Senior Thesis

Nutrient Concentrations in the Scioto River and the Relative Importance to the Problem of Hypoxia in the Gulf of Mexico

By

Robert Sigler

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Approved by:

Frank W. Schwartz

Dr. Frank Schwartz

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1.0 Abstract

Nutrients from the Mississippi-Atchafalaya River Basin have been found to be a principal cause of the hypoxic zone that forms every spring and summer on the Louisiana-Texas continental shelf in the northern Gulf of Mexico. Water that has less than 2 mg/l of dissolved oxygen content is referred to as hypoxic. The low levels of oxygen cause stress and can prove to be lethal to immobile bottom-dwelling species, thus altering the food chain and energy relationships. The hypoxic zone has been growing since it first mapped.

Fertilizers applied in agricultural lands are the primary source of nutrients that contribute to hypoxia. The Mississippi River Basin drains some of the most productive, and most fertilized, agricultural land in the world. The goals of this study are to 1) gain a better understanding about the problem of hypoxia in general 2) investigate the relative importance of the different sources of nutrients and the contributions of sub basins in the Mississippi River Basin and to 3) examine available data in the Upper Scioto River Basin to assess it's contribution of nutrients and identify trends of nutrient concentrations.

This thesis is divided into five chapters. Section 2 presents an overview of nutrient chemistry, sources, and different factors that govern nutrient loading in streams, with an emphasis on agricultural settings. Section 3 describes the problem of hypoxia in the northern Gulf of Mexico and the factors that control its year-to-year extent. Section 4 examines the Scioto River Basin and nutrient data from Griggs and O'Shaughnessy Reservoirs, which are feed by the Scioto River near Columbus Ohio. These data sets were taken monthly over a 15-year period and provides the basis to understand the local contribution to the hypoxic zone, suggest factors that control nutrient concentrations in

the Scioto River, and to understand the trends in nutrient levels near Columbus, Ohio. Section 5 summarizes the major conclusions of the study.

2.0 Chemistry and sources of Nutrients

2.1 Overview

Nutrients are chemical compounds that are essential for plant and animal life. However, if they occur in high concentrations in water they can be a contaminant. They occur in a variety of forms. The ones that this report will concentrate on are nitrate, nitrite, ammonia, phosphorus, and silica. They are affected by chemical and biological processes that can change their form and transfer them from or to water, soil, biological organisms, and the atmosphere (USGS, 2001). They are usually reported in mg/l.

Excess nutrients in water have a variety of detrimental effects on the health of an aquatic ecosystem and the health of the people who drink the water. Eutrophication occurs as a result of high concentrations of nitrate and phosphorus in the water. Algae feed on the nutrients to such an extent that an unsightly scum appears on the water surface. This decreases recreational value, clogs water intake pipes, and can result in fishkills (USGS, 2001). The decaying mats of algae produce foul tastes and odors in water. The overgrowth of algae also depletes the oxygen supply in water, which can lead to hypoxia.

Nitrate is the primary form of nitrogen dissolved in streams and groundwater. Nitrogen also occurs in the forms of nitrite and ammonia. Nitrite does not occur in large concentrations as compared to nitrate, so throughout this report concentrations will be reported with nitrate values. Nitrate is highly soluble and thus is easily transferred in water. It is stable under a wide range of environmental conditions.

Ammonia is a dissolved form of nitrogen that is less common than nitrate. Total ammonia includes the ammonium ion and un-ionized ammonia. The un-ionized form is more toxic to fish. It is not stable in most surface environments, if there is an ample supply of oxygen present, it is converted to nitrate. It is soluble in water.

The most common form of phosphorus in water is phosphate. Phosphate can be present in several forms. It is less soluble than nitrate and usually attaches themselves to soil and aquifer particles. Thus, eroded soil can transport significant amounts of phosphorus to lakes and streams. The concentration of phosphorus in water has decreased in recent years despite an increase in urban population. This is probably due to restrictions of the use of detergents that contain phosphorus. Orthophosphates are the main type that leads to eutrophication (USGS, 2000).

2.2 Origin of Nutrients

There are several sources of nutrients in streams and groundwater. They are generally split into two categories of point and nonpoint. Point sources have a known input site such as a wastewater treatment plant and other municipal and industrial sources. Nonpoint sources are diffuse sources, that are difficult to locate. They might originate from precipitation, widespread mineralization of soils, fertilizer and pesticide application, livestock and pet wastes, septic systems and atmospheric deposition. Nonpoint contamination starts with precipitation that falls on and moves over and through soils carrying away contaminants to streams, wetlands, lakes, and groundwater.

The Clean Water Act of 1972 helped provide the funding and political capital to begin cleaning up pollution from point sources. Now, point sources are regulated by laws that restrict the type and amount of contaminants that may be discharged to water. This approach has reduced the quantity of water pollution from point sources. However, similar progress has not been made with nonpoint sources, which contribute far more nutrients to the environment (USGS, 2000).

Precipitation is a major source. The atmosphere is 71% nitrogen, mainly in the form of elemental gas but also in the form of nitrogen and oxygen compounds made by naturally occurring reactions. These compounds are also released into the atmosphere by the combustion of fossil fuels such as gas, oil, and coal. Nitrate is dissolved in rainwater and enters streams or groundwater through runoff and seepage.

The atmosphere deposits over 3 million tons of nitrogen to the land surface each year in the United States (USGS, 2000). Some of it is deposited as a result of naturally occurring chemical reactions and from the combustion of fossil fuels. Local contributions come from evaporation of open-air manure lagoons. The deposition is not uniform across the United States. The highest rate of deposition (greater than 2 tons per square mile) occurs in a wide swatch from the Upper Midwest to the Northeast (USGS, 2001). There are two forms of atmospheric deposition. Wet deposition comes in the form of dissolved nutrients in rainwater. Dry deposition is particles or vapor being deposited in times of no precipitation.

Large amounts of nutrients also enter the hydrologic system through soil mineralization. The majority of nitrogen and phosphorus in soils is organic (microbial biomass, crop remains, immobile fertilizer and manure) which cannot be used by higher plants (Goolsby et al., 1999). Mineralization is a process converting organic nitrogen and phosphorus to inorganic forms such as nitrate, ammonia, and orthophosphate. The inorganic forms are then either used by the plant or leached from the soil to enter the water system.

The rate of soil mineralization is a function of soil moisture content, temperature, cover type, land management, and soil organic content (Troeh and Thompson, 1993). If the temperature and soil organic content are high, then soil mineralization can be a significant source of nitrate. Soil mineralization rates are higher in cultivated soils compared to uncultivated soils (Troeh and Thompson, 1993). The availability of inorganic phosphorus is a function of solubility, which varies with soil pH, the presence of iron, aluminum, and manganese containing minerals, organic matter content, microbial activity, and temperature.

The usage of commercial fertilizers also adds a significant amount of nutrients to the environment. Approximately 12 million tons of nitrogen and 2 million tons of phosphorus are added to the environment each year in the form of commercial fertilizer (USGS, 2000). The most common fertilizers contain nitrogen in the form of nitrate or ammonia. Animal manure, which contains organic nitrogen and urea, which in turn, combine to make ammonia, is also often used as fertilizer. An additional seven million tons of nitrogen and 2 million more tons of phosphorus are applied as animal manure each year (USGS, 2001). The highest rates of usage in the country occur in the Upper Midwest with other high usage rates along the East Coast, the Southeast, and in agricultural areas of the West. Nitrogen not used by crops is either carried away to streams or enters the groundwater. Streamflow levels strongly affect the relative importance of point source nutrients. It is lower in high streamflow because of the process of dilution (Goolsby et al., 1999).

Point sources of contamination include discharge from wastewater treatment plants. The effluent contains organic nitrogen, ammonia, and organic phosphorus. The phosphorus occurs as a component of detergents and other cleaning products. Nutrients in the effluent have been targeted by pollution control legislation, starting with the Clean Water Act of 1972. Improvements in treatment plants have largely taken care of the problem posed by organic forms of nutrients. The plants also convert ammonia to nitrate, thus lowering the risk posed to fish but not decreasing the total amount of nitrogen in the water. Other point sources include plastics and fertilizer manufacturers, individual septic tanks, beef cattle feedlots, wet corn milling, steel mills and petroleum refineries (USGS, 2001).

2.3 Factors in Nutrient Concentrations

In order to discern the effects of human actions on the amount of nutrients in the environment, it is necessary to know what the naturally occurring concentrations are. This is done by testing and sampling streams that drain watersheds that are relatively unaffected by agricultural activities, urbanization, and other land use. This background concentration is controlled by naturally occurring minerals, biological activity in soils, and streambed sediments. Atmospheric deposition and rainwater have the capability to higher the background amounts.

In general, the concentration of nutrients in streams is higher than in shallow groundwater. Geology and hydrogeology control the movement of shallow groundwater to deep aquifers. This process can take many years. Elevated concentrations in shallow groundwater may be a precursor to the contamination of deep aquifers. This is especially important where deep aquifers are used as the public drinking supply.

Phosphorus usually attaches to soil particles and thus does not flow downward to the water table. It is moved primarily by soil erosion. As the phosphorus levels increase in soil more is available to be dissolved and carried away by water. This amount is dependent on the phosphorus absorption capacity of the soil (USGS, 2001). Thus, areas with high levels of phosphorus in the soil relative to their soil absorption capacity will discharge high amounts of phosphorus to streams.

The geology of an area and soil type control nutrient yields to streams and groundwater (USGS, 2000). However, the impact is greater on groundwater than for streams. For instance, groundwater in regions of well-drained soils, high amounts of naturally occurring phosphate minerals, or underlain by Karst formations will have a high concentration of nutrients compared to the input. On the other hand, groundwater will have a low concentration of nutrients compared to the input if the area of concern is underlain by relatively impermeable rock, silt, or clay.

The interactions that exist between groundwater and surface water also affect the concentrations of nutrients. A stream that receives a significant portion of its total streamflow from groundwater discharges will have a relatively low level of nutrients because groundwater is typically low in nutrients (USGS, 2000). Also, in times of high flow nutrients from the stream will enter the groundwater system, while in times of low flow groundwater will discharge into the stream and thus diluting it.

Nitrate does pose a health risk for those people who receive their drinking water from deep aquifer. Those at most risk get their drinking water from shallow wells in agricultural areas. This is where the highest concentrations of nitrogen and phosphorus are found (USGS, 2001). Shallow domestic supply wells are more prone to nitrate contamination, especially if they are close to agricultural fields, septic systems, or animal feeding areas. Many municipalities, including Columbus, have surface water sources for drinking water. Streams feed into a reservoir, which collects the water for the usage of the city. Surface water drinking sources are at risk for nitrate contamination, especially if there is agricultural land nearby, as there is near Columbus.

