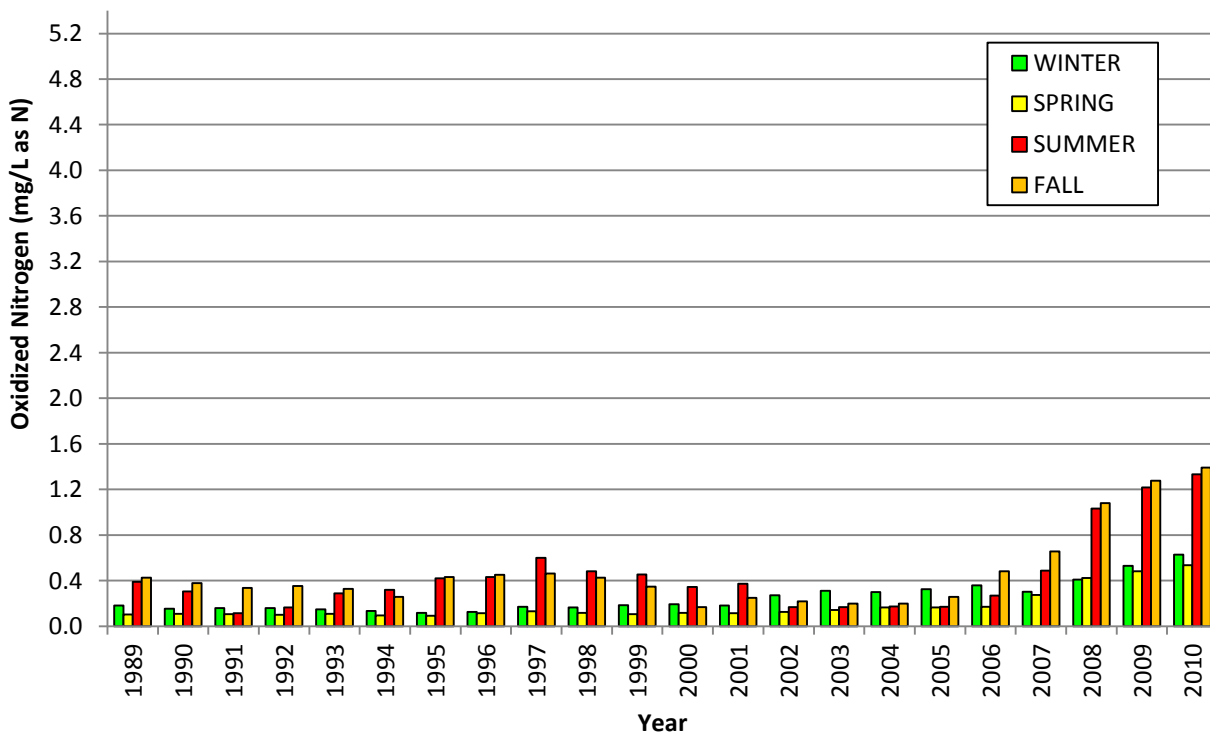


Figure 5-48 Five Year Running Average of Oxidized Nitrogen for Station BR06

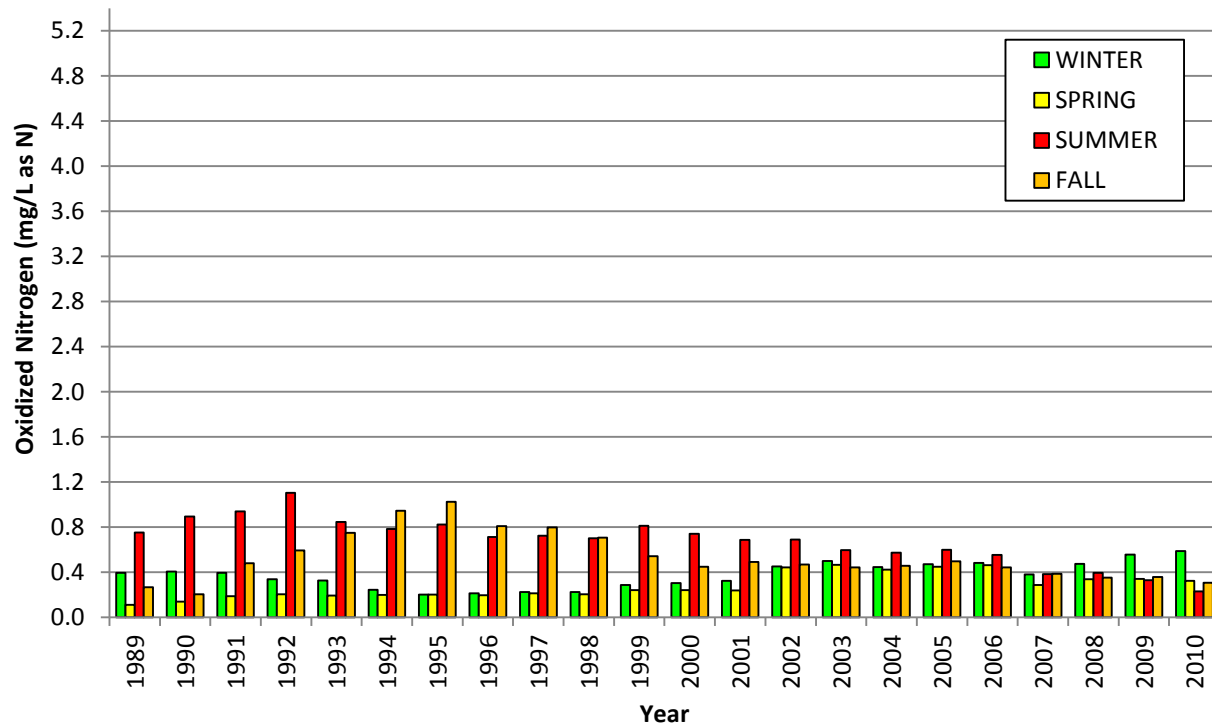


Figure 5-49 Five Year Running Average of Oxidized Nitrogen for Station BR07

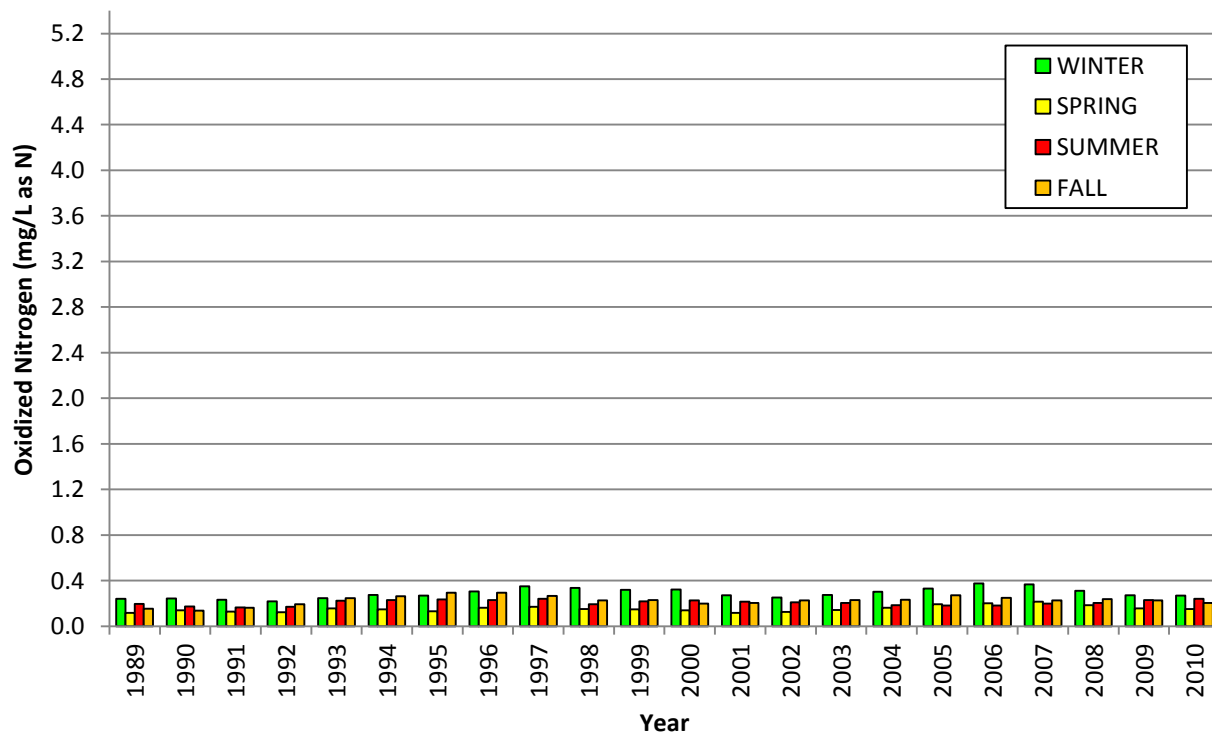


Figure 5-50 Five Year Running Average of Oxidized Nitrogen for Station ST70

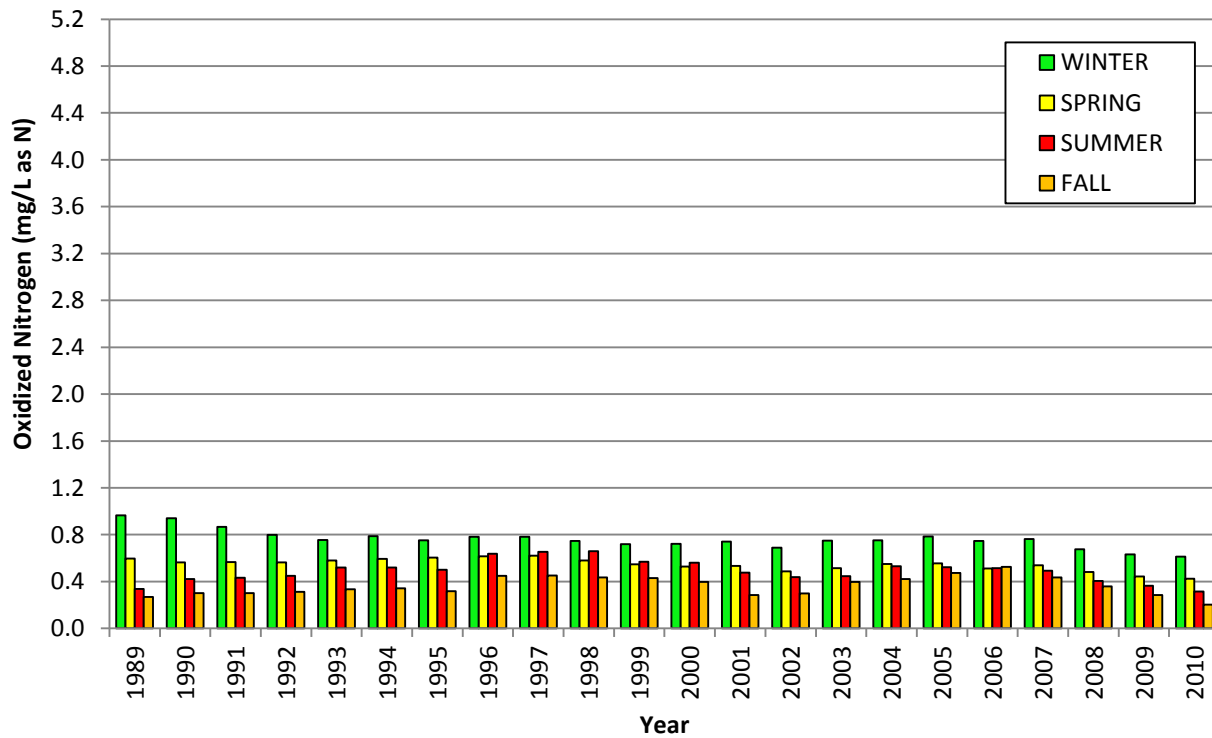


Figure 5-51 Five Year Running Average of Ammonia Nitrogen for Station BR02

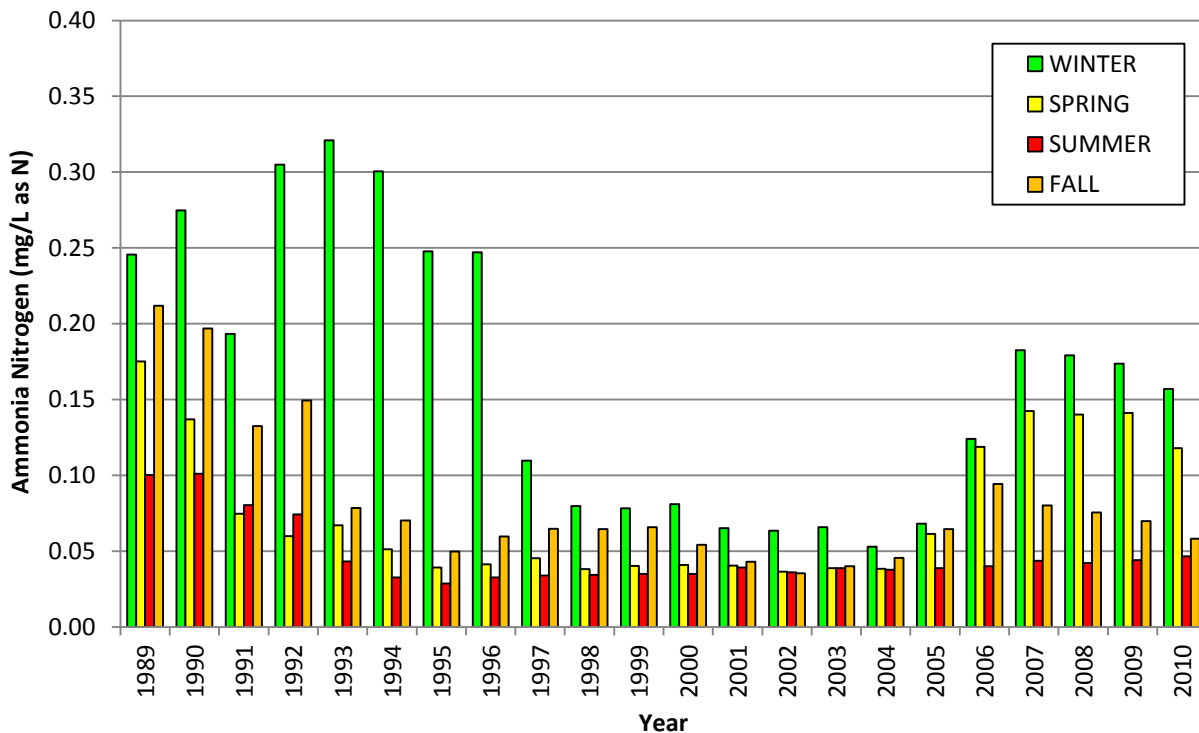


Figure 5-52 Five Year Running Average of Ammonia Nitrogen for Station BR03

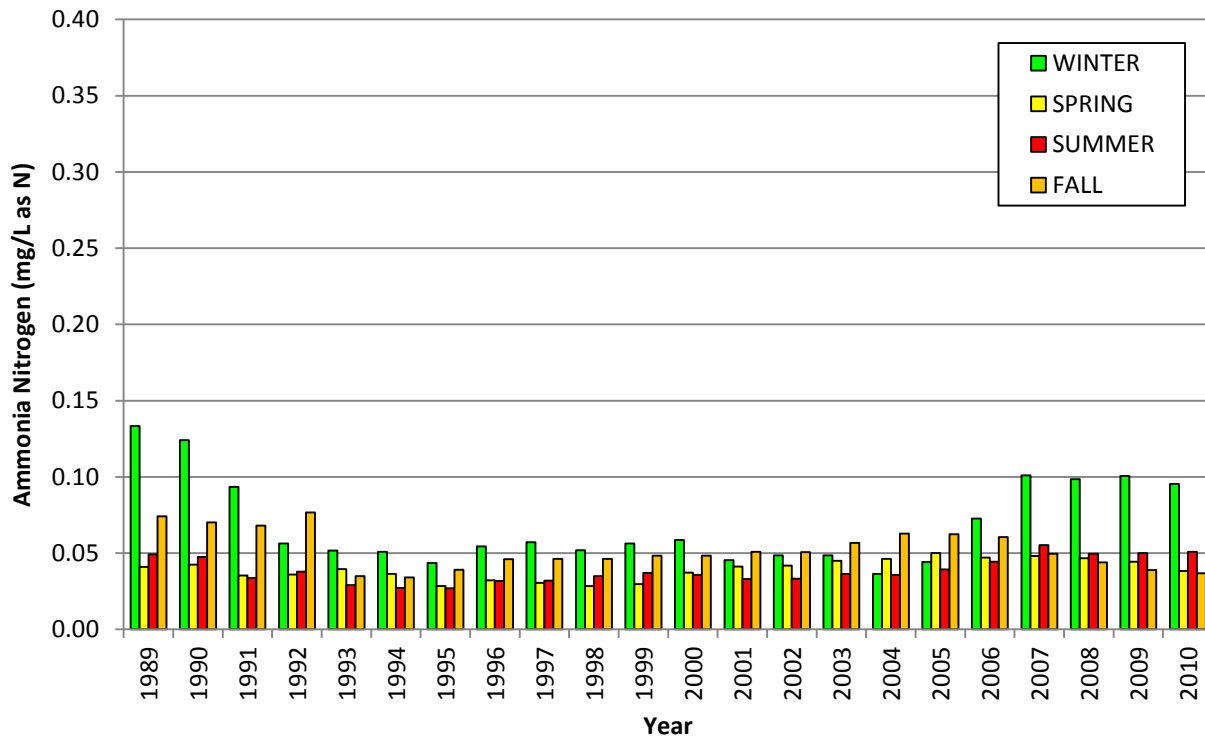


Figure 5-53 Five Year Running Average of Ammonia Nitrogen for Station BR04

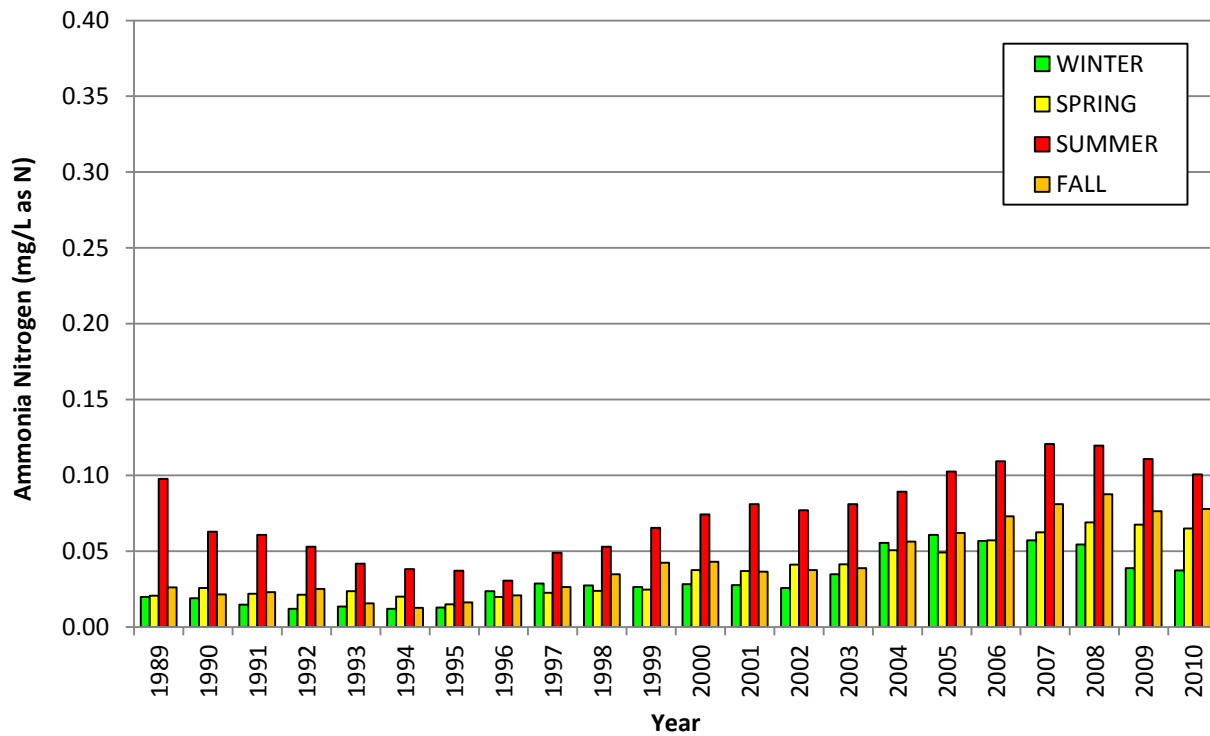


Figure 5-54 Five Year Running Average of Ammonia Nitrogen for Station BR05

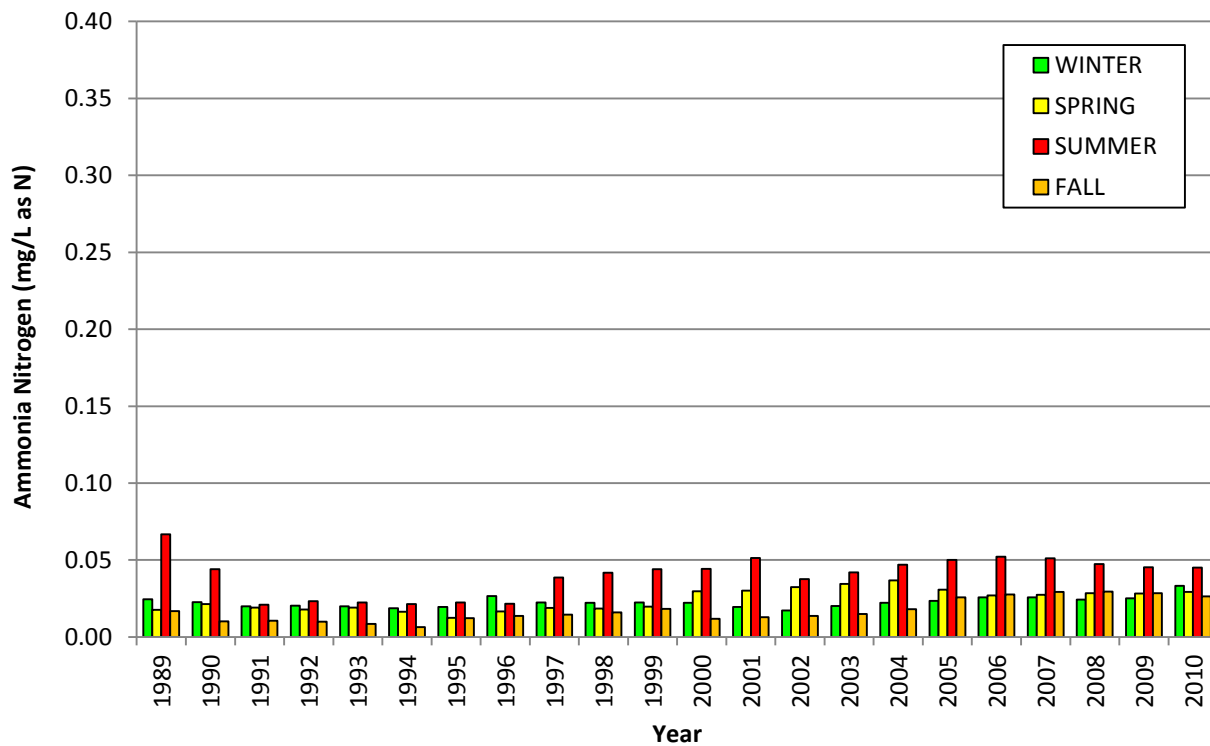


Figure 5-55 Five Year Running Average of Ammonia Nitrogen for Station BR06

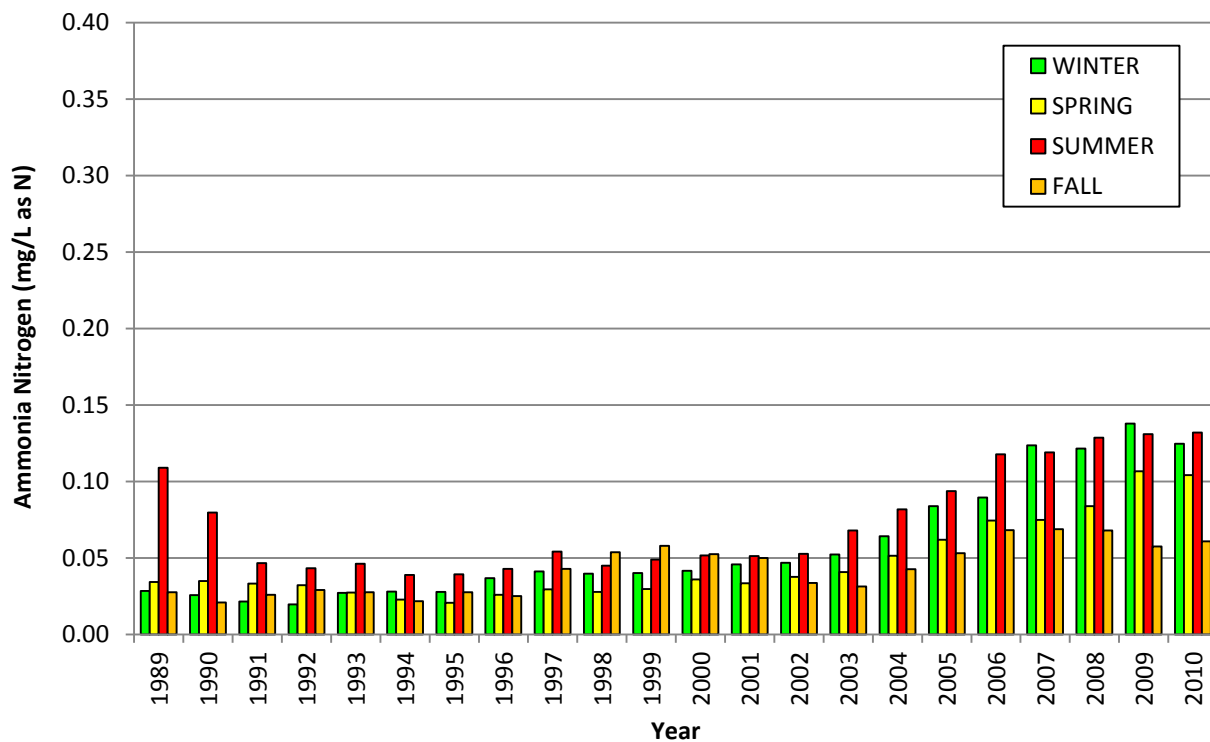


Figure 5-56 Five Year Running Average of Ammonia Nitrogen for Station BR07

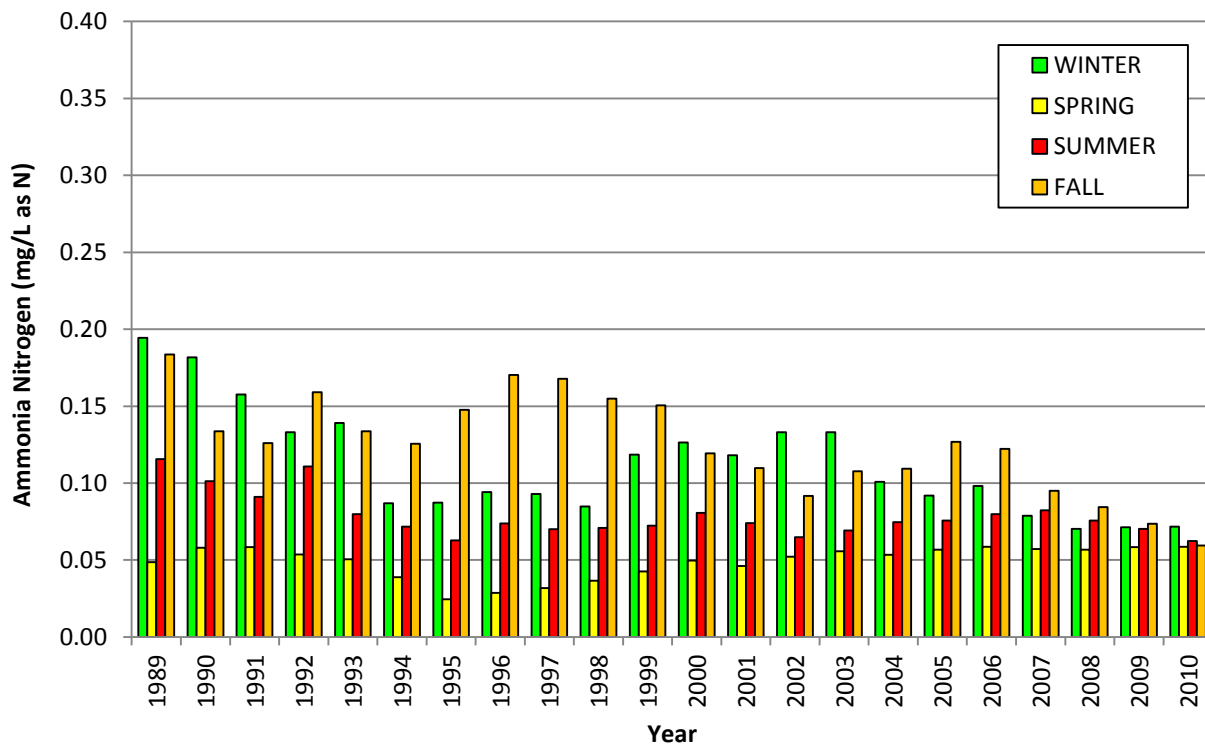


Figure 5-57 Five Year Running Average of Ammonia Nitrogen for Station ST70

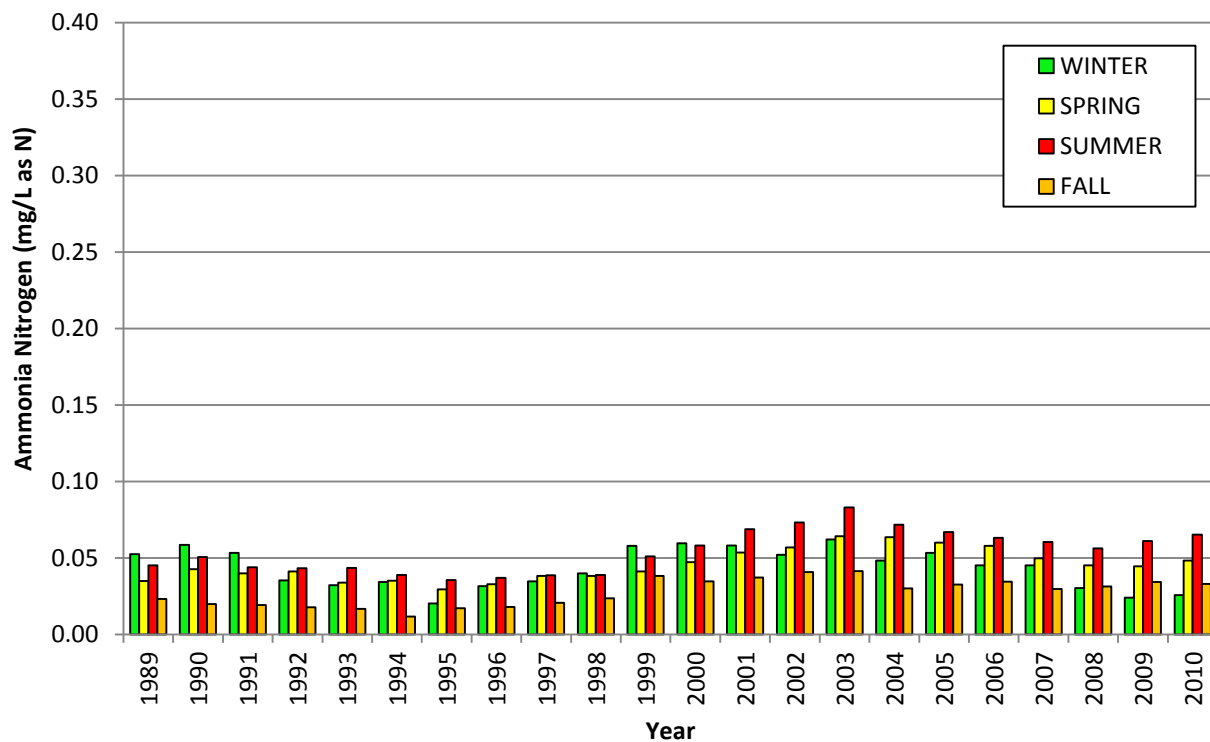


Figure 5-58 Five Year Running Average of TKN for Station BR02

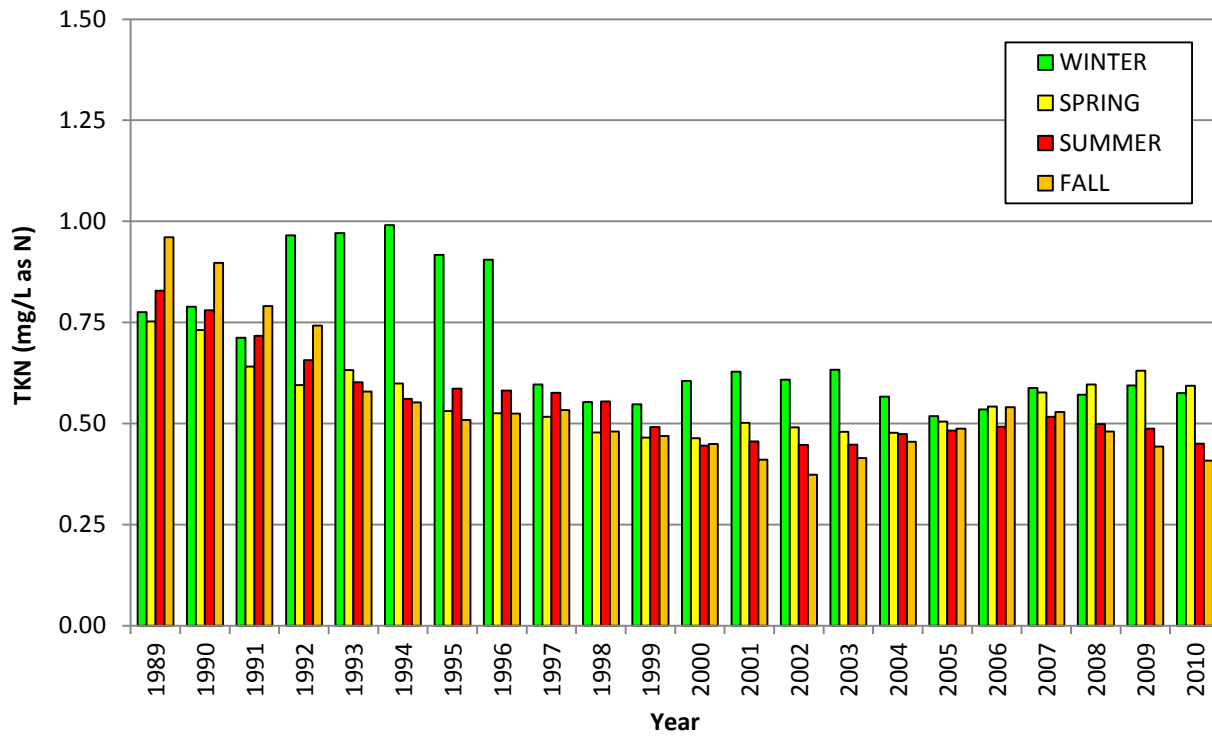


Figure 5-59 Five Year Running Average of TKN for Station BR03

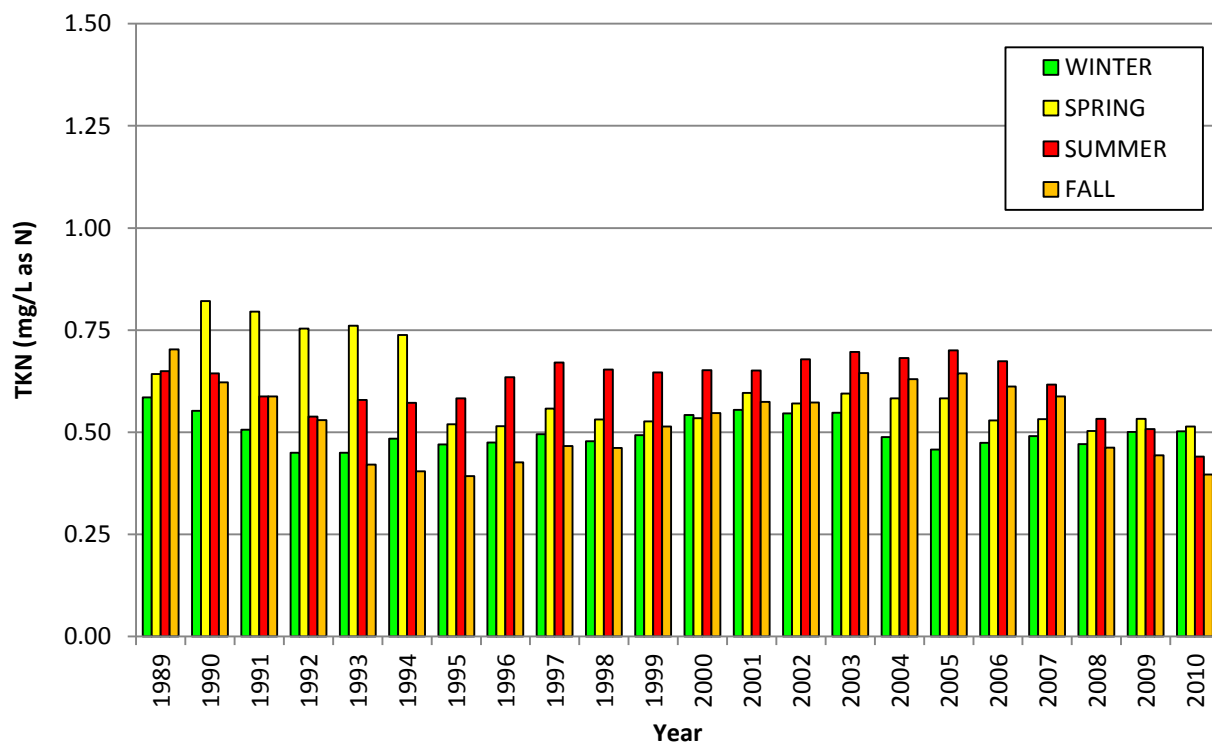


Figure 5-60 Five Year Running Average of TKN for Station BR04

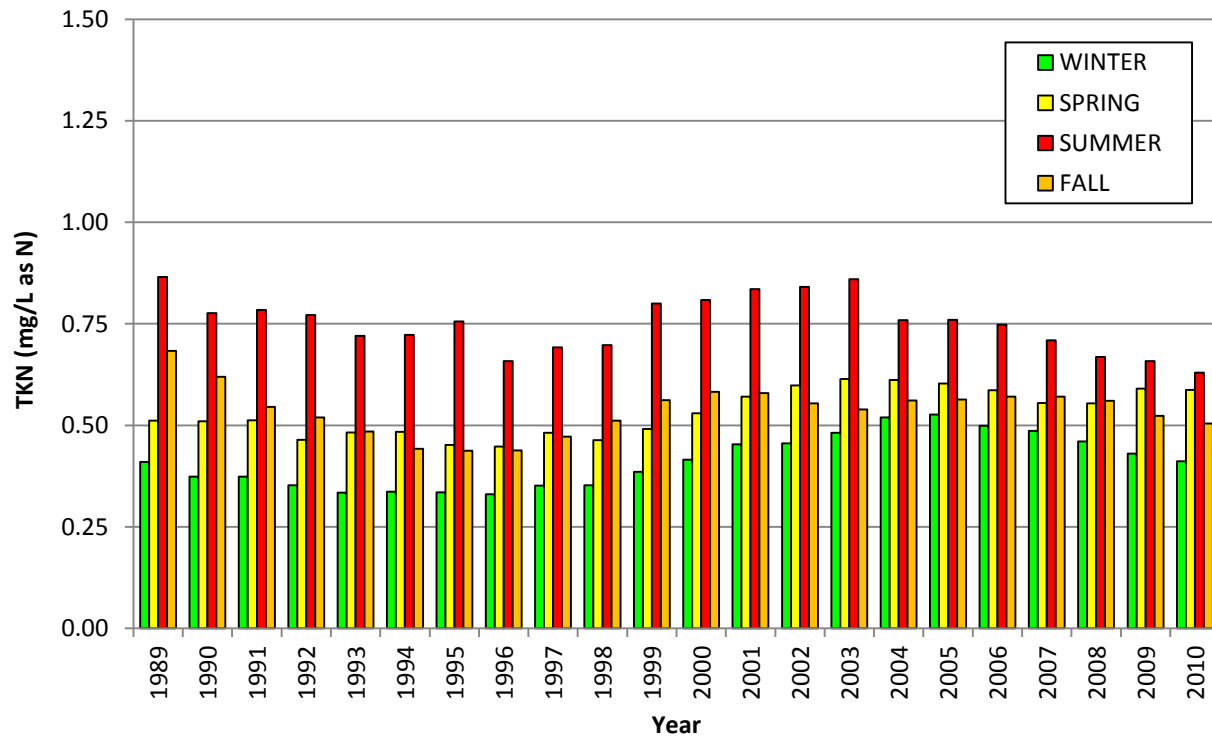


Figure 5-61 Five Year Running Average of TKN for Station BR05

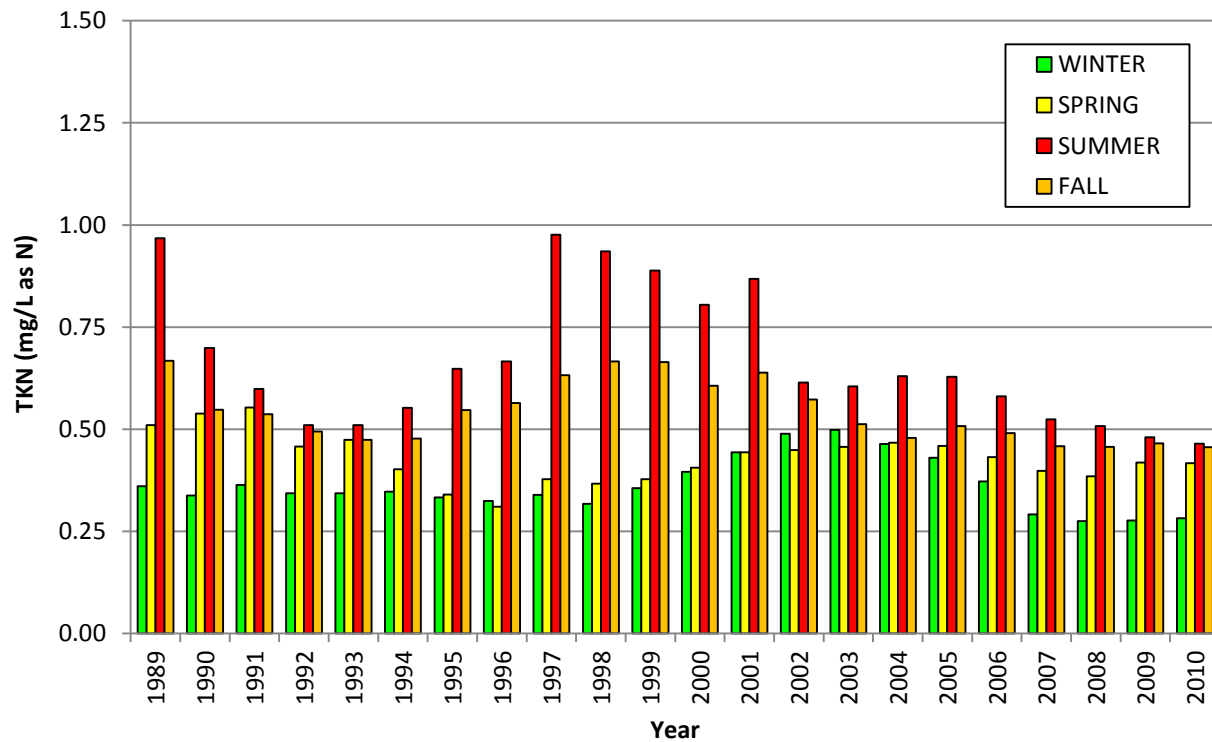


Figure 5-62 Five Year Running Average of TKN for Station BR06

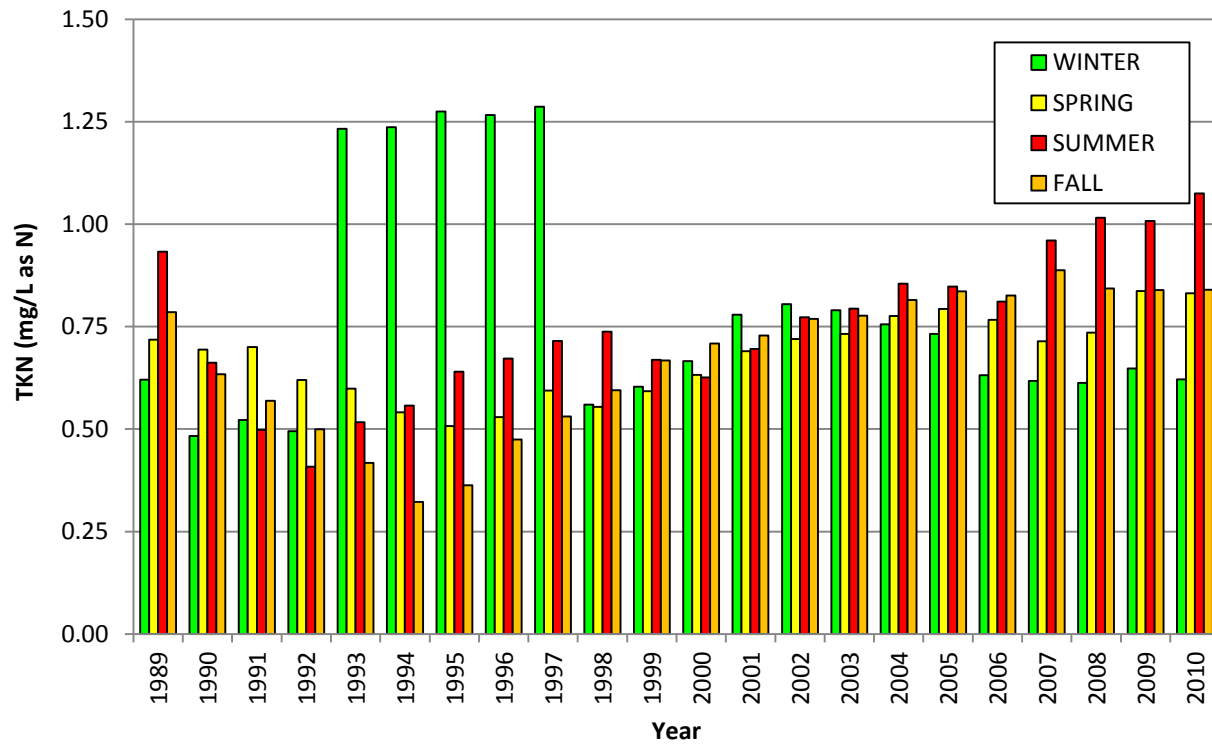


Figure 5-63 Five Year Running Average of TKN for Station BR07

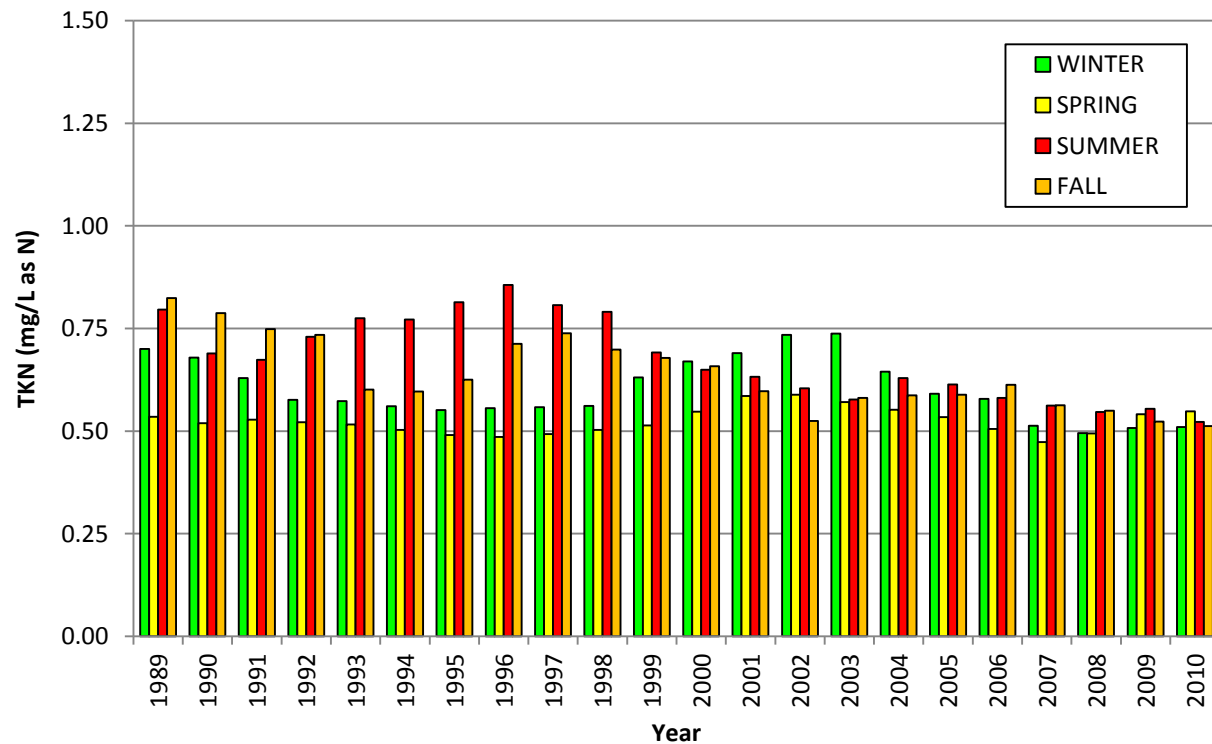


Figure 5-64 Five Year Running Average of TKN for Station ST70

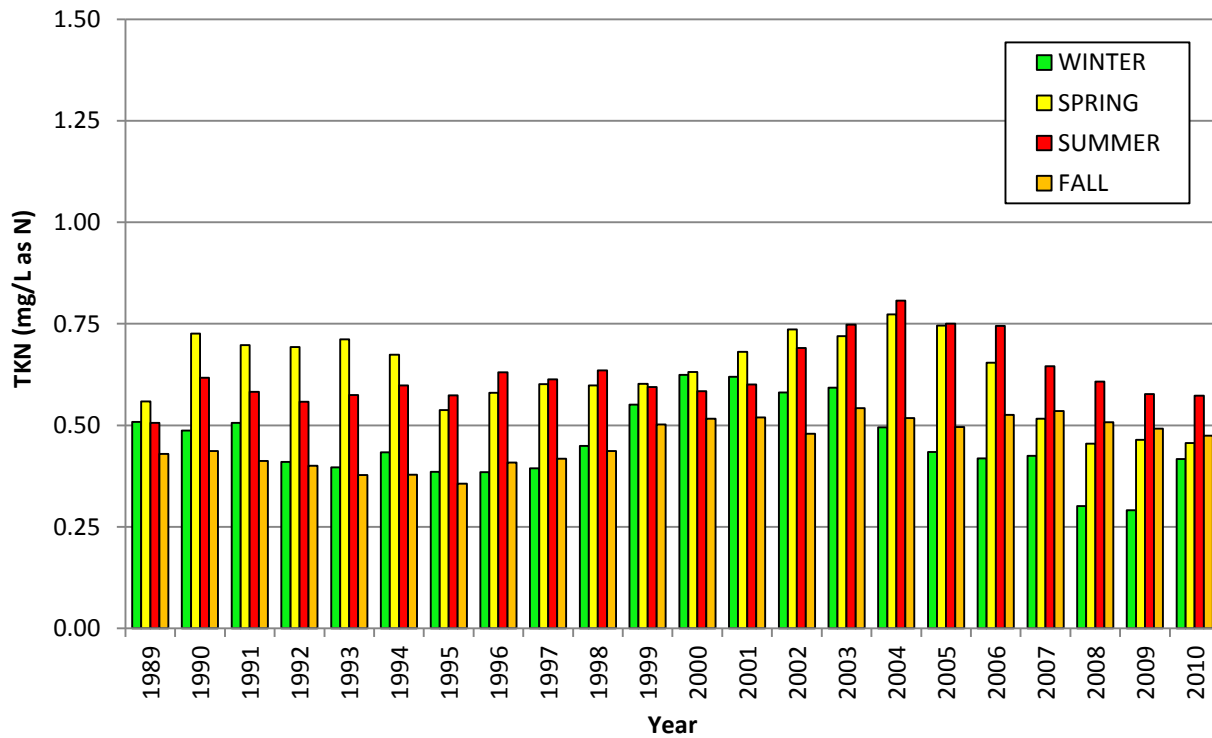


Figure 5-65 Five Year Running Average of TN for Station BR02

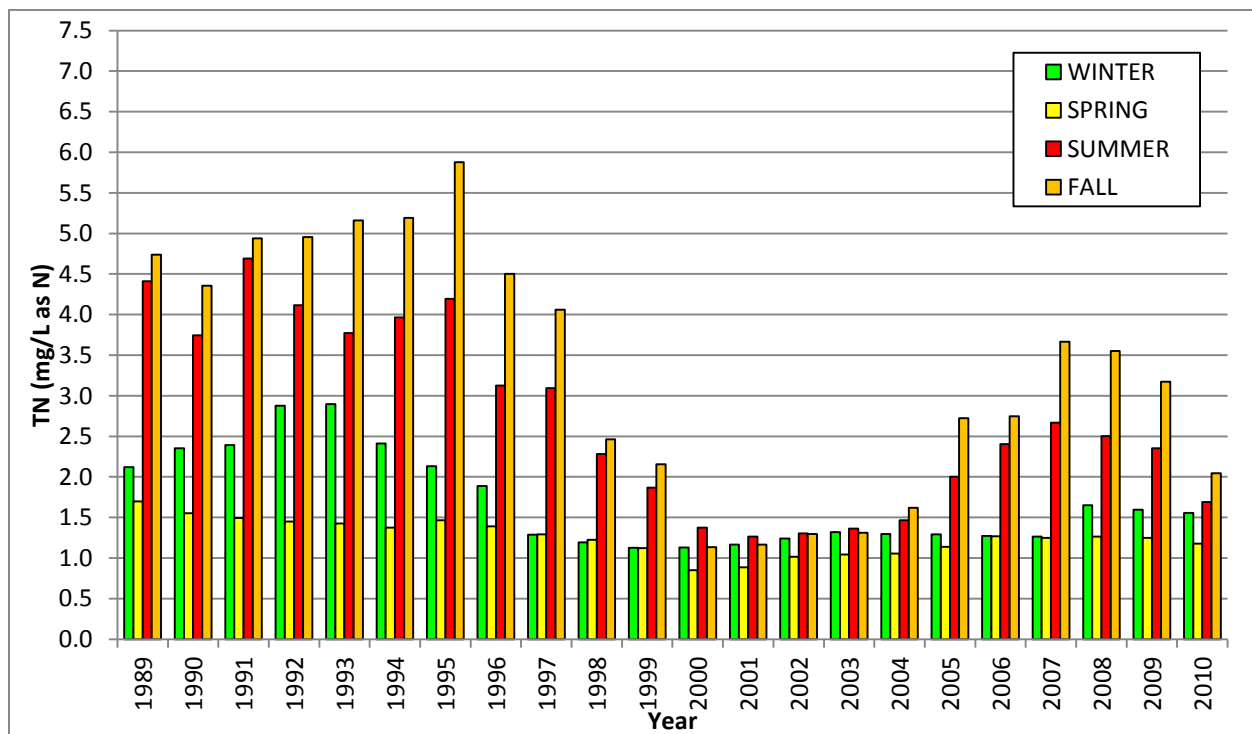


Figure 5-66 Five Year Running Average of TN for Station BR03

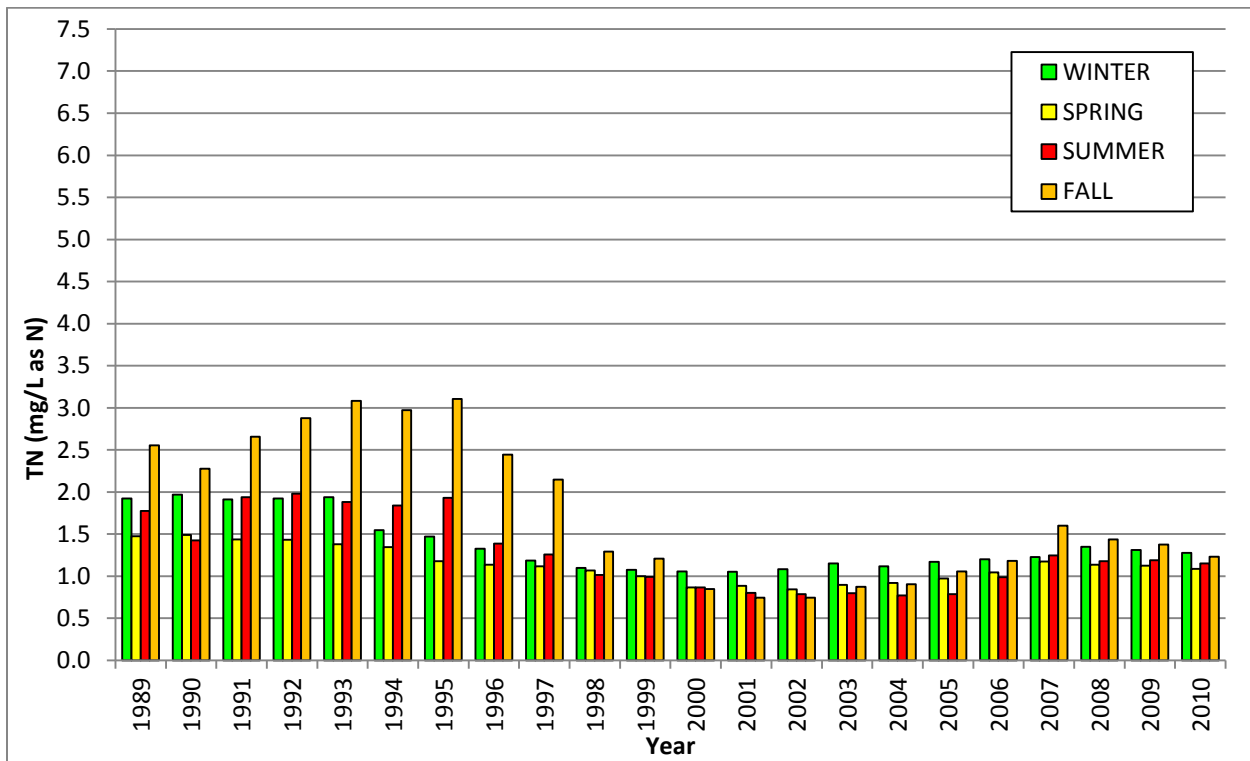


Figure 5-67 Five Year Running Average of TN for Station BR04

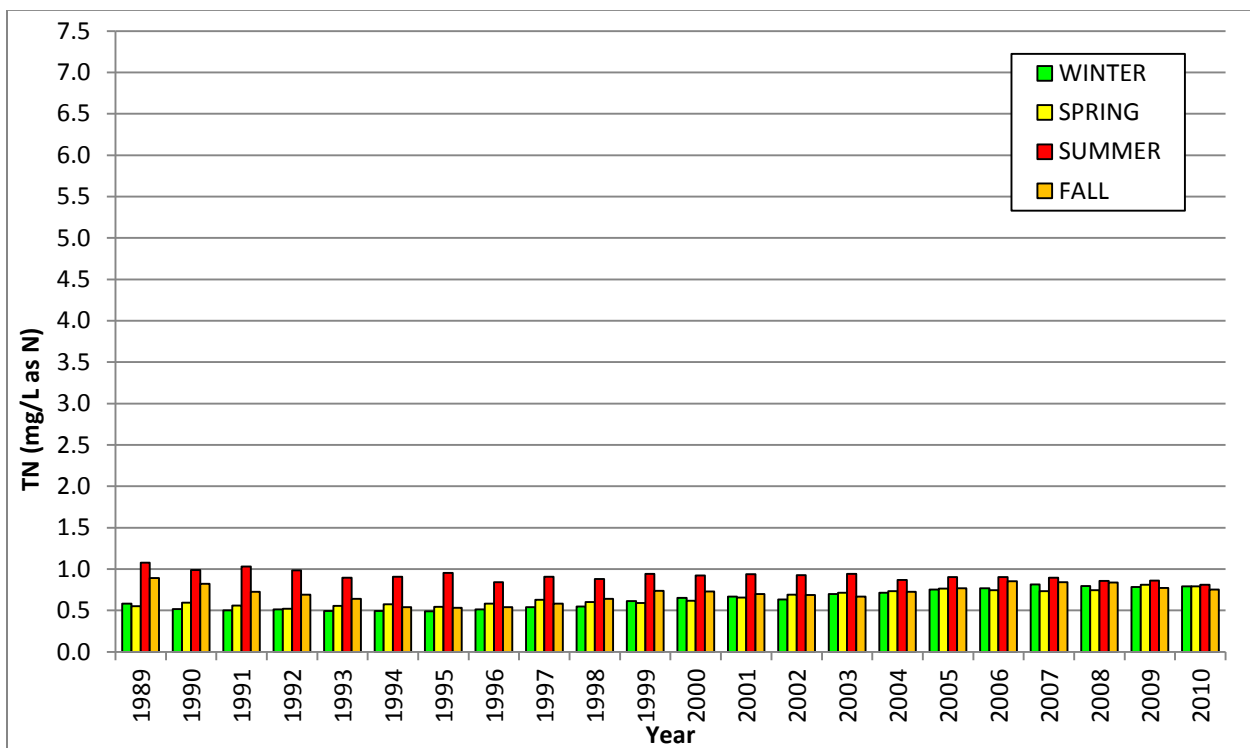


Figure 5-68 Five Year Running Average of TN for Station BR05

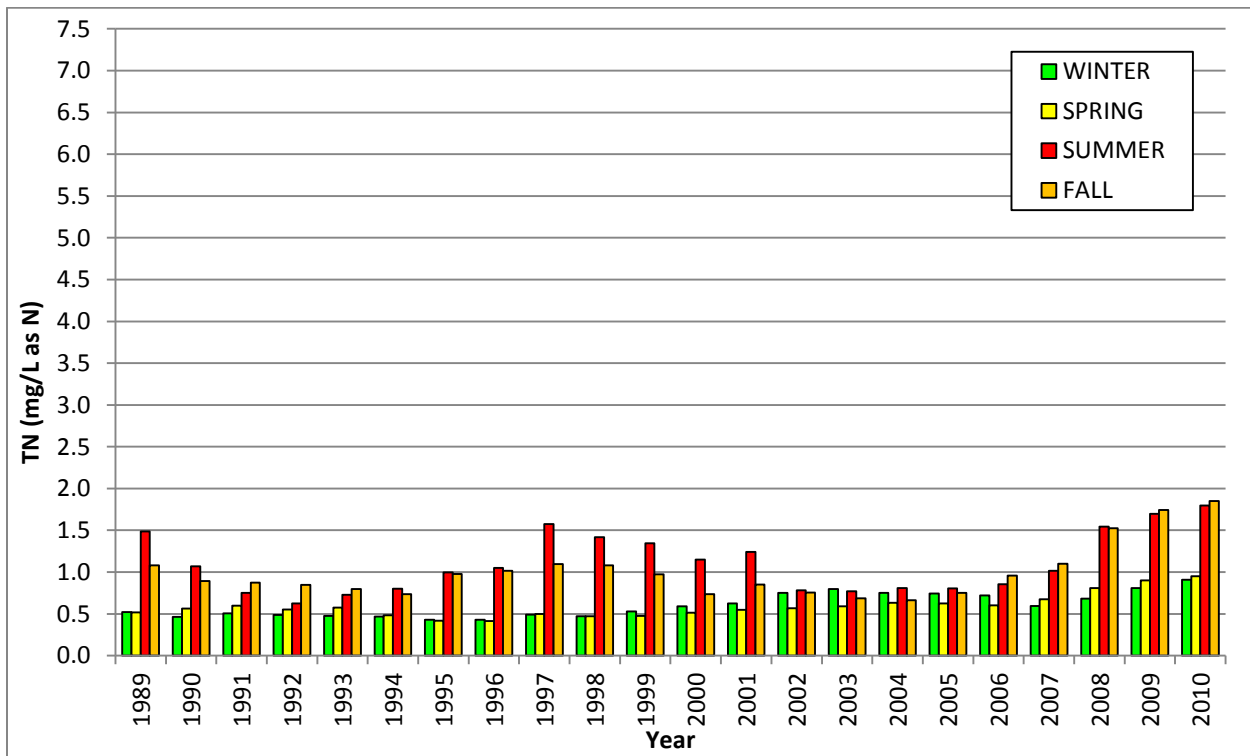


Figure 5-69 Five Year Running Average of TN for Station BR06

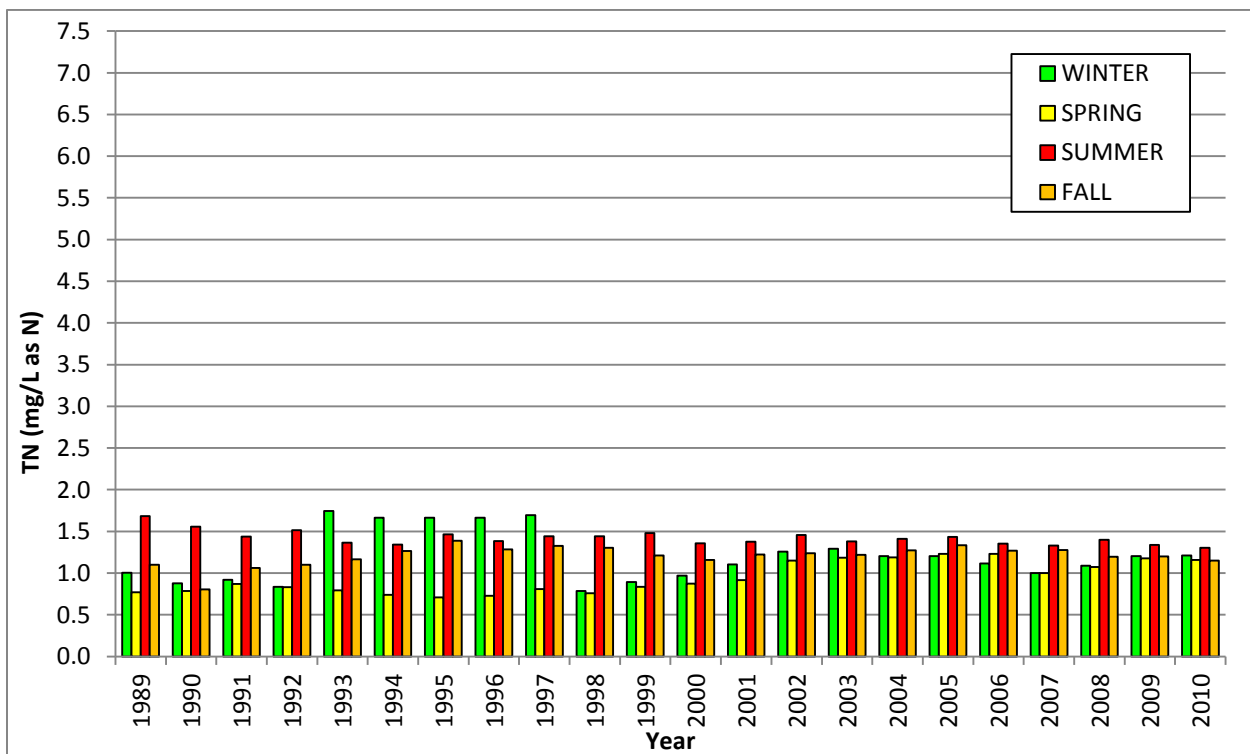


Figure 5-70 Five Year Running Average of TN for Station BR07

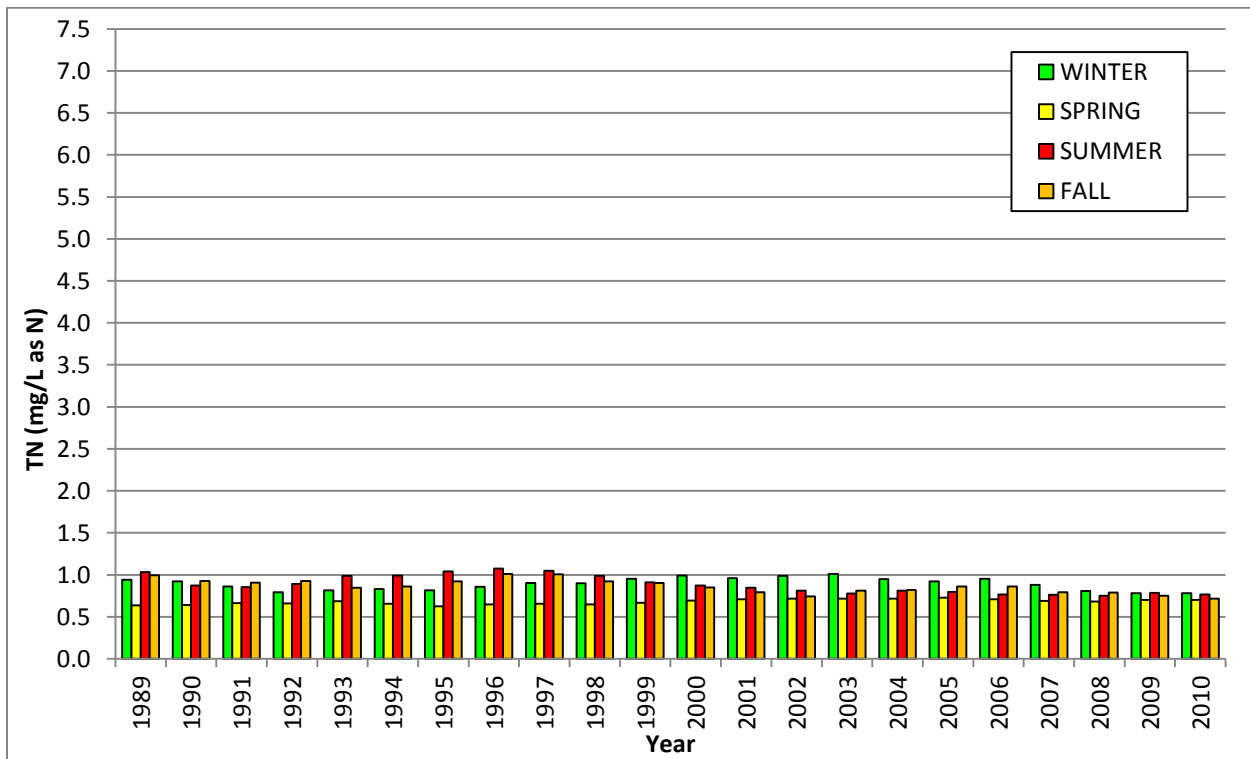
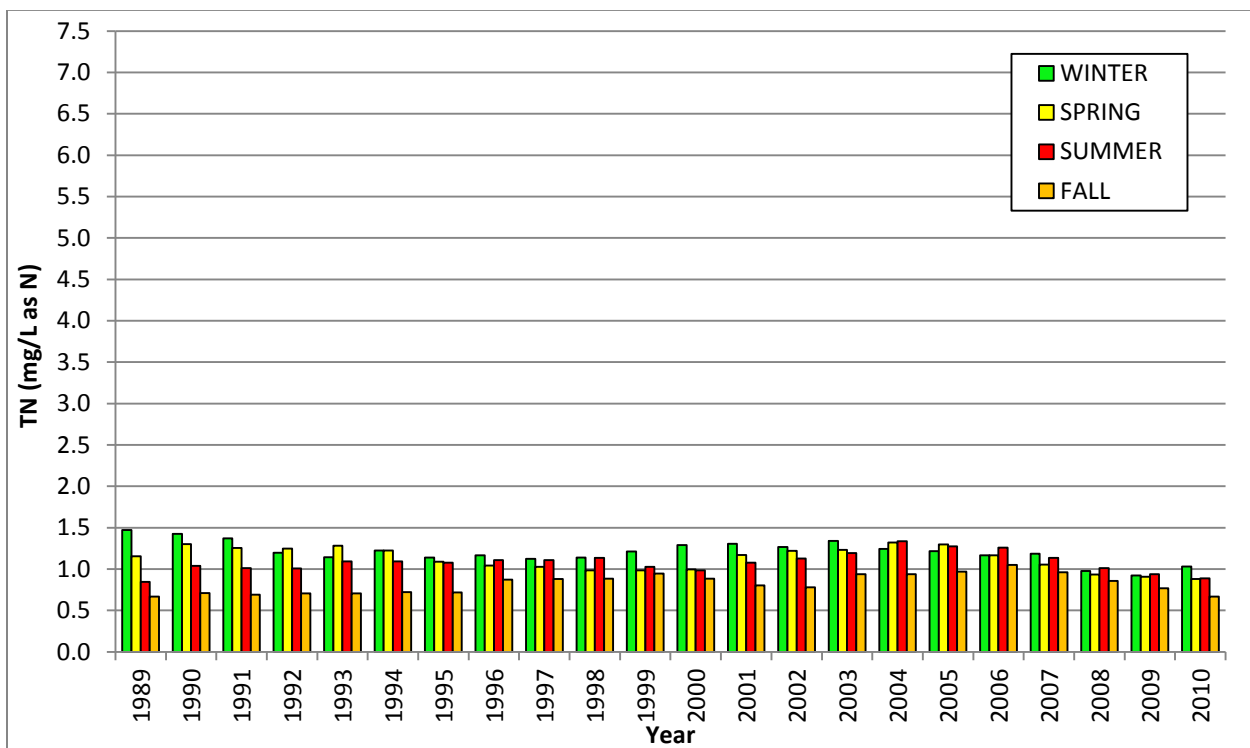


Figure 5-71 Five Year Running Average of TN for Station ST70



Phosphorus

Phosphorus is considered in most systems, including the Lake Manassas Reservoir, to be a limiting nutrient. That is, phosphorus is generally found in smaller concentrations when compared to nitrogen and other water quality constituents. Phosphorus plays a large role in the ecological distribution within a reservoir due largely in part to its role in biological metabolism. Phosphorus may be found in several different forms within a water body. However, orthophosphate phosphate (PO_4^{3-}) generally accounts for greater than 90 percent of all phosphorus within a system (Wetzel 2001). The OWML monitors for two forms of phosphorus: orthophosphate phosphorus and total phosphorus.

Five-year running averages for orthophosphate phosphorus (OP) concentrations for each stream sampling station are depicted in Figures 5-72 through 5-78.

- Orthophosphate phosphorus concentrations for the 1984 to 2010 period range from 0.1 mg/L as P to 1.55 mg/L as P, with the highest concentration of 1.55 mg/L as P detected at sampling station BR06 on 7-OCT-2005. The average orthophosphate phosphorus concentration for all sampling stations during this period was calculated to be 0.03 mg/L as P.
- Orthophosphate phosphorus nitrogen concentrations for the 2006 to 2010 period range from 0.01 mg/L as P to 0.96 mg/L as P, with the highest concentration of 0.96 mg/L as P detected at sampling station BR02 on 22-OCT-2007. The average orthophosphate phosphorus concentration for all sampling stations during this period was calculated to be 0.03 mg/L as P.
- The Mann-Kendall Seasonal Analysis for orthophosphate phosphorus concentrations shows an increasing trend at sampling station BR07, a decreasing trend at gaging station ST70 and no other significant trends detected at the remaining sampling stations for the 2006 to 2010 period.

As shown in Figure 5-69 there is an apparent significant increase in orthophosphate phosphorus concentrations at sampling station BR06 during the 2005 to 2009 (fall) period. However, this increase appears to be a result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with fall five year running averages from 2000 to 2005 is a result of a single sampling event with an elevated orthophosphate phosphorus concentration: 1.9 mg/L as P on 7-OCT-2005.

Five-year running averages for total phosphorus (TP) concentrations for each stream sampling station are depicted in Figures 5-79 through 5-85.

- Total phosphorus concentrations for the 1984 to 2010 period range from 0.005 mg/L as P to 2.03 mg/L as P, with the highest concentration of 2.03 mg/L as P detected at sampling station BR06 on 7-OCT-2005. The average total phosphorus concentration for all sampling stations during this period was calculated to be 0.08 mg/L as P.
- Total phosphorus nitrogen concentrations for the 2006 to 2010 period range from 0.005 mg/L as P to 0.94 mg/L as P, with the highest concentration of 0.94 mg/L as P detected at sampling station BR02 on 22-OCT-2007. The average total phosphorus concentration for all sampling stations during this period was calculated to be 0.08 mg/L as P.
- The Mann-Kendall Seasonal Analysis for total phosphorus concentrations shows an increasing trend at sampling station BR03, decreasing trends at stations BR04, BR05 and ST70 and no other significant trends detected at the remaining sampling stations for the 2006 to 2010 period.

As shown in Figure 5-76 there is an apparent significant increase in total phosphorus concentrations at sampling station BR06 during the 2005 to 2009 (fall) period. However, this

increase appears to be a result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with fall five year running averages from 2000 to 2005 is a result of a single sampling event with an elevated total phosphorus concentration: 2.03 mg/L as P on 7-OCT-2005.

