MODELLING OF WATER QUALITY DETERIORATION IN THE DISTRIBUTION NETWORK OF KADUNA METROPOLIS USING MATLAB

BY

MUSA HASSAN

B.ENG (CHEMICAL ENGINEERING, UNIMAID)

M.SC/ENG./23088/2012 – 2013

A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES AHMADU BELLO UNIVERSITY, ZARIA IN PARTIAL FULFILLMENT FOR THE AWARD OF MASTER OF SCIENCE IN WATER RESOURCES AND ENVIRONMENTAL ENGINEERING

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING,

AHMADU BELLO UNIVERSITY,

ZARIA, NIGERIA

NOVEMBER, 2017

DECLARATION

I declare that the work in this dissertation entitled 'Modelling of Water Quality Deterioration in the Distribution Network of Kaduna Metropolis using MATLAB' has been performed by me in the Department of Water Resources and Environmental Engineering under the supervision of Engr. (Prof.) D.B. Adie and Professor C. A. Okuofu.

The information derived from literature have been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at any university.

_____ _____

MUSA HASSAN **Signature/Date**

(M.SC./ENG/23088/12-13)

CERTIFICATION

This dissertation entitled: "**MODELLING OF WATER QUALITY DETERIORATION IN THE DISTRIBUTION NETWORK OF KADUNA METROPOLIS USING MATLAB"** by Musa Hassan meets the regulations governing the award of the degree of Masters of Science in Water Resources and Environmental Engineering of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

…… Date: ……...

Engr. (Prof.) D.B. Adie
Chairman, Supervisory Committee

…… Date: ……...

Prof. C. A. Okuofu
Member, Supervisory Committee

…… Date: ……..

Prof. A. Ismail
Head of Department

…… Date: ……...

Prof. Sadiq Z. Abubakar
Dean, School of Postgraduate Studies

DEDICATION

I dedicate this dissertation to Allah (SWT), Most Gracious, Most Merciful, Who gave me everything in completing this research.

ACKNOWLEDGEMENT

All praise is due to Allah (SWT) who created man in the best form, guided him through His Messengers and made all that is between the heavens and the earth subservient to him towards discharging his responsibility as Allah's servant and vicegerent on earth.

First and foremost, I would like to express my sincere gratitude to my major supervisor, Engr. (Prof.) Donatus B. Adie, for his excellent guidance and patience, and for providing me with an excellent atmosphere for doing research; also for his encouragement and support from the initial to the final level, which enabled me to develop an understanding of this field. Special thanks also to my co-supervisor Prof. Charles Amen Okuofu for his helpful suggestions, evaluations and guidance in completing this research.

I wish to thank all staff of the Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, for their involvement, comments and help regarding this research. Also without the kind cooperation of those involved in the field research at the Central Laboratory and Kaduna North Water Works of Kaduna State Water Board who have been involved in the data collection, this study would not have been possible; I am grateful.

This dissertation would not have been possible without the generous support of my extended family and friends. I would especially like to express my deepest gratitude to my wife, Subai'a Abubakar Shehu for supporting my decision to embark on attaining the M.Sc., and sacrifices made over the course of completing this work.

ABSTRACT

Public water supply is distributed through water pipe network, which affects the quality of water that gets to the consumers when the integrity of the pipe distribution network is compromised. Hence, this study aimed at investigating and modelling water quality deterioration in the distribution network of Kaduna Metropolis. In order to achieve this water samples were obtained from selected points along the distribution network of Kaduna metropolis for water quality analysis. The parameters analyzed were residual chlorine concentration, pH, turbidity and dissolved oxygen. Linear regression equations obtained from the relationship between pairs of parameters were used in a MATLAB/SIMULINK environment to model the change in the various water quality parameters along the network. The results clearly showed that the quality of water produced at the treatment plant is below standard water specifications (Nigerian Standard for Drinking Water Quality, 2007) with turbidity and pH having average values of 9.5 NTU and 5.7 respectively; this quality deteriorates significantly along the network. Residual chlorine concentration was below 0.35mg/l at all points in the network and ranged from 0 to 0.3 mg/l; turbidity levels varied between 2.6 to 10.6 NTU were observed at the treatment plant and reservoirs/booster stations; pH and dissolved oxygen levels varied slightly between 5.4 to 7.4 and 0.4 to 0.7 mg/l along the network. Leakages were also observed along the network. On an average, the model was 77% accurate in predicting values of water quality parameters along the network. Also significant differences observed between the water quality values at Kaduna North Water Works and the selected sampling points. This indicates that the quality of water deteriorates along the network and is not safe for human consumption. Improvement of treatment processes and rehabilitation of the water distribution network were suggested to improve quality of water produced and distributed to the consumers in Kaduna metropolis.

TABLE OF CONTENTS

Contents Page

Title page …….…….. i

Declaration …….…….. ii

Certification …….……. iii

Dedication …….…….. iv

Acknowledgement …….…….. v

Abstract …….……. vi

Table of Contents …….…… vii

List of Figures …….…… xv

List of Tables …….…….. xvi

List of Plates …….……..xvii

Abbreviations …… xviii

Symbols …… xx

CHAPTER ONE: INTRODUCTION …… 1

1.1 Preamble …….…….. 1

1.1.1 Water supply in Nigeria …...……6

1.1.2 Water supply in Kaduna metropolis ……. 9

1.2 Statement of Research Problem ……10

1.3 Justification of the Study ……10

1.4 Aim and Objectives ……11

1.4.1 Aim ……..…….. 11

1.4.2 Objectives ……..…… 11

1.5 Scope of Research …….. 11

1.5.1 Scope …….. 12

1.5.2 Limitations …….. 12

CHAPTER TWO: LITERATURE REVIEW ……..…….. 13

2.1 The Study Area ……... 13

2.2 Domestic Water Supply in Metropolis ……..18

2.3 Water Treatment Processes …… 21

2.3.1 Abstraction …….....21

2.3.2 Balancing ……..... 21

2.3.3 Mixing chamber (coagulation and flocculation) …… 22

2.3.4 Sedimentation ……..... 23

2.3.5 Filtration ……..... 23

2.3.6 Disinfection ……..... 23

2.4 Water Quality …… 24

2.5 Chlorine ……..... 25

2.5.1 Chlorination ……..... 27

2.5.2 Chlorine Demand and Breakpoint Chlorination ……. 27

2.6 Stages in Chlorine disinfection …… 28

2.6.1 Primary Disinfection ……..…….. 28

2.6.2 Secondary or Post Disinfection ……..…… 29

2.6.3 Booster disinfection …… 29

2.7 Disinfection-By-Products (DBPs) …… 29

2.8 Chlorine Decay Kinetics …… 31

2.8.1 Bulk decay coefficient (K_b) determination ……. 31

2.8.2 Wall reaction decay coefficient (K_w) …….. 32

2.8.3 Overall chlorine decay constant …….. 32

2.9 pH ……..…… 33

2.9.1 Factors affecting the pH …….. 33

2.10 Turbidity ……... 34

2.11 Dissolved Oxygen ……. 36

2.12 Water Quality Deterioration Factors ……...… 36

2.12.1 Structural factors …….. 37

2.12.2 Operational factors ……..…… 38

2.12.3 Water quality factors ……. 39

2.13 Contamination Prevention and Control …… 39

2.14 Modifications to System Operation ……... 40

2.15 Water Quality Modelling for Water Distribution Networks …….40

2.15.1 Water quality models …….. 44

2.16 Previous Studies on Water Quality Modelling in …… 46
Distribution Networks

2.17 History of Kaduna State Water Board ……...……... 49

2.17.1 Description of Kaduna metropolis water distribution network …… 50

2.17.2 Responsibilities of KSWB ……... 51

2.17.3 Code of practice of KSWB ……..…. 52

2.17.3.1 *Water quality* ……..… 52

2.17.3.2 *Quality of treated water in Kaduna North Water Works* ……52

2.17.3.3 *Water consumption standards* ……. 53

CHAPTER THREE: MATERIALS AND METHODS …… 55

3.1 Materials 55

3.2 Water Treatment Processes and Distribution in Kaduna Metropolis …. 56

3.3 Methods ……. 58

3.3.1 Sampling points ……. 58

3.3.2 Sample collection ……. 59

3.3.3 Water quality analysis …….. 60

3.3.4 Procedures for measuring water quality parameters ……. 60

3.3.4.1 *Procedure for measuring residual chlorine* …… 60

3.3.4.2 *Procedure for measuring pH* …….. 62

3.3.4.3 *Procedure for measuring turbidity* ……... 62

3.3.4.4 *Procedure for measuring dissolved oxygen* ……62

3.3.5 Effects of months and seasons on water quality ……. 62

3.3.6 MATLAB …….. 63

3.2.6 SIMULINK ……... 63

3.2.7 Water quality model using SIMULINK ……... 64

CHAPTER FOUR: RESULTS AND DISCUSSION …… 58

4.1 Introduction …….. 66

4.2 Variation in Residual Chlorine along Distribution …….. 66
Network

4.3 pH Variations along Distribution Network ……..... 68

4.4 Turbidity Variations along Distribution Network ……. 70

4.5 Dissolved Oxygen Variation along Distribution ……..… 71
Network

4.6 Effects of Months and Seasons on Water Quality …… 74

4.6.1 Effects of months and seasons on residual chlorine levels…… 74

4.6.2 Effects of months and seasons on pH …… 75

4.6.3 Effects of months and seasons on turbidity…… 75

4.6.4 Effects of months and seasons on dissolved oxygen …… 76

4.7 Relationship between Water Quality Parameters …….. 76

4.7.1 Relationship between residual chlorine and pH ……... 76

4.7.2 Relationship between residual chlorine and ……... 77
turbidity

4.7.3 Relationship between residual chlorine and ……. ……. 78
dissolved oxygen

4.7.4 Relationship between pH and turbidity …….. 79

4.7.5 Relationship between turbidity and dissolved oxygen ……,……..79

4.7.6 Relationship between pH and dissolved oxygen ……. 80

4.8 Water Quality Model ……. 81

4.8.1 Bulk decay coefficient (K_b) determination……. 81

4.8.3 Wall reaction decay coefficient (K_w) determination …… 82

4.8.4 Overall chlorine decay …….. 82

4.8.5 MATLAB/SIMULINK Prediction Model …….. 82

4.8.6 Comparison of modelled results with observed field measurements ……..……. 83

4.9 Likely Causes of Water Quality Deterioration …….. 86

4.9.1 Inefficient Treatment Processes ……..…..... 86

4.9.2 Leakage …….……... 86

4.9.3 Age of Pipe ……..… 86

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION …….. 87

5.1 Summary ……. 87

5.2 Conclusion …… 88

5.3 Recommendations …… 88

REFERENCES ……..….. 90

APPENDICES …… 99

Appendix 1: Schematic of Kaduna Metropolis Water …….. 99
Distribution Network (showing sampling points)

Appendix 2: Pump Capacity of KNWW ……... 100

Appendix 3: Average Water Quality Data for KNWW …… 101
Final Water

Appendix 4: Model Structure ……. 104

Appendix 5: Tabular Comparison of Average Observed Water …. 106
Quality Parameter Measurements and SIMULINK Model Results

Appendix 6: Leakage Sites and GPS Locations …….. 107

LIST OF FIGURES

Figure 2.1: Map of Nigeria Showing Kaduna State …… 14

Figure 2.2: Map of Kaduna showing 23 Local Government Areas. 15

Figure 2.3: Map of Kaduna Metropolis, Kaduna State ……. 17

Figure 2.4: Branched Network ……..…….. 20

Figure 2.5: Looped Network …….. 20

Figure 3.1: Flow chart for SIMULINK model……..... 65

Figure 4.1: Relationship of pH to residual chlorine (mg/l) …… 77
in distribution network

Figure 4.2: Relationship of residual chlorine (mg/l) ……... 77
to turbidity (NTU) in distribution network

Figure 4.3: Relationship of residual chlorine (mg/l)…… 78
to dissolved oxygen (mg/l) in distribution network

Figure 4.4: Relationship of pH to turbidity (NTU) ……..…. 79
in distribution network

Figure 4.5: Relationship of turbidity (NTU) to dissolved oxygen …80
(mg/l) in distribution network.

Figure 4.6: Relationship of pH to dissolved oxygen (mg/l) ….. 80

Figure 4.7: Relationship of residual chlorine to time in bulk water 82

Figure 4.8(a): Comparison of modelled and field observed ….. 84
values of residual chlorine concentration at
sampling points

Figure 4.8(b): Comparison of modelled and field observed …… 84
values of pH at sampling points

Figure 4.8 (c): Comparison of modelled and field observed …… 85
values of turbidity at sampling points

Figure 4.8 (d): Comparison of modelled and field observed …. 86
values of dissolved oxygen concentration at
the sampling points

LIST OF TABLES

Table 2.1: Existing Water Reservoirs in Kaduna Township …. 51

Table 2.2: Average Measurements of Water Quality ……. 53
Parameters at KNWW, Malali (for 5 years)

Table 4.1: Variation of Residual Chlorine along the ……. 67
Network

Table 4.2: Variation in pH along the Network ……..… 69

Table 4.3: Variation in Turbidity along the Network ……. 71

Table 4.4: Variation in Dissolved Oxygen along the ……... 73
Network

Table 4.5: ANOVA of Residual Chlorine ……. 74

Table 4.6: ANOVA of pH …….. 75

Table 4.7: ANOVA of Turbidity …….. 75

Table 4.8: ANOVA of Dissolved Oxygen …….. 76

Table 4.9: Bulk Decay of Residual Chlorine …….. 81

LIST OF PLATES

Plate I: Labelled Plastic Containers of Water Samples …… 59

Plate II: Leakage at Kawo ($10^0$19’23.5” N and $7^0$13’12.2”E) …….. 107

Plate III: Leakage at Tudun wada ($10^0$29’13.5” N and $7^0$13’11.2”E) …… 107

ABBREVIATIONS

ANOVA: Analysis of Variance

AOC: Assimilable organic carbon

AWWA: American Water Works Association

DBP: Disinfection By Products

DO: Dissolved Oxygen

FCT: Federal Capital Territory

HAA: Halo Acetic Acid

HRT: Hydraulic Retention Time

KNWW: Kaduna North Water Works

KSWB: Kaduna State Water Board

KSWW: Kaduna South Water Works

LHR: Lugard Hall reservoir

MAC: *Mycobacterium avium* complex

MATLAB: Matrix Laboratory

MLD: Million Litres per Day

NDAR: NDA Reservoir

NOM: Natural Organic Matter

NPC: National Population Commission

NSDWQ: Nigerian Standard for Drinking Water Quality

NTU: Nephelometric Turbidity Unit

PVC: Polyvinyl chloride

PWI: Presidential Water Initiative

SHBS: State House Boosting Station

SWAs: State Water Agencies

THM: Trihalomethanes

TOC: Total Organic Carbon

TTHM: Total Trihalomethane

TWBS: Tudun Wada Boosting Station

U.V: Ultra Violet

UNDP: United Nations Development Project

UNICEF: United Nations Children's Fund

W.H.O: World Health Organization

WDS: Water Distribution system

WQ: Water Quality

WTP: Water Treatment Plants

WUP: Water Utility Partnership

YDMH: Yusuf Dantsoho memorial Hospital

SYMBOLS

%	-	Percentage
1/day	-	litres per day
A	-	Cross-sectional Area
C	-	Residual chlorine concentration
D	-	Pipe diameter
d^{-1}	-	per day
E_x	-	Axial dispersion coefficient
K	-	Overall decay constant
K_b	-	Bulk decay coefficient
Km	-	kilometre
K_w	-	Wall reaction decay coefficient
l	-	litre
m	-	metre
mg/l	-	milligrams per litre
$mg/m^2/day$	-	milligrams per square metre per day
mm	-	millimetre
n	-	Reaction order
ϕ_i	-	Production term and index, i = ith pipe
ppm	-	Parts per million
R	-	Reaction rate
R^2	-	Correlation coefficient
V	-	Flow velocity

CHAPTER ONE

INTRODUCTION

1.1 Preamble

Safe drinking water and basic sanitation are extremely important to the preservation of human health, especially among children. Water-related diseases are the most common cause of illness and death among the poor of developing countries (World Water Council, 2005). The World Health Organization (WHO) has observed that about 80 percent of diseases in the world are water related. Currently, about 20% of the world's population lacks access to safe drinking water and more than 5 million people die annually from illness associated with safe drinking water or inadequate sanitation. If everyone had safe drinking water and adequate sanitation services, there would be 200 million fewer cases of diarrhoea and 2.1 million fewer deaths caused by diarrhoea illness each year (Hunt *et al*., 2001). In addition to these 'direct health' effects of inadequate water supply provision, there is an additional cost in time and energy expended in carrying water from the supply to the family dwelling.

Improving water supplies has been a high priority activity for most developing country governments, donor agencies and communities for many years now so as to achieve the Millennium Development Goal 7 target 10 (halving by 2015, the proportion of people without sustainable access to safe water and basic sanitation), with the reference year of 1990. In order to achieve this goal, the federal and the state governments of Nigeria have step up efforts in expanding

the various water corporations' distribution networks, which are charged with the responsibilities of delivery potable water to the populace. In spite of these recent efforts, water and sanitation coverage rates in Nigeria are among the lowest in the world. According to WHO/UNICEF (2006) drinking water coverage in Nigeria fell from 49 percent in 1990 to 48 percent in 2004 as against the expected 65 percent coverage.

A large number of those with access to the public water systems in Nigeria are not completely free from water borne diseases, because the quality of the water that eventually get to the consumers may not be guaranteed. Although protected water sources and modern, well-maintained drinking water treatment plants can provide water adequate for human consumption; ageing, stressed or poorly maintained distribution systems can cause the quality of piped drinking water to deteriorate below acceptable levels and pose serious health risks to its consumers (Lee and Schwab, 2005).

