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Residual Chlorine Decay Modeling in Drinking Water Supply

Distribution System of Bahir Dar Town

By

Belayneh Abel Minale

Bahir Dar, Ethiopia.

July , 2021

RESIDUAL CHLORINE DECAY MODELING IN DRINKING WATER SUPPLY
DISTRIBUTION SYSTEM OF BAHIR DAR TOWN, AMHARA REGION, ETHIOPIA

Belayneh Abel Minale

A thesis submitted to the school of Research and Graduate Studies of Bahir Dar Institute of Technology, BDU in partial fulfillment of the requirements for the degree of Masters of Science in the Water Supply and Sanitary Engineering in the faculty of Civil and Water Resources Engineering.

Advisor Name: Tamru Tesseme (Ph.D.)

Bahir Dar, Ethiopia.

July, 2021

Declaration

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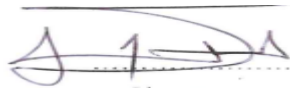
Date of submission: July 19, 2021

Place: Bahir Dar

This thesis has been submitted for examination with my approval as a university advisor.

Advisor Name: Tamru Tesseme (Ph.D.)

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DEDICATION

This thesis is dedicated to my father and mother.

ACKNOWLEDGMENTS

First of all, I praise my almighty God since He took care of me, from beginning to end of this study.

Secondly, I would like to thank and give great appreciation and respect to my advisor Dr. Tamru Tesseme for his guidance and critical comments during the preparation of this research, I would also like to express my appreciation to the staff of the water supply and sanitary engineering department Bahir Dar university, and Bahir Dar town Water supply and Sewerage office.

Finally, I would like to thank Amhara Design & Supervision Works Enterprise Water Quality and Laboratory division and individuals because their contribution was invaluable for my study in one way or another and preparation of my thesis.

ABSTRACT

To prevent bacterial regrowth, it is desirable to maintain a disinfectant residual in the water distribution network. Therefore, the aim of the study was to determine the variation in residual chlorine degradation in Bahir Dar drinking water distribution system. The study was conducted to assess chlorine dosing and model for residual chlorine using EPANET software. The First-order decay equation was used to describe both bulk and wall chlorine consumption. A total of 30 water samples were collected from different taps in the water distribution network. To model the residual chlorine content, three scenarios were developed. Scenario I and II were developed with the existing chlorine dose with demand-based and pipe diameter; whereas, scenario III was developed by determining the initial chlorine dose in the laboratory with two injection points. The study results showed that the minimum and maximum residual chlorine concentrations in the existing water distribution system were found to be 0.04 and 0.23 mg/l, respectively. The analysis results demonstrated that the residual chlorine most of the distribution system was almost less than the minimum recommended residual chlorine value by the World Health Organization standard which is (0.2mg/l). The study revealed that two new injection points were needed within 0.45 and 0.6 mg/l initial chlorine concentration to solve the minimum residual chlorine problem in the distribution system. In conclusion, the present study results demonstrated that the modeling of chlorine residual in Bahir Dar water supply networks using EPANET software is a promising tool in managing disinfectant concentrations throughout the water distribution systems.

Keywords: - Residual chlorine, Water quality, Distribution system, Modeling, Scenario, EPANET, Bahir Dar.

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LIST OF ABBREVIATIONS

asl	above sea level
BDWSS	Bahir Dar Water Supply & Sewerage
CSA	Central Statistical Agency
CT	Contact Time
DI	Ductile Iron
DBP	Disinfection by product
DPD	Diethyl-p-phenylenediamine
DVM	Discrete volume method
EPA	Environmental Protection Agency
EPS	Extended period simulation
EU	End-User
Gpm	gallon per minute
GS	Galvanized steel
HGL	Hydraulic grade line
a.m.s.l	Meter Above Sea Level
NOM	Natural organic matter
NRC	National Research Council
PVC	Polyvinyl chloride

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1. INTRODUCTION

1.1 BackGround

Drinking water should have a high quality so that it can be consumed without the threat of immediate or long-term adverse impacts on health. Such water is commonly called “potable water”. Inadequately treated drinking water supplies remain the greatest threat to public health, especially in developing countries, where nearly half of the population is drinking water that does not meet World Health Organization drinking water quality guidelines (de França Doria, 2010).

Most of the world, drinking water that contains pathogens or unacceptable levels of dissolved and suspended pollutants. Such polluted water is not suitable for drinking because it may cause widespread acute and chronic diseases resulting in a large number of deaths in many developing countries like Ethiopia. Over 100 million people do not have access to an adequate supply of safe water for household consumption (Parashar et al., 2003). According to World Health Organization, every year 1.8 million people die from diarrheal diseases including cholera. 88% of the diarrheal diseases are attributed to the contaminated water supply and inadequate sanitation. Over 1.3 million people die of malaria every year and there are 1.5 million cases of hepatitis each year.

Similar to many African countries, parts of Ethiopia face water shortages, poor sanitation, and a lack of access to clean water sources. Water disinfection is an essential component of the prevention strategy for enteric infections. In developing countries, surface water may be highly contaminated with human waste. Ethiopia is located in Africa's Horn where drought and politics are two leading causes of water shortage. In a study conducted by World Health Organization, they found that "42% of the population has access to a clean water supply" and only "11% of that number has access to adequate sanitation services". In rural areas of the country, these figures drop even lower, resulting in health problems in the villagers as well as their animals.

There are several types of disinfection methods available such as physical (includes ultrasound, ultrafiltration, reverse osmosis, heating, freezing, and ionizing radiation) and chemical (includes ozonation, hydrogen peroxide, chlorination). The physical methods do not generate significant residual disinfection products but these are costly methods and cannot be used for the community water supplies in developing countries (Fuqua, 2010). Chlorine disinfection presents the advantages of efficiency and durability along with cost-effectiveness.

Chlorine disinfection is of great importance in maintaining drinking water quality related to pathogens and viruses throughout the water distribution system (Berry et al., 2006). Diseases like cholera and typhoid fever have virtually been eliminated in the developed countries since continuous chlorination practice started in the 20th century. Drinking water filtration and the use of chlorine are the most significant public health advance of the last century. Along with the control of microorganisms in the water distribution system, chlorine also removes the objectionable taste and odor from the water. Not amazingly, chlorine is the most widely used water disinfection in the world (Shah et al., 2012).

In the study area, water supply disinfection of chlorine is by mixing manually in the service reservoir due to the failure of pump. When dissolved chlorine travels through the distribution system, it reacts with natural organic matter in the bulk water, with Biofilms and tubercles on the pipe walls, or with the pipe wall material itself. This reaction results in a decrease in the chlorine residual and a corresponding increase in disinfection by-products (Grayman, 2018).

“The residual chlorine in water distribution can be affected by different factors like temperature, pH, and turbidity. Temperature is one of the important parameters of water and it is important for its effects on the chemistry and biological reactions of the organisms in the water which will lead to the reduction in the amount of residual chlorine that can enhance the growth of microorganisms” (Shah et al, 2012).

Water quality within the water distribution system may vary with both location and time. Water quality models are used to predict the spatial and temporal variation of water quality throughout the water system (Shah et al., 2012). Chlorine is an efficient and inexpensive disinfectant and is widely used in drinking waterworks all over the world. Maintaining residual chlorine in the whole water distribution system can prevent water quality microbiological degradation. Chlorine is relatively unstable, may react with a variety of organic and inorganic compounds in bulk water or on the pipe wall, and there are reactions of biofilm with chlorine (Li et al., 2003). All this result is the consumption of residual chlorine in the distribution system. It is very difficult to precisely predict the chlorine concentration in the specific location of the whole distribution system, because of its complexity of water distribution system, and uncertainty by in reactivity of chlorine, but modeling the kinetics of residual chlorine decay in the distribution system is necessary, to ensure delivery of high-quality drinking water. The kinetic model most describing chlorine decay in the

water distribution system is the first-order decay model in which the chlorine concentration is assumed to decay exponentially. The decay constant values vary with water quality, water temperature, flow rate and pipe roughness. The decay constant values are determined by using the regression method, considering the factors. The purpose of this study is to evaluate chlorine residual concentration by modeling the water distribution system. The aim of the study also tries to propose the rechlorination station location in a distribution network.

1.2 Problem statements

The unorganized growth of Bahir Dar town is due to the quick rate of urbanization, construction, and conversion of agricultural land for other developmental objectives. The distribution system in this area is severely damaged, exposing several pollutants that harm the water quality system, causing the chlorine dosage consumption to rise in tandem with the distribution system.

In Bahir Dar town, the majority of the people is raising their ideas for solving the water quality problem. The occurrence of numerous waterborne diseases is increasing as a result of contaminated drinking water, according to several health institutions' top ten diseases lists, the majority of patients treated for cause of waterborne diseases. As a result, in-line water treatment of Bahir Dar drinking water pipes is required to prevent water-borne diseases linked with water quality. However, if algae, residual iron or aluminum floc, suspended solids, or significant amounts of chlorine are permitted to remain in the distribution system, no practical level of residual chlorine can prevent problems with aftergrowth. Therefore, it's critical to check that the chlorine level in the line is within the town distribution pipe system's specified residual chlorine limit.

1.3 Research Questions

- I. Is there temporal variation of residual chlorine in the distribution system ?
- II. How to reduce chlorine residual problems in the distribution system?
- III. How much chlorines residual is remaining at the end-user tap below or above the standard?

1.4 Objective

1.4.1 General objective

The general objective of the study is to evaluate the residual chlorine decay in the drinking water supply distribution system of Bahir dar town.

1.4.2 Specific objectives

- I. To determine the initial chlorine concentration required at the system entry to achieve the target concentration.
- II. To model chlorine residual concentration in the network.
- III. To Location optimal position and dose for rechlorination to maintain appropriate concentration

1.5 Significance of the Study

Pipe repair, relining, or replacement, changes in the re-chlorination booster, delineation of new pressure zones, and modifications to system operation, such as keeping less water in storage, are all actions that can be taken to improve hydraulic performance and water quality deterioration in the distribution system.

The results of this study will be used to indicate the effects of distance on chlorine residual demand through the distribution system and used as input for the designer to consider the distance between the reservoir and the end-user of rural and urban water supply distribution system. It is very important to understand the amount and type of chlorine that must be added to overcome the difficulties in the strength of the disinfectant which results from the water's characteristics.

Hopefully, the insights that can be drawn from this study will initiate further research on similar other sites and will contribute to solving the existing problems of the water distribution system.

1.6 Scope of Work

The present study was initiated with an objective to identify a modeling of chlorine residual in water distribution network. The scope of work focuses on collecting samples and data from the service reservoir and its networks from the study area by determining the sampling points in the system. After that, compares were made the data or levels of chlorine from the network with the levels of chlorine at the service reservoir. It may be noted that the water should tested in laboratory validation of chlorine concentration as predicted at different junction of pipe network system by EPANET. The water distribution network model, which was considered in the current analyses, consists of main and secondary pipelines and feeders, neglecting the network distributaries and laterals.

1.7 Limitations of the study

Taking into account the lack of qualitative model calibration, the obtained results should be treated as preliminary and approximate due to intermittent data. Intermittent of full water supply in the pipe, and existing data availability of the existing distribution network are all some of the data limitations in this study.

2. LITERATURE REVIEW

2.1. General

At the beginning of the country, Harriet Chick postulated that forgiven disinfection and concentration, the death of microorganisms follows first-order kinetics concerning time. Chick's Law can also apply to express the decrease in titer of the microbial population due to other inactivating factors in an unfavorable environment.

$$-\frac{dx}{dt} = kx \dots\dots\dots 2. 1$$

X = Concentration of living microorganisms at the time, t

k = first-order decay rate (1/time)

$$X = X_0 e^{-kt} \dots\dots\dots 2. 2$$

X = Concentration of living microorganisms at time, t (number/unit volume)

X₀ = initial concentration of living microorganisms (number/unit volume)

k = decay rate (1/time)

t = time

When chlorine is used as a disinfectant agent in a piped distribution system, it is desirable to maintain a free chlorine residual of 0.2 - 0.5 mg/L throughout, to reduce the risk of microbial re-growth and the health risk of recontamination. In an emergency, for example, in refugee camps during the outbreaks of potentially waterborne disease, or when fecal contamination of a water supply is detected, the concentration of free chlorine should be increased to greater than 0.5 mg/L throughout the system. High levels of turbidity can protect microorganisms from the effects of disinfection agents, simulated the growth of bacteria, and give rise to significant chlorine demand. Chlorine can be easily monitored and controlled as a drinking water disinfectant, and regular, frequent monitoring is recommended wherever chlorination is practiced. So, along with the piped system when the distances are increased, the chlorine residual will decrease because the chlorine will react with the microorganisms along the piped line(Carrico et al., 2008).

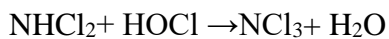
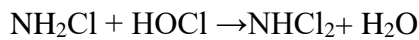
2.2. Chlorination process

Chlorine is the most important disinfecting agent for the protection of drinking water. It may furthermore have a beneficial effect on the water quality through its oxidation reactions with e.g., Ammonia (NH_3 , NO_3^-), iron, manganese, and sulfide. However, phenols, form the unwanted chloro-phenols imparting a bad taste to the water. With some organics, it may also form carcinogenic disinfection by-products such as trihalomethanes (especially chloroform (CHCl_3)).

When added into water, Cl_2 hydrolyses according to the following reaction, which is shifted to the right for $\text{pH} > 2$:



On the other hand, the weak acid hypochlorous acid (HOCl) is in equilibrium with its anion hypochlorite ion (OCl^-). As bacteria carry a small negative charge on the outside, undissociated hypochlorous acid (HOCl) is far more effective for penetration into the cell than the negatively charged hypochlorite ion (OCl^-); thus, the effectiveness of chlorination will strongly depend on pH. hypochlorous acid (HOCl) reacts with inorganic as well as organic reducing agents; the latter reactions normally proceed slowly. In the presence of ammonia chloramines are formed:



The inorganic hydrolysis products of Cl_2 , i.e., hypochlorous acid (HOCl) and hypochlorite ion (OCl^-) are called free available chlorine, whereas the chloramines and possible other chloro-derivatives are called combined available chlorine. The disinfecting properties of the two types of available chlorine differ considerably, the killing power of chloramines being much less acute than that of hypochlorous acid (HOCl). The slow reaction of the chloramines can be used to advantage by adding a little to the water before it is pumped into the distribution system. There they last, protecting the water against infection until the user's tap.

Several titrimetric and colorimetric methods are available for the analysis of chlorine. They are based on reactions with reducing agents, most of which are not specific. They also respond to oxidizing agents other than chlorine and its derivatives.