Figure 5-72 Five Year Running Average of Orthophosphate Phosphorus for Station BR02

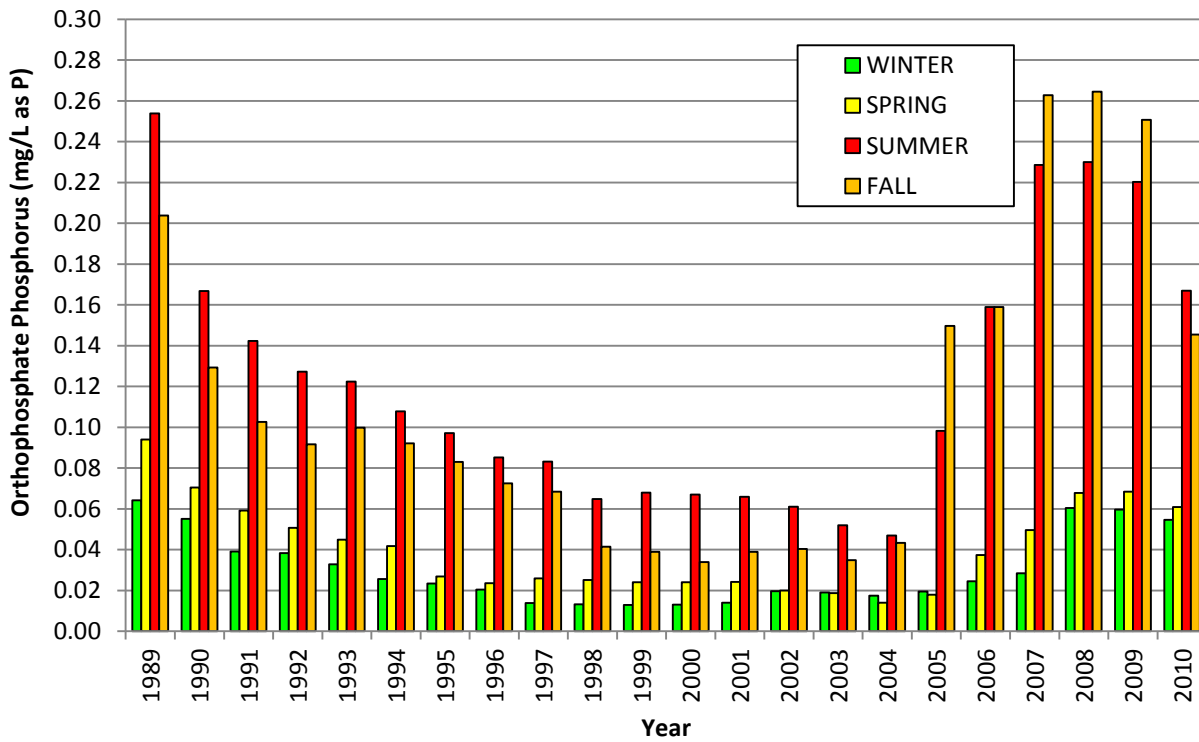


Figure 5-73 Five Year Running Average of Orthophosphate Phosphorus for Station BR03

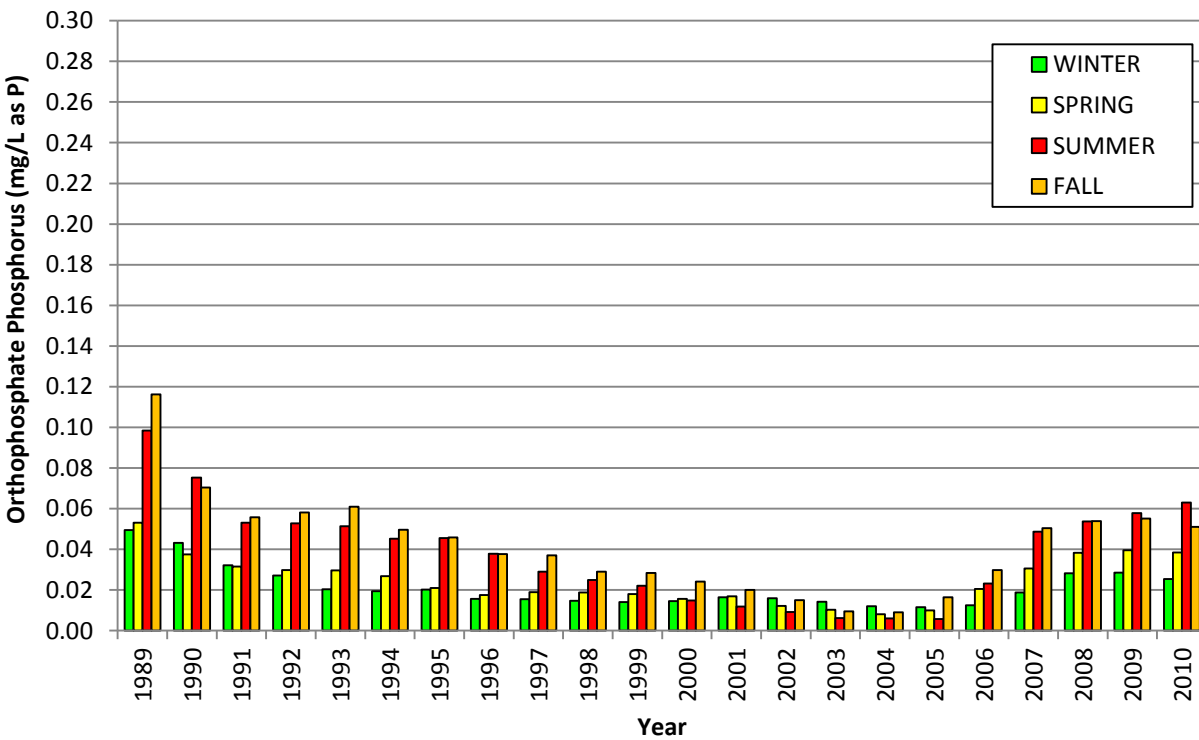


Figure 5-74 Five Year Running Average of Orthophosphate Phosphorus for Station BR04

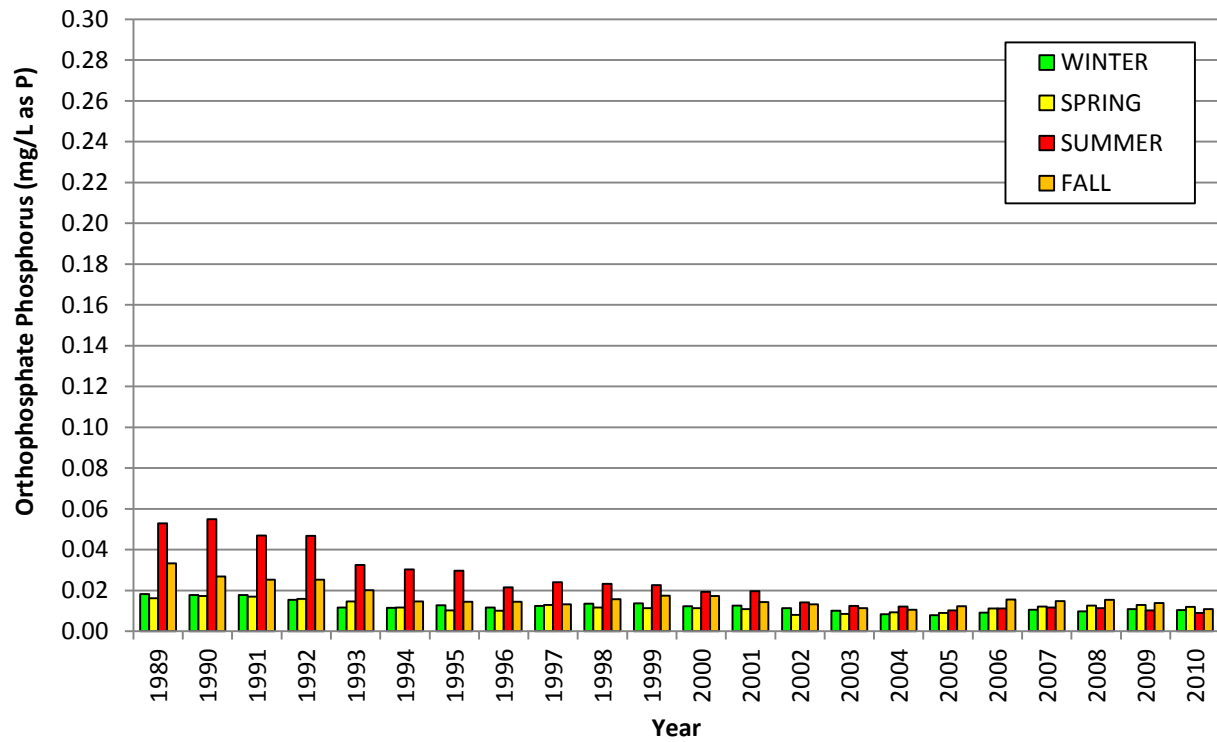


Figure 5-75 Five Year Running Average of Orthophosphate Phosphorus for Station BR05

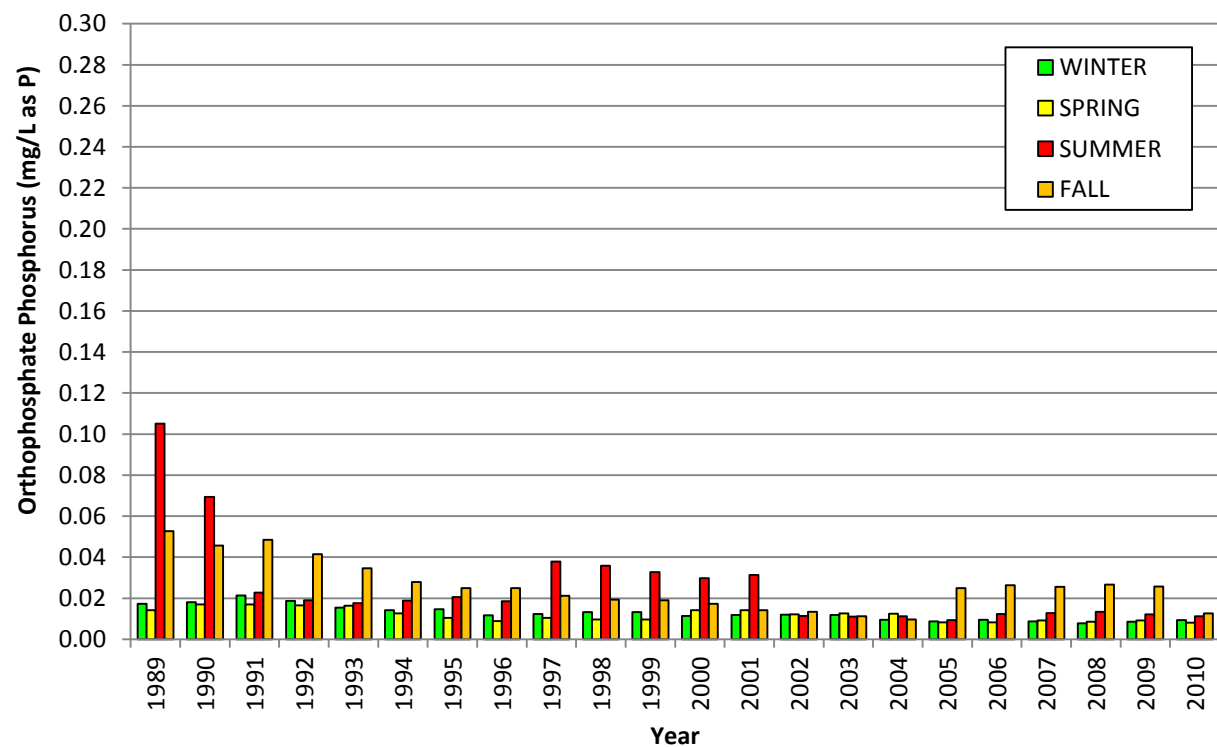


Figure 5-76 Five Year Running Average of Orthophosphate Phosphorus for Station BR06

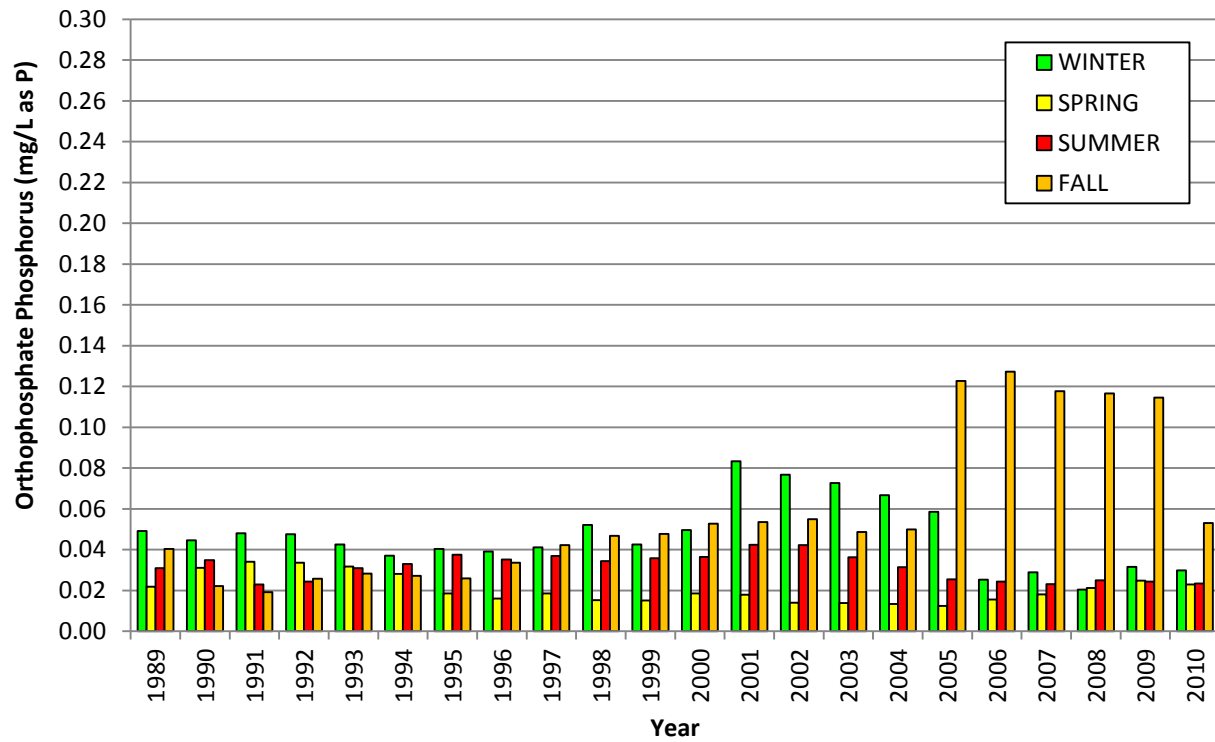


Figure 5-77 Five Year Running Average of Orthophosphate Phosphorus for Station BR07

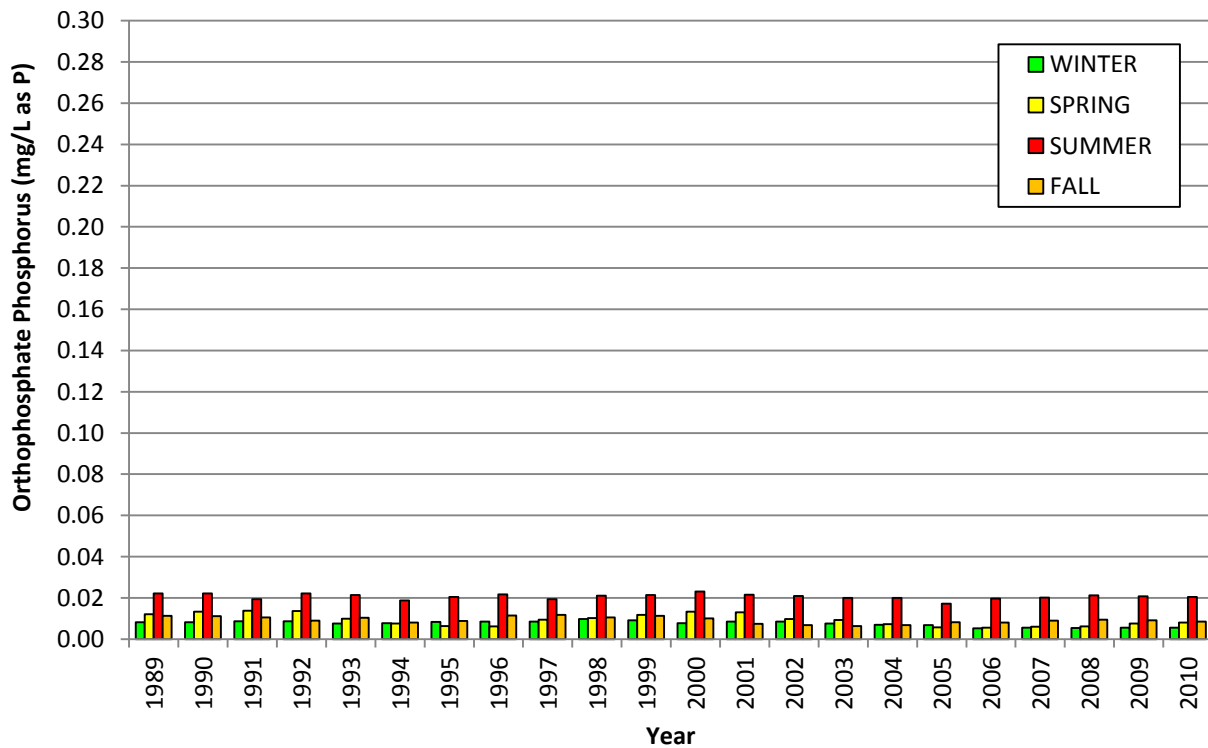


Figure 5-78 Five Year Running Average of Orthophosphate Phosphorus for Station ST70

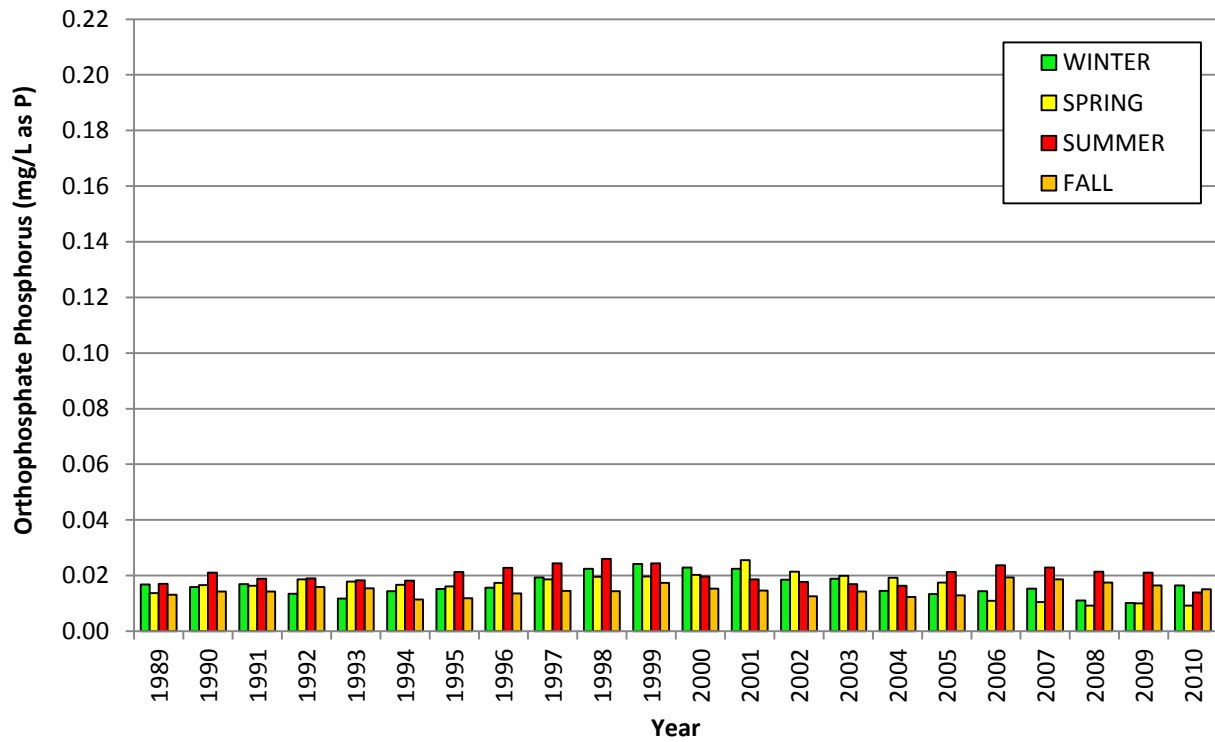


Figure 5-79 Five Year Running Average of Total Phosphorus for Station BR02

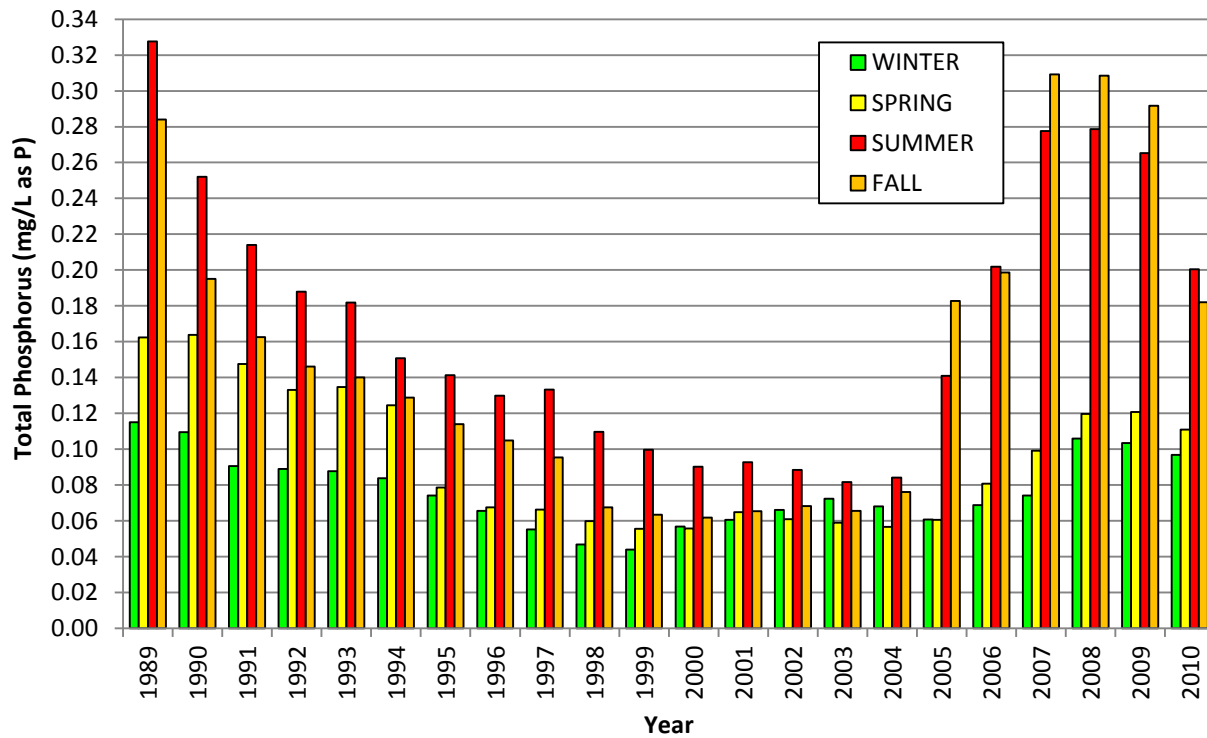


Figure 5-80 Five Year Running Average of Total Phosphorus for Station BR03

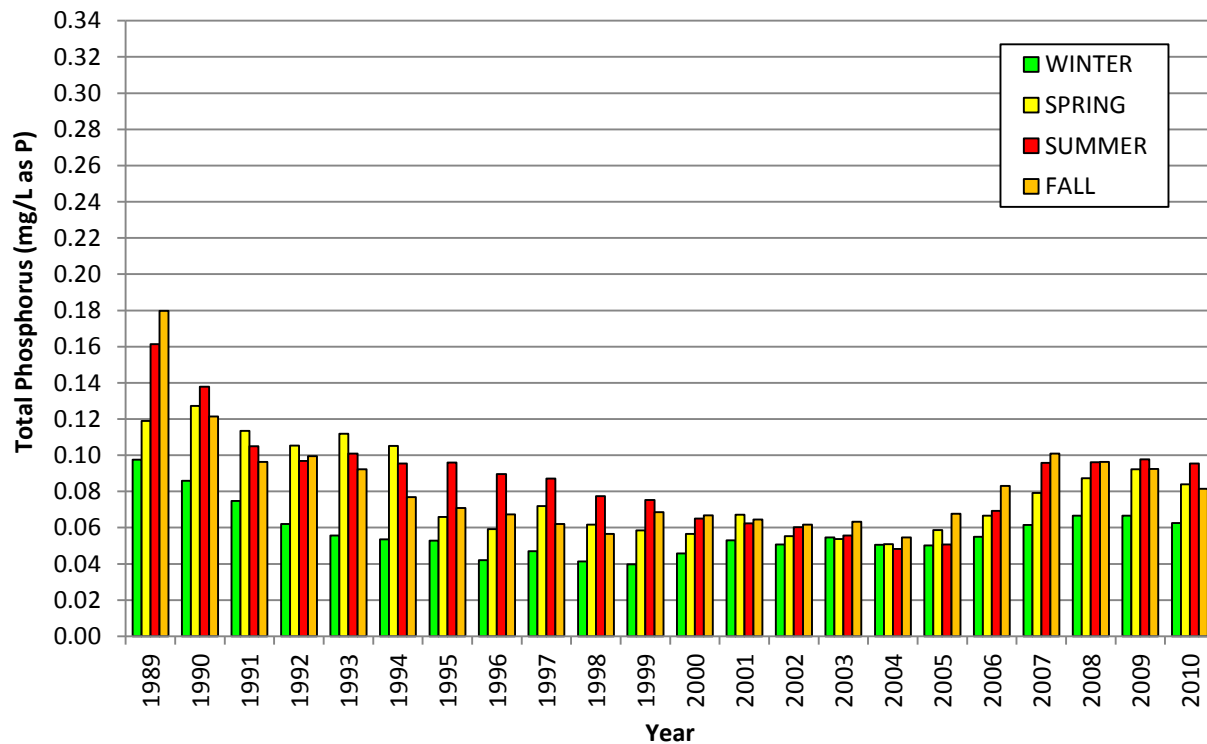


Figure 5-81 Five Year Running Average of Total Phosphorus for Station BR04

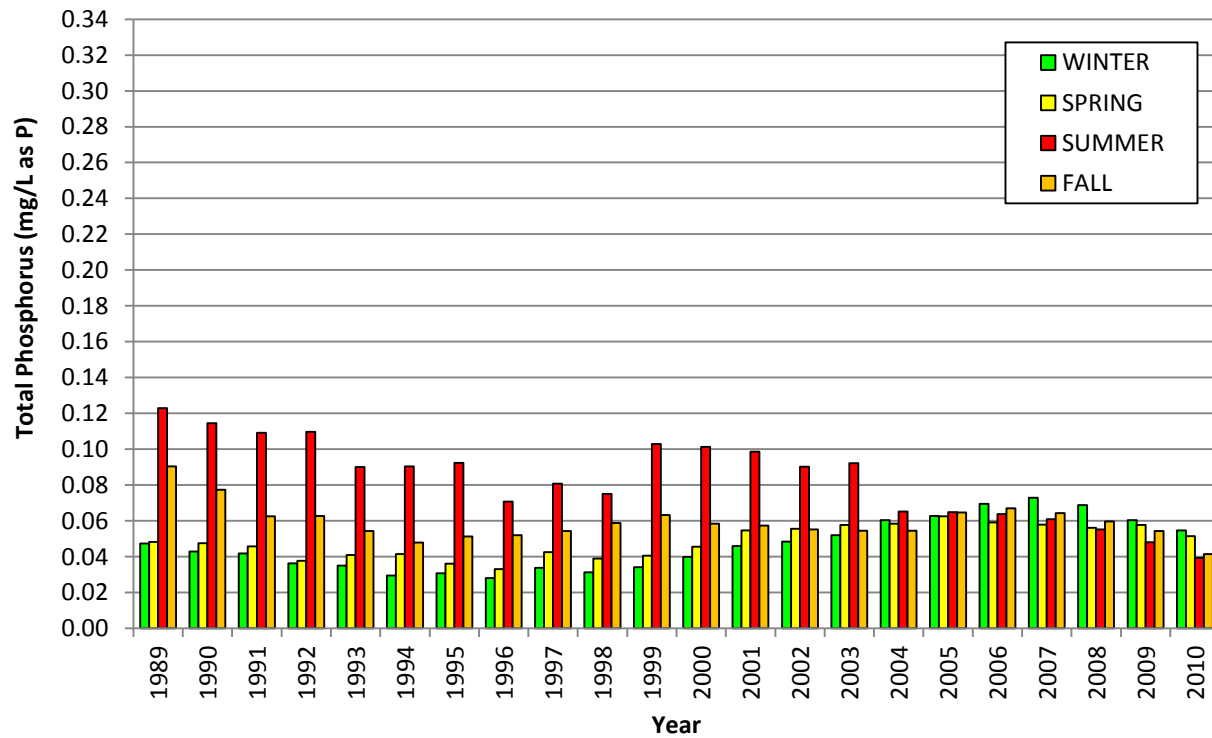


Figure 5-82 Five Year Running Average of Total Phosphorus for Station BR05

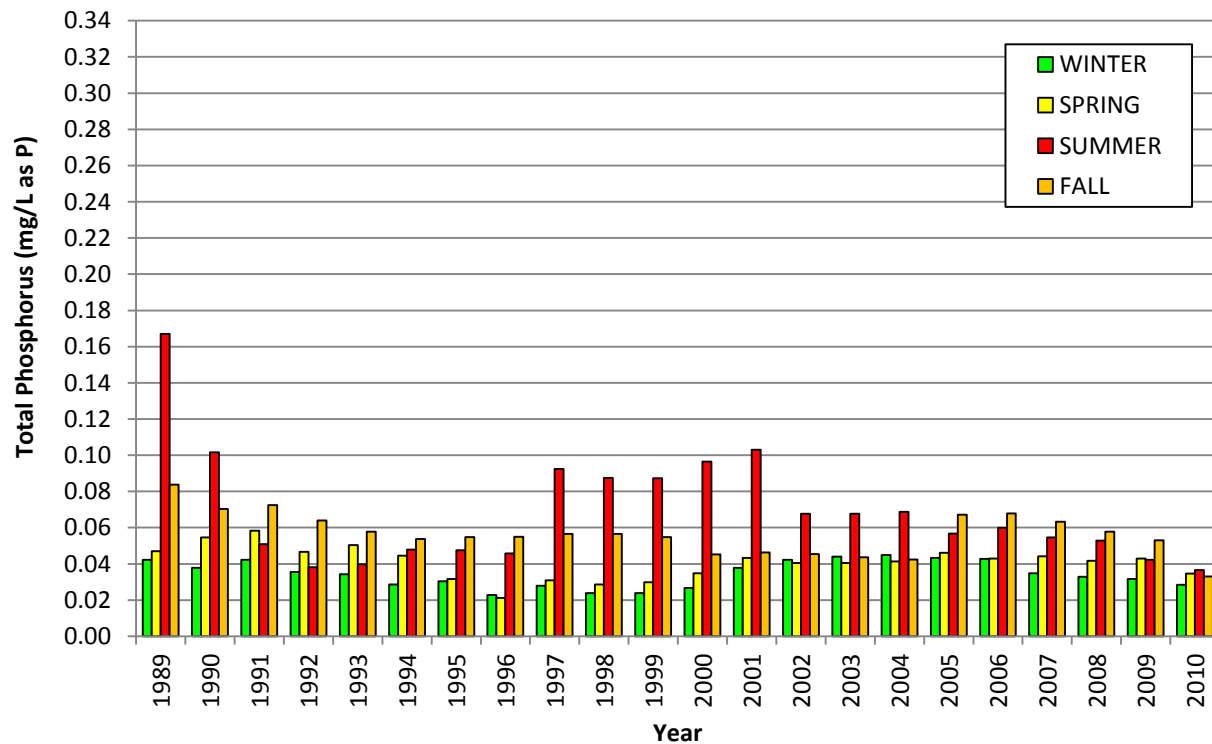


Figure 5-83 Five Year Running Average of Total Phosphorus for Station BR06

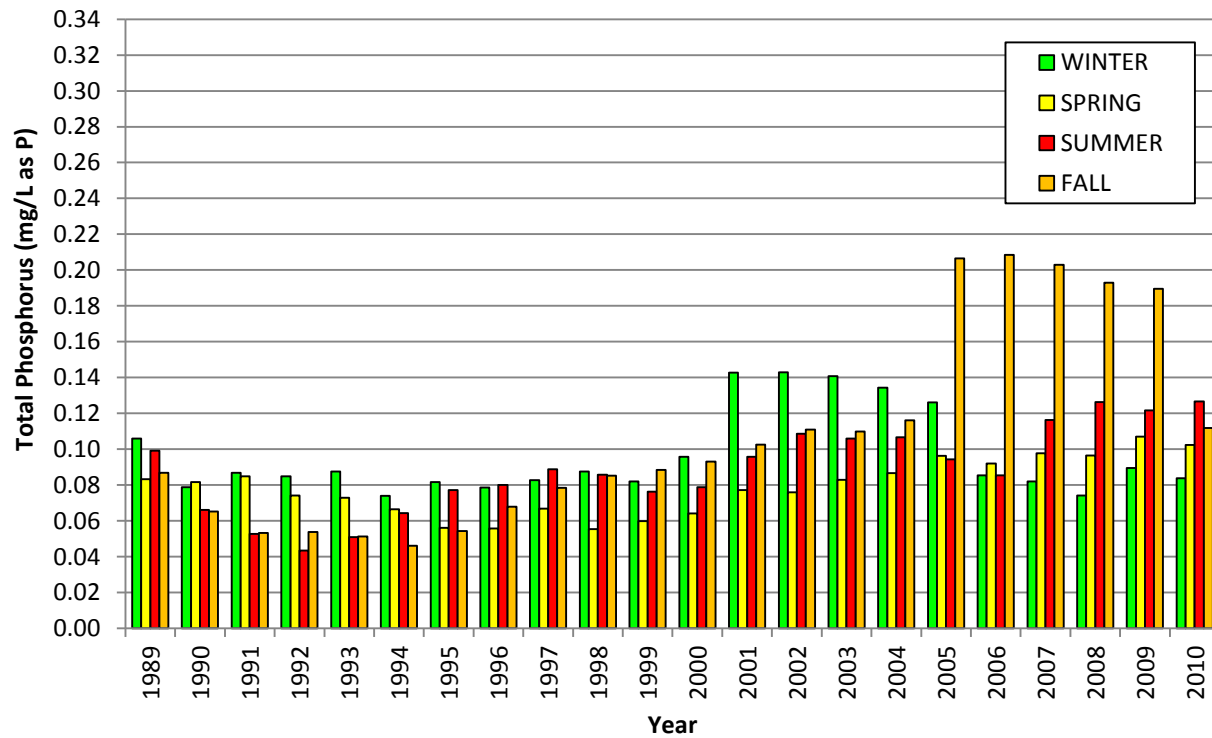


Figure 5-84 Five Year Running Average of Total Phosphorus for Station BR07

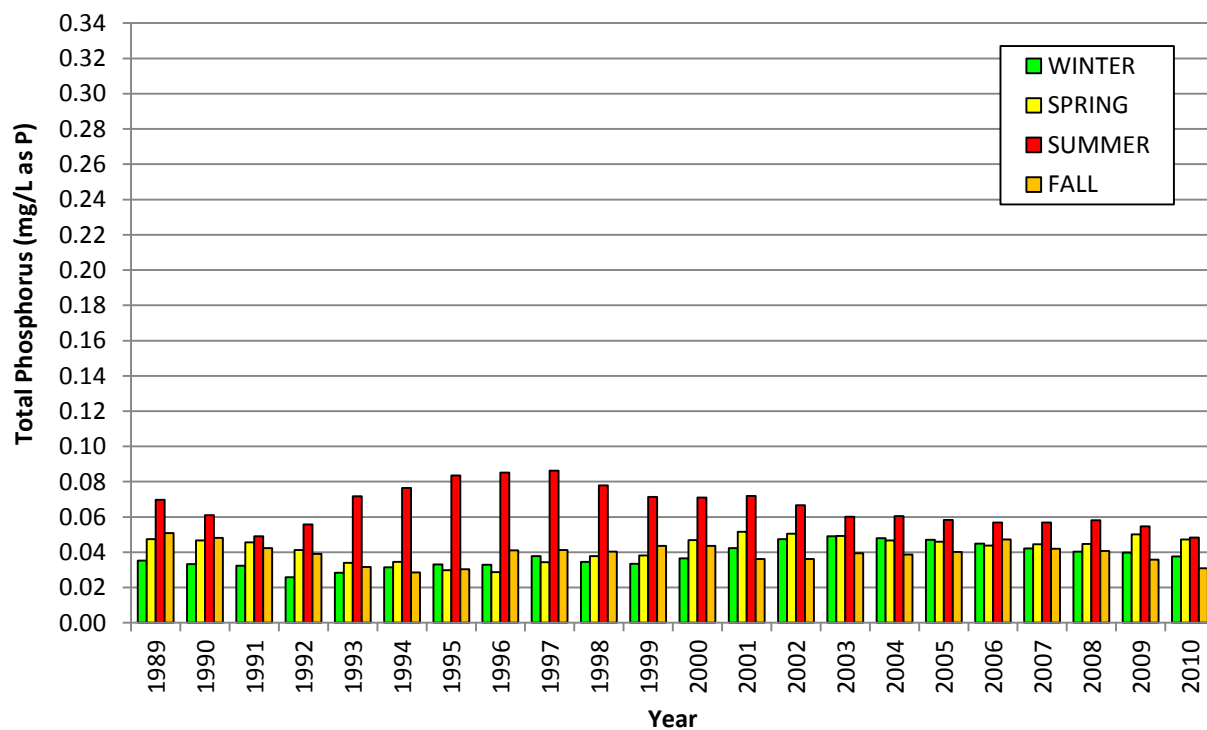
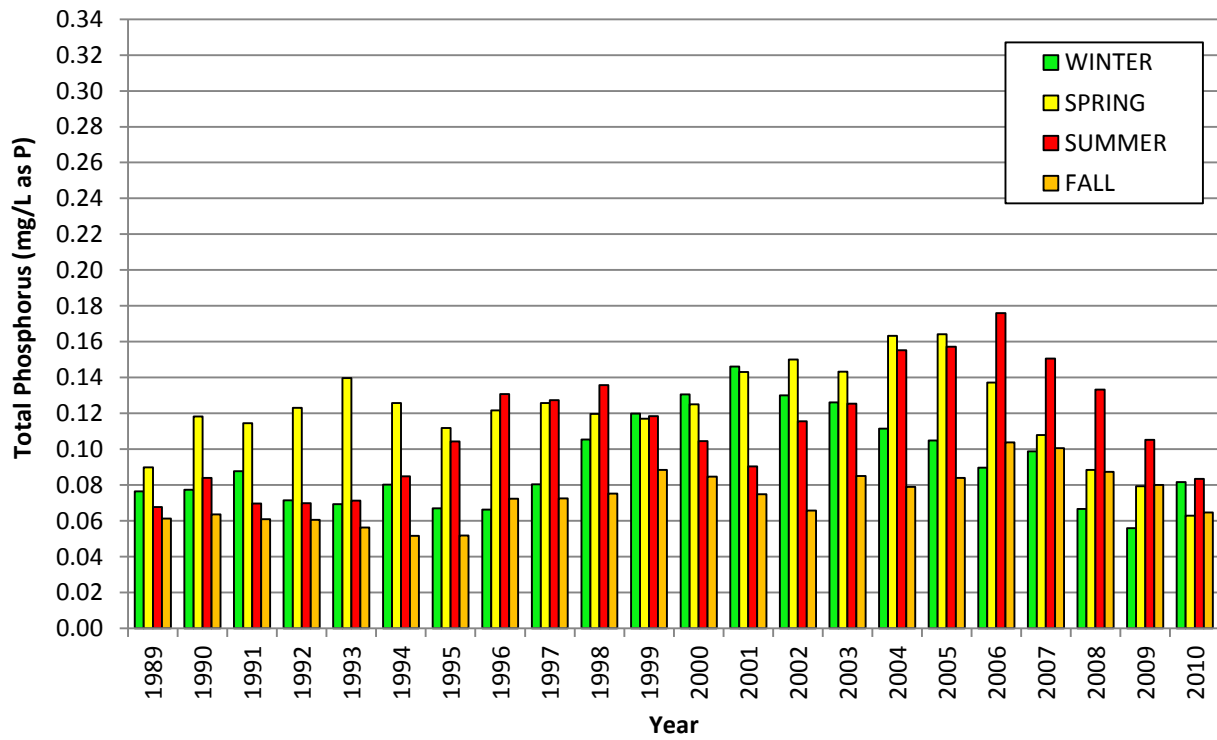


Figure 5-85 Five Year Running Average of Total Phosphorus for Station ST70



Nutrient Loading Rates to Lake Manassas from Broad Run

As discussed in previous chapters of this report, nutrient loading plays a large role in the enrichment of a lake or reservoir. As part of the OWML’s monitoring program, loading rates are determined for Lake Manassas for the constituents listed in Table 5-3. Because Broad Run represents approximately 70 percent of the contribution associated with Lake Manassas, stream sampling station ST70 is used to determine these loading rates.

The method for determining these loading rates is discussed in further detail in Chapter 4 of this report. As shown in Table 5-3, the loading rates of nutrients per day during the 2006 to 2010 baseline period have decreased for all constituents considered. This trend correlates with the observations discussed above where Mann-Kendall seasonal analysis trends reported decreasing concentrations for total phosphorus, oxidized nitrogen and total Kjeldahl nitrogen. This trend is encouraging, as the 2001-2005 baseline period showed increases for all constituents over the 1996-2000 period. However, it should be noted that 2010 represented the highest loading values measured during the new 2006-2010 baseline period.

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

Nutrient (lbs/day)	Period					
	1981 - 1985	1986 - 1990	1991 - 1995	1996 - 2000	2001 - 2005	2006 - 2010
Oxidized Nitrogen (Ox-N)	215.8	125.6	180.3	112.9	188.7	131.3
Ammonia Nitrogen (NH ₃ -N)	16.7	8.5	6.3	9.4	13.1	9.8
Total Kjeldahl Nitrogen (TKN)	205.2	143.5	113.8	134.4	171.4	126.5
Total Phosphorus (TP)	39.2	26.2	24.3	34.4	38.2	21.1
Nutrient (lbs/day)	Period					
	2006	2007	2008	2009	2010	
Oxidized Nitrogen (Ox-N)	169.5	116.6	92.2	98.3	179.3	
Ammonia Nitrogen (NH ₃ -N)	9.7	2.67	13.4	9.3	13.8	
Total Kjeldahl Nitrogen (TKN)	150.2	40.2	91.0	150.0	200.5	
Total Phosphorus (TP)	38.2	5.7	10.9	17.0	33.6	

A second loading analysis was conducted for comparative purposes. As previously described, the gauging station used to determine daily flow values is located on Broad Run which represents approximately 70 percent of the load entering Lake Manassas. This analysis presents a scaled up estimate of the total loading in Lake Manassas. It should be noted that these calculations do not give consideration to the nutrient concentrations found in other tributaries to Lake Manassas. Instead the values collected at sampling station ST70 are used alongside scaled up daily flow values to estimate a total (100 percent) load. Table 5-4 presents the scaled-up loading values for the 2006 to 2010 baseline period.

Table 5-4 Average “Scaled Up” Nutrient Loading Rates in Broad Run (ST70)

Nutrient (lbs/day)	Period				
	2006	2007	2008	2009	2010
Oxidized Nitrogen (Ox-N)	242.1	166.6	131.8	140.4	256.2
Ammonia Nitrogen (NH ₃ -N)	13.8	3.8	19.1	13.2	019.7
Total Kjeldahl Nitrogen (TKN)	214.6	57.5	130.1	214.3	286.4
Total Phosphorus (TP)	54.6	8.1	15.5	24.3	48.0

Drainage Basin Analysis – Unnamed Tributary Monitored by Station BR05

Lake Manassas sampling station LM05 is located on an unnamed tributary that generally flows north to south and enters the lake along the northwestern shore. As discussed above, increasing trends for five-year running averages in pH, total alkalinity, specific conductivity, oxidized nitrogen and total suspended solids are apparent for the new baseline period from December 2005 to November 2010. For example, five-year running averages for pH during summer months increase from approximately 6.8 in 2005 to approximately 7.4 in 2010. The trend for five-year running averages is even more apparent for total alkalinity at station BR05 which increases from approximately 80 mg/L as CaCO₃ in summer 2005 to over 200 mg/L as CaCO₃ in summer 2010.

In response to these increasing trends, a limited analysis of the drainage area surrounding this unnamed tributary was conducted to evaluate the potential impacts that recent development may be having. Because a five-year running average value for any given year also includes data collected from the four years prior to that year, this limited analysis looks at the roughly 10 year period leading up to the significant increases measured during the 2006 to 2010 baseline period.

The unnamed tributary drains an area encompassing approximately 850 acres in Gainesville, Virginia (USGS 2009). Figures 5-86 through 5-88 depict the approximate drainage area boundaries on available historical aerial photographs. As shown in the progression from December 2002 (Figure 5-86) to September 2005 (Figure 5-87) to April 2011 (Figure 5-88), the area has been subject to increasing development and land use changes. Most notable are the four residential communities that have been constructed. Centrally located within the drainage area is the Estates at Breyerton residential community which first appears under construction in 2005. This community, now complete, includes approximately 112 single-family homes and transects the unnamed tributary. The Regents at Lake Manassas residential community which is still under construction is located along the eastern shore of the unnamed tributary just south of Lee Highway (Route 29). This community appears to be slated for a total of 64 single-family homes. The third residential community, which is apparent in the southeastern portion of the drainage area, is a portion of the Stonewall Country Club residential development which appears under construction in the 2002 aerial photograph and complete in the 2005 aerial photograph. A fourth residential community (The Reserve at Lake Manassas) is located along the western shore of the unnamed tributary south of Lee Highway and is only partially located within the drainage area associated with the unnamed tributary. Additionally apparent in the 2011 aerial photograph is the Shops at Stonewall retail center and associated parking lot.

Figure 5-86 Aerial View of the Unnamed Tributary Drainage Area Associated with Sampling Station BR05 (December 2002)



Source: 38°47'20.05" N, 77°39'05.63" W. [Google Earth](#). December 30, 2002. Accessed April 2013.

Figure 5-87 Aerial View of the Unnamed Tributary Drainage Area Associated with Sampling Station BR05 (September 2005)



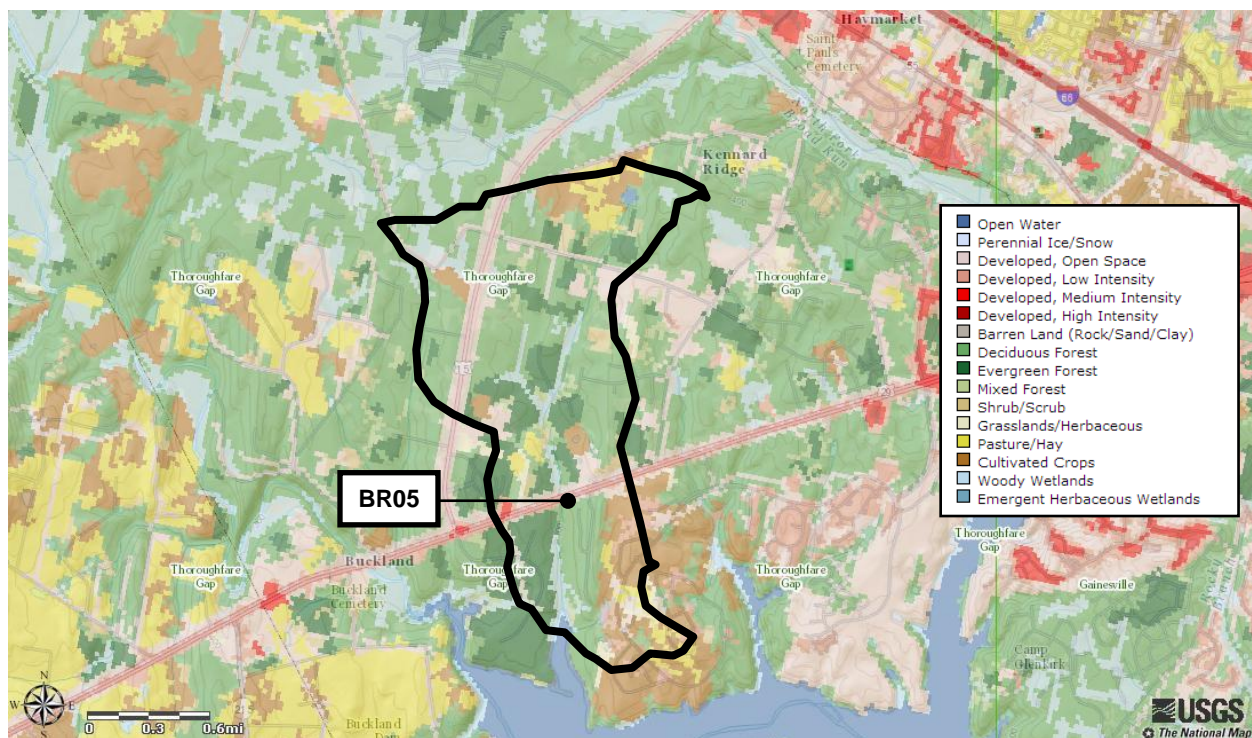
Source: 38°47'20.05" N, 77°39'05.63" W. [Google Earth](#). September 22, 2005. Accessed April 2013.

Figure 5-88 Aerial View of the Unnamed Tributary Drainage Area Associated with Sampling Station BR05 (April 2011)



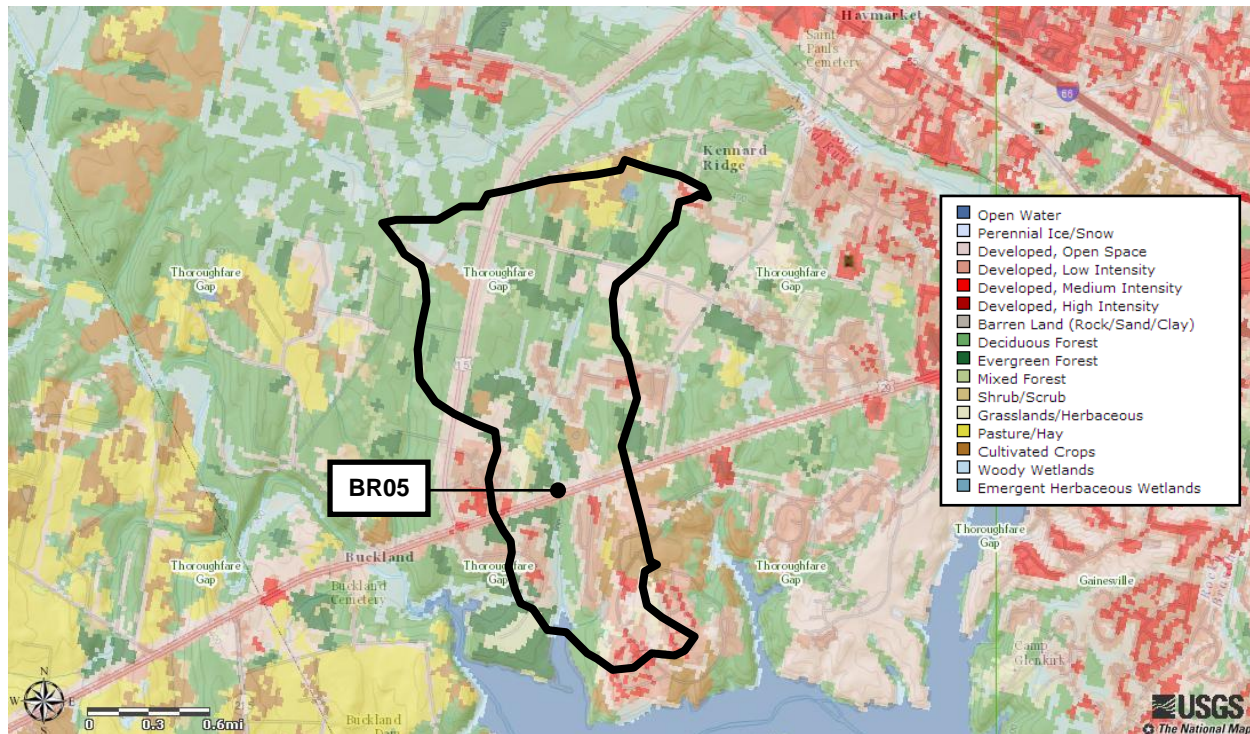
Source: 38°47'20.05" N, 77°39'05.63" W. [Google Earth](#). April 30, 2011. Accessed April 2013.

Figure 5-89 Generalized Land Use Cover within the Drainage Area Associated with Stream Sampling Station BR05 (2001)



Source: (USGS 2013)

Figure 5-90 Generalized Land Use Cover within the Drainage Area Associated with Stream Sampling Station BR05 (2006)



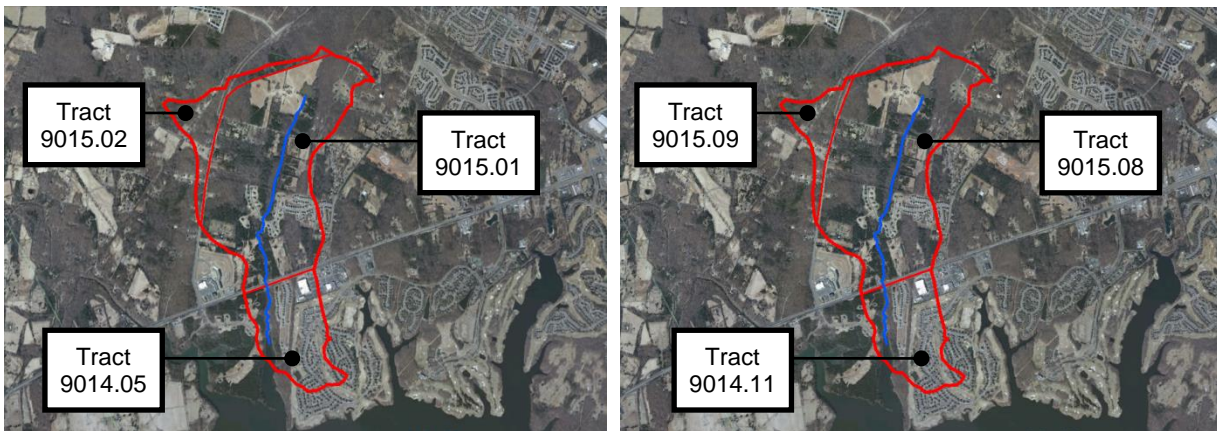
Source: (USGS 2013)

In addition to using historical aerial photographs to analyze land use changes over time within the drainage area, land cover maps prepared by the USGS Land Cover Institute (LCI) and made available through the National Map (USGS 2013) were imported and overlain with the drainage area boundaries associated with the unnamed tributary. Land coverage maps were available for 2001 and 2006 and are presented above in Figures 5-89 and 5-90. Consistent with the aerial photograph analysis, low and medium intensity developments are apparent in the areas where residential developments have been constructed. Apparent in Figure 5-90 is an approximate 20 percent increase in developed areas (i.e., developed, open space, low, medium and high density combined) within the outline drainage boundary.

As a result of the increase in available residential dwellings, the population within the drainage area has also increased over the period from 2000 to 2010. Utilizing available census tract

maps, Figure 5-91 were created to show the tract boundaries associated with the drainage area for both the 2000 and 2010 census periods. Table 5-5 summarizes the population per square mile for each census tract and the resulting estimated population associated with the drainage period for both 2000 and 2010. As the table shows, the population residing within the drainage area has increased from approximately 242 to 380 in ten years, which represents a growth rate that is greater than 50 percent.

Figure 5-91 Census Tracts Associated with Unnamed Tributary Drainage Area Associated with Sampling Station BR05 for 2000 (Left) and 2010 (Right)



Sources: 38°47'20.05" N, 77°39'05.63" W. [Google Earth](#). April 30, 2011. Accessed April 2013. (Census 2000, Census 2010)

Table 5-5 Population Associated with Unnamed Tributary Drainage Area Associated with Sampling Station BR05

Census Tract	Population / Square Mile	Associated Drainage Area (mile ²)	Approximate Population in Drainage Area
2000			
9014.05	245	0.28	69
9015.01	168	0.9	151
9015.02	140	0.16	22
Total Population (2000)			242
2010			
9014.11	492	0.28	138
9015.08	245	0.95	233
9015.09	80	0.11	9
Total Population (2010)			380

Sources: (Census 2000, Census 2010)

Based on this limited analysis of the drainage area associated with the unnamed tributary that is

monitored by stream sampling station BR05, the significant rise in physical parameters that are discussed earlier in this chapter may potentially be attributed to the significant growth and development that has occurred during the 2000 to 2010 time period. As construction and development appears to have been ongoing during this entire period, future data should be monitored to determine whether the significant increase in pH, total alkalinity, specific conductivity, oxidized nitrogen and total suspended solids are associated with development activities (e.g., construction run-off) or if they represent a new trend in land use as it contributes to the water quality of Lake Manassas (e.g., excessive fertilization).

Chapter 6 Lake Results

Lake Water Quality

This section includes a summary of the analyses performed on the water quality of Lake Manassas. Data analyzed as part of this report includes sampling conducted from 1984 through 2010. Table 6-1 includes a list of the parameters analyzed as part of the stream water quality analysis.

Table 6-1 Physical/Chemical Parameters Used in Lake Water Quality Analysis

Abbreviation	Parameter	Units
DO	Dissolved Oxygen	mg/L
TEMP	Temperature	°C
TALK	Total Alkalinity	mg/L as CaCO ₃
NH ₃ -N	Ammonia Nitrogen	mg/L as N
TKN	Total Kjeldahl Nitrogen	mg/L as N
OX-N	Oxidized Nitrogen	mg/L as N
OP	Orthophosphate Phosphorus	mg/L as P
TP	Total Phosphorus	mg/L as P
TSS	Total Suspended Solids	mg/L
CHLA	Chlorophyll <i>a</i>	µg/L

Table 6-2, below depicts the statistical trends calculated based on the data collected from the Lake Manassas stations for the new baseline period beginning in Winter 2006 and continuing through Fall 2010. The Mann-Kendall Seasonal analysis was conducted on a four season (winter, spring, summer, fall) correlation for five-year running averages and any overall increasing or decreasing trends are depicted below. Trends detected in surface samples (1 foot) for the same five year period are presented in Table 6-1 (95 percent confidence), and trends detected in bottom samples (depths vary, but typically collected about 1 foot above the bottom sediment layer at that location) are presented in Table 6-2 (95 percent confidence).

Table 6-2 Mann-Kendall Seasonal Analysis – Surface Stations

Parameter	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
Dissolved Oxygen (DO)	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-
Orthophosphate Phosphorus (OP)	-	-	-	-	-	-	-	-
Total Phosphorus (TP)	-	-	L	-	-	-	-	-
Total Kjeldahl Nitrogen (TKN)	-	-	-	-	-	-	-	-
Oxidized Nitrogen (Ox-N)	L	L	L	L	L	-	-	L
Chlorophyll a (CHLa)	-	-	-	-	-	-	-	-

Notes:

U – Increasing Trend

L – Decreasing Trend

- – No Trend Observed

Table 6-3 Mann-Kendall Seasonal Analysis – Bottom Stations

Parameter	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
Dissolved Oxygen (DO)	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-
Orthophosphate Phosphorus (OP)	-	-	-	-	-	-	L	-
Total Phosphorus (TP)	-	-	-	-	L	-	-	L
Total Kjeldahl Nitrogen (TKN)	U	U	U	U	-	-	U	-
Oxidized Nitrogen (Ox-N)	L	L	-	-	-	-	-	-

Notes:

U – Increasing Trend

L – Decreasing Trend

- – No Trend Observed

The following sections include a summary of the findings for the analyte values evaluated with regards to the new baseline period. Each section includes summary statistics that present average and maximum concentrations for both the 1984 to 2010 and 2006 to 2010 periods. If a statistical trend has been identified it is discussed in further detail within these sections of the report. In addition, an analysis of the trophic state of Lake Manassas is discussed within this section of the report, specifically using the models developed by Carlson and Vollenweider (Vollenweider 1973, Carlson 1977).

Temperature

Temperature isopleths for sampling station LM01 during the 2006 to 2010 base period are depicted in Figure 6-1. Sampling station LM01 is located proximal to the T. Nelson Elliott Dam and therefore is the deepest sampling station and, thus, has the greatest tendency to stratify. Thermal stratification is apparent between early spring and late fall at this station.

Five-year running averages for surface temperature (TEMP) measurements for each lake sampling station are depicted in Figures 6-2 through 6-9.

- Surface temperature measurements for the 1984 to 2010 period range up to 32 °C, with the highest measurement of 32 °C detected at sampling station LM03 on 5-AUG-1987. The average surface temperature measurement for all sampling stations during this period was calculated to be 18.7 °C.
- Surface temperature measurements for the 2006 to 2010 period range up to 30.9 °C, with the highest measurement of 30.9 °C detected at sampling station LM07 on 26-JUL-2006. The average surface temperature measurement for all sampling stations during this period was calculated to be 18.8 °C.
- The Mann-Kendall Seasonal Analysis for surface temperature measurements shows no increasing or decreasing trends for the 2006 to 2010 period.
- The seasonal trend for surface temperature measurements at all sampling stations generally shows Winter-TEMP < Spring-TEMP < Fall-TEMP < Summer-TEMP.

Five-year running averages for bottom temperature measurements for each lake sampling station are depicted in Figures 6-10 through 6-17.

- Bottom temperature measurements for the 1984 to 2010 period range up to 31.7 °C, with the highest measurement of 31.7 °C detected at sampling station LM03 on 27-JUL-

2005. The average bottom temperature measurement for all sampling stations during this period was calculated to be 16.3 °C.

- Bottom temperature measurements for the 2006 to 2010 period range up to 30.6 °C, with the highest measurement of 30.6 °C detected at sampling station LM08 on 11-AUG-2010. The average bottom temperature measurement for all sampling stations during this period was calculated to be 16.3 °C.
- The Mann-Kendall Seasonal Analysis for bottom temperature measurements shows no increasing or decreasing trends for the 2006 to 2010 period.

Annualized surface and bottom temperatures for the 2006 to 2010 period are presented in Figure 6-18.

- The data points represent the average temperature for each season during 2006 to 2010 with the average surface temperature on the y-axis and the average bottom temperature along the x-axis. The diagonal line represents a 1:1 linear relationship for comparative purposes. The temperatures, with the exception of summer averages tend to fall generally along the 1:1 line. The deviations from the 1:1 line represent varying levels of stratification. A completely mixed system would fall directly along this line as temperatures throughout the water column are the same.

Figure 6-19 depicts selected 2006 temperature profiles for lake sampling station LM01 and Figure 6-20 depicts selected 2010 temperature profiles for lake sampling station LM01.

- These figures were developed to evaluate when Lake Manassas becomes stratified. As shown, stratification began as early as mid-April 2006 and late-March 2010. These differences could be attributed to different levels of rainfall or seasonal climate variations.

- Additionally shown is that the thermocline, or the boundary between the epilimnion and hypolimnion occurs between depths of approximately 3 feet and 30 feet depending on the strength of the stratification.

The VDEQ has published a maximum acceptable temperature of 32 °C for nontidal waters (Coastal and Piedmont zones). As stated previously, the VDEQ “recognizes that the natural quality of these waters may fluctuate” and these water quality standards are established to consider potential human impact to natural systems (VDEQ 2010). There have been no measurements above the VDEQ acceptable maximum for surface or bottom temperatures.

