Chemical Monitoring of a Primary Water Supply: Lake Pelham in Culpeper, Virginia.

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ABSTRACT

Over the last decade there has been an increase in public and government concern over water quality in the United States, especially water bodies that are sources of drinking water. A study conducted by the United States Geologic Survey (USGS) and the National Water-Quality Assessment (NAQWA), has indicated that nutrient concentrations in streams and groundwater in basins with significant agricultural or urban development are substantially greater than naturally occurring or "background" levels (Dubrovsky, 2010). Various academic studies throughout the United States have demonstrated that many water sources are in danger of being severely polluted, with accelerated eutrophication occurring in many lakes. Specifically, the EPA, who has the task of monitoring these water bodies along with the USGS, has tightened the regulations about point and non-point sources of pollution, in an attempt to reduce the amount of eutrophication in sensitive water bodies. Lake Pelham, located in Culpeper, Virginia has experienced an increase in water quality problems; specifically an increase in nutrients in the lake, causing significant algae blooms. Increasing concern over the amount of nutrients found in lakes, rivers, streams and other water ways (i.e. the Chesapeake Bay) have yielded an increase in the amount of money spent on studies, both at the Federal (EPA) and state level (DEQ). Furthermore, several counties and towns have taken it upon themselves to conduct monitoring programs on their local water sources, to ensure the health of potable water as well as the health of their constituents. The objectives of this research program for Lake Pelham were to: 1.) conduct a literature review of similar surface water systems to highlight current trends in nutrient concentrations 2.) measure and monitor the total phosphorus and nitrogen levels in the lake and examine relationships between nutrient concentrations, water temperature, dissolved oxygen content, and pH and 3.) outline future actions for monitoring Lake Pelham and possible preventive actions for nutrient control. In 2010, the interaction between pH, temperature, nitrogen and phosphorous was investigated. The total nitrogen concentration of Lake Pelham is highly dependent on the leachate entering the lake. Large increases in nitrogen occur during even the smallest rainfall events, suggesting nitrogen is entering the lake from the surrounding environment. The current study indicates that the mean annual average total nitrogen concentration of the lake is approximately 10 mg/l. This value provides a baseline which can be used while the total nitrogen is being monitored over the next several years. In previous years, an increase in pH values (< 1.0 between test dates) was associated with algal blooms in the lake and necessitated the treatment with copper sulfate. Between 1992 and 2010, the nitrogen concentration doubled and the phosphorus concentration increased 7 fold. Algae concentrations and pH fluctuation decrease as the water temperature decreases. Similar to nitrogen, phosphorus concentrations in the lake increase with rainfall events suggesting a realtionship to runoff and/or leeching entering from the surrounding watershed. Even during lower water levels, similar to what occurred in August of 2010, when the lake was 15 inches below peak level, a small rainstorm had a large impact on the amount of phosphorus entering the lake requiring the addition of copper sulfate. The trophic state for Lake Pelham was calculated from the average values of the total phosphorus measured in the lake over 2010 and the Secchi disk readings from the same time period. The Tropic State Index (TSI) was calculated to be 59.75 when using the total concentration of phosphorus in Lake Pelham. The TSI calculated from the Sechhi Disk values was 54.5. This gives a average TSI value of 57.1, which indicates that the lake is in a eutrophic state. This was the first attempt at determining the trophic state of Lake Pelham. The study is an important first step for understanding nutrient loading in Lake Pelham and applying protective measures to preserve water quality. Similar to a study conducted in King County, Washington, long term data (decade or more) and in depth statistical analysis will be needed to explain the seasonal variability of Lake Pelham.

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INTRODUCTION

Over the last decade, public and government concern about the water quality of the United States lakes and streams has increased, especially water bodies that are sources of drinking water. A study conducted by the United States Geologic Survey (USGS) and the National Water-Quality Assessment (NAQWA), has indicated that nutrient concentrations in streams and groundwater in basins with significant agricultural or urban development are substantially greater than naturally occurring or "background" levels (Dubrovsky, 2010). Specifically, the EPA, who has the task of monitoring these water bodies along with the USGS, has tightened the regulations applied to all surface and groundwater. Various other academic studies throughout the United States have demonstrated that many water sources are in danger of being severely polluted, with accelerated eutrophication occurring. Many water bodies are failing to even meet the federal Clean Water Act standards, with high level of nutrients damaging fisheries and aquatic habits and leading to restricted recreational use (Hogan, 2010).

Eutrophication is the process whereby lakes, or other slow moving waters, become enriched with nutrients, resulting in the production of biomass, which dies, decays, and settles to the bottom. The ultimate conclusion to this process is when such biomass, along with materials washed in from the tributary watershed, fills the lake, and the lake is slowly transformed into a peat bog or meadow. This is a natural process that all lakes undergo, but anthropothic activities may accelerate the export of nutrients into lake systems, either through point source or non-point source pollution (e.g. "cultural eutrophication"). This man-made acceleration of eutrophication can reduce the time of this cycle to a period of decades rather than millennia. In freshwater lakes, the rate of the eutrophication is most often governed by the availability of the plant nutrients nitrogen and phosphorus; therefore the amount of nitrogen or phosphorus discharge from either point source or non-point source is critical to the overall health of the water system (Draper, 1988). Recently, a new study conducted by the United States Geological Survey indicates that elevated concentrations of nitrogen and phosphorus have remained the same or increased in many U.S. streams and aquifers since the 1990's (Dubrovsky, 2010). This type of pollution has consistently ranked as one of the top three causes of degradation of U.S. streams and rivers (Buringame, 2010).

Although an excess of nutrients in lakes and reservoirs does not interfere with the designated use, the biological growth of algae as a result of these nutrients can create a very serious problem, especially in reservoirs used for drinking water production (Younos, 2007). Large concentrations of nutrients in reservoirs can lead to algae blooms, an overabundance of aquatic plants, low dissolved oxygen levels, fish kills, and species shifts of flora and/or fauna. Over-enrichment of nutrients may also pose human health risks through the development of harmful algal blooms (Yoounos, 2007; U.S. EPA 2020). In a drinking water facility, large algae blooms can lead to many problems including taste and odor issues in drinking water, oxygen depletion which can lead to a release of chemically reduced iron and manganese from sediment, more frequent backwashes of filters, disinfection byproducts (trihalomethanes and haloacetic acids) which are harmful when consumed by humans, and fouling of the distribution system by increased biological growth (Younos, 2007). Although increases in the concentrations of nitrogen and phosphorus can cause an increase in algal biomass, the relation can be weak, vary geographically, or can be opposite of what one would expect (Munn, 2010). It is, therefore, critical to consider a mixture of variables like spacial currents, surrounding topography and climate when determining whether water bodies meet nutrient criteria.

The Town of Culpeper, located in central Virginia, uses two lakes as a primary and secondary source of drinking water: Lake Pelham and Mountain Run Lake. These lakes have been in service to the town since 1958 (for Mountain Run Lake) and 1972 (for Lake Pelham). Mountain Run Lake feeds a stream, Mountain Run Stream, which is surrounded by several large farms prone to large amounts of agricultural runoff. This is the stream that feeds Lake Pelham. Over the last 15 years, urban development around these lakes has increased substantially. Visual evidence of the effects of this development indicates that a potential sedimentation and nutrient problem could be developing, but test data on these lakes has been limited. In 1985 a proposal written by Espey, Huston and Associates and Draper and Associates, two engineering firms hired by the town, developed a program to monitor both Mountain Run and Lake Pelham in 1988. The final goal of this study was to estimate the amount of non-point source pollution entering the lakes. Draper and Associates conducted a sedimentation and water quality study. The results of this study developed the baseline contours of the bottom of the lake, which could be used in future studies to determine impacts of urbanization and neighboring agriculture The Draper study also proposed 6-site sampling plan to further define the sedimentation conditions of the lakes and define future impacts associated with non-point source pollution. Neither of the suggested studies from these proposals were fully implemented by the town, due to costs and lack of personel.

In 2003, Hayes and Sawyers developed a Water Supply Master Plan (HSMM, 2004). The purpose of this study was to find a method to increase the water production capacity of both Lake Pelham and the water production facility. This proposal defined a 5% increase in the amount of sedimentation in the lakes, and in the associated nutrient loading (HSMM, 2004). The reduction of the storage capacity of the lake has created a situation in which that, even if the nutrient input concentrations were remained constant between the 1988 (the Draper study) and the 2004 (the Hayes, Seay, Mattern & Mattern study), the impact of the nutrients could be much greater as the volume of water has decreased. The increase in the sediments in the lake has increased the amount of nutrients that can be retained in the lake, as the nutrients will bind with the sediment particles until they can be used. Seasonal turn-over of the lake will then draw these materials to the top of the lake for biological consumption. Both the Draper study and the HSMM study concluded that the sedmient concentrations are increasing, which increases the nutrient concentration and decreases the water quality of lake. Both reports suggested that the Town of Culpeper invest in frequent monitoring of the lakes to measure the decreasing water quality in Lake Pelham.

The primary goal of conducting a monitoring program is to accurately define the temporal and spatial variability of the watershed and the tropic state of the water body. The successful management of water bodies such as Mountain Run Lake and Lake Pelham that are used for both drinking water and recreation requires a thorough understanding of the pollutant types and concentrations likely to be introduced into the system (Draper, 1988). It has been noted that well-designed and properly funded monitoring programs are the key to measuring real water quality improvements, and a vital mechanism for ensuring the public money dedicated to this issue is spent wisely (Hogan, 2010). Experience has shown that the most ubiquitous non-point pollution problems in watershed/reservoir systems exhibiting mixes of undeveloped, agricultural, and urban land uses are those related to the export of plant nutrients and trace metals. There are other potential problems associated with such systems, including the export of organic matter, which can affect the oxygen resources of the receiving system, and synthetic organics (i.e. pesticides, herbicides, pharmaceuticals) which can have toxic effects on receiving water biota, and on secondary users of the water (Draper, 1988). It would be in the best interest of the Town of Culpeper to implement a lake monitoring program, to determine the overall concentrations of the contaminants listed above, as they could potentially create human health problems during the production and consumption of drinking water.

The proposal by Espey and the suggestions in this paper followed procedures outlined by the U.S. Environmental Protection Agency (EPA) in their Non-Point Source Monitoring and Evaluation Guide and the Virginia Department of Environmental Quality (DEQ) (Espey, 1988). Using a modified and updated version of the original monitoring program designed by Draper and Associates and Espey, Huston and Associates, Inc, and the staff of the Town of Culpeper have done a superior job in defining the current tropic state of the lake, as well as determining where conservation should be enforced, for the protection of both drinking water sources (Draper, 1988; Espy, 1989). This is an ambitious program that will take the next five years to complete and can be divided into several phases. The long-term objectives of the monitoring program are:

- Define the current watershed, soil taxanomy, and lake inputs including metals, organics, nutrients and sediments.
- Identify the current tropic state of Lake Pelham and the changes it has undergone over the last 20 years.
- Further develop baseline information for current assessment and generate sufficient data for trend analysis on nutrient concentrations, rain and snow precipition trends, chemical, and physical properties of the water source.
- Evaluation of the effectiveness of algal control measures and to document the possible effectiveness of Best Management Practices (BMP's) that may be instituted at either lake.

With the primary drinking water source for the Town of Culpeper being Lake Pelham, the town's chief concern is keeping the lake in a healthy condition. The largest easily identifiable problem facing the lake is the overabundance of nutrients in the lake, causing significant algae blooms. It is the hope of the water production facility staff that this study will provide the necessary data to implement management practices that will ensure the health of the lake for years to come. With this data, more effective process parameters could be defined for the water plant, thus optimizing the amount of treatment chemicals used on a daily basis. The first two objectives of the monitoring program were investigated in 2010. These objectives were achieved by conducting several activities over the last year. These activities included: 1.) Conduct a literature review of similar water production systems to highlight certain current trends in nutrient concentrations 2.) Measure and monitor the amount of phosphorus and nitrogen compounds and determine if any relationships exist between nutrient concentrations and the other parameters measured and, 3.) Outline future actions for measurement of lake parameters and possible preventive actions for nutrient control. The first two overall objectives of the study also provide the baseline data needed to truly establish the overall health of the water system. This paper offers some of the historical data that has been published and a summary of the data collected over the last 12 months.

BACKGROUND INFORMATION: SITE SURVEY

Lake Pelham Watershed Definition, Topography and Features:

The Town of Culpeper is located entirely within the Rappahannock River drainage basin, which drains into the Chesapeake Bay. The Rappahannock River is one of the most pristine drainage basins in Virginia (Town, 2002). The Rappahannock River, from the western corporate limits of the City of Fredericksburg to its headwater, is designated as a State Scenic River. The Town of Culpeper drains into the Rappahannock River by its direct tributary, Mountain Run, and its sub-tributaries are distributed throughout the Town. Mountain Run has an average stream flow of 1.29 million gallons per day (MGD). On most occasions, Mountain Run is a briskly flowing stream, especially when the release of water impounded by Lake Pelham occurs. This flow volume equates to a well–aerated, rolling stream flow. Rocky or gravel stream bottom is found only in a few locations in the Town. The portion of the lakeshore of Lake Pelham within the corporate limits is about 0.5 miles (Town, 2002). The stream of Mountain Run is the most important watershed within the town limits. Mountain Run bisects the town with bridge crossings at Sperryville Pike, Main Street, and Madison Road. The original reason for the construction of Lake Pelham was flood control. Mountain Run was the source of occasional flooding until the Town constructed Lake Pelham in 1972. High water may occur during heavy seasonal rains and/or release of water from Lake Pelham (Town, 2002).

Lake Pelham is located in the southern half of Culpeper County, Virginia (Figure 1). It is a part of the upland drainage of the Rappahannock River Basin (Draper, 1988). It is primarily fed by Mountain Run Lake, which was impounded in 1958, while Lake Pelham was finished in 1972. The drainage area of Lake Pelham encompasses 16,530 acres west of the Town of Culpeper. The Mountain Run Lake watershed drains 4,000 acres in the upper reaches of the Lake Pelham Watershed. Another impoundment, Mountain Run Watershed Dam 8a, is also located in the upper reaches of the Lake Pelham Watershed, and drains 5,848 acres (Rappahannock-Rapidan Planning District Commission, 1987).

The primary functions of these lakes are: flood control, recreational use and as primary water supply. The Water Production Facility uses Lake Pelham as a primary drinking water source for the Town of Culpeper. This water plant is allowed to draw a maximum of 4 million gallons/day for the production of potable water. Over the course of the last several years, housing construction has increased substantially around the lake and the creeks that drain in to it. Improper or nonexistent sedimentation barriers, improper topsoil applications or dramatic changes in the surrounding topography have coincided with the increase in the construction activity. The contractors responsible for the construction were in too much of a hurry to concern themselves with the proper resolution of these issues or were uneducated on how their activities could impact Lake Pelham. This has altered the bottom surface of the lake with the advancement of sedimentation into Lake Pelham, altering the total storage volume. In 1988, the storage capacity was calculated to be 1,824 acre/ft for Lake Pelham and 588 acre/ft for Mountain Run Lake. In 2004, a study conducted by Hayes, Seay, Mattern, & Mattern (HSMM) concluded that the storage capacity for both lakes was reduced by ~5%, largely due to inputs of sediment into both lakes (Hayes et al., 2004).

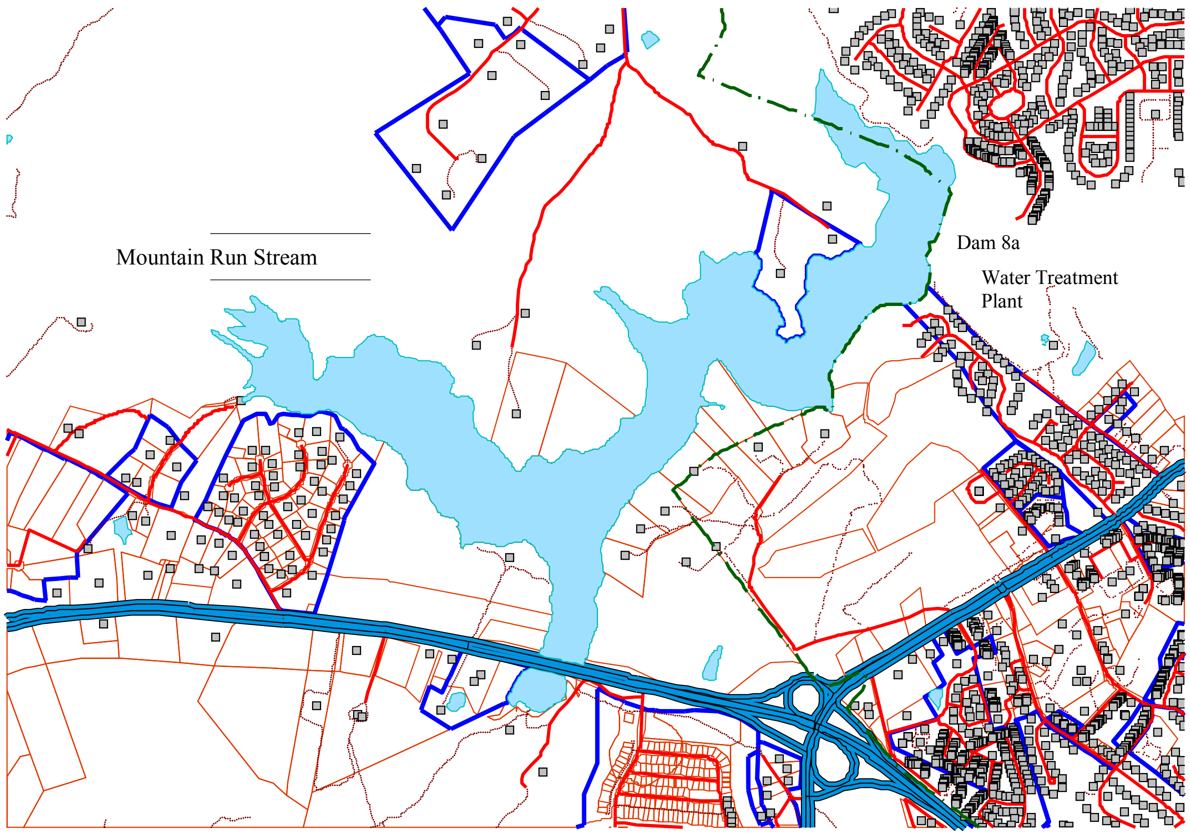

Figure 1: Lake Pelham, Culpeper, Virginia (courtesy of The County of Culpeper GIS System).

Soil and Land Use Survey:

A soil survey conducted in 1988 concluded that the soil in the surrounding area of Lake Pelham was of the Elioak (Fine kaolinitic, mesic Typic Hapludults), Glenelg (Fine-loamy, mixed, semiactive, mesic Typic Hapludults) and Culpeper (Fine, kaolinitic, mesic Typic Haludults) series with subordinate areas of Hazel and Albemarle. The soils are described as well-drained and fairly deep with a shallow A horizon and a deep, plastic B Horizons, containing colors from yellow-red (Elioak) to light yellow-brown (Albemarle) (Adams, 1980; Draper, 1988). Due to urban development over the last 10 years, a significant amount of soil has been deposited into Lake Pelham, especially in the south end of the lake.

Climate Data and Precipitation Summary:

The Town and County of Culpeper has a temperate climate with generally mild winters and warm summers. It is a continental-type climate with moderate humidity and well-defined seasons. The mountains to the west, the Chesapeake Bay and Atlantic Ocean to east are major factors in moderating climate. The average annual daily temperature is 55.8 °F. Mean monthly temperatures vary from 34.6 °F in January (the coldest month) to 75.9 °F in July (the warmest month). Precipitation is fairly uniform throughout the year; with a mean annual precipitation of 40.76 in, mostly in the form of rain, although some snow and sleet occurs during the winter months. Damaging weather events, like hurricanes, tornadoes and blizzards are rare. The growing season, defined as the period between the last freezing temperature in the spring (around April 20th) and the first freezing temperature in the fall (typically about October 18th) is 181 days (Town, 2002).

Agriculture and Urban Runoff Survey:

There are 421.9 acres of floodplain within the Town of Culpeper. This amounts to 9.6 % of the total land area. Floodplains provide natural storm drainage systems that are susceptible to erosion and pollution resulting from urbanization. Development increases the amount of impervious surface and storm water runoff. Increased runoff may exceed the capacity of the natural floodplain to contain the flow, resulting in flood damage. In addition, contaminants washed into the runoff contribute to the pollution of surface and groundwater downstream. The community, therefore, has a vital interest in the protection of floodplains. Watershed boundaries are also important to the community as they affect the location of sewer lines and pumping stations, and thus the cost of sewer service. The majority of the Town's floodplain surrounds Mountain Run and its tributaries. The Mountain Run drainage system is well distributed throughout the Town. This land is considered appropriate for agriculture, parks and recreation, parking and utilities.

Water Plant Treatment Operation:

Near the north shore of Dam 8A is the raw water intake for the Town of Culpeper's Water Production Facility. Lake Pelham is the only source of water for this facility. The Water Production Facility uses it as a primary drinking water source for the Town of Culpeper. This water plant is allowed to draw a maximum of 4 million gallons/day for the production of potable water. As a pretreatment step, the Town of Culpeper applies a small volume of potassium permanganate to the lake for metal oxidation and oxidation of certain organic species. Also, copper sulfate treatments are periodically conducted, in an efforts to control the algae level of the lake.

BACKGROUND INFORMATION: NUTRIENT CHEMISTRY AND TOPIC STATE WATERS

The amount of usable drinking water has been an increasing concern globally since the 1970's. Throughout the world, the amount of water sources that have been contaminated or compromised by human activities have grown exponentially (Novotny, 2003). Typical sources are industrial activities, urbanization and agriculture. The EPA and associated state agencies in the U.S. over the last 20 years, have defined many parameters that should be monitored frequently, to determine the health of a given water body. The EPA's focus has been on the amount of nutrients, nitrogen and phosphorus, and the amount of sediments entering a water body. High concentrations of these materials can adversely affect water quality, and environmental and human health.

Nitrogen is a required macronutrient for all forms of life, in that, it is essential for the formation of amino acids and proteins. Hence, some subsistent levels of nitrogen compounds like nitrate and ammonium are needed for development of microorganisms, plant and aquatic life. Unfortunately, human interaction with the environment has led to an excess of nitrogen ending up in water sources. Nitrogen compounds in a natural water body can effect the ecosystem in several ways. It can act as a stimulant to the excessive growth of phytoplankton. The phytoplankton causes the consumption of the oxygen during respiration and decompostion. They can act as a toxicant to aquatic life and they can induce some human health problems when consumed (Draper, 1988). Therefore, it is critical to control nitrogen inputs in surface waters that act as drinking water sources. It is also known that many of algae species create unsightly floor mats, causing taste and odors, and secreting extra-cellular toxins. In most systems, the inorganic nitrogen concentration needed to support significant algal growth is at the 0.2 to 0.3 mg/L level (Draper, 1988). Excessive concentrations of nitrates, specifically, in public water supply reservoirs can also be a problem from the a human health (i.e.methermoglobinemia, or the so-called blue baby disease). Hence, the maximum contaminant level for nitrates only has been set at 10 mg/L and it is very rare for surface water bodies to exceed this level (Draper, 1988).

The nitrogen cycle in aquatic water bodies is as important as the organic matter-dissolved oxygen cycle. Nitrogen transformations can also affect the dissolved oxygen balance, which could adversely affect other water properties. In fact, 1 mg/L of reduced nitrogen may be responsible for the exertion of an oxygen demand of 4.6 mg/L, which in the summer when the dissolved oxygen is lower, could have a large impact on the oxygen content and overall lake health (Novonty, 2003). For nitrates, subsurface flow and not erosion may be the primary transport processes that carries nitrogen from the source area to the receiving water bodies. The monitoring of nitrogen compounds will help establish the extent of ammonification and nitrification in the water system (Novotny, 2005). Sources of nitrogen compounds in soils include fertilizers, N fixation from the atmosphere by rhizobium bacteria, plant residues and precipitation. The amount of nitrogen needed for plant uptake versus the amount applied to the soil by humans can often differ by a large amount in both urban and agriculural settings. Hence urban and agriculture nitrogen inputs and subsequent leeching into nearby water bodies are responsible for large inputs of nitrogen to surface water bodies, especially in the spring when large amounts of fertilizers are applied that leech with the spring precipitation (Clark et al., 2003).

Phosphorous is another element that is necessary for algal growth and eutrophication. The presence of nitrogen compounds in lakes is used to support plant life, including algae; but in freshwater lake systems, the rate of the eutrophication process is most often governed by the availability of phosphorus. In soil environments, inorganic phosphorus is largely unavailable for plants or leaching because it is strongly adsorbed to mineral surfaces and or precipitated/coprecipitated in solid phases. Any additon of phosphorus to the soil could also be bound by the soil matrix or immediately taken up by plants. To initiate the proper crop response, fertlizer applicators often over-fertlize to compensate for this phosphorus fixation that can occur.

In acidic soils, aluminum and iron are involved with phosphorpus fixation while in basic soils calcium is important (Novotny, 2003). In Lake Pelham, a large concentration of iron does exist year round. The iron present in the lakes is often subjected to seasonal oxidation during lake turnover and reduction once the material settles to the bottom of the lake. The phosphorus can chemically bond to the oxidized iron species (i.e. Fe-oxyhydroxides) on the lake surface, but as these compounds settle to the oxygen deprived bottom of the lake, the phosphorus will be released again into the water as the Fe-oxyhydroxide is reduced (Novotny, 2003) This increases soluble phosphorous concentrations which can lead to large algal blooms and a reduction in water quality. Therefore, most attempts to manage the rate of eutrophication of impoundment center on the reduction of phosphorus loads to the system, whether from point or nonpoint sources (Draper, 1988).

When evaluating nutrient data, one fact must always be kept in mind, the effects of stratification. Stratification is the presence of horizontal layers in the water body, typical in deep areas that are separated into three zones based on density or salinity. The three zones are epilimnion (the surface zone), the thermocline (the middle zone), and the hypolimnion (the bottom zone). The upper epilimnion is the productive layer, where algae develops (Novotny, 2003). Oxygen levels are highest in the epilimnion, due to direct transfer from the atmosphere (Younos et al., 2007). In contrast, the hypolimnion tends to have low levels of oxygen because of the lack of vegetation and it can not be recharged by the atmosphere. Nutrient levels can increase in the hypolimnion for several reasons. Dead organisms fall to this layer and decompose, releasing their nutients back into the water. Also, a large amount of sediment can be found in this layer where nitrogen and phosphorus compounds can be bound by clay particles. This creates a pool of liable nutrients at the bottom of the lake. The colder water will be at the bottom of the lake in the hypolimnion and the warmer waters will be in the epilimnion zone. In the spring and the fall, the temperature profile changes as the surface waters will either heat or cool. As the surface temperatures reach the same temperature as the bottom waters the layers become thermodynamically similar and the water circulates among all three layers. This will draw any precipitates and organic material that happen to have settled to the bottom over the winter or summer months. The nutrients, the metal complexes, and the sediments concentrations in these three areas will reach equilibrium in all three layers. Once the nutrients have been depleted in the early spring, the turnover of these layers recharges the amount of nutrients in the epilimnion layer. The surge of nutrients from the bottom of the lake and the influx of nutrients from either runoff and leeching creates a lot of raw materials to create large algae blooms that are difficult to control. In this study, only the epilimnion was investigated, but future actions will investigate the effects that depth has on nutrient, metal and oxygen concentrations (Younos et al., 2007). The thermocline is where the intake pipe for the water treatment plant is located, so future studies will include this layer and the hypolimnion.

Many of the studies that have been conducted over the last several years are using the tropic state or the biological activity of a water source. This index is an easy to understand and a graphic way to determine the water quality of a given water body. This method of classifying a lake or river was developed by Robert Carlson in 1977, which takes three parameters; Secchi Disk (SD) or clarity of a lake, the total phosphorus concentration in parts per billion and the amount of chlorophyll a in parts per billion (Carlson, 1977; Younos et al., 2007). The chlorophyll concentration represents the amount of algal biomass present in a lake. The Secchi disk is a 8-inch black and white plastic disk that is lowered into the water until it can not be visible from the surface of the water. The rope is marked off in 1/2 meter sections and the point where the disk is no longer visible is recorded. Each one of these parameters can be used to calculate the Tropic State Index (TSI), which is a scale from 0-100, where each division of 10 represents a doubling of algal biomass (King County, 2001). The TSI Index can be calculated using the following formulas (Table 1)

Parameter	Designation	Formula
Secchi Disk Depth (SD)	TSI (SD)	10 *(6-(ln(SD)/ln2))
Chlorophyll A (chl a)	TSI (CHA)	10 *(6-((2.04)-(0.68*ln(chlorophyll a))/ln2)
Total Phosphorus (TP)	TSI (TP)	10 *(6-(ln(48)/(Total P concentration)/ln2))

Table 1: Formulas for Tropic State Index (Calson, 1977; King County, 2001)

Once the TSI index for each parameter has been calculated, the three values are typically averaged together to give the TSI index of the water source. The TSI has broken down the productivity of the algal biomass into four categories. They are oligotrophic (least productive), mesotrophic (moderately productive), eutrophic (very productive), and hypereutrophic (highly productive). Carlson further defined these categories into typical symptoms observed, represented in Figure 2 (King County, 2001). The lake water quality can therefore be judged by where it ends up on this index, which then can be represented by the following graphic (Figure 2). At certain points in the testing of Lake Pelham, this graphic will be used to inform the Town Council and the general public about the data generated and what can be done to reduce the TSI number and improve the water quality of the lake.

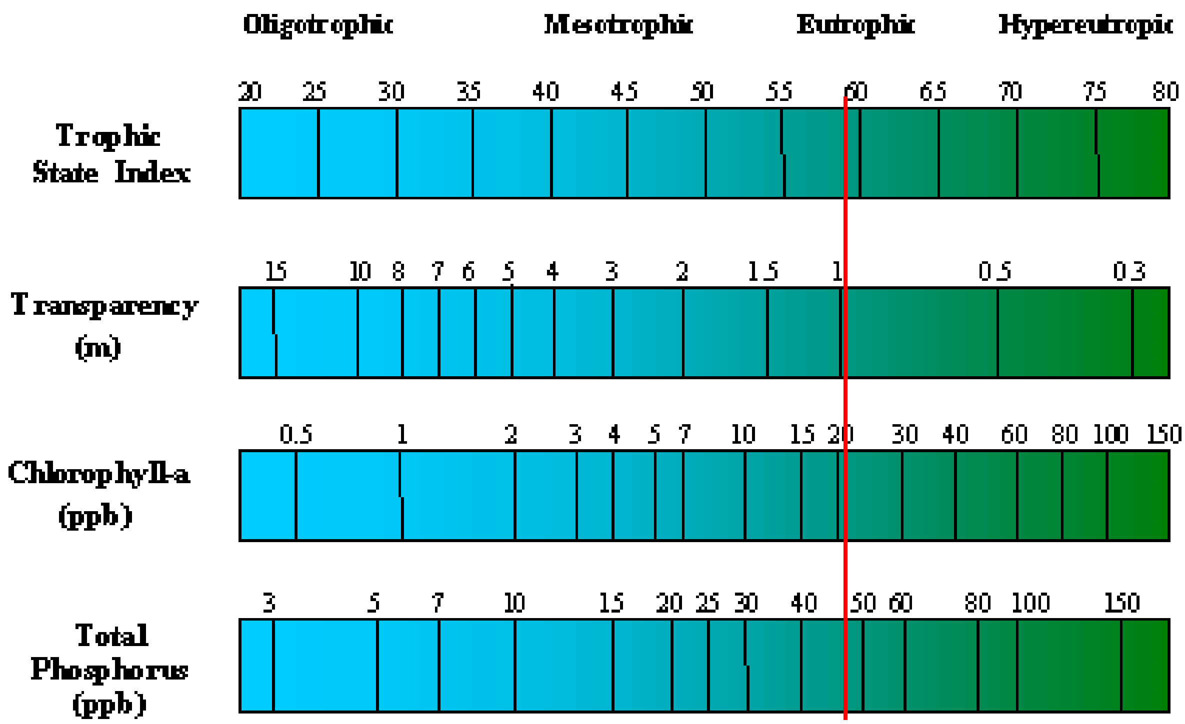

Figure 2: Carlson's Trophic State Index for Lake Pelham, 2010
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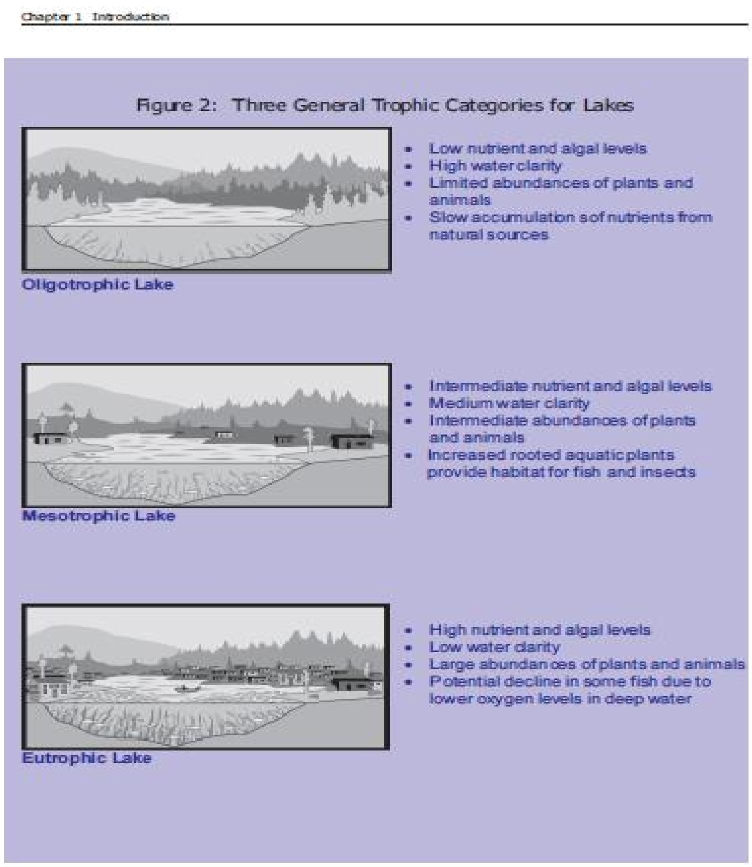

Figure 3: Three General Trophic Categories for Lakes (King County, 2001).

LITERATURE REVIEW

Over the last 15 years, numerous studies have been conducted on the water quality of the United States waterways. Increasing concern over the amount of nutrients found in lakes, rivers, streams and other water ways (i.e. the Chesapeake Bay) have yielded an increase in research on the tropic state of surface water both at the Federal (EPA) and State level (VA DEQ). More importantly, several counties and towns have taken it upon themselves to conduct studies on their local drinking water source, to ensure the health of their constituents. When the Town of Culpeper began to consider a surface water monitoring program, several studies conducted by other municipalities were used as a models.

The first such study was a historical trend study conducted in 2000 for 51 lakes in King County, Washington. Each of the lakes had been monitored for years for physical and chemical parameters, including temperature, water clarity, nitrogen, phosphorus and chlorophyll a (King County, 2001). In 1995, a small group of volunteers gathered all the data that had been collected since 1985 and merged it into a final report on the overall health of the lakes. The ultimate goal was to determine those lakes which may be in serious danger of eutrophication and identify what Best Management Practices could be put in place to reduce the cultural impact on these lakes and possibly increase the water quality. Once the data was tabulated, each lake was given a TSI number to determine the water quality of the lakes. Fourteen of the lakes were rated as oligotrophic, with high water quality and low chlorophyll a concentrations. Twenty lakes were rated as mesotrophic, with mid-range water clarity, chlorophyll a and total phosphorus values. Thirteen of these lakes were found to be eutrophic, having poor summer water quality and high chlorophyll a values. Finally, two of the lakes were found to be hypereutrophic, which are extremely productive for algae and the water quality is in severely degraded. The data also indicated that wetlands installed adjacent to the lakes had a positive impact on the amount of nutrients entering the lake. The wetland installation significantly reduced the nutrient concentrations so that two lakes were reduced from eutrophic to mesotrophic. Unfortunately, most of the other lakes in King County saw an average increase in the TSI number. Some sources of the nutrients included the increased development of the lake shoreline, removal of the natural vegetation and the increase in logging in the area which increased the amount of erosion and adversely affected the surrounding lakes. The King County officials offered four solutions to reduce some of the non-point sources entering the lakes. The action items included 1) include more lakes on the sensitive list, which would give them additional legal and regulatory protection, 2) encourage the restoration of shorelines that have been clear cut for industrial and residential development, 3) the implementation of stewardship activates as a way of life, not a choice for the developers, and finally, 4) apply watershed Best Management Practices that protect and possibly reduce the amount of nutrients entering these lakes (King County, 2001). The King County Lake study is a great example of how identification of cultural eutrophication sources depends on long term monitoring which eliminates the year-year variability of water quality based on the complexities of the processes occurring in the lakes (King County, 2001). The study conceded that the amount of development that is occurring in this area can not be stopped, but that greater pressure should be placed on the developers to reduce the impact that they are having on the surrounding lakes. (King County, 2001).

In 1999, the Cooperative Lakes Area Monitoring Project (CLAMP) began in Iowa. The purpose was to organize a detailed study of Iowa lakes using the vast volunteer work force available. The ultimate goal was to assess the water quality of 10 lakes in northwest Iowa, focusing on nutrient monitoring. Once completed, the study concluded that in the 10 lakes, the amount of total phosphorus was the limiting factor controling the amount of algae growing in the lakes. The amount of phorphorus was not high enough to create a significant algae problem. All of the lakes in this study were found to be mesotrophic, healthy and containing an adequate balance between water quality and algae/fish production (Iowa. 2007).

A study conducted by Dr. David Johnson examined the tropic state of both Smith Mountain Lake and Claytor Lake in Bedford and Pulaski Counties in Virginia, respectively. Although Lake Pelham pales in comparison to the size of these two lakes, the amount of development around Smith Mountain Lake over the last ten years and the receational use of Claytor Lake are similar to Lake Pelham. The study noted that as the Secchi disk visibility depth decreased in both lakes, so too did total phosphorus concentrations. This was due to an increase in colloidial material which acted as adsorbents for dissolved phosphorous. However, this is a dynamic system and the adsorbed phsophorous can be quickly desorbed with changes in the water chemsitry (i.e. pH, Eh, and alkalinity). The presence of suspended sediment reduces the clarity of the water however due to adsorption reduces phosphorus concentrations which reduces chlorphyll a. The tropic states on both lakes were measured over the last fifteen years, and have changed little in that time (Younos, 2007).

The Bills Lake Association, located in Newaygo County, Michigan, conducted a Trophic State Index study in 2007 on Bills Lake, a 90-acre recreational lake that has experienced an increase in residential development over the last five years. The study measured the Secchi Disk, the chlorophyll-a concentration, the total phosphorus concentration several times during 2007 and calculated the TSI value from these results. The study found that for the last five years, the lake TSI number was stable and was just barely mesotrophic, with a average value of 38. One critical error in this study did occur in the measurement of the total phosphorus concentration. For the chorophyll-a and the Seechi disk, 17 samples were collected over the year. For the total phosphorus, only 2 samples were collected, in the early spring and the late fall. Compared to the other TSI numbers, the resulting TSI (TP) value could be considered artificially low because of the mathematical weight placed on two samples. The other TSI values were 5-10 points higher than the TSI value, but the TSI (TP) value brought the ultimate TSI value down. Despite this lack of phosphorus sampling, the lake appears to be in very good shape, as far as water quality goes, and appears to be stable after five years of intense residential development. The study is worth noting because, once concluded, they produced a document and mailed it to all residents in the county, much like a Consumer Confidence Report on water quality that is mandated in Virginia for all drinking water producers. The document clearly identified and defined all terms associated with this study. This was a great PR tool directed to the residents Newaygo County which allowed them to understand the results of the study and why this information is important for assuring the water quality of drinking water sources. (Bills, 2008).

Reservoirs are similar to natural lakes; the water quality is influenced by the geology of the watershed, climate and land use surrounding the waterway (Younos, 2007). Unlike lakes, reservoirs have few inputs other than precipitation and a few feeder streams (Ford, 1990; Thornton, 1990b, Younos, 2007). Reservoirs can be more complex systems compared to natural lakes. Because of the fewer inputs by streams or rivers, rapid changes in the amount of nutrients, sediments and even lake levels can occur in a very short period of time. The two lakes currently used for the water source for the Town of Culpeper are Mountain Run Lake and Lake Pelham. Like a reservoir, these two man-made lakes are primarily influenced by precipitation and runoff and have few natural inputs to influence the chemical composition of the lakes. Frequently, the amount of precipitation and the physical/chemical changes in the lake can be quite dramatic. A study conducted in 1980 indicated that the dry density of deposited sediments in Mountain Run Lake in Culpeper, Virginia were reported to have an average value of 57.15 lbs/ft^3. Assuming typical lake trap efficiencies of 90 percent, that all sediments are derived from erosive processes in the watershed(s), and that transport to the reservoir is 100 percent, average erosion rates may be calculated from the deposited sediment data. The 1988 calculated annual erosion of material from the watershed of Mountain Run Lake was found to be 1,468 lb/acre/yr. The rate in the upland portion of the watershed draining to Dam 8A is assumed to be the same (Draper, 1988). This lake directly feeds Lake Pelham and could have a direct effect on the solids level in Lake Pelham. Silt and clay particles have high sorptive capacities, particularly for phosphorus. The sediments carried into Lake Pelham, therefore, may frequently carry high levels of nutrients (Thornton, 1990: Duffy et al., 1978, McCallister and Logan, 1978, Schreiber and Rausch, 1979, Sharpley and Syers, 1979, Sharpley et al, 1987, Younos, 2007). The sediment fluctuations can bind or release phosphorus, creating a P sink/source that can have an adverse affect on the amount of algae and chlorophyll in the lake. Internal loading of nutrients can be quite significant in reservoirs like Lake Pelham (Wetzel, 1990; Younos, 2007). Nutrient laden material may contribute to excessive primary prodcution. Suspended solids can be a source of organic matter containing nitrogen and studies conducted on the Yellowstone River and it's tributaries, the Montana and the Wyoming indicate that the relationship of suspended solids and total nitrogen concentration can have a linear relationship (Dubrovsky et al., 2010). Under anoxic conditions, typically in the hypolimnion layer of a resevoir, phosphorus can be released from the sediments and made available to the primary producers, like algae (Thornton, 1990b; Baker, 1996; Younos, 2007).

The evaluation of Lake Pelham in 1988 yielded some interesting data. The report found that the apparent annual erosion of material from the Lake Pelham watershed is somewhat lower than that for the upper basin that consists of Mountain Run Lake. Normally, this would be expected, because the sediment delivery ratio is known to decrease with increasing drainage area (Novotony, 1981; Draper, 1988). However, in this case one must remember that the two upstream reservoirs, with their assumed sediment trap efficiencies of 90%, have reduced the apparent rate of erosion for the entire Lake Pelham Watershed. Because the two reservoirs drain 59.6% of the Lake Pelham Watershed, and may be assumed to reduce the effective erosion rate of that portion of the watershed to 147 lb/acre/yr, it seems likely that the actual rates of erosion in the lower watershed are substantially higher than the calculated value of 1350 lb/acre/yr. The adjusted 1988 annual erosion rates for the portions of the drainage basin between the upstream reservoirs and Lake Pelham were found to be 3100 lb/acre/yr. This adjusted erosion rate is over two times higher than that computed for the upland basins, after adjusting for sediment trapping upstream (Draper, 1988).

Several conclusions did come from this study conducted at 1988 (the focus of this paper is in bold).

1. The accumulation of sediment in Mountain Run Lake and Lake Pelham was computed from bottom contour and verified with sediment probe measurements and forum to be 59 acre/ft for Mountain Run Lake and 118 acre/ft for Lake Pelham.
2. Characterization of the sediments in both lakes showed them to be consistent with the native soils, and reinforced the conclusion that sediment accumulation in the system is a function of watershed erosion, and not a product of material within the lake. This is a characteristic of a system with only moderate nutrient enrichment.
3. Based on the published design sediment storage volumes, and current life of the reservoirs, the accumulation of sediment to date (1988) would indicated a date of 2014 for Mountain Run Lake and 2089 for Lake Pelham before the deposition of sediment intrudes into the design water supply storage volume. The effects of the upstream reservoir trapping of eroded materials in reducing the accumulation in Lake Pelham may be clearly seen.
4. If needed, modest draw-downs of the reservoir pool could help with excavations of some of the trapped sediments in shallower areas.
5. Significant alterations in land use patterns in the watershed may be anticipated to change the rate of transport of sediments and other stormwater-borne pollutants to the lakes. From the perspective of erosion control only, conservative engineering practice would dictate, at a minimum, the institution of stormwater management practices in new urban developments that restrict the discharge of runoff form developed parcels to rates that do not exceed those experienced in the undeveloped state. This will reduce the amount of new stream channel erosion, and subsequent increases in sediment yield, taking place in the basin.
6. **Plant nutrient (nitrogen and phosphorus) transport into Mountain Run Lake and Lake Pelham from their tributary drainage basins represent the most clear threat to lake water quality.**
7. **Because of anticipated development activity in the watershed(s) it would be prudent for the Town of Culpeper to consider implementing a more regular program of lake examination to assay the effects of changing sediment deposition patterns on available storage. An interval of 5 years would seem to provide such data with an adequate frequency. (Draper, 1988)**

The greatest threat to lake quality is from plant nutrient (nitrogen and phosphorous) transport. The Watershed Protection Ordinance establishes a management system based on technology implementation, restrictions on grading and impervious surface, incentives to employ cluster styles of development, mandatory pollution reduction by way of best management practices (BMP's) and natural buffers, the extension of water and sewer services (to replace private septic systems), and restrictions on hazardous materials. In the Lake Pelham Watershed Management Plan, conducted by Espey, Huston & Associates and based on the Draper and Associates study, the impact of future development on phosphorous concentrations in the lakes was assessed under four different density scenarios. According to the model, which was developed, concentrations of phosphorous can be expected to increase by 25% to 30% by 2010. The low nutrient loading from future development was estimated, but needs to be confirmed to establish a baseline health of the water supplies. An update study on the phosphorus concentrations has occurred in 2010 and will be reported in the results section (Espey et al, 1988).

SAMPLING AND TESTING PROTOCOL

A sampling and monitoring program was established to fully evaluate the tropic state of Lake Pelham. Mountain Run Lake was excluded from this study, for the time being, as a cost savings. Sampling protocol and preliminary data are listed below. It should be noted that the sampling and monitoring program are still on going.

Climate/Precipitation Monitoring Program

The primary method for nutrient and sediment loading into the lakes is via precipitation and the accompanying runoff. Precipitation data was obtained from the NOAA website, which estimates the amount of precipitation by hundredths of an inch. This data was accompanied with nutrient, pH, and DO sampling data to examine the infuence of precipitation on nutrient loading into the two lakes.

Lake Sampling Protocol

A large part of materials being deposited into both Lake Pelham and Mountain Run is in the form of sediments, which also have large amounts of adsorbed nutrients and metals. This study consisted of collecting samples at the intake structure twice a week. The samples were taken to the water treatment facility and tested immediately for three nitrogen compounds (nitrate, nitrite, ammonium), total inorganic phosphorus, dissolved oxygen, and pH. A Secchi disk reading was also taken at the intake structure. The collection of samples was conducted for a 1-year interval in 2010. Initially, the sampling was only conducted once a week, when the sampler could penetrate the ice on the lake. The frequency was increased in August of 2010, as the algae concentration was visibly higher while a small drought was occurring. When possible, the samples were collected twice a week and the tests were conducted at the Water Treatment Plant in Culpeper, Virginia. The sample containers did not contain preservative, as the analysis in the following sections were conducted immediately after collection The water treatment operators conducted the tests and the results were reported to the chief operator for tabulation.

Nitrogen Compound Testing

Samples were analyzed for nitrite, nitrate, and ammonium and total nitrogen was the sum of these three values. The methods used are based in part by the Standards Method For Water And Wastewater Analysis Manual, 22 edition. These are standards that are the approved by the EPA for water and wastewater analysis. If the methods were not derived from Standard Methods, they were dervived from the Hach DR 2800 Spectorphotometer Manual. The analysis for the nitrite and nitrate compounds were conducted on a Hach DR 2800 Spectorphotometer. Validation on the accuracy of this instrument was conducted prior to each test using a purchased certified standard.. Two 25 ml samples were placed in a sample cell, along with a distilled water blank. A pre-made analysis pillow for nitrate and nitrite were added to a sample cell and allowed to react for ten minutes. The sample cells were immediately analyzed by the Hach DR 2800 and the results were recorded. Ammonium concentration analysis was conducted on a Denver Instruments 200A pH meter with a Denver Instuments Ammonia Selective probe. A 100 ml sample was prepared with a sodium hydroxide buffer solution and allowed to mix for 4 minutes. The ammonia probe was then placed in the sample and the ammonia concentration was recorded.

Phosphorus Compound Monitoring

The inorganic phosphorus concentration was measured using a Hach DR 2800 spectometer. The method was dervived from the Hach DR 2800 Spectormeter Manual. A 25 ml sample was placed in a sample cell, along with a distilled water blank. A pre-made analysis pillow for phosphorus was added to a sample cell and allowed to react for ten minutes. The sample cells were immediately analyzed by the Hach DR 2800 and the results were recorded for the concentration of total inorganic phosphorus. Validation of the meter's accuracy was conducted using a certified purchased standard prior to each test.

Physical and Chemical Properties Monitoring: pH, Turbidity and Color

The pH of the samples were conducted on a Denver Instrument 200A pH meter, calibrated daily with 3 buffers for accuracy. A 150 ml sample was placed into a beaker with a stir bar and the pH probe was placed into the sample with the stir setting on high. The temperature and the pH were allowed to stablize, typically taking approximately 2 minutes. The results were recorded by the operators.

Tudbity and color measurements were conducted on a HF Scientific 1000 Micro IR trubidity meter. The samples were placed in a sample cell and immediately placed into the meter. The turbidity measurement was recorded after 30 seconds. The same sample was then recorded for a color measurement using the Hach 2800 DR meter. A blank color sample using distilled water was prepared and placed into the 2800 DR as a reference blank. The color program was selected and the blank was used to zero the meter. The turbidity sample cell was placed into the 2800 DR and the results were recorded. The meter is then validated using a purchased 500 Pt/Co standard.

Lake Properties Effects on Water Plant Efficiencies and Chemical Usage

During the evaluation period of Lake Pelham, the chemicals used at the water facility to maintain the high level of water quality, were monitored through the water plants Supervisory Control and Data Aquistion software (SCADA). Large chemical changes in a short period of time were noted in this study.

RESULTS AND DISCUSSION

During the last ten years, the Town of Culpepper has experienced a great deal of urban development which has negatively impacted the surrounding watershed The Town of Culpeper has contracted several environmental engineer firms to determine the best course of action that could improve surface water quality. All firms suggested that a continuous monitoring program was needed to evaluate key water quality parameters. If a monitoring program was implemented shortly after the initial recommendation, seasonal variation could have been predicted and the amount of pretreatment necessary on Lake Pelham and Mountain Run Lake may have been reduced. Significant increases in the amount of alum, carbon and lime have dramatically increased the cost of treating the water. In 2010, the testing regime recommended by Espey, Huston, and Associates, as well as the Virginia Water Resources Research Center, was implemented with the hopes that seasonal variation and other notable trends in the lake water could help reduce the cost of treatment either by anticipating seasonal changes or finding alternate ways of treatment (Espey, 1992; Virginia, 2005).

The testing conducted over the last 12 months had similar results to the study conducted 15 years ago by Espey, Huston and Associates for the parameters like pH and Secchi disk. The nutrient concentration, however, did increase subtantially. In that study, it was suggested, that a weekly monitoring program was in the best interest of the Town of Culpeper and the community at large (Espey, 1992). The summary of the results of the two studies is listed in Table 2. The notable increase was in the amount of both nitrogen and phosphorus in Lake Pelham. The amount of nitrogen found in the lake has nearly doubled over the 18 years between the studies. Also, the total phosphorus concentrations in the lake increased seven-fold. The increase in the urbanization and land-use changes are most likely the primary reasons for the dramatic change in these numbers. The amount of chlorophyll-a in this table is a calculated value; back calculated from the TSI values for total P and the Secchi Disk.

	Lake Pelham, Culpeper, Virginia Water Quality Study 1992	Lake Pelham, Culpeper, Virginia Water Quality Study 2010		
Test	Average Value	Average Value	STD	CI ($\alpha < 0.05$)
Total Phosphorus	85.00 ppb	594.90 ppb	86.7	0.22
Total Nitrogen	8.29 ppm	13.6 ppm	5.48	1.39
Secci Disk Value	1.50 Meters	1.49 meters	0.33	0.11
TSI (TP)	59.3	59.75	0.25	1.07
TSI (SD)	54.15	54.58	3.47	1.07
Calculated Chl-a	7.5 ppb	6.24 ppb	1.43	0.37

Table 2: Water Quality Study for Lake Pelham Conducted in 1992 and 2010.

The total nitrogen (calculated) was plotted against the amount of precipitation received in Culpeper for 2010 (Figure 4). The total nitrogen concentration of Lake Pelham is highly dependent on the precipitation that enters the lake. In general large spikes in the data occur during even the smallest rainfall events, indicating a large amount of leeching that may be entering the lake from the surrounding environment. This occurs during the late spring and early summer months, when the local farmers are increasing the amount of fertilizer and manure to the local fields. The value then immediately declines 48 hours after the rain event. This can be attributed to the activity of primary producers, mainly algae, that use the readily available nitrates at the surface of the water. Total nitrogen mean low value of ~10 mg/l, gives a baseline in which a true trend can be established over the next several years. Spring and autumn total nitrogen concentration mean values are much higher (17 mg/L). The large changes in the total nitrogen in the lake can be attributed to the leeching effects from surrronding landscape. A decrease in the total nitrogen concentration means the algae already present in the lake are multiplying quickly, using the nitrates in the water to form new cells. With this increase in the activity in reproduction by a primary producer, it would be expected that the nutrient levels would decrease. The nitrogen concentrations has a cyclic effect, an increase in concentration followed by an immediate decrease within one week of a rain event as indicated by Figure 4. This relationship seems to be stronger in the summer months, when the activity of the algae is at its highest. During July, several large rain events occurred, with more than 3 inches of rain falling on the watershed within 7 days. The total nitrogen concentration, increased along with this increase in water in the lake two days after the rain occurred. The nitrogen concentration then decreased to the level prior to the rain event, indicating that the nutrient input decreased from algae production. The testing also indicates that the nitrate concentration, specifically, was found to be above the critical 10 mg/l during this time period. The EPA contamination limit is 10 mg/l, higher values result in higher health risks for humans, especially in the elderly and newborns. This is a concern during the treatment of the lake in the water plant, but the increase in the concentration of nitrates has not translated into an increase in the nitrate concentration in the water plant.

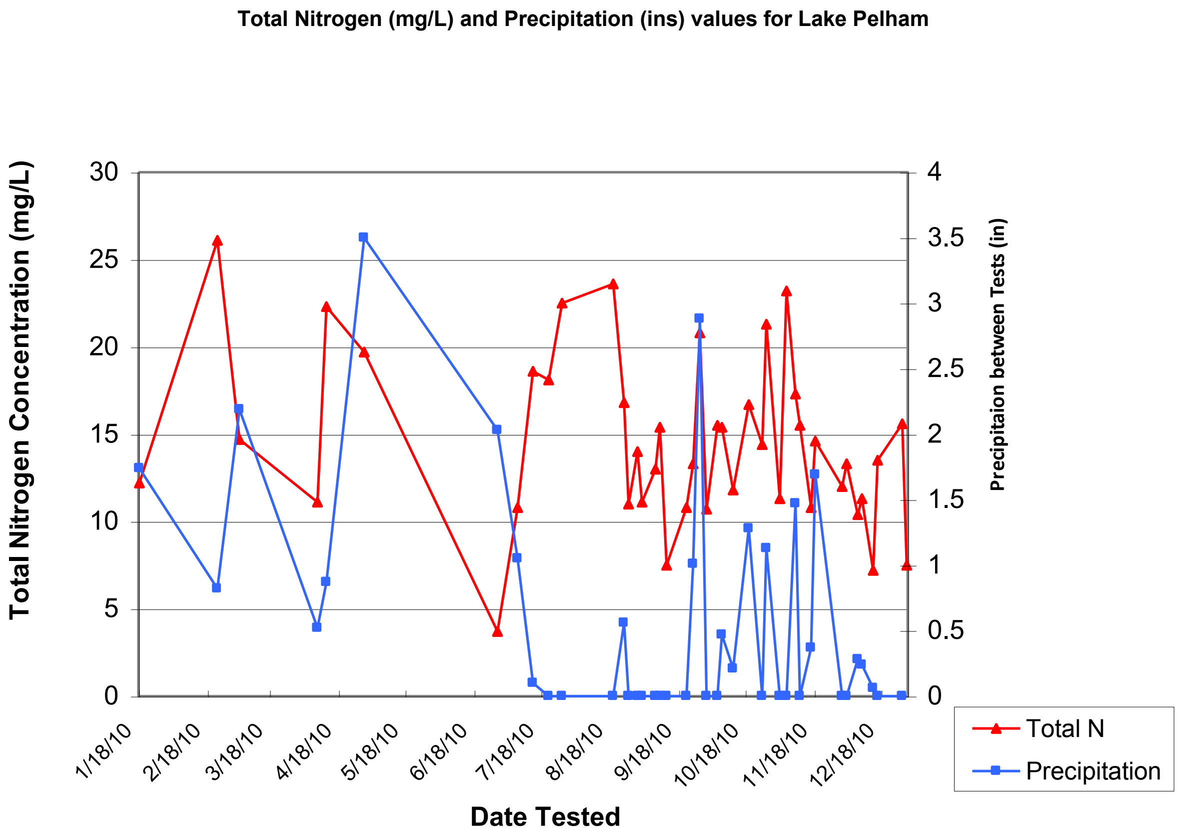

Figure 4: Total Nitrogen vs. Precipitation for 2010.

In Figure 5, the total nitrogen values were plotted with the corresponding pH values for the sample dates. An increase in pH is accociated with an increase in total nitrogen.. The increase in pH and total nitrogen during the months of May thru September occurred after a rain event. This is an indication of leeching and runoff effects on the lake. Zeng et al. conducted a study in 2009 that indicates that the algae and bacterial communities in a lake are effected by pH fluctuations in two ways. The first is that a change in the pH will alter the concentrations of ions and trace metals needed for cell growth. The second and possibly more significant consequence is that environmental pH will influence the biological mechanisms involved with cell growth and reproduction, at both higher and lower pH ranges. (Zeng et al., 2009). The increase in pH and associated nitrogen concentrations cooresponded to large algal blooms. This necessitated the addition of copper sulfate that resulted in a pH drop of 0.50 to 1.0 pH unit. During the fall and winter months, cyclic changes in the total nitrogen concentrations did occur, but the pH was relatively stable. This may be due to the lack of primary producers due to colder temperatures or a reduction in the sediment load during this time. The pH fluccuations in the lake will continue to be used as an indication of the need for copper sulfate treatments in Lake Pelham, as it has been proven in the past to be an excellent algae bloom predictor. The relationship between total nitrogen and the lake can be complicated and further investigation on the relationship between the nitrate concentrations specifically and the activity of primary producers on Lake Pelham will continue.

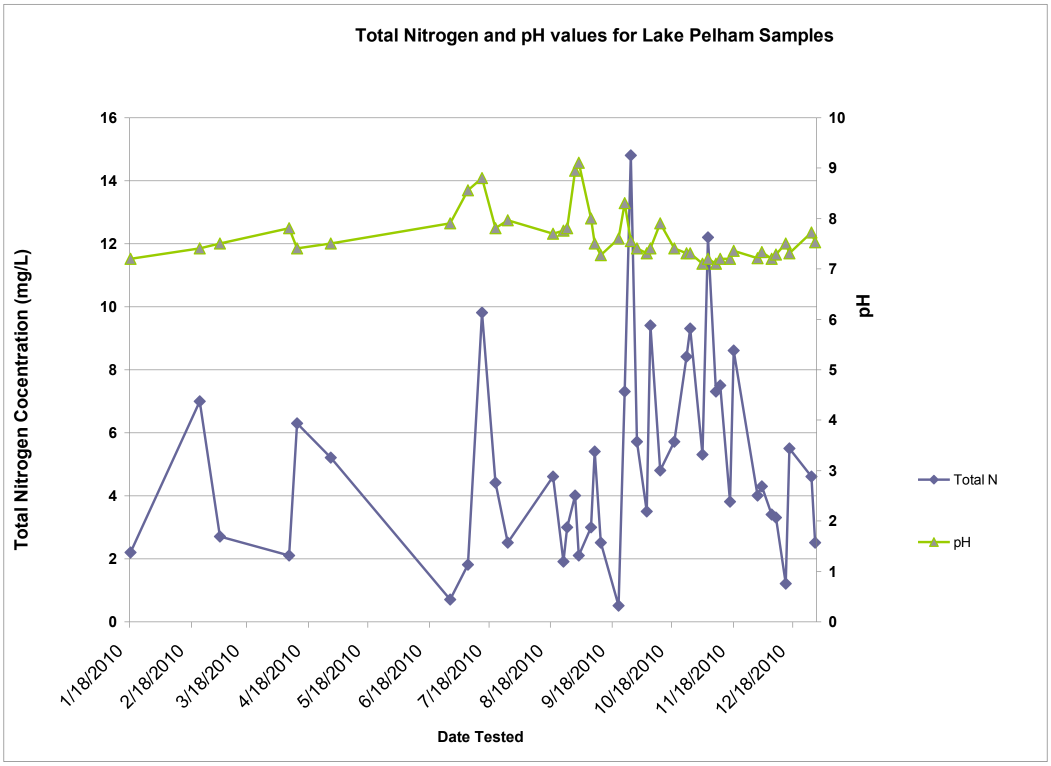

Figure 5: Total Nitrogen and pH values for 2010.

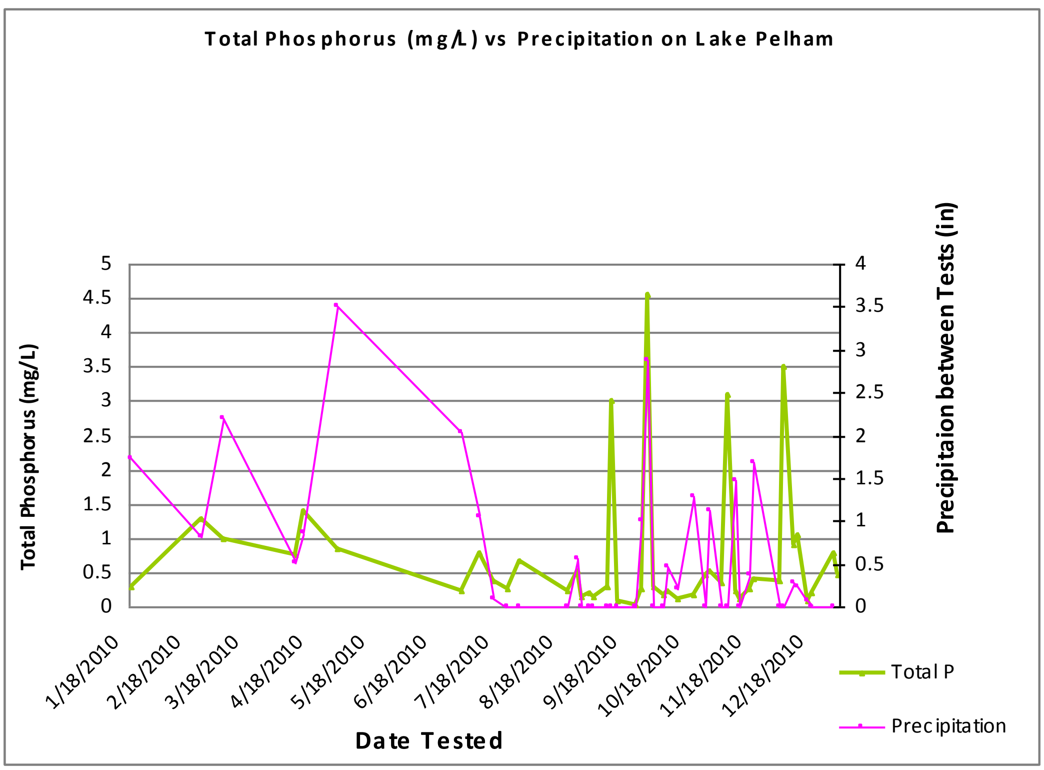

Figure 6: Total Phosphorus vs. Precipitation for 2010.

The phosphorous data (Figure 6) followed the same trends as the total nitrogen concentration versus precipitation. Lee et al (1978) suggested that a lake could be considered eutrophic if the phosphorus concentration of a lake was above 20 µg/L. The typical values for Lake Pelham through out 2010 were found to be 29.5 times that value (average values of 590 µg/L). The amount of phosphorus in the lake at a given point seems to be largely dependent on the precipitation entering the lake. The primary mechanism for transportation of phosphorus is through runoff from the surrounding landscape. Figure 6 demonstrates this trend that when a rainfall event occurs, the phosphorus concentration increases. There is a time delay in this increase, however. This indicates that the main sources of phosphorus entering the lake are upstream from Lake Pelham, in either Mountain Run Lake or Mountain Run Stream. Both of these water bodies are surrounded by agricultural lands. Even during lower water conditions, like what occurred in August of 2010, when the lake was 15 inches below peak level, a small rainstorm that occurred had a large impact on the amount of phosphorus in the lake,. Lower values for the total phosphorus were noticed in the August-September time frame, which was in agreement with observations noticed by the Virginia Water Resources Research Center (Virginia, 2005). This relationship demonstrates the height in activity of primary producers in the water, which will need large amounts of phosphorus for reproduction (Younos, 2007). This relationship may help to determine the amount of chlorophyll-a in the lake by Carlson's Trophic State Index and help predict the amount of algecide treatments needed during these months. The chlorophyll a calculation using the Carlson's Index and the phosphorus concentration has been argued to only be a rough estimation of the amount of chlorophyll in the reservoir system.

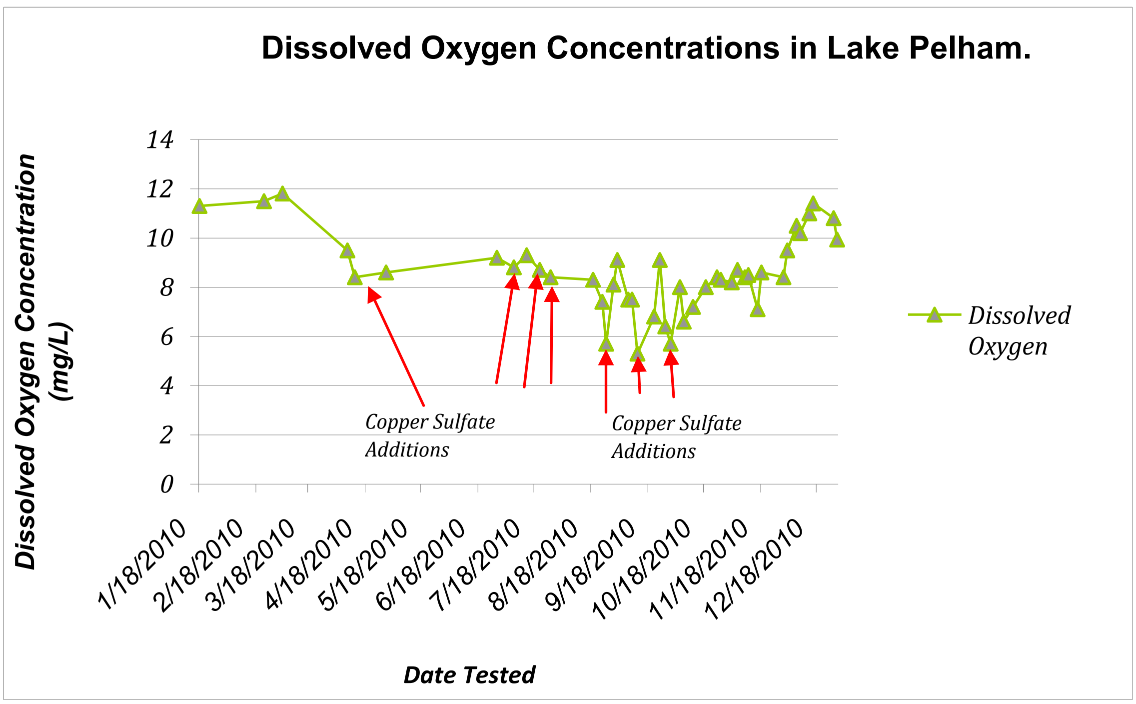

Figure 7: Dissolved Oxygen Concentrations for 2010 (at surface).

The dissolved oxygen concentrations of the surface water is typically higher during the winter months and decreases as the algae concentration increase in the lake (Figure 7). The copper sulfate treatments that occurred during the spring and summer months were placed on the figure. As the algae forms a film across the top of the lake in the summer months, the amount of oxygen in the water is about 8.0 mg/L. After a treatment with copper sulfate, a dramatic decrease in dissolved oxygen always occurs for approximately 24 hours. The concentration of dead algae increases and the bacteria responsible for decomposition increases as well, depressing the amount of oxygen in the lake as decomposition continues. The concentration of the dissolved oxygen in a lake may have a tremendous effect on the water quality and health of a lake. If a large decrease in the dissolved oxygen were to occur, this could result in major changes to the physical, chemical, and biological cycles of the lake resulting in a decrease in water quality. If the dissolved oxygen were to drop dramatically, it may lead to increases in hydrogen sulfide, ammonia and phosphorus, and the release of reduced iron and manganese from the sediments (Younus, 2007). There is not an existing D.O. level established for water supplies in Virginia, although values from 3-5 mg/l are suggested values in several states (Younus, 2007). For 2010, the overall trend is that as the water heats up, the dissolved oxygen decreases, which is expected. The application of copper sulfate, which creates a rapid algae die-off, creates depressions in the dissolved oxygen concentration. The dissolved oxygen concentration never went below 5.0 mg/l. During the month of September, the dissolved oxygen concentration started fluctuating, which may be due to the increasing die off of the algae as the water temperature decreased. It could also be a result of the lake turn over, where the lakes epilimnion and the hypolimnion mix together and bring the very low oxygen water from the bottom mixing it with the surface water. Until the water reaches equilibrium in the late fall, fluctuations are expected. The turn-over also drags metals and sediments from the bottom to the surface. The metals begin to oxidize as they rise from the bottom, further depressing the oxygen levels in the water (Novotny, 2003). Studying the lake's dissolved oxygen concentration and the layers due to stratification needs further investigation.

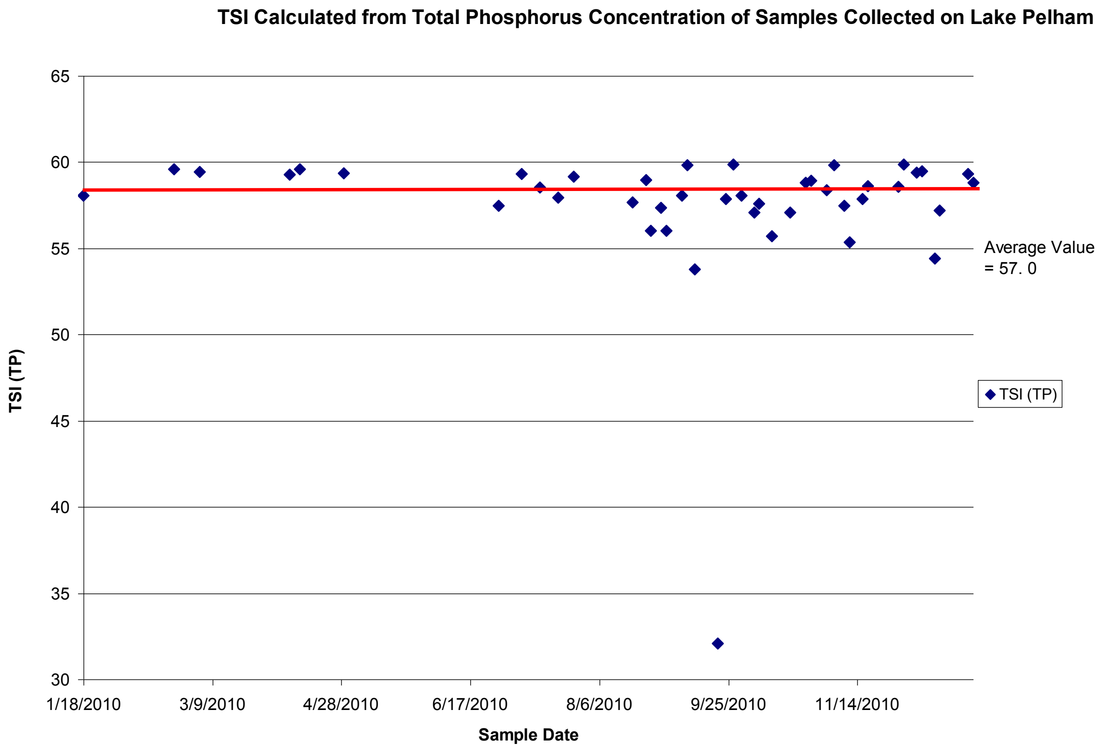

Figure 8: Calculated TSI (TP) values for Lake Pelham.

The Tropic State Index (TSI) can be calculated by using one of three testing parameters: the total phosphorus concentration, the Secchi Disk readings, and the chlorophyll-a concentrations (Table 2). Each calculated value should agree with the other 2 calculated TSI values, so the TSI value of one parameter can be used to calculate the value of the other two parameters. The Town of Culpeper does not have a reliable method for measuring chlorophyll-a, so the operators decided to record the TSI using the total phosphorus data and the Secchi disk testing. If the TSI values for these parameters agree, either one can be used to calcluate the concentration of chlorophyll-a in Lake Pelham. For the first TSI values that were calculated using the total phosphorus concentration, designated as TSI (TP) for Lake Pelham. Other than one outlier, the data series lied between 57 and 60, on the TSI scale (Figure 8). The average value was calculated to be 59.75 ± 0.25. Even the large changes in the total phosphorus concentration that occurred in September and October of 2010 resulted only in a small change in the calculated TSI values. The second TSI values calculated were from the Secchi disk testing, designated as TSI (SD). The Secchi disk testing was conducted during the second half of the 2010 (Figure 9), so the number of samples is less. The Secchi disk results demonstrated little difference in the clarity of the lake over those 6 months, with values between June to December being 1-2 meters. There was no coorelation between precipitation events and the Secchi disk readings. The Secchi disk test is very subjective and can be dependent on the interpertation of the operator. The Total Suspsended Solids (TSS) in Lake Pelham can have a dramatic effect on the Secchi disk values, as well (the TSS was not recorded during this study). Turbidity is a much more accurate and reliable test for lake clarity. The tudbidity values for January thru December of 2010 also did not coorespond to precipitition data; only very large storm events (> 2 in) resulted in a small change in Lake Pelham's turbidity. Also, the turbidity data can not be used to caluclated the Trophic State Index, so the Secchi disk values were used to calculate a set of TSI values. The TSI (SD) (Figure 10) had a calculated average value of 54.5 ± 3.47. The calculated values for TSI from total phosphorus and Secchi disk are slightly different, due to the subjectivity of the Secchi disk readings. It is encouraging that the values were not very far off, within the calculated standard deviation of each test. So the two values from each test date were averaged together for a value of 57.1. Using Carlson's Index (Carlson, 1977) this value indicating that Lake Pelham falls into the eutrophic state (Figure 2). This indicates that there are high nutrient and algal levels, low water clarity and a potential decline in some fish due to lower oxygen levels in the deep water (King County, 2007). The Secchi Disk or clarity of the lake has not changed much from the values obtained in 1992. So visually, the lake looks exactly the same as it did 20 years ago. The amount of nutrients, however, has increased substaintially. The Carlson Index has not significantly change over the last 20 years. This seems to indicate that the large amount of development over the last several years has not adversely hurt Lake Pelham. The results from the TSI calculations are a good tool for communication to the public.

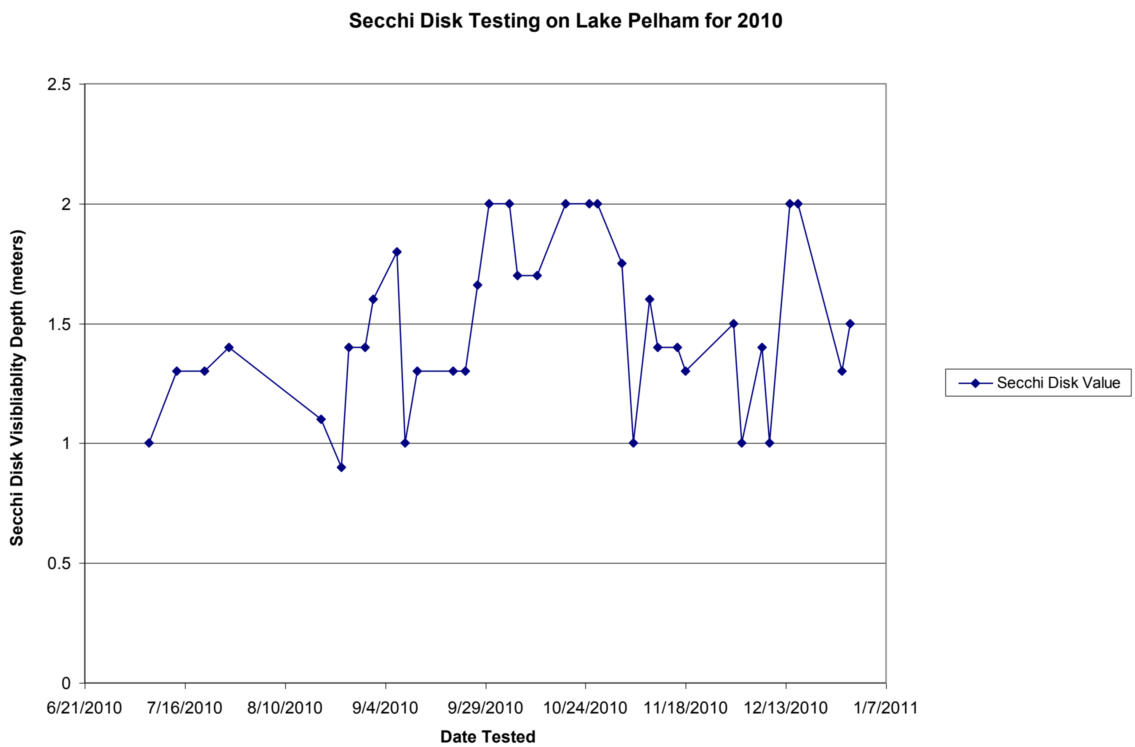

Figure 9: Secchi disk values from Lake Pelham for 2010.

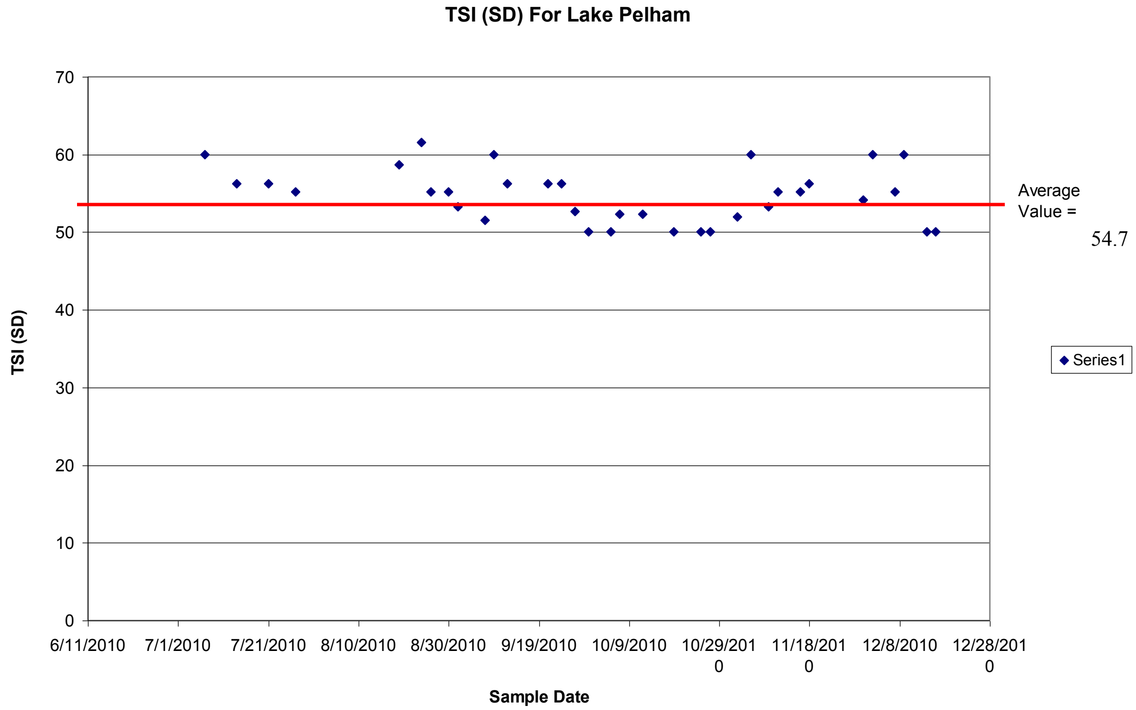

Figure 10: TSI caluclated from Secchi disk readings from Lake Pelham.

In the spring, the amount of nutrients are at their highest concentrations in a lake, from the runoff and leeching during the fall and winter months and the nutrients that are released from the bottom during the spring turnover of the lake. This can lead to a large amount of algae forming in the lakes, once the water temperture is warm enough to support algal growth. The increase in the raw water pH can create problems in the water treatment plant, especially in the clarifing step of the process, where pH is critical to optimum treatment. Also, increase in the carbon feed system is needed to combat the change in the taste of the water and the odor that the presence of algae (both alive and deceased) can create.

In the summer months, the algae levels in both Mountain Run Lake and Lake Pelham reach levels that affect the taste of the finished water produced at the water plant. It can also adversely affect the amount of dissolved oxygen in water, reducing the levels to the point of killing aquatic life in the lakes. To combat this problem, the lakes are treated with copper sulfate (both in solid and liquid forms). Copper–based algaecides damage and kill algal cells, which leads to the release of algal toxins into the surrounding water (Hullenbusch et al., 2002). Once in the water, toxins can pass more easily through the water treatment filters. If algaecides are used in potable water supply reservoirs the water should not be used until the toxins and odors degrade. This could take several months. It is also a lot more difficult to detect algal toxins than whole algal cells. Once algal cells are killed, the only way to determine whether algal toxins are still present in the water is through toxin testing, which can take up to a week and is far more expensive than testing for algal cells. The toxins produced by blue–green algae are generally very stable compounds that are resistant to chemical breakdown and may remain in natural waters for several months. Under natural conditions, sunlight and bacteria may cause the breakdown of some toxins (New South Wales, 2005).

Several problems can occur with this treatment. Part of the need for frequent application of copper sulfate to both reservoirs appears to be the binding of copper to particles (possibly inorganic colloids, and other organic material) and/or the precipitation of copper which settles to the bottom of the lake as bed sediment. This is substantiated by the presence of more than 50 percent of the total copper in the suspended form in most water-column samples and greater concentrations of copper at depth in both reservoirs even though copper sulfate is applied at the surface in a dissolved form. The application of copper sulfate in heavy amounts could rapidly deplete the amount of dissolved oxygen in the water. The death of the algae is almost immediately after application and the depletion of the DO occurs within 6 hours. The DO has depleted to observed values of 2-3mg/l on Lake Pelham within 24 hours after application This could result in a serious issue with fish kill in the lakes and a large mortality rate in the bait and sport fish population. Although the primary responsibility of the water treatment operators is to maintain the health of the lake for water production, a large fish kill has a very negative impact on public perception. The precise amounts of copper sulfate needed to control the algae blooms are difficult to predict, but are typically estimated (from years of experience treating the lake) towards the lower amount of application. If the amount of algae could be predicted or monitored closely, the amount of copper sulfate could be altered or reduced, ensuring the health of the fish and overall health of the lake.

The changes in the nutrient concentrations result in changes in the algae concentration in the lake. As a result, the presence and/or the decay of large amounts of algae leave a very unpleasant taste in the water, and the filtration system for the Town of Culpeper can not remove the taste or odor without the use of powdered carbon. The summer months can see a large increase in the amount of carbon needed to treat the water for the moldy or dusky taste. The algae also increases the pH in the water to values > 8.0. This severely limits the ability of the water treatment process to remove iron from the water. Iron removal typically requires a lower pH (~6,5) to remove in the filtration process. The presence of iron will cause staining issues in the distribution system, especially when the customers are doing laundry or washing dishes. Also, a higher pH's reduces the effectiveness of the aluminum sulfate (alum) and the polymer system used in the sedimentation process. At higher pHs, the floc formed by the aluminium sulfate is very small and will not bind materials properly. Also, the small floc will bind the filters and reduce the turbidity of the filter effluent water. The treatment process requires twice as much alum in the summer months (June-September) than the rest of the year. This increase in alum, polymer and carbon, of course, increases the chemical cost of the water treatment process, but also decreases the filter run time in the plant, as the filters are overloaded with the light, fluffy floc that the increase in alum creates. Typically, 45% of the Town of Culpeper's water treatment budget, or $80,000, is spent during the summer months (June – September) to correct the pH values in the plant to achieve appropriate treatment and the addition of carbon to produce better tasting water. If a 50% reduction in the amount of chemicals was obtained due to improved raw water quality, there is a potential chemical cost savings of $40,000 per year. Restocking fish that die off due to a dissolved oxygen depression can also cost $10,000 per stock and fish kills have a very negative impact on the public image of the treatment plant.

CONCLUSIONS

This was a successful first attempt at understanding the water quality at Lake Pelham. As in the study conducted in King County, Washington, long term data (decade or more) will need to be compiled to apply seasonal variability and in-depth statistical analysis. The study was a success, in that, it is getting the Town of Culpeper and the operators that work for the town to perceive the lake in a whole new light; a resource that is beginning to deteriorate and action needs to be taken to preserve this resource. As noted in the Virginia Water Resources Center, both the TN and TP can be useful as predictors for chlorophyll-a (Virginia, 2005). This could help with predicting the annual amount of copper sulfate needed in the lake and when pretreatment of the lake should begin. This study has given the water treatment staff for the Town of Culpeper a better understanding of the biogeochmical reactions that are affecting the lake and what actions need to be done in the water treatment process to enhance water quality.

It is interesting that based on the limited data from 1992 and the data collected in 2010 that the lake parameters have not changed as much as one would predict. Increased urbanization, large amounts of sediments entering the lake and other cultural activities appear to have had an effect on the amount of nutrients in the lake, but the data still suggests that the lake is in the same state that it was in 1992, based on TSI values. However, the nutrient levels have increased over the last several years and need to be monitored closely, to ensure that the nitrate level specifically, will not violate EPA standards for drinking water. The monitoring for Lake Pelham will continue and there are several actions items to enhance this study.

FUTURE ACTIONS

Several action items have been noted as this study continues into 2011 and beyond.

Customer Communication:

The data tabulated in this report shall be communicated to the Town Council and the citizens of the Town of Culpeper. The overall public perception about Lake Pelham and the treatment of drinking water has to change in the town, and this may be a first step to open up the doors of communication. With these public meetings, the Town and the public can come to a concensus on a method to reduce the amount of nutrients entering the lake. Future communication plans include presenting this data either at the Virginia Rural Water Conference or the American Water and Wastewater conference, to demonstrate the importance of this type of study even for a small municipality like Culpepper, Virginia.

Sedimentation Evaluation:

The soil loss for each rain event shall be monitored using the Revised Universal Sole Loss Equation (RUSLE), the most common and best known estimator of soil loss caused by upland erosion (Novotny, 2003). The RUSLE is as follows:

$$A = RK(LS)CP$$

Where A = Average soil loss (tons/ha) for a given storm or period
R = Rainfall Runoff Erosivity Factor
K = Soil erodibility factor
LS = Slope-length Factor
C = Cropping management (vegetative cover) factor
P = Erosion control practice factor.
(Prasad, 2005)

Most of these values have been well established for this area with the onset of the Chesapeake Bay Initiative and can be obtained either through literature or the U.S. Department of Agriculture.

Once the data has been obtained for this equation, the analysis of the predicted values of the phosphorus and nitrogen loading can begin, using a computer program called Eutromod. This program has been in use for 12 years and was recently modify by W. Cully Hession at Virginia Tech so it could be used in Microsoft Excel (Hession, 2006). Once all the input parameters have been established, Eutromod will calculate the following for Lake Pelham:

1.) Runoff Volume
2.) Soil Loss
3.) Sediment Load
4.) Dissolved Nutrients; both Phosphorus and Nitrogen
5.) Sediment-attached nutrients; both Phosphorus and Nitrogen
6.) Total Nutrients; both Phosphorus and Nitrogen
7.) Breakdown of nutrient input by land usage.

This data will help better quantify the amount of total water volume lost each year, the amount of sediment discharged into the lakes, and the amount of nutrients that are carried into the lakes by these sediments. In addition, the Total Dissolved Solids will be measured in the laboratory, to examine the effects that this may have on the Secchi Disk values and the overall amount of sediment that may be in the lake.

Organic Chemical Monitoring:

Total Organic Carbon (TOC) has been monitored at Lake Pelham, via the Virginia Department of Health. These compounds are present due to erosion from the urban environments, farmlands, and the decay of other organic materials (algae, other biological lifeforms). These compounds, along with the removal ratio from the water production facility, will be recorded monthly in an attempt to correlate these results to other system changes in the lake and/or seasonal changes in the region. The Town of Culpeper has recently purchase the required equipment for this test and will be conducting independent testing periodically, to see when wide changes in these parameter occur. Also, a reliable instrument for measuring chlorophyll-a shall be purchased, so all three TSI values can be obtained, instead of the back calculation that occurred in this study.

Trace Element Monitoring:

Trace element cations are added to surface and groundwater through a combination of natural and anthropogenic activities. Their solubility and potential bioavailability will depend on a myriad of chemical reactions that take place in natural systems. In general the solubility of trace element cations decreases with an increase in pH due to the adsorption on mineral surfaces and the precipitation/coprecipitation as metal oxyhydroxides.

Manganese is a naturally-occurring element that ubiquitous in the soil, and water and is often found at elavated concentrations in surface water bodies that undergo eutrophication. It may exist in oxidation states ranging from –3 to +7; the manganous (Mn^{2+}) and manganic (Mn^{4+}) oxidation states are the most important for aquatic systems (U.S. EPA, 2004) Manganese is an essential nutrient for humans and animals. Adverse health effects can be caused by inadequate intake or over exposure (U.S. EPA, 1990). As an element, manganese cannot go through typical metabolic transformation in humans, but it can exist in many oxidative states and can be converted from one oxidative state to another within the body. In order to enhance consumer acceptance of water resources, the EPA recommends reducing manganese concentrations to or below 0.050 mg/L, the EPA's Secondary Maximum Contaminant Level (SMCL) for Mn. The SMCL is based on staining and taste considerations (U.S. EPA, 2004).

Several other trace elements that affect the receiving water bodies including cadmium, copper, chromium, lead, mercury, nickel and zinc. These trace element can occur in water from several sources including industrial operations, ores, mining, deteriorating infrastructure, traffic, and agricultural use (Novotny, 2005). For Lake Pelham, most of the inputs of trace elements would be directly from traffic corridors and agricultural sources. The trace elements have various health effects, depending on the metal species, including carcinogenetic potential with several of the species listed above.

The most problematic elements that exists in this water shed would have to be iron and manganese. Previous studies have indicated large changes in the concentrations of these metals can occur rapidly, especially during the spring and autumn lake "turn-over", when the cool water from the bottom of a water body and the warmer waters at the top literally flip over, bringing the metals from the bottom sediments to the surface of the lake. The presence of these metals, in high enough concentrations (especially in the spring and fall), may create several operational problems at the Water Production Facility, resulting in high concentrations in the distribution system. Lake Pelham and Mountain Run Lake shall be monitored for both iron and manganese monthly, to find the highest concentrations that could occur and a potential source that could be creating large spikes in the concentrations.

Stream and Intake Monitoring:

Stream monitoring in between Mountain Run Lake and Lake Pelham has been in place since 1970, monitored by the USGS gage. This data will be analyzed along with the parameter testing already conducted at this site. Also, periodic measurements of stream width, depth, and current velocity will be taken using a hand-held current meter, which will allow the development of an empirical rating curve for each sampling station over a period of years. Also, the USGS shall be contacted to investigate the possibility of taking over the sample site, which has been dormant since 1999. With this site, the Town of Culpeper could resume the testing that was being conducted by the USGS and obtain useful data about surface water entering Lake Pelham.

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