Biofilms, which are coatings of organic and inorganic materials in water pipe distribution systems, has generated health concerns because they harbour, protect and allow the proliferation of several bacteria pathogens, including *Legionella* and *Mycobacterium avium* complex (MAC). Bacteria growth in biofilms is affected by several factors, including water temperature, type of disinfectant and residual concentration, biodegradable organic carbon level, degree of pipe corrosion and treatment/distribution system characteristics. Hence, Lahlou (2002) noted that the water quality of a drinking water system might be acceptable when the water leaves a treatment plant. However, a variety

of physical, chemical, and biological transformations can happen once the water enters and travels through a distribution system, which can result to objectionable taste and odour and the risk of gastrointestinal illnesses. This situation was confirmed by Frederick (2007) who reported that microorganisms in municipal drinking water supplies have led to several outbreaks of water-borne diseases in the United States. For instance, cryptosporidium in Milwaukee's water supply resulted in some 400, 000 serious illnesses and 50 deaths in the spring of 1993. In 1983, contaminated drinking water in Luzerne County, Pennsylvania caused an outbreak of giardiasis-a common diarrhoea that left 6, 000 people ill and forced 75, 000 others to obtain more expensive alternative sources of drinking water.

The integrity of water distribution networks in Nigeria and in particular in Kaduna State is highly questionable, as it is characterized with leaky pipe joints, pipe breaks, corrosive pipes, intermittent supply etc. which may impact negatively on water quality through contamination before it gets to the consumer. But unfortunately, most people used to assume that if water entering into a distribution system were of high quality, its quality would still be good at the tap (AWWA, 2013). Therefore, people consume tap water without any doubt of its quality. This situation can be very dangerous if actually the quality of water that gets to the consumer has been compromised.

Although water is a scarce commodity, its quality should be assured no matter how small the quantity may be. Thus, the goal of a water treatment and

distribution network is to deliver water in sufficient quantities and of good quality where and when it is needed at the required pressure.

First, this quality can be expressed in terms of the water being physically and chemically free from carcinogens and contaminants that impart colour, taste and odour. Secondly, water quality can be expressed as water devoid of pathogenic microorganisms. This suggests that ideally, treatment processes at water treatment plants as well as pipes and storage facilities of a good drinking water distribution network should constitute a network of uncontrolled chemical and biological reactors capable of withstanding significant variations to maintain water quality. But unfortunately, even before these pipes are networked to form a distribution system, their sterility may not be guaranteed during storage and transportation to construction sites and they may have been left outdoors for months or years leading to contamination potentially caused by a variety of animals, plants and microbiological life entering it (Kofi, 2012).

Consequently, after installation, if such mains are not properly "purified" and flushed, then although treated water may meet the required quality criteria when it leaves the treatment head-works and travels through such a distribution network, the quality will deteriorate. In cases where these distribution mains are properly disinfected and flushed after installation, as water continues to run through for some number of years, there may be sediment build up (which may lead to encrustation), corrosion and subsequent leaching of pipe materials, formation of biofilms etc. These occurrences normally compromise the quality

of the distributed water. Generally, some indicators of water quality deterioration in distribution networks include (Kofi, 2012);

1. Loss of disinfectant residual
2. Corrosion of iron pipes
3. Dissolution of Pb and Cu from pipe walls
4. Biofilm formation
5. Occurrence of compounds that confer poor taste and odour
6. Formation of disinfection by-products (some of which are carcinogens). These compounds are normally products of reactions between organic and/or inorganic soluble compounds and disinfectants.
7. Increased turbidity caused by particulate re-suspension.

To attain microbiological safety, potable water should be free of pathogenic microorganisms, and this is achieved through purification by a specific treatment step called disinfection (Kofi, 2012).

Generally, disinfection can be defined as the inactivation of pathogenic microorganisms and is purposed to eliminate any microbiological risks of water-related diseases. The use of Ultra Violet (U.V) light, ozonation and chlorination are all forms of disinfection, but chlorination is usually preferred and employed in most drinking water systems because of its efficiency and durability (leaves adequate residuals) and it is relatively cheap (Mays, 2000).

Thus, to reduce the microbiological risk of potable water, it should have adequate residual chlorine to ensure the bacteriological safety of the water. In

view of this, the World Health Organization (W.H.O) recommends a chlorine residual concentration of 0.5mg/l in final water whereas the Nigerian Standard for Drinking Water Quality (NSDWQ) recommends a concentration not less than 0.35mg/l at the point of consumption. To ensure that potable water is bacteriologically safe at the taps, a chlorine residual concentration between 0.20 to 0.5 mg/l should be maintained in the treated water (WHO, 1997).

However, the physical, chemical and microbiological transformations (existing pipe material/age, water age, biofilm formation, encrustation etc.) occurring within and along a distribution network may defeat this purpose by "using up" the chlorine thereby enhancing its decay. This decay may occur within the bulk of the water (bulk decay) or as a result of the interaction between the water and pipe walls (wall decay). Therefore, to ensure that adequate chlorine residuals persist in distribution lines till consumption, studies must be done to find out how these transformations occurring along a particular distribution network contribute to the bulk and wall reactions.

1.1.1 Water supply in Nigeria

Water supply and sanitation in Nigeria is characterized by low levels of access to improved water source and limited access to improved sanitation. Responsibility for water supply is shared between three levels of government – federal, state and local governments. The federal government is in charge of water resources management; state governments have the primary responsibility for urban water supply; and local governments together with communities are

responsible for rural water supply. The responsibility for sanitation is not clearly defined. Water supply service quality and cost recovery are low. Water tariffs are low and many water users do not pay their bills. Service providers thus rely mostly on occasional subsidies to cover their operating costs. Investments are mainly financed by foreign donors and fall short of what is needed to achieve a significant increase in access (WHO/UNICEF, 2010a).

Water and sanitation coverage rates in Nigeria are among the lowest in the world. Access to improved water sources stagnated at 47% from 1990 to 2006, but increased to 54% in 2010. In urban areas, access to improved water sources actually decreased from 80% to 65% in 2006, but it then recovered to 74% in 2010. However, in urban areas access to standpipes substituted to a large extent to piped water access. Access to adequate sanitation decreased from 39% in 1990 to 35% in 2010, with a particularly marked decrease in urban areas. 25% of Nigerians have to use shared sanitation facilities, which are not considered as adequate. 22% are estimated to use other inadequate facilities and another 22% are estimated to defecate in the open (WHO/UNICEF, 2010b).

According to the World Bank, in 2010 water production facilities in Nigeria were "rarely operated to capacity due to broken down equipment, or lack of power or fuel for pumping." The operating cost of water agencies is increased by the need to rely on diesel generators or even having to build their own power plants, since power supply is erratic. Equipment and pipes are poorly

maintained, leading to intermittent supply and high levels of non-revenue water (World Bank, 2010)

In 2003, a "Presidential Water Initiative (PWI): Water for People, Water for Life" was launched by the then-President Olusegun Obasanjo. The initiative had ambitious targets to increase access, including a 100% water access target in state capitals, 75% access in other urban areas, and 66% access in rural areas. Little has been done to implement the initiative and targets have not been met (USAID, 2007).

In 2011, the government voted in the United Nations in favour of a resolution making water and sanitation a human right. However, it has not passed legislation to enshrine the human right to water and sanitation in national law. The country is not on track to reach the Millennium Development goal for water and sanitation (Vanguard, 2012)

In 2015, 67% of the total population had access to "at least basic water supply". This was 82% of the urban population and 54% of the rural population. In 2015, around 60 million people lacked access to "at least basic" water. (WHO/UNICEF, 2015)

Most Nigerian water supply connections are not metered. The metering ration varies from 7% in Katsina to 16% in Kaduna and 24% in Lagos in 2007. Unmetered customers are charged a flat rate independent of consumption. For

unmetered residential customers the monthly flat rate was USD 3 in Lagos, USD 5 in Katsina and USD 11 in Kaduna (Banerjee, 2008).

In Yobe state it was only N100 (USD0.60) per month, the lowest level in the country according to the Yobe State Water Corporation. The tariff revenues covered only 2% of the costs of supplying water (Daily Trust, 2010). The statistics on access to water and sanitation are conflicting, due to divergent definitions, indicators and methodologies applied by different agencies. There is hardly any sector monitoring. (John, 2015). Water supply and sanitation are not provided efficiently in Nigeria (Obeta, 2015).

1.1.2 Water supply in Kaduna metropolis

Responsibility for potable water supply is entrusted to State Water Agencies (SWAs) or state water departments in the 36 Nigerian states. The SWAs are responsible to their state governments, generally through a State Ministry of Water Resources. SWAs are responsible for urban water supply, and in some states also for rural water supply. In the year 2000, 22 states had separate state rural water and sanitation agencies, mostly set up to implement a UNICEF program (World Bank/Federal Republic of Nigeria, 2012).

58% of the population in Kaduna State is served with water supply by Kaduna State Water Board. A State-Wide Water Resources Master plan is being developed to improve coverage to more than 70 per cent covering a projected population of 7.1 million by the year 2020. However, with the on-going awareness campaign being intensified for consumers to realize that fund for

providing potable water must be generated from the volume of water sold, things are changing. As such Kaduna State Water Board (one of the 37 SWAs in the country) has been operating as a commercial entity, since 1993, paying for nearly all its operational expenses from internally generated revenue (Ajibike, 2013).

In Kaduna Metropolis, there are two treatment plants; Kaduna North Water Works (KNWW) and Kaduna South Water Works (KSWW). Both facilities work hand in hand to produce and distribute consumable water to the inhabitants of Kaduna Metropolis; although KNWW is of a larger capacity than KSWW which makes KSWW more or less dependent on KNWW for continuous supply of water to its service areas. The source of raw water for treatment and eventual distribution is the River Kaduna.

1.2 Statement of Research Problem

Water quality generally deteriorates along distribution network because of microbiological and chemical activities taking place within the bulk water and between the water and the walls of pipes (Kofi, 2012). Residual chlorine decays naturally in water distribution networks. This consequently affects pH levels. Turbidity and dissolved oxygen levels could also vary along the network due to contamination at points of leakage in the network, corrosion of pipe materials etc. When these parameters are altered beyond certain standard levels, water quality at the taps may be compromised at the expense of the consumer's health. However, there is no empirical data to predict chlorine loss and to substantiate

top-up quantities, pH levels, turbidity and dissolved oxygen in the distribution network. Thus, it is necessary to predict these variations in water quality parameters in order to maintain a good water quality throughout the distribution network.

1.3 Justification of the Study

This research intends to determine the factors responsible for deterioration in water quality in Kaduna metropolis water distribution network. The water quality parameters to be considered are; residual chlorine, pH, turbidity and dissolved oxygen. Laboratory analysis done on water samples from clear well of treatment plant, booster stations, reservoirs and other nodes will help in predicting values of water quality parameters along the network using a model. Therefore, specific treatment that is to be done at particular points in the network would be identified, thus maintaining a good water quality throughout the distribution network.

1.4 Aim and Objectives

1.4.1 *Aim*

To investigate and model the water quality deterioration in the distribution network of Kaduna Metropolis.

1.4.2 *Objectives*

i. To determine the variations in residual chlorine levels, pH, turbidity and dissolved oxygen in the water flowing in the Distribution Network

ii. To identify the causes of water quality deterioration in the water distribution network.

iii. To produce a MATLAB based prediction model for the four parameters along the distribution network.

1.5 Scope of Research

1.5.1 *Scope*

In this research, water quality parameters such as disinfectant residual, turbidity, pH and dissolved oxygen throughout the distribution network will be modelled but bacterial growth and corresponding depletion of Assimilable Organic Carbon (AOC) will not be determined. The study also focuses on Kaduna North Water Works and its service areas.

1.5.1 *Limitations*

The major limitation encountered in this study was the difficulty in accessing walls of the pipes in the distribution network to understand the wall reactions. This would involve excavating pipes and examining the walls of the pipes. Alternatively, various readings were taken for the water quality parameters for observation and analysis.

CHAPTER TWO

LITERATURE REVIEW

2.1 The Study Area

Kaduna state is located at the centre of Northern Nigeria. Kaduna State covers a land area of 5,100 square kilometers. It has a population of 6, 029,427 and comprises of 23 Local Government Areas. The capital of the state is Kaduna and has a land area covering some 14,000 hectares with an average density of about 75 persons per square kilometers (National Population Commission, 2006).

It has a political significance as the former administrative headquarters of the North Region of Nigeria during the colonial era. The state shares boundaries with Niger State to the west, Zamfara, Katsina and Kano states to the North, Bauchi and Plateau States to the East and FCT Abuja and Nassarawa state to the South. Figure 2.1 is the Map of Nigeria showing Kaduna State (Ajibike, 2013).



Figure 2.1: **Map of Nigeria Showing Kaduna State (https://www.google.com.ng/ map+of+kaduna+town, 2016)**



Figure 2.2: **Map of Kaduna showing its 23 Local Government Areas (http://www.nigerianmuse.com/pictures-maps-cartoons/maps-of-various- states-and-their-local-governments-in-nigeria, 2016)**

The red dot in the figure above indicates the location of Kaduna North Local Government Area.

Kaduna city is situated at 10.52° North latitude, 7.44° East longitude and 614 meters elevation above the sea level. Its total land area is 1,190 sq. mi

(3,080 km^2). According to population census data for 2006, Kaduna town has a population of 760,084 with a 2.53% growth rate per annum. Kaduna city is the capital of Kaduna State in North Western Nigeria. The urban part of the city largely lies in Kaduna North, Kaduna South and Chikun local government areas.

There are two head works located in Kaduna, which are; Kaduna North Water Works (KNWW) and Kaduna South Water Works (KSWW). These two headworks together supply the city with its potable water needs. This study, however, focuses on Kaduna North Water Works and the areas of its supply. KNWW consists of two head works; the old and the new water works. The old water works has a design capacity of producing 90 million litres per day (MLD) of water, while the new is able to produce 150 million liters per day (MLD) (Kaduna State Water Board, 2015).

The raw water source for these water works is River Kaduna. It is characterized by high fluctuation in volume in the course of a year with high turbidity values during the wet (rainy) season. The Galma catchment is one of the tributaries of River Kaduna from the North and it is used for water supply in Kaduna. Figure 2.3 shows Kaduna Metropolis, Kaduna State.

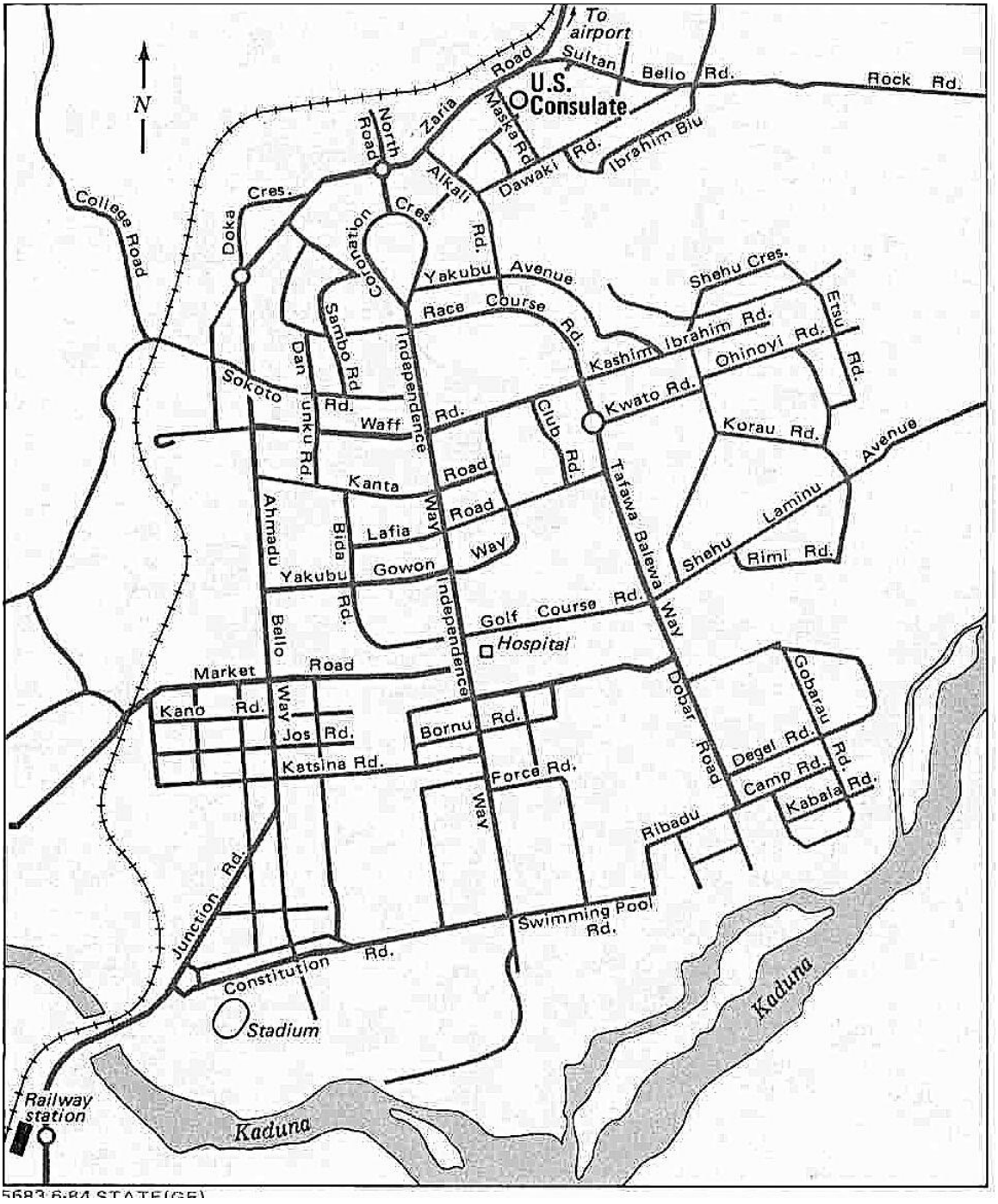


Figure 2.3: **Map of Kaduna Metropolis, Kaduna State ((https://www.google.com.ng/ map+of+kaduna+town, 2016)**

2.2 Domestic Water Supply in Metropolis

Access to clean and healthy water is one basic problem that has remained unsolved in Nigeria for several decades. It is common to see people conveying water from streams, wells and public or commercial borehole facilities in steel or plastic buckets, cans, and other containers by hand, on their heads, on motorcycles and vehicles. The Agencies or corporations tasked with the provision of water in many states are not functional. The bodies responsible for providing drinking water are essentially states water agencies. The States' Water Agencies are State Water Boards/Corporations, which mostly serve urban areas greater than 20,000 inhabitants, small water town agencies, which mostly serve semi – urban areas with population between 5,000 to 20,000 inhabitants, and Rural Water Supply and Sanitation Agencies, which operate in rural areas and usually serve communities of 500 to 5,000 inhabitants (Areola *et al*., 1997).