2.4 Major Influences on Nutrient Concentrations

The occurrence of nutrients in a water system is dependent upon the interconnections between surface and groundwater, atmospheric contributions, natural landscape features, human activities, and aquatic health. The risk of water contamination from nutrients depends upon the geology, topography, soils, climate, and land management practices.

The level of nutrients in water varies seasonally (USGS, 2000). This is due to changes in precipitation, the timing of the application of fertilizers and pesticides, and peak irrigation periods. The concentrations are higher in the spring and early summer because of the increased precipitation that occurs during this time. High flows also coincide with the most common timing of the fertilizer application in early spring. The levels of nutrients are also higher following irrigation in the regions that use that practice. The land management practices of a region will have a significant impact on nutrient levels, even in agricultural areas. Examples of different types of land use are forestland, rangeland, agricultural land, urban, and wetlands. The highest concentrations of nutrients in water end up coming from agricultural lands, especially if extensive crop-row agriculture such as corn, cotton, or vegetables is utilized (USGS, 2001). If pasture and woodlands occupy the same watershed as crop-row agriculture, lower concentrations of nutrients will result.

The movement of water and dissolved nutrients from the ground surface to aquifers and streams is greatly influenced by the ability of water to move through soil. Water moves relatively quickly through well-drained soils and slowly through poorly drained soils. Thus, nitrate levels are typically higher in groundwater below well-drained soils compared to poorly drained soils (USGS, 2001). Poorly drained soils are typically fine-grained silts and clays, which provide limit the downward migration of water and nitrate to the water table. Poorly drained soils are often low in oxygen, which is the limited reactant for the conversion of ammonia to nitrate and favors the reaction of nitrate to nitrogen gas.

Widespread installation of tile drainage also results in higher nutrient levels in streams. Tile drainage involves the usage of perforated pipelines that are used to remove excess water from croplands, thus diverting flow to streams rather than groundwater (Baker, 1985). It is more commonly used in areas of poorly drained soils.

Geology of the region is another governing factor for nutrient concentrations in water. Nitrate levels are highest in agricultural regions that are underlain by unconsolidated sand and gravel or Karst, and to a lesser extent by alluvium deposits and non-fractured carbonates. Low nitrate levels are associated with groundwater in cemented sandstones and crystalline rock.

Nitrate levels in groundwater are the highest in the Northeast, the Great Plains, and along the West Coast, where crop-row agriculture is common, soils are generally well drained, and is underlain by unconsolidated material such as sand and gravel (USGS, 2000). The latter two allow easier flow to the water table. These areas also have the highest rates of irrigation and fertilizer application rates in the country.

3.0 Hypoxia in the Gulf of Mexico

A hypoxic zone covers a broad region of the Louisiana-Texas continental shelf in spring and mid-summer. It is the third largest hypoxic zone in the world, behind the northwestern shelf of the Black Sea and the Baltic basins (Boesch and Rabalais, 1991). In 1985-1992 the mid-summer bottom areal extent averaged 8,000-9,000 km^2. It increased in size between 1993-1999 to 16,000-18,000 km^2. The largest mapped hypoxic zone to date occurred in 1999 when it measure more than 24,000 km^2 (Rabalais and others, 1999). In 2000, it was one of the smaller zones on record, measuring only 4,400 km^2 following drought conditions in much of the basin (Rabalais, 2000).

There are two necessary components for the formation of a hypoxic zone. A stratification of the water column and the presence of organic matter to consume oxygen. The Mississippi River meets both these requirements with large inputs of freshwater and large amounts of nutrients. The warmer, less dense freshwater discharge overlies the colder, denser salt water creating the stratification. The excess nutrients promote algal growth, and the organic matter from the algae and other aquatic organisms migrates downward to the bottom waters. Bacteria in the benthic zone decomposes the organic matter in an oxygen consuming process, which results in a hypoxic zone in the bottom waters. The stratification of the water column prevents the reoxygenation from surface waters (Goolsby and Battaglin, 2000). The stratification breaks up in the late summer or fall due to decreased freshwater inputs, cooler temperatures, and ocean water mixing events such as storms.

Hypoxic waters can occur at shallow depths near shore (4-5m) to as deep as 60 m but have a usual range of 5-30m (Rabalais and others, 1999). The slope of the continental shelf helps control the shape of the hypoxic zone. The continental slope is relatively steep off of southeastern Louisiana where the zone generally reaches 55 km offshore. The slope is more gradual on the central and southwestern Louisiana shelf where the zone has an average extent of 130 km (Rabalais and others, 1999).

3.1 Seasonal Pattern of Hypoxia

The hypoxic zone of the Gulf of Mexico is at its largest in the months of June, July, and August (Rabalais et al., 1991). The dissolved oxygen content gradually falls in the spring, with some reoxygenation occurring due to isolated wind mixing events and isolated upwelling of more oxygenated water. After a mixing event, the dissolved oxygen concentration declines gradually, in a similar manner to the spring. In late summer and early fall, the occurrence of tropical storms, hurricanes, and cold fronts that cause enough mixing that no prolonged periods of hypoxia develop until the following spring.

The seasonal pattern of hypoxia in the Gulf of Mexico is strongly correlated to the streamflow level, and thus nutrient load, of the Mississippi River. The Mississippi River flooded in 1993 the hypoxic zone was twice its normal size and it lasted longer than usual (Rabalais et al., 1991). On the other hand, during the drought year of 1988, when the discharge of the Mississippi River hit a 52-year low, the hypoxic zone formed as usual in the spring but was not sustained (Rabalais et al., 1991).

3.2 Ecological Effects of Excess Nutrients and Hypoxia

There is a direct connection between productive and healthy aquatic regions and nutrients. The majority of the most productive fisheries around the world are associated with either significant nutrients from runoff or deep oceanic derived nutrients (Diaz and Solow, 1999). Nutrients enter the food chain through increased phytoplankton production and are passed to other species. However, problems arise when the levels of nutrients exceed the ability of the food chain to process them. Ecological responses to the increased nutrient flux are increased primary production in the water column, increased flux of organic matter to the bottom, bottom-water hypoxia, altered energy flow, and stressed fisheries (Diaz and Solow, 1999).

The benthic zone is most adversely affected by hypoxic waters. It experiences more mortality, elimination of longer-lived species, and a shifting of productivity to non-hypoxic periods, called energy pulsing. Hypoxia causes a loss of bottom and near bottom habitats, for few if any mobile organisms remain in the oxygen depleted waters (Pavela et al., 1983; Leming and Stuntz, 1984). The energy pulsing favors opportunistic species that have shorter life spans that take advantage of the shorter period of bottom habitat.

The reduction of the longer-lived, burrowing species adversely affects the ecosystem in two ways. First, as they tend to be larger, they store large amounts of energy as biomass that buffers the system against energy pulsing. Secondly, the burrowing process helps cycle nutrients (Odum, 1991) and other sediment bound substances. The cycling aerates the sediment (Rhoads, 1974) and prevents the buildup of organic matter (Aller and Aller, 1998). The shorter-lived species do not perform these tasks near as well.

Hypoxia also harms pelagic species that are dependent upon bottom waters. This leads to other pelagic species to take a more prominent role in the ecosystem, diverting energy from invertebrates to microbes (Pearson and Rosenberg, 1992).

Excess nutrients in coastal waters have adverse effects besides hypoxia. They include decrease light penetration, which reduces the photic zone, loss of aquatic habitat, algal blooms, lowering of dissolved oxygen content in the pelagic zone, and altering the energy relationships within the ecosystem (Rabalais and others., 1999).

3.3 Occurrences and Origin of Nutrients

The Mississippi-Atchafalaya River Basin (MARB) is the third largest in the world, behind the Amazon and the Congo. It drains almost 3,208,700 km^2, including all or part of 30 states having a population of more than 70 million. The MARB is bounded by the Appalachian Mountains in eastern Pennsylvania and New York to the east, the Rocky Mountains in western Montana in the west, southern Canada to the north, and finally the Gulf of Mexico to the south. It is also one of the most productive farming regions on the planet. Cropland makes up 58% of the total land in the basin, 18% is woodland, 21% is range or barren land, 2.4% is wetlands or surface water, and 0.6% is urban (Rabalais and others., 1999). Streamflow is lowest in the fall and begins to increase in mid-winter peaking in May.

Climate, land use, soils, and population, all of which affect the concentration of nutrients in water, vary widely across the basin. The western portion of the basin receives significantly less precipitation than the eastern portion. The central portion of the basin is mainly agricultural. Wheat, corn, soybeans, and sorghum are some of the more common crops grown here. The majority of the fertilizers and pesticides that are applied each year in the U.S. are applied in the central region (Goolsby et al., 1999). There is also a significant number of livestock and poultry raised in the central portion. Large parts of the central region are tile drained, which provides control on the water table to make farming more efficient. Woodlands are common in the eastern, north central, and south central parts of the basin. Wetlands are found in the extreme northern and southern reaches of the basin. Most of the population resides in the eastern regions, primarily in the Ohio River Basin.

The mean annual flux of total nitrogen from 1980 to 1996 from the Mississippi-Atchafalaya River Basin. River Basin to the Gulf of Mexico was 1.6 million metric tons (Goolsby et al., 1999). During the same period, the total flux of phosphorus was about 136,000 metric tons. Of the total nitrogen flux, 61% is nitrate, 37% is dissolved and particulate organic nitrogen, and 2% is ammonium. Of the total phosphorus flux, 69% is in particulate and/or organic material. The remaining 31% occurs as dissolved orthophosphate. The concentration of nitrate in the Mississippi River and its tributaries in the Upper Midwest has increased two to fivefold in the last century. This is due in part to increased precipitation that resulted in a 30% increase in streamflow in the Mississippi River from 1970-1983 (Goolsby et al., 1999)

The total nitrogen flux has been variable with a direct correlation to precipitation and runoff. As mentioned previously, nitrate flux to the Gulf of Mexico was nearly double the yearly average after significant flooding in 1993. A much lower flux after the abnormally dry year of 1989. Higher streamflow leads to higher nitrate concentrations in several ways. First, there is a greater volume of water to dissolve nutrients. Then, increase precipitation leads to increased leaching of soils, groundwater systems, and unsaturated zones beneath cropland that store nitrogen, during years of low crop yield and below average precipitation. Finally, there is less time for dentrification, the natural conversion of nitrate to elemental nitrogen gas, to occur, because the stream is flowing much more rapidly.

The principal source of nitrogen to the Gulf of Mexico is from streams that drain heavily farmed areas in southern Minnesota, Iowa, Illinois, Indiana, and Ohio (Goolsby et al., 1999). Streams draining Iowa and Illinois contribute as much as 35% of the total nitrogen flux during years of average precipitation, despite making up only 9% of the total area of the Mississippi-Atchafalaya River Basin.

For purposes of comparison, in 1999 Goolsby and his coworkers split the MARB into nine smaller basins. On average, 34% of the nitrate and 32% of the total nitrogen to the Gulf of Mexico originates in the Upper and Lower Ohio River Basins, and 15% of the total nitrogen in the Missouri River Basin. The Upper and Middle Mississippi River Basins combine to contribute 39% total nitrogen, the Lower Mississippi 9%, and the combined Arkansas, Red, and Ouachita Basins contribute less than 8%. The Middle

Mississippi River Basin also contributes 33% of the total nitrate. The higher concentrations in the Middle Mississippi and the Ohio River Basins are due to the extensive agriculture in those regions. The largest loads from all 41 sub basins were all found in the regions with the largest percentage of agriculture lands. Lower loading rates in the western portions of the MARB are due to a drier climate, lower run-off, and different land use.

The Middle Mississippi and the Ohio River Basins are also the largest contributors to the total phosphorus flux to the Gulf. The Ohio River Basins contribute 29%, the Middle Mississippi 25%, the Missouri 19%, and the Lower Mississippi and Arkansas Basins 12%, with the remaining basins combing for the remaining 15% (Goolsby et al., 1999). The highest concentrations of orthophosphates in the sub basins are in areas of high population density or in watersheds with a high proportion of cropland. The highest phosphorus loads come from the Upper Illinois Basin that includes the third largest city in the country, Chicago.

Nonpoint sources contribute almost 90% of the total nitrogen and phosphorus that is discharged into the Gulf of Mexico. Fertilizers and mineralized soil organic nitrogen represent 50% of the total nitrogen flux, atmospheric deposition, groundwater discharge, and soil erosion are about 24%, animal manure is 15%, and municipal and industrial point sources account for 11% (Goolsby et al., 1999). Of the total phosphorus flux, 31% is from fertilizers, 18% is from animal manure, and 10% is from municipal and industrial point sources. The remainder is associated with basin run-off, especially soil erosion.

Atmospheric deposition is a small but significant contributor of nitrogen to the Gulf of Mexico. For the deposition of nitrate, it is most important in watersheds of the

Upper Ohio River Basin. Deposition of ammonia is high in Iowa and parts of Illinois and Minnesota, but is still relatively low compared to other sources (Goolsby et al., 1999). Deposition directly to the Gulf of Mexico is insignificant, as compared to other sources, and thus does not contribute to hypoxia in the gulf, as is the case with Chesapeake Bay.

4.0 The Scioto River Basin

The Scioto River originates near Roundhead, Ohio in Hardin County, flows through Marion, Delaware, Franklin, Pickaway, Ross, Pike, and Scioto Counties, and empties into the Ohio River in Portsmouth, Ohio. It is Ohio's second largest watershed, draining almost 16,800 km^2, which represents 16% of Ohio's total land area. It is subdivided into three sub basins, the Upper Scioto River, Olentangy River and Big Walnut Creek. The Upper Scioto River and Big Walnut Creek are surface water sources for drinking water in the Columbus metropolitan area.

The Big Walnut Creek sub basin has an area of almost 190 mi^2 of moderately to well drained soils of the Alexandria-Bennington-Cardington association laid down on Wisconsian low-lime glacial till (ODNR, 1973;1985). These soils are underlain by the Olentangy Shale, Ohio Shale, Delaware Limestone, and Columbus Limestone (Babcock, 2001). The growth of soybeans and corn occupy 60% of the land use (ODNR, 1973). There is a gently sloping topography in the sub basin. The Big Walnut Creek flows into Hoover Reservoir and provides instream storage for the Hap Cremean Water Plant.

The Olentangy River separates the Upper Scioto River sub basin from the Big Walnut Creek. Only 15 miles separates them at Hoover Reservoir. The Upper Scioto River drains 980 mi^2 and has relatively flat topography. The soil type is of Blount-

Pewarmo association, which is poorly drained. It was formed by glacial till that is rich in carbonate minerals. The Delaware Limestone and Columbus Limestone underlie the soil in the city of Columbus quadrangle (Babcock, 2001). Good soils from the parent glacial materials provides the basis for large-scale crop-row production of corn and soybeans (ODNR, 1973; 1985). However, due to the poorly drained character of the soil extensive subsurface drainage systems are required, in contrast to the Big Walnut Creek sub basin. Approximately 80% of the land in the Upper Scioto River is used for agricultural purposes (ODNR, 1973). Griggs Reservoir and O'Shaughnessy Reservoirs retain water from the Upper Scioto River for the Dublin Road Water Plant.

The Scioto River flows through several different soil associations in its path. A soil association is a combination of soil series that are common in certain areas. The Blount-Pewamo-Glynwood association is in Hardin, Marion, and Delaware counties, then the Miamian-Kokomo-Eldean association in Franklin, Pickaway and half of Ross counties, then the Clermont-Rossmoyne-Avonburg-Cincinnati association in the other half of Ross and part of Pike counties, and then Shelocta-Brownsville-Latham-Steinsburg association in the rest of Pike and Scioto counties.

In the northern part of the Scioto River Basin the stratigraphically youngest formation is the Olentangy Shale and in descending order, the Ohio Shale, Delaware Limestone, and Columbus Limestone. All these formations originate from the Devonian Period, formed in a shallow epicontinental sea. Ohio was located just south of the equator during this time and was a basin receiving sediments from the Taconic Mountains to the east.

The Olentangy and Ohio Shales are of late Devonian age. The Olentangy Shale is bluish to greenish gray, has thin interbeds of limestones, and contains flattened, disc-shaped concretions. It is 28 ft thick in central Ohio and fossils are uncommon. The Ohio Shale is much thicker, 250-500 ft in outcrops in Ohio. It is black due to its high organic content and contains heavy metals and uranium. The Ohio Shale is subdivided into three members, the Huron Shale, the Chagrin Shale, and the Cleveland Shale Members.

The Delaware and Columbus Limestones were formed in the Middle Devonian. They were first named and subdivided by Edward Orten in 1878. The Delaware Limestone is the younger of the two and is nearly 1/3 as thick. It has a higher silt content that imparts a darker gray to bluish color that differentiates it from other limestones. The Columbus Limestone is dolomitic in the lower part and very fossiliferous in the upper part. The Delaware Limestone is not separated into members but the Columbus Limestone is split into the Bellepoint, the Eversole, and the Delhi Members. These two formations extend northward to Lake Erie and pinch out to the south.

4.1 Differences in Nutrient Concentrations between Sub basins

Nutrient data from the reservoirs in or near Columbus shows that ones that are fed by the Upper Scioto have higher nitrate concentrations than Big Walnut Creek or the Olentangy River (Shamblin and Binder, 1996). This variation is due to several factors including differences in reservoir volumes, watershed areas, and land management. Hoover Reservoir has a larger volume and residence time than Griggs and O'Shaughnessy combined. The longer residence time and the dilution that results lowers the nitrate concentrations. The Big Walnut Creek watershed is five times smaller than

Upper Scioto River and thus has less nutrient inputs. The nitrate-loading rate in the Upper Scioto River is nearly double than that of the Big Walnut Creek. It has much higher peaks as well as higher deviations from the average.

Tile drainage is used extensively in the Upper Scioto River sub basin while it is not in the Big Walnut Creek. This means that the Scioto River receives more direct agricultural run-off than its counterpart. It has been shown that subsurface discharges can account for more than half of average annual stream flow (Burwell et al., 1976). Subsurface discharges also increase leaching of residual nitrate in the soil so nitrate concentrations are usually higher in subsurface discharge than in surface run-off (Baker, 1985; Logan et al., 1994).

The differences in the nitrate loading rates between the different water plants is in line with correlations found by other researchers. Watersheds with lots of crop-row agriculture and subsurface drainage have increased nitrate loading rates and higher variability (Neilson et al., 1977; Baker, 1985). There are three watersheds in northwestern Ohio that have crop-row agriculture and subsurface drainage have similar nitrate loading rates to the Upper Scioto River, approximately 12 pounds per acre (Shamblin and Binder, 1996).

4.2 Griggs and O'Shaughnessy Reservoirs

The major objective of this study is to learn more about nutrient loading in the Scioto River system. The City of Columbus monitors the Griggs and O'Shaughnessy Reservoirs, which are fed by the Scioto River, as part of compliance for the Clean Water Act. Samples are collected monthly and analyzed for nitrate, ammonia, and orthophosphates. The data is tabulated annually and a 15-year period of data became available for the following analysis.

Construction on Griggs Reservoir started in 1903 and was dedicated in 1908. It was built to provide a drinking water source for the city of Columbus, which it still does after all these years. It is named after Julian Griggs who was the city's Chief Engineer at the time. It is a long, narrow reservoir with an area of 365 acres and has 15 miles of shore land. It is located in Dublin, Oh, just to the northwest of Columbus. It has a normal pool of 755.9 (feet above msl), has a surface water area of 522 acres, a volume of water of 1.4 billion gallons, a length of 5.9 miles, a maximum width of 800 ft, spillway length of 500 ft, and a maximum height of spillway of 46 ft.

The O'Shaughnessy Reservoir was completed in 1925. It was built as an alternative to increasing the height of Griggs Reservoir. It was built by the City of Columbus Waterworks and was named after a former superintendent, Jerry O'Shaughnessy. It is located in southern Delaware County, only a few miles north of Griggs Reservoir. It has a water surface area of 943 acres, a volume of water of 4.8 billion gallons, a length of 6.5 miles, a maximum width of 1900 ft, and an 880-foot long spillway that is 75 ft at its tallest.

4.3 Analysis of Nutrient Data

The O'Shaughnessy Reservoir shows consistently higher nitrate concentrations than Griggs Reservoir. Over the last fifteen years every monthly mean nitrate concentration in O'Shaughnessy is higher than Griggs. For every year on record the total yearly concentration in O'Shaughnessy is higher than Griggs. The average monthly nitrate concentration for Griggs Reservoir is 3.60, while the monthly mean concentration for O'Shaughnessy is 3.9. Thus, although Griggs and O'Shaughnessy are located only a few miles apart, they exhibit a significant variation in their nitrate levels.

If it can be assumed that there are no significant inputs between the two reservoirs then the difference must be due to either the physical differences between them or losses due to interactions in the river channel between the reservoirs. O'Shaughnessy has nearly triple the water surface area, 2.5 times the volume, is higher, longer, and wider than Griggs Reservoir. Since Griggs is shorter and skinnier more of its volume of water it is contact with the benthic zone, where the process of dentrification occurs. Thus, a higher percentage of nitrates are converted to nitrogen gas in Griggs compared to O'Shaughnessy. Due to the larger surface area of O'Shaughnessy, it receives more atmospheric deposition of nitrate than its smaller counterpart. Atmospheric deposition can be a significant source of nitrate in this portion of the country (see above) and it probably is partly culpable for the difference in nitrate concentrations.

Despite the slight differences in nitrate concentrations between the two reservoirs, the time variation in the nitrate concentration showed a similar pattern in each. There are peaks in early spring time (March and April). Concentrations slowly fall until late summer/early fall when they plummet in the autumn months, and rise again in early winter. There are of course many exceptions to this pattern over the past 15 years but they can usually be explained by the previous months data. For instance, an abnormally high value in September is due to low values in the few months preceding it.

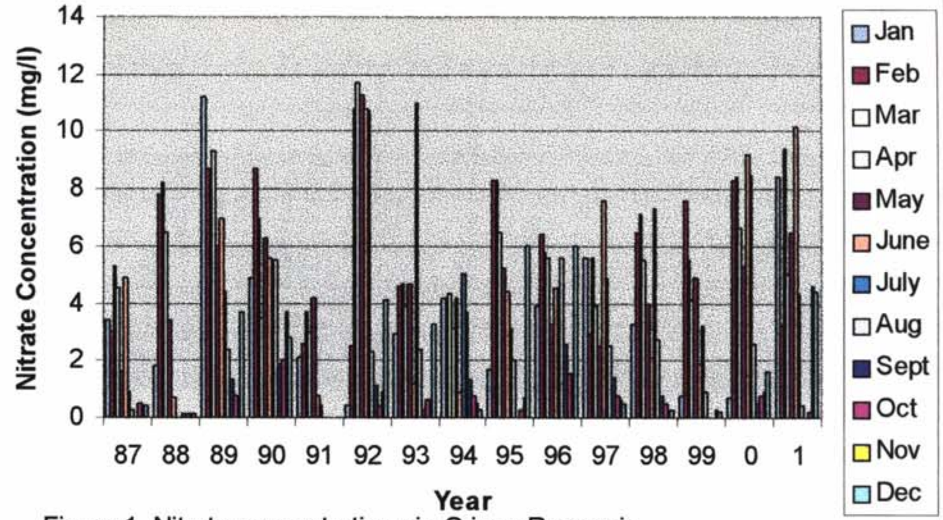

Figure 1 Nitrate concentrations in Griggs Reservoir

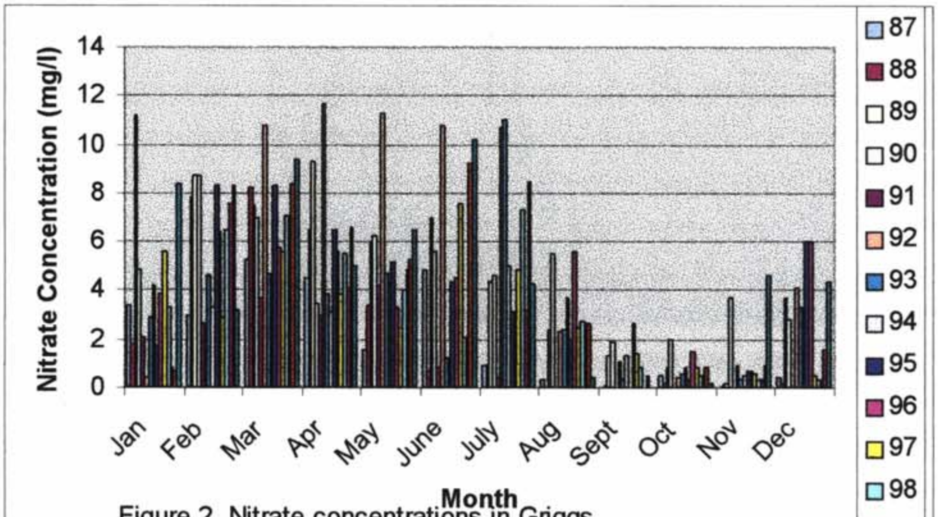

Figure 2 Nitrate concentrations in Griggs

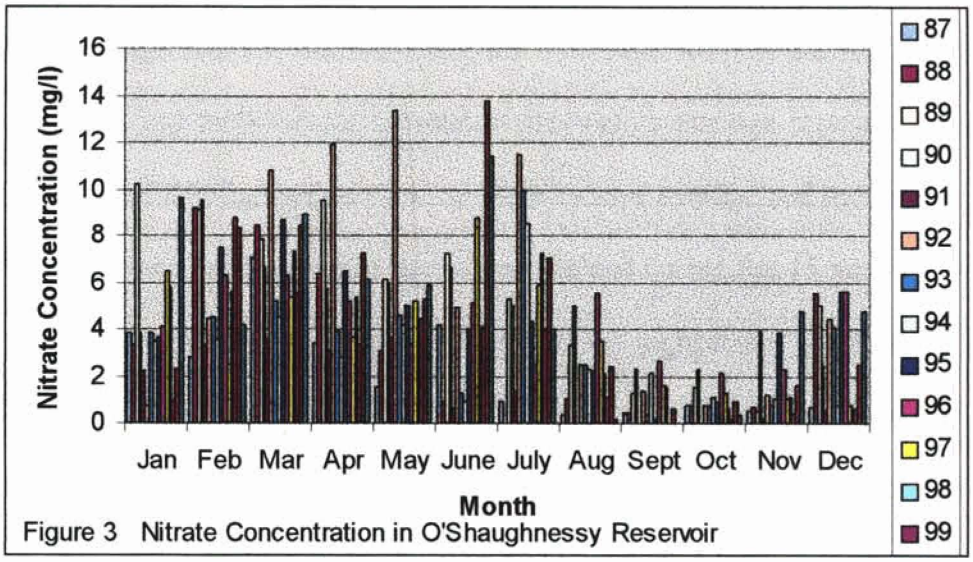

Figure 3 Nitrate Concentration in O'Shaughnessy Reservoir

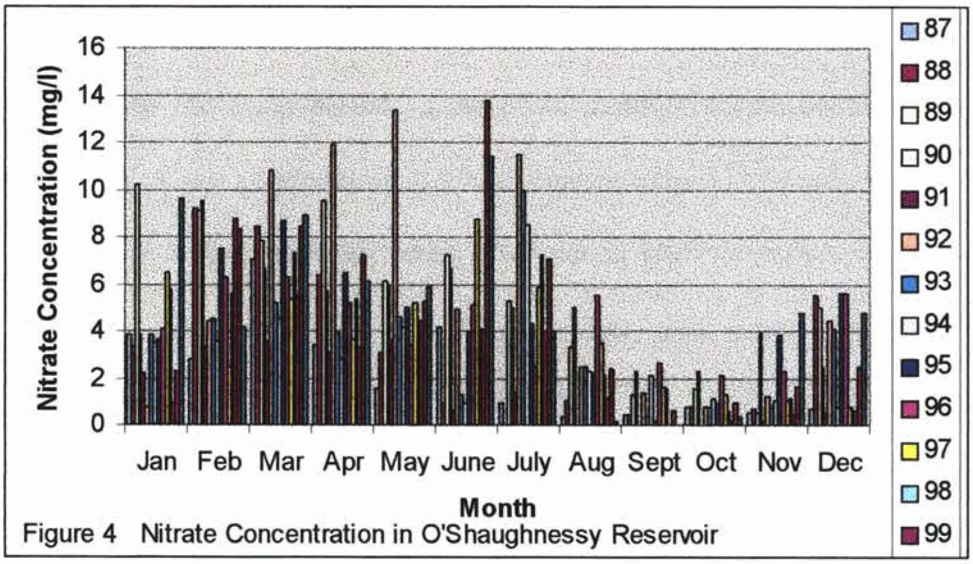

Figure 4 Nitrate Concentration in O'Shaughnessy Reservoir

Nitrate concentrations in the Scioto River exhibits a strong correlation with precipitation levels. Nitrate concentrations are at their highest in months that receive the most rainfall, i.e. March, April, and May. Abnormally low concentrations in these months are almost always explained by below average precipitation in the month. The same goes for other months that have an aberrantly high value, more precipitation than usual.

The average monthly nitrate totals for both reservoirs of interest were below average in 1987 and 1988, which correlates with below average precipitation data in Central Ohio. In 1989, rainfall was several inches above average and the mean monthly nitrate totals for both reservoir were the second highest during the 15 year period. The following year of 1990, the precipitation levels were the highest they reached in the study period and the average monthly nitrate totals were well above average for both reservoirs. The reason why 1990 does not represent the year of the highest monthly nitrate totals is because of the significant leaching of the soil that occurred in the previous year, thus eliminating much of the source material. A similar pattern was followed for the remaining years of the study period. Low mean monthly nitrate concentration totals occurred in years of low precipitation and high concentrations occurred in years of high precipitation. The average monthly totals were not as high in years of above average rainfall if the preceding year also had a higher than usual amount of precipitation, leaching much of the available nitrate from the soils.

The average value for January is 3.69 (all values are mg/l) for Griggs Reservoir and 4.39 for O'Shaughnessy. The nitrate level in Griggs in January has an all time high (for years on record) of 11.2, in 1989 while the all time high in O'Shaughnessy Reservoir was 10.2, also in 1989. These high values are not indicative of the usual values of nitrate for January, as shown by the monthly averages. However, January usually represents the beginning of the winter growth in nitrate values. Also, there can be a spike in nitrate values if lower than normal values were evident in the previous months, as happened in late 1988. These are the two only times nitrate levels have exceeded the MCL in January.

The lows for both the reservoirs in January also occurred in the same year of 1992, with a value of 0.4 for Griggs and 0.8 in O'Shaughnessy.

For the month of February, the monthly average for Griggs is 5.63 and 6.08 for O'Shaughnessy. Nitrate levels hit an all time high for both the reservoirs in 1990, when Griggs reported a value of 8.7 and O'Shaughnessy 9.5. The all time low values are 2.5 for both the reservoirs, which occurred in 1992 for Griggs, and 1997 for O'Shaughnessy. This follows the pattern of growth in nitrate values as the winter months continue.

The monthly average for nitrate in Griggs is 6.78 and 6.79 in O'Shaughnessy for March. It is the month averaging the highest nitrate values for either reservoir. This follows the general pattern stated above, as the big spring pulse following the farmer's application of fertilizers. March is also one of the months in central Ohio that receives the largest amount of precipitation. The all time high value for Griggs is 11.7 in 1992, which also is the single highest value ever recorded at the reservoir. The all time high for O'Shaughnessy was 10.8, which was also recorded in 1992. These are the only two times the MCL was exceeded in the month of March. The lows for both happened in 1991 with a value of 3.0 for Griggs and 3.6 for O'Shaughnessy. As further evidence of the high early spring pulse, both the lows exceed the averages tabulated for the months of August, September, October, November, and December for both reservoirs.

The monthly mean of nitrate dropped in April for both reservoirs, 5.52 for Griggs and 5.73 for O'Shaughnessy, but still remained one of the higher monthly values. The highest values recorded were 11.7 in 1992 and 11.9 also in 1992 at Griggs and O'Shaughnessy respectively. These are the only two times the MCL was exceeded. The low value at Griggs was 1.6 in 1987 and 3.0 at O'Shaughnessy.

The average monthly values of nitrate continued a slow decline in the month of May. A 4.89 average was calculated for Griggs and a 5.19 for O'Shaughnessy. Griggs had a high value of 11.3 and O'Shaughnessy 13.4, both recorded in the abnormally wet year of 1992. These are the only two occasions where the MCL was exceeded in the month of May. The low values were 1.6 at Griggs in 1987 and 2.8 at O'Shaughnessy in 1994.

While the monthly mean values for June continued a slow decline, they stayed relatively level with Griggs averaging 4.79 and O'Shaughnessy 4.82. The MCL was exceeded twice at each reservoir with the single highest value recorded at either reservoir being a 13.8 at O'Shaughnessy in 2000, while the high at Griggs for the month was 10.7 in 1992. A low value of 0.7 was recorded for Griggs in 1988 and 0.9 at O'Shaughnessy in 1988 and 1994, when precipitation levels were very low. As the high and low values would indicate, the month nitrate concentrations in June were highly variable.

In July, the monthly average nitrate concentrations stayed relatively stable. Griggs showed a slight decline down to 4.73 and O'Shaughnessy had a small raise to 5.11. The high value for Griggs was 10.7 and O'Shaughnessy 11.5 both in 1992. O'Shaughnessy also exceeded the MCL in 2000 giving July three violations. The low values for both reservoirs was less than the detection limit of 0.2, which occurred at both reservoirs in 1988. July had a wide range of nitrate values, as the only month that exceeded the MCL and had lower than detectable concentrations.

The mean monthly data for August showed a shows a sharp decline. Griggs had a value of 2.25 while O'Shaughnessy dropped to 2.26, once again only slightly higher than its southern neighbor. 5.6 in 1996 was the high value for Griggs and 5.5 for

O'Shaughnessy in 1993. A concentration of less than 0.2 was recorded at both reservoirs in 1998 and 1991 for Griggs.

The average nitrate concentrations were typically low during the month of September. The mean at Griggs dropped to 0.91 and 1.03 at O'Shaughnessy. Both reservoirs had high values of 2.6 measured in 1992. September was the month with the most samples with concentrations below the detection limit. Below detection concentrations were evident in Griggs in 1987, 1991, 1995, 1999, and 2001 and O'Shaughnessy in 1991, 1999, and 2001.

The monthly mean concentrations of nitrate plateau during the month of October. Griggs showed a small decline compared to the previous months data to 0.63 while O'Shaughnessy showed a slight increase to 1.07. The high value for Griggs was1.5 and 2.3 for O'Shaughnessy, both in 1986. The detection levels were not met in 1991 for both reservoirs and in 1999 in Griggs.

Nitrate levels typically exhibited a small increase in the month of November, with Griggs growing to 0.94 and O'Shaughnessy to 1.68. High values were 4.6 for Griggs and 4.8 for O'Shaughnessy both recorded in 2001. Nitrate concentrations did not exceed detection limit for both reservoirs in 1991 and Griggs in 1987.

In December, nitrate levels were significantly higher than in the fall months. The monthly average for Griggs was 2.25 and O'Shaughnessy 2.97. The high values were 6.0 for Griggs and 5.6 for O'Shaughnessy, which were reported in 1995 and 1996. The low value for O'Shaughnessy was 0.5 in 1991; the same year detection levels were not met in Griggs.

Ammonia concentrations near Columbus show a different seasonal pattern as compared to nitrates. Concentrations are highest in the late winter months, with February having the highest mean monthly concentration for both reservoirs. The ammonia levels slowly decrease from this point, reaching a low point in August, which has the lowest monthly average of ammonia concentrations. A slow rise begins in ammonia concentrations in September reaching their peak once again in the month of February. The 15-year highs of ammonia concentration occurred in February for both reservoirs, a 0.38 for Griggs in 2001 and 0.55 for O'Shaughnessy also in 2001. The only months that did not have a detection limit (<0.02) met were January, February, and March, for both reservoirs and December in Griggs.

There is very little difference in the ammonia concentrations between the two reservoirs, but O'Shaughnessy exhibited slightly higher concentrations. The difference is not nearly as pronounced as for nitrate. The mean monthly concentrations were higher in eight months in O'Shaughnessy, though only by a small amount, and two months were statistically the same. O'Shaughnessy had a higher total yearly ammonia load in nine of the years in the study. It also had a higher average monthly ammonia concentration with a 0.10, compared to Griggs with a 0.09.

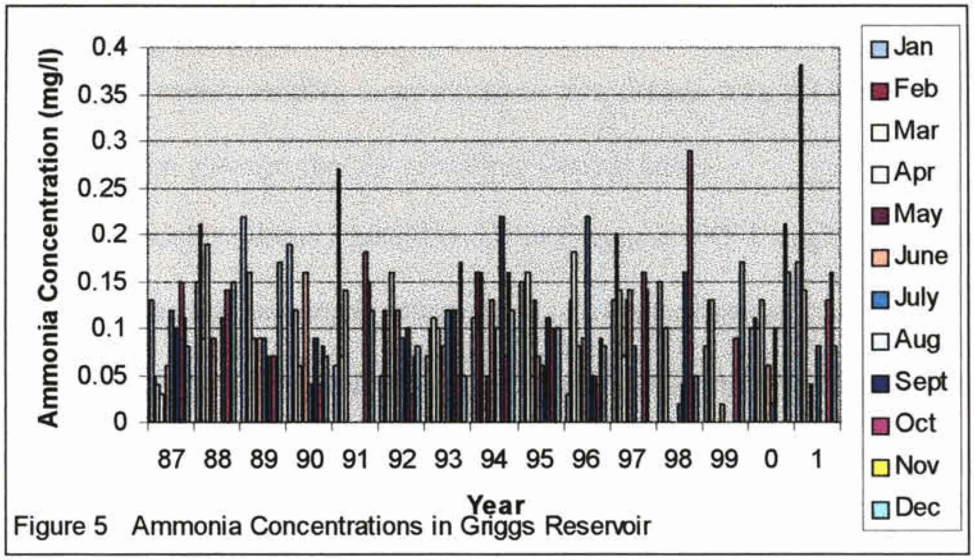

Figure 5 Ammonia Concentrations in Griggs Reservoir

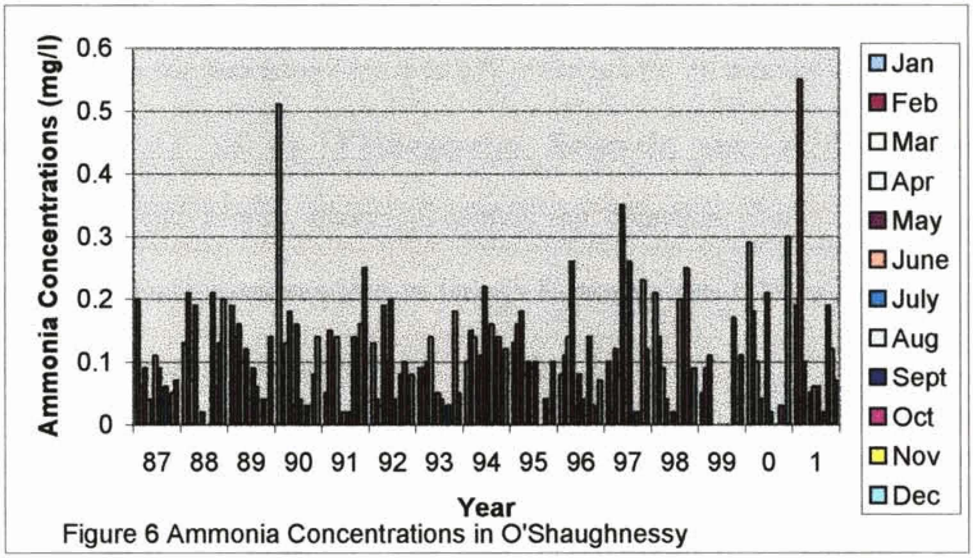

Figure 6 Ammonia Concentrations in O'Shaughnessy

There is a correlation between ammonia concentrations and rainfall but it is not as strong as the connection between nitrate and rainfall. Ammonia concentrations were generally higher in years of above average precipitation and lower in years of below average precipitation. By year, the highest mean monthly concentration for O'Shaughnessy Reservoir was 0.18, and it occurred in the wettest year in the study period, of 1990. The lowest monthly average concentrations by year were 0.05 for

O'Shaughnessy and Griggs, with a 0.06, occurred in the driest year of 1999. However, the highest mean monthly concentrations for Griggs was 0.11 in 1994, which was a slightly below average year for rainfall in Central Ohio.

Orthophosphorus concentrations in Griggs and O'Shaughnessy Reservoirs follow a similar seasonal pattern to ammonia. Orthophosphorus concentrations are at their highest in early winter, decline slightly in spring, stay relatively stable until late summer when they decline to almost nondetectable levels in fall, and rise again in early winter. For Griggs Reservoir, the highest mean monthly concentration of orthophosphorus was in February at 0.17, while for O'Shaughnessy it was in January at 0.20. Concentrations were below the detection limit (<0.02) in Griggs for all months except March during the study period. In the O'Shaughnessy Reservoir, samples for December, January, February, and March always exceeded the detection limit. The 15-year high of orthophosphate concentrations in Griggs Reservoir was 0.39 in December 2001 and for O'Shaughnessy it was 0.44 in also in 2001.

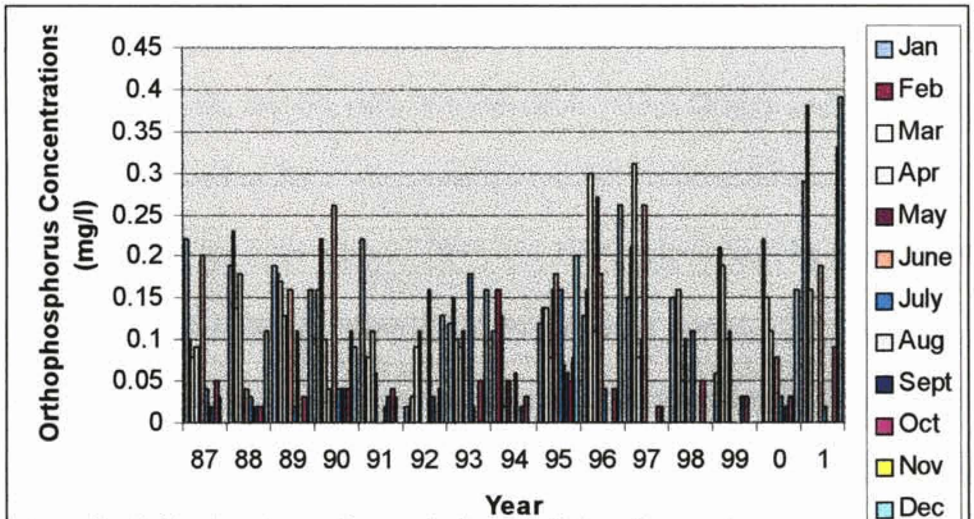

Figure 7 Orthophosphorus Concentrations in Griggs Reservoir

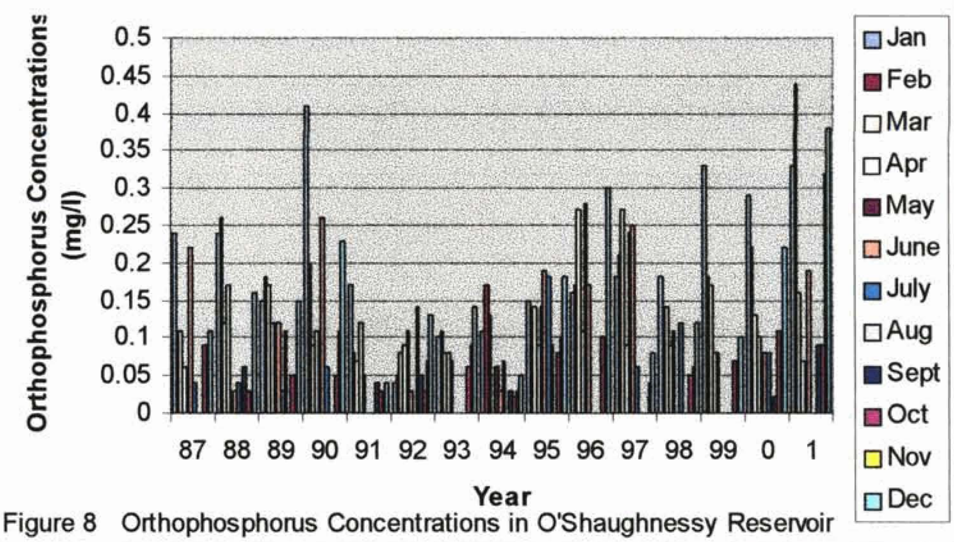

Figure 8 Orthophosphorus Concentrations in O'Shaughnessy Reservoir

The orthophosphorus levels were slightly higher in O'Shaughnessy, as compared to Griggs. The mean monthly concentrations were higher in O'Shaughnessy for seven months, with four statistical ties. O'Shaughnessy had a higher yearly total than Griggs in 13 years out of the 15 year study. O'Shaughnessy also has a higher mean monthly load at 0.10, compared to 0.08 for Griggs.

Orthophosphorus concentrations are less correlated to precipitation levels than either nitrate or ammonia, but do show a connection. Both Griggs and O'Shaughnessy had its highest yearly load in 2001 when average rainfall occurred in central Ohio, but the next two highest years for both were in 1995 and 1996, which had the second and third highest amounts of precipitation respectively, in the study period. The study year with the highest rainfall was 1990, but the orthophosphate concentration for Griggs was only slightly above average and O'Shaughnessy had the fourth highest yearly total on record. The lowest amount of rainfall during the study period fell during 1999, Griggs had the fourth lowest yearly total but O'Shaughnessy was a little below the yearly average.

O'Shaughnessy had its lowest yearly total in 1991, the second lowest year in terms of precipitation, but Griggs had its lowest yearly total of orthophosphorus in 1992, a year of just about average rainfall.

4.4 Relative Importance of Scioto River's Nutrient Contribution to Gulf of Mexico

Goolsby and his coworkers split the MARB into 9 smaller basins and 42 interior subbasins. The sub basins represent about 70% of the total land area of the MARB. Three rivers in Ohio are included in the 42 subbasins, the Scioto, Muskingham, and Great Miami Rivers. The Scioto River Basin has one of the higher nitrate concentrations. This is because of a high population density (compared to other sub basins) and crop-row agriculture.

The Scioto River, as well as the other Ohio streams in Goolsby's study, is located within the Upper Ohio River Basin. The Upper Ohio is second only to the Middle Mississippi River Basin in nitrate contributions to the Gulf of Mexico. The Middle Mississippi River Basin drains the heavily cultivated areas of Iowa, Illinois, southern Wisconsin, and northern Missouri, similar to the area drained by the Upper Ohio.

The Scioto River Basin ranks as the ninth highest sub basin in terms of average nitrate concentration. The sub basins that have a higher contribution of nitrate to the Gulf of Mexico are all located in Iowa or Illinois, and one each in southern Minnesota, western Ohio, and northern Missouri. Nitrate contributions from the Scioto are all the more impressive in light of the eight basins that have a higher average concentration, only three have less area, and only the Miami River Basin is smaller by more than a 1000 km^2. Of the nine sub basins, the Scioto ranks third in population density and last in percentage of cropland. For purposes of comparison, out of all 42 sub basins the Scioto River still ranks in population density and ninth in percentage of cropland.

5.0 Summary

Nutrients are necessary in water for a healthy aquatic environment. They are also essential for terrestrial plant life. Consequently, they are often applied to crops in the form of commercial fertilizers. However, not all the nutrients are used by the crops and the remainder enters the water supply through runoff and leaching of soils. This loading presents a problem because nutrients in large concentrations have adverse effects on aquatic health.

There are other sources of nutrients besides fertilizers, including animal manure, soil mineralization, atmospheric deposition, and point sources. However, excess fertilizers is the most common source. Nitrate is the most important nutrient in terms of risk of contamination but ammonia and orthophosphates also play a role.

The Mississippi River Basin is the third largest in the world. It drains all or part of 30 states, including almost all of Ohio. Large tracts of land in the basin are used for extensive crop row agriculture, which almost always involves the use of fertilizers. As a result, large amounts of nutrients enter the Mississippi River and end up being discharged into the Gulf of Mexico. The largest amounts of nutrients enter the Gulf in early spring and summer, when streamflow is highest for the Mississippi River.

Excess nutrients in the Gulf of Mexico fuel an increased production of algae. The overgrowths of algae appear as a green scum on the water and harms recreational and commercial uses of the water. The overproduction of algae is referred to as eutrophication. When the algae die, their remains fall down the water column eventually reaching the bottom as a collection of organic matter. Bacteria decompose the algae in an oxygen consuming process, which depletes the supply of oxygen in the bottom waters. The warm, freshwater from the Mississippi River also floats on the top of the benthic zone and the stratification that results with the colder, salt water of the ocean prevents the reoxygenation of the bottom waters. Each year in the early spring the dissolved oxygen content falls below 2 mg/l, a condition known as hypoxia, and usually remains that way until late summer/early fall.

The Scioto River Basin is an interior sub basin of the Mississippi River. It contributes a relatively large amount of nutrients to the Gulf of Mexico, as compared to other interior sub basins. The Scioto River is also a surface water-drinking source for the City of Columbus, Ohio. Water is collected in Griggs and O'Shaughnessy Reservoirs, where water quality samples are taken. This researcher obtained nutrient concentration data and analysis was performed to understand trends and factors involved in nutrient concentrations.

A seasonal pattern of nitrate concentrations was found. Nitrate levels are at their highest in the spring. The concentrations gradually fall through late summer when they drop dramatically. Nitrate concentrations then stay low until mid-winter when they begin to rise again. The pattern can be explained in terms of timing of fertilizer application, usually in early spring when the growing season begins in Central Ohio and precipitation levels. Nitrate concentrations are directly related to rainfall; in years of higher rainfall there will be higher concentrations of nitrate and vice versa. A similar pattern was found with both ammonia and orthophosphates, but neither was as pronounced as nitrate.

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Appendix A

Nutrient Data for O'Shaughnessy and Griggs Reservoirs

Nitrate/Nitride Concentrations in O'Shaughnessy Reservoir

	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
Jan	3.8	3.3	10.2	3.8	2.2	0.8	3.8	3.5	3.7	4.1	6.5	5.8	0.9	2.3	9.6
Feb	2.8	9.2	9.1	9.5	3.3	4.4	4.5	3.6	7.5	6.3	2.5	5.6	8.8	8.3	4.2
Mar	7.1	8.4	7.8	6.6	3.6	10.8	5.2	4.5	8.7	6.3	5.4	7.3	5.5	8.4	8.9
Apr	3.4	6.4	9.5	5.7	3.1	11.9	3.9	2.8	6.5	5.2	3.7	5.4	3.3	7.2	6.1
May	1.5	3.1	6.1	6	3.7	13.4	4.6	4.2	5	3.4	5.2	3.9	4.4	5.3	5.9
June	4.2	0.9	7.2	6.6	0.6	4.9	1.3	0.9	4	5.1	8.8	1.9	4.1	13.8	11.4
July	0.9	<0.2	5.3	5	1.4	11.5	10	8.5	4.3	2.5	5.9	7.2	4	7.1	4
Aug	0.3	1	3.3	5	<0.2	2.5	2.5	2.3	2.2	5.5	3.5	2.1	1.1	2.4	0.2
Sept	0.4	0.4	1.3	2.3	<0.2	1.4	0.3	2.1	0.2	2.6	1.6	1.5	<0.2	0.6	<0.2
Oct	0.8	0.8	1.5	2.3	<0.2	0.8	0.8	1.1	0.9	2.1	1.3	0.6	0.2	0.9	0.3
Nov	0.5	0.7	0.5	3.9	0.2	1.2	0.8	1	3.8	2.3	1	1.1	0.4	1.6	4.8
Dec	0.7	5.5	5	2.5	0.5	4.4	4.1	0.8	5.6	5.6	0.8	0.6	0.6	2.5	4.8

Ammonia Concentrations in O'Shaughnessy Reservoir

	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
Jan	0.2	0.13	0.19	0.51	0.05	0.13	0.09	0.1	0.13	0.08	0.1	0.21	0.05	0.29	0.19
Feb	0.06	0.21	0.14	0.1	0.15	0.04	0.09	0.15	0.16	0.11	0.02	0.14	0.09	0.18	0.55
Mar	0.09	0.07	0.16	0.13	0.09	0.03	0.1	0.14	0.18	0.14	0.12	0.09	0.11	0.1	0.1
Apr	0.04	0.19	0.1	0.18	0.14	0.19	0.14	<0.02	0.08	0.26	0.08	0.04	<0.02	0.04	<0.02
May	<0.02	<0.02	0.12	0.03	0.02	0.1	<0.02	0.11	0.1	0.03	0.35	<0.02	<0.02	<0.02	0.05
June	0.11	0.02	0.04	0.16	0.02	0.2	0.05	0.22	0.09	0.08	0.16	0.02	<0.02	0.21	0.06
July	0.09	<0.02	0.09	0.04	<0.02	0.04	0.04	<0.02	0.1	0.04	0.26	<0.02	<0.02	0.02	0.06
Aug	0.04	<0.02	0.06	<0.02	0.02	<0.02	<0.02	0.16	<0.02	<0.02	<0.02	0.2	<0.02	<0.02	<0.02
Sept	0.06	0.21	<0.02	0.03	0.14	0.08	0.03	0.05	<0.02	0.14	0.02	0.02	<0.02	<0.02	0.02
Oct	<0.02	0.06	0.04	<0.02	0.05	0.1	<0.02	0.14	0.04	0.03	<0.02	0.25	0.17	0.03	0.19
Nov	0.05	0.13	0.04	0.08	0.16	0.06	0.18	0.06	0.02	0.02	0.23	<0.02	<0.02	<0.02	0.12
Dec	0.07	0.2	0.14	0.14	0.25	0.08	0.05	0.12	0.1	0.07	0.12	0.09	0.11	0.3	0.07

Orthophosphorus Concentrations in O'Shaughnessy Reservoir

	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
Jan	0.24	0.24	0.15	0.41	0.17	0.04	0.1	0.11	0.15	0.16	0.18	0.18	0.33	0.29	0.33
Feb	0.04	0.26	0.18	0.2	0.08	0.05	0.11	0.17	0.14	0.17	0.21	0.14	0.18	0.22	0.44
Mar	0.11	0.12	0.17	0.09	0.07	0.08	0.08	0.13	0.14	0.27	0.27	0.14	0.17	0.13	0.16
Apr	0.06	0.17	0.12	0.11	0.12	0.09	0.08	<0.02	0.09	0.11	0.09	0.09	0.08	0.1	0.07
May	<0.02	<0.02	0.1	0.03	0.05	0.11	0.07	0.06	0.14	0.28	0.24	0.11	0.08	<0.02	<0.02
June	0.22	0.03	0.12	0.26	<0.02	0.03	<0.02	0.03	0.19	0.17	0.25	<0.02	<0.02	0.08	0.19
July	0.04	0.04	0.03	0.06	<0.02	<0.02	<0.02	0.07	0.18	<0.02	0.06	0.12	<0.02	0.08	<0.02
Aug	<0.02	<0.02	0.11	<0.02	<0.02	0.14	<0.02	<0.02	0.09	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Sept	<0.02	0.06	<0.02	<0.02	0.04	0.05	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	0.02	0.09
Oct	0.09	0.03	0.05	0.05	0.03	0.03	0.06	0.02	0.08	0.1	<0.02	0.05	0.07	0.11	0.09
Nov	0.06	0.02	<0.02	0.11	0.03	0.07	0.09	0.03	0.1	0.07	0.04	0.06	<0.02	0.1	0.32
Dec	0.11	0.16	0.15	0.23	0.04	0.13	0.14	0.05	0.18	0.3	0.08	0.12	0.1	0.22	0.38

Nitrate/Nitride Concentrations in Griggs Reservoir

	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
Jan	3.4	1.8	11.2	4.9	2.1	0.4	2.9	4.2	1.7	3.9	5.6	3.3	0.8	0.7	8.4
Feb	3	7.8	8.7	8.7	2.6	2.5	4.6	3.3	8.3	6.4	2.9	6.5	7.6	8.3	3.2
Mar	5.3	8.2	7.5	7	3.7	10.8	4.7	4.3	8.3	5.8	5.6	7.1	5.5	8.4	9.4
Apr	4.5	6.5	9.3	3.5	3	11.7	3.9	3.1	6.5	5.6	3.9	5.5	4.1	6.6	5
May	1.6	3.4	6	6.3	4.2	11.3	4.7	4.2	5.2	3.3	2.5	4	4.9	5.3	6.5
June	4.9	0.7	7	5.6	0.8	10.8	1.2	0.9	4.4	4.5	7.6	2.1	1.9	9.2	10.2
July	0.9	<0.2	4.4	4.6	0.4	10.7	11	5	3.1	2.7	4.9	7.3	3.2	8.5	4.3
Aug	0.3	>0.2	2.4	5.5	<0.2	2.3	2.4	3.7	2	5.6	2.5	2.7	0.9	2.6	0.4
Sept	<0.2	0.11	1.3	1.9	<0.2	1.1	0.3	1.3	<0.2	2.6	1.4	0.8	<0.2	0.5	<0.2
Oct	0.5	0.14	0.8	2	<0.2	0.4	0.6	0.8	0.3	1.5	0.8	0.5	<0.2	0.8	0.2
Nov	<0.2	0.09	0.2	3.7	<0.2	0.9	0.3	0.5	0.7	0.7	0.6	0.3	0.3	0.9	4.6
Dec	0.4	0.15	3.7	2.8	<0.2	4.1	3.3	0.3	6	6	0.5	0.3	0.2	1.6	4.4

Ammonia Concentrations in Griggs Reservoir

	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
Jan	0.13	0.15	0.22	0.19	0.06	0.05	0.07	0.11	0.15	0.03	0.13	0.15	0.08	0.1	0.17
Feb	0.05	0.21	0.1	0.11	0.27	0.12	0.1	0.16	0.11	0.13	0.2	0.08	0.13	0.11	0.38
Mar	0.04	0.09	0.16	0.12	0.07	0.05	0.11	0.16	0.16	0.18	0.14	0.1	0.13	0.1	0.14
Apr	0.03	0.19	0.09	0.06	0.14	0.16	0.1	<0.02	0.05	0.08	0.07	<0.02	<0.02	0.13	<0.02
May	0.03	0.06	0.08	0.04	<0.02	0.04	<0.02	0.05	0.13	0.07	0.13	<0.02	<0.02	<0.02	0.04
June	0.06	0.09	0.09	0.16	<0.02	0.12	0.08	0.13	0.07	0.09	0.14	<0.02	0.02	0.06	<0.02
July	0.12	<0.02	0.09	0.04	<0.02	0.09	0.12	<0.02	0.06	0.22	0.08	0.02	<0.02	0.02	0.08
Aug	0.03	<0.02	0.06	<0.02	<0.02	0.03	0.04	0.1	<0.02	<0.02	<0.02	0.04	<0.02	0.1	<0.02
Sept	0.1	0.11	0.07	0.09	<0.02	0.1	0.12	0.22	0.11	0.05	<0.02	0.16	<0.02	<0.02	<0.02
Oct	0.15	0.14	0.07	0.04	0.18	0.03	0.05	0.07	0.1	0.04	0.16	0.29	0.09	<0.02	0.13
Nov	0.11	0.09	0.04	0.08	0.15	0.07	0.17	0.16	0.09	0.09	0.14	<0.02	0.03	0.21	0.16
Dec	0.08	0.15	0.17	0.07	0.12	0.08	0.05	0.12	0.1	0.08	<0.02	0.05	0.17	0.16	0.08

Orthophosphorus Concentrations in Griggs Reservoir

	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
Jan	0.22	0.19	0.19	0.16	0.22	0.02	0.12	0.11	0.12	0.13	0.15	0.15	0.06	<0.02	0.29
Feb	0.1	0.23	0.18	0.22	0.07	<0.02	0.15	0.16	0.14	0.16	0.21	0.13	0.21	0.22	0.38
Mar	0.08	0.14	0.17	0.1	0.08	0.03	0.1	0.13	0.14	0.3	0.31	0.16	0.19	0.15	0.16
Apr	0.09	0.18	0.13	0.04	0.11	0.09	0.09	0.02	0.08	0.11	0.08	0.05	0.1	0.11	<0.02
May	<0.02	<0.02	0.1	0.03	0.06	0.11	0.11	0.05	0.16	0.27	0.1	0.1	0.11	<0.02	<0.02
June	0.2	0.04	0.16	0.26	<0.02	<0.02	<0.02	<0.02	0.18	0.18	0.26	<0.02	<0.02	0.08	0.19
July	0.04	0.03	0.02	0.04	<0.02	<0.02	0.18	0.06	0.16	0.04	<0.02	0.11	<0.02	0.03	0.02
Aug	0.02	0.02	0.11	<0.02	0.02	0.16	0.02	<0.02	0.07	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Sept	0.02	0.02	<0.02	0.04	0.03	0.03	<0.02	0.02	0.06	<0.02	<0.02	<0.02	0.03	0.02	<0.02
Oct	0.05	0.02	0.03	0.04	0.04	<0.02	0.05	0.03	0.05	0.04	0.02	0.05	0.03	0.03	0.09
Nov	0.03	<0.02	<0.02	0.11	0.03	0.04	0.04	<0.02	0.08	<0.02	0.02	<0.02	<0.02	0.03	0.33
Dec	<0.02	0.11	0.16	0.09	<0.2	0.13	0.16	<0.02	0.2	0.26	<0.02	<0.02	<0.02	0.16	0.39

Appendix B

Station: (331786) COLUMBUS_WSO_AIRPORT, OH
Element: Precipitation (in)

Jan	1987	1.14	1986	1.54	1971-2000	2.53
Feb	1987	0.59	1986	2.96	1971-2000	2.20
Mar	1987	2.04	1986	2.61	1971-2000	2.89
Apr	1987	2.02	1986	1.31	1971-2000	3.25
May	1987	2.85	1986	2.47	1971-2000	3.88
Jun	1987	3.60	1986	5.53	1971-2000	4.07
Jul	1987	3.89	1986	3.60	1971-2000	4.61
Aug	1987	2.96	1986	1.61	1971-2000	3.72
Sep	1987	1.53	1986	3.44	1971-2000	2.92
Oct	1987	1.57	1986	4.16	1971-2000	2.31
Nov	1987	1.63	1986	3.00	1971-2000	3.19
Dec	1987	2.88	1986	2.81	1971-2000	2.93
Tot	1987	26.70	1986	35.04	1971-2000	38.50
Jan	1988	2.23	1987	1.14	1971-2000	2.53
Feb	1988	4.26	1987	0.59	1971-2000	2.20
Mar	1988	2.54	1987	2.04	1971-2000	2.89
Apr	1988	2.24	1987	2.02	1971-2000	3.25
May	1988	2.27	1987	2.85	1971-2000	3.88
Jun	1988	1.34	1987	3.60	1971-2000	4.07
Jul	1988	7.80	1987	3.89	1971-2000	4.61
Aug	1988	2.68	1987	2.96	1971-2000	3.72
Sep	1988	3.52	1987	1.53	1971-2000	2.92
Oct	1988	1.70	1987	1.57	1971-2000	2.31
Nov	1988	3.59	1987	1.63	1971-2000	3.19
Dec	1988	2.49	1987	2.88	1971-2000	2.93
Tot	1988	36.66	1987	26.70	1971-2000	38.50
Jan	1989	1.97	1988	2.23	1971-2000	2.53
Feb	1989	3.10	1988	4.26	1971-2000	2.20
Mar	1989	4.16	1988	2.54	1971-2000	2.89
Apr	1989	3.30	1988	2.24	1971-2000	3.25
May	1989	4.69	1988	2.27	1971-2000	3.88
Jun	1989	6.36	1988	1.34	1971-2000	4.07
Jul	1989	6.79	1988	7.80	1971-2000	4.61
Aug	1989	4.30	1988	2.68	1971-2000	3.72
Sep	1989	2.16	1988	3.52	1971-2000	2.92
Oct	1989	2.49	1988	1.70	1971-2000	2.31
Nov	1989	2.65	1988	3.59	1971-2000	3.19
Dec	1989	1.79	1988	2.49	1971-2000	2.93
Tot	1989	43.76	1988	36.66	1971-2000	38.50
Jan	1990	2.43	1989	1.97	1971-2000	2.53

Feb	1990	5.15	1989	3.10	1971-2000	2.20
Mar	1990	1.32	1989	4.16	1971-2000	2.89
Apr	1990	2.82	1989	3.30	1971-2000	3.25
May	1990	7.01	1989	4.69	1971-2000	3.88
Jun	1990	5.25	1989	6.36	1971-2000	4.07
Jul	1990	8.00	1989	6.79	1971-2000	4.61
Aug	1990	1.86	1989	4.30	1971-2000	3.72
Sep	1990	5.26	1989	2.16	1971-2000	2.92
Oct	1990	5.05	1989	2.49	1971-2000	2.31
Nov	1990	2.03	1989	2.65	1971-2000	3.19
Dec	1990	6.98	1989	1.79	1971-2000	2.93
Tot	1990	53.16	1989	43.76	1971-2000	38.50
Jan	1991	1.97	1990	2.43	1971-2000	2.53
Feb	1991	2.30	1990	5.15	1971-2000	2.20
Mar	1991	3.97	1990	1.32	1971-2000	2.89
Apr	1991	4.15	1990	2.82	1971-2000	3.25
May	1991	2.47	1990	7.01	1971-2000	3.88
Jun	1991	2.81	1990	5.25	1971-2000	4.07
Jul	1991	2.14	1990	8.00	1971-2000	4.61
Aug	1991	2.02	1990	1.86	1971-2000	3.72
Sep	1991	4.05	1990	5.26	1971-2000	2.92
Oct	1991	1.76	1990	5.05	1971-2000	2.31
Nov	1991	1.31	1990	2.03	1971-2000	3.19
Dec	1991	3.79	1990	6.98	1971-2000	2.93
Tot	1991	32.74	1990	53.16	1971-2000	38.50
Jan	1992	1.79	1991	1.97	1971-2000	2.53
Feb	1992	0.85	1991	2.30	1971-2000	2.20
Mar	1992	3.40	1991	3.97	1971-2000	2.89
Apr	1992	2.83	1991	4.15	1971-2000	3.25
May	1992	3.40	1991	2.47	1971-2000	3.88
Jun	1992	2.33	1991	2.81	1971-2000	4.07
Jul	1992	12.36	1991	2.14	1971-2000	4.61
Aug	1992	3.75	1991	2.02	1971-2000	3.72
Sep	1992	2.14	1991	4.05	1971-2000	2.92
Oct	1992	1.40	1991	1.76	1971-2000	2.31
Nov	1992	4.03	1991	1.31	1971-2000	3.19
Dec	1992	1.32	1991	3.79	1971-2000	2.93
Tot	1992	39.60	1991	32.74	1971-2000	38.50
Jan	1993	4.14	1992	1.79	1971-2000	2.53
Feb	1993	1.82	1992	0.85	1971-2000	2.20
Mar	1993	3.50	1992	3.40	1971-2000	2.89
Apr	1993	4.49	1992	2.83	1971-2000	3.25
May	1993	2.47	1992	3.40	1971-2000	3.88
Jun	1993	3.33	1992	2.33	1971-2000	4.07
Jul	1993	5.95	1992	12.36	1971-2000	4.61
Aug	1993	0.74	1992	3.75	1971-2000	3.72
Sep	1993	1.75	1992	2.14	1971-2000	2.92
Oct	1993	3.05	1992	1.40	1971-2000	2.31
Nov	1993	4.45	1992	4.03	1971-2000	3.19
Dec	1993	2.16	1992	1.32	1971-2000	2.93

Tot	1993	37.85	1992	39.60	1971-2000	38.50
Jan	1994	3.79	1993	4.14	1971-2000	2.53
Feb	1994	1.56	1993	1.82	1971-2000	2.20
Mar	1994	1.94	1993	3.50	1971-2000	2.89
Apr	1994	3.64	1993	4.49	1971-2000	3.25
May	1994	1.69	1993	2.47	1971-2000	3.88
Jun	1994	1.93	1993	3.33	1971-2000	4.07
Jul	1994	6.02	1993	5.95	1971-2000	4.61
Aug	1994	3.29	1993	0.74	1971-2000	3.72
Sep	1994	1.68	1993	1.75	1971-2000	2.92
Oct	1994	0.92	1993	3.05	1971-2000	2.31
Nov	1994	2.94	1993	4.45	1971-2000	3.19
Dec	1994	2.22	1993	2.16	1971-2000	2.93
Tot	1994	31.62	1993	37.85	1971-2000	38.50
Jan	1995	4.54	1994	3.79	1971-2000	2.53
Feb	1995	1.64	1994	1.56	1971-2000	2.20
Mar	1995	1.61	1994	1.94	1971-2000	2.89
Apr	1995	3.17	1994	3.64	1971-2000	3.25
May	1995	4.86	1994	1.69	1971-2000	3.88
Jun	1995	5.30	1994	1.93	1971-2000	4.07
Jul	1995	6.99	1994	6.02	1971-2000	4.61
Aug	1995	7.56	1994	3.29	1971-2000	3.72
Sep	1995	1.15	1994	1.68	1971-2000	2.92
Oct	1995	4.04	1994	0.92	1971-2000	2.31
Nov	1995	2.47	1994	2.94	1971-2000	3.19
Dec	1995	1.97	1994	2.22	1971-2000	2.93
Tot	1995	45.30	1994	31.62	1971-2000	38.50
Jan	1996	3.73	1995	4.54	1971-2000	2.53
Feb	1996	2.14	1995	1.64	1971-2000	2.20
Mar	1996	3.40	1995	1.61	1971-2000	2.89
Apr	1996	6.39	1995	3.17	1971-2000	3.25
May	1996	5.81	1995	4.86	1971-2000	3.88
Jun	1996	3.82	1995	5.30	1971-2000	4.07
Jul	1996	5.09	1995	6.99	1971-2000	4.61
Aug	1996	1.58	1995	7.56	1971-2000	3.72
Sep	1996	5.50	1995	1.15	1971-2000	2.92
Oct	1996	1.44	1995	4.04	1971-2000	2.31
Nov	1996	3.20	1995	2.47	1971-2000	3.19
Dec	1996	3.46	1995	1.97	1971-2000	2.93
Tot	1996	45.56	1995	45.30	1971-2000	38.50
Jan	1997	2.19	1996	3.73	1971-2000	2.53
Feb	1997	1.50	1996	2.14	1971-2000	2.20
Mar	1997	3.96	1996	3.40	1971-2000	2.89
Apr	1997	1.65	1996	6.39	1971-2000	3.25
May	1997	5.58	1996	5.81	1971-2000	3.88
Jun	1997	6.62	1996	3.82	1971-2000	4.07
Jul	1997	2.91	1996	5.09	1971-2000	4.61
Aug	1997	5.76	1996	1.58	1971-2000	3.72

Sep	1997	1.36	1996	5.50	1971-2000	2.92
Oct	1997	1.58	1996	1.44	1971-2000	2.31
Nov	1997	2.92	1996	3.20	1971-2000	3.19
Dec	1997	2.13	1996	3.46	1971-2000	2.93
Tot	1997	38.16	1996	45.56	1971-2000	38.50
Jan	1998	2.32	1997	2.19	1971-2000	2.53
Feb	1998	2.48	1997	1.50	1971-2000	2.20
Mar	1998	1.88	1997	3.96	1971-2000	2.89
Apr	1998	6.51	1997	1.65	1971-2000	3.25
May	1998	3.09	1997	5.58	1971-2000	3.88
Jun	1998	6.99	1997	6.62	1971-2000	4.07
Jul	1998	2.75	1997	2.91	1971-2000	4.61
Aug	1998	1.99	1997	5.76	1971-2000	3.72
Sep	1998	1.27	1997	1.36	1971-2000	2.92
Oct	1998	3.05	1997	1.58	1971-2000	2.31
Nov	1998	1.99	1997	2.92	1971-2000	3.19
Dec	1998	3.25	1997	2.13	1971-2000	2.93
Tot	1998	37.57	1997	38.16	1971-2000	38.50
Jan	1999	2.87	1998	2.32	1971-2000	2.53
Feb	1999	2.77	1998	2.48	1971-2000	2.20
Mar	1999	1.88	1998	1.88	1971-2000	2.89
Apr	1999	4.65	1998	6.51	1971-2000	3.25
May	1999	1.80	1998	3.09	1971-2000	3.88
Jun	1999	0.65	1998	6.99	1971-2000	4.07
Jul	1999	3.02	1998	2.75	1971-2000	4.61
Aug	1999	2.40	1998	1.99	1971-2000	3.72
Sep	1999	1.91	1998	1.27	1971-2000	2.92
Oct	1999	1.00	1998	3.05	1971-2000	2.31
Nov	1999	1.95	1998	1.99	1971-2000	3.19
Dec	1999	2.69	1998	3.25	1971-2000	2.93
Tot	1999	27.59	1998	37.57	1971-2000	38.50
Jan	2000	3.53	1999	2.87	1971-2000	2.53
Feb	2000	2.79	1999	2.77	1971-2000	2.20
Mar	2000	2.70	1999	1.88	1971-2000	2.89
Apr	2000	4.15	1999	4.65	1971-2000	3.25
May	2000	5.42	1999	1.80	1971-2000	3.88
Jun	2000	3.50	1999	0.65	1971-2000	4.07
Jul	2000	4.10	1999	3.02	1971-2000	4.61
Aug	2000	4.10	1999	2.40	1971-2000	3.72
Sep	2000	4.18	1999	1.91	1971-2000	2.92
Oct	2000	2.70	1999	1.00	1971-2000	2.31
Nov	2000	2.13	1999	1.95	1971-2000	3.19
Dec	2000	3.59	1999	2.69	1971-2000	2.93
Tot	2000	42.89	1999	27.59	1971-2000	38.50
Jan	2001	1.31	2000	3.53	1971-2000	2.53
Feb	2001	1.37	2000	2.79	1971-2000	2.20
Mar	2001	1.03	2000	2.70	1971-2000	2.89

Apr	2001	3.39	2000	4.15	1971-2000	3.25
May	2001	7.03	2000	5.42	1971-2000	3.88
Jun	2001	2.30	2000	3.50	1971-2000	4.07
Jul	2001	4.66	2000	4.10	1971-2000	4.61
Aug	2001	4.14	2000	4.10	1971-2000	3.72
Sep	2001	1.60	2000	4.18	1971-2000	2.92
Oct	2001	3.32	2000	2.70	1971-2000	2.31
Nov	2001	3.69	2000	2.13	1971-2000	3.19
Dec	2001	3.01	2000	3.59	1971-2000	2.93
Tot	2001	36.85	2000	42.89	1971-2000	38.50