

Kwame Nkrumah University of Science and Technology

College of Engineering

Department of Civil Engineering

Kumasi – Ghana

RESIDUAL CHLORINE DECAY IN THE KUMASI WATER DISTRIBUTION NETWORK



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Technology



**RESIDUAL CHLORINE DECAY IN THE KUMASI WATER DISTRIBUTION
NETWORK**

By

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Certification

I hereby declare that this thesis is my own work towards the Master of Science (MSc) and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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Dedication

Dedicated to

The Almighty God, my family and friends

Abstract

The potential for microbiological regrowth in a water distribution network is minimized by chlorinating finished water to obtain residual chlorine. However, residual chlorine decays naturally within a water distribution network due to many varied reasons. Currently, there is no empirical data on chlorine decay which can guide the prediction of this chlorine loss and the top up quantity needed to ensure that a minimum residual chlorine concentration of 0.20 mg/L is attained throughout the Kumasi water distribution network. This necessitated field monitoring exercises and an assessment to be conducted so as to determine the bulk, wall and the overall chlorine decay coefficients and also a correlation on residual chlorine loss as a function of pipe materials and various water quality parameters. Based on the data obtained and the existing SynerGEE hydraulic model for the Kumasi network, the probable locations in the network where stepwise chlorination is necessary were predicted. From the modified Rossman's equation, the first order reaction kinetic model was adopted and used for the determination of the chlorine decay coefficients. The global bulk decay coefficient was obtained under laboratory conditions and found to be 0.05/ hour. The overall and wall chlorine decay coefficients were determined in situ on a dedicated pipeline from Barekese Headworks to Adum in the Kumasi Central district which consist mainly of 900 mm steel pipes and cast iron pipes of various diameters. Under the conditions tested and analysed, the overall decay coefficient was found to be 0.38/ hour whilst the wall decay coefficients due to the steel pipes, cast iron pipes and the concrete reservoirs were found to be 0.15, 0.58 and 0.29/ hour respectively. Again, about 66 % of the residual chlorine loss in water supply to the Kumasi network is attributed to wall demand with 34% being due to bulk demand. From the study, the major water quality parameters that contributed to this chlorine loss were Iron, Manganese and Microbes such as *Coliforms*, *E.Coli* and *Salmonella species*.

Under steady state conditions, with a mean of 0.60 mg/L residual chlorine value at the Barekese Headworks, areas in the Kumasi network where stepwise chlorination is necessary together with their respective recommended concentrations are Achiase Booster Station – 1.50 mg/L; Kodie – 1.0 mg/L; Ahinsan – 0.50 mg/L; Pankrono Booster Station – 0.50 mg/L; Buokrom Booster Station – 0.50mg/L and KNUST Booster Station – 0.50 mg/L.

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List of Abbreviations

GUWL – Ghana Urban Water Limited

GWCL – Ghana Water Company Limited

GSA – Ghana Standards Authority

WHO – World Health Organisation

WQA – Water Quality Assurance

GIS – Geographic Information Systems

BWTP – Barekese Water Treatment Plant

KWDN – Kumasi Water Distribution Network

MGD – Million Gallons per Day

AWWA – American Water Works Association

AWWARF – American Water Works Association Research Fellowship

USEPA – United States Environmental Protection Agency

THM's – Trihalomethanes

HAA – Halo acetic acids

DBP's – Disinfection By- products

UNDP – United Nations Development Programme

HDR – Human Development Report

CHAPTER ONE - INTRODUCTION

1.0 BACKGROUND

According to the UNDP (Human Development Report (2006)), every year, some 1.8 million children die as a result of diarrhea and other diseases caused by unclean water and poor sanitation. At the start of the 21st century, unclean water is the world's second biggest killer of children (www.hdr.undp.org).

Access to water for life is a basic human need and a fundamental human right. Yet in our increasingly prosperous world, more than 1 billion people are denied the right to clean water and 2.6 billion people lack access to adequate sanitation (HDR, 2006).

In Ghana, potable water supply to the urban populace is a joint responsibility of the Ghana Urban Water Limited (GUWL) and the Ghana Water Company Limited (GWCL). GWCL acts as the asset owners and are also responsible for planning and development of the water systems. GUWL, as operators of the water systems, is charged with the responsibility of meeting the increasing demand for better service delivery through efficient and effective management of production, transmission and distribution of potable water to the urban populace in Ghana. In order to achieve this objective, the GUWL operates and maintains Eighty three (83) different Water Supply Systems with different treatment processes throughout the country. However, disinfection with chlorine is a common practice in all the treatment plants. Chlorination, which has been in practice since the beginning of the nineteenth century, is the most commonly used method of disinfection in most water treatment facilities because it is cheap, easy to use and effective in killing bacteria in water and can be maintained as a residual.

Residual chlorine is the excess chlorine concentration that remains in water after the breakpoint chlorine demand of the water has been achieved in the chlorination process. Its' presence in detectable quantity at the consumer tap assures water free from bacteriological contamination. It also helps to control biofilms, recontamination of water due to either burst or leakages which may arise in the water transportation process and finally, it addresses other public health concerns like outbreak of water borne diseases which may arise as a result of drinking contaminated water.

To guarantee the integrity of the quality of the treated water in the distribution lines, a residual concentration of chlorine between the range of 0.20mg/L to 0.50mg/L is maintained in the treated water to prevent recontamination by pathogens which can originate in the biofilms formed in the pipes or in negative pressure areas caused by pipe cracks, burst and leakages. The World Health Organisation (WHO, 2004) has a guideline of 0.5mg/L acceptable minimum residual chlorine concentration to be in drinking water whilst the Ghana Standards Authority (GSA) recommends 0.2mg/L in the farthest point of the distribution network to handle bacteriological contamination of water and 0.5mg/L to deal with viral contamination of drinking water (GSA,1997).

However, as the water flows through the pipe distribution network, the residual chlorine decays to the point of complete depletion due to many varied reasons and sometimes these recommended standards are not achieved.

Notable among the varied reasons why residual chlorine depletes in a water distribution network are the Physico-chemical and Bacteriological quality of the water, the flow regime, the nature and age of pipe materials in the network, the length of pipes, water age and the Biofilms in the pipes.

Although the main objectives of water transport and distribution systems are to supply adequate water quantities and to maintain the water quality that was achieved by the treatment process, this is hardly achieved due to the inadequacies of the quantity of water produced and transported together with the velocities of flow and pressure within the network. This makes the chlorine demand in the network to be very high and hence when chlorinated water enters the distribution network, it takes a very short time for the chlorine to become depleted hence compromising the drinking water quality.

1.1 PROBLEM STATEMENT/JUSTIFICATION

Residual chlorine decays naturally within a water distribution system. Currently, there is no empirical data on residual chlorine decay which can guide the prediction of this chlorine loss and the top up quantity needed to ensure a minimum residual chlorine concentration of 0.20mg/L throughout the network. It is possible that some of the administrative districts of the Kumasi water distribution network are having negligible to insignificant residual chlorine values.

It is therefore necessary for this study to be conducted because it will help identify locations in the distribution network where stepwise chlorination is necessary so as to improve water disinfection.

It will also provide useful information that can help with the effective management of the Kumasi water distribution network under the prevailing conditions.

Finally, very useful data can be acquired for future research work, planning and design of water distribution network by the utility provider.

1.2 OBJECTIVE OF STUDY

The overall objective of the study is to determine the chlorine decay coefficients and the effect of various water quality parameters and pipes on residual chlorine.

1.2.1 Specific Objectives

- To assess and measure chlorine residual in the Kumasi water distribution network and to determine the bulk, wall and the overall chlorine decay coefficients.
- To correlate the residual chlorine decay as a function of pipe materials and treated water quality.
- To predict probable positions along the distribution network where stepwise chlorination is necessary based on the data obtained.

1.3 SCOPE OF THE STUDY

Taking into consideration availability of time, cost of equipment and that of the Physico-chemical analysis together with the duration for this work, the research was limited to water supply from the Barekese Water Treatment Plant to Adum. This involved monitoring the flow from the plant through the 900 mm steel pipes to the Suame Reservoir site and subsequently to the study area at Adum in the Kumasi Central District of the Ghana Urban Water Limited. The total length of Steel pipe from the Plant to Suame is 18km whilst that of the cast iron pipes of varying diameters from the Suame Reservoir site to the study area at Adum is about 2.7 km.

The Kumasi Central district was chosen because the district is known to have the oldest pipes in the distribution network which is cast iron. Cast Iron pipe is known from literature to have the

highest reactivity to chlorine compared to other pipe materials. The interaction between the residual chlorine and the cast iron leads to high encrustation levels in the lumen of the pipes making the volume of water that the pipelines carry to reduce and the residual chlorine content in the water to become depleted.



Plate 1.1 A section of cast iron pipe from Adum

1.4 ORGANISATION OF THE REPORT

This thesis consists of five chapters. Chapter one, gives the introduction, provides the problem statement; justification; research objectives; and the scope of study. Chapter Two focuses on review of literature. Chapter Three presents the general background of the study area and the research methodology, explaining how the study was carried out. Then Chapter Four presents and discusses the findings from the study. Finally, Chapter five presents the conclusions and recommendations based on findings from the study.

CHAPTER TWO – LITERATURE REVIEW

2.0 THE CONCEPT OF WATER DISINFECTION

Disinfection is the killing or removal of pathogenic microorganisms. It is employed in health delivery, food processing, milk production, water supplies and wastewater treatment, and many other activities.

In water supplies, disinfection is employed to kill or remove pathogenic microorganisms such as *salmonella typhi* and *vibrio cholera* that would have rendered the water unwholesome thereby affecting public health.

It is worth distinguishing between disinfection and sterilization. Disinfection is selective in its application as not all organisms are destroyed during the process as only the pathogenic microbes are destroyed whereas sterilization involves the destruction of all microorganisms (Tchobanoglous, and Burton, 1991).

In public water supplies, different physical, chemical and biological processes are employed to transform raw water into potable water. The treatment processes employed depend on the quality and nature (surface or ground water) of the raw water source. However, disinfection is common to all the different processes and this is due to the fact that water that is efficiently clarified could contain large numbers of pathogenic microorganisms (Tchobanoglous, and Burton, 1991).

The primary objective of disinfection in water supplies is the killing or removal of pathogenic microorganisms that cause water- borne disease and thereby render the water bacteriologically unwholesome at the treatment point.

Disinfection also protects the treated water against microbial contamination incidental to the distribution network, reservoirs, elevated tanks and other water supply infrastructure. This

ensures that the treated water remains wholesome from the point of treatment to the end user or the consumer's point.

2.1 METHODS AND AGENTS OF WATER DISINFECTION

Several methods and agents of disinfection are available and these include physical, radiation and chemical agents. It is important that the disinfectant should not only be safe to handle but also its concentration in treated water should be measurable.

The physical agents of disinfection include heat from boiling water and light from sunlight. The efficiency of the process depends on the penetration of the rays into water since suspended matter, dissolved organic molecules and water itself, as well as microorganisms all absorb the radiation (Degremont, 1979).

The radiation agents also include electromagnetic, acoustic and particle. Radioisotopes such as cobalt 60 emit gamma rays, which are used to either sterilize or disinfect both water and waste water.

Chemical agents, which are usually in the form of solutions, are also used in disinfection. Among the chemical disinfectants that are used include Chlorine and its derivatives, Ozone, Bromine, Iodine, Alcohols, Phenols and phenolic compounds, Heavy metals and related compounds, Soaps and synthetic detergents, Quaternary ammonium compounds, Hydrogen peroxides, various alkalis and acids and Potassium permanganate (Pelczar and Chan, 1986).

2.2 MODE OF ACTION OF DISINFECTANTS

The mode of action of disinfectants is explained based on four mechanisms, (Pelczar and Chan, 1986).

These include;

2.2.1 Inhibition of enzyme activity

Enzymes in bacteria can be deactivated by the alteration of their chemical arrangement through the action of oxidizing agents such as chlorine.

2.2.2 Alteration of the colloidal nature of the protoplasm

Disinfection agents such as heat, radiation and highly acidic or alkaline agents alter the colloidal nature of the protoplasm of bacteria cell. A lethal effect is produced when heat coagulates the cell protein whereas acids or bases denature proteins.

2.2.3 Alteration of cell permeability

Disinfectants such as phenolic compounds and detergents destroy the selective permeability of the membrane and allow vital nutrients, such as phosphorous and nitrogen to escape. Thus the permeability of the cytoplasmic membrane is altered.

2.2.4 Damage to the cell wall

Some disinfection agents such as penicillin inhibit the synthesis of the bacterial cell wall. This leads to damage or destruction of the cell wall which results in cell lyses and death.

2.3 FACTORS AFFECTING THE ACTION OF DISINFECTANTS

The efficacy of the disinfection process is influenced by several factors. Notable among these factors are (Pelczar and Chan, 1986); contact time, concentration and type of chemical agent, intensity and nature of physical agent, temperature, number of organisms, type of organisms and nature of suspending liquid.

2.4 DISINFECTION WITH CHLORINE

Sim Woodhead carried out the first practical application of chlorination to public water supplies in 1887 (Race, 1918). Chlorine inactivates a microorganism by damaging its cell membrane. Once the cell membrane is weakened, the chlorine can enter the cell and disrupt cell respiration and DNA activity (two processes that are necessary for cell survival).

Some of the reasons that account for the widespread use of chlorine include;

- Availability of chlorine in various forms such as gaseous, liquid and solid form (in the form of powder or granules) and it is also cheap.
- Solubility of chlorine is very high and it is temperature dependent.

Table 2. 1: Solubility of chlorine at different temperatures

Temperature (°C)	0	20	33
Solubility (mg/L)	14600	7000	5000

(Race, 1918)

- In its application, chlorine leaves a residual in solution that handles recontamination hence protects the water in the distribution system.
- Chlorine is very toxic to most microorganisms rendering their metabolic activities ineffective.

The commonly used chlorine compounds in water and waste water disinfection are chlorine gas, calcium hypochlorite, chloride of lime (bleaching powder) and sodium hypochlorite (Cox, 1964).

2.4.1 Chlorine gas (Cl₂)

Chlorine gas has a greenish – yellow colour, a pungent odour and causes irritation when inhaled. It could give rise to serious damage to lungs and other tissues, which may result in death.

Chlorine gas can be compressed under pressure to form liquid chlorine. Liquid chlorine is very corrosive and so it is stored in steel containers. Dry chlorine gas is not corrosive and may be sold and transported in iron cylinders. Chlorine gas is produced as an industrial product and sold in available chlorine in strength.

2.4.2 Calcium hypochlorite [Ca(OCl)₂] (HTH)

Several commercial brands of calcium hypochlorite are available as fine granular material. The content of chlorine is 65 – 70% by weight (Cox, 1964). It is more stable than chloride of lime, so it deteriorates much less on storage, especially in tropical conditions.

2.4.3 Chloride of lime or bleaching powder

Chloride of lime or bleaching powder can be prepared by the action of chlorine gas on lime.



Commercial chloride of lime varies in strength from about 25 – 37% available chlorine by weight (Cox, 1964).

2.4.4 Sodium hypochlorite (NaOCl)

Sodium hypochlorite solution may be prepared by adding chloride of lime and sodium hydroxide.



Solutions containing 3 – 15% available chlorine are commercially available. The solution can be diluted as needed to a strength of 1.0% for a more convenient application with a solution feed equipment (Cox, 1964).

Sodium hypochlorite is also produced by the electrolysis of sodium chloride (brine).

2.5 REACTIONS OF CHLORINE IN WATER

When a chlorine compound is dissolved in water, two types of reactions take place leading to the formation of the hypochlorous acid, HOCl, which is the active disinfecting agent in chlorination.

- Calcium hypochlorite [$\text{Ca}(\text{OCl})_2$];



- Chloride of Lime or Bleaching Powder (CaOCl_2)

The active form of chloride of lime is $\text{CaOCl}_2 \cdot 2\text{H}_2\text{O}$ and this reacts with water according to the reaction (Lamber and Muir, 1965);



- Sodium Hypochlorite (NaOCl)



When chlorine in the form of a gas is added to water, two reactions take place; Hydrolysis and Ionization.

- Hydrolysis



The Equilibrium constant for this reaction is given by

$$K = [\text{HOCl}] [\text{H}^+] [\text{Cl}^-] / [\text{Cl}_2] = 4.5 * 10^{-4} \text{ at } 25^\circ\text{C} \quad (2.7)$$

The magnitude of this coefficient accounts for the high solubility of chlorine in water.

- Ionization



The ionization constant, K_i , for this reaction is given by;

$$K_i = [\text{H}^+] [\text{OCl}^-] / [\text{HOCl}] = 2.9 * 10^{-8} \text{ at } 25^\circ\text{C} \quad (2.9)$$

K_i varies with temperature. The table below shows the variation of K_i with temperature.

Table 2. 2: Variations of K_i with temperature

Temperature $^\circ\text{C}$	0	5	10	15	20	25
$K_i * 10^{-8} \text{ mol/L}$	1.49	1.75	2.03	2.32	2.62	2.90

(Tchobanoglous and Burton, 1991)

The quantity of hypochlorous acid (HOCl) and hypochlorite ion (OCl^-) in water is called the free available chlorine. The relative distribution of these two species is very important because the disinfecting efficiency of HOCl is about 40 to 80 times that of OCl^- .

2.5.1 Purpose and Principles of Chlorination

Chlorination of potable water aims at the destruction of bacteria through germicidal effects of chlorine. Other important uses of chlorination include oxidation of iron, manganese and hydrogen sulphide; destruction of some taste and odour producing compounds; control of algae and slime organisms in treatment plants and as an aid to coagulation (Cox, 1964).

The problem of effective chlorination is ensuring that:

- Uniform application of the disinfectant to all portions of the water being treated.
- Uninterrupted application of chlorine
- Selection of the dose of the chlorine to meet the current needs of the specific water being treated.
- The control of the chlorination process so as to produce safe potable water that is at the same time of attractive character.

2.6 Factors that affect the Disinfection Efficiency of Chlorine

The effectiveness of chlorine as a disinfectant is a function of the contact time, pH, temperature, bacterial population, concentration of disinfectant, initial mixing and the condition of the water.

2.6.1 Contact Time

The effectiveness of chlorine is time – dependent, because chlorine reacts with different constituents of the water. The contact time can be described by the relationships:

$$N_t = N_o e^{-kt} \quad (2.10)$$

By finding the Natural log of both sides of the equation

$$\ln N_t = \ln N_o - kt \quad (2.11)$$

$$t = -\frac{1}{K} \ln \frac{N_t}{N_o} \quad (2.12)$$

$$t = \frac{1}{K} \ln \frac{N_o}{N_t} \quad (2.13)$$

$$t = \frac{2.303}{K} \log \frac{N_o}{N_t} \quad (2.14)$$

Where: N_o = number of organisms initially present at time t_o

N_t = number of organisms present at time t

t = Contact time

The minimum contact time should be 10 – 15 minutes and preferably several hours for effective disinfection to be ensured (Cox, 1964). In view of the importance of contact time, a batch flow reactor should be used for effective disinfection to be achieved (Tchobanoglous and Burton, 1991).

2.6.2 pH

In the absence of ammonia, chlorine reacts in water as follows;



Thus the pH of the medium (water) influences the effectiveness of chlorination. At pH 4, dissociation of HOCl is suppressed hence practically all the available chlorine is present as HOCl, which is more effective as a disinfectant. At pH above 7, the OCl⁻ ions increase until pH 10 when all the available chlorine exists as OCl⁻ (Fair *et al.*, 1947) and the disinfection action of chlorine is lost.

2.6.3 Temperature

The rate of chlorination reactions (that is, both germicidal and absorption of chlorine) is proportional to the temperature of the water. For instance, for a given contact time, it requires four times as much chlorine to obtain the same bactericidal effect at 2°C – 5°C as at 20°C – 25°C (Public Health Bulletin, 1946).

2.6.4 Nature of Microorganisms

Another important variable in the chlorination process is type, number and age of microorganisms. For instance, viable growing bacterial cells are easily killed whilst bacterial spores and viral cells are extremely resistant and hence require higher disinfectant concentration within a given contact time to handle the contamination. Also, the larger the organism population, the higher the concentration of the disinfectant and the longer the contact time required for a given kill. (Fair *et al.*, 1948)

2.6.5 Concentration

It has been observed that the effectiveness of disinfection is related to the concentration of the disinfectant. The empirical relation that governs the effect of concentration is (Fair *et al.*, 1948).

$$C^n t_p = \text{Constant} \quad (2.18)$$

Where C = concentration of disinfectant

$$n = \text{constant}$$

$$t_p = \text{time required to effect a constant percentage kill}$$

A plot of the concentration versus the time required to effect a given percentage kill on log – log paper can be used to evaluate the constants in the equation (2.18). The slope of the line then corresponds to the value of $-1/n$. In general, if n equals 1, the effects of time and dosage are virtually the same, but if n is greater than 1, the contact time is more important than the dosage (Fair *et al.*, 1948).

However, the higher the concentration of the chlorine dosage applied, the higher the residual levels will be in the supply network and the better or longer the chemical will be able to protect the system from contamination. The high levels of chlorine although effective in killing microorganisms make the water smell and also give it a bad taste. This discourages people from drinking it and this is mostly experienced by consumers who live close to the treatment plant or closer to the chlorine boosting points.

2.6.6 Initial Mixing

The importance of initial mixing in the disinfection process cannot be over emphasized. It has been shown that the application of chlorine in a highly turbulent regime (Reynolds Number $> 10^4$) will result in kills two orders of magnitude greater than when chlorine is added separately to a completely – mixed reactor under similar conditions (Tchobanoglous and Burton, 1991).

2.6.7 Quality of the Water

The water to be chlorinated should be reasonably clear and bright. The presence of suspended matter impedes chlorination by absorbing chlorine and also protecting bacteria. Substances such as organic matter, sulphides, ammonia, nitrites, manganese and iron, if present in water, absorb or destroy chlorine and their demands must be satisfied before any chlorine is available for germicidal action.

2.7 Methods of Chlorination

Chlorination can be practiced by different methods. These include Marginal Chlorination, Pre Chlorination, Post Chlorination, Super Chlorination, Free – Residual Chlorination and Breakpoint Chlorination.

2.7.1 Marginal Chlorination

In this method, chlorine is dosed at concentrations that provide a concentration of residual chlorine of 0.1 to 0.2 mg/L after 10minutes contact time, regardless of whether this is free- or combined – residual chlorine. This method is obsolete and is not in use these days.

2.7.2 Prechlorination

This is chlorination prior to filtration. The advantages of prechlorination include;

- i. The prolonged retention time in sedimentation basin allows the maintenance of high concentrations of free residual chlorine long enough to ensure very effective disinfection need for the treatment of heavily polluted water.
- ii. Iron and manganese will be oxidized, colouring matter bleached and coagulation improved.

- iii. Prechlorination also prevents the growth of algae on basin walls. It assists in the removal of algae by coagulation and sedimentation.
- iv. Chlorine in the settled water destroys slime organisms on the filter media and thus prolongs filter runs and facilitates washing.

The demerits of prechlorination are the higher chlorine demand of raw water compared to filtered water, hence higher and more costly doses of chlorine are required than with post chlorination. Also there exist the probability of the formation of trihalomethanes (THM's) which are carcinogenic substances when the organic load of the water is high.

2.7.3 Post Chlorination

This is chlorination after filtration, chlorine being added to the filter effluent. Where prechlorination is practiced, post chlorination provides relatively small doses of chlorine to provide a safety factor and facilitate the maintenance of residual chlorine in distribution systems.

2.8 Chloramine Treatment

The reaction between chlorine and ammonia produces residuals in the form of chloramines. Chloramines are mild disinfectants because they are less active chemically and hence less likely to form chlorinous tastes. The slower disinfecting action of chloramines coupled with the high cost of chemicals and equipment for the simultaneous application of chlorine and ammonia gas or ammonia sulphate make this treatment process unfavourable.

2.9 Free Residual Chlorination and Breakpoint Chlorination

The principle of free Residual Chlorination or break – point chlorination is to add sufficient chlorine to oxidize all the organic matter, iron, manganese and other reduced substances in the

water being treated and also to oxidize ammonia in the raw water and leave behind a remaining residual chlorine that is called free residual chlorine. This residual chlorine is more reactive than the combined chlorine or chloramines.

In breakpoint chlorination, the stepwise phenomena that result when chlorine is added to water containing ammonia, NH_3 , can be explained as follows:

As chlorine is added, readily oxidizable substances such as Fe^{2+} , Mn^{2+} , H_2S and organic matter react with chlorine, that is, hypochlorous acid HOCl and reduces most of it to the chloride ion.

The chlorine continues to react with the ammonia to form chloramines in successive reactions to form dichloramines and monochloramines.



Between this step and the breakpoint, some chloramines will be converted to nitrogen trichloride, NCl_3 as follows:



The remaining chloramines will be oxidized to nitrous oxide N_2O and Nitrogen (N_2) and the chlorine will be reduced to the chloride ion.

With continued addition of chlorine, most of the chloramines will be oxidized at the breakpoint. The possible reactions that account for the formation of these gases (N_2O and N_2) and the disappearance of chloramines are as follows (Tchobanoglous and Burton, 1991).





From the foregoing, the “breakpoint” which is observed in waters containing ammonia, is the point at which there is a sudden reduction in the remaining concentration of residual chlorine as a result of the more active chemical reactions leading to the oxidation of ammonia.

Continued addition of chlorine beyond the breakpoint will result in a directly proportional increase in the available chlorine. The amount of chlorine that must be added to reach a desired level of residual is called the chlorine demand.

An overall reaction that describes the breakpoint phenomenon is



Theoretically, it would be expected that the three moles of hydrochloric acid, HCl, formed would cause a significant drop in the pH. In practice, the pH drop is slight because the HCl produced reacts with the alkalinity of the water.

The term “Superchlorination” is used to signify heavier than usual chlorine doses.

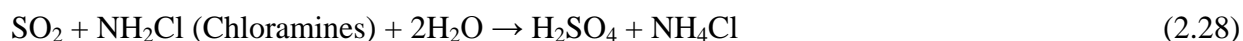
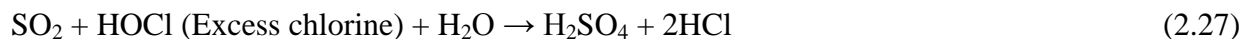
- **Dechlorination**

An excess of chlorine in water, beyond the breakpoint, could result in high levels of residual chlorine that may affect the physiological functions of many systems including the systems of higher organisms such as man. There is therefore the need to remove excess chlorine, through sulphonation or application of activated carbon.

- **Sulphonation**

Dechlorination can be achieved when sulphur dioxide (SO₂) is passed through the water to remove free chlorine, chloramines and nitrogen trichloride (USEPA, 1986).

Reactions involved include



- **Activated Carbon**

Dechlorination can also be achieved by the use of Activated Carbon (USEPA, 1986).

The following reactions show the interaction of activated carbon with excess chlorine in water.



2.10 Effect of Chlorine on Organic Compounds in Water

Because chlorine is such a strong oxidizer, it reacts with a wide range of chemicals. Some of these initial reactions involve organic materials which when reacting with chlorine may form compounds that are potentially carcinogenic. These compounds are generally classified as Disinfection By – Products (DBP). State and federal regulations limit the levels to which they can exist in drinking water. The regulations focus on trihalomethanes (THM) and haloacetic acids (HAAS) as primary indicators of this occurrence. The specific chemicals forming these groups are:

- Total THM: chloroform, bromodichloromethane, dibromochloromethane and bromoform
- Haloacetic acids – 5: monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid and dibromoacetic acid.

The reason why DBP's have become a topic of concern is that some toxicological and epidemiologic studies have identified a number of compounds to be carcinogenic to animals and humans in epidemiological meta - analyses.

Standards for THMs in drinking water vary between 50 and 300ppb worldwide with the WHO guideline value for chloroform (the most common THM) being 300ppb. These concentrations are not commonly found in drinking water. The benefit of reduced infectious disease through the appropriate chlorination of drinking water is generally considered to outweigh the risk of cancer caused by the trihalomethanes. The trihalomethane of most concern is chloroform, also called trichloromethane. It was once used as an anaesthetic during surgery, but is now used in the process of making other chemicals. About 900 ppm of chloroform can cause dizziness, fatigue, and headaches. Chronic exposure may cause damage to the liver and kidneys (Clark, 1998).

Chlorine also reacts with phenols to produce monochlorophenols, dichlorophenols, or trichlorophenols, which cause taste and odour problem even at low levels. At higher levels, chlorophenols are toxic and affect the respiration and energy storage process. Chlorophenols are mainly man-made compounds, but can be found naturally in animal wastes and decomposing organic material. Trihalomethanes are associated with several types of cancerous diseases and are to be considered carcinogenic. Other harmful disinfection by-products are: trichloroacetic acid, dichloroacetic acid, some haloacetonitriles, and chlorophenols (Clark, 1998).

Trichloroacetic acid is produced commercially for use as a herbicide and is also produced in drinking water. This chemical is not classified as a carcinogen for humans, and there is limited

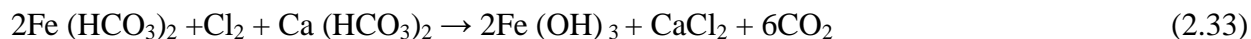
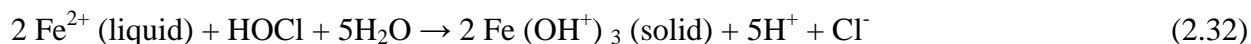
information for animals. Dichloroacetic acid is an irritant, corrosive, and destructive against mucous membranes. This is also not currently classified as a human carcinogen. Haloacetonitriles were used as pesticides in the past, but are no longer manufactured. They are produced as a result of a reaction between chlorine, natural organic matter, and bromide. Chlorophenols cause taste and odour problems. They are toxic, and when present in higher concentrations, affect the respiration and energy storage process in the body.

2.11 Effect of Free Chlorine on Iron and Manganese

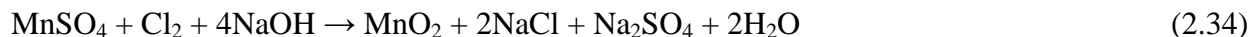
Chlorine can react with a number of different substances. In raw water, there may be a number of different impurities that react with the added chlorine, resulting in an increase in the chlorine demand. As a result, more chlorine will need to be added for the same level of inactivation. Some major impurities that may exist in water include: dissolved iron, hydrogen sulphide, bromine, ammonia, nitrogen dioxide, and organic material. In some cases, the result of chlorine reacting with impurities will increase the quality of the water (by eliminating the undesired elements), while in other cases, the chlorine-impurity reactions will create undesired side products that are harmful to human health. Chlorine will first react with inorganic impurities (dissolved iron, bromine, ammonia, etc.) before reacting with the organic compounds (dissolved organic material, bacteria, viruses, etc).

Iron, which will give water an undesirable metallic taste if present, is one of the inorganic compounds that will react with hypochlorous acid (the stronger form of free chlorine that is produced after pure chlorine is added to water). By reacting with hypochlorous acid, the dissolved iron will go from a soluble state to an insoluble state, as a precipitate is formed as a

result of the reaction. The iron precipitate, in its insoluble state, can be removed by filtration process within the water treatment centre.



Manganese also reacts with the chlorinated water according to the reaction below;



The MnO_2 form insoluble precipitates that can settle or be filtered out of the water.

2.12 CHLORINE DECAY

When chlorinated water is introduced in the distribution system, the residual chlorine gradually dissipates. The exhaustion of the residual chlorine may then result in undesirable effects including biological recontamination in the distribution system.

The following four factors influencing chlorine consumption are among those often cited:

- The consumption of chlorine as it reacts with organic and inorganic chemicals (eg., ammonia, sulphides, ferrous iron, manganous ion, humic material) in the bulk aqueous phase;
- The consumption of chlorine due to reactions with biofilms and tubercles at the distribution pipe wall; and
- The consumption of chlorine in the corrosion process or reactions with the pipe material itself.
- Natural evaporation. This is because the chlorine compound is very volatile and can be lost naturally in the water.

Ideally, if the chlorinated water was pure and the material of the pipes was inert, the only mechanism leading to the decay would be that of natural evaporation, especially in particular areas of the distribution system, namely reservoirs and other free surface flows.

The consumption of chlorine by the reaction with organic and inorganic chemicals in the bulk aqueous phase is reasonably well defined and is known as the Bulk Chlorine Demand. Certain chemical constituents of the water react rather quickly and the reaction rate is reasonably well characterized as a simple first – order decay process (Characklis *et al.*, 1990) or to a much lesser extent, a second – order rate process (Clark *et al.*, 1993).

The first – order kinetic model for the disappearance of residual chlorine due to reactions with materials in the aqueous phase at different residence times in the network may be expressed as:

$$\frac{dC}{dt} = -Kt \quad (2.35)$$

Where C is the chlorine concentration (mg/L) and k is the first – order decay constant (min^{-1}).

The residence time and/ or travel time is defined as the pipe length divided by the mean flow velocity in the pipe.

Integrating the equation gives:

$$C_t = C_o e^{-kt} \quad (2.36)$$

Where C (t) is the chlorine concentration (mg/L) at time t, C_o is the initial concentration (mg/L), and t is the residence or travel time in the pipe (min). The chlorine decay constant (k) is site specific and must be verified by field measurements. Gotoh (1988) reported k values that vary with water quality, water temperature, flow velocity, pipe material, and area of contact with the

pipe. Sharp *et al.*, (1991) described k values as a function of pipe diameter, pipe material and inlet volumetric flow rate.

The temporal and spatial consumption of chlorine is caused by chemical reactions of the chlorine with water constituents and with both the biofilms and tubercles formed on the pipe wall, as well as reactions with the pipe wall material itself.

Reactions with the pipe materials and the reaction with both the biofilm and tubercles formed on the pipe wall are known as the pipe wall demand. Digano and Zhang (2005) pointed out that reaction of chlorine on the scales coating the inner pipe surfaces is the main reason for the loss of disinfectant within distribution networks. These reactions cause a decrease in the chlorine content needed for disinfection. Maul *et al.*, (1985a) observed that there was a rapid decrease in both free and total chlorine residuals in the water in the distribution system, as residence time increases while travelling from the treatment plant.

Chlorine consumption was observed to be in two phases (Zhang *et al.*, 1992). The first phase occurs during the first 1 to 2 hours, or 4 hours (Jadas – Hecart *et al.*, 1992) and corresponds to reactions of the chlorine with oxidizable compounds. This is normally completed in the reservoir of the treatment plant. The second phase, or long term chlorine consumption, is slower than the first phase and occurs in the distribution system. The second phase is normally described in terms of an apparent first – order equation.

DiGiano and Zhang (2005) concluded that a zero – order overall kinetic model is well suitable for describing the overall chlorine decay in a heavily tuberculated cast iron pipe, whereas, a first – order overall kinetic model is found suitable for a new cement – lined ductile iron pipe.

The overall chlorine decay constant during the second phase as defined by AWWARF (1996) and used by many researchers (eg., Rossman *et al.*, 2001, Hallam *et al.*, 2002), is the sum of the bulk decay, (K_b) and the effective chlorine wall decay constant, (K_w). Units of both constants are 1/time.

In this work, it will be assumed that the overall, bulk and wall decay constants will be of a first – order kinetics.

- **Effect of water age**

Unlike specific degradative processes that affect residual chlorine decay and general water quality in a distribution network, retention time in a pipe line or water age is a characteristic that only has an indirect effect. Many degradative processes are time dependent and, therefore, more adversely affect water quality with increasing retention time. The degradative processes that are most influenced by residence time can be attributed to reactions occurring in the bulk water and at the pipe wall interface. Some of these degradative processes are biological nitrification and processes involving iron and manganese. These are very important processes which are facilitated by long retention times in water distribution systems and leads to the loss of disinfectant residuals. Other substances in the network such as reduced iron in corrosion deposits, ammonia, and natural organic matter (NOM) both on the pipe surface also leads to decay of chlorine in the bulk phase. In so far as residual chlorine in the distribution system is inadequate, the microbial integrity of the system is compromised. Increased occurrence of microorganisms such as coliforms is associated with the loss of disinfectant residual (Wolfe *et al.*, 1988, 1990).

The precise influence of water age on water quality is complex and clearly system specific, complicating potential control strategies. Water age, unlike other causes of distribution system water quality degradation, such as backflow, cannot be eliminated, only managed within the framework of numerous constraints. Water age is determined by flow rate and the internal volume of the distribution system network, and it can be estimated using tracer studies, mathematical models, system models, and computational fluid dynamics models. The physical aspects of pipe sizes and network layout are important considerations in minimizing water age. Research indicates that “dead ends” and low velocities should be avoided (AWWARF, 2004). This would favor the use of small diameter pipes and careful consideration of flow paths (“looped” geometry). Current design practice, however, typically dictates a design not based on water needed at the tap but on peak flows associated with fire fighting. This tends to result in a design incorporating comparatively large pipes with resulting lower flow rates. Network operation is also an important determinant of water age at any particular point in the system. Water may be routed to avoid excessively long residence times. Periodic flushing of system elements associated with long water age may also minimize water quality degradation by removal of pipe scales and sediment associated with disinfectant consumption and release of iron into the water. Finally, in the case of systems with multiple sources of supply, hydraulic modeling can be used to assess system operations to reduce maximum water age.

- **Effect of biofilms**

One way in which water quality can be degraded in the distribution system is due to the growth of bacteria on surfaces as biofilms. According to the Center for Biofilm Engineering at Montana State University, biofilms form when bacteria adhere to surfaces in aqueous environments and

begin to excrete a slimy, glue-like substance that can anchor them to all kinds of material – such as metals, plastics, soil particles, medical implant materials and, most significantly, human or animal tissue. The first bacterial colonists adhere to a surface initially by inducing weak, reversible bonds called van der Waals forces. If the colonists are not immediately separated from the surface, they can anchor themselves more permanently using cell adhesion molecules, proteins on their surfaces that bind other cells in a process called cell adhesion.

Virtually every water distribution system is prone to the formation of biofilms regardless of the purity of the water, type of pipe material, or disinfectant used. The extent of biofilm formation and growth, the microbial ecology that develops, and the subsequent water quality changes depend on surface-mediated reactions (e.g., corrosion, disinfectant demand, immobilization of substrates for bacterial growth), mass transfer and mass transport processes, and bulk fluid properties (concentration and type of disinfectants, general water chemistry, organic concentration, etc.). These interactions can be exceedingly complex, which typically means that the mechanisms leading to biofilm growth may not be obvious and are often system specific.

Bacteria growing in biofilms can subsequently detach from the pipe walls. Because these organisms must survive in the presence of the disinfectant residual present in the distribution system, the interaction between the suspended organisms and residual is critical. If the residual has decayed due to reactions with compounds in the water or with the pipe wall, intrusion, or other sufficient external contamination, it is possible for attached bacteria to be released into water that contains insufficient disinfectant to cause their inactivation. The potential for this to occur is higher in premise plumbing, which generally has longer water residence times that may lead to very low disinfectant concentrations.

2.12.1 Chlorine Decay in a Water Treatment System

Teefy and Singer (1990) proposed that the free residual chlorine decay in a water treatment system follows the first order reaction kinetic model with the decay coefficient (K) ranging from 0.162 to 0.0624/hour. Lawler and Singer (1993) suggested that a decay coefficient of 0.2/hour is acceptable. Other research works conducted by Gawad and Bewtra (1998) proposed that the free chlorine residual concentration during the physical and chemical treatment of a river water is also a first order reaction and this mainly leads to bulk chlorine decay. In addition, other parameters that were included are the effect of flows, evaporation, photolysis and temperature and these were captured in the resultant equation;

$$K_T = FTB (K_{ev} + K_s + K_{ox}) q (T-20) \quad (2.35)$$

Where K_T is the coefficient rate at temperature T , FTB is a tabular factor, K_{ev} is evaporation constant, K_s is the rate of photo-oxidation, K_{ox} is the oxidation state of free radical chlorine, q , is the Arrhenius constant, T is temperature ($^{\circ}\text{C}$).

FTB = 2.05 for turbulent flow and 1.0 for laminar flow;

$K_{ev} = 0.013/H \text{ d}^{-1}$ (where H is the depth of flow in meter);

$K_s = 0.03 \text{ d}^{-1}$; $K_{ox} = 0.065 \text{ d}^{-1}$ and $q = 1.08$

Nowell and Hoigne (1992) reported that the photo degradation of the chlorine is the first order reaction and found that the hypochlorite ion is more sensitive to sunlight than the hypochlorous acid.

2.12.2 Chlorine decay along a Water Distribution Network

A water distribution system is not generally uniform in structure but consists of a network of various elements having different physical, chemical, and biological characteristics such as differing size pipes and pipe materials, occurrence of pipe scales, and biofilms. Furthermore,

some characteristics such as surface roughness may change with time, which in turn may influence the hydraulic residence time and the path the water takes as it flows through the system.

Calculating the decay rate of free chlorine in piping system of a distribution network is a great challenge. The rate should be associated with hydraulic study parameters such as flow rate, flow pattern, networking, contour, pipe sizing, retention time or water age, age of the system, and the distances as well. The effect of biofilms should also not be underestimated.

In general, Euler and Lagrange are the two common models out of the several models that are used to define numerically the free chlorine residual decay within a distribution system.

The Euler technique applies the finite different method (FDM) by dividing the pipe into the segments at the same volume. Chaundhry and Islam (1994) proposed the partial derivative technique to estimate the chlorine decaying in a single pipe as;

$$\frac{dc(x,t)}{dt} + v \frac{dc(x,t)}{dx} = KC(x,t) \quad (2.36)$$

Where, $c(x,t)$ is the concentration of free chlorine at node x , v the velocity of water, and K the reaction order. By assuming a complete mixing in every junction, the chlorine residual model proposed by Rossman *et al.*, (1993, 1994) and Rossman and Boulos (1996) can estimate the concentration of the free chlorine. For a single pipe, Rhee *et al.*, (1986) proposed an exact solution for equation as;

$$C(x,t) = \begin{cases} c(x-vt)e^{-kt} & \text{for } x-vt > 0 \\ c(0,t-x/v)e^{-\frac{kx}{v}} & \text{for } x-vt < 0 \end{cases} \quad (2.37)$$

Zierolf *et al.*, (1998) developed the drinking water distribution network input-output (IO) model to express the chlorine concentration at the pipe junction and time as a weighted average of exponentially decayed values of the concentrations at all adjacent upstream junctions.

The chlorine decay due to reaction with the pipe wall should consider the rate constant, mass transfer limitations, and available surface area-to-volume geometry. Rossman (2000) expressed the wall reaction rate:

$$R = \frac{4K_f K_w}{D} (K_f + K_w) \quad (2.38)$$

Where R= wall reaction rate; K_w = wall decay;

D = pipe diameter (meter);

K_f = mass transfer coefficient (/hr) and is given by;

$$K_f = Sh \frac{D}{d} \quad (2.39)$$

Where

Sh = Sherwood number

D = Diffusivity and d = diameter of pipe

The definition of the Sherwood number depends on the hydraulic conditions.

For Reynolds number (R) ≥ 2300 ;

$$Sh = 0.023 R^{0.83} Sc^{0.33}$$

This signifies turbulent flow conditions which usually exist in water distribution networks.

For Reynolds number (R) < 2300 ;

$$Sh = 3.65 + \frac{0.0668 \left(\frac{d}{L}\right) RSc}{1 + 0.04 \left[\left(\frac{d}{L}\right) RSc\right]^{0.57}} \quad (2.40)$$

Where R = Reynolds Number = $\mu d/v$

Sc = Schmidt Number = v/D

μ = flow velocity

L = Pipe Length

v = Kinematic Viscosity

These equations help to generate the mass transfer coefficient and subsequently the wall decay coefficient for the pipe walls.

2.13 Water Quality Modeling

Although the use of mathematical models for hydraulic analysis of distribution systems dates back to the 1930's, (Cross, 1936), water quality models of distribution systems are relatively recent development. Early works were limited to steady – state representations of networks. Wood (1980) presented an extension to a steady – state hydraulic model in which a series of simultaneous equations are solved for each node resulting in an extended state time varying analysis.

It is difficult to use monitoring data alone to understand the fate and transformation of substances in drinking water as the water moves through a distribution network. The flow pathways and travel times of water through these systems are highly variable because of the looped layout of the pipe network and the continuous changes in water usage over space and time.

At different times of the day, a location might be receiving relatively new water from the treatment works when storage tanks are being refilled or old water when storage tanks are being emptied.

It is usually impractical to experiment on the entire distribution system by seeing how changes in pumping schedules, storage facility operations, or treatment methods affect the quality of water received by the consumer.

For these reasons, mathematical modeling of water quality behavior in distribution systems has become an attractive supplement to monitoring. These models offer a cost effective way to study the spatial and temporal variations of a number of water quality constituents including the following;

- The amount of water originating from a particular source
- The age of water in the distribution system
- The concentration of a non reactive tracer compound either added or removed from the system such as fluoride.
- The concentration and decay rate of a secondary disinfectant such as chlorine.
- The concentration and growth rate of disinfection by products such as THM's
- The numbers and mass of attached and free – flowing bacteria in the distribution system

The models can be used to assist managers of utility companies to perform a variety of water quality – related systems such as locating and sizing of storage facilities whilst modifying system operations to reduce water age.

Examples of hydraulic and water quality models in use worldwide are the EPANET and SynerGEE.

2.13.1 Water Quality Modeling with SynerGEE Software

SynerGEE Water is a simulation software package used to model and analyze closed conduit networks of pipes, regulators, valves, pumps, reservoirs, tanks, wells and boreholes.

Over 600 utilities and consulting engineering firms worldwide have taken advantage of SynerGEE's versatile modelling environment and comprehensive analyses. Not only does SynerGEE perform a host of useful analyses, it can do it on extremely large systems of over 100,000 elements comprising all mains and operational equipment.

SynerGEE is highly flexible. It is possible to choose the level of detail from simple hydraulic analysis of a single pressure zone to the twin substance propagation of water quality in a multi-zoned system. Additionally, SynerGEE can model complex control arrangements for pumps, valves and regulators in any operational scenario. It can also be used successfully for water quality modeling.

Water quality modeling with SynerGEE is very tightly linked with hydraulic modeling. System hydraulic behavior determines the flowpaths taken by the water from source to consumer, the mixing of water from multiple sources, the dilution of contaminants, and the travel and retention time of the water. Therefore, an accurate and calibrated hydraulic model of the system—one that produces both accurate flow rates and velocities—is required for water quality modeling.

The SynerGEE software is compatible with the Geographic Information System (GIS) software and because of this interphase, when there is an existing digitized GIS map of a water distribution network, it can be adopted and migrated to the SynerGEE software for modeling and

simulation. This feature gives SynerGEE an advantage over the other hydraulic modeling softwares such as Epanet. This was the main consideration which was taken into account for the purpose of this research work.

CHAPTER THREE – STUDY AREA/ METHODOLOGY

3.0 STUDY AREA

Water supply in Ghana is divided into Urban Water Supply and Rural Water Supply. The Community Water and Sanitation Agency (CWSA) manages the rural water supply whilst Ghana Water Company through its' subsidiary company, Ghana Urban Water Limited manages the urban water supply. GWCL/ GUWL operate in all ten (10) regions of Ghana including the Ashanti Region with regional offices sited in all the regional capitals.

3.1 Ashanti region

The Ashanti Region of the Ghana Urban Water Limited has twelve (12) administrative districts. However, eight (8) of these districts make up the distribution network of Kumasi and these are Kumasi North, Kumasi North East, Kumasi East, Kumasi South East, Kumasi South, Kumasi Central, Kumasi West and Kumasi North West.

The four other districts not considered to be part of the Kumasi network are Offinso, Mampong, Konongo and Obuasi. In GUWL parlance, they are considered as Ashanti Rural networks.

The GUWL administrative districts coincide with seven out of the twenty seven political districts within the geographical boundaries of the Ashanti Region of Ghana. These include; the Kumasi Metropolis, Afigya Sekyere, Kwabre, Ejisu Juabeng, Bosomtwe/ Atwima/ Kwanwoma, Atwima Nwabiagya and Offinso South districts.

3.1.1 Location and Size

The Ashanti Region is centrally located in the middle belt of Ghana with Kumasi being the Regional capital. It lies between longitudes 0.15W and 2.25W, and latitudes 5.50N and 7.46N.

The region shares boundaries with four of the ten political regions, Brong-Ahafo Region in the north, Eastern region in the east, Central region in the south and Western region in the South west and is divided into 27 political administrative districts. These political districts are different from the GUWL administrative districts.

The region occupies a total land area of 24,389 square kilometers representing 10.2 per cent of the total land area of Ghana. More than half of the region lies within the wet, semi-equatorial forest zone.

3.1.2 Population

The region is the most populous and one of the most rapidly growing regions in the country. The region's population is 3,612,950, representing 19.1 per cent of the country's population with a current growth rate of 3.4% and a population density of 148.1/sqkm. There are slightly more males (50.3%) than females (49.7%) in the region (GSS, 2002).

3.1.3 Drainage and Climate

Much of the region is situated between 150 and 300 meters above sea level. The region is endowed with a spectacular geography-lakes, scarps, forest reserves, waterfalls, national parks, birds and wildlife sanctuaries.

Notable among them are the Owabi Arboretum and Bomgobiri wildlife sanctuaries. The region is drained by Lake Bosomtwe, the largest natural lake in the country, and Rivers Offin, Prah,

Afram and Owabi. There are other smaller rivers and streams which serve as sources of drinking water for residents of some localities in the region.

Due to human activities and bushfires, the forest vegetation of parts of the region, particularly the north-eastern part, has been reduced to savanna. The region has an average annual rainfall of 1270 mm and two rainy seasons. The major rainy season starts in March, with a major peak in May. There is a slight dip in July and a peak in August, tapering off in November. December to February is usually dry, hot, and dusty. The average daily temperature is about 27 degrees Celsius.

3.1.4 Geology and Soils

The Study area lies within the Birimian meta-sediments and associated Dixcove granitoids which intrude the Birimian. Typical lithologies of the Birimian meta sediments are tuffaceous phyllite, schist and meta-greywacke. These meta-sediments are generally strongly foliated and jointed with weathering profiles reaching 100 m in depth. Therefore, moderate quantities of water are expected under suitable conditions in regolith aquifers. The Dixcove granite which is typically dioritic in composition dominates the catchment area and may possess minor secondary porosity (Eisenlohr and Hirdes, 1992).

3.2 Water Supply to Kumasi

Kumasi, which is the regional capital of the Ashanti Region, receives its water supply from Barekese and Owabi Water Treatment Plants where pumping is done to the Suame Reservoir site.

The Owabi Water Treatment Plant produces averagely Two Million, Six Hundred gallons of water per day (2,6 MGD). This volume of water is pumped to serve mainly the drinking

populace in the North West administrative district of GUWL whilst the surplus is sent to Suame Reservoir site to add on to the supply from the Barekese Headworks.

The Barekese Water Treatment Plant, which has a design capacity of Twenty Four Million gallons (24 MGD) but averagely produces Twenty Million gallons of water per day (20 MGD) takes its source from the Offin River. The raw water goes through various treatment processes such as screening, aeration, coagulation, sedimentation, filtration, pH correction and then finally disinfection using either chlorine gas or the other derivatives of chlorine such as Calcium Hypochlorite. The chlorine gas is mainly used on the plant with the hypochlorite being used in times of chlorine gas shortages.

The final water from this plant is pumped to the Achiase Booster Station which is about 7.5km from the treatment plant. From the Booster Station, water is subsequently pumped to the Suame Reservoir Site which is about 10.5km from the booster station where there are four interconnected reservoirs of different capacities. The pipes from the Barekese Headworks to the Suame Reservoir site are made of steel with an internal diameter of 900mm uniformly.

Since the reservoir site is of a higher elevation, 300 mean sea level, the water then flows by gravity to the distribution networks of the other administrative districts. However, this supply is still not enough to meet the water demand of the study area and hence some people depend on other sources of water for their domestic activities. GUWL is also forced to resort to water demand management practices such as water rationing to be able to serve the increasing customer numbers. This is done with the help of the SynerGEE hydraulic model to ensure efficient and equitable water distribution practices that satisfies the suppressed nodal demands.

The entire distribution network consist of pipes of varying diameters, materials and proportions and these include 48% Polyvinyl Chloride (PVC), 35% Asbestos Cement (AC), 5% Cast Iron (CI), 8% High Density Polyethylene pipes (HDPE), 3.4% Steel, 0.033% Galvanized Iron and 0.005% Copper pipe (GUWL, Kumasi). The total length of pipes in the KWDN is about 1,016,958 m (GUWL, Kumasi).

The Cast iron pipes are the oldest of the pipes in the network and some are as old as Eighty Four (84) years since they were laid when the Owabi Water Treatment Plant was constructed in 1928 (GUWL, Kumasi).

Most of these old pipes are in the central business district of Kumasi which is located in the Kumasi Central district of GUWL. The cast iron pipes are known to cause the most decay of chlorine in distributed water due to reactive nature of cast iron with chlorine.

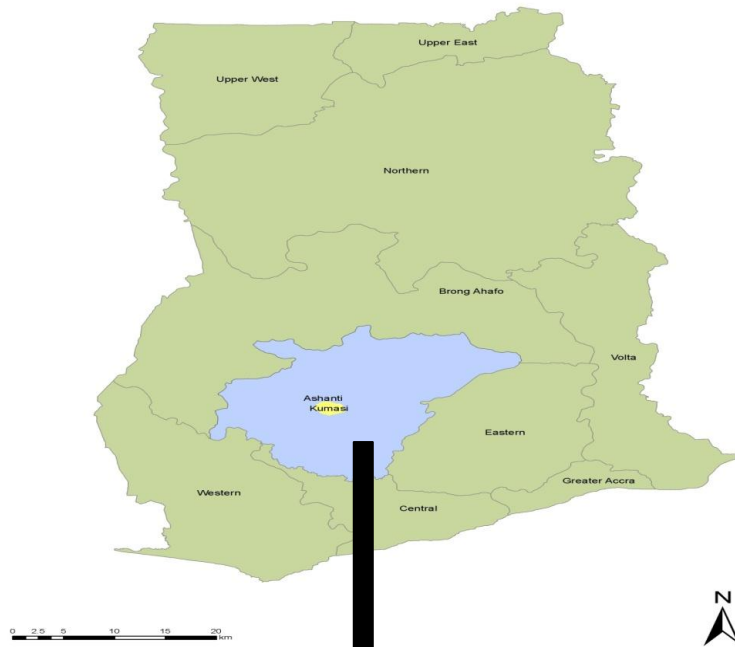


Figure 3.1 Map of Ghana showing Ashanti Region



Figure 3. 2 Map of Ashanti Region showing Kumasi

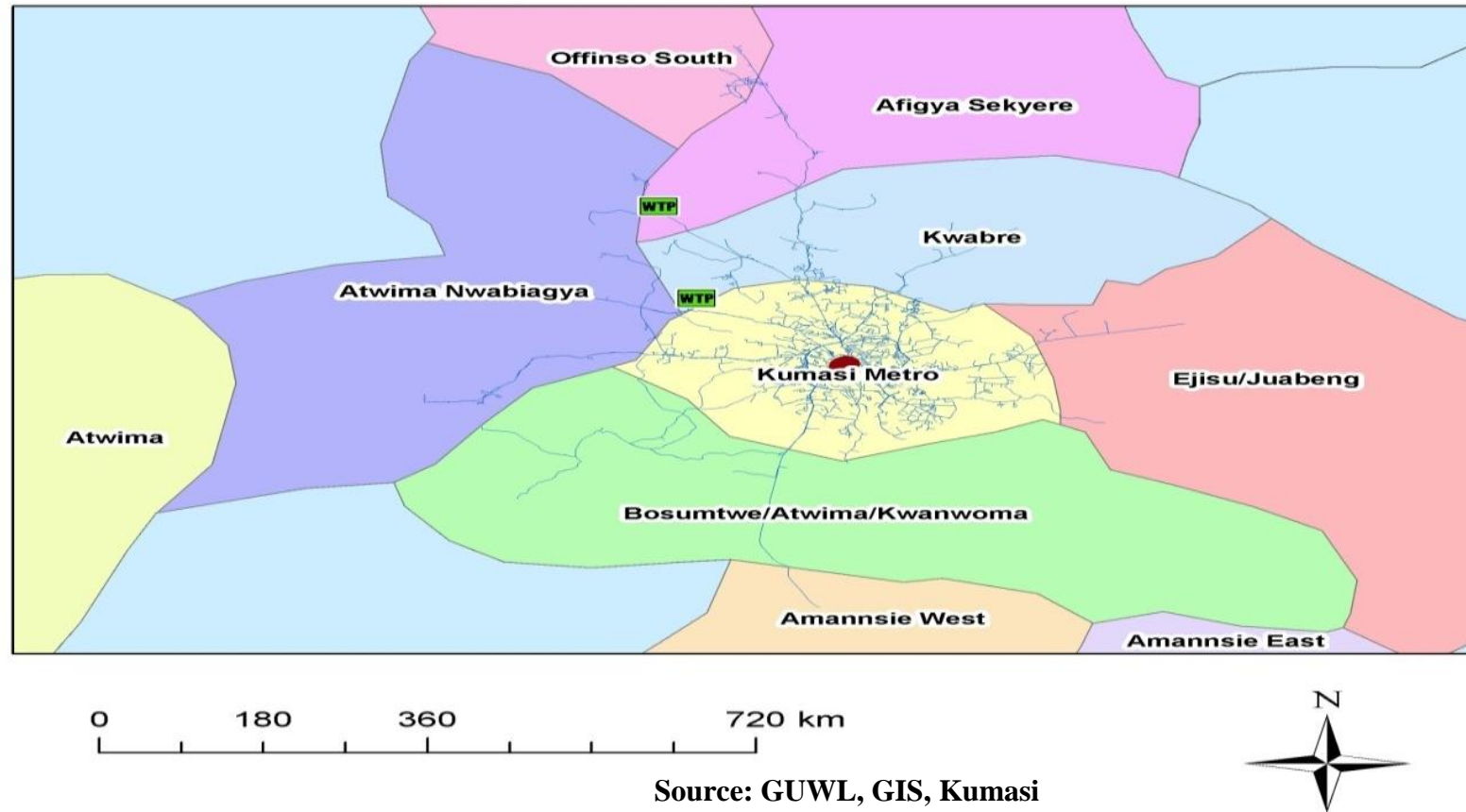


Figure 3.3 Map of study area showing political districts that lie within KWDN

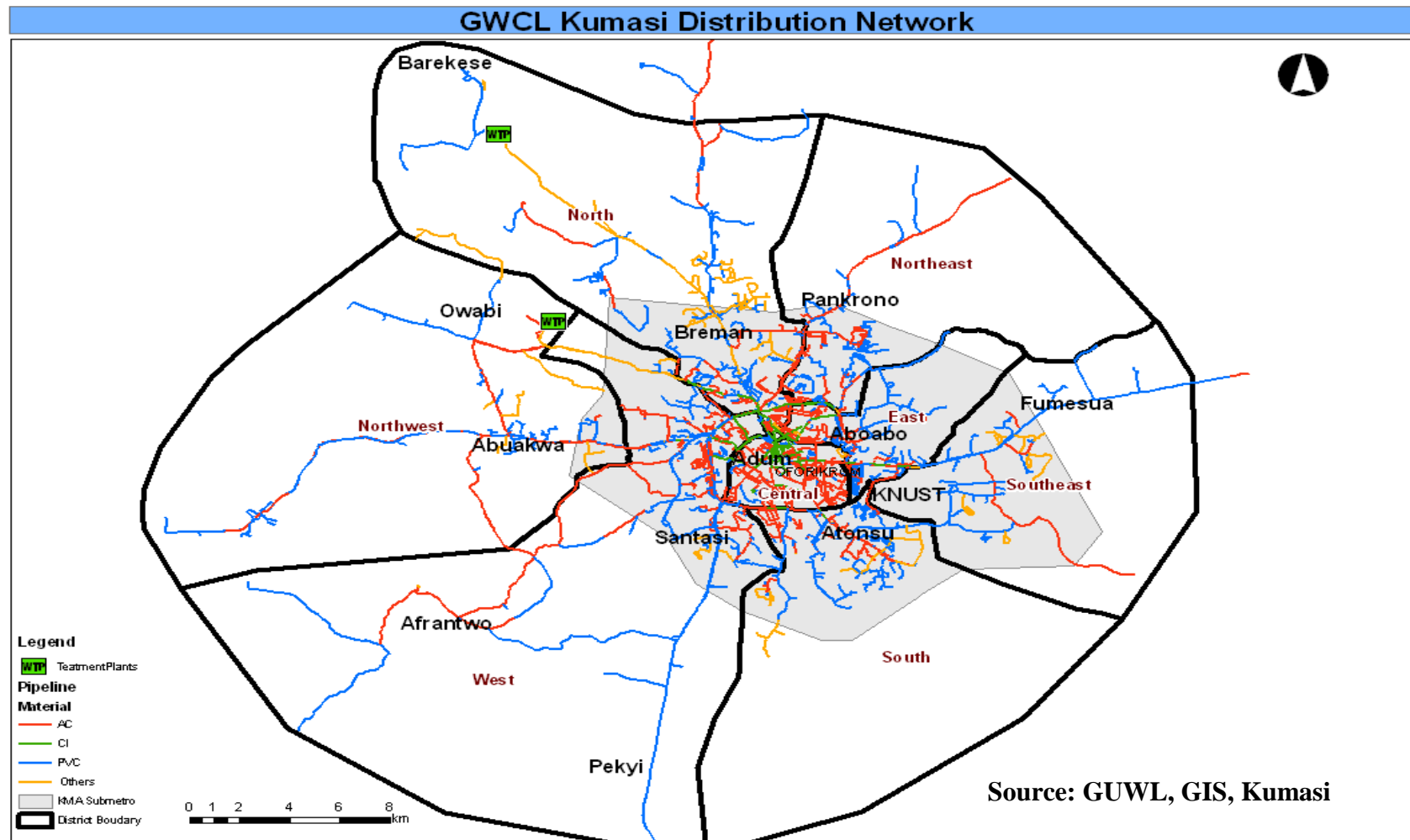


Figure 3.4 Map of KWDN showing GUWL administrative districts

3.3 METHODOLOGY

3.3.1 Desk Study

Desk study was carried out on information obtained from the internet, journals on related works, other relevant information obtained from the GUWL. A three year water quality data spanning from 2009 to 2011 was obtained from the Water Quality Assurance Department of GUWL, Kumasi. The hydraulic model data was obtained at the GUWL's GIS Office.

3.3.2 Identification and Selection of Sampling Sites

An initial five sampling sites were selected and these included Barekese Headworks, Owabi Headworks and the 2 Million gallon reservoir at the Suame Reservoir site. Also included in the sampling points are a dedicated tap connected directly on the distribution line at Agyaba House, Adum in the Kumasi Central district and a House tap connected to the distribution line at Agyaba House as seen in figure 3.5.

Barekese and Owabi Headworks were selected as sampling points because they serve as the water treatment plants for the study area. The quality of the water at the treatment plants gives the initial quality of the water including the residual chlorine concentration of the water before water distribution starts.

The 2 Million gallon reservoir at the Suame reservoir site was also selected as a sampling point because it is the dedicated reservoir from which water is supplied to Adum in the Kumasi Central district of GUWL. The distribution line that is at Agyaba House was also selected because it conformed to the diameter of the pipe required for the scope of this work which is 150 mm cast iron pipe.

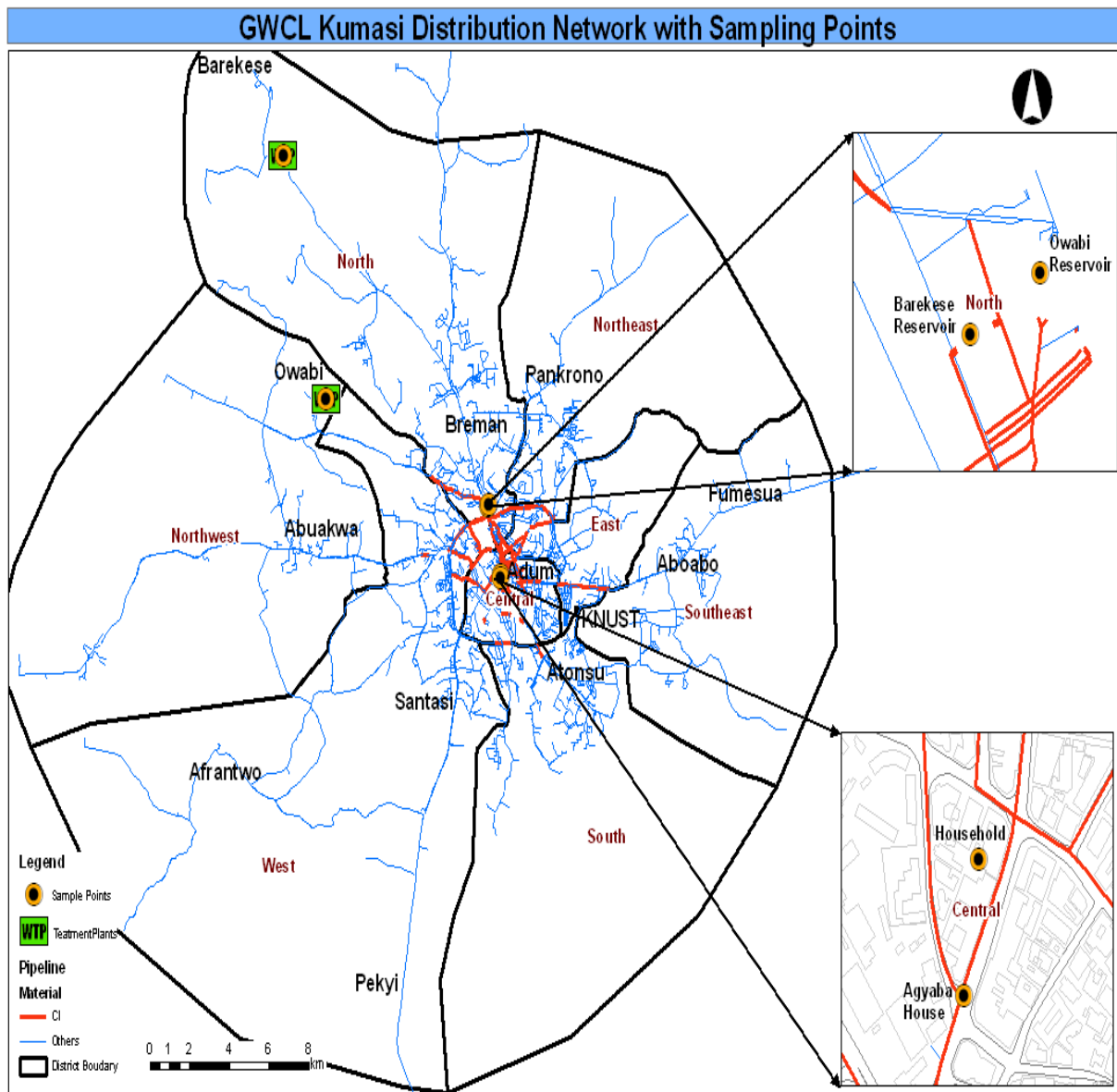


Figure 3.5 Map of KWDN with sampling points

After five sampling episodes, the sampling sites were modified to include the Barekese Headworks, Achiase Booster Station and a Public Stand pipe at Kronom, in the Kumasi North district of GUWL. The 2 Million gallon reservoir at Suame Reservoir site, a sampling tap right on the selected reservoir, the dedicated tap connection on the Agyaba House distribution line and

finally, the house tap connected to the selected distribution line at Agyaba House on the Prempeh II Street, Adum – Kumasi, were all included as seen in figure 3.6.

Owabi Headworks sampling point was taken off since it was realised that water supply from the plant does not get to the Suame Reservoir site.

The sampling points at Achiase Booster Station and Kronom were included because they are connected directly to the 900 mm steel pipe and therefore helped to establish the residual chlorine decay due to the interaction between the steel pipe and the bulk water.

The sampling tap on the 2 Million gallon reservoir at the Suame reservoir site also helped to establish the residual chlorine concentration of the water just before it leaves the reservoir to Adum in the Kumasi Central district.

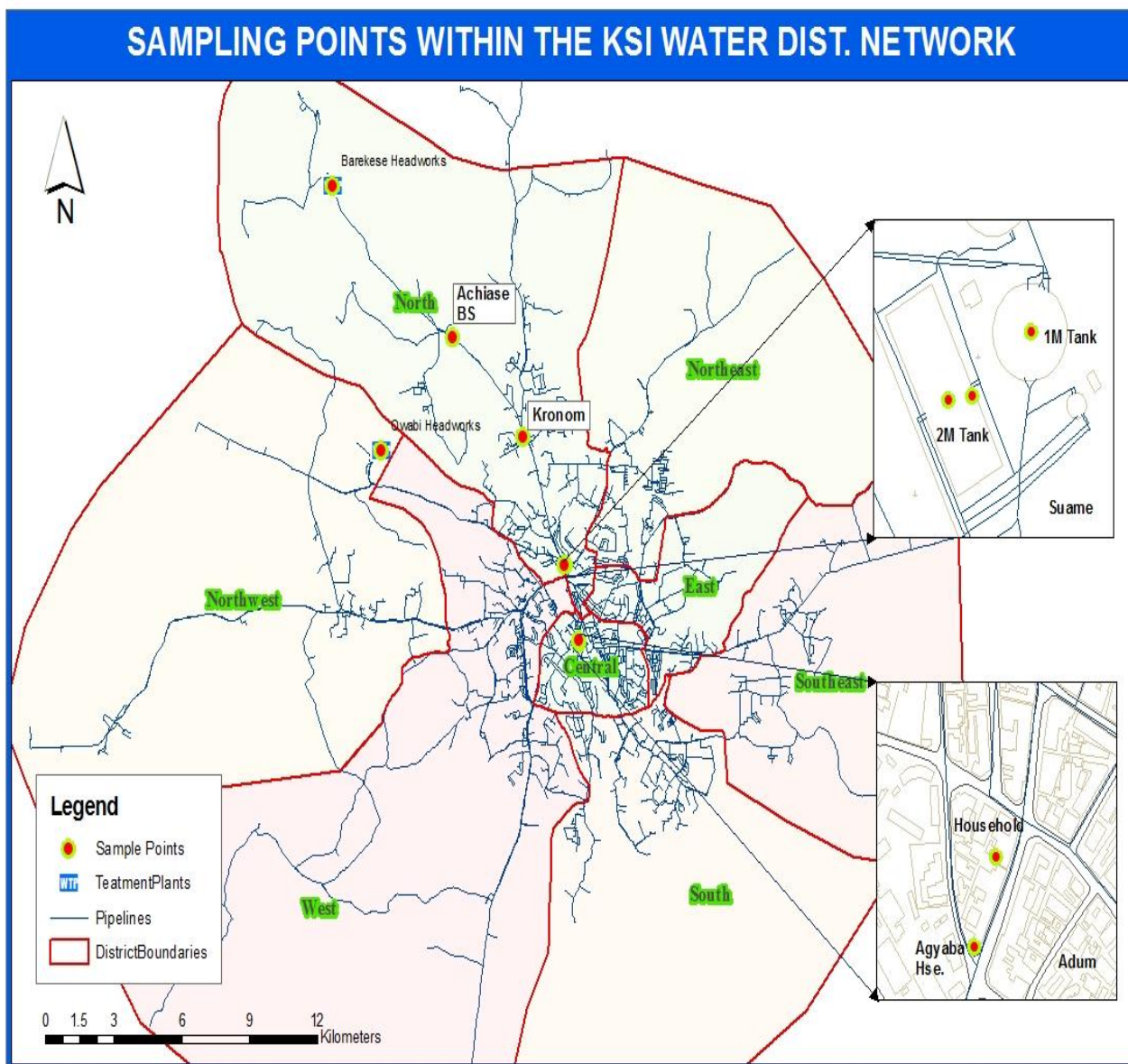


Figure 3.6 Map of KWDN with revised sampling points

3.3.3 Sampling

The initial sampling regime involved the collection of duplicate water samples from the initial selected points at 9am, 1pm and 4pm at the same time. The sampling time and points were selected based on the hydraulic model of the Kumasi water distribution network.

The sampling regime involved twice a week sampling sessions (i.e. Tuesday's and Thursday's) and the regime repeated every other week. Forty eight (48) water samples were collected in a week for Physico- chemical and Bacteriological analysis with the breakdown in Table 3.1.

After the initial five sampling episodes, a total of One Hundred and Twenty (120) water samples were taken for analyses.

Table 3.1: Detailed initial sampling regime

Sampling Points	Number of samples per each sampling time per day			Total Number of samples per day of sampling
	9am	1pm	4pm	
Barekese	2	2	-	4
Owabi	2	2	-	4
Suame Reservoir (1MG)	1	1	-	2
Suame Reservoir (2MG)	1	1	-	2
Agyaba House Transmission Line Tap	2	2	2	6
Adum House Tap	2	2	2	6
Total	10	10	4	24

After the sampling points were reviewed, three sampling episodes were embarked on and a total number of Forty two (42) water samples were collected and analysed. Fourteen (14) water samples were taken per day as indicated in Table 3.2 below.

Table 3. 2: Detailed revised sampling regime

SAMPLING POINT	SAMPLING TIME	NUMBER OF SAMPLES/SAMPLING POINT/SAMPLING DAY
Barekese Headworks	9:00AM	2
Achiase Booster Station	10:30AM	2
Kronom Public Stand Pipe	12:00PM	2
Suame Reservoir (2MG)	1:30PM	2
Suame Reservoir (2MG) Tap	2:00 PM	2
Agyaba House Transmission Line Tap	4:00PM	2
Adum House Tap	5:00PM	2
TOTAL		14

In all, a total of One Hundred and Sixty two (162) water samples covering both the dry and wet seasons were taken from the sampling points and analysed Physico- chemically and bacteriologically.

This formed the bases for determining the Wall and the Overall chlorine decay coefficients.

3.4 ANALYTICAL PROCEDURE

The Physico-chemical and bacteriological parameters carried out after every sampling episode is given in Table 3.3 below;

Table 3. 3: Water Quality Parameters and the Methods of Analyses

PARAMETER	METHOD OF ANALYSIS
pH	Electrometric Method
Temperature	Thermometric Method
Total Dissolved Solids	Electrometric Method
Colour	Spectrophotometric Method
Turbidity	Photometry
Conductivity	Electrometric Method
Calcium	Atomic Absorption Spectroscopy
Magnesium	Atomic Absorption Spectroscopy
Ammonia	Spectrophotometric Method
Nitrates	Spectrophotometric Method
Iron	Atomic Absorption Spectroscopy
Manganese	Atomic Absorption Spectroscopy

PARAMETER	METHOD OF ANALYSIS
Free Chlorine Residual	Colorimetric Method
Total Chlorine	Colorimetric Method
Total Coliforms	Membrane Filtration
E. Coli	Membrane Filtration
Salmonella Spp	Membrane Filtration

The Free Chlorine residual, Total Chlorine, and Turbidity were analysed in situ using a Hannah Chlorine Photometer. The pH and Temperature were also done in situ using the Mettler Toledo pH meter.

Portions of the water samples were acidified and analyses for determination of occurrence of the mentioned metals in Table 3.1 were conducted with Atomic Absorption Spectrophotometer at the Soil Research Institute Laboratory of the CSIR – Kumasi.

The Bacteriological analyses were conducted at the Environmental Quality Engineering Laboratory of the Civil Engineering Department, KNUST – Kumasi using membrane filtration and chromocult agar as the culturing media.

3.5 EXPERIMENTAL DETERMINATION OF DECAY COEFFICIENTS

3.5.1 Bulk Decay Coefficient Determination

In the determination of the Bulk chlorine decay coefficient, 250 ml transparent glass bottles with glass stoppers were used. Freshly treated water samples from the Barekese Headworks were collected into the 250 ml bottles. The bottles were protected from sunlight by the use of aluminum foil and packed into a dark cupboard. Residual chlorine test were conducted hourly for

eight hours on each sampling day. Other Physico- chemical and bacteriological analyses were conducted on the hourly samples alongside the residual chlorine concentration determination.

The bulk decay coefficient determination test was carried out at the Barekese Headworks on three different sampling days.



Plate 3. 1 Bottle test used for bulk decay coefficient determination

3.6 Overall decay coefficient determination

3.6.1 Residual Chlorine Decay Modeling

The results obtained from the bulk, wall and overall decay coefficients were then used for the water quality modeling to predict the probable positions where stepwise chlorination is necessary in the network.

Steady state and extended time varying water quality modeling was done using initial residual chlorine values of 0.6mg/L and 2.0mg/L at the Barekese Headworks. The software used was SynerGEE hydraulic and water quality model. The modeling was done with SynerGEE because there is an existing calibrated hydraulic model for the KWDN and therefore the model results will be more reliable and can be validated.

The experimentally determined bulk decay coefficient and the wall decay coefficients of the concrete reservoirs, steel and cast iron pipes were used for the modeling.

The bulk decay coefficient was used as an attribute of the source water and kept constant through the entire modeling process. For the other pipe materials, such as the polyvinyl chloride pipes (PVC), the high density polyethylene pipes (HDPE), ductile iron and the copper pipes, the experimentally determined wall decay coefficient of the cast iron pipe was used as the pipe attribute to depict the worst case scenario.

This was used to predict the probable locations where stepwise chlorination was deemed to be necessary in the distribution network.

CHAPTER FOUR – RESULTS AND DISCUSSIONS

4.0 Introduction

This chapter presents results of the desk study on the water quality data, the Physico- chemical and bacteriological analyses conducted on all the water samples taken during the eight sampling episodes, outcome of the residual chlorine decay modeling with the SynerGEE software and discussions on how residual chlorine decays together with the decay coefficients in the Kumasi water distribution network.

4.1 Existing Data on Residual Chlorine

A three year water quality data, spanning from January 2009 to December 2011 obtained from the Water Quality Assurance department of GUWL, Kumasi on treated water from the Barekese Headworks gave a mean residual chlorine concentration of 0.70 mg/L.

From GWCL/GUWL internal quality standards, residual chlorine concentration of treated water from any of the headworks must fall within the range of 0.50 mg/L to 2.0 mg/L.

The 0.70 mg/L mean residual chlorine concentration of the treated water from Barekese Headworks therefore complied with the GWCL acceptable internal standards since it falls within the range. Table 4.1 gives the averages of the rest of the other Physico- chemical parameter values.

Table 4.1: Mean Barekese Treated Water Quality Data (2009 - 2011)

PARAMETER	AVERAGE RESULTS
pH	7.13
Temperature °C	25.6
Colour (HU)	7.4
Turbidity (NTU)	2.2
Residual Chlorine (mg/L)	0.7
E-coli (cfu/100ml)	0
Conductivity (uS/cm)	99.8
Total Dissolved Solid (mg/L)	69.86
Iron (mg/L)	0.2
Manganese (mg/L)	0
Nitrate (mg/L)	0.2
Nitrite (mg/L)	0
Ammonia (mg/L)	0

Source: WQA Monthly Reports (GUWL, 2012)

In the distribution network, a desk study was also conducted on a three year data and the findings are given in table 4.2 below.

Table 4.2: Mean values of Residual Chlorine in KWDN

ADMINISTRATIVE DISTRICT	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2009	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2010	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2011	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2009 - 2011
Kumasi Central	0.098	0.07	0.067	0.078
kumasi North	0.103	0.066	0.118	0.096
Kumasi North West	0.087	0.129	0.148	0.121
Kumasi North East	0.099	0.059	0.076	0.078

ADMINISTRATIVE DISTRICT	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2009	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2010	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2011	MEAN RESIDUAL CHLORINE VALUES (mg/L) 2009 - 2011
Kumasi East	0.1	0.056	0.051	0.069
Kumasi South East	0	0.033	0.031	0.021
Kumasi South	0.08	0.056	0.039	0.058
Kumasi West	0.082	0.064	0.057	0.068

Source: WQA Monthly Reports (GUWL, 2012)

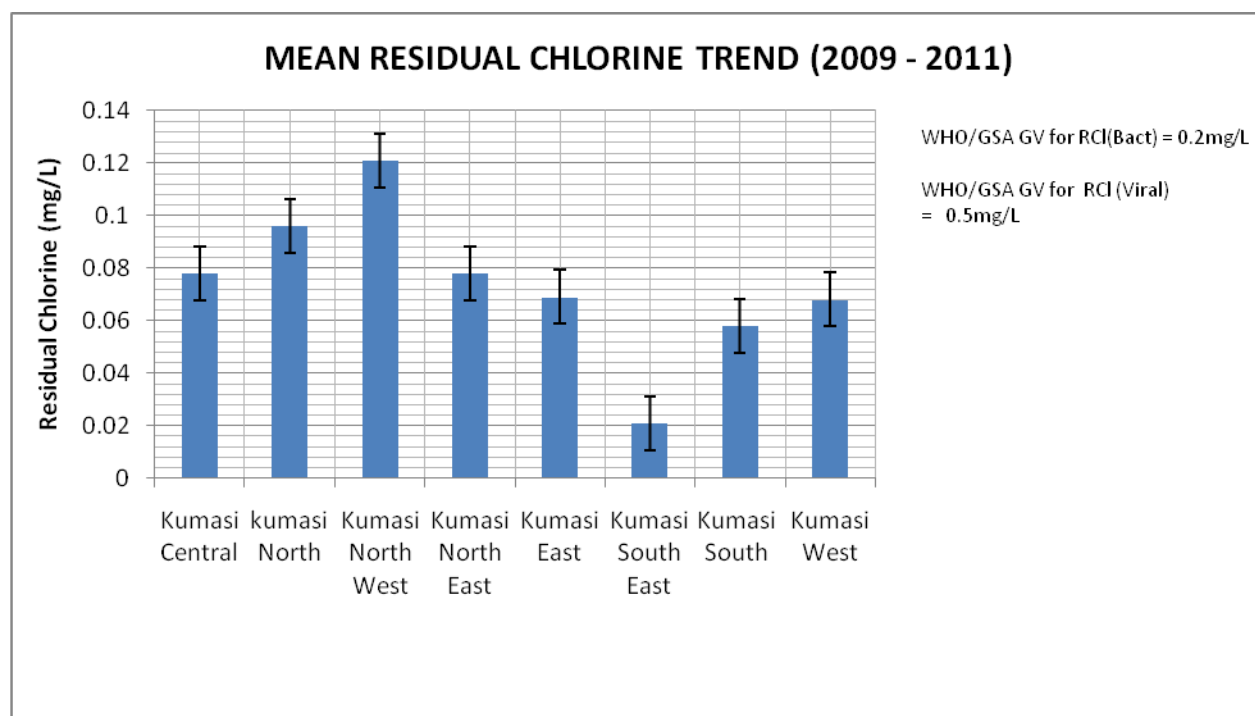


Figure 4.1 Mean Residual Chlorine trend in KWDN (2009 - 2011)

Data analysis on the trend indicates that for the past three years, no administrative district has its water supply having residual chlorine value conforming to the recommended minimum Ghana standard of 0.2mg/L at the farthest end needed for handling bacteriological contamination.

Kumasi North West district which receives water from the Owabi Headworks has considerable better residual chlorine values than the rest of the districts.

With the other administrative districts, Kumasi North which accommodates the Barekese Headworks has highest residual chlorine concentration in the distributed water quality. This is rightly so because of proximity of the supply areas to the treatment plant. Kumasi South East district is the worst in the distribution system as seen in figure 4.1. The south east district is worse because it is the farthest in terms of distance from the Barekese Headworks. The mean residual chlorine concentration in the districts' distributed water is 0.021mg/L which is negligible and compromises the bacteriological quality of the water.

Presently, there is also no post chlorination or stepwise chlorination done in the network to boost the residual chlorine levels to that farthest point.

4.2 Bulk Decay

The bulk decay of residual chlorine in water follows a first order decay mechanism (Characklis *et al.*, 1990). Figure 4.2 shows the bulk chlorine decay trend of treated water from Barekese Headworks which conformed to the first order reaction kinetic.

The initial mean residual chlorine concentration was 0.79 mg/L. After the hourly monitoring and residual chlorine analysis for 8 hours, the final mean residual chlorine concentration reduced to 0.52mg/L. This implies that about 34% of the chlorine losses in the water can be attributed to the bulk decay demand over the eight hour period since the lost residual chlorine is 0.27 mg/L. Readily oxidizable ions like Fe^{2+} and Mn^{2+} and microbes that were present in the water may be the cause of this loss of chlorine from the water as indicated by Jadas – Hecart *et al.*, 1992.

The bulk decay coefficient obtained from the trend line in figure 4.2 is 0.05 h^{-1} . This signifies that Bulk decay coefficient for water from Barekese Headworks is 0.05 h^{-1} which according to Lawler and Singer (1993) is acceptable because it is below the recommended maximum acceptable bulk decay coefficient limit of 0.2 h^{-1} .

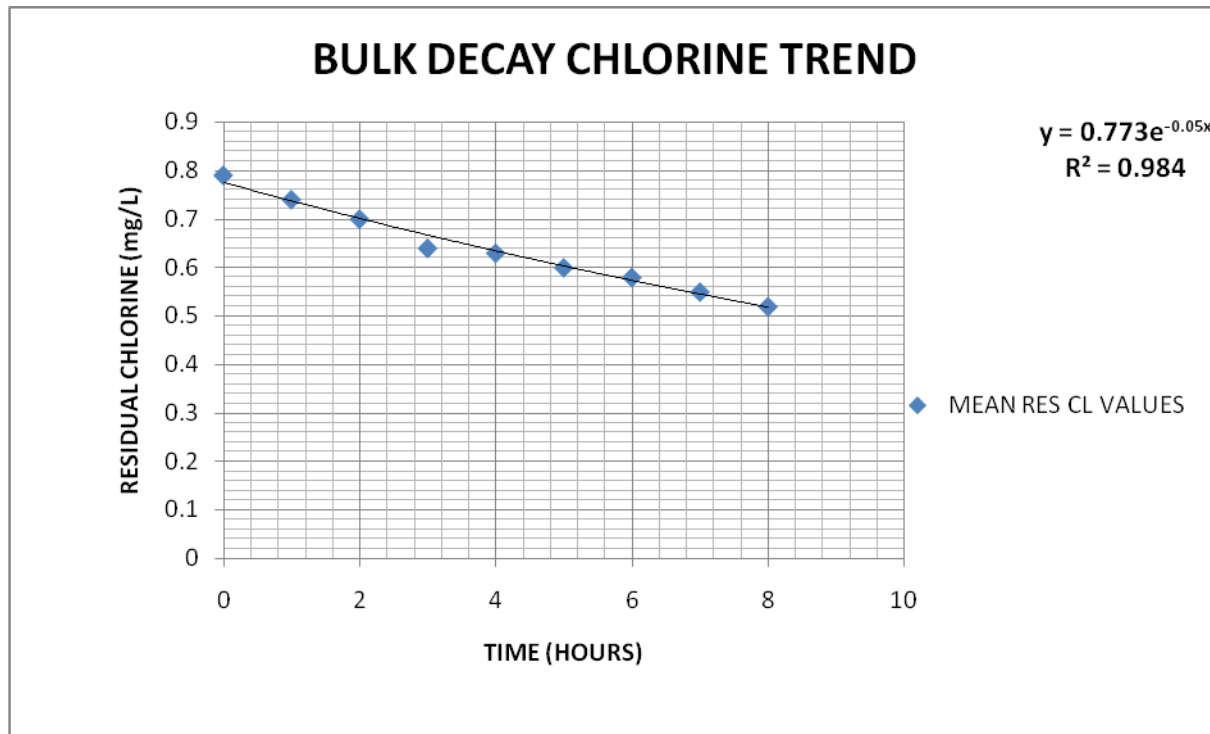


Figure 4. 2: Bulk Residual Chlorine decay trend at Barekese Headworks

4.3 Overall and Wall Chlorine Decay

From literature, it is known that the overall and the wall chlorine decay processes follow either the zero order or the first order reaction kinetics based on the condition of the pipe materials (DiGiano and Zhang, 2005). From figure 4.3, it is seen that the overall chlorine decay process follow the first order reaction kinetic model since the equation of the line depicts it.

Due to the aged nature of the pipelines, the wall demand for residual chlorine is the major cause of residual chlorine decay in the distribution system. This is confirmed from the experimental

results and bulk decay computations, because with the 34% bulk demand requirement for 8 hours in the water supply from Barekese Headworks, about 66% of residual chlorine loss in the KWDN can be attributed to the pipe wall demand. The cast iron pipes are about eighty four years, the Asbestos cement pipes are over fifty years whilst that of the polyvinyl chloride (PVC) are twenty years and these impart negatively on residual chlorine and compromises the distributed water quality.

From the computations using the hydraulic data of the distribution system, it takes about eight hours for water to travel from Barekese Headworks to Adum in the Kumasi Central district of GUWL, a distance of about 20.7 Km. Over this distance and period, the residual chlorine decays from an initial mean value of 0.60mg/L to 0.021mg/L. This range of values was consistently obtained for the eight sampling episodes. This indicates that the decay is very rapid.

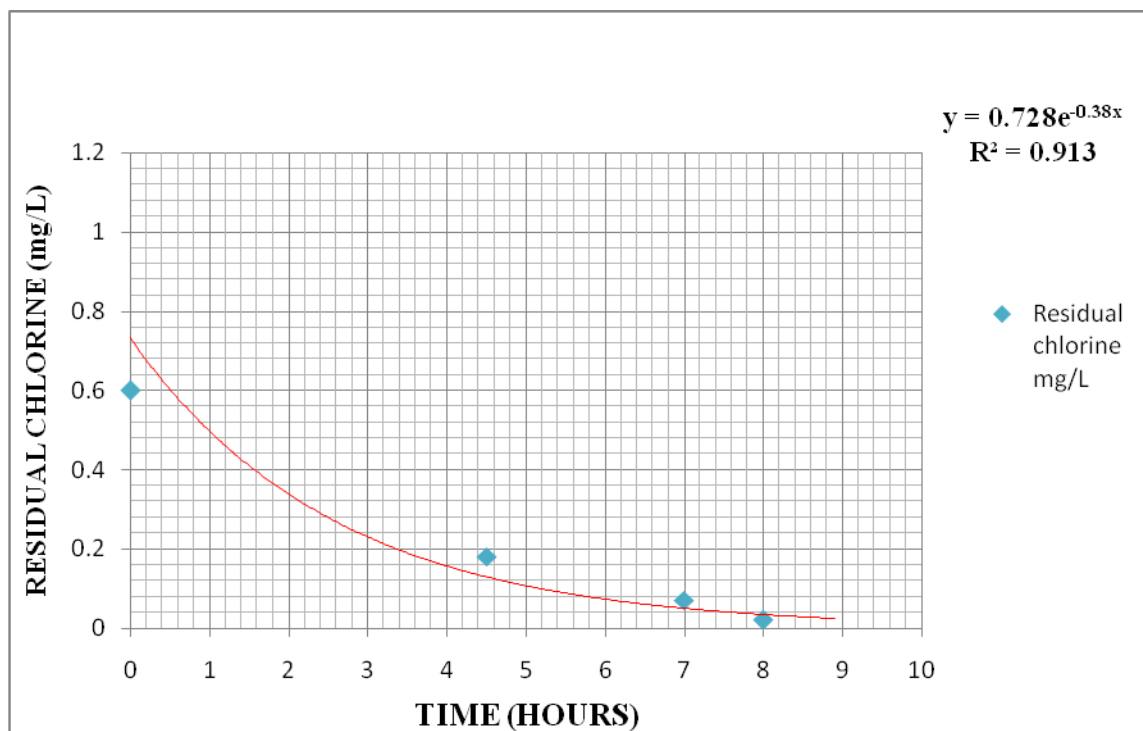


Figure 4.3: Overall Residual Chlorine decay trend in KWDN

From Figure 4.3, it takes an average travel time of 3hours for the residual chlorine to decay from the initial concentration of 0.6mg/L to the minimum acceptable standard of 0.20mg/L. This implies that after every one hour of travel time a decay factor of 0.20 mg/L is observed.

The overall chlorine decay coefficient is 0.38 h^{-1} since the coefficient from the trend line in figure 4.3 is 0.38.

Since both the bulk and the wall decay processes follow a first order reaction kinetic, the wall decay coefficient is obtained when the bulk decay coefficient is subtracted from the overall decay coefficient as reported by Rossman *et al.*, 2001 and Hallam *et al.*, 2002.

$$K_{\text{overall}} = K_w + K_b$$

$$K_w = (0.38 \text{ h}^{-1}) - (0.05 \text{ h}^{-1})$$

$$K_w = 0.33 \text{ h}^{-1}$$

Since the pipe materials from Barekese Headworks to Adum in the Kumasi Central district is made up of 18km stretch of 900mm steel pipes and about 2.7 km of various diameters of cast iron pipes, with some concrete reservoirs at the Achiase Booster Station and the Suame Reservoir site, an effort was made to distinguish between the decay due to the steel pipes and the cast iron pipes and finally that of the concrete reservoirs.

4.3.1 Overall chlorine decay due to steel pipes

The residual chlorine decay taking place in the 18 km stretch of 900mm steel pipes from the Barekese Headworks through the Achiase Booster station was monitored. The total travel time is 4hours and the residual chlorine decayed from an initial mean value of 0.84mg/L to 0.38 mg/L.

The overall decay coefficient is 0.2 h^{-1} and the wall decay due to the steel pipes is 0.15 h^{-1} as demonstrated in the mathematical equations below.

$$K_{\text{overall}} = K_w + K_b$$

$$K_w = K_{\text{overall}} - K_b$$

$$K_w = (0.20 \text{ h}^{-1}) - (0.05 \text{ h}^{-1})$$

$$K_w = 0.15 \text{ h}^{-1}$$

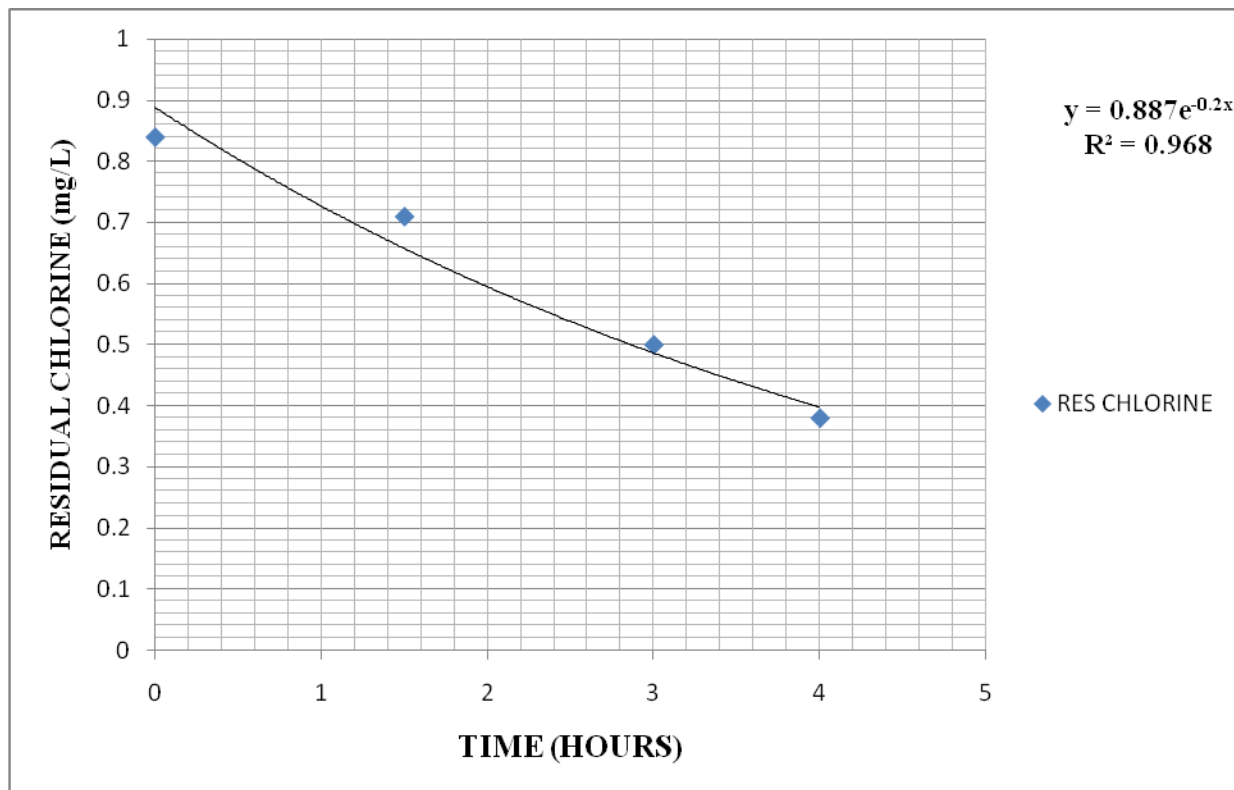


Figure 4.4: Overall Residual Chlorine decay due to the steel pipes in KWDN

4.3.2 Overall Chlorine decay due to Cast iron pipes

The residual chlorine decay taking place in the 2.7 km stretch of various diameters of the cast iron pipes from the Suame Reservoir site to the house connected to the distribution line serving

Agyaba House in Adum located in the Kumasi Central district in the distribution network was also monitored. The total travel time is 3 hours. The residual chlorine decayed from an initial mean value of 0.27 mg/L to 0.04 mg/L as seen in figure 4.5 below. The overall decay coefficient is 0.63 h^{-1} and the wall decay due to the steel pipes is 0.58 h^{-1} .

$$K_{\text{overall}} = K_w + K_b$$

$$K_w = K_{\text{overall}} - K_b$$

$$K_w = (0.63 \text{ h}^{-1}) - (0.05 \text{ h}^{-1})$$

$$K_w = 0.58 \text{ h}^{-1}$$

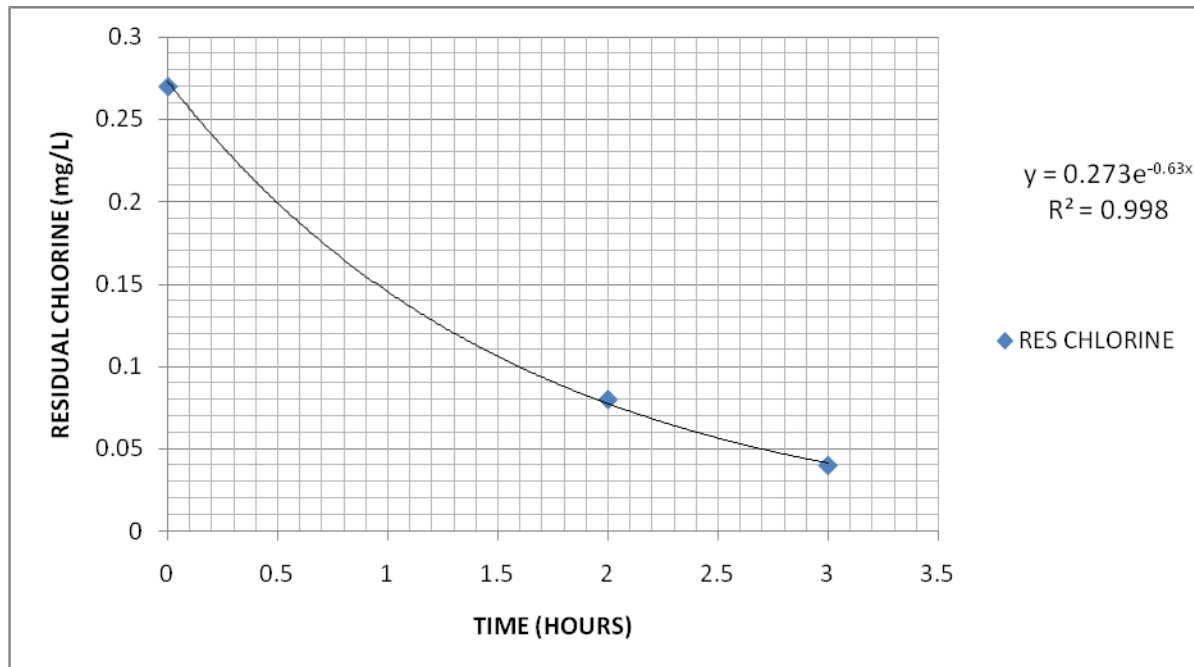


Figure 4.5: Overall Residual Chlorine decay due to the cast iron pipes in KWDN

This clearly indicates that a lot of residual chlorine decay takes place in the cast iron pipes over a short distance compared to that of the steel pipes and this may be due to very high levels of encrustations that have taken place in the lumen of the pipes and the velocities of flow.

The velocity of flow in the cast iron pipes from the hydraulic computations is between 0.3 m/s to 0.4 m/s compared to that of the steel pipe which is 1.67 m/s. This implies that with this slower travel pace, the water is retained longer in the cast iron pipes hence more contact with the lumen of encrusted pipes.

The encrustations also serve as attachment sites for biofilms. The iron and manganese oxides in the encrusted pipes also react with the free residual chlorine in the water to deplete further the residual chlorine concentration in the distributed water. This accounts for the rapid loss of residual chlorine in the water traveling in the cast iron pipes.

4.3.3 Overall chlorine decay due to concrete reservoir

According to Zhang *et al.*, 1992, residual chlorine also decays in a water reservoir due to reactions of chlorine with oxidizable compounds and the decay process follows a first order kinetic model. The longer the water is retained in the reservoir, the more the chlorine decays due to further reactions that can take place with the walls of the reservoir.

The residual chlorine decay taking place in the two million capacity concrete reservoir at the Suame was monitored. The retention time of the water in the reservoir ranged from 30 minutes to 1 hour depending on the water demand and the areas to be served. From figure 4.6, the equation of the line shows that the decay process in the concrete reservoir follows the first order reaction kinetics. The free residual chlorine decayed from an initial mean value of 0.38 mg/L to 0.27 mg/L. Chemical reactions between the free residual chlorine with concrete lining of the reservoir together with reactions with other Physico- chemical and microbiological constituents of the water may be the cause of this chlorine loss.

The overall decay coefficient was found to be 0.34 h^{-1} and from the mathematical computations below, the wall decay due to the concrete reservoir is 0.29 h^{-1} .

$$K_{\text{overall}} = K_w + K_b$$

$$K_w = K_{\text{overall}} - K_b$$

$$K_w = (0.34 \text{ h}^{-1}) - (0.05 \text{ h}^{-1})$$

$$K_w = 0.29 \text{ h}^{-1}$$

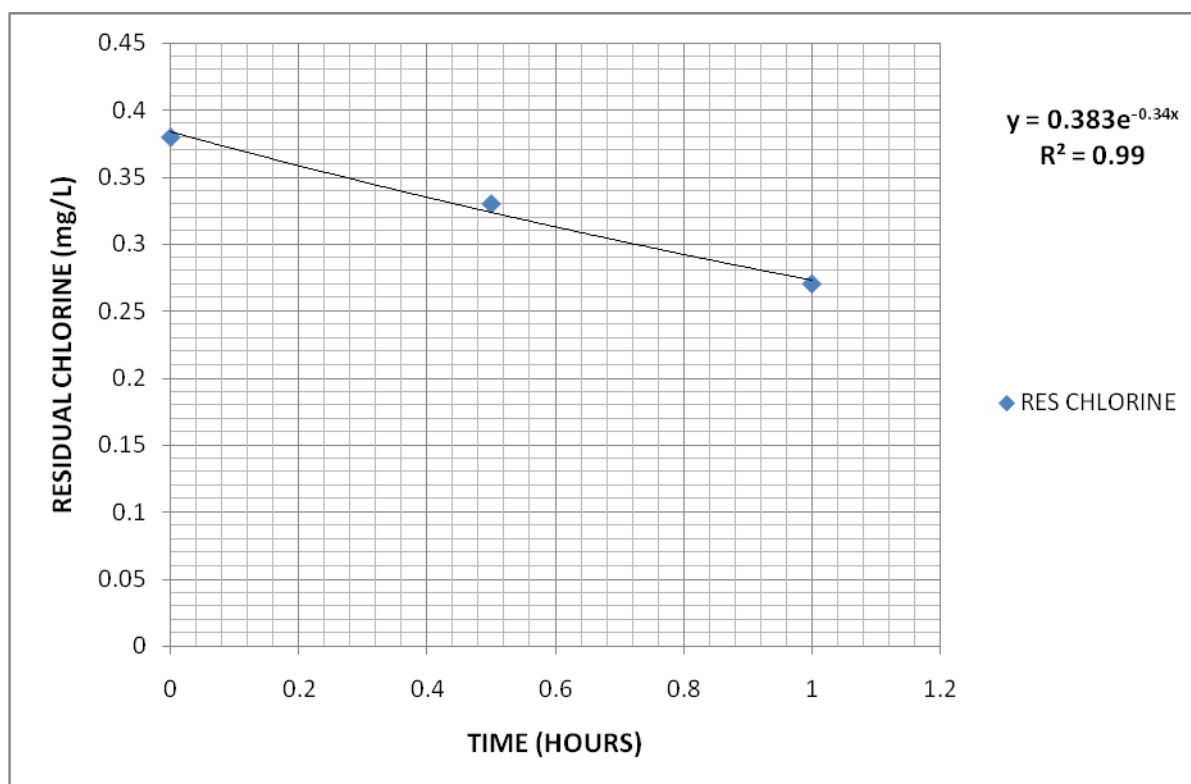


Figure 4.6: Overall Residual Chlorine decay due to the concrete reservoir at Suame

4.3.4 Residual Chlorine interaction with Physico- chemical Parameters

When chlorine compound is dissolved in water, the residual chlorine content is affected by various physical and chemical constituents in the water. Among the physical parameters that

affect the level of the residual chlorine in water and subsequently affect its disinfecting ability are temperature, pH, turbidity, sediments or suspended solids, total dissolved solids and total solids.

Due to the volatile nature of chlorine, it may either be lost through the process of evaporation or reactions with various chemical constituents of the water. Organic and inorganic constituents of water such ferrous ion, manganous ion, sulphides, ammonia, total organic compounds also undergoes various reactions with the residual chlorine concentration in the water.

The physical parameters such as suspended solids and total solids renders disinfection ineffective since they serve as attachment sites for microbes and therefore shield them from the bactericidal actions.

4.3.5 Effect of Conductivity and Total Dissolved Solids on Residual Chlorine

Electrical conductivity (EC), is affected by temperature and the presence of inorganic dissolved ions such as chloride, nitrate, sulphate, and phosphate anions, or sodium, magnesium, calcium, iron, and aluminum cations in the water (Spellman, 2003).

The experimentally determined mean conductivity value reduced from 140.35 $\mu\text{S}/\text{cm}$ to 134.46 $\mu\text{S}/\text{cm}$ as the water flows from the headworks to the Suame reservoir site. The total dissolved solids value also reduced correspondingly from an initial mean value of 90.33 mg/L to 71.08 mg/L as seen in figure 4.7. This implies that certain ions such as ferrous and manganese (II) which hitherto were dissolved in the water have been oxidized by the residual chlorine in the water and as such been transformed from the dissolved state to the insoluble iron (III) and manganese (III) state. These insoluble particles are either deposited in the pipelines or carried along depending on the pressure and the velocity of flow in the pipeline into the reservoir. This

increases the turbidity and the total suspended solids values in the water, whilst reducing the electrical conductivity. This phenomenon is observed in the high turbidity value of the water in the Suame reservoir and confirms that the insoluble particles are carried into the Suame reservoir as seen in figure 4.10.

However from the reservoir, as the water flows into the cast iron pipes some more ions are dissolved back into the water due probably to the anoxic or anaerobic conditions that prevail in the reservoir which facilitates the reduction of the oxidized forms of iron and manganese. Eventually, the concentrations of these ions increases and this accounts for the increase in both the conductivity and the total dissolved solids as the water travels through the cast iron pipes to Adum as seen in figure 4.7.

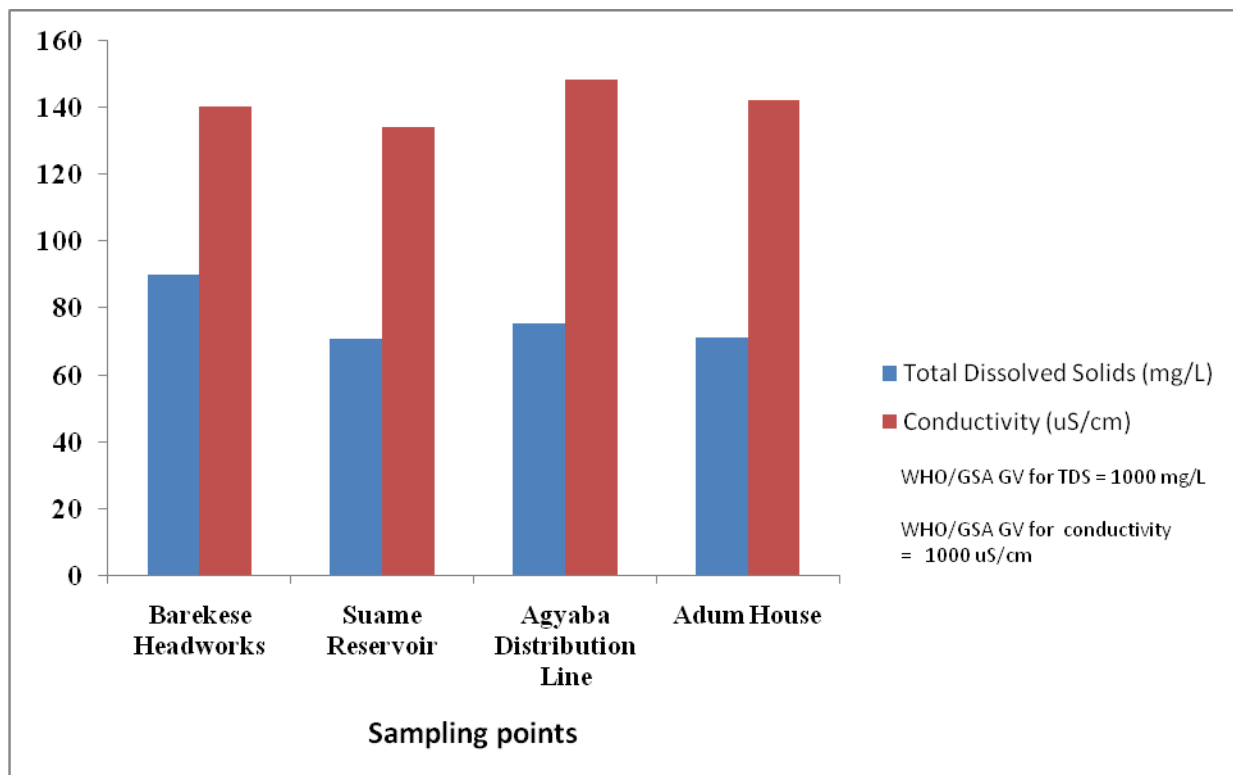


Figure 4.7: Mean Conductivity and Total Dissolved Solids values in KWDN

4.3.6 Effect of Iron and Manganese on Residual Chlorine

Chlorine, being such a strong oxidizing agent, reacts rapidly with a wide range of chemicals in water. The consumption of chlorine by the reaction with both the soluble iron (II) and manganese (II) results in the formation of oxidized insoluble forms of iron (III) and manganese (IV) that settles out of the water. As these reactions take place, the concentration of the residual chlorine in the water depletes. The higher the initial values of these ions the more rapid the oxidation reactions take place thereby reducing the residual chlorine values to insignificant values.

From the experimental results, the iron concentration reduced from an initial mean value of 0.122 mg/L to 0.093 mg/L and that of manganese also reduced from 0.032 mg/L to 0.023 mg/L as the water travels from Barekese Headworks to Suame as seen in figure 4.8. This can be attributed to some of the iron and manganese ions in the water being oxidized and settling out.

However, from the Suame reservoir to Adum, the mean concentration of iron and manganese ions increases 0.185 mg/L and 0.138 mg/L respectively as the mean value of the residual chlorine goes to insignificant value of 0.07 mg/L. This trend indicates that more of the iron and manganese ions get re - dissolved in the water as it flows through the cast iron pipes to Adum and can be attributed to the reductive conditions that prevail within the pipe network. Also, it is possible that the encrusted cast iron pipes may be leaching some of its iron and manganese constituents into the water during times of low water pH values.

Water containing excessive amount of iron and manganese has no adverse health effects; they are in fact essential to the human diet. However, they can stain clothes and plumbing fixtures and sometimes add a rusty taste and look to water. Iron and manganese also promotes the growth of iron bacteria, a group of organisms that obtains its energy for growth from the chemical reactions

when iron and manganese mix with dissolved oxygen in water. The growth of these iron bacteria in the pipelines are effectively handled by chlorination and residual chlorine in the water.

From the experimental results, the mean values of iron and manganese are lower than both the WHO and the GS maximum acceptable value of 0.3 mg/L and 0.40 mg/L respectively.

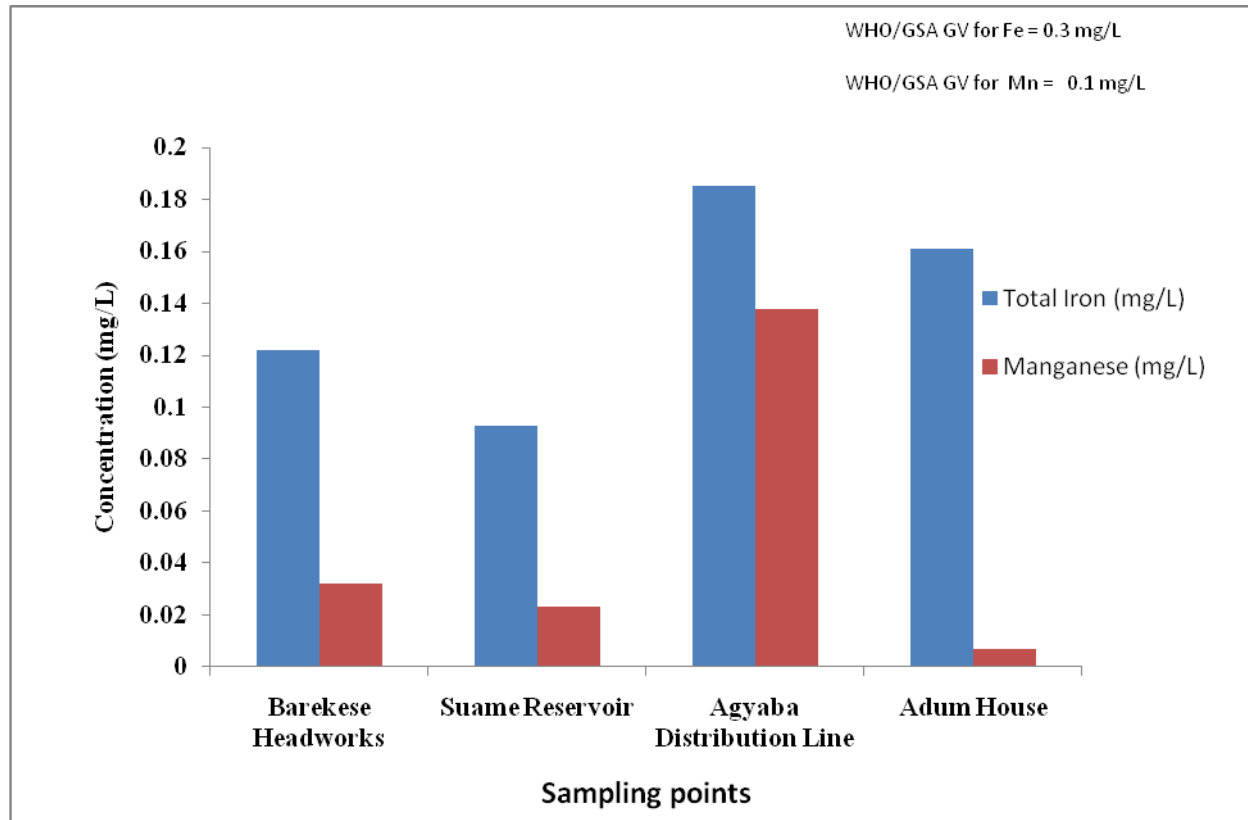


Figure 4.8: Mean Total Iron and Manganese values in the KWDN

4.5.3 Effect of Nitrates on Residual Chlorine

Residual chlorine has no known effect on the nitrates in water. However, when the nitrogenous compounds are in the intermediate nitrite state, they can be oxidized to the nitrates state by the presence of the residual chlorine in the water. Chloramines can also be formed which is a weak disinfectant.

From the experimental results, the nitrates, no matter the concentration of the residual chlorine in the water did not vary significantly as the mean values at all the sampling points ranged from 1.483mg/L to 1.78mg/L as seen in figure 4.9. These values are far lower than the maximum WHO and GSA standard of 50.0mg/L.

The trend indicates that the possibility of occurrence of biofilms in the network may probably be very low since nitrates as a nutrient, supports biofilms and microbial growth in the network and hence the concentration would have been depleted.

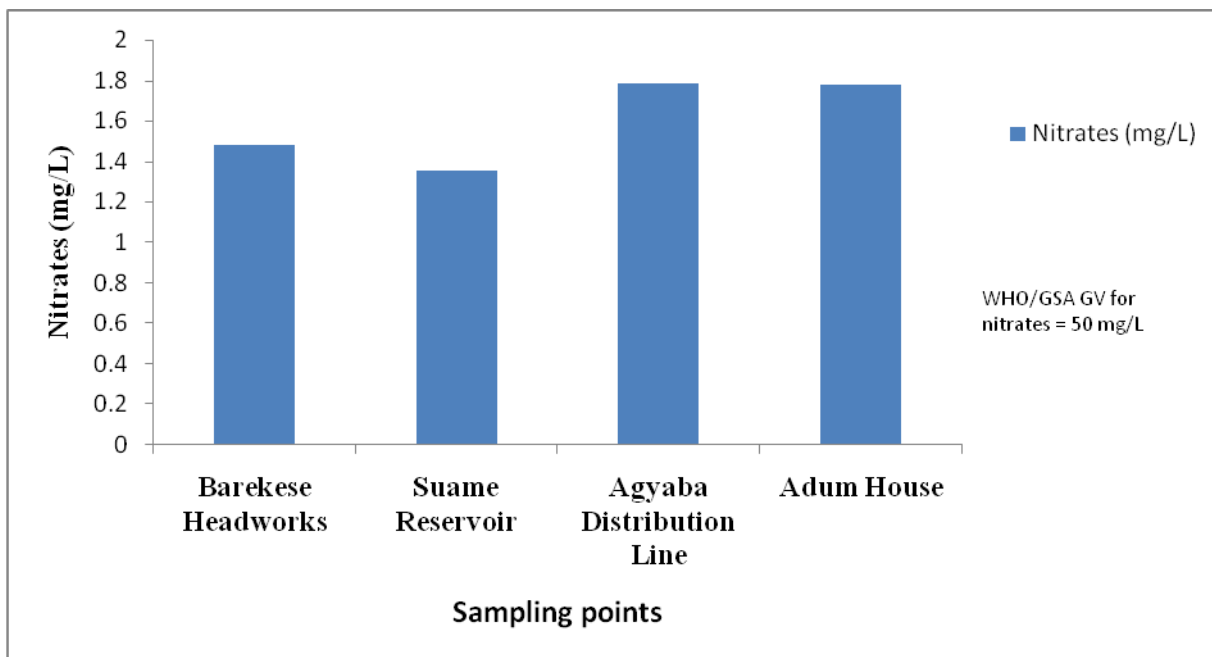


Figure 4.9: Mean Nitrates values in the KWDN

4.3.7 Effect of Metals on Residual Chlorine

Residual chlorine in water can react with metals such as calcium and magnesium to form the insoluble chlorides which are chalky sediments and settles as the water flows through the pipe network. The source of the calcium and magnesium in water comes from the rock formations of which the river bed and also from the lime which is used for pH correction of the final water.

From figure 4.10, the experimental values of calcium concentration in the distributed water ranged from an initial mean value of 14.85mg/L to 18.89mg/L. This can be attributed to the lime used for pH correction. The magnesium concentration also ranged from an initial mean value of 11.073mg/L to 11.654mg/L which does not show any significant variation.

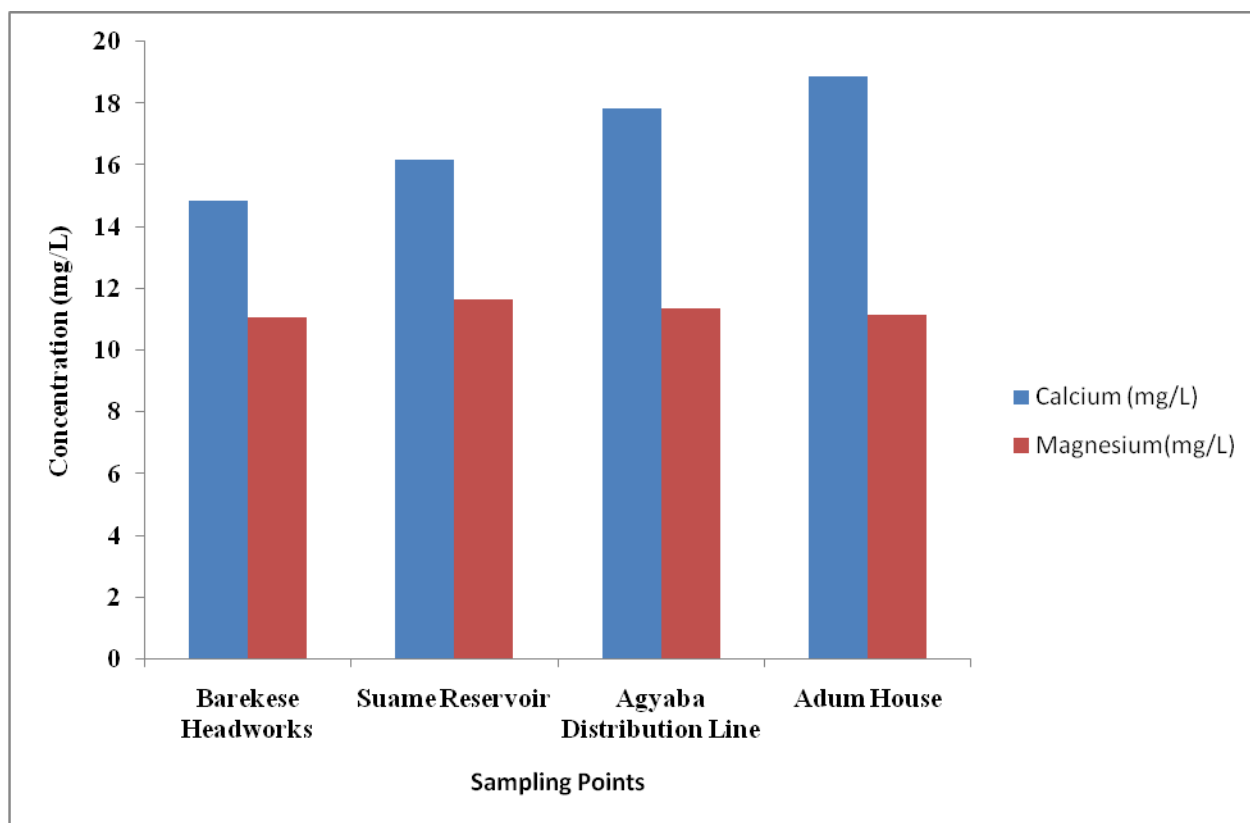


Figure 4.10: Mean Calcium and Magnesium values in the KWDN

4.3.8 Effect of Turbidity on Residual Chlorine

The turbidity of water is one of the most important parameters which is considered during the disinfection of water at the treatment point. For chlorination of water to be very effective, the turbidity of the water should be preferably below 1 NTU. However, when it is higher than 1 NTU, water disinfection can still be done although more chlorine will be required to disinfect the same quantity of water. Beyond the 5 NTU, the water will necessitate filtration before

chlorination should be done. The challenges with turbidity are the constituents of the turbidity causing agents in the water. These are mainly sediments or solids that serve as shielding materials for microbes against the chlorine disinfectant. Hence when the water is very turbid, water disinfection will be ineffective.

From the study, the turbidity of the water ranged from an initial mean value of 1.09 NTU at the headworks to a mean value of 1.78 NTU at the Suame reservoir. As the water travels further to Adum in Kumasi Central district, the mean turbidity value reduces to 0.92 NTU in the network. This signifies that with adequate residual chlorine concentration in the water coupled with the reservoir at Suame being cleaned to be free from sediments, disinfection will be enhanced and public health will be protected since the turbidity values are satisfactory.

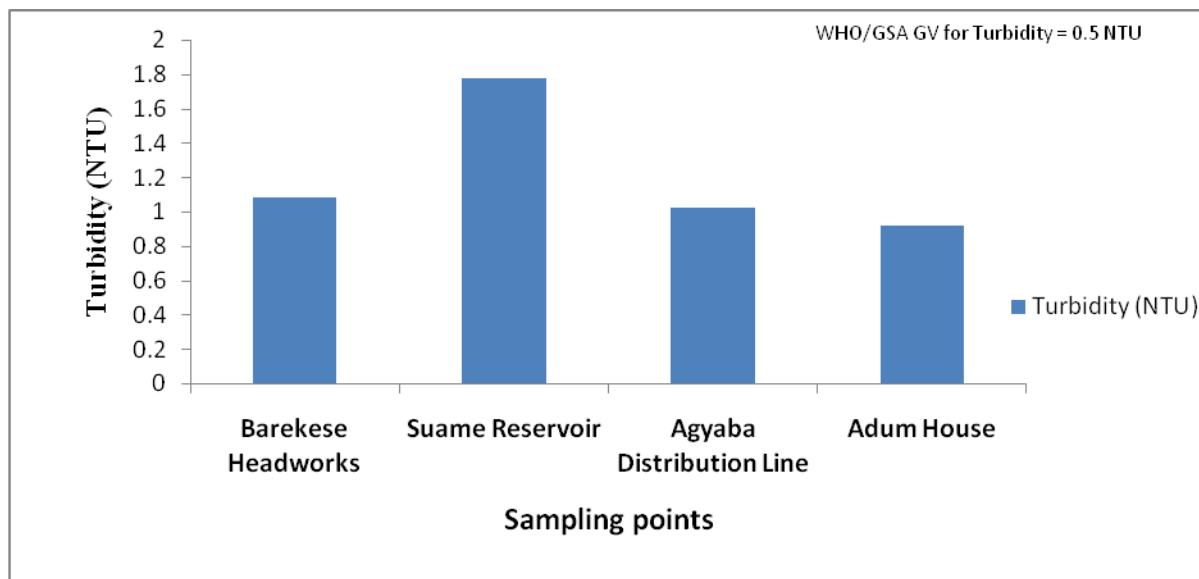


Figure 4.11: Mean Turbidity values in the KWDN

4.3.9 Effect of Microbes on Residual Chlorine

In water microbiology, the microorganisms of interest are the *Coliforms*, *E.Coli* and *Salmonella spp.*, *Streptococcus faecalis* and *Clostridium spp.* Their presence in water indicates contamination

and renders the distributed water unwholesome or unfit for drinking purposes. From the Ghana Standard Authority document on drinking water quality requirement (GS 175, 1997), it states that water for drinking purposes must be free from *coliform bacteria*, *escherichia coli* and *salmonella species*.

Experimental results indicate the presence of these microbes even at the treatment plant in spite of the rigorous treatment processes that the water goes through. The mean residual chlorine concentration in the water at the treatment plant is 0.6mg/L and this should have been significant enough to kill all these microbes. However, the mean microbial load at the plant are; 3cfu/100ml Coliforms, 2cfu/100ml E.Coli and 2cfu/100ml Salmonella spp. Above pH 7, the formation OCl^- ions are favoured rather than HOCl and since pH correction is done on the plant before chlorination it is possible that the residual chlorine in the water may be existing in the inferior OCl^- form. The contact time, which from the design of the plant should have been 2 hours, is also not strictly adhered to due to the mounting pressure on the utility company to always be supplying water to meet the ever increasing demand. Hence the clear water well is behaving as a holding tank with a very short retention time which is insufficient to ensure effective disinfection. All these contribute to the survival and growth of microbes thereby compromising of the bacteriological quality of the water. Hence more residual chlorine will be needed for complete water disinfection.

As the residual chlorine concentration decreases to insignificant levels in the distribution network, bacteriocidal activity becomes ineffective and the microbes are able to continue with normal life cycle and multiply their population in the water.

During the sampling episodes, it was observed that loads of sediment and settleable solids were deposited in the 2 Million gallon reservoir at Suame and this could account for the high colonies coliforms, *E.Coli* and *Salmonella* that were isolated in the culturing media from the Suame reservoir samples. It presupposes that the reservoir is currently serving as a breeding ground for microbes. In the event of adequate residuals, these sediments also shield these microbes from the disinfection ability of the chlorine. Hence more of the residual chlorine will be needed to safeguard the water quality since the sediments render water disinfection ineffective.

Finally, the high level of encrustation also serves as adsorption sites for biofilms and other microbes and may even promote their growth in the pipes especially the cast iron pipes at Adum. This is seen in the high mean microbial growth of 13cfu/100ml for *coliform bacteria*, 5cfu/100ml of *E.Coli* and 3cfu/100ml of *Salmonella spp* in the distribution line at Adum.

It is also evident that the more the residual chlorine concentration becomes insignificant or depleted in the distributed water, the more the microbes multiply in the water.

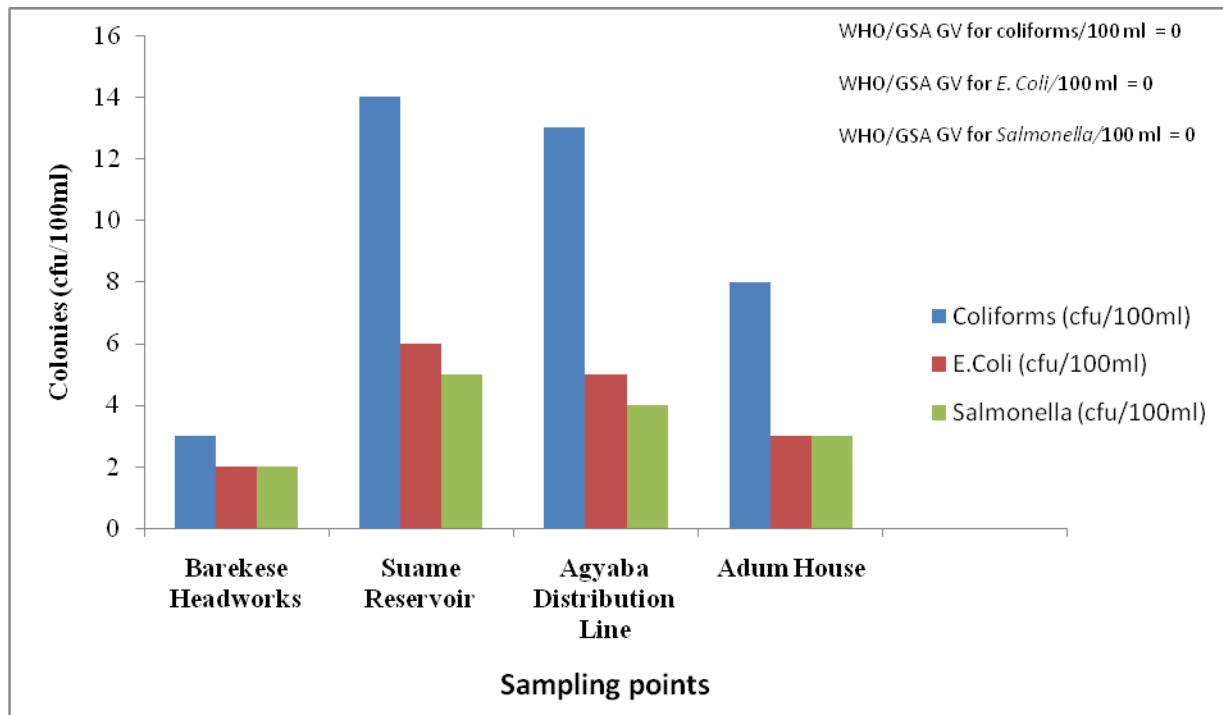


Figure 4.12: Mean counts of Coliforms, E.Coli and Salmonella in the KWDN

4.4 Residual Chlorine decay modeling using 0.60mg/L initial value

Free residual chlorine decay modeling in the Kumasi water distribution network using SynerGEE was conducted in order to predict areas in the network where the residual chlorine concentration will be lower than the recommended Ghana Standard of 0.2 mg/L so that stepwise chlorination can be advised for implementation.

When the experimental initial mean residual chlorine value of 0.60 mg/L was used for the modeling, most of the nodes in the entire network gave residual chlorine values below the recommended 0.20 mg/L as depicted in figures 4.13 and 4.14 which shows the nodal values at 9:00 am and 4:00 pm when the water supply would have reached Adum in the Kumasi Central district.

For ease of identification of nodal residual chlorine values, unless otherwise stated, the following colour codes were adopted;

- Red - For nodes with residual chlorine concentration < 0.20 mg/L
- Blue – For nodes with residual chlorine concentration ranging ≤ 0.20 mg/L to ≤ 0.50 mg/L
- Green – For nodes with residual chlorine concentration > 0.50 mg/L
- Purple – For nodes with poor or no base flows in the hydraulics which might unduly affect the residual chlorine concentrations obtained from the model.

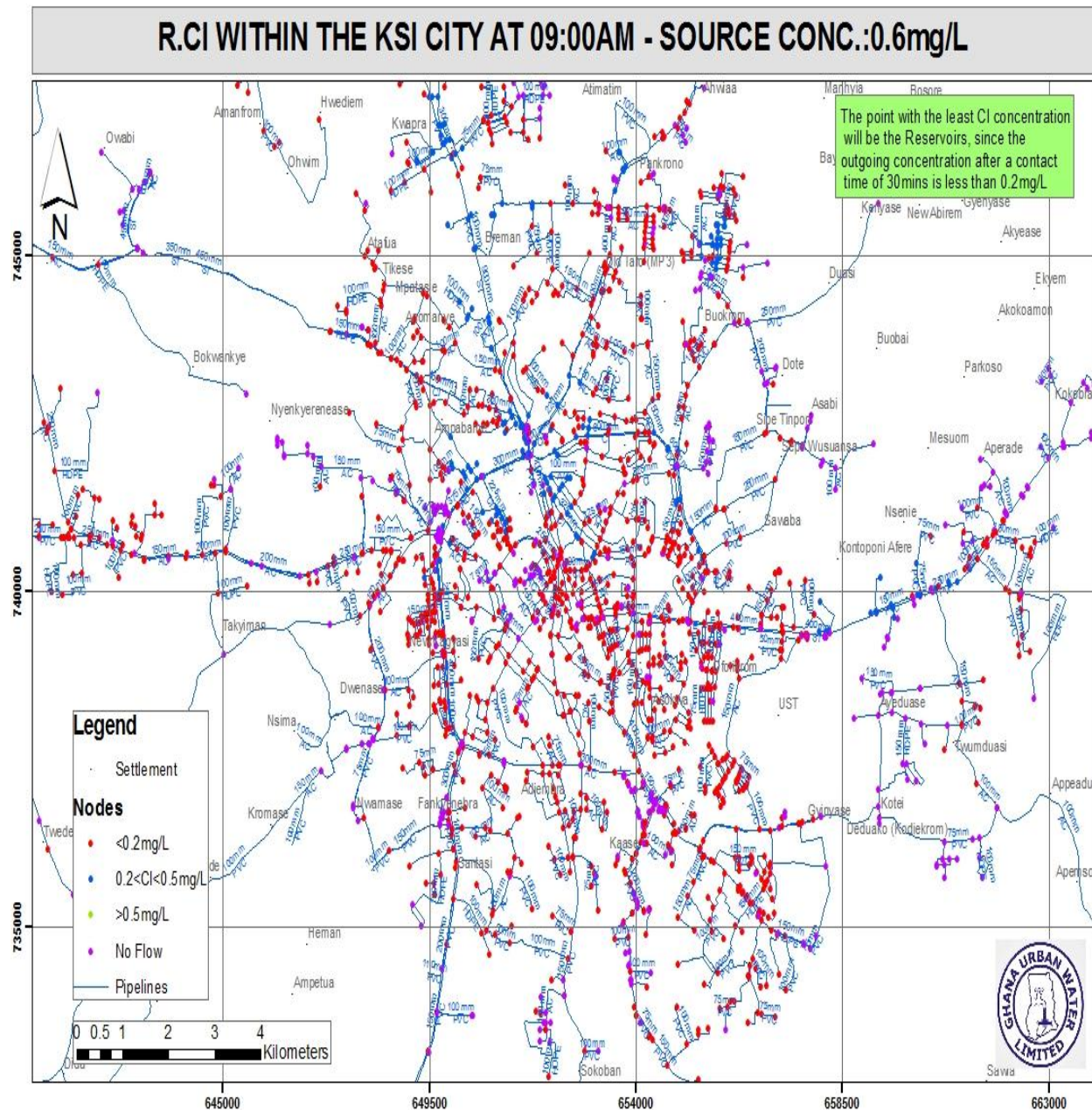


Figure 4.13 Map showing Results of Nodal Residual Chlorine values from SynerGEE model at 9am

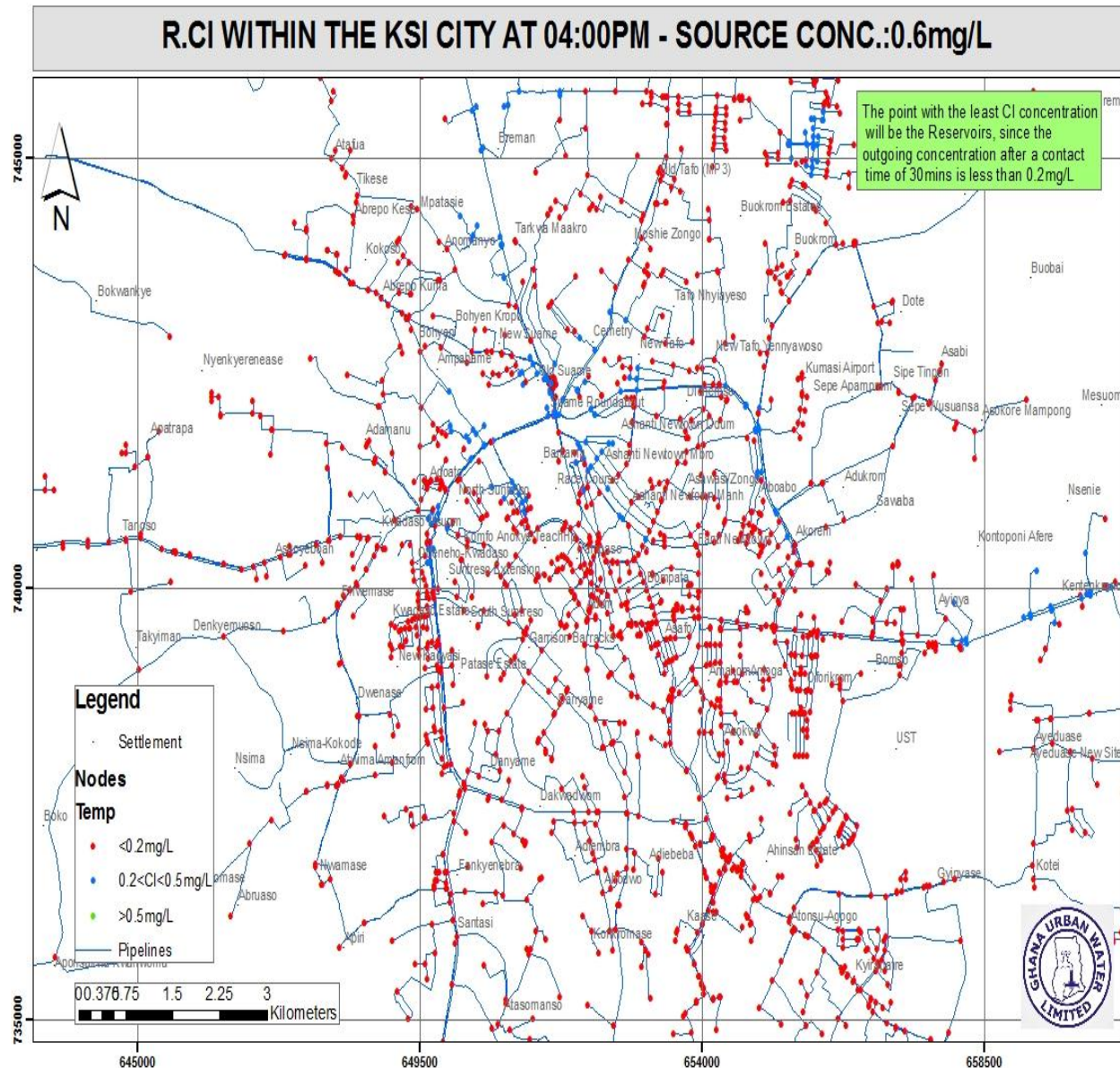


Figure 4. 14 Map showing Nodal Residual Chlorine model values at 4pm

The model results at 9:00 am and 4:00 pm indicate that only the nodes on the 900 mm high pressure steel pipe line which carries bulk water from Barekese Headworks to Suame Reservoir site had adequate residual chlorine values.

However, during this 18 km bulk water transport, the residual chlorine concentration reduces from the initial 0.60 mg/L value to 0.28mg/L as seen in figure 4.15 below. After a residence time

of 30 minutes in the 2 Million gallon reservoir, the residual chlorine concentration reduces further to 0.18mg/L which is below the minimum acceptable value of 0.20 mg/L as still seen in Figure 4.15. This therefore necessitates a chlorine boosting point at Suame.

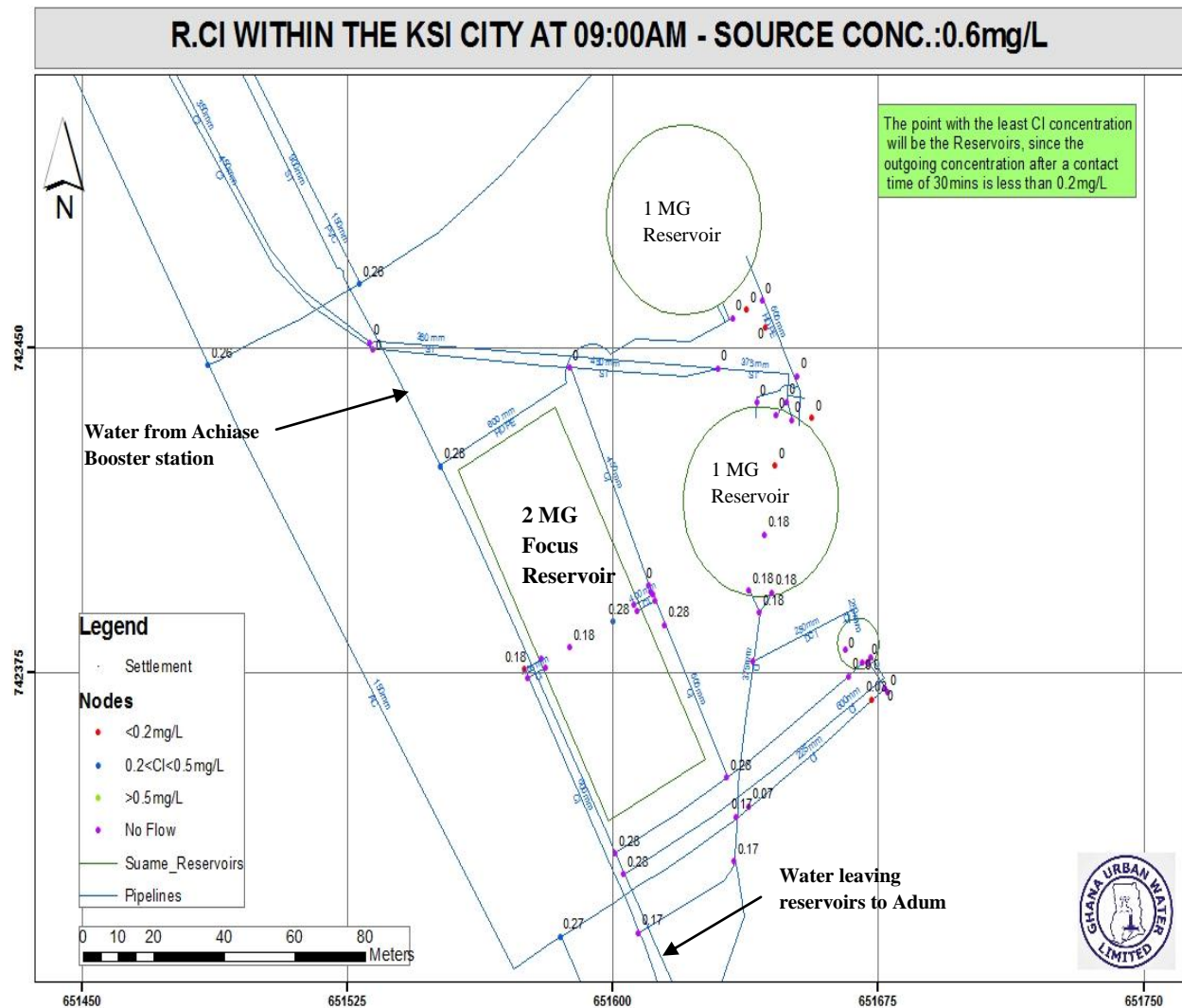


Figure 4. 15 Map showing Suame Residual Chlorine model values at 9am

The focus reservoir is the rectangular one because it supplies water to the Kumasi Central District and many other areas in the network.

However, from the operations in the distribution network, some areas are served directly from the high pressure 900 mm Steel pipeline and therefore not all the water goes into the interconnected reservoirs before water distribution starts. This implies that for effective stepwise chlorination process the boosting point should be located before the node where the water is divided into their respective outlets of the network as seen in figure 4.16 below.

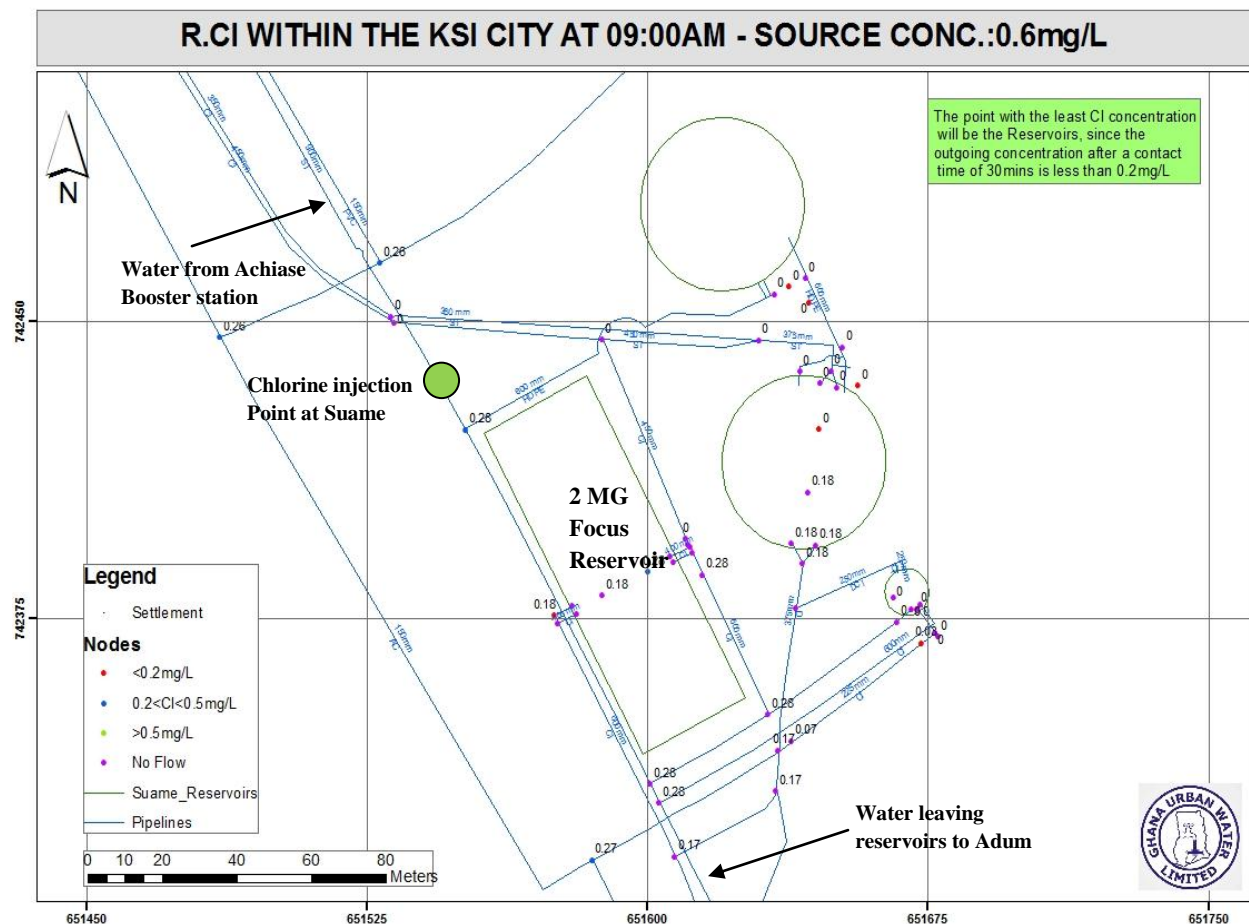


Figure 4. 16: Map showing Chlorine injection point at Suame

However, the feasibility of implementing this chlorine boosting point on the 900 mm high pressure steel pipe was considered and it was realized that there will be challenges. However,

when the boosting point is located at the Achiase Booster Station and a residual chlorine dosage of 1.50 mg/L is applied, the results were better and implementable.

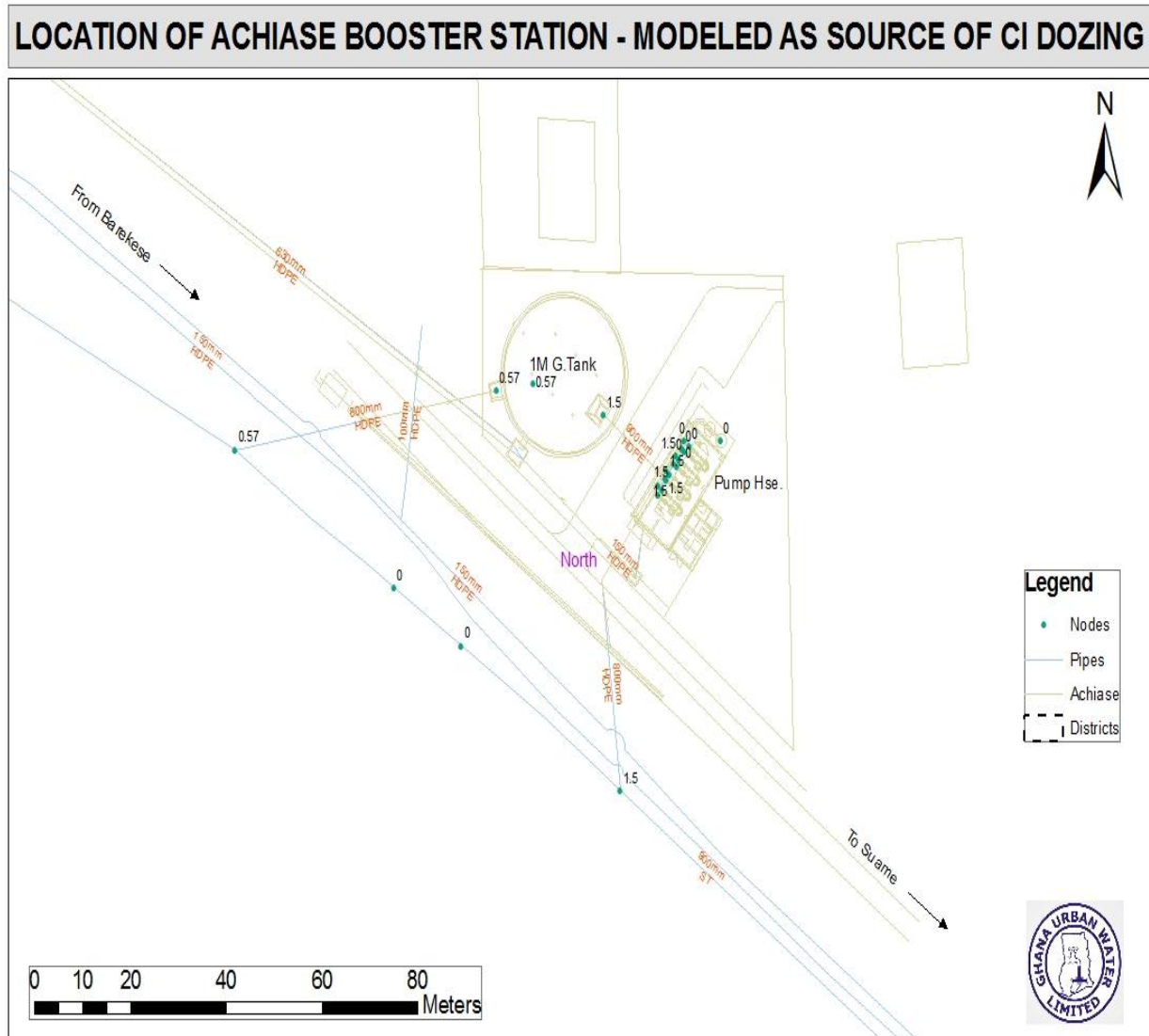


Figure 4. 17: Map showing residual chlorine boosting at Achiase

Further detailed analysis of the modeling results indicated that there were still challenges of low residual chlorine nodal values at the peripherals of the network.

To solve the problem totally whilst maintaining the initial mean residual chlorine concentration of 0.60 mg/L at the Barekese Headworks and 1.50 mg/L residual chlorine boosting at Achiase Booster Station, other chlorine boosting points should be located at Pankrono and Buokrom Booster Stations in the Kumasi North East district, the node before the Coca Cola Bottling Company at Ahinsan in the Kumasi South district, KNUST Booster Station in the South East district and finally a node at Kodie on the Offinso transmission line as indicated in figure 4.19.

This will make the entire distribution network to have nodal residual chlorine values which are appreciable and adequate enough to handle biofilms and other pathogenic microorganism in the network thereby rendering the distributed water wholesome enough to safe guard public health.

The only nodes that may have challenges with low residual chlorine values are those with no or poor base flow pattern. Also, nodes that receive water from the Owabi WTP continued to show red spots indicating low or even no chlorine residuals since they were not considered within the scope of the work.

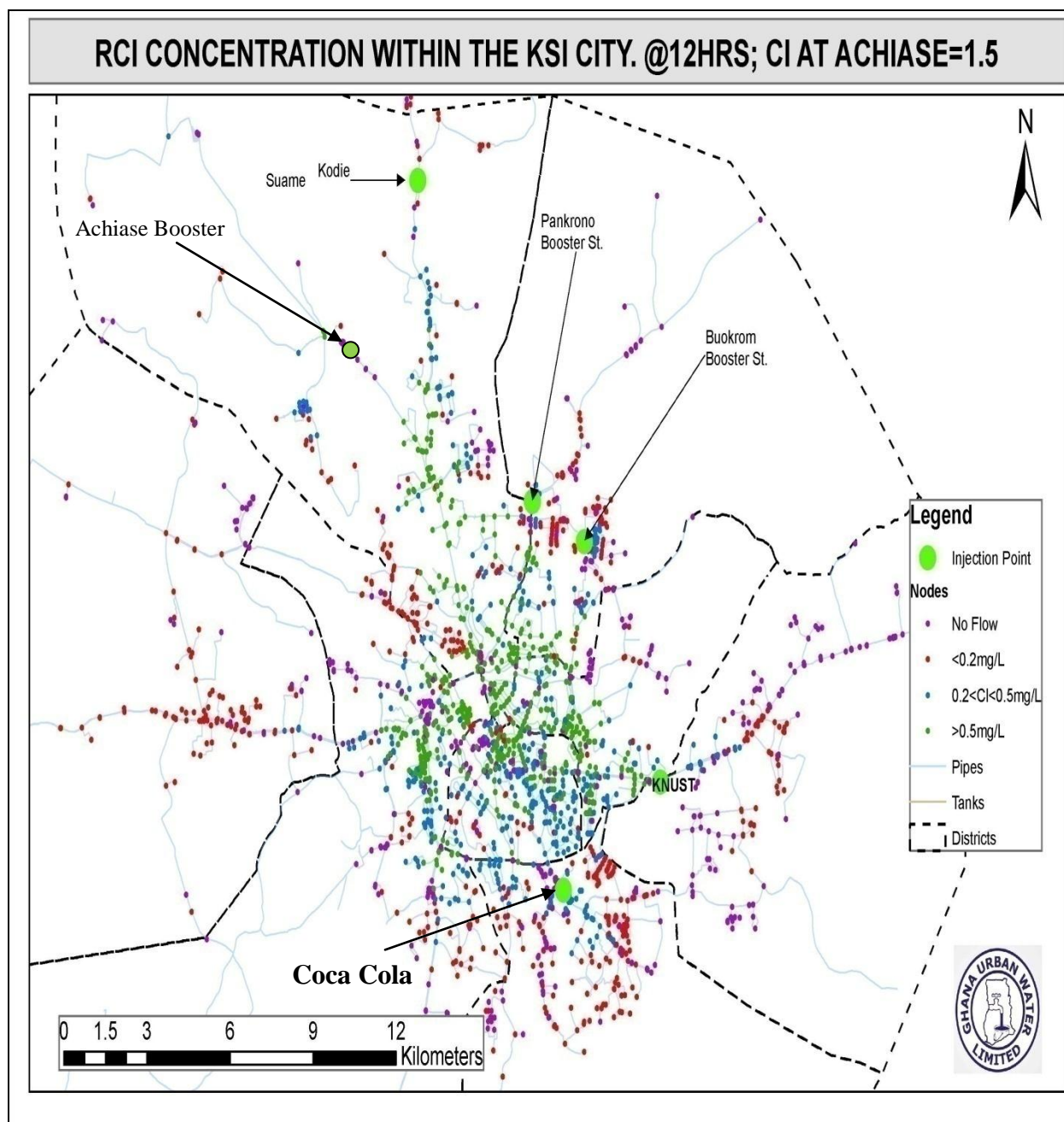


Figure 4.18 Map showing Recommended Chlorine boosting points when the initial chlorine value is 0.60 mg/L

4.5 Residual Chlorine decay modeling using 2.0 mg/L initial value

When the initial residual chlorine concentration of 2.0 mg/L was used for the SynerGEE modeling under steady state and extended time varying conditions, the entire network showed good results with the water travelling longer distances from the Barekese Headworks through Suame reservoir to the general network before the residual chlorine concentration dropped lower than the minimum acceptable value of 0.20 mg/L as seen in figures 4.18 and 4.19 below.

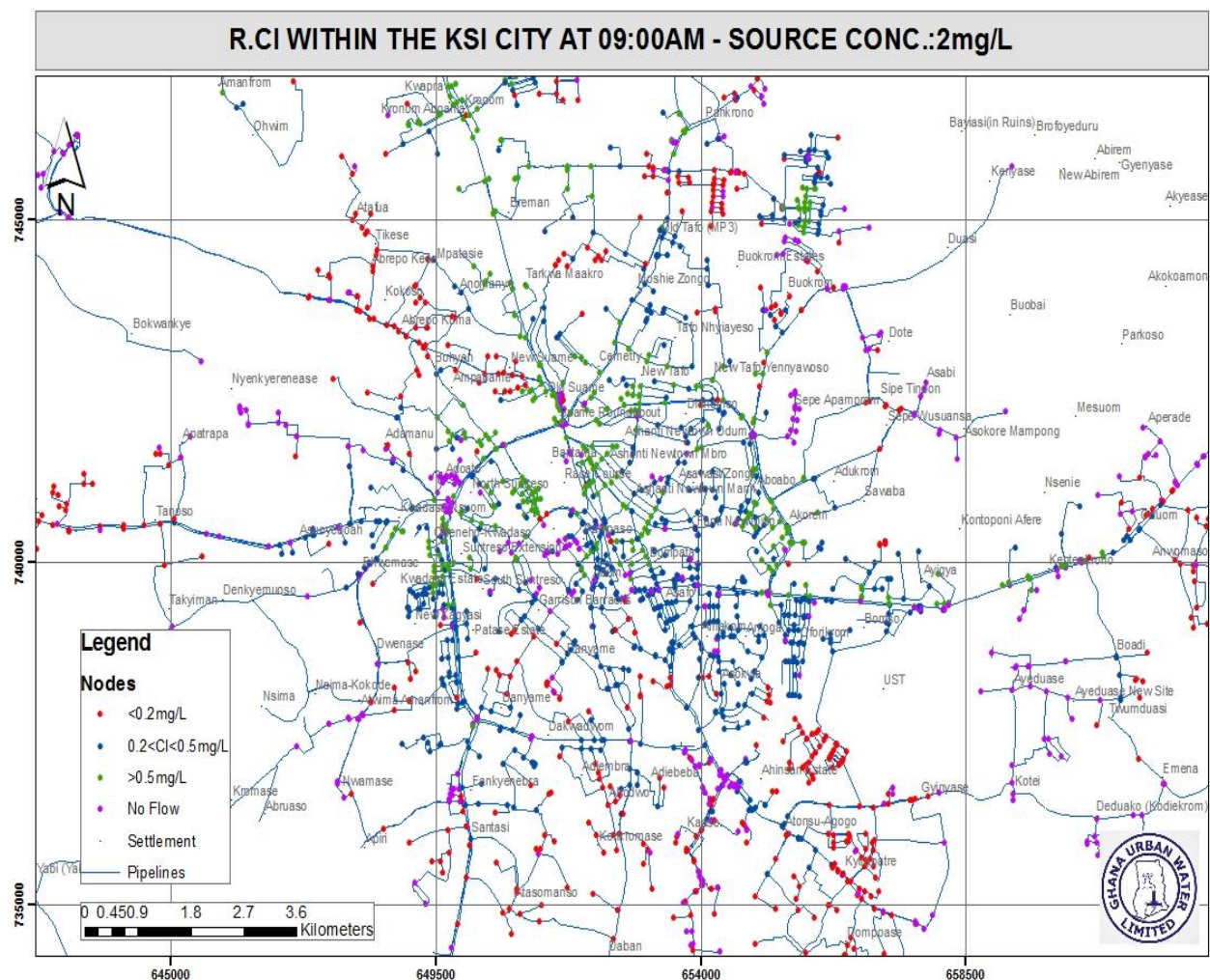


Figure 4.19 Map showing Nodal Residual Chlorine values using 2.0 mg/L initial value at 9:00 am

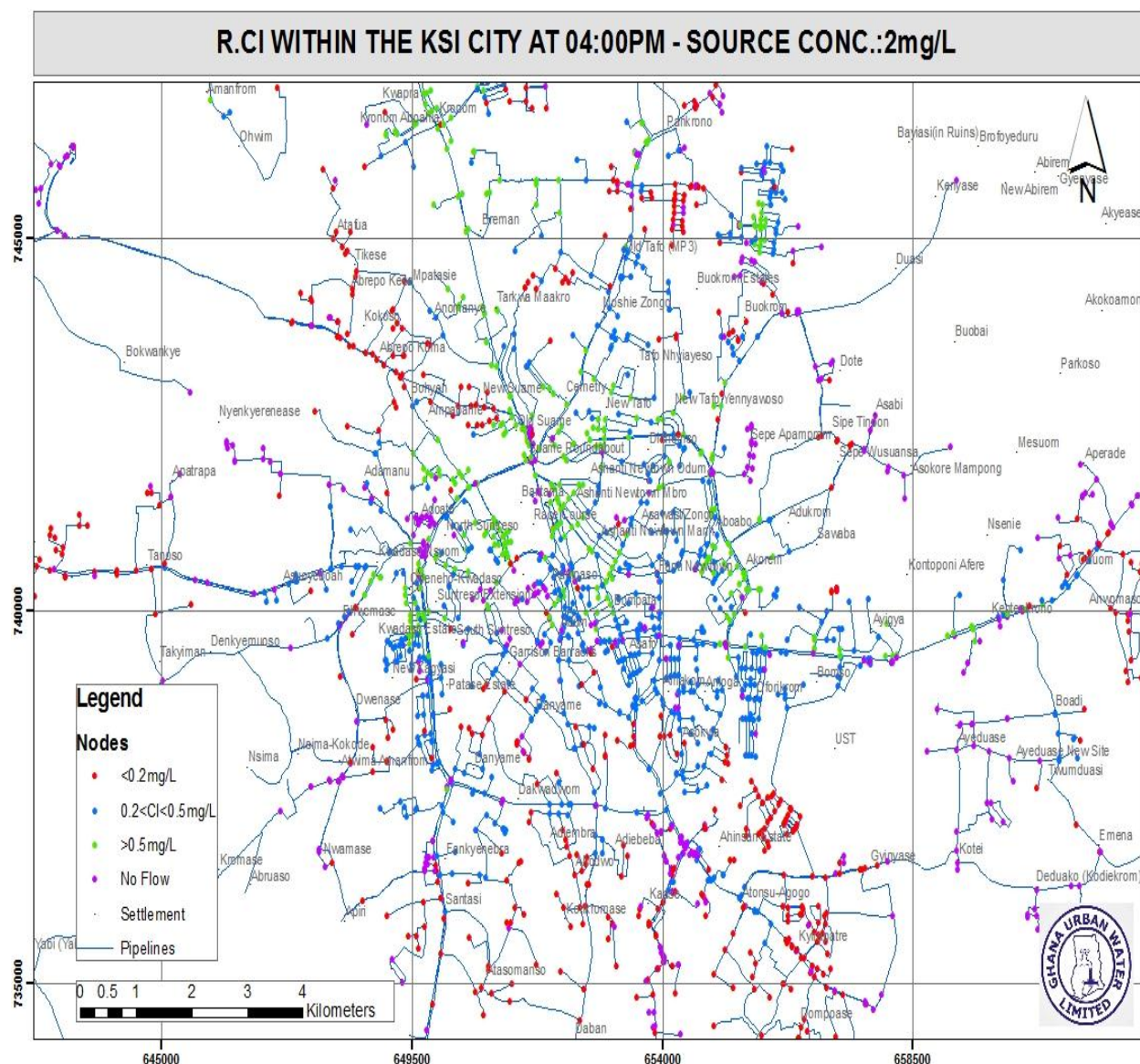


Figure 4. 20 Map showing Nodal Residual Chlorine model values at 4:00 pm using initial value of 2 mg/L

It must however be emphasized that, the 2.0 mg/L chlorine concentration level is the maximum concentration of residual chlorine in final treated water leaving a plant that is permissible by GUWL/GWCL and it is used to depict the worst case scenario. This is so because of challenges with offensive chlorine odour, disinfection by products and a bitter taste that is imparted to drinking water by the presence of very high residual chlorine concentration. This affects people who live close to the treatment plant and use the water for drinking purposes and other domestic

activities. Such people would need education on how to handle water with high residual chlorine values.

Detailed analysis of the model and the water transport process under this condition indicate that by the time the water travels a total distance of 18 km from the Barekese Headworks to the Suame Reservoir site, the residual chlorine concentration would have been reduced from the initial 2.0 mg/L to 0.92 mg/L as seen in figure 4.21.

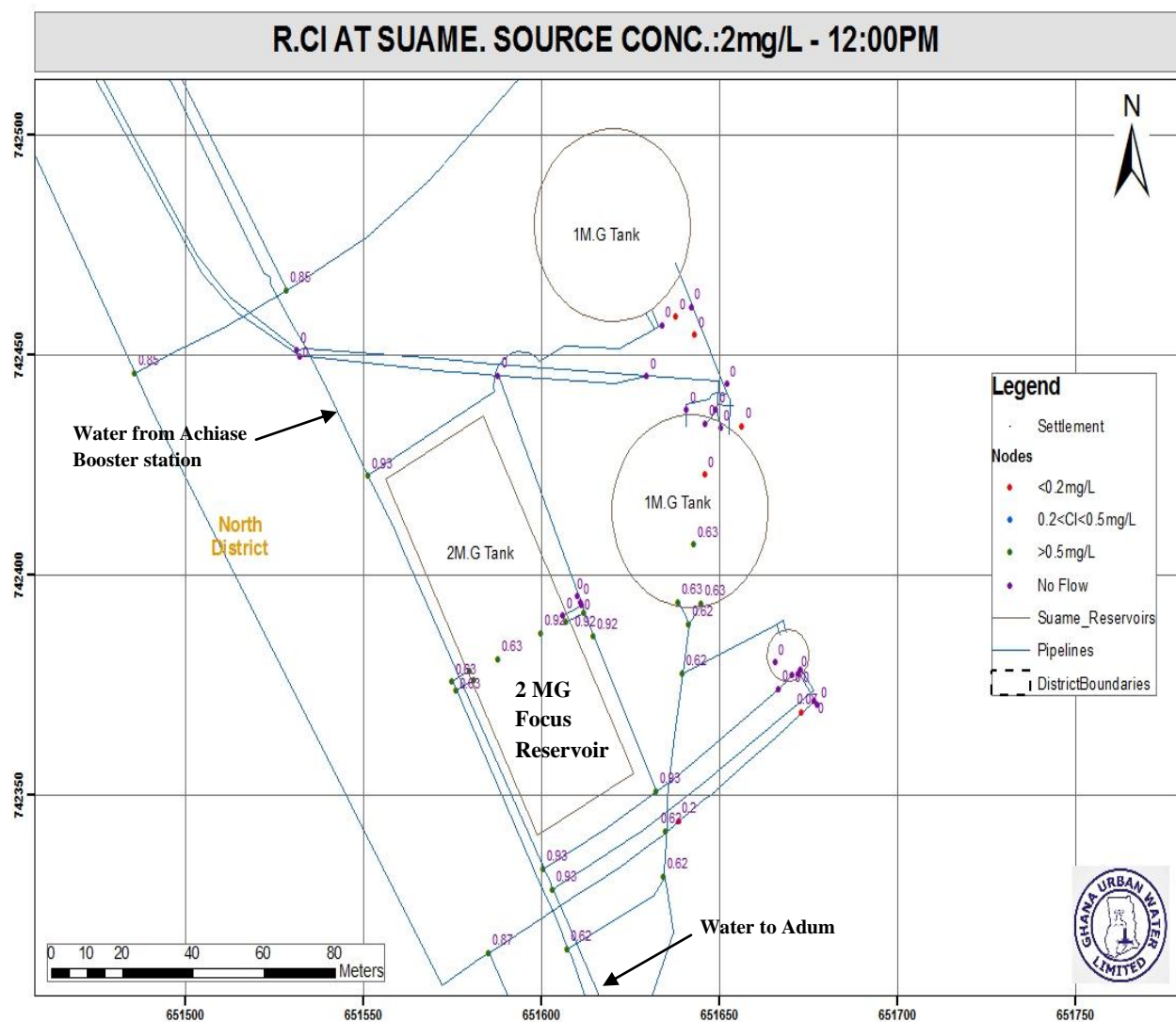


Figure 4. 21 Map showing Suame Residual Chlorine model values using an initial value of 2.0 mg/L

After a residence time of 30 minutes, the water leaving the reservoir is observed to have the residual chlorine concentration reducing further to 0.63 mg/L which is above the minimum acceptable value of 0.20 mg/L as again seen in Figure 4.20. Hence, no stepwise chlorination is required at Suame and the water can be subsequently released into the distribution network. The probable areas in the network that will require stepwise chlorination process under this circumstance (after the 2 mg/L initial residual chlorine concentration dosage) are the Pankrono and Buokrom Booster Stations in the Kumasi North East district and the node before the Coca Cola Company at Ahinsan in the Kumasi South district. All other challenges are largely due to poor or no flow situations in the network.

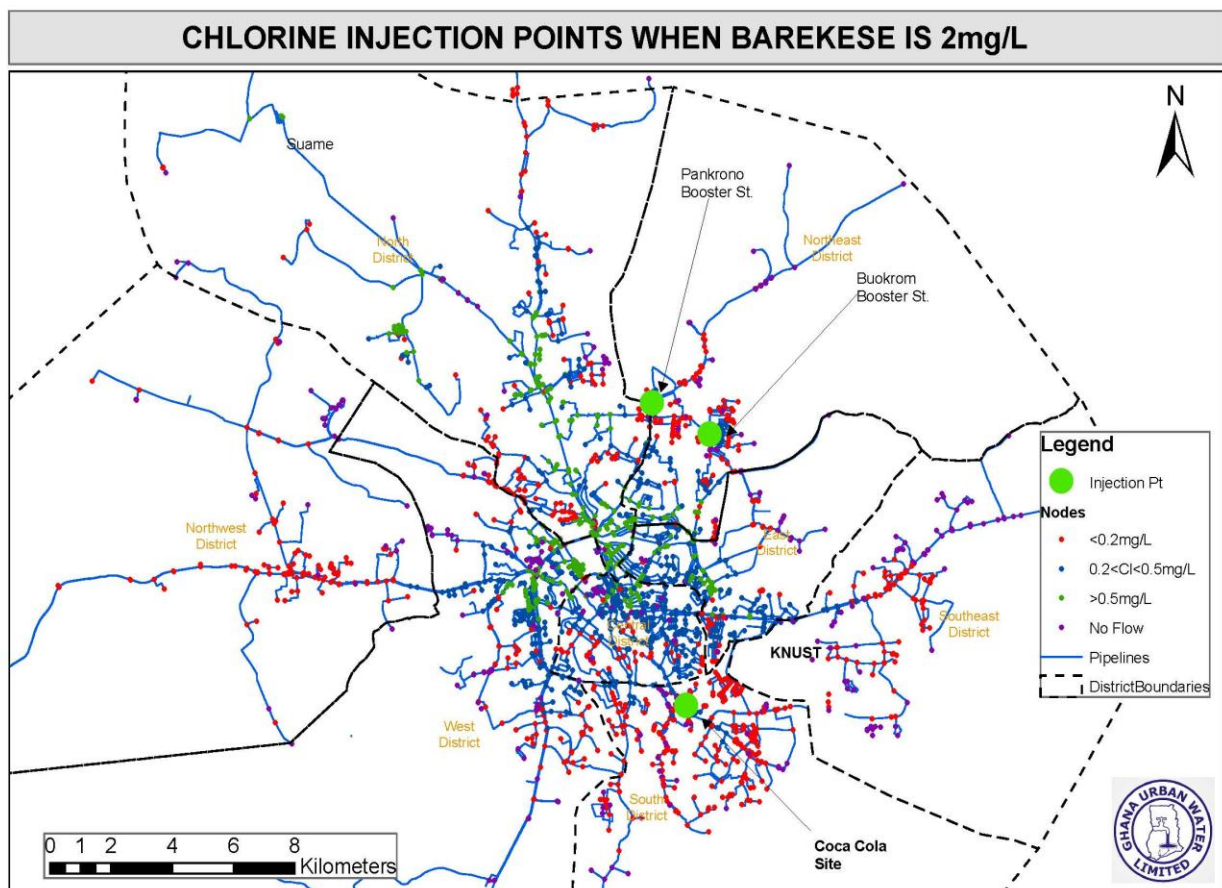


Figure 4.22 Map showing Required Chlorine injection points using 2 mg/L initial model value

The residual chlorine concentrations at all the nodes that receive water supply from the Barekese Headworks are then seen to be adequate enough to handle microbial contamination thereby protecting public health.

CHAPTER FIVE - CONCLUSIONS AND RECOMMENDATIONS

5.0 Conclusions

The following conclusions are drawn from the study.

- The residual chlorine concentration in the entire distribution network is low under the existing conditions with a lot of areas having very low to insignificant values thereby compromising the bacteriological quality of the distributed water.
- Under the prevailing conditions, the overall residual chlorine decay coefficient in the distribution network was found to be 0.38/ hour and that of the bulk decay coefficient was 0.05/ hour
- Also, under the conditions tested and analysed, the Global wall decay coefficient for the entire distribution network was found to be 0.33/ hour with the wall decay due to the steel pipe being 0.15/ hour, cast iron pipes being 0.58/ hour and that of the concrete reservoirs being 0.29/ hour. The residual chlorine decay coefficient in the cast iron pipes is therefore approximately about four times that of the steel pipes and twice that of the concrete reservoir.
- 34% of chlorine loss in the network is attributed to bulk demand with 66% being due to wall chlorine demand. Physico-chemical and bacteriological parameters such as dissolved solids, iron, manganese, *Coliform bacteria*, *Escherichia .Coli* and *Salmonella species* also contribute further to residual chlorine decay in distributed water in the Kumasi network.

- It was also evident that most of the loss of residual chlorine in distributed water in the Kumasi network is due largely to the interaction of the water with the cast iron pipes than the steel pipes.
- Under the existing situation, after about 18 km of water transport in the high pressure 900 mm steel pipeline from the Barekese Headworks, the residual chlorine concentration reduces to a value lower than the recommended 0.20 mg/L minimum acceptable level in drinking water necessitating stepwise chlorination.
- The residual chlorine concentration of the final water leaving the Barekese Headworks should be maintained at 0.60 mg/L. However, areas in the Kumasi Water distribution network where stepwise chlorination is necessary together with their respective recommended concentrations are Achiase Booster Station – 1.50 mg/L; Kodie on the Offinso pipeline – 1.0 mg/L; the node before Coca Cola Company Limited at Ahinsan – 0.50 mg/L; Pankrono Booster Station – 0.50 mg/L; Buokrom Booster Station – 0.50mg/L and KNUST Booster Station – 0.50 mg/L.

5.1 Recommendations

The following recommendations are made from this study;

- The cast iron pipes in the network should be replaced since they are causing more depletion of residual chlorine in the distributed water and other challenges with water quality.
- Future expansion works at the Barekese Headworks should incorporate in the design, a chlorine contact time of at least 4 hours in the clear water wells for effective water disinfection.

- Further studies should also be conducted on the impact of residual chlorine on the Total Organic Carbon and Dissolved Organic Carbon in water so that empirically, the level of trihalomethanes and other disinfection by products can be established in the water supplied to the entire Kumasi water distribution network.
- Residual chlorine decay coefficients determination and modeling should also be conducted for areas in the distribution network supplied with water from the Owabi Water Treatment Plant so as to predict their probable areas where stepwise chlorination is necessary is also recommended for further study.
- GWCL and GUWL may consider adopting the locations such as Achiase, Pankrono, Buokrom and KNUST Booster Stations that were predicted by the model as stepwise chlorination points and implementing same together with the recommended chlorine dosages in the KWDN.
- GWCL and GUWL need both hydraulic and water quality models in all ten regions of Ghana to help with efficient management, operations and maintenance of all their distribution networks under the prevailing conditions.

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APPENDICES

APPENDIX 1: RESIDUAL CHLORINE VALUES (mg/L) OBTAINED DURING THE SAMPLING EPISODES

	Bare	Achiase	Kronom	Suame-Bare Res.	Suame Tap	Agyaba Dist. Line	Adum House
Day	9:00 AM	10:30AM	12:00 PM	13:00 PM	14:00 PM	16:00 PM	17:00 PM
FIRST SAMPLING SESSION							
1	0.12			0.00		0.00	0.00
2	0.15			0.04		0.00	0.00
3	0.25			0.01		0.05	0.05
4	0.75			0.18		0.11	0.00
5	1.00			0.06		0.06	0.00
SECOND SAMPLING SESSION							
6	0.84	0.60	0.40	0.36	0.25	0.16	0.06
7	1.02	0.95	0.60	0.41	0.30	0.10	0.05
8	0.66	0.58	0.50	0.36	0.25	0.05	0.01
MEAN	0.5988	0.7100	0.5000	0.1775	0.2667	0.0663	0.0213

APPENDIX 2: TOTAL IRON VALUES

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	0.077	0.055	0.118	0.104
2	0.063	0.103	0.037	0.087
3	0.1695	0.014	0.123	0.138
4	0.013	0.029	0.222	0.034
5	0.165	0.198	0.213	0.267
6	0.29	0.047	0.172	0.219
7	0.03	0.007	0.112	0.176
8	0.166	0.29	0.48	0.261
MEAN	0.1216875	0.092875	0.184625	0.16075

APPENDIX 3: MANGANESE VALUES AT SAMPLING POINTS (mg/L)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) [4:00 PM]	AGYABA HOUSE (5:00 PM)
1	0.0065	0.012	0.008	0.007
2	0.012	0.011	0.007	0.005
3	0.0075	0.013	0.026	0.007
4	0.186	0.1	1.01	0.005
5	0.008	0.01	0.011	0.012
6	0.01	0.024	0.01	0.007
7	0.014	0.01	0.018	0.012
8	0.013	0.005	0.015	0.001
MEAN	0.032125	0.023125	0.138125	0.007

APPENDIX 4: NITRATES VALUES AT SAMPLING POINTS (mg/L)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) [4:00 PM]	AGYABA HOUSE (5:00 PM)
1	0.5	0.44	0.78	0.33
2	0.335	0.33	0.11	0.44
3	1.39	0.89	1.44	2.11
4	0.11	0.22	0.22	0.56
5	1.56	1.67	2.56	3.89
6	2.63	2.59	2.11	2.39
7	2.71	2.11	4.95	2.11
8	2.63	2.59	2.11	2.39
MEAN	1.483125	1.355	1.785	1.7775

APPENDIX 5: CALCIUM VALUES AT SAMPLING POINTS (mg/L)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) [4:00 PM]	AGYABA HOUSE (5:00 PM)
1	18.04	16.03	22.04	22.04
2	17.035	18.37	22.04	20.04
3	14.03	20.04	18.04	20.04
4	14.03	16.03	14.03	18.04
5	14.03	14.03	20.04	18.04
6	14.43	16.03	19.24	16.03
7	12.83	12.83	14.43	14.43
8	14.43	16.03	12.83	22.45
MEAN	14.856875	16.17375	17.83625	18.88875

APPENDIX 6: MAGNESIUM VALUES AT SAMPLING POINTS (mg/L)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) [4:00 PM]	AGYABA HOUSE (5:00 PM)
1	17.03	13.65	13.37	18.23
2	11.55	15.02	8.51	14.59
3	12.44	13.04	16.08	13.65
4	12.43	13.65	14.86	13.65
5	15.06	15.79	12.51	10.04
6	7.03	10.04	5.02	6.02
7	7.02	7.02	10.54	8.03
8	6.02	5.02	10.04	5.02
MEAN	11.0725	11.65375	11.36625	11.15375

APPENDIX 7: TURBIDITY VALUES AT SAMPLING POINTS (NTU)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	0.3	2.21	0.32	0.45
2	1.3	2.12	1.58	1.42
3	1.7	3.97	1.58	1.64
4	0.65	1.01	1	0.54
5	3.3	2.54	1.84	1.6
6	0.67	0.88	0.64	0.63
7	0.29	0.42	0.49	0.38
8	0.47	1.07	0.72	0.69
MEAN	1.085	1.7775	1.02125	0.91875

APPENDIX 8: COLIFORMS AT SAMPLING POINTS (cfu/100ml)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	5	13	20	3
2	5	40	19	15
3	4	22	27	14
4	2	0	1	3
5	2	28	2	3
6	1	2	18	10
7	2	3	6	5
8	0	2	10	5
MEAN	2.625	13.75	12.875	7.25

APPENDIX 9: E.COLI COUNTS AT SAMPLING POINTS (cfu/100ml)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	1	4	0	0
2	0	4	0	0
3	5	19	12	7
4	0	0	0	0
5	2	8	9	3
6	0	2	6	4
7	1	4	4	5
8	0	2	3	2
MEAN	1.125	5.375	4.25	2.625

APPENDIX 10: SALMONELLA COUNTS AT SAMPLING POINTS (cfu/100ml)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	1	10	7	0
2	4	7	5	3
3	5	20	11	6
4	0	0	0	3
5	1	2	2	2
6	0	5	5	2
7	0	2	5	3
8	0	0	0	0
MEAN	1.375	5.75	4.375	2.375

APPENDIX 11: pH VALUES AT SAMPLING POINTS

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE RESERVOIR (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	6.4	7.22	6.9	7.05
2	6.5	7.05	6.97	7.08
3	6.3	6.74	7.12	7.03
4	6.8	6.69	7.35	7.21
5	6.5	6.94	7.23	7.17
6	6.3	5.8	6.92	7.36
7	6.2	6.16	6.39	6.86
8	6.3	6.03	6.91	6.74
MEAN	6.4125	6.57875	6.97375	7.0625

APPENDIX 12: CONDUCTIVITY VALUES AT SAMPLING POINTS (US/CM)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L) (4:00 PM)	AGYABA HOUSE (5:00 PM)
1	148.5	129	148.7	120.4
2	134.4	123.3	148.5	138.5
3	141.4	117.4	141.9	141.5
4	142.5	144	139.5	139.6
5	154.1	143.1	150.5	151.2
6	127.6	137.7	164.6	155.4
7	139.8	147.2	151.3	150.2
8	134.5	134	142.4	141.4
MEAN	140.35	134.4625	148.425	142.275

APPENDIX 13: TOTAL DISSOLVED SOLID VALUES AT SAMPLING POINTS (mg/L)

SAMPLING DAY	BAREKESE (9:00AM)	SUAME BARE (1:00PM)	ADUM (T.L)[4:00 PM)	AGYABA HOUSE (5:00 PM)
1	52.6	64.1	74.2	60.2
2	90	62.1	76	69
3	100	58.5	70.7	70.9
4	100	72.7	69.5	69.8
5	110	70	68.8	70
6	90	80.4	82.6	77.6
7	90	80.3	82	76.4
8	90	80.5	82.3	76.2
MEAN	90.325	71.075	75.7625	71.2625

APPENDIX 14: BULK DECAY EXPERIMENT - BAREKESE (DAY 1)

TIM E	RES CHLORINE (mg/L)	TOTAL CHLORIN E (mg/L)	pH	COND uS/cm	TDS (mg/L)	TEM P (0C)	COLO UR (HU)	TURBIDI TY (NTU)	COLIFO RMS (CFU)	E.COL I (CFU)	SALMON ELLA (CFU)
9:00 AM	0.54	0.95	6.50	138.0	100.0	26.0	5	0.67	1	2	1
10:00 AM	0.51	0.90	6.40	139.6	100.0	24.4	5	0.58	1	1	1
11:00 AM	0.49	0.80	6.30	138.8	100.0	25.0	5	0.54	1	0	0
12:00 PM	0.45	0.75	6.20	137.7	100.0	24.0	5	0.52	0	0	0
1:00 PM	0.44	0.70	6.50	139.1	100.0	25.0	5	0.50	0	0	0
2:00 PM	0.44	0.66	6.50	139.1	100.0	26.0	5	0.50	0	0	0
3:00 PM	0.43	0.63	6.50	141.1	100.0	25.2	5	0.56	0	0	0
4:00 PM	0.38	0.62	6.52	139.2	100.0	25.0	5	0.50	0	0	0
5:00 PM	0.33	0.60	6.58	139.4	100.0	25.5	5	0.55	0	0	0

APPENDIX 15: BULK DECAY EXPERIMENT – BAREKESE (DAY 2)

TIM E	RES CHLORINE (mg/L)	TOTAL CHLORIN E (mg/L)	pH	COND uS/cm	TDS (mg/L)	TEM P (0C)	COLO UR (HU)	TURBIDI TY (NTU)	COLIFO RMS (CFU)	E.COL I (CFU)	SALMON ELLA (CFU)
9:00 AM	1.3	1.74	6.2	133.7	90	24.7	5	0.28	1	2	1
10:00 AM	1.2	1.52	6.2	134.2	100	24.9	5	0.28	0	1	0
11:00 AM	1.16	1.48	6.2	134.9	90	25.1	5	0.3	1	0	0
12:00 PM	1.04	1.46	6.1	133.5	100	25.3	5	0.34	0	0	0
1:00 PM	1.02	1.41	6.1	134.5	90	25.3	5	0.33	0	0	0
2:00 PM	0.95	1.35	6.1	134.5	90	25.8	5	0.32	0	0	0
3:00 PM	0.92	1.32	6.1	133.9	90	25.8	5	0.3	0	0	0
4:00 PM	0.9	1.3	6.1	132.8	90	25.8	5	0.3	0	0	0
5:00 PM	0.89	1.25	6	133	90	26	5	0.28	0	0	0

APPENDIX 16: BULK DECAY EXPERIMENT - BAREKESE (DAY 3)

TIME	RES CHLORINE (mg/L)	TOTAL CHLORIN E (mg/L)	pH	COND uS/cm	TDS (mg/L)	TEM P (0C)	COLOU R (HU)	TURBIDI TY (NTU)	COLIFOR MS (CFU)	E.COL I (CFU)	SALMONE LLA (CFU)
9:00 AM	0.53	0.88	6.1	124.5	100	25.1	5	0.38	2	1	1
10:00 AM	0.5	0.85	6.1	134.5	100	25.6	5	0.44	1	0	0
11:00 AM	0.46	0.8	6	126.5	90	25.7	5	0.5	0	0	0
12:00 PM	0.43	0.76	6	124.7	90	25.9	5	0.41	0	0	0
1:00 PM	0.42	0.74	6	124.9	90	26.3	5	0.4	0	0	0
2:00 PM	0.4	0.7	5.9	124.7	90	26.2	5	0.36	0	0	0
3:00 PM	0.38	0.67	5.9	124.1	90	26	5	0.32	0	0	0
4:00 PM	0.36	0.65	5.9	125.8	90	26.2	5	0.31	0	0	0
5:00 PM	0.35	0.62	5.9	134.5	90	26.5	5	0.3	0	0	0