In Nigeria, sustainable delivery of water and sanitation services is one of the most challenging issues in meeting basic needs and a critical link in successfully achieving poverty reduction strategies (Areola *et al*., 1997). More than 90% of urban water supply in developing countries has been provided by public utilities for many years (UNDP, 2003). However, most of these public managed utilities in the developing countries have been inefficient, thus prompting a need for proper evaluation and broad reforms in the public sector in many African countries. The evaluation and reform have been driven by a combination of economic, social and political factors and this have generated the search for

efficiency and cost reduction in public service delivery (Onjali, 2002; WUP, 2003).

Water distribution systems (WDS) serve the community and help power the economy by delivering water from source(s) to its consumers. WDS comprises of three primary components; water source, water treatment plant, and distribution network. Water sources can be reservoirs, rivers, and groundwater. Water treatment facilities disinfect the water to drinking water quality standards prior to delivering it to consumers. The distribution network is responsible for delivering water from the treatment facilities to its consumers at serviceable pressures; and mainly consists of pipes, pumps, junctions (nodes), valves, fittings, and storage tanks (Aral, 1996)

The design of WDS including how the system supplies water to its consumers and the schematic layout is critical to their performance. WDS can be designed to supply to its consumers through gravity flow, using mechanical pumping, or both. Gravity flow can be used when there is an elevated water source (river or lake) with enough head to meet consumer demands. Gravity flow is rarely used to meet all demands in urban WDS because of the lack of practicality and flexibility. Gravity flow is more common in rural areas that lack pumping capability. Due to varying water demand patterns, most urban distribution networks utilize pumps with elevated storage tanks. These tanks help meet fluctuating consumer demands, accommodate fire flow during emergency conditions, and stabilize operating pressures. Typically, tanks are used during

peak hours of the day and refilled during low demand times. Networks can also be designed to have loop or branch schematics (Aral, 1996).

A branched network, as shown in Figure 2.4, includes several independent links with many terminals that prevent circulation of water throughout the entire network and water is supplied to end users through one pipe. One problem with a branched network is if one pipe is disabled even for routine maintenance, some consumer demands will not be met.

A looped network, as shown in Figure 2.5, is one that has multiple pipes at every single node so that water can be supplied to any point through more than one pipe. The problem with a looped network is the additional cost of constructing and maintaining redundant pipes. Most networks are a combination of these two schematic layouts.

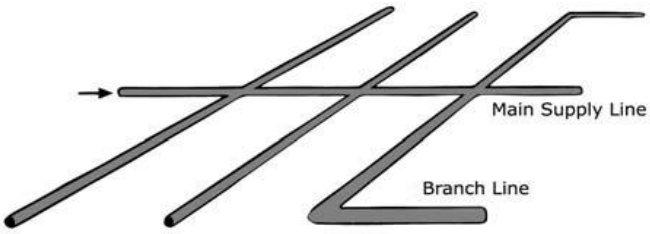


Figure 2.4: Branched Network

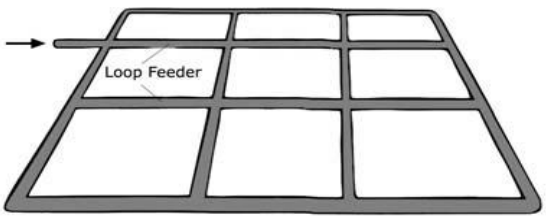


Figure 2.5: Looped Network

2.3 Water Treatment Processes

Water treatment involves obtaining raw water from a source (abstraction) and passing it through some processes of treatment till it is suitable for various domestic uses like drinking, cooking, washing etc. This treated water is eventually distributed to end-users for consumption. There are certain standards that must be met in the water supplied to the end-users to ensure that the water supplied is safe for consumption. Certain parameters of water are thus measured to ascertain that these standards are met. These include; pH, residual chlorine level, turbidity, Biological Oxygen Demand, Chemical Oxygen Demand, Dissolved Oxygen etc.

The processes involved in water production in water works are as follows:

2.3.1 Abstraction

This involves the use of low-lift pumps and an intake structure to take in raw water from its source to the treatment plant. In some water works, the intake structure consists of screening bars which protect the pumps from logs and other impurities of large sizes. There are also valves for controlling the inflow of water into the treatment plant.

2.3.2 Balancing

At this stage, the raw water is made to flow at low pressure into a balancing tank (that is, the pressure is cut off). Pre-sedimentation takes place in the balancing tank. Due to low pressure of flow, settleable solids (i.e. solids that settle on their own without the aid of chemicals) are allowed to settle. Aeration also takes

place in the balancing tank. The stage is usually skipped in some treatment plants.

2.3.3 Mixing chamber (coagulation and flocculation)

This is where chemicals are mixed with the raw water. The chemicals include; alum (for coagulation), liming (for pre-liming) and chlorine (pre-chlorination). Alum is usually added for coagulation. Lime is added for pH correction of water. The sulphate in the alum makes the water acidic, thus lime is added to reduce acidity. Lime is also added for the removal of hardness of water. Pre-chlorination is done to kill algae to reduce the amount of oxygen in water, because too much oxygen hampers coagulation and flocculation. Mixing could be hydraulic, mechanical or diffusal. Hydraulic mixing occurs as a result of the energy of the system (water). Structures are put in place to generate this energy as the water flows through them. Mechanical mixing is done with the aid of pumps.

A jar test is usually carried out from time to time to determine the amount of alum to be added to raw water. This is usually carried out on an hourly basis. During the rainy season coagulant aids like hydrated lime and sodium alginate could be used speed up coagulation reaction due to rush of dirty water.

The dissolution of alum in water results in the formation of positively charged ions. When the dissolved alum is added to raw water during the treatment process, the positive ions are attracted to the negatively charged colloidal impurities in water. This combination brings about an increase in mass and

formation of flocs, which begin to settle. The resulting water from this stage is called flocs water.

2.3.4 Sedimentation

The flocs water is then made to flow under very low pressure in sedimentary tanks (clarifiers or clear water tank). As the water flows through the sedimentary tanks flocculation continues and the flocs settle so that at the end of the sedimentation tank the water is clear. The sedimentation tanks are connected to desludging valves, which reduce the amount of sludge that settles at the bottom of the tanks. Decanting chambers collects clear water from sedimentation tanks after flocculation and sedimentation. The water is then transferred for filtration.

2.3.5 Filtration

The water from the sedimentation tanks are made to pass through a filter medium. Filters are usually made up of sand and gravels (mono-filters) sand, gravel and granite (dual filters). Multi-filters have activated charcoal in addition to sand, gravel and granite. As water passes through the filter medium, the particles/impurities in water are trapped by the medium. The water is then transferred to a reservoir for disinfection.

2.3.6 Disinfection

In water supplies, disinfection may be defined as the process of using chemical or physical means to inactivate harmful microorganisms that might be present inside the lumen of distribution mains or in filtered water in order to protect distributed water from pathogen re-growth or recontamination (May, 2000). The

use of Ultra Violet (U.V) light, ozonation and chlorination are all forms of disinfection, but chlorination is usually preferred and used in most drinking water systems because of its efficiency and capacity to leave adequate residuals, and it is relatively cheaper to apply. However, it must be noted, that certain enteroviruses, cysts of *Giardia intestinalis* and Oocysts of *Cryptosporidium* are resistant to the bactericidal effects of chlorine and its residual compounds (Kofi, 2012). After treatment, the treated water is then pumped with the aid of high lift pumps to booster stations for onward distribution to consumers.

2.4 Water Quality

The major objective of water treatment is to produce good quality treated water and to maintain that quality while in the distribution network. Since the early 20^{th} century, disinfection has been performed in Water Treatment Plants (WTP) clear well before the finished water leaves the water treatment plant. One goal is to provide a residual disinfectant that will be maintained in the distribution network. A proper residual disinfectant concentration in the water distribution network ensures chemical and microbiological stability of the water, microbiological control, and the minimization of the formation of Disinfection By Products (DBPs) (Letterman, 1999).

Assessing water quality within the water distribution network can be costly and difficult to measure. This is where a computer model can be helpful (Aral, 1996). The water quality model should be able to identify potential water quality problem areas within the network, and be used to understand the variability of water quality within the network, both spatially and temporally. Requirements

for the water quality model include water quality field measurements as a reference.

2.5 Chlorine

Due to low cost and high oxidizing potential, chlorine and chlorine compounds are the most popular disinfectants for water treatment (Sadiq and Rodriguez, 2004). Chlorine is an unstable compound that reacts with both organic and inorganic compounds. Chlorine can be consumed through reactions in the bulk water, with the bio-films on the pipe walls, and in the corrosion process.

The pipe size and the pipe wall affect the consumption of free chlorine in the water. As the pipe diameter increases, the overall decay rate of free chlorine decreases. Also, as pipe age increase (most especially, cast iron pipes) the chlorine decay rate increases (Li *et al*., 2003). Biofilms attached to the pipe walls are composed of several types of microorganisms and can consume significant amounts of free chlorine residual as well as corrode pipe walls (Letterman, 1999; Rossman *et al*., 2001). Corrosion has a substantial effect on residual chlorine consumption in old metallic conduits. Chlorine supports the corrosion of ferrous metals (Li *et al*., 2003).

The major difference between bulk decay and wall decay is where the reaction between the chlorine and constituents in the pipe network occurs (that is, the reaction sites). The bulk decay is the decay of chlorine during reactions between the chlorine and constituents in the water column. These reactions occur within the volume of water that is not in contact with the wall of the pipe. The wall

decay is the decay of chlorine during reactions between the chlorine and pipe wall materials and other water-quality constituents attached to the pipe wall (that is, biofilm and corrosion products) (Haestad Methods, 2003; Mays, 2000).

Aspects of the pipe network affect the consumption of free chlorine. Dead ends in the water distribution network can have detrimental effects on water quality. In dead ends of the network, water has higher water age and lower free chlorine residual (Li *et al*., 2003). Like dead ends, storage tanks can have a severe effect on water quality. Water stored in storage tanks tends to have much higher mean hydraulic retention time compared to the water in the pipe network of the water distribution network. Most of the water in the tank is not cycled frequently due to design requirements of the tank (Clark *et al*., 1994). As a result, chlorine residual is hard to maintain and the potential for the formation of Disinfection By Products (DBPs) is increased. Between 25 to 30% of the water stored in a tank is regularly cycled and fed to the network. The remaining 70 to 75% of the water in the tank rarely is fed back out to the system since this volume is dedicated as fire storage and for emergency situations (that is, power outages) (Grayman and Clark, 1993).

When modelling chlorine decay within a water distribution network, a first order decay model is usually implemented and thus chlorine is assumed to decay exponentially. The decay rates are influenced by changes in the water quality, temperature, flow rate, pipe diameter, pipe materials, biofilm, and pipe roughness (Li *et al*., 2003).

2.5.1 Chlorination

Chlorination is a chemical disinfection method that uses various types of chlorine or chlorine-containing substances. Apart from its ability to disinfect, chlorine controls taste, odour and colour in water. Chlorine was first discovered in Sweden by a Chemist, Karl W. Scheele in 1774 and it was used to remove odour from water in 1835. It was not until 1890 that chlorine was found to be an effective agent for disinfecting, a way to reduce the amount of disease transmitted through water. With this new find, chlorination began in Great Britain and then the United States in 1908; and Canada by 1917. Today, chlorination is the most popular method of disinfection and it is used for water treatment all over the world. 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 (Kofi, 2012).

In order to guarantee the water supply systems' disinfection, adequate residual concentrations are needed to prevent re-contamination by pathogenic or indicator micro-organisms, which can originate in the biofilm formed or in negative pressure areas (created by pipe cracks, fissures etc.) of the water supply system (Kofi, 2012).

2.5.2 Chlorine Demand and Breakpoint Chlorination

Chlorine demand may be defined as the difference between the amount of chlorine added to a water system and the amount of free available chlorine or

combined available chlorine remaining at the end of a specified time period. In other words, the demand is the amount of chlorine consumed by oxidation or substitution reactions with microbiological, organic and inorganic materials, such as H_2S, Fe^{2+}, Mn^{2+}, NH_3, phenols, amino acids, proteins, and carbohydrates. When all these demands are met, a point is reached when any further addition of chlorine to a water supply system leaves adequate residuals for the purposes of disinfection (Mays, 2000).

2.6 Stages in Chlorine Disinfection

To ensure efficiency, chlorine disinfection is typically carried out in three stages. These are primary, secondary and booster disinfection.

2.6.1 Primary disinfection

Primary disinfection is the treatment step used to inactivate pathogens at the treatment head works. It is accomplished by using a variety of chemicals, the three most common being (Mays, 2000);

i. Liquid chlorine (Cl_2) which is usually available in 45.5kg or 68 kg pressurized containers,
ii. Sodium hypochlorite (NaOCl) which is a liquid stored in glass, rubber-lined or plastic containers of varying sizes. It is usually 5 – 15 % chlorine but it has finite shelf-life,
iii. Calcium hypochlorite ($Ca(OCl)_2$) which is approximately 65% chlorine by weight.

2.6.2 Secondary or post disinfection

Secondary of Post disinfection refers to the practise of adding additional disinfectant to the treated water before it is released to the distribution network to maintain a residual (leftover) disinfection capability.

2.6.3 Booster disinfection

Booster disinfection is the practise of adding disinfectants at points in the distribution network beyond the point of raw water treatment. It is typically used at the entrance point to a service area being supplied by a wholesale provider or at distant points in a system subject to large disinfectant demands.

2.7 Disinfection-By-Products (DBPs)

A disadvantage of disinfection treatment and the presence of chlorine residual in water is the production of DBPs. Disinfection reduces the risk of disease due to pathogens in the water. However, due to the formation of DBPs, disinfection could pose a chemical threat to human health. Since the 1970's, focus has been p1aced on understanding DBPs and their formation. Organic DBPs are the result of chlorine residual reacting with Natural Organic Matter (NOM) in the water (McClellan, 2000; Rodriguez and Serodes, 2001). Some DBPs are believed to be cancer causing if one is exposed to an excess amount of them for a period of time (Bull and Kopfler, 1991). Two of the most common, and of most concern, DBPs are Total Trihalomethane (TTHMs) and Halo Acetic acid (HAA).

The formation of TTHM is a function of Total Organic Carbon (TOC), temperature, and initial chlorine level (Lee, 2004). The understanding of DBPs has led to research on alternate disinfectants and new treatment technologies. Removing NOM from the water at the WTP will reduce DBP formation (Sadiq and Rodriguez, 2004). HAA are another class of DBPs, and like TTHMs, their formation generally increases as Hydraulic Retention Time (HRT) increases. Several authors have performed research that suggests that, unlike TTHMs, HAA begin to degrade after long HRTs, due to microbial activity in the 'pipe network (Chen and Weisel, 1998). Singer (2003) found HAAs began to decline once the chlorine residual decreased to below 0.1mg/l. Based on laboratory analyses, Kansas (2004) hypothesized that HAAs began to decline once the free chlorine residual decreased to below 0.2 mg/l.

According to Regli (2003), the main factors influencing formation of DBPs include; temperature, pH, contact time, chlorine dose and residual, concentration of precursors and bromide ions. pH can increase in some storage facilities due to the leaching of hydroxides and carbonates from concrete surfaces, thereby increasing the potential for formation for trihalomethanes (THMs).

Generally, chlorine half-lives might be reduced to only few hours in systems with large demands. This reduction of half-life is termed chlorine decay.

2.8 Chlorine Decay Kinetics

Chlorine decay is represented by the equation below (Mays, 2000):

$$\frac{dC}{dt} = K_b C + \frac{4}{D} K_w \quad (2.1)$$

C: Residual chlorine concentration (mg/l)

K_b: First-order bulk decay coefficient (1/day)

K_w: Zero-order wall reaction decay coefficient (mg/m^2/day)

D: Pipe diameter (mm)

2.8.1 Bulk decay coefficient (K_b) determination

Bulk reactions are reactions that are unaffected by processes involving the pipe walls and can be described by nth order kinetics (Clark, *et al.*, 1998):

$$R(C) = K_b C^n \quad (2.2)$$

Where: R = reaction rate, C = reactant concentration, K_b = bulk reaction rate coefficient and n = reaction order.

Chlorine decay is usually represented as first order (that is, n = 1), with the decay coefficients typically being between 0.05 and 15 d^{-1}; noting that coefficients for decay reactions can be reported as negative values. The site-specific decay coefficient is typically determined using bottle tests where chlorine decay in a particular volume of water is monitored over the natural maximum water age of the system. The chlorine values of the finished water are the target chlorine concentrations for determining the chlorine dosage to the filtered water in a water treatment plant (Ahn, *et al.*, 2012).

A plot of the natural logarithm of residual chlorine concentration versus time gives the value of K_b which is the slope of the graph.

2.8.2 Wall reaction decay coefficient (K_w)

Wall reactions depend on the bulk conditions, pipe dimensions (i.e., pipes with smaller diameters encourage greater solution/wall interaction and therefore greater reaction rates), and pipe wall condition (Mays 2000):

$$R = \left(A/V\right)K_w C^n \quad (2.3)$$

Where: K_w = wall reaction rate coefficient and (A/V) = surface area per unit volume within a pipe (which is equivalent to 4 divided by the pipe diameter). The dependency of K_w and the reaction order on pipe material and condition (i.e., age, encrustation and corrosion) makes determining the coefficients difficult. Although conceptually K_w may be measured under ideal conditions (i.e., long isolated pipes, no connections, controlled flow, inline chlorine measurements), in real-world conditions such measurements are infeasible (Walski, 2003); therefore, models generally incorporate a calibrated Kw with initial estimates based on pipe roughness coefficients, flow velocity, and pipe diameter.

2.8.3 Overall chlorine decay constant

The overall decay constant, K, is the sum of the bulk and wall decay constant, thus (Mays 2000);

$$K = K_b + K_w. \quad (2.4)$$

2.9 pH

pH is a measure of the activity of hydrogen ions present in water. It is the negative logarithm of hydrogen ion concentrations. It can be written as; (Al-Mutaz, 1999)

$$pH = -\log[H^+] \quad (2.5)$$

Water molecules dissociate into hydrogen and hydroxyl ions. The multiplication of these ions is a constant known as dissociation constant, K (Al-Mutaz, 1999).

$$K = [H^+][OH^-] = 10^{-14} \quad (2.6)$$

At neutral conditions, equal concentrations of hydrogen and hydroxyl ions are present. So the pH is equal to 7. When pH value is below 7, more hydrogen ions exist and water trends to be acidic.

pH is often measured by the electrometric method. In this method, an electrode and a calibrated meter with a solution of known pH are used. At least 25 ml of sample should be taken in plastic or glass bottles. Samples should be collected without agitation to avoid any loss of carbon dioxide, which may lead into an increase in the pH. pH measurements should be performed as soon as possible after sample collection. It should not be performed longer than 6 hours after collection (Al-Mutaz, 1999).

2.9.1 *Factors affecting the pH*

pH reflects the acidity or the basic nature of water. It is affected by the chemical constituents of water, for example, carbon dioxide (CO_2), bicarbonate ions

(HCO_3^-), carbonate ions (CO_3^-), hydroxyl ions (OH^-) and the equilibrium among these constituents. Temperature affects this equilibrium. The pH values decreases by 0.45 as the temperature increases by 25 °C (Langelier, 1946).

Carbon dioxide dissolves in water forming carbonic acid according to the following reaction (Langelier, 1946):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \quad (2.7)$$

Carbonic acid is then ionized into HCO^{3-} species (Langelier, 1946)

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad (2.8)$$

The ionization constant for this reaction is 4.31 x 10^{-7} at 25°C. The pH value is reduced to about 6.0 by dissolving carbon dioxide. Evolution of carbon dioxide from water leads an increase in the pH value according to the reverse of the net reaction of the preceding two reactions (Langelier, 1946):

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \quad (2.9)$$

The decrease in the carbon dioxide concentration in water is due to the conversion of bicarbonate into carbonate. Carbon dioxide at concentrations of about 100 parts per million (ppm) or more increases water corrosivity significantly especially if trace amounts of oxygen are present (Sarbar, 1992).

2.10 Turbidity

Turbidity is the amount of cloudiness in water. This can vary from a river full of mud and silt, where it would be impossible to see through the water (high

turbidity), to spring water which appears to be completely clear (low turbidity). Turbidity can be caused by (WHO, 2003);

i. silt, sand and mud ;

ii. bacteria and other germs ;

iii. chemical precipitates.

It is very important to measure the turbidity of domestic water supplies, as these supplies often undergo some types of water treatment which can be affected by turbidity. For example, during the rainy season when mud and silt are washed into rivers and streams, high turbidity can quickly block filters and stop them from working effectively. High turbidity will also fill tanks and pipes with mud and silt, and can damage valves and taps (WHO, 2003)

Where chlorination of water is practised, even quite low turbidity will prevent the chlorine killing the germs in the water efficiently. Some treatment systems, such as sedimentors, coagulators and gravel prefilters are designed to remove turbidity. It is important for operators of both large and small treatment systems to know how well these systems are working. Measuring the turbidity of the water before and after each part of the network can tell the operator where maintenance or cleaning is needed. Turbidity can be measured using a turbidity meter or a turbidity tube (WHO, 2003).

For drinking water supplies, the following guidelines should be taken into consideration (WHO, 2003):

i. Drinking water should have a turbidity of 5 NTU or less. Turbidity of more than 5 NTU would be noticed by users and may cause rejection of the supply.

ii. Where water is chlorinated, turbidity should be less than 5 NTU and preferably less than 1 NTU for chlorination to be effective

2.11 Dissolved Oxygen

There are both positive and negative attributes of having dissolved oxygen in domestic drinking water. Although corrosion within older cast iron water supply systems is a result of oxidative processes due to the presence of dissolved oxygen, the effects of oxygen are mostly beneficial. Dissolved oxygen prevents the chemical reaction and leaching of iron and manganese from the sediments in source water, which otherwise would stain plumbing fixtures and cause taste problems. It facilitates the biochemical oxidation of ammonia to nitrate, reduces the chlorine demand of waters and increases the disinfection efficiency of chlorination (NAS/NAE, 1972). Also, a high level of dissolved oxygen is generally considered to make water more palatable, as opposed to there being a 'flat' taste. Dissolved oxygen criteria for drinking water is at least 5mg/l (Alberta Environment, 1977). However, high dissolved oxygen levels speed up corrosion in water pipes.

2.12 Water Quality Deterioration Factors

A distribution network's pipes and storage facilities constitute a complex network of uncontrolled physical, chemical, and biological reactors that can

produce significant variations in water quality. The principal factors that affect water degradation during distribution are; the network's structure, its operation, and a number of water quality factors including Structural factors, Operational factors and Quality factors (Michael, 2002).

2.12.1 Structural factors

Drinking water distribution networks are typically thought of as the underground network of interconnecting mains or pipes. They also can include storage facilities, valves, fire hydrants, service connections, and pumping stations. Historically, water system designers tended to create oversized pipelines and storage facilities. While system designers may be considering an area's future drinking water needs, oversized facilities result in long detention times, loss of chlorine residual, taste and odour concerns, and other water quality problems (Mays 2000).

Furthermore, some of the materials that designers choose to install in distribution networks create suitable environments for microorganism growth. Materials, such as cast or ductile iron, asbestos cement, or pressurized concrete, can pit and make way for microorganisms to colonize (AWWA, 2001).

In addition, oxidant-resistant microorganisms settle on pipe surfaces and produce a complex micro environment known as biofilm. Biofilms form when organisms enter the distribution network and become entrapped in slow-flow areas, line obstructions, or dead-end sections. They usually appear as a patchy mass in pipe sections or as a uniform layer along the inner walls of a storage

tank. While not all biofilm is bad, researchers are currently unsure of its exact effect. Coliform bacteria may colonize it, and biofilm may interfere with coliform detection. It may also cause taste and odour problems. Designers now theorize that the material manufacturers use in pipes, as well as the condition of pipes, valves, and storage facilities, may exert a high-chlorine demand (Michael, 2002).

Pipe materials can cause water quality to deteriorate in other ways. Iron pipes can corrode, and lead and copper from pipe walls can dissolve. For example, unlined or exposed ferrous materials in pipelines can corrode and cause red or rusty-coloured water. To avoid corrosion problems, systems are turning to plastic materials, such as polyethylene and polyvinyl chloride (PVC) (AWWA, 2001).

Finally, contamination via cross-connection, leaky pipe joints, or pipe breaks may influence water quality. Pathogens, such as *Cryptosporidium* and *Giardia lamblia*, may enter the network through contaminated raw water, in-line reservoirs, or breaks in pipelines. System personnel need to carefully and thoroughly perform flushing and disinfection procedures after repairs (Michael, 2002).

2.12.2 Operational factors

From an operations standpoint, network operating conditions – such as slow water velocities, supply sources going on and off-line, and the amount of time that systems store water – greatly affect water quality. Any of these factors can

cause chlorine residual to fade, and, thus, allow microbial growth in the network. Further, hydraulic conditions can cause sediment to deposit, accumulate, and serve as both habitat and protection from disinfectants for microbial growth. What's more, many storage facilities are kept full so that the system can be better prepared for emergency conditions. However, the long detention times result in degraded water quality (Kirmeyer *et al* 2001).

2.12.3 Water quality factors

Some of the factors that provide optimal conditions for microorganisms to multiply include long water-detention times in tanks and pipes, adequate nutrient levels, and warm temperatures. In addition, research has shown that the level of biodegradable organic matter in the distribution network strongly affects bacterial re-growth and harbours opportunistic pathogens. An opportunistic pathogen can be any disease-causing organism (bacterium, virus, helminth, or protozoan) that slips through the treatment processes or enters the distribution network during pressure loss and finds the opportunity or favourable circumstances to lodge or reproduce in organic material, bacterial slime, or other material that it finds attractive (Besner, 2001).

A number of other conditions also can affect water quality. For example, as explained earlier, disinfectants may react with organic and inorganic compounds and cause taste and odour problems or form disinfection by-products. Also, particulate re-suspension may cause increased turbidity (AWWA, 1999).

2.13 Contamination Prevention and Control

Drinking water systems can improve water quality or prevent its deterioration in the distribution network. They can modify system operations and maintenance alternatives, make changes in treatment practices, and improve water quality monitoring and modelling. Generally, systems need to find an optimal combination of these actions, which can involve trade-offs between cost, water supply needs, and water quality considerations (AWWA, 1999).

2.14 Modifications to System Operation

Systems can use five primary operation procedures to maintain water quality (AWWA, 1999):

i. minimize bulk water detention time,
ii. maintain positive pressure,
iii. control the direction and velocity of the bulk water,
iv. maintain a disinfectant residual in the distribution network (Disinfectant residual, usually chlorine, provides a relatively effective barrier to the growth of microorganisms in bulk water and biofilm.), and
v. prevent cross-connections and backflow.

2.15 Water Quality Modelling for Water Distribution Networks

Water quality models use the output of hydraulic models in conjunction with additional inputs to predict the temporal and spatial distribution of a variety of

constituents within a distribution system. These constituents include (USEPA, 2005):

i. The fraction of water originating from a particular source.
ii. The age of water (e.g., duration since leaving the source).
iii. The concentration of a non-reactive constituent or tracer compound either added to or removed from the system (e.g., chloride or fluoride).
iv. The concentration of a reactive compound including the concentration of a secondary disinfectant with additional input of its loss rate (e.g., chlorine or chloramines) and the concentration of disinfection by-products with their growth rate (e.g., THMs).

Grayman and Clark (1990) give an overview of water quality modelling for distribution systems. They distinguished three different types of models of water distribution systems:

i. hydraulic models; which simulate the flow quantity, flow direction and pressure in the system,
ii. steady state water quality models; which determine the movement of contaminants, their flow paths and travel times through the network under steady state operational and demand conditions and
iii. dynamic water quality models which simulate the movement and transformation of substances in the water under time varying conditions, that is, demand, pressure or flow very, for example, diurnally (or in other words, transient phenomena are also modelled).

In addition to these type of models discussed above, other models which focus more on biological processes have been developed (Gujer *et al.*, 1990, Dukan *et al.,* 2002)

Various water quality processes are occurring in water distribution systems that can lead to introduction of contaminants and water quality transformations as water moves through the distribution system. Cross connections, failures at the treatment barrier, and transformations in the bulk phase can all degrade water quality. Corrosion, leaching of pipe material, biofilm formation, and scour can occur at the pipe wall to degrade water quality. Bacteriological quality changes may cause aesthetic problems involving taste and odour development, discoloured water, and other adverse impacts (USEPA, 2005).

In addition to basic hydraulic modelling equations, the water quality models utilize various mathematical equations that are based on conservation of constituent mass. These models represent the following phenomena occurring in a distribution system (Rossman, 2000):

i. Advective transport of mass within pipes: A dissolved substance will travel down the length of a pipe with the same average velocity as the carrier fluid while at the same time reacting (either growing or decaying) at some given rate. Longitudinal dispersion is not an important transport mechanism in turbulent flow, which is normal inside transmission mains under most operating conditions. It may, however, be an important factor in dead-end pipes or in low and intermittent flow scenarios.

ii. Mixing of mass at pipe junctions: All water quality models assume that, at junctions receiving inflow from two or more pipes, the mixing of fluid is complete and instantaneous. Thus, the concentration of a substance in water leaving the junction is simply the flow-weighted sum of the concentrations in the inflowing pipes.

iii. Mixing of mass within storage tanks: Most water quality models assume that the contents of storage tanks are completely mixed.

iv. Reactions within pipes and storage tanks: While a substance moves down a pipe or resides in storage, it can undergo reaction. The rate of reaction, measured in mass reacted per volume of water per unit of time, will depend on the type of water quality constituent being modelled. Some constituents, such as fluoride, do not react and are termed "conservative." Other constituents, such as chlorine residual, decay with time; while the generation of DBPs, such as THMs, may increase over time. Some constituents, such as chlorine, will react with materials both in the bulk liquid phase and at the liquid-pipe wall boundary.

Water quality models represent these phenomena (transport within pipes, mixing at junctions and storage tanks, and reaction kinetics in the bulk liquid phase and at the liquid-pipe wall boundary) with a set of mathematical equations. These equations are then solved under an appropriate set of boundary and initial conditions to predict the variation of water quality throughout the distribution system.

Several solution methods are available for dynamic water quality models (Rossman and Boulos, 1996). All of these methods require that a hydraulic analysis be run first to determine how flow quantities and directions change from one time period to another throughout the pipe network. The water quality constituent is subsequently routed through each pipe link and then mixed at downstream nodes with other inflows into the node. For non-conservative substances, concentrations are continuously adjusted to accommodate the decay or growth of the constituent with time. This concentration is then released from the node into its out-flowing pipes. This process continues for all pipes and for the duration of the simulation.

The methods described above are also applied when modelling water age and source-tracing in water quality models. Water age is equivalent to modelling a reactive constituent that ages and combines linearly. For example, for every hour that a "packet" of water spends in a tank, its age will increase by one hour. Additionally, combining a volume of water that is four days old with a similar volume of water that is eight days old will result in an average age of six days. When modelling the fraction of water coming from a designated source (source tracing), this parameter is modelled as a conservative substance and is linearly combined. For example, combining a volume of water that is entirely from the designated source with a similar volume of water from a different source will provide a mixed volume calculated as 50 percent from the designated source (USEPA, 2005).

2.15.1 Water quality models

Rossman (1993) describes EPANET, a public domain program package for hydraulic and water quality modelling developed by the U.S. Environmental Protection Agency.

Rossman gives the equations of the hydraulic model (possible utilisation of Hazen-Williams, Darcy-Weisbach or Chezy-Manning formulas) and the water quality model equations together with a short introduction to the computer implementation. EPANET can model the propagation of conservative and reactive substances (that is, free chlorine). The chlorine decay coefficient, K for first order chlorine decay depends on both bulk water demand, k_b and wall demand, k_w. Thus,

$$K = k_b + \frac{k_w k_f}{R_H (k_w + k_f)} \qquad (2.10)$$

Where: k_f = mass transfer coefficient between bulk flow and pipe wall and R_H = hydraulic radius). The mass transfer coefficient k_f depends among other things on the Reynolds number and therefore on the flow.

The chlorine dynamics are

$$\frac{\partial c(x,t)}{\partial t} = \frac{f}{A}\frac{\partial c(x,t)}{\partial t} - Kc(x,t) \qquad (2.11)$$

Where c = chlorine concentration, t = time, x = axial distance, f = flow, A (area) and the solution is

$$c(x_2, t_2) = c(x_1, t_1) \,.\, e^{K(t_2 - t_1)} \qquad (2.12)$$

with

$$x_2 - x_1 = v\,.(t_2 - t_1) \qquad (2.13)$$

Where t_1, t_2 represent time, x_1, x_2 represent upstream and downstream distance along the pipe, respectively, and $v = \frac{f}{A}$ is the constant velocity of water in the pipe.

Colin and Grapin (1991) combined their own hydraulic model (AREMAN) with a water quality model of the form

$$\frac{\partial c_i}{\partial t} = E_x \frac{\partial c_i}{\partial x^2} - v\frac{\partial c_i}{\partial t} + \phi_i \qquad (2.14)$$

With c_i = chlorine concentration, E_x = axial dispersion coefficient, v = water velocity in the pipe, x = space variable, ϕ_i = production term and index, i = ith pipe.

They use highly parallel hardware and thus can solve systems with up to 10000 of these partial differential equations (PDE).

In Biswas *et al* (1993), a more complicated model of chlorine decay, incorporating the biofilm demand is given. The model equations are derived by methods of fluid dynamics and are valid only for steady state, that is,

$$\frac{\partial c}{\partial t} = 0 \qquad (2.15)$$

With c = chlorine concentration

2.16 Previous Studies on Water Quality Modelling in Distribution Networks

Wable *et al.* (1991) used Piccolo to model chlorine concentrations in water distribution systems.

First order kinetics for chlorine decay are derived from the chemical equations. The network model is based on a hydraulic model and plug flow, no radial or axial diffusion, perfect mixing at node, and conservation of fluxes are assumed. After the hydraulic regime is known they find the residence time, the concentration of any compound, and the origin of the considered water volumes. The procedure to achieve this requires the integration of the kinetics over the residence time for each pipe, and for each node the mean of the concentration is averaged by the flow rate.

They considered single pipes in an actual distribution system (Paris) to determine the free chlorine demand and showed that a log-linear relationship between the decay coefficient and temperature exists. Similarly, TOC is related to free chlorine decay.

Sharp *et al* (1991) attempted to measure free chlorine decay through measuring flow (that is, travel time) and chlorine concentrations. An uncertainty analysis was done and results from experiments in an actual system were given.

Liou and Kroon (1987) gave another example of the application of a dynamic model of the propagation of conservative substances to an actual distribution system and outline the theory used for non-conservative substances. LIQVARS by Stoner Associates was used to develop the steady state hydraulic model. The

additional dynamic model divides the pipes the pipes in volume elements and propagates them with every time step.

Hunt and Kroon (1990) tuned first order free chlorine decay coefficients to actual data. Chambers and Joy (1993), in a Water Research Centre (WRC) report prepared for Thames Water, aimed to validate first-order kinetics for free chlorine decay. They did an extensive sampling programme, but less extensive statistical analysis. Problems occurring during the project were discussed (for example, some of the measurements were discarded because the sampling locations were not representative for what they theoretically should stand for). The precision of the chlorine measurements could be significantly improved through the adoption of an accurate sampling procedure.

Clark *et al.* (1994) presented a case example of modelling chlorine decay in an actual distribution system. In this system, there is a high wall demand. It is remarked that storage tanks, due to long retention times, may cause serious water quality problems.

Heraud et al (1997) presented results from sampling in a real system together with the application of chlorine models incorporated into Piccolo. Sampling in a real distribution system brings the draw-back of fluctuations in inlet chlorine (0.28 – 0.97 mg/l) and temperature (11.6 – 24.1^{0}C). Sampling was performed at hydrants at a flow rate of about 1.41 l/s.

Today, several software solutions are available for water quality, such as Epanet (2013) and Epanet-based software, Piccolo (2013), SynerGee Water (2013),

InfoWater (2013), Sir 3S (2013) and Porteau (2013). Porteau is designed and developed by Irstea for hydraulic and quality modeling in WDNs; it uses a different algorithm than in Epanet (Rossman and Boulos, 1996).

Dandy et al. (2013) studied the advantages and the limitations of the use of water age as a surrogate for water quality in WDN. They worked out the chlorine concentration from the residence time. Their motivation is that the simulation code for residence time may be 30% and 40% faster than for the chlorine concentration because of reaction terms. Their main findings are that in certain situations, water age gives an approximate estimate of water quality and disinfection by-product formation. However, this estimate may be inaccurate due to mixing in tanks and at nodes and is inappropriate for systems with several water sources and/or re-chlorination.

2.17 History of Kaduna State Water Board

Kaduna State Water Board (KSWB) was established by Edict No. 2 of 1971 as a body Corporate with perpetual succession and common seal and has the power to sue and be sued in its corporate name. This edict was replaced with Kaduna State Water Board law that came into effect on July 1, 2004. The functions of KSWB include (Kaduna State Water Utility Board, 2007):

a.) To control and manage all water works

b.) To ensure that water is supplied to consumers at reasonable charges and in potable quality and adequate quantity.

c.) To enter into agreement or delegate authority for the exercise of any of the functions performed or provided by the Board to increase coverage and quality of service, by encouraging participation of the private sector, communities and Non-Governmental Organizations (NGOs) in project identification, planning, design, implementation, financing and management of its water supply systems.

2.17.1 Description of Kaduna metropolis water distribution network

There are two treatment plants serving the water supply need of the populace in Kaduna metropolis. These are the Kaduna North Plant at Malali (New and Old plants) and the Kaduna South Plant located downstream of the railway bridge across river Kaduna.

Treated water is pumped from Kaduna North Water Treatment plant reservoir in Malali with high lift pumps to reservoirs and booster stations in Kaduna Metropolis. The treated water is conveyed through pipes (asbestos cement pipes) of different diameters and lengths to the various reservoirs along the network. Water is then distributed to consumers from the reservoirs through pipes of lesser diameters. A schematic of the distribution network is shown in Appendix 1.

Table 2.1: **Existing Water Reservoirs in Kaduna Township**

S/No.	Location	Type of reservoirs	Capacity	Date Commissioned	Present Status
1	Lugard Hall	Braithwaite	4,500m^3 12,700 m^3	1971	Functional
2.	State House Kawo	Concrete	9,100 m^3	1971	Functional
3.	NDA	Braithwaite	4,800 m^3	1975	Functional
4.	Old Airport	Braithwaite	2,500 m^3	1978	Functional
5.	Mando	Concrete	2,500 m^3	1984	Functional
6.	Rigasa	Concrete	11,000 m^3	1986	Functional
7.	Tudun wada	Concrete	12,300 m^3	1987	Functional
8.	Kakuri	Concrete	63,000 m^3	N/A	Functional
9.	Barnawa	Braithwaite	2,500 m^3	1978	Functional
10.	Kamazo	Concrete	30,000 m^3	1987	Functional
11.	Ungwan Muazu	Braithwaite	2,500 m^3	1985	Functional

Source: Kaduna State Water Utility Board (2007)

2.17.2 Responsibilities of KSWB

The responsibilities of KSWB include:

a.) To produce and distribute water to the people of Kaduna State for domestic, commercial and industrial purposes;

b.) To maintain the distribution network;

c.) To charge water fees and other services rendered by the Board, with the approval of the State Government, in such a way that the revenue for each

year would be sufficient or as nearly as may be to pay for all working expenses.

d.) To collect fees for water consumed by customers

2.17.3 Code of practice of KSWB

2.17.3.1 *Water quality*

The code of practice for water quality in KSWB includes:

i. The drinking water quality standards shall conform to the WHO drinking water quality guidelines.
ii. All waterworks serving 5,000 people and above to be equipped with a functional water quality laboratory of appropriate capacity.
iii. Monitor and protect the quality of raw water sources for drinking.

2.17.3.2 *Quality of treated water in Kaduna North Water Works*

Table 2.1 shows the quality of treated water produced at Kaduna North Water Treatment plants from past records. A 5 year average (from 2011 – 2015) is presented for each parameter, while the detailed data is shown in Appendix 3.

Table 2.2: Average Measurements of Water Quality Parameters at KNWW, Malali (for 5 years)

S/No.	Parameters	Average Value	NSDWQ Standard
1	Turbidity (NTU)	9.5	0 – 5.0
2	pH Value	5.7	6.5 – 8.5
3	Conductivity µS/cm at 25^0C	59.0	1000 (Max.)
4	Chlorides as Cl mg/L	21.0	250
5	Nitrates as N mg/L	0.01	10
6	Bicarbonate Alkalinity as $CaCO_3$ mg/L	28	
7	Carbonate alkalinity as $CaCO_3$ mg/L	0	
8	Total alkalinity as $CaCO_3$ mg/L	28	
9	Total hardness as $CaCO_3$ mg/L	23.4	150
10	Total Iron as Fe mg/L	0.124	0.5
11	Sulphate as SO_4	13.2	250
12	Free CO_2 mg/L	25.8	
13	Calcium mg/L	19.6	100
14	Total dissolved solid mg/L	30.2	250
15	Ammonium (NH_4^+)	0	0.5

Source: Kaduna State Water Works, Malali (2011-2015)

2.17.3.3 *Water consumption standards*

The code of practice for water consumption in KSWB includes:

i. Urban areas as 120 litres per capita per day to be served by full reticulation and consumer premises connection.

ii. Semi – urban areas as 90 litres per capita per day with reticulation and limited or full house connections.

iii. Rural areas as 30 litres per capita per day from stand pipes preferably within 250 meters of the community and not exceeding 500 meters, serving about 250 persons.

iv. Peri – urban areas as at least 60 litres per capita per day with reticulation limited or full house connections.

Kaduna township has the highest concentration of the KSWB's installations and offices within the state. The district offices in Kaduna township are at: Makera, Barnawa, Doka, Tudun Wada, Rigasa and Kawo. The other district offices are in Zaria town, Kafanchan, Birnin Gwari, Saminaka, Ikara, Zonkwa and Kwoi. There are two treatment plants serving the water supply need of the populace in Kaduna metropolis. These are the Kaduna North Plant at Malali (New and Old plants) and the Kaduna South Plant located downstream of the railway bridge across river Kaduna (Ajibike, 2013).

The methodology used in this work to model the water quality deterioration in the distribution network of Kaduna metropolis is given in chapter three.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

(a) Apparatus

The apparatus used in this work include;

i. Lovibond (S1000) comparator made by Tinton Ltd., Salisbury, England.

ii. pH tester/meter, HI 96107 phep made by HANNA, Ltd, USA (1986)

iii. HACH 2100Q Portable Turbidimeter made by HANNA, Ltd., USA (2009)

iv. Palintest Comparator, PAL – PT520T

v. Portable Dissolved Oxygen Analyzer, JPB-607, 2000 (CHINA)

vi. Glass bottle with a string attached (to collect water samples from reservoirs)

vii. Plastic containers for storing water samples.

The reagents, software and other materials used are as follows:

(b) **Reagents**

i. Orthotolidine (OT)

Software: MATLAB/SIMULINK R2009b, EXCEL 2010

Other materials: Network Layout of Kaduna State Water Distribution Network.

3.2 Water Treatment Processes and Distribution in Kaduna Metropolis

The source of raw water for treatment and eventual distribution for KNWW is the River Kaduna. Raw water is abstracted from River Kaduna with the aid of low-lift pumps and an intake structure into the treatment plant. In KNWW, the intake structure consists of screening bars which protect the pumps from logs and other impurities of large sizes. There are also valves for controlling the inflow of water into the treatment plant.

In KNWW, the old treatment plant consists of seven pumps which work in combinations to pump in 90 MLD water to the treatment plant; three of the pumps are for pre-settling (50 MLD) while four pumps are for balancing (40 MLD). The new treatment plant consists of seven pumps with a joint capacity of 150 MLD. The pump capacities are stated in the Appendix 2. There are always pumps (as well valves and tanks) on standby.

Pre-sedimentation takes place in the balancing tank. Due to low pressure of flow, settleable solids are allowed to settle. Aeration also takes place in the balancing tank. Chemicals are mixed with the raw water in the mixing chamber. The chemicals include; alum (for coagulation), liming (for pre-liming) and chlorine (pre-chlorination). Alum is added for coagulation. Lime is added for pH correction of water. In KNWW, the mixing is hydraulic.

In KNWW, Aluminium Sulphate (alum) is used as coagulant. The alum is first of all dissolved in water by agitation to form a solution. This is done in a chemical room. Pellets of alum are added to water in two 23,000L tanks (only one is

usually operational, the other is used as standby). An air blower scours air into the tank to cause agitation for proper mixing between the alum and the water. A jar test is usually carried out from time to time to determine the amount of alum to be added to raw water. This is usually carried out on an hourly basis. During the rainy season coagulant aids like hydrated lime and sodium alginate are used speed up coagulation reaction due to rush of dirty water.

The flocs water is then made to flow under very low pressure in sedimentary tanks (clarifiers or clear water tank). The sedimentation tanks are connected to desludging valves, which reduce the amount of sludge that settles at the bottom of the tanks. During dry season, desludging is done once or twice daily in KNWW, but hourly during rainy reason due to high turbidity of raw water. Decanting chambers collects clear water from sedimentation tanks after flocculation and sedimentation. The water is then transferred for filtration.

KNWW makes use of mono-filters and the filter medium is sand. The water from the sedimentation tanks are made to pass through the sand medium and the particles/impurities in water are trapped in the pore spaces of the sand. The water is then transferred to a reservoir for disinfection. Backwashing is done to wash the sand media when its pore spaces are filled up with impurities from water. This is done with the aid of an air scourer.

Disinfection is done with hypochlorite powder. It is dissolved in water and added to the reservoir of water. In KNWW, the reservoir is 14 feet deep. Laboratory analysis is also done to measure pH, turbidity and chlorine levels.

After treatment, the treated water is then pumped with the aid of eight high lift pumps to booster stations for onward distribution to consumers.

3.3 Methods

3.3.1 Sampling points

Water samples were taken from various points in the water distribution network for quality analysis. The points are; treated water reservoir of the water treatment plant at Malali (KNWW), State House Booster station, Nigerian Defence Academy (NDA) Reservoir, Lugard Hall Reservoir and Tudun Wada Booster Station. Samples were also taken from a health facility (Yusuf Dantsoho Memorial Hospital, Tudun wada) in order to monitor further changes of water quality along the network.

The State House Boosting Station is the closest sampling point to the treatment plant at Malali. It is about 7.1 km along the main road from Malali. The length of the main pipeline from the treatment plant is about 8 km. The next sampling point, NDA reservoir is about 3.4 km along the main road from the State House Booster Station with length of the main pipeline being about 5.6 km from the State House Booster Station. Lugard hall reservoir is 3 km along the main road from NDA. Tudun wada booster station is about 5.2 km from Lugard Hall.

3.3.2 Sample collection

Water samples were obtained from reservoirs and booster stations with the aid of a glass bottle with a string attached to its neck. The bottle was rinsed thoroughly with distilled water to prevent it from contaminating the water flowing in the network. It was then carefully dipped into the reservoir to collect water. The water sample obtained was then transferred to a plastic bottle which had been rinsed with distilled water and the water sample obtained from the reservoir respectively to ensure accuracy of results; as small quantities of water already present in the plastic containers could affect results obtained from analysis. The plastic containers were then labeled (using a masking tape) with the names of the sampling points for easy identification.



Plate I: Labelled Plastic Containers of Water Samples (KSWB Central Laboratory, 2015)

3.3.3 Water quality analysis

The following water quality parameters were obtained; residual chlorine, turbidity, pH and dissolved oxygen. Measurements of residual chlorine were done on site in order to get accurate results, but to observe the decay rate of chlorine over a period of 6 hours; measurements were taken with Lovibond comparator in the Department of Water Resources and Environmental Engineering Laboratory, Ahmadu Bello University, Zaria. Turbidity, pH and dissolved oxygen were measured on site using a portable turbidity meter, pH meter and dissolved oxygen meter respectively from the Kaduna State Water Board Central Laboratory.

Water quality tests were conducted from January to August 2015 to identify sections in the network where water quality deterioration occurs and to monitor the seasonal variation in water quality along the network.

3.3.4 Procedures for measuring water quality parameters

3.3.4.1 *Procedure for measuring residual chlorine*

Free chlorine in water is unstable and the amount of chlorine in water may go down quickly, especially in warm climates. Sunlight and mixing of the water will allow free chlorine to disappear more rapidly. For this reason, chlorine testing was carried out on-site, because if samples were to be taken back to the laboratory for analysis, the results would have been inaccurate.

The method used for measuring chlorine residual in the water employed the use of OT (Orthotolidine) and Lovibond comparator as follows:

The cells in the comparator were rinsed three times with the water which is to be tested. The cells were then filled with the same water. 2 drops of OT were added to one of the cells for Chlorine testing. The lid on the comparator was replaced and the comparator was shaken for proper mixture of the OT and water sample. A brown coloration indicated the presence of chlorine.

This colour was then matched to the nearest colour on the colour scale which is permanently fixed to the comparator and the amount of chlorine from the scale was read.

When the test was completed, the top of the container was removed and the water in the cells poured onto the soil, not into the water supplies or other water sources. The comparator was then washed with clean water and stored in a place where it cannot be damaged.

Precautions taken

When taking readings, the comparator was held up to allow plenty of daylight to enter the cells in order to ensure accurate matching of colours. The cells were also rinsed with water samples to be tested.

3.3.4.2 *Procedure for measuring pH*

pH was measured using a pH tester/meter (HI 96107 phep made by HANNA, Ltd, USA, 1986)

25 ml of the water sample was taken in a glass bottle (after rinsing the glass bottle 3 times with the water sample). Samples were collected without agitation to avoid

any loss of carbon dioxide, which may lead to an increase in the pH. pH measurements were performed as soon as possible after sample collection by dipping the probe of the pH meter into the water till a stable reading is obtained.

3.3.4.3 *Procedure for measuring turbidity*

Turbidity was measured using a turbidity meter (HACH 2100Q Portable Turbidimeter made by HANNA, Ltd., USA, 2009)

The cell in the meter was removed, rinsed thrice with the water to be tested, filled with the same water and inserted back into the meter for turbidity reading. After pressing the read button, the turbidity of the water sample was displayed on the meter screen after few seconds.

3.3.4.4 *Procedure for measuring dissolved oxygen*

Dissolved oxygen was measured using a dissolved oxygen meter (Portable Dissolved Oxygen Analyzer, JPB-607, 2000, CHINA). Water samples were put in the cuvette of the dissolved oxygen meter and readings were taken from the dissolved oxygen meter.

3.3.5 Effects of months and seasons on water quality

The effects of months and seasons on the quality of treated water at KNWW were determined using Analysis of Variance (ANOVA).

3.3.6 MATLAB

MATLAB (Matrix Laboratory) is a high-performance language for technical computing. It integrates computation, visualization, and programming environment. Furthermore, MATLAB is a modern programming language environment with sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming. These factors make MATLAB an excellent tool for teaching and research (Chadwick, 2005).

MATLAB has many advantages compared to conventional computer languages (for example, C, FORTRAN) for solving technical problems. MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. The software package has been commercially available since 1984 and is now considered as a standard tool at most universities and industries worldwide. It has powerful built-in routines that enable a very wide variety of computations. It also has easy to use graphics commands that make the visualization of results immediately available. Specific applications are collected in packages referred to as toolbox. There are toolboxes for signal processing, symbolic computation, control theory, simulation, optimization, and several other fields of applied science and engineering (Chadwick, 2005).

3.3.7 SIMULINK

Simulink is a block diagram environment for multi-domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems.

Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. Simulink software requires MATLAB to run, and it depends on it to define and evaluate model and block parameters. Simulink can also use many MATLAB features. For example, Simulink can use the MATLAB environment to (Mathworks, 2015):

a.) Define model inputs.

b.) Store model outputs for analysis and visualization.

c.) Perform functions within a model, through integrated calls to MATLAB operators and functions.

3.2.7 Water quality model using SIMULINK

Modeling is a process in which a dynamic system is described with mathematical equations after which a simplified representation of the system is created. The equations define the science of the system and the model uses the equations to define the time-varying behavior (MathWorks, 2015).

The steps taken in modeling the water quality deterioration along the Kaduna metropolis distribution network involves:

i. Reservoirs/Booster stations are represented as components of the distribution network with subsystem blocks and labeled appropriately.

ii. The water quality parameters, namely, residual chlorine concentration, pH, turbidity and dissolved oxygen concentration are represented in each subsystem with linear regression equations linking them.

iii. The simulation parameters are inputed.

iv. The simulation is run

v. Results are taken.

Figure 3.1 indicates the flow chart for a SIMULINK model.

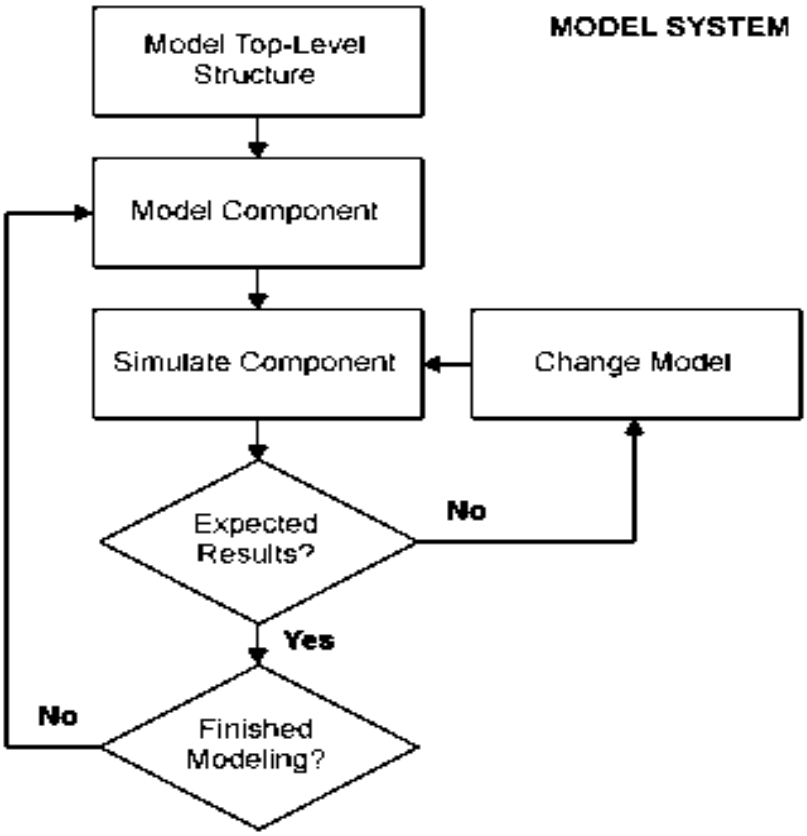


Figure**. 3.1: Flow chart for SIMULINK model** (MathWorks, 2015)

The results obtained in this work and discussions arising therefrom are given in chapter four.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from laboratory and field measurements of water quality parameters. Analysis of the variation in water quality in Kaduna metropolis distribution network is done with the use of tables and charts. Model parameters are also presented, as well as likely causes of deterioration in water quality in the distribution network.

4.2 Variation in Residual Chlorine along Distribution Network

Table 4.1 shows how residual chlorine varies along the distribution network. It can be seen that the treatment plant produces treated water with residual chlorine levels between 0.2 and 0.3 mg/l which is very low.

Table 4.1: Variation of Residual Chlorine along the Network

SAMPLING POINTS	Dry Season								Wet Season							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug	
		Time		Time		Time		Time		Time		Time		Time		Time
KNWW	0.30	10:15	0.21	10:05	0.21	10:18	0.20	9:55	0.21	9:47	0.23	10:11	0.23	10:10	0.26	9:58
SHBS	0.21	10:47	0.10	10:40	0.20	10:47	0.20	10:12	0.10	10:05	0.10	10:47	0.20	10:48	0.24	10:37
NDA	0.10	11:05	0.10	11:00	0.10	11:05	0.10	10:35	0.10	10:25	0.10	11:05	0.10	11:04	0.20	11:05
LHR	0.10	11:28	0	11:26	0.10	11:28	0	11:28	0	10:48	0	11:28	0.10	11:25	0.10	11:20
TWBS	0.10	12:01	0	12:05	0	12:01	0	12:19	0.10	11:31	0	12:01	0	11:58	0.10	12:06
YDMH	0	12:15	0	12:13	0	12:15	0	12:15	0	11:38	0	12:15	0	12:10	0	12:17

The result of this is that residual chlorine is not detected at the point of use by consumers since the residual chlorine is exhausted along the distribution network. Thus, inadequate residual chlorine is available for disinfection along the pipes in the distribution network. This is a clear indication of the danger that the consumers are facing in consuming this water. Should any contamination happen within this distribution network, people might consume this contaminated water and get sick or even die. A high decay rate of residual chlorine can also be seen from the water treatment plant clear well to the various sampling points. This implies high chlorine demand of treated water. In August however, the decay rate is not as high as other months. This is due to the fact that during rainy season, the turbidity levels are high, which in turn hinders proper disinfection by chlorine, thus decreasing its rate of reaction in water (Mark *et al.*, 1980).

4.3 pH Variations along Distribution Network

According to the Nigerian Standard for Drinking Water Quality (NSDWQ), the pH of drinking water should be between 6.5 to 8.5. If the pH of drinking water goes out of this range, it is considered unfit for human consumption. pH of water can be affected by residual chlorine concentration. Removal of chlorine from water makes it less acidic. Table 4.2 shows how pH varies along the distribution network. It can be seen that there is a slight increase in pH along the distribution network, except at Lugard Hall reservoir where a slight drop occurs.

Table 4.2: Variation in pH along the Network

SAMPLING POINTS	Dry Season								Wet Season							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug	
		Time		Time		Time		Time		Time		Time		Time		Time
KNWW	7.1	10:15	7.1	10:05	7.1	10:18	7.1	9:55	5.6	9:47	6.2	10:11	6.2	10:10	5.4	9:58
SHBS	7.2	10:47	7.2	10:40	7.2	10:47	7.2	10:12	5.6	10:05	6.2	10:47	6.1	10:48	5.5	10:37
NDA	7.3	11:05	7.3	11:00	7.3	11:05	7.3	10:35	5.7	10:25	6.3	11:05	6.3	11:04	5.7	11:05
LHR	7.3	11:28	7.2	11:26	7.3	11:28	7.3	11:28	5.7	10:48	6.3	11:28	6.2	11:25	5.7	11:20
TWBS	7.4	12:01	7.3	12:05	7.4	12:01	7.4	12:19	5.8	11:31	6.5	12:01	6.6	11:58	5.9	12:06
YDMH	7.4	12:15	7.4	12:13	7.4	12:15	7.3	12:15	6	11:38	6.7	12:15	6.5	12:10	5.8	12:17

The slight increase in pH along the network is caused by reduction in residual chlorine, since chlorine is acidic in water. Other factors that bring about reduction in pH include; increase in temperature and dissolution of carbon dioxide. pH levels were lowest in the month of August 2015.

4.4 Turbidity Variations along Distribution Network

It is expected that treated water should have turbidity levels of 0 – 5 NTU according to the Nigerian Standard of Drinking Water Quality (NSDWQ). Excess turbidity in water makes it unfit for consumption. Table 4.3 below shows turbidity measurements along the distribution network.

Table 4.3 presents the variation in turbidity over the study period. At the water treatment plant, it was expected that the turbidity will be zero. The fact that water exiting the plant already indicated some turbidity readings (even beyond 5 NTU in the months of May, June and August) confirmed that the plant is not operating efficiently.

Table 4.3: Variation in Turbidity along the Network

SAMPLING POINTS	Dry Season								Wet Season							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug	
		Time		Time		Time		Time		Time		Time		Time		Time
KNWW	2.6	10:15	2.7	10:05	4.2	10:18	4.2	9:55	5.2	9:47	6.43	10:11	6.43	10:10	7.24	9:58
SHBS	2.73	10:47	2.85	10:40	4.5	10:47	5.2	10:12	5.8	10:05	6.54	10:47	6.54	10:48	7.5	10:37
NDA	4.3	11:05	4.37	11:00	5.23	11:05	5.72	10:35	5.42	10:25	6.73	11:05	6.73	11:04	6.8	11:05
LHR	3.51	11:28	4.15	11:26	4.3	11:28	4.4	11:28	4.2	10:48	6.54	11:28	6.54	11:25	4.76	11:20
TWBS	6.3	12:01	6.3	12:05	6.43	12:01	6.5	12:19	6.82	11:31	6.96	12:01	6.96	11:58	9.43	12:06
YDMH	6.4	12:15	6.6	12:13	6.64	12:15	6.8	12:15	7.3	11:38	7.64	12:15	7.64	12:10	10.6	12:17

Turbidity levels were noticed in the months of May, June and August. This is due to the fact that turbidity values of raw water are high thus resulting in treated water with substantial turbidity. Turbidity also increases along the distribution network due to bacteria and other germs and chemical precipitates from reaction of chemicals in water. Low levels of turbidity were recorded at Lugard Hall reservoir throughout the study period. Turbidity in water deters the effect of chlorine disinfection along the distribution network (Mark, *et al.*, 1980).

4.5 Dissolved Oxygen Variation along the Distribution Network

Dissolved oxygen is important in water for aeration. It gives water a refreshing taste. Treated water supplied to consumers is expected to have some level of dissolved oxygen (about 5 mg/L) but not excessively high as these could corrode pipes thereby contaminating water. Table 4.4 presents dissolved oxygen measurements at the sampling points.

From Table 4.4, it can be seen that dissolved oxygen level is too low at the sampling points.

Table 4.4: Variation in Dissolved Oxygen along the Network

SAMPLING POINTS	Dry Season								Wet Season							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug	
		Time		Time		Time		Time		Time		Time		Time		Time
KNWW	0.6	10:15	0.6	10:05	0.6	10:18	0.5	9:55	0.5	9:47	0.6	10:11	0.5	10:10	0.5	9:58
SHBS	0.5	10:47	0.5	10:40	0.5	10:47	0.6	10:12	0.5	10:05	0.5	10:47	0.5	10:48	0.5	10:37
NDA	0.4	11:05	0.5	11:00	0.5	11:05	0.5	10:35	0.4	10:25	0.6	11:05	0.4	11:04	0.4	11:05
LHR	0.6	11:28	0.6	11:26	0.5	11:28	0.5	11:28	0.6	10:48	0.7	11:28	0.6	11:25	0.6	11:20
TWBS	0.5	12:01	0.4	12:05	0.4	12:01	0.4	12:19	0.3	11:31	0.4	12:01	0.4	11:58	0.4	12:06
YDMH	0.5	12:15	0.4	12:13	0.5	12:15	0.5	12:15	0.4	11:38	0.4	12:15	0.4	12:10	0.4	12:17

The amount of dissolved oxygen in the water depends on temperature and pressure. The solubility of oxygen increases with decreasing temperature and decreases with decreasing pressure. Low dissolved oxygen levels in water, makes it have a 'flat' taste. The highest dissolved oxygen levels occur at Lugard Hall reservoir while the lowest levels occur at Tudun wada booster station.

4.6 Effects of Months and Seasons on Water Quality

The Analysis of Variance for some water quality parameters are presented below.

4.6.1 Effect of months and seasons on residual chlorine levels

Table 4.5 shows the analysis of variance of residual chlorine.

Table 4.5: ANOVA of Residual Chlorine

Source of Variation	*Sum of Squares*	*Degree of Freedom*	*Mean Squares*	*F Values*	*P-value*	*F crit*
Collection points	0.16	5	0.034	11.78	1.5E-07	2.49
Within month and season	0.02	7	0.003	1.04	0.144623	2.29
Error	0.10	35	0.002			
Total	0.28	47				

From table 4.5, it can be seen that there is significant differences between residual chlorine in water along the collection points with $F_{5, 35} = 11.78$; $p = 1.5 \times 10^{-7}$. The months and season have little effect on dissolved oxygen in the distribution network ($F_{7, 35} = 1.04$; $p = 0.144623$)

4.6.2 Effect of months and seasons on pH

Table 4.6 shows the analysis of variance of pH.

Table 4.6: ANOVA of pH

Source of Variation	*Sum of Squares*	*Degree of Freedom*	*Mean Squares*	*F Values*	*P-value*	*F crit*
Collection points	0.60	5	0.12	27.83	2.02E-10	2.53
Within month and season	20.50	7	3.42	797.33	1.12E-31	2.42
Error	0.13	35	4.29E-03			
Total	21.23	47				

From table 4.6, it can be seen that there is significant differences between pH of the water along the collection points with $F_{5, 35} = 27.83$; $p = 2.02 \times 10^{-10}$ and within the months and season with $F_{7, 35} = 797.33$; $p = 1.12 \times 10^{-31}$. Table 4.2 shows that pH values were highest at the Tudun wada Booster station and lowest at KNWW. pH values were also higher in the dry season than in the wet season with lowest pH values in the month of August.

4.6.3 Effect of months and seasons on turbidity

Table 4.7 shows the analysis of variance of turbidity

Table 4.7: ANOVA of Turbidity

Source of Variation	*Sum of Squares*	*Degree of Freedom*	*Mean Squares*	*F Values*	*P-value*	*F crit*
Collection points	50.43	5	10.09	18.78	4.83E-09	2.49
Within month and season	60.58	7	8.65	16.11	2.92E-09	2.29
Error	18.80	35	0.54			
Total	129.80	47				

From table 4.7, it can be seen that there is significant differences between turbidity of the water along the collection points with $F_{5, 35} = 18.78$; $p = 4.83 \times 10^{-9}$ and within the

months and season with $F_{7, 35} = 16.11$; $p = 2.92 \times 10^{-31}$. Table 4.3 shows that turbidity values were highest in wet season.

4.6.4 Effect of months and seasons on dissolved oxygen

Table 4.8 shows the analysis of variance of dissolved oxygen

Table 4.8: ANOVA of Dissolved Oxygen

Source of Variation	*Sum of Squares*	*Degree of Freedom*	*Mean Squares*	*F Values*	*P-value*	*F crit*
Collection points	0.20	5	0.040	13.89	1.7E-07	2.49
Within month and season	0.03	7	0.005	1.64	0.156891	2.29
Error	0.10	35	0.003			
Total	0.34	47				

From table 4.8, it can be seen that there is significant differences between dissolved oxygen of the water along the collection points with $F_{5, 35} = 13.89$; $p = 1.7 \times 10^{-7}$. The months and season have little effect on dissolved oxygen in the distribution network ($F_{7, 35} = 1.64$; $p = 0.156891$).

4.7 Relationship between Water Quality Parameters

The average values for the parameters were plotted against each other using Excel 2010 to examine the relationship that exists between them.

4.7.1 Relationship between residual chlorine and pH

Figure 4.1 shows the relationship between residual chlorine and pH. pH generally decreases with increasing residual chlorine concentration.

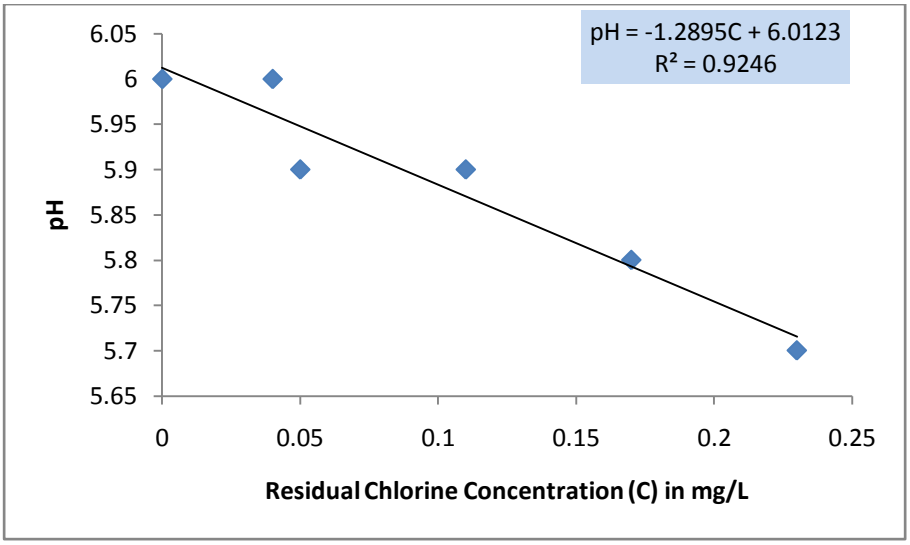


Figure 4.1: Relationship of pH to residual chlorine (mg/l) in distribution network

The correlation coefficient, R^2 = 0.9246 shows that a strong relationship exists between pH and residual chlorine in mg/l. This pattern of relationship exists between pH and residual chlorine because chlorine is acidic in nature, thus, a decrease in residual chlorine concentration along the network results in a corresponding increase in pH.

4.7.2 Relationship between residual chlorine and turbidity

Figure 4.2 shows the relation that exists between residual chlorine and turbidity along the water distribution network.

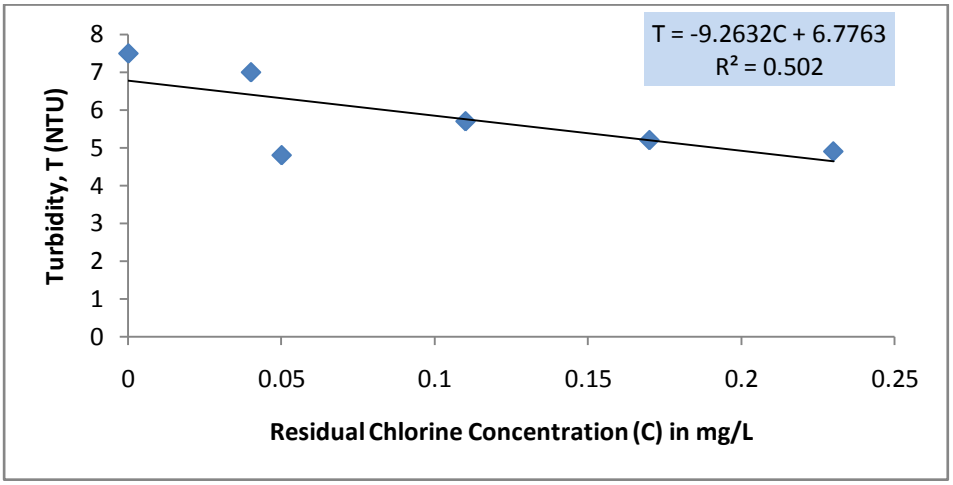


Figure 4.2: Relationship of residual chlorine (mg/L) to turbidity (NTU) in distribution network

From Figure 4.2, the turbidity varies inversely with residual chlorine concentration. The correlation is fair (R^2 = 0.502). At higher turbidity values, the efficiency of chlorine is reduced. Also, when chlorine is being used up in water, its reaction with organic compounds results in precipitation of particles which increases turbidity (Mark *et al.*, 1980).

4.7.3 Relationship between residual chlorine and dissolved oxygen

Figure 4.3 shows the relation that exists between residual chlorine and turbidity along the water distribution network.

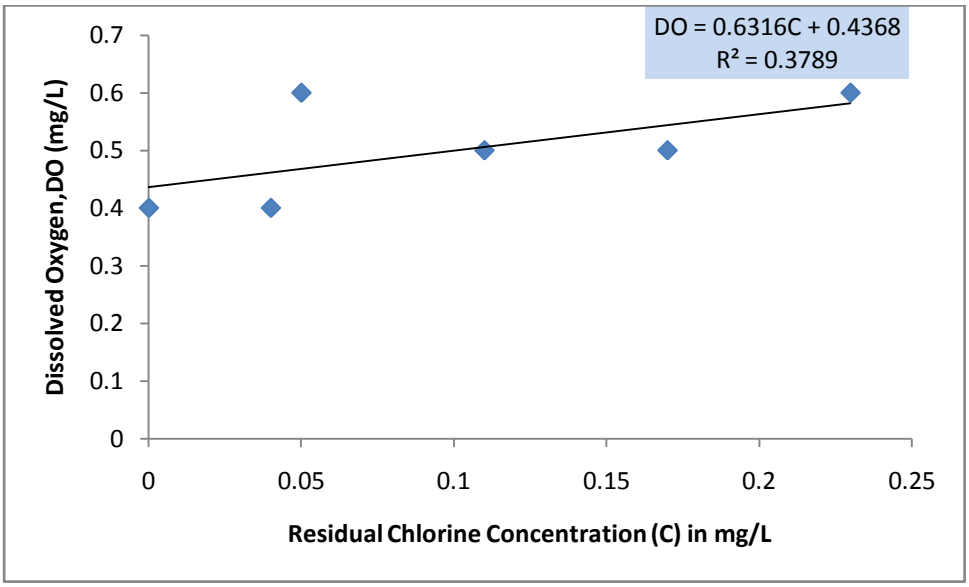


Figure 4.3: Relationship of residual chlorine (mg/l) to dissolved oxygen (mg/l) in distribution network

Figure 4.3 shows a very weak correlation between the amount of dissolved oxygen and the residual chlorine concentration of the water flowing in the distribution network (R^2 = 0.3789).

4.7.4 Relationship between pH and turbidity

Figure 4.4 shows the relation that exists between pH and turbidity along the water distribution network.

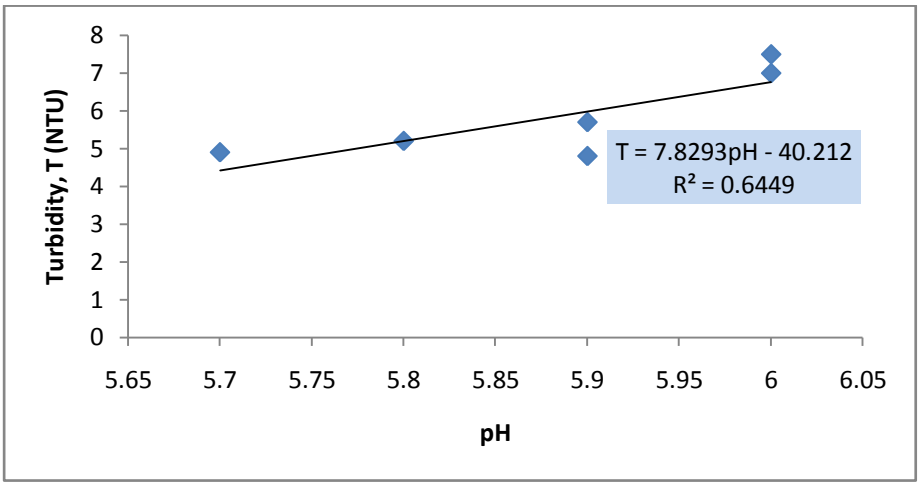


Figure 4.4: Relationship of pH to turbidity (NTU) in distribution network

The correlation coefficient value, $R^2 = 0.6449$, shows a fair relationship between pH and turbidity. Also, turbidity increases with increase in pH. This is because the reaction of chlorine with inorganic compounds in water results in turbidity and as lesser concentrations of residual chlorine in water results in higher pH.

The chemical used in treating turbidity in water (alum) has significant effect on the pH of water. Alum is acidic in nature and thus reduces the pH of water.

4.7.5 Relationship between turbidity and dissolved oxygen

Figure 4.5 shows the relation that exists between turbidity and dissolved oxygen along the water distribution network.

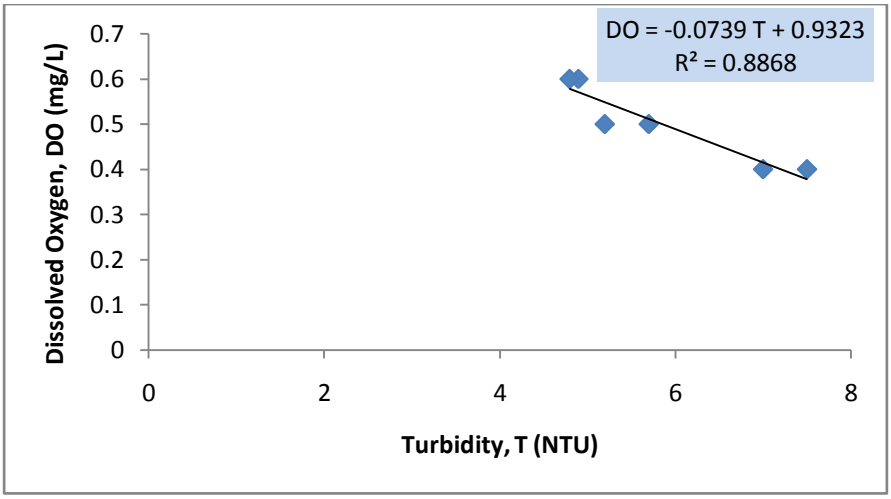


Figure 4.5: Relationship of turbidity (NTU) to dissolved oxygen (mg/L) in the distribution network.

A strong correlation exists between turbidity and dissolved oxygen (R^2 = 0.8868). Dissolved oxygen reduces with increasing turbidity.

4.7.6 Relationship between pH and dissolved oxygen

Figure 4.6 shows the relation that exists between pH and dissolved oxygen along the water distribution network.

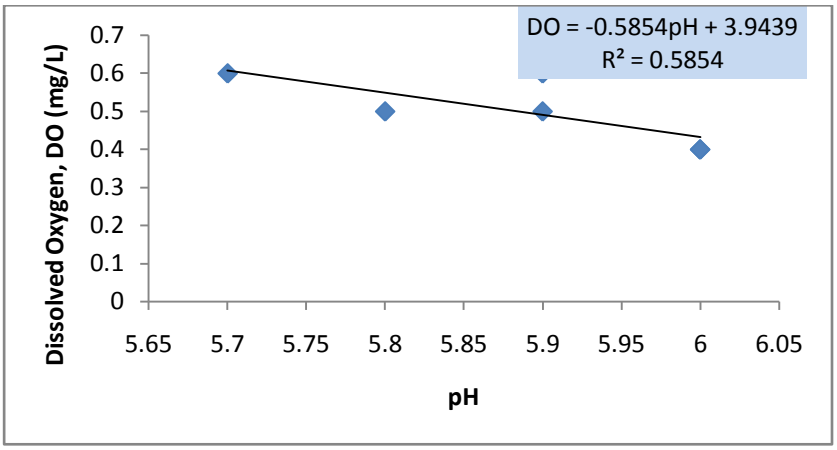


Figure 4.6: Relationship of pH to dissolved oxygen (mg/L) in distribution network.

There exists some level of relationship between pH and dissolved oxygen (R^2 = 0.5854). Dissolved oxygen reduces with increasing pH.

4.8 Water Quality Model

Based on the relationship between residual chlorine and the other parameters, it was used as a base parameter in the model; that is, its value determined the value of the other parameters

4.8.1 Bulk decay coefficient (K_b) determination

Experiments were carried out to determine the residual chlorine decay rate in the bulk volume of the water over a period of 6 hours. Table 4.8 shows the results obtained from the hourly measurements of residual chlorine in bulk water.

Table 4.9: Bulk Decay of Residual Chlorine

Time (h)	Residual Chlorine (C) (mg/L)	ln C
0	0.3	-1.20
1	0.28	-1.27
2	0.25	-1.39
3	0.23	-1.47
4	0.22	-1.51
5	0.21	-1.56
6	0.21	-1.56

The first-order decay kinetics was assumed in determining the bulk decay coefficient (K_b) for the chlorinated water. Figure 4.7 shows a plot of the natural logarithm of residual chlorine concentration versus time.

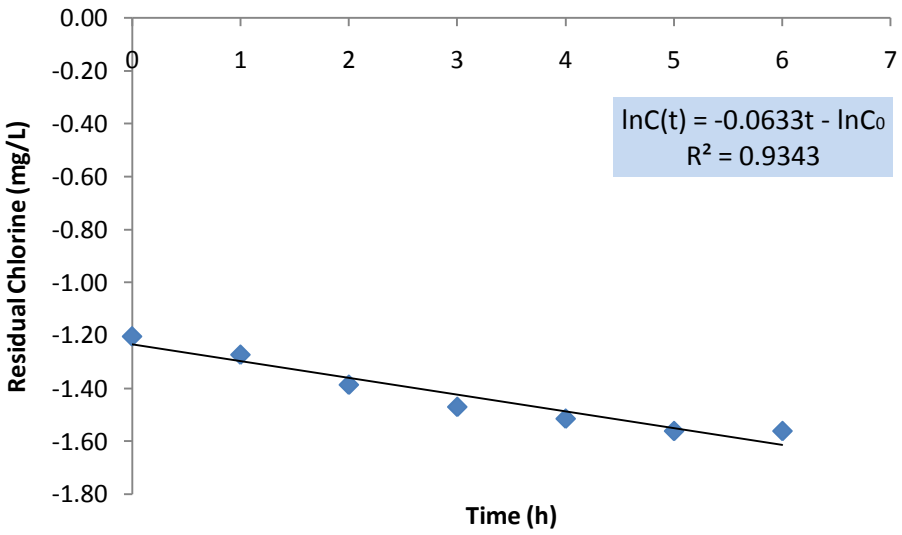


Figure.4.7: Relationship of residual chlorine to time in bulk water volume

The value of $K_{b,}$ which is the slope of the graph is equal to - 0.063hr^{-1}.

4.8.2 Wall reaction decay coefficient (K_w) determination

In this study, the model incorporated a calibrated K_w. An initial estimate of 1 hr^{-1} was made due to high degree of pipe roughness as a result of pipe age (over 30 years). This value was then adjusted continually till model results were as close as possible to measured data.

4.8.3 Overall chlorine decay

The overall chlorine decay constant, K, is the sum of the bulk and wall decay constant. The model incorporated equation 2.1 to calculate overall chlorine decay.

4.8.5 MATLAB/SIMULINK prediction model

Linear regression equations describing the relationship between the water quality parameters constituted the mechanism for prediction of the water quality parameters at different points along the network. The equations are as follows:

$$pH = -1.2895C + 6.0123 \quad (R^2 = 0.9246) \qquad (4.1)$$

$$T = -9.2632C + 6.7763 \quad (R^2 = 0.502) \qquad (4.2)$$

$$DO = 0.6316C + 0.4368 \quad (R^2 = 0.3789) \qquad (4.3)$$

$$T = 7.8293pH - 40.212 \quad (R^2 = 0.6449) \qquad (4.4)$$

$$DO = -0.0739\ T + 0.9323 \quad (R^2 = 0.8868) \qquad (4.5)$$

$$DO = -0.5854pH + 3.9439 \quad (R^2 = 0.5854) \qquad (4.6)$$

N.B.: pH = H^+ concentration in water, C = residual chlorine concentration in mg/L, T = turbidity in NTU (Nephelometric turbidity units), DO = Dissolved oxygen concentration in mg/L, R^2 = correlation coefficient.

The strength of correlation that exists between parameters (R^2 value) was considered in selecting specific equations for a pair of parameters. Equations with higher R^2 value, indicating strong correlation were preferred. Thus, equations 4.1, 4.4 and 4.5 were used. As stated earlier, equation 2.1 was used to model chlorine decay.

The selected equations were used to construct the SIMULINK model. Details of the structure of the model can be seen in Appendix 4

4.8.6 Comparison of modelled results with observed field measurements

Figure 4.8 (a) below shows the comparison of modelled and field observed values of residual chlorine concentration at the sampling points.

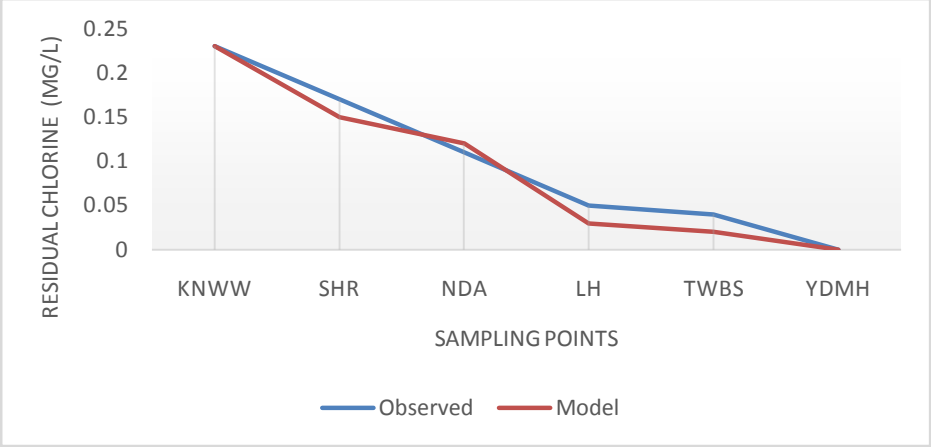


Figure 4.8(a): Comparison of modelled and field observed values of residual chlorine concentration at sampling points

The percentage accuracy of the model in predicting residual chlorine concentrations at the sampling points is 77.8%. It also follows a similar pattern in the variation of residual chlorine concentration along the network.

Figure 4.8 (b) shows the comparison of modelled and field observed values of pH at the sampling points.

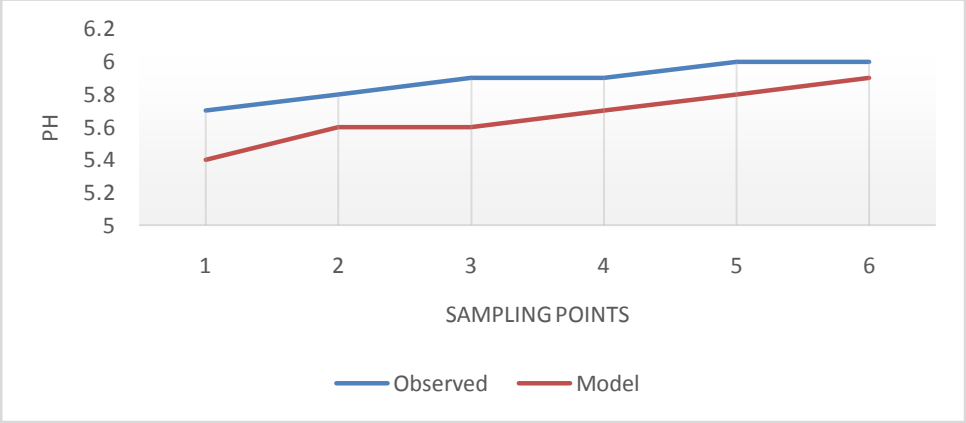


Figure 4.8(b): Comparison of modelled and field observed values of pH at sampling points

The percentage accuracy of the model in predicting pH values at the sampling points is 96.3%. A similar trend in values is also observed.

Figure 4.8 (c) shows the comparison of modelled and field observed values of turbidity at the sampling points.

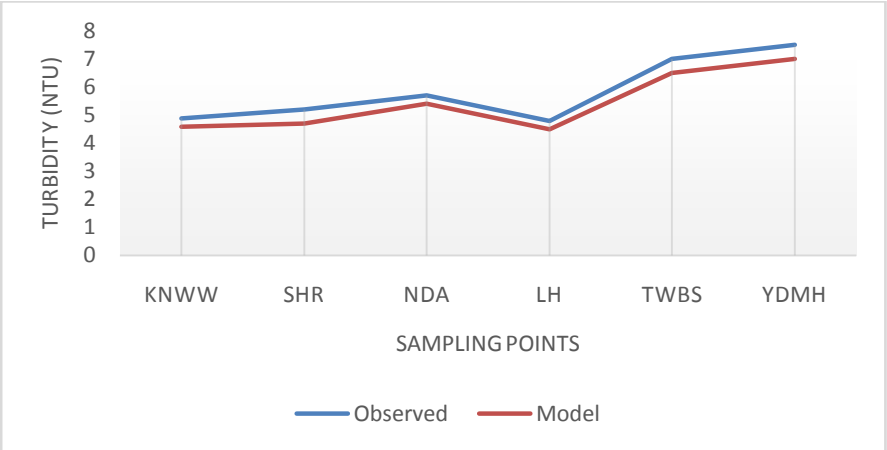


Figure 4.8 (c): Comparison of modelled and field observed values of turbidity at sampling points

The percentage accuracy of the model in predicting turbidity values at the sampling points is 93.2%. A similar trend is observed.

Figure 4.8 (d) shows the comparison of modelled and field observed values of dissolved oxygen concentration at the sampling points.

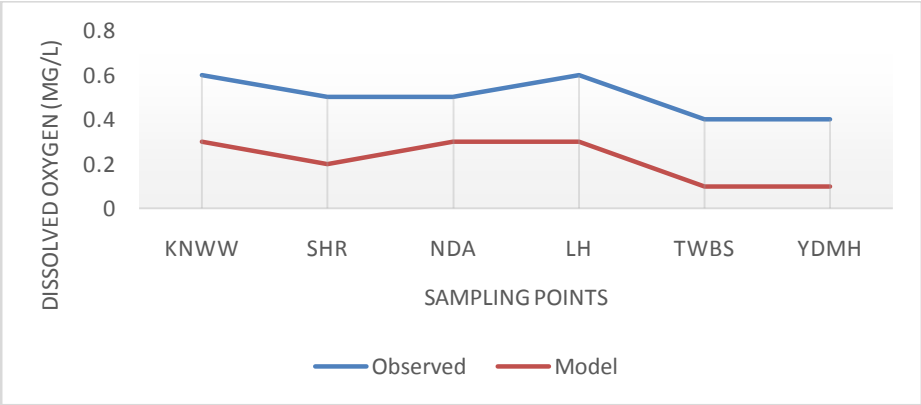


Figure 4.8 (d): Comparison of modelled and field observed values of dissolved oxygen concentration at the sampling points

The percentage accuracy of the model in predicting residual chlorine concentrations at the sampling points was 41.7%.

Average percentage accuracy of the model was 77%.

4.9 Likely Causes of Water Quality Deterioration

4.9.1 Inefficient treatment processes

The occurrence of turbidity above 5 NTU even at the treatment plant is an indication that the treatment processes are not efficient in producing water of good quality. Also residual chlorine and dissolved oxygen at treatment plant reservoir are not high enough to sustain a good water quality along the distribution network.

4.9.2 Leakage

Leakages exist at various points in the distribution network. This brings about negative pressure and ingress of contaminants into the water distribution network, thus, contributing to deterioration of water quality. Some leakage sites are captured in Appendix 6.

4.9.3 Age of pipe

Most of the pipes in the networks have not been changed since the installation of the network in 1971 and rehabilitation in 1978 (Table 3.1). Thus, the age of pipes ranges from 38 to 45 years. Old pipes are characterized with encrustations, biofilms and sediments which negatively affect the water quality (Kofi, 2012).

Chapter five gives the summary, conclusion and recommendations derived from this work.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary

The findings made from this study are summarised below:

i. The quality of water produced at Kaduna North Water Works is below standard (that is, Nigerian Standard for Drinking Water Quality). Residual chlorine levels of treated water at KNWW range from 0.2 – 0.3 mg/L, turbidity levels are above 5 NTU and dissolved oxygen levels are too low (less than 1.0 mg/L) .

ii. The quality of treated water deteriorates considerably along the distribution network. Variations exist in water quality parameters of the water samples taken from the selected sampling points.

iii. Water quality deterioration within Kaduna metropolis distribution network varied with season in terms of residual chlorine concentration which was between 0.0 and 0.21 mg/l in dry season, 0.0 and 0.26 mg/l in the wet season; pH was between 7.1 to 7.4 in dry season, 5.4 and 6.0 in the wet season; turbidity was between 2.6 and 2.8 NTU in dry season, 4.2 and 10.6 NTU in the wet season; dissolved oxygen was between 0.4 and 0.6 mg/l in the dry season, 0.3 and 0.7 mg/l in the wet season.

iv. Leakages exist majorly along the distribution mains and service connections in the network.

v. Strong correlation exists between some of the parameters – residual chlorine and pH, pH and turbidity etc.

vi. Modelled parameters yielded values close to field observation results

5.2 Conclusion

Most of the quality parameters are not within the WHO thresholds. There are noticeable variations of their values from Kaduna North Water Works (KNWW) to the various sampling points where water samples were collected. The ANOVA statistical analysis revealed that there were significant differences between the measured quality parameter values at KNWW with the various sampling points. This is a clear indication that the integrity of the treated water transported to Kaduna metropolis through the pipe distribution network has been compromised. Therefore, the safety of the consumption of the tap water may not be guaranteed

5.3 Recommendations

Based on the findings of this study, the following recommendations are made:

i. Kaduna State Water Board should improve on the treatment processes, since quality of treated water at Kaduna North Water Works is below standard. Proper monitoring of water quality parameters should be done and adequate actions taken to produce water of good quality.

ii. Further treatment and monitoring of water quality should be done at booster stations and reservoirs, namely; State House booster station, NDA reservoir, Lugard Hall Reservoir and Tudun wada booster station.

iii. Rehabilitation of the water distribution network should be considered by Kaduna State Water Board. Old pipes should be replaced with new ones.

iv. Leakages at various points in the network should be repaired to prevent contamination of treated water.

v. Regular flushing of pipes with highly pressurized water should be done to remove Fe and Mn deposits, because their presence in the distribution network increases chlorine demand.

vi. Further studies should be carried out using higher doses of chlorine to ascertain decay coefficients

REFERENCES

Ahn, J.C., Lee, S.W., Choi, K.Y. and Koo, J. Y. (2012). *Application of EPANET for the determination of chlorine dose and prediction of THMs in a water distribution system*. Sustain. Environ. Res., 22(1), 31-38.

Ajibike, M. A. (2013); *Evaluating Service Delivery Performance of Water Utilities in Kaduna State Water Board, Nigeria*; a PhD Dissertation submitted to the School of Post-Graduate Studies, Ahmadu Bello University, Zaria.

Alberta Environment (1977). *Alberta Surface Water Quality Objectives.* Water Quality Branch, Standards and Approvals Division. 17p.

Al-Mutaz, I. S., Al-Ghunaimi, M. A. and Al-Busaili, S. A. (1999). *pH Increase in Water Distribution Pipes*, IDA World Congress on Desalination and Water Re-Use, San Diego, USA.

American Journal of Water Resources, 2014, Vol. 2, No. 5, 110-117 Available online at http://pubs.sciepub.com/ajwr/2/5/2 © Science and Education Publishing DOI:10.12691/ajwr-2-5-2

American Water Works Association (1999). *Water Distribution Operator Training Handbook.* Denver, CO. http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2015].

American Water Works Association (2001). *Rehabilitation of Water Mains (M28).* Denver, CO. http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2015].

American Water Works Research Foundation (2000). *Guidance Manual for Maintaining Distribution System Water Quality*. Denver, CO http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2015].

Aral, M. M. (1996), *Estimating Exposure to Volatile Organic Compounds from Municipal Water-Supply Systems: Use of a Better Computational Model*. Archives of Environmental Health, 51, (4): 300-309

Areola, O.A. and Festus, O. (1997). *Manpower and Institutional Constraints on Urban Water Supply in Nigeria:* A case study of the northwest zone. GeoJournal, 43(2), 125 – 133.

AWWA Research Foundation, "*Advancing the science of water: AwwaRF and distribution system water quality"* [Online]Available: http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2013].

Besner J. (2001). "Understanding Distribution System Water Quality." *Journal of the American Water Works Association*. July, 101–114.

Biswas, P., Lu, C. and Clark, R. M. (1993). *A Model for Chlorine Concentration Decay in Pipes*. Water Research, 27(12):1715-1724

Bull, R. J. and Kopfler, R.C. (1991). *Health Effects of Disinfectants and Disinfection By-Products*. Denver, CO. American Water Works Association Research Foundation, 1991.

Chadwick, M., Boyd, M. J. and Cathers B. A. (2005). *A water quality modelling tutorial using Simulink* pg 487-491

Chambers, V. K. and Joy, J. S. (1993). *Validity of Modelling Chlorine Residuals in Distribution*, Technical Report UC 1942. WRc Swindon, Frankland Road, Blagrove, Swindon, Wilts. Apr.

Chen, W. J., Weisel, C. P. (1998). "Halogenated DBP Concentrations in a Distribution System". *Journal AWWA*, 90, (4): 151-162.

Clark R. M. (1994). *Measuring and Modelling Chlorine Propagation in Water Distribution Systems"*. Journal of Water Resources Planning and Management – ASCE, 120, (6): 871-887.

Clark, R. M., Grayman, W. M., Goodrich, J. A., Deininger, R. A. and Skov, K. (1994). Measuring and Modeling Chlorine Propagation in Water Distribution Systems. *Journal of Water Resources Planning and Management*, 120(6):871-887.

Clark, R. M. and Grayman, W. M. (1998). *Modeling Water Quality in Drinking Water Distribution Systems*. American Water Works Association, Denver, CO. http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2015].

Colin, F. and Grapin, G. (1991). *Design of a hydraulic and water quality model of a meshed distribution network: The case of chemical species in a single kinetics reaction. In Water Quality Modeling in Distribution Systems*. 141 – 153. Cincinnati, Ohio, American Water Works Association. http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2015].

Dandy, G., Mantopoulos, A., Qiu, M., Shizas, G. and Yao, Z.. (2013). *Advantages and Limitations of the Use of Water Age as a Surrogate for Water Quality in Water Distribution Systems.* [pdf slides], EWRI 2013, ASCE, Cincinnati, personal communication.

Dukan S., Levi Y., Piriou, P., Guyon, F and Villon, P. (2002). *Dynamic modelling of bacterial growth in drinking water networks*. Water Research, 30(9):1991-2002.

Frederick, K.D, "*America's water supply: status and prospects for the future", Consequences*, 1(1), 34 - 39, [Online] Available: http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 September, 2015].

Grayman, W.M. and Clark, R. M. (1990). *An overview of water quality modelling in a distribution system.* In the 1990 Annual conference Proceedings, pages 81 – 92, Cincinnati, Ohio, 1990. American Water Works Association.

Grayman, W. M. and Clark, R.M. (1993). *Using Computer Models to Determine the Effect of Storage on Water Quality.* Journal AWWA, 85, (7): 67-77.

Haestad Methods, Walski, T. M., Chase, D. V., Savic, D. A., Grayman, W. M., Beckwith, S. and Koelle, E. (2003). *Advanced Water Distribution Modeling and Management*. Haestad Press, Waterbury, CT.

Heraud, J., Kiene, L., Detay, M. and Levi, Y. (1997). Optimised Modelling of Chlorine Residuals in a Drinking Water Distribution System with a Combination of On-line Sensors. *Journal of Water Supply Research and Technology*. Aqua 46(2):59 – 70

http://www.nigerianmuse.com/20100527092749zg/sections/pictures-maps-cartoons/maps-of-various-states-and-their-local-governments-in-nigeria/

https://www.google.com.ng/search?client=ucweb-b-bookmark&ei=T7UPWvK9NsT4aoGltuAI&q=map+of+kaduna+town&oq=map+of+kaduna+state&gs_l=mobile-gws-serp.1.0.0i71k1l5.0.0.0.1563.0.0.0.0.0.0.0.0.0.0.1.64.mobile-gws-

Hunt, W. A. and Kroon, J. R. (1991). *Model calibration for chlorine residuals in distribution systems*. In Water Quality Modeling in Distribution Systems, 237 – 261. Cincinnati, Ohio, Feb. 1991. American Water Works Association.

John G.L. (2015). *Water and Sanitation Monitoring Platform (WSMP),* Nigeria: Nigeria Water and Sanitation Summary Sheet, 2015. http://www.gerio.org/CONSEQUENCES/sprint95/water.html. [Accessed 13 October, 2015]

Kaduna State Water Board, (2007). "Technical and Operational Report guidelines for water operations for Kaduna State Water Board".

Kansas, G. (2004) *"Assessment of Water Age and Quality in the Stamford, Connecticut Water Distribution System"*. Masters Dissertation. University of Massachusetts - Amherst.

Kirmeyer, B. (2001). *Practical Guidelines for Maintaining Distribution System Water Quality*. Journal of the American Water Works Association. July: 62–73. [Online] Available: http://www.waterrf.org/resources/StateOfTheScienceReports/DistributionSystemWaterQualityResearch.pdf.[Accessed 5 July, 2015].

Kofi, A (2012). *Modelling and Simulating Free Chlorine Decay using a Pilot Distribution System*; A Thesis submitted to the Department of Civil Engineering, Kwame Nkrumah University of Science and Technology.

Lahlou, M. Z, *"Water quality in distribution systems".* Tech. Brief: A National Drinking Water Clearing House Fact Sheet, 2002. Available: http://www.waterrf.org/resources/Factsheet/DistributionSystemWaterQualityFactsheet.pdf.[Accessed 5 June, 2015].

Langelier, W.F. (1946). *Effect of Temperature on the pH of Natural Waters,* Journal of the American Water Works Association 38, 179.

Lee, E. J and Schwab, K. J. (2005). "Deficiencies in drinking water distribution systems in developing countries", *Journal of Water and Health*, 3.2, 109-127.

Lei, J. and Saegrov, S. (1998). *Statistical Approach for Describing Failures and Lifetimes of Water Mains*. Water Science and Technology. 38:6:209 - 214.

Letterman, R. D. (1999). *Water Quality and Treatment: A Handbook of Community Water Supplies.* American Water Works Association, McGraw-Hill, Inc., New York, 3.12-3.13, 7.26-7.28.

Li, X., Gu, D. M., Qi, J.Y., Ukita, M., and Zhao, H. B. (2003). *Modelling of Residual Chlorine in Water Distribution System.* Journal of Environmental Science – China, 15, (1): 136-144.

Liou, C. P. and Kroon, J. R. (1987). Modeling the propagation of waterborne substances in distribution networks. *Journal of the American Water Works Association*, 32(3): 54 – 58.

Mark, W. L., Evans, T. M. and Ramon, J. S. (1980). *Effect of Turbidity on Chlorination Efficiency and Bacterial Persistence in Drinking Water*. Journal on Applied and Environmental Microbiology, July, 42 (2), 159-167 DOI:10099-2240/81/070159-09$02.00/0..

Mays, L. W (2000). *Water Distribution System Handbook*, Mc-Graw Hill, New York, USA. 2nd Edition.

McClellan, J. (2000) *Modeling Chlorine Decay and Chlorination By Product Formation in Water Treatment and Distribution*. Doctoral Dissertation. University of Massachusetts-Amherst.

Michael, L. (2002). *Water Quality in Distribution Systems*. A National Drinking Water Clearinghouse Fact Sheet. Available: http://www.waterrf.org/resources/Factsheet/DistributionSystemWaterQualityFactsheet.pdf.[Accessed 5 June, 2015]

National Academy of Science/National Academy of Engineering (NAS/NAE, 1972). *Water Quality Criteria.* A Report of Committee on Water Quality Criteria. Washington, D.C. 594 p.

National Population Commission (2006). *2006 Population and Housing Census of the Federal Republic of Nigeria*. 1(1), 23 – 25.

Obeta M.C., Nwankwo, C.F. (2015). "Factors Responsible for Rural Residential Water Supply Shortage in south Eastern Nigeria". *Journal of Environmental Geography*. 8(3-4):21-32.

Onjali, J., (2002). *Good intentions, structural pitfalls: Early Lessons from Urban Water Commercialization Attempts in Kenya*. Centre for Development Research, Copenhagen.

Regli, S. (2003). *Intent of the D/DBP Rule and Regulatory Framework,* Proceedings of the AWWA Satellite Teleconference: Disinfection and Disinfection-By-Products: Understanding the Proposed D/DBP Rule: Participant Guide, AWWA, Denver, CO.

Rodriguez, M. J., Serodes, J. B. (2001) *Spatial and Temporal Evolution of Trihalomethanes in Three Water Distribution Systems*. Water Research, 35(6): 1572-1586.

Rossman L. A., Brown, R. A., Singer, P. C. and Nuckols, J. R. (2001). *DBP Formation Kinetics in a Simulated Distribution System.* Water Research, 35, (14): 3483-3489.

Rossman, L.A. (2000). *EPANET Version 2 User's Manual*, Drinking Water Research Division, EPA, Cincinnati, OH. 2000.

Rossman, L.A. (1993). The EPANET water quality model. In B. Coulbeck, editor. *Integrated computer applications in Water supply; Applications and Implementations for Systems Operation and Management,* 2(2), *79, 93.* Research Studies Press Ltd., Taunton, England.

Rossman, L. A., and Boulos P. F. (1996). "Numerical Methods for Modeling Water Quality in Distribution Systems: A Comparison." *Journal Water Resources Planning and Management*, ASCE, 122(2):137-146.

Sadiq, R. and Rodriguez, