ABSTRACT

ERIC J. KELLY: An Analysis of Jordan Lake Water Quality and its Impact on the Cary/Apex Water Treatment Facility
(Under the direction of Dr. Philip C. Singer)

Understanding the variability in raw water quality at water treatment plant intakes is important because the variations will affect the water treatment plant's processes, chemical usage, and chemical costs. The variation in raw water quality of Jordan Lake was analyzed to evaluate its influence on the Cary/Apex water treatment facility. This process included assessing seasonal fluctuations in coliform bacteria, examining correlations between coliform bacteria and other source water quality parameters such as turbidity and temperature, and exploring relationships between source water quality parameters and chemical usage and corresponding chemical costs using linear regression analysis. The results obtained for Jordan Lake and the Cary/Apex water treatment facility were compared to those for Falls Lake and the Raleigh water treatment facility.

A strong correlation was observed between coliform bacteria counts and water temperature for both of the source waters. Surprisingly, a weak correlation was observed between coliform bacteria counts and turbidity, despite the fact that turbidity is used as a surrogate for microbial contamination. The extent of microbial inactivation, in terms of residual disinfectant concentrations times contact time (CT), ranged between 3 and 38 times and between 3 and 24 times the required CT for the Cary/Apex and Raleigh water treatment plants, respectively. A greater excess inactivation potential was exhibited during the warmer

summer months, the period of the year when consumer water demand and coliform bacteria counts are at their highest levels. A multiple linear regression analysis relating chemical cost with various source water quality parameters at the Cary/Apex facility proved to be insignificant at best, with an R^2 value of 0.30. Alum dosages were relatively constant throughout the year, despite seasonal fluctuations in source water quality.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Philip Singer for serving as my advisor during this ordeal. Dr. Singer is an excellent teacher, facilitator, and mentor and I am extremely fortunate to have had the opportunity to experience his tutelage. I would also like to extend my gratitude to Dr. Francis DiGiano and Dr. Gregory Characklis for volunteering their time to be on my committee. I know it was a tough sacrifice for both of them to make.

I would like to thank all the taxpayers for providing the funding for tuition and the United States Army for allowing me the time and opportunity to attend Graduate School at the University of North Carolina. Without the time, this would not have been possible. Also, I would like to thank all the men and women serving in the military for their dedication and duty to the Nation. HOOAH!

Thanks also to Don Johnson at the Cary/Apex Water Treatment Plant and the plant manager at the Raleigh Water Treatment Plant for providing electronic copies of the plants' monthly operating reports. Without these reports, this work would not have been possible.

Lastly, I would like to thank my wife and children for their support and sacrifices over the past two years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1. Introduction

Clean water is vitally important for human health and well-being. In today's society, the majority of the United States' citizens expect high-quality drinking water. While the United States' drinking water supply is vastly superior to that of many other countries, waterborne disease outbreaks still occur and pose a health risk to the population (Hrudey and Hrudey, 2004). The main forms of drinking water contaminants are chemical, physical and/or microbial agents. The focus of this report is on the microbial contamination of downstream water sources by impaired streams, more specifically the impact of Northeast Creek (impaired by bacteria, fecal coliforms) on B. Everett Jordan reservoir.

Northeast Creek, located in eastern Durham County, North Carolina, in the upper Cape Fear River Basin, exceeds the state water quality standard for bacteria (fecal coliforms). The creek is 13 miles long with a 9.6 mile segment listed on the 303(d) list as impaired (NCDWQ, 2006). Northeast Creek is a tributary to the B. Everett Jordan reservoir, which serves as a drinking water source for the communities of Cary, Apex, Morrisville and northern Chatham County with an estimated population of 125,000 people.

In 1990, the Environmental Protection Agency reported microbial contamination (*i.e.*, bacteria, protozoa, and viruses) of drinking water as the greatest human health-risk management challenge for water treatment facilities (USEPA, 2006). The Safe Drinking Water Act and the Clean Water Act address microbial contamination from two different perspectives. The Safe Drinking Water Act regulates the quality of drinking water and the protection of water sources used for drinking water (42 U.S.C. § 1423) while the Clean Water Act lists requirements for the protection of surface waters which may be used for potable water and recreational purposes (33U.S.C. § 1251).

Although not specifically written as a separate rule, the concept of multiple barriers is incorporated in the Safe Drinking Water Act. Most water treatment facilities in the United States practice the concept of multiple barriers as the guiding principle for providing safe drinking water. The premise behind multiple barriers is that the use of several barriers is effective in preventing pathogenic microorganisms and other contaminants from reaching the consumer (AWWA, 1999). Therefore, if one barrier fails, the remaining barriers will minimize the presence of pathogenic microorganisms in the finished water. Multiple barriers in a drinking water system involve: source water protection; physical removal of pathogens (e.g. by filtration); inactivation of pathogens (i.e. disinfection); and proper maintenance and operation of the distribution system. In order to ensure proper effectiveness for each of the barriers, a comprehensive monitoring and sampling program must be in place.

For purposes of this report, source water protection means assuring the highest quality of source water possible by various watershed protection and land management strategies. The physical removal barrier for pathogenic microorganisms encompasses technologies like coagulation coupled with granular media filtration and membrane separation processes such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. The inactivation barrier includes the use of chemical disinfectants, such as chlorination or ozonation, and physical processes such as irradiation with ultraviolet (UV) light (MWH, 2005). The number of pathogenic microorganisms present in the water can be reduced to varying degrees by all the water treatment technologies mentioned.

The EPA uses the CT concept to determine the degree of inactivation of pathogenic microorganism in drinking water treatment. CT is the product of the residual disinfection concentration (C) in mg/L and the contact time (T) in minutes. The calculated CT value for a drinking water treatment plant is compared to EPA established tables for specific pathogenic microorganisms (i.e. viruses and Giardia) to determine the inactivation level and assure regulatory compliance.

The objectives of this study were threefold: 1) examine relationships between the presence of coliform bacteria at the Cary/Apex water treatment plant intake and other physical demand factors that influence water quality; 2) compare the actual CT values achieved by the Cary/Apex water treatment facility against required CT values in accordance with regulatory requirements; and 3) establish a correlation between chemical usage by the Cary/Apex water treatment facility and raw water quality parameters using multiple linear regression analysis. The raw water quality parameters used in the regression analysis are turbidity, temperature, pH, rainfall, total organic carbon concentration and coliform concentration. The relationship establishes a basis for determining chemical usage and ultimately chemical costs per million gallons of water processed. The regression model developed for the Cary/Apex water treatment facility on Jordan Lake was compared to the treatment of another nearby impounded raw water source (Falls Lake), used as a raw water supply for the city of Raleigh, North Carolina.

Chapter 2. Literature Review

2.1. Pathogenic Microorganisms of Concern in Drinking Water

All natural water bodies support microbial communities, some of which are pathogenic and of public health concern. Pathogenic microorganisms in drinking water can be classified into three primary groups: bacteria, viruses and protozoan parasites.

2.1.1. Bacteria

Bacteria are single-cell prokaryotic organisms typically consisting of a cell wall, cytoplasmic membrane, ribosomes and a nucleoid (Madigan et al, 2006) and range in size between 0.1 and 10 μm. Most bacteria of public health concern can be grouped into four general categories by morphology: coccus (spheroid); rod; spirilla (spiral or curved); and filamentous. Bacteria are able to proliferate through the means of DNA replication and cell division. Types of bacteria of public health concern include *Escherichia coli*, *Clostridium perfringens* and *Mycobacterium*.

2.1.2. Viruses

Viruses are organisms composed of either deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) and a protective protein coat. Viruses are typically 0.01 to 0.1 μm in size and shaped like a spear, sphere or wire (Madigan et al, 2006). All viruses are parasites and completely dependent upon the host for cell metabolism and replication. Thus, when viruses are outside of host cells, they become inactive and remain static in number or die off. Viruses are species-specific with respect to infection and typically attack only one type of host. More than 140 different enteric viruses are known to infect humans, such as Hepatitis A virus (HAV), Rotavirus, and Enterovirus (Hurst et al, 2002).

2.1.3. Protozoan Parasites

Protozoa are single-cell eukaryotic organisms that lack cell walls and range in size from 1 to 300 μm (Madigan et al, 2006). Protozoa possess a very complex metabolism structure and utilize other microorganisms (i.e. bacteria) for food. Like viruses, protozoan parasites rely on host organisms for replication. Host organisms for protozoan parasites vary from algae to highly complex organisms, such as humans and animals.

Two protozoan parasites of greatest concern in drinking water are *Cryptosporidium parvum* and *Giardia lamblia*. The transmissible stage of *Cryptosporidium parvum* and *Giardia lamblia* is a thick-walled oocyst, 4 to 6 μm in size, and a thick-walled cyst, 7 to 14 μm in size, respectively (Cloete et al, 2004). The wall of an oocyst and cyst provides a protective layer, allowing the parasite to live for extended periods of time (up to months or years) outside the host. The transmission of *Cryptosporidium parvum* and *Giardia lamblia* between hosts occurs mainly through contact with contaminated drinking or recreational water.

2.1.4. Waterborne Outbreaks

Data from the Centers for Disease Control and Prevention (CDC) indicate that 379 waterborne disease outbreaks were reported between 1980 and 1996, with over 500,000 cases of illness. However, a number of reports (Craun, 1992; Morris and Levin, 1995; Craun and Calderon, 1996; Ford, 1999) indicate that waterborne illness may be more prevalent than actually reported. Craun (1992) infers that only one-half to one-tenth of waterborne outbreaks in the United States are actually detected, investigated and reported. Morris and Levin (1995) suggest that the incidence of waterborne illness in the United States could be 7-8 million cases annually.

Over the past 40 years in the United States, Giardiasis and Cryptosporidiosis have become common causes of waterborne disease. Since the first documented Giardiasis outbreak in 1965 at Aspen, CO, 122 outbreaks involving 27,000 patients have been reported (Craun, 1996; Cloete et al, 2004). Also, since the first reported outbreak in 1984, *Cryptosporidium* has caused ten outbreaks in drinking water with approximately 421,000 cases of illness (USEPA, 2006). *Cryptosporidium parvum* was responsible for the largest waterborne outbreak ever reported in the United States, in Milwaukee, Wisconsin in 1993, with an estimated 403,000 illnesses and 50 deaths (MacKenzie et al. 1994; Hoxie et al. 1997).

Not every person that comes in contact with contaminated water becomes ill. The odds of infection depend upon many factors, including: the type of pathogen; the manner in which the pathogen is transferred; the resistance of the individual that is infected; and the infective dose and persistence of the pathogen. The infective dose refers to the number of pathogens that need to enter the host before the disease occurs.

In general, viruses and parasitic protozoa have very low infective doses, typically between 1 and 50 microorganisms (Hurst et al, 2002). Larger infective doses of bacteria tend to be required to cause infection; on the order of 10^2 to 10^8 organisms are needed (Hurst et al, 2002). Figure 2.1 illustrates the "typical" median infectious dose, N_{50}, required by various pathogenic microorganisms for infection in humans (MWH, 2005). Ultimately, the goal of water treatment is to reduce the number of active pathogens in drinking water to a safe and non-infectious level when consumed.

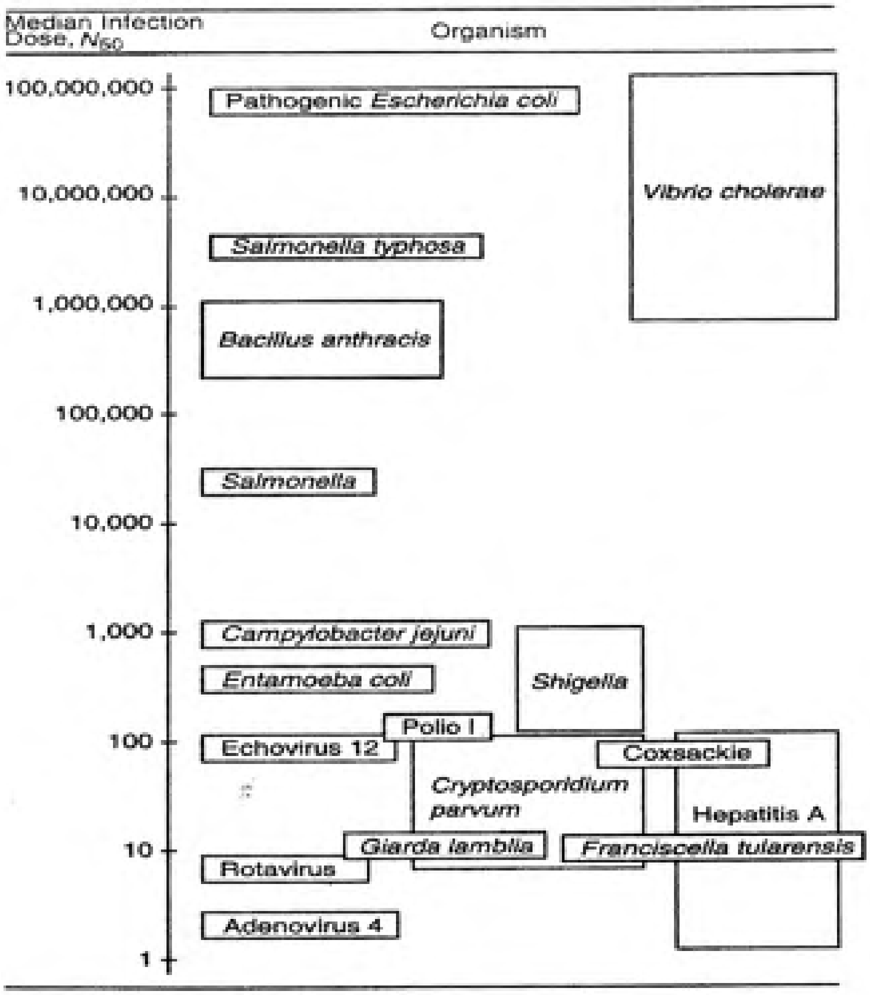


Figure 2.1: "Typical" median dose of pathogenic microorganisms required in drinking water to cause infection (Adapted from MWH, 2005)

2.2. Water Treatment Processes for Removal and Inactivation of Pathogenic Microorganisms

The practice of drinking water treatment has been widely established for over 100 years. The technologies were originally modeled on the processes of subsurface filtration that naturally purify groundwater sources (Hrudey and Hrudey, 2004). Water treatment processes generally include a combination of some or all of the following: coagulation, flocculation and sedimentation; filtration; membrane separation; and disinfection.

2.2.1. Coagulation, Flocculation, & Sedimentation

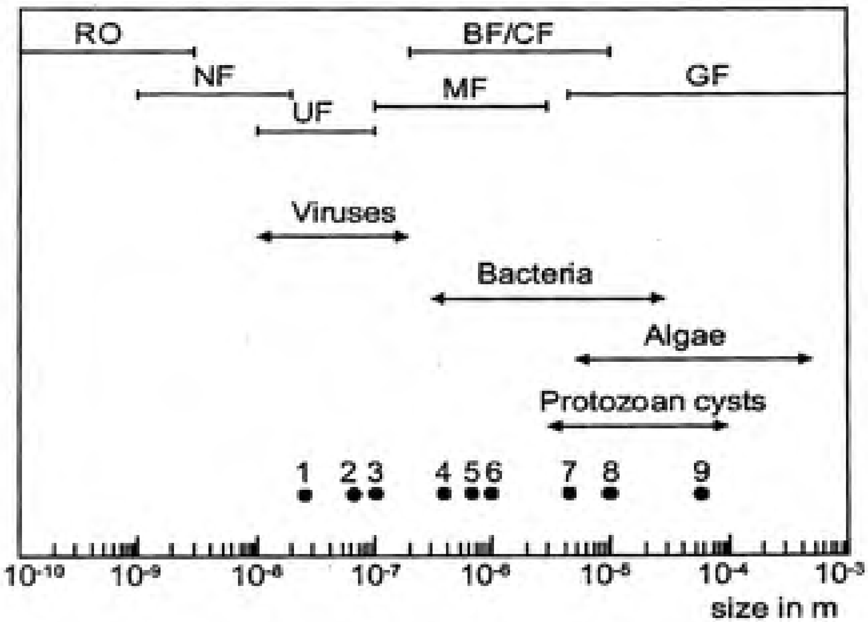
Conventional clarification typically refers to coagulation, flocculation and sedimentation. The removal of particles (colloids) in water depends on the surface loading rate of the basin and the terminal settling velocity of the particles. Some particles will spontaneously settle out of water while other particles are slow to settle or are non-settling. Chemical coagulants such as alum or ferric salts may be added to the water to assist in the removal of non-settling or slow-to-settle particles. Chemical coagulants destabilize the charge repulsion of the particles (e.g. by neutralizing or reducing their surface electrical charge, enmeshing them in a floc particle or creating bridges between them), and allow particles to come into contact with one another (MWH, 2005). This allows for the particles to coalesce into larger aggregates.

Flocculation is the physical process of producing larger particles through interparticle contact. The larger size and weight of the aggregated flocs allow for sufficient settling velocities for removal of the particles in the sedimentation basin. Chemical coagulation and flocculation are very effective at removing fine suspended particles that attract and bind pathogens to their surface, since microorganisms are themselves particles and need to be destabilized. In the absence of a chemical coagulant, the removal of pathogens is relatively low because particle settling velocities are generally low (Medema et al., 1998).

2.2.2. Filtration

Various filtration processes are used in drinking-water treatment. Figure 2.2 shows the most commonly used filtration processes in potable water treatment, the pore size of the filter media, and the sizes of different microbial particles.

One of the oldest processes used to treat water and remove particulate matter (including pathogenic microorganisms) is by passing the water through a packed bed of granular material. Pathogens and pathogen-associated particles are removed as they deposit on the granular material. Granular filters may be constructed as monomedia (e.g. silica sand), dual media (e.g. anthracite coal and sand), or trimedia (e.g., coal, sand and garnet). Depending on raw water quality, granular filtration can be operated in three different modes: conventional, direct, and in-line.



Key:
RO: reverse osmosis. NF: nanofiltration. UF: ultrafiltration. MF: microfiltration. BF/CF: bag and cartridge filters. GF: granular filtration including slow sand filtration (slow sand filters have lower pore sizes than rapid-rate filters)
1. MS2 bacteriophage. 2. Rotavirus. 3. PRDI bacteriophage. 4. *Mycobacterium avium* complex (represents smallest size). 5. *Yersinia* spp. 6. Coliform bacteria. 7. *Cryptosporidium* oocysts. 8. *Giardia* cysts. 9. *Balantidium coli* cysts.

Figure 2.2: Commonly used filtration process pore sizes and various pathogenic microorganism sizes (Adapted from MWH, 2005)

Conventional filtration includes coagulation, flocculation, and sedimentation prior to filtration. Conventional water treatment configurations are typically used to treat source waters with high turbidity (>20 NTU), high color (> 20 CU) or high TOC (> 4mg/L). In general, conventional treatment process trains have more operational flexibility, are hydraulically stable, and require relatively less operator attention than other types (MWH, 2005). However, conventional treatment plants generally require a larger footprint.

Direct filtration consists of coagulation and flocculation without a sedimentation basin. Direct filtration treatment trains are typically used to treat higher quality source waters with low turbidity (< 15 NTU), moderate to low color (<20 CU) and low TOC (< 4mg/L) (MWH, 2005).

Inline filtration is the same as direct filtration, except flocculation is incidental and occurs in conveyance between the coagulation process and filter instead of in a dedicated flocculation basin. Inline filtration process trains are used to treat even higher quality source waters, meaning very low turbidity (< 5 NTU), low color (<10 CU) and low TOC (< 4mg/L) (MWH, 2005).

A specific type of granular media filtration is slow sand filtration. Slow sand filtration is the process of passing raw water, without the use of a coagulant, through a bed of sand at low velocity (generally less than 0.4 m/h), resulting in substantial particulate and microorganism removal. Although removal of microbial pathogens in slow sand filters is complex, it is believed that removal occurs through a combination of physical, chemical, and biological mechanisms (Weber-Shirk and Dick, 1997a&b). Biological activity in the upper layers of the filter promotes microbial removal.

Cake or precoat filtration is another specific form of granular media filtration. The process involves forcing water through a uniformly thin layer of filtering material precoated on a permeable, rigid, septum. Precoat materials include diatomaceous earth (DE) and perlite, with DE more commonly used in drinking water treatment. As water passes through the filter media, the filter captures particles, including pathogens, by physical straining. As the cake becomes thicker due to the captured particles, head loss increases until further filtration is impractical and the filter cake is removed and disposed.

Because the major removal mechanism is physical straining, efficiency of precoat filtration depends to a large extent on the size of the coating materials and on the size of the microbes. Chemical pretreatment of the raw water is usually not necessary; however, the raw water must be of high quality (low turbidity) to maintain a reasonable filter run time.

2.2.3. Membrane Processes

In membrane processes, a thin semipermeable membrane is used as a selective barrier to remove pathogenic microorganisms from water by size exclusion; that is, microbes larger than the membrane pores are removed. The membrane processes most commonly used to remove pathogens from drinking water are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), with RO being the most effective.

Chemical coagulation is not generally needed before membrane treatment to remove pathogens. However, some degree of pretreatment is usually employed to reduce membrane fouling and to avoid membrane degradation. Membrane fouling reduces membrane productivity, which will require the membranes to be chemically cleaned in order to restore productivity.

MF membranes have a nominal pore size of 0.1 μm or greater. Theoretically, MF can effectively remove protozoa and most bacteria. However, factors such as bacterial growth in the membrane systems can lead to fouling. Viruses generally pass through MF membranes, but may be removed if the viruses are associated with larger particles.

UF membranes have pores of 0.01 μm to 0.1 μm, which are small enough to remove some viruses along with bacteria and protozoa. Jacangelo, Adham & Lainé (1995) found that

UF could act as an absolute barrier to protozoan cysts as long as membranes remained intact. NF membranes can remove particles ranging in size from approximately 0.001 μm or greater from water. NF membranes are capable of complete removal of viruses, bacteria and protozoa as long as the membranes remain intact.

RO is the finest available membrane separation technique. Although, RO is capable of removing viruses, bacteria and protozoa, it is generally not used specifically for removal of pathogenic microorganism from drinking water, but rather for desalination.

Similar to membrane processes are bag and cartridge filters. A bag filter has a non-rigid fabric medium for the filter, with the water flow usually pressure-driven from the inside of the filter bag to the outside. A cartridge filter has a rigid fabric medium or membrane for the filter with the water flow usually pressure-driven from the outside of the filter to the inside. Since bag and cartridge filters remove microorganisms by physical straining, the removal efficiency depends on the pore size of the filter medium and on the size of the pathogen. The typical bag and cartridge pore size range is from 0.2 μm to about 10 μm. Therefore, these filters are small enough to remove protozoa but generally not viruses and most bacteria, unless they are associated with larger particles.

2.2.4. Pathogen Inactivation Processes

Water is disinfected to inactivate any pathogens that may remain in the water supply after physical removal processes. The principal factors that affect pathogen inactivation are: type of disinfectant, concentration of disinfectant, contact time, concentration of pathogens, specific pathogen, temperature, and pH (Hendrick, 2006). The two most common methods to inactivate pathogenic microorganisms are oxidation with chemicals (e.g. chlorine or ozone) or irradiation with ultra-violet (UV) radiation.

2.2.4.1. Kinetics of Microbial Inactivation

In 1908, Dr. Harriet Chick and Herbert Watson developed the governing mathematical concepts for the inactivation of pathogens. The combined Chick–Watson equation expresses the rate of inactivation of pathogens as dependent upon the concentration of the disinfectant, C, (mg/L) and contact time, T, (min) as follows (Logsdon et al., 2004):

$$r=-kC^nN \qquad (2.1)$$

Equation 2.2 represents the integrated form of Equation 2.1

$$\ln (N_0/N_T) = kC^nT \qquad (2.2)$$

where,

r = rate of pathogenic microorganism inactivation
k, n = empirical constants
C = disinfectant concentration
N_T = pathogenic microorganism concentration at time T
N_0 = initial pathogenic microorganism concentration
T = contact time

The right side of Equation 2.2 simplifies to kCT when n (sometimes termed the coefficient of dilution) is equal to 1.

$$\ln (N_0/ N_T) = kCT \qquad (2.3)$$

The level of inactivation is generally referred to in terms of "log inactivation" since inactivation is generally measured on a logarithmic scale (i.e., orders of magnitude reduction). Log inactivation is a measure of the percent of pathogenic microorganisms that are inactivated during the disinfection process and is defined as:

$$\text{Log Inactivation} = \text{Log} (N_0/N_T) \qquad (2.4)$$

where,

Log = logarithm to base 10

Equation 2.3 can be rearranged to terms of the product of disinfectant concentration and contact time (CT) as follows:

$$CT = (2.3*\text{Log}\ (N_0/\ N_T))/k \qquad (2.5)$$

2.2.4.2. Chemical Disinfectants

A variety of oxidizing chemicals may be used to inactivate pathogens in drinking water. The most commonly used oxidants for disinfection are chlorine, monochloramine (chlorine combined with ammonia), chlorine dioxide, and ozone. The use of free chorine is the most prevalent oxidant of choice for primary disinfection.

Chlorine has been used as an effective disinfectant for over 100 years. Chlorine is a greenish yellow gas, which will react with water to form hypochlorous acid (HOCl). In turn, the HOCl dissociates into the hypochlorite ion (OCl^-) and the hydrogen ion (H^+), according to the following reactions:

$$Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^- \qquad (2.6)$$

$$HOCl \leftrightarrow H^+ + OCl^- \qquad (2.7)$$

The reactions are reversible and pH-dependent, with HOCl as the predominant species below pH 7.5 and OCl^- predominant above pH 7.5. HOCl is a much stronger disinfectant than OCl^- (MWH, 2005).

Chlorine reacts with ammonia to form monochloramine in dilute aqueous solutions:

$$HOCl + NH_3 \rightarrow NH_2Cl\ \text{(monochloramine)} + H_2O \qquad (2.8)$$

The rate of the reaction is dependent upon pH, and the extent of the reaction depends on the relative chlorine to nitrogen concentration (Cl_2:N). The reaction of HOCl and ammonia will convert all the free chlorine to monochloramine over a pH range of 7–8.5 when the Cl_2:N ratio is equimolar (5:1 by weight) or less. Monochloramine is a much weaker disinfectant than free chlorine.

Chlorine dioxide is a strong oxidant that is highly soluble in water (particularly at low temperatures) and effective over a range of pH values (pH 5–10). Theoretically, chlorine dioxide undergoes five valence changes when it is reduced to chloride ion:

$$5ClO_2 + 5e^- \rightarrow 5Cl^- + 5O_2 \qquad (2.9)$$

However, in practice, chlorine dioxide is rarely reduced completely to chloride ion (White 1999), but is reduced instead to chlorite, ClO_2^-.

$$ClO_2 + e^- \rightarrow ClO_2^- \qquad (2.10)$$

Chlorine dioxide inactivates pathogenic microorganisms by the direct oxidation of proteins (Gates 1998).

Ozone has been used for more than a century for water treatment in Europe. The mechanism by which ozone inactivates microbes is not well understood. Ozone is known to attack unsaturated bonds, forming aldehydes, ketones or carbonyl compounds (Langlais et al, 1991). Ozone is likely to inactivate pathogenic microorganisms through action on cytoplasmic membranes (due to the large number of functional proteins), the protein structure of virus capsids, or nucleic acids of microorganisms (Langlais et al, 1991). Ozone is a more powerful disinfectant than free chlorine.

2.2.4.3. Physical Inactivation

Pathogen inactivation can also be physically accomplished by irradiation with UV light. Physical inactivation of pathogens parallels the Chick-Watson equation, with dose equal to the intensity of UV radiation, I, multiplied by the contact time, T.

$$\ln (N_0/N_T) = IT \qquad (2.11)$$

Dose is the energy per unit area (J/m^2) needed for effective inactivation of pathogens by inhibiting cellular transcription and replication of nucleic acids through the formation of dimers. Dimers can be repaired in a process termed "photoreactivation" in the presence of light, or "dark repair" in the absence of light (Jagger, 1967; Madigan et al, 2006). As a result, UV irradiation must be provided at a sufficiently high dosage to ensure that nucleic acids are damaged beyond repair. The UV light effective for inactivating pathogens is in the UV-B and UV-C ranges of the spectrum (200–310 nm), with maximum effectiveness around 265 nm (Hendrick, 2006).

2.3. Regulations for Control of Pathogenic Microorganisms

Drinking water standards and regulations are designed to protect human health. The Safe Drinking Water Act (SDWA) passed in 1974 authorizes the EPA to set standards and regulations for drinking water quality and the protection of source waters (MWH, 2005). Since its passage in 1974, the SDWA has been re-authorized and amended (MWH, 2005). Although the SDWA was amended slightly in 1977, 1979, and 1980, the most significant changes occurred in 1986. To safeguard public health, the 1986 amendments required EPA to set health goals, or maximum contaminant level goals (MCLGs) and maximum contaminant levels (MCLs) for 83 named contaminants to include microbial contaminants (USEPA, 2006).

In 1989, EPA issued the Total Coliform Rule (TCR) and the Surface Water Treatment Rule (SWTR). Since coliforms are easily detected in water, they are used to indicate a water system's vulnerability to pathogens in the water (USEPA, 2006). In the TCR, EPA set a MCLG of zero for total coliforms. EPA issued the SWTR in response to Congress' mandate requiring disinfection and, where necessary, filtration of systems that draw their water from surface sources before distribution. The SWTR applies to all systems that use surface water or ground water under the direct influence of surface water (GWUDI). The Rule sets MCLGs for *Legionella, Giardia lamblia*, and viruses at zero since any exposure to these contaminants presents some level of health risk. Specifically, the Rule requires that a surface water system have sufficient treatment to reduce the source water concentration of *Giardia lamblia* and viruses by at least 99.9 percent (3 logs) and 99.99 percent (4 logs), respectively. However, the SWTR does not account for source waters with high pathogen concentrations that, when treated at the levels required under the SWTR, may still not meet this health goal. The Rule also does not specifically control for the protozoan parasite, *Cryptosporidium*.

The Interim Enhanced Surface Water Treatment Rule (IESWTR) builds on the SWTR by adding protection from *Cryptosporidium* (USEPA, 2002). Passed in 1998, the IESWTR set enforceable drinking water treatment requirements to reduce the risk of *Cryptosporidium* from surface waters or GWUDI systems serving at least 10,000 persons by requiring a minimum 2-log removal for *Cryptosporidium* (USEPA, 1998). The Rule also strengthens filter performance requirements to ensure 2-log *Cryptosporidium* removal. Four years after passage of the IESWTR, the Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) was published and requires all water systems serving fewer than 10,000 people and using surface water or GWUDI of surface water to achieve 2-log (99%) *Cryptosporidium* removal (USEPA, 2002).

The concern about source waters with high pathogen concentrations propelled the EPA to draft and promulgate the Long Term 2 Enhanced Surface Water Treatment Rule (USEPA, 2006). Promulgated in 2006, the LT2ESWTR requires systems that use a surface water or GWUDI source and provide filtration to conduct source water monitoring to determine average *Cryptosporidium* concentrations. Based on its average source water *Cryptosporidium* concentration, a system will be classified in one of four possible bins. A system's bin assignment determines the extent of any additional *Cryptosporidium* treatment requirements.

Filtered public water systems with average *Cryptosporidium* concentrations of less than 0.075 oocysts per liter are placed in Bin 1, for which no additional treatment is required. Systems with average concentrations of 0.075 oocysts per liter, but less than 1.0 oocyst per liter are placed in Bin 2. Systems with concentrations of 1.0 oocyst per liter, but less than 3.0 oocysts per liter are placed in Bin 3. Lastly, systems with concentrations of greater than 3.0 oocysts per liter are placed in Bin 4 and additional treatment is required on top of that required by existing rules. The additional treatment required for each bin, specified in terms of log removal, depends on the type of treatment. The total *Cryptosporidium* treatment required for bins 2, 3, and 4 is 4.0 logs, 5.0 logs, and 5.5 logs, respectively (Table 2.1).

Table 2.1: Bin classification and required microbial log removal (adapted from USEPA, 2006)

Bin Classification	Bin Concentration (oocysts/L)	Total Number of Credits Required from Microbial Toolbox for Facilities in compliance with LT2ESWTR that have:		Log Removals Needed
		at least one clarification step and one filtration step (Conventional, Slow sand, Diatomaceaous Earth filtration)	at least one filtration step, but do not have a preceding clarification step (Direct filtration)	Total
Bin 1	<0.075	None	None	2.0
Bin 2	≥0.075 to <1.0	1.0	1.5	4.0
Bin 3	≥1.0 to <3.0	2.0†	2.5†	5.0
Bin 4	≥3.0	2.5†	3.0†	5.5

† At least 1.0 credit for facilities in bins 3 or 4 must be from from using ozone, chlorine dioxide, UV, membranes, bag/cartridge filters, or bank filtration.

2.4. Effectiveness of Pathogen Removal Processes

When properly performed, coagulation, flocculation and sedimentation can result in 1–2 log removals of bacteria, viruses and protozoa (Gimbel and Clasen, 1998). Chemical coagulation pretreatment is important in the removal of pathogens by granular media filtration. Al-Ani et al. (1986) conducted a pilot-scale filtration study that demonstrated adding alum and polymer filter aids increases the removal efficiency to more than 1.30 logs for *Giardia* and 2 logs for coliform bacteria, regardless of filtration mode (direct and in-line filtration), filter media (monomedia with sand, and dual-media with sand and anthracite), or water temperature (5°C and 18°C).

A study conducted by Jacangelo et al. (1995) concluded that MF could act as an absolute barrier to protozoan cysts, provided that the membrane remained intact, while the removal of MS2 bacteriophage by MF membranes was less than 1 log because the size of the phage is 0.025μm and the pore size of the membranes is 0.08–0.22 μm. Removal of viruses by UF was significantly better than removal by MF and depends essentially on the pore size of the membranes (States et al., 1999). A bench-scale study of five different RO membranes demonstrated a virus reduction from 2.7 logs to more than 6.5 logs (Adham et al., 1998).

Previous studies conducted on various water treatment removal technologies allowed the Environmental Protection Agency to develop a list of microbial log removal credits by various removal technologies. Table 2.2 lists the microbial log removal credits which the EPA awards to water treatment facilities using each of the removal technologies listed (USEPA, 2006). The listed log credits coincide with the removal requirements by the LT2ESWTR for *Cryptosporidium* treatment.

Table 2.2: EPA microbial log removal credits (adapted from USEPA, 2006)

Removal Technology	Log Credit Allowed	Suitable for Bin 3 & 4 Credits?
Watershed Protection and Source Water Control Approaches		
Watershed Control Program (WCP)	0.5	No
Pre-Treatment		
Riverbank filtration	0.5, 1.0	Yes
Pre-sedimentation	0.5	No
Improved Treatment		
Enhanced filtration –<0.15 NTU in >95% of monthly combined filter effluent (CFE) samples	0.5	No
Enhanced filtration –<0.15 NTU in >95% in each individual filter effluent (IFE)	1.0	No
Second stage lime softening w/coagulant	0.5	No
Additional Treatment		
Slow Sand Filtration	2.5	Yes
Membranes	Challenge Test	Yes
Bag filters	1.0	Yes
Cartridge filters	2.0	Yes
Filtration		
Conventional Filtration	3.0	No
Direct Filtration	2.5	No
Slow Sand Filtration	3.0	No
Diatomaceaous Earth Filtration	3.0	No

2.5. Effectiveness of Pathogen Inactivation Technologies

The effectiveness of pathogen inactivation is quantified by the CT concept as depicted by Equation 2.5. CT is the product of the disinfectant concentration (C) and contact time (T). The CT value achieved by treatment is compared against established CT tables (standards) to determine compliance with safe drinking water regulations. The CT value required for achieving a specified level of inactivation for a specific pathogen under like conditions is a useful means of comparing alternate disinfectants (MWH, 2005). Certain disinfectants are more effective in inactivating different pathogenic microorganisms than others. Therefore, required CT values will vary by disinfectant, as well as by the type of microorganism. Also, the pH of the water and temperature affect the rate of inactivation by selected chemical oxidants such as chlorine.

Figure 2.3 illustrates the CT or IT required to achieve 2 logs inactivation of various microorganisms by the five most commonly used disinfectants in water treatment practice. As illustrated by the greater required CT values, the weakest chemical disinfectant is monochloramine (combined chlorine), while ozone is the strongest disinfectant.

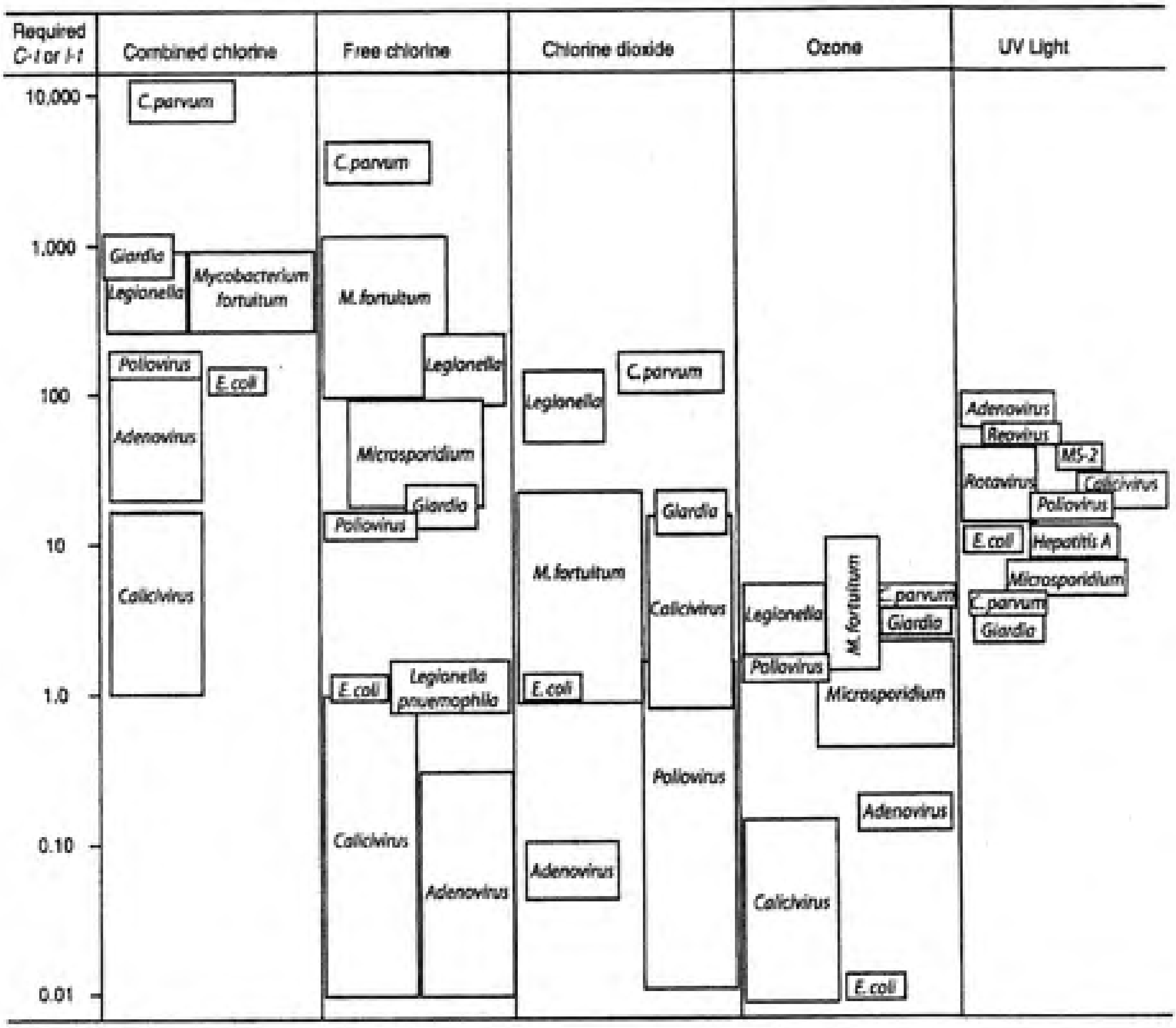


Figure 2.3: CT values for inactivation of various pathogenic microorganisms by different disinfectants (Adapted from MWH, 2005)

For the chemical disinfectants a greater CT is required to inactivate protozoa than for bacteria or viruses. Studies have shown that *Cryptosporidium* oocysts are highly resistant to standard chemical disinfectants like chlorine and chloramines (Korich et al. 1990, Ransome et al. 1993, Finch et al. 1997). However, the opposite holds true for UV irradiation. Protozoa require a lesser IT for inactivation than bacteria or viruses as depicted in Figure 2.3. Protozoa are of a greater size than bacteria and viruses, thus they are more readily radiated by the UV light waves.

In order to inactivate a greater percentage of pathogens by a disinfectant, the CT or IT value must increase. Therefore, the level of pathogen inactivation can be increased by either applying greater doses of the disinfectant or by increasing the time the water is in contact with the disinfectant.

Chapter 3. Methods

Jordan Lake serves as the raw water source for the Cary/Apex water treatment facility. As mentioned previously, Northeast Creek, which is biologically impaired by coliforms, ultimately empties into Jordan Lake and therefore, into the source water for the Cary/Apex water treatment facility. The Cary/Apex water treatment facility was studied to analyze the degree of pathogen removal and inactivation by comparing the actual CT values achieved by the facility to the required CT values in accordance with regulatory requirements, to establish a correlation between source water quality parameters and chemical usage, and the chemical costs associated with effectively removing and inactivating pathogenic microorganisms. Multiple linear regression analysis was used for the latter two objectives. The Raleigh water treatment facility was studied to compare against the results from the Cary/Apex water treatment facility analysis. The two water treatment facilities evaluated both utilize impounded surface waters, Jordan Lake and Falls Lake, respectively, as raw water sources. The location of both water sources and the respective water treatment facilities are illustrated in Figure 3.1.

Each facility provided the data used for this comparative analysis. Monthly operating reports for the years 2002 through 2006 were provided by both water treatment facilities. The data were analyzed to assess seasonal fluctuations in coliform bacteria; correlations between coliform bacteria and other raw water quality parameters, such as turbidity and temperature; regulatory compliance for the log removal/inactivation of pathogenic microorganisms; and the chemical use and chemical costs associated with treatment.

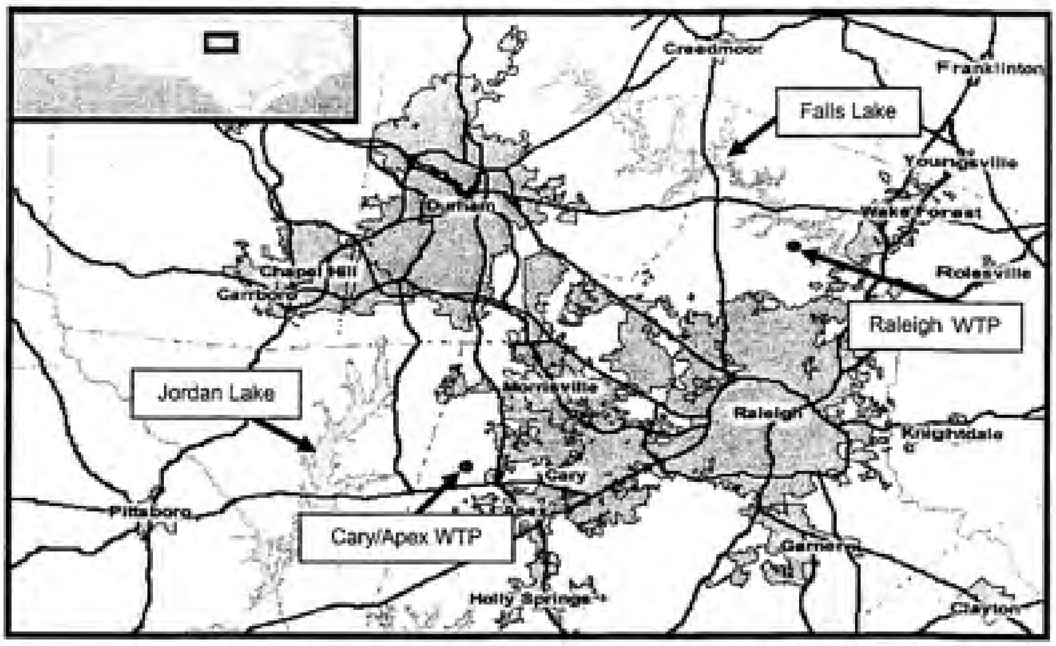


Figure 3.1: Locations of Cary/Apex and Raleigh water treatment facilities and Jordan and Falls Lakes

3.1. Information Collected

The monthly operating reports for each water treatment facility contained data for source water quality, microbial (coliform) counts, chemical dosage, and, to some extent, associated chemical cost. Source water quality data included turbidity, temperature, total organic carbon (TOC), and pH. Microbial data included total coliform counts for the raw and treated waters. Chemical dosages for alum (Cary/Apex) or ferric sulfate (Raleigh), powdered activated carbon, caustic, chlorine, and ozone were obtained, along with the total flow rate of treated water. Data for the chemical costs were obtained for the Cary/Apex water treatment plant. The same unit chemical cost values were used for the Raleigh water treatment plant in order to be able to compare associated chemical treatment costs between the two facilities.

Daily rainfall data were obtained through the website for the State Climate Office of North Carolina (Raleigh, North Carolina) for the following five weather stations: Siler City Airport, Chapel Hill-Williams Airport, Reedy Creek field laboratory, Lake Wheeler Road field laboratory, and Raleigh-Durham Airport. The rainfall values from the five locations were averaged to determine the amount of rainfall for Jordan Lake. The rainfall for Falls Lake was calculated by averaging the values for Reedy Creek field laboratory, Lake Wheeler Road field laboratory, and Raleigh-Durham Airport since these three weather stations are closest in proximity to Falls Lake.

3.1.1 Cary/Apex Water Treatment Plant

The Cary/Apex Water Treatment Plant uses conventional water treatment processes (i.e. coagulation, flocculation, sedimentation, filtration and disinfection with ozone and chlorine) to produce drinking water (Figure 3.2). The plant uses alum as a coagulant. The facility is capable of producing 40 million gallons of water per day for the communities of Apex, Cary, and Morrisville. The water plant is located six miles east of Jordan Lake, which is the source water for the plant.

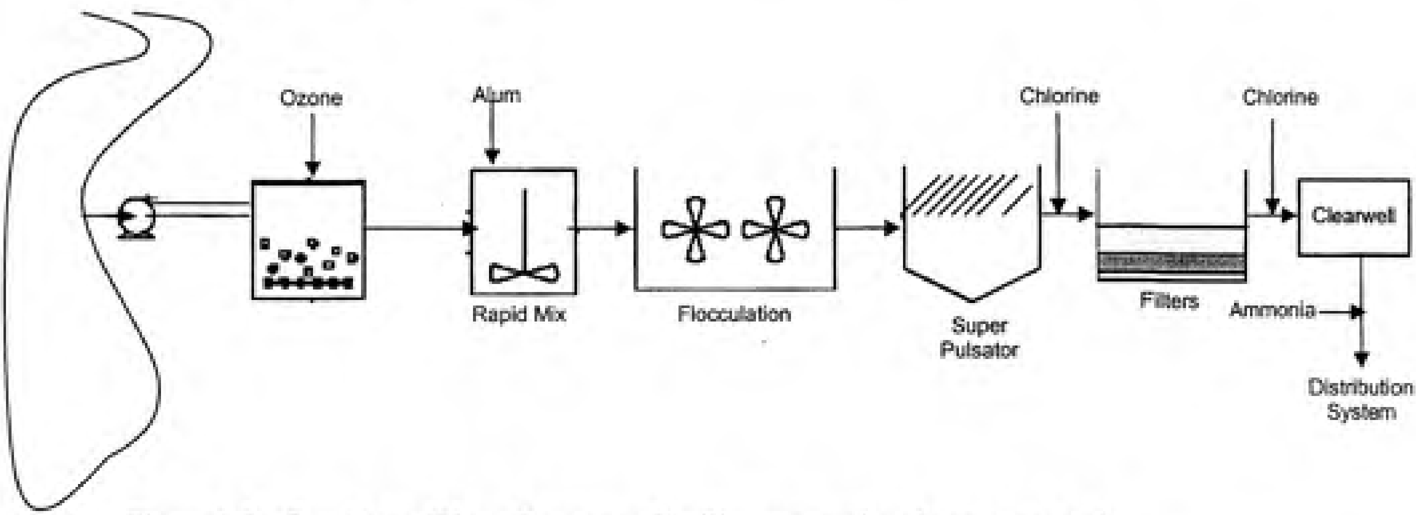


Figure 3.2: Cary/Apex Water Treatment Facility conventional treatment train

Jordan Lake is a man-made lake and reservoir within the Cape Fear River basin created in 1981 by impounding the Haw River, New Hope Creek, Morgan Creek, Northeast Creek and White Oak Creek. Jordan Lake extends 17.9 miles up the New Hope River and 4.7 miles up the Haw River within the New Hope River valley. The lake covers an area of 13,940 acres at its standard operating water level of 216 feet mean sea level.

3.1.2 Raleigh Water Treatment Plant

The Raleigh water treatment plant also uses conventional water treatment processes to produce drinking water (Figure 3.3). Ferric sulfate is the coagulant for this plant. The Raleigh water treatment plant is capable of producing 47 million gallons of water per day for Raleigh, Rolesville and part of Wake Forest. The raw water source for the Raleigh water treatment plant is Falls Lake.

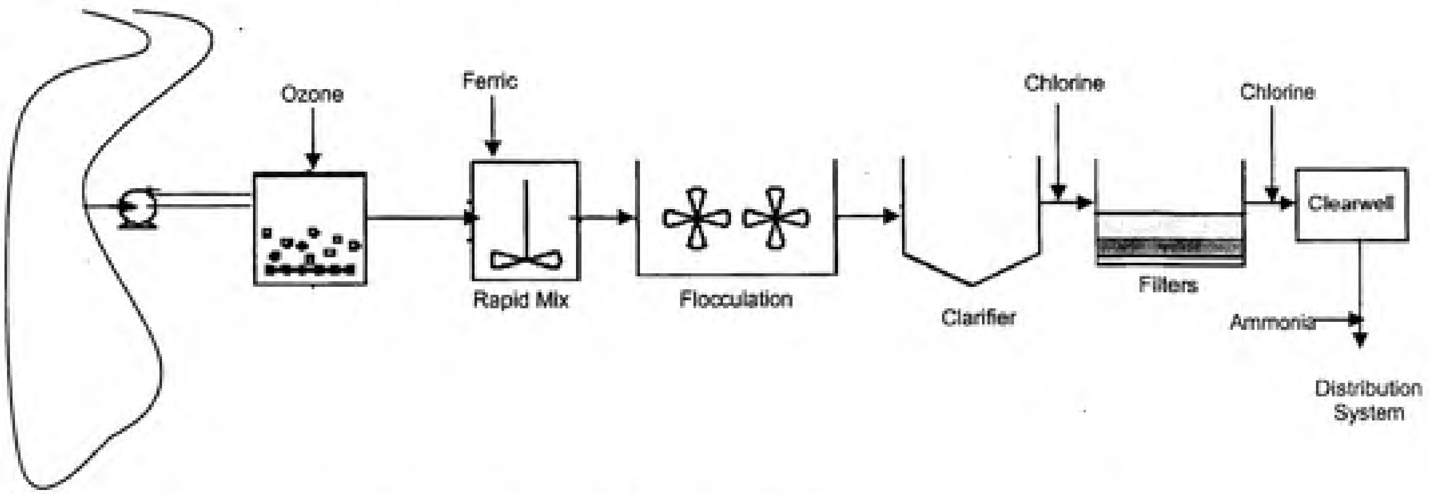


Figure 3.3: Raleigh Water Treatment Facility conventional treatment train

Falls Lake is a man-made lake created by a dam on the Neuse River located in the upper portion of the Neuse River Basin. Falls Lake extends 28 miles up the Neuse River to just above the confluence of the Eno and Flat Rivers. Falls Lake has a surface area of over 12,410 acres at its standard operating water level of 251.5 feet mean sea level.

Cary/Apex and Raleigh water treatment plants both use ozone as an oxidant for taste and odor control and chlorine as the primary disinfectant for microbial inactivation. No microbial inactivation credit is awarded for the ozone concentration used.

3.2. Source Water Quality Trend Analysis

A trend analysis of various raw water quality parameters was performed on the two source waters. An analysis was conducted for each water source to determine if correlations exist between turbidity and coliform bacteria counts; temperature and coliform bacteria counts; rainfall and coliform bacteria counts; TOC and turbidity; and rainfall and turbidity. A comparison of the trends for the two sources was performed to determine possible similarities in coliform bacteria occurrence between the two impounded water sources. Comparisons between chemical dosages and source water quality and treated water quantity were performed as well. The comparisons between the various chemical dosages and water parameters were performed to determine correlations between the raw water quality and chemical dosages used.

3.3. CT Analysis

A CT analysis of the two water treatment plants was conducted to determine the log inactivation of pathogenic microorganisms by the primary disinfectant (chlorine) used by the two facilities. Chick-Watson kinetics was assumed (with n=1) to calculate microbial inactivation, Equation 2.5. For the CT calculations, both water treatment facilities furnished predetermined T_{10} contact times (time within a treatment unit at which 10 percent of the water passes through the treatment unit) for their respective facilities. The actual CT achieved for each facility was compared to the CT values required by the regulatory agency to assess regulatory compliance by each facility. Even though both water treatment facilities used ozone in the treatment train, the ozone is used only as an oxidant and no disinfection credit is accrued by the use of ozone.

3.4. Chemical Cost

Monthly chemical costs provided by the Cary/Apex water treatment plant were used to determine the chemical cost associated with producing one million gallons of treated drinking water. A multiple linear regression analysis of the data was performed to develop a chemical cost relationship with source water quality. The source water quality parameters of coliform bacteria counts, temperature, turbidity and TOC were used as the independent variables for this analysis.

Chapter 4. Results and Discussion

The analyses described in Chapter 3 were performed to the extent possible by the information contained in the monthly operating reports provided by the Cary/Apex and Raleigh water treatment facilities. The results of these analyses are discussed in the following sections.

4.1. Cary/Apex Water Treatment Facility

4.1.1. Raw Water Quality

A summary of Jordan Lake's water quality at the intake of the Cary/Apex water treatment plant is shown in Table 4.1.

Table 4.1: Summary of daily average water quality values at the Cary/Apex Water Treatment Plant intake for years 2002 to 2006

Parameter	Average	Maximum	Minimum
Temperature (°C)	19.8	31.8	7.0
PH	6.9	7.3	6.1
Turbidity (NTU)	6.2	50.6	1.2
TOC (mg/L)	6.4	7.8	5.4
Total Coliforms (#/100ml)	4,492	104,620	4

Indicator organisms or surrogates are often used to assess the potential presence, removal, and inactivation efficiency of pathogenic microorganisms. Typical indicators include total coliforms, fecal coliforms and heterotrophic bacteria (NAS, 2004). Other indicators may include bacteriophage, *Clostridium* oocysts, or turbidity as a surrogate for *Giardia* cysts and *Cryptosporidium* oocysts. The seasonal variation in monthly average total coliform bacteria counts and turbidity are illustrated in Figure 4.1. Figures 4.2a and 4.2b show scatter plots of the daily coliform bacteria counts versus turbidity (Figure 4.2b is an expanded version of the cluster of data for turbidity values less than 14 NTU). Although both total coliform bacteria and turbidity are used as surrogates to indicate the potential presence of pathogenic microorganisms, little correlation between the two parameters is evident at the Cary/Apex water treatment plant intake for the five-year period.

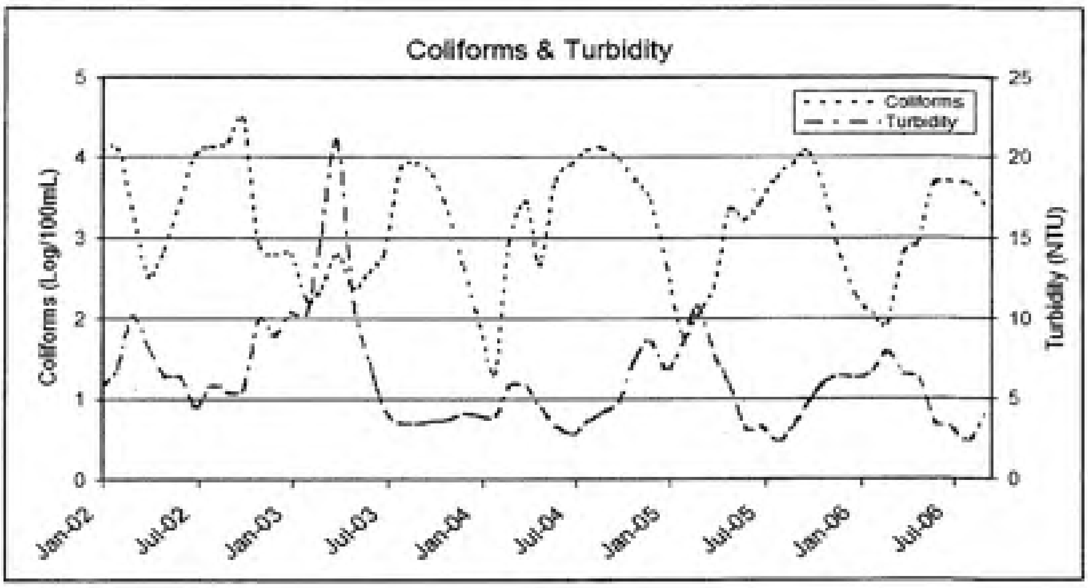


Figure 4.1: Monthly average raw water coliform bacteria and turbidity data from 2002-2006 for Cary/Apex Water Treatment Plant

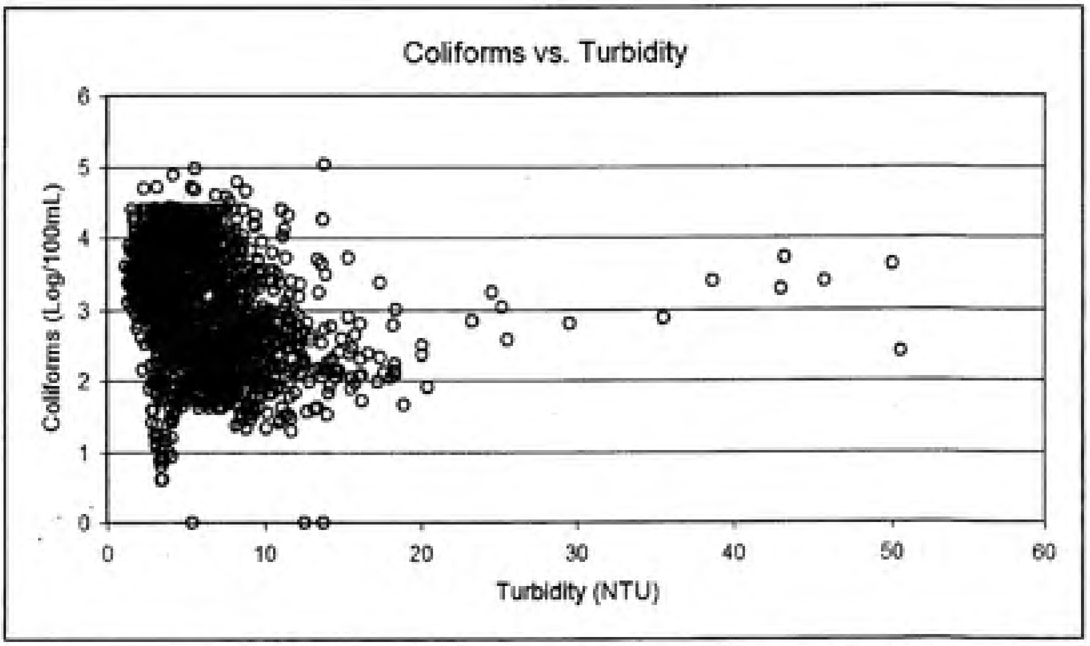


Figure 4.2a: Scatter plot of daily coliform bacteria counts versus turbidity for Cary/Apex Water Treatment Plant raw water from 2002-2006

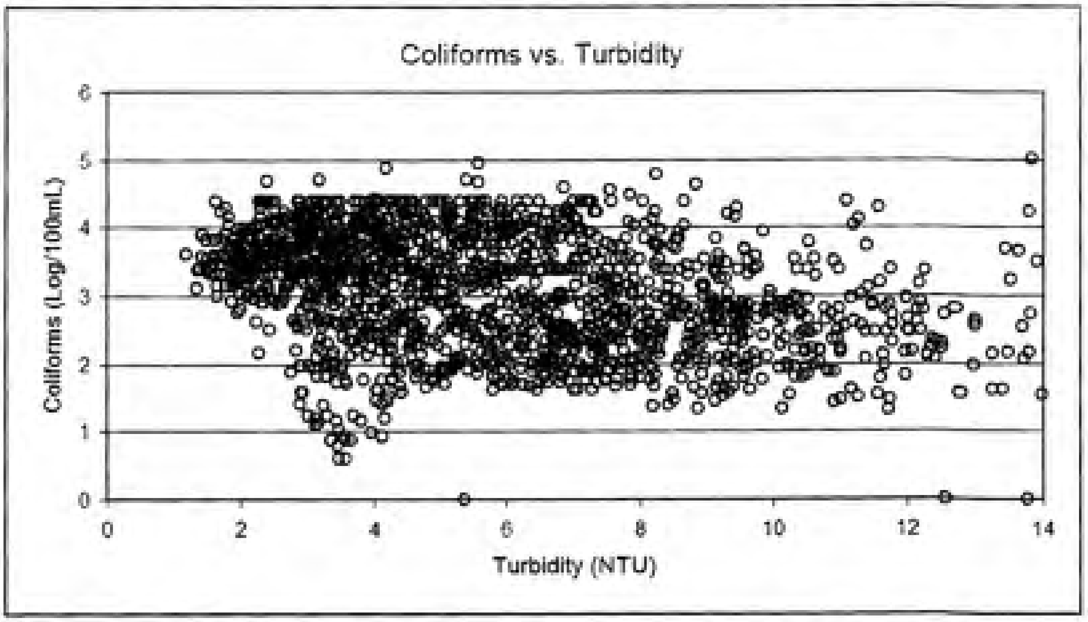


Figure 4.2b: Expanded scatter plot of daily coliform bacteria counts versus turbidity for Cary/Apex Water Treatment Plant raw water from 2002-2006

The seasonal variations in monthly average coliform bacteria counts and water temperature at the Cary/Apex water treatment plant are illustrated in Figure 4.3. The figure shows a strong correlation between coliform bacteria counts and water temperature. The monthly average temperature ranged from 8.2 °C to 30.2 °C with an overall average of 19.7 °C for the five-year period of analysis. The analysis shows that during the summer months, there are a greater number of coliform bacteria detected in the water than in the colder winter months. As shown in Figure 4.4, the daily total coliform bacteria counts tend to increase as the water temperature increases.

Hydrologic events can directly impact pathogen levels in bodies of water. For example, rainfall can wash microbes into receiving streams and increased stream flow can resuspend pathogenic microorganism deposited in streambed sediments. *Cryptosporidium* levels were shown to peak when associated with rainfall and with subsequent increases in

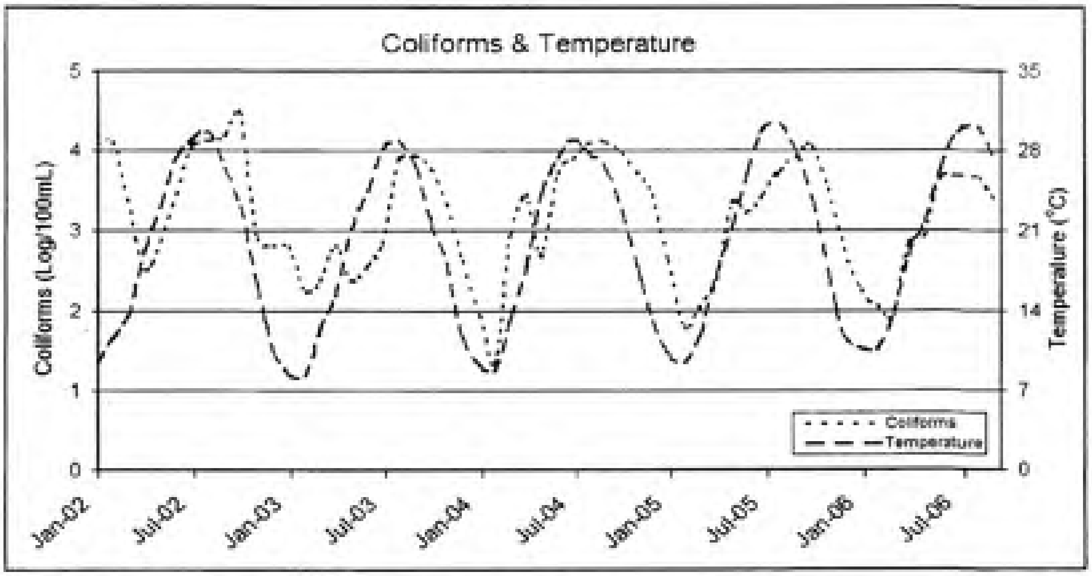


Figure 4.3: Monthly average raw water coliform bacteria counts and temperature data from 2002-2006 for Cary/Apex Water Treatment Plant

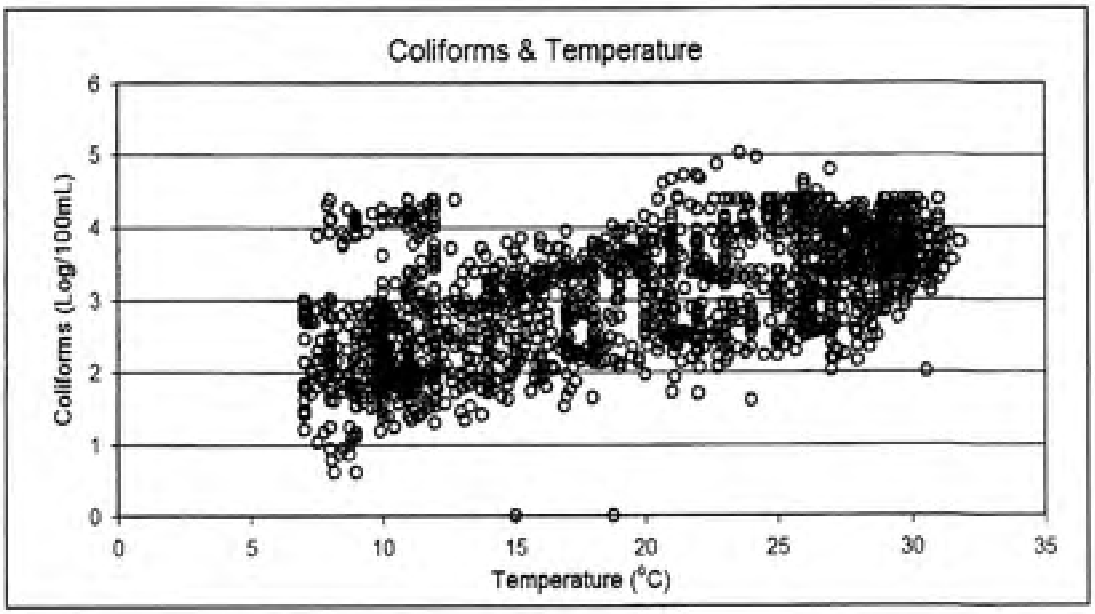


Figure 4.4: Scatter plot for daily coliform bacteria counts versus temperature for Cary/Apex Water Treatment Plant raw water from 2002-2006

river flow and turbidity levels (Atherholt et al., 1998). Similar increases in total coliforms and fecal coliforms with rainfall and stream flow have been seen in other studies (Davis et al, 1977).

The monthly average coliform bacteria counts and total monthly rainfall over Jordan Lake are depicted in Figure 4.5. The monthly average rainfall was 3.5 inches for the five-year period examined in this study, with a maximum and minimum total monthly rainfall of 10.2 inches and 0.5 inch, respectively. While there is some correspondence between peak rainfall periods and peak coliform bacteria counts, rainfall events tend to be short in duration (i.e. typically lasting just a few hours) so the effect of rainfall on coliform bacteria counts are not captured by analysis of monthly averages. An examination of daily average rainfall and coliform bacteria counts was performed for Jordan Lake, as Figures 4.6a and 4.6b illustrate, with no significant trend observed between daily rainfall and total coliform bacteria counts. (Figure 4.6b is an expanded version of Figure 4.6a for rainfall less than 2.0 inches.)

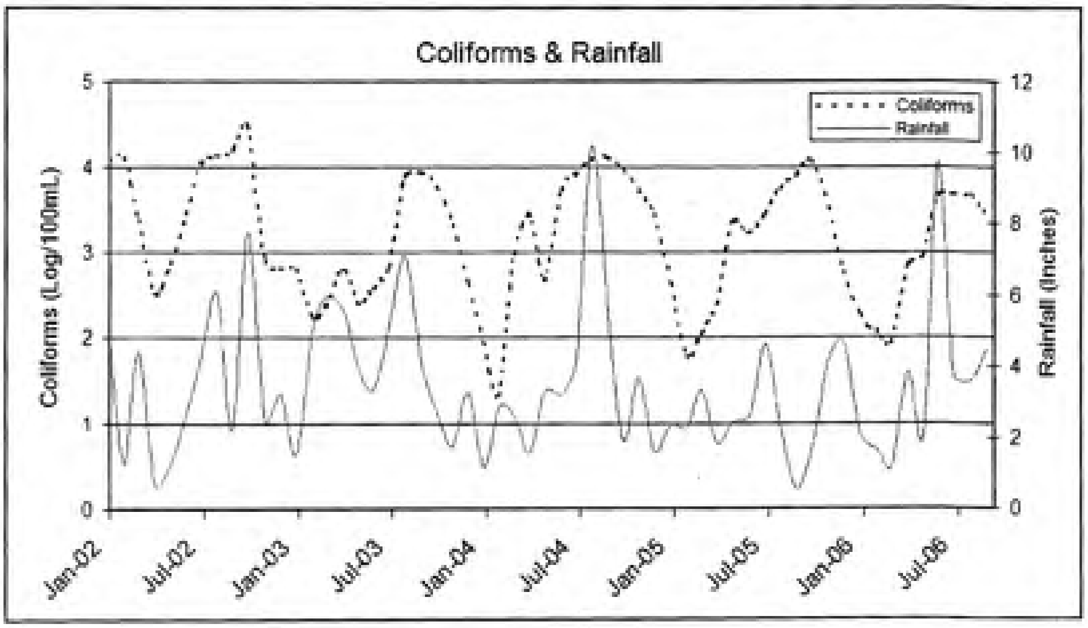


Figure 4.5: Monthly average raw water coliform bacteria counts and rainfall data from 2002-2006 for Cary/Apex Water Treatment Plant

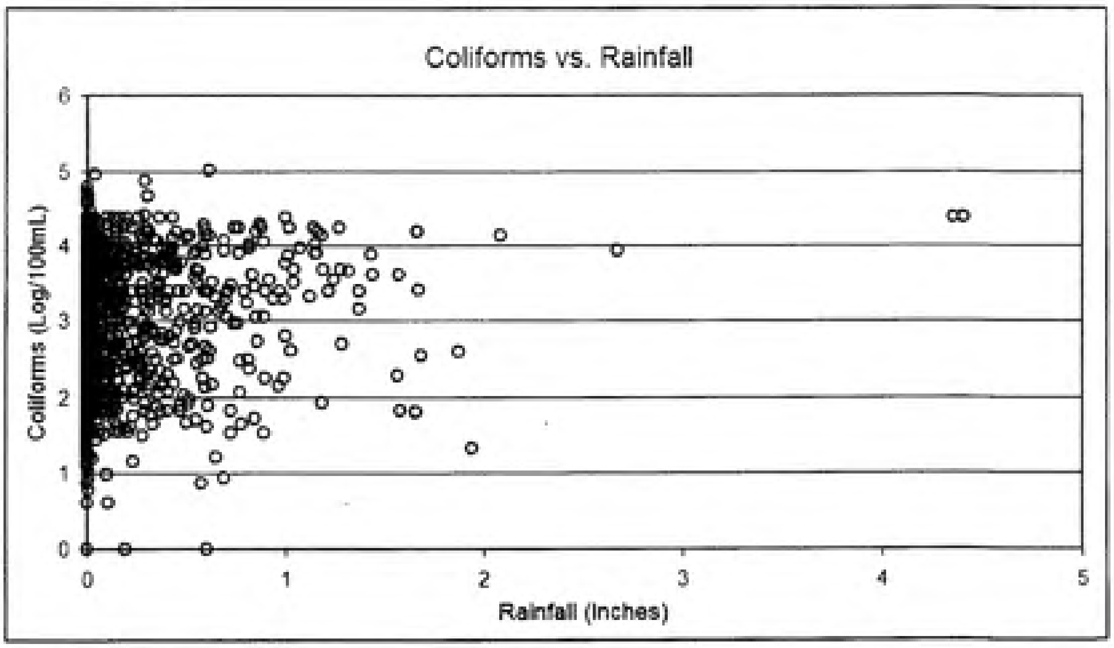


Figure 4.6a: Scatter plot for coliform bacteria counts versus daily average rainfall for Cary/Apex Water Treatment Plant raw water data from 2002-2006

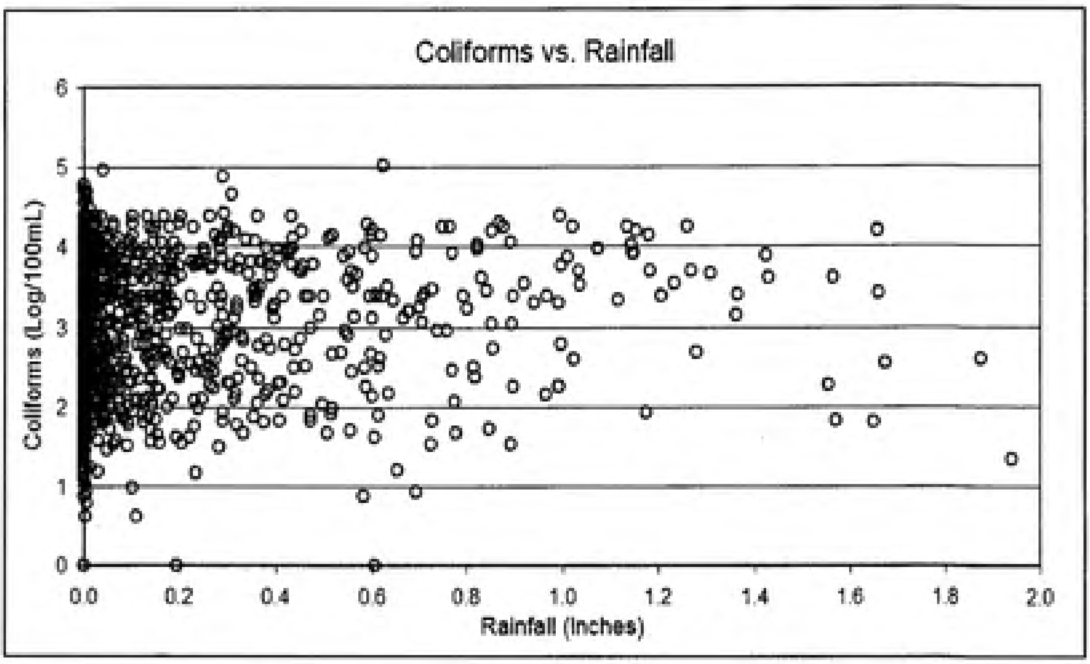


Figure 4.6b: Expanded scatter plot for coliform bacteria counts versus daily average rainfall for Cary/Apex Water Treatment Plant raw water data from 2002-2006

In lakes and reservoirs, turbidity tends to be relatively stable over time and ranges from about 1 to 20 NTU (Crittenden et al, 2005). The average turbidity at the Cary/Apex water treatment plant intake was 6.2 NTU for the same five-year period. Turbidity tended to peak in February/March of each year, while the total monthly rainfall tended to be highest during the month of July, as depicted in Figure 4.7. To minimize the effect of smoothing when considering monthly averages, daily average turbidity and rainfall values were analyzed as illustrated in Figures 4.8a and 4.8b. (Figure 4.8b is an expanded version of 4.8a for turbidity less than 1 NTU.) Again, no significant trend was observed between these two parameters.

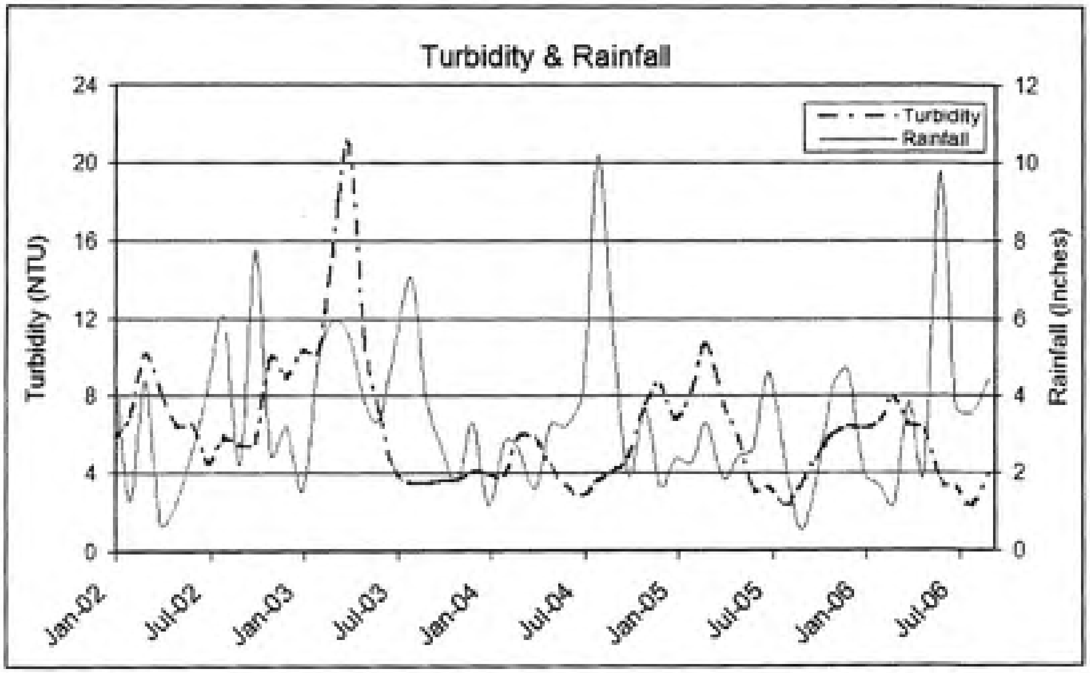


Figure 4.7: Monthly average raw water turbidity and rainfall data from 2002-2006 for Cary/Apex Water Treatment Plant

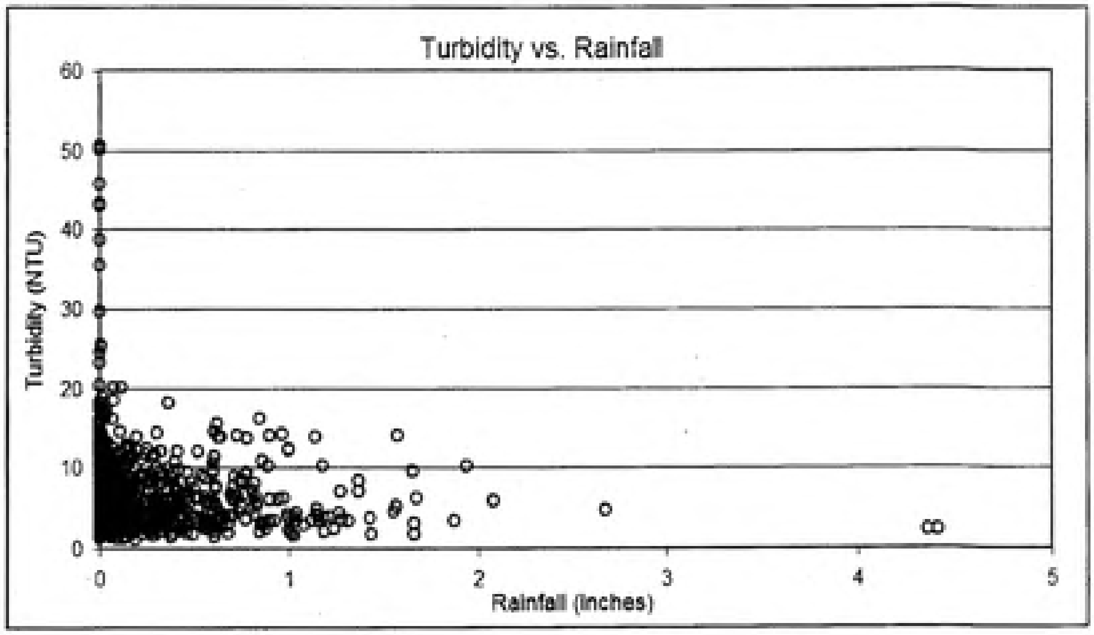


Figure 4.8a: Scatter plot of turbidity versus daily average rainfall for Cary/Apex Water Treatment Plant raw water from 2002-2006

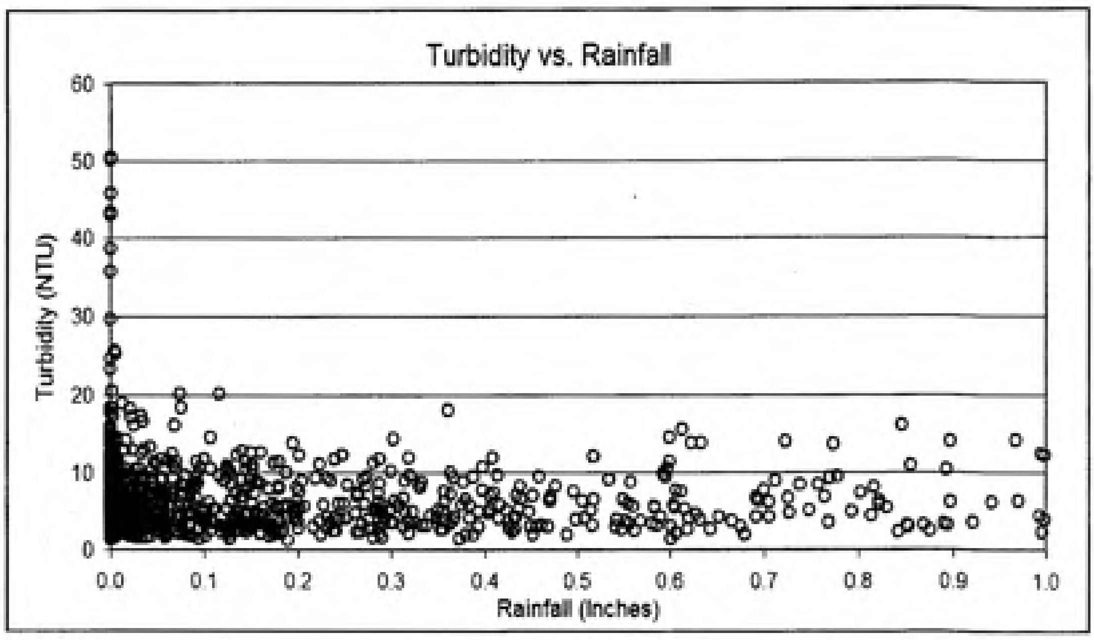


Figure 4.8b: Expanded scatter plot of turbidity versus daily average rainfall for Cary/Apex Water Treatment Plant raw water from 2002-2006

The average monthly raw water TOC concentrations for the Cary/Apex water treatment facility over the five-year time period were compared to the corresponding turbidity values as shown in Figure 4.9. In general, TOC appears to increase with increasing turbidity, suggesting that both parameters are related.

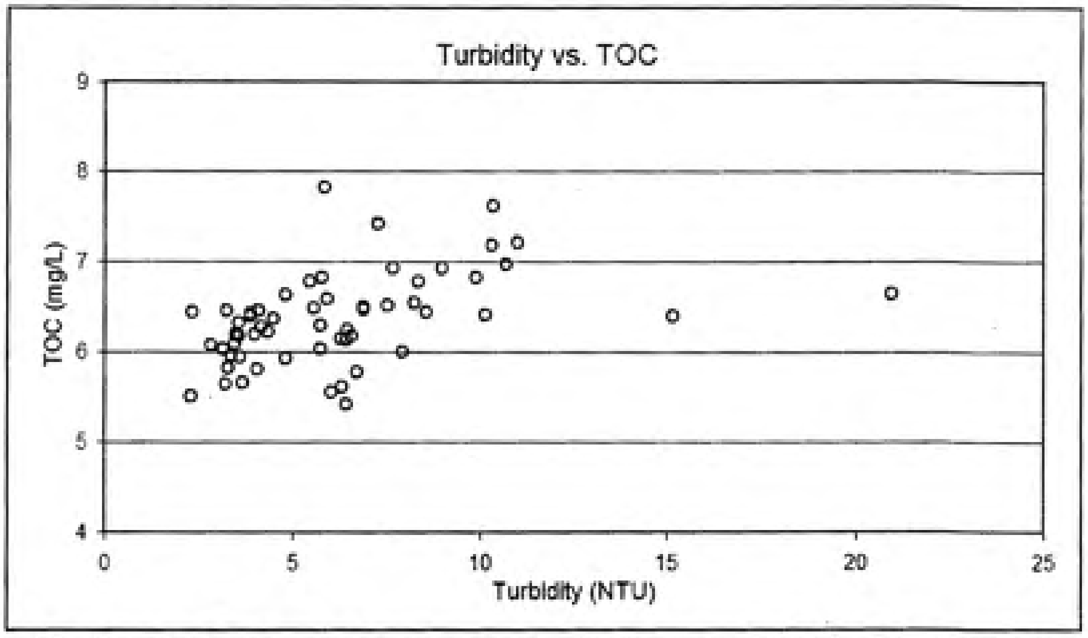


Figure 4.9: Scatter plot of monthly averages of turbidity versus TOC for Cary/Apex Water Treatment Plant daily raw water from 2002-2006

4.1.2. Chemical Usage and Raw Water Quality

To treat Jordan Lake water to meet drinking water quality standards and to account for the variability in raw water quality, a variety of chemicals may be utilized. Conventional treatment plants generally add a coagulant, such as alum or ferric salts, a pre-oxidant (e.g. chlorine or ozone) for iron and manganese oxidation and for taste and odor control, a primary disinfectant to inactivate remaining pathogenic microorganisms after filtration, and a secondary disinfectant for residual protection of the distribution system (MWH, 2005). In this section, the primary chemicals used by the Cary/Apex water treatment facility will be reviewed and compared to the raw water quality of Jordan Lake discussed above.

The primary chemicals used by the Cary/Apex water treatment facility include alum, caustic (sodium hydroxide) for pH control, chlorine as a primary disinfectant, and ozone as a pre-oxidant. Figure 4.10 shows the monthly average chemical dosages for these additives and the average monthly treated water in million gallons per day (MGD). There is seasonal variability in the amount of treated water produced, with greater production of water in the summer. The chemical dosages appear to vary to a lesser degree. The average alum dosage was 42.5 mg/L for the five-year period, while the average dosages for caustic, chlorine, and ozone were 12.1 mg/L, 8.0 mg/L, and 4.7 mg/L, respectively, for the same time period.

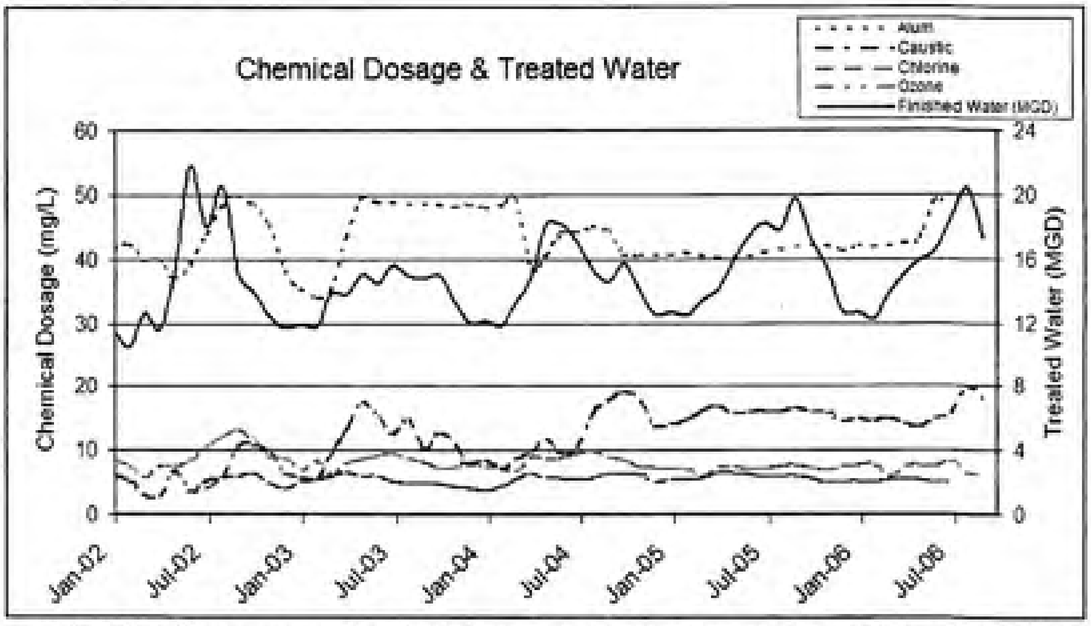


Figure 4.10: Monthly average chemical dosage and treated water flow at Cary/Apex Water Treatment Plant from 2002-2006

Figure 4.11 illustrates the chemical dosages and raw water coliform bacteria counts over the five-year period. Chemical dosages for chlorine tended to reasonably track with the fluctuation in coliform bacteria counts in the source water. The primary disinfectant dosage is probably influenced by the higher chlorine demand because of increased temperatures and increased reactivity. As illustrated in Figure 4.3, coliform bacteria also tends to coincide with temperature fluctuations; therefore, chlorine dosage reasonable tracking with coliform bacteria counts.

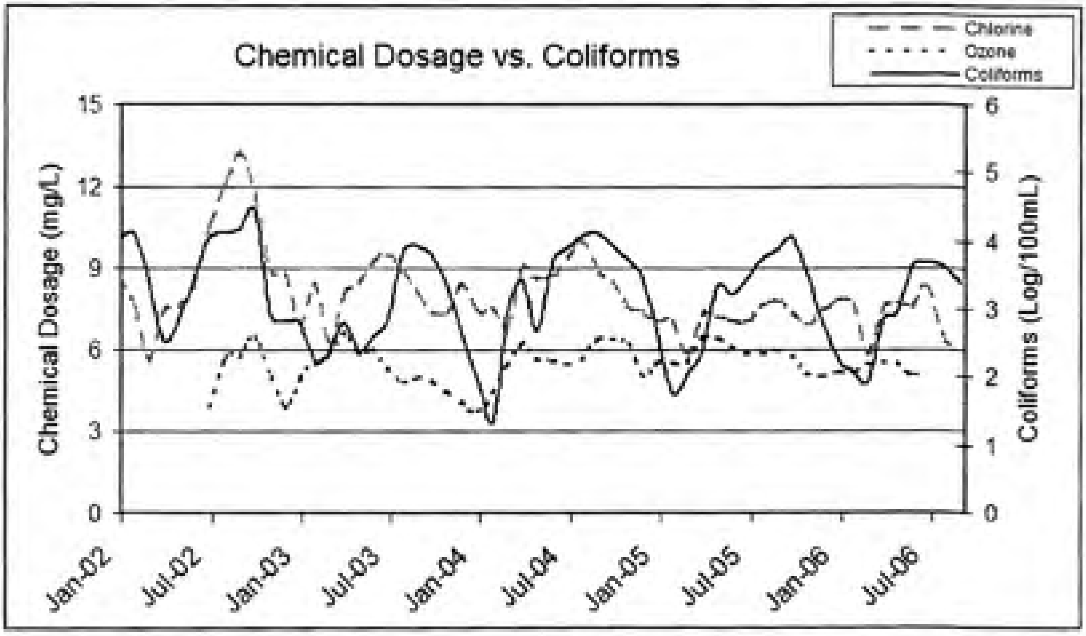


Figure 4.11: Monthly average chemical dosage and monthly average coliform bacteria counts from 2002-2006 at Cary/Apex Water Treatment Plant

The effect of turbidity on chemical dosages is depicted in Figure 4.12. Since turbidity in water is caused by the presence of suspended particles, a coagulant is required to destabilize the particles. The expectation is that alum dosage would change according to the fluctuations in turbidity of the source water. Figure 4.12, however, shows this is not the case for the Cary/Apex water treatment plant. In fact, for the last 2½ years, alum doses were relatively constant (see Figure 4.10) despite the variation in raw water quality. As depicted in Figures 4.13a and 4.13b, the daily average alum dosage ranged between 30 mg/L and 55 mg/L, with an average of 42 mg/L, and did not correlate with raw water turbidity.

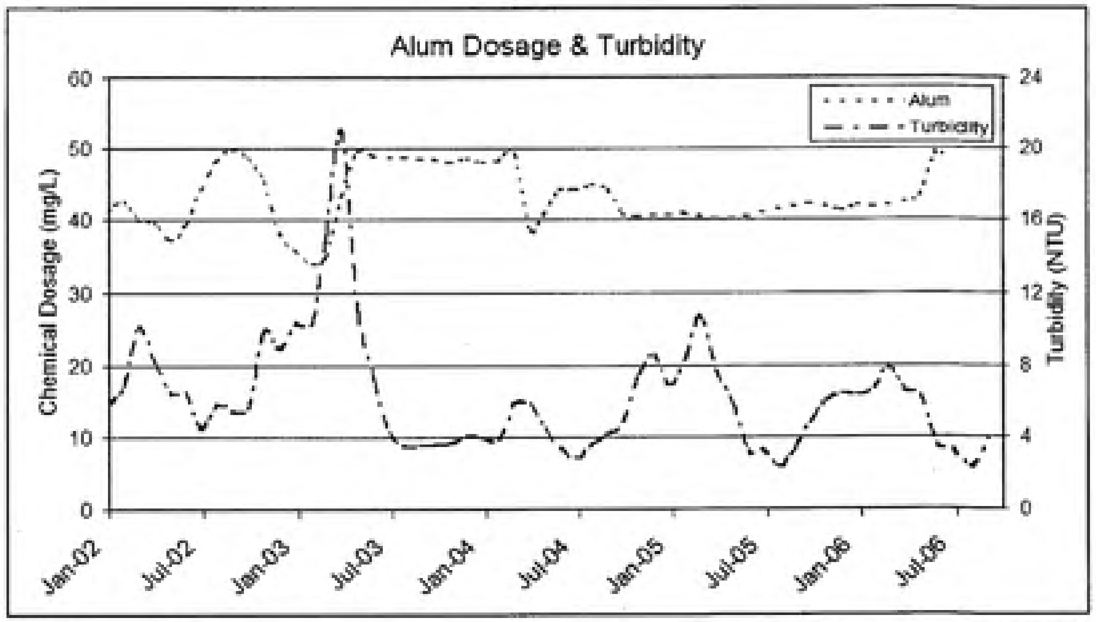


Figure 4.12: Monthly average alum dosage and monthly average turbidity from 2002-2006 at Cary/Apex Water Treatment Plant

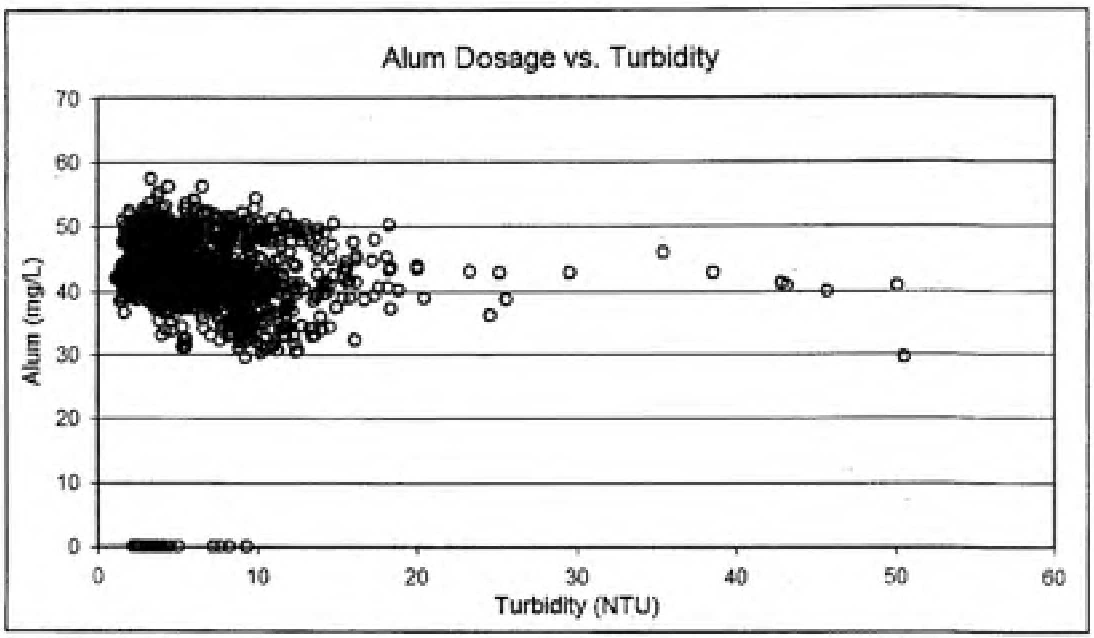


Figure 4.13a: Daily average alum dosage versus daily average turbidity at Cary/Apex Water Treatment Plant from 2002-2006

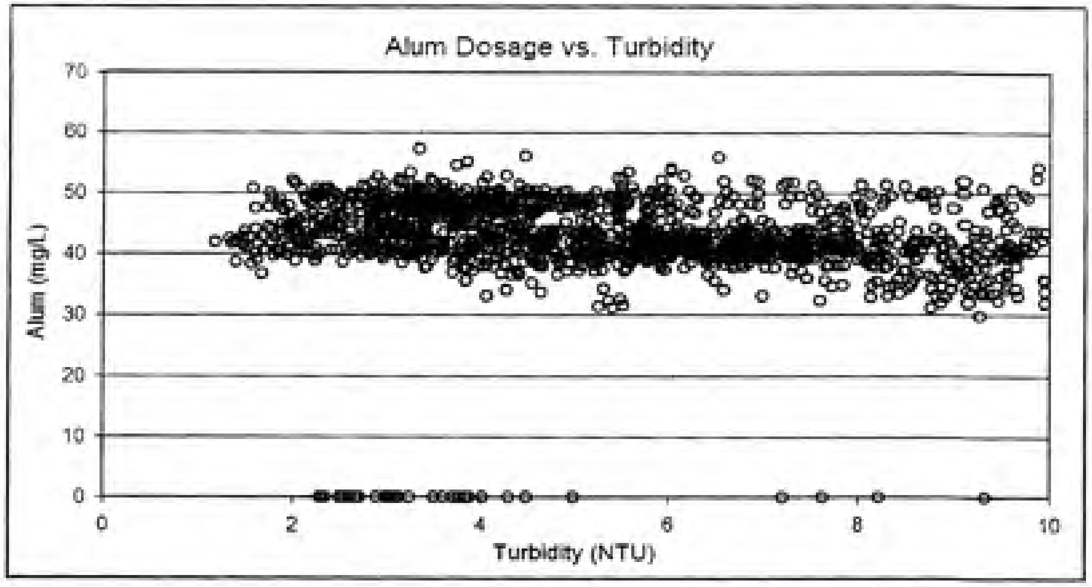


Figure 4.13b: Expanded daily average alum dosage versus daily average turbidity at Cary/Apex Water Treatment Plant from 2002-2006

4.1.3. CT Analysis

As stated in Section 2.4, pathogenic microorganisms are subject to physical removal by chemical coagulation, flocculation, sedimentation and filtration. The EPA assigns a 2.5 log removal credit for *Giardia* by conventional treatment plants; therefore, an additional 0.5 log of inactivation by chemical disinfection is required. However, based on the formula of uses, the State of North Carolina requires the Cary/Apex water treatment facility to provide an additional 0.62 log inactivation of *Giardia* after removal credits for conventional treatment are awarded. In this analysis, it is assumed that *Giardia* removal and inactivation is the driver for disinfection, i.e. *Giardia* is the "limiting" organism.

Measuring disinfection effectiveness is difficult to accomplish with great precision because inactivation is influenced by the chemistry of the disinfectant as well as the nature of the organism (MWH, 2005). Therefore, as detailed in Chapter 3, CT calculations, which are the regulatory approach used by the EPA, were employed for this analysis.

CT is a measure of disinfection effectiveness and the result of multiplying the disinfectant residual concentration, C, (measured in mg/L) at peak hourly flow by the time, T, (measured in minutes) that the disinfectant is in contact with the water at peak hourly flow. The contact time used in the calculation (T_{10}) is the detention time within a treatment unit at which 10 percent of the water passes through the treatment unit. T_{10} can be determined for a treatment unit through a tracer study or it can be estimated based on assigned baffling factors and the theoretical detention time for the unit. For the Cary/Apex water treatment plant, the disinfectant contact time is measured from the point of primary disinfectant injection to the point where the residual disinfectant is measured at the point of entry to the distribution system. The T_{10} for the Cary/Apex water treatment plant was provided by the facility and is 120 minutes. Equation 4.1 was used to calculate the actual CT values achieved by the water treatment facility (see Appendix C).

$$CT_{Actual} = C * T_{10} \qquad (4.1)$$

To determine if sufficient microbial inactivation was achieved to meet regulatory compliance, the actual CT values achieved must be compared to the established regulatory CT values developed by EPA. The EPA publishes CT tables to define specific degrees of microbial inactivation. The required CT value for a desired log inactivation with chlorine is dependent upon pH, temperature, and residual disinfectant concentration. Separate CT tables are used for each type of disinfectant and for different microorganisms because the effectiveness of different disinfectants varies with each type of microorganism, as depicted by Figure 2.3.

The following steps were used to obtain the required CT values from the CT tables. First, the appropriate table based on chlorine was selected (see Appendix B). Then the water temperature was utilized to determine which portion of the table to use. Lastly, the intersection of the chlorine residual row and pH column of 0.62 logs *Giardia* inactivation indicated the required CT value to meet regulatory compliance.

Figure 4.14 shows the actual CT values achieved by the Cary/Apex water treatment facility as shown in their monthly operating reports, the required CT values extracted from the EPA CT tables to meet regulatory compliance for *Giardia* inactivation, and the $CT_{Actual}/CT_{Required}$ ratio (a measure of excess CT) for the five-year period. The actual CT values achieved ranged between 3 to 38 times the CT values required, resulting in a "buffer" of 1.86 to 23.5 logs of additional *Giardia* inactivation. There appears to be little seasonal

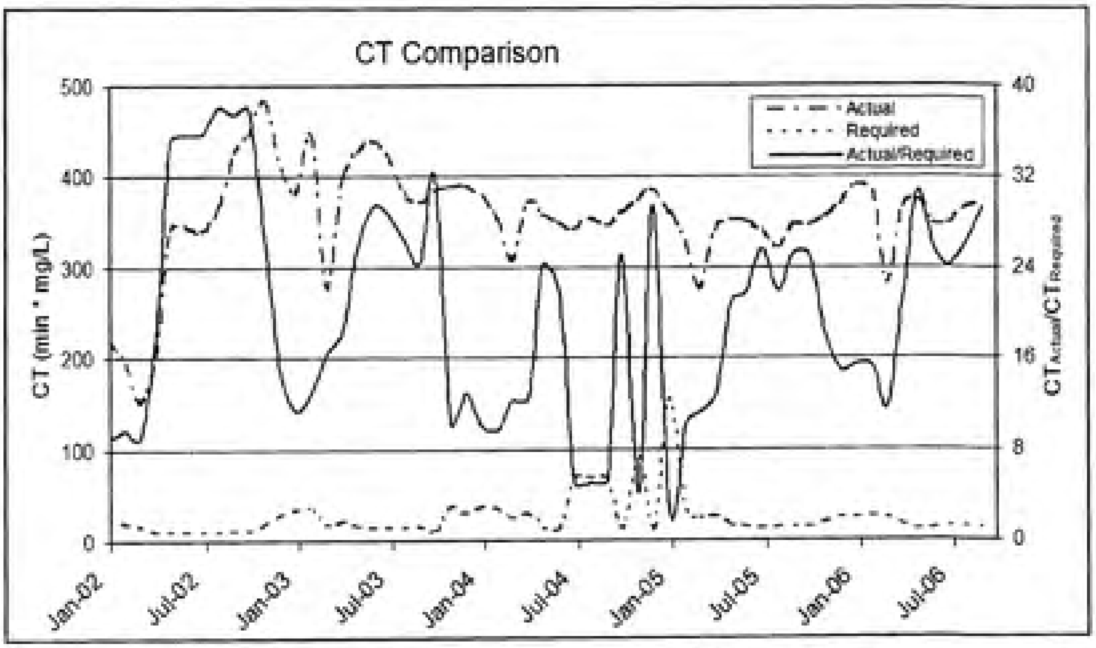


Figure 4.14: Plot of actual CT achieved to required CT and CT_{Actual} / $CT_{Required}$ ratio for Cary/Apex Water Treatment Plant from 2002-2006

pattern with respect to excess inactivation. Also, only chlorine is used for the CT calculations. Ozone, while a very effective disinfectant, is used only as a pre-oxidant so no disinfection credit is accrued.

Figure 4.15 shows a comparison between coliform bacteria counts and the ratio of CT_{Actual} to $CT_{Required}$ (i.e. excess CT) for the Cary/Apex water treatment plant over the five-year period. The excess CT ratio follows closely to the seasonal fluctuation of coliform bacteria counts. Thus, when a higher risk for waterborne illness is present, as represented by the higher concentration of coliforms, the greatest amount of excess disinfectant for microbial inactivation is available.

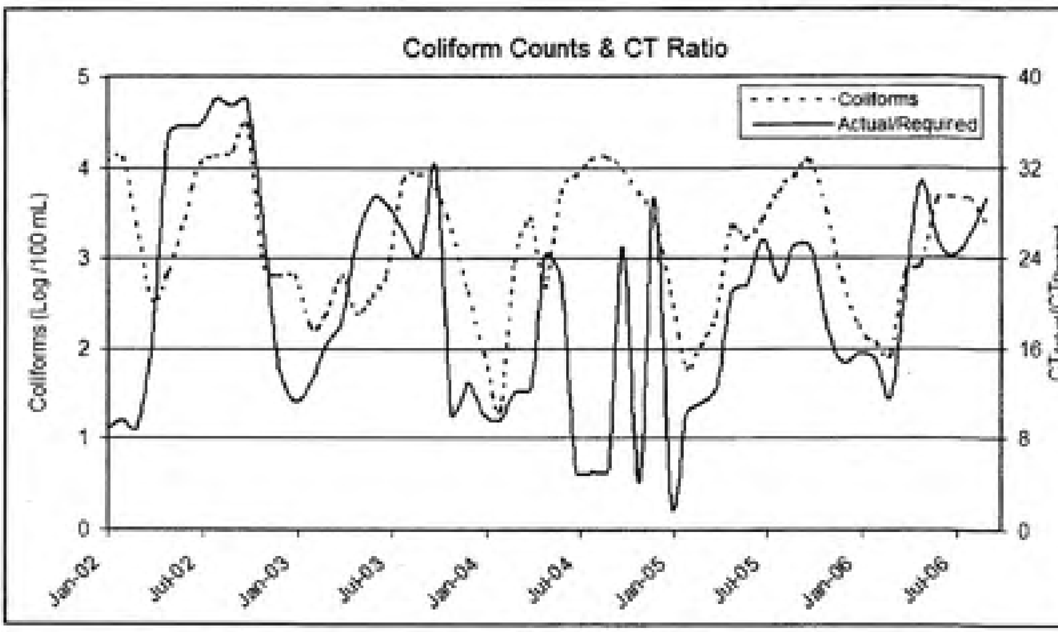


Figure 4.15: Plot of coliform bacteria counts and $CT_{Actual}/CT_{Required}$ ratio for Cary/Apex Water Treatment Plant from 2002-2006

4.1.4. Chemical Cost Analysis

This section analyzes the chemical cost incurred by the Cary/Apex water treatment facility for the years 2002 to 2006, as taken from their monthly operating reports. Table 4.2 shows the average annual cost for the chemicals used by the facility. The total annual chemical cost fluctuated between $59,500 and $77,100 for this time period.

Table 4.2. Average monthly chemical cost for Cary/Apex Water Treatment Plant from Years 2002-2006

Average Monthly Chemical Costs					
	2002	2003	2004	2005	2006
Alum	$13,504	$14,763	$15,226	$17,257	$18,330
Caustic	$4,140	$7,331	$6,693	$11,670	$11,764
Carbon	$30,089	$17,263	$12,761	$12,935	$8,873
Ammonia	$1,857	$1,377	$1,262	$1,272	$1,538
Chlorine	$2,944	$1,870	$1,938	$2,166	$2,520
Ozone†	$16,931	$14,755	$16,288	$19,349	$16,746
Total Chemical Cost	$77,104	$62,910	$59,511	$70,044	$64,758

† Includes the cost of liquid oxygen and the cost of electricity to generate the ozone on-site.

To obtain a better understanding of the chemical cost, the cost was standardized per one million gallons of treated water as shown in Figure 4.16. The costs ranged from $120 to $185 per million gallons of treated water. Figure 4.17 illustrates the average monthly cost for each chemical and the total monthly chemical cost, compared to the amount of water treated. As one would expect, the total monthly chemical cost correlates closely with the amount of treated water produced. Hence, the greater the amount of treated water, the greater the associated chemical cost to treat the water.

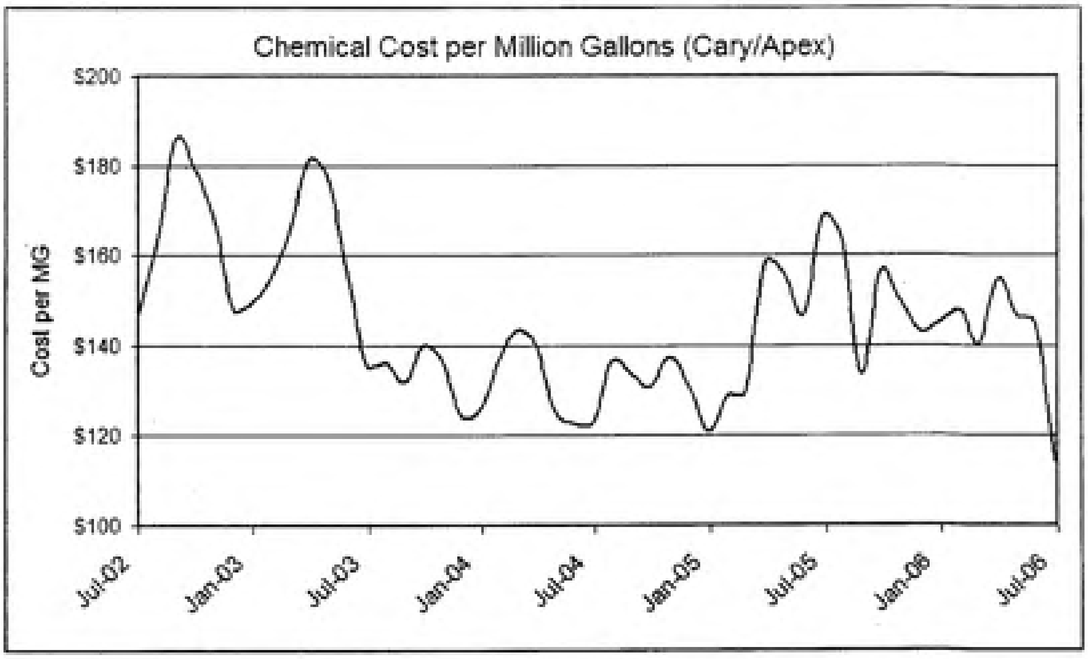


Figure 4.16: Average monthly chemical costs per million gallons of treated water for Cary/Apex Water Treatment Plant from 2002-2006

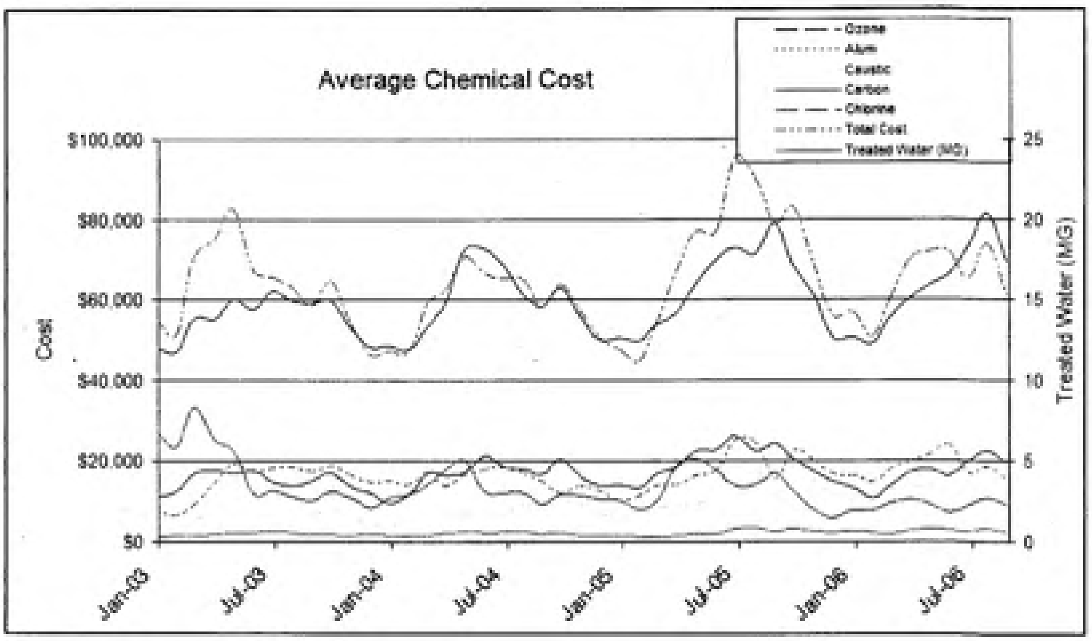


Figure 4.17: Average monthly cost of chemicals for Cary/Apex Water Treatment Plant from 2002-2006

Table 4.3 shows a correlation matrix between several relevant raw water quality parameters, rainfall, and the chemical cost per million gallons of water produced by the Cary/Apex water treatment plant. The values shown are the regression values between the two variables indicated in the various rows and columns. The absolute value of the correlations shown in the table represent the square root of the amount of variance shared between each of the variables (Veney, 2003). When looking at the table, the highest correlation is between temperature and coliform bacteria counts, which would be expected based on Figure 4.3 shown earlier. Since none of the correlations between the predictor variables exceed 0.90, the effects of multicolinearity are not a concern (Veney, 2003).

Table 4.3: Cross correlation between variables (Cary/Apex Water Treatment Plant)

		Cost/MG	Coliforms	Temp	Turbidity	TOC	pH	Rainfall
Cost/MG		1						
Coliforms (log CFU/100ml)		-0.005	1					
Temperature	(°C)	-0.093	0.641	1				
Turbidity	(NTU)	0.498	-0.404	-0.512	1			
TOC	(mg/L)	0.167	-0.197	-0.217	0.453	1		
PH		-0.097	-0.300	-0.477	0.028	0.215	1	
Rainfall	(inches)	0.066	0.322	0.297	0.006	0.001	-0.170	1

Equation 4.2 depicts the equation developed from a multiple linear regression analysis for predicting chemical cost based on the raw water quality parameters at the intake to the plant. Table 4.4 shows the associated statistics for the multiple linear regression

analysis. As depicted in the table, Equation 4.2 possesses a low R^2 value, 0.30. Also, there is a very high intercept, which tends to "swamp" the other terms in the equation.

$$\text{Cost/MG} = 3.44\,(\log \text{Coliform}) + 0.25\,(\text{Temp}) + 3.07\,(\text{Turb}) - 2.12\,(\text{TOC}) + 122.7 \qquad (4.2)$$

Table 4.4: Regression coefficients for cost regression equation (Cary/Apex Water Treatment Plant)

Regression Statistics						
R Square		0.30				
		Coefficients	*t Stat*	*Lower 95%*	*Upper 95%*
Intercept		122.77	4.83	71.73	173.81
Coliforms (log CFU/100ml)		3.44	1.10	-2.83	9.71
Temperature	(°C)	0.25	0.73	-0.44	0.94
Turbidity	(NTU)	3.07	4.38	1.66	4.48
TOC	(mg/L)	-2.12	-0.55	-9.91	5.67

The regression equation was used to predict chemical cost for the Cary/Apex water treatment plant and to compare the predicted costs to the actual chemical costs. Figure 4.18 shows that Equation 4.2 is not a good predictor for chemical cost since many of the points diverge away from the 1 to 1 line of perfect agreement and the error is not uniformly distributed about the 1 to 1 line. This is as expected since the R^2 value for the equation was only 0.30 and the intercept was so large. The poor correlation between the actual chemical cost per MG and the cost predicted by Equation 4.2 indicates that chemical usage and therefore chemical cost for the Cary/Apex water treatment plant are not significantly driven by fluctuations in source water quality, or that the raw water quality parameters selected in this modeling exercise are not the best determinants of the chemical treatment requirements.

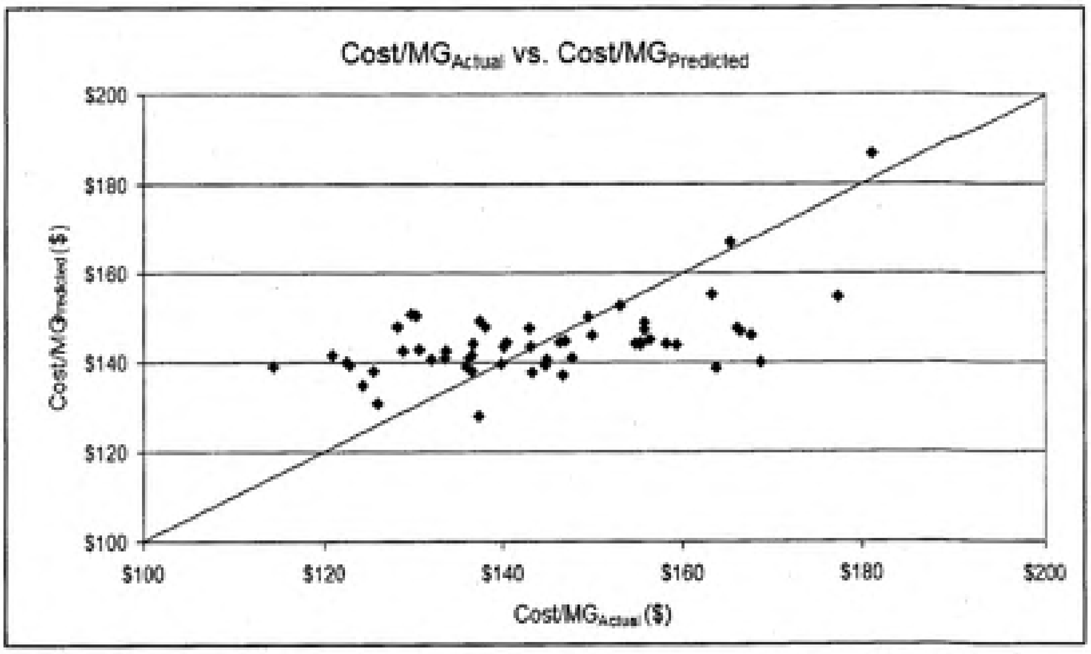


Figure 4.18: Comparison of actual and predicted chemical cost for Cary/Apex Water Treatment Plant by average monthly raw water from 2002-2006. The predictions were made using Equation 4.2.

4.2. Raleigh Water Treatment Facility

4.2.1. Raw Water Quality

A summary of Falls Lake's water quality at the intake of the Raleigh water treatment plant is shown in Table 4.5. This information is derived from monthly operating reports provided by the Raleigh water treatment plant.

Table 4.5: Summary of daily average water quality at the Raleigh Water Treatment Plant intake for years 2002 to 2006

Parameter	Average	Maximum	Minimum
Temperature (°C)	19.7	31.6	5.9
pH	6.7	7.4	5.9
Turbidity (NTU)	4.7	28.9	0.5
TOC (mg/L)	5.8	8.4	4.6
Coliforms (#/100ml)	5,107	241,960	1

The monthly average coliform bacteria counts and turbidity are illustrated in Figure 4.19. As with Jordan Lake, little correlation between the two parameters is evident for the raw water of Falls Lake during the five-year period, as shown from the daily scatter plot (Figures 4.20) of coliform bacteria counts versus turbidity.

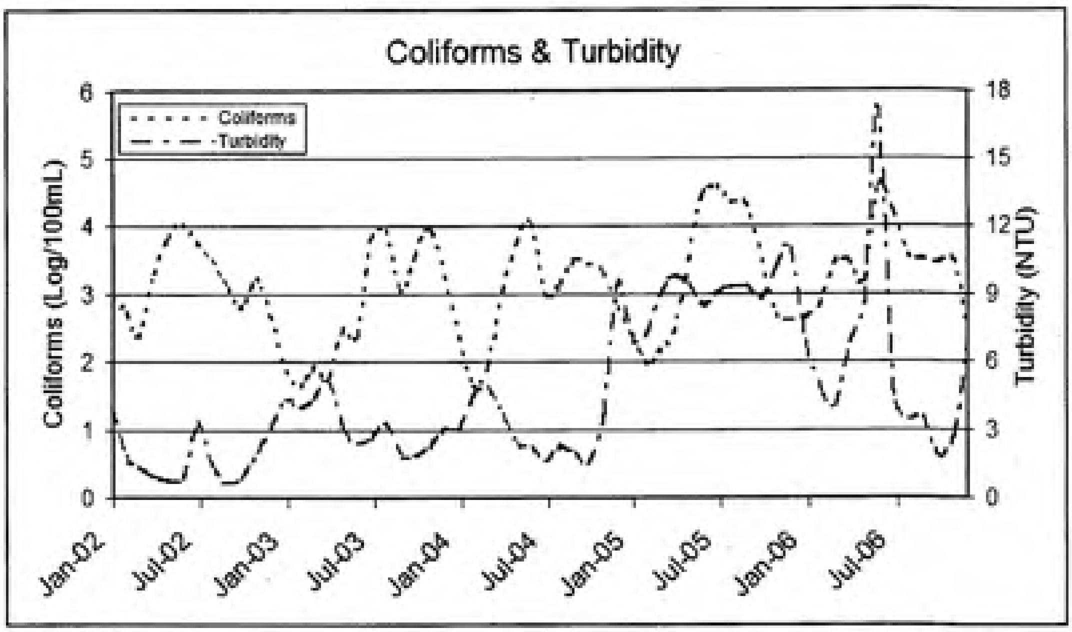


Figure 4.19: Monthly average raw water coliform bacteria and turbidity data from 2002-2006 for Raleigh Water Treatment Plant

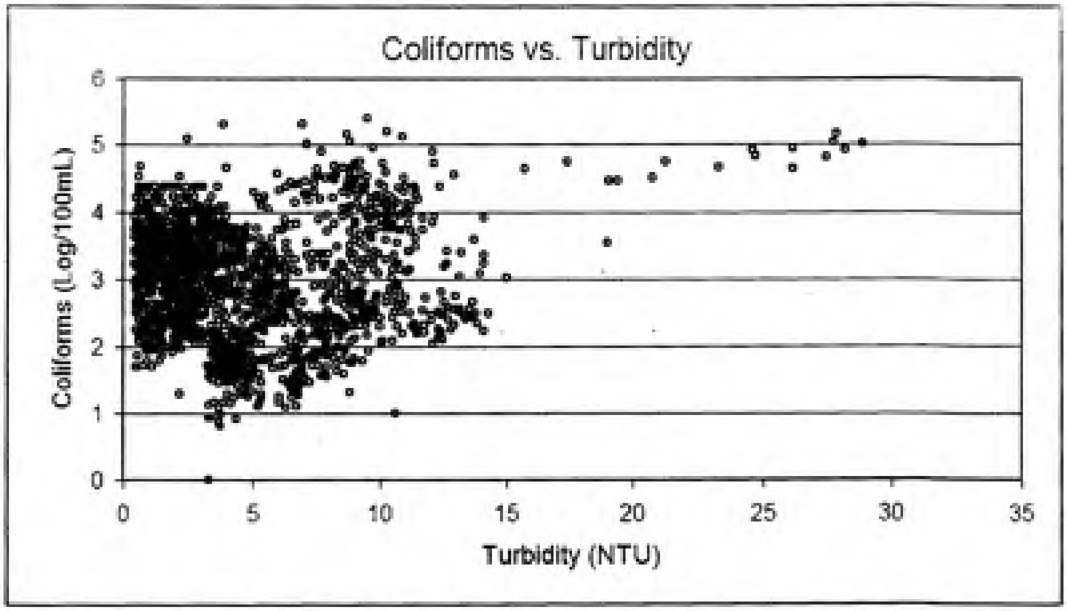


Figure 4.20: Scatter plot of daily coliform bacteria counts versus turbidity for Raleigh Water Treatment Plant raw water from 2002-2006

The monthly average coliform bacteria counts and water temperature of Falls Lake are illustrated in Figure 4.21. The figure shows a strong correlation between coliform

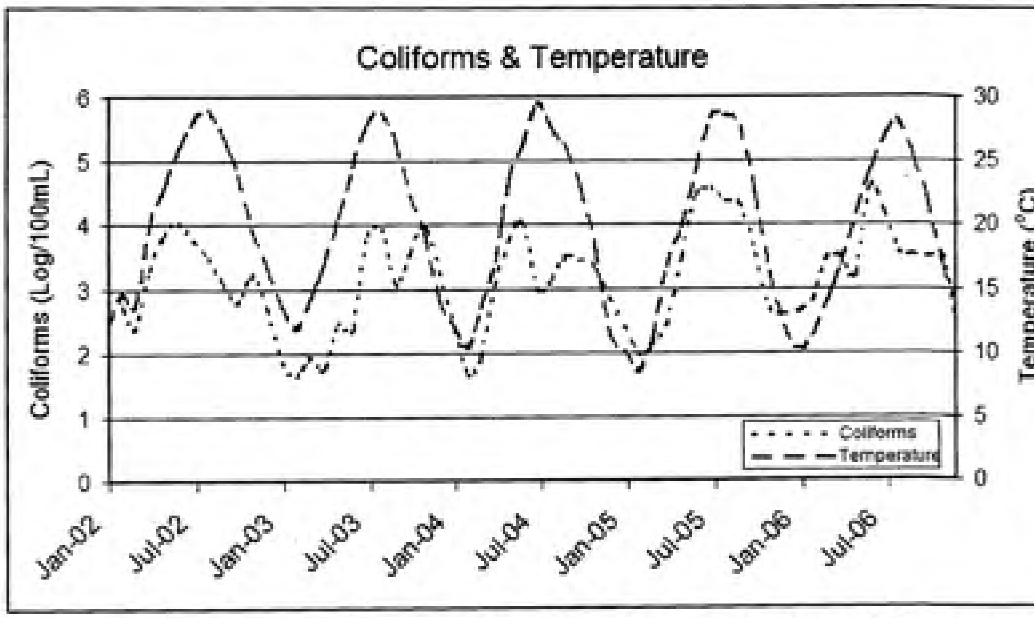


Figure 4.21: Monthly average raw water total coliform bacteria counts and temperature data from 2002-2006 for Raleigh Water Treatment Plant

bacteria counts and water temperature. The monthly average temperature ranged from 8.6 °C to 29.5 °C with an overall average of 19.8 °C for the five-year period of analysis. The analysis shows similarities to that for Jordan Lake, i.e. there are a greater number of total coliform bacteria present in the water during the summer months than in the colder winter months. As depicted in Figure 4.22, total coliform bacteria counts tend to increase as the water temperature increases.

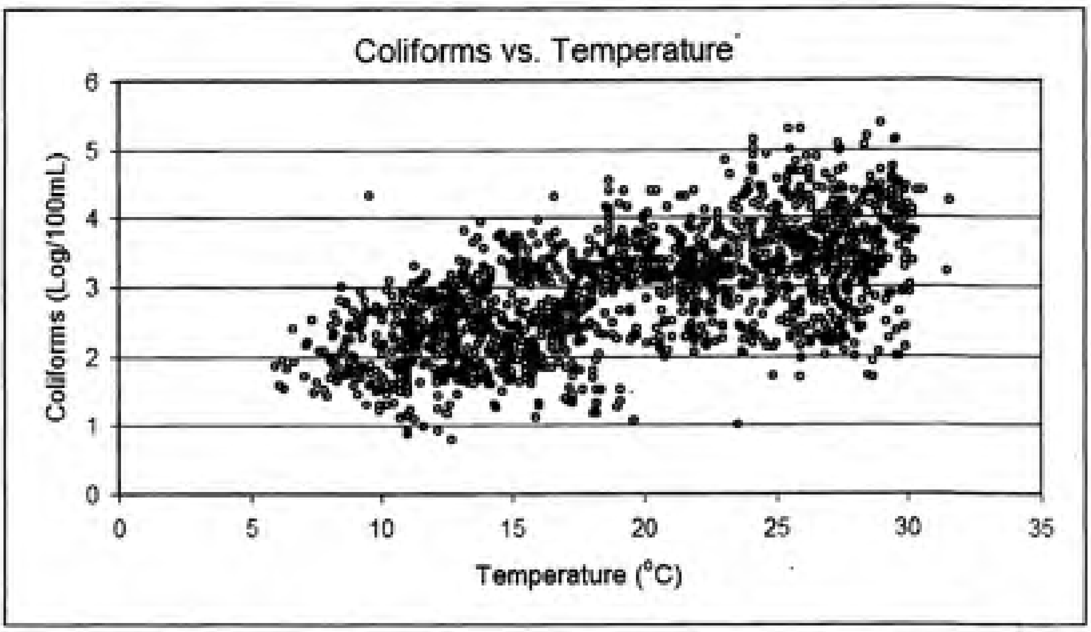


Figure 4.22: Scatter plot of daily coliform bacteria counts versus temperature for Raleigh Water Treatment Plant raw water from 2002-2006

The monthly average coliform bacteria counts and monthly rainfall over Falls Lake are depicted in Figure 4.23. Again, the smoothing effect from taking monthly coliform count averages and total monthly rainfall values masks any possible short-term relationships between rainfall and total coliform bacteria counts. As Figures 4.6a and 4.6b illustrated for Jordan Lake, Figure 4.24 illustrates that rainfall has an insignificant contribution to total coliform bacteria counts at the Raleigh water treatment plant intake.

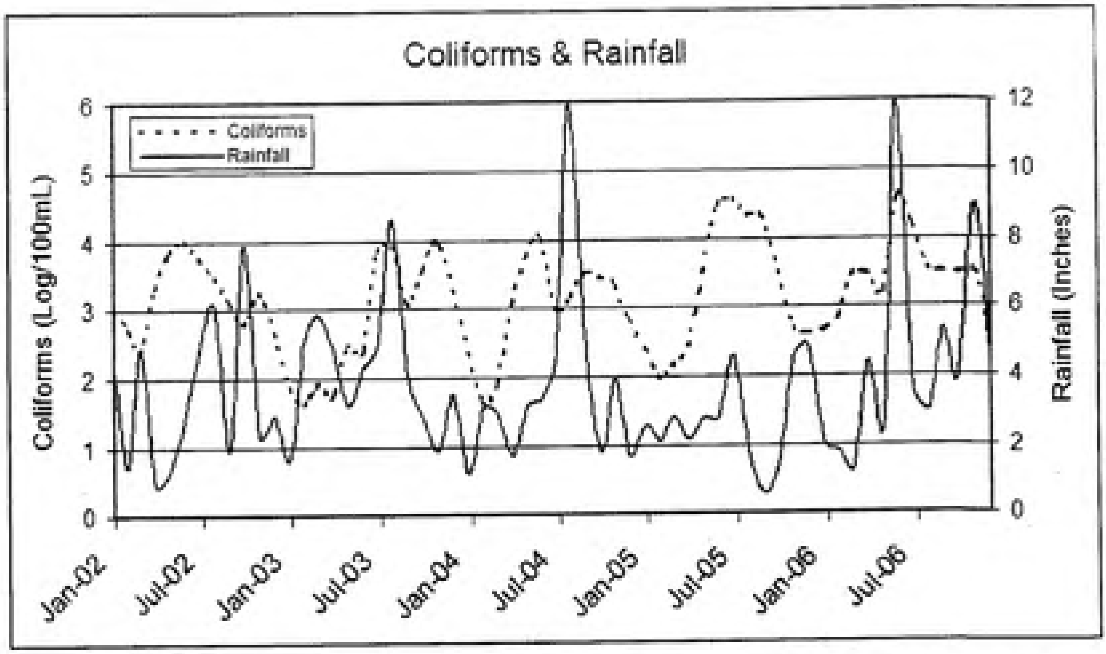


Figure 4.23: Monthly average raw water coliform bacteria counts and rainfall data from 2002-2006 for Raleigh Water Treatment Plant

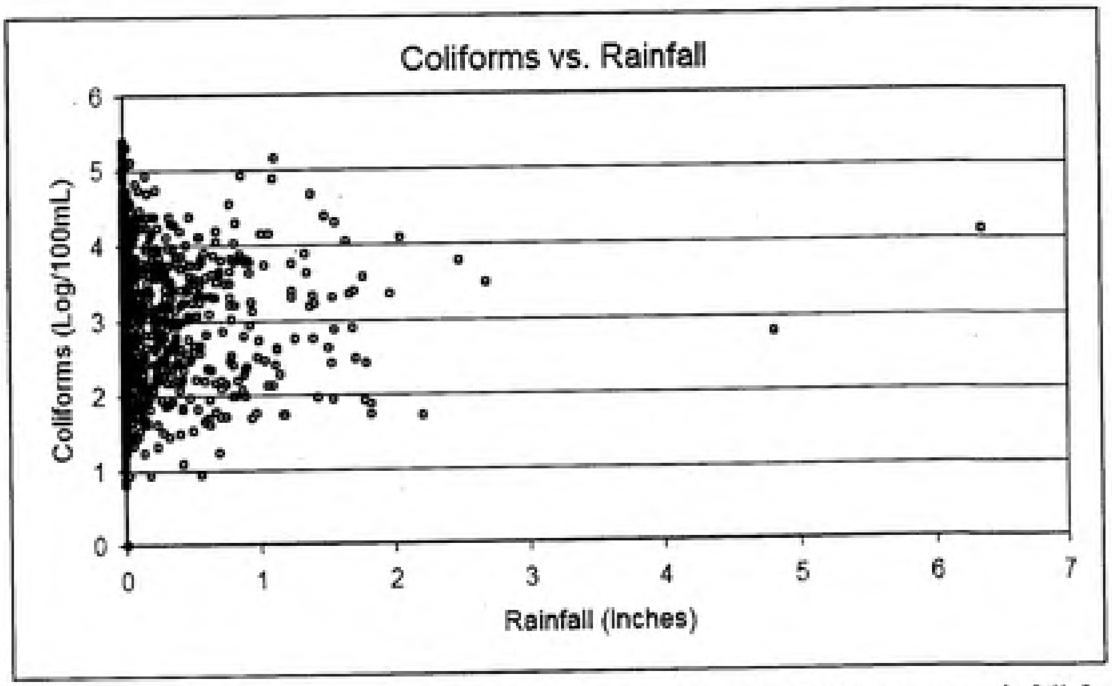


Figure 4.24: Scatter plot of daily coliform bacteria counts versus daily average rainfall for Raleigh Water Treatment Plant raw water from 2002-2006

The monthly average total rainfall was 3.7 inches for the five-year time period, with a maximum and minimum monthly total rainfall of 12.0 and 0.6 inches, respectively. The average turbidity for Falls Lake was 4.7 NTU for the years 2002 to 2006. The average turbidity for Jordan Lake was 6.2 NTU for the same time period. Similar to the situation for Jordan Lake, turbidity for Falls Lake tended to peak in March of each year except for in 2004, as depicted in Figure 4.25. To eliminate the effect of smoothing by monthly averaging, daily turbidity and rainfall values were analyzed as illustrated in Figure 4.26. Again, no significant trend was determined between the two parameters, except possibly for year 2006.

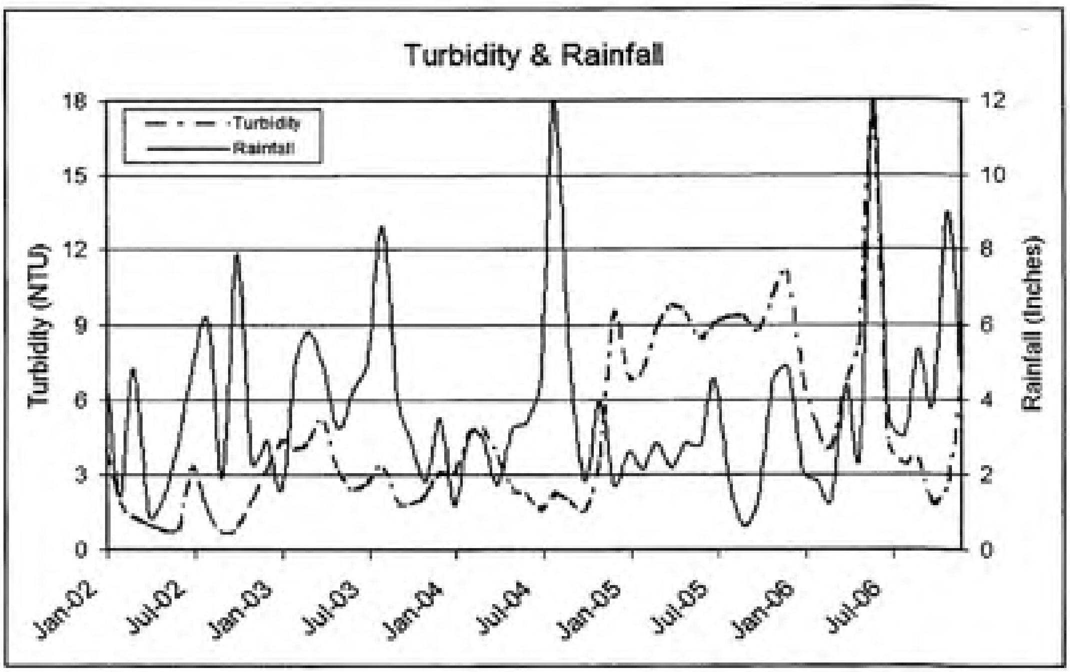


Figure 4.25: Monthly average raw water turbidity and rainfall data from 2002-2006 for Raleigh Water Treatment Plant

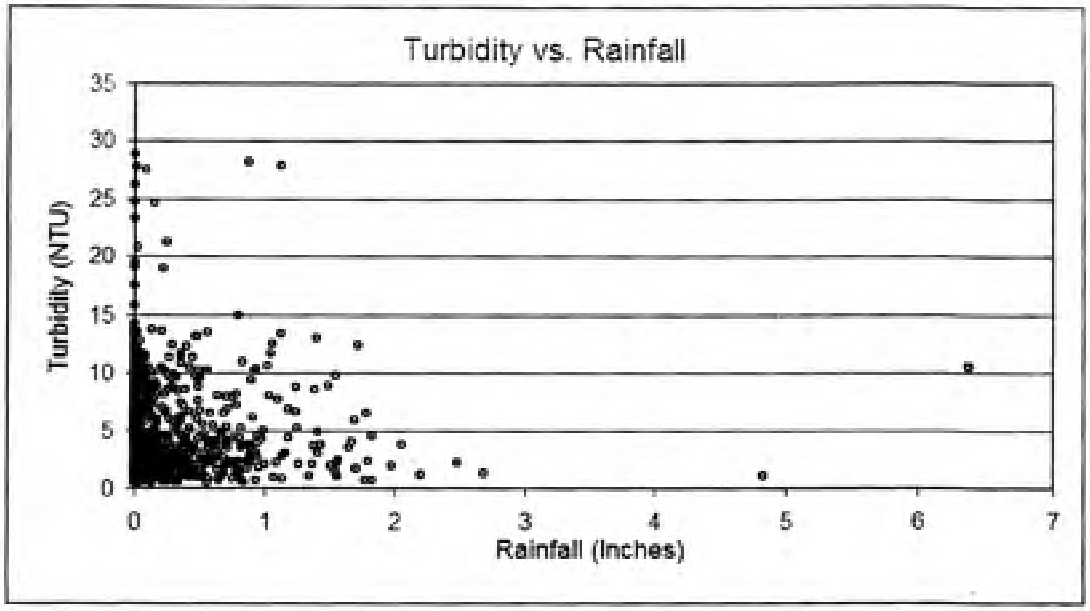


Figure 4.26: Scatter plot of turbidity versus daily average rainfall for Raleigh Water Treatment Plant raw water from 2002-2006

4.2.2. Chemical Usage and Raw Water Quality

The primary chemicals used by the Raleigh water treatment facility include ferric sulfate as a coagulant, caustic (sodium hydroxide), chlorine as a primary disinfectant, and ozone as a pre-oxidant. Figure 4.27 shows the monthly average chemical dosages for these chemicals and the average monthly treated water in million gallons per day. Just like with the Cary/Apex water treatment facility, there is seasonal variability in the amount of treated water produced, with greater usage of water in the summer. The average ferric sulfate dosage was 57.5 mg/L for the five-year time period, while caustic, chlorine, and ozone dosages were 23.1 mg/L, 6.2 mg/L, and 1.5 mg/L respectively, for the same time period.

Figure 4.28 illustrates the chemical dosages and raw water coliform bacteria counts over the five-year period. Chemical dosages for chlorine tended to increase over the past 2 ½ years compared to the normal fluctuation in coliform bacteria counts in the source water. Ozone, which is used as a pre-oxidant, tends to exhibit a seasonal pattern to coincide with the seasonal fluctuations in iron and manganese and taste and odor, and variations in temperature.

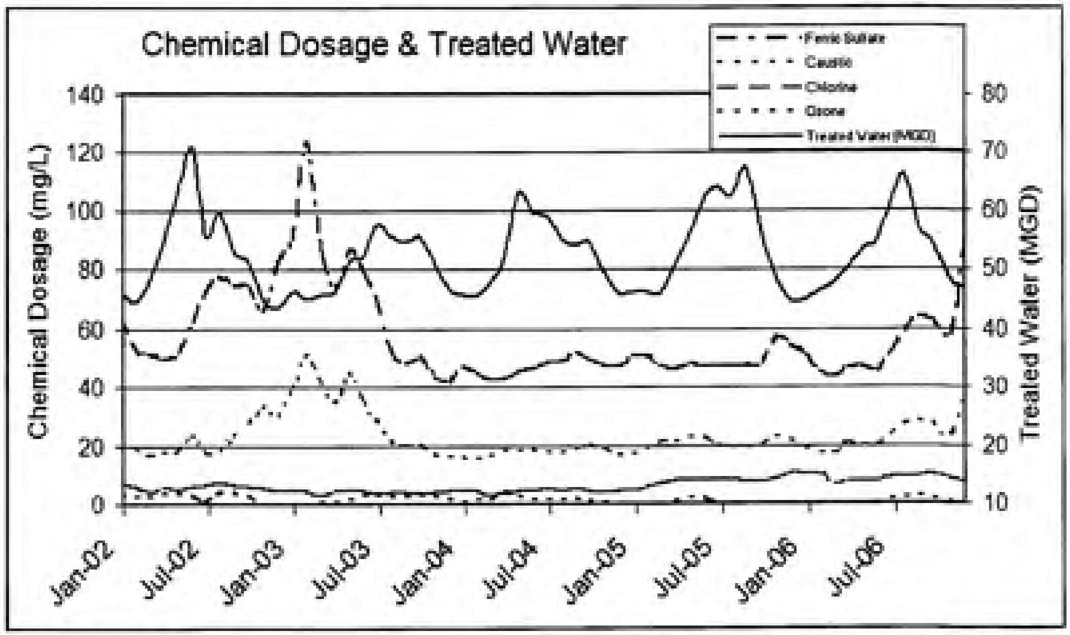


Figure 4.27: Monthly average chemical dosage and treated water flow from 2002-2006 at Raleigh Water Treatment Plant

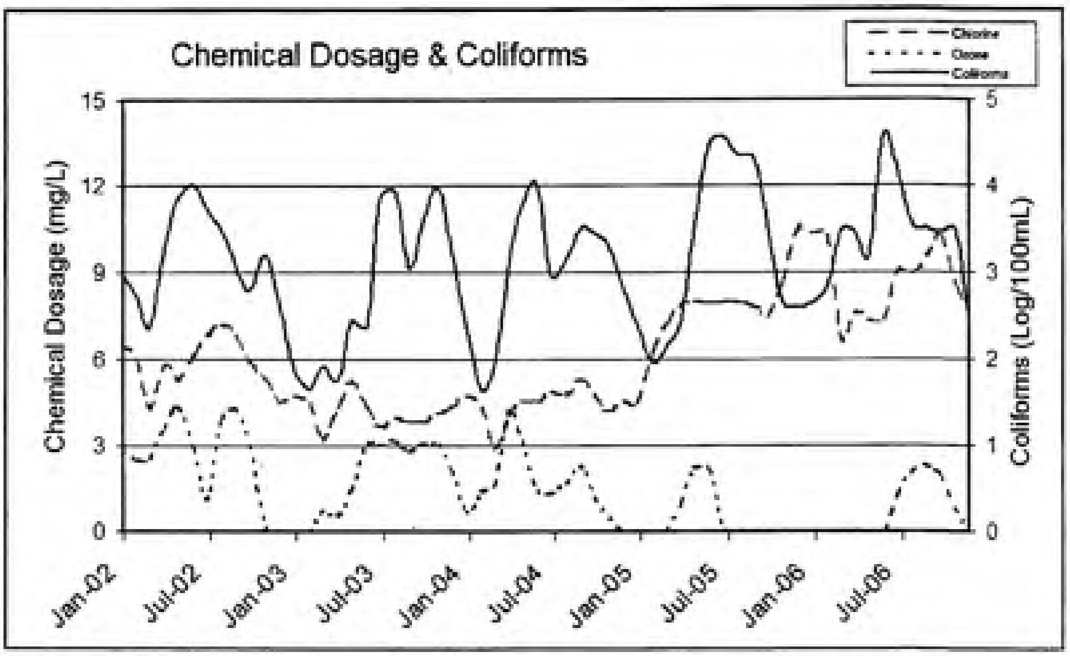


Figure 4.28: Monthly average chemical dosage and monthly average coliform bacteria counts at Raleigh Water Treatment Plant from 2002-2006

The effect of turbidity on coagulant dosages is depicted in Figure 4.29. Since turbidity in water is caused by the presence of suspended particles, the expectation is that the ferric sulfate dosage would change according to the fluctuations in turbidity of the source water. Figure 4.29, however, shows this is not the case. In fact, for the last 3½ years, ferric sulfate doses have remained relatively constant, despite the variation in raw water turbidity. As depicted in Figures 4.30, the daily average ferric sulfate dosage ranged between 50 mg/L and 125 mg/L until 2004. Thereafter the dose has been approximately 50 mg/L and did not vary with raw water turbidity.

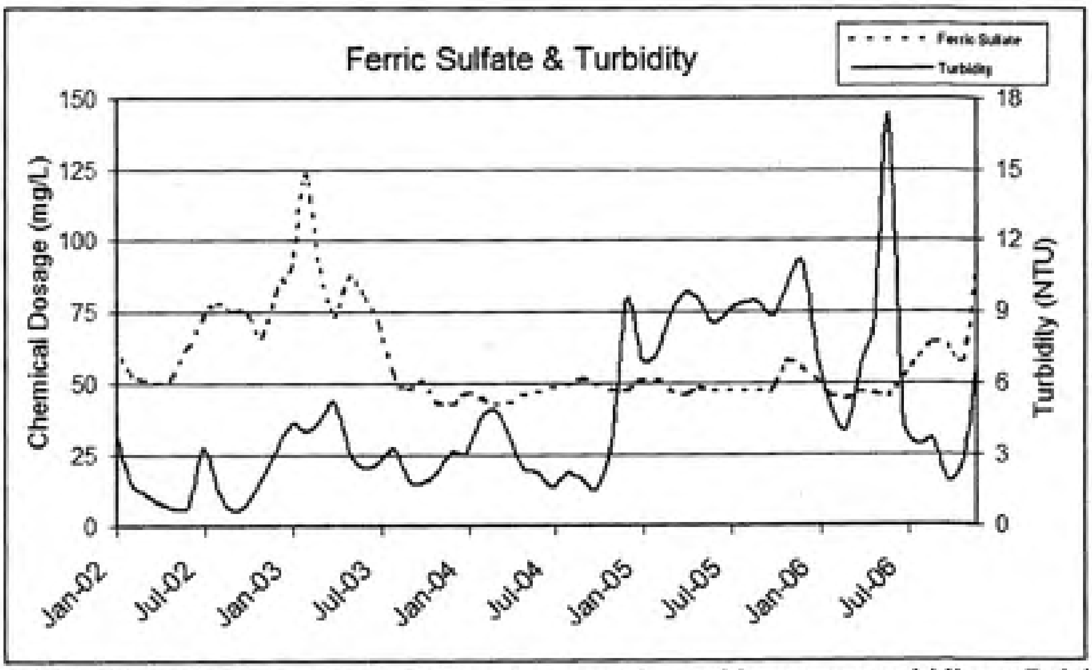


Figure 4.29: Monthly average ferric sulfate dosage and monthly average turbidity at Raleigh Water Treatment Plant from 2002-2006

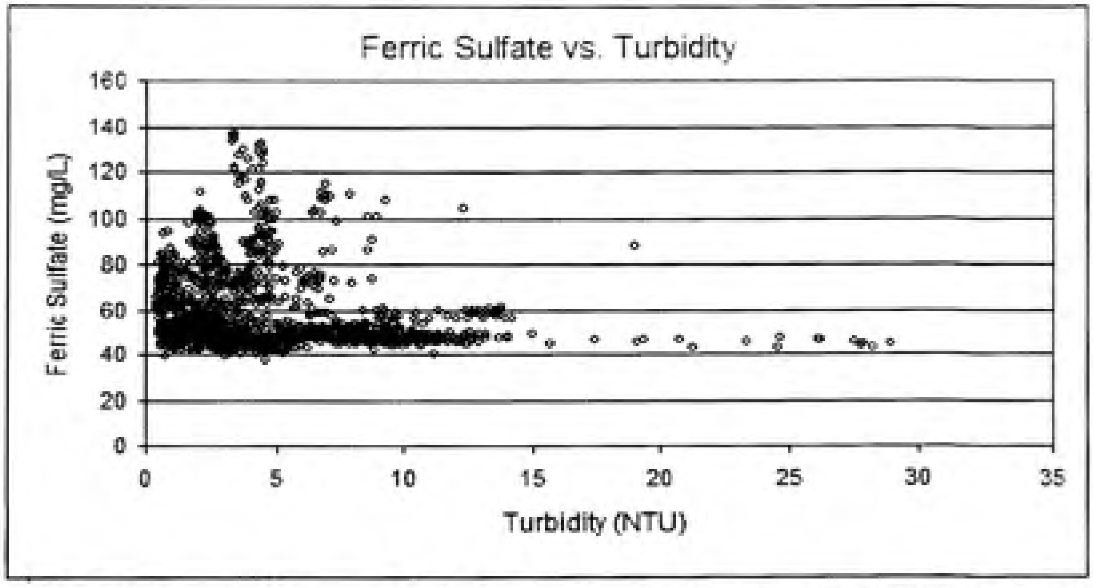


Figure 4.30: Daily average ferric sulfate dosage versus daily average turbidity at Raleigh Water Treatment Plant from 2002-2006

4.2.3. CT Analysis

An alternative method for calculating required CT values for chlorine, instead of determining values from the CT tables, is the use of Equation 4.3 obtained from Wilkes University (Wilkes University, 2006). This equation is widely used by many utilities and primary agencies. Equation 4.3 provides interpolated values from the EPA published CT tables for chlorine.

$$CT_{Equation} = 0.2828(pH)^{2.69}(Cl)^{0.15}0.933^{(Temp-5)}(\text{Log Inactivation}) \quad (4.3)$$

where
pH = pH of treated water
Cl = chlorine residual (mg/L)
Temp = water temperature (^{o}C)
Log Inactivation = microbial inactivation remaining after removal credits are awarded

Figure 4.31 is a comparison of the two methods for determining required CT values: use of the CT tables (CT_{Table}) and Equation 4.3 ($CT_{Equation}$). The line on the graph depicts the one to one slope of perfect agreement and therefore the line along which all the points should theoretically lie. Figure 4.31 suggests that calculations using Equation 4.3 closely match values extracted from the CT tables.

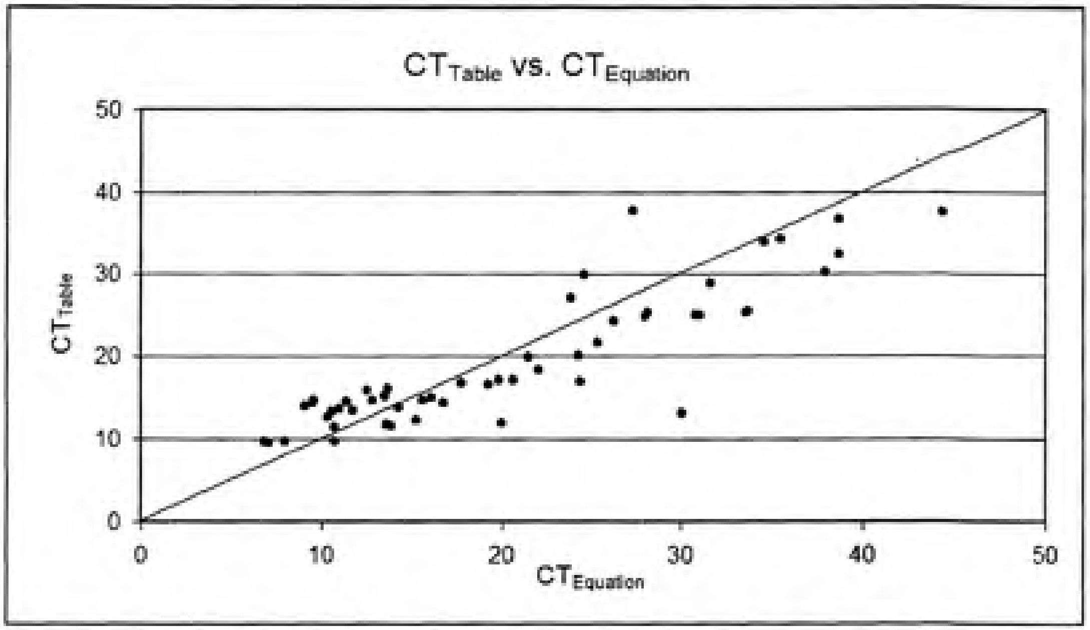


Figure 4.31. Comparison of CT values from EPA tables versus CT values calculated using Equation 4.3 for Cary/Apex Water Treatment Plant for selected conditions

In October of 2003, the Raleigh water treatment plant switched from using CT tables for calculating required CT values to using Equation 4.3. For the Raleigh water treatment facility, the State of North Carolina requires an additional 0.6 log inactivation of *Giardia* after removal credits are awarded. Figure 4.32 shows the actual CT value achieved by the facility, the CT value required to meet regulatory compliance, and the actual CT value to required CT value ratio for the five-year time period. The actual CT to required CT ratio ranged between 3 and 24 times the required CT values, corresponding to a "buffer" of 1.8 to 14.4 logs of additional *Giardia* inactivation. Although there appears to be a drastic increase in the actual CT achieved after switching to the equation, the reason for this increase is not clear. Figure 4.31 indicates that Equation 4.3 gives the same CT values as those obtained from EPA's CT tables. It is possible that the CT values were being calculated incorrectly prior to 2003.

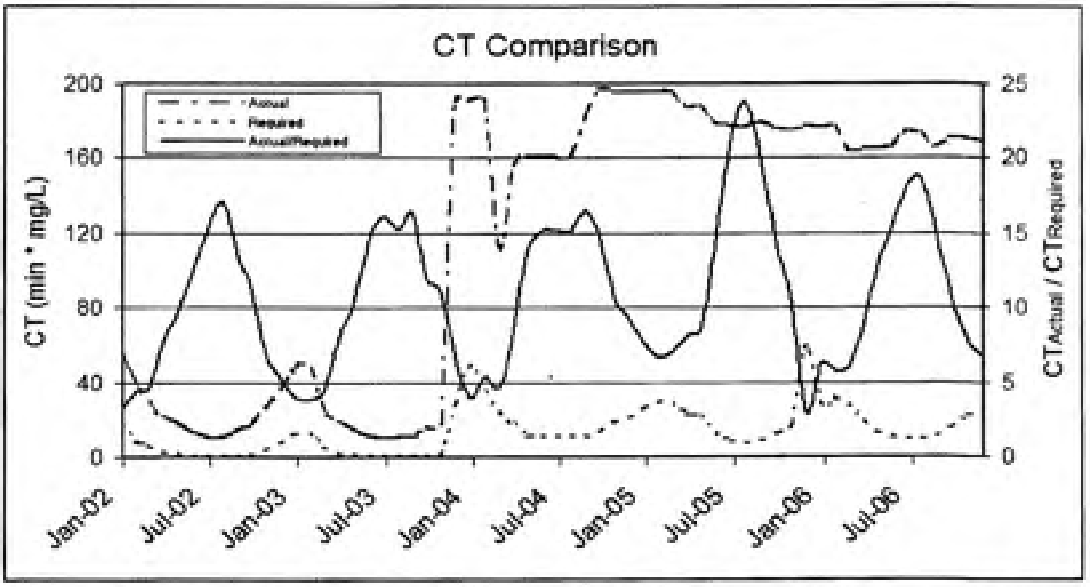


Figure 4.32: Plot of actual CT achieved to required CT and $CT_{Actual}/CT_{Required}$ ratio for Raleigh Water Treatment Plant from 2002-2006

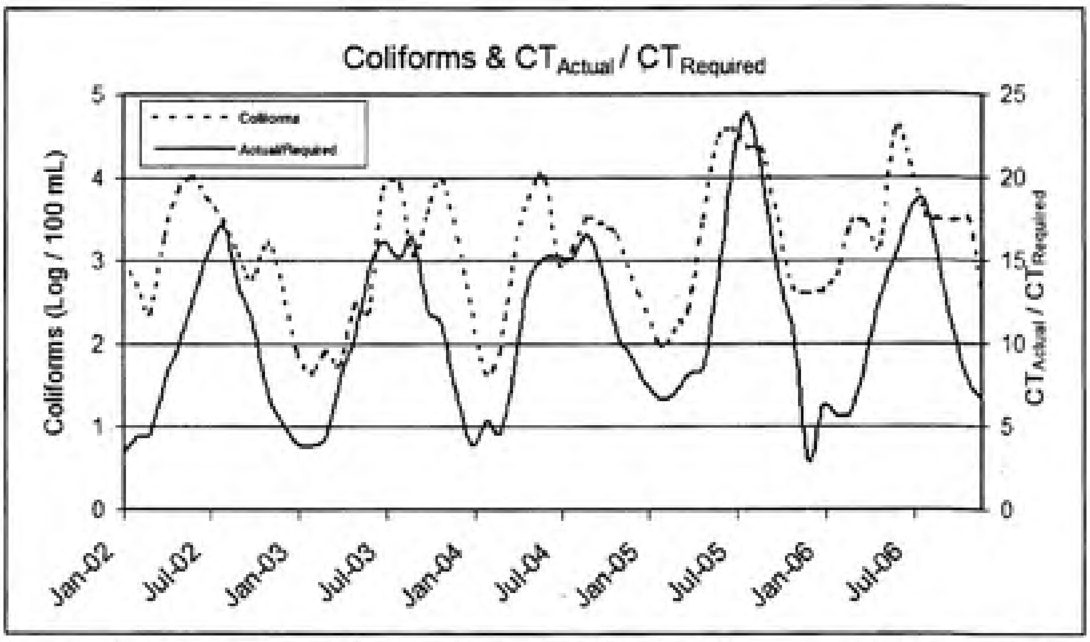


Figure 4.33: Plot of coliforms bacteria counts and $CT_{Actual}/CT_{Required}$ ratio for Raleigh Water Treatment Plant from 2002-2006

Figure 4.33 shows the comparison of total coliform bacteria counts and the actual CT to required CT ratio for the Raleigh water treatment plant over the five-year time period. The excess CT required, as depicted by the ratio, follows closely to the seasonal fluctuation of total coliform bacteria counts, as was also seen with the Cary/Apex water treatment plant.

4.2.4. Chemical Cost Analysis

This section analyzes the chemical cost incurred by the Raleigh water treatment facility for the years 2002 to 2006. Table 4.6 shows the average annual cost for the chemicals used by the facility. The total annual cost fluctuated between $122,250 to $193,500 for this time period.

Table 4.6. Average monthly chemical cost for Raleigh Water Treatment Plant from Years 2002-2006

Average Monthly Chemical Cost					
	2002	2003	2004	2005	2006
Ferric Sulfate	$60,190	$62,108	$43,473	$46,500	$50,826
Caustic	$26,347	$35,000	$21,920	$25,782	$28,526
Carbon	$55	$1,038	$0	$1,416	$85
Ammonia	$1,860	$1,789	$1,929	$1,809	$1,642
Chlorine	$2,675	$1,788	$2,003	$3,883	$3,873
Ozone†	$70,670	$74,816	$42,953	$12,421	$20,917
Total Chemical Cost	$172,444	$193,493	$124,749	$122,247	$122,316

† Includes the cost of liquid oxygen and the cost of electricity to generate the ozone on-site.

Table 4.7 shows the correlation matrix between the raw water quality parameters of interest, rainfall, and chemical cost for the Raleigh water treatment plant. The highest correlation is between temperature and coliform bacteria counts, as it was for the Caty/Apex water treatment plant. Since none of the correlations between the predictor variables exceed 0.90, there is no concern for the effects of multicolinearity (Veney, 2003).

Table 4.7: Cross correlation between variables (Raleigh Water Treatment Plant)

	Cost/MG	Coliforms	Temperature	Turbidity	TOC	pH	Rainfall
Cost/MG	1						
Coliforms (log CFU/100ml)	0.119	1					
Temperature (°C)	0.276	0.719	1				
Turbidity (NTU)	0.460	0.064	0.219	1			
TOC (mg/L)	0.382	0.402	0.209	0.066	1		
PH	0.306	0.284	0.468	0.185	0.100	1	
Rainfall (inches)	0.145	0.109	0.270	0.067	0.007	0.264	1

Equation 4.4, developed from a multiple linear regression analysis, depicts the regression equation for predicting chemical costs based on the raw water quality at the intake

$$\text{Cost/MG} = -25.1(\log \text{Coliform}) + 4.7\,(\text{Temp}) - 4.9\,(\text{Turb}) + 18.6\,(\text{TOC}) + 119.8 \qquad (4.4)$$

Table 4.8: Regression coefficients for cost regression equation (Raleigh Water Treatment Plant)

Regression Statistics						
R Square		0.45				
		Coefficients	*t Stat*	*Lower 95%*	*Upper 95%*
Intercept		119.77	2.31	15.73	223.81
Coliforms (log CFU/100ml)		-25.10	-2.14	-48.66	-1.55
Temperature	(°C)	4.65	3.39	1.90	7.39
Turbidity	(NTU)	-4.94	-2.77	-8.51	-1.36
TOC	(mg/L)	18.58	3.04	6.35	30.81

to the plant. Table 4.8 shows the associated statistics for the multiple linear regression analysis. Equation 4.4 has a higher R^2 value, 0.45, than the equation used to model the chemical cost for the Cary/Apex water treatment plant. Although the R^2 value is slightly higher, the intercept value still remains large, which tends to "swamp" the other terms in the equation.

The regression equation was used to predict chemical cost for the Raleigh water treatment plant, and to compare the predicted chemical cost to the actual chemical cost. Figure 4.34 shows that Equation 4.4 is not a good predictor for chemical cost since many of the points diverge away from the 1 to 1 slope line, and the error is not uniformly distributed about the line of perfect agreement. As with the cost model for the Cary/Apex water treatment plant, Equation 4.4 is not significantly driven by fluctuations in source water quality, and the model appears to be driven by other parameters not included in the model.

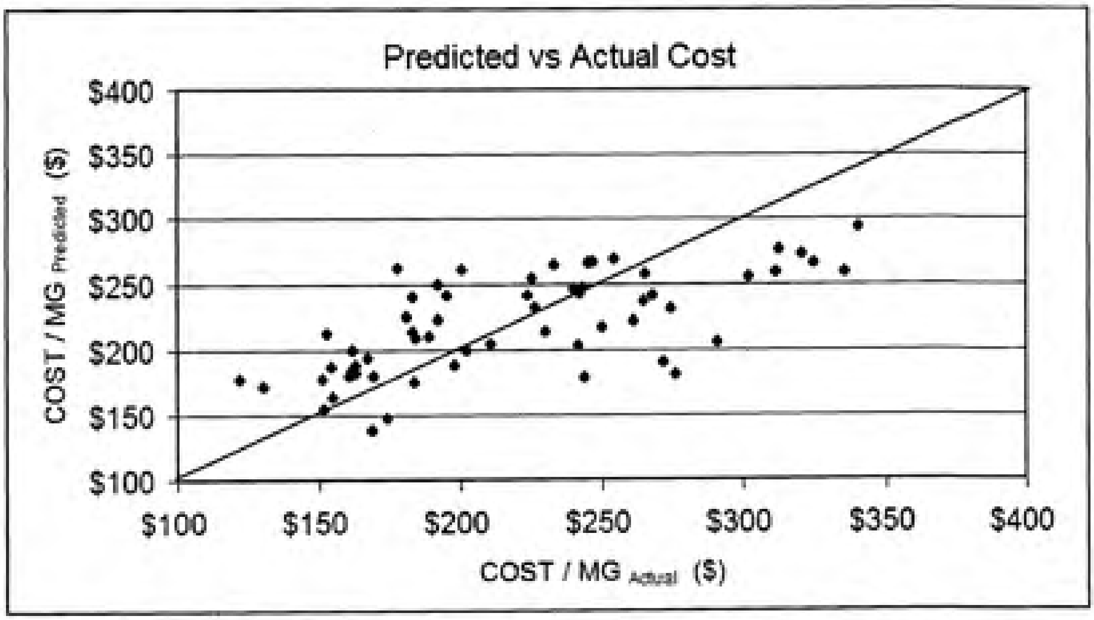


Figure 4.34: Comparison of actual and predicted chemical cost using Equation 4.4 developed for the Raleigh Water Treatment Plant

Chapter 5. Summary and Conclusions

Understanding the variability in source water quality is important to water treatment facilities because the variations in water quality will affect the plant's treatment processes, chemical usage, and chemical costs. The variation in water quality of Jordan Lake was analyzed to evaluate its influence on the Cary/Apex water treatment facility. This process included assessing seasonal fluctuations in coliform bacteria, examining correlations between coliform bacteria and other source water quality parameters, such as turbidity and temperature, and exploring relationships between source water quality parameters and chemical usage and corresponding chemical costs using linear regression analysis. The results obtained for Jordan Lake and the Cary/Apex water treatment facility were compared to those for Falls Lake and the Raleigh water treatment facility.

The analyses were completed using available data from monthly operating reports provided by each respective water treatment facility. A strong correlation was observed between coliform bacteria counts and water temperature for both of the source waters, with the coliform bacteria counts increasing with increasing temperature. Surprisingly, a weak correlation was observed between coliform bacteria counts and turbidity for both of the source waters, despite the fact that turbidity is used as a surrogate for the presence of microorganisms in water.

Water production fluctuated seasonally for both facilities. Higher production of water was observed to occur in the warmer summer months, as expected, with lesser production during the cooler winter months. The same trend was observed by both facilities for raw water coliform bacteria counts, with higher counts occurring during the summer months than during the cooler months.

A CT analysis for both plants illustrated similar trends with respect to the $CT_{Achieved}/CT_{Required}$ ratio, a significant observation since the ratio represents excess in microbial inactivation employed to meet regulatory requirements. The ratio ranged between 3 to 38 times the required CT for the Cary/Apex water treatment plant and 3 to 24 times the required CT for the Raleigh water treatment plant, with the greater excesses exhibited during the warmer summer months. The excess inactivation potential during the summer months serves as a protective buffer for potential fluctuations in pathogenic microorganism counts during the period of the year when consumer water demand is at its highest and coliform counts are at their highest levels.

The multiple linear regression analyses relating chemical cost to source water quality for both facilities proved to be insignificant at best, with an R^2 value of 0.30 and 0.45 for the Cary/Apex and Raleigh water treatment plants, respectively. Alum dosages for the Cary/Apex water treatment plant and ferric sulfate dosages for the Raleigh water treatment plant were relatively constant over the past 3½ years, despite significant seasonal fluctuations in raw water turbidity, TOC concentrations, and temperature. The daily operation of both plants appear to be based on parameters other than raw water quality.

The maximum protection against pathogenic microorganisms in drinking can be accomplished through the concept of multiple barrier practices employed by most water treatment facilities. Although the analyses of the Cary/Apex and Raleigh water treatment facilities showed an excess CT buffer for microbial inactivation, emphasis should be placed on source water protection to minimize future potential health risks by the increased loading of pathogens from biologically impaired streams into raw drinking water sources. This process of source water protection and management must take into account human health, economic, political, and environmental considerations to ensure proper implementation.

References

Aboytes, Ramon, G. Di Giovanni, F. Abrams, C. Rheinecker, W. McElroy, N. Shaw, and M.W. LeChevallier. 2004. Detection of Infectious *Cryptosporidium* in Filtered Drinking Water. *Journal of AWWA*, 96(9):88–97.

Adham S.S., R.S. Trussell, P.F. Gagliardo, and R.R. Trussell. 1998. Rejection of MS-2 virus by RO membranes. *Journal of AWWA*, 90(9):130–135.

Ainsworth, R. 2004. Safe Piped Water: Managing Microbial Water Quality in Piped Distribution Systems. World Health Organization. IWA Publishing. London. UK.

Al-Ani, M.Y., D.W. Hendricks, G.S. Logsdon, and C.P. Hibler. 1986. Removing Giardia cysts from low turbidity waters by rapid filtration. *Journal of AWWA*, 78(5):66–73.

American Water Works Association. 1999. Manual of Water Supply Practices Waterborne Pathogens. 1st Edition. AWWA. Denver, CO.

Atherholt, T.B., M.W. LeChevallier, W.D. Norton, and J.S. Rosen. 1998. Effect of rainfall on Giardia and Crypto. *Journal of the AWWA*, 90(9):66–80.

Bukhari, Z., T. Hargy, J. Bolton, B. Dussert, and J. Clancy. 1999. Medium-pressure UV for oocyst inactivation. J. AWWA. 91:3:86–94.

Clancy, J., Z. Bukhari, T. Hargy, J. Bolton, B. Dussert, and M. Marhsall. 2000. Using UV to inactivate *Cryptosporidium*. J. AWWA. 92(9):97–104.

Clark, R., M. Sivagensan, E. Rice, and J. Chen. 2002a. Development of a CT equation for the inactivation of *Cryptosporidium* oocysts with ozone. Wat. Res. 36: 3141– 3149.

Clark, R., M. Sivagensan, E. Rice, and J. Chen. 2002b. Development of a CT equation for the inactivation of *Cryptosporidium* oocysts with chlorine dioxide. Wat. Res. 36: 3150-3157.

Clean Water Act, Pub L. 95-217, 1566.

Cloete, T.E., J. Rose, L.H. Nel, and T. Ford. 2004. Microbial Waterborne Pathogens. IWA Publishing. London. UK.

Craun, G.F. 1986. Waterborne Diseases in the United States of America. CRC Press. Boca Raton, FL.

Craun, G.F. 1992. Waterborne Diseases Outbreaks in the United States of America: Causes and Preventions. CRC Press. Boca Raton, FL.

Craun, G.F., and R. Calderon. 1996. Microbial risks in groundwater systems: Epidemiology of waterborne outbreaks. Under the Microscope: Examining microbes in groundwater. Proceedings of the Groundwater Foundation's 12th Annual Fall Symposium, Boston. September.

Crittenden, J.C., R.R. Trussell, D.W. Hand, K.J. Howe and G. Tchobanoglous. 2005. Water Treatment: Principles and Design. 2nd Edition. John Wiley & Sons. New Jersey.

Davis, E.M., D.M. Casserly, and J.D. Moore. 1977. Bacterial relationships in stormwaters. *Water Resources Bulletin*, 13(5):895–905.

Dugan, N., K. Fox, J. Owens, and R. Miltner. 2001. Controlling *Cryptosporidium* oocysts using conventional treatment. J. AWWA. 93:12: 64–76.

Dwyer, P., M. Collins, A. Margolin, and Hogan. 1995. Assessment of MS2 Bacteriophage *Giardia* Cysts *Cryptosporidium* Oocysts and Organic Carbon Removals by Hollow Fiber Ultrafiltration. AWWA Membrane Technology Conference Proceedings, Reno NV, pp. 487.

Fayer, R., and B. Ungar. 1986. *Cryptosporidium spp.* and cryptosporidiosis. Microbial Review. 50(4):458–483.

Finch, G.R., L.L. Gyurek, L. Liyanage, M. Belosevic. 1997. *Effect of Various Disinfection Methods on the Inactivation of* Cryptosporidium. Denver, CO, American Water Works Association Research Foundation and the American Water Works Association.

Ford, T.E. 1999. Microbiological Safety of Drinking Water: United States and Global Perspectives. Environmental Health Perspective. 107: 191.

Gates, D. 1998. The chlorine dioxide handbook: water disinfection series. American Water Works Association, Denver, CO

Gimbel, R. and J. Clasen. 1998. International report: removal of micro-organisms by clarification and filtration processes. *Water Supply*, 16:203–208.

Hagen, K. 1998. Removal of Particles, Bacteria and Parasites With Ultrafiltration for Drinking Water Treatment. Desalination: The International Journal on the Science and Technology of Desalting and Water Purification. 1(3): 85–91.

Hammer, M.J. and M.J. Hammer Jr. 2004. Water and Wastewater Technology. 5th Edition. Pearson Prentice Hall, Upper Saddle River, New Jersey.

Hendrick, D.W. 2006. Water Treatment Unit Processes, Physical and Chemical. CRC Press, Boca Raton, Florida.

Hoxie, N., J. Davis, J. Vergeront, R. Nashold, and K. Blair. 1997. Cryptosporidiosis-associated mortality following a massive waterborne outbreak in Milwaukee, Wisconsin. Amer. J. Publ. Health. 87(12):2032–2035.

Hrudey, S.E. and E.J. Hrudey. 2004. Safe Drinking Water, Lessons from Recent Outbreaks in Affluent Nations. TJ International, Padstow, Cornwall, UK.

Hurst, C., R. Crawford, G. Knudsen, M. McInerney, and L. Stetzenbach. 2002. Manual of Environmental Microbiology. 2nd Edition. ASM Press. Washington D.C.

Jacangelo, J.G, M.E. Aeita, K.E. Carns, E.W. Cummings, and J. Mallevialle. 1989. Assessing Hollow-Fiber Ultrafiltration for Particle Removal. J. AWWA, 81:11:68.

Jacangelo, J., S. Adham and J. Lainé. 1995. Mechanism of *Cryptosporidium, Giardia*, and MS2 virus removal by MF and UF. J. AWWA 87(9):107–21.

Jagger, J.H. 1967. *Introduction to Research in UV Photobiology*. Englewood Cliffs, NJ, Prentice- Hall, Inc.

Korich, D.G., J.R. Mead, M.S. Madore, N.A. Sinclair, and C.R. Sterling. 1990. Effects of ozone, chlorine dioxide, chlorine, and monochloramine on *Cryptosporidium parvum* oocyst viability. Appl. Environ. Microbiol. 56(5)1423–1428.

Kramer MH, Herwaldt BL, Craun GF, Calderon RL, Juranek DD. Surveillance for waterborne-disease outbreaks—United States, 1993-1994. MMWR Morb Mortal Wkly Rep 1996;45:1-33.

Langlais, B., D.A. Reckhow, D.R. Brink. 1991. *Ozone in Water Treatment, Applications and Engineering*. Chelsea, MI, Lewis Publishers, Inc.

LeChevallier MW, Norton WD, Lee RG. 1991. Occurrence of *Giardia* and *Cryptosporidium* spp. in surface water supplies [published erratum appears in Appl Environ Microbiol 1992 Feb;58:780]. Appl Environ Microbiol 1991;57:2610-6.

LeChevallier, M. and W. Norton. 1995. *Giardia* and *Cryptosporidium* in raw and finished water. J. AWWA. 87(9):54–68.

Logsdon, G.S. 1990. *Microbiology and Water Filtration*. New York, Springer–Verlag.

Logsdon, G.S., S.D.N. Freeman, R.A. Hulsey, and s. Veerapaneni. 2004. *Cryptosporidium* and *Giardia* Contamination and Removal. ASCE. Advances in Water and Wastewater Treatment, pp 487-519.

MacKenzie, W.R., N.J. Hoxie, M.E. Proctor, M.S. Gradus, K.A. Blair, and D.E. Peterson. 1994. A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply. N Engl J Med 1994;331:161-7.

Madigan, Michael T. and J.M. Martinko. 2006. Brock Biology of Microorganisms, 11[th] Edition. Pearson Prentice Hall, New Jersey.

Medema, G.J., F.M. Schets, P. Teunis, and A.H. Havelaar. 1998. Sedimentation of free and attached *Cryptosporidium* oocysts and *Giardia* cysts in water. *Applied and Environmental Microbiology*, 64:4460–4466.

Morris, R.D. and R. Levin. 1995. Estimating the Incidence of Waterborne Infectious Disease Related to Drinking Water in the United States. Assessing and Managing Health Risks from Drinking Water Contamination: Approaches and Applications. 75-88. International Association of Hydrological Sciences. Wallingford, UK.

MWH. 2005. Water Treatment: Principles and Design, 2[nd] Edition. John Wiley and Sons, Hoboken, New Jersey.

NAS. 2004. Indicators of Waterborne Pathogens. National Academy of Sciences. Washington D.C.

Nieminski, E. and J. Ongerth. 1995. Removing *Giardia* and *Cryptosporidium* by conventional treatment and direct filtration. J. AWWA 87(9):96–106.

North Carolina Division of Water Quality, Basinwide Planning Program: 2000 Cape Fear River Basinwide Water Quality Plan, Chapter 5 from http://h2o.enr.state.nc.us/basinwide/Capefear/capefearindex.htm

North Carolina Division of Water Quality. 2006. North Carolina Impaired Waters 303(d) List. Raleigh, North Carolina, Modeling and TMDL Unit.

Ongerth, J. and P. Hutton. 2001. Testing of diatomaceous earth filtration for removal of *Cryptosporidium oocysts*. J. AWWA. 93(12): 54–63.

Owens J., R. Miltner, E. Rice, C. Johnson, D. Dahling, F. Schaefer, and H. Shukairy 2000. Pilot-scale ozone inactivation of *Cryptosporidium* and other microorganisms in natural water. Ozone Sci. Eng. 22:5:501–517.

Ransome, M.E., T.N. Whitmore, and E.G. Carrington. 1993. Effects of Disinfectants on the Viability of *Cryptosporidium parvum* oocysts. Water Supply. 11:75–89.

Rennecker J., B. Marinas, J. Owens and E. Rice. 1999. Inactivation of *Cryptosporidium parvum* oocysts with ozone. Wat. Res. 33(11):2481–2488.

Ruffell K., J. Rennecker, and B. Marinas. 2000. Inactivation of *Cryptosporidium parvum* oocysts with chlorine dioxide. Wat. Res. 34(3):868–876.

Shin, G., K. Linden, M. Arrowood, and M. Sobsey. 2001. Low-Pressure UV Inactivation and DNA Repair Potential of *Cryptosporidium parvum* Oocysts. Appl. Environ. Microbiol. 67(7):3029–3032.

State Climate Office of North Carolina. 2007. from http://www.nc-climate.ncsu.edu/

States, S., et al. 1999. Removal of *Cryptosporidium* by membrane filtration. Proceedings of the American Water Works Association Water Quality Technology Conference. Denver, CO, American Water Works Association.

Stumm, W. and J.J. Morgan. 1996. Aquatic Chemistry. New York, John Wiley & Sons, Inc.

USEPA. 1998. National Primary Drinking Water Regulations; Interim Enhanced Surface Water Treatment Rule. 63 FR 69477, December 16, 1998.

USEPA. 2001. Low-Pressure Membrane Filtration for Pathogen Removal: Application, Implementation and Regulatory Issues. EPA 815–C–01–001.

USEPA. 2002. National Primary Drinking Water Regulations: Long Term 1 Enhanced Surface Water Treatment Rule; Final Rule. Federal Register. January 14, 2002. 67 FR 1812. EPA 815–Z–02–001.

USEPA. 2006. National Primary Drinking Water Regulations: Long Term 2 Enhanced Surface Water Treatment Rule; Final Rule. Federal Register. January 5, 2006. Vol 71, 3.

USEPA. 2007. Regulation website. Major Environmental Laws. from http://www.epa.gov/epahome/laws.htm

Veney, J.E. 2003. *Statistics for Health Policy and Administration Using Microsoft Excel.* Jossey-Bass. San Fransico, California.

Weber-Shirk, M.L. and R.I. Dick. 1997a. Biological mechanisms in slow sand filters. *Journal of AWWA*, 89(2):72–83.

Weber-Shirk, M.L. and R.I. Dick. 1997b. Physical–chemical mechanisms in slow sand filters. *Journal of AWWA*, 89(2):87–100.

White, G.C. 1999. *Handbook of Chlorination and Alternative Disinfectants*. New York, John Wiley & Sons, Inc.

Wilkes University, Center for Environmental Engineering and Earth Sciences. 2007. from http://www.water-research.net/watertreatment/chlorinecontact.htm

World Health Organization. 2004. *Guidelines for drinking-water quality*, 3rd ed., World Health Organization, Geneva.

Appendix A – Average Monthly Raw Water Quality Values for Cary/Apex and Raleigh Water Treatment Plant's for 2002-2006

	CARY/APEX						RALEIGH					
DATE	TEMP (°C)	COLIFORMS #/100mL	TURBIDITY (NTU)	pH	TOC (mg/L)	RAINFALL (inches)	TEMP (°C)	COLIFORMS #/100mL	TURBIDITY (NTU)	pH	TOC (mg/L)	RAINFALL (inches)
Jan-02	9.21	11,539	5.75	7.04	6.03	4.90	12.17	927	4.01	6.86	5.34	4.68
Feb-02	11.45	12,820	6.88	7.04	6.5	1.27	14.60	541	1.85	6.86	5.01	1.41
Mar-02	13.38	2,429	10.12	7.09	6.41	4.40	13.65	236	1.42	7.04	5.23	4.85
Apr-02	19.29	337	8.23	6.90	6.55	0.71	19.89	1,992	1.01	6.90	5.22	0.90
May-02	22.98	724	6.44	6.95	6.25	1.24	23.05	7,102	0.78	6.79	5.63	1.32
Jun-02	27.31	2,747	5.40	6.98	6.13	2.64	26.06	9,968	0.82	6.68	5.67	2.89
Jul-02	28.98	11,248	4.48	7.00	6.36	4.30	28.21	5,358	3.30	6.69	6.08	4.90
Aug-02	29.56	13,136	5.79	7.05	6.83	6.04	28.87	2,947	1.42	6.68	6.26	6.10
Sep-02	26.36	15,177	5.47	7.12	6.78	2.21	26.92	1,212	0.64	6.48	5.44	1.88
Oct-02	23.06	29,484	5.54	6.91	6.48	7.76	23.86	625	0.93	6.44	5.55	7.90
Nov-02	16.32	797	9.89	6.88	6.82	2.50	19.52	1,627	1.99	6.72	6.95	2.33
Dec-02	10.33	631	8.97	7.00	6.93	3.24	16.58	470	3.16	6.84	8.09	2.93
Jan-03	8.40	618	10.35	7.06	7.61	1.56	13.46	74	4.33	6.74	8.35	1.62
Feb-03	8.23	168	10.29	7.16	7.19	4.90	11.92	45	4.01	6.83	7.81	5.09
Mar-03	12.34	238	15.19	6.93	6.39	5.96	14.19	82	4.40	6.68	6.49	5.82
Apr-03	15.32	633	20.98	6.76	6.65	5.59	16.90	57	5.16	6.35	6.29	4.88
May-03	21.00	239	11.03	6.73	7.22	3.90	20.60	293	3.12	6.11	7.23	3.24
Jun-03	24.43	384	7.27	6.81	7.42	3.37	24.61	237	2.42	6.23	7.02	4.32
Jul-03	28.13	668	4.18	6.76	6.27	5.14	28.05	7,202	2.68	6.25	6.22	4.95
Aug-03	28.69	7,498	3.52	6.73	6.19	7.08	28.69	8,560	3.25	6.40	5.87	8.60
Sep-03	26.60	8,571	3.48	6.83	6.08	4.04	26.45	1,133	1.94	6.47	5.88	4.02
Oct-03	21.59	5,942	3.61	6.85	5.94	2.70	22.29	3,745	1.81	6.63	5.80	2.87
Nov-03	18.16	2,104	3.67	6.83	5.65	1.76	19.15	9,839	2.25	6.78	5.48	1.83
Dec-03	11.57	424	4.08	6.99	5.8	3.30	14.05	1,822	3.09	6.99	5.40	3.51
Jan-04	9.17	86	3.99	7.15	6.19	1.17	12.02	234	3.06	6.89	6.01	1.19
Feb-04	8.76	21	3.88	7.16	6.4	2.83	10.38	44	4.55	7.04	5.90	3.13
Mar-04	13	925	5.84	7.11	7.82	2.62	13.51	89	4.84	7.10	6.06	2.96
Apr-04	17.75	2,722	5.75	7.02	6.29	1.57	17.01	1,153	3.73	7.01	5.45	1.71
May-04	24.08	479	4.37	6.92	6.22	3.27	23.63	5,688	2.44	6.94	5.03	3.20
Jun-04	27.34	5,215	3.38	6.98	5.95	3.22	26.32	10,261	2.22	6.94	5.11	3.39
Jul-04	28.95	8,037	2.82	6.90	6.07	4.08	29.45	935	1.63	6.89	4.72	4.53
Aug-04	27.80	11,886	3.56	6.86	6.17	10.18	27.45	1,408	2.27	6.79	4.56	12.00
Sep-04	26.40	13,134	4.10	6.80	6.46	5.54	25.98	3,222	1.94	6.75	5.32	5.07
Oct-04	22.77	9,089	4.81	6.82	6.64	1.94	22.91	2,823	1.57	6.68	5.84	1.63
Nov-04	18.01	5,303	7.50	6.68	6.51	3.70	18.06	2,028	3.68	6.71	5.25	3.98
Dec-04	13.02	2,817	8.52	6.84	6.44	1.64	11.25	647	9.45	6.74	5.85	1.72
Jan-05	10.20	422	6.86	6.98	6.47	2.36	10.12	259	6.96	6.95	6.22	2.60
Feb-05	9.43	60	8.33	7.05	6.78	2.30	8.55	90	7.24	7.01	6.38	2.14
Mar-05	11.67	110	10.70	7.03	6.98	3.32	11.04	143	8.86	6.91	7.28	2.87
Apr-05	17.09	245	7.66	6.81	6.93	1.85	16.72	268	9.79	6.79	6.26	2.18
May-05	21.22	2,170	5.91	6.62	6.59	2.43	19.82	3,225	9.49	6.57	6.10	2.84
Jun-05	26.00	1,658	3.15	6.68	6.03	2.63	24.38	31,508	8.48	6.40	5.40	2.64
Jul-05	29.87	2,846	3.24	6.86	5.63	4.62	28.45	36,738	9.06	6.41	4.68	4.59

	CARY/APEX						RALEIGH					
DATE	TEMP (°C)	COLIFORMS #/100mL	TURBIDITY (NTU)	pH	TOC (mg/L)	RAINFALL (Inches)	TEMP (°C)	COLIFORMS #/100mL	TURBIDITY (NTU)	pH	TOC (mg/L)	RAINFALL (Inches)
Aug-05	30.23	5,634	2.32	6.85	5.51	2.27	28.71	22,647	9.32	6.78	4.88	1.78
Sep-05	28.04	7,830	3.29	6.85	5.81	0.54	27.68	21,129	9.34	6.50	4.63	0.59
Oct-05	23.86	11,459	4.82	6.80	5.92	1.80	22.49	3,237	8.81	6.53	4.79	1.49
Nov-05	17.44	3,350	6.01	6.83	5.55	4.21	16.16	461	10.16	6.60	5.25	4.55
Dec-05	11.64	583	6.41	6.93	5.41	4.65	11.93	397	11.02	6.64	4.97	4.86
Jan-06	10.64	177	6.31	6.94	5.6	2.03	10.26	440	6.93	6.64	4.70	2.09
Feb-06	10.60	116	6.69	6.99	5.77	1.67	11.38	689	4.82	6.68	5.06	1.82
Mar-06	13.41	84	7.90	6.98	6	1.19	13.97	2,962	4.03	6.90	5.36	1.29
Apr-06	18.80	674	6.57	6.89	6.17	3.83	16.86	2,917	6.82	6.48	5.36	4.42
May-06	21.77	894	6.25	6.94	6.15	2.03	20.81	1,517	8.53	6.55	4.76	2.48
Jun-06	26.31	4,475	3.57	6.94	6.32	9.74	24.25	38,706	17.27	6.37	5.73	12.05
Jul-06	29.68	4,836	3.24	6.89	6.45	3.70	26.86	14,820	4.17	6.64	7.59	3.51
Aug-06	30.05	4,521	2.33	6.87	6.44	3.56	28.05	3,438	3.44	6.60	6.59	2.99
Sep-06	27.33	2,497	3.90	6.86	6.42	4.48	25.09	3,278	3.59	6.57	6.82	5.35
Oct-06							21.92	2,923	1.84	6.64	6.29	3.86
Nov-06							16.60	3,094	2.74	6.76	6.15	8.99
Dec-06							13.69	212	7.27	6.58	5.98	3.63

Appendix B – CT Tables

Table C.1. CT Table for 3 log inactivation of *Giardia* cysts by Free Chlorine (from USEPA 2002)

Chlorine Concentration (mg/L)	Temperature <=0.5°C							Temperature =5°C							Temperature = 10°C						
	pH							pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	137	163	195	237	277	329	390	97	117	139	166	198	236	279	73	88	104	125	149	177	209
0.6	141	168	200	239	286	342	407	100	120	143	171	204	244	291	75	90	107	128	153	183	218
0.8	145	172	205	246	295	354	422	103	122	146	175	210	252	301	78	92	110	131	158	189	226
1.0	148	176	210	253	304	365	437	105	125	149	179	216	260	312	79	94	112	134	162	195	234
1.2	152	180	215	259	313	376	451	107	127	152	183	221	267	320	80	95	114	137	166	200	240
1.4	155	184	221	266	321	387	464	109	130	155	187	227	274	329	82	98	116	140	170	206	247
1.6	157	189	226	273	329	397	477	111	132	158	192	232	281	337	83	99	119	144	174	211	253
1.8	162	193	231	279	338	407	489	114	135	162	196	238	287	345	86	101	122	147	179	215	259
2.0	165	197	236	286	346	417	500	116	138	165	200	243	294	353	87	104	124	150	182	221	265
2.2	169	201	242	297	353	426	511	118	140	169	204	248	300	361	89	105	127	153	186	225	271
2.4	172	205	247	298	361	435	522	120	143	172	209	253	306	368	90	107	129	157	190	230	276
2.6	175	209	252	304	368	444	533	122	146	175	213	258	312	375	92	110	131	160	194	234	281
2.8	178	213	257	310	375	452	543	124	148	178	217	263	318	382	93	111	134	163	197	239	287
3.0	181	217	261	316	382	460	552	126	151	182	221	268	324	389	95	113	137	166	201	243	292

Chlorine Concentration (mg/L)	Temperature = 15°C							Temperature = 20°C							Temperature = 25°C						
	pH							pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	49	59	70	83	99	118	140	36	44	52	62	74	89	105	24	29	35	42	50	59	70
0.6	50	60	72	86	102	122	146	38	45	54	64	77	92	109	25	30	36	43	51	61	73
0.8	52	61	73	88	105	126	151	39	46	55	66	79	95	113	26	31	37	44	53	63	75
1.0	53	63	75	90	108	130	156	39	47	56	67	81	98	117	26	31	37	45	54	65	78
1.2	54	64	76	92	111	134	160	40	48	57	69	83	100	120	27	32	38	46	55	67	80
1.4	55	65	78	94	114	137	165	41	49	58	70	85	103	123	27	33	39	47	57	69	82
1.6	56	66	79	96	116	141	169	42	50	59	72	87	105	126	28	33	40	48	58	70	84
1.8	57	68	81	98	119	144	173	43	51	61	74	89	108	129	29	34	41	49	60	72	86
2.0	58	69	83	100	122	147	177	44	52	62	75	91	110	132	29	35	41	50	61	74	89
2.2	59	70	85	102	124	150	181	44	53	63	77	93	113	135	30	35	42	51	62	75	91
2.4	60	72	86	105	127	153	184	45	54	65	78	95	115	138	30	36	43	52	63	77	92
2.6	61	73	88	107	129	156	188	46	55	66	80	97	117	141	31	37	44	53	65	78	94
2.8	62	74	89	109	132	159	191	47	56	67	81	99	119	143	31	37	45	54	66	80	96
3.0	63	76	91	111	134	162	195	47	57	68	83	101	122	146	32	38	46	55	67	81	97

Appendix C – Monthly Average CT Data and Calculations for Cary/Apex Water Treatment Plant (all CT values in mg-min/L)

DATE	TEMP (°C)	pH	Chlorine (Minimum)	T_{10} (Minutes)	CT_{Actual}	$CT_{Required}$ (Tables)	$CT_{Required}$ (Equation)	$CT_{Actual}/CT_{Required}$ (Tables)
Jan-02	9.21	6.88	3.27	120	219.15	24.82	29.78	8.83
Feb-02	11.45	6.96	2.90	120	194.20	20.13	25.02	9.65
Mar-02	13.38	6.88	2.26	120	151.10	17.09	21.53	8.84
Apr-02	19.29	6.90	2.99	120	200.49	11.52	13.87	17.40
May-02	22.98	6.92	2.84	120	341.23	9.73	10.83	35.06
Jun-02	27.31	6.94	2.87	120	344.00	9.66	8.14	35.60
Jul-02	28.98	6.93	2.83	120	339.48	9.50	7.30	35.74
Aug-02	29.56	6.92	3.05	120	366.23	9.63	7.22	38.03
Sep-02	26.36	7.47	3.55	120	426.40	11.37	9.48	37.51
Oct-02	23.06	7.47	3.72	120	446.32	11.76	11.07	37.97
Nov-02	16.32	7.48	4.03	120	483.20	18.37	17.63	26.30
Dec-02	10.33	7.39	3.42	120	409.94	28.74	27.36	14.26
Jan-03	8.40	7.30	3.19	120	382.84	33.90	31.63	11.29
Feb-03	8.23	7.28	3.71	120	444.86	34.24	34.05	12.99
Mar-03	12.34	7.22	2.32	120	277.94	17.03	21.86	16.32
Apr-03	15.32	7.76	3.32	120	398.80	21.58	17.52	18.48
May-03	21.00	8.07	3.56	120	427.74	16.65	11.81	25.69
Jun-03	24.43	8.24	3.67	120	440.00	14.98	9.64	29.37
Jul-03	28.13	8.37	3.52	120	422.32	14.72	7.27	28.69
Aug-03	28.69	8.15	3.19	120	382.45	14.49	6.80	26.39
Sep-03	26.60	8.26	3.10	120	372.40	15.27	8.17	24.39
Oct-03	21.59	8.36	3.20	120	384.39	11.98	11.72	32.08
Nov-03	18.16	8.60	3.24	120	389.20	37.70	14.73	10.32
Dec-03	11.57	8.20	3.18	120	389.81	30.07	24.69	12.96
Jan-04	9.17	8.17	3.15	120	377.81	37.48	30.95	10.08
Feb-04	8.76	7.72	2.94	120	352.97	36.66	31.69	9.63
Mar-04	13.33	7.78	2.56	120	307.74	25.20	22.16	12.21
Apr-04	17.75	8.20	3.09	120	371.20	29.68	16.21	12.51
May-04	24.08	8.16	2.99	120	358.45	14.78	10.00	24.25
Jun-04	27.34	8.20	2.92	120	350.40	15.95	8.15	21.97
Jul-04	28.95	8.21	2.85	120	342.19	67.55	7.03	5.07
Aug-04	27.80	8.09	2.95	120	354.19	69.27	7.55	5.11
Sep-04	26.40	8.03	2.88	120	345.60	65.84	8.09	5.25
Oct-04	22.77	8.10	3.00	120	359.61	14.34	10.53	25.08
Nov-04	18.01	8.07	3.06	120	374.80	90.56	13.92	4.14
Dec-04	13.02	7.80	3.21	120	385.55	13.08	21.15	29.47
Jan-05	10.20	7.97	3.01	120	360.77	152.24	26.88	2.37
Feb-05	9.43	7.88	2.73	120	327.86	32.41	28.65	10.12
Mar-05	11.67	7.77	2.30	120	276.39	24.84	23.75	11.13
Apr-05	17.09	8.00	2.85	120	341.60	27.06	15.47	12.63
May-05	21.22	7.97	2.93	120	351.87	16.83	11.68	20.90
Jun-05	26.00	8.19	2.93	120	352.00	16.17	8.59	21.77
Jul-05	29.87	8.21	2.84	120	340.26	13.30	6.49	25.58
Aug-05	30.23	8.02	2.68	120	321.68	14.67	6.26	21.92

DATE	TEMP (°C)	pH	Chlorine (Minimum)	T_{10} (Minutes)	CT_{Actual}	$CT_{Required}$ (Tables)	$CT_{Required}$ (Equation)	$CT_{Actual}/CT_{Required}$ (Tables)
Sep-05	28.04	7.95	2.88	120	345.20	13.71	7.35	25.18
Oct-05	23.86	7.88	2.88	120	345.29	13.83	9.64	24.97
Nov-05	17.44	7.75	2.97	120	356.40	19.98	15.28	17.84
Dec-05	11.64	7.62	3.09	120	370.84	24.97	23.91	14.85
Jan-06	10.64	7.64	3.25	120	389.81	25.19	25.93	15.48
Feb-06	10.60	7.65	3.19	120	383.14	25.44	26.46	15.06
Mar-06	13.41	7.63	2.36	120	282.97	24.20	20.70	11.70
Apr-06	18.80	7.90	3.06	120	366.80	17.14	14.31	21.41
May-06	21.77	7.62	3.12	120	373.94	12.20	11.93	30.65
Jun-06	26.31	7.79	2.91	120	349.20	13.55	8.60	25.76
Jul-06	29.68	7.87	2.89	120	347.23	14.38	6.67	24.14
Aug-06	30.05	7.77	3.04	120	364.65	14.00	6.50	26.05
Sep-06	27.33	7.59	3.09	120	371.20	12.67	7.84	29.31

Appendix D – Monthly Chemical Usage and Cost Data for Cary/Apex Water Treatment Plant

	Monthly Chemical Usage						Chemical Cost					
DATE	Treated Water (MGD)	Alum (lbs)	Caustic (lbs)	Carbon (lbs)	Chlorine (lbs)	Ozone (lbs)	Alum	Caustic	Carbon	Chlorine	Ozone	Total Cost Cost
Jan-03	11.93	119,271	18,544	52,029	22,209	15,586	$7,891.77	$2,206.72	$26,534.64	$1,332.57	$11,003.40	$57,113.08
Feb-03	11.75	101,437	15,910	45,901	24,202	17,447	$6,541.66	$1,893.34	$23,409.66	$1,452.09	$12,317.38	$52,377.83
Mar-03	13.83	141,122	40,137	65,145	25,161	23,323	$9,100.96	$4,776.26	$33,224.08	$1,509.65	$16,400.01	$73,465.58
Apr-03	13.80	170,764	48,875	59,547	29,476	24,560	$14,344.21	$9,061.36	$25,009.62	$1,768.56	$17,339.54	$79,094.96
May-03	15.03	224,593	76,256	53,458	36,250	23,750	$18,865.84	$14,137.87	$22,452.52	$2,175.00	$16,767.54	$87,527.95
Jun-03	14.43	204,196	60,096	28,058	36,730	24,602	$17,152.45	$11,141.84	$11,784.56	$2,203.78	$17,369.13	$72,062.58
Jul-03	15.60	217,271	52,958	30,101	40,754	20,732	$18,250.80	$9,818.41	$12,642.42	$2,445.27	$14,636.78	$70,863.42
Aug-03	14.98	219,137	55,278	26,387	36,573	19,370	$18,407.51	$10,248.62	$11,082.56	$2,194.37	$13,674.96	$70,472.20
Sep-03	14.76	204,370	38,745	23,941	32,093	21,319	$17,167.11	$7,183.37	$10,055.17	$1,925.57	$15,051.23	$65,711.33
Oct-03	14.93	222,667	54,405	28,873	32,841	24,007	$18,704.00	$7,950.83	$12,126.67	$1,970.45	$16,949.14	$72,844.93
Nov-03	13.19	194,302	39,002	25,491	27,999	19,057	$16,321.35	$5,690.35	$10,706.33	$1,679.93	$13,454.24	$60,304.98
Dec-03	12.00	178,214	26,437	19,355	29,743	17,048	$14,613.59	$3,657.15	$8,129.25	$1,784.60	$12,035.79	$52,534.31
Jan-04	12.09	183,114	28,969	25,873	26,435	13,672	$15,015.32	$4,226.60	$10,866.81	$1,586.11	$9,652.68	$53,056.43
Feb-04	11.89	171,226	20,630	27,948	24,462	16,546	$14,040.53	$3,009.98	$11,738.18	$1,467.72	$11,681.45	$52,467.64
Mar-04	13.31	207,054	30,572	33,283	26,202	23,827	$16,978.39	$4,460.43	$13,978.75	$1,572.09	$16,821.58	$65,960.25
Apr-04	14.88	168,162	38,182	42,293	36,954	23,048	$13,789.32	$5,570.81	$17,763.16	$2,217.26	$16,272.02	$69,817.57
May-04	16.18	202,015	47,930	47,347	39,182	24,172	$16,565.22	$6,993.06	$19,885.63	$2,350.91	$17,065.43	$76,862.99
Jun-04	18.14	217,841	40,618	29,418	39,921	30,092	$17,863.00	$5,524.00	$12,354.81	$2,115.81	$21,245.10	$74,814.45
Jul-04	17.15	223,203	48,290	28,223	48,306	25,961	$18,302.66	$6,567.50	$11,853.48	$2,401.14	$18,328.61	$74,151.92
Aug-04	15.35	205,312	65,433	28,655	44,166	25,367	$16,835.60	$8,898.84	$12,035.06	$2,340.81	$17,909.45	$72,862.36
Sep-04	14.56	182,766	68,036	22,107	35,780	23,586	$14,986.84	$9,252.96	$9,284.99	$1,896.36	$16,651.64	$65,621.44
Oct-04	15.71	186,546	83,734	23,109	37,830	28,488	$12,030.38	$9,964.36	$11,785.67	$2,269.82	$20,112.79	$72,024.25
Nov-04	13.94	167,713	67,681	26,666	30,270	22,387	$13,752.45	$9,204.64	$11,199.70	$1,604.31	$15,805.53	$64,728.56
Dec-04	12.51	153,044	48,844	24,722	27,058	19,695	$12,549.60	$6,642.82	$10,383.04	$1,434.08	$13,904.98	$56,951.28
Jan-05	12.69	155,020	49,504	19,957	25,655	20,052	$9,997.22	$5,890.98	$10,177.93	$1,539.33	$14,156.97	$52,022.13
Feb-05	12.44	139,644	45,822	19,134	22,992	18,780	$11,450.81	$6,231.76	$8,036.38	$1,218.57	$13,258.42	$48,898.82
Mar-05	13.41	167,017	60,098	23,559	22,814	23,251	$13,695.40	$8,173.35	$9,894.66	$1,209.15	$16,415.40	$58,533.74
Apr-05	14.15	170,317	64,089	44,673	29,037	26,017	$13,965.96	$8,716.12	$18,762.65	$1,538.98	$18,367.65	$71,851.60
May-05	15.95	196,690	70,093	48,578	33,323	31,523	$16,128.61	$9,532.58	$20,402.83	$1,766.13	$22,255.55	$82,361.75
Jun-05	17.51	212,580	75,348	41,276	34,837	32,109	$17,431.54	$10,247.40	$17,336.05	$1,846.35	$22,668.78	$83,011.83
Jul-05	18.22	234,418	82,283	30,510	37,430	37,139	$25,082.70	$16,925.14	$13,729.38	$3,181.51	$26,220.08	$103,552.93
Aug-05	17.83	228,085	78,879	31,381	39,482	31,924	$24,403.00	$18,142.24	$14,121.52	$3,356.01	$22,538.39	$98,558.15
Sep-05	19.77	242,082	69,358	33,002	42,967	34,508	$15,609.93	$10,633.65	$16,831.03	$2,577.41	$24,362.70	$89,188.10
Oct-05	17.11	211,795	74,885	27,465	35,352	28,616	$22,662.10	$17,223.66	$12,359.17	$3,004.92	$20,203.10	$90,470.12
Nov-05	15.26	187,654	64,340	17,121	29,205	24,217	$20,078.92	$14,798.31	$7,704.23	$2,482.45	$17,097.32	$75,098.30
Dec-05	12.68	154,878	50,122	13,035	26,776	20,735	$16,571.95	$11,527.98	$5,865.77	$2,275.97	$14,638.65	$61,782.39
Jan-06	12.67	153,306	51,270	16,902	27,604	18,578	$16,403.77	$11,792.04	$7,606.11	$2,346.33	$13,115.92	$61,281.00
Feb-06	12.28	138,145	45,196	16,766	24,664	15,417	$14,781.54	$10,395.17	$7,544.84	$2,096.41	$10,884.59	$54,804.48
Mar-06	13.85	165,758	55,733	20,936	22,079	19,348	$17,736.06	$12,818.61	$9,421.31	$1,876.75	$13,659.48	$65,050.29
Apr-06	15.10	186,719	58,494	23,291	31,384	24,149	$19,978.90	$13,453.68	$10,481.07	$2,667.61	$17,049.00	$74,874.11
May-06	15.87	201,338	59,863	20,663	34,837	25,212	$21,543.21	$13,768.41	$9,298.56	$2,961.13	$17,799.73	$77,702.75
Jun-06	16.56	225,031	64,994	15,716	33,928	23,239	$24,076.30	$14,948.55	$7,072.22	$2,883.90	$16,406.65	$77,652.71
Jul-06	18.43	261,187	78,654	17,353	43,132	28,322	$16,843.95	$9,359.79	$8,850.18	$2,587.93	$19,995.00	$74,531.88
Aug-06	20.38	283,450	92,678	20,781	49,683	31,890	$18,279.67	$11,028.73	$10,596.58	$2,980.95	$22,514.38	$84,473.14
Sep-06	17.34	237,587	69,818	17,616	38,002	27,318	$15,321.98	$8,308.30	$8,984.26	$2,280.11	$19,284.94	$69,758.13

Appendix E – Monthly Average CT Data and Calculations for Raleigh Water Treatment Plant (all CT values in mg-min/L)

	RALEIGH						
DATE	TEMP (°C)	pH	Chlorine (Minimum)	T_{10} (Minutes)	CT_{Actual}	$CT_{Required}$ (Equation)	$CT_{Actual}/CT_{Required}$ (Equation)
Jan-02	12.17	8.86	3.50	45	56.55	17.77	3.18
Feb-02	14.60	8.92	3.36	45	39.85	8.93	4.46
Mar-02	13.65	7.75	2.55	45	29.76	6.42	4.64
Apr-02	19.89	8.84	3.31	45	22.47	2.90	7.75
May-02	23.05	8.87	3.45	45	18.87	1.92	9.85
Jun-02	26.06	8.47	3.29	45	13.63	1.08	12.64
Jul-02	28.21	7.94	3.25	45	11.14	0.72	15.38
Aug-02	28.87	7.76	3.33	45	10.90	0.64	17.10
Sep-02	26.92	8.57	3.51	45	14.29	1.05	13.65
Oct-02	23.86	8.85	3.90	45	17.80	1.57	11.35
Nov-02	19.52	9.02	3.62	45	26.98	3.86	6.99
Dec-02	16.58	9.04	3.54	45	36.45	6.97	5.23
Jan-03	13.46	9.12	3.73	45	48.35	12.18	3.97
Feb-03	11.92	9.17	3.74	45	48.04	12.41	3.87
Mar-03	14.19	7.77	2.05	45	26.33	5.96	4.42
Apr-03	16.90	8.82	3.03	45	19.67	2.47	7.97
May-03	20.60	8.72	3.12	45	15.34	1.47	10.42
Jun-03	24.61	8.59	3.18	45	11.21	0.78	14.44
Jul-03	28.05	8.58	3.31	45	10.26	0.64	16.14
Aug-03	28.69	8.25	3.22	45	10.85	0.71	15.22
Sep-03	26.45	8.46	3.61	45	10.94	0.67	16.35
Oct-03	22.29	8.39	3.68	45	15.57	1.29	12.07
Nov-03	19.15	8.49	3.81	45	17.36	1.57	11.09
Dec-03	14.05	8.43	3.82	45	191.53	29.00	6.61
Jan-04	12.02	8.39	3.85	45	191.53	48.77	3.93
Feb-04	10.38	8.45	3.75	45	191.83	35.68	5.38
Mar-04	13.51	7.56	2.33	45	112.51	23.97	4.69
Apr-04	17.01	8.44	3.12	45	156.89	18.00	8.72
May-04	23.63	8.36	3.22	45	161.29	11.68	13.81
Jun-04	26.32	8.40	3.63	45	160.74	10.60	15.16
Jul-04	29.45	8.35	3.71	45	161.22	10.61	15.19
Aug-04	27.45	8.30	3.73	45	161.22	10.61	15.19
Sep-04	25.98	8.23	3.69	45	181.99	11.00	16.54
Oct-04	22.91	8.25	4.07	45	196.75	13.44	14.63
Nov-04	18.06	8.30	4.02	45	196.31	18.41	10.66
Dec-04	11.25	8.33	3.91	45	195.79	21.21	9.23
Jan-05	10.12	8.33	3.87	45	195.79	25.71	7.62
Feb-05	8.56	8.26	3.88	45	195.90	29.28	6.69
Mar-05	11.04	8.17	3.85	45	195.79	27.91	7.02
Apr-05	16.72	8.86	3.83	45	187.02	23.00	8.13
May-05	19.82	8.84	3.76	45	188.09	21.97	8.56
Jun-05	24.38	8.64	3.75	45	179.18	12.36	14.50
Jul-05	28.45	8.53	3.71	45	177.31	8.42	21.05

	RALEIGH						
DATE	TEMP (°C)	pH	Chlorine (Minimum)	T_{10} (Minutes)	CT_{Actual}	$CT_{Required}$ (Equation)	$CT_{Actual}/CT_{Required}$ (Equation)
Aug-05	28.71	8.44	3.52	45	176.47	7.40	23.84
Sep-05	27.68	7.48	3.70	45	179.84	8.95	20.09
Oct-05	22.49	8.04	3.67	45	176.41	12.15	14.52
Nov-05	16.16	8.12	3.53	45	174.74	16.61	10.52
Dec-05	11.93	8.18	3.57	45	176.68	59.47	2.97
Jan-06	10.26	8.27	3.60	45	176.10	28.33	6.22
Feb-06	11.38	8.30	3.57	45	176.37	31.20	5.65
Mar-06	13.97	7.52	3.48	45	163.74	27.20	6.02
Apr-06	16.86	8.32	3.36	45	164.75	18.06	9.12
May-06	20.81	8.45	3.39	45	164.71	12.82	12.85
Jun-06	24.25	8.36	3.45	45	165.75	10.73	15.44
Jul-06	26.86	8.52	3.63	45	173.70	9.61	18.07
Aug-06	28.05	8.25	3.41	45	172.32	9.28	18.57
Sep-06	25.09	8.19	3.41	45	164.99	11.06	14.92
Oct-06	21.92	8.40	3.62	45	170.20	15.63	10.89
Nov-06	16.60	8.75	3.53	45	170.07	22.16	7.67
Dec-06	13.69	8.81	3.35	45	168.07	25.56	6.57

Appendix F – Monthly Chemical Usage and Cost Data for Raleigh Water Treatment Plant

	Monthly Chemical Usage						Chemical Cost					
DATE	Treated Water (MGD)	Ferric Sulfate (lbs)	Caustic (lbs)	Chlorine (lbs)	Carbon (lbs)	Ozone (lbs)	Ferric Sulfate	Caustic	Chlorine	Carbon	Ozone	Total Cost Cost
Jan-02	45.90	25421	8297	2510	0	1070	$ 4,448.64	$1,908.24	$ 213.32	$ -	$ 5,459.27	$ 12,670.25
Feb-02	44.43	19610	7095	2219	0	945	$ 3,431.67	$1,631.74	$ 188.60	$ -	$ 4,844.73	$ 10,731.70
Mar-02	47.99	20525	6737	1745	0	1006	$ 3,591.85	$1,549.52	$ 148.32	$ -	$ 5,160.55	$ 11,052.84
Apr-02	54.68	22743	7959	2615	0	1642	$ 3,980.10	$1,830.46	$ 222.27	$ -	$ 7,654.17	$ 14,283.73
May-02	63.32	27578	9350	2739	0	2263	$ 4,826.23	$2,150.58	$ 232.81	$ -	$ 9,557.65	$ 17,398.25
Jun-02	70.75	36039	13613	3632	0	1754	$ 6,306.87	$3,131.02	$ 308.72	$ -	$ 7,976.39	$ 18,992.03
Jul-02	55.54	33447	8065	3184	0	1441	$ 5,853.19	$1,854.92	$ 270.60	$ -	$ 6,840.20	$ 16,691.37
Aug-02	59.63	37688	9134	3602	0	1944	$ 6,595.37	$2,100.92	$ 306.14	$ -	$ 6,743.73	$ 18,650.84
Sep-02	52.89	33271	10243	3049	121	1889	$ 5,822.50	$2,355.92	$ 259.15	$ 54.56	$ 7,730.33	$ 17,200.78
Oct-02	51.27	31698	11827	2505	0	1285	$ 5,547.14	$2,720.32	$ 212.94	$ -	$ 6,648.38	$ 15,993.88
Nov-02	44.92	24781	10861	2024	0	38	$ 4,336.69	$2,498.07	$ 172.04	$ -	$ 152.92	$ 8,615.17
Dec-02	43.59	31139	11371	1647	0	0	$ 5,449.30	$2,615.40	$ 140.03	$ -	$ -	$ 10,162.91
Jan-03	46.37	34645	14020	1813	623	0	$ 6,062.80	$3,224.50	$ 154.14	$ 280.19	$ -	$ 11,793.24
Feb-03	44.94	46607	19201	1682	746	0	$ 8,156.19	$4,416.31	$ 142.94	$ 335.52	$ -	$ 15,090.29
Mar-03	45.84	35263	15119	1226	0	1209	$ 6,171.04	$3,477.41	$ 104.19	$ -	$ 4,160.25	$ 15,249.03
Apr-03	46.19	28575	13584	1674	186	221	$ 5,000.61	$3,124.21	$ 142.25	$ 83.52	$ 25,182.92	$ 35,137.24
May-03	51.27	36049	18475	2190	262	1235	$ 6,308.63	$4,249.28	$ 186.16	$ 117.99	$ 8,376.83	$ 20,509.53
Jun-03	52.39	34864	15293	1902	490	1324	$ 6,101.13	$3,517.40	$ 161.69	$ 220.71	$ 6,031.25	$ 17,850.47
Jul-03	57.69	34295	14391	1774	0	1451	$ 6,001.69	$3,309.89	$ 150.79	$ -	$ 5,413.04	$ 17,446.30
Aug-03	55.71	24249	9965	1794	0	1617	$ 4,243.52	$2,291.96	$ 152.51	$ -	$ 4,828.35	$ 14,183.94
Sep-03	54.73	21926	8983	1747	0	1389	$ 3,837.07	$2,066.11	$ 148.49	$ -	$ 7,078.96	$ 14,146.27
Oct-03	55.41	23113	9306	1741	0	1402	$ 4,044.75	$2,140.30	$ 147.96	$ -	$ 5,379.38	$ 12,556.35
Nov-03	50.91	18700	7461	1780	0	1269	$ 3,272.48	$1,716.02	$ 151.28	$ -	$ 4,344.15	$ 10,270.60
Dec-03	46.84	16617	6378	1714	0	814	$ 2,908.05	$1,466.87	$ 145.68	$ -	$ 4,019.64	$ 9,259.32
Jan-04	45.77	17628	6146	1792	0	234	$ 3,084.86	$1,413.55	$ 152.30	$ -	$ 1,154.52	$ 6,988.67
Feb-04	45.87	17377	6050	1667	0	527	$ 3,041.00	$1,391.43	$ 141.70	$ -	$ 2,599.80	$ 8,392.79
Mar-04	47.82	16987	6699	1156	0	692	$ 2,972.70	$1,540.67	$ 98.23	$ -	$ 3,416.87	$ 9,175.20
Apr-04	52.20	18877	7958	1743	0	1608	$ 3,303.56	$1,830.34	$ 148.18	$ -	$ 6,923.93	$ 15,196.21
May-04	63.00	23795	9523	2369	0	1613	$ 4,164.11	$2,190.33	$ 201.39	$ -	$ 7,933.49	$ 15,763.66
Jun-04	59.69	23292	9317	2234	0	676	$ 4,076.16	$2,142.83	$ 189.87	$ -	$ 3,338.08	$ 10,780.19
Jul-04	58.92	23699	8831	2339	0	639	$ 4,147.39	$2,031.03	$ 198.65	$ -	$ 3,153.37	$ 10,465.41
Aug-04	55.22	22637	8173	2228	0	788	$ 3,961.40	$1,879.84	$ 189.41	$ -	$ 3,891.82	$ 10,772.62
Sep-04	54.12	23268	8717	2400	0	1009	$ 4,071.86	$2,004.83	$ 204.00	$ -	$ 4,976.76	$ 12,120.83
Oct-04	54.67	22881	9166	2161	0	507	$ 4,004.16	$2,108.29	$ 183.66	$ -	$ 2,501.96	$ 9,999.17
Nov-04	49.45	19565	8039	1752	0	215	$ 3,423.93	$1,848.88	$ 148.88	$ -	$ 1,060.53	$ 7,977.80
Dec-04	46.05	18412	6684	1721	0	0	$ 3,222.08	$1,537.31	$ 146.30	$ -	$ -	$ 7,116.48
Jan-05	46.38	19381	6656	1774	0	0	$ 3,391.65	$1,530.81	$ 150.75	$ -	$ -	$ 7,161.21
Feb-05	46.27	19630	7235	2286	0	0	$ 3,435.29	$1,664.07	$ 194.31	$ -	$ -	$ 7,728.52
Mar-05	45.97	18543	8175	2751	1203	0	$ 3,244.95	$1,880.23	$ 233.81	$ 541.54	$ -	$ 8,458.37
Apr-05	50.56	19416	8907	3310	529	471	$ 3,397.60	$2,048.50	$ 281.33	$ 237.87	$ 2,324.02	$ 10,649.39
May-05	55.96	22311	10640	3807	1384	1009	$ 3,904.49	$2,447.31	$ 323.61	$ 622.84	$ 4,977.41	$ 15,231.30
Jun-05	61.71	24174	11760	4075	32	1155	$ 4,230.37	$2,704.71	$ 346.37	$ 14.42	$ 5,119.82	$ 15,382.36
Jul-05	63.95	25097	10890	4267	0	0	$ 4,391.95	$2,504.77	$ 362.66	$ -	$ -	$ 10,804.30
Aug-05	62.22	24490	10158	4199	0	0	$ 4,285.77	$2,336.40	$ 356.89	$ -	$ -	$ 10,122.29

	Monthly Chemical Usage						Chemical Cost					
DATE	Treated Water (MGD)	Ferric Sulfate (lbs)	Caustic (lbs)	Chlorine (lbs)	Carbon (lbs)	Ozone (lbs)	Ferric Sulfate	Caustic	Chlorine	Carbon	Ozone	Total Co Cost
Sep-05	67.37	26633	10832	8389	0	0	$ 4,660.75	$2,491.34	$ 713.07	$ -	$ -	$ 10,813.43
Oct-05	56.39	22614	9496	3577	0	0	$ 3,957.44	$2,184.15	$ 304.05	$ -	$ -	$ 9,166.88
Nov-05	48.73	22694	9048	3394	0	0	$ 3,971.43	$2,081.12	$ 288.52	$ -	$ -	$ 8,927.80
Dec-05	44.84	20732	8299	3859	0	0	$ 3,628.11	$1,908.87	$ 328.01	$ -	$ -	$ 7,801.55
Jan-06	44.99	18949	7377	3905	0	0	$ 3,316.15	$1,696.71	$ 331.95	$ -	$ -	$ 6,824.95
Feb-06	46.51	17826	6848	3961	0	0	$ 3,119.54	$1,574.97	$ 336.64	$ -	$ -	$ 6,062.81
Mar-06	47.84	17516	6880	2792	0	0	$ 3,065.29	$1,582.43	$ 237.35	$ -	$ -	$ 5,820.03
Apr-06	50.29	19365	8491	3127	21	0	$ 3,388.94	$1,953.04	$ 265.76	$ 9.39	$ -	$ 7,602.90
May-06	53.48	20973	8847	3290	136	0	$ 3,670.22	$2,034.74	$ 279.67	$ 61.20	$ -	$ 8,621.05
Jun-06	54.82	20912	9314	3352	0	0	$ 3,659.53	$2,142.32	$ 284.91	$ -	$ -	$ 9,227.47
Jul-06	60.80	26148	11932	4509	33	764	$ 4,575.90	$2,744.37	$ 383.23	$ 14.69	$ 3,780.13	$ 12,425.19
Aug-06	66.06	32522	15078	4981	0	1144	$ 5,691.35	$3,467.95	$ 423.42	$ -	$ 5,648.59	$ 16,237.74
Sep-06	57.20	30463	13656	4560	0	1097	$ 5,330.97	$3,141.30	$ 387.63	$ -	$ 5,413.04	$ 15,204.98
Oct-06	54.50	28323	12175	4617	0	877	$ 4,956.44	$2,800.25	$ 392.46	$ -	$ 4,326.82	$ 13,348.12
Nov-06	48.24	23383	9453	3493	0	354	$ 4,092.07	$2,174.25	$ 296.88	$ -	$ 1,748.16	$ 9,395.84
Dec-06	46.72	34054	13971	2977	0	0	$ 5,959.48	$3,213.37	$ 253.06	$ -	$ -	$ 11,545.35