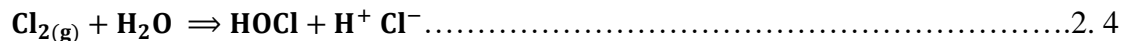
2.3. Chlorine dosage and Residual

The total amount of chlorine fed into a volume of water by the chlorine feed equipment is referred to as dosage and is calculated in mg/L. Chlorine is a very active chemical oxidizing agent. When injected into water, it combines readily with certain inorganic substances that are oxidizable (e.g., hydrogen sulfide, ferrous iron, etc.) and with organic impurities including microorganisms and nitrogen compounds (e.g., animal wastes, ammonia from fertilizers, etc.). This reaction consumes some of the chlorine. The amount of chlorine added is called the chlorine dose and the amount of chlorine consumed is called chlorine demand. Then chlorine residual is estimated from the following equation.

$$\text{Chlorine Residual} = \text{Chlorine Dose} - \text{Chlorine Demand} \dots \dots \dots 2. 3$$

2.4. Chlorine Reaction in water

Regardless of the form of chlorine used, the reaction in water is the same. The chlorine mixed with water will produce hypochlorous acid (HOCl). The following equation presents the hydrolysis reaction (USEPA 199; White):



The addition of chlorine gas to water reduces the pH of the water due to the production of hydrogen ions. Hypochlorous acid is a weak acid, meaning it dissociates slightly into hydrogen and hypochlorite ions as noted in Equation.



The measurement of hypochlorous acid (HOCl) and hypochlorite ion (OCl⁻) is called free chlorine residual (Figure 2.1). Between a pH of 6.5 and 8.5, this dissociation is incomplete and both hypochlorous acid (HOCl) and hypochlorite ion(OCl⁻) species are present to some extent (Shamrukh and Hassan, ,2005). Below a pH of 6.5, no dissociation of hypochlorous acid (HOCl) occurs, while above a pH of 8.8, complete dissociation to hypochlorite ion (OCl⁻) occurs. As the

germicidal effects of hypochlorous acid (HOCl) are much higher than that of hypochlorite ion (OCl^-), chlorination at a lower pH is preferred. This is due to the more facile movement of the uncharged acid through the bacterial cell wall compared to the hypochlorite ion (OCl^-). For this reason, careful regulation of pH is necessary to assure maximum disinfection with a minimum chlorine dose. In the case of potable water, however, it is also necessary that waters with relatively low pH (below 7.5) tend to be corrosive.

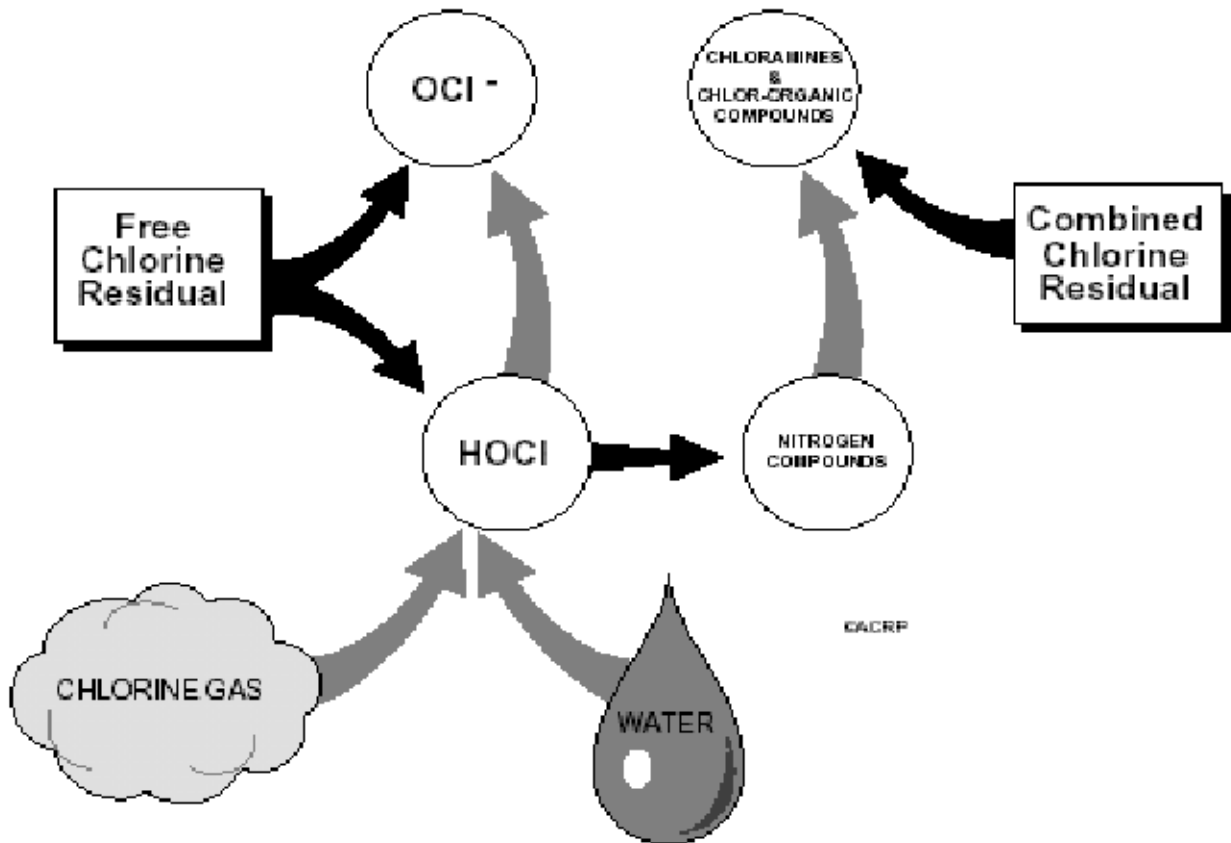


Figure 2. 1-Chlorine reactions with water

If the organic or inorganic compounds are available in the water, particularly nitrogen compounds, the hypochlorous acid will combine with these compounds to produce chloramines and /or chloro-organic compounds. The measurement of the presence of these compounds is called combined chlorine residual. Free chlorine has proven to be a more effective disinfectant than combined chlorine compounds. The measurement of both the free and combined chlorine residuals is called total residual as following.

Free residual chlorine + combined residual chlorine = Total chlorine Residual2. 6

If there are organic and inorganic compounds in the water, then enough chlorine has to be added to complete the reaction with these compounds before an adequate free residual can be produced. This process is called breakpoint chlorination which is represented from the plotting of applied chlorine dose versus total chlorine. This curve evolves four distinct areas are (Figure 2.2). The first is represents the oxidation of more reactive compounds than NH_3 by chlorine added is an inorganic demand phase. The second area represents an increase in combined (chloramines). The residual begins to drop because of the destruction of the combined chloramines. At this point, the nitrogen is given off as a gas and is lost to the atmosphere. Phase three continues until breakpoint, all NH_3 products have been fully oxidized and free chlorine residual begins to form phase four. As a rule of thumb, the free residual should be at least 85% of the total residual to prevent chlorine taste and odor problems and ensure an adequate free residual for effective disinfection (Shamrukh et al.,2006).

Disinfection with chlorine is not instantaneous. Time is required so that any pathogens present in the water are inactivated. The time taken for different types of microbes to be killed varies widely, therefore need an adequate contact time; this is usually 30 minutes. one of the most important factors for determining or predicting the germicidal efficiency of any disinfectant is the Contact time factor. The contact time factor is defined as the product of residual disinfectant concentration, (C), in mg/L, and the contact time, (T), in minutes that residual disinfectant is in contact with the water.

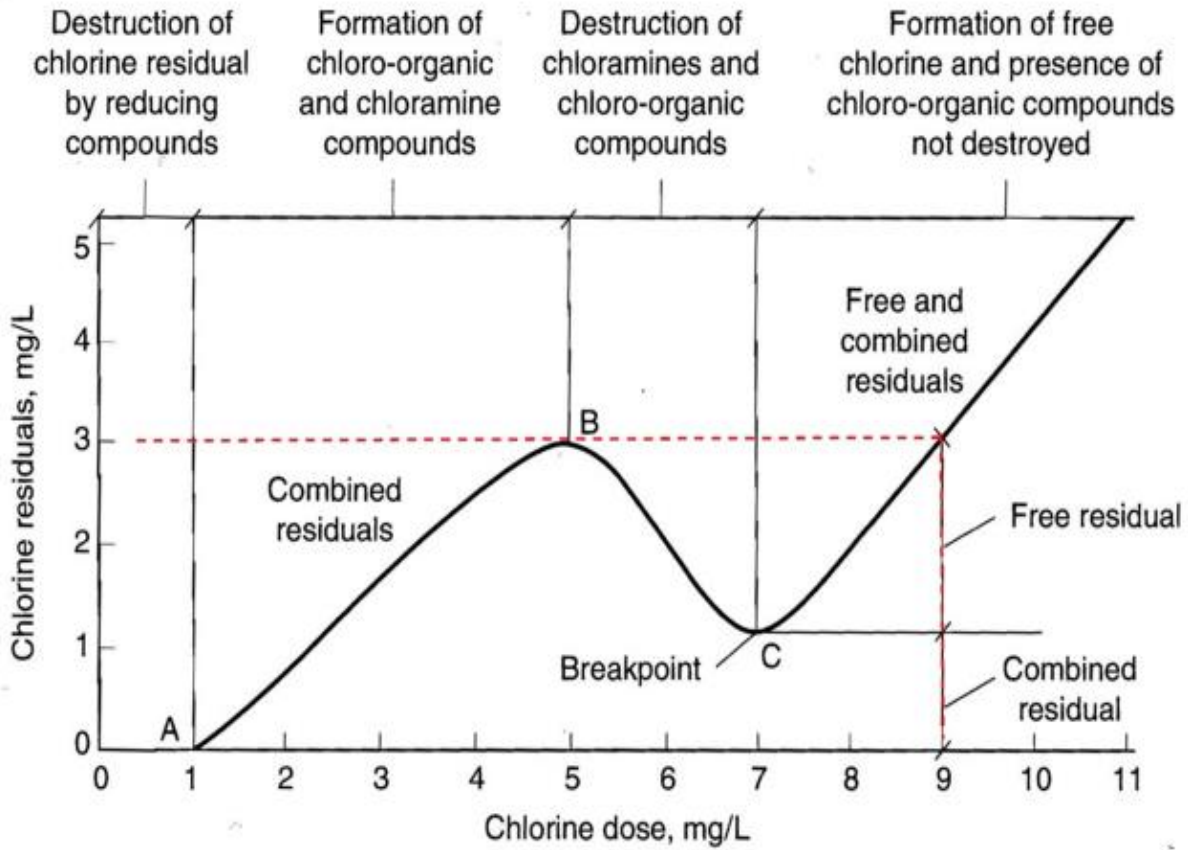


Figure 2. 2-Breakpoint chlorination curve, (EPA, 1990)

2.5. Distribution System Modeling

A water distribution system is principally made of links and nodes. Links are pipe sections which can contain valves and bends. The nodes can be categorized as junction nodes, which join pipes and are the points of input or output of flow, and fixed-grade nodes such as tanks and reservoirs with fixed pressure and elevation. As defined in water distribution system models, reservoirs are nodes that represent infinite sources or sinks of water, such as lakes. Tanks are nodes with fixed storage capacity and varying volumes during distribution.

The two fundamental concepts of distribution network hydraulics are conservation of mass and energy. For energy, the Bernoulli equation states that the sum of the elevation, pressure and velocity heads between two points must be constant. Due to losses because of friction during flow through the pipe, this equation does not hold precisely in practice. Frictional head loss is accounted for with head loss factors typically based on the Hazen-Williams, Chezy-Manning or Darcy-Weisbach equations. Head loss can be described as $h_l = Aq^B$

Where A is the resistance coefficient, B is the flow exponent and q is the flow rate.

2.6. Water Quality Modeling

In a water distribution network system, water quality transformation and deterioration can occur in the bulk water phase and through interaction with the pipe wall. These transformations may be physical, chemical, or microbiological (Mays, 2004). Transport, mixing, and decay are the fundamental physical and chemical processes typically represented in water quality models (Walski et al., 2001).

For water quality integrity to be compromised, specific reactions must occur that introduce undesirable compounds or microbes into the bulk fluid of the distribution system. These reactions can occur either at the solid-liquid interface of the pipe wall or in solution. Obvious microbial examples include the growth of biofilms and detachment of these bacteria within distribution system pipes and the proliferation of nitrifying organisms. Important chemical reactions include the leaching of toxic compounds from pipe materials, internal corrosion, scale formation and dissolution, and the decay of disinfectant residual that occurs over time as water moves through the distribution system (Council, 2007)

The two main mechanisms for water quality deterioration are interactions between the pipe wall and the water, and reactions within the bulk water itself. As the bulk water travels through the distribution system, it undergoes various chemical, physical and aesthetic transformations, impacting water quality. Depending on the water flow rate, finished water quality, pipe materials, and deposited materials (i.e., sand, iron, manganese), these transformations will proceed to a greater or lesser extent (EPA, 2004).

2.7. Chemical Reaction Terms

After the water leaves the treatment plant and enters the distribution system, it is subject to many complex physical and chemical processes, some of which are poorly understood, and most of which are not modeled. However, three chemical processes that are frequently modeled, are bulk fluid reactions, reactions that occur on a surface (typically the pipe wall), and formation reactions involving a limiting reactant (Walski et al., 2003).

2.7.1. Bulk Reactions

As a substance travels down a pipe or resides in storage, it can undergo a reaction with constituents in the water column (Mays, 2000). According to (Rossman, (2000) cited in (Walski et al., 2001), ‘Bulk fluid reactions occur within the fluid volume and are a function of constituent concentrations, reaction rate and order, and concentrations of the formation products’. A comprehensive expression for nth-order bulk fluid reactions is developed in Equation 2.7.

$$\theta(C) = \pm K C^n \dots \dots \dots 2.7$$

Where, $\theta(C)$ = reaction term (M/L³/T)

K = reaction rate coefficient [(L³/M)ⁿ⁻¹/T]

C = concentration (M/L³)

n = reaction rate order constant

The rate expression accounts for only a single reactant concentration, tacitly assuming that any other reactants (if they participate in the reaction) are available over the concentration necessary to sustain the reaction. The sign of the reaction rate coefficient, k, signifies that a formation reaction (positive) or a decay reaction (negative) is occurring. The units of the reaction rate coefficient depend on the order of the reaction. The decay reactions frequently used to model chemical processes that occur in water distribution systems are zero-, first-, and second-order. Using the generalized expression in Equation 2.8, these reactions can be modeled by letting n equal 0, 1, or 2 and subsequently performing a regression analysis to experimentally determine the rate coefficient (Walski et al., 2003).

The most frequently used reaction model is the first-order decay model. ‘This has been applied to chlorine decay, radon decay, and other decay processes. Equation 2.8 represents a first-order decay which is equivalent to an exponential decay (Walski et al., 2003).

$$C_t = C_0 e^{-kt} \dots \dots \dots 2.8$$

Where, C_t = concentration at time t (M/L³)

C_0 = initial concentration (at time zero)

K = reaction rate (1/T)

For first-order reactions, the units of reaction rate (k) are (1/T) with values generally expressed in 1/ days or 1/hours.

The time it takes for the concentration of a substance to decrease to 50 percent of its original concentration is termed half-life. For instance, ‘the half-life of radon is approximately 3.8 days, and the half-life of chlorine can vary from hours to many days. The relationship between the decay rate, k , and half-life is obtained by solving Equation 2.15 for the time t when C_t/C_o is equal to a value of 0.5(Walski et al., 2003).

$$T = \left(\frac{0.693}{K} \right) \dots\dots\dots 2.9$$

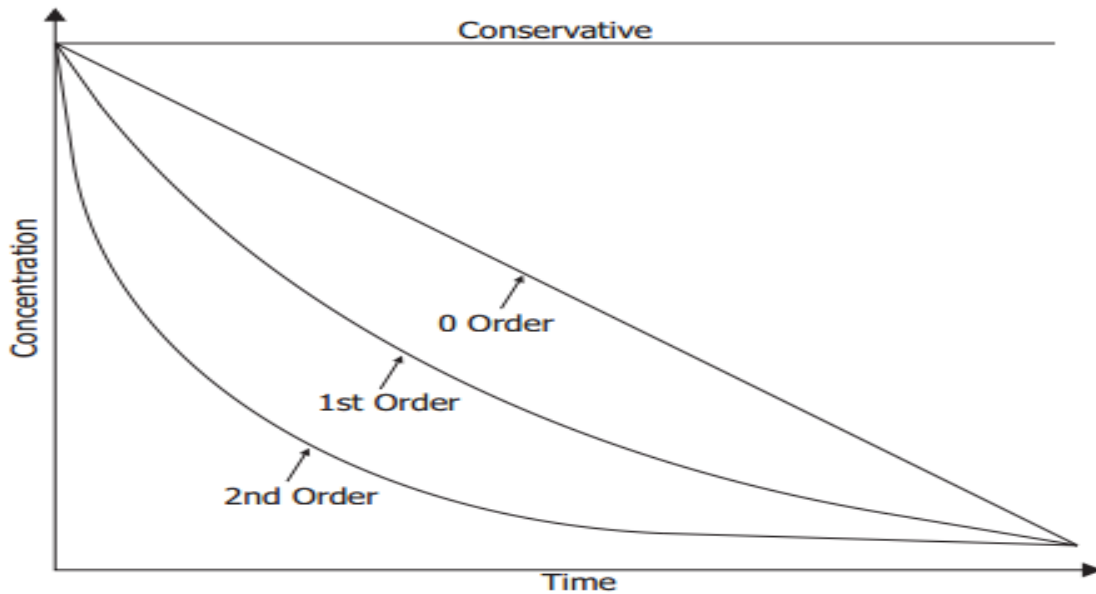


Figure 2. 3-Conceptual illustration of concentration versus time for zero, first-, and second-order decay reactions

2.7.2. Pipe Wall Reactions

While flowing through pipes, dissolved substances can be transported to the pipe wall and react with materials, such as corrosion products or biofilm that are on or close to the wall. The amount of wall area available for reaction and the rate of mass transfer between the bulk fluid and the wall also will influence the overall rate of this reaction. The surface area per unit volume, which for a pipe equals two divided by the radius, determines the former factor. The latter factor can be represented by a mass transfer coefficient, the value of which depends on the molecular diffusivity of the reactive species and the Reynolds number of the flow (*Digiano and Zhang, 2005*). For first-order kinetics, the rate of a pipe wall reaction can be expressed as:

$$r = \frac{2K_w K_f C}{R(K_w + K_f)} \dots \dots \dots 2. 10$$

Where, k_w = wall reaction rate constant (L/T),

k_f = mass transfer coefficient (L/T), and

R = pipe radius (L).

If a first-order reaction with rate constant k_b also is occurring in the bulk flow, then an overall rate constant k (T^{-1}) that incorporates both the bulk and wall reactions can be written as

$$K = K_b + \frac{2K_w K_f C}{R(K_w + K_f)} \dots \dots \dots 2. 11$$

2.8. Other Types of Water Quality Simulations

Along with the constituent analysis, source trace and water age analyses are the most common types of water quality simulations. The solution methods used in both of these simulations are specific applications of the method used in the constituent analysis (Walski et al., 2003).

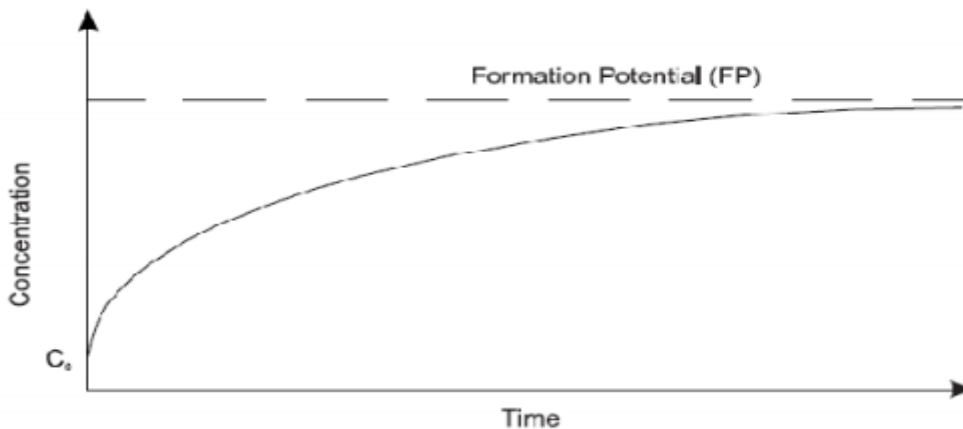


Figure 2. 4-First-order growth rate to a limiting value

2.8.1. Source Trace Analysis

Source tracing is a useful tool for analyzing distribution systems drawing water from two or more different raw water supplies. It can show to what degree water from a given source blends with that from other sources, and how the spatial pattern of this blending changes over time (Rossman, 2000).

Source trace analysis is useful to identify areas within the distribution system influenced by a particular source. In addition, it helps identify areas where the mixing of water from various sources has occurred. The significance of source mixing depends on the quality characteristics of the waters. Sometimes, mixing can reduce the aesthetic qualities of the water (for example, creating cloudiness as solids precipitate, or causing taste and odor problems to develop), and can contribute to disinfectant residual maintenance problems. Water quality problems related to storage tanks can also be analyzed using source trace analysis. (Walski et al., 2003).

For better handling of these situations a source trace analysis is a useful tool. ‘Specifically, it can be used to determine the percentage of water originating from a particular source for each junction node, tank, and reservoir in the distribution system model’. The advective transport and mixing equations are used to simulate the transport pathways through the network and the influence of transport delays and dilution on the trace constituent concentration. The values computed by the simulation are then read directly as the percentage of water arriving from the source location (Walski et al., 2003).

2.8.2. Water Age Analysis

Many water distribution systems experience long retention times or increased water age, in part due to the need to satisfy fire fighting requirements. Although not a specific degradative process, water age is a characteristic that affects water quality; because, many deleterious effects are time-dependent (NRC, 2006). Typically, the loss of disinfectant residuals and the formation of disinfection by-products are due to increased water age.

The chemical processes that can affect distribution system water quality are a function of water chemistry and the physical characteristics of the distribution system itself (for example, pipe material and age). More generally, however, these processes occur over time, making residence time in the distribution system a critical factor influencing water quality (Walski et al., 2003). The cumulative residence time of water in the system, or water age, has come to be regarded as a reliable surrogate for water quality. Water age is of particular concern when quantifying the effect of storage tank turnover on water quality. It is also beneficial for evaluating the loss of disinfectant residuals and the formation of disinfection by-products in distribution systems.

The chief advantage of a water age analysis when compared to a constituent analysis is that once the hydraulic model has been calibrated, no additional water quality calibration procedures are required. The water age analysis, however, will not be as precise as a constituent analysis in determining water quality; nevertheless, it is an easy way to leverage the information embedded in the calibrated hydraulic model. Consider a project in which a utility is analyzing mixing in a tank and its effect on water quality in an area of a network experiencing water quality problems. If a hydraulic model has been developed and adequately calibrated, it can immediately be used to evaluate water age. The water age analysis may indicate that excessively long residence times within the tank are contributing to water quality degradation. Using this information, a more precise analysis can be planned (such as an evaluation of tank hydraulic dynamics and mixing characteristics, or a constituent analysis to determine the impact on disinfectant residuals), and preliminary changes in design or operation can be evaluated' (Walski et al., 2003).

2.9. Model Calibration and Validation

For the majority of water distribution models, calibration is an iterative procedure of parameter evaluation and refinement, as a result of comparing simulated and observed values of interest. Model validation is in reality an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort.

2.9.1. Hydraulic Model Calibration

Hydraulic behavior refers to flow conditions in pipes, valves, and pumps, and pressure/head levels at junctions and tanks. According to (EPA, 2005) for hydraulic model calibration Parameters that are typically set and adjusted include pipe roughness factors, minor losses, demands at nodes, the position of isolation valves (closed or open), control valve settings, pump curves, and demand patterns. 'When initially establishing and adjusting these parameters, care should be taken to keep the values for the parameters within reasonable bounds. The use of unreasonable values may lead to a better match for one set of data, but will typically not provide a robust set of parameters that would apply in other situations.

2.9.2. Water Quality Model Calibration

After the proper calibration of a hydraulic model, additional calibration of parameters in a water quality model may be required. ‘The following parameters are used by water quality models that may require some degree of calibration’ (EPA, 2005):

- **Initial Conditions:** Defines the water quality parameter (concentration) at all locations in the distribution system at the start of the simulation.
- **Reaction Coefficients:** Describes how water quality may vary over time due to chemical, biological or physical reactions occurring in the distribution system.
- **Source Quality:** Defines the water quality characteristics of the water source over the period being simulated.

2.9.3. Calibration and Validation using Time-Series data

According to (Walski et al., 2003) a vital step in calibrating and validating an extended-period simulation is to compare time-series field data to model results. ‘If the field data and model results are acceptably close, the model is calibrated. If significant variations exist, adjustments can be made to various model parameters to improve the match. Ideally, one set of data should be available for calibration, and another set of data should be available to validate that the model is properly calibrated. Hydraulic measurements, water quality data, and tracer data are frequently used in combination in the extended period simulation calibration and validation process.

2.9.4. Acceptable Levels of Calibration

Each application of a model is unique, and thus it is impossible to derive a single set of guidelines to evaluate calibration. The guidelines presented below give some numerical guidelines for calibration accuracy; however, they are in no way meant to be definitive. A range of values is given for most of the guidelines to reflect the differences among water systems and the needs of model users. The higher numbers generally correspond to larger, more complicated systems, and the lower end of the range is more relevant to smaller, simpler systems. The words “to the accuracy of elevation and pressure data” mean that the model should be as good as the field data. If the Hydraulic Grade Line is known to within (2.5 m), then the model should agree with field data to within the same tolerance. It is important to remember that these guidelines need to be tempered

by site-specific considerations and an understanding of the intended use of the model (Walski et al., 2003).

- **Master planning for smaller systems [(600-mm) pipe and smaller]:** The model should accurately predict hydraulic grade line to within (1.5–3 m) (depending on the size of system) at calibration data points during fire flow tests and to the accuracy of the elevation and pressure data during normal demands. It should also reproduce tank water level fluctuations to within (1–2 m) for extended-period simulation runs and match treatment plant/pump station/ well flows to within 10–20 percent.
- **Master planning for larger systems [(600-mm) and larger]:** The model should accurately predict Hydraulic Grade Line to within (1.5–3 m) during times of peak velocities and to the accuracy of the elevation and pressure data during normal demands. It should also reproduce tank water level fluctuations to within (1–2 m) for extended-period simulation runs and match treatment plant/ well/pump station flows to within 10–20 percent.
- **Pipeline sizing:** The model should accurately predict Hydraulic Grade Line to within (1.5–3 m) at the terminal point of the proposed pipe for fire flow conditions, and to the accuracy of the elevation data during normal demands. If the new pipe impacts the operation of a water tank, the model should also reproduce the fluctuation of the tank to within (1–2 m).
- **Fire flow analysis:** The model should accurately predict static and residual Hydraulic Grade Line to within (1.5–3 m) at representative points in each pressure zone and neighborhood during fire flow conditions and to the accuracy of the elevation data during normal demands. If fire flow is near maximum fire flow such that storage tank sizing is important, the model should also predict tank water level fluctuation to within (1–2 m).
- **Subdivision design:** The model should reproduce Hydraulic Grade Line to within (1.5–3 m) at the tie-in point for the subdivision during fire flow tests and to the accuracy of the elevation data during normal demands.

- **Rural water system (no fire protection):** The model should reproduce Hydraulic Grade Line to within (3–6 m) at remote points in the system during peak demand conditions and to the accuracy of the elevation data during normal demands.
- **Distribution system rehabilitation study:** The model should reproduce static and residual Hydraulic Grade Line in the area being studied to within (1.5–3 m) during fire hydrant flow tests and to the accuracy of the elevation data during normal demands.
- **Flushing:** The model should reproduce the actual discharge from fire hydrants or distribution capability [such as the fire flow delivered at a (138 kPa) residual pressure] to within 10–20 percent of observed flow.
- **Energy use:** The model should reproduce total energy use over 24 hours to within 5–10 percent, energy consumption on an hourly basis to within 10–20 percent, and peak energy demand to within 5–10 percent.
- **Operational problems:** The model should reproduce problems occurring in the system such that the model can be used for decision-making for that particular problem.
- **Emergency planning:** The model should reproduce Hydraulic Grade Line to within (3–6 m) during situations corresponding to emergencies (for example, fire flow, power outage, or pipe out of service).
- **Disinfectant models:** The model should reproduce the pattern of observed disinfectant concentrations over the time samples were taken to an average error of roughly 0.1 to 0.2 mg/l, depending on the complexity of the system.

The true test of model calibration is that the end-user (for example, the pipe design engineer or chief system operator) of the model results feels comfortable using the model to assist in decision making. To that end, calibration should be continued until the cost of performing additional calibration exceeds the value of the extra calibration work (Walski et al., 2003).

3. MATERIAL AND METHODS

3.1. Description of the Study area

Bahir Dar town, which is a fast-growing town with its current status as a regional state of the Amhara Region. The town is located in the North-Western part of the country at a distance of 565 km by a road from Addis Ababa on the Gondar highway. The town is bounded to the north by Lake Tana and marks the sources of the great Blue Nile River. The Population and Household Census conducted by CSA in 2007 gave the population of Bahir Dar urban as 180,174.

The town is approximately enclosed between 11°32' 0" N and 11°38'0"N latitudes and 37°20'0" E and 37°27' 40" E longitudes. The landscape is flat with some small hills to the east and west. The estimated area of the town is 62.22 Km²with an average elevation of 1795 a.m.s.l. The mean annual ambient temperature is 16 °c. The maximum temperature usually occurs from March to May. The mean monthly maximum temperature exceeds 26 °c. Minimum temperatures are at their lowest from November to February. The location of the study area in Figure 3.1.

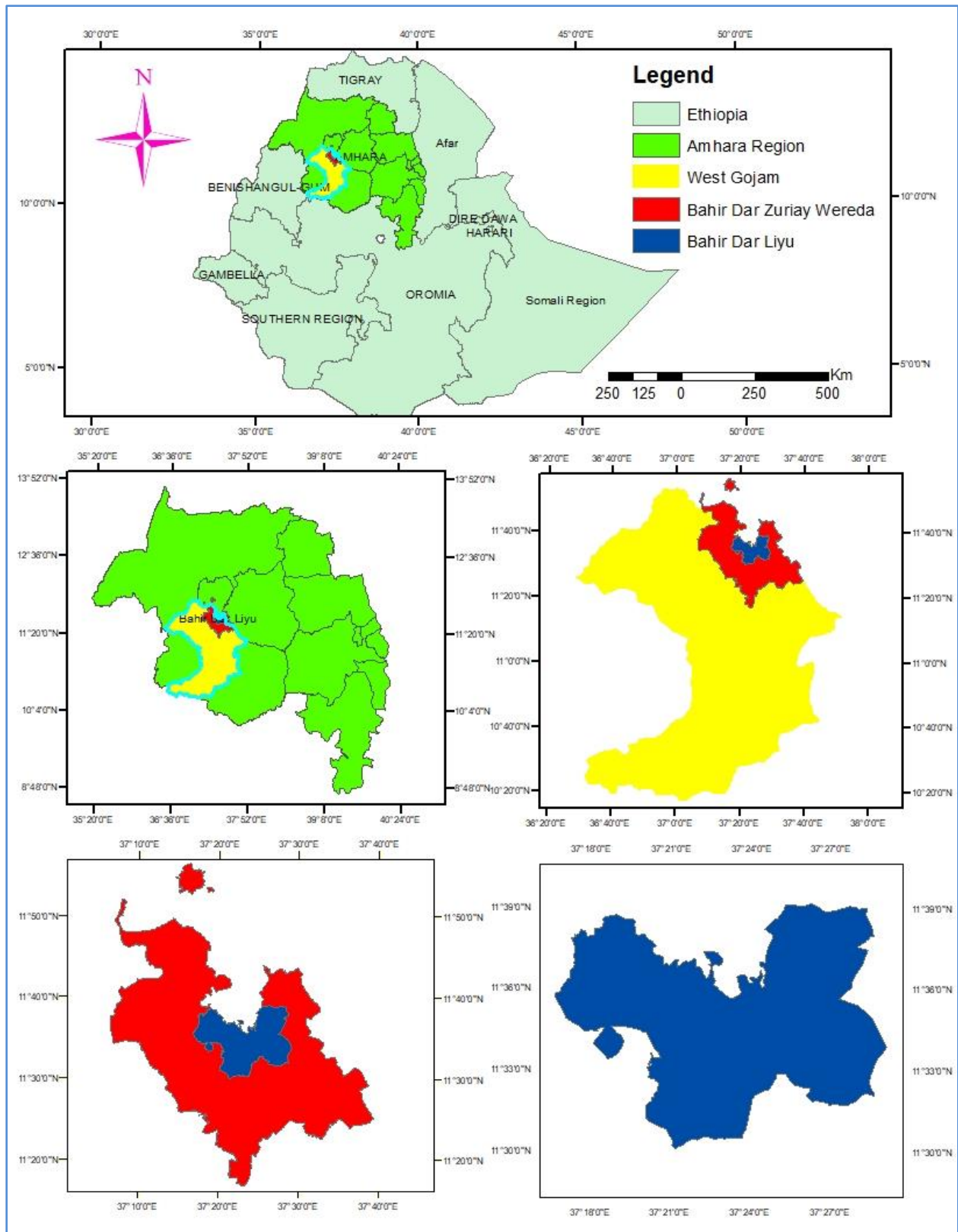


Figure 3. 1-Location map of the Study Area

3.2. Description of the existing water supply system

3.2.1. Water Source

The water is extracted from Areki and Lomi Springs. Four boreholes situated in the town are also augmenting the supply of water for the town since 2008. Description and available data on the springs and boreholes are presented in Table 1.

Table 1- Description of Springs and Boreholes in Bahir Dar

I. No	Type of Source	UTM Easting	UTM Northing	Elevation	Yield (l/s)
1	Areki Spring	312562	1281495	1841	220
2	Lomi spring	311960	1282130	1846	60.0
3	Gordoma borehole	323954	1278667	1801	5.00
4	Eyerusalem borehole	327132	1284307	1798	8.50
5	Gudo Bahir borehole	320611	1280765	1806	20.0
6	Ashraf borehole	328668	1281850	1819	12.5

3.2.2. Reservoirs

There are five reservoirs and one booster storage in the distribution system located at four places.

The Kotetina reservoirs which are in good condition at the time of visit receive water from the spring sources. The reservoirs are 1000m³ and 2000m³ in capatown bringing the overall capatown of the reservoirs to 3000m³. These reservoirs are not fulfilling their intended purpose of water storage due to water shortage. They are more or less serving as a conveyance route.

The Gabriel reservoirs with capacities of 1000m³ and 150m³ are receiving water from the Abay booster Station. Similar to the other reservoirs, the operation of these reservoirs encounters limitations due to water shortage. Summary of the reservoirs, which are all functional, is given in Table 2.

Table 2-Existing Reservoirs of Bahir Dar town

Site name	Easting(m)	Northing (m)	Elevation(m)	Capacity (m ³)
Kotita reservoir/A & B/	321110	1282210	1870	2000 & 1000
Kotetina reservoir	321859	1278930	1841	500
St. Gebriel reservoir/A& B/	329636	1282502	1900	1000 & 150
Booster Storage	326558	1283239	1809	500

3.2.3. Distribution Network

System maps are typically the most useful documents for gaining an overall understanding of a water distribution system because they illustrate a wide variety of valuable system characteristics. System maps may include information such as pipe alignment, connectivity, material, diameter, and so on, the locations of other system components, such as tanks and valves, pressure zone boundaries, elevations, miscellaneous notes or references for tank characteristics, background information, such as the locations of roadways, streams, planning zones, and so on. For this study system maps were collected from Bahir Dar Water Supply and Sewerage Authority and Tropics Consulting Engineers Private Limiting Company.

The distribution system consists of polyvinyl chloride pipes ranging from Nominal Diameter 50 to 350mm and Ductile Iron pipes ranging from Nominal Diameter 400 to 600mm. The system appurtenance contains: 10 fire hydrants with a nominal diameter of 80mm, 10 aeration valves with a nominal diameter of 50mm fixed on 350mm Ductile Iron pipes, and 8 flushing devices installed on different pipes ranging from Nominal Diameter 50 to 300mm.

Table 3- Existing Pipes of Bahir Dar Water Supply Scheme

Diameter (mm)	Material	Length (m)
50	Polyvinyl chloride	1,736
80	Polyvinyl chloride	17,221
100	Polyvinyl chloride	11,379
150	Polyvinyl chloride	19,488
200	Polyvinyl chloride	5,980
250	Polyvinyl chloride	5,794
300	Polyvinyl chloride	10,420
350	Polyvinyl chloride	897
400	Ductile Iron	6,444
600	Ductile Iron	510
Total		79,869

3.3. Sampling Site

Selecting water quality sample points was one of the most important steps for designing and exploiting water quality monitoring in the network. Water quality is usually specified by physical,

chemical, and biological parameters. water quality sample corrected and determining their relations is complicated. However, these are necessary for specifying of water sample point but measuring all of them is not economical, so sampling selected depend on the Ethiopian Water Quality Standard Agency, (2013). According to Ethiopian Water Quality Standard Agency, (2013) sampling for bacteriological examination and other water quality parameters should be regular and its frequency and size would mainly depend on the different types of factors. These are the quality of the water harnessed, type of treatment for drinking worthiness, risks of contamination, background of the public water supply network, and the number of people served.

The minimum sample size for drinking water in the distribution population served sample was taken based on the population. Based on Ethiopia water quality standards Agency, 2013 for the population which is less than 5,000, one sample, for 5,000-10,000 one sample per 5,000 population and above 100,000 one sample per 10,000 population plus 10 sample additional.

3.4. Sampling and Laboratory analysis

After fixing the number of sampling sites, the next step was collecting water samples to examined different physical-chemical and biological parameters that have adverse impacts on chlorine demand. Based on this addition to secondary and primary data were collected from the selected thirteen sampling points labeling as shown in the Table 4. Based on this locations and number of sampling points were selected according to populated zones, sampling point accessibility, the existence of additional treatment units, and the sustainability of sampling points. The evaluation and modeling of the amount of residual chlorine in the distribution system were carried out with the help of EPANETE software.

Table 4- Location of Sampling point

Pt	Sampling point	Labeling sample	Pt	Sampling point	Labeling sample
1	ERA	SP1	16	Papyrus	SP16
2	Catholic	SP2	17	Wisdom tour	SP17
3	Bata road	SP3	18	Peda	SP18
4	Homeland	SP4	19	ACSI	SP19
5	Chaina Camp	SP5	20	Poly	SP20
6	Medroc	SP6	21	St. George	SP21
7	Afrata	SP7	22	Bus station	SP22
8	Behind Condominium	SP8	23	Beg tera	SP23
9	Kobil stone joint	SP9	24	Gabriel sefer	SP24
10	Kidane Mihrete	SP10	25	Tyema school	SP25
11	Condeminium End	SP11	26	Hidar 11 Keble	SP26
12	AWWCE Cobleston	SP12	27	St. Mikael church	SP27
13	Fasilo	SP13	28	ADSWE	SP28
14	Dev"t Bank	SP14	29	Diaspora End	SP29
15	Mulalem	SP15	30	Ayer tena-3	SP30

3.5. The analytical procedure of chlorine

Water samples can be prepared by collecting the water from taps along the study area of the selected point distribution system when the chlorine is added to the reservoir. Analysis procedures of sample were conducted based on standard procedure (Beeharry, 2018).

Using the Diethyl-p-phenylenediamine colorimetric method Using photometer 9300 a 24mm vial filled with 10 mL of zero process sample. Take one Chlorine complete Diethyl-p-henylenediamine powder pack, carefully tap it down, and tear it open in the text's direction. Fill the sample container with the contents. To dissolve the powder, tighten the cap on the vial and whirl it vigorously. If chlorine is present, a pink color will appear. Place the prepared sample into the sample chamber as soon as possible. Use the crucial cover to protect your work. To measure a sample, press the key.

The instrument will begin a two-minute countdown before displaying the result as mg/l (or ppm) total chlorine residual in the display.

It's because of the high chlorine levels that the monitor flashes "overrun." Dilley a new sample and run the test again.

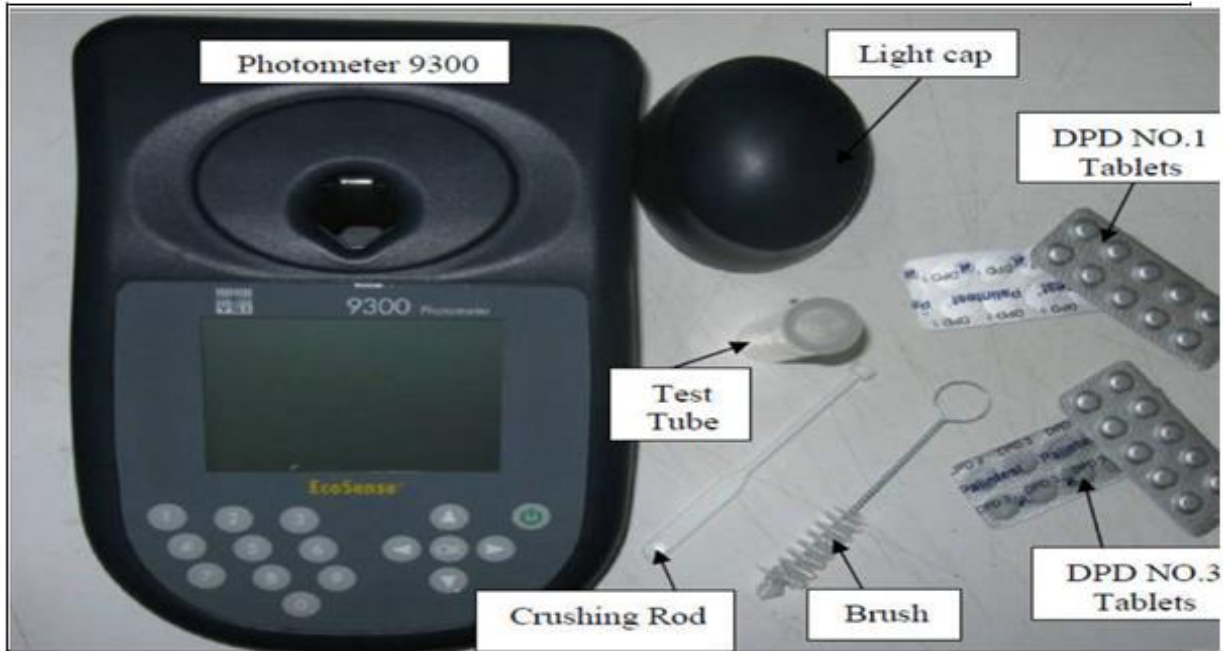


Figure 3. 2-Photometer 9300 device, testing equipment, and reagents

The instrument used to measure pH and temperature as ATC Meter that shows both temperature and PH at the same time (Figure 3.3).



Figure 3. 3-ATC Meter for measurement of PH and Temperature

3.6. Bulk chlorine decay coefficient

With the Photometer 9300, the bulk chlorine decay coefficient K_b was calculated in the laboratory. All of the glassware was washed in distilled water. A normal mercury thermometer was used to take temperature readings. 1 Litter of chlorinated sample water was collected in a 1 Litter dark glass bottle for each experiment. The bottle was sealed with a glass stopper. To improve the homogeneity of the sample, the bottle was gently shaken for around 60 seconds following chlorination. To guarantee complete mixing of water, the first measurement was taken 10 to 15 minutes after chlorination. Following the last measurement, the chlorine concentration was lowered to 0.1 to 0.2 mg/l by taking additional readings from the container at regular intervals. To determine the bulk chlorine decay coefficient, graphs were produced between residual chlorine concentrations and time.

After measure, the chlorine residual Bulk chlorine decay coefficients (K_b) were determined from residual chlorine Vs time graph, whereas wall chlorine decay coefficients (K_w) were determined through EPANET simulation by trial and error

3.7. Modeling Tool

Water distribution network mathematical models have become increasingly accepted within the water industry as a mechanism for simulating the behavior of water distribution systems. They are intended to replicate the behavior of an actual or proposed system under various demand loading and operating conditions. their purpose is to support the decision -making processes in various utility management applications including planning, design, operation, and water quality improvement of water distribution systems.

For this study EPANET modeling software was preferred as analyzing tool due to its Hydraulic and Water Quality modeling capabilities. EPANET is an open -structured, public domain hydraulic and water quality model developed by the EPA, and is used worldwide (E. Hickey, 2008). Beside this, EPANET is user friendly and accessible modeling software.

EPANET has gained wide acceptance world -wide; for the merely fact that it provides quantitative basis for undertaking new modeling activities and assessment of existing water distribution system. It has been used for: Long -range master planning, including new development and rehabilitation, Fire protection studies, Water quality investigations, Energy

management, System design, daily operational uses including operator training, emergency response, and Troubleshooting (EPA,2005).

In addition to hydraulic modeling, EPANET provides the following water quality modeling capabilities: models the movement of a non-reactive tracer material through the network over time, models the movement and fate of a reactive material as it grows (e.g., a disinfection byproduct) or decays (e.g., chlorine residual) with time,models the age of water throughout a network, models reactions both in the bulk flow and at the pipe wall, uses n-th order kinetics to model reactions in the bulk flow, and uses zero or first order kinetics to model reactions at the pipe wall etc.

3.8. Initial chlorine concentration

To determine the initial chlorine concentration intering the system, free chlorine water samples of raw water were collected at service reservoirs. This free chlorine water sample was collected from the inlet of reservoirs. The collected samples were analyzed using a Photometer 9300 instrument.

Diethyl-p-phenylenediamine indicator (N, Diethyl-p-phenylenediamine) was used as a chemical reagent for chlorine measurements. Free available chlorine (Cl_2 , HOCl, OCl) oxidizes Diethyl-p-phenylenediamine to produce a red color. This color is then measured using Photometer 9300. Quality characteristics of reservoir water at the sampled location were then analyzed.

In the experiment, varying amounts of chlorine (0.5, 1.0, 1.5, 2.0, 2.5 , 3.5, 4.5, and 5.5 mL chlorine solution) were added; the corresponding residual chlorine was then analyzed.

3.9. Determining Re-Chlorination Points

An optimization model was proposed in this study to determine the re-chlorination facility or point location and the doses for the Bahir dar water supply distribution system, which require maintenance to ensure appropriate residual chlorine concentrations for faucets at the end of the pipeline under the present and future conditions.

The calculation results for the optimal solutions were obtained by setting the number of re-chlorination point by using model analysis of the distribution system, therefore optimization techniques of re chlorination point have been applied to the same hydraulic design parameter, such as the node pressure and pipe flow velotown, only trial -and-error-based techniques currently used

for water quality modeling. Therefore, this model will be useful for the design of a new water distribution system of the re-chlorination point of the Bahir dar town distribution system.

4. RESULT AND DISCUSSION

4.1. Assessment of existing residual chlorine

Figure 4.1 shows the residual chlorine values that were measured in the selected point. The results of the sampling motions revealed that chlorine residual levels varied significantly from hour to hour throughout the day. From one hour to the next on the same day, there were temporal changes in residual chlorine levels, and these patterns were heavily driven by differences in features. Levels of free residual chlorine, as well as the distribution system that varies from system to system. The temporal variability of the concentrations of the various factors observed along with the distribution network is due to an increase in water residence time along with the distribution network, which is accompanied by a decreasing gradient of free and total residual chlorine concentrations.

The existing maximum residual chlorine concentration at the sample point through the distribution system shown in Figure 4.1 was almost less than the minimum recommended by the World Health Organization standard (0.2mg/l). From the total residual chlorine, analysis samples were taken at consumer taps, 40% of the result has recorded above 0.2 mg/l but, less than 0.23 mg/l and the other 60% have resulted below 0.1 mg/l. Generally the

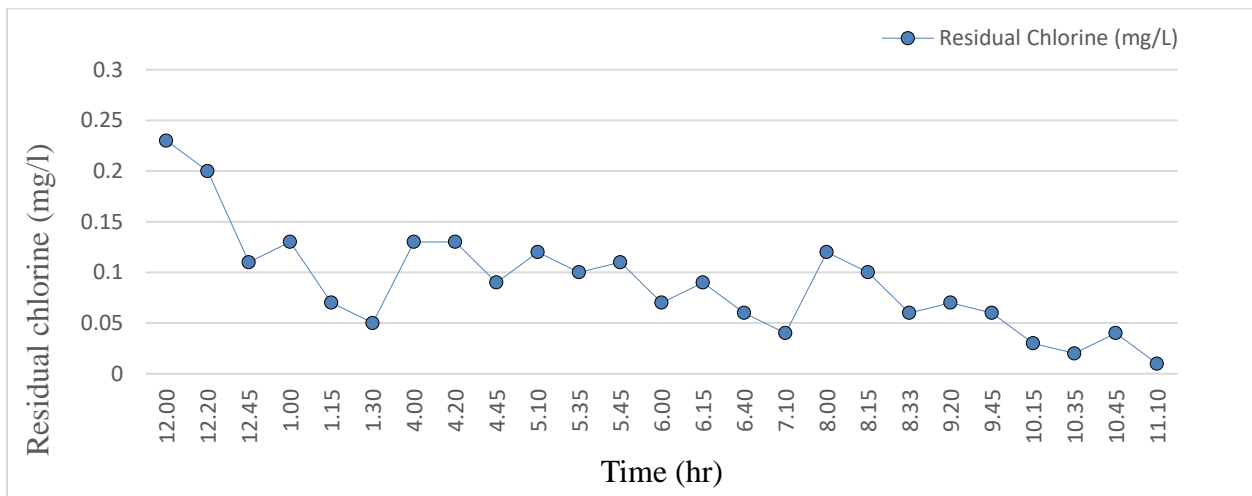


Figure 4. 1-Chlorine residual mesearad value at the selected points

4.2. Determination of initial chlorine concentration

Bahir Dar Water Supply and Sewerage Authority recommended that a dose of 1.5 to 2 mg/l be applied to both water storage service reservoirs in the study area. These numbers do not remain consistent overtime for all of the reservoirs in the research area. For the chlorination of the Bahir Dar Water Supply and Sewerage Authority water source, no breakpoint curves have been tested experimentally.

The chlorine demand and breakpoint of the water to be treated must be calculated to properly treat drinking water with chlorine. Table 5 shows the results of the bottle analysis for chlorine dose and residuals. At several stages during the chlorine dosages, free residuals were measured. Chlorine requirements were determined using equation 2.3. Table 5 shows that the total residuals (combined and free), free, and demand of chlorine added to the water sample are all increasing.

Table 5-Chlorine doses and residuals measurements

Order no. 100 mL flask	1	2	3	4	5	6	7	8
Chlorine dose (mg/L)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Chlorine residual (mg/L)	0.2	0.6	0.96	1.3	0.46	0.35	0.33	0.18
Free chlorine (mg/L)	0.13	0.26	0.33	0.45	0.56	1.24	1.9	2.8
Total chlorine residual	0.33	0.86	1.29	1.75	1.02	1.59	2.23	2.98
Chlorine demand (mg/L)	0.3	0.4	0.5	0.7	2.0	2.7	3.2	3.8

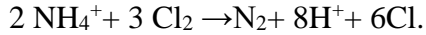
As illustrated in Figure 4.2, the findings of chlorine measurements were used to graph the breakpoint chlorination. Breakpoint reactions occur when increasing levels of chlorine are added to water containing ammonia. The "breakpoint curve" is the graph of chlorine vs. measured residual chlorine.

The reaction of HOCl with NH_4^+ to produce mono-chloramine, NH_2Cl , is shown in part 1 of the breakpoint curve. Effectively, 1 mole/L of residual chlorine will be detected for every mole/L of HOCl injected, resulting in "combined available chlorine."

NH_2Cl is further oxidized by the addition of chlorine as follows:



The latter constituents are broken down here, giving rise to the overall reaction:



Both ammonia and residual chlorine levels drop as a result of this. As a result, the most appropriate chlorine dose is 2.5 mg/l, as shown in Figure 4.2, which yields free chlorine of 0.56 mg/l at the distribution system's entrance. This chlorine dose must be added to maintain a free chlorine residual of 0.2-0.5 mg/l in the study area system.

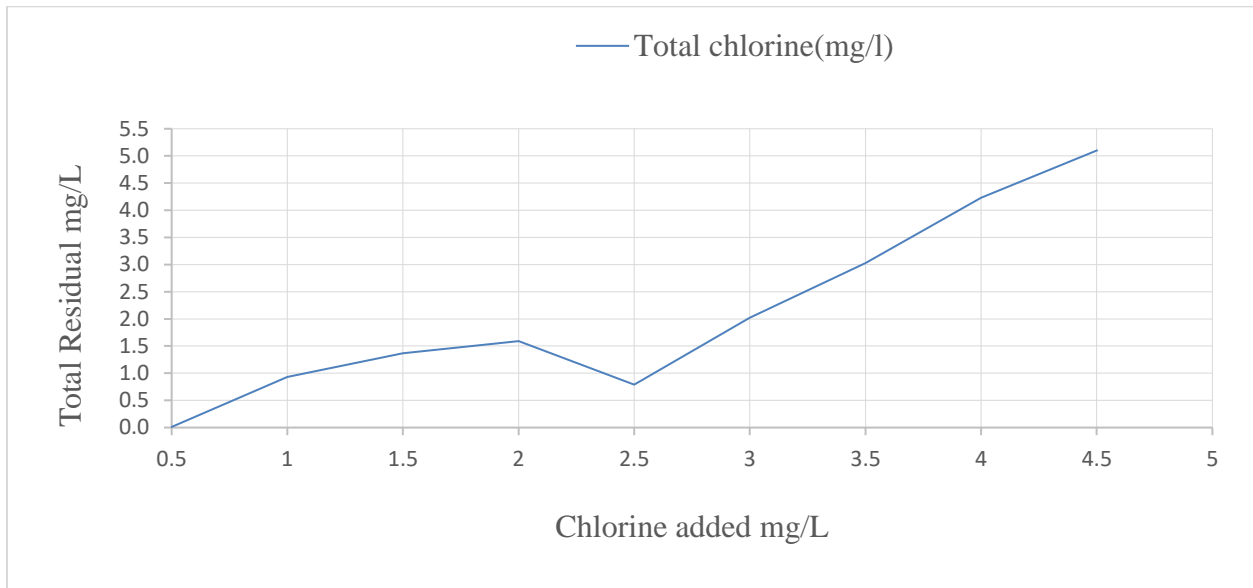


Figure 4. 2- Breakpoint chlorination curve for raw water sample at Reservoir

4.3. Bulk chlorine decay coefficient

With the Photometer 9300, the bulk chlorine decay coefficient K_b was calculated in the lab. The laboratory tests incorporating time-based measurements (12:00 to 11:10 hours) were carried out. Because there is no standard method for determining bulk chlorine decay coefficient K_b , Philip,(2007) used the following procedure to eliminate interference from external factors such as temperature, contamination, Ultra Violet light, and evaporation, among others. The values of the bulk chlorine decay coefficient are 0.76 and 0.94 as shown in the graph given in Figure 4.3 and 4.4.

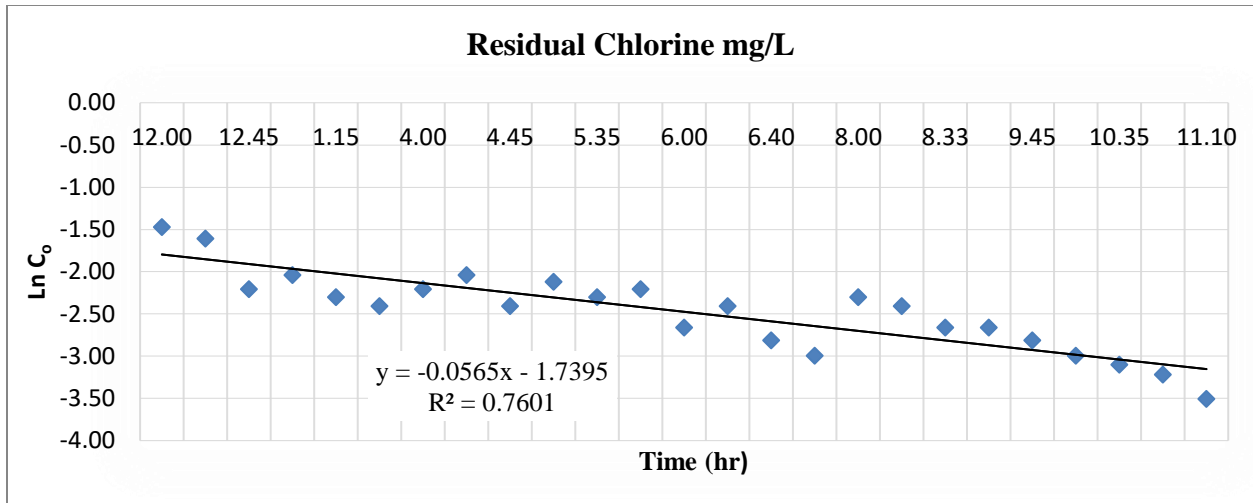


Figure 4. 3- Plot of residual chlorine Vs time for source from Kotetina and Lideta Reservoir

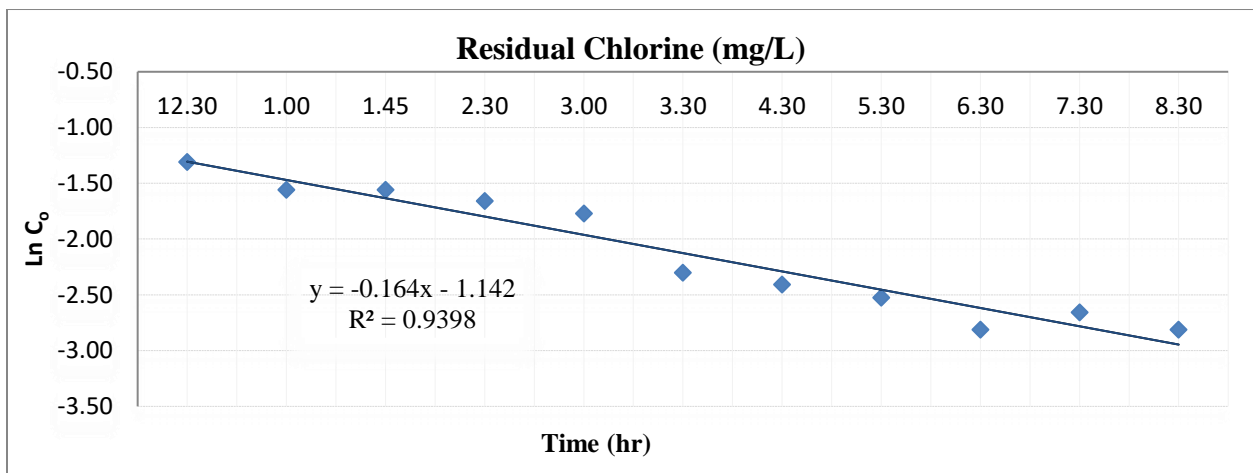


Figure 4. 4- Plot of residual chlorine Vs time for source from Gabriel Reservoir

4.4. Model Run and Calibration

The objective of calibration of the water quality model is to minimize the difference between the field observed and model simulation value for chlorine concentration. For calibrations that were selected the most appropriate fit of the trial results were overlaid above correlation line with the value of observed and simulated results. So that from trial option it was assessed with 1.5mg/L chlorine dose observed residual chlorine result had recorded with the recommended values when compared to it used for model calibration as observed data.

As computed values are within an average error of 0.12 mg/l to observed values. Hence, the model is well-calibrated within the recommended values were taken to an average error of roughly 0.1 to 0.2 mg/l (Walski et al., 2003).

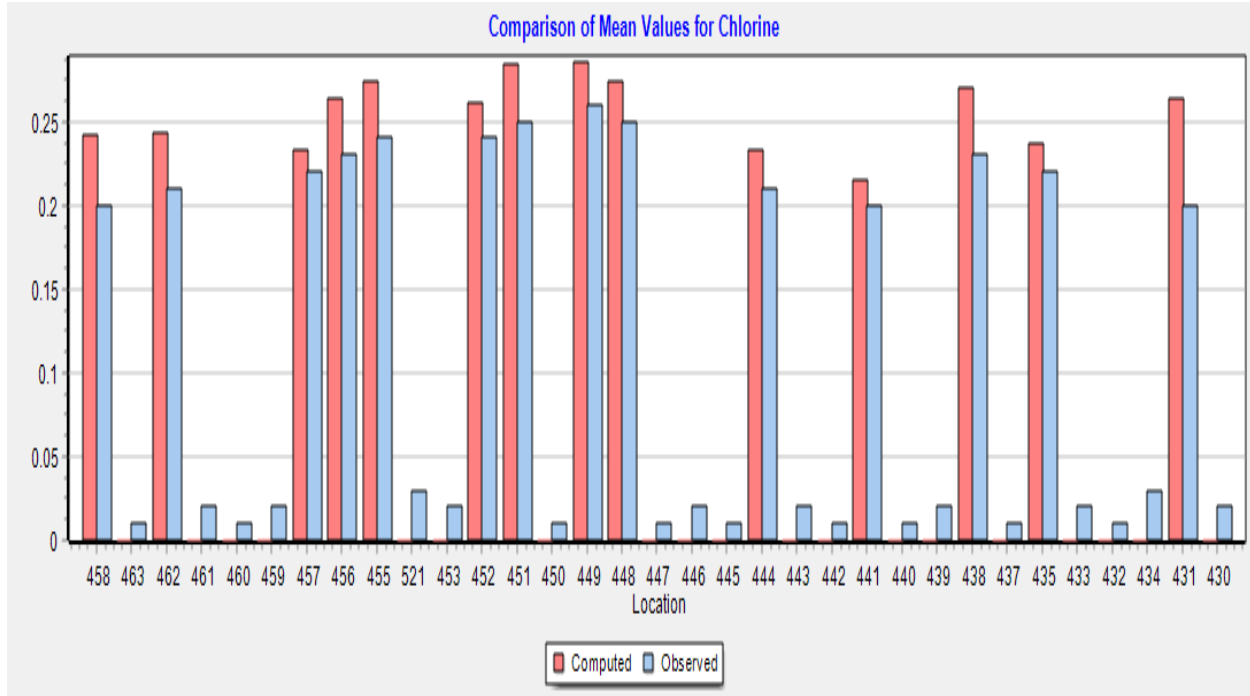


Figure 4. 5-Water quality model calibration

4.5. EPANET Residual Chlorine Model

For modeling of residual chlorine by EPANET, bulk chlorine decay coefficient (K_b) is determined from the laboratory result, which is considered as the fixed-parameter, whereas wall chlorine decay coefficient (K_w) is determined through EPANET simulation by the trial-and-error method which is -0.35.

Single period and extended period simulations were subsequently performed. It was required to run Single period simulation at the beginning of the simulation to observe the model under the snapshot situation. In line with this, running a single-period simulation was helpful while performing preliminary model calibration. However, it should not be used for network assessment as the water distribution system is likely to experience variations. Hence, only extended period simulation was exclusively used for the entire model calibration and model assessment effort.

4.6. Model scenarios by Existing Initial chlorine Dose of 1.5mg/l

Scenario I entails studying water quality as a function of changes in water demand. To examine the situation at peak and minimum demand, water age and residual chlorine were utilized as water quality measures.

(a) Water age at peak and low hour flow

The water age analysis was conducted on the assumption that the distribution system was fully loaded with continuous flow. Table 6 show the distribution of water age at peak and low hour flow.

Table 6-Water age distribution at low hour flow and peak hour flow

Age (hr.)	Nodes	Percentage (%)
	at low hour flow	
< 2	50.0	20.08
5-20	196	78.71
>20	3.00	1.20
	at peak hour flow	
< 5	150	60.24
5-20	98	39.36
>20	1.00	0.40

Table 6 demonstrates that when the hourly flow is low, the majority of nodes (78.71%) receive water that is 5-20 hours. Only 20% of nodes under the age of 2 hours have access to water. During peak hour flow, the percentage of nodes receiving water with an age of 5-20 hours is reduced to 39.36%. There is a substantial difference in the age of the water reaching nodes during high and low water consumption times.

As shown in figure 4.6, water age rises in areas far from sources and low-velocity flows. In areas where tanks congregate, the average water age rises considerably, and all nearby nodes receive water with a long residence period, increasing the danger of disinfection by-product formation.

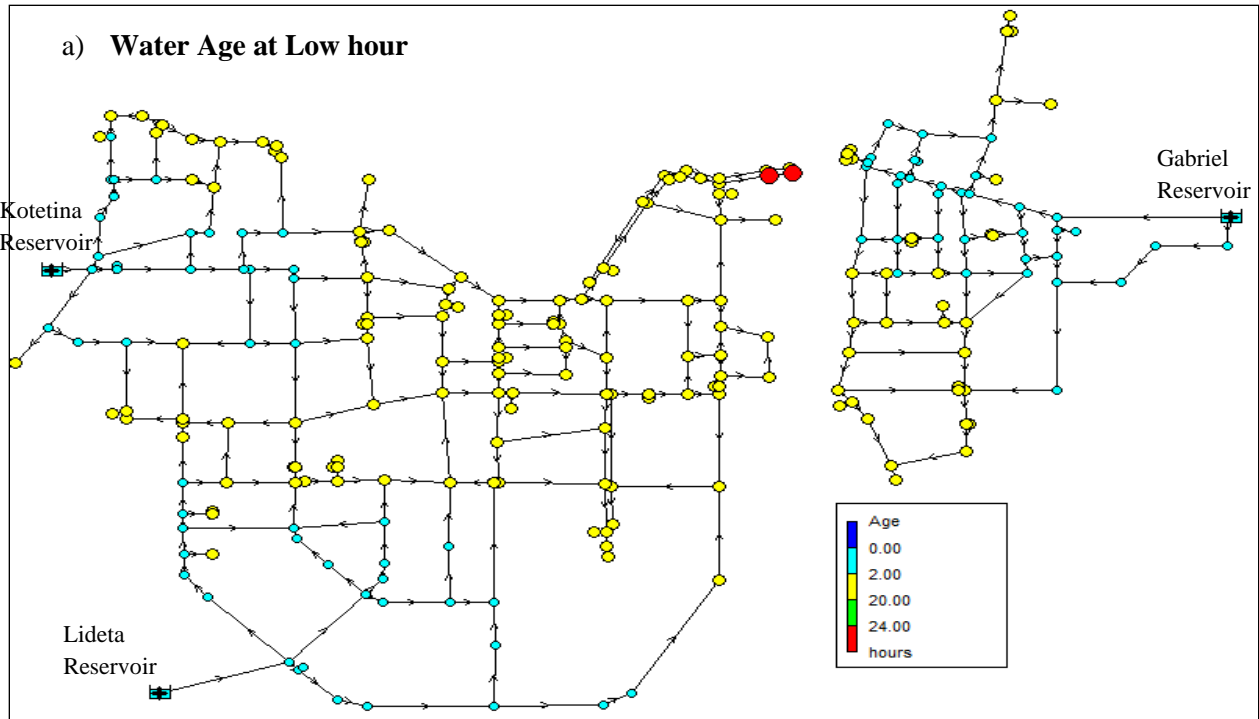


Figure 4. 6-Water age plot at(a) low and (b) peak hour flow

(b) Residual chlorine at peak and low hour flow

The most common technique for preventing recontamination is to ensure that residual chlorine is present in the water distribution system. As recommended by the World Health Organization, residual chlorine at the taps of users should be between 0.2 mg/l and 0.5 mg/l. Tables 7 shows the distribution of residual chlorine concentrations at low and peak hour flow.

Table 7-Residual chlorine distribution at low hour flow and peak hours flow

Residual chlorine (mg/l)	Nodes	Percentage (%)
	at low hour flow	
0	23	9.24
0.01-0.1	146	58.63
0.1-0.2	67	26.91
0.2-0.5	13	5.22
	at peak hour flow	
0	10	4.02
0.01-0.1	134	53.82
0.1-0.2	80	32.13
0.2-0.5	25	10.04

At low hour flow, only 26.91% of nodes receive water with residual chlorine between 0.1-0.2mg/l, as shown in Table 7. Around 9.24% of nodes receive water with no residual chlorine. While, as at peak hour flow, 32.13% of nodes receive water with a residual chlorine level of 0.1–0.2mg/l. This suggests that the distribution system's water quality is substantially better during peak hours than during low hours.

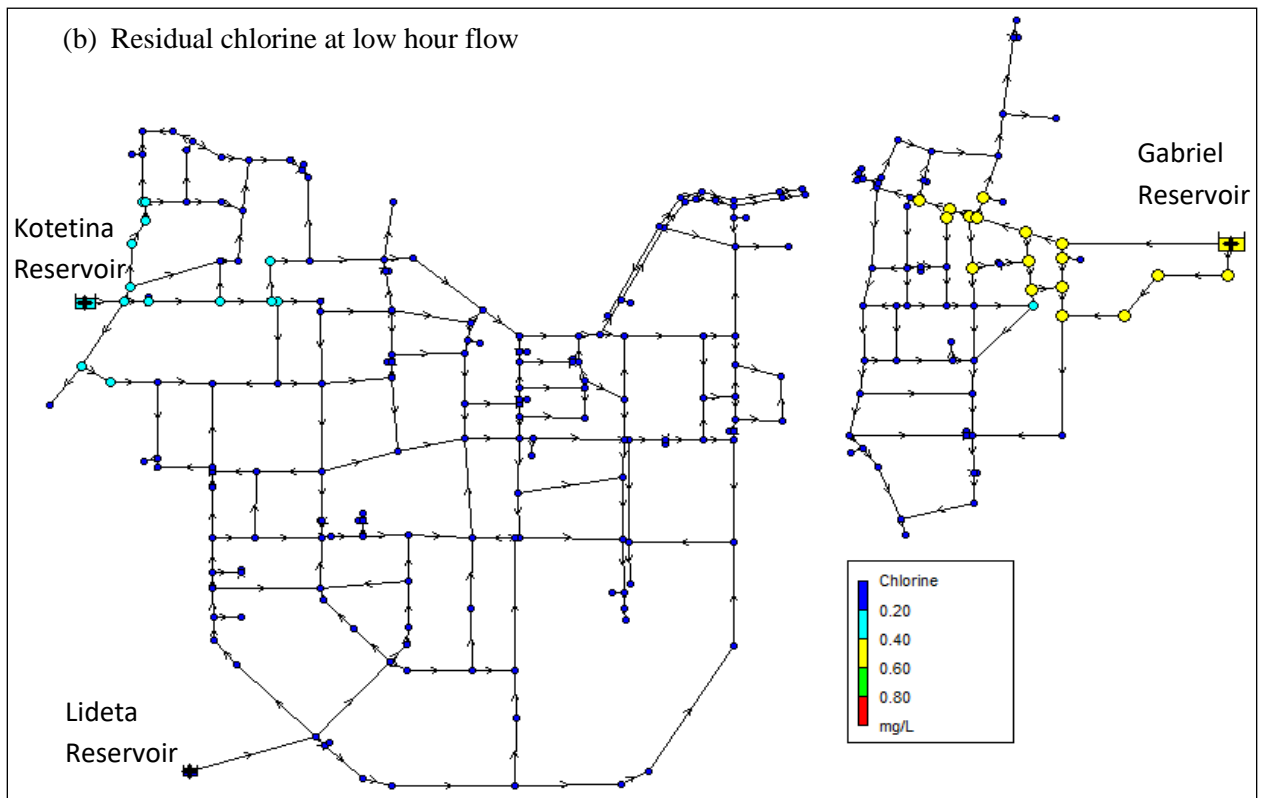
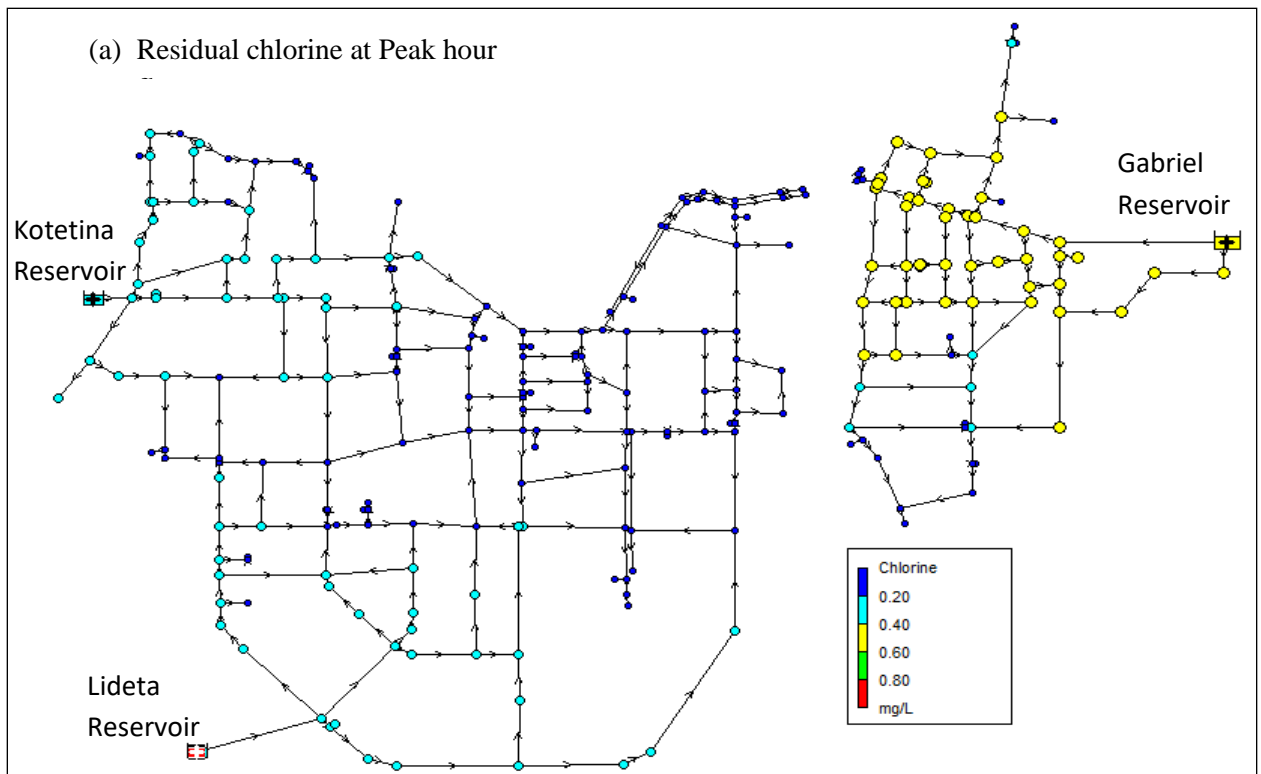


Figure 4. 7-Residual chlorine plot at (a) peak and (b) low hour flow

In Scenario II, the impact of pipe shape on water quality in the Bahir Dar distribution system is investigated. When actual pipe sizes are reduced, the first occurs, but when actual pipe sizes are increased, the second occurs.

Table 8 -Actual and modified pipe sizes

Link ID	Actual Diameter (mm)	Modified Diameter (mm) Down sized	Modified Diameter (mm)Upper sized
Pipe-384	600	500	700
Pipe-474	600	500	700
Pipe-475	600	500	700
Pipe-169	300	250	400
Pipe-694	200	150	300
Pipe-397	300	250	400
Pipe-500	400	300	500
Pipe-503	300	250	400
Pipe-492	300	250	400
Pipe-711	300	250	400
Pipe-712	300	250	400
Pipe-713	300	250	400
Pipe-396	400	300	500

a. Water age for actual and modified pipe sizes

Table 9, depicts the average water age distribution at nodes for actual pipe sizes, downsized pipes, and upper-sized pipes.

Table 9 -Average water age distribution for actual, downsized, and upper-sized pipes.

Age (hr.)	Nodes	Percentage (%)
	actual pipe sizes	
< 5	69	27.71
5-20	178	71.49
>20	2	0.80
	downsized pipes	
< 5	50	20.08
5-20	196	78.71
>20	3	1.20
	upper sized pipes	
< 5	46	18.47
5-20	197	79.12
>20	6	2.41

In the case of actual pipe sizes, the majority of nodes (71.4 %) receive an average water age of 5 hours or less, as indicated in Table 9. The water reaches only 0.8 % of nodes with an average age of fewer than 20 hours. The average water age of 78.1% of nodes with shrunk pipes is 5-20 hours, as indicated in Table 9. Water is only available to 1.2% of nodes with an average age of fewer than 20 hours.

In the case of larger pipelines, 79.12 % of nodes have an average water age of 5-20 hours. Water is obtained by 2.41% of nodes with an average water age below 20 hours. Actual and adjusted pipe sizes have no significant differences in water age, as seen in the table above.

b. Residual chlorine for actual and modified pipe sizes

Table 10 -Minimum residual chlorine for actual, downsize, and upper pipe sizes

Residual chlorine (mg/l)	Nodes	Percentage (%)
	actual pipe sizes	
0	10	4.02
0.01-0.1	134	53.82
0.1-0.2	80	32.13
0.2-0.5	25	10.04
	downsized pipes	
0	15	6.02
0.01-0.1	161	64.66
0.1-0.2	63	25.30
0.2-0.5	10	4.02
	upper sized pipes	
0	6	2.41
0.01-0.1	104	41.77
0.1-0.2	112	44.98
0.2-0.5	27	10.84

As shown in table 10, only 10.04%, 4.02%, and 10.84 %, of nodes, obtain water with residual chlorine in the recommended range of (0.2 – 0.5 mg/l) the whole day for actual, downsized, and upper sized pipes respectively. While 4.02%, 6.02%, and 2.41% of nodes of actual pipe sizes, downsized and upper sized pipes receive water with nil residual chlorine. For the case of downsized pipes percent obtaining optimum residual chlorine is decreased in comparison to existing pipe sizes. For the case of upper-sized pipes percent receiving residual chlorine in the range of (0.2 – 0.5 mg/l) is increased in comparison to actual pipe sizes.

In general, both situations are indicated as current contributors to water quality decline in the Bahir Dar town distribution system. However, due to considerable variances in measured characteristics, scenario I is the most important element for water age and residual chlorine. Scenario II is considered a small contributor to water quality degradation because the significant variance is only detected in the case of residual chlorine measurement. In the case of water age, Scenario II revealed no significant differences.

In both scenarios, residual chlorine concentrations in the distribution system were below the required levels. To overcome the problem of minimum residual chlorine, scenario III was created with two new injection points that result in residual chlorine levels that are within the recommended range.

4.7. Model scenarios: using injection Points

Injection points are used to validate places where the network's minimum chlorine level is not being met. To balance residual chlorine throughout the distribution system, a starting concentration of 2.5 mg/l was used, with two additional chlorine injection points at 0.45 and 0.6 mg/l. Trial and error were used to install injection base chlorine concentrations.

When the water quality responses of the preceding two scenarios are examined, it is clear that the suggested models do not fall below the 0.20 mg/l minimal chlorine residuals for all networks. The highest chlorine residual values are produced near the service reservoir. However, the variances aren't considered, and the maximum chlorine residuals were still within acceptable limits. The average residual values for all networks were found to be in the range of 0.20 - 0.55 mg/l, with more uniform residual distributions observed around injection points and surrounding areas.

In this model scenario, as shown in figure 4.8, the town water distribution networks have more than 90% part of the pipes, and nodes have residual chlorine value within the range of 0.2-0.55 mg/l in all distribution networks. So that, additional two chlorine injection points with initial concentration at service reservoir 2.5 mg/l and using 0.45 & 0.6 mg/l dose injection points respecting location it addresses all networks with recommended values at short time. Generally, additional chlorine injection points are very essential for supply adequate all the networks because; reservoir chlorination was not overlaid all the networks in a short time and also not got the minimum recommended result at the dead-end of the pipes.

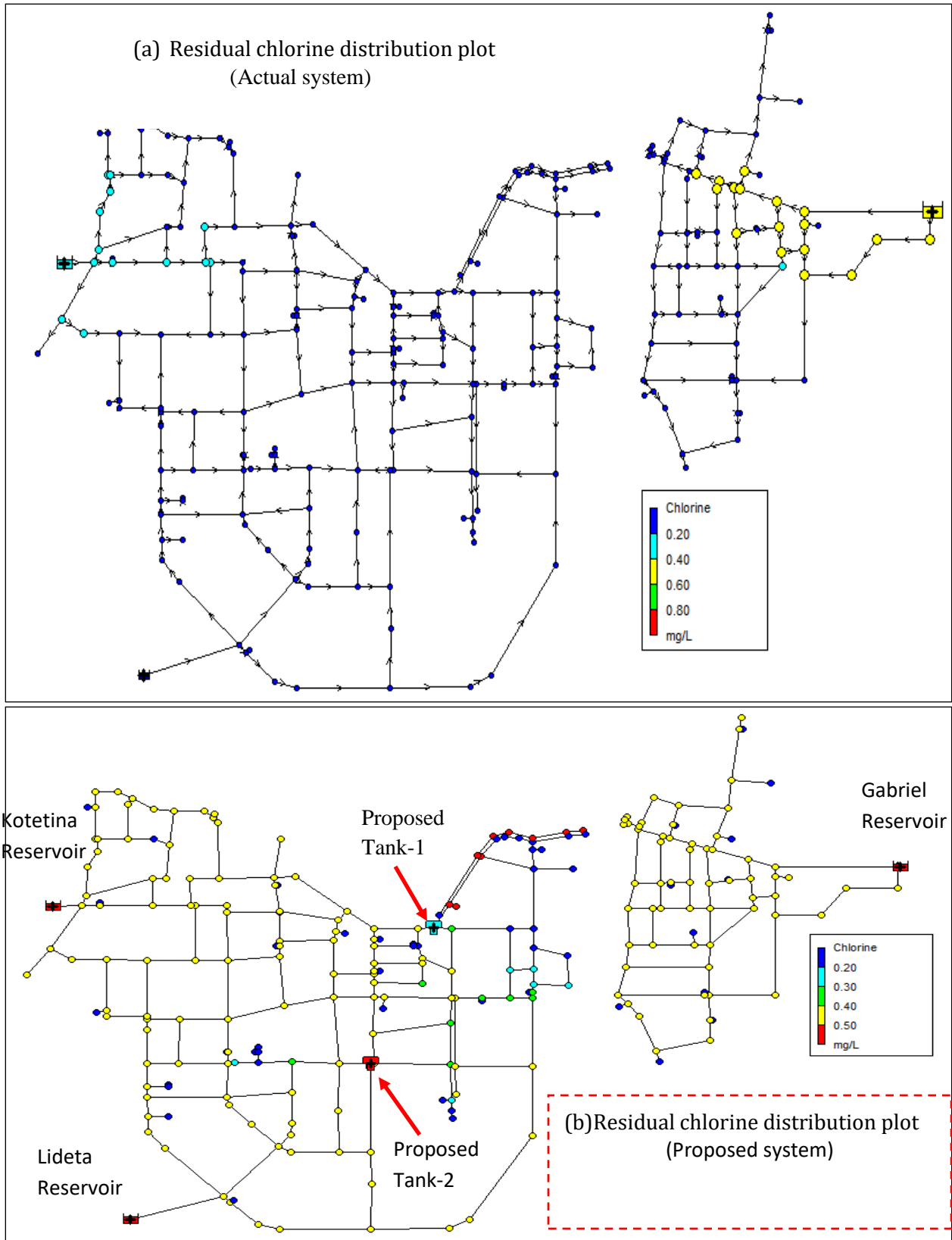


Figure 4. 8-Residual chlorine distribution plot for(a) the actual and (b) proposed system

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

From the study was undertaken and modeling results the variational change in residual chlorine decay within the entire distribution networks under existing conditions has below 0.23 mg/l. Chlorination level current practice 60% of collected samples do not fulfill WHO minimum limit (0.2 mg/l). In general, modeling results revealed that the town water supply system is currently performing poorly in terms of water quality.

Several findings are obtained from the study conducted to evaluate the variational change in residual chlorine decay in the water distribution network that will assist the water board and water service providers. Planning, a simplified approach to predicting residual chlorine in pipe of varying diameters, and formulating a proper dosage approach for the water treatment plant to achieve a desirable and long-lasting residual chlorine at the consumer water outlet

The results of disinfection modeling revealed that the distribution system is unable to fully distribute microbiologically safe water due to a lack of minimum allowable residual chlorine. Based on the simulation results, a portion of the distribution system is vulnerable to the transmission of water-borne disease due to a lack of residual chlorine in the system.

5.2. Recommendation

Based on the main finding of the present study the following recommendations are drawn herein:

- A booster disinfection station has to be established to maintain a life guarantee minimum residual chlorine across the distribution system. If the implementation of booster disinfection is not possible, local disinfection mechanisms at a home level such as the use of household chemicals before consumption have to be promoted.
- The model is good for predicting water quality parameters in the distribution system. However, early and late simulation results were found less agree with observed measured values outstanding to limitation of the recorded data. Thus, a model result for early and late simulation is not recommended to be used for system assessment.
- To have a more complete understanding, future works are suggested to focus on water quality transformations in the water distribution system by recording seasonal data.

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APPENDIX

Appendix A

Pressure at peak flow

Node ID	Pressure m H₂O
Jun 31	77.73
Junc 32	77.58
Junc 33	77.44
Junc 34	75.90
Junc 35	71.52
Junc 36	89.62
Junc 37	77.62
Junc 38	71.82
Junc 39	74.33
Junc 40	76.05
Junc 41	76.63
Junc 42	77.04
Junc 43	76.93
Junc 44	76.93
Junc 45	72.45
Junc 46	90.03
Junc 47	89.83
Junc 48	77.61
Junc 49	86.36
Junc 50	75.02
Junc 51	49.58
Junc 52	76.38
Junc 53	79.53
Junc 54	76.70
Junc 56	5.71
Junc 57	78.69
Junc 58	77.40
Junc 59	72.75
Junc 60	68.44
Junc 61	69.63
Junc 62	76.96
Junc 63	76.27
Junc 64	77.66
Junc 65	77.57
Junc 66	78.10

Junc 67	71.80
Junc 68	76.80
Junc 69	72.10
Junc 70	72.45
Junc 71	68.02
Junc 72	75.44
Junc 73	75.68
Junc 74	75.86
Junc 75	75.82
Junc 76	75.55
Junc 77	77.16
Junc 78	78.62
Junc 79	77.66
Junc 80	77.24
Junc 81	77.21
Junc 82	76.44
Junc 83	76.17
Junc 84	75.98
Junc 85	74.63
Junc 86	75.07
Junc 87	75.16
Junc 88	75.18
Junc 89	74.48
Junc 90	74.46
Junc 91	74.80
Junc 92	76.19
Junc 93	76.26
Junc 94	74.60
Junc 95	75.52
Junc 96	79.02
Junc 97	76.65
Junc 98	77.63
Junc 99	77.94
Junc 100	78.68
Junc 101	76.06
Junc 102	76.22
Junc 103	71.76
Junc 104	76.43
Junc 105	76.31
Junc 106	73.89
Junc 107	74.03
Junc 108	77.39
Junc 109	74.09

Junc 110	75.59
Junc 111	74.73
Junc 112	75.53
Junc 113	77.60
Junc 114	78.06
Junc 115	77.26
Junc 116	86.67
Junc 117	100.96
Junc 118	73.87
Junc 119	75.18
Junc 120	75.36
Jun 121	71.40
Junc 122	67.76
Junc 123	67.90
Junc 124	62.39
Junc 125	91.72
Junc 126	90.92
Junc 127	79.27
Junc 128	76.10
Junc 129	81.11
Junc 130	82.70
Junc 131	77.91
Junc 132	71.43
Junc 133	68.91
Junc 134	89.05
Junc 135	81.05
Junc 136	75.03
Junc 137	71.50
Junc 138	69.35
Junc 139	68.72
Junc 140	70.14
Junc 141	69.12
Junc 142	74.92
Junc 143	79.19
Junc 144	74.14
Junc 145	73.48
Junc 146	91.05
Junc 147	82.03
Junc 148	76.38
Junc 149	77.07
Junc 150	70.99
Junc 151	73.50
Junc 152	74.32

Junc 153	74.47
Junc 154	74.31
Junc 155	74.09
Junc 156	65.45
Junc 157	64.73
Junc 158	64.78
Junc 159	48.88
Junc 160	56.03
Junc 161	54.28
Junc 162	76.82
Junc 163	77.55
Junc 164	53.70
Junc 165	68.26
Junc 166	84.72
Junc 167	70.12
Junc 371	73.22
Junc 374	70.01
Junc 377	77.03
Junc 394	7.82
Junc 399	62.81
Junc 402	50.70
Junc 406	18.92
Junc 409	32.46
Junc 412	77.31
Junc 415	77.57
Junc 418	77.11
Junc 421	78.92
Junc 424	71.04
Junc 427	74.15
Junc 430	73.22
Junc 431	77.46
Junc 432	95.14
Junc 433	70.62
Junc 434	73.81
Junc 435	71.98
Junc 437	69.42
Junc 438	64.87
Junc 439	70.78
Junc 440	103.35
Junc 441	57.23
Junc 442	98.46
Junc 443	73.13
Junc 444	62.67

Junc 445	64.89
Junc 446	68.91
Junc 447	54.65
Junc 448	68.91
Junc 449	41.71
Junc 450	67.95
Junc 451	73.66
Junc 452	66.25
Junc 453	51.79
Junc 454	89.27
Junc 455	68.80
Junc 456	67.74
Junc 457	70.97
Junc 458	54.90
Jun 459	94.31
Junc 460	103.45
Junc 461	65.93
Junc 462	69.96
Junc 463	72.82
Junc 465	76.78
Junc 469	75.77
Junc 473	73.36
Junc 477	76.20
Junc 486	78.27
Junc 489	95.89
Junc 493	94.99
Junc 496	101.31
Junc 502	91.25
Junc 505	91.78
Junc 508	82.30
Junc 511	82.04
Junc 514	81.34
Junc 517	78.03
Junc 521	80.29
Junc 523	76.59
Junc 527	77.78
Junc 531	80.33
Junc 535	72.59
Junc 539	79.16
Junc 543	74.85
Junc 547	76.50
Junc 551	73.63
Junc 555	64.75

Junc 559	66.05
Junc 563	72.08
Junc 566	71.36
Junc 569	70.60
Junc 572	69.32
Junc 575	75.76
Junc 578	76.47
Junc 581	76.86
Junc 586	79.13
Junc 589	78.68
Junc 592	63.29
Junc 595	76.38
Junc 599	76.12
Junc 603	74.90
Junc 607	74.54
Junc 611	76.58
Junc 615	76.23
Junc 619	71.56
Junc 623	69.22
Junc 627	88.28
Junc 633	74.97
Junc 637	77.35
Junc 641	86.52
Junc 645	82.16
Junc 648	80.12
Junc 651	78.62
Junc 654	54.01
Junc 658	50.37
Junc 662	51.90
Junc 666	75.21
Junc 670	68.81
Junc 674	68.81
Junc 677	73.60
Junc 681	77.67
Junc 684	77.23
Junc 687	75.45
Junc 690	73.10
Junc 693	72.60
Junc 696	77.63
Junc 700	77.61
Junc 706	76.95
Junc 710	1.56
Resvr 385	0.00

Resvr 386	0.00
Resvr 388	0.00
Tank -1	9.98
Tank -2	2.00

Appendix B

Average water age for actual pipe sizes

Node ID	Age hours
Jun 31	2.96
Junc 32	2.28
Junc 33	1.61
Junc 34	1.34
Junc 35	2.22
Junc 36	1.25
Junc 37	4.81
Junc 38	4.85
Junc 39	4.72
Junc 40	2.95
Junc 41	1.24
Junc 42	3.38
Junc 43	3.48
Junc 44	4.41
Junc 45	4.47
Junc 46	1.28
Junc 47	1.12
Junc 48	6.01
Junc 49	1.83
Junc 50	10.38
Junc 51	2.39
Junc 52	1.95
Junc 53	1.52
Junc 54	1.14
Junc 56	0.7
Junc 57	1.97
Junc 58	1.66
Junc 59	3.88
Junc 60	1.51

Junc 61	1.32
Junc 62	2.07
Junc 63	2.05
Junc 64	2.58
Junc 65	2.42
Junc 66	3.08
Junc 67	0.64
Junc 68	2.64
Junc 69	3.71
Junc 70	4.19
Junc 71	2.21
Junc 72	3.31
Junc 73	3.06
Junc 74	3.04
Junc 75	3.38
Junc 76	3.64
Junc 77	3.79
Junc 78	4.06
Junc 79	5.41
Junc 80	3.13
Junc 81	4.81
Junc 82	3.91
Junc 83	3.76
Junc 84	3.96
Junc 85	3.67
Junc 86	4.06
Junc 87	5.1
Junc 88	4.93
Junc 89	4.63
Junc 90	4.96
Junc 91	4.53
Junc 92	4.99
Junc 93	3.86
Junc 94	7.02
Junc 95	5.71
Junc 96	7.1
Junc 97	5.14
Junc 98	4.71
Junc 99	5.72
Junc 100	5.9
Junc 101	5.41
Junc 102	4.78
Junc 103	0.77

Junc 104	5.17
Junc 105	5.27
Junc 106	6.36
Junc 107	6.81
Junc 108	6.66
Junc 109	6.52
Junc 110	7.75
Junc 111	7.45
Junc 112	7.39
Junc 113	8.86
Junc 114	9.35
Junc 115	8.79
Junc 116	1.63
Junc 117	1.88
Junc 118	1.49
Junc 119	1.39
Junc 120	1.97
Junc 121	1.29
Junc 122	1.19
Junc 123	1.09
Jun 124	1.95
Junc 125	2.07
Junc 126	2.25
Junc 127	1.94
Junc 128	1.79
Junc 129	2.04
Junc 130	2.31
Junc 131	1.04
Junc 132	2.09
Junc 133	1.77
Junc 134	2.35
Junc 135	2.47
Junc 136	1.89
Junc 137	2.96
Junc 138	3.63
Junc 139	1.65
Junc 140	1.03
Junc 141	1.45
Junc 142	1.57
Junc 143	1.48
Junc 144	1.79
Junc 145	1.38
Junc 146	1.28

Junc 147	1.38
Junc 148	1.63
Junc 149	3.02
Junc 150	3.15
Junc 151	1.28
Junc 152	2.3
Junc 153	2.61
Junc 154	2.64
Junc 155	2.48
Junc 156	1.84
Junc 157	1.36
Junc 158	1.18
Junc 159	1.27
Junc 160	1.71
Junc 161	1.28
Junc 162	1.54
Junc 163	2.27
Junc 164	0.88
Junc 165	0.98
Junc 166	1.96
Junc 167	2.36
Junc 371	7.12
Junc 374	7.75
Junc 377	24
Junc 394	0.72
Junc 399	1.63
Junc 402	1.22
Junc 406	0.82
Junc 409	0.94
Junc 412	2.17
Junc 415	2.64
Junc 418	3.3
Junc 421	1.42
Junc 424	1.39
Junc 427	1.59
Junc 430	9.33
Junc 431	3.57
Junc 432	4.74
Junc 433	4.11
Junc 434	5.96
Junc 435	6.19
Junc 437	4.08
Junc 438	3.06

Junc 439	5.95
Junc 440	5.73
Junc 441	8.43
Junc 442	4
Junc 443	6.1
Junc 444	5.61
Junc 445	3.57
Junc 446	2.93
Junc 447	2.39
Junc 448	2.65
Junc 449	1.7
Junc 450	3.7
Junc 451	1.78
Junc 452	3.81
Junc 453	3.4
Junc 454	0.82
Junc 455	2.63
Junc 456	3.59
Junc 457	4.24
Junc 458	5.55
Junc 459	6.65
Junc 460	4.12
Junc 461	1.64
Junc 462	5.51
Junc 463	5.36
Junc 465	2.82
Jun 469	3.32
Junc 473	0.74
Junc 477	1.78
Junc 486	1.38
Junc 489	1.18
Junc 493	1.38
Junc 496	1.28
Junc 502	0.93
Junc 505	1.03
Junc 508	1.17
Junc 511	1.35
Junc 514	1.56
Junc 517	2.13
Junc 521	1.41
Junc 523	4.01
Junc 527	5.25
Junc 531	2.57

Junc 535	2.9
Junc 539	2.69
Junc 543	3.92
Junc 547	2.99
Junc 551	2.2
Junc 555	2.34
Junc 559	1.19
Junc 563	7.25
Junc 566	7.35
Junc 569	7.48
Junc 572	7.88
Junc 575	7.68
Junc 578	7.9
Junc 581	8.34
Junc 586	1.42
Junc 589	1.52
Junc 592	2.05
Junc 595	5.07
Junc 599	3.86
Junc 603	3.8
Junc 607	5.63
Junc 611	6
Junc 615	2.34
Junc 619	3.06
Junc 623	3.11
Junc 627	1.35
Junc 633	5.67
Junc 637	8.89
Junc 641	1.73
Junc 645	2.52
Junc 648	2.88
Junc 651	3.23
Junc 654	2.05
Junc 658	2.29
Junc 662	0.98
Junc 666	1.49
Junc 670	1.55
Junc 674	2.53
Junc 677	3.47
Junc 681	3.96
Junc 684	3.23
Junc 687	12.92
Junc 690	1.17

Junc 693	1.02
Junc 696	2.55
Junc 700	5.64
Junc 706	24
Junc 710	0.6
Resvr 385	0.5
Resvr 386	0.5
Resvr 388	0.5
Tank 1	24

Appendix C

Minimum residual chlorine for actual pipe sizes

Node ID	Chlorine mg/L
Junc 31	0.09
Junc 32	0.09
Junc 33	0.10
Junc 34	0.10
Junc 35	0.09
Junc 36	0.10
Junc 37	0.08
Junc 38	0.08
Junc 39	0.08
Junc 40	0.09
Junc 41	0.10
Junc 42	0.09
Junc 43	0.09
Junc 44	0.09
Junc 45	0.09
Junc 46	0.10
Junc 47	0.10
Junc 48	0.08
Junc 49	0.09
Junc 50	0.07
Junc 51	0.09
Junc 52	0.09
Junc 53	0.10
Junc 54	0.10
Junc 56	0.10
Junc 57	0.09

Junc 58	0.10
Junc 59	0.09
Junc 60	0.10
Junc 61	0.10
Junc 62	0.09
Junc 63	0.09
Junc 64	0.09
Junc 65	0.09
Junc 66	0.09
Junc 67	0.10
Junc 68	0.09
Junc 69	0.09
Junc 70	0.09
Junc 71	0.09
Junc 72	0.09
Junc 73	0.09
Junc 74	0.09
Junc 75	0.09
Junc 76	0.09
Junc 77	0.09
Junc 78	0.09
Junc 79	0.08
Junc 80	0.09
Junc 81	0.08
Junc 82	0.09
Junc 83	0.09
Junc 84	0.09
Junc 85	0.09
Junc 86	0.09
Junc 87	0.08
Junc 88	0.08
Junc 89	0.08
Junc 90	0.08
Junc 91	0.08
Junc 92	0.08
Junc 93	0.09
Junc 94	0.08
Junc 95	0.08
Junc 96	0.08
Junc 97	0.08
Junc 98	0.08
Junc 99	0.08
Junc 100	0.08

June 101	0.08
June 102	0.08
June 103	0.10
June 104	0.08
June 105	0.08
June 106	0.08
June 107	0.08
June 108	0.08
June 109	0.08
June 110	0.07
June 111	0.08
June 112	0.08
June 113	0.07
June 114	0.07
June 115	0.07
June 116	0.10
June 117	0.09
June 118	0.10
June 119	0.10
June 120	0.09
June 121	0.10
June 122	0.10
June 123	0.10
June 124	0.09
June 125	0.09
June 126	0.09
June 127	0.09
June 128	0.09
June 129	0.09
June 130	0.09
June 131	0.10
June 132	0.09
June 133	0.09
June 134	0.09
June 135	0.09
June 136	0.09
June 137	0.09
June 138	0.09
June 139	0.10
June 140	0.10
June 141	0.10
June 142	0.10
June 143	0.10

Junc 144	0.09
Junc 145	0.10
Junc 146	0.10
Junc 147	0.10
Junc 148	0.10
Junc 149	0.09
Junc 150	0.09
Junc 151	0.10
Junc 152	0.09
Junc 153	0.09
Junc 154	0.09
Junc 155	0.09
Junc 156	0.09
Junc 157	0.10
Junc 158	0.10
Junc 159	0.10
Junc 160	0.10
Junc 161	0.10
Junc 162	0.10
Junc 163	0.09
Junc 164	0.10
Junc 165	0.10
Junc 166	0.09
Junc 167	0.09
Junc 371	0.08
Junc 374	0.07
Junc 377	0.00
Junc 394	0.10
Junc 399	0.10
Junc 402	0.10
Junc 406	0.10
Junc 409	0.10
Junc 412	0.09
Junc 415	0.09
Junc 418	0.09
Junc 421	0.10
Junc 424	0.10
Junc 427	0.10
Junc 430	0.07
Junc 431	0.09
Junc 432	0.08
Junc 433	0.09
Junc 434	0.08

Junc 435	0.08
Junc 437	0.09
Junc 438	0.09
Junc 439	0.09
Junc 440	0.08
Junc 441	0.07
Junc 442	0.09
Junc 443	0.08
Junc 444	0.08
Junc 445	0.09
Junc 446	0.09
Junc 447	0.09
Junc 448	0.09
Junc 449	0.10
Junc 450	0.09
Junc 451	0.09
Junc 452	0.09
Junc 453	0.09
Junc 454	0.10
Junc 455	0.09
Junc 456	0.09
Junc 457	0.09
Junc 458	0.08
Junc 459	0.08
Junc 460	0.09
Junc 461	0.10
Junc 462	0.08
Junc 463	0.08
Junc 465	0.09
Junc 469	0.09
Junc 473	0.10
Junc 477	0.09
Junc 486	0.10
Junc 489	0.10
Junc 493	0.10
Junc 496	0.10
Junc 502	0.10
Junc 505	0.10
Junc 508	0.10
Junc 511	0.10
Junc 514	0.10
Junc 517	0.09
Junc 521	0.10

Junc 523	0.09
Junc 527	0.08
Junc 531	0.09
Junc 535	0.09
Junc 539	0.09
Junc 543	0.09
Junc 547	0.09
Junc 551	0.09
Junc 555	0.09
Junc 559	0.10
Junc 563	0.08
Junc 566	0.08
Junc 569	0.07
Junc 572	0.07
Junc 575	0.07
Junc 578	0.07
Junc 581	0.07
Junc 586	0.10
Junc 589	0.10
Junc 592	0.09
Junc 595	0.08
Junc 599	0.09
Junc 603	0.09
Junc 607	0.08
Junc 611	0.08
Junc 615	0.09
Junc 619	0.09
Junc 623	0.09
Junc 627	0.10
Junc 633	0.08
Junc 637	0.07
Junc 641	0.10
Junc 645	0.09
Junc 648	0.09
Junc 651	0.09
Junc 654	0.09
Junc 658	0.09
Junc 662	0.10
Junc 666	0.10
Junc 670	0.10
Junc 674	0.09
Junc 677	0.09
Junc 681	0.09

Junc 684	0.09
Junc 687	0.05
Junc 690	0.10
Junc 693	0.10
Junc 696	0.09
Junc 700	0.08
Junc 706	0.00
Junc 710	0.10
Resvr 385	0.10
Resvr 386	1.5
Resvr 388	1.5
Tank 1	0.45
Tank 2	0.60

Appendix F

Residual chlorine Test Results

Pt	Sampling point	Labeling sample	Pt	Sampling point	Labeling sample
1	ERA	SP1	16	Papyrus	SP16
2	Catholic	SP2	17	Wisdom tour	SP17
3	Bata road	SP3	18	Peda	SP18
4	Homeland	SP4	19	ACSI	SP19
5	Chaina Camp	SP5	20	Poly	SP20
6	Medroc	SP6	21	St. George	SP21
7	Afrata	SP7	22	Bus station	SP22
8	Behind Condominium	SP8	23	Beg tera	SP23
9	Kobil stone joint	SP9	24	Gabriel sefer	SP24
10	Kidane Mihrete	SP10	25	Tyema school	SP25
11	Condeminium End	SP11	26	Hidar 11 Keble	SP26
12	AWWCE Cobleston	SP12	27	St. Mikael church	SP27
13	Fasilo	SP13	28	ADSWE	SP28
14	Dev't Bank	SP14	29	Diaspora End	SP29
15	Mulalem	SP15	30	Ayer tena-3	SP30

Appendix G

Water quality model calibration data

ID	Time	Observed (mg/l)	Computed (mg/l)	Difference (mg/l)
458	12.00	0.20	0.40	0.20
463	12.20	0.01	0.10	0.09
462	12.45	0.21	0.41	0.20
461	1.00	0.02	0.01	0.01
460	1.15	0.01	0.03	0.02
459	1.30	0.02	0.20	0.18
457	4.00	0.22	0.39	0.17
456	4.20	0.23	0.44	0.21
455	4.45	0.24	0.46	0.22
521	5.10	0.03	0.00	0.03
453	5.35	0.02	0.00	0.02
452	5.45	0.24	0.44	0.20
451	6.00	0.25	0.47	0.22
450	6.15	0.01	0.00	0.01
449	6.40	0.26	0.48	0.23
448	7.10	0.25	0.46	0.21
447	8.00	0.01	0.10	0.09
446	8.15	0.02	0.20	0.18
445	8.33	0.01	0.02	0.01
444	9.20	0.21	0.39	0.18
443	9.45	0.02	0.05	0.03
442	10.15	0.01	0.09	0.08
441	10.35	0.20	0.36	0.16
440	10.45	0.01	0.12	0.11
439	11.10	0.02	0.10	0.08
Average				0.12