Figure 6-1 Station LM01 Temperature Isopleths

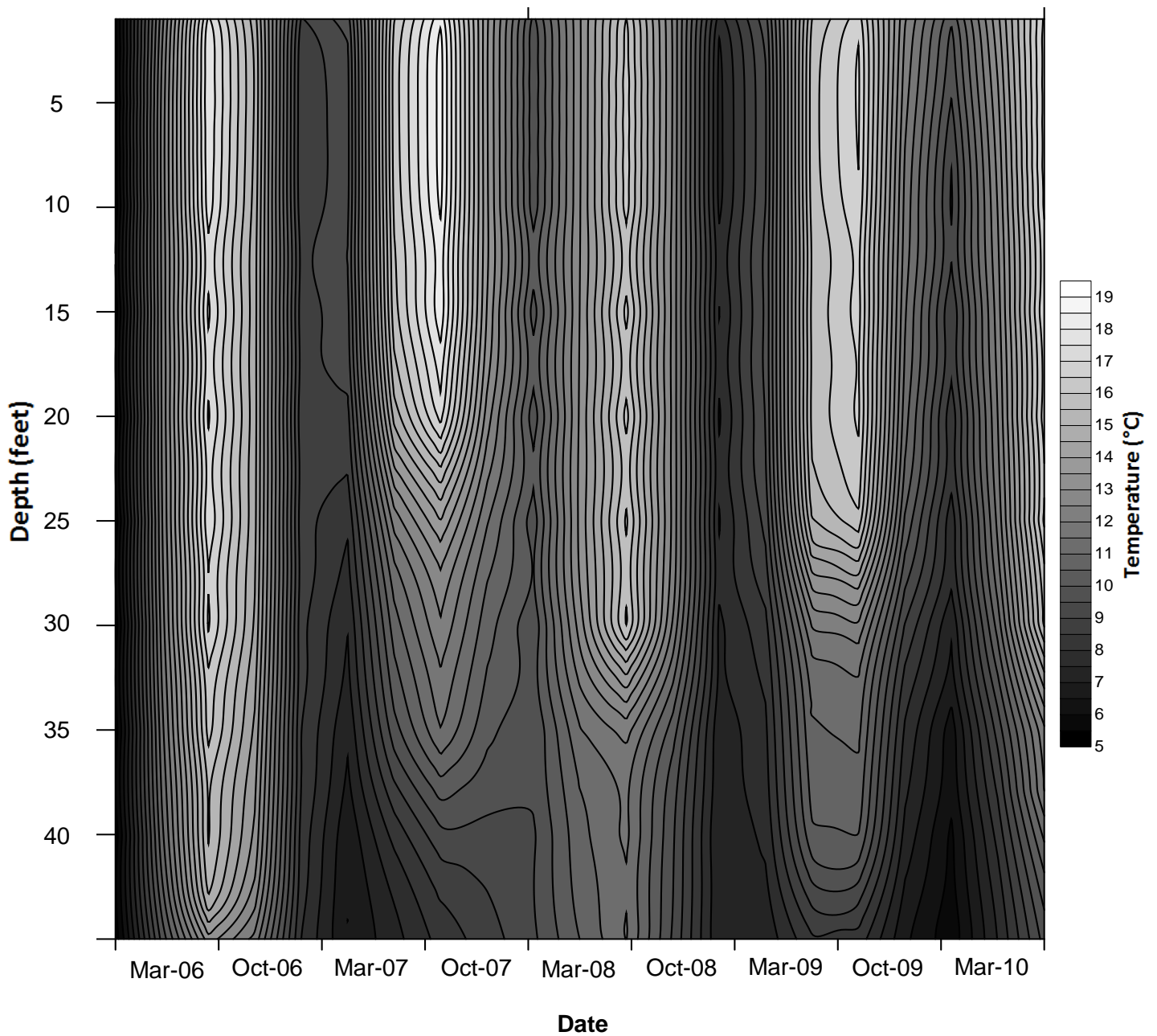


Figure 6-2 Five Year Running Average of Surface Temperature for Station LM01

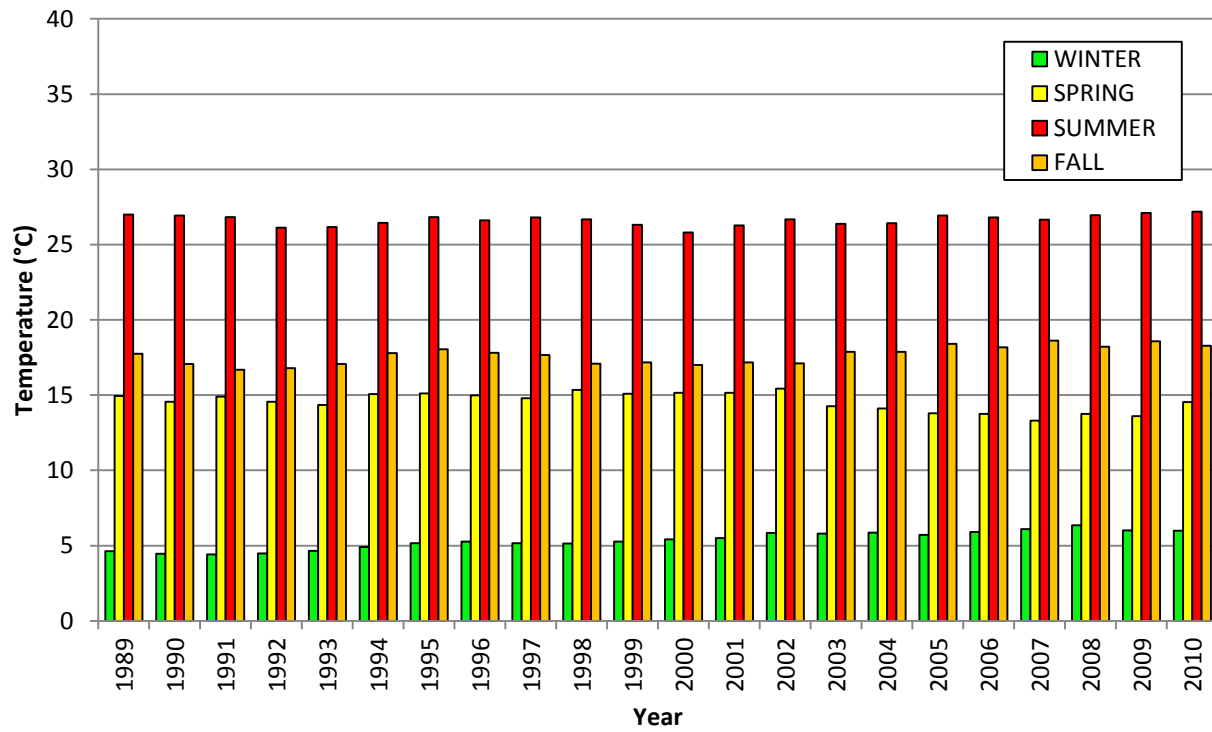


Figure 6-3 Five Year Running Average of Surface Temperature for Station LM02

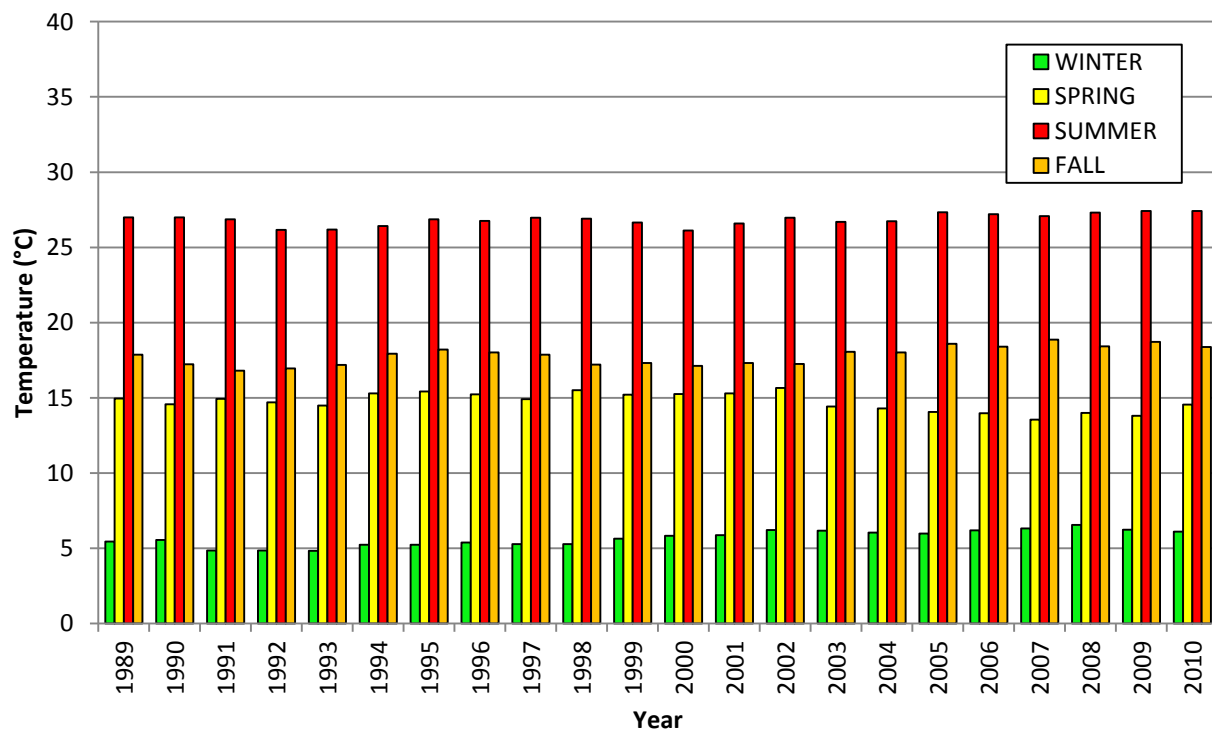


Figure 6-4 Five Year Running Average of Surface Temperature for Station LM03

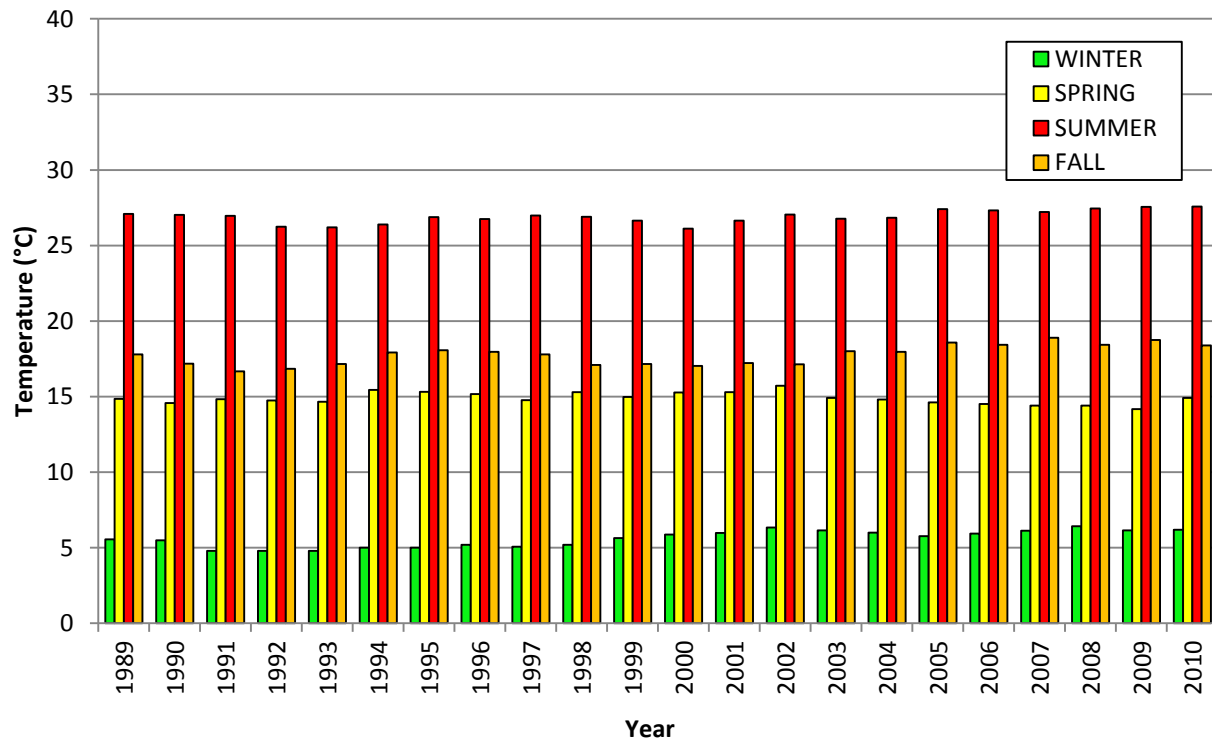


Figure 6-5 Five Year Running Average of Surface Temperature for Station LM04

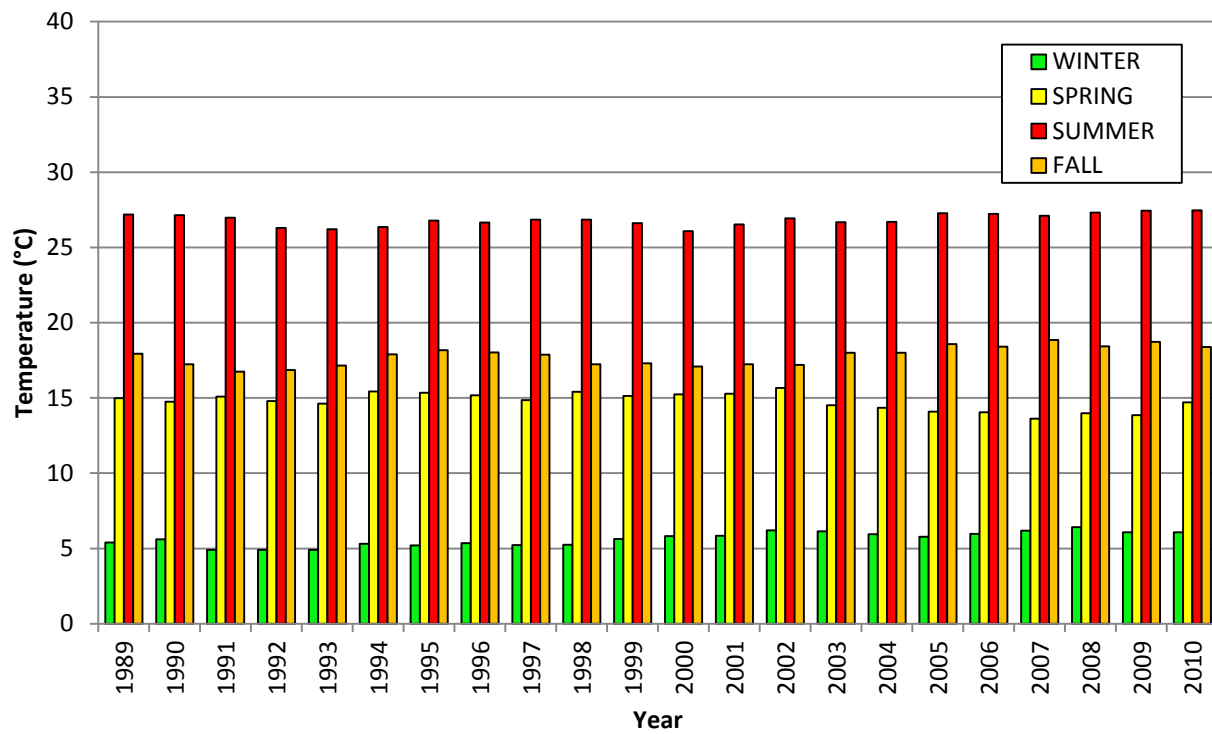


Figure 6-6 Five Year Running Average of Surface Temperature for Station LM05

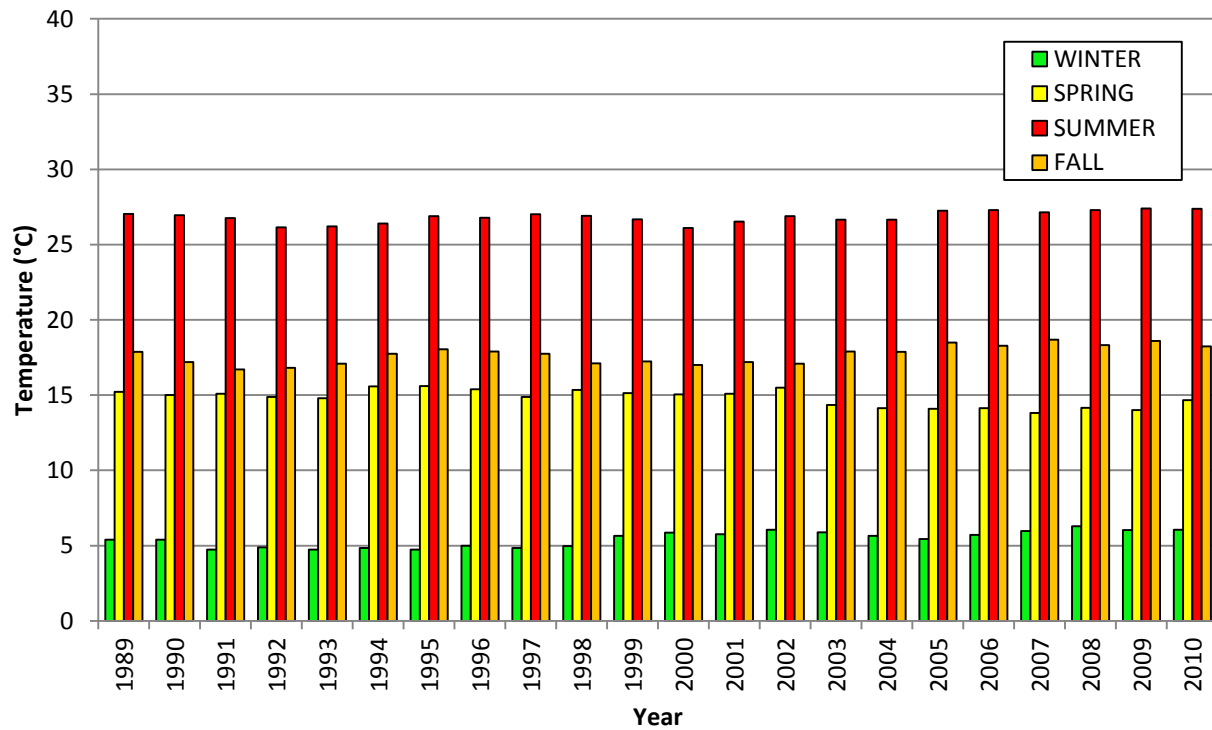


Figure 6-7 Five Year Running Average of Surface Temperature for Station LM06

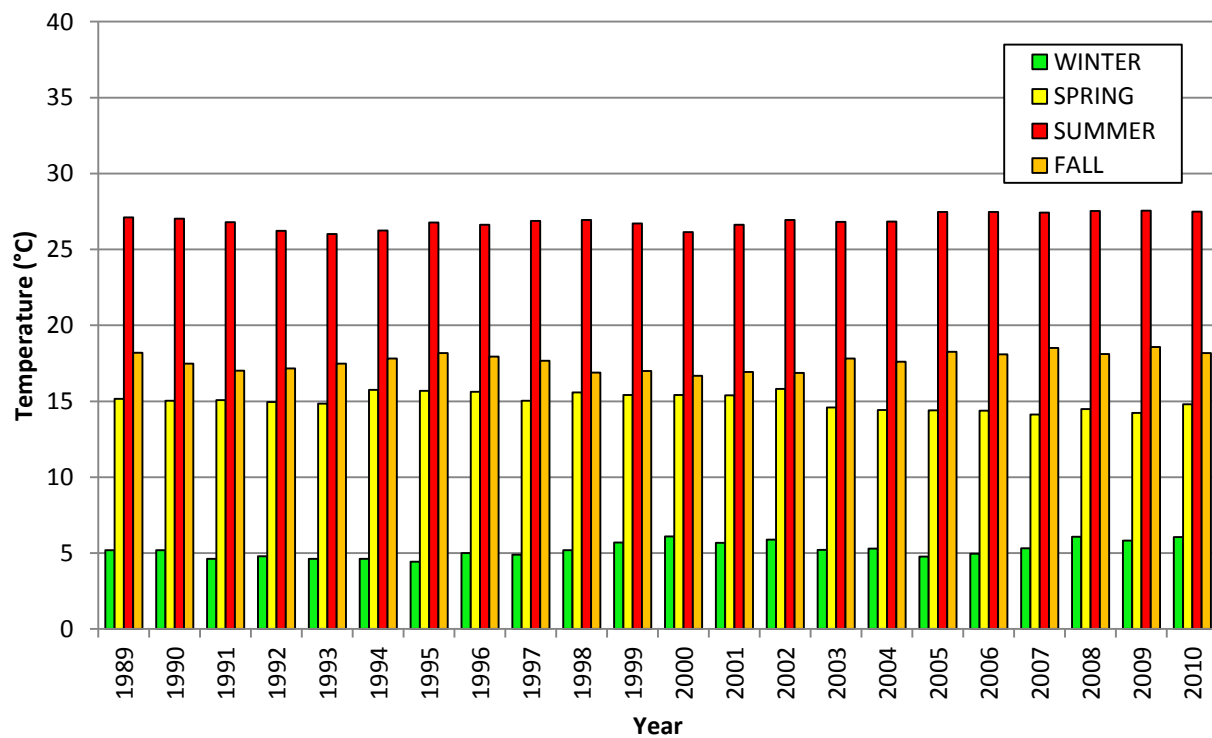


Figure 6-8 Five Year Running Average of Surface Temperature for Station LM07

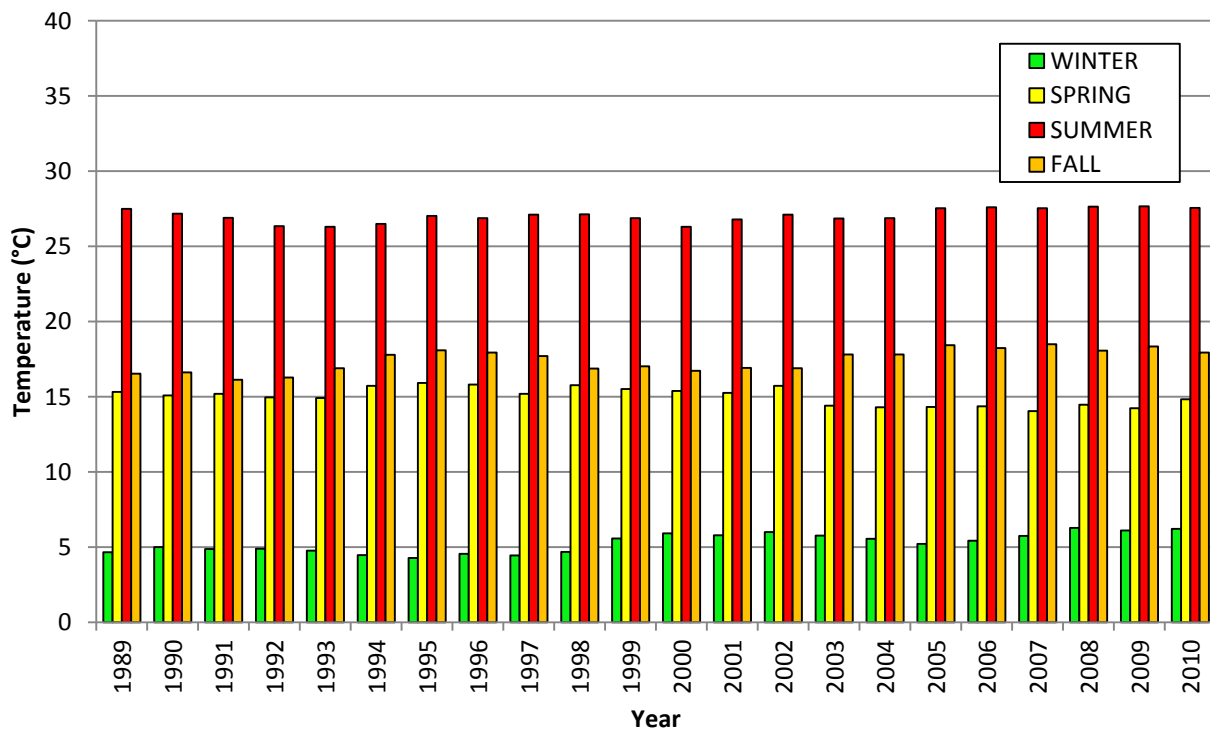


Figure 6-9 Five Year Running Average of Surface Temperature for Station LM08

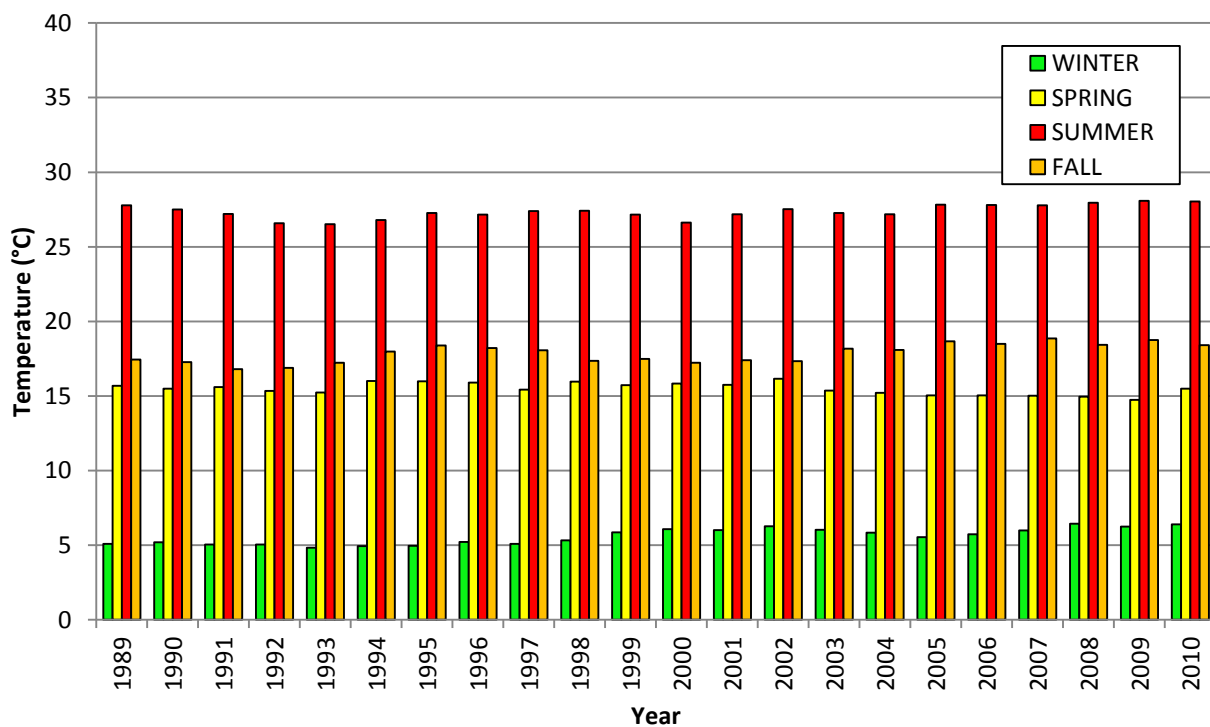


Figure 6-10 Five Year Running Average of Bottom Temperature for Station LM01

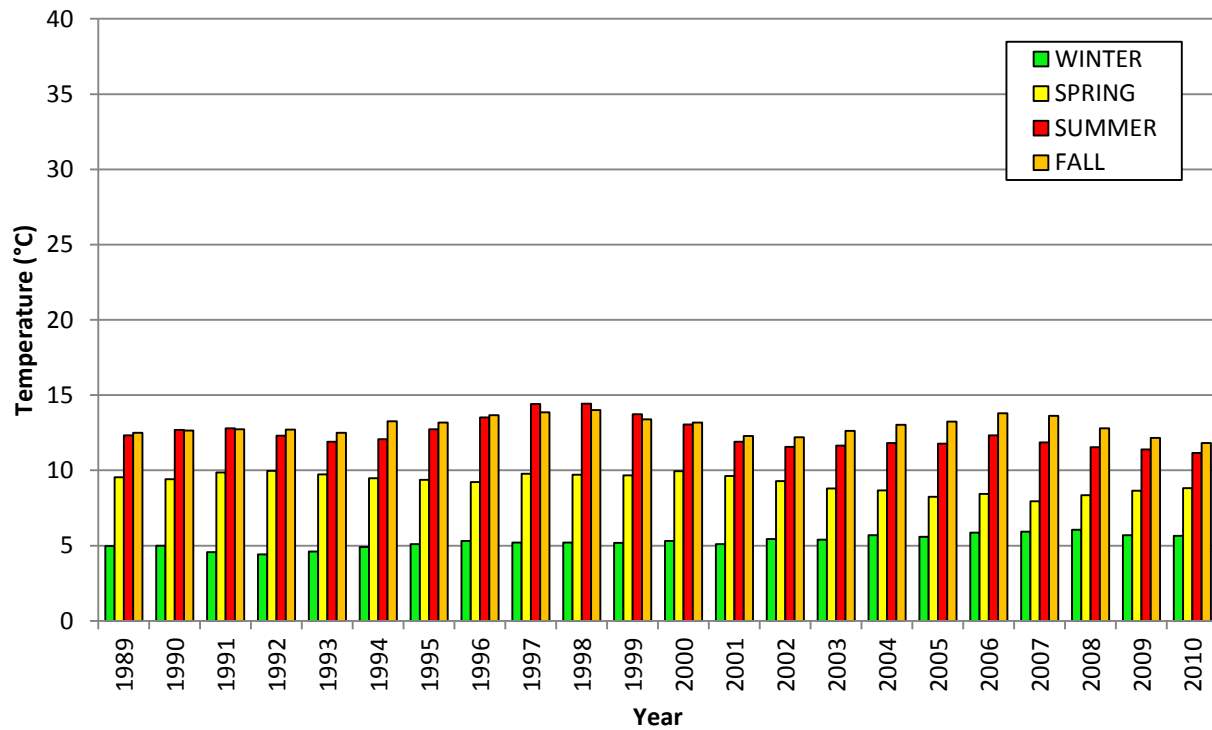


Figure 6-11 Five Year Running Average of Bottom Temperature for Station LM02

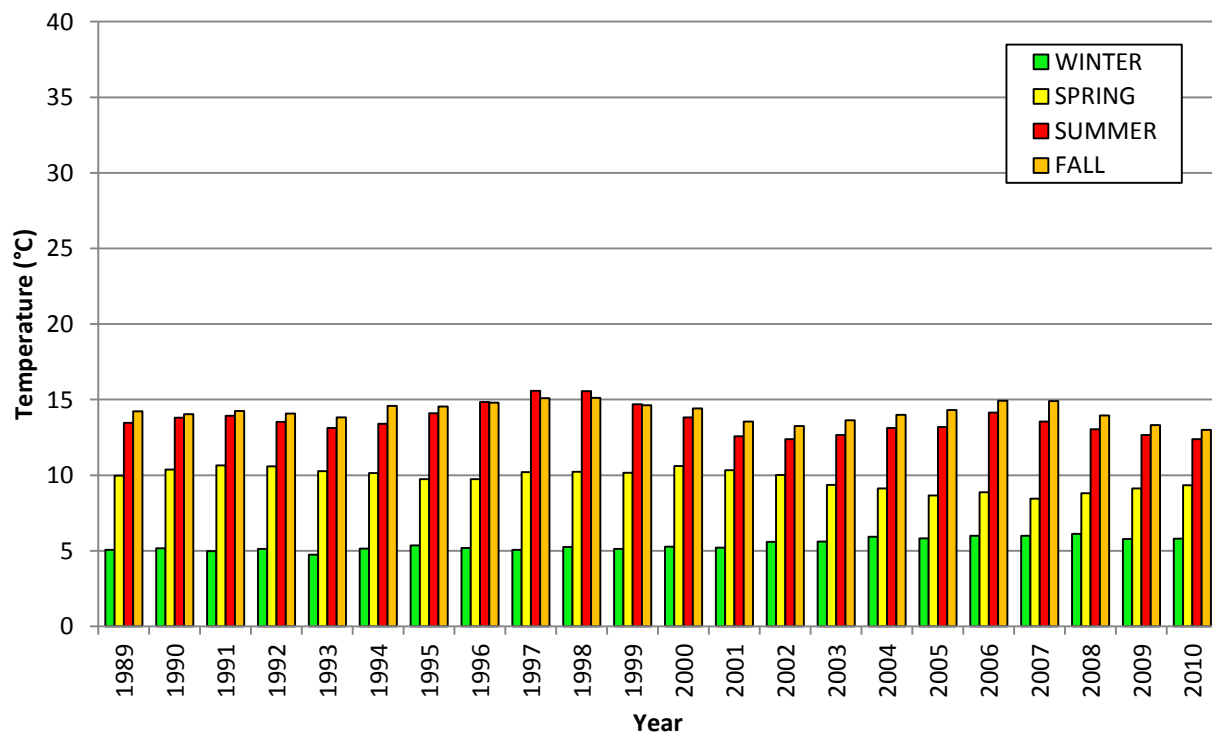


Figure 6-12 Five Year Running Average of Bottom Temperature for Station LM03

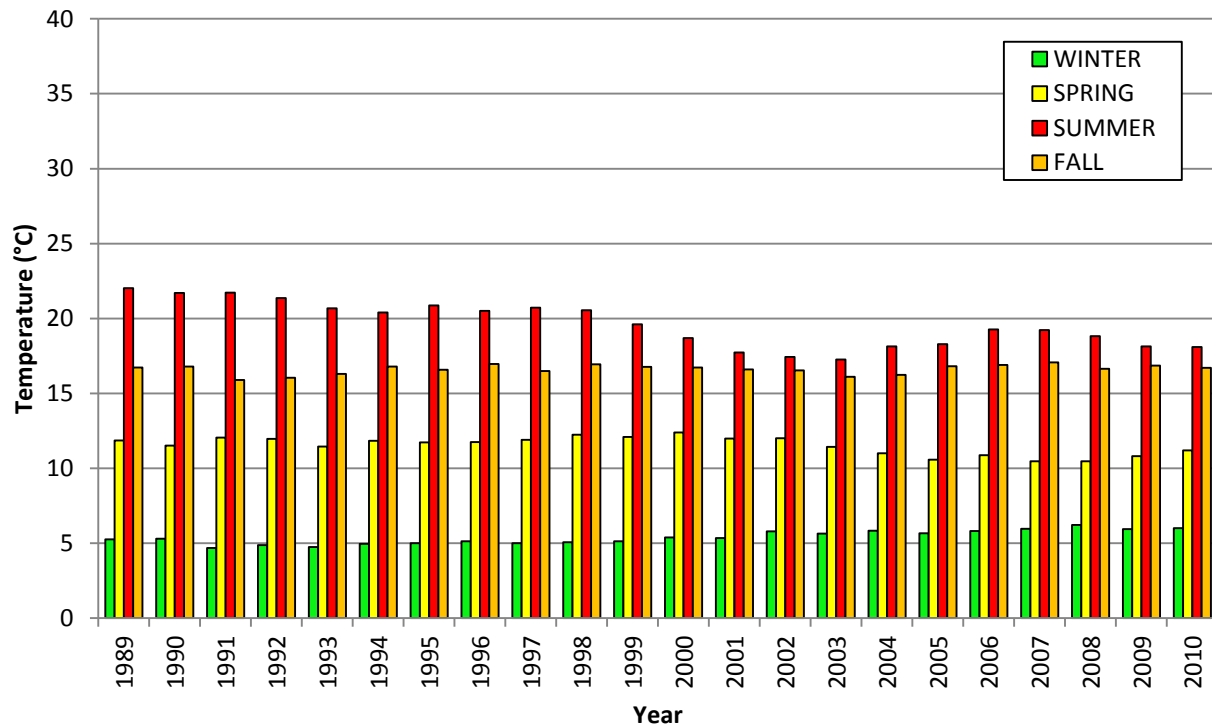


Figure 6-13 Five Year Running Average of Bottom Temperature for Station LM04

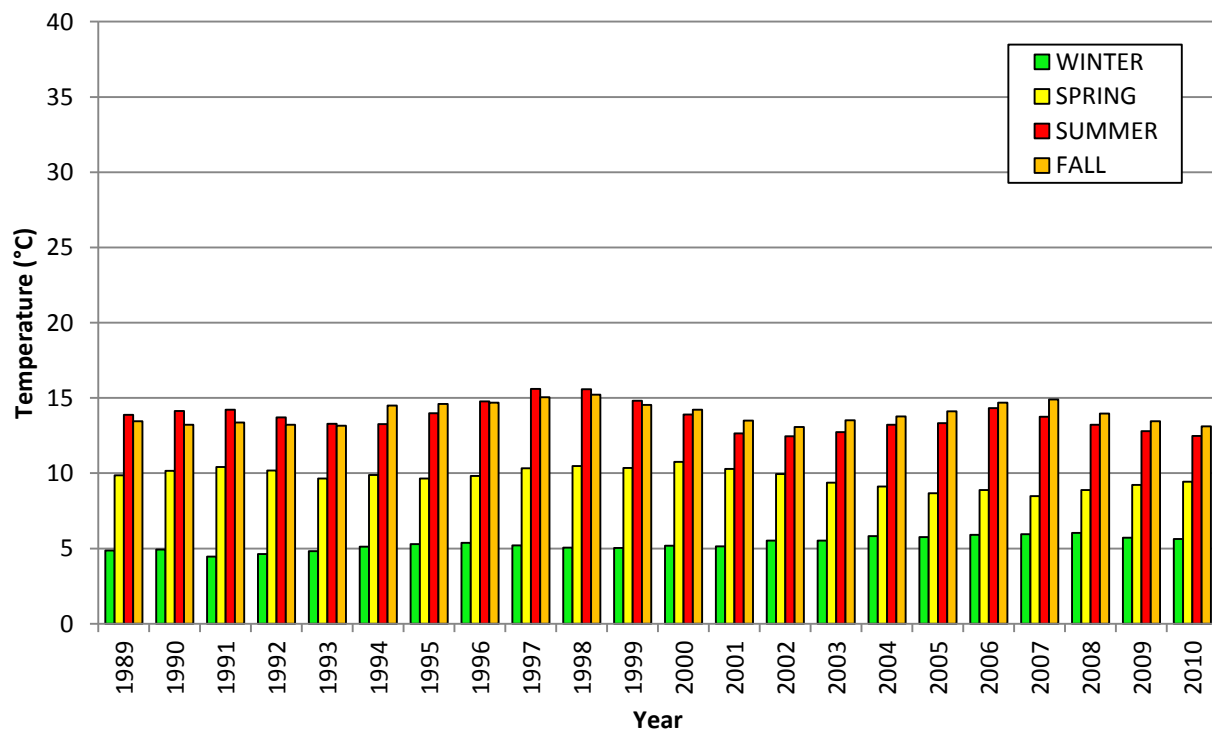


Figure 6-14 Five Year Running Average of Bottom Temperature for Station LM05

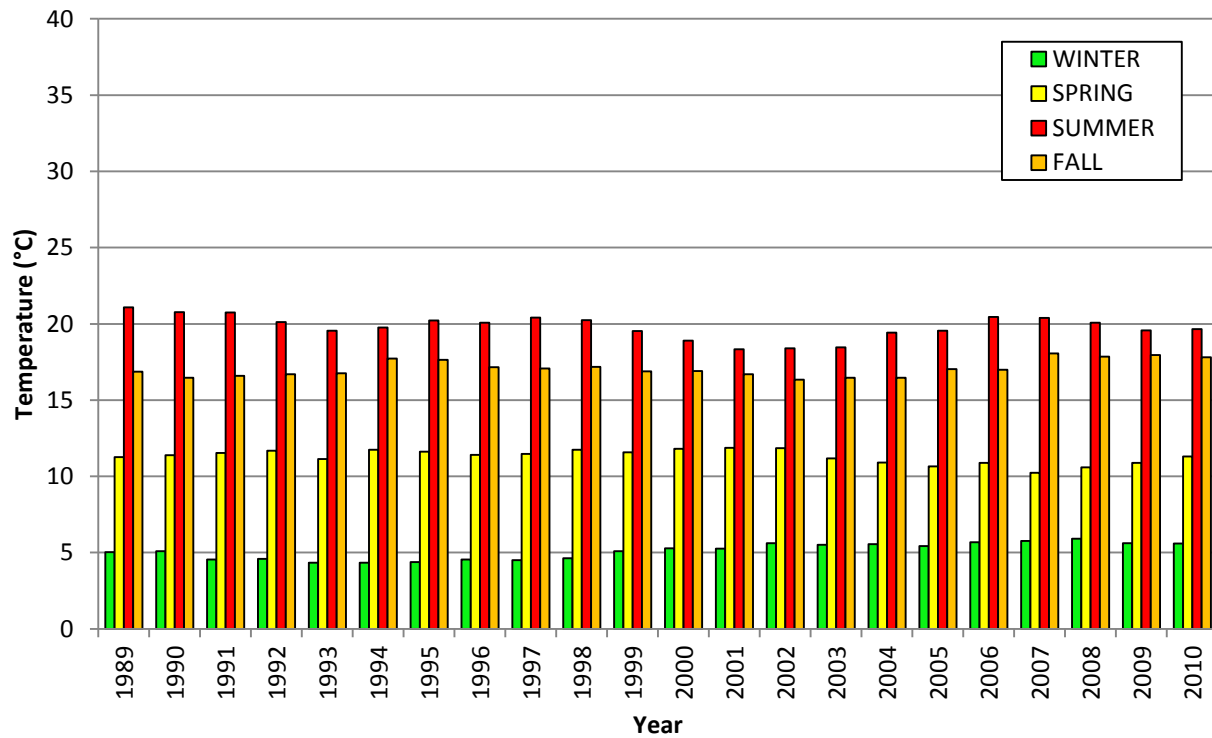


Figure 6-15 Five Year Running Average of Bottom Temperature for Station LM06

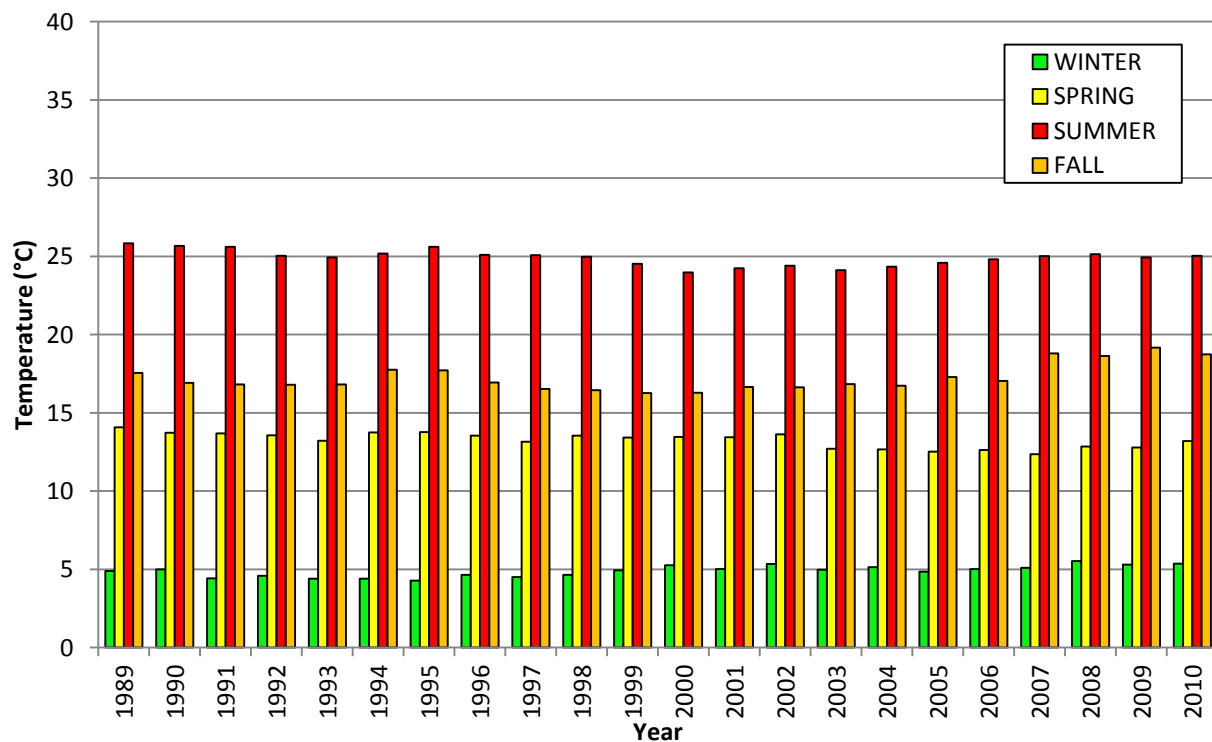


Figure 6-16 Five Year Running Average of Bottom Temperature for Station LM07

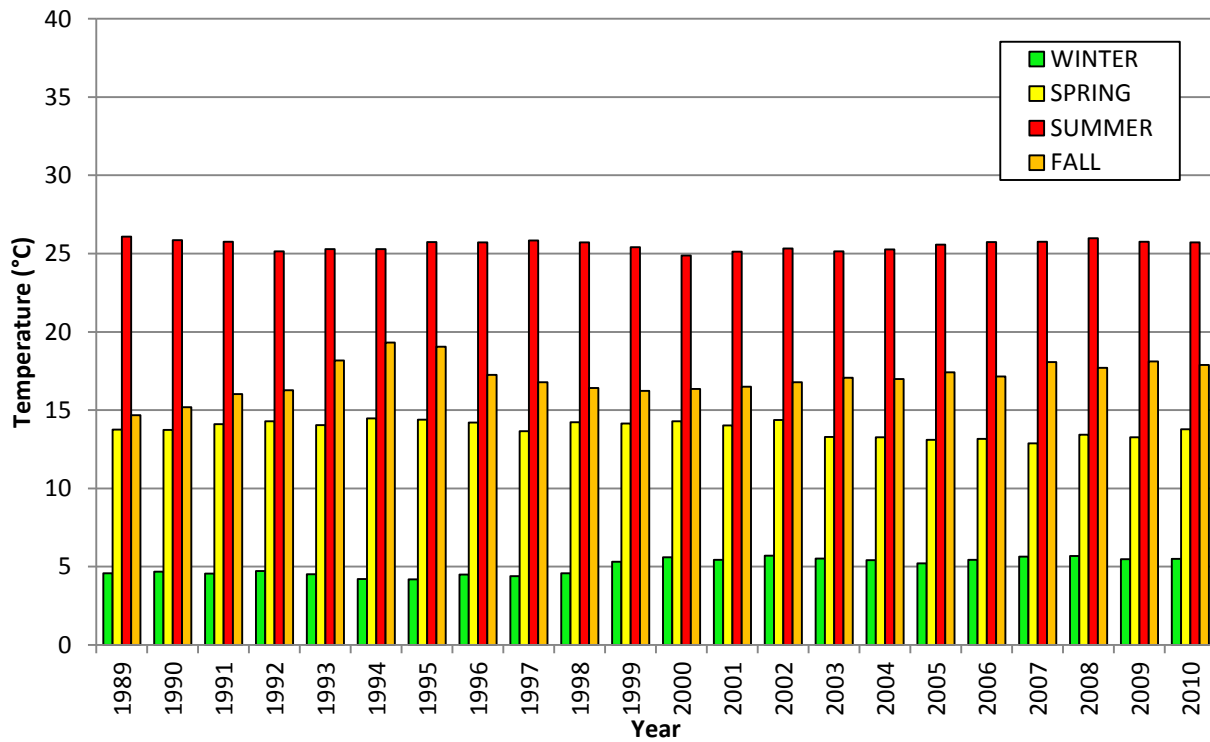


Figure 6-17 Five Year Running Average of Bottom Temperature for Station LM08

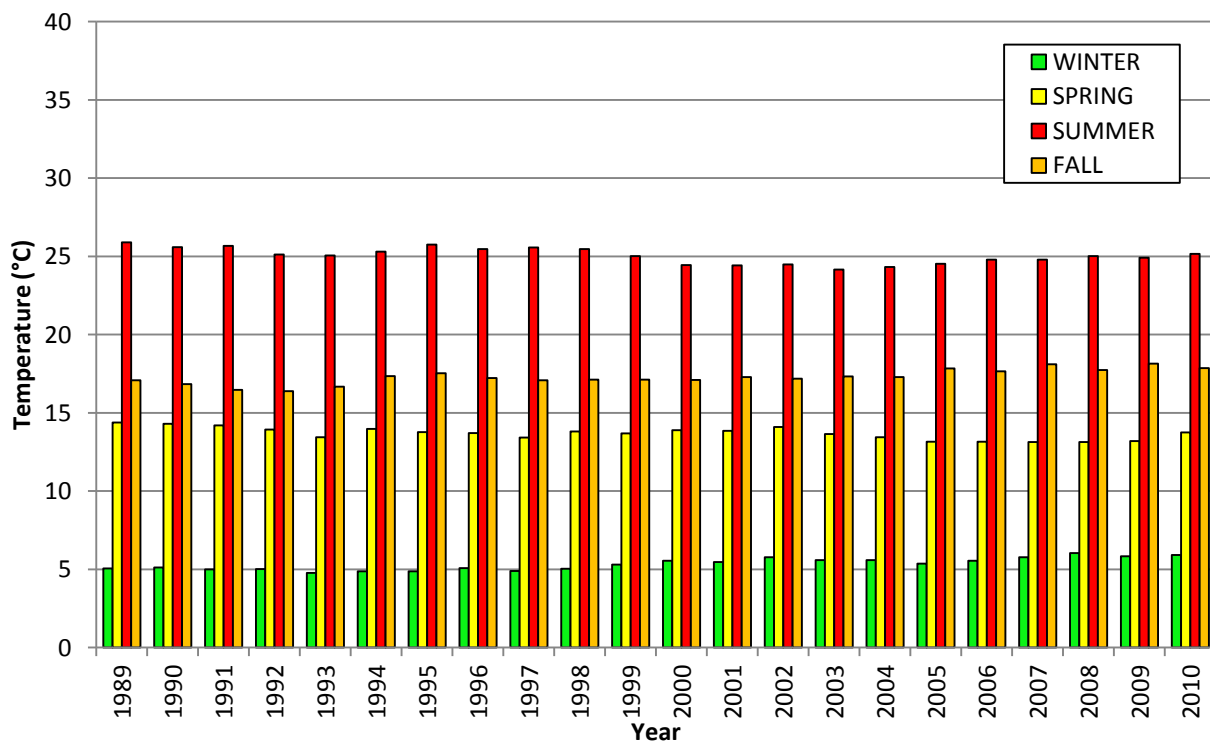


Figure 6-18 Average Lake Surface and Bottom Temperatures All Stations (2006 – 2010)

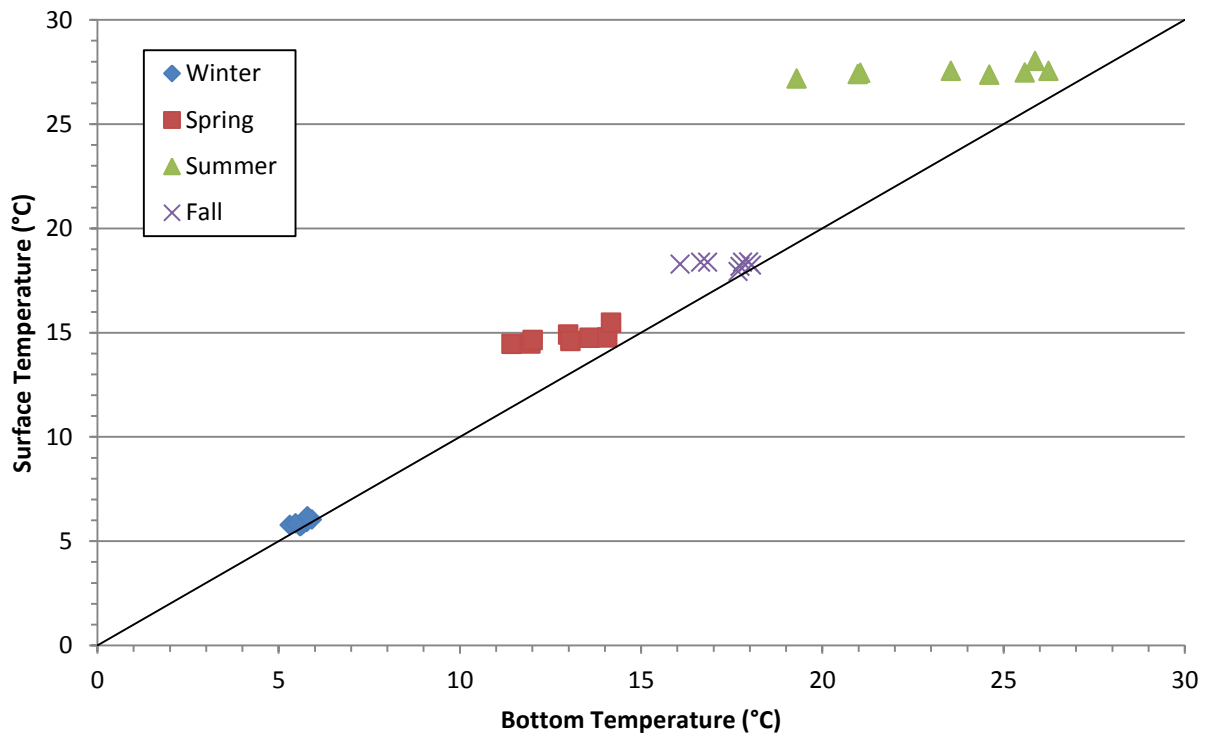


Figure 6-19 Temperature Profiles for Station LM01 (2006)

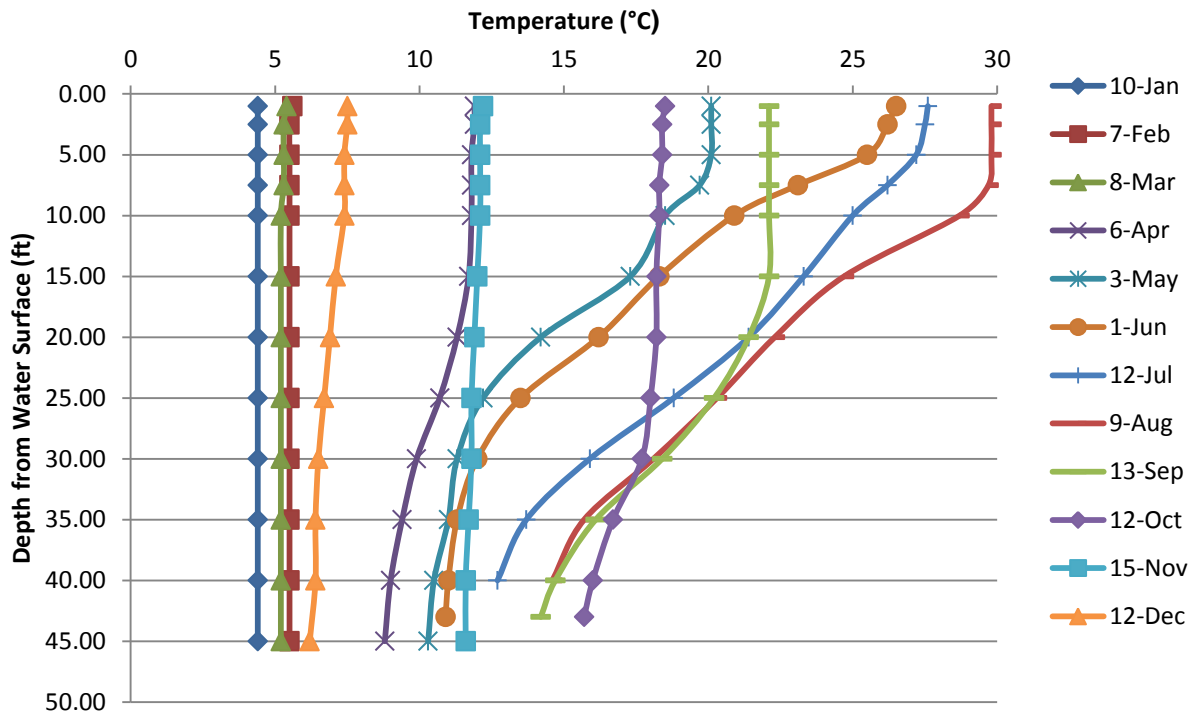
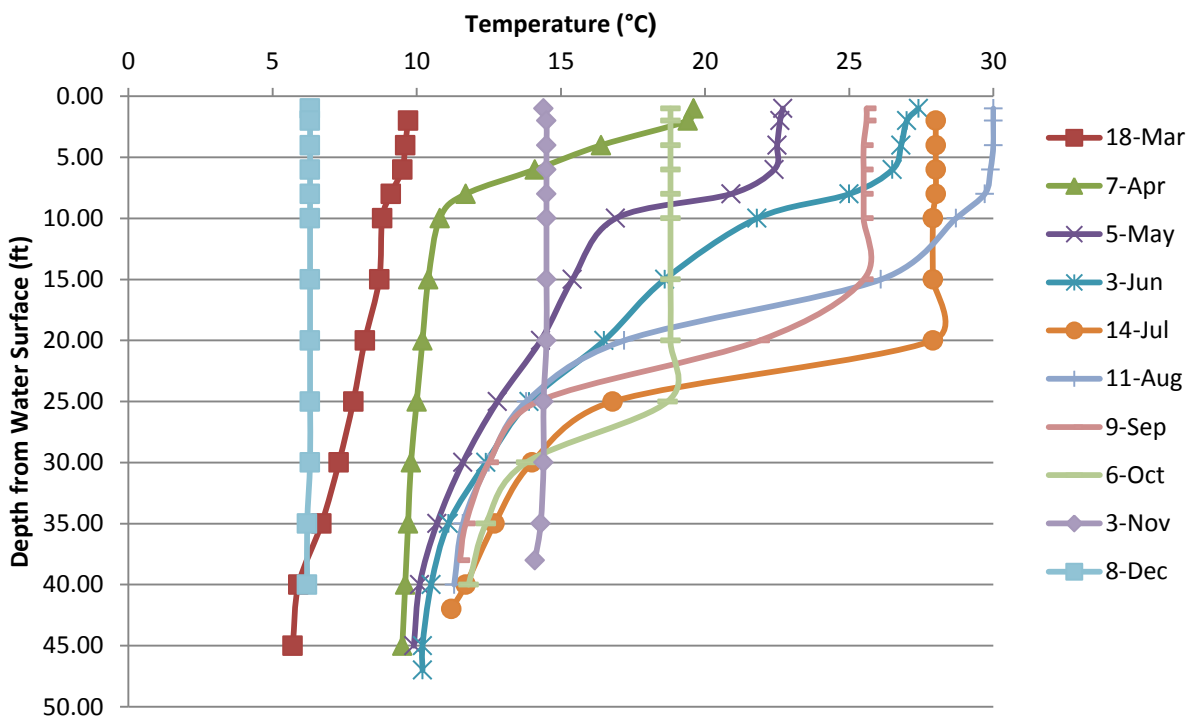


Figure 6-20 Temperature Profiles for Station LM01 (2010)



Dissolved Oxygen

Isopleths for dissolved oxygen and percent saturation oxygen are presented in Figures 6-21 and 6-22, respectively, for sampling station LM01 during the 2006 to 2010 base period. These figures show similar stratification trends as the temperature isopleths discussed previously. This is because during stratification periods, the metalimnion acts as a barrier and prevents diffusion between the epilimnion and hypolimnion. While dissolved oxygen concentrations decrease in the hypolimnion, diffusion across the air-water interface is capable of readily replenishing dissolved oxygen concentrations in the epilimnion. Percent saturation oxygen is calculated using the following formula (Lindeburg 2005):

$$\text{Percent Saturation Dissolved Oxygen} = \frac{\text{Dissolved Oxygen (Measured)}}{\text{Dissolved Oxygen Saturation Level}} * 100$$

Five-year running averages for surface dissolved oxygen (DO) concentrations for each lake sampling station are depicted in Figures 6-23 through 6-30.

- Surface dissolved oxygen concentrations for the 1984 to 2010 period range from 2.58 mg/L to 15.43 mg/L, with the lowest concentration of 2.58 mg/L detected at sampling station LM04 on 3-MAY-2000 and the highest concentration of 15.43 mg/L detected at sampling station LM08 on 2-MAR-2004. The average surface dissolved oxygen concentration for all sampling stations during this period was calculated to be 9.21 mg/L.
- Surface dissolved oxygen concentrations for the 2006 to 2010 period range from 4.44 mg/L to 13.9 mg/L, with the lowest concentration of 4.44 mg/L detected at sampling station LM03 on 11-OCT-2007 and the highest concentration of 13.9 mg/L detected at sampling station LM06 on 9-MAY-2007. The average surface dissolved oxygen concentration for all sampling stations during this period was calculated to be 9.34 mg/L.

- The Mann-Kendall Seasonal Analysis for surface dissolved oxygen concentrations shows no increasing or decreasing trends for the 2006 to 2010 period.

Five-year running averages for bottom dissolved oxygen concentrations for each lake sampling station are depicted in Figures 6-31 through 6-38.

- Bottom dissolved oxygen concentrations for the 1984 to 2010 period range up to 15.54 mg/L, with the highest concentration of 15.54 mg/L detected at sampling station LM08 on 3-MAR-2004. The average bottom dissolved oxygen concentration for all sampling stations during this period was calculated to be 7.16 mg/L.
- Bottom dissolved oxygen concentrations for the 2006 to 2010 period range up to 14 mg/L, with the highest concentration of 14 mg/L detected at sampling stations LM06 and LM07 on 9-MAY-2007. The average bottom dissolved oxygen concentration for all sampling stations during this period was calculated to be 7.39 mg/L.
- The Mann-Kendall Seasonal Analysis for bottom dissolved oxygen concentrations shows no increasing or decreasing trends for the 2006 to 2010 period.
- The seasonal trend for bottom dissolved oxygen concentrations at all sampling stations generally shows Summer-DO < Fall-DO < Spring-DO < Winter-DO.

Percent dissolved oxygen saturations for the 1985 to 2010 period are presented for lake sampling station LM01 and LM06 in Figures 6-39 and 6-40, respectively.

- As these figures show, dissolved oxygen concentrations tend to have a generally inverse relationship with depth. For percent dissolved oxygen saturation at both sampling stations LM01 and LM06, bottom percent dissolved oxygen decreases during summer and fall months when Lake Manassas is thermally stratified. During this same period,

surface percent dissolved oxygen increases as oxygen is diffused across the air-water interface.

Seasonal comparisons for surface and bottom dissolved oxygen and percent dissolved oxygen concentration changes are depicted in Figures 6-41 and 6-42, respectively, for the 2006 to 2010 period.

- A 1:1 relationship line is shown on both figures for comparative purposes. A completely mixed lake would have equal dissolved oxygen and percent dissolved oxygen saturation concentration at the surface as well as at the bottom. Deviations from this line represent stratification within Lake Manassas. As would be expected, winter months track closely to the 1:1 line because this is when the system is closest to being completely mixed.

Figure 6-43 depicts selected 2006 dissolved oxygen profiles for lake sampling station LM01.

- Based on this figure, thermal (and subsequently dissolved oxygen) stratification began in early April and thermocline depths ranged from 3 to 20 feet in 2006 at sampling station LM01.

Figure 6-44 depicts selected 2010 dissolved oxygen profiles for lake sampling station LM01.

- As with Figure 6-43, this figure indicates that thermal stratification began in early April; however, thermocline depths appear to have ranged up to 35 feet in early October.

Figure 6-45 depicts selected 2006 percent dissolved oxygen saturation profiles for lake sampling station LM01.

- This figure presents information consistent with that found in Figure 6-43, with thermal stratification occurring between early April and December.

Figure 6-46 depicts selected 2010 percent dissolved oxygen saturation profiles for lake sampling station LM01.

- This figure presents information consistent with that found in Figure 6-44, with thermal stratification occurring between early April and December.

The Virginia Department of Environmental Quality (VDEQ) has published a minimum dissolved oxygen concentration value of 4.0 mg/L and a daily average of 5.0 mg/L for nontidal waters (i.e., Coastal and Piedmont zones). As stated previously, the VDEQ “recognizes that the natural quality of these waters may fluctuate” and these water quality standards are established to consider potential human impact to natural systems (VDEQ 2010). There have been a total of 5 occurrences with DO concentrations measured below 4.0 mg/L in Lake Manassas surface sampling stations. These standard violations represent less than 0.01 percent of all lake surface station sampling events where a dissolved oxygen concentration was measured. No measurements below the VDEQ acceptable minimum of 4.0 mg/L were detected during the 2006 to 2010 baseline period for surface waters.

Figure 6-21 DO Isopleths for Station LM01 (2000 – 2005)

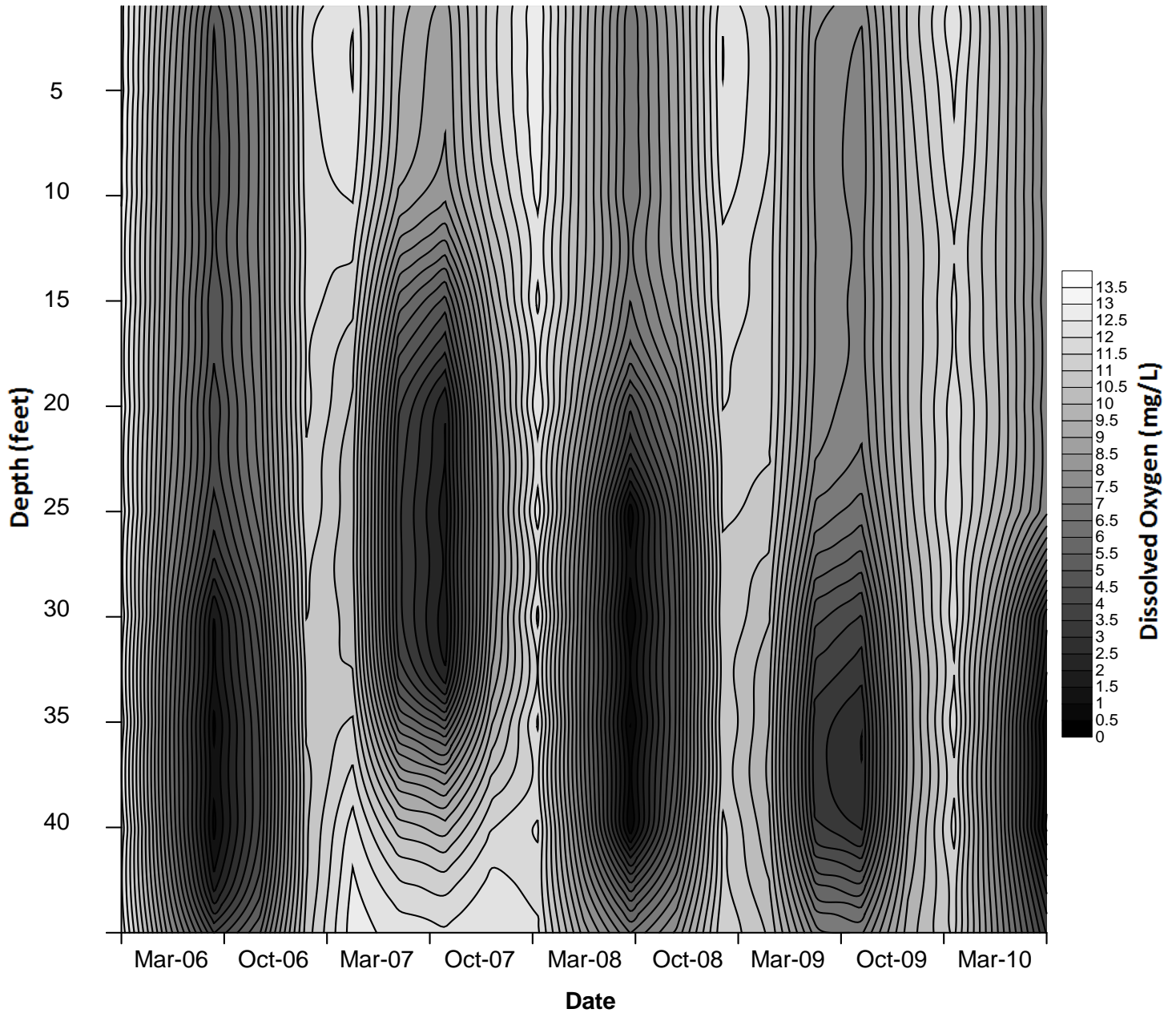


Figure 6-22 Percent DO Saturation Isopleths for Station LM01 (2000 – 2005)

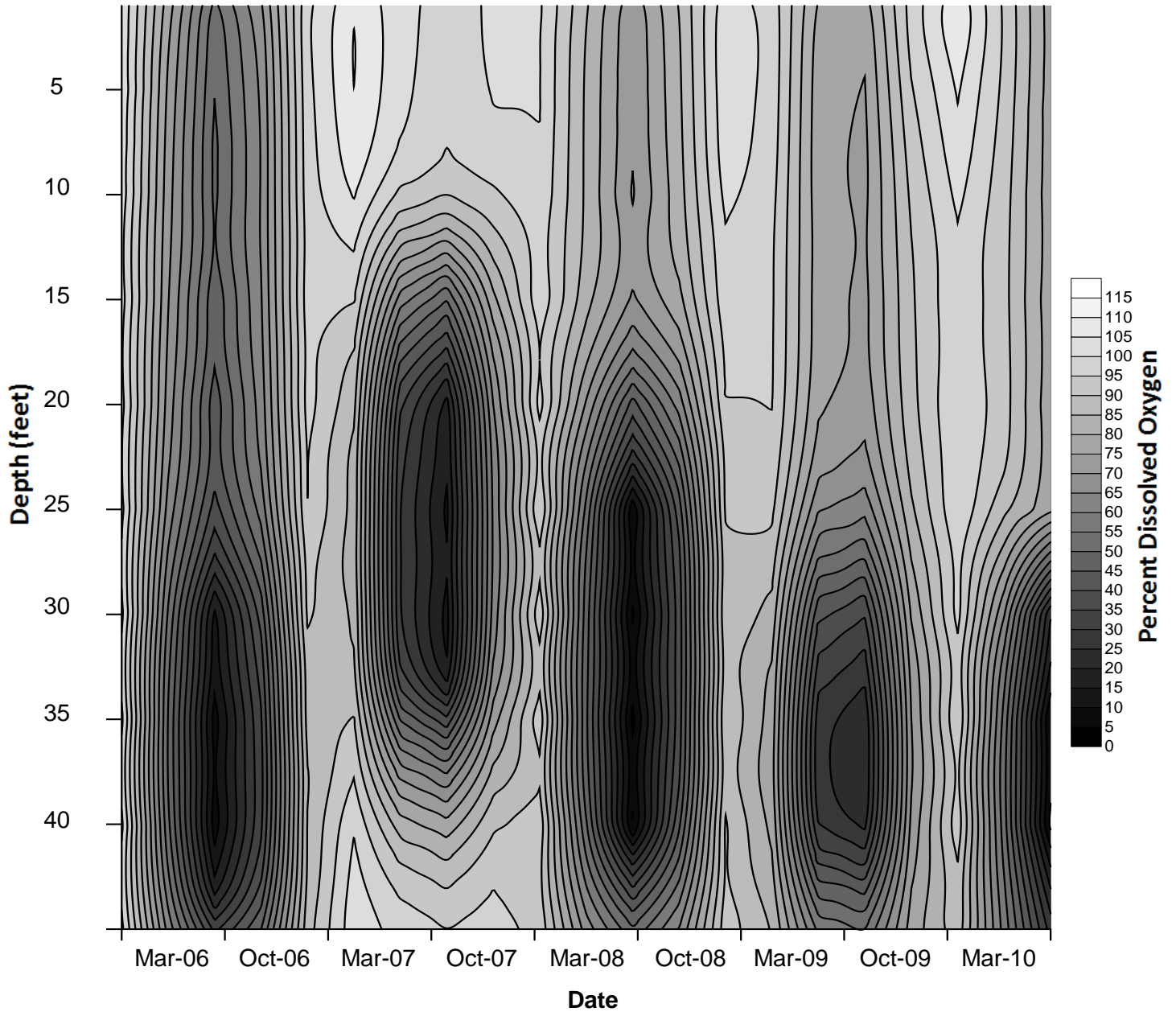


Figure 6-23 Five Year Running Average of Surface DO Concentrations for Station LM01

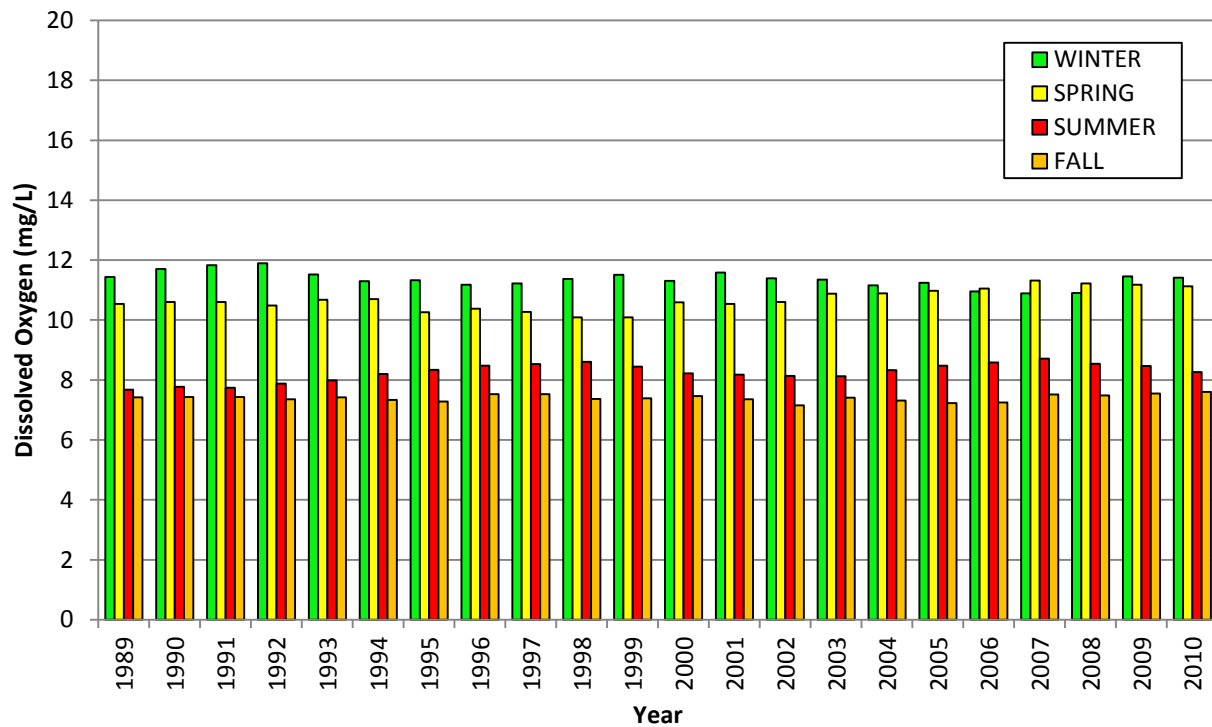


Figure 6-24 Five Year Running Average of Surface DO Concentrations for Station LM02

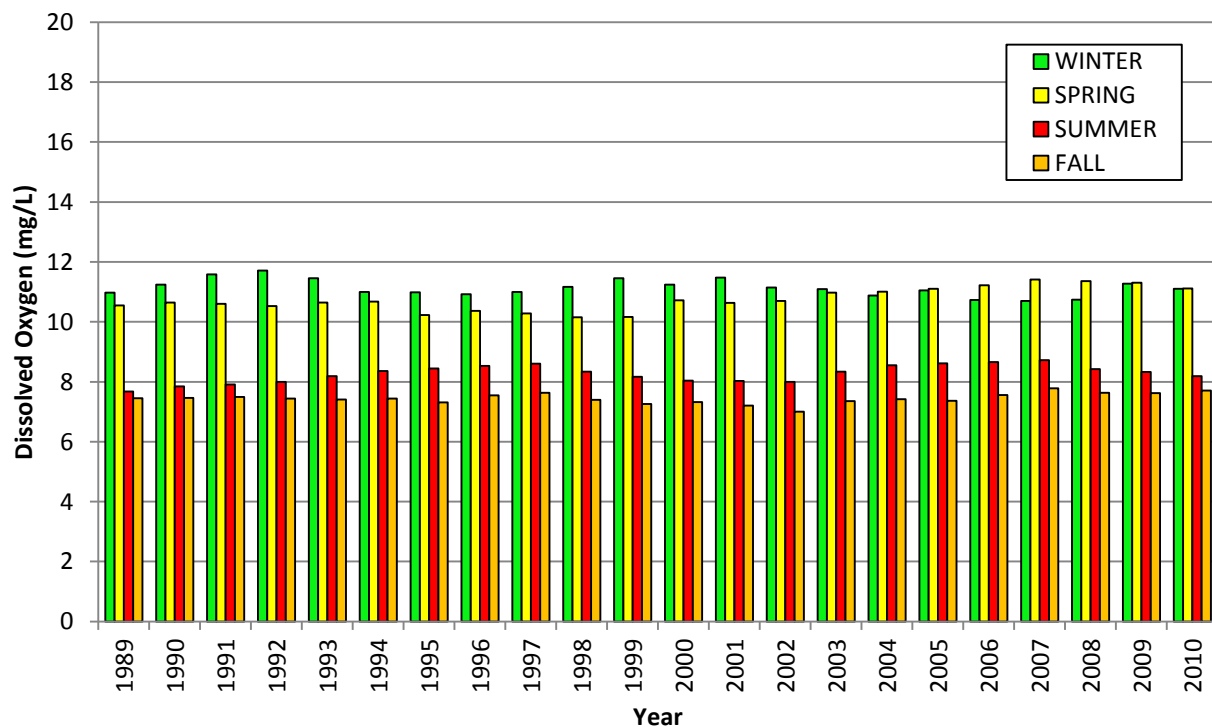


Figure 6-25 Five Year Running Average of Surface DO Concentrations for Station LM03

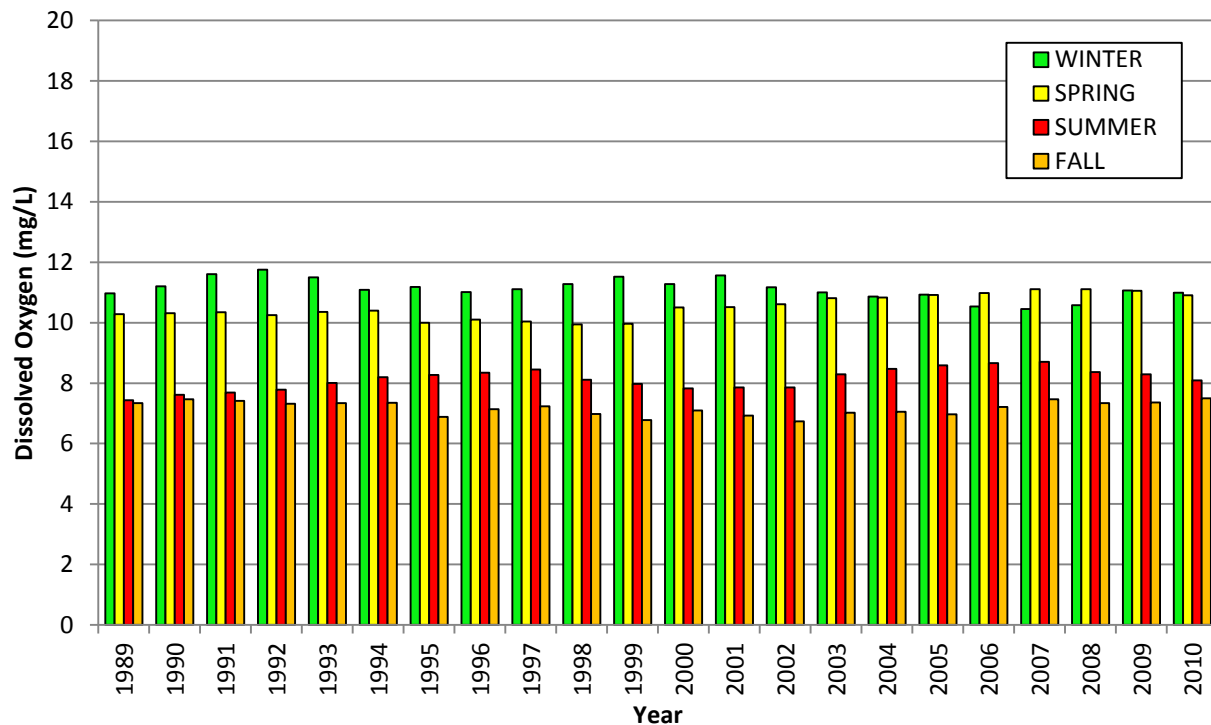


Figure 6-26 Five Year Running Average of Surface DO Concentrations for Station LM04

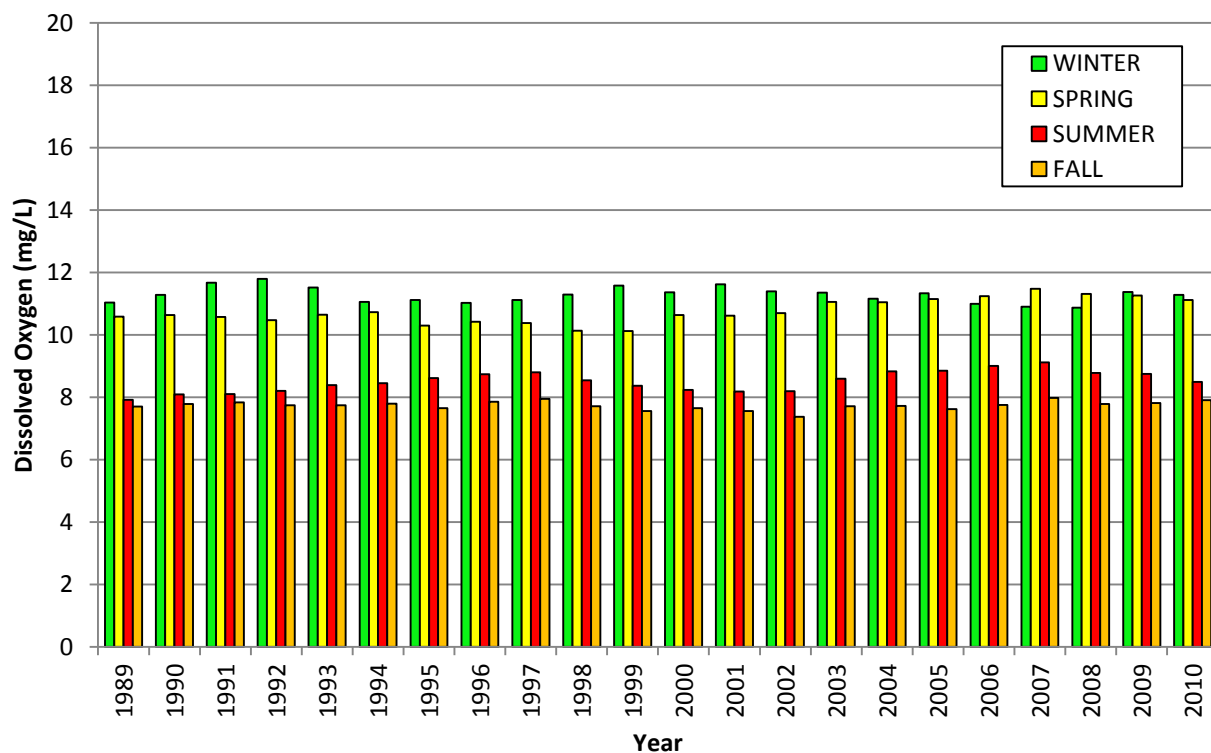


Figure 6-27 Five Year Running Average of Surface DO Concentrations for Station LM05

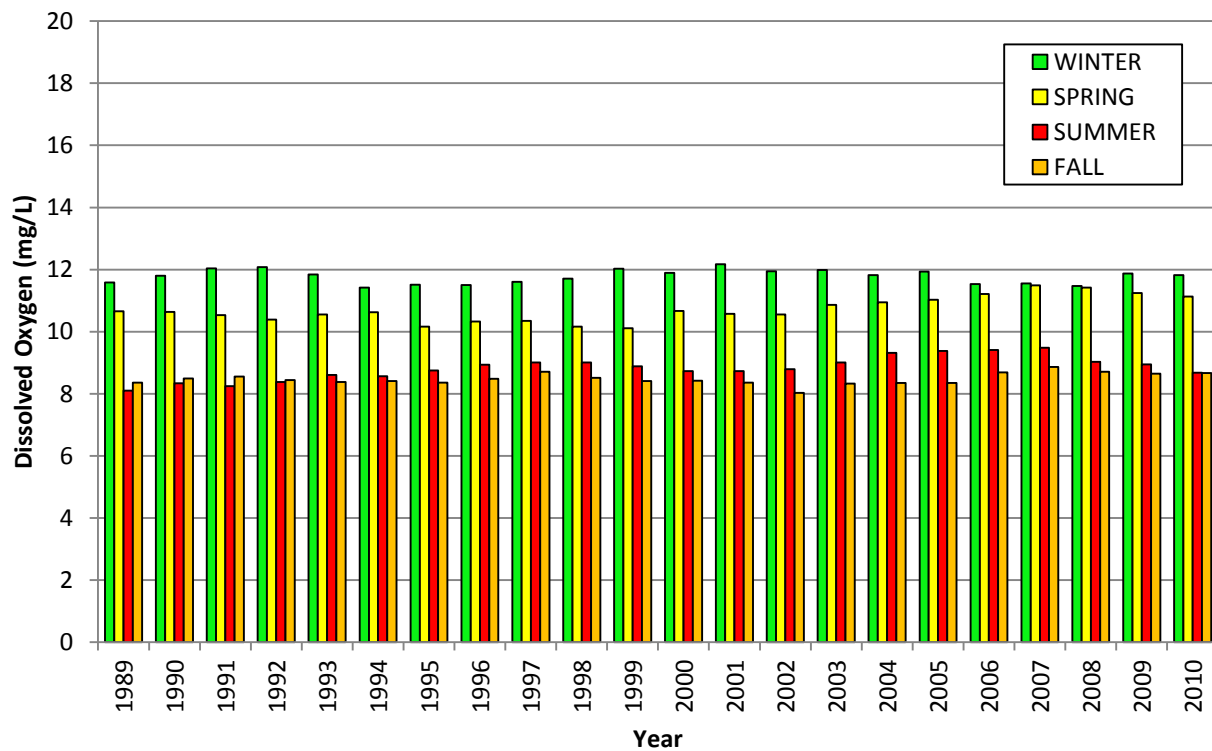


Figure 6-28 Five Year Running Average of Surface DO Concentrations for Station LM06

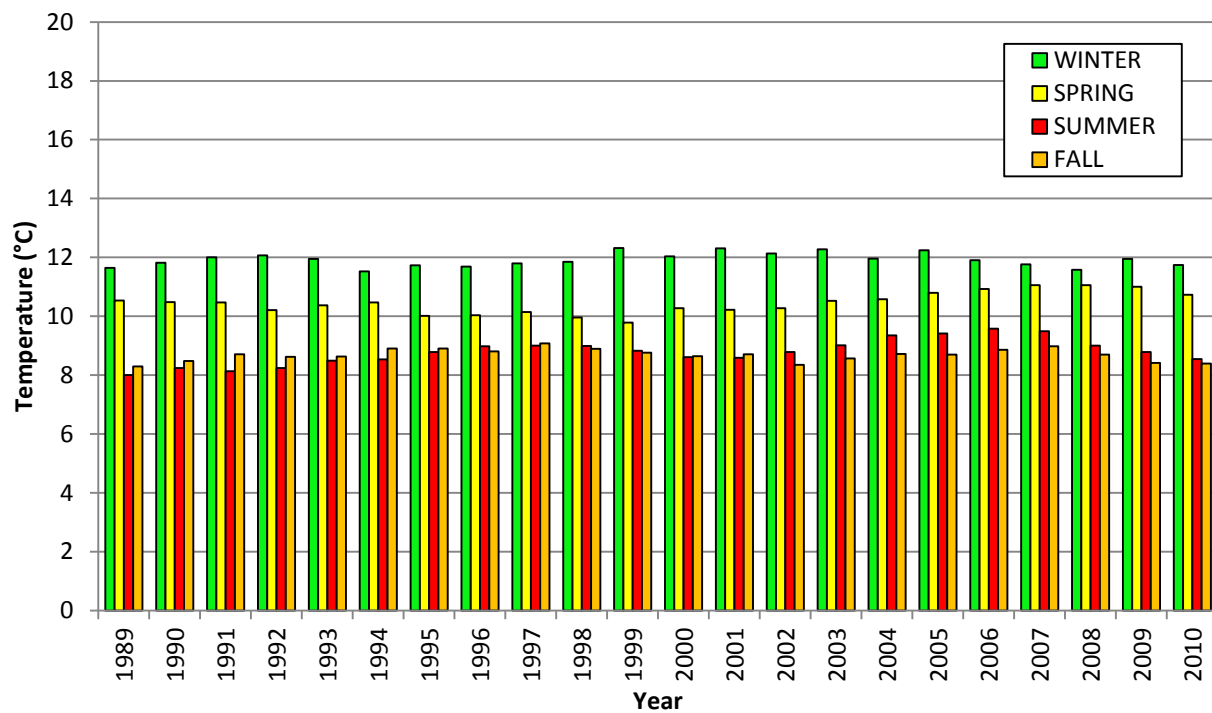


Figure 6-29 Five Year Running Average of Surface DO Concentrations for Station LM07

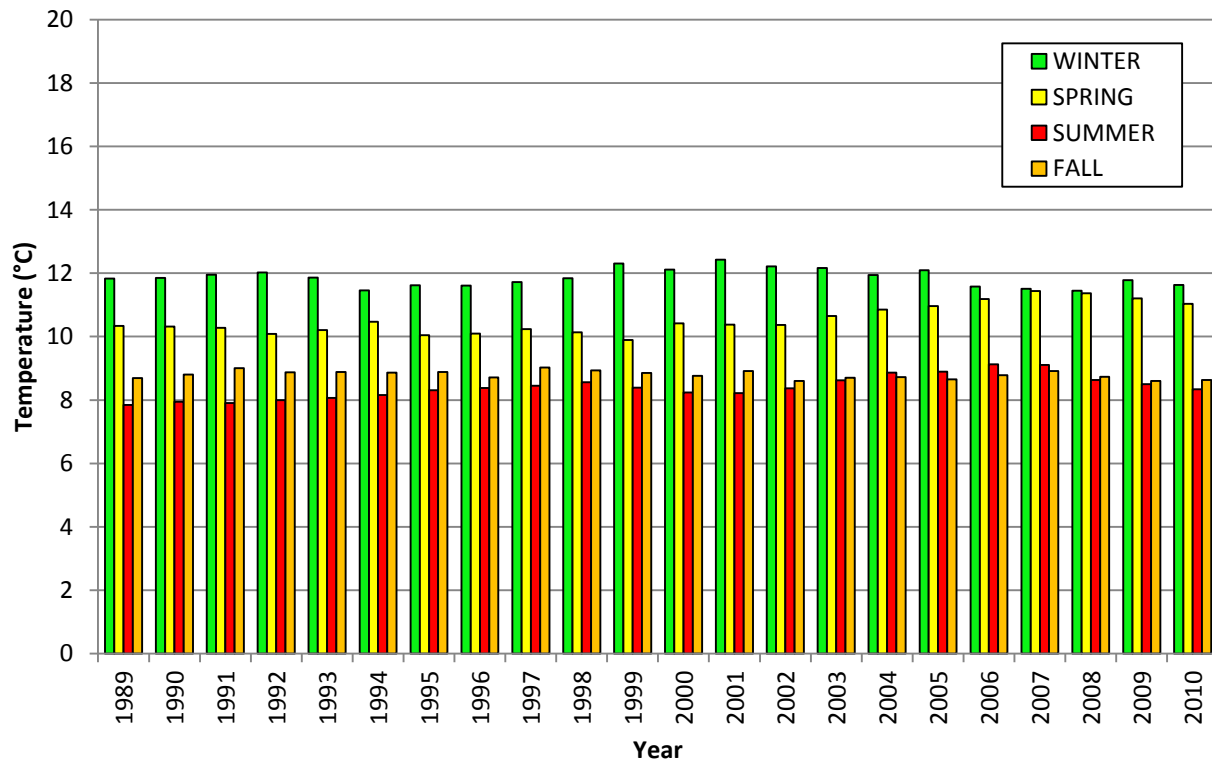


Figure 6-30 Five Year Running Average of Surface DO Concentrations for Station LM08

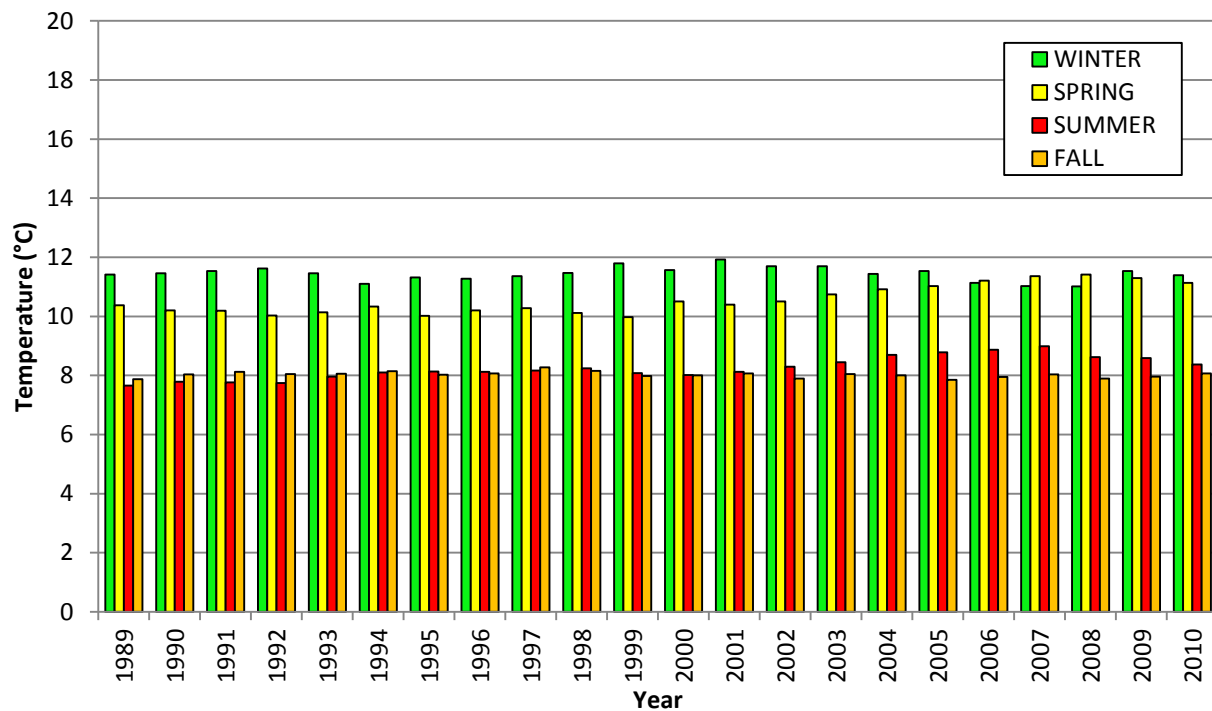


Figure 6-31 Five Year Running Average of Bottom DO Concentrations for Station LM01

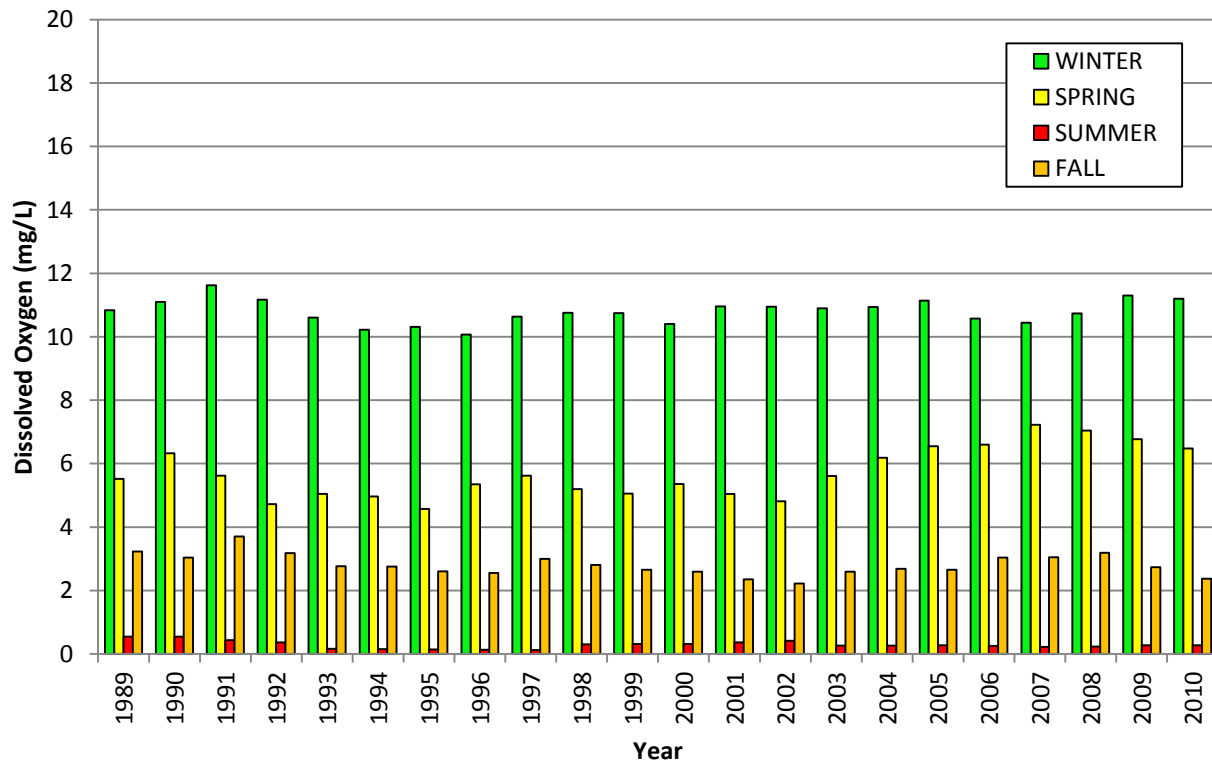


Figure 6-32 Five Year Running Average of Bottom DO Concentrations for Station LM02

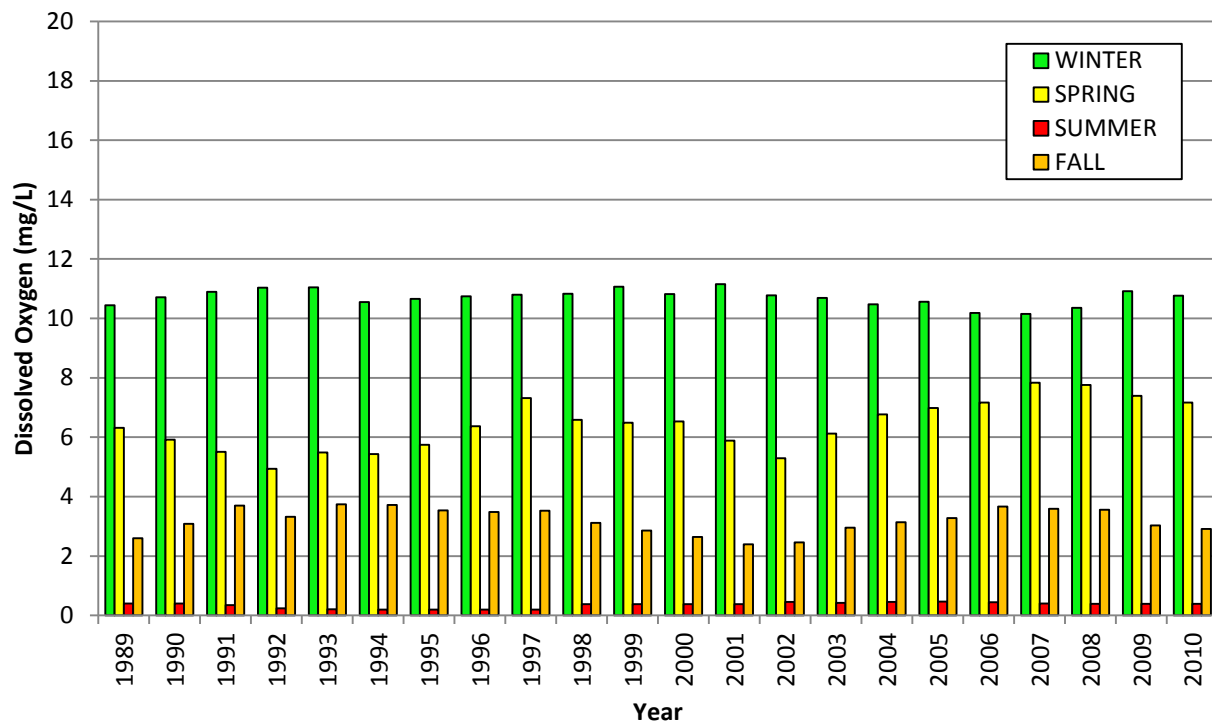


Figure 6-33 Five Year Running Average of Bottom DO Concentrations for Station LM03

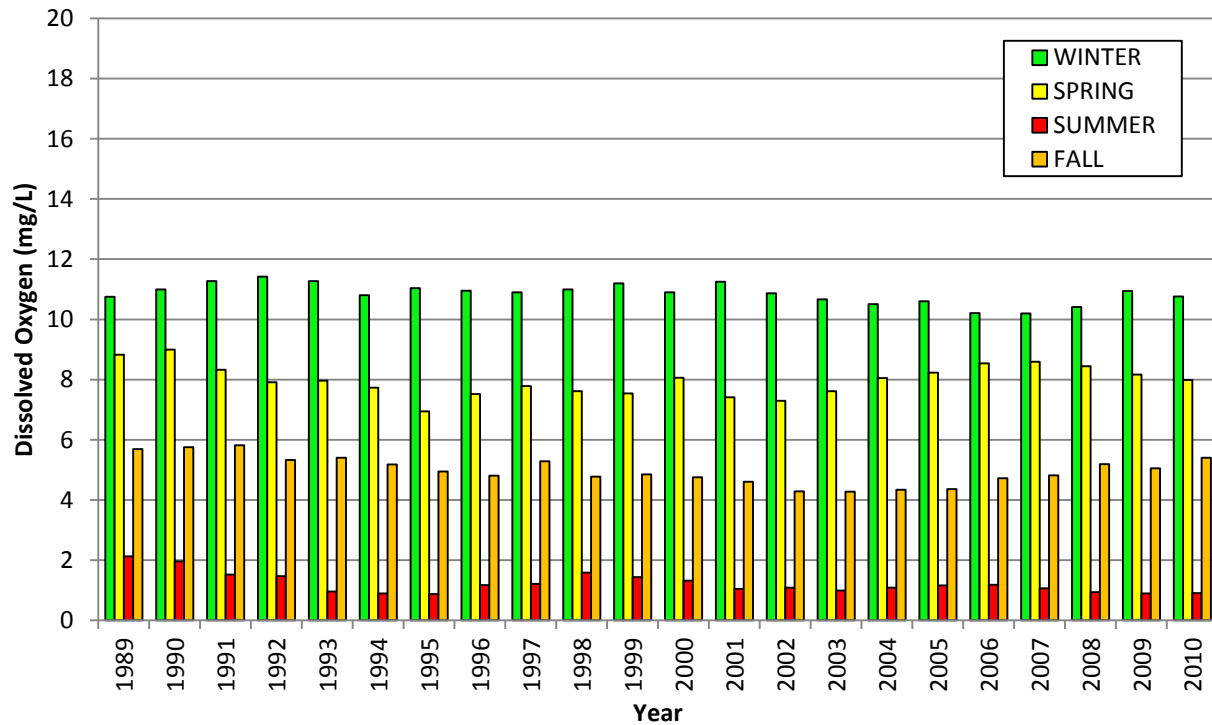


Figure 6-34 Five Year Running Average of Bottom DO Concentrations for Station LM04

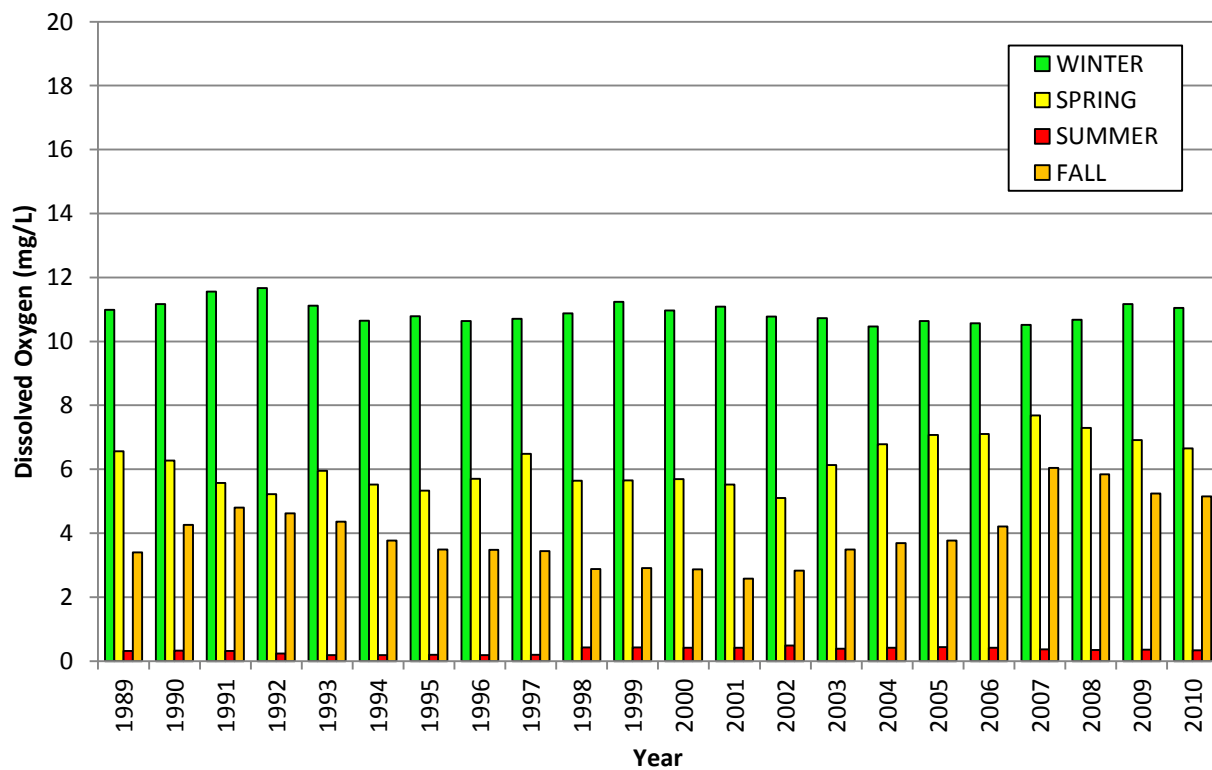


Figure 6-35 Five Year Running Average of Bottom DO Concentrations for Station LM05

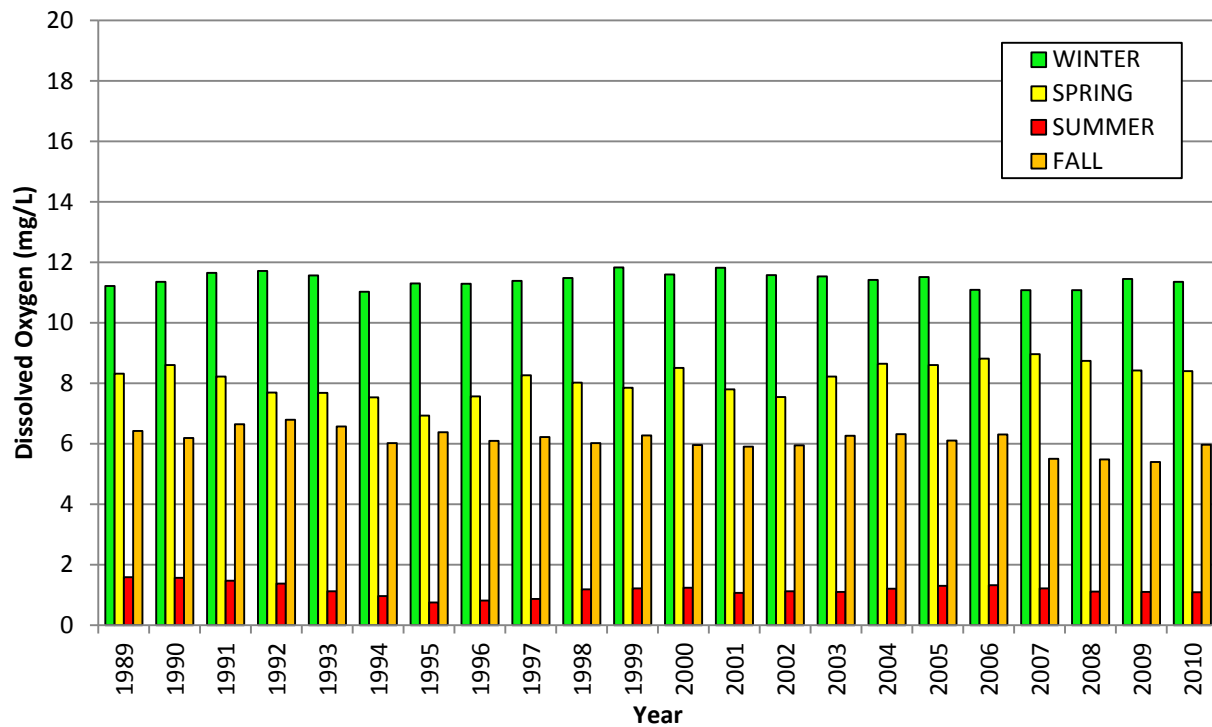


Figure 6-36 Five Year Running Average of Bottom DO Concentrations for Station LM06

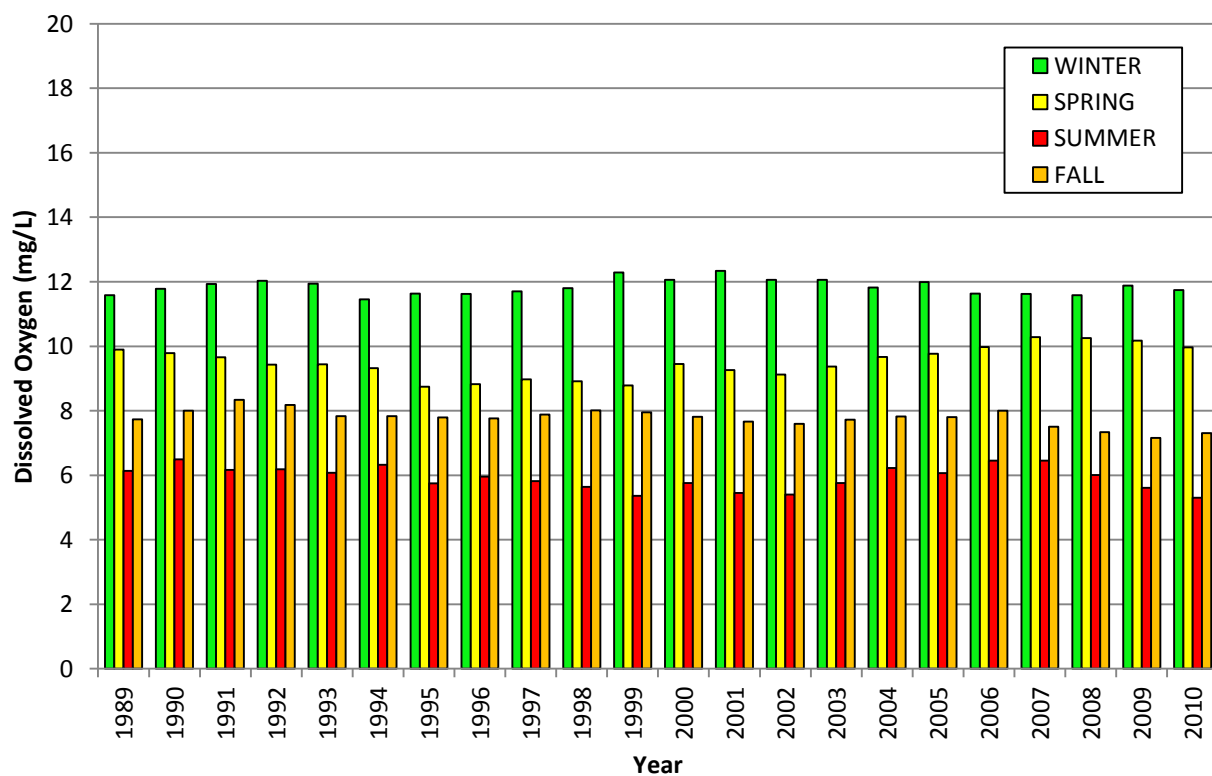


Figure 6-37 Five Year Running Average of Bottom DO Concentrations for Station LM07

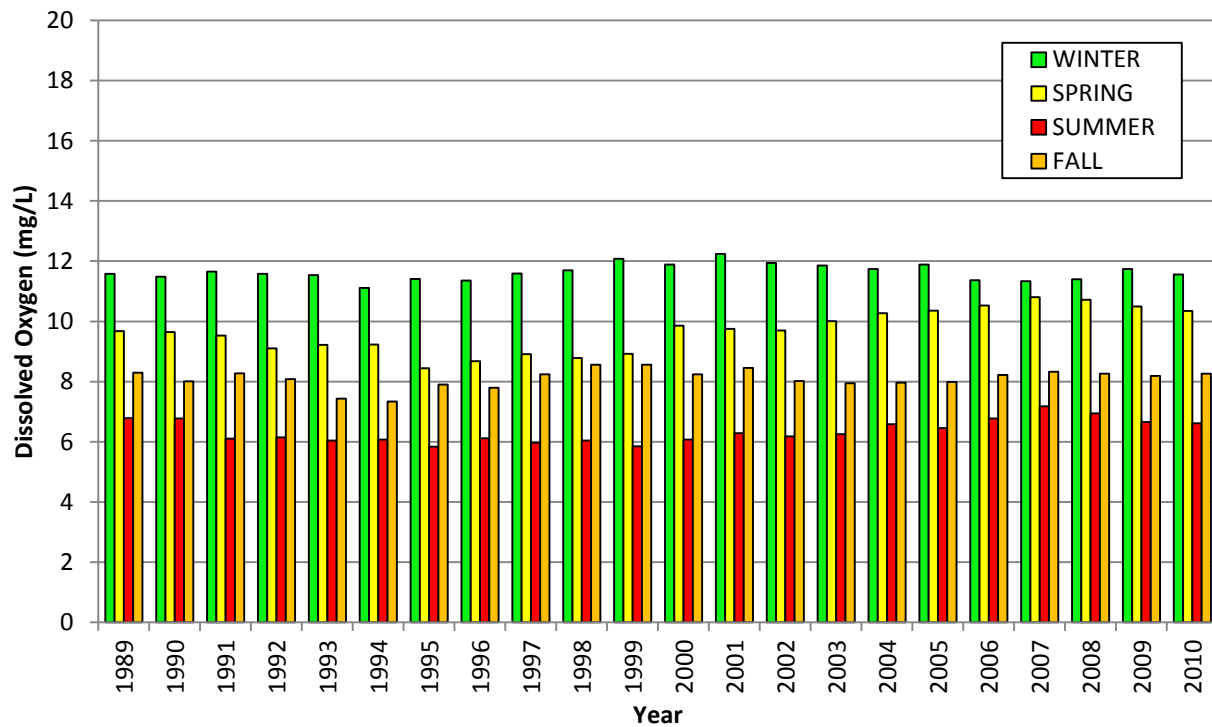


Figure 6-38 Five Year Running Average of Bottom DO Concentrations for Station LM08

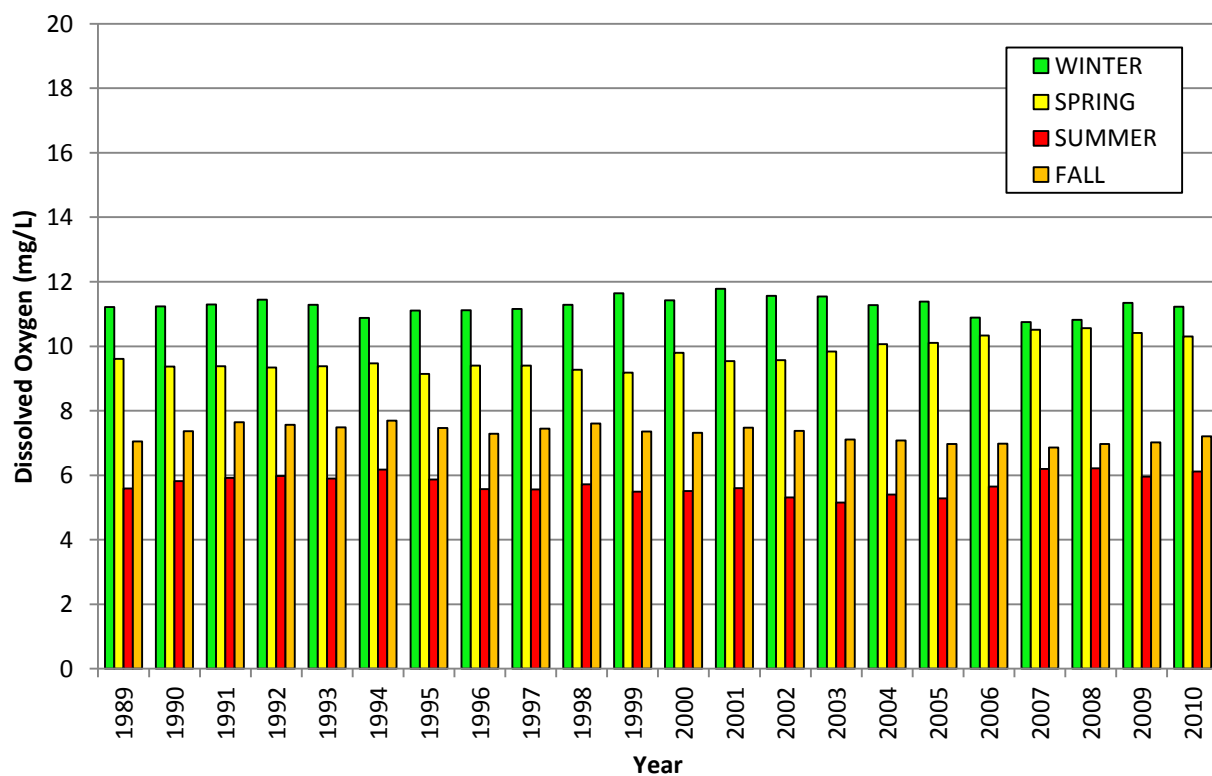


Figure 6-39 Percent DO Saturation Over Time for Station LM01

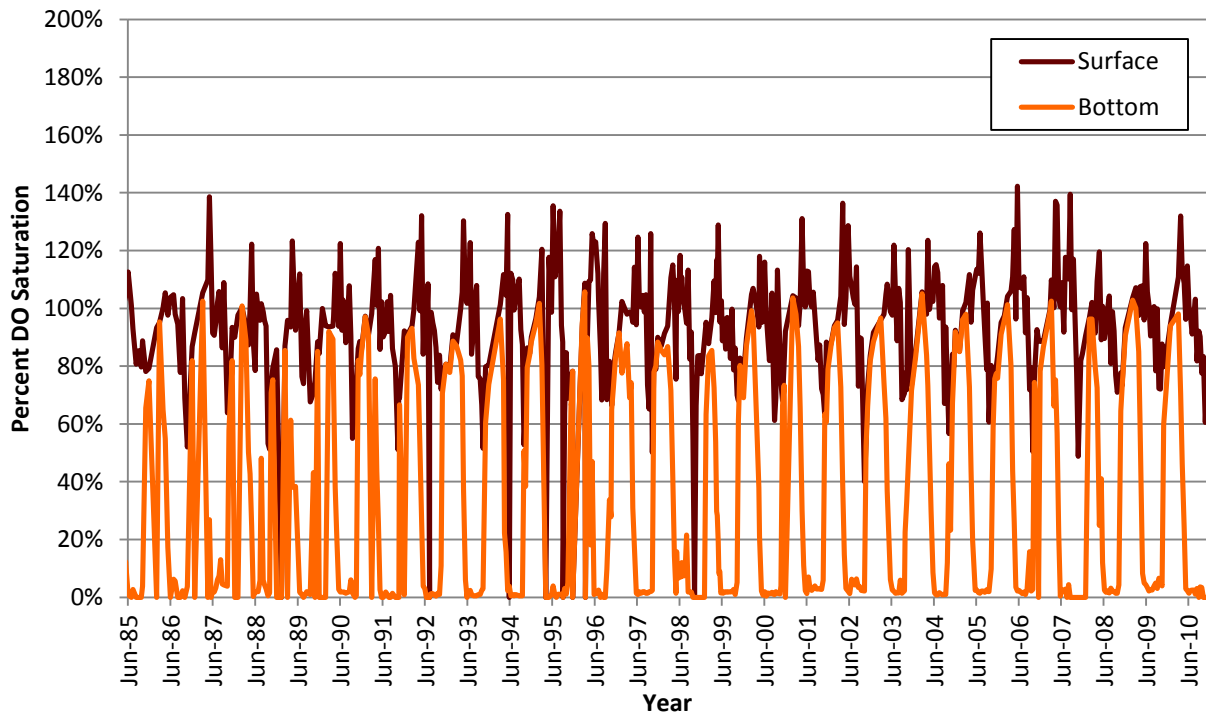
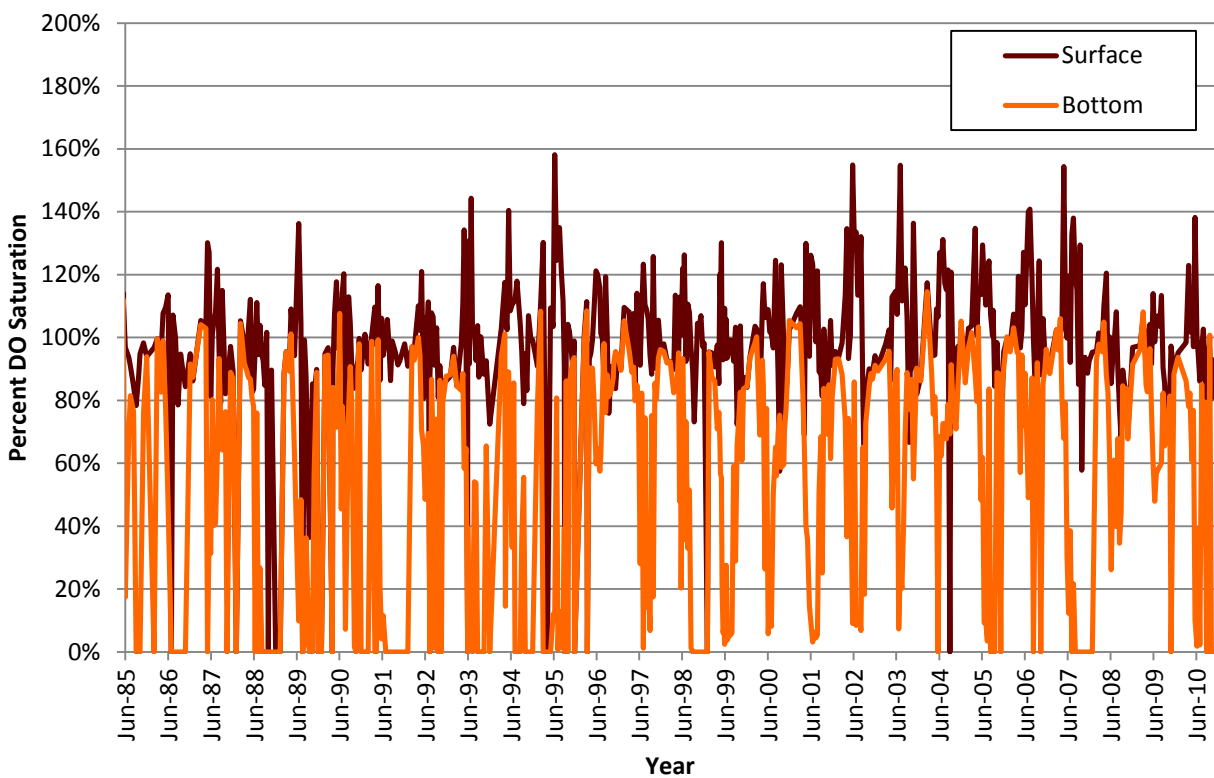
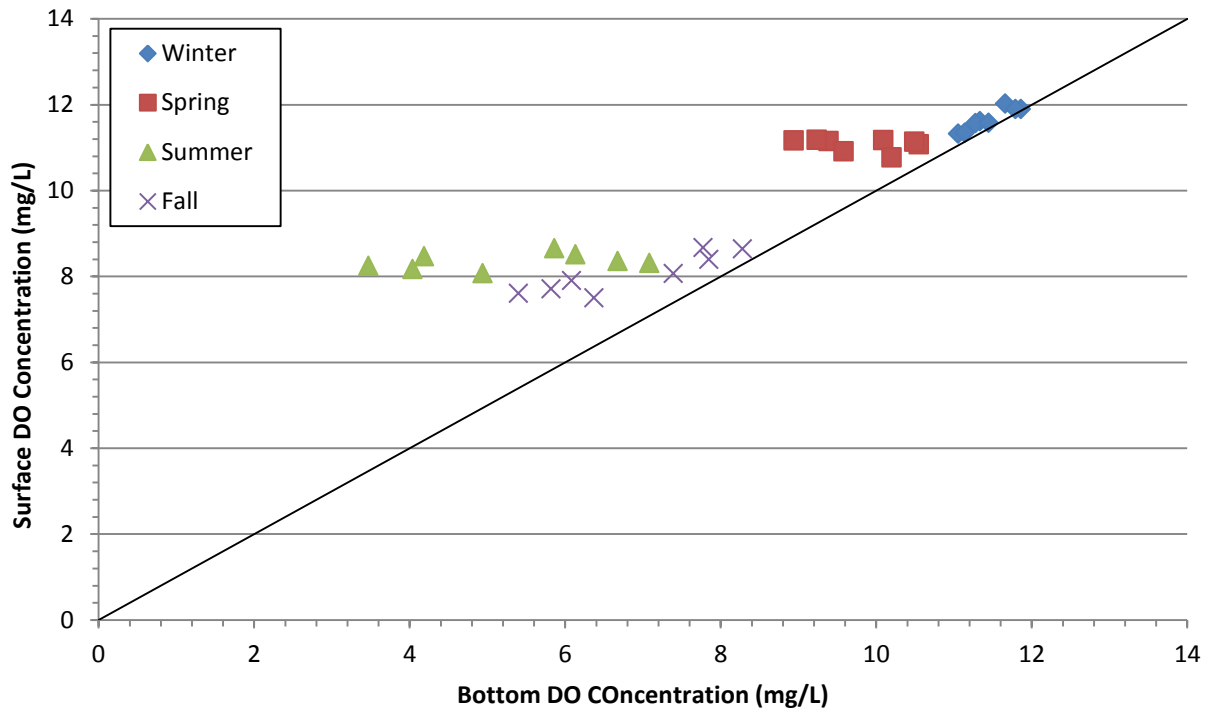


Figure 6-40 Percent DO Saturation Over Time for Station LM06



**Figure 6-41 Surface vs. Bottom Seasonal DO Concentration Comparison
 All Stations (2006 – 2010)**



**Figure 6-42 Surface vs. Bottom Seasonal Percent DO Saturation Comparison
 All Stations (2006 – 2010)**

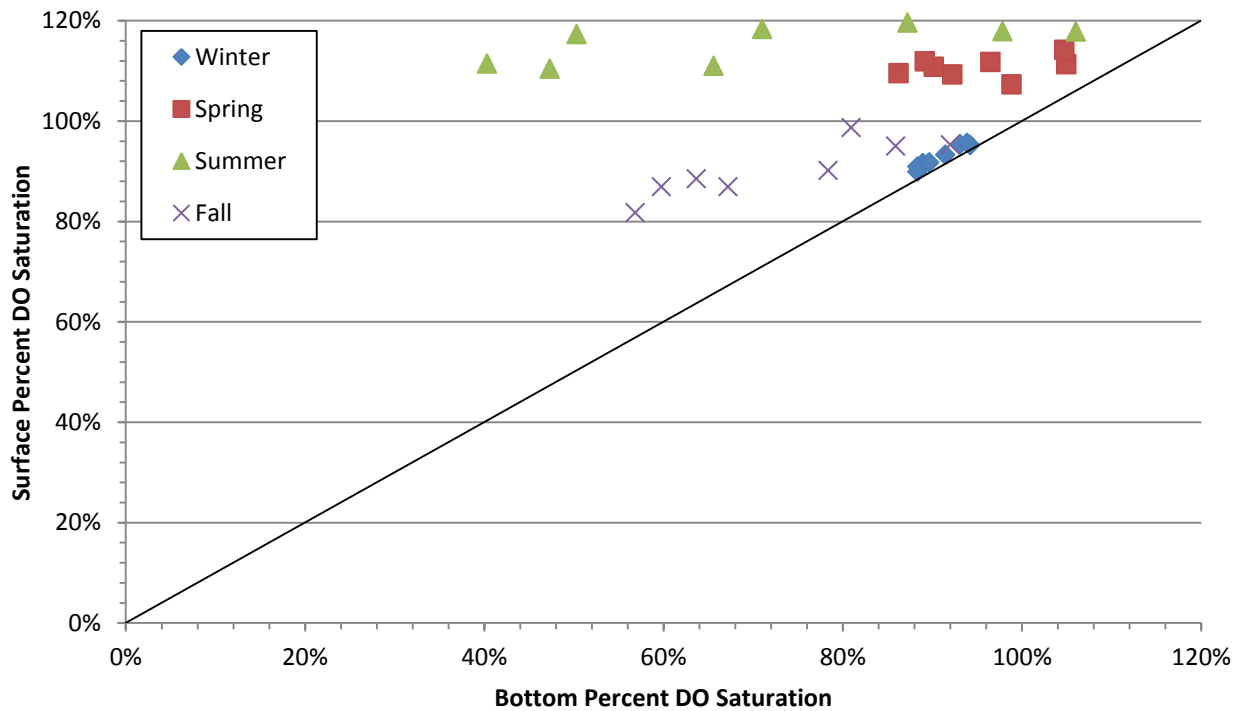


Figure 6-43 Dissolved Oxygen Profiles for Station LM01 (2006)

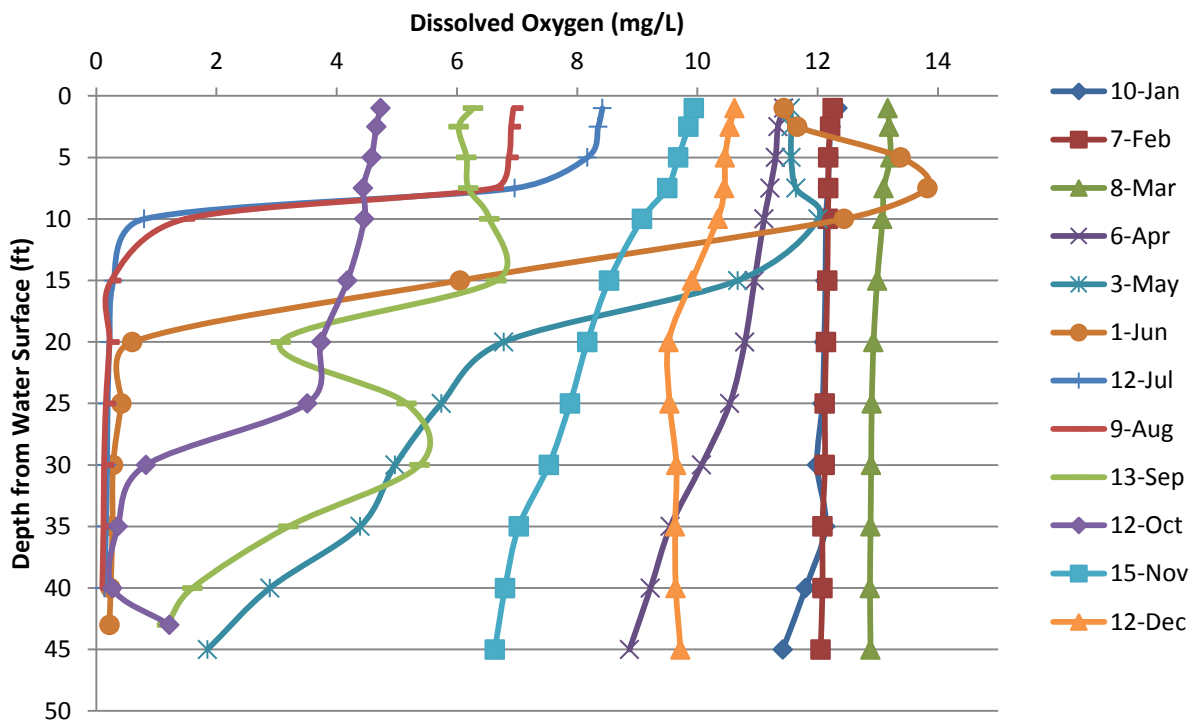


Figure 6-44 Dissolved Oxygen Profiles for Station LM01 (2010)

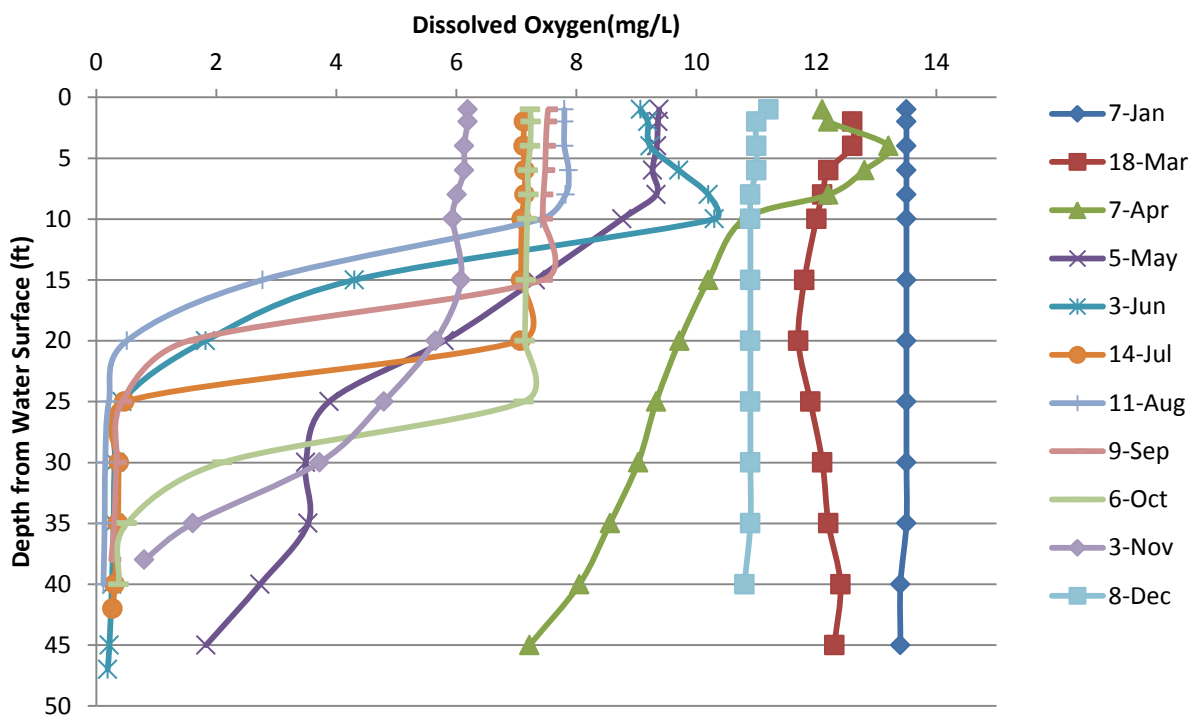


Figure 6-45 Percent Dissolved Oxygen Profiles for Station LM01 (2006)

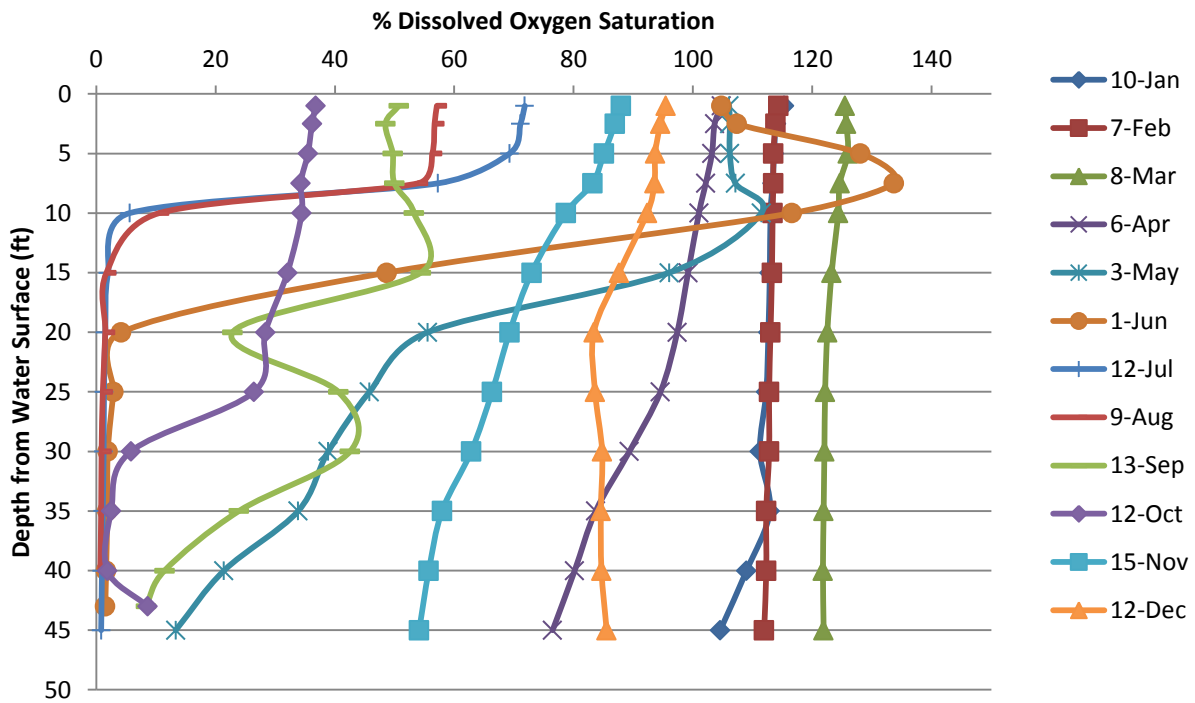
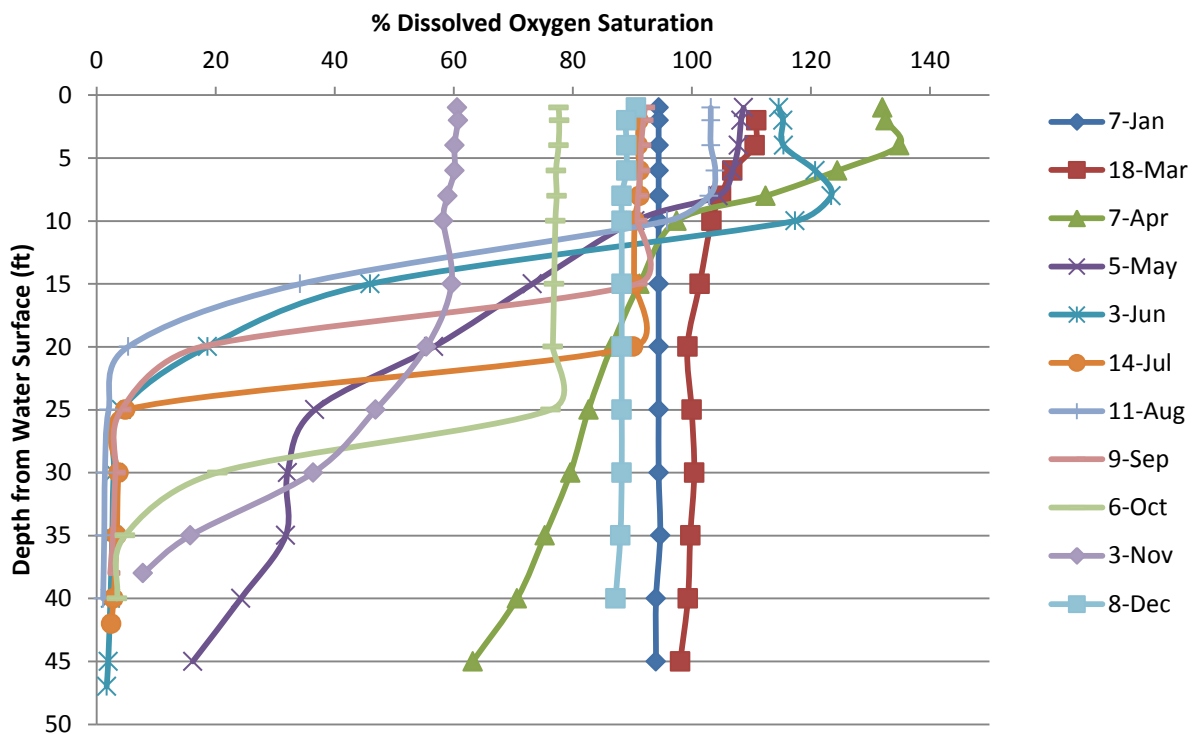


Figure 6-46 Percent Dissolved Oxygen Profiles for Station LM01 (2010)



Nitrogen

Five-year running averages for surface total Kjeldahl nitrogen (TKN) concentrations for each lake sampling station are depicted in Figures 6-47 through 6-54.

- Surface TKN concentrations for the 1984 to 2010 period range from 0.02 mg/L to 3.69 mg/L, with the highest concentration of 3.69 mg/L detected at sampling station LM03 on 7-JAN-2010. The average surface TKN concentration for all sampling stations during this period was calculated to be 0.61 mg/L.
- Surface TKN concentrations for the 2006 to 2010 period range from 0.1 mg/L to 3.69 mg/L, with the highest concentration of 3.69 mg/L detected at sampling station LM03 on 7-JAN-2010. The average surface TKN concentration for all sampling stations during this period was calculated to be 0.56 mg/L.
- The Mann-Kendall Seasonal Analysis for surface TKN concentrations shows no increasing or decreasing trends for the 2006 to 2010 period.

As shown in Figure 6-49 there is an apparent significant increase in surface TKN concentrations at sampling station LM03 during 2010 (winter). However, this increase appears to be the result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with winter five year running averages for 2010 is a result of a single sampling event with an elevated surface TKN concentration: 3.64 mg/L as N on 7-JAN-2010.

In addition, As shown in Figure 6-53 there is an apparent significant increase in surface TKN concentrations at sampling station LM07 during the 2007 to 2010 (winter) period. However, this increase is associated with a two sampling events with elevated surface TKN concentrations: 1.12 mg/L as N on 12-SEP-2007 and 1.08 on 27-SEP-2007.

Five-year running averages for bottom TKN concentrations for each lake sampling station are depicted in Figures 6-55 through 6-62.

- Bottom TKN concentrations for the 1984 to 2010 period range up to 9.1 mg/L, with the highest concentration of 9.1 mg/L detected at sampling station LM01 on 26-SEP-1990. The average bottom TKN concentration for all sampling stations during this period was calculated to be 0.62 mg/L.
- Bottom TKN concentrations for the 2006 to 2010 period range up to 3.29 mg/L, with the highest concentration of 3.29 mg/L detected at sampling station LM 01 on 27-SEP-2006. The average bottom TKN concentration for all sampling stations during this period was calculated to be 0.61 mg/L.
- The Mann-Kendall Seasonal Analysis for bottom TKN concentrations shows increasing trends at all sampling stations for the 2006 to 2010 period with the exception of stations LM05, LM06 and LM08.

Seasonal comparisons for surface and bottom TKN concentration changes for all lake sampling stations are depicted in Figure 6-63 for the 2006 to 2010 period.

- The data points represent the average TKN concentration for each season during the 2006 to 2010 with the average surface TKN concentration on the y-axis and the average bottom TKN concentration along the x-axis. The diagonal line represents a 1:1 linear relationship for comparative purposes. The TKN concentration ratios, in general, cluster close to and below the 1:1 line. The deviations from the 1:1 line suggest TKN values being much greater in the hypolimnion than in the epilimnion which suggests the release of NH_4^+ from the bottom sediments during stratification periods. Alternatively it is

possible that the deviations from the 1:1 line indicate ammonium oxidation within the epilimnion, although less likely.

Five-year running averages for surface oxidized nitrogen (Ox-N) concentrations for each lake sampling station are depicted in Figures 6-64 through 6-71.

- Surface oxidized nitrogen concentrations for the 1984 to 2010 period range from below detection limits to 2.67 mg/L, with the highest concentration of 2.67 mg/L detected at sampling station LM06 on 12-JUN-1995. The average surface oxidized nitrogen concentration for all sampling stations during this period was calculated to be 0.17 mg/L.
- Surface oxidized nitrogen concentrations for the 2006 to 2010 period range from below detection limits to 0.75 mg/L, with the highest concentration of 13.9 mg/L detected at sampling station LM06 on 7-JAN-2010. The average surface oxidized nitrogen concentration for all sampling stations during this period was calculated to be 0.16 mg/L.
- The Mann-Kendall Seasonal Analysis for surface oxidized nitrogen concentrations shows decreasing trends at all sampling stations for the 2006 to 2010 period with the exception of sampling stations LM06 and LM07.
- The seasonal trend for surface oxidized nitrogen concentrations at all sampling stations generally shows Summer-Ox-N < Fall-Ox-N < Spring-Ox-N < Winter-Ox-N.

Five-year running averages for bottom oxidized nitrogen concentrations for each lake sampling station are depicted in Figures 6-72 through 6-79.

- Bottom oxidized nitrogen concentrations for the 1984 to 2010 period range up to 2.05 mg/L, with the highest concentration of 2.05 mg/L detected at sampling station LM07 on 20-MAY-1998. The average bottom oxidized nitrogen concentration for all sampling stations during this period was calculated to be 0.17 mg/L.

- Bottom oxidized nitrogen concentrations for the 2006 to 2010 period range up to 0.74 mg/L, with the highest concentration of 0.74 mg/L detected at sampling station LM06 on 7-JAN-2010. The average bottom oxidized nitrogen concentration for all sampling stations during this period was calculated to be 0.17 mg/L.
- The Mann-Kendall Seasonal Analysis for bottom oxidized nitrogen concentrations shows slight decreasing trends at sampling stations LM01 and LM02 and no other significant trends at other sampling stations for the 2006 to 2010 period.
- The seasonal trend for bottom oxidized nitrogen concentrations at all sampling stations generally shows Summer-Ox-N < Fall-Ox-N < Spring-Ox-N < Winter-Ox-N.

Seasonal comparisons for surface and bottom oxidized nitrogen concentration comparisons for all lake sampling stations are depicted in Figure 6-80 for the 2006 to 2010 period.

- The data points represent the average oxidized nitrogen concentration for each season during the 2006 to 2010 with the average surface oxidized nitrogen concentration on the y-axis and the average bottom oxidized nitrogen concentration along the x-axis. The diagonal line represents a 1:1 linear relationship for comparative purposes. The oxidized nitrogen concentration ratios, in general cluster close to and below the 1:1 line.

Figure 6-47 Five Year Running Average of Surface TKN Concentrations for Station LM01

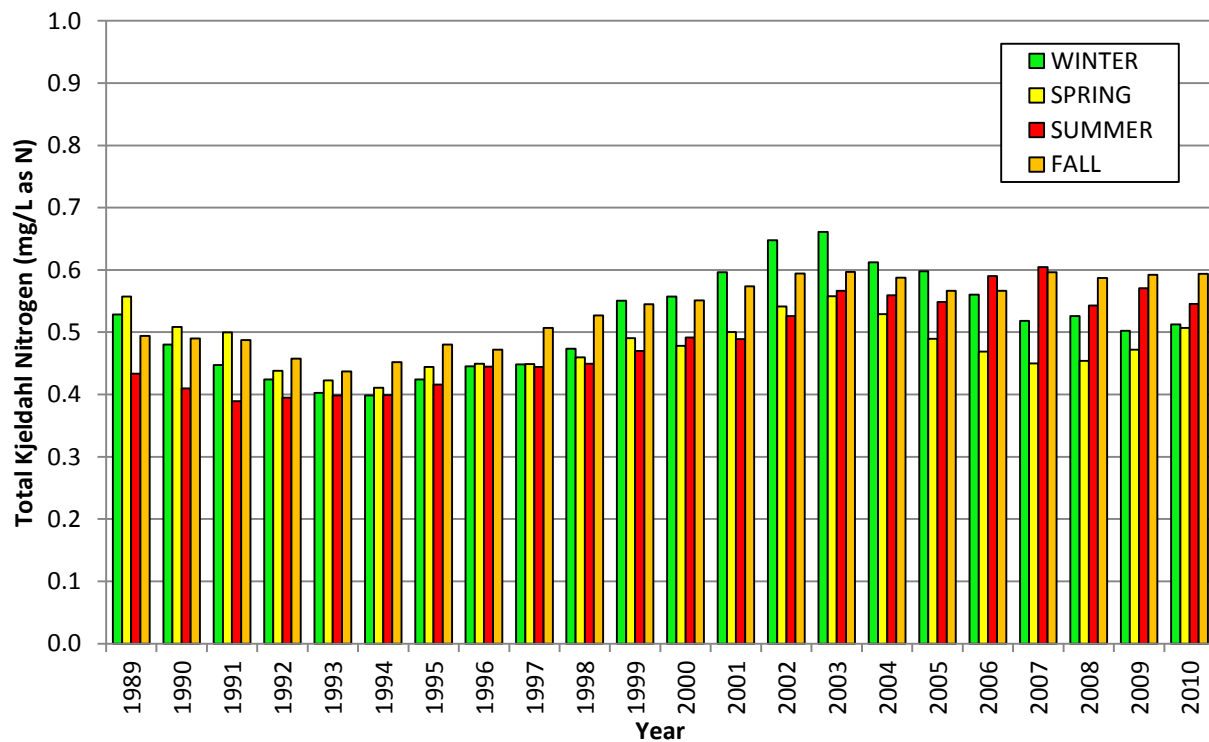


Figure 6-48 Five Year Running Average of Surface TKN Concentrations for Station LM02

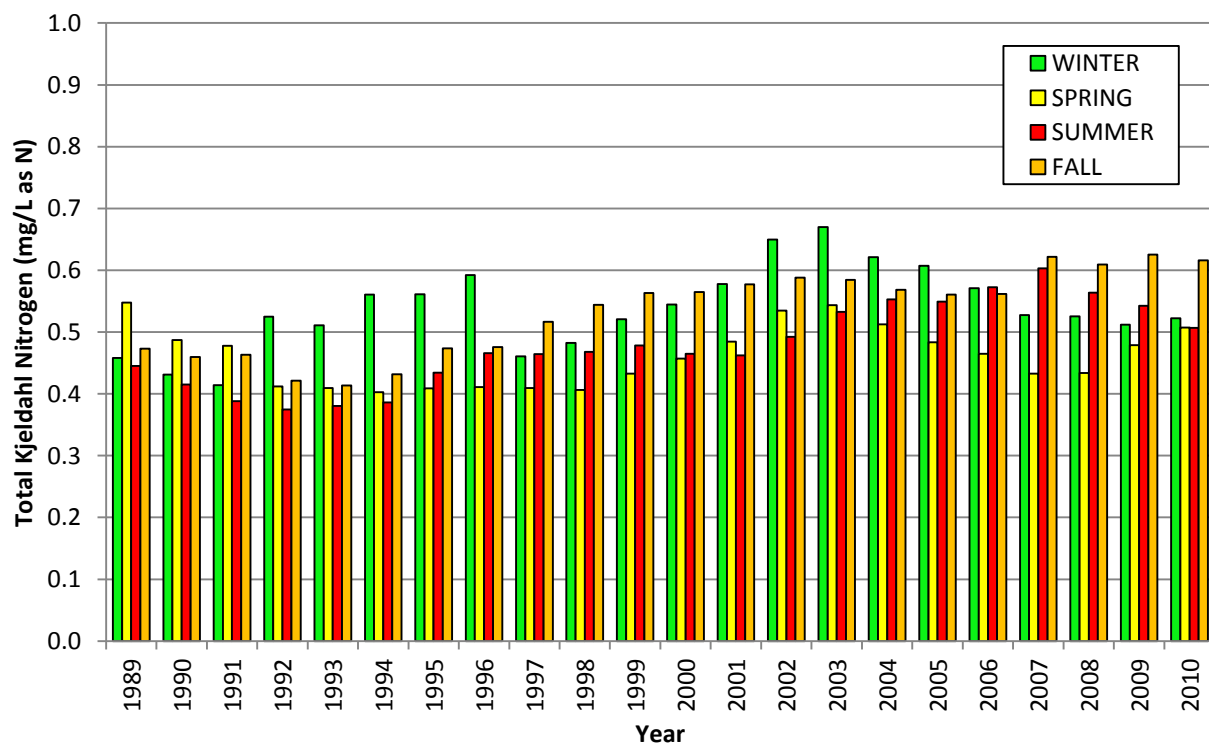


Figure 6-49 Five Year Running Average of Surface TKN Concentrations for Station LM03

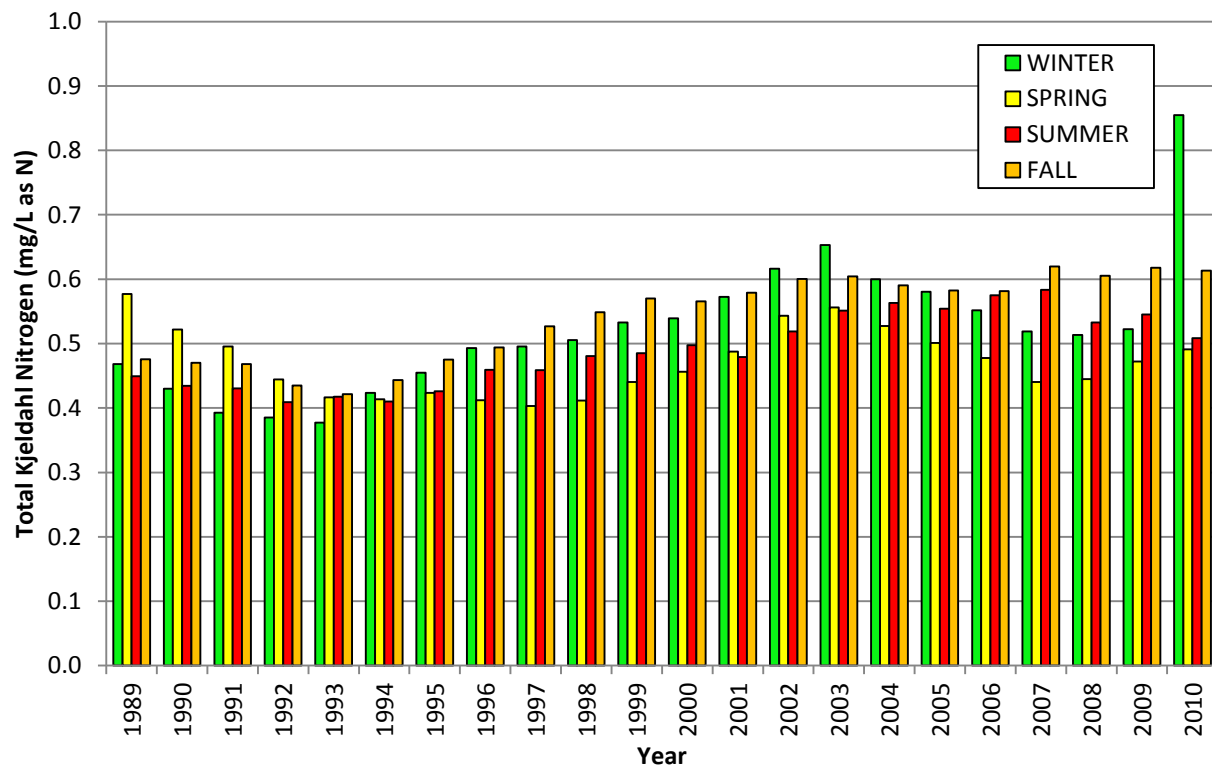


Figure 6-50 Five Year Running Average of Surface TKN Concentrations for Station LM04

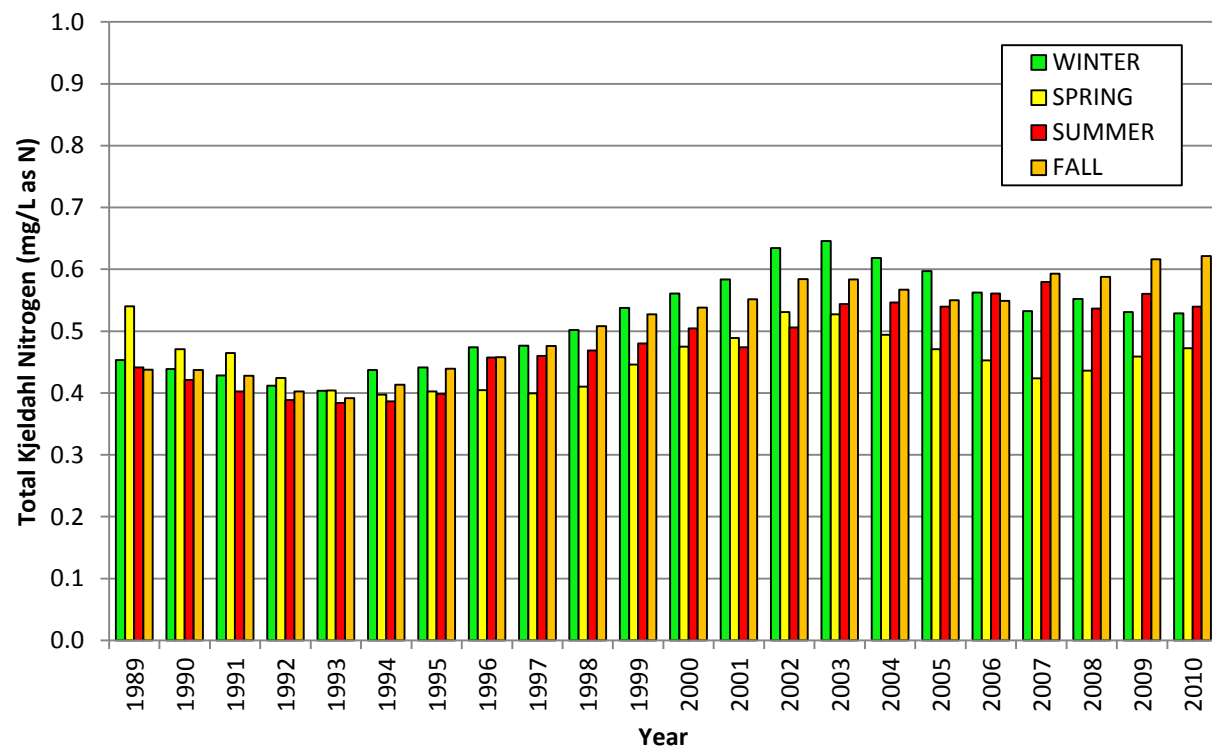


Figure 6-51 Five Year Running Average of Surface TKN Concentrations for Station LM05

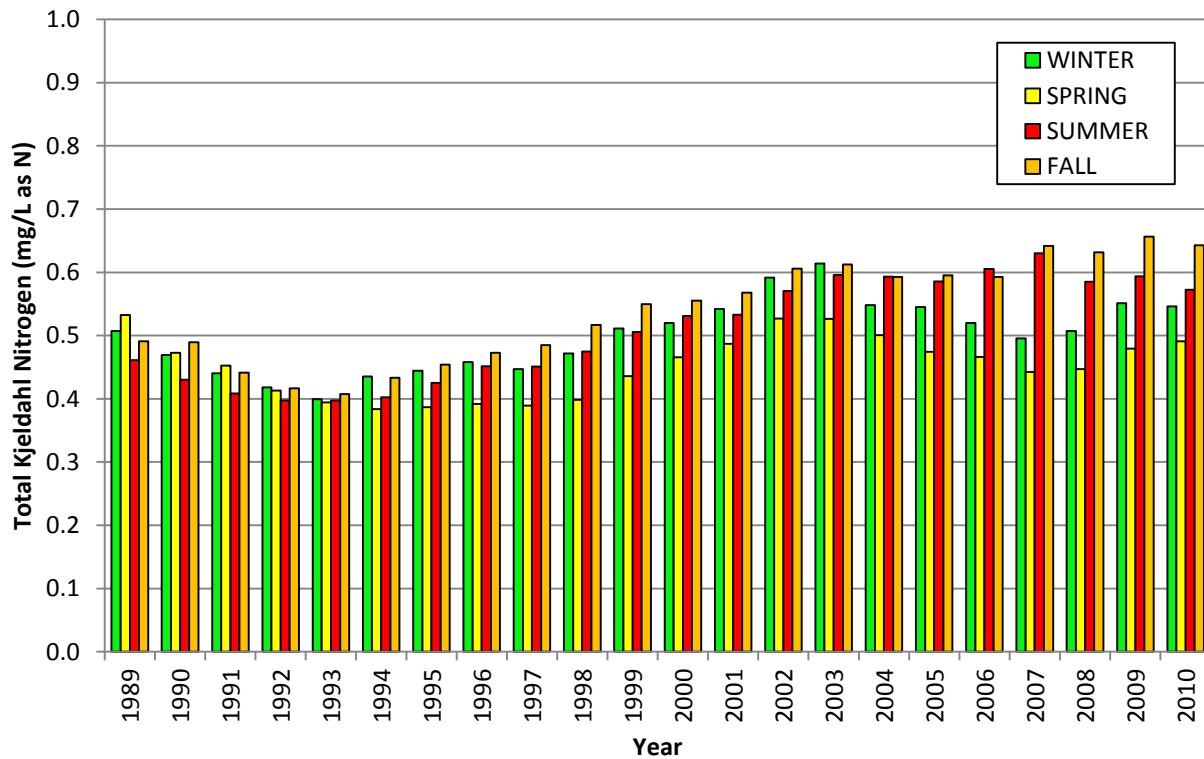


Figure 6-52 Five Year Running Average of Surface TKN Concentrations for Station LM06

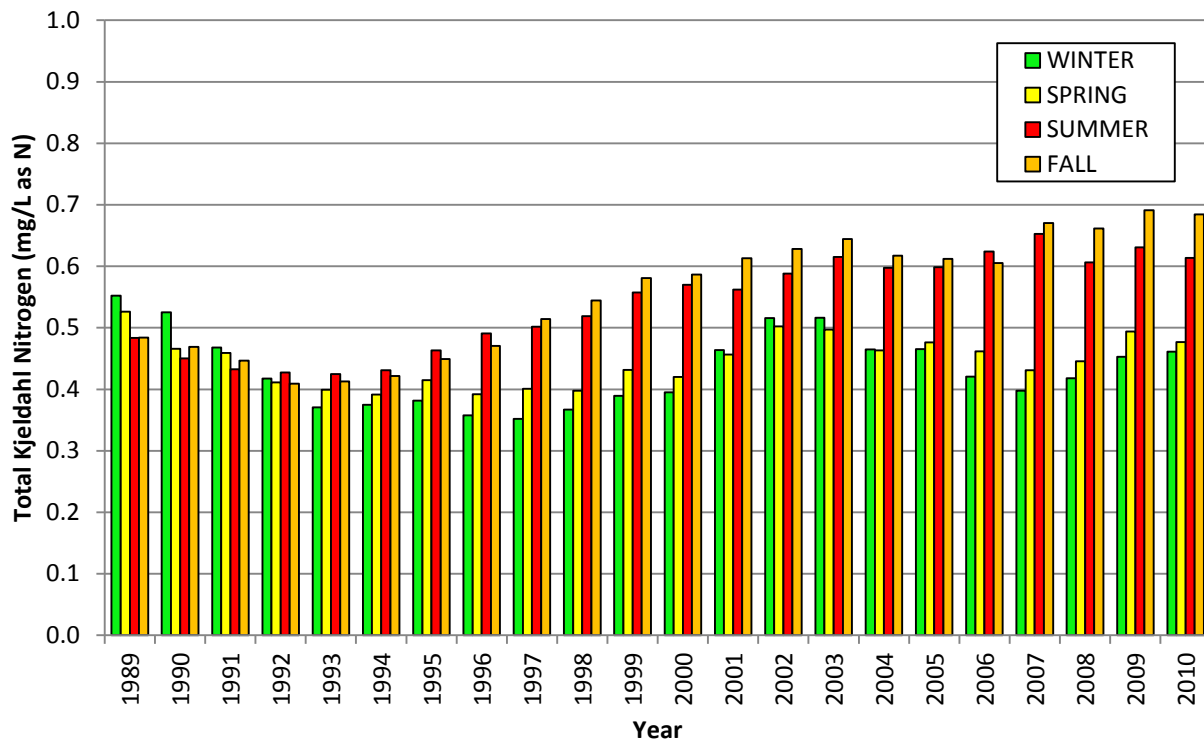


Figure 6-53 Five Year Running Average of Surface TKN Concentrations for Station LM07

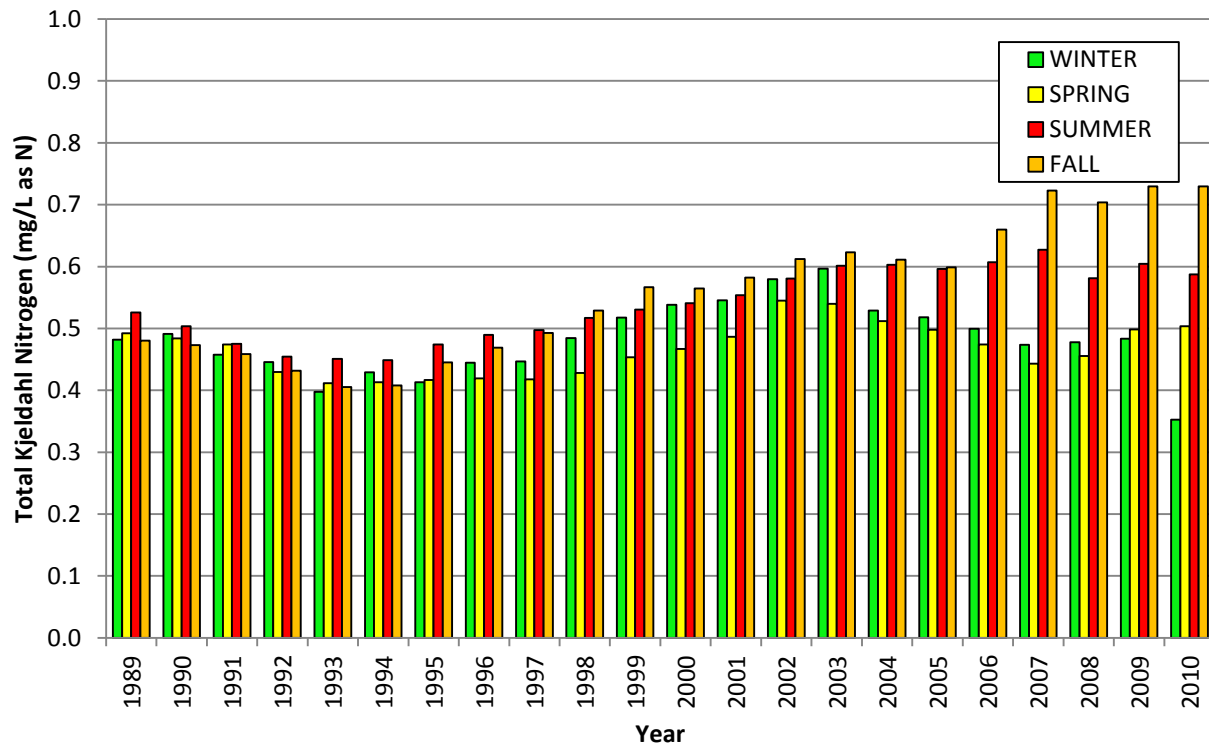


Figure 6-54 Five Year Running Average of Surface TKN Concentrations for Station LM08

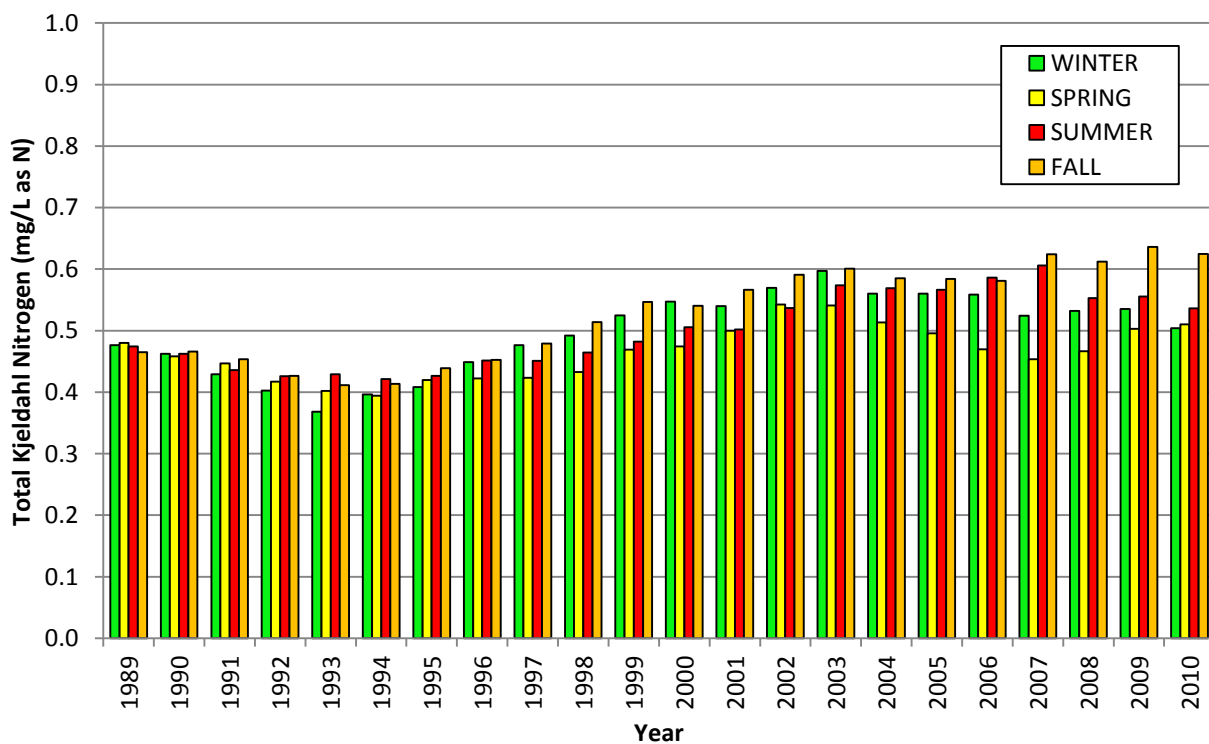


Figure 6-55 Five Year Running Average of Bottom TKN Concentrations for Station LM01

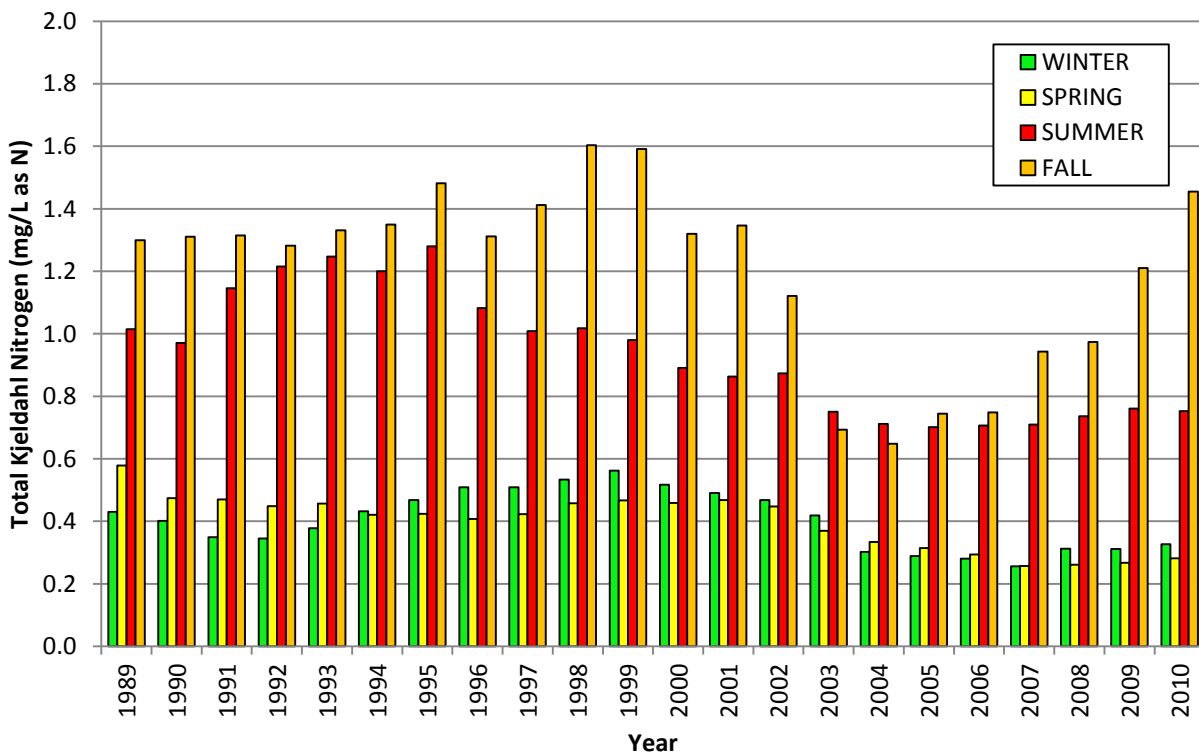


Figure 6-56 Five Year Running Average of Bottom TKN Concentrations for Station LM02

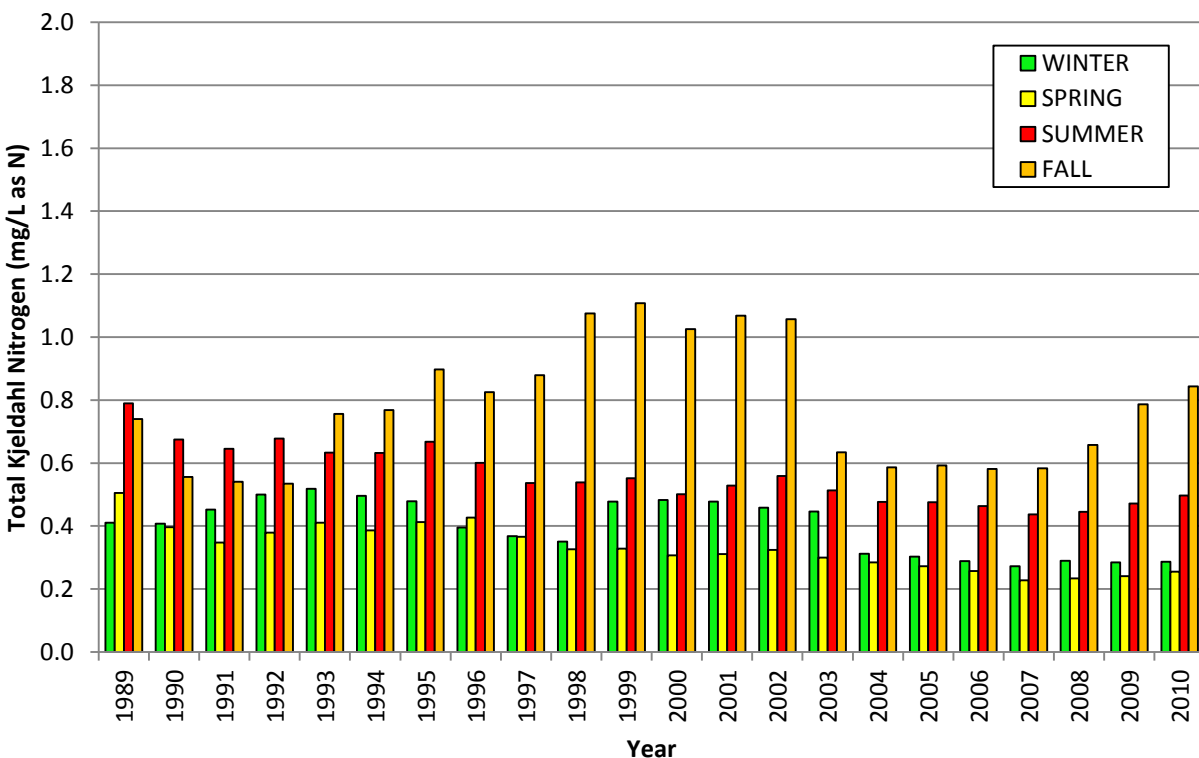


Figure 6-57 Five Year Running Average of Bottom TKN Concentrations for Station LM03

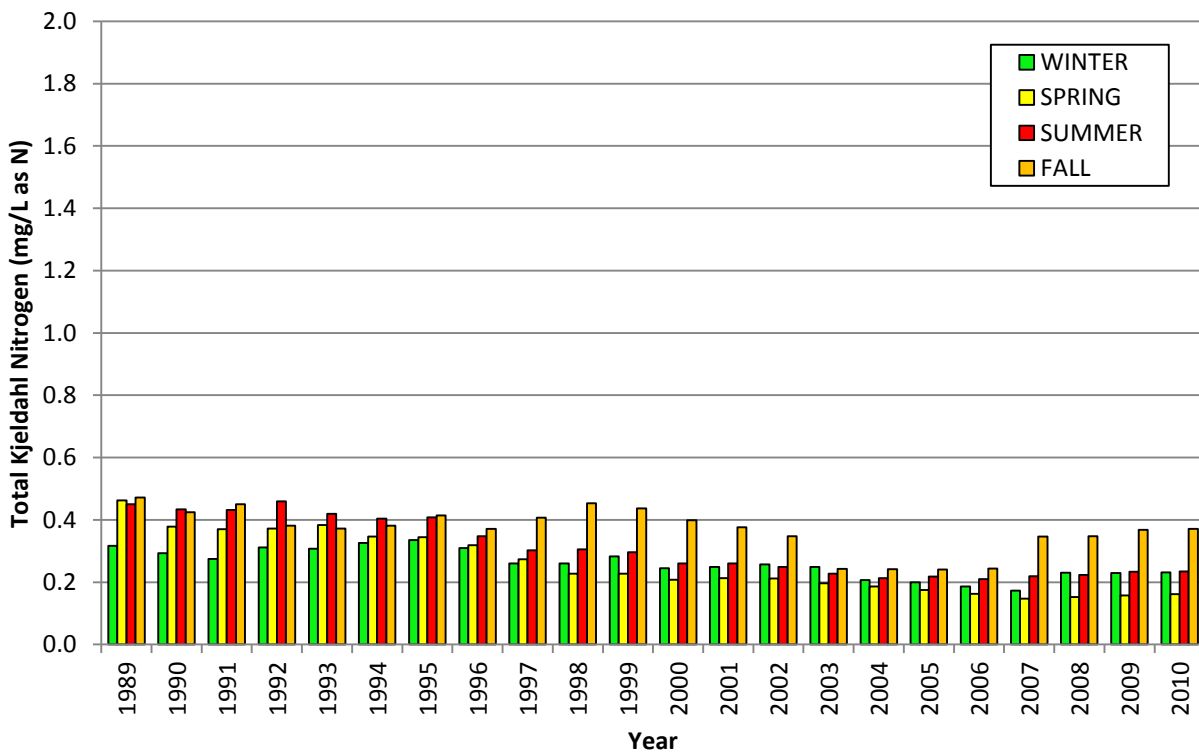


Figure 6-58 Five Year Running Average of Bottom TKN Concentrations for Station LM04

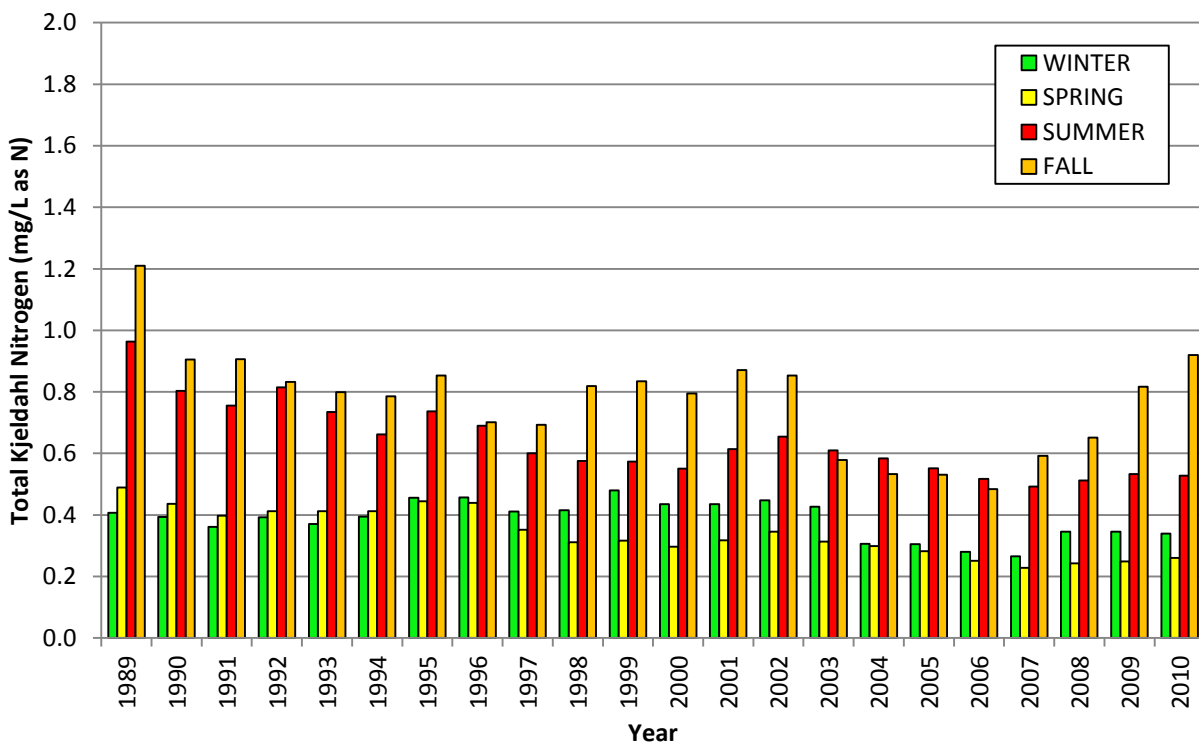


Figure 6-59 Five Year Running Average of Bottom TKN Concentrations for Station LM05

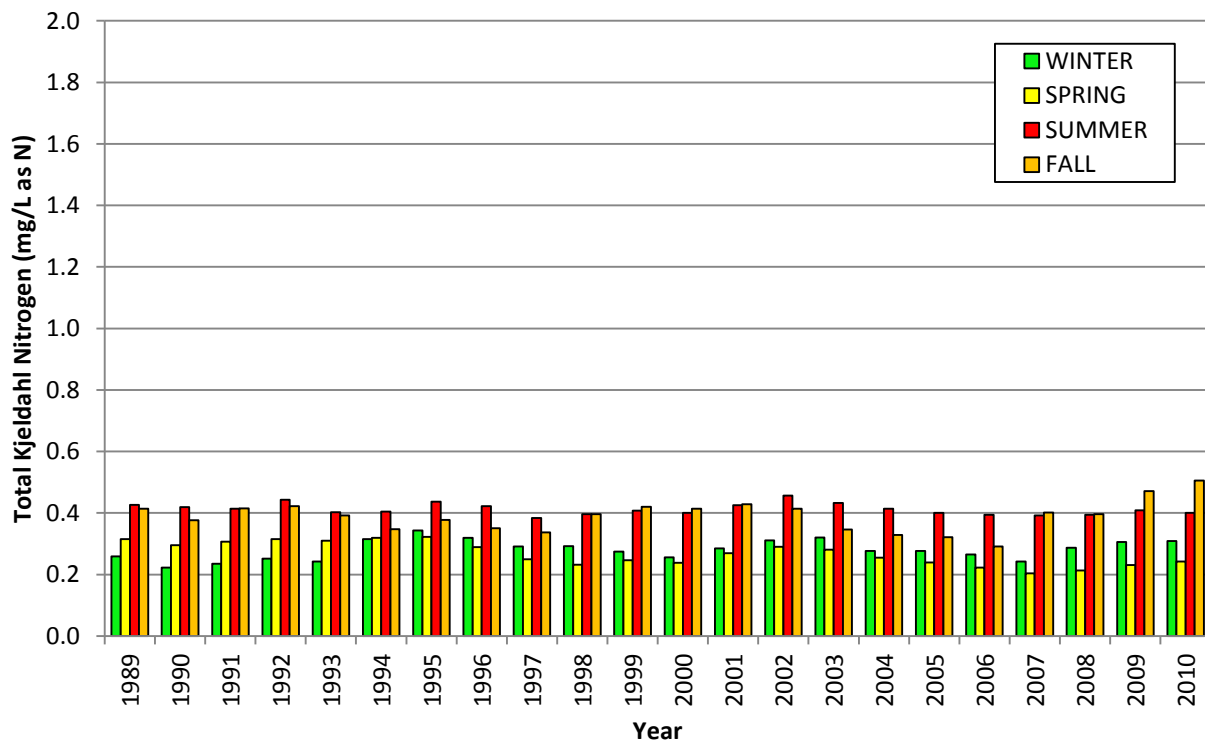


Figure 6-60 Five Year Running Average of Bottom TKN Concentrations for Station LM06

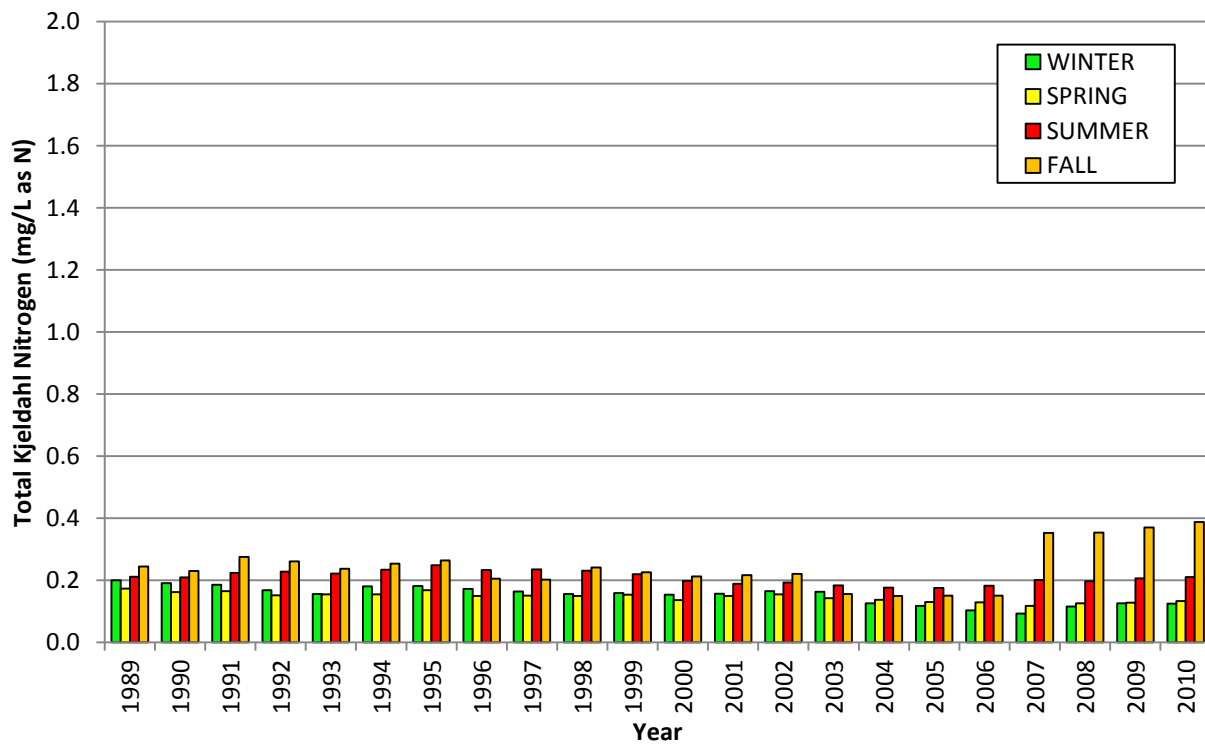


Figure 6-61 Five Year Running Average of Bottom TKN Concentrations for Station LM07

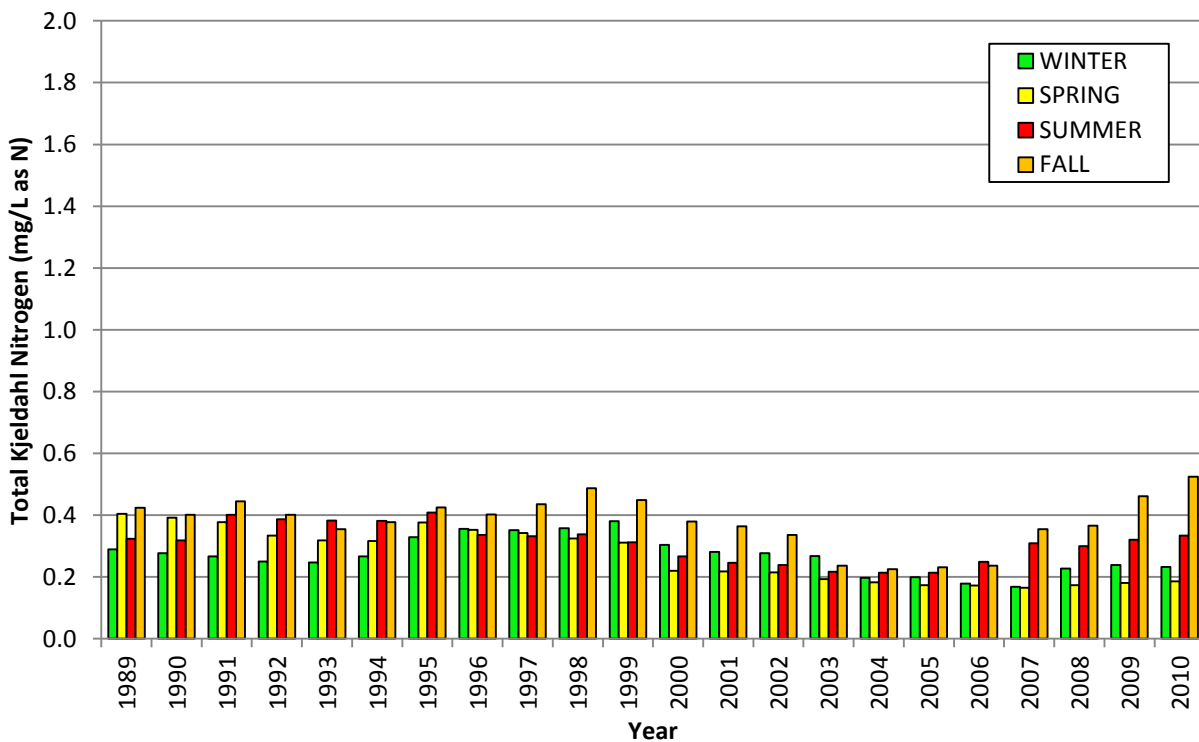


Figure 6-62 Five Year Running Average of Bottom TKN Concentrations for Station LM08

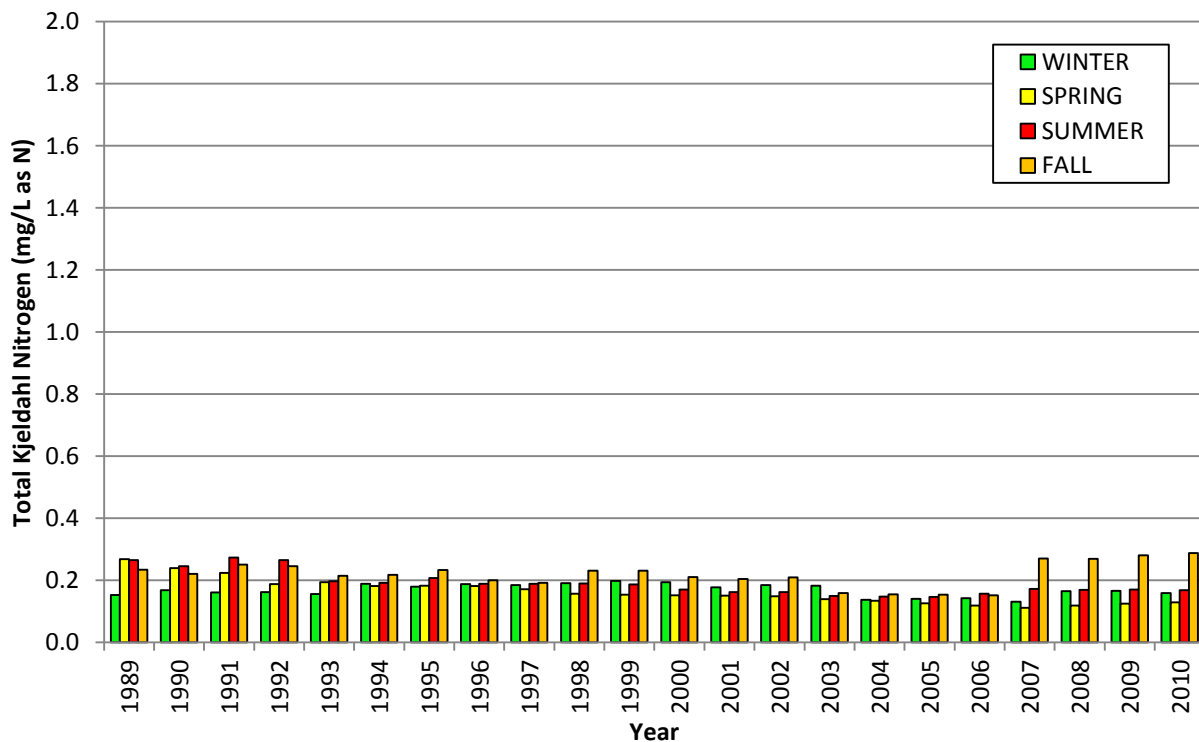


Figure 6-63 Surface vs. Bottom Seasonal TKN Concentrations All Stations (2006 – 2010)

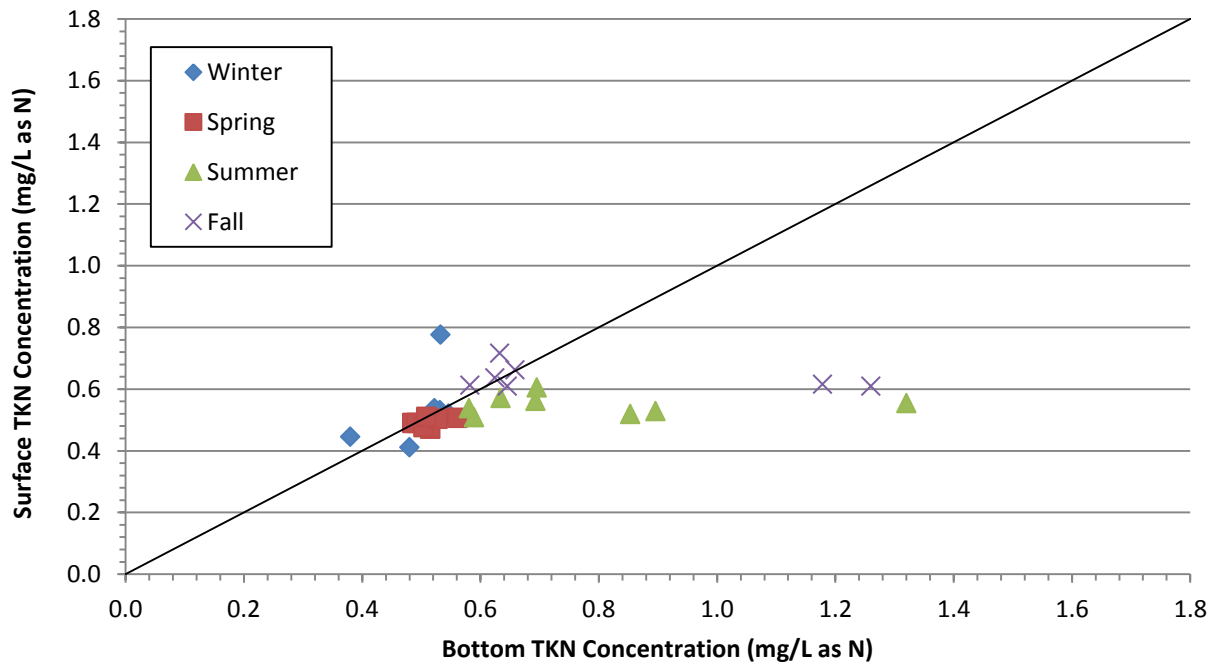


Figure 6-64 Five Year Running Average of Surface Ox-N Concentrations for Station LM01

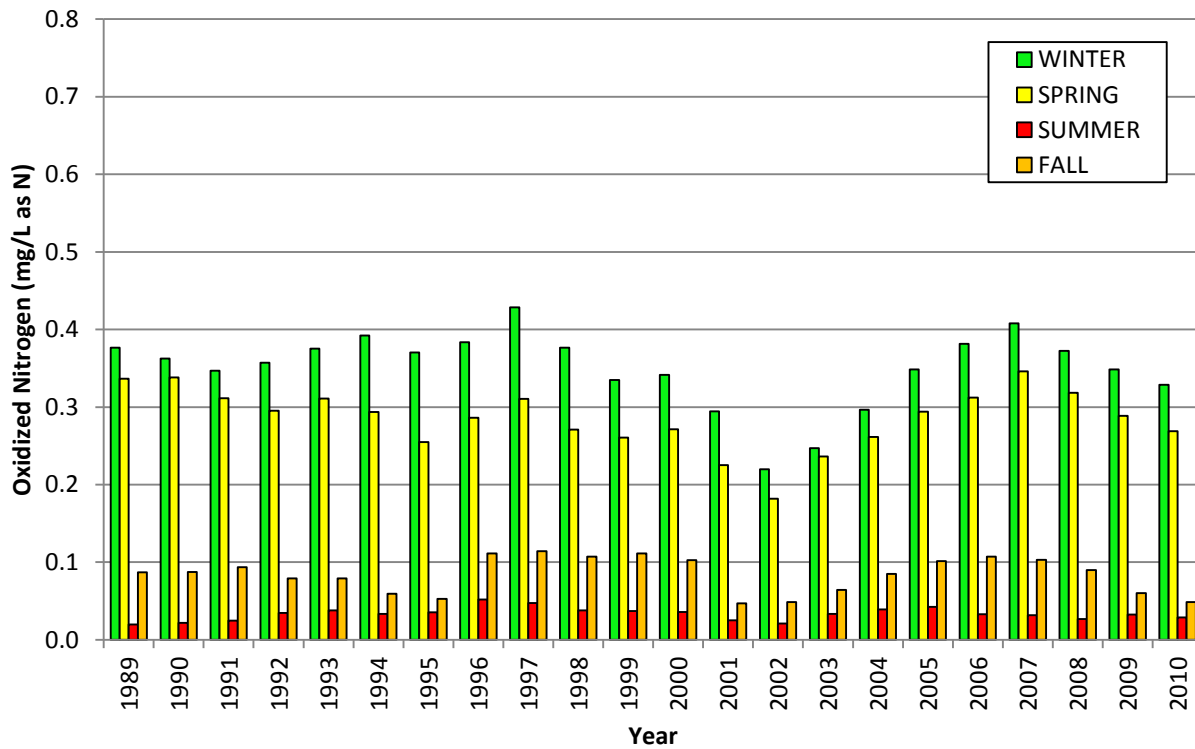


Figure 6-65 Five Year Running Average of Surface Ox-N Concentrations for Station LM02

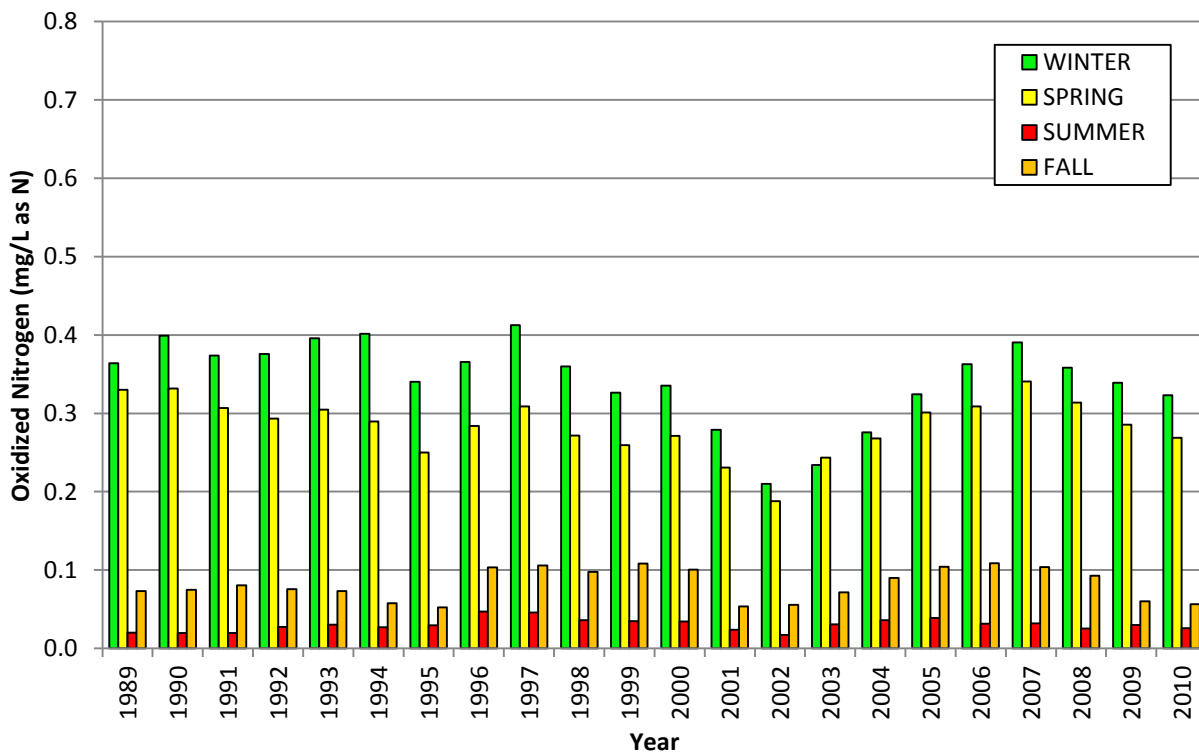


Figure 6-66 Five Year Running Average of Surface Ox-N Concentrations for Station LM03

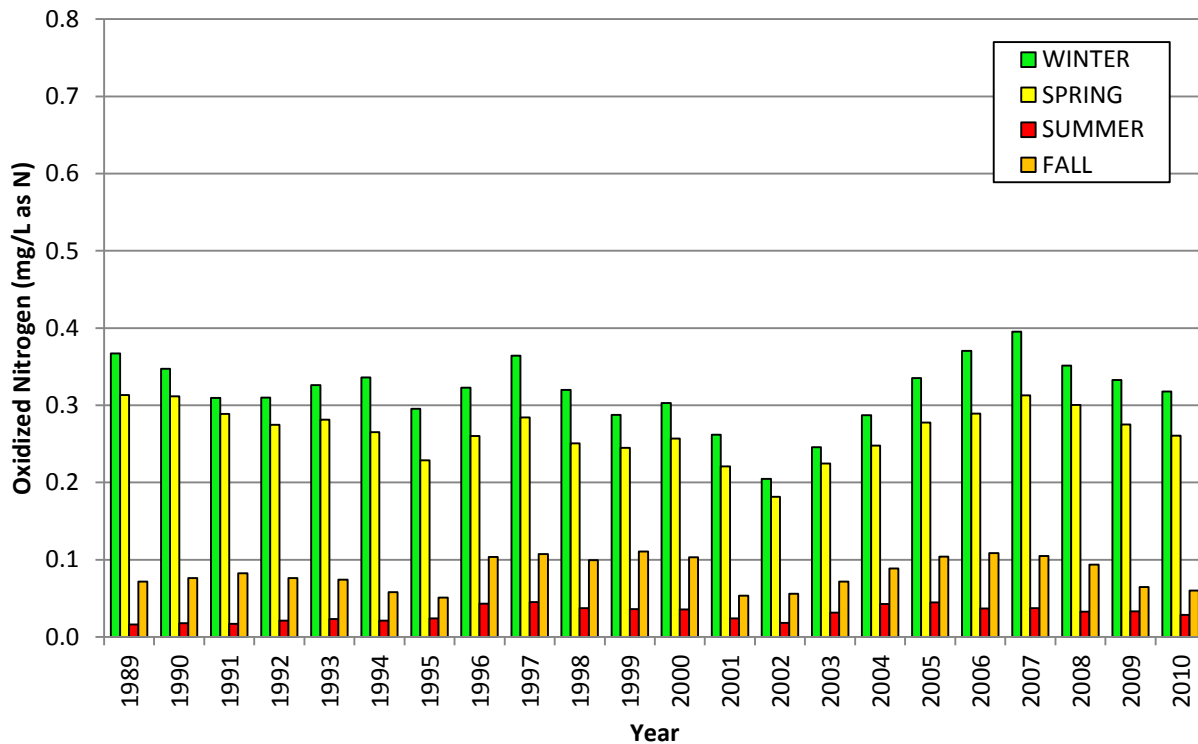


Figure 6-67 Five Year Running Average of Surface Ox-N Concentrations for Station LM04

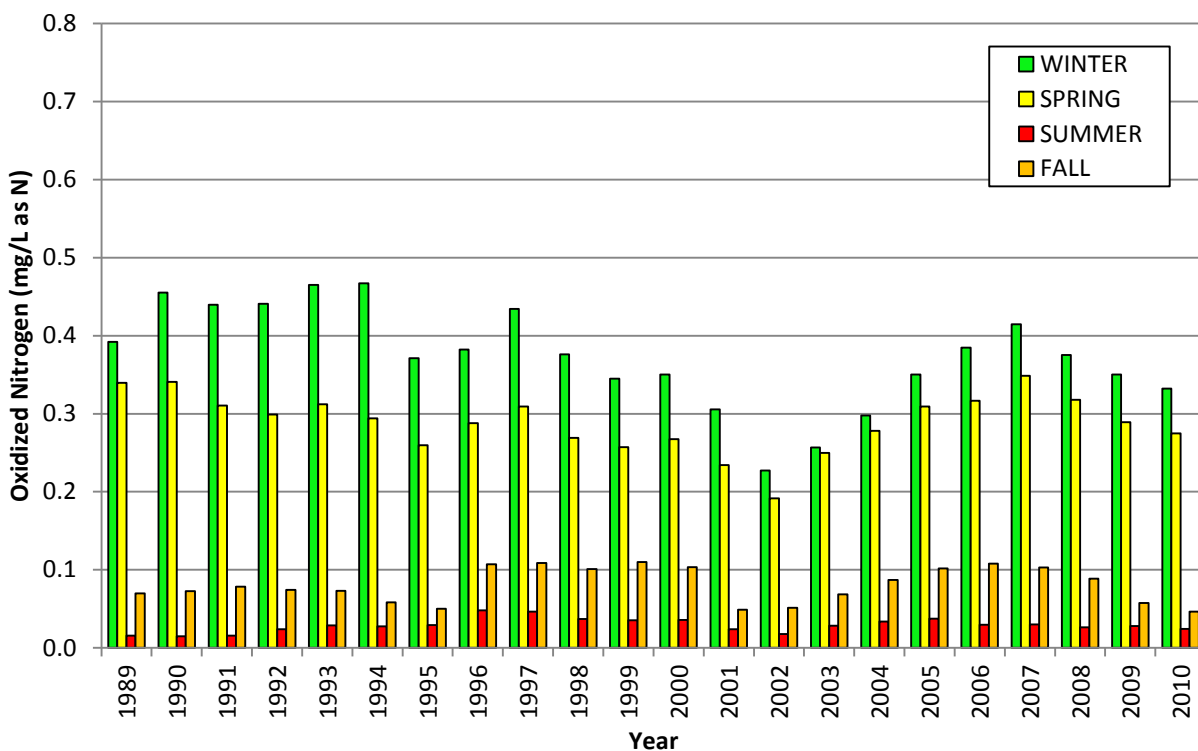


Figure 6-68 Five Year Running Average of Surface Ox-N Concentrations for Station LM05

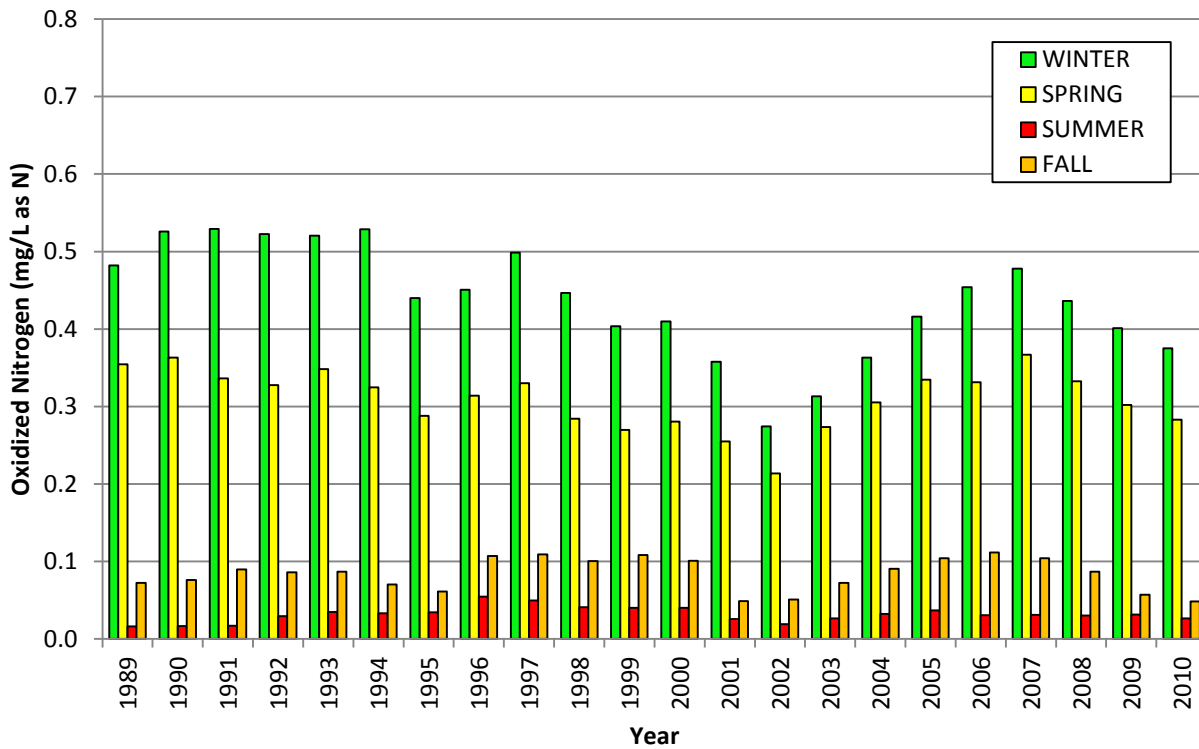


Figure 6-69 Five Year Running Average of Surface Ox-N Concentrations for Station LM06

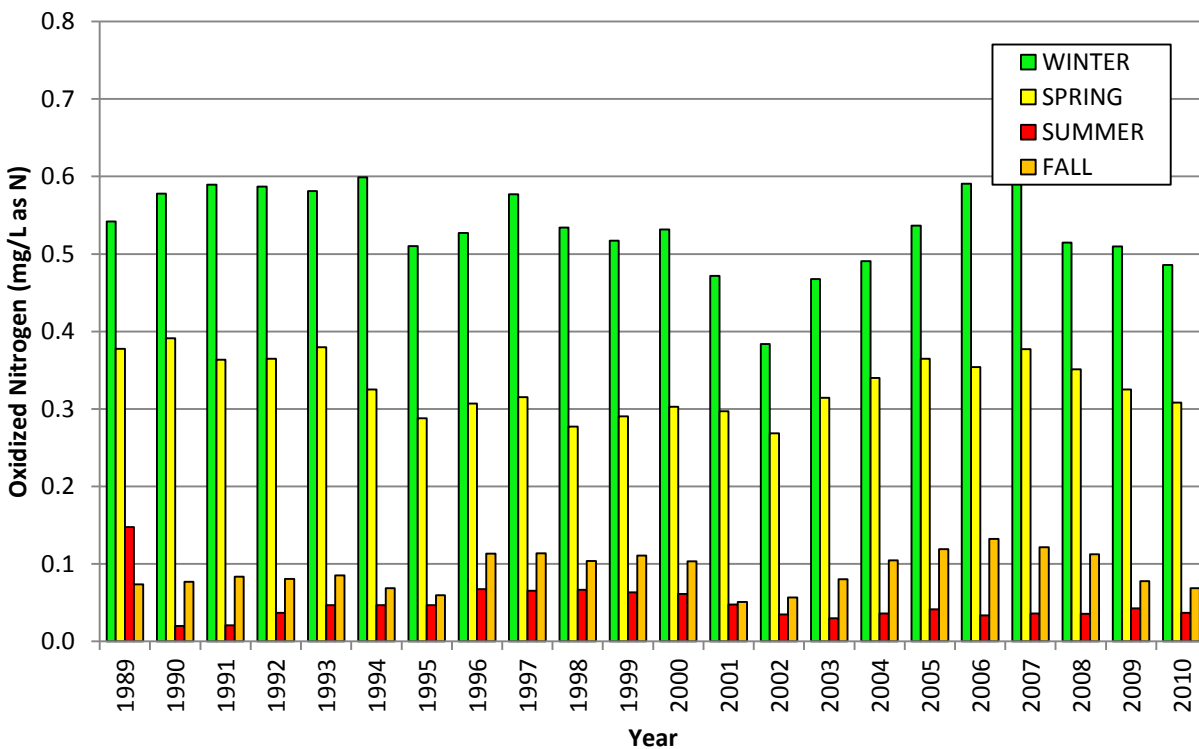


Figure 6-70 Five Year Running Average of Surface Ox-N Concentrations for Station LM07

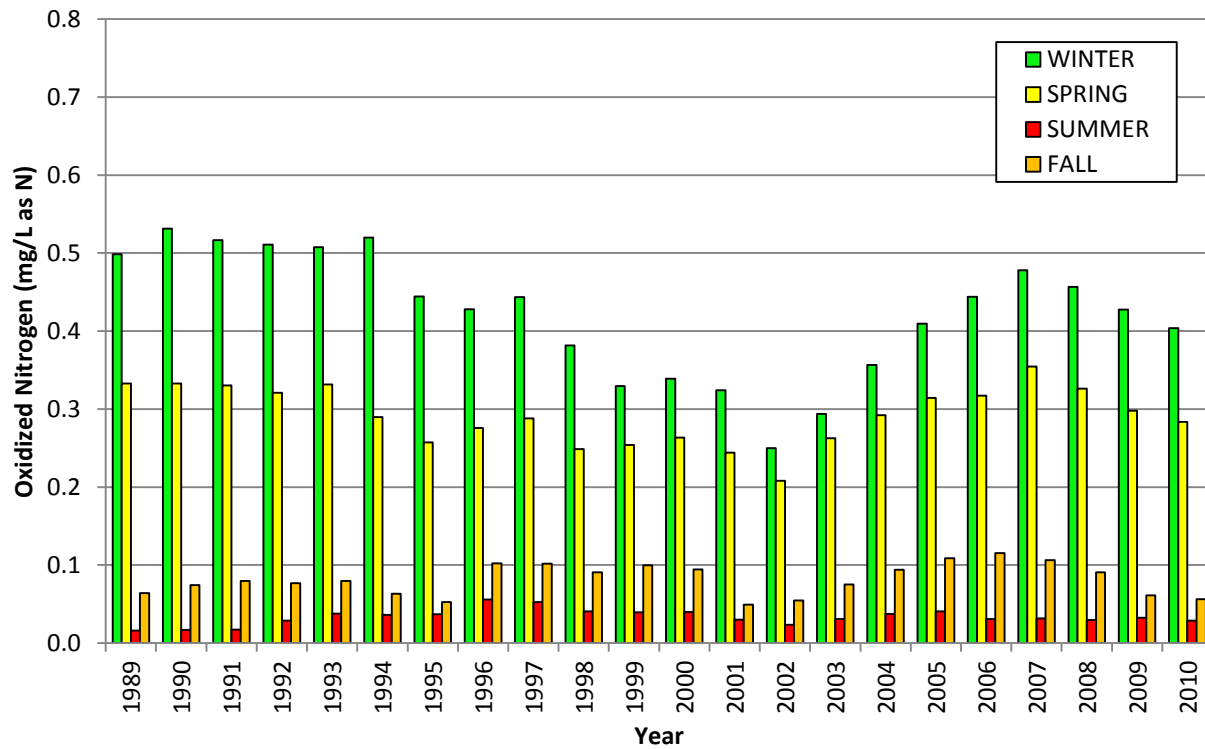


Figure 6-71 Five Year Running Average of Surface Ox-N Concentrations for Station LM08

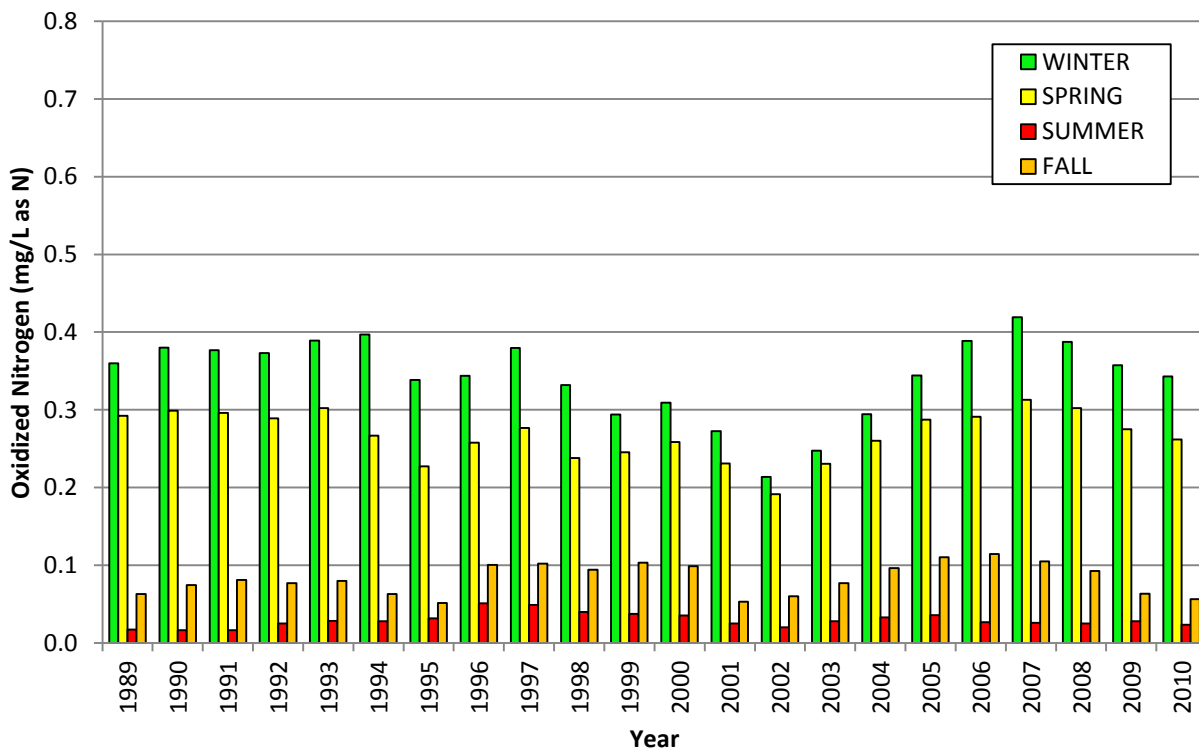


Figure 6-72 Five Year Running Average of Bottom Ox-N Concentrations for Station LM01

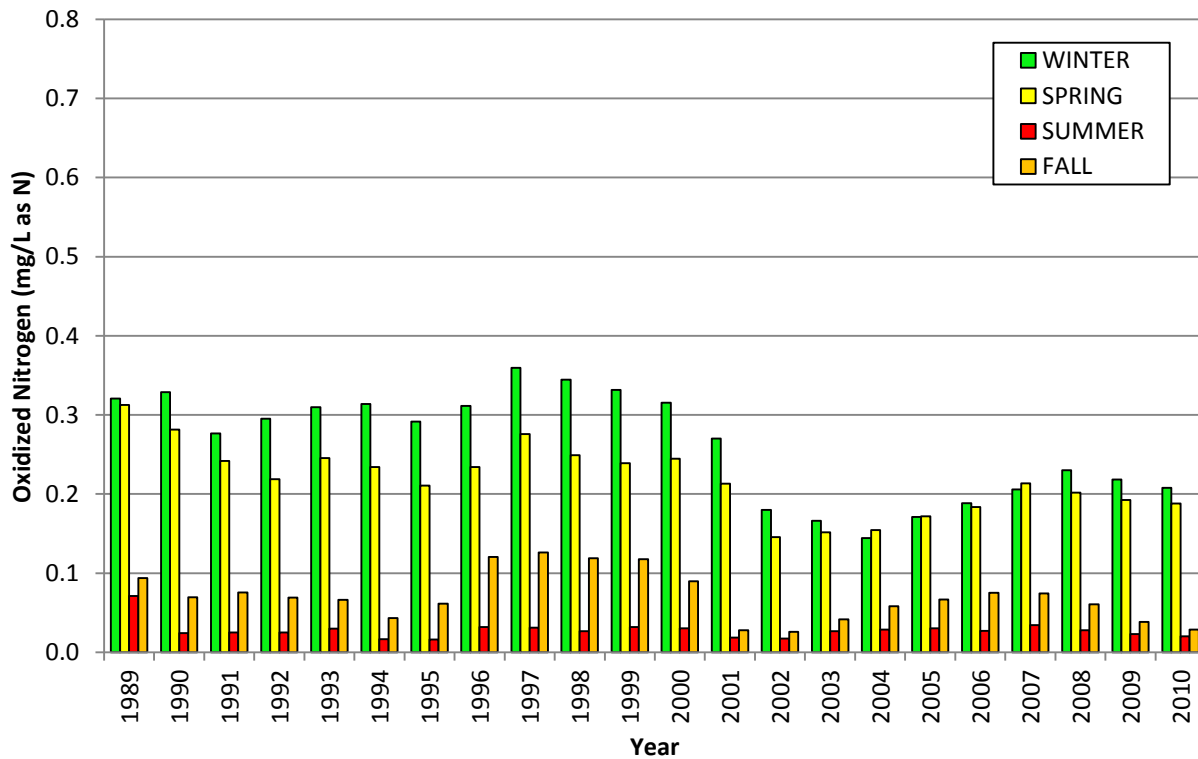


Figure 6-73 Five Year Running Average of Bottom Ox-N Concentrations for Station LM02

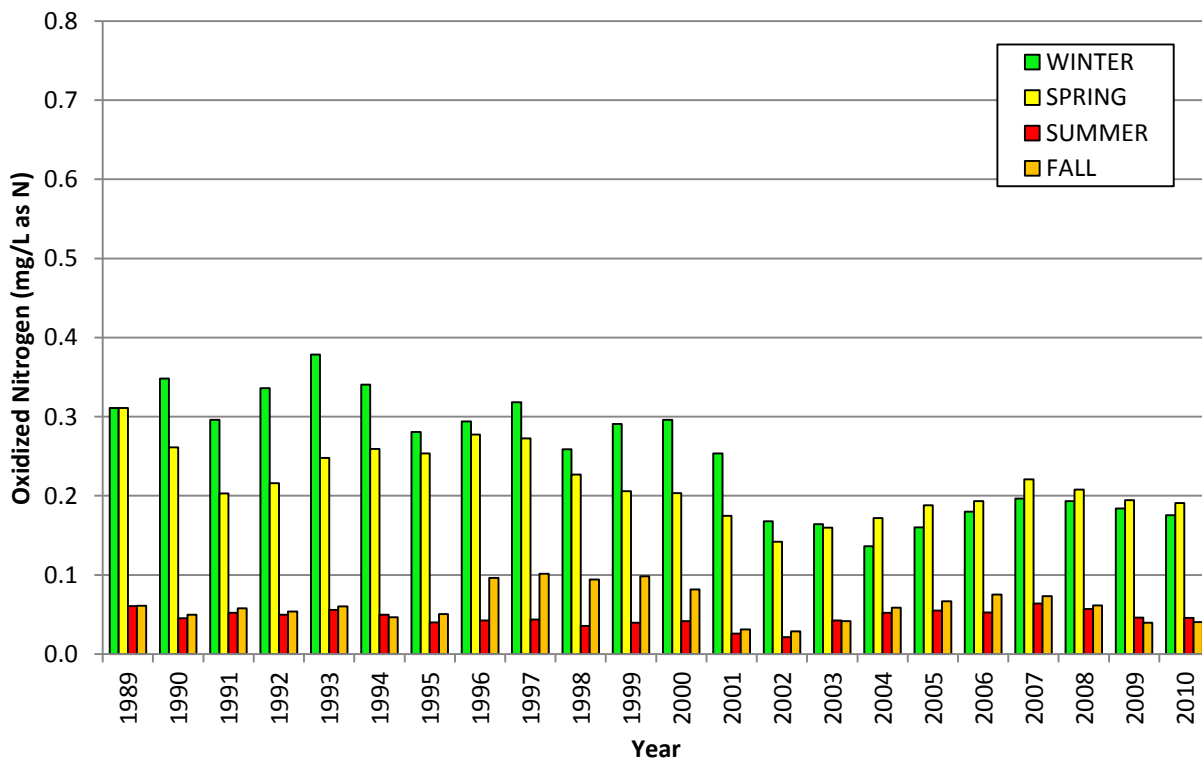


Figure 6-74 Five Year Running Average of Bottom Ox-N Concentrations for Station LM03

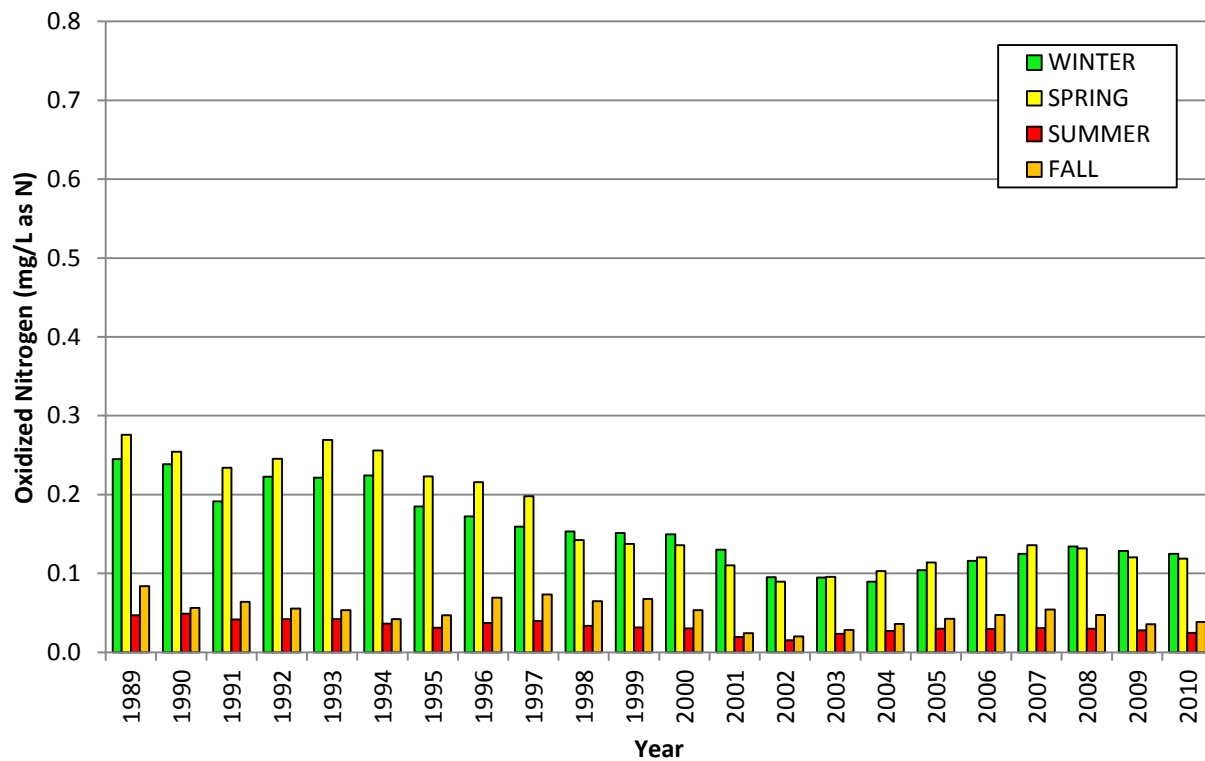


Figure 6-75 Five Year Running Average of Bottom Ox-N Concentrations for Station LM04

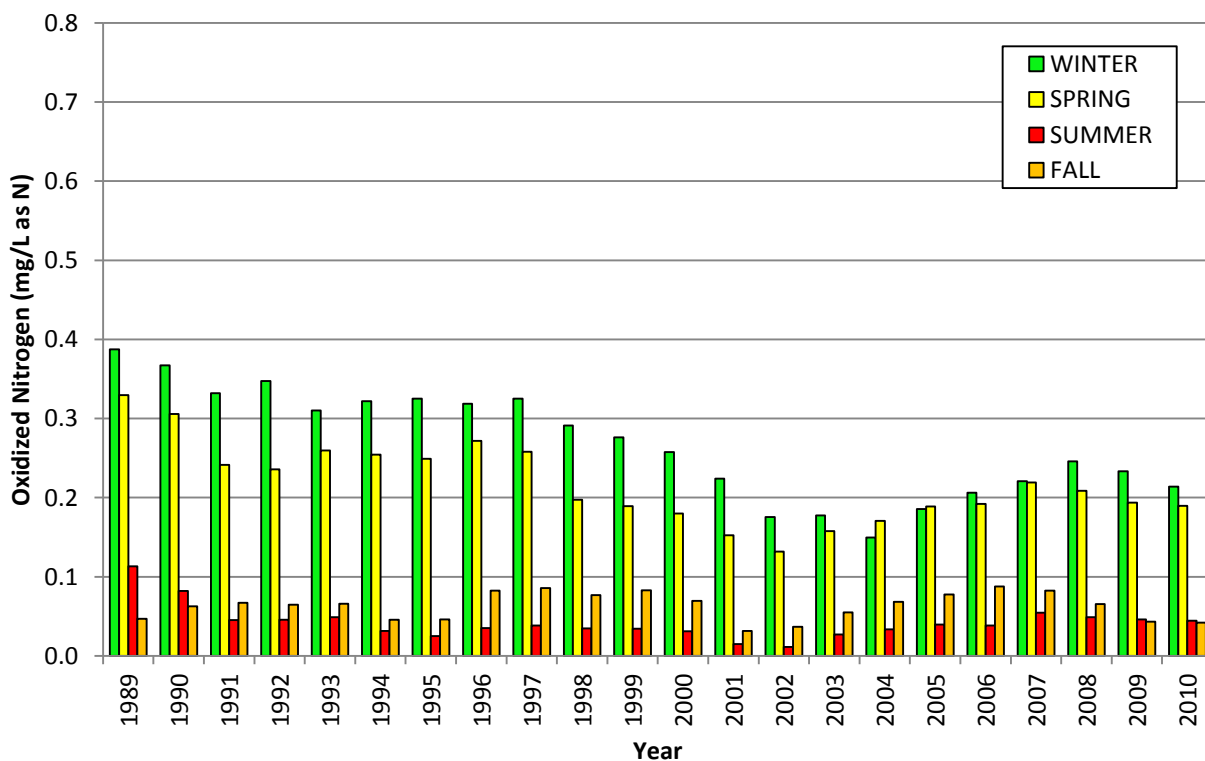


Figure 6-76 Five Year Running Average of Bottom Ox-N Concentrations for Station LM05

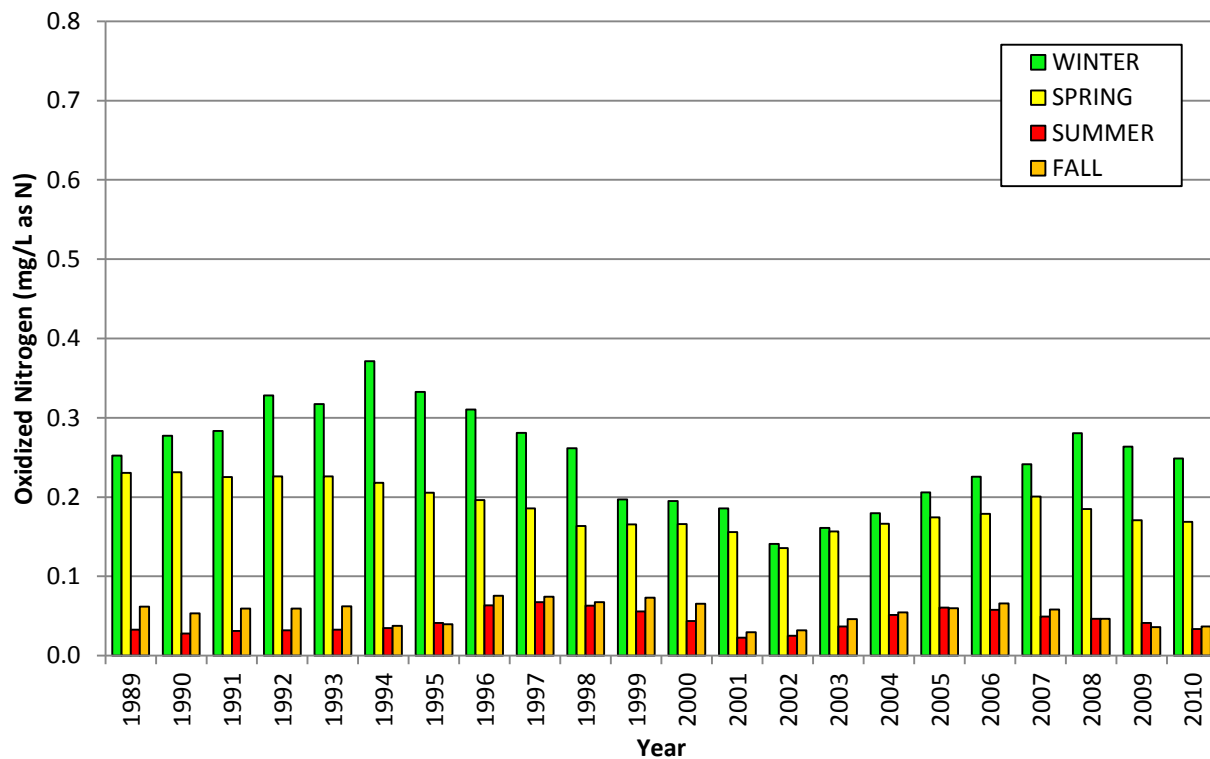


Figure 6-77 Five Year Running Average of Bottom Ox-N Concentrations for Station LM06

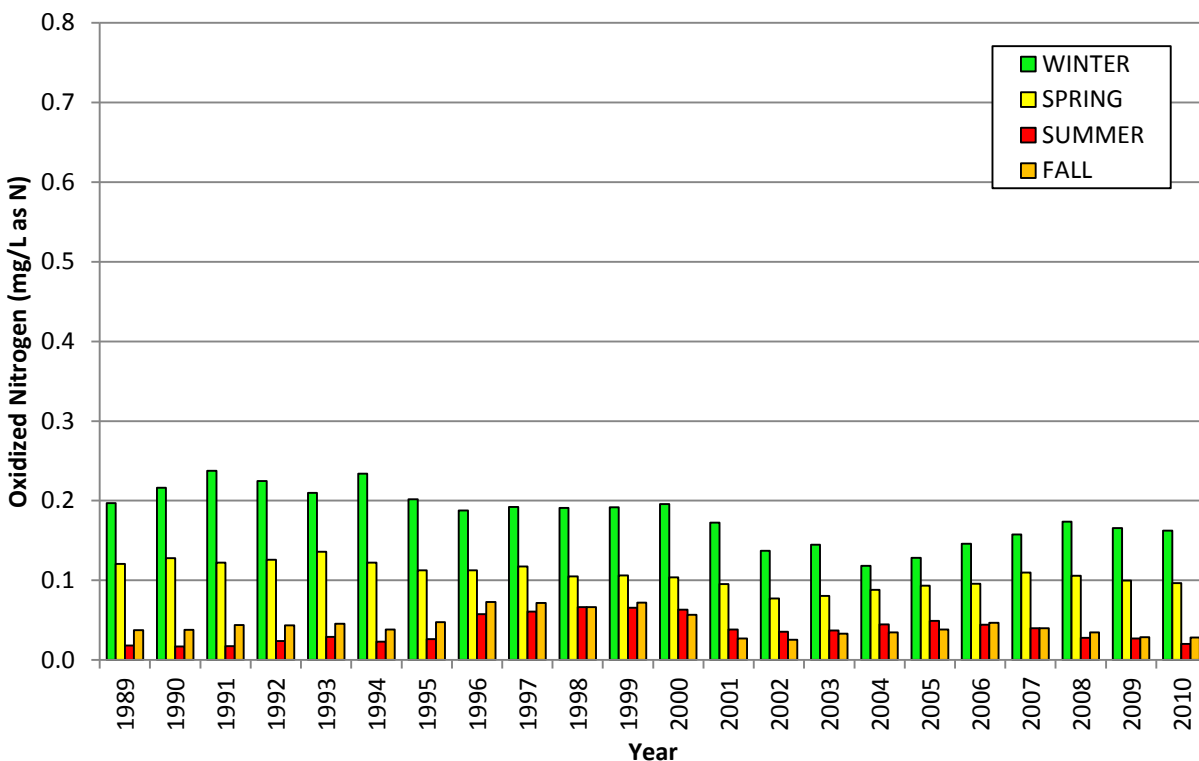


Figure 6-78 Five Year Running Average of Bottom Ox-N Concentrations for Station LM07

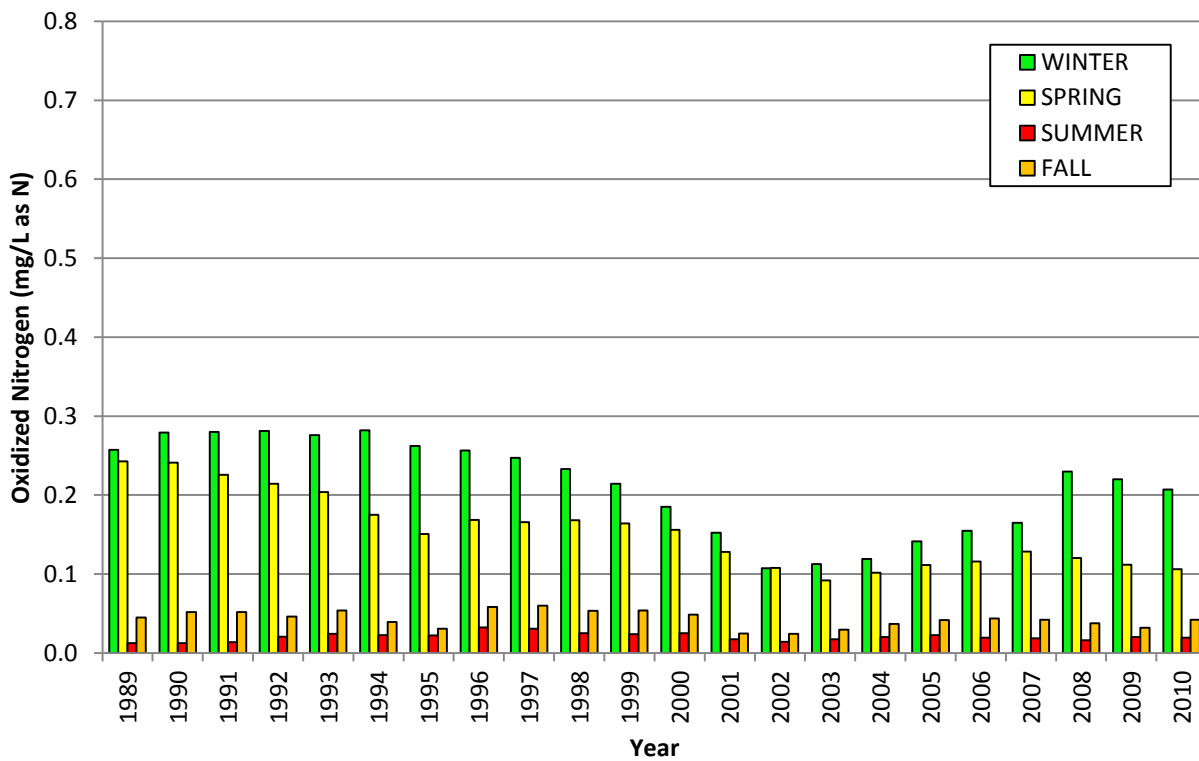


Figure 6-79 Five Year Running Average of Bottom Ox-N Concentrations for Station LM08

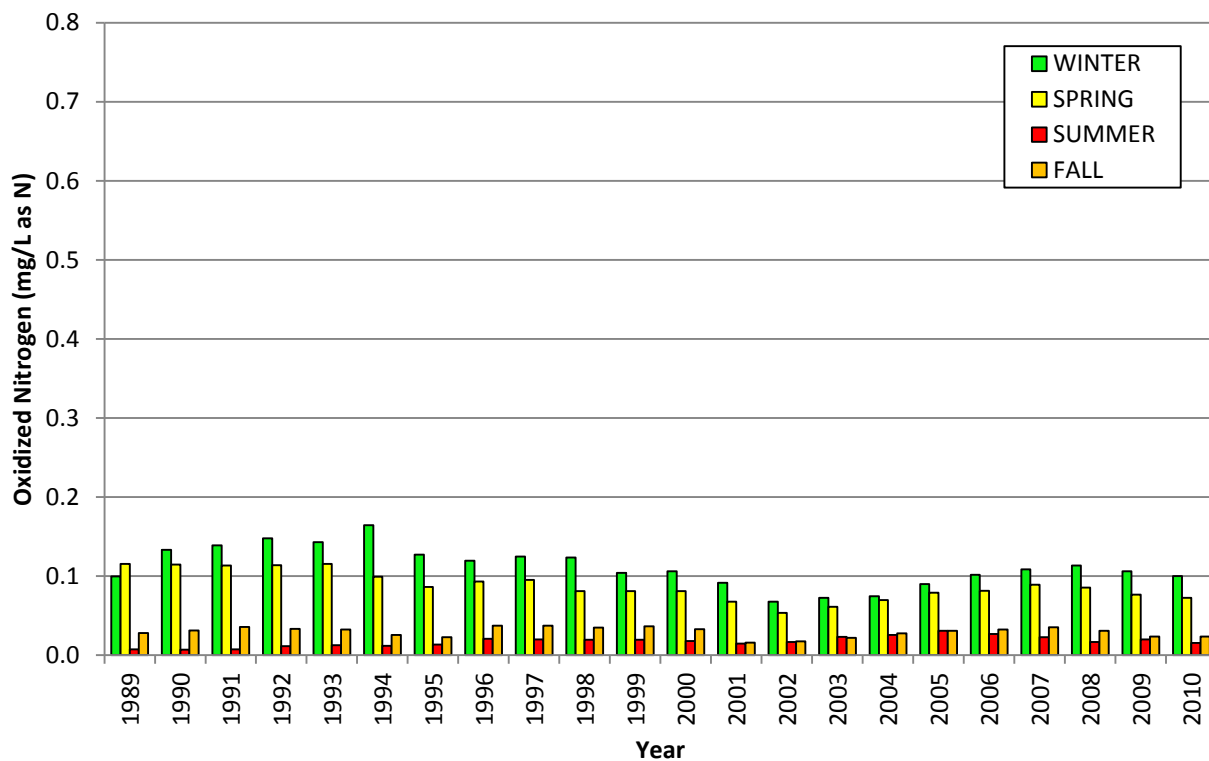
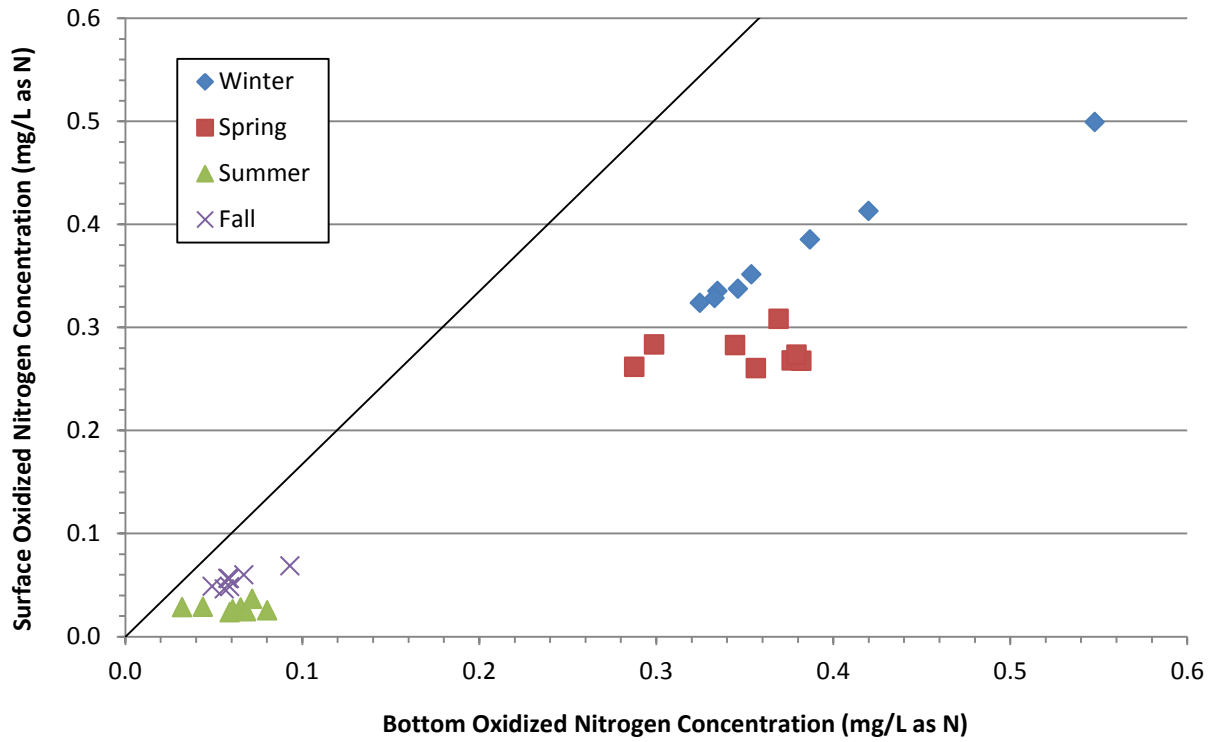


Figure 6-80 Surface vs. Bottom Seasonal Oxidized Nitrogen Concentration Changes All Stations (2006 – 2010)



Phosphorus

Five-year running averages for surface total phosphorous (TP) concentrations for each lake sampling station are depicted in Figures 6-81 through 6-88.

- Surface TP concentrations for the 1984 to 2010 period range from below detection limits to 0.37 mg/L, with the highest concentration of 0.37 mg/L detected at sampling station LM08 on 1-AUG-1990. The average surface TP concentration for all sampling stations during this period was calculated to be 0.04 mg/L.
- Surface TP concentrations for the 2006 to 2010 period range from below detection limits to 0.32 mg/L, with the highest concentration of 0.32 mg/L detected at sampling station LM05 on 17-FEB-2009. The average surface TP concentration for all sampling stations during this period was calculated to be 0.04 mg/L.
- The Mann-Kendall Seasonal Analysis for surface TP concentrations shows a slight decreasing trend at sampling station LM03 and no other significant trends at other sampling stations for the 2006 to 2010 period.

As shown in Figure 6-85 there is an apparent significant increase in surface total phosphorus concentrations at sampling station LM05 during the 2009 to 2010 (winter) period. However, this increase appears to be the result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with winter five year running averages for 2009 to 2010 is a result of a single sampling event with an elevated surface total phosphorus concentration: 0.32 mg/L as P on 17-FEB-2009.

Five-year running averages for bottom TP concentrations for each lake sampling station are depicted in Figures 6-89 through 6-96.

- Bottom TP concentrations for the 1984 to 2010 period range up to 1.64 mg/L, with the highest concentration of 1.64 mg/L detected at sampling station LM08 on 3-AUG-1988. The average bottom TP concentration for all sampling stations during this period was calculated to be 0.04 mg/L.
- Bottom TP concentrations for the 2006 to 2010 period range up to 0.46 mg/L, with the highest concentration of 0.46 mg/L detected at sampling station LM01 on 27-SEP-2006. The average bottom TP concentration for all sampling stations during this period was calculated to be 0.04 mg/L.
- The Mann-Kendall Seasonal Analysis for bottom TP concentrations shows decreasing trends at sampling stations LM05 and LM08 and no other significant trends at other sampling stations for the 2006 to 2010 period.

Seasonal comparisons for surface and bottom TP concentration comparisons for all lake sampling stations are depicted in Figure 6-97 for the 2006 to 2010 period.

- The data points represent the average total phosphorous concentration for each season during the 2006 to 2010 with the average surface TP concentration on the y-axis and the average bottom TP concentration along the x-axis. The diagonal line represents a 1:1 linear relationship for comparative purposes. The TP concentration ratios, in general all fall below the 1:1 line suggesting TP values in the hypolimnion are greater than in the epilimnion.

Five-year running averages for surface orthophosphate phosphorus (OP) concentrations for each lake sampling station are depicted in Figures 6-98 through 6-105.

- Surface OP concentrations for the 1984 to 2010 period range from below detection limits to 0.37 mg/L, with the highest concentration of 0.37 mg/L detected at sampling station

LM08 on 1-AUG-1990. The average surface OP concentration for all sampling stations during this period was calculated to be 0.01 mg/L.

- Surface OP concentrations for the 2006 to 2010 period range from below detection limits to 0.165 mg/L, with the highest concentration of 0.165 mg/L detected at sampling station LM06 on 6-NOV-2008. The average surface OP concentration for all sampling stations during this period was calculated to be 0.01 mg/L.
- The Mann-Kendall Seasonal Analysis for surface OP concentrations shows no increasing or decreasing trends for the 2006 to 2010 period.

As shown in Figure 6-102 there is an apparent significant increase in surface orthophosphate phosphorus concentrations at sampling station LM05 during the 1994 to 1998 (winter) period. However, this increase appears to be the result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with winter five year running averages for 1994 to 1998 is a result of a single sampling event with an elevated surface orthophosphate phosphorus concentration: 0.05 mg/L as P on 13-DEC-1993.

Five-year running averages for bottom OP concentrations for each lake sampling station are depicted in Figures 6-106 through 6-113.

- Bottom OP concentrations for the 1984 to 2010 period range up to 0.37 mg/L, with the highest concentration of 0.37 mg/L detected at sampling station LM01 on 27-SEP-2006. The average bottom OP concentration for all sampling stations during this period was calculated to be 0.01 mg/L.
- Bottom OP concentrations for the 2006 to 2010 period range up to 0.37 mg/L, with the highest concentration of 14 mg/L detected at sampling station LM01 on 27-SEP-2006.

The average bottom OP concentration for all sampling stations during this period was calculated to be 0.01 mg/L.

- The Mann-Kendall Seasonal Analysis for bottom OP concentrations shows a slight decreasing trend at sampling station LM07 and no other significant trends at other sampling stations for the 2006 to 2010 period.

As shown in Figure 6-110 there is an apparent significant increase in bottom orthophosphate phosphorus concentrations at sampling station LM05 during the 2006 to 2010 (summer) period. However, this increase appears to be the result of a significantly elevated concentration being measured during a single sampling event. This occurrence, in general does not represent typical measurements. The increase associated with summer five year running averages for 2006 to 2010 is a result of a single sampling event with an elevated bottom orthophosphate phosphorus concentration: 0.04 mg/L as P on 26-JUL-2006.

Figure 6-81 Five Year Running Average of Surface TP Concentrations for Station LM01

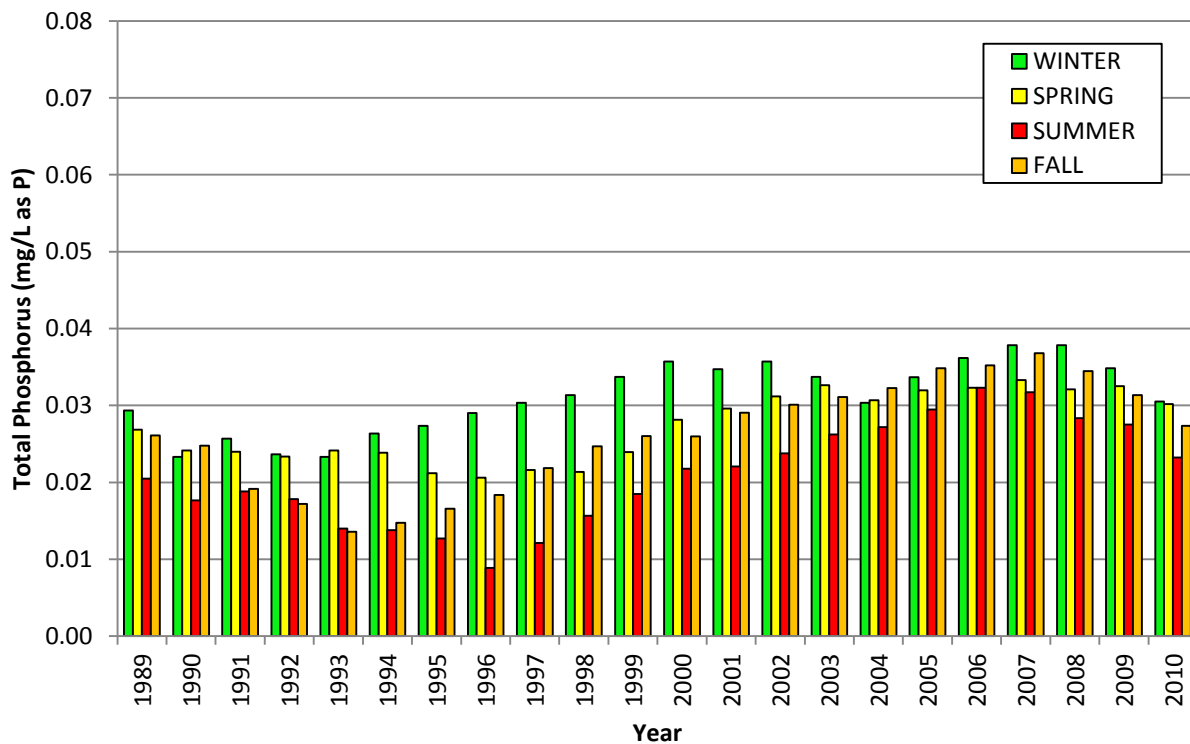


Figure 6-82 Five Year Running Average of Surface TP Concentrations for Station LM02

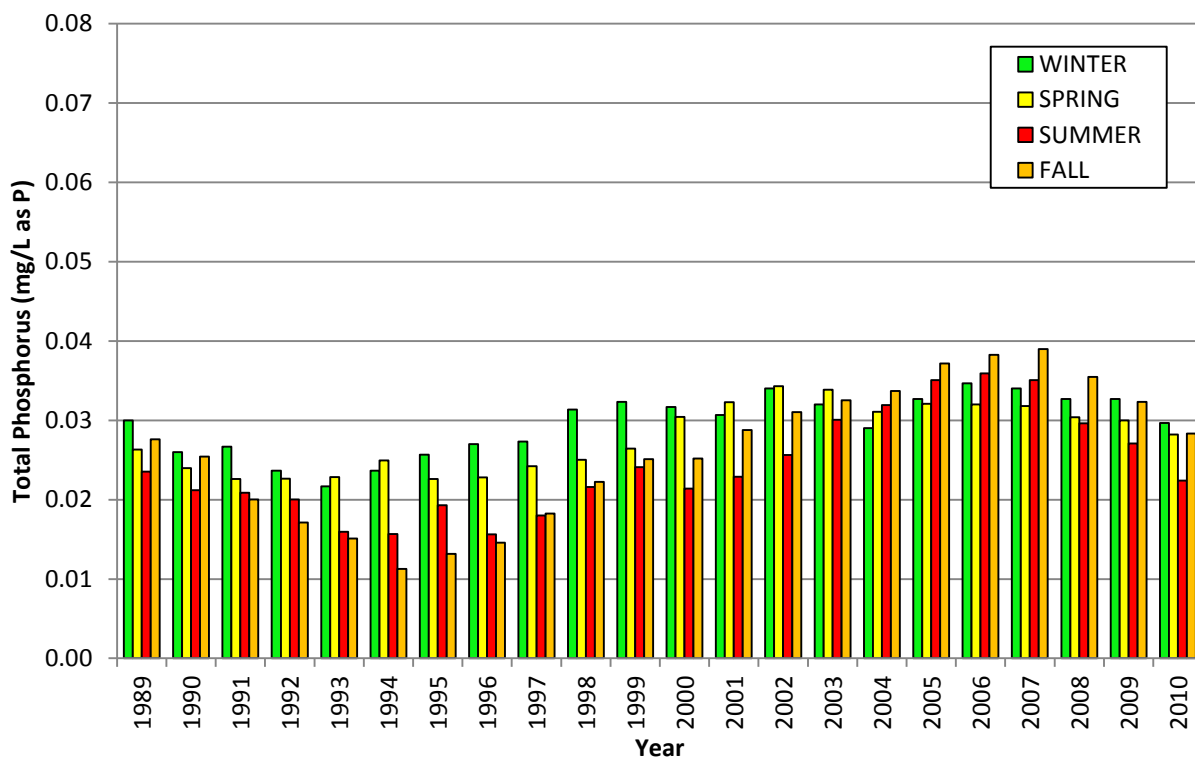


Figure 6-83 Five Year Running Average of Surface TP Concentrations for Station LM03

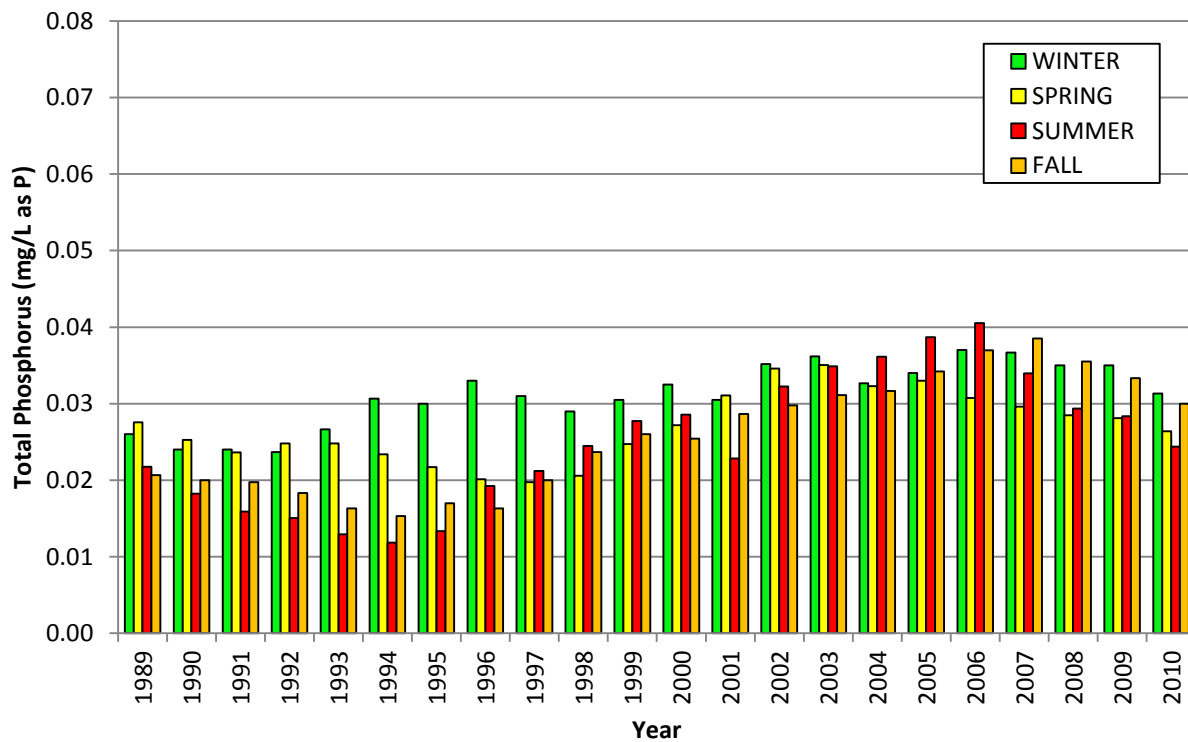


Figure 6-84 Five Year Running Average of Surface TP Concentrations for Station LM04

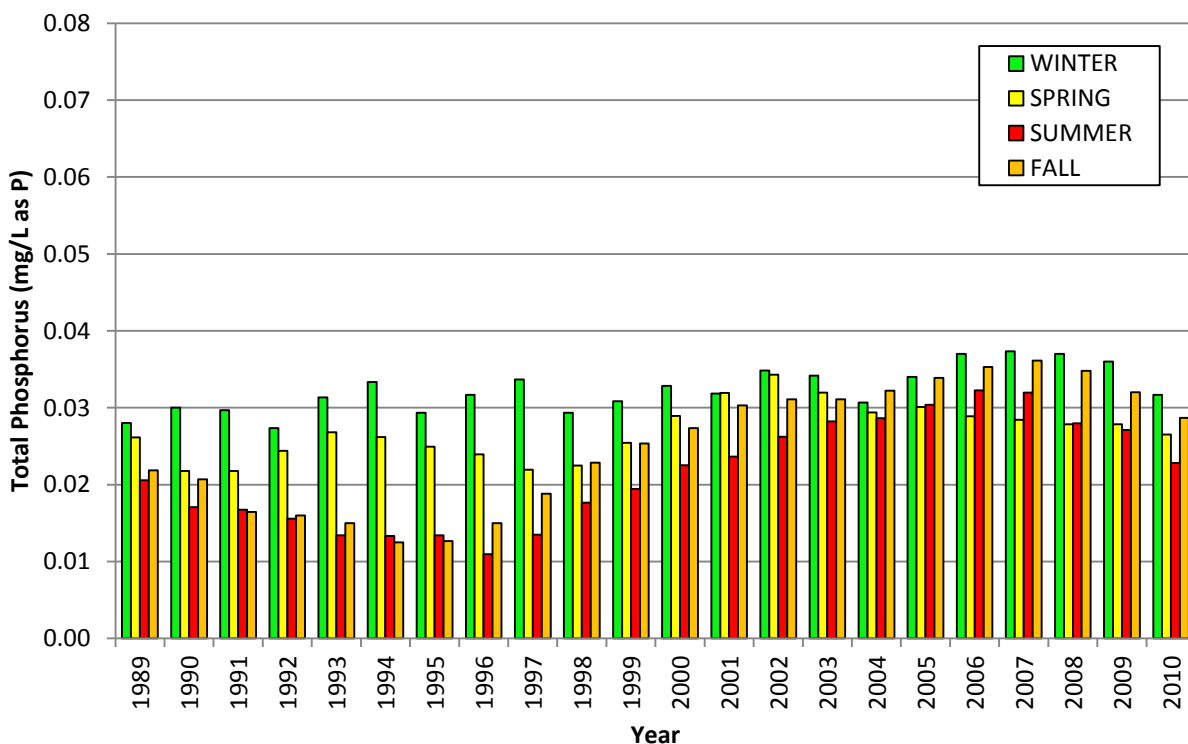


Figure 6-85 Five Year Running Average of Surface TP Concentrations for Station LM05

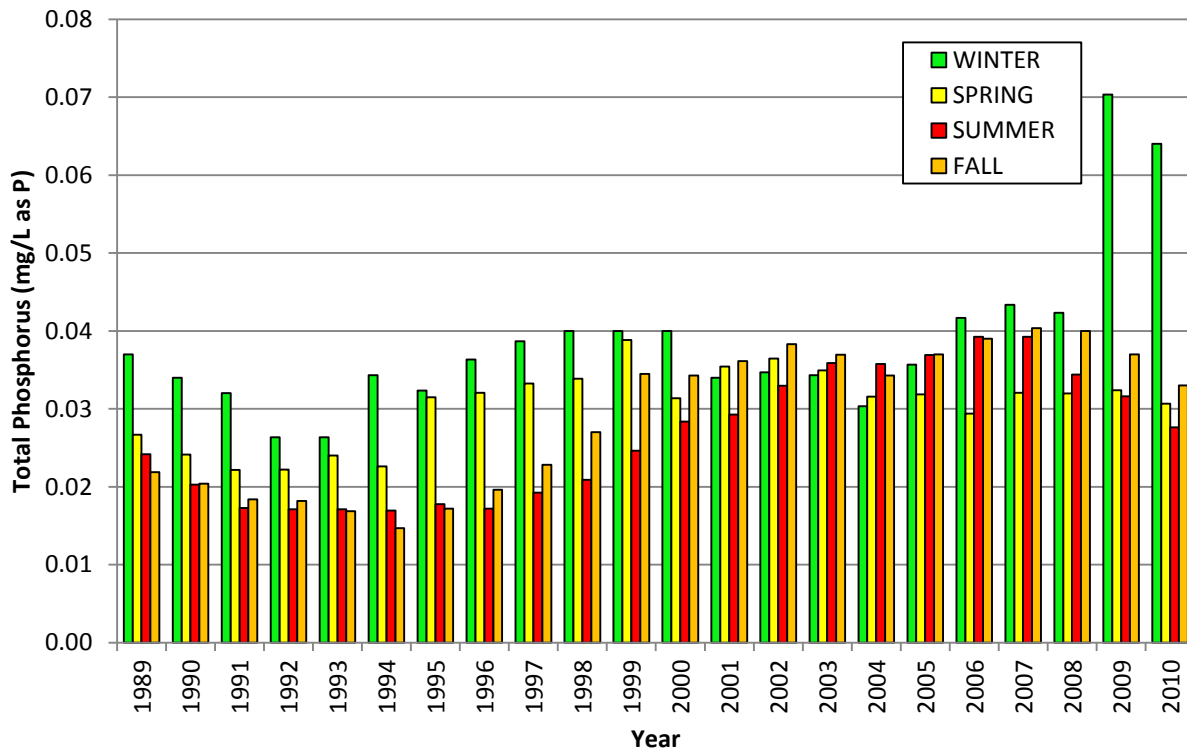


Figure 6-86 Five Year Running Average of Surface TP Concentrations for Station LM06

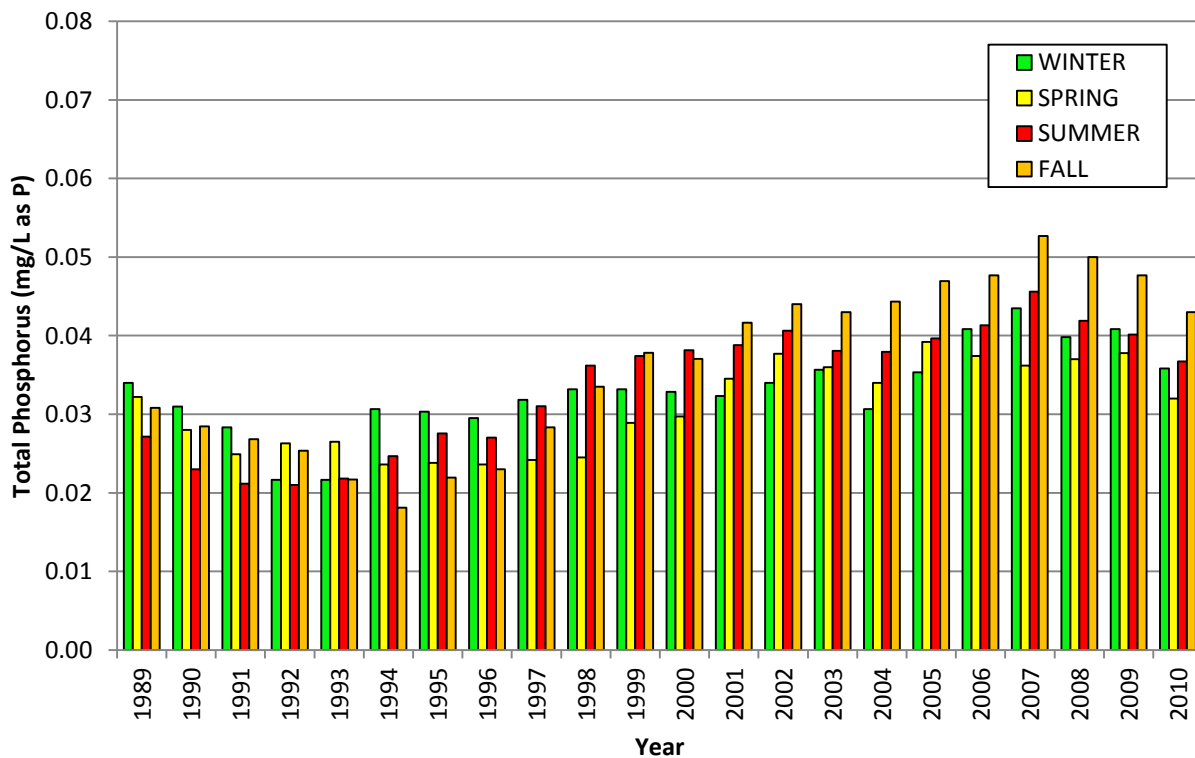


Figure 6-87 Five Year Running Average of Surface TP Concentrations for Station LM07

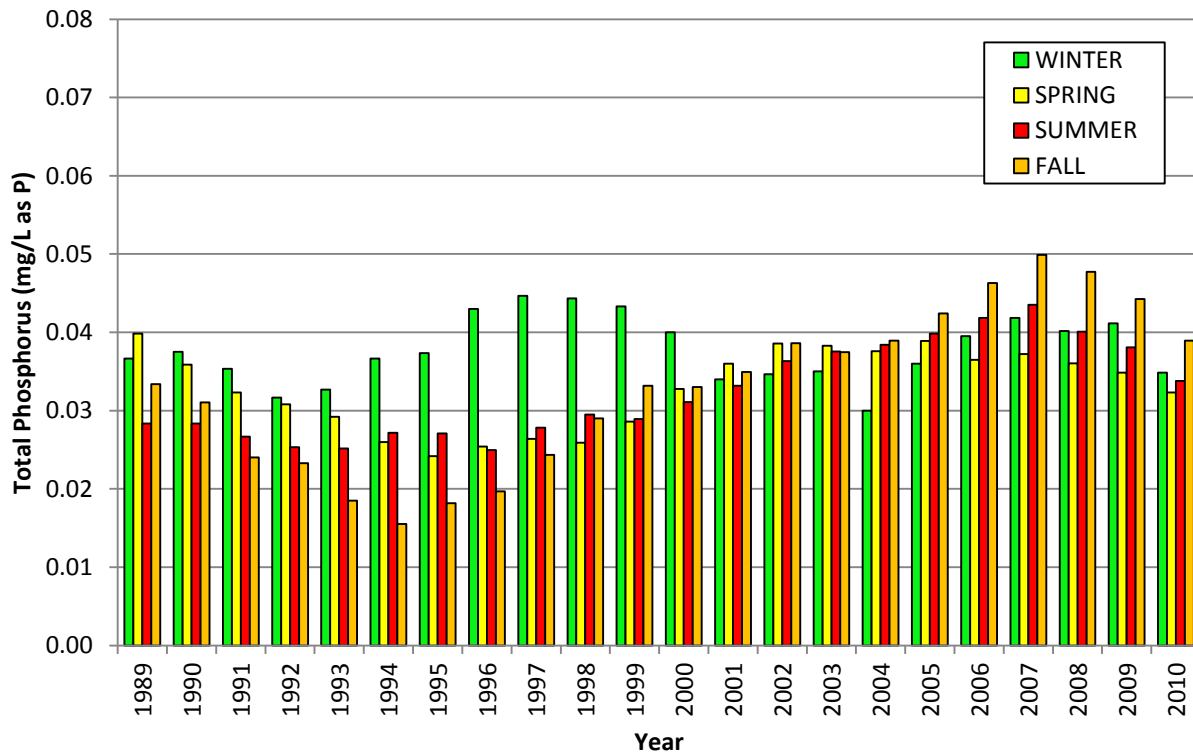


Figure 6-88 Five Year Running Average of Surface TP Concentrations for Station LM08

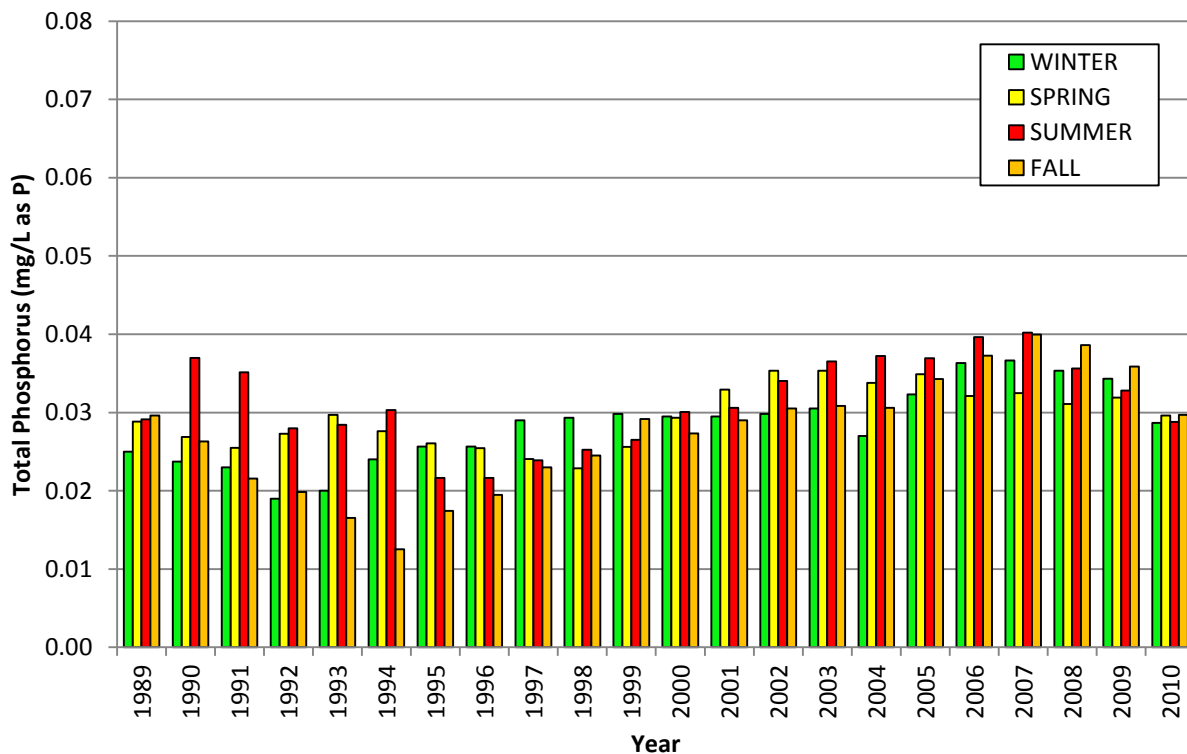


Figure 6-89 Five Year Running Average of Bottom TP Concentrations for Station LM01

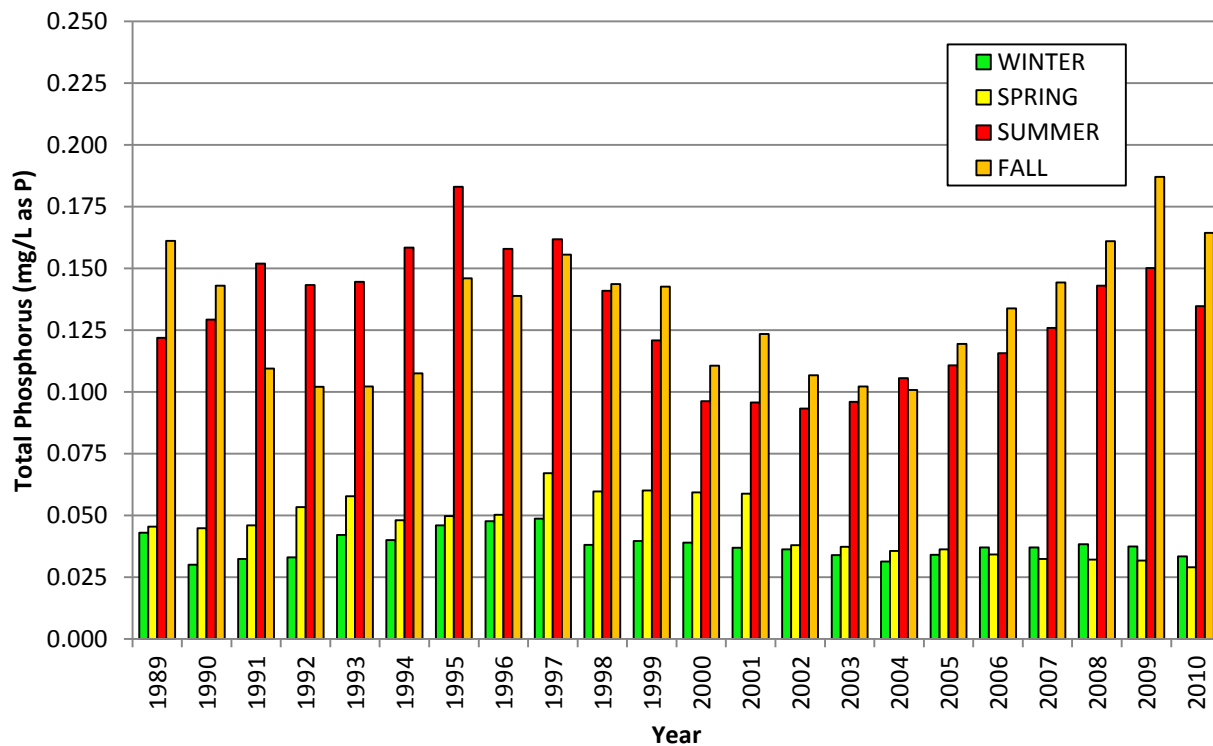


Figure 6-90 Five Year Running Average of Bottom TP Concentrations for Station LM02

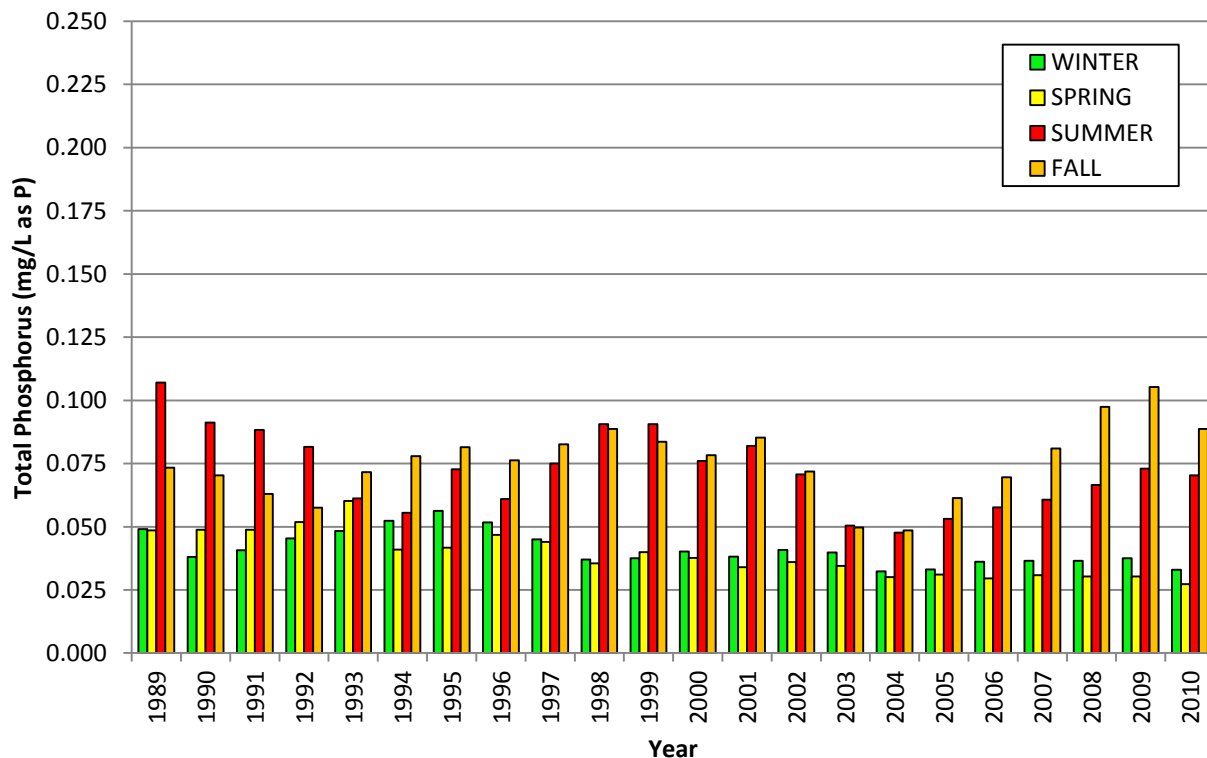


Figure 6-91 Five Year Running Average of Bottom TP Concentrations for Station LM03

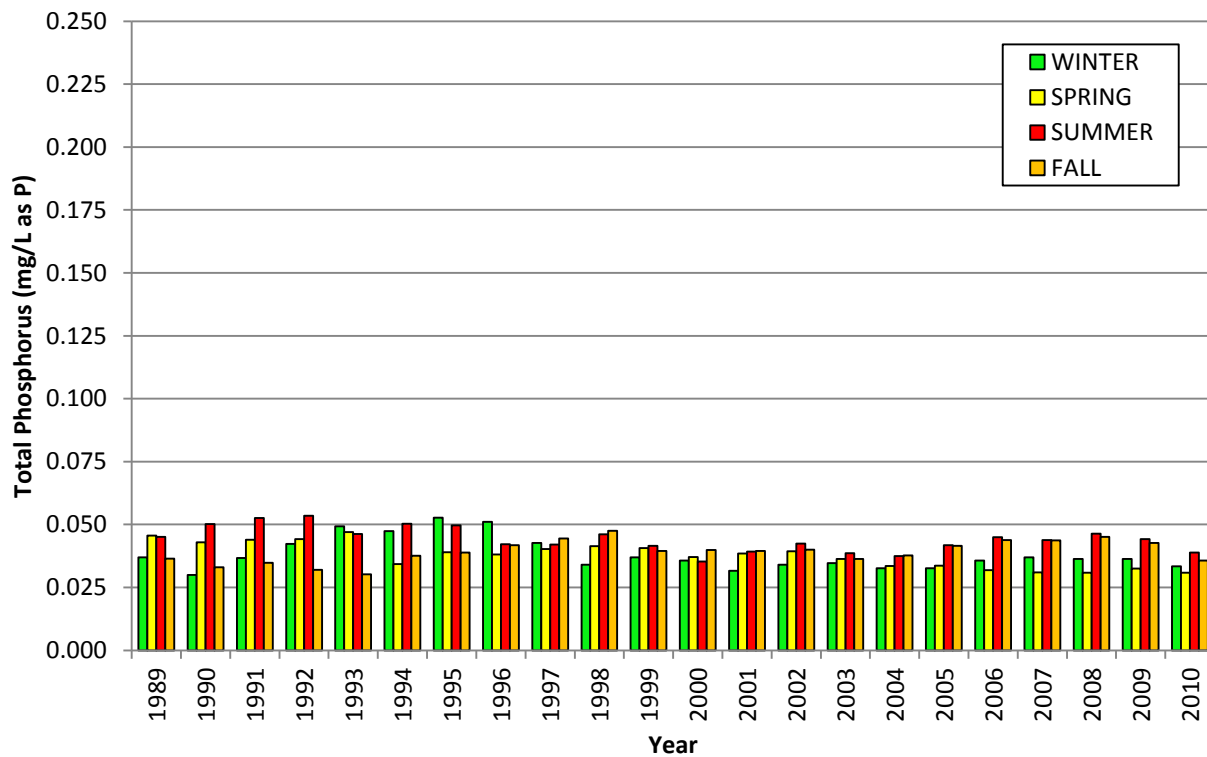


Figure 6-92 Five Year Running Average of Bottom TP Concentrations for Station LM04

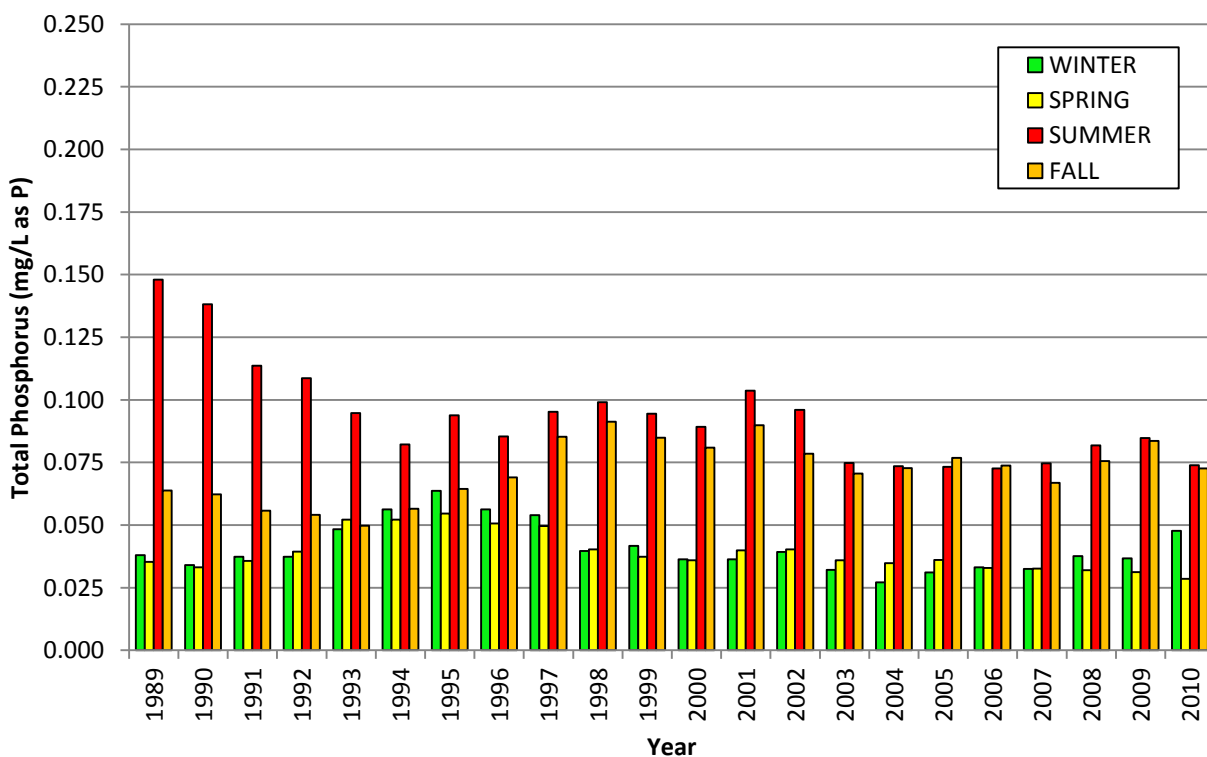


Figure 6-93 Five Year Running Average of Bottom TP Concentrations for Station LM05

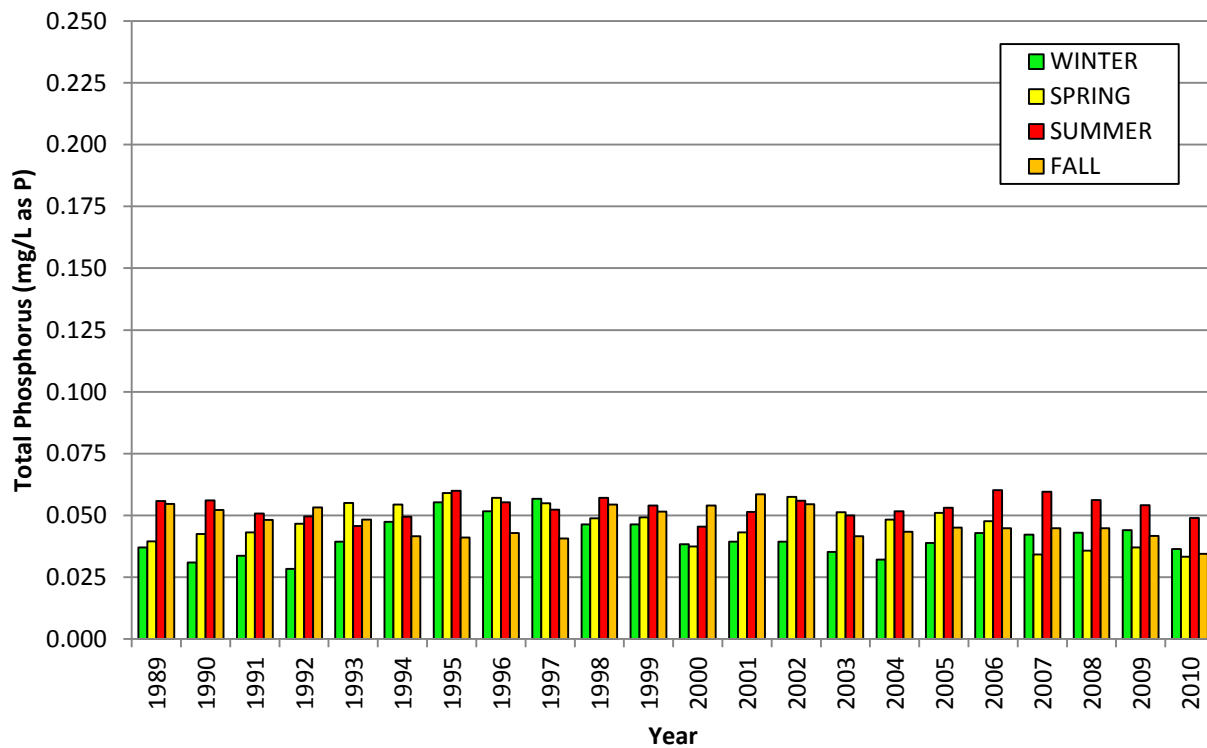


Figure 6-94 Five Year Running Average of Bottom TP Concentrations for Station LM06

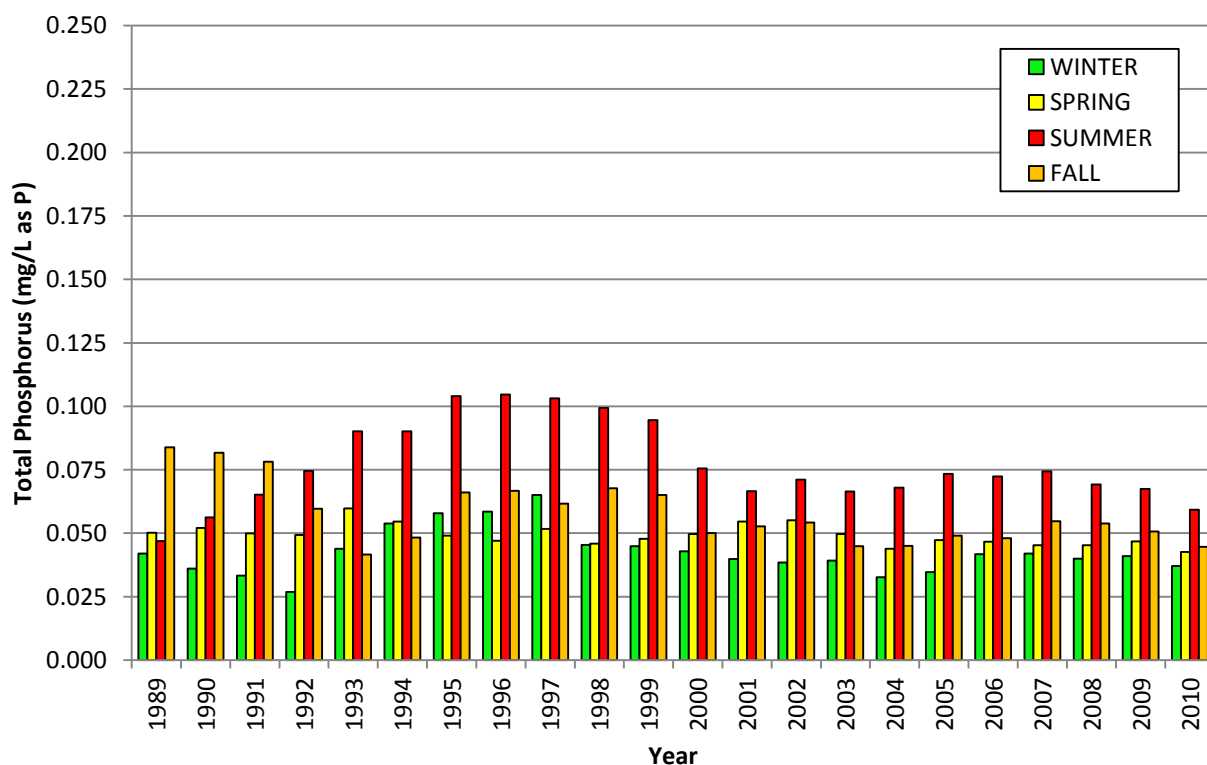


Figure 6-95 Five Year Running Average of Bottom TP Concentrations for Station LM07

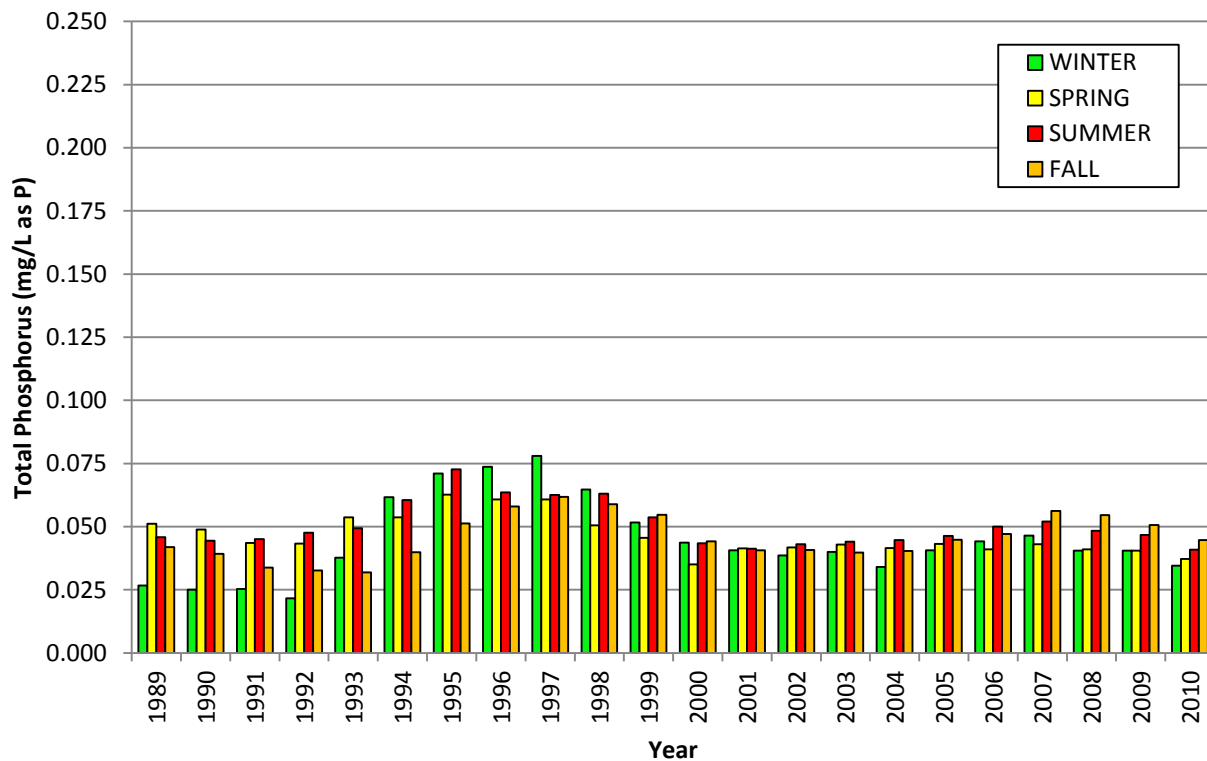


Figure 6-96 Five Year Running Average of Bottom TP Concentrations for Station LM08

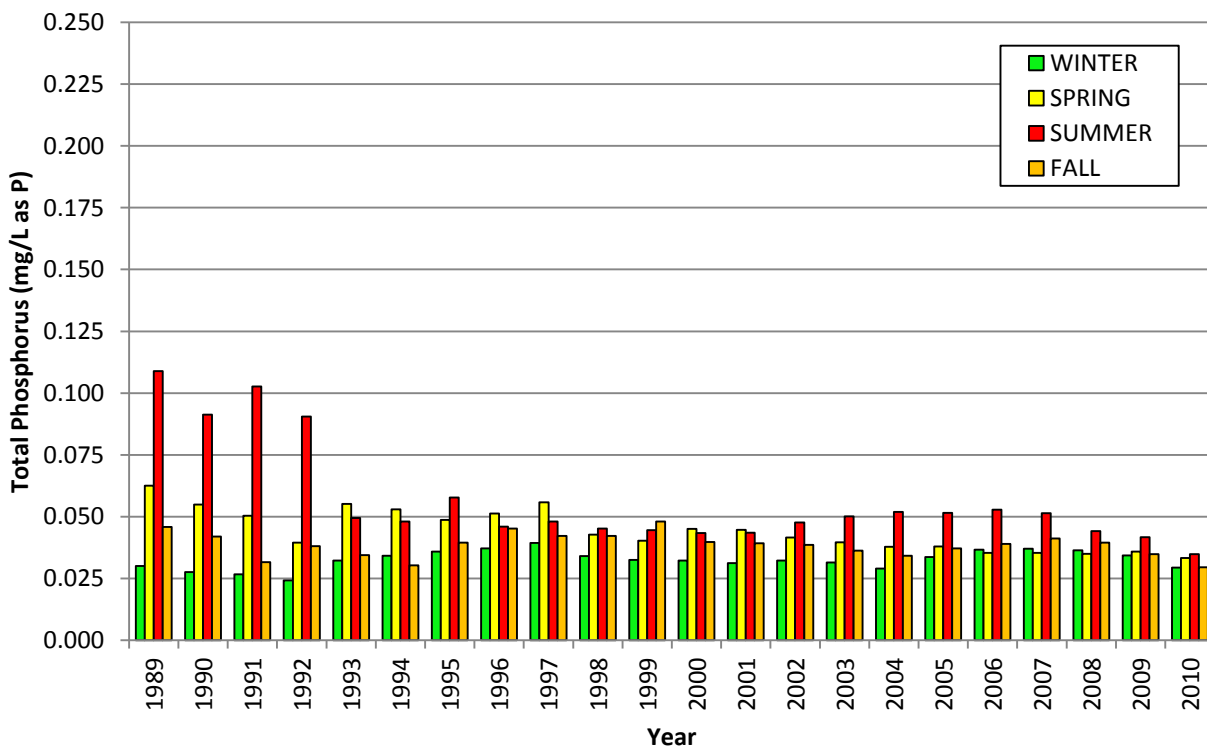


Figure 6-97 Surface vs. Bottom Seasonal Total Phosphorus Changes All Stations (2006 – 2010)

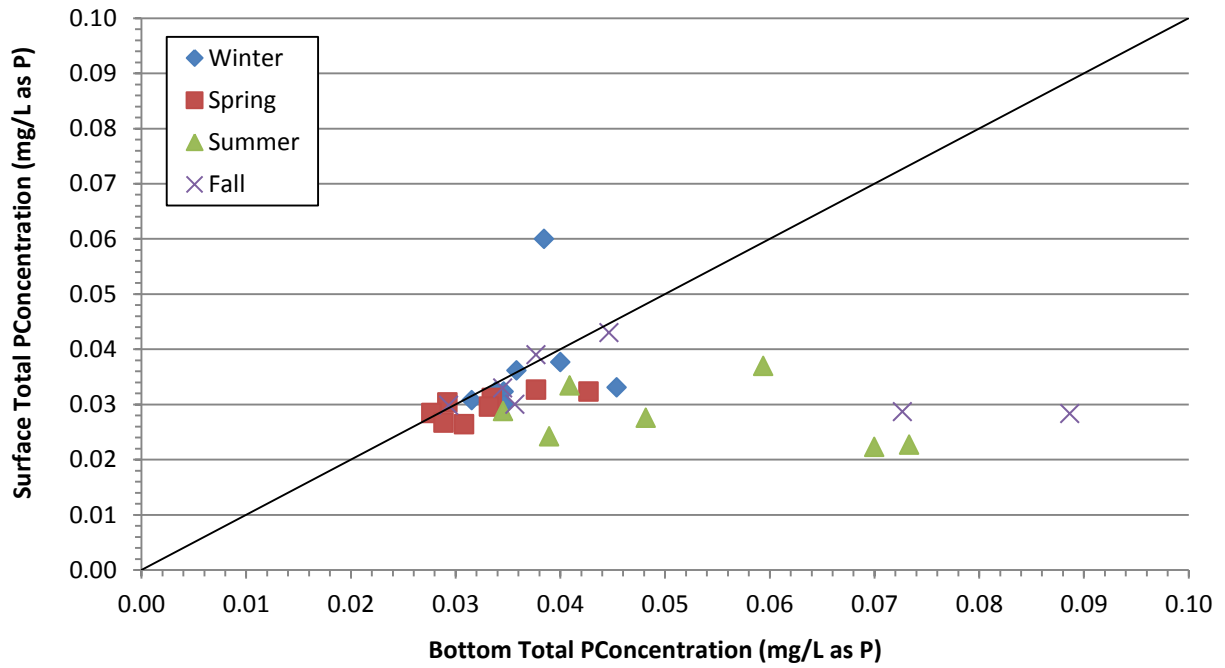


Figure 6-98 Five Year Running Average of Surface OP Concentrations for Station LM01

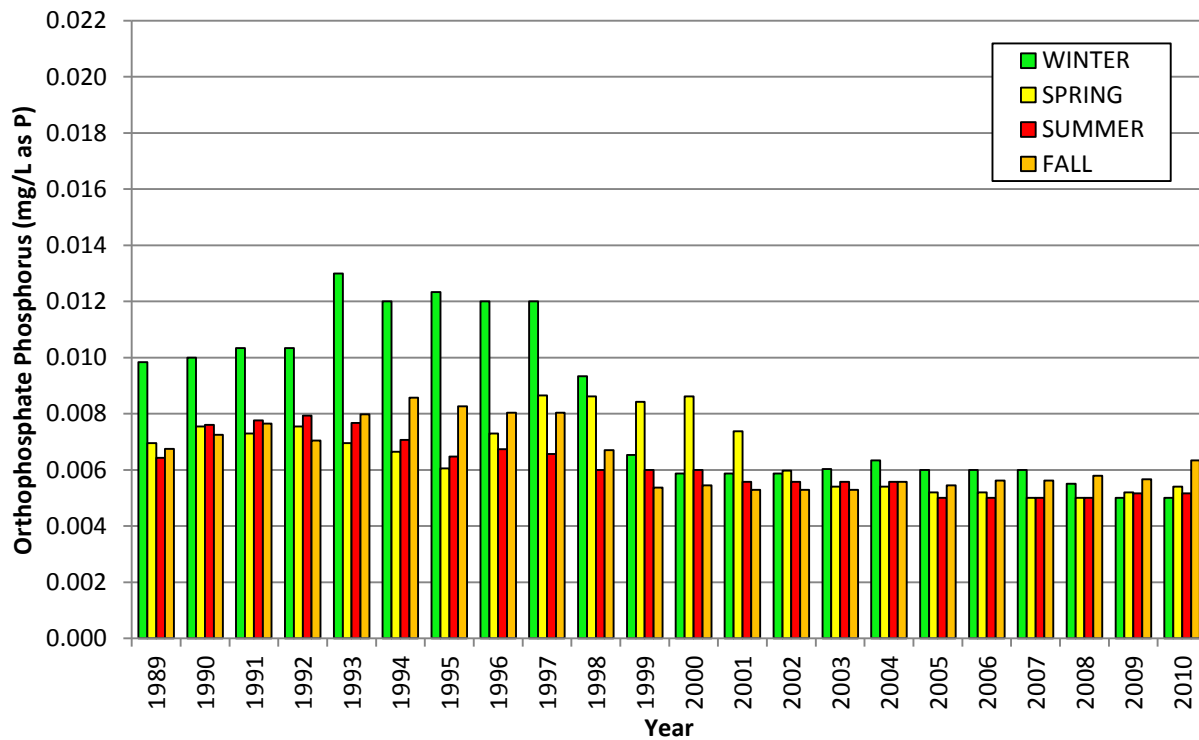


Figure 6-99 Five Year Running Average of Surface OP Concentrations for Station LM02

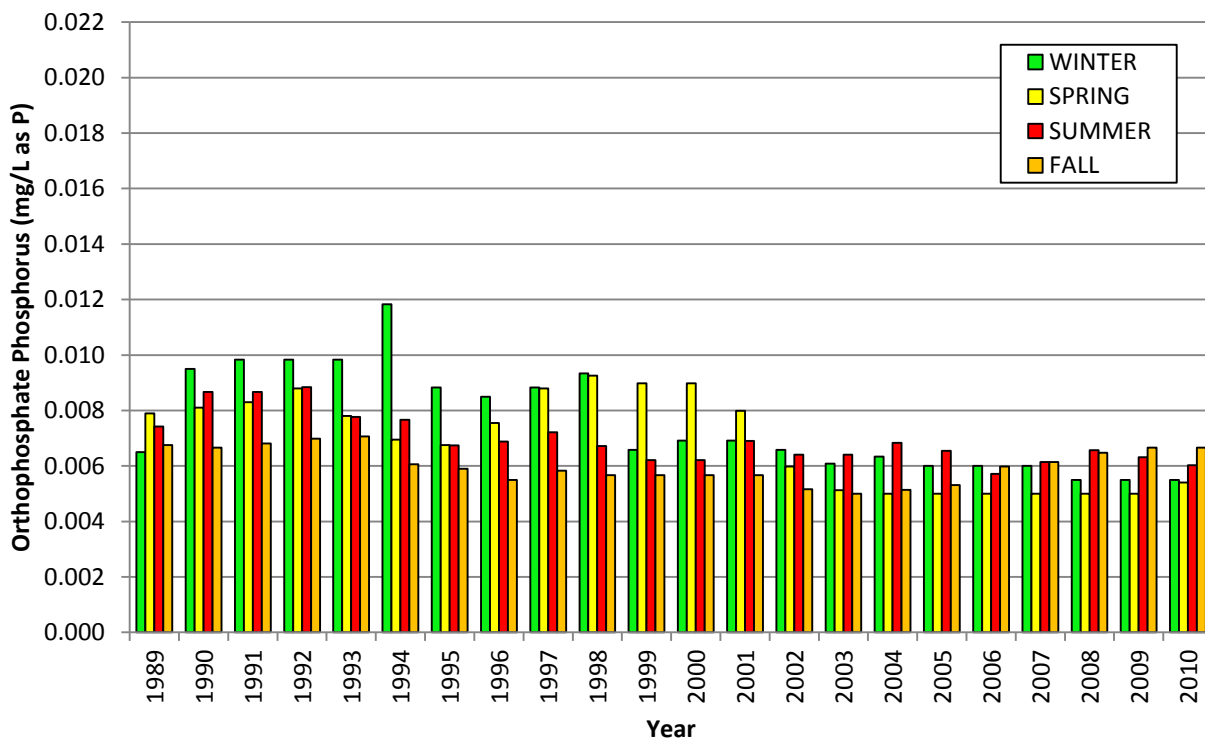


Figure 6-100 Five Year Running Average of Surface OP Concentrations for Station LM03

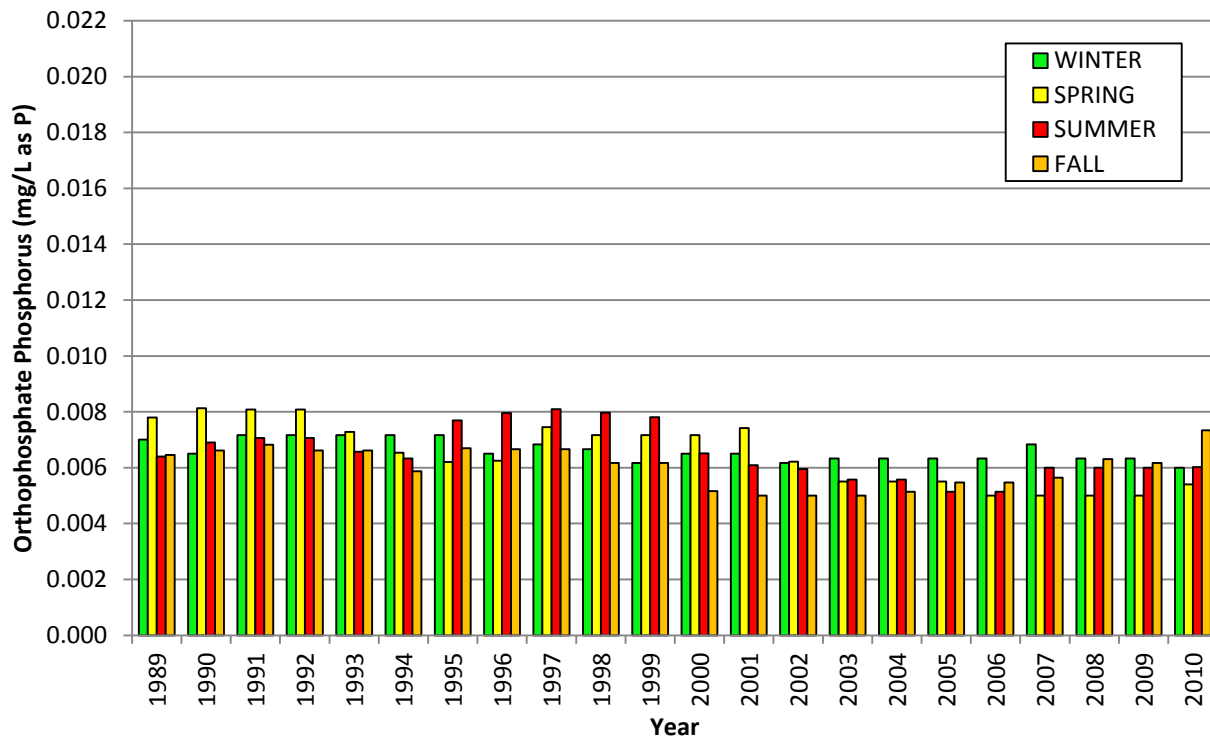


Figure 6-101 Five Year Running Average of Surface OP Concentrations for Station LM04

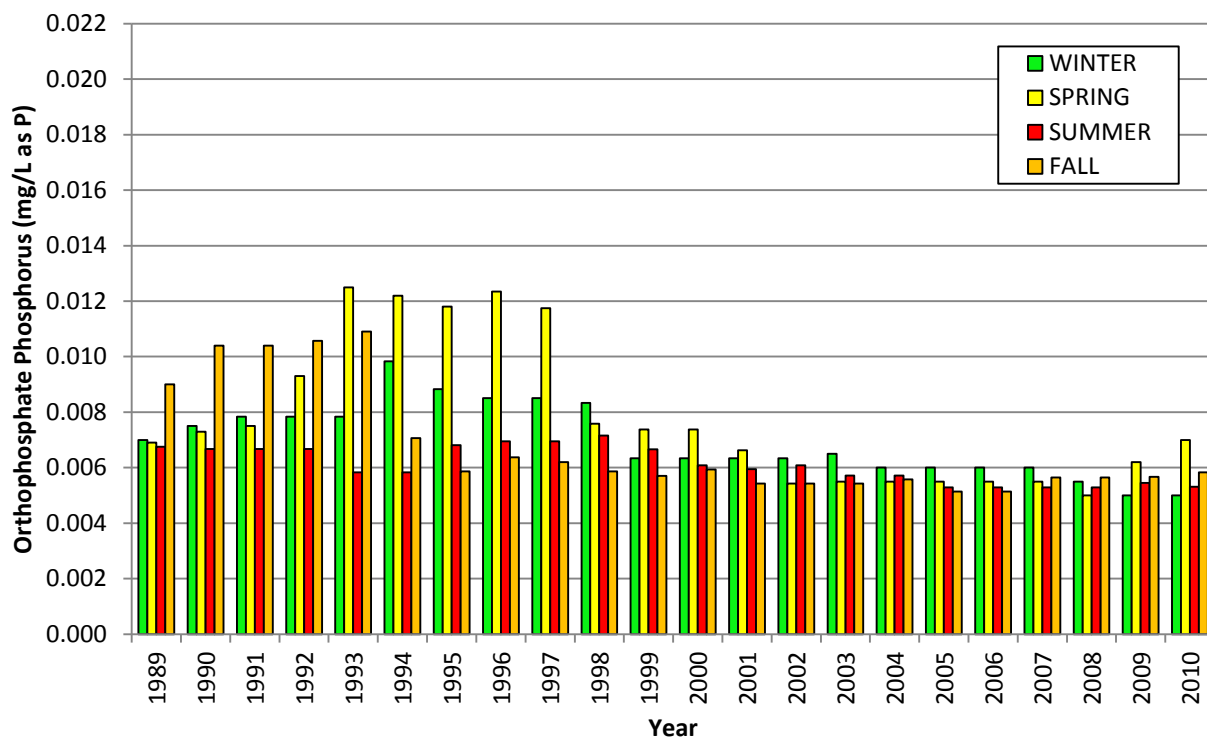


Figure 6-102 Five Year Running Average of Surface OP Concentrations for Station LM05

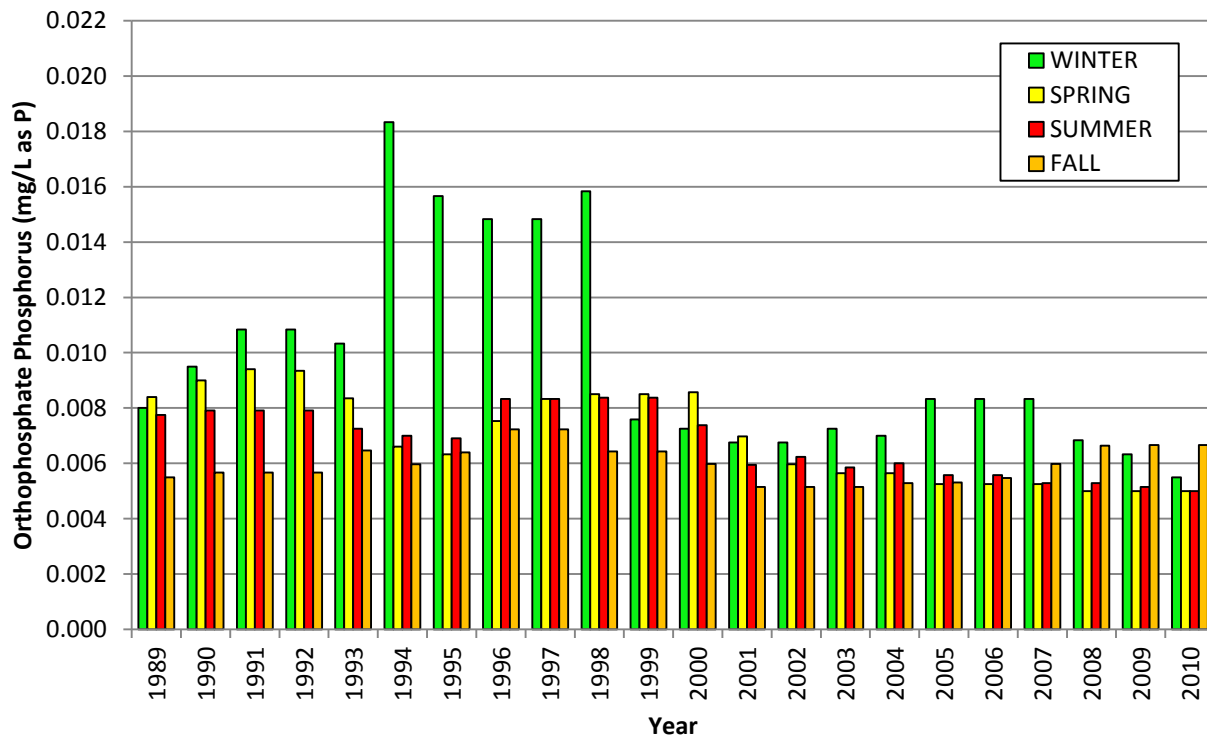


Figure 6-103 Five Year Running Average of Surface OP Concentrations for Station LM06

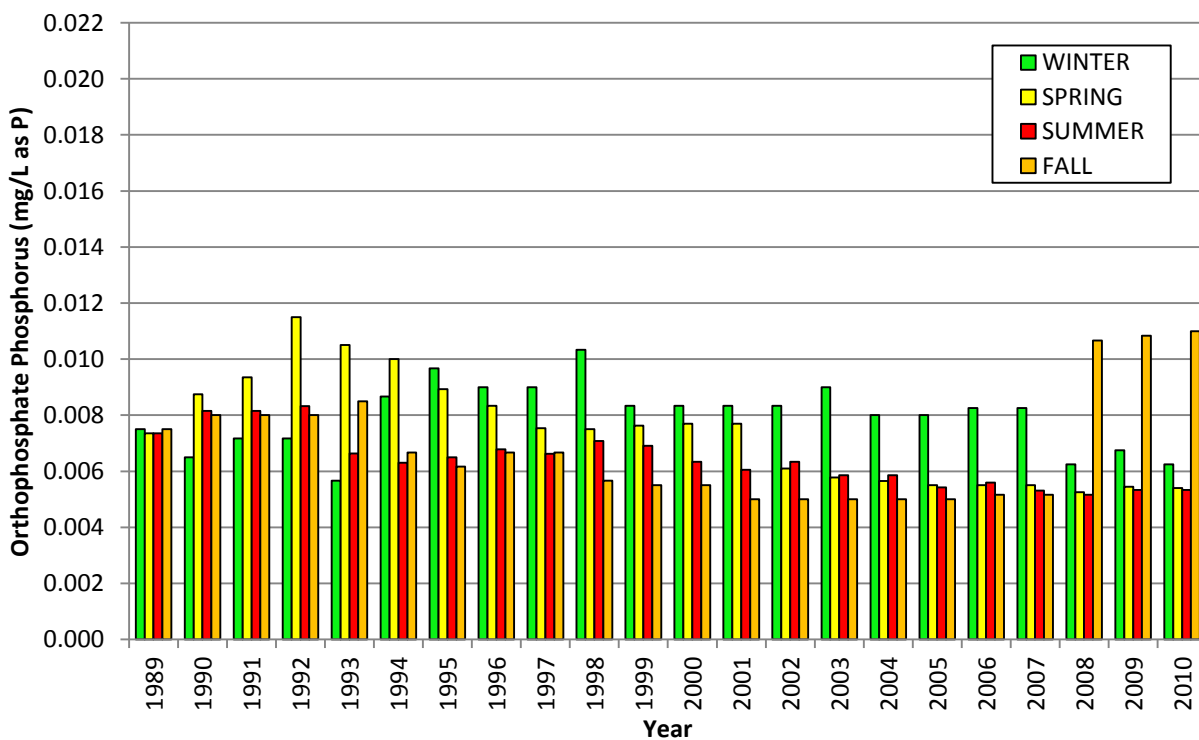


Figure 6-104 Five Year Running Average of Surface OP Concentrations for Station LM07

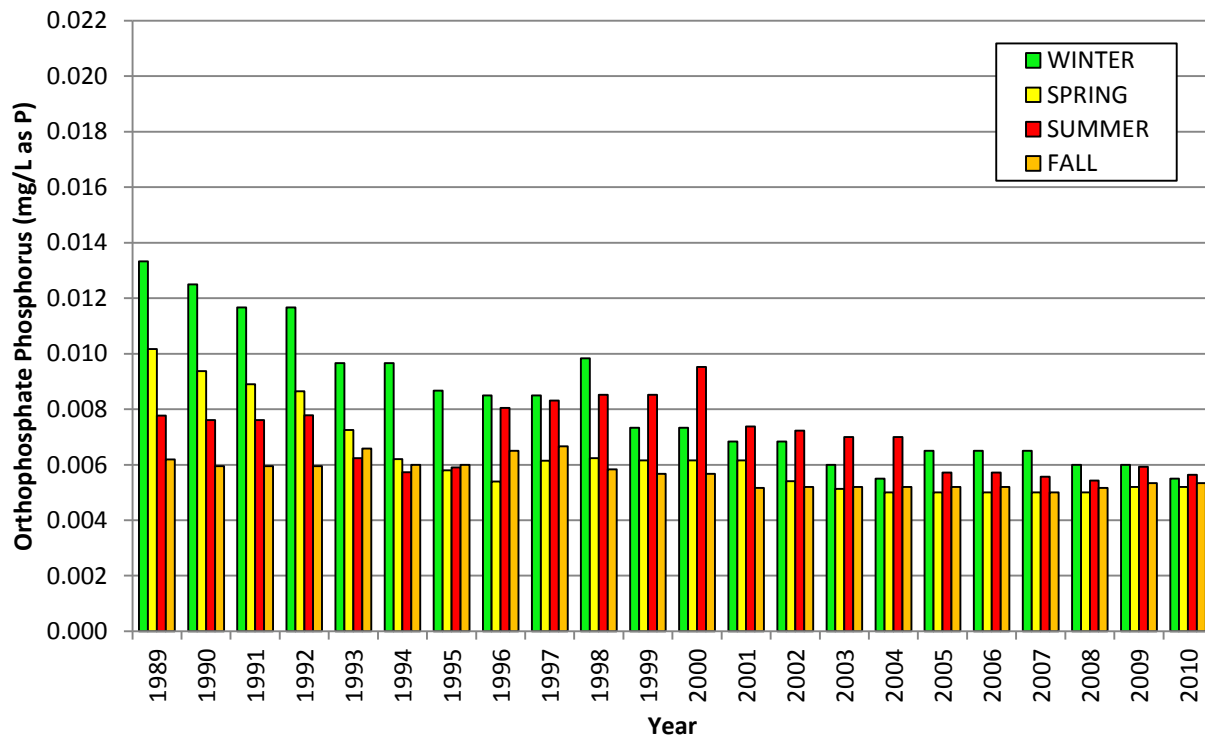


Figure 6-105 Five Year Running Average of Surface OP Concentrations for Station LM08

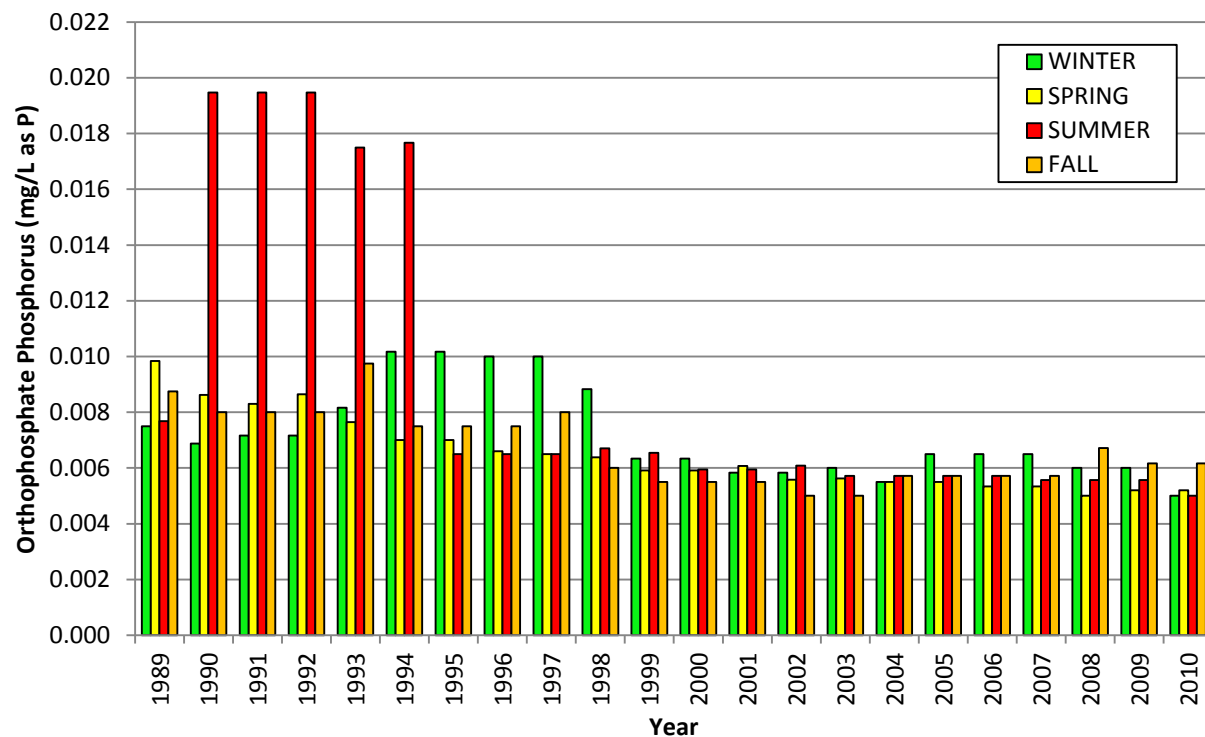


Figure 6-106 Five Year Running Average of Bottom OP Concentrations for Station LM01

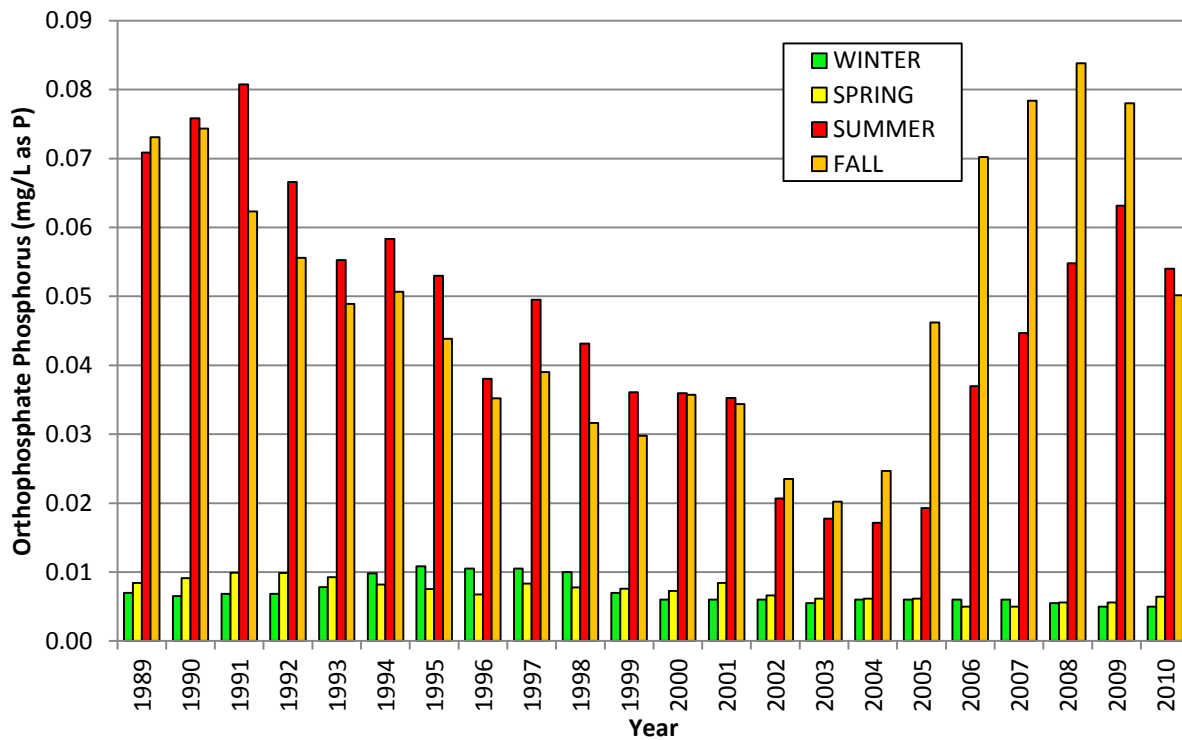


Figure 6-107 Five Year Running Average of Bottom OP Concentrations for Station LM02

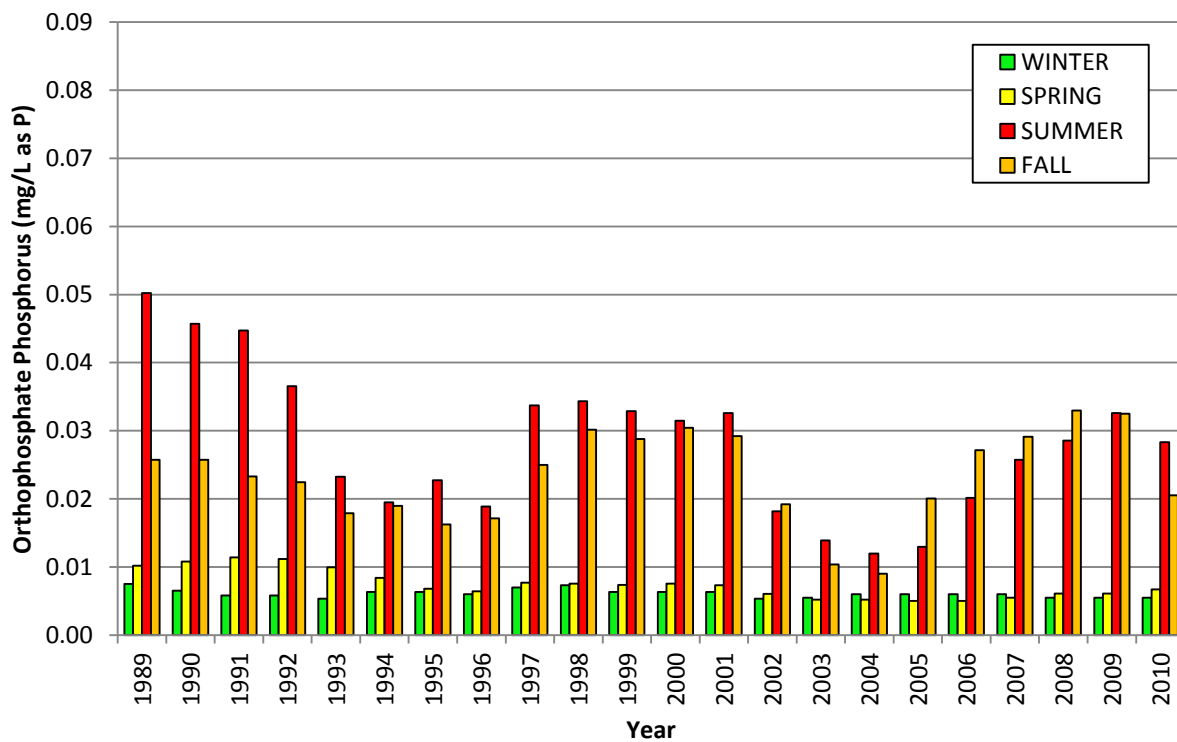


Figure 6-108 Five Year Running Average of Bottom OP Concentrations for Station LM03

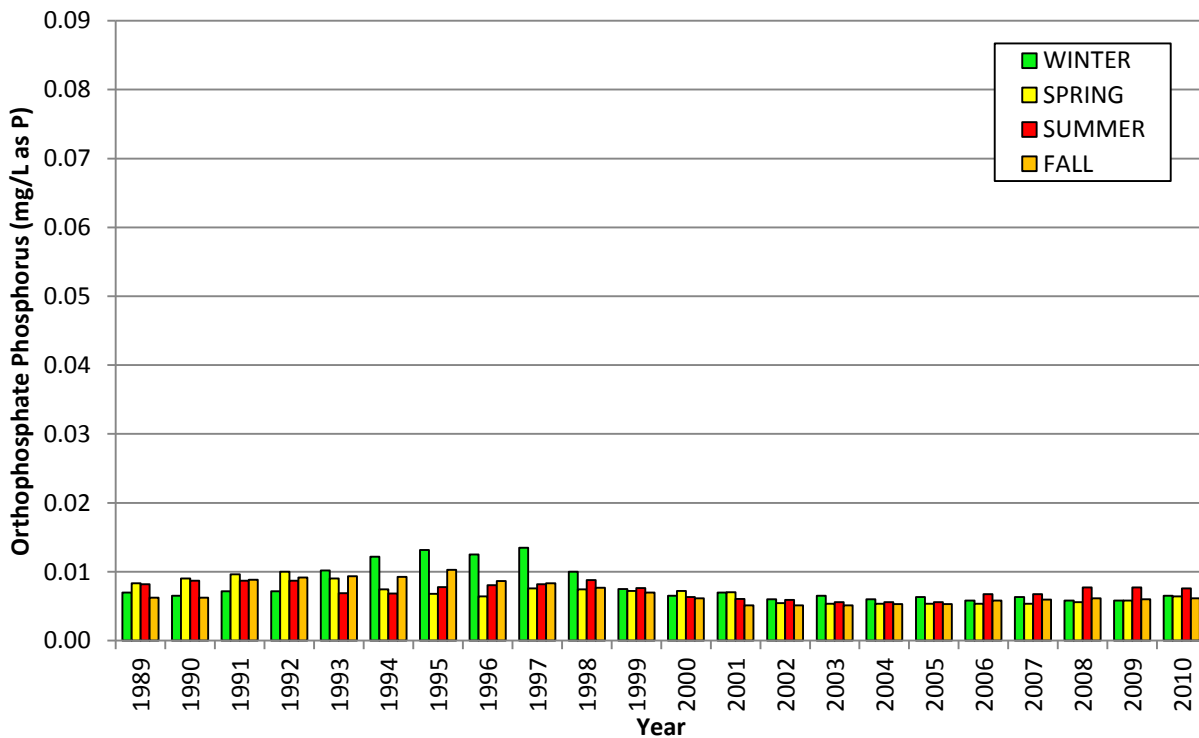


Figure 6-109 Five Year Running Average of Bottom OP Concentrations for Station LM04

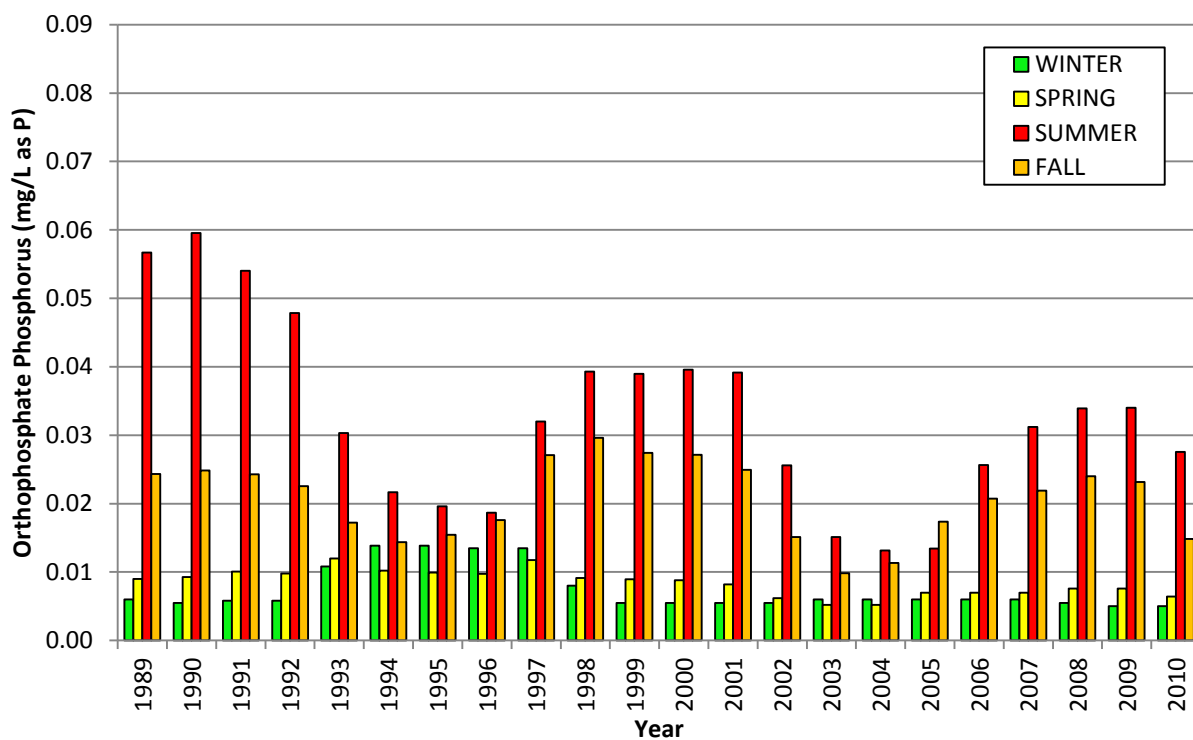


Figure 6-110 Five Year Running Average of Bottom OP Concentrations for Station LM05

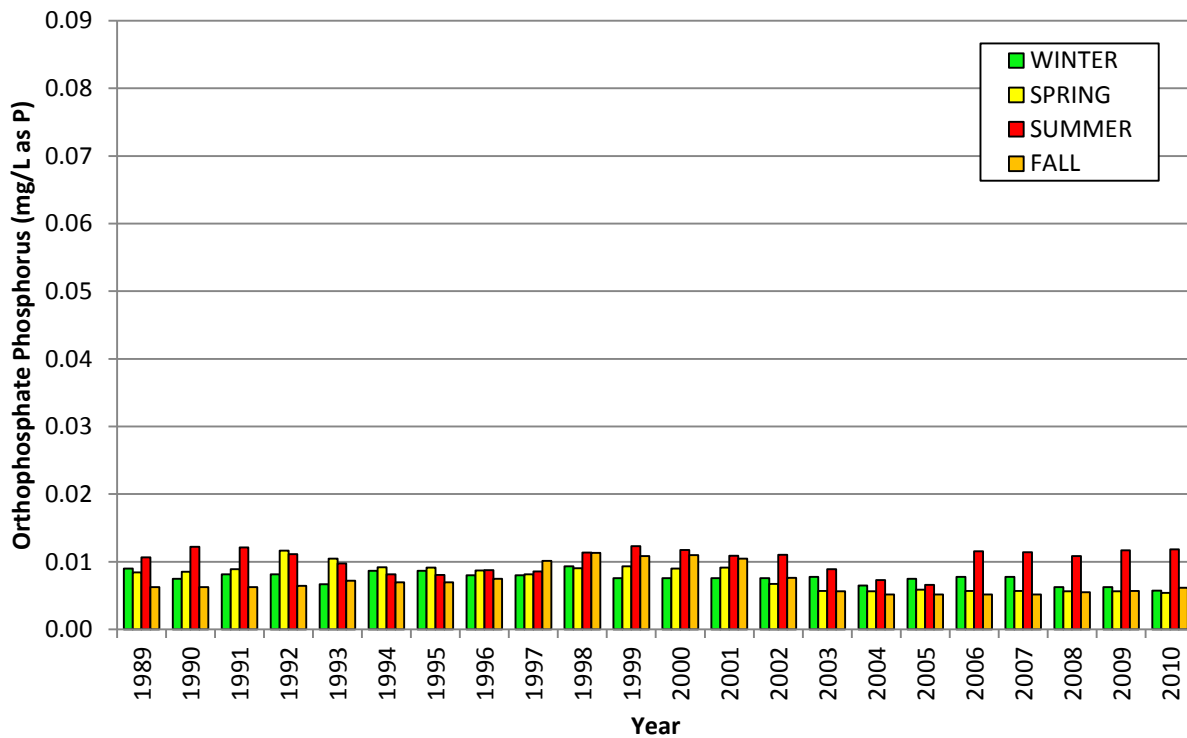


Figure 6-111 Five Year Running Average of Bottom OP Concentrations for Station LM06

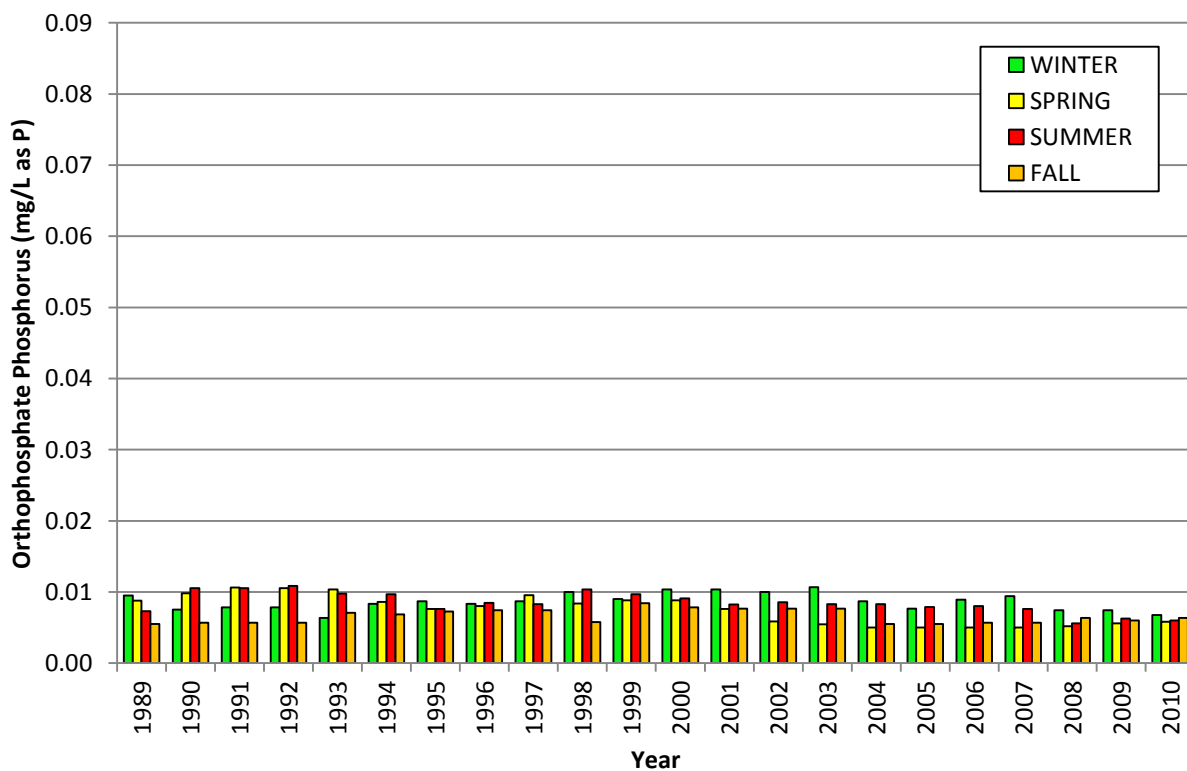


Figure 6-112 Five Year Running Average of Bottom OP Concentrations for Station LM07

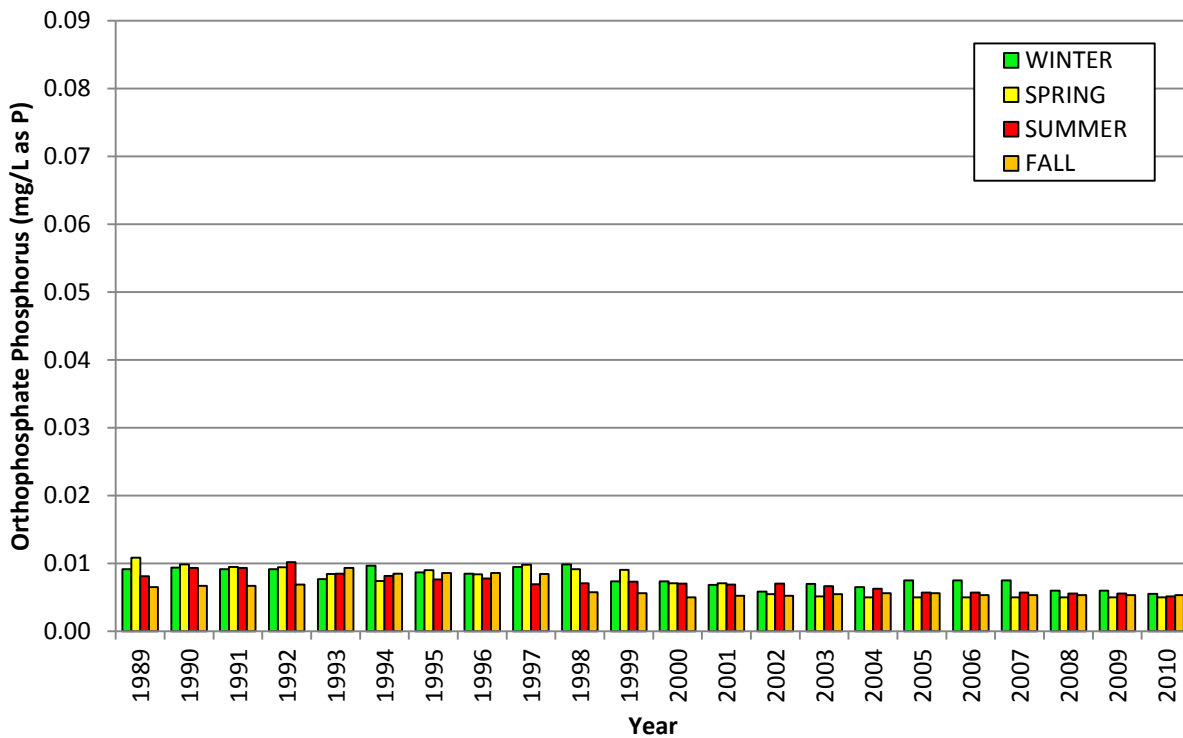
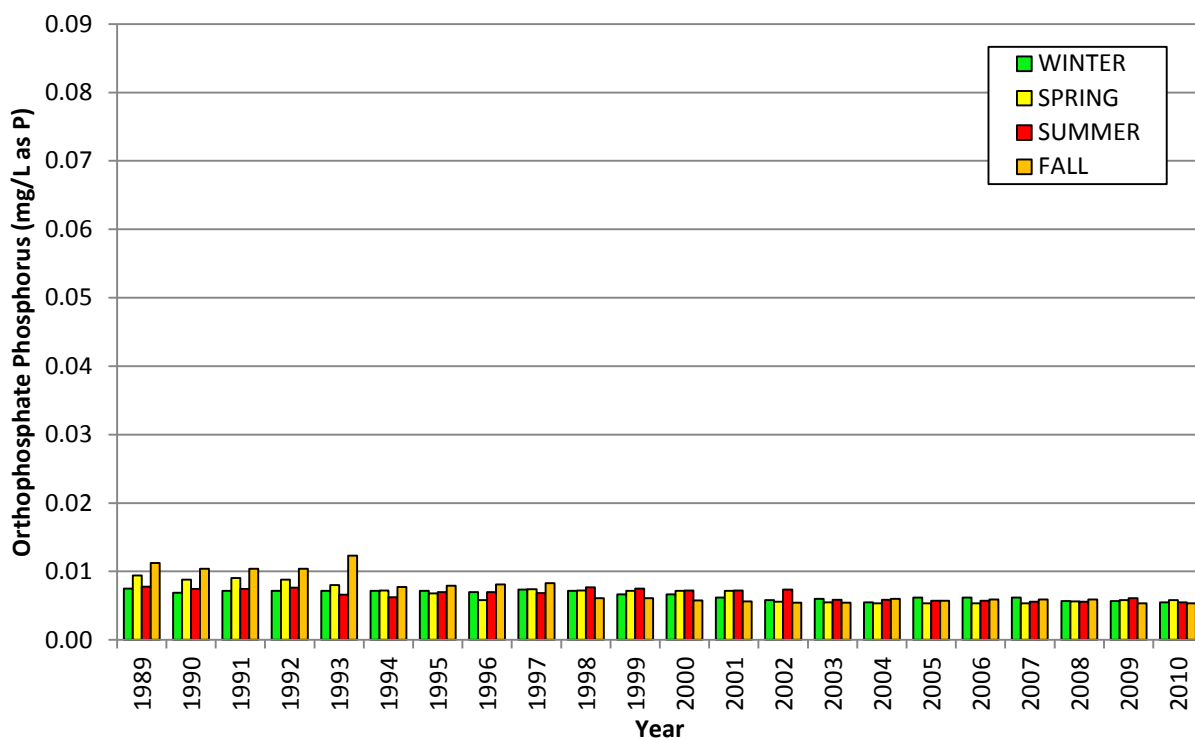


Figure 6-113 Five Year Running Average of Bottom OP Concentrations for Station LM08



Nutrient Summary

Figures 6-114 and 6-115 show the pattern between nutrient concentrations during the 1984 to 2010 period for surface and bottom conditions, respectively. Both figures include measurements for dissolved oxygen, total phosphorous and oxidized nitrogen. The pattern between nutrients generally follows changes in the seasons. Dissolved oxygen and oxidized nitrogen concentrations fall in the spring and summer, and once exhausted completely, total phosphorus concentrations begin to increase. This increase in phosphorus is the result of phosphorus release from the bottom sediments when the redox potential in the hypolimnion has decreased.

Alternatively, after the fall turnover, oxidized nitrogen and dissolved oxygen concentrations increase while total phosphorus decreases as it becomes consumed. As shown in Figure 6-114, the release of total phosphorus does not generally occur at the surface because there is a readily available source of dissolved oxygen at the air-water interface. Alternative, Figure 6-115 shows the significant total phosphorus increases after dissolved oxygen and oxidized nitrogen concentrations are depleted.

Figure 6-114 Surface TP, OX-N and DO vs. Time for Station LM01

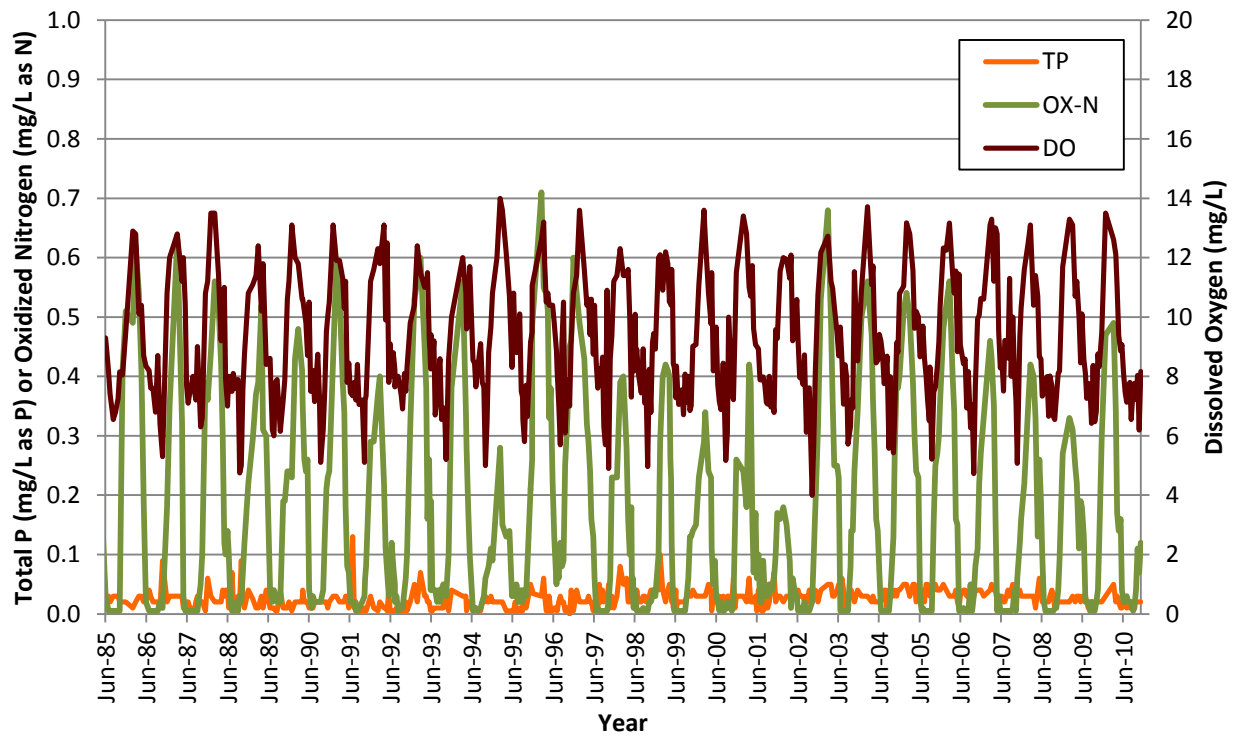
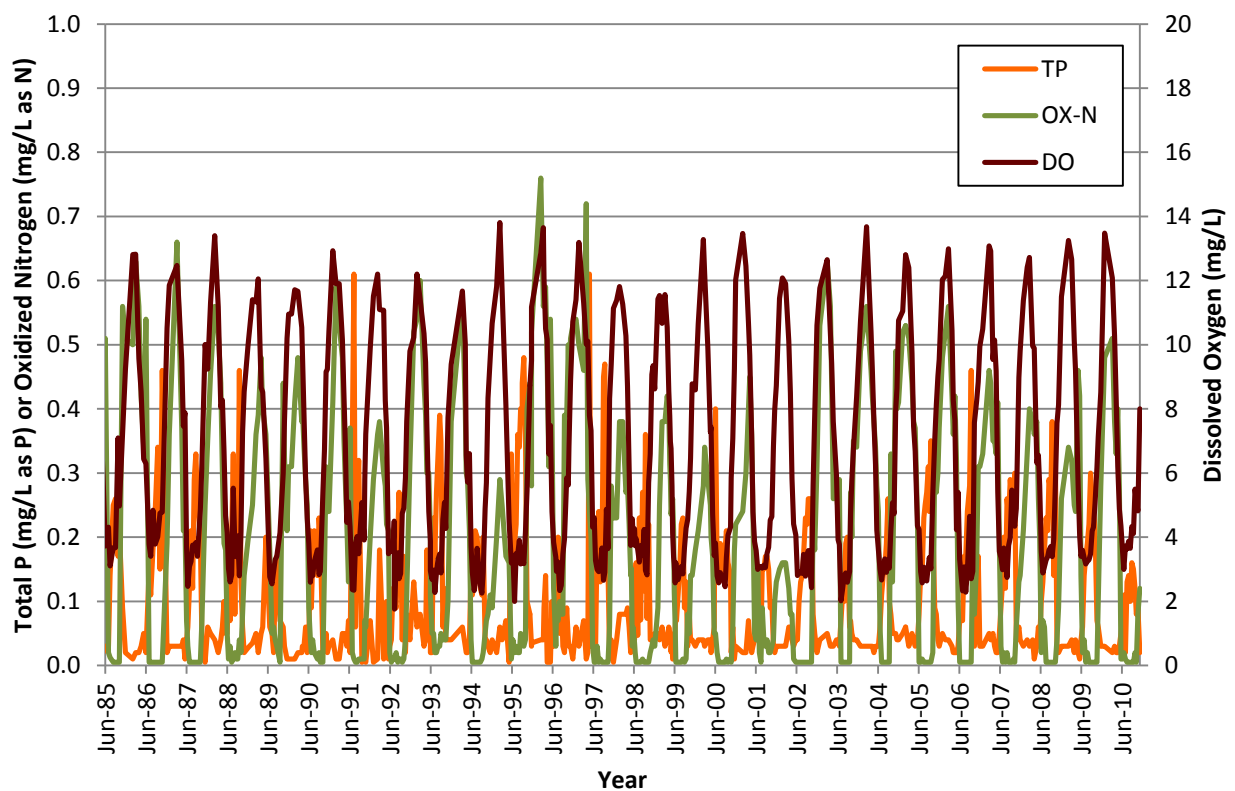


Figure 6-115 Bottom TP, OX-N and DO vs. Time for Station LM01



Nitrogen to Phosphorus Ratios

As discussed previously in this report, nitrogen and phosphorus are considered to be the most common limiting nutrients in a lake or reservoir system, where the limiting nutrient inhibits algal growth. One method for determining which nutrient is limiting is to examine TN:TP ratios. With a ratio greater than 20:1 indicating phosphorus limited systems, a ratio less than or equal to 5:1 is considered to be a nitrogen-limited system (Wetzel 2001).

TN:TP ratios for each lake sampling station are depicted in Figures 6-116 through 6-123 for the 1985 to 2010 period, with each bar representing a yearly average for total nitrogen and phosphorus. Both surface and bottom ratios are present in each figure.

- Because algal growth is generally limited to the epilimnion, surface TN:TP ratios are of greater concern. All annual TN:TP stations during the 2006 to 2010 period exceeded 15:1 with the majority greater than 20:1, suggesting a moderate to strongly phosphorus-limited system at the surface. An increase in TN:TP ratios is apparent during the 2006 to 2010 baseline period, especially in surface samples, suggesting a reduction in phosphorus within the lake.

Seasonal surface TN:TP ratios for each lake sampling station are depicted in Figures 6-124 through 6-131 for the 1985 to 2010 period, with each bar representing a seasonal average for total nitrogen and phosphorus.

- Winter and spring months tend to have the greatest TN:TP ratio, almost always greater than 20:1. Similar to the annualized figures, there is an increase in TN:TP ratios at each station, most evident in summer and fall months.

Bottom surface TN:TP ratios for each lake sampling station are depicted in Figures 6-132 through 6-139 for the 1985 to 2010 period, with each bar representing a seasonal average for total nitrogen and phosphorus..

- Winter and spring months tend to have the greatest TN:TP ratio, almost always greater than 20:1. Unlike the surface ratios, there is no apparent increasing or decreasing trend in TN:TP ratios.

Figure 6-116 Surface and Bottom Yearly Averages for TN:TP for Station LM01

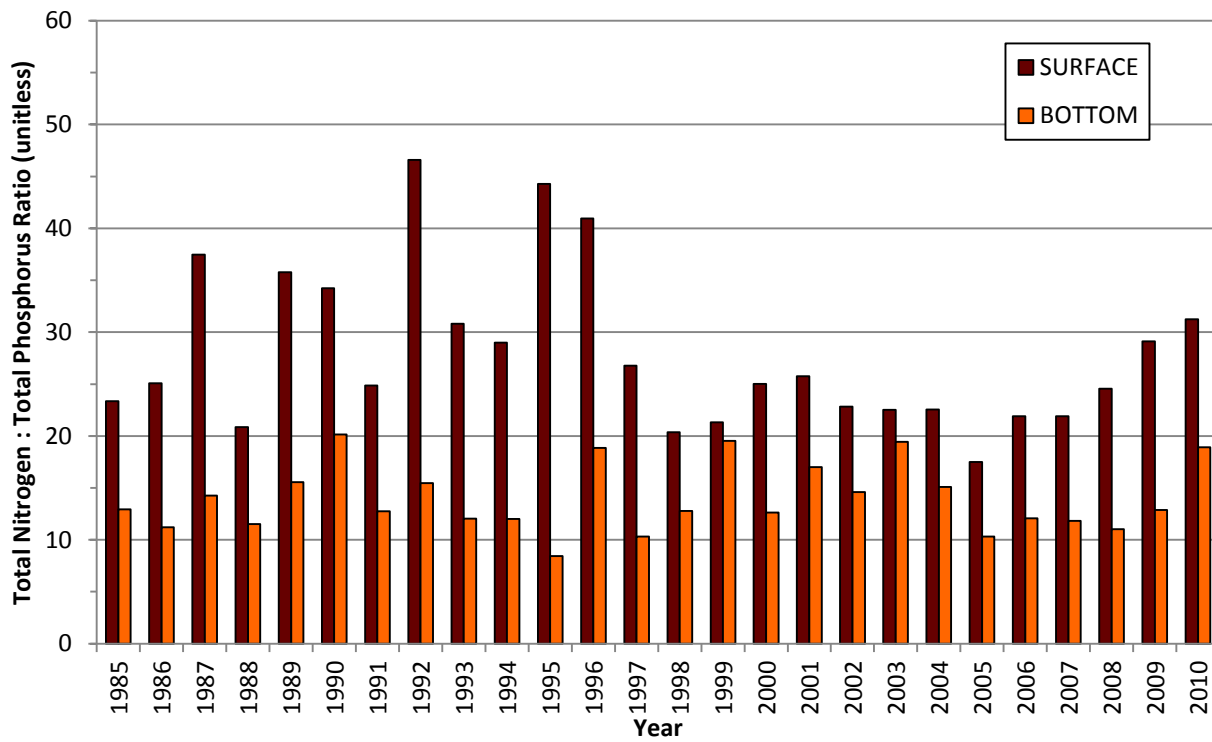


Figure 6-117 Surface and Bottom Yearly Averages for TN:TP for Station LM02

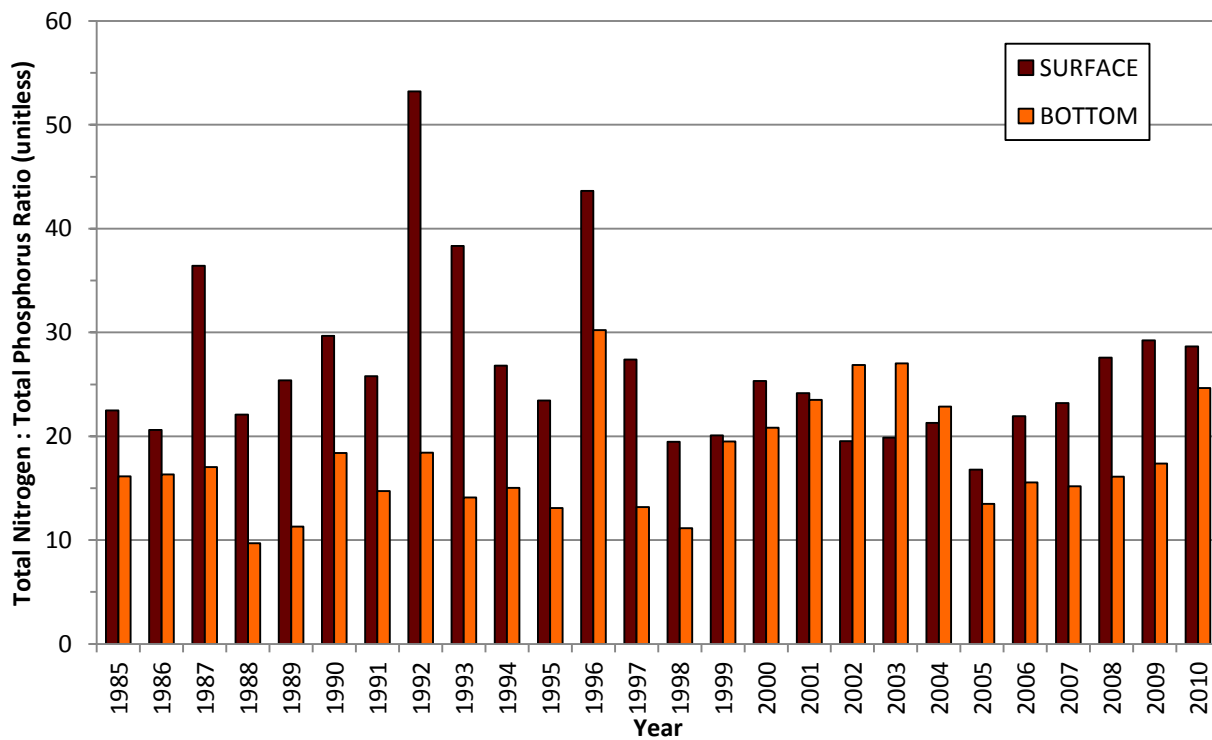


Figure 6-118 Surface and Bottom Yearly Averages for TN:TP for Station LM03

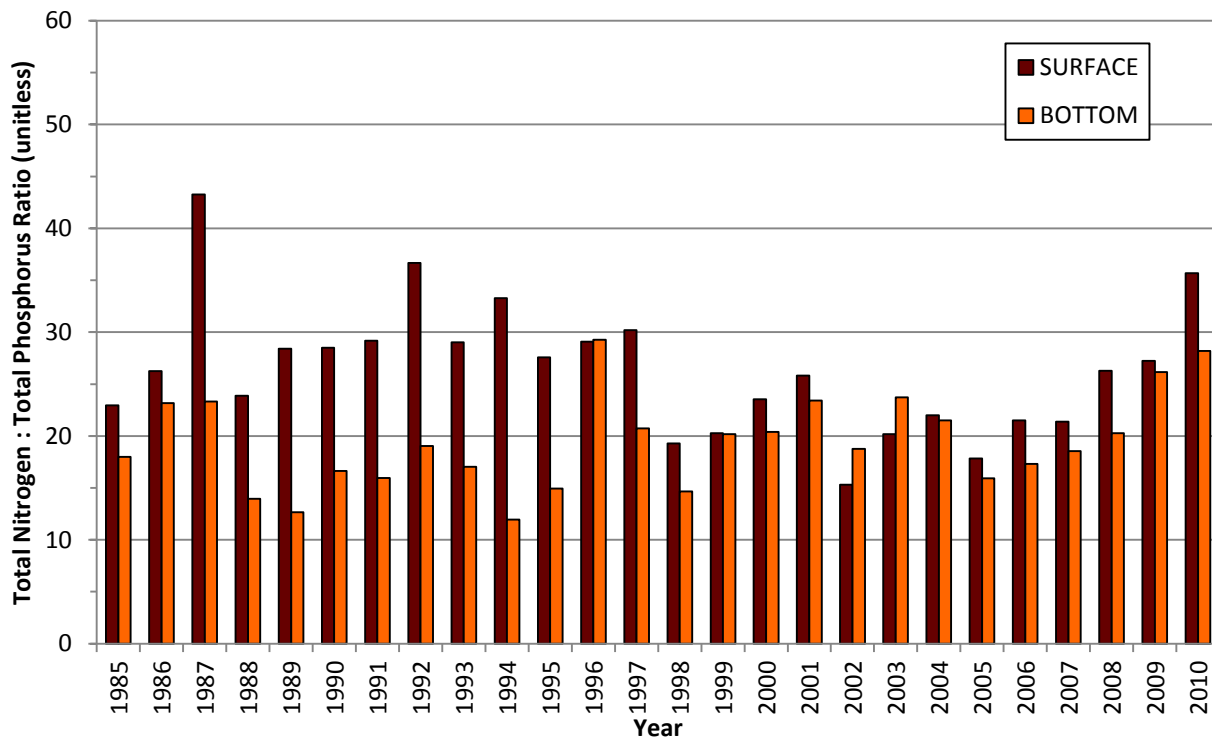


Figure 6-119 Surface and Bottom Yearly Averages for TN:TP for Station LM04

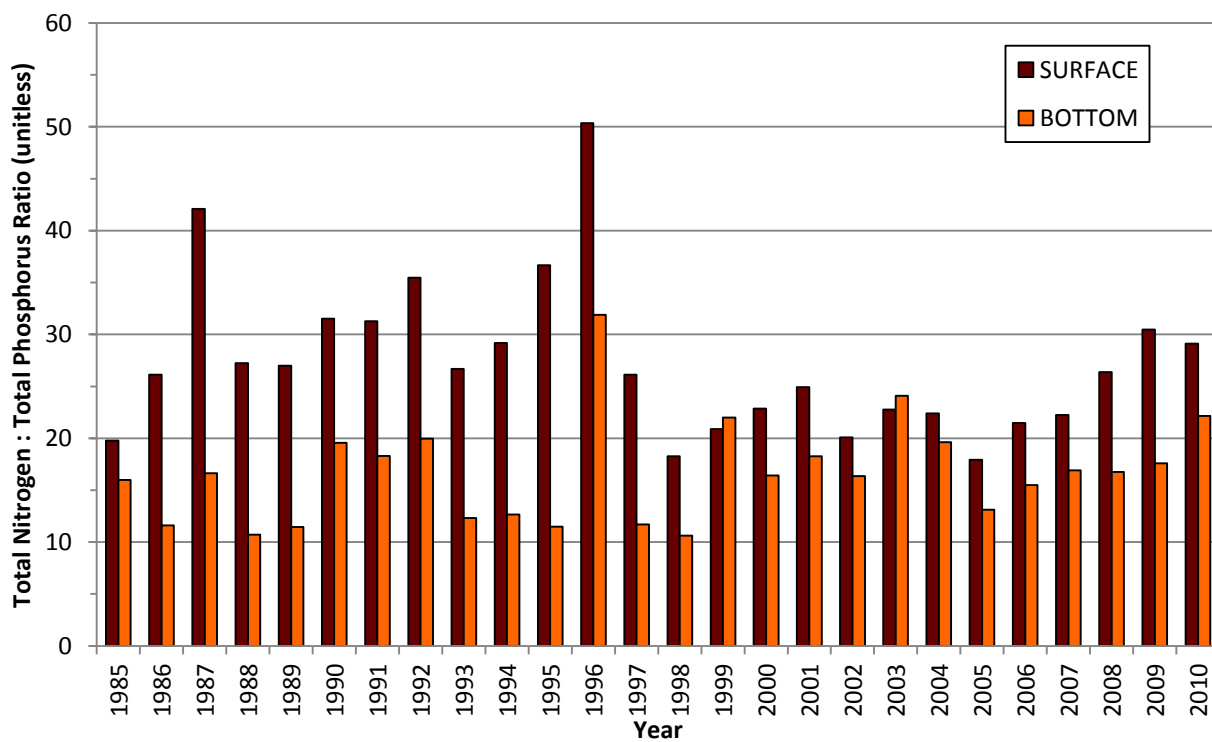


Figure 6-120 Surface and Bottom Yearly Averages for TN:TP for Station LM05

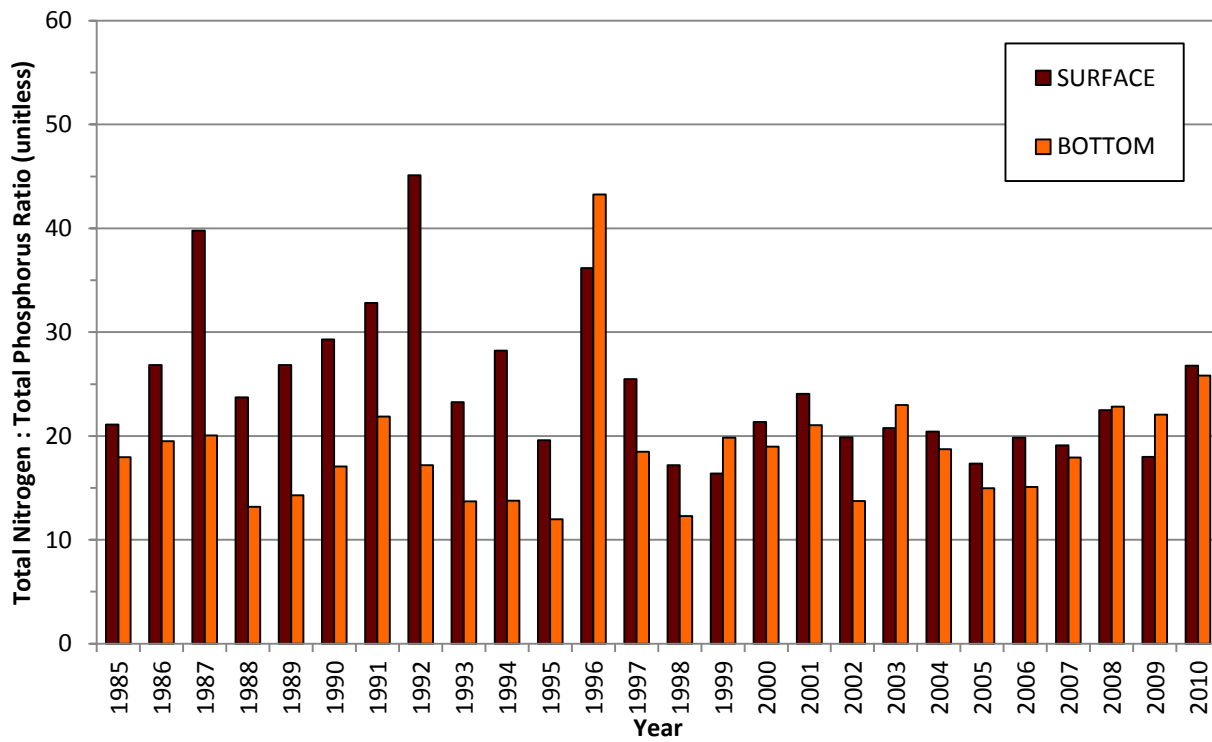


Figure 6-121 Surface and Bottom Yearly Averages for TN:TP for Station LM06

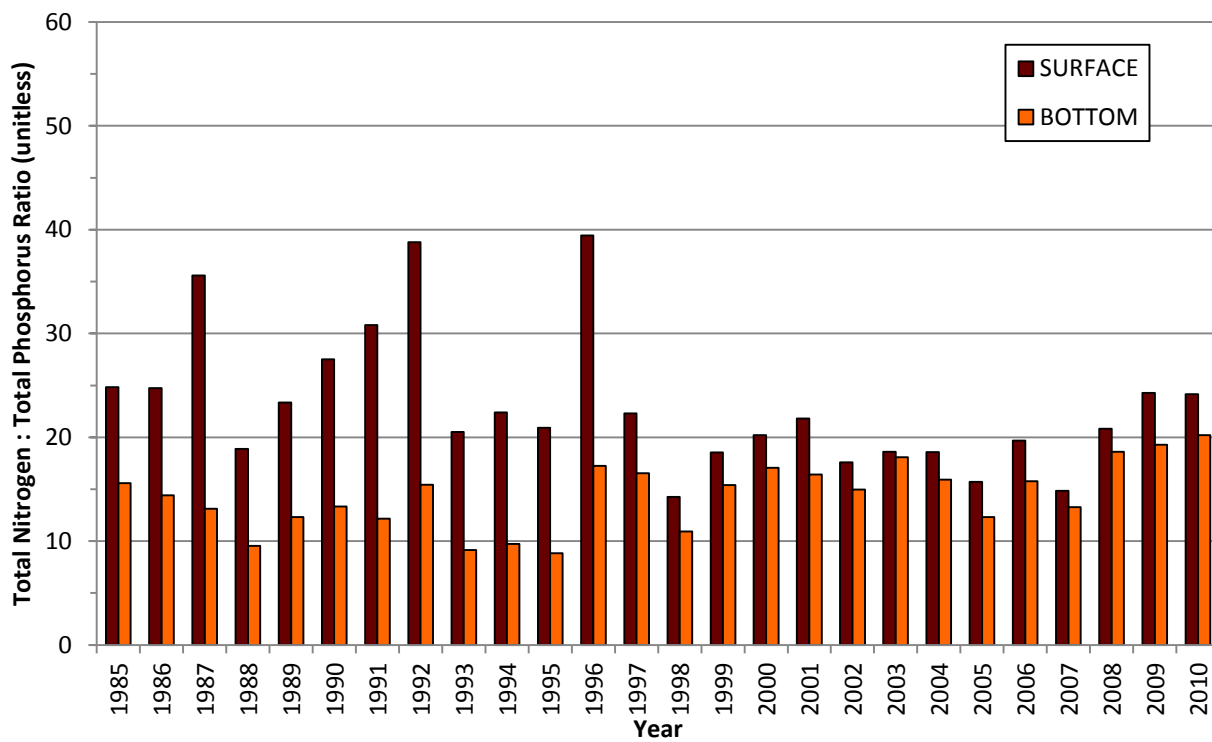


Figure 6-122 Surface and Bottom Yearly Averages for TN:TP for Station LM07

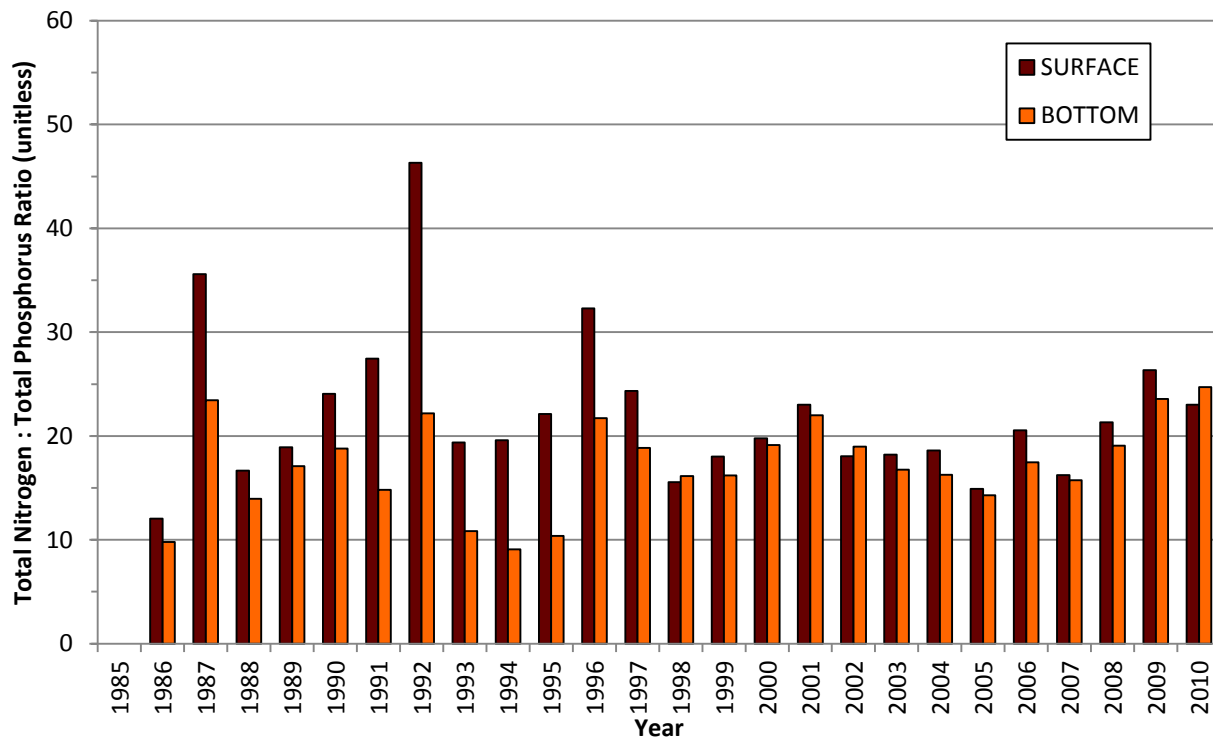


Figure 6-123 Surface and Bottom Yearly Averages for TN:TP for Station LM08

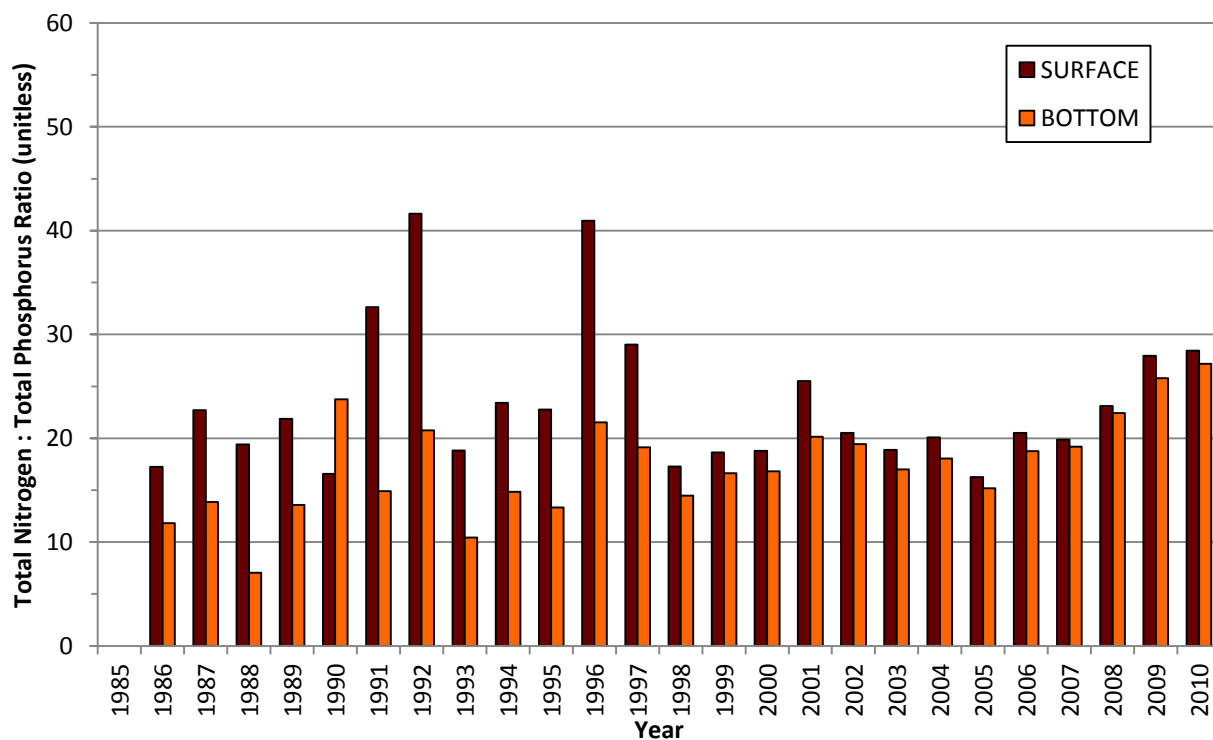


Figure 6-124 Five Year Running Average of Surface TN:TP Ratio for Station LM01

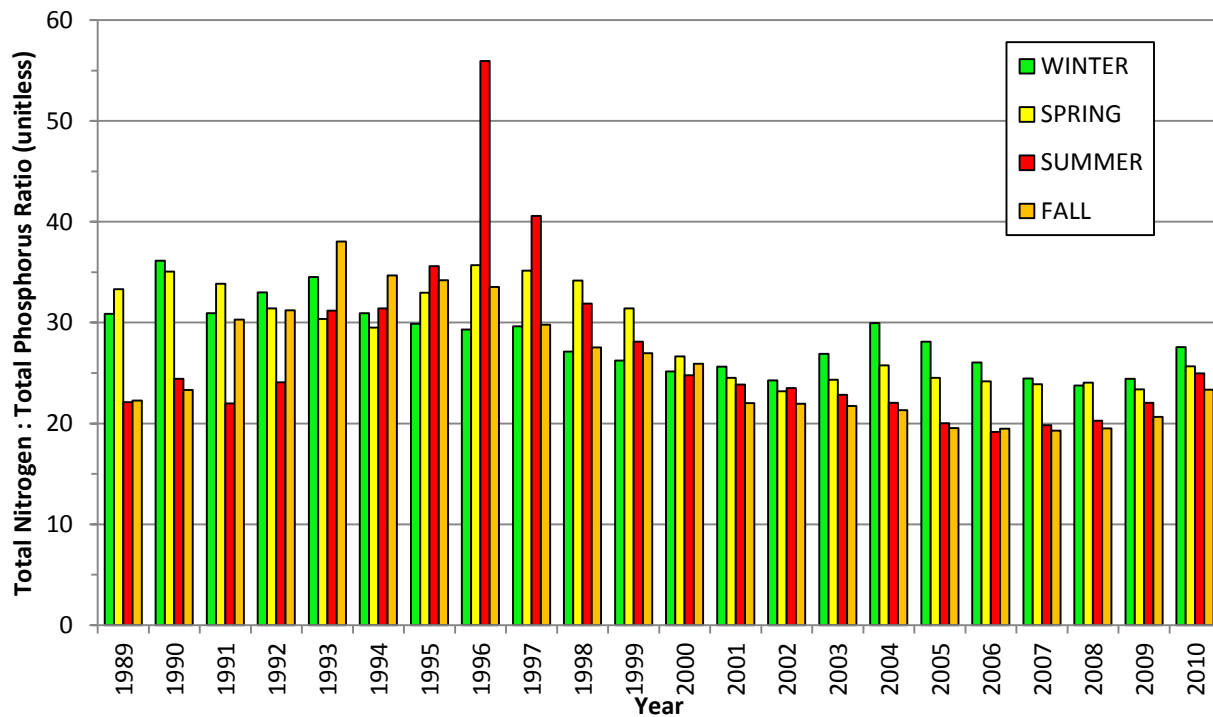


Figure 6-125 Five Year Running Average of Surface TN:TP Ratio for Station LM02

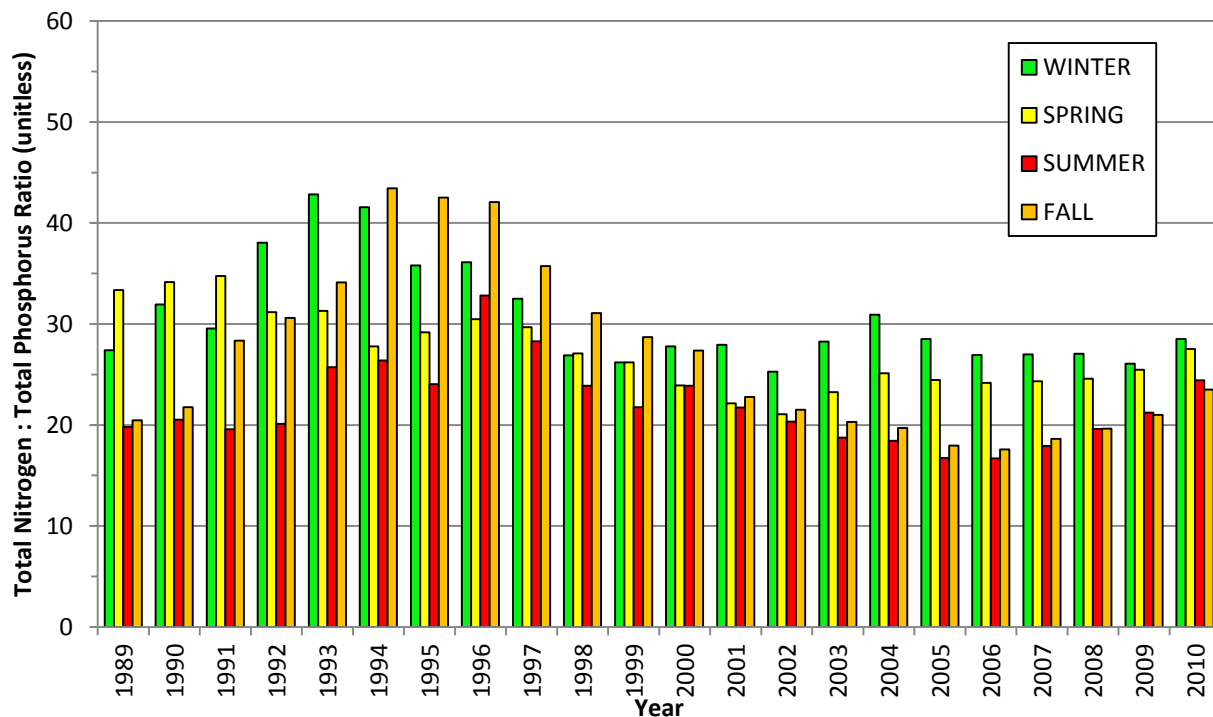


Figure 6-126 Five Year Running Average of Surface TN:TP Ratio for Station LM03

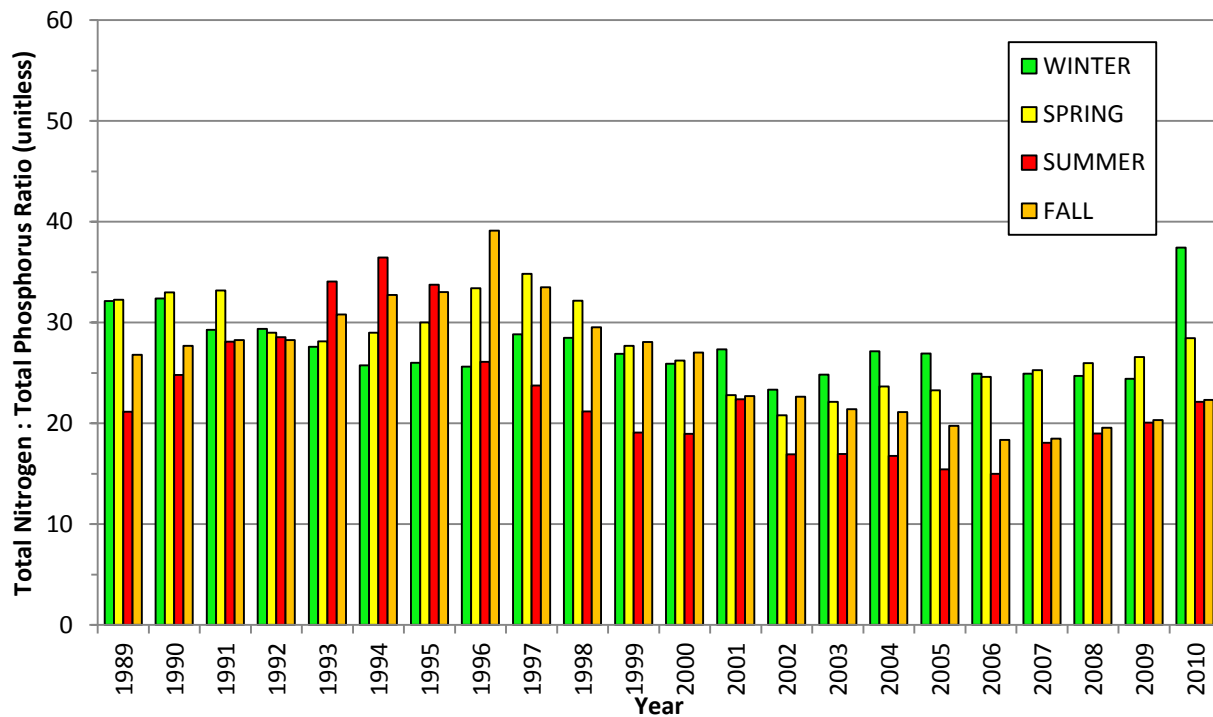


Figure 6-127 Five Year Running Average of Surface TN:TP Ratio for Station LM04

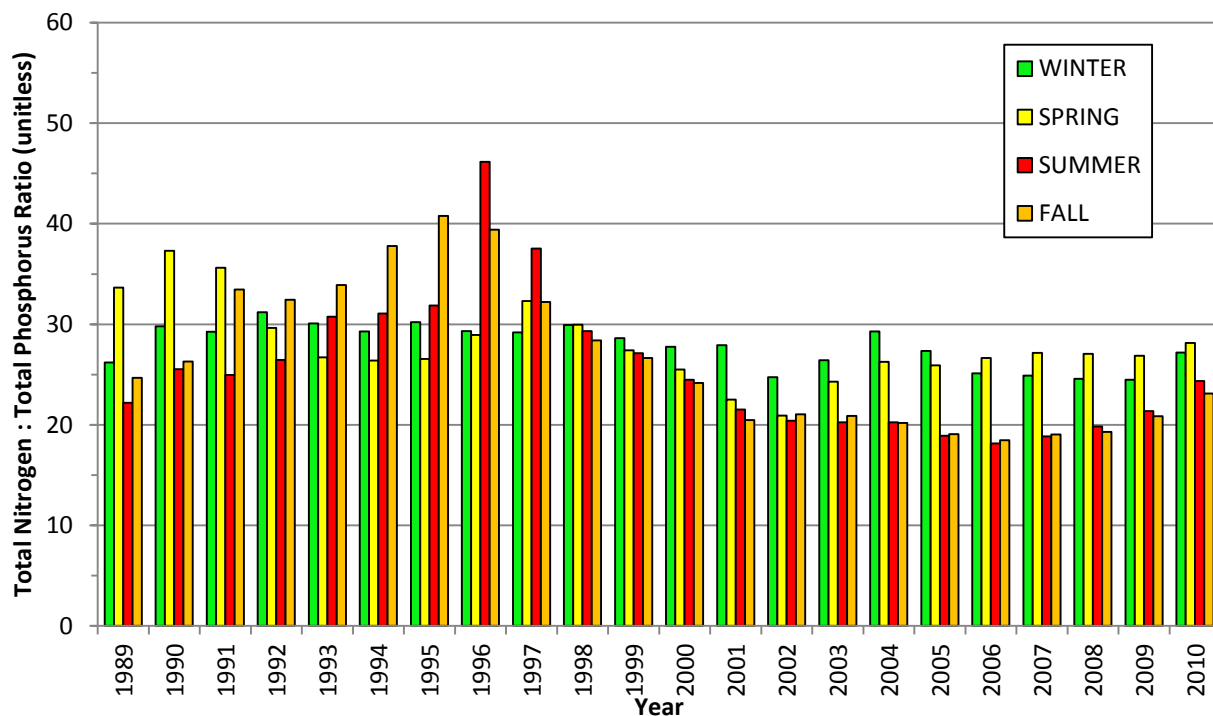


Figure 6-128 Five Year Running Average of Surface TN:TP Ratio for Station LM05

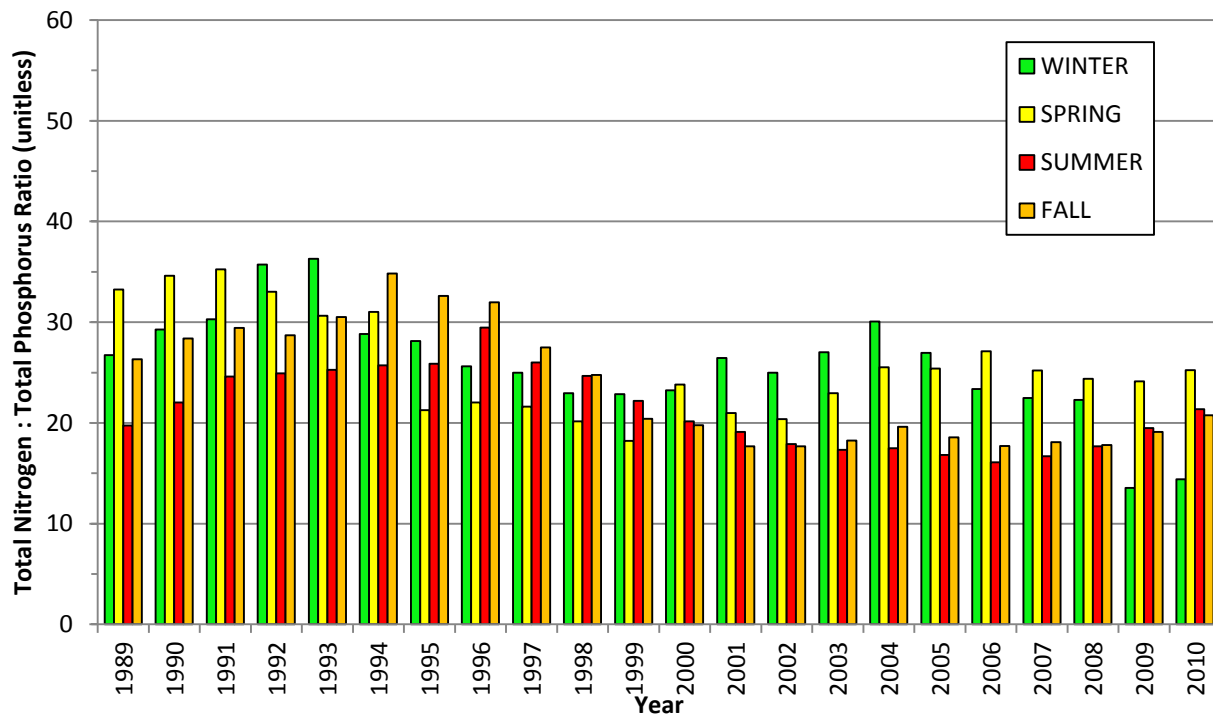


Figure 6-129 Five Year Running Average of Surface TN:TP Ratio for Station LM06

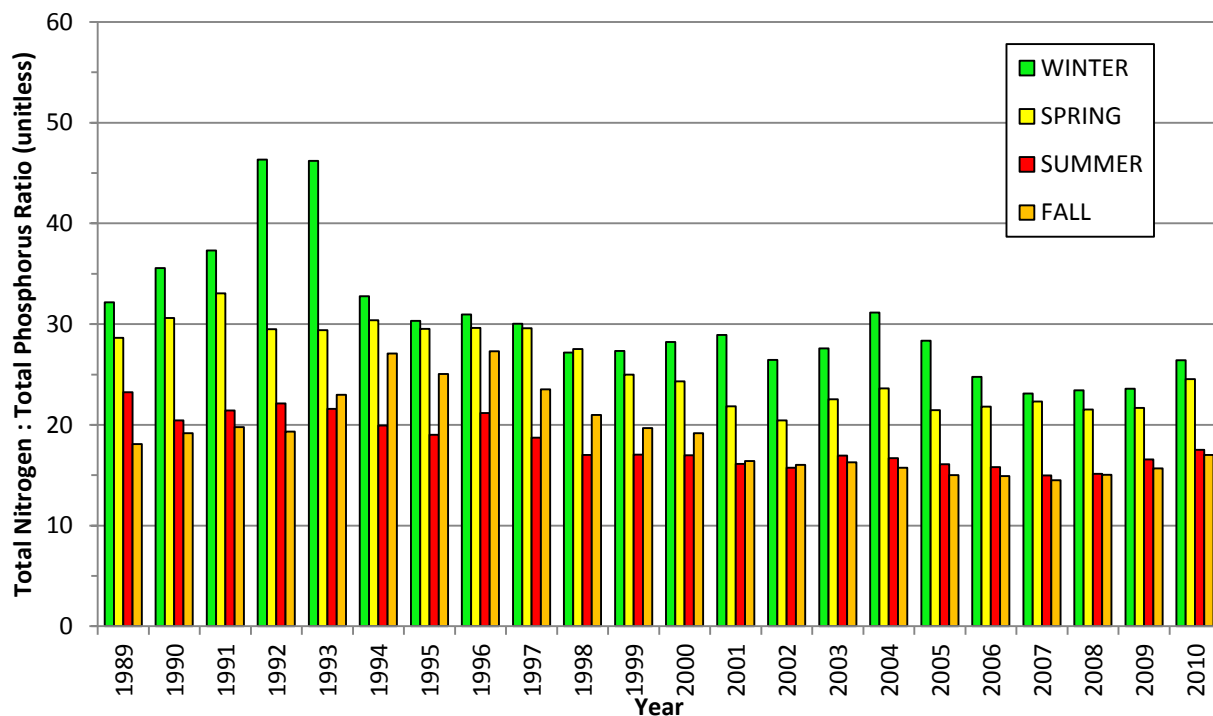


Figure 6-130 Five Year Running Average of Surface TN:TP Ratio for Station LM07

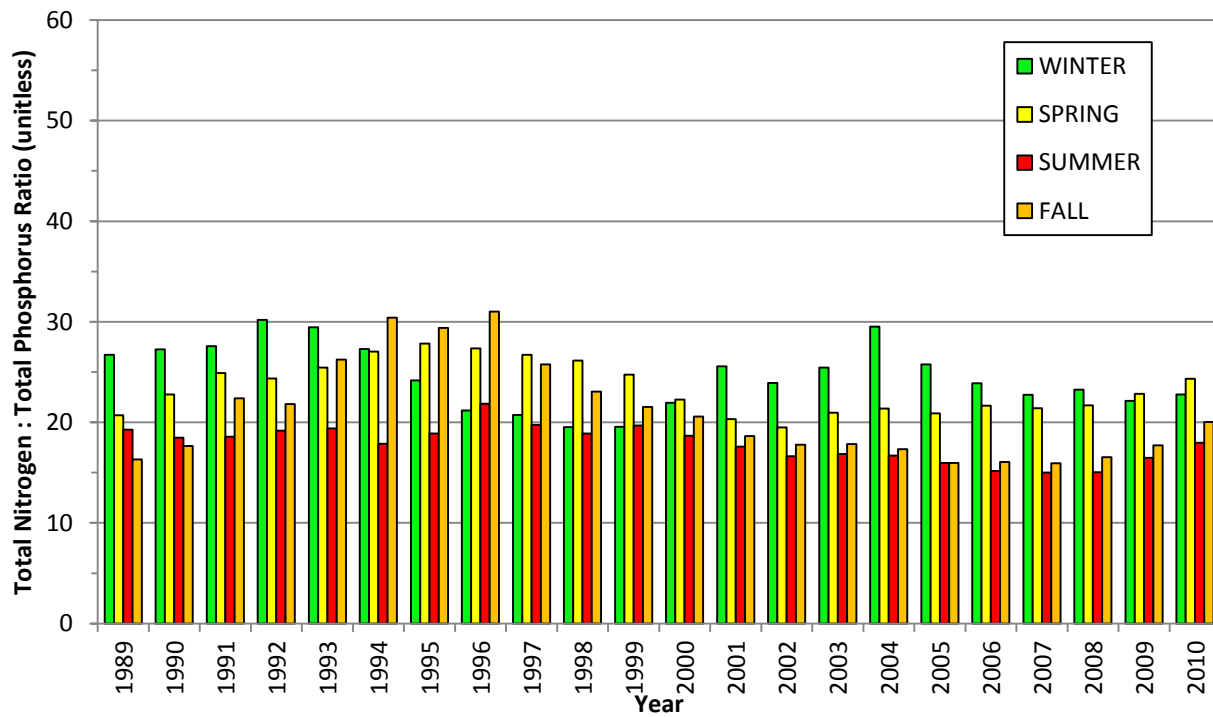


Figure 6-131 Five Year Running Average of Surface TN:TP Ratio for Station LM08

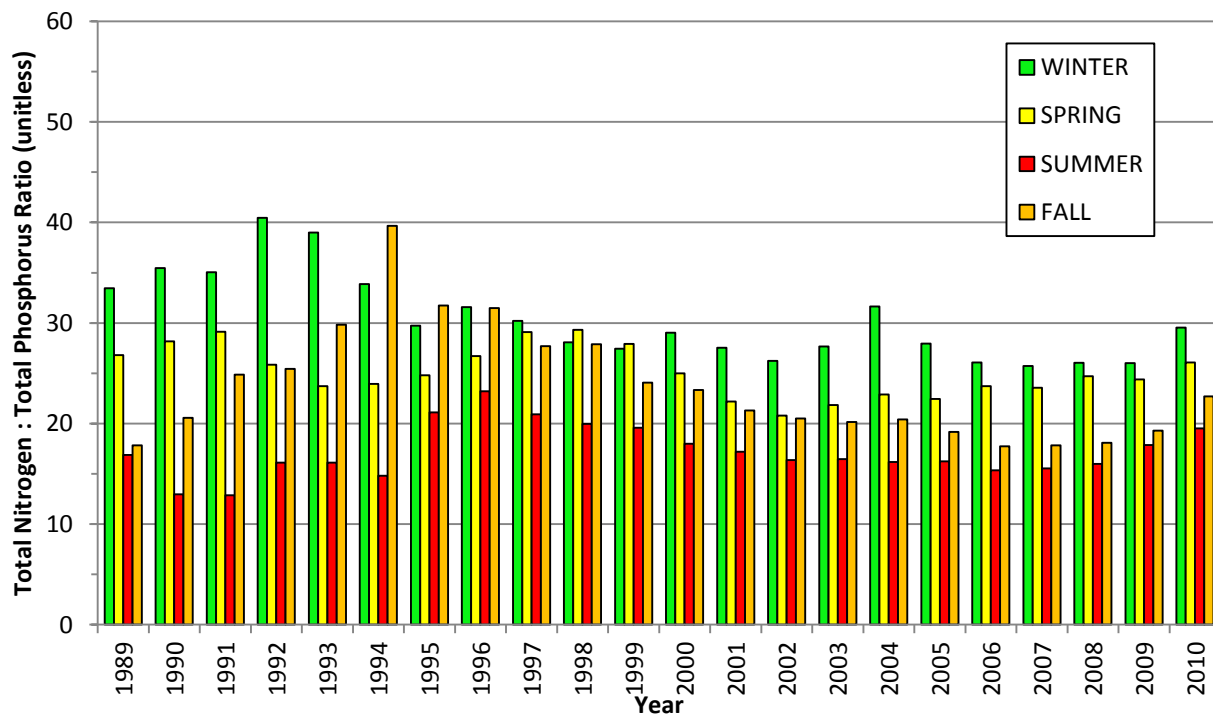


Figure 6-132 Five Year Running Average of Bottom TN:TP Ratio for Station LM01

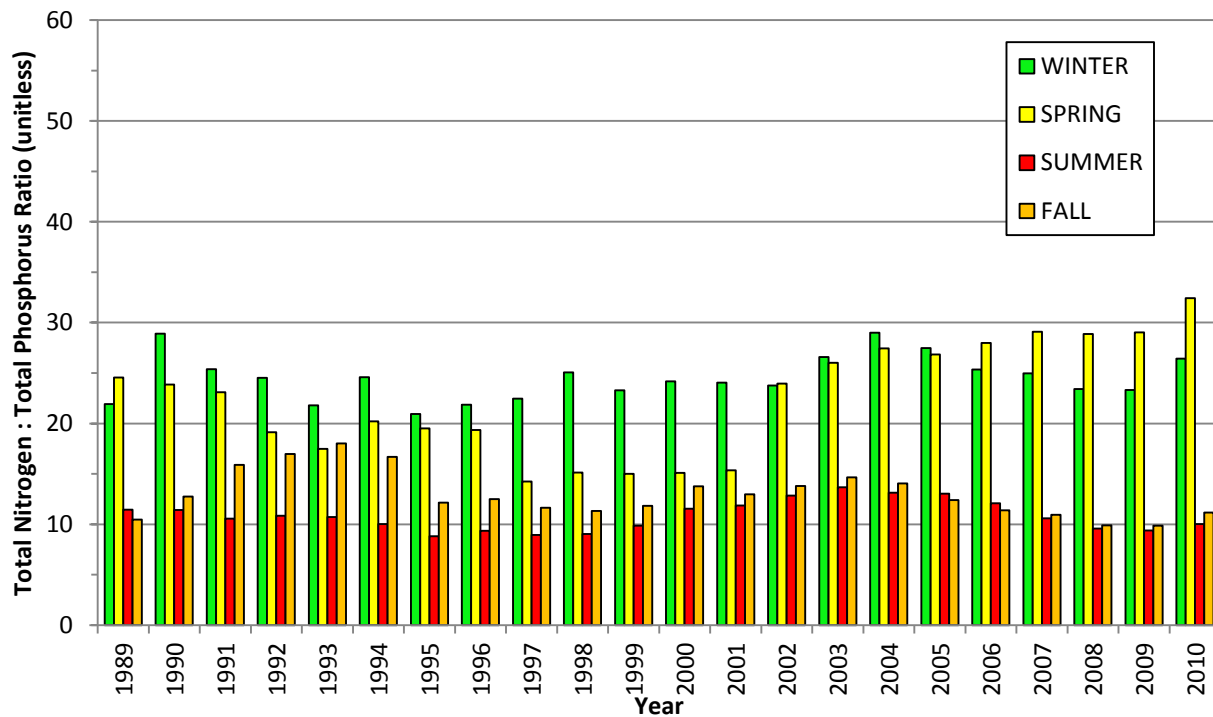


Figure 6-133 Five Year Running Average of Bottom TN:TP Ratio for Station LM02

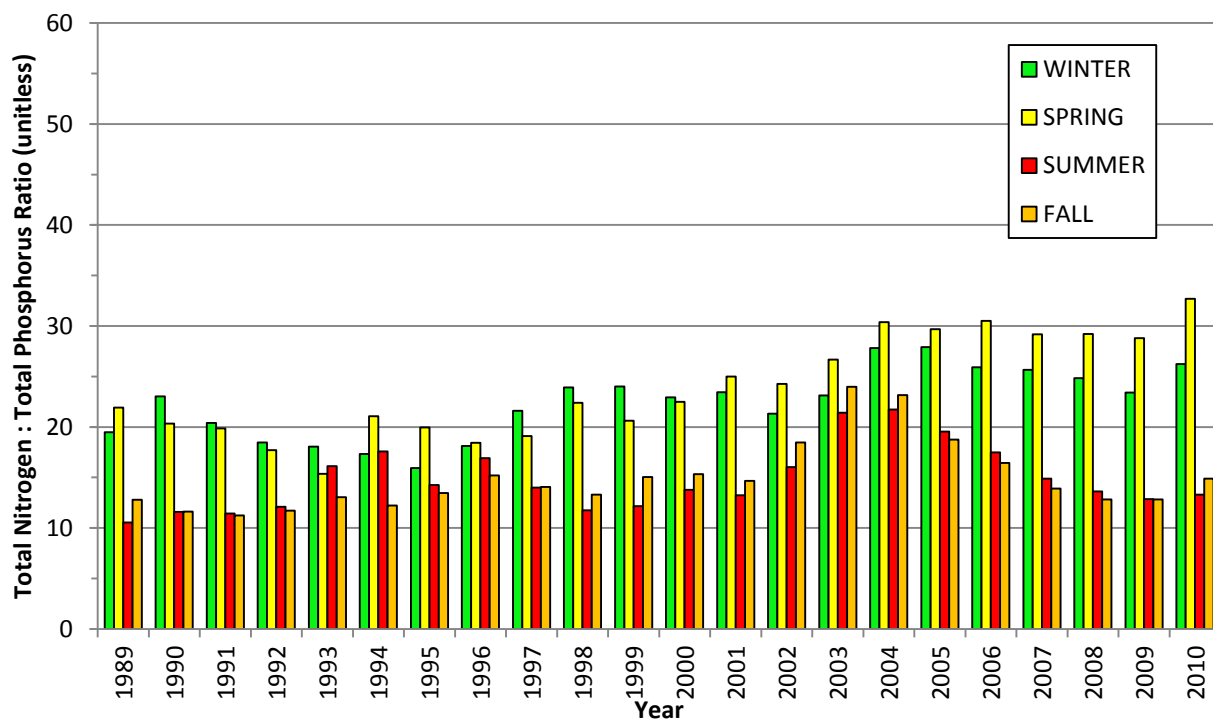


Figure 6-134 Five Year Running Average of Bottom TN:TP Ratio for Station LM03

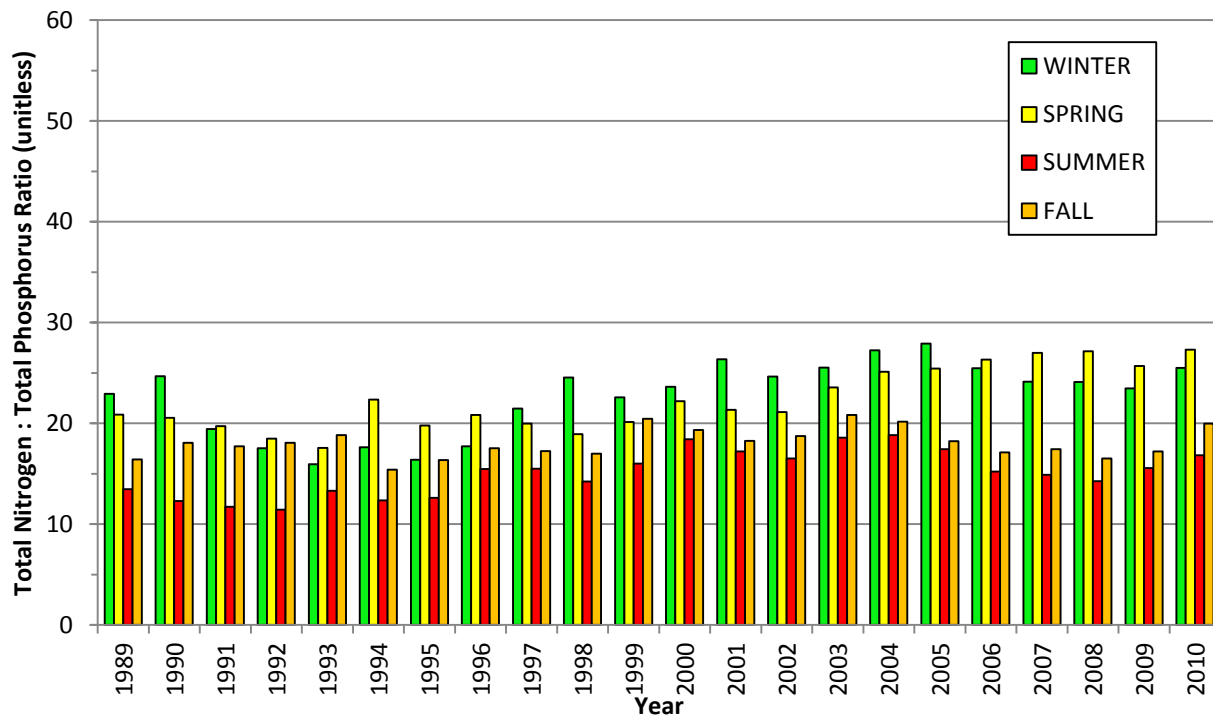


Figure 6-135 Five Year Running Average of Bottom TN:TP Ratio for Station LM04

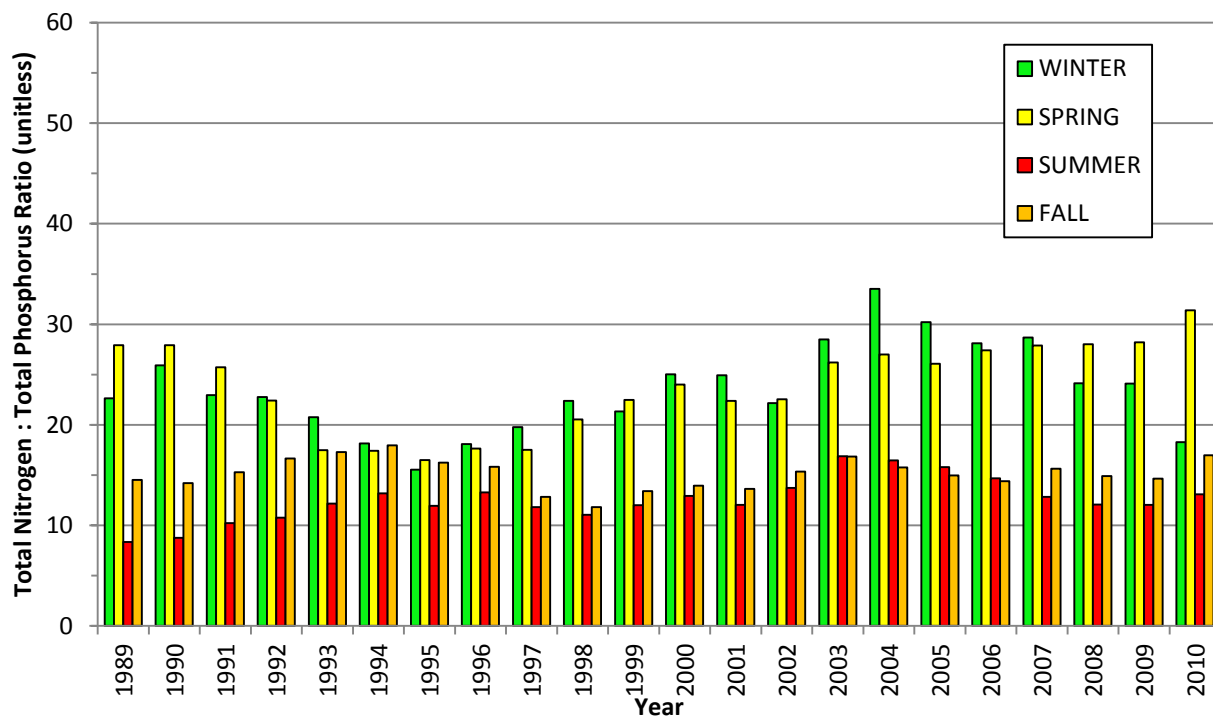


Figure 6-136 Five Year Running Average of Bottom TN:TP Ratio for Station LM05

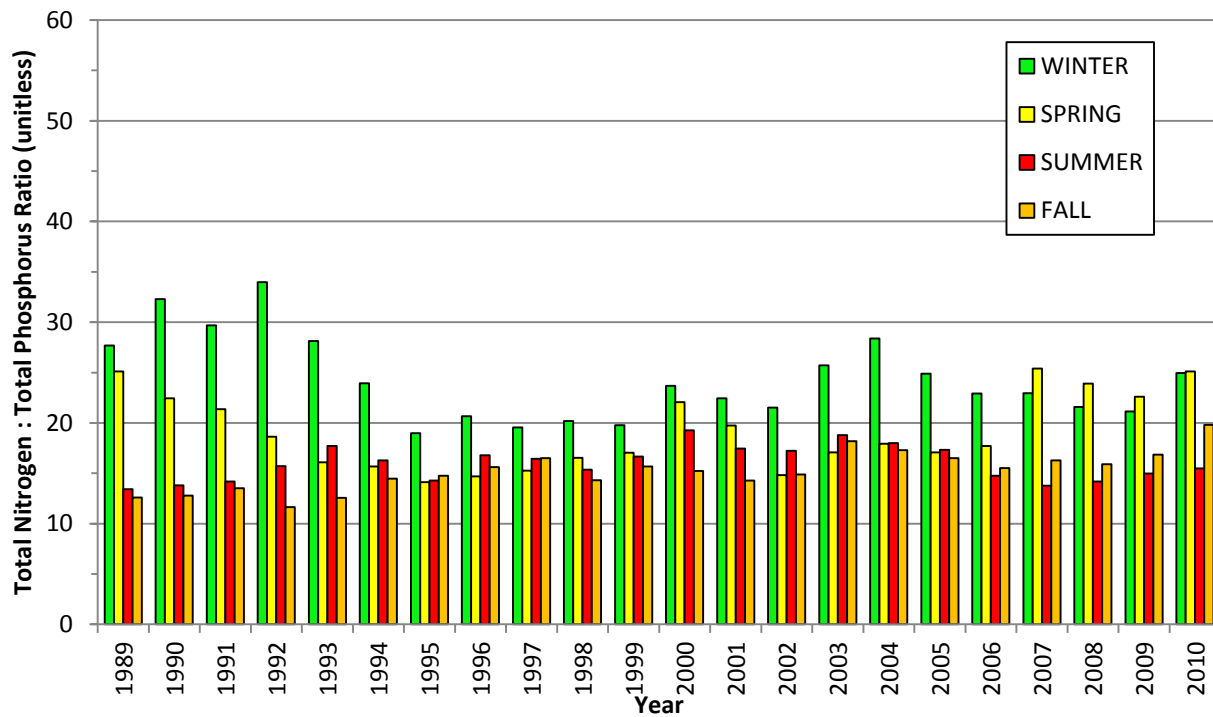


Figure 6-137 Five Year Running Average of Bottom TN:TP Ratio for Station LM06

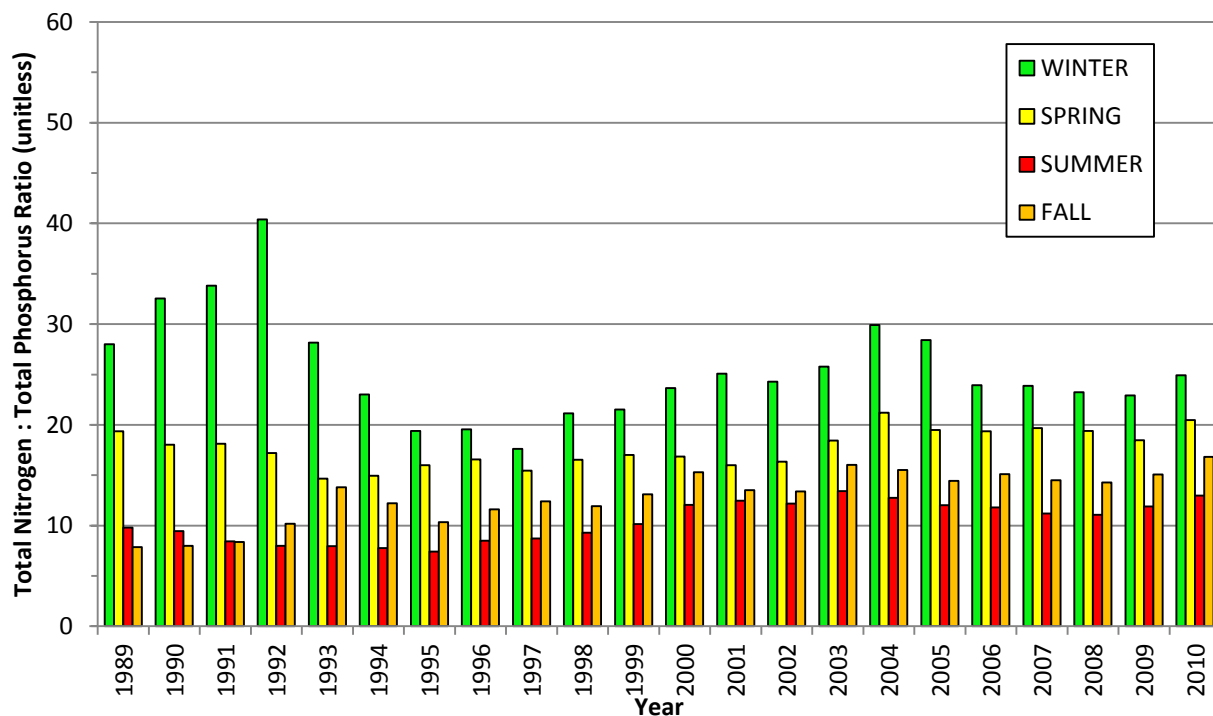


Figure 6-138 Five Year Running Average of Bottom TN:TP Ratio for Station LM07

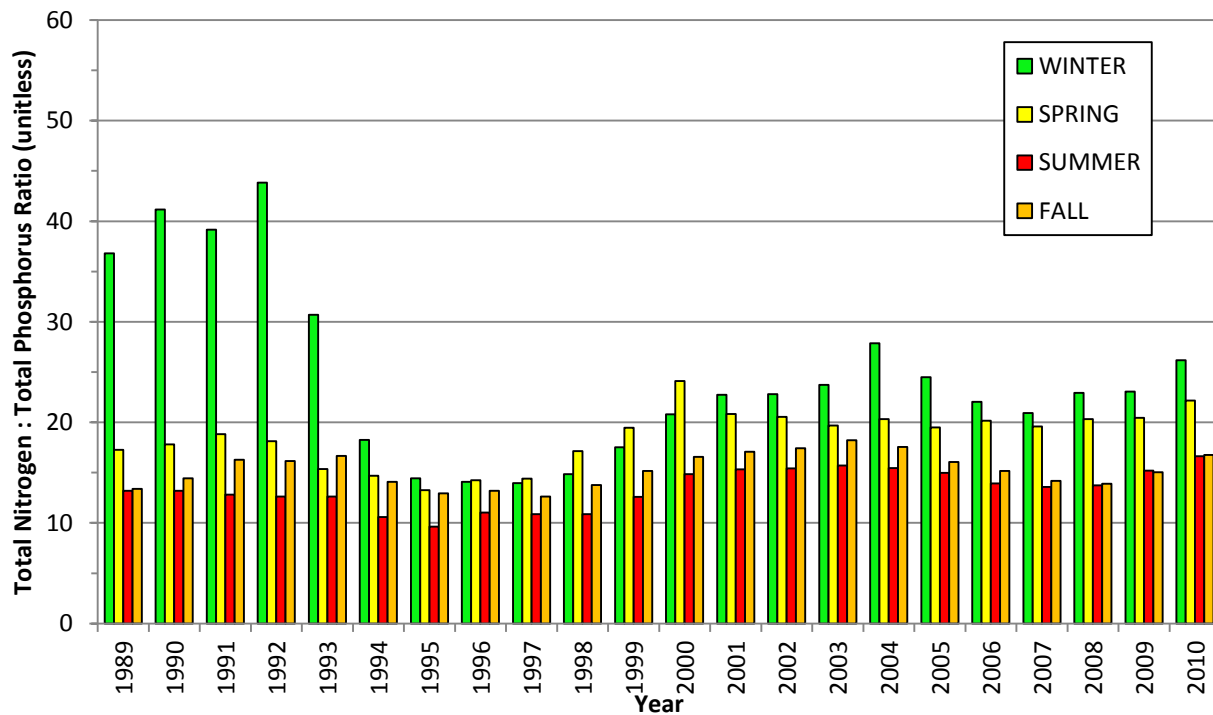
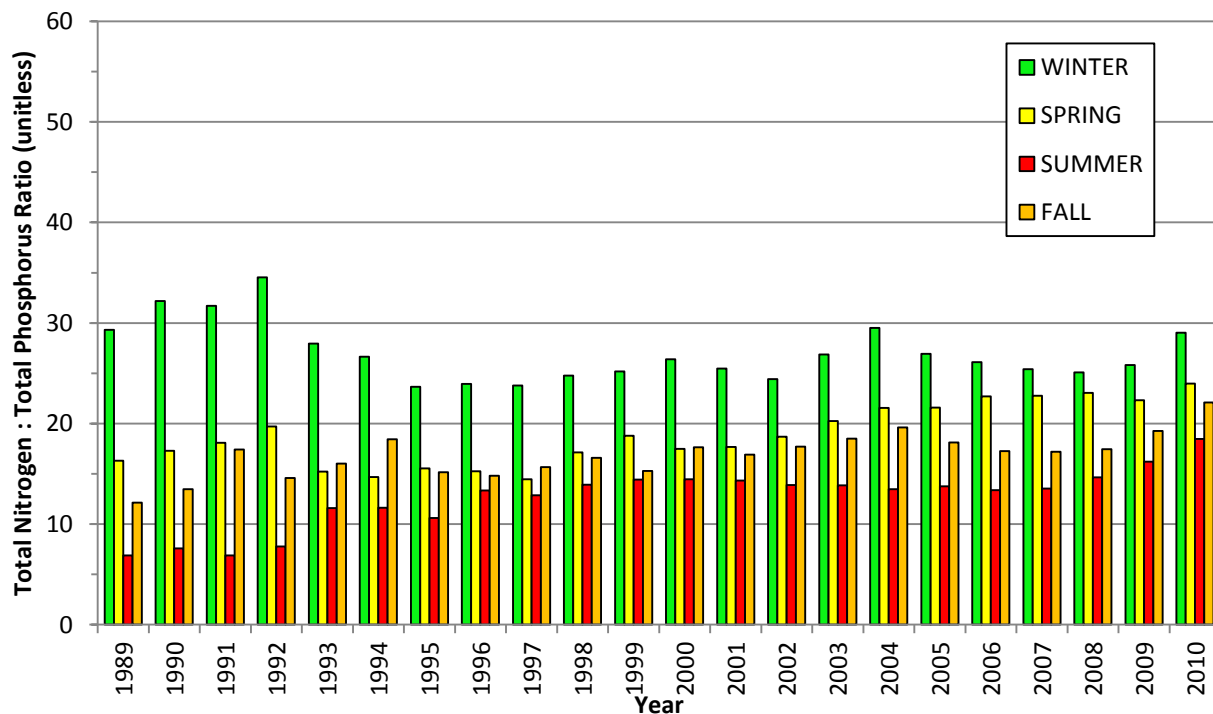


Figure 6-139 Five Year Running Average of Bottom TN:TP Ratio for Station LM08



Chlorophyll a

Chlorophyll a is monitored within the surface waters of Lake Manassas because it is generally the most common photosynthetic pigment found in plants, algae and cyanobacteria. Algal blooms and increased biomass production can be monitored using chlorophyll a data with high concentrations suggesting potential eutrophic conditions. Because the highest algae growth is typically found around two to three meters below the surface (Harper 1992), surface chlorophyll a measurements are used to evaluate water quality within Lake Manassas.

Five-year running averages for chlorophyll a (CHLA) concentrations for each lake sampling station are depicted in Figures 6-142 through 6-147.

- Surface chlorophyll a concentrations for the 1984 to 2010 period range from 0.5 mg/L to 117 mg/L, with the highest concentration of 117 mg/L detected at sampling station LM06 on 5-NOV-2003. The average surface chlorophyll a concentration for all sampling stations during this period was calculated to be 12.2 mg/L.
- Surface chlorophyll a concentrations for the 2006 to 2010 period range from 1.0 mg/L to 52.8 mg/L, with the highest concentration of 52.8 mg/L detected at sampling station LM07 on 24-OCT-2007. The average surface chlorophyll a concentration for all sampling stations during this period was calculated to be 10.9 mg/L.
- The Mann-Kendall Seasonal Analysis for chlorophyll a concentrations shows no increasing or decreasing trends for the 2006 to 2010 period; however, an apparent decreasing trend is apparent at all sampling stations from 2007 to 2010. During the 2006 to 2010 baseline period, 2007 had the highest seasonally adjusted concentrations.

Figure 6-140 Five Year Running Average of CHLa Concentrations for Station LM01

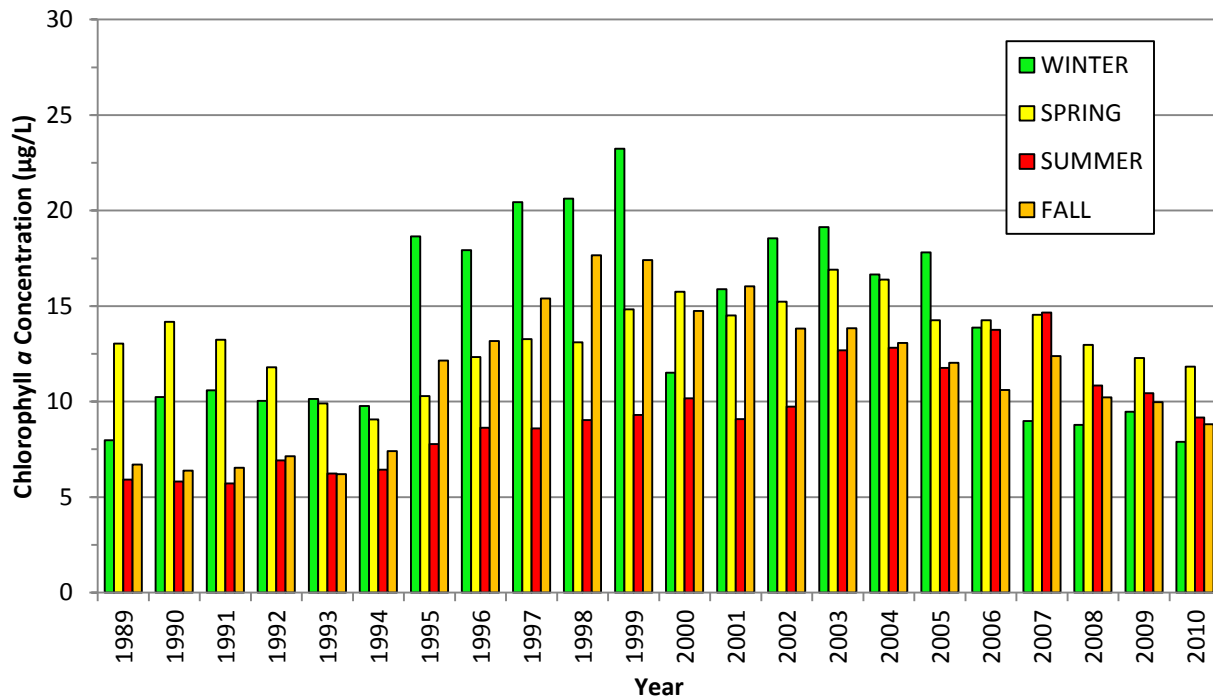


Figure 6-141 Five Year Running Average of CHLa Concentrations for Station LM02

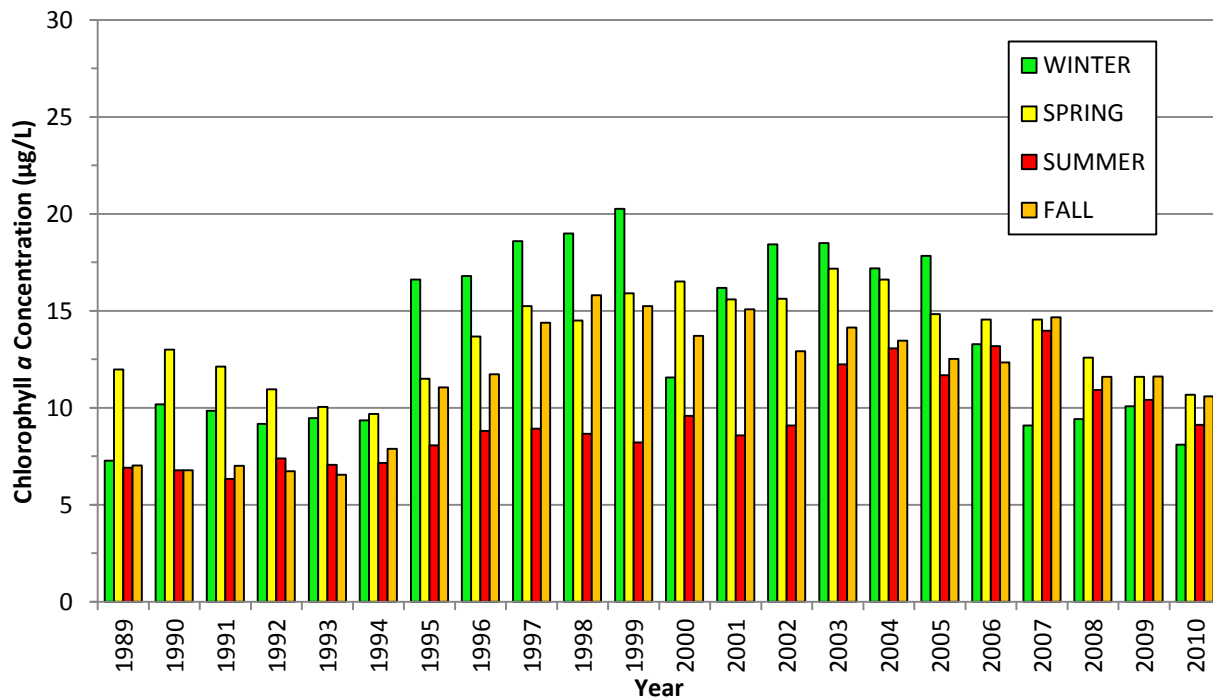


Figure 6-142 Five Year Running Average of CHLa Concentrations for Station LM03

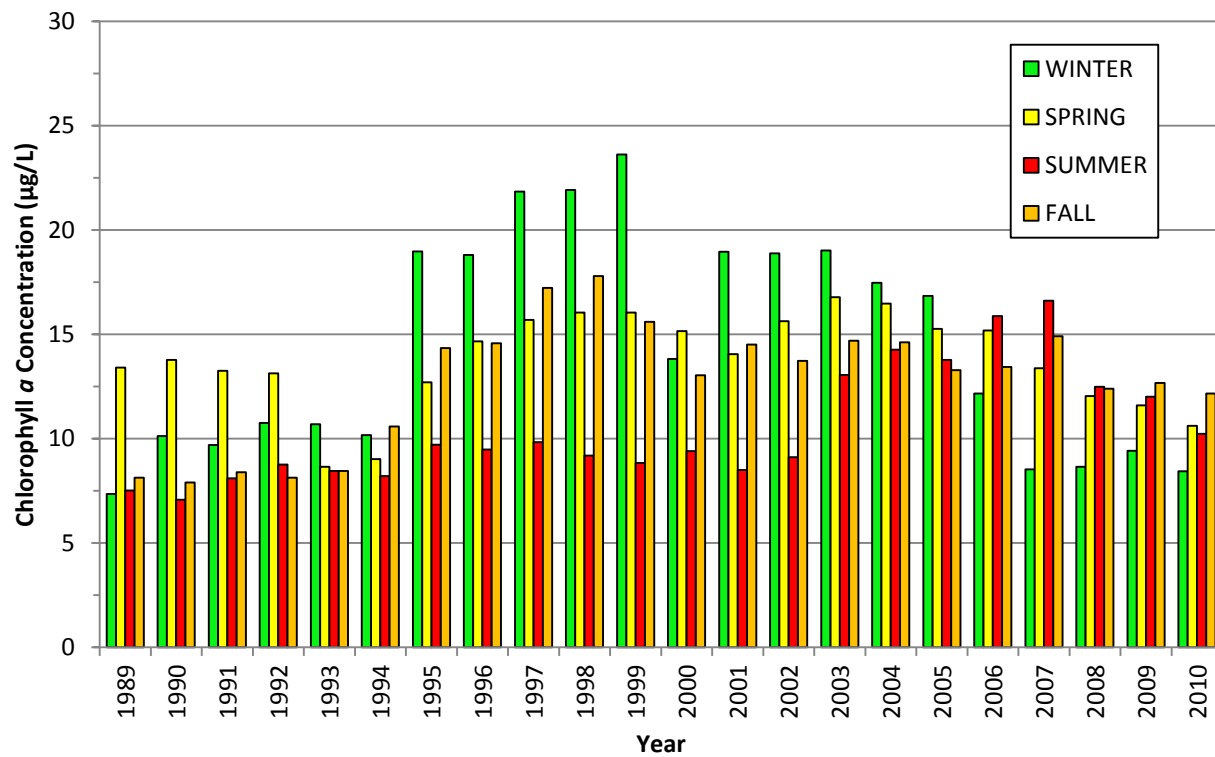


Figure 6-143 Five Year Running Average of CHLa Concentrations for Station LM04

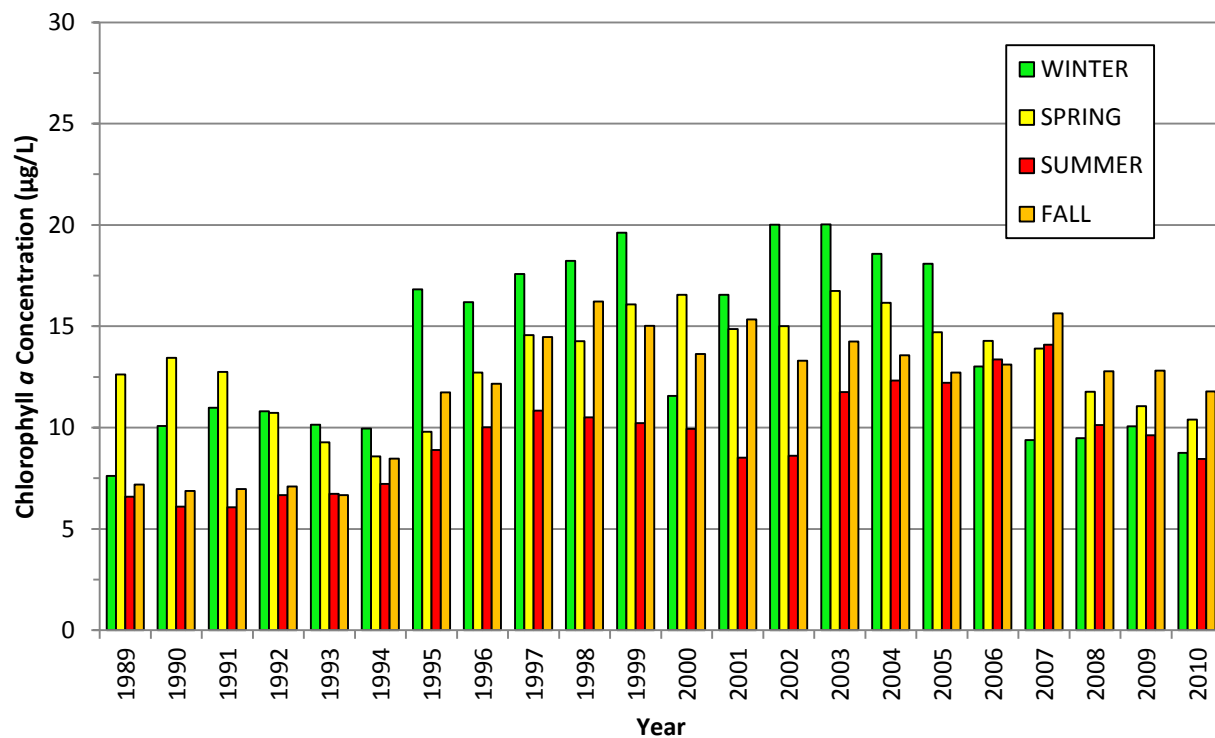


Figure 6-144 Five Year Running Average of CHLa Concentrations for Station LM05

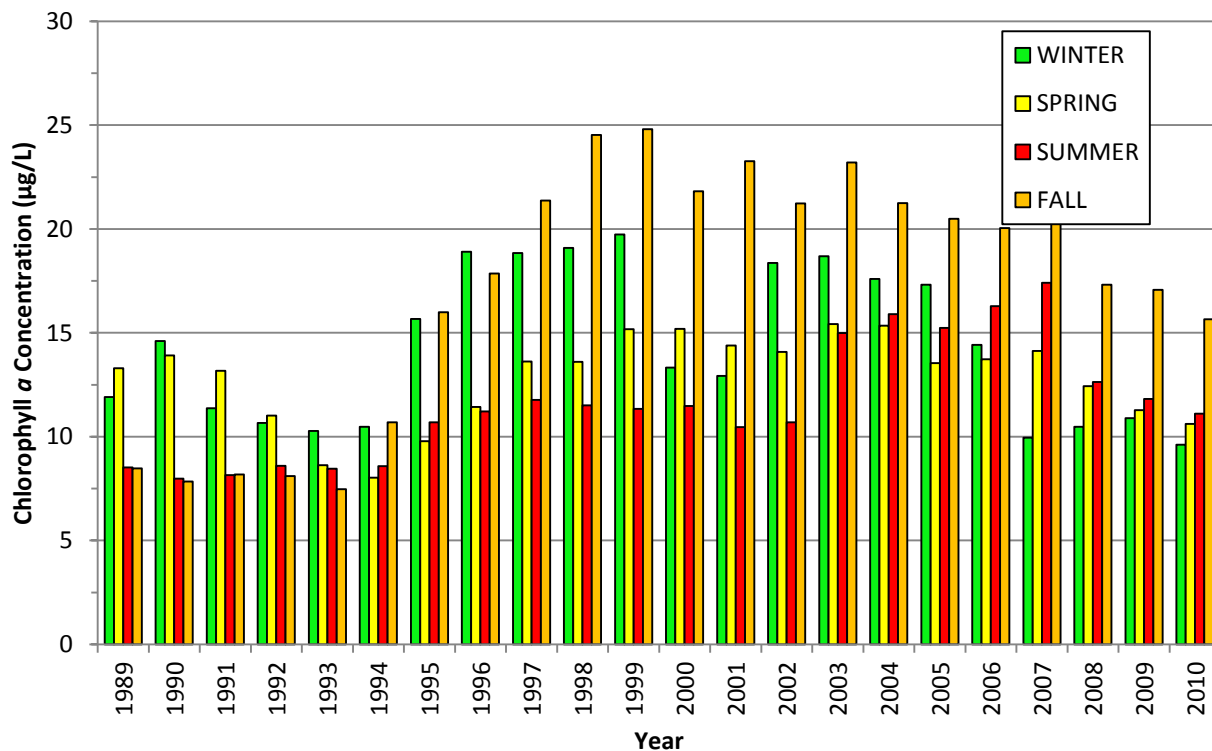


Figure 6-145 Five Year Running Average of CHLa Concentrations for Station LM06

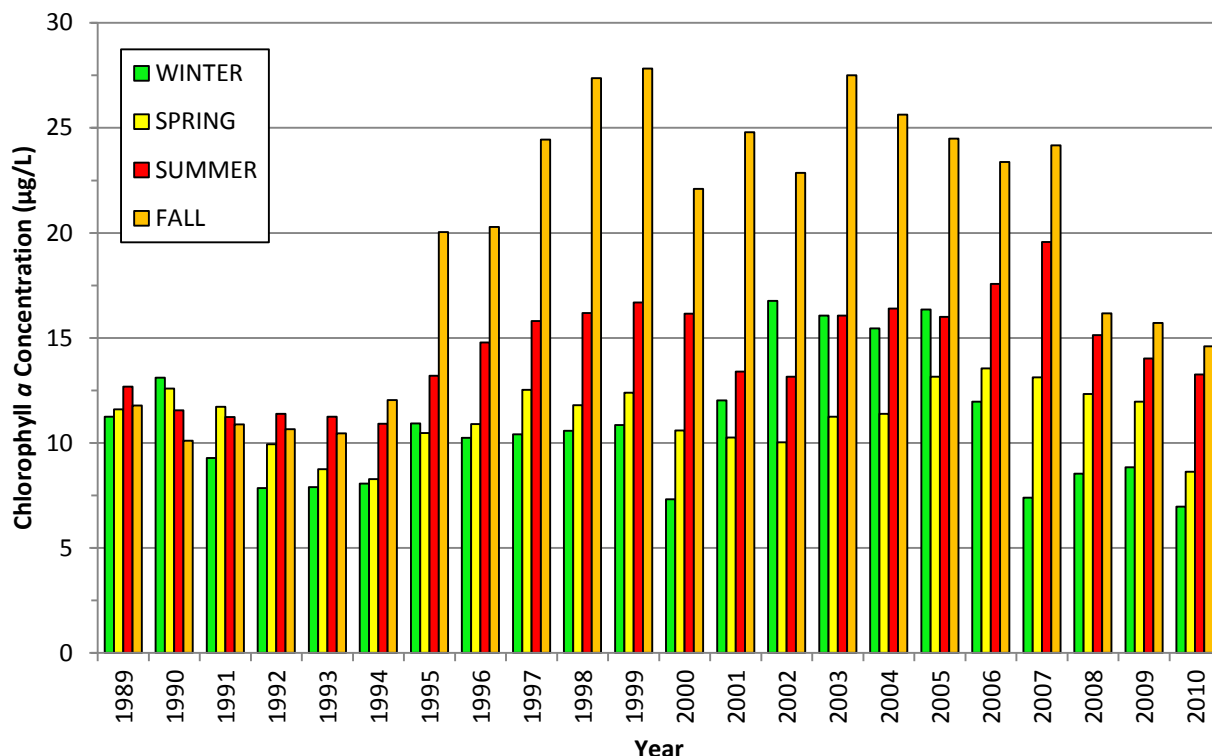


Figure 6-146 Five Year Running Average of CHLa Concentrations for Station LM07

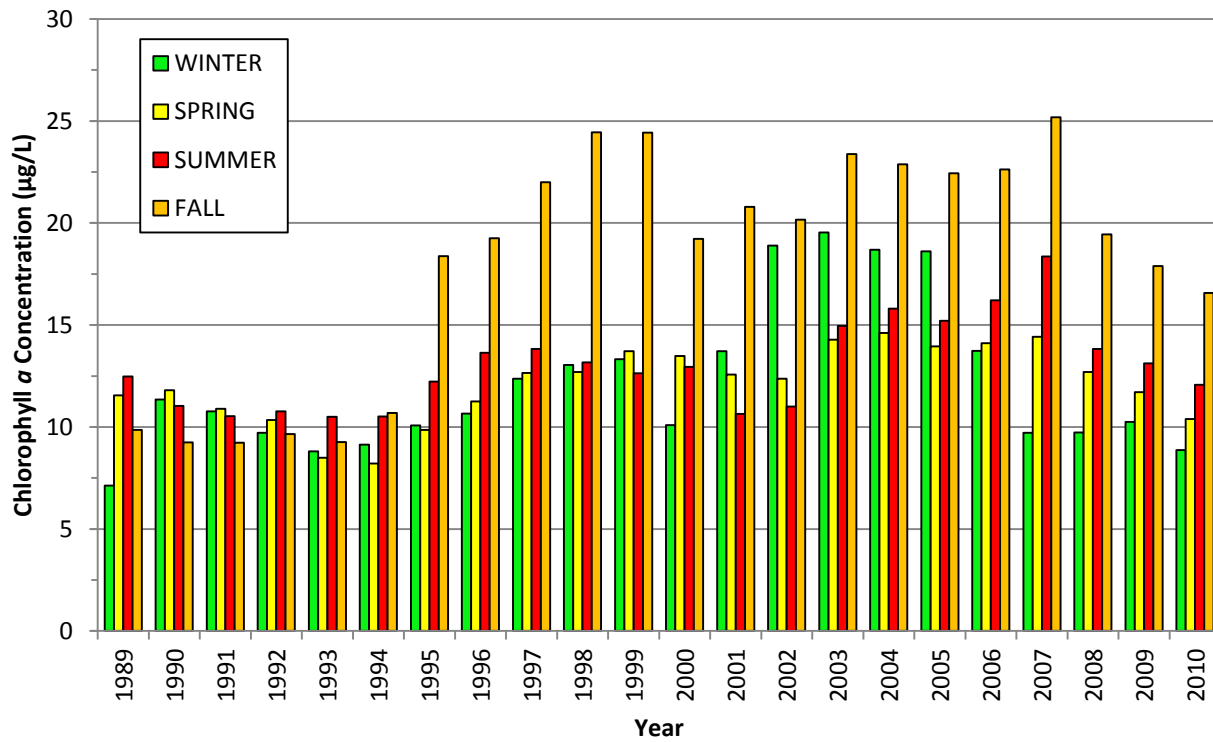
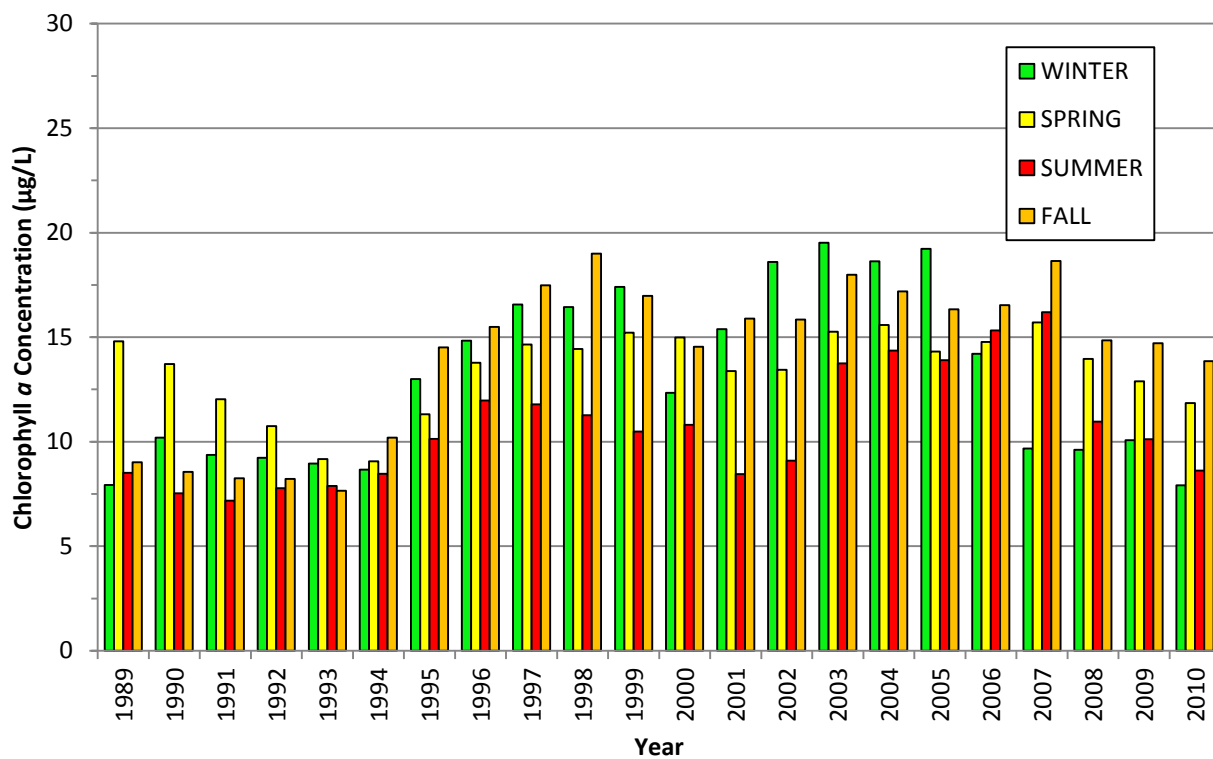


Figure 6-147 Five Year Running Average of CHLa Concentrations for Station LM08



Trophic State

Two models for determining the trophic state within Lake Manassas are now presented. The trophic state refers to the level of enrichment or biological productivity within a lake or reservoir system. As discussed previously in Chapter 3 of this report, the trophic state for a given system can range from oligotrophic (little biological productivity) to mesotrophic (mid-level enrichment) to eutrophic (enriched) to hypereutrophic (highly enriched) (Wetzel 2001).

The two models considered for the analysis of Lake Manassas include the Vollenweider model (Vollenweider 1973) and the Carlson Trophic State Index (Carlson 1977). While the Vollenweider model considers the limiting nutrient balance within a system (phosphorus for Lake Manassas), the Carlson Trophic State Index estimates algal biomass based on chlorophyll *a*, total phosphorus and Secchi depth, independently (Wetzel 2001). It should be noted that both models make assumptions and consider only available empirical data. Professional judgment should be used when considering the results of a trophic state analysis (Wetzel 2001).

Vollenweider Model

The Vollenweider model is a tool for predicting eutrophication within a lake or reservoir. The Vollenweider equation, presented below, takes a mass balance approach to evaluating the amount of phosphorus within a system, including consideration for inflow and outflow (Vollenweider 1973, Wetzel 2001).

$$P_{lake} = \frac{P_{in}}{q_s + v_s}$$

$$P_{lake} = \text{Phosphorus concentration} \left(\frac{g}{m^3} \right)$$

$$P_{in} = \text{Areal phosphorus load} \left(\frac{g}{m^2 yr} \right)$$

$$q_s = \text{Flushing rate} \left(\frac{\bar{z}}{T_w} \right)$$

$$v_s = \text{Settling rate} \left(\frac{m}{yr} \right) = \sim 10 \text{ m yr}^{-1}$$

$$\bar{z} = \text{mean depth (m)}$$

$$T_w = \text{hydraulic detention time (year)}$$

The Vollenweider model assumes the following (Vollenweider 1973, Wetzel 2001):

1. The lake is well mixed (i.e., ignores the effect of stratification).
2. Loading, flushing and sedimentation rates are constant.
3. Sedimentation is a first order process relative to the amount of phosphorus present.
4. Internal loading of phosphorus is negligible.

Figure 6-148 presents the annual values representing the empirical relationship between phosphorus loading, flushing rate and trophic state. The plotted values include trophic estimates for the 1991, 1995, 2000, 2005 and 2010 baseline periods. Model parameters for each baseline are presented in Table 6-4. For illustrative purposes, a second point for 2010 is plotted in Figure 6-148 based on the scaled up loading values presented in Table 5-4. These values represent an estimated total nutrient loading as the gauging station (ST70) used for calculating the 2010 point only represents approximately 70 percent of the water draining into Lake Manassas. The 2010 –

“Scaled Up” data point represents the loading value that would result if the entire drainage had similar flow and concentration characteristics as those at ST70.

Figure 6-148 Lake Manassas Vollenweider Input-Output Phosphorus Loading Model

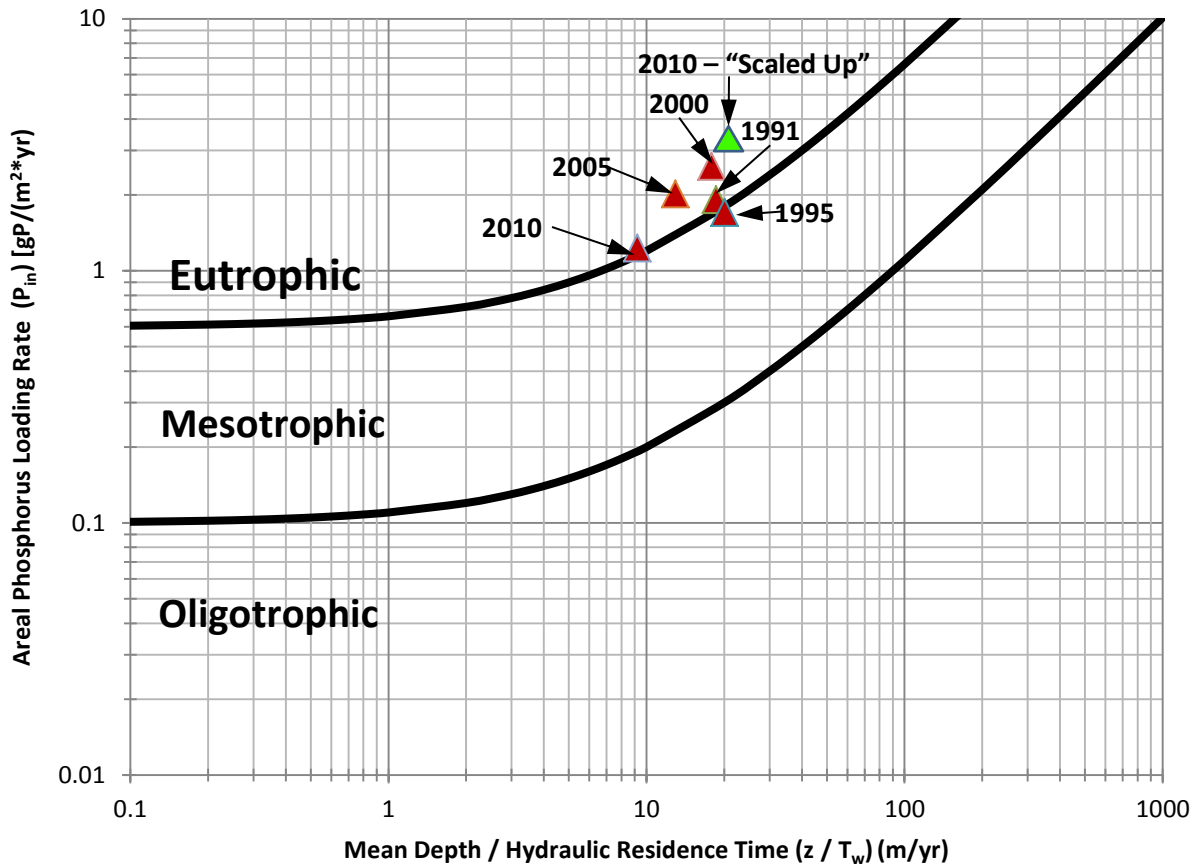


Table 6-4 Vollenweider Model Input Parameters

Parameter	1991 Baseline	1995 Baseline	2000 baseline	2005 Baseline	2010 Baseline
TP (lbs/day)	32.4	28.8	44.1	55	33.6
Flow Rate (cfs)	47.5	51.3	44.3	65.5	46.69
Lake Volume (gal)	4.2 x 10 ⁹	4.2 x 10 ⁹	4.08 x 10 ⁹	8.34 x 10 ⁹	8.35 x 10 ⁹
Mean Depth (m)	5.6	5.6	7.0	7.0	7.0
Lake Surface (ac)	694	694	697	1,119	1,119
Phosphorus Loading (g/m ² /yr)	1.9	1.7	2.6	2.0	1.2
Mean Depth / Mean Residence Time (z/t), (m/yr)	15	16.1	14.0	13.0	9.2

Sources: (Eggink 2001, Gorrie 2007)

Carlson Trophic State Indices

The Carlson trophic state indices were developed to consider a single trophic criterion as an index for other criteria to be compared to as a means of establishing an overall trophic status for a lake or reservoir system. Carlson chose algal biomass as this criterion and established equations based on the measurements of Secchi depth, total phosphorus and chlorophyll a concentrations. These equations and the trophic state indices (TSI) established by Carlson in 1977 are presented below (Carlson 1977):

Table 6-5 Carlson's Trophic State Index

TSI	Secchi Disk Depth (m)	Surface Total Phosphorus (µg/L)	Surface Chlorophyll a (µg/L)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1183

Source:(Carlson 1977)

$$TSI_{Secchi} (SD) = 10 * \left(6 - \left(\ln \left(\frac{SD}{2} \right) \right) \right)$$

$$TSI_{Total Phosphorus} (TP) = 10 * \left(6 - \left(\frac{\ln \frac{48}{TP}}{2} \right) \right)$$

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

The Carlson Trophic State Indices use a scale similar to that used by Vollenweider, in that they both assume a phosphorus-limited system. As shown in Table 6-5, TSI values range from 0 to 100; however, the index is theoretical and has no upper or lower bounds. Because TSI values are calculated independently, total phosphorus, chlorophyll *a* and Secchi depth will vary for a given sampling station. However, they are expected to be relatively close and any noticeable trends should be parallel between indices. Additionally, because chlorophyll *a* is the most accurate predictor for the development of algal biomass, it is given the highest weighting when considering the trophic state of a lake or reservoir. Table 6-6, below, depicts the anticipated water quality associated TSI ranges.

Table 6-6 Carlson's Trophic State Index Descriptions

TSI Value	Interpretation
< 30	Classic Oligotrophy. Clear water, oxygen throughout the year in the hypolimnion, salmonid fisheries in deep lakes.
30 – 40	Deeper lakes will exhibit classical Oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.
40 – 50	Water moderately clear, but increasingly 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 hypolimnion 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.

Source:(Carlson 1977)

Five-year running averages for TSI values based on chlorophyll a (CHLA) concentrations for each lake sampling station are depicted in Figures 6-149 through 6-156. Five-year running averages for TSI values based on total phosphorus (TP) concentrations for each lake sampling station are depicted in Figures 6-157 through 6-164. Five-year running averages for TSI values based on Secchi depth (SD) values for each lake sampling station are depicted in Figures 6-165 through 6-172. Box-and-whisker plots for calculated TSI values for Lake Manassas, including for each TSI parameter are presented in Figure 6-173. All three parameters indicate Lake Manassas is at the lower boundary of eutrophic conditions. The box-and-whisker plots include mean, minimum, maximum values and the 25% / 75% boundaries.

A Mann-Kendall seasonal analysis was performed on the TSI values for each parameter for the 2006 to 2010 baseline period and the findings are presented below in table 6-7 (95 percent confidence). As opposed to the 2005 baseline, no increasing trends were observed with the TSI parameters and at any of the Lake Manassas sampling stations. Alternatively, decreasing trends for at least one parameter were observed in each lake sampling station.

Table 6-7 Mann-Kendall Seasonal Analysis – TSI Values

Parameter	LM01	LM02	LM03	LM04	LM05	LM06	LM07	LM08
TSI – Chlorophyll a (CHLa)	L	L	-	-	L	-	L	L
TSI – Total Phosphorus (TP)	-	L	L	L	-	L	-	L
TSI – Secchi Depth (SD)	L	-	L	-	-	-	-	L

Notes:

U – Increasing Trend

L – Decreasing Trend

- – No Trend Observed

Figure 6-149 Five Year Running Average of TSI Based on CHLa for Station LM01

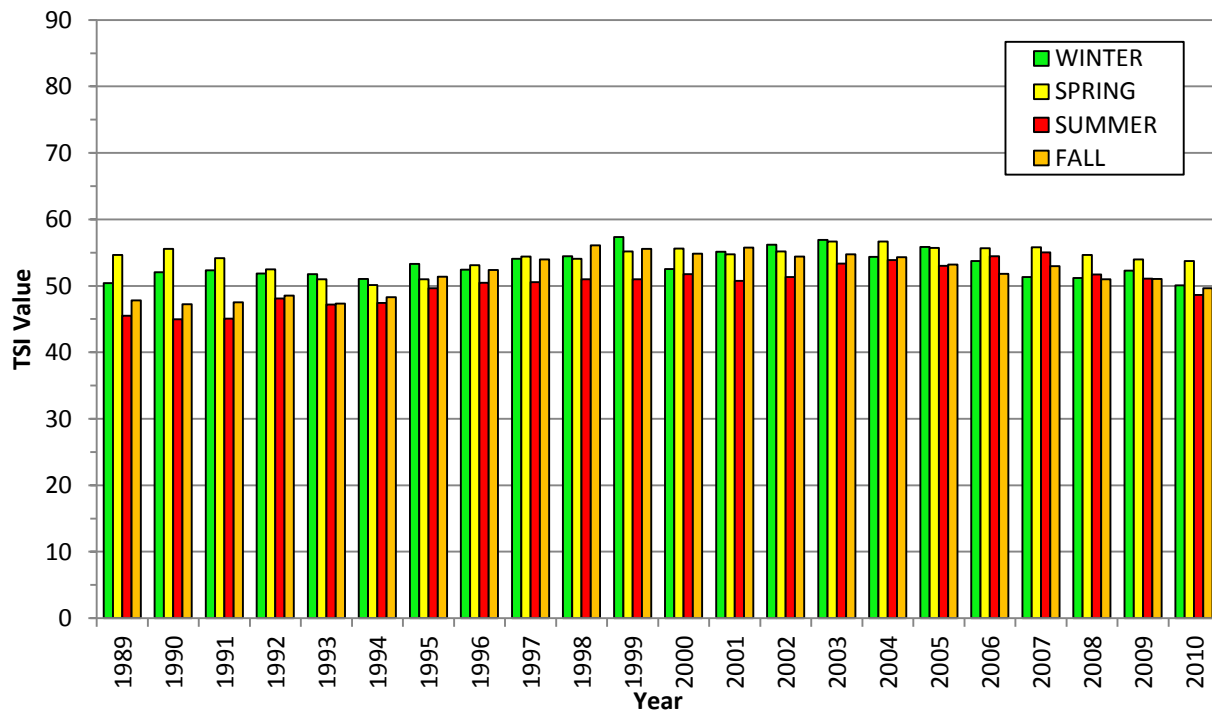


Figure 6-150 Five Year Running Average of TSI Based on CHLa for Station LM02

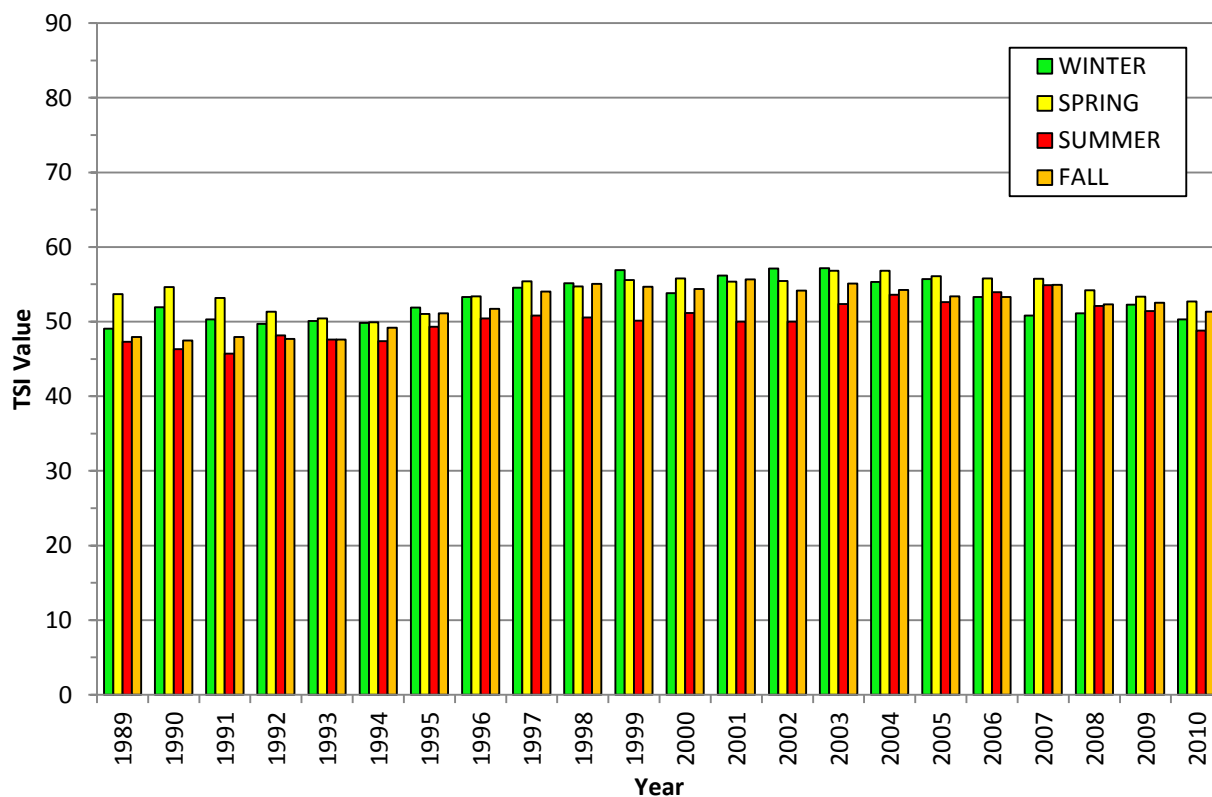


Figure 6-151 Five Year Running Average of TSI Based on CHLa for Station LM03

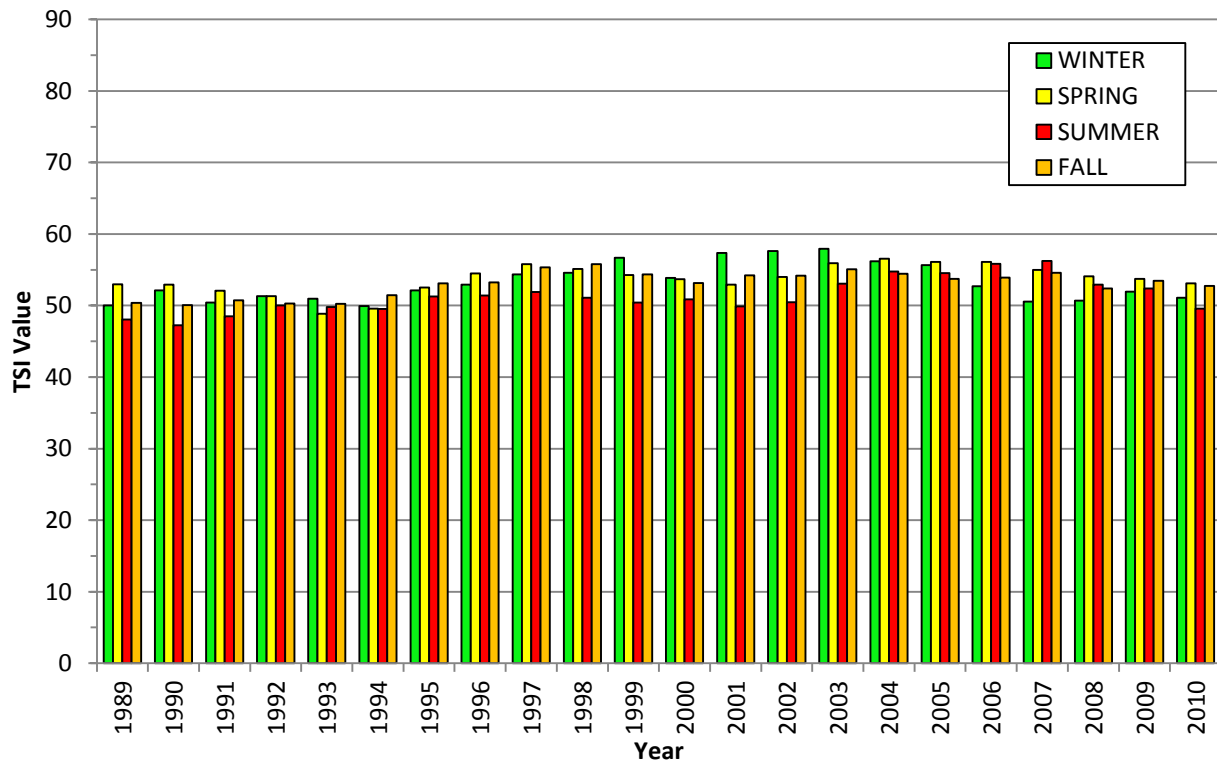


Figure 6-152 Five Year Running Average of TSI Based on CHLa for Station LM04

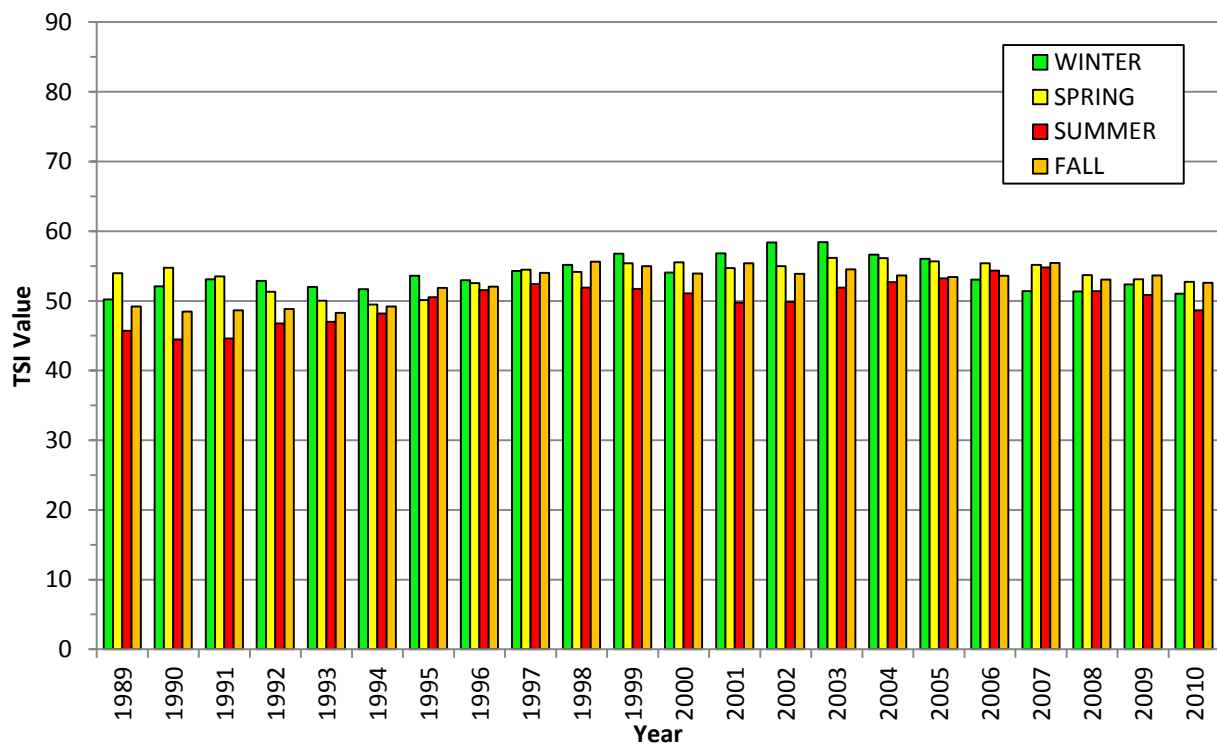


Figure 6-153 Five Year Running Average of TSI Based on CHLa for Station LM05

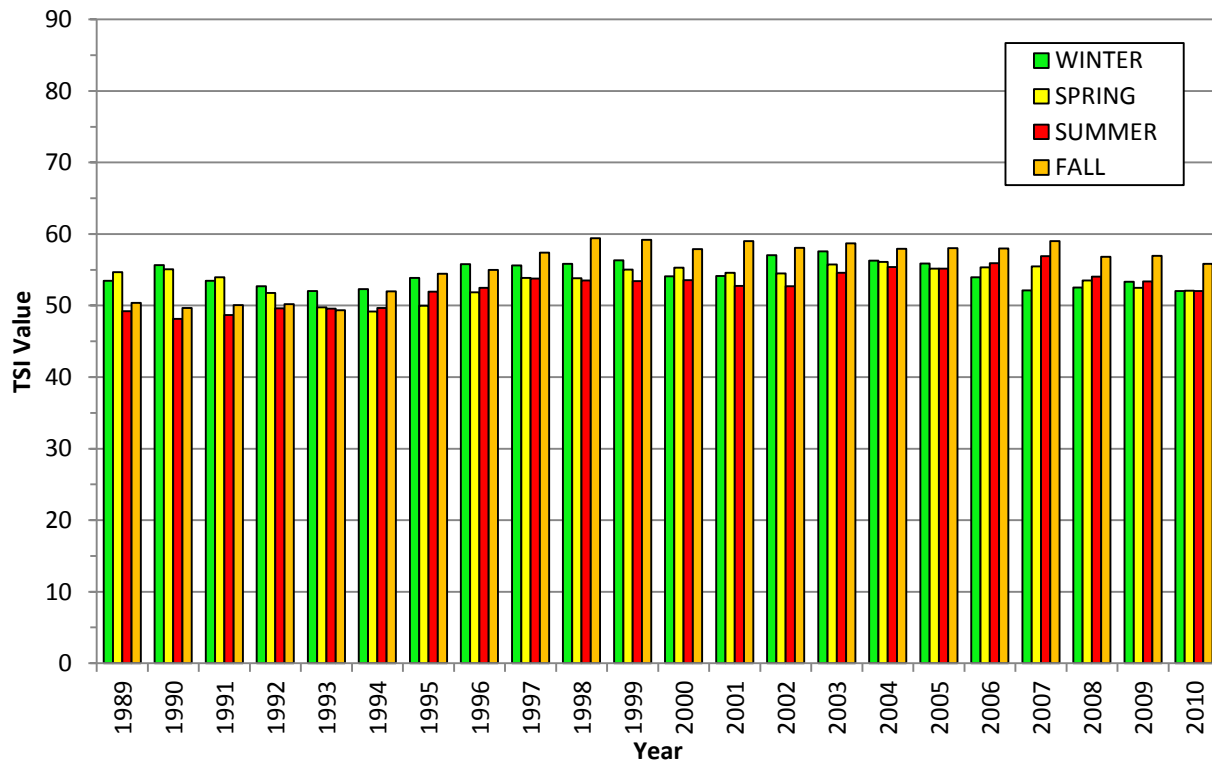


Figure 6-154 Five Year Running Average of TSI Based on CHLa for Station LM06

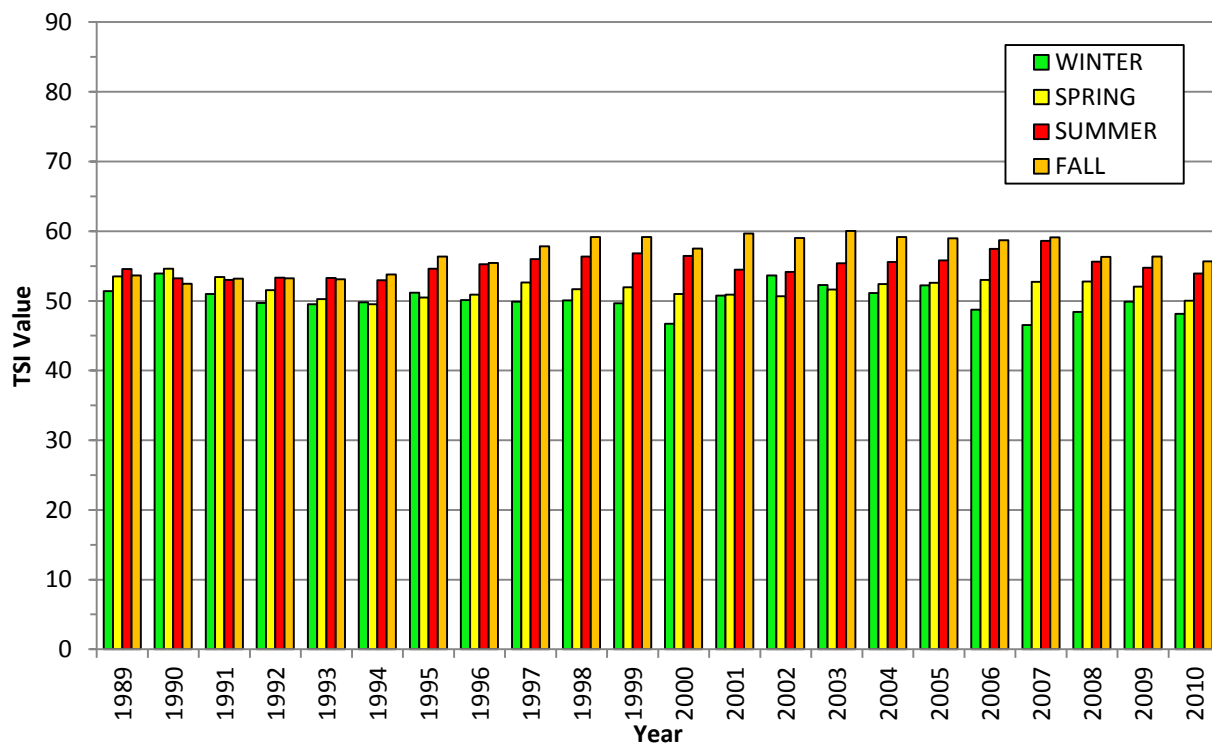


Figure 6-155 Five Year Running Average of TSI Based on CHLa for Station LM07

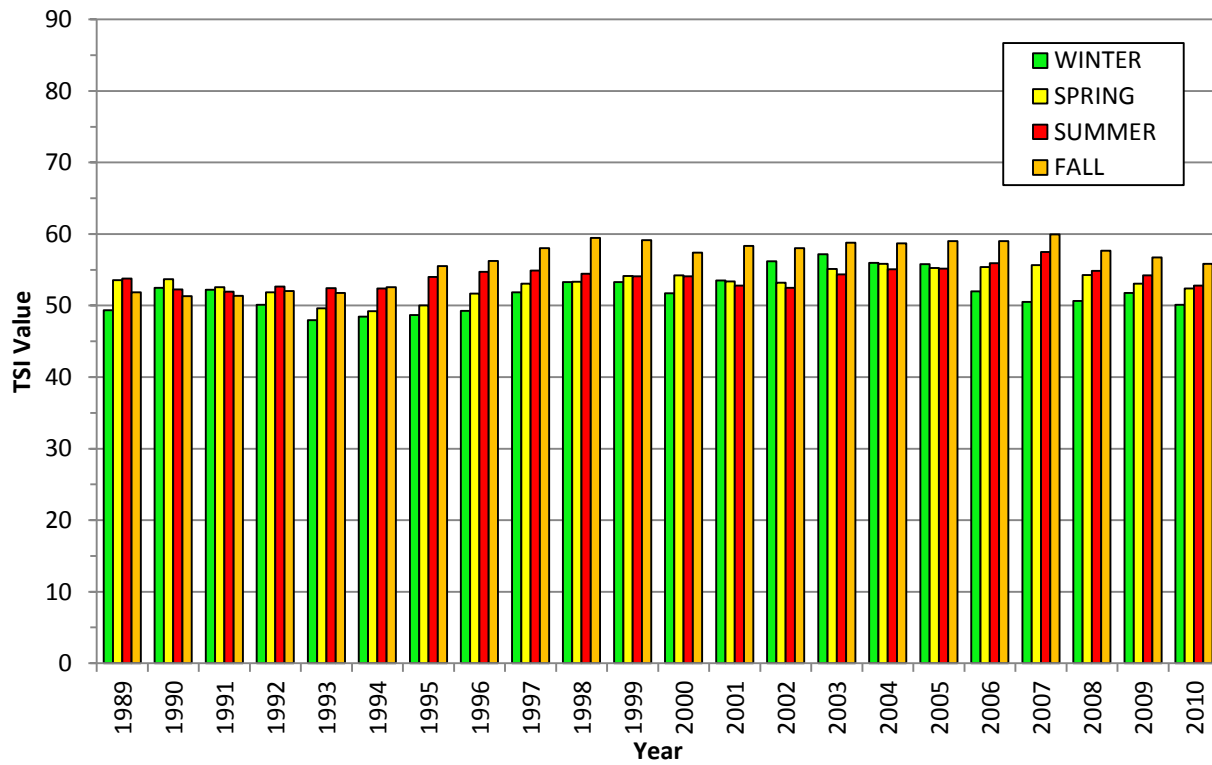


Figure 6-156 Five Year Running Average of TSI Based on CHLa for Station LM08

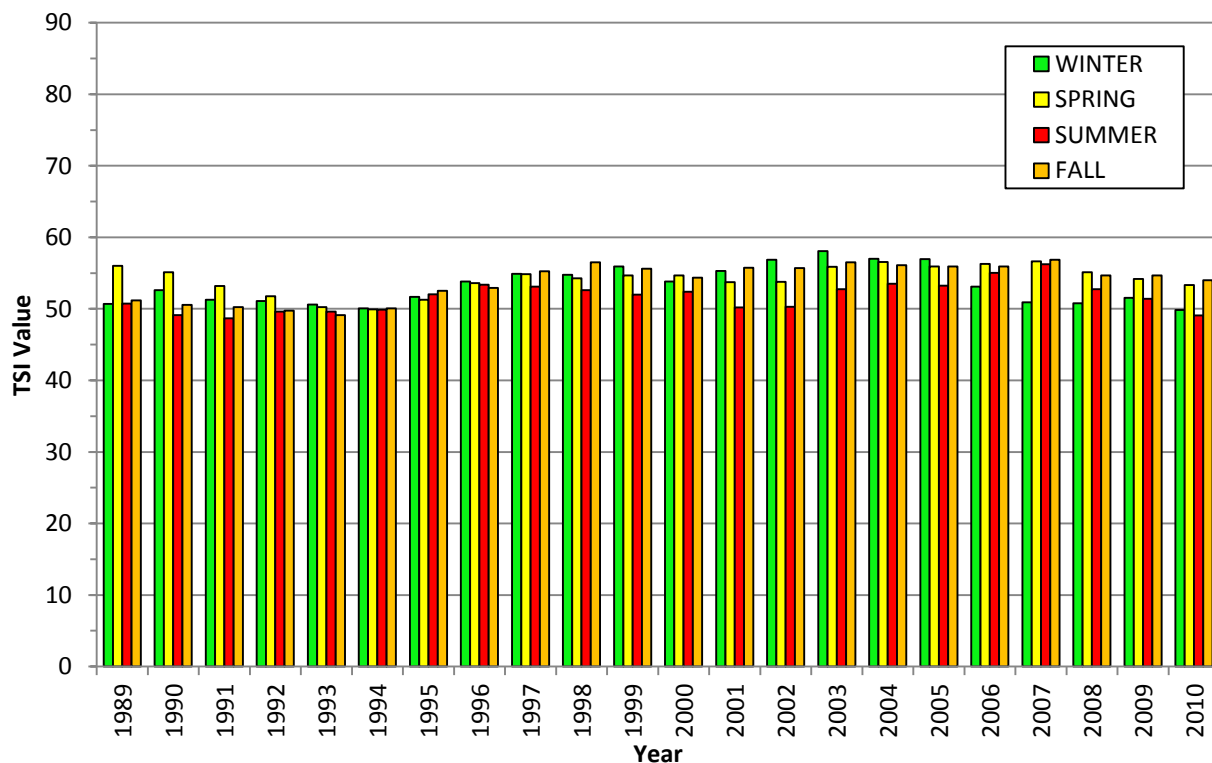


Figure 6-157 Five Year Running Average of TSI Based on TP for Station LM01

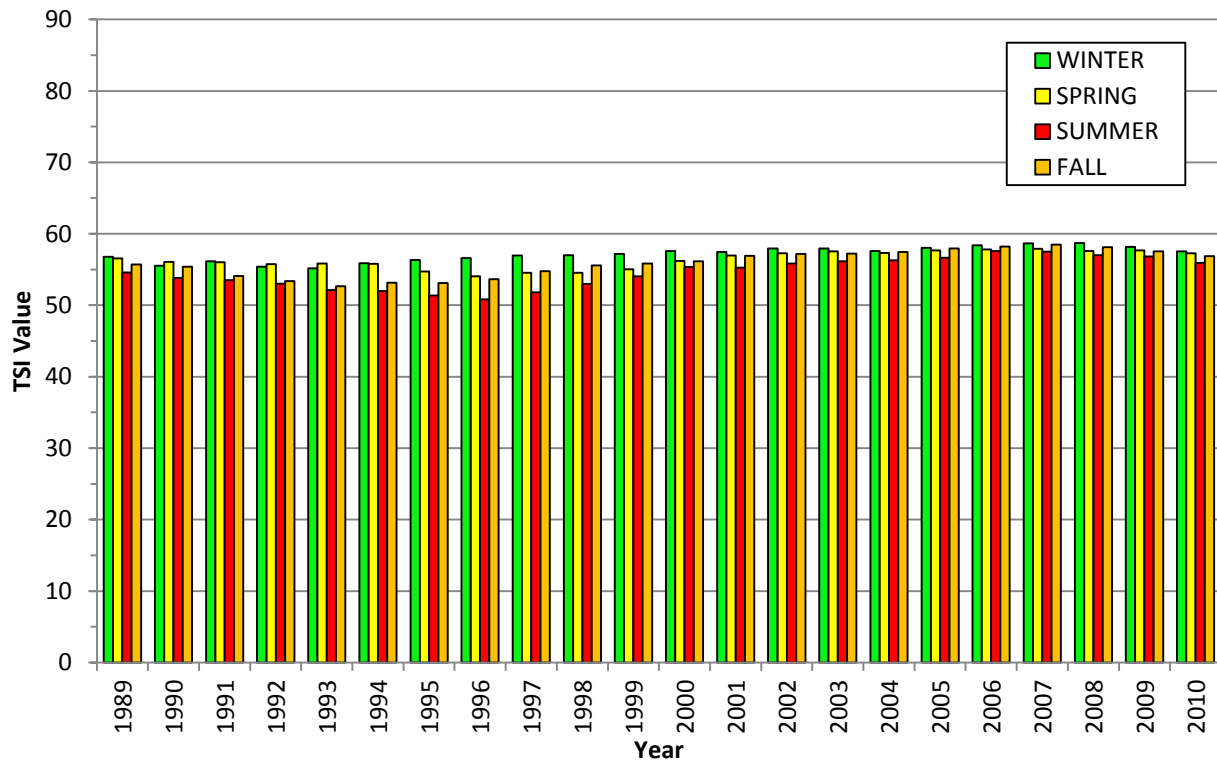


Figure 6-158 Five Year Running Average of TSI Based on TP for Station LM02

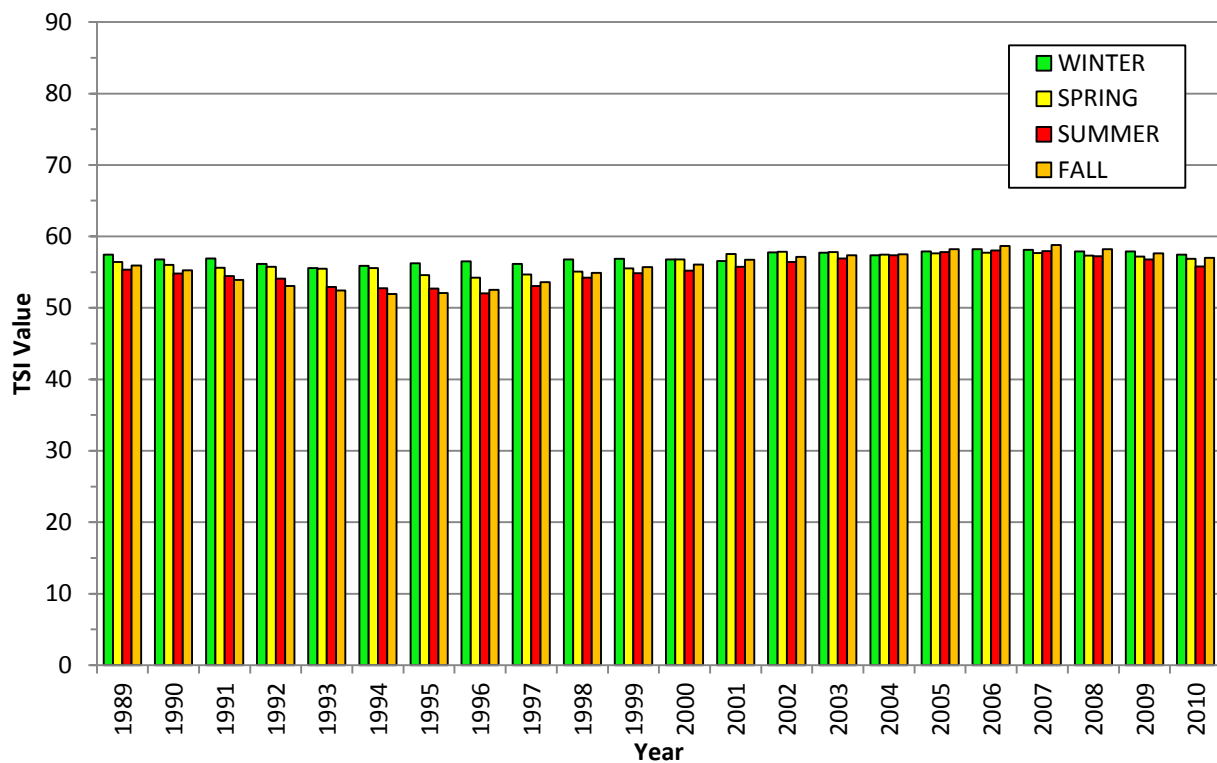


Figure 6-159 Five Year Running Average of TSI Based on TP for Station LM03

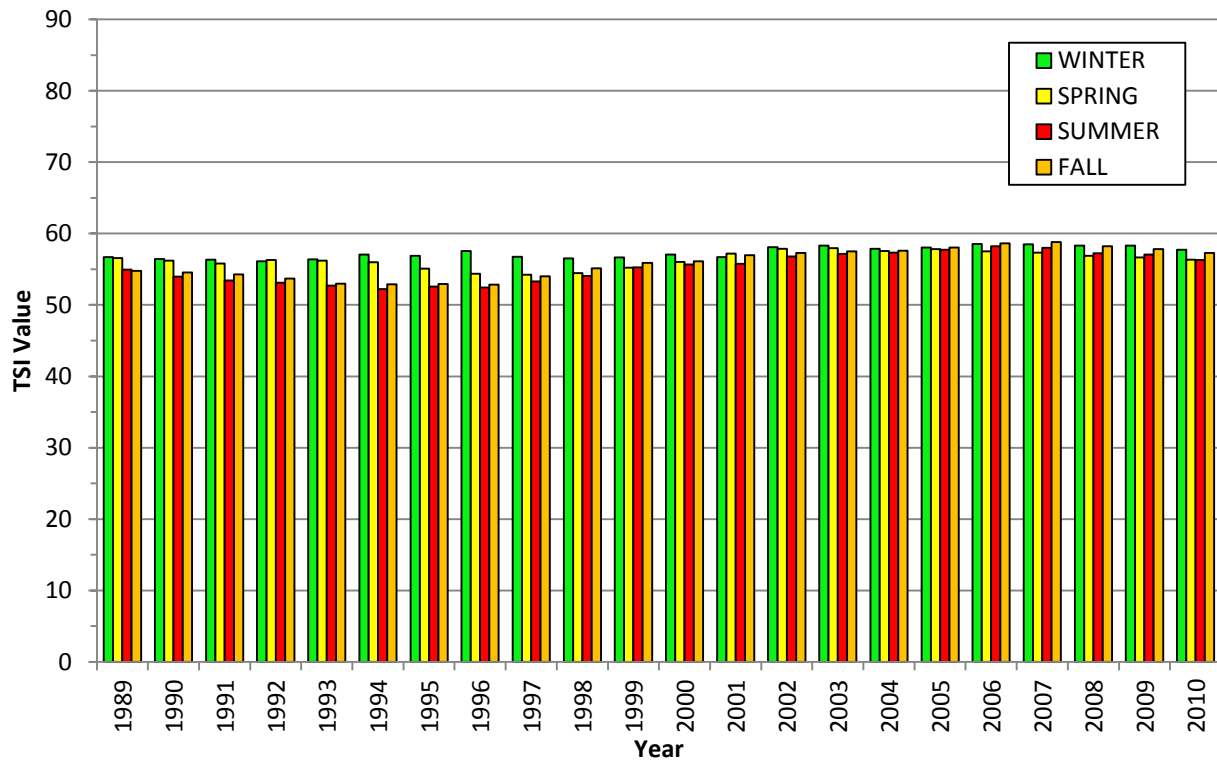


Figure 6-160 Five Year Running Average of TSI Based on TP for Station LM04

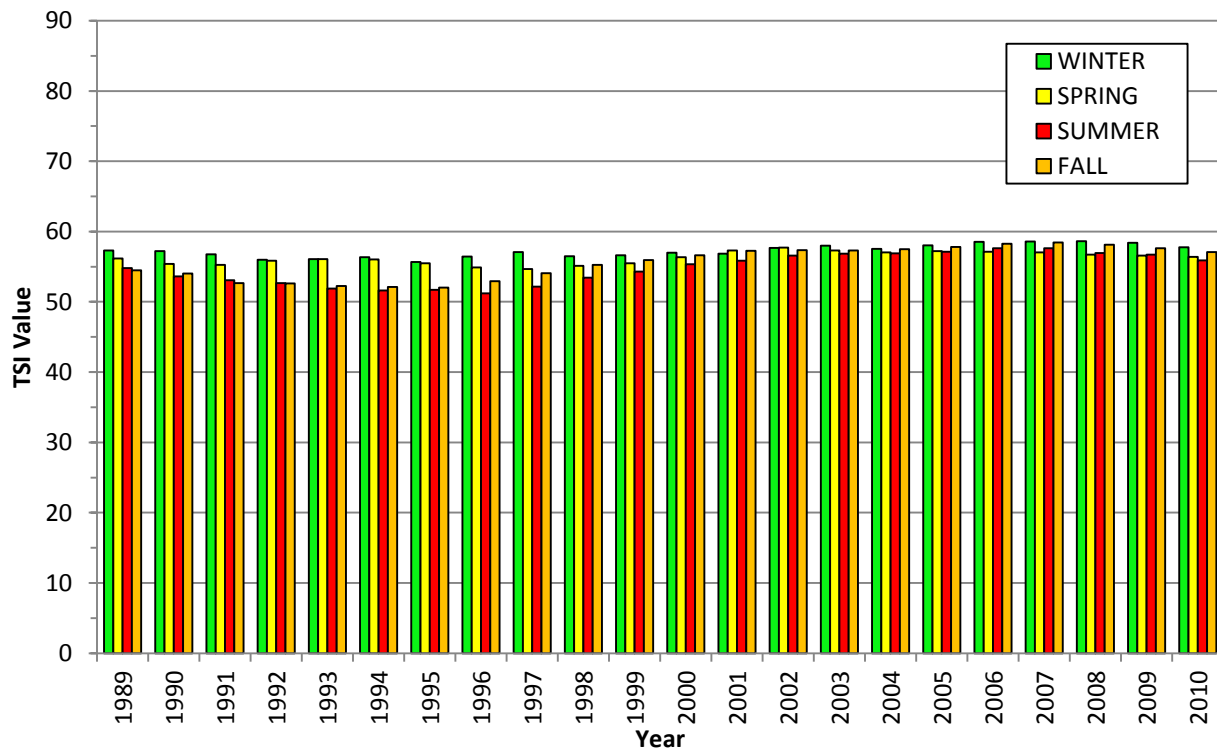


Figure 6-161 Five Year Running Average of TSI Based on TP for Station LM05

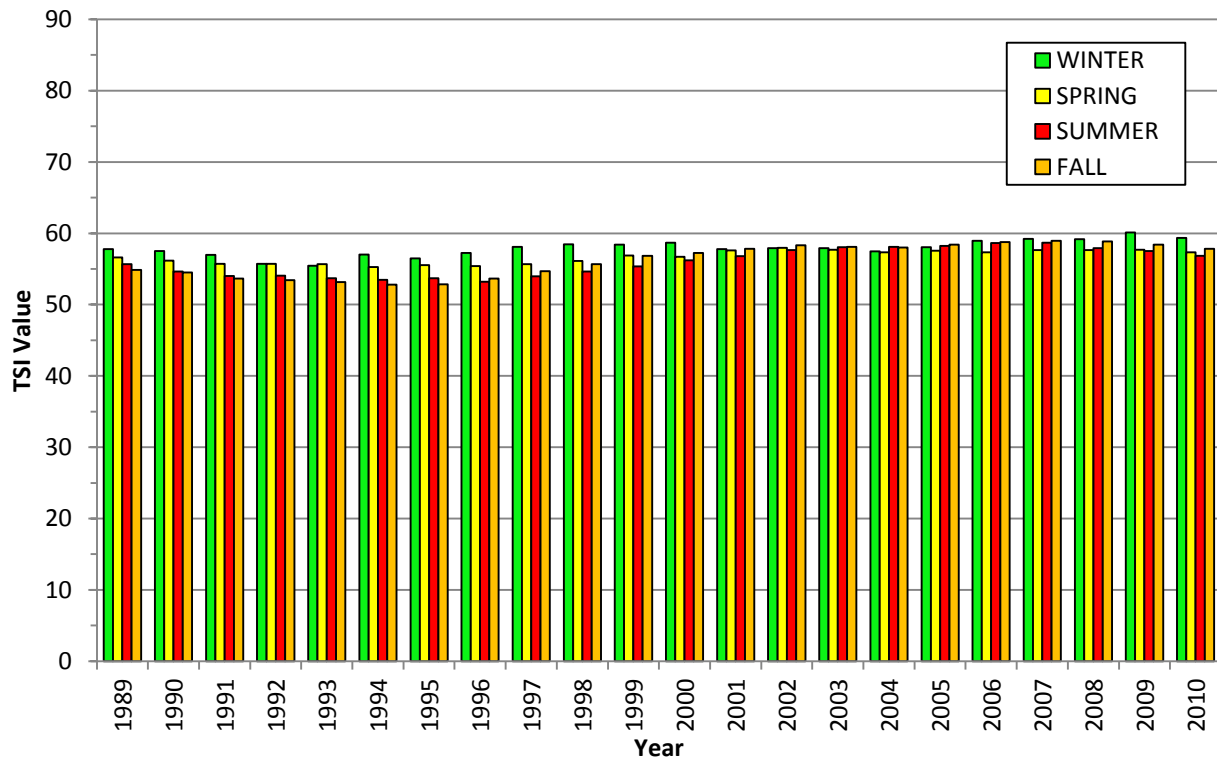


Figure 6-162 Five Year Running Average of TSI Based on TP for Station LM06

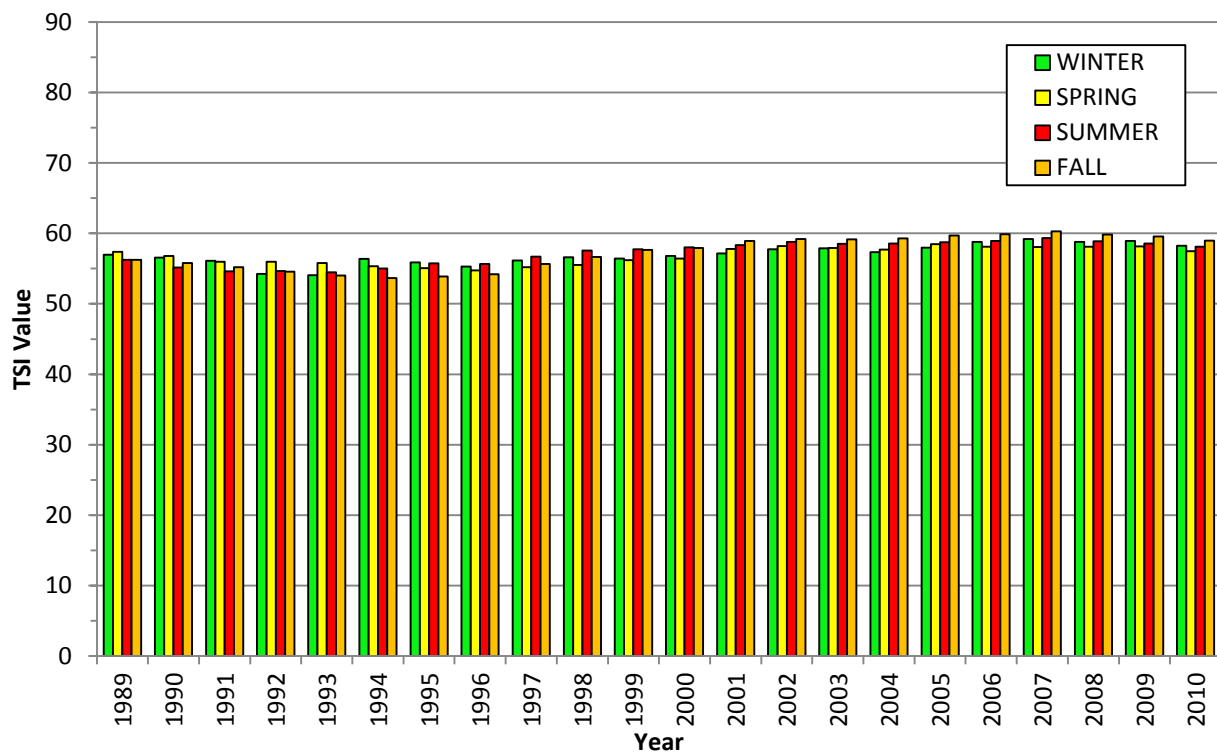


Figure 6-163 Five Year Running Average of TSI Based on TP for Station LM07

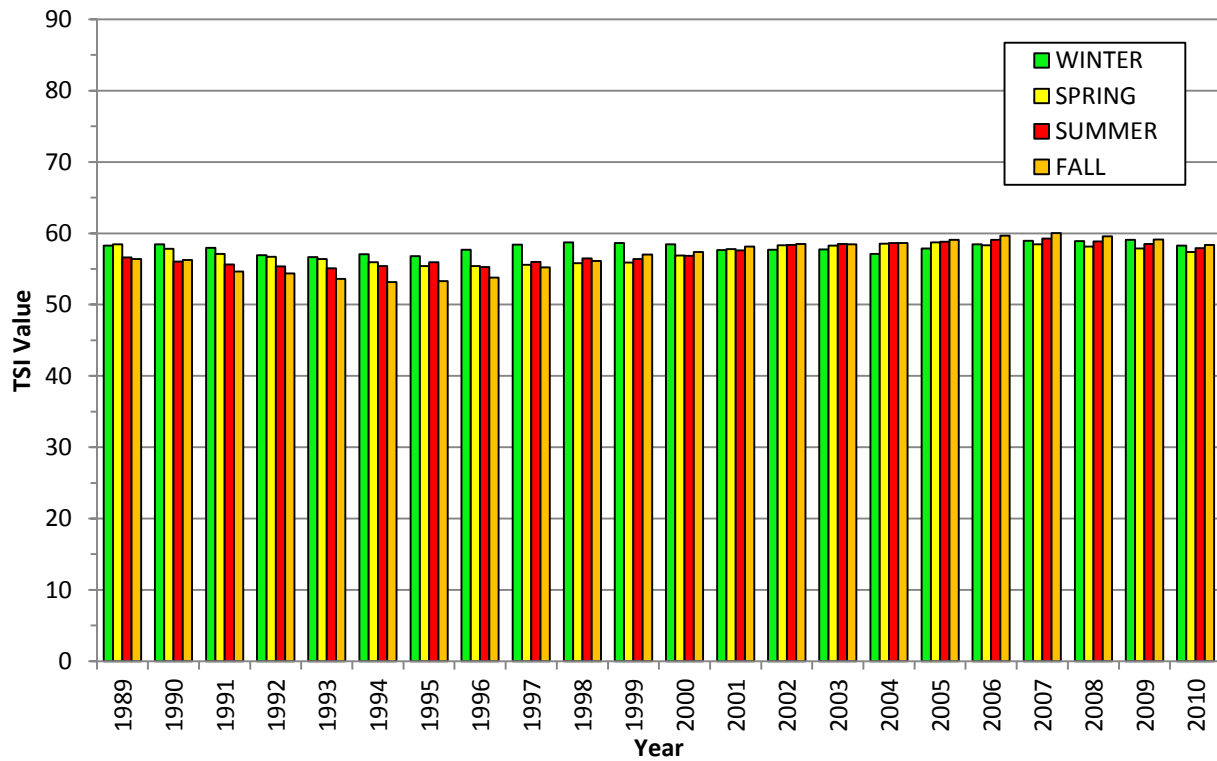


Figure 6-164 Five Year Running Average of TSI Based on TP for Station LM08

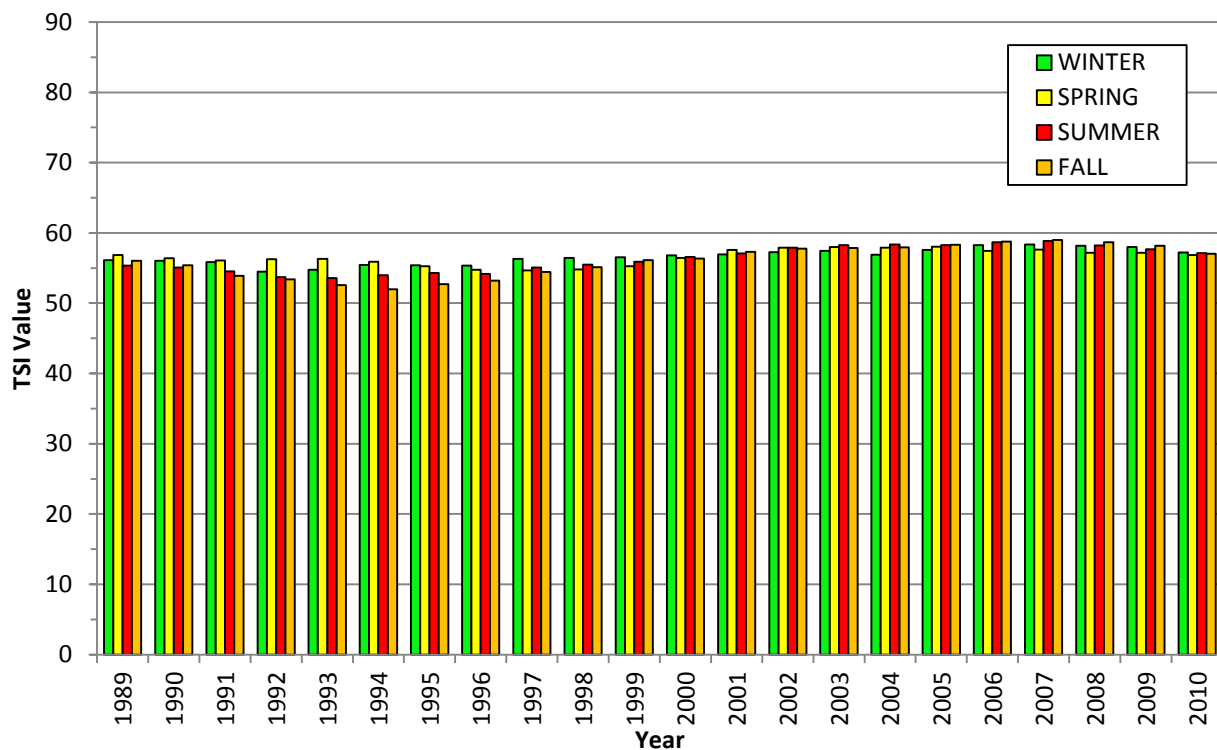


Figure 6-165 Five Year Running Average of TSI Based on Secchi Depth for Station LM01

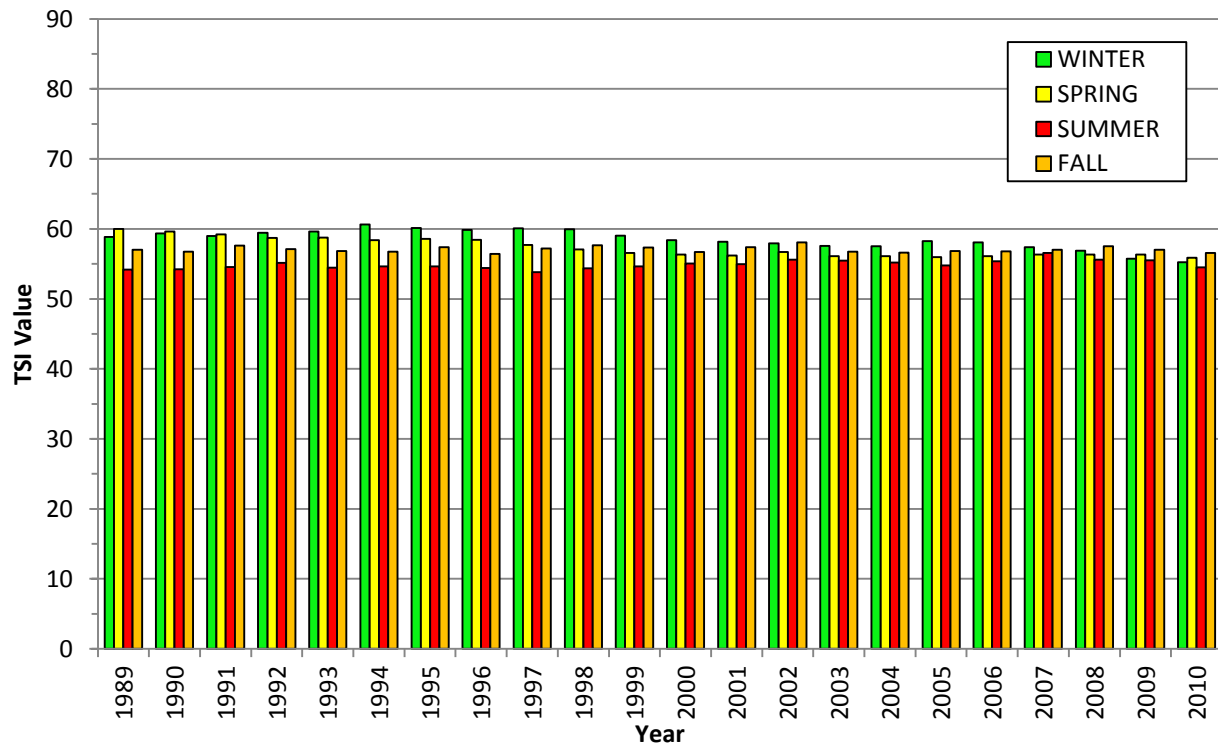


Figure 6-166 Five Year Running Average of TSI Based on Secchi Depth for Station LM02

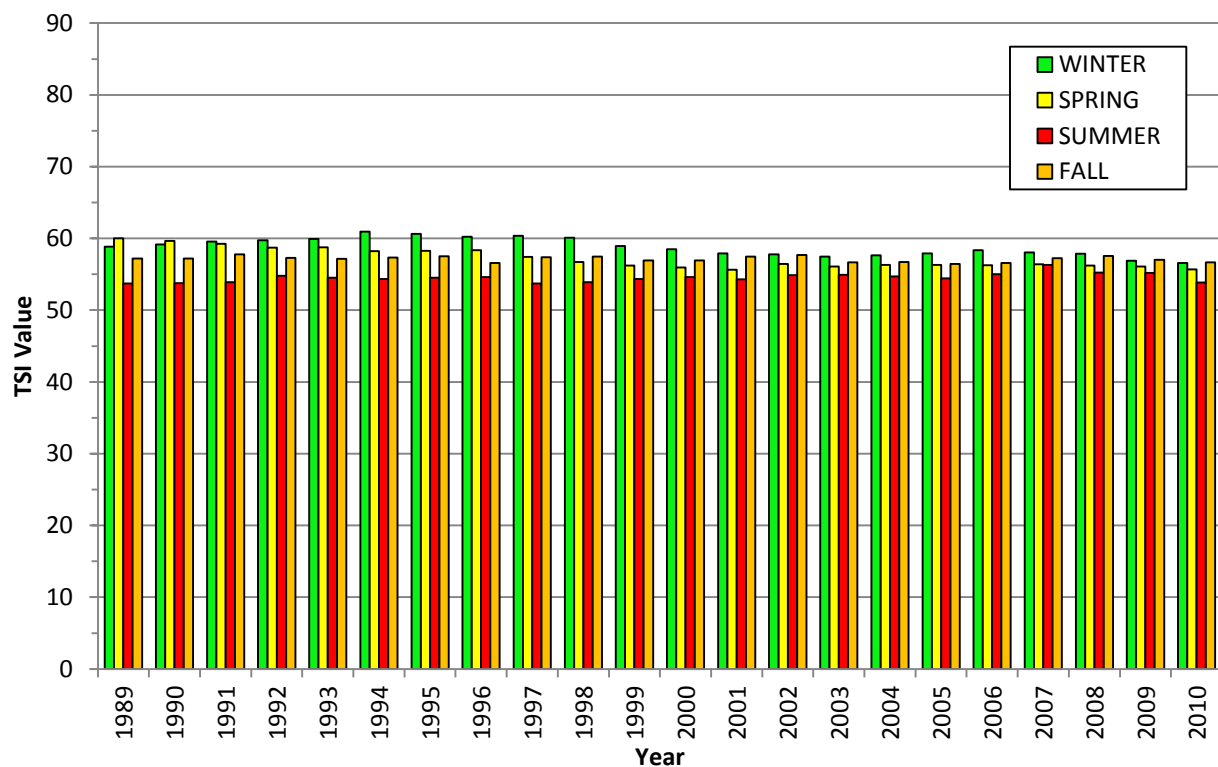


Figure 6-167 Five Year Running Average of TSI Based on Secchi Depth for Station LM03

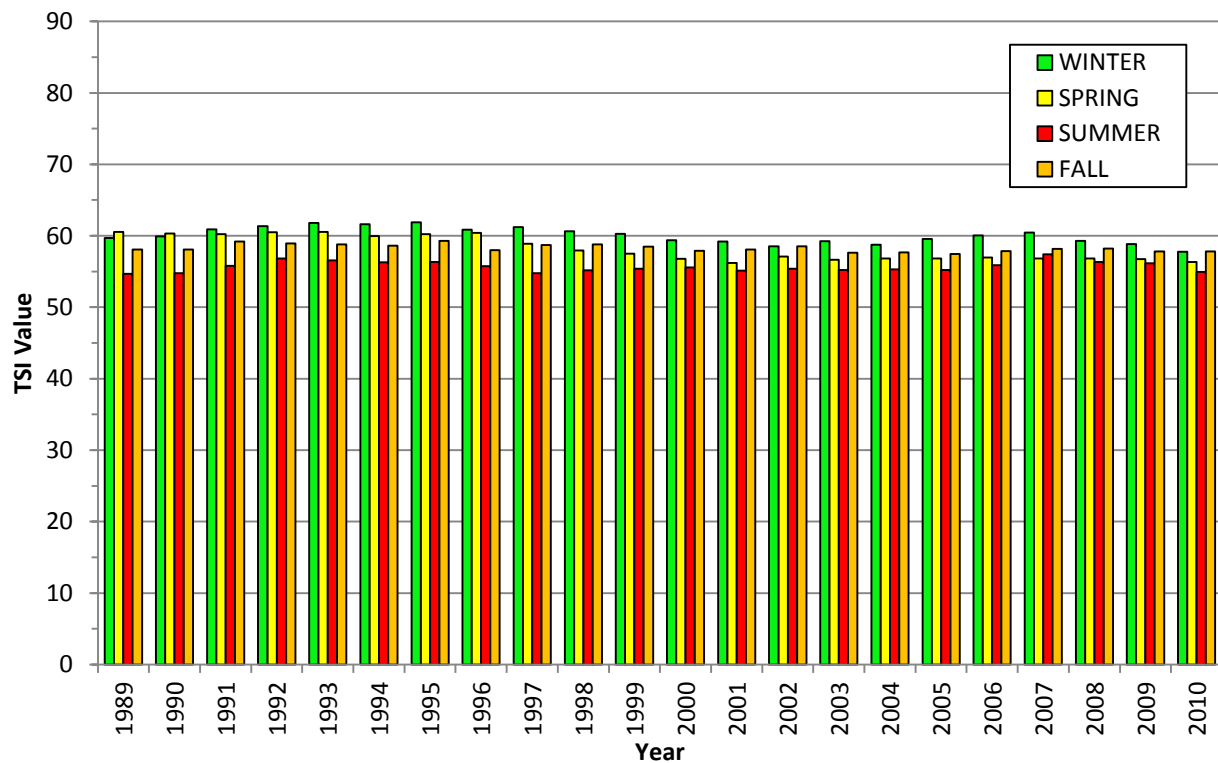


Figure 6-168 Five Year Running Average of TSI Based on Secchi Depth for Station LM04

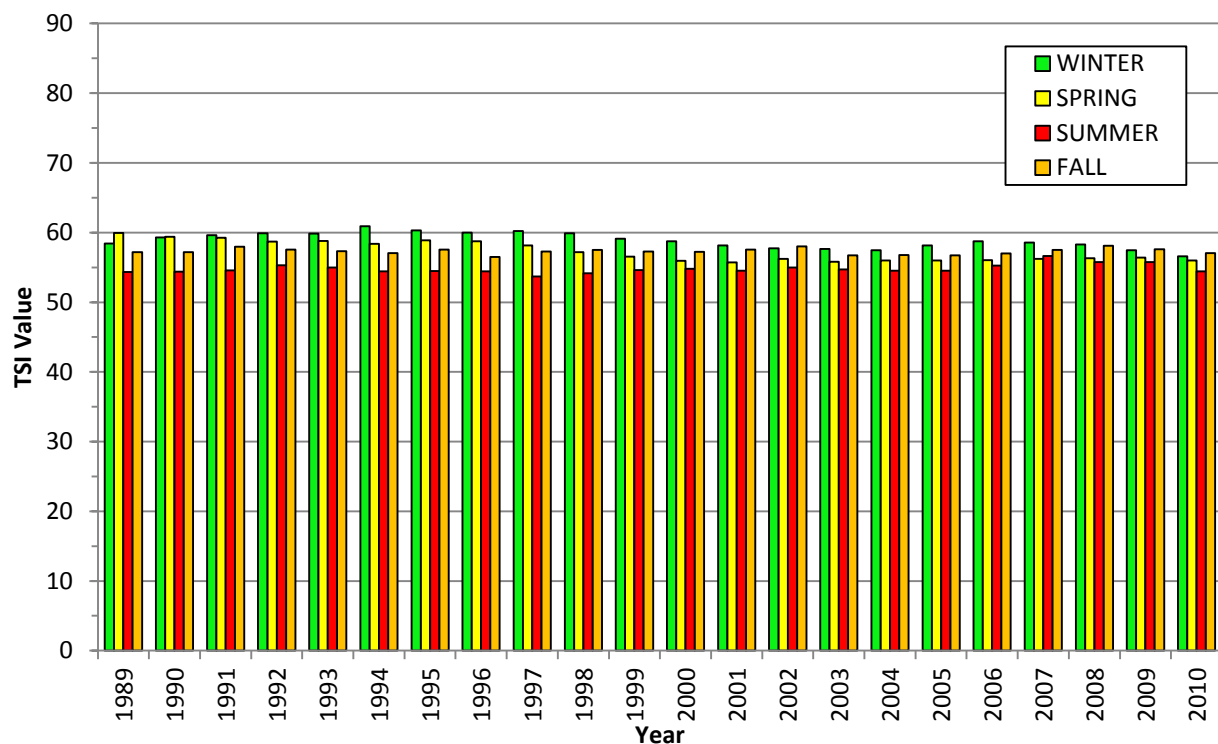


Figure 6-169 Five Year Running Average of TSI Based on Secchi Depth for Station LM05

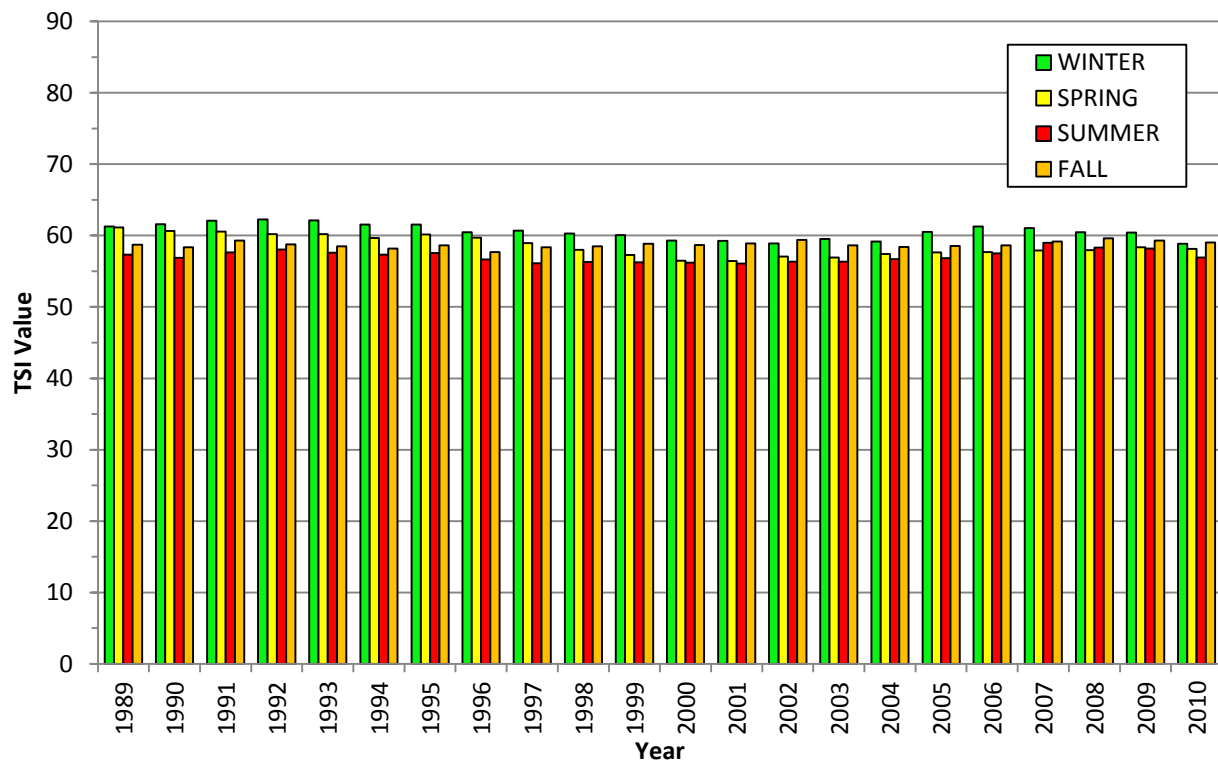


Figure 6-170 Five Year Running Average of TSI Based on Secchi Depth for Station LM06

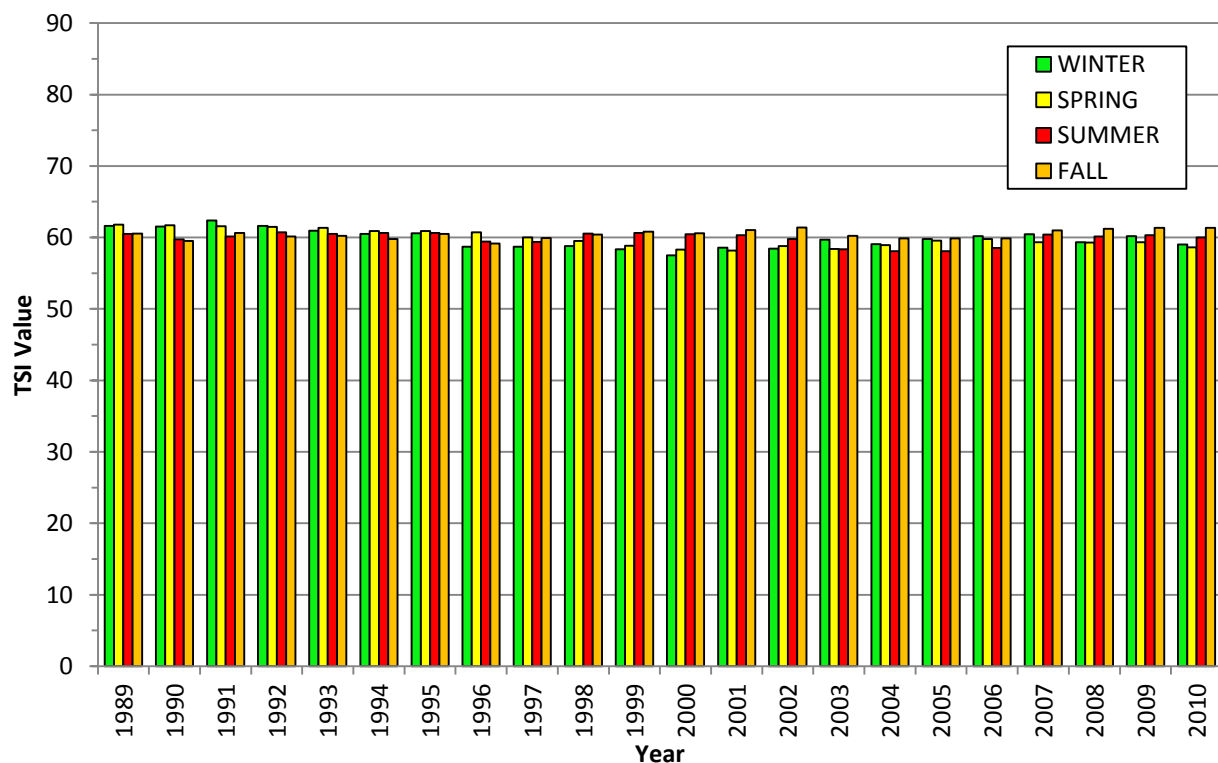


Figure 6-171 Five Year Running Average of TSI Based on Secchi Depth for Station LM07

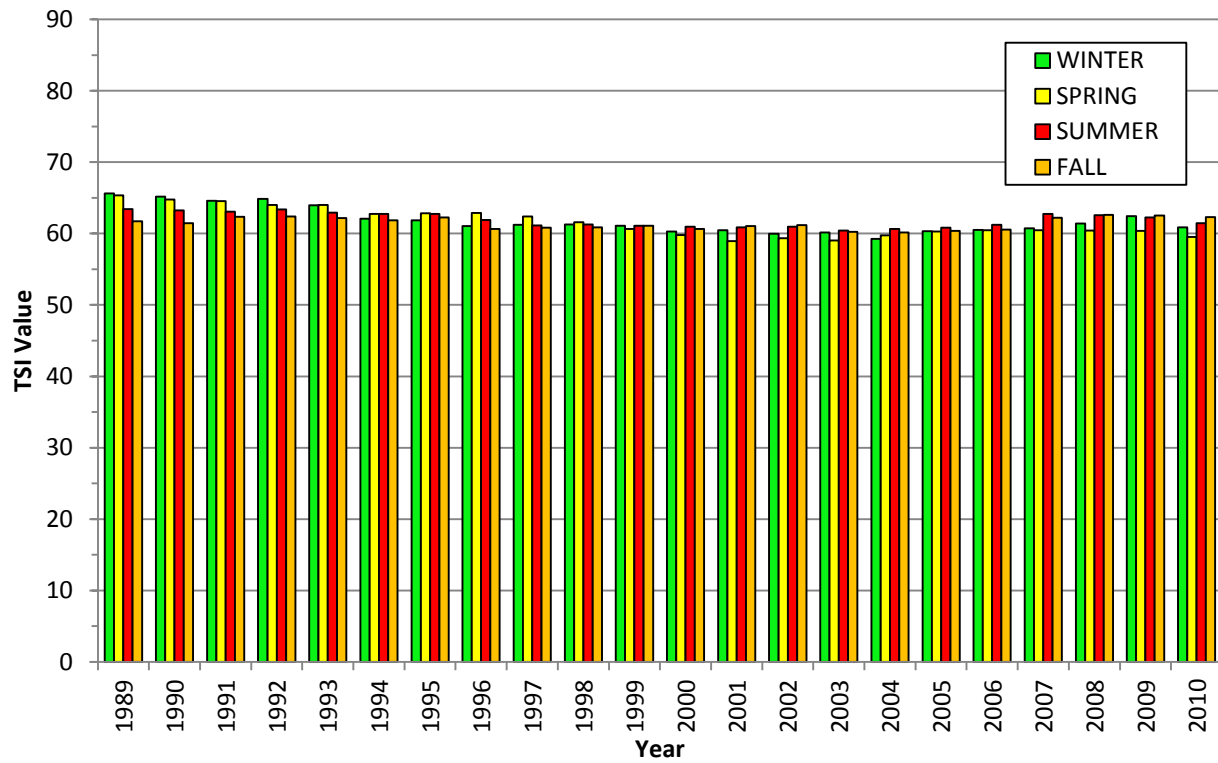


Figure 6-172 Five Year Running Average of TSI Based on Secchi Depth for Station LM08

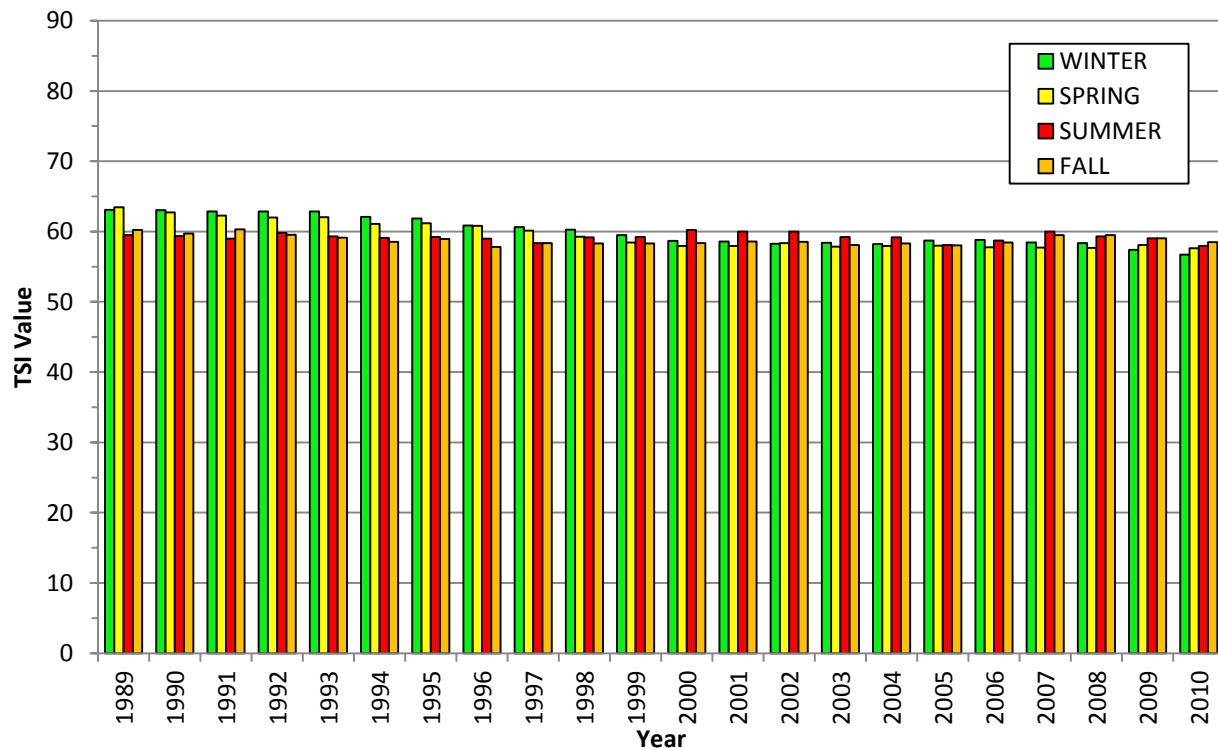
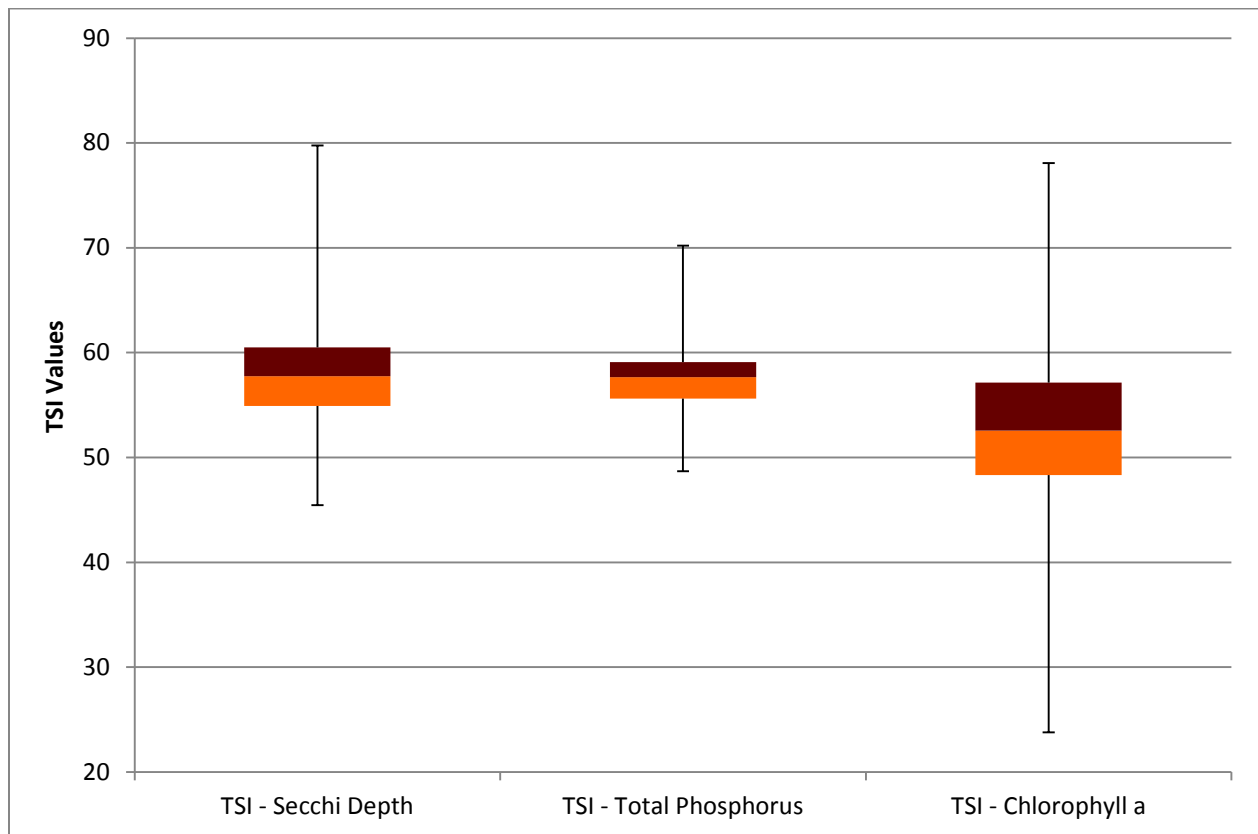


Figure 6-173 Average of Carlson's Trophic State Index for Lake Manassas (2006 – 2010)



Model Results

Based on the findings of the Vollenweider and Carlson trophic state indices analyses, the water quality of Lake Manassas has not changed significantly since the 2005 baseline. Both the Vollenweider and Carlson TSI calculations suggest Lake Manassas is on the lower boundary of eutrophic. However, both models suggest there are decreasing trends, suggesting a slight improvement in water quality (Gorrie 2007). However, if the scaled up loading values are used to determine the trophic state, Lake Manassas appears to be more strongly eutrophic, as shown on Figure 6-148, than the current methodology estimates.

Chapter 7 Conclusions and Recommendations

Based on the findings presented within the text of this report, a summary of conclusions reached, followed by recommendations for future research is presented below.

Conclusions

1. Lake Manassas remains a eutrophic system. The trophic status for the lake remains unchanged since the 2005 baseline period. Both the Vollenweider and Carlson Trophic Indices analysis show that Lake Manassas is slightly eutrophic and close to being mesotrophic.
2. The amount of phosphorus entering the lake is high; however, the tributaries to Lake Manassas show varying levels of phosphorus entering the system. Both orthophosphate and total phosphorus show significant (95 percent confidence) decreasing trends at sampling station ST70, located on Broad Run. Stations BR03 and BR07 have increasing trends for total and orthophosphate phosphorus, respectively. In addition there are apparent trends of increasing phosphorus during summer and fall months at several locations, although not statistically significant. These variations in phosphorus loading are likely the result of fluctuating precipitation levels as well as development activities within the watershed.
3. Nitrogen to phosphorus ratios show slight increases, particularly at surface sampling stations within Lake Manassas. Lake Manassas remains a phosphorus-limited system. The nutrient loading rate for the 2006 to 2010 baseline period shows a significant decrease over the 2001 to 2005 baseline period; however, in 2010, the highest nutrient loading values for the past five years were detected and were above the averages for the 2001 to 2005 baseline period. Although the overall measured decrease is

encouraging, if the 2010 values represent an increasing trend, this may be cause for some concern.

4. Specific conductivity levels show a significant increase at all stream sampling stations and total alkalinity has increased in all but two stream sampling stations. This is a continuing pattern as seen in the 2005 baseline report and may be attributed to an increase in nutrients and dissolved solids entering the lake as a result of fluctuating precipitation levels.
5. Although no statistically significant trends were detected for chlorophyll *a* for the entire 2006 to 2010 baseline period, there was an apparent decreasing trend from 2007 to 2010 at all stations. From 2006 to 2007, there was an increasing trend in chlorophyll *a* concentrations which was consistent with the findings in the 2001 to 2005 baseline report.
6. With regards to the significant increases in pH, total alkalinity, conductivity and nutrients observed in the unnamed tributary monitored by sampling station BR05, it appears that increased development within the associated drainage area is likely resulting in an increase in run off and contributing to the trends identified for the water quality in the unnamed tributary. Specifically, the development of four residential neighborhoods, a retail shopping center and population growth rate over the decade leading up to 2010 may be impacting the water quality entering Lake Manassas.

Recommendations

1. The monitoring program at Lake Manassas should continue to monitor changes in water quality data. The collection of future data will aid in evaluating impacts from development within the watershed.

2. The methodologies used within this baseline analysis should be reviewed now that an abundance of data has been collected and several trends in the calculations have been identified. Specifically some consideration should be given to the following:
 - a. Five-year averages can be impacted significantly by a single data point which may not represent actual conditions. The nature of a five-year average carries all validated data points for five years and falsely depicts a sharp increase in concentrations. Consideration should be given regarding appropriate approaches for dealing with these potential outliers.
 - b. Consistent with reviewing how five-year averages are calculated, consideration should be given to when to use the Mann-Kendall seasonal analysis. As discussed above, a single data point can alter the five-year average values and subsequent increasing or decreasing trends may not be apparent when conducting the Mann-Kendall seasonal analysis.
 - c. The method for determining loading rates within Lake Manassas should also be reconsidered as they are currently based on data collected from a single gauging station that represents only 70 percent of the water entering the Lake. Ideally, a gauging station would be located along each tributary; however, estimating total loading may be possible by extrapolating the data currently collected. This may for example, include an analysis of the stability within the lake.
3. Further analysis of the land use changes within the drainage areas that contribute to Lake Manassas should be conducted to determine if any specific contributors can be identified. This may aid in determining whether any mitigation to prevent further influx of nutrients to the Lake is warranted.

4. Best Management Practices (BMPs) should be employed for any new developments within the Lake Manassas watershed to ensure nutrient loading rates do not increase.

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Appendix A – Photographs



Figure A-1: Entrance to Lake Manassas Residential Community and Robert Trent Jones Golf Course – Facing East (NOV-2012)



Figure A-2: North Fork tributary to Lake Manassas at US Highway 29 (Lee Highway) – Facing South (NOV-2012)



Figure A-3: Lake Manassas from the Saranac at Lake Manassas Residential Community – Facing North (NOV-2012)



Figure A-4: Lake Manassas from the Saranac at Lake Manassas Residential Community – Facing West (NOV-2012)



Figure A-5: Lake Manassas from the Saranac at Lake Manassas Residential Community – Facing South (NOV-2012)



Figure A-6: T. Nelson Elliott Dam at Glenkirk Road showing rubber bladder on top – Facing North (NOV-2012)



Figure A-7: Broad Run at Glenkirk Road, immediately downstream of the T. Nelson Elliott Dam – Facing Southeast (NOV-2012)



Figure A-8: Unnamed tributary to Lake Manassas near sampling station BR06 at Route 215 (Vint Hill Road) – Facing North (NOV-2012)



Figure A-9: South Run at Route 215 (Vint Hill Road) – Facing North (NOV-2012)



Figure A-10: South Run at Route 215 (Vint Hill Road) – Facing South (NOV-2012)



Figure A-11: South Run at County Road 652 (Finch Road) – Facing Southwest (NOV-2012)



Figure A-12: Lake Brittle – Facing Northwest (NOV-2012)



Figure A-13: Earthen Dam at Lake Brittle – Facing North (NOV-2012)



Figure A-14: South Run immediately below discharge from Lake Brittle at County Road 1306 (Lake Drive) – Facing West (NOV-2012)



Figure A-15: Broad Run tributary to Lake Manassas at US Highway 29 (Lee Highway) – Facing Southeast (NOV-2012)

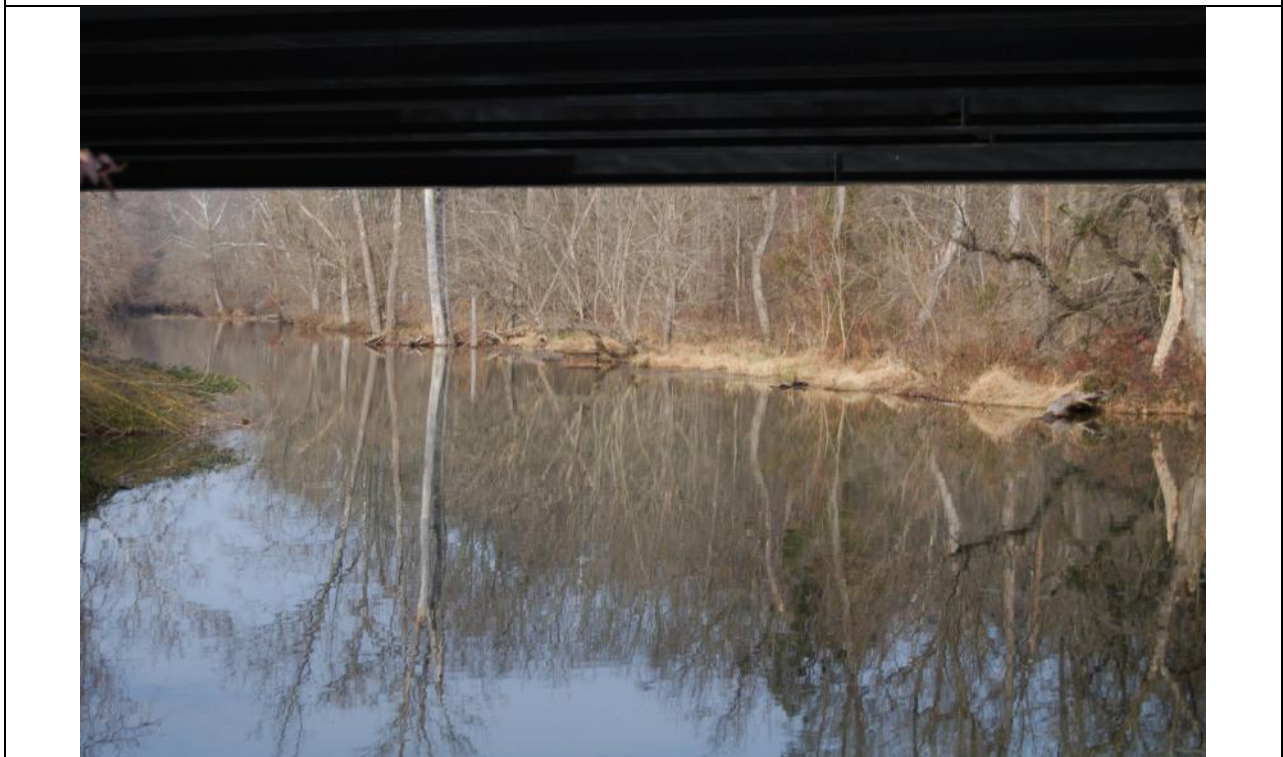


Figure A-16: Broad Run tributary to Lake Manassas at US Highway 29 (Lee Highway) – Facing Northwest (NOV-2012)



Figure A-17: Lake Manassas at Stonewall Country Club Golf Course – Facing South (NOV-2012)



Figure A-18: Unnamed Tributary to Lake Manassas at US Highway 29 (Lee Highway) – Facing South (NOV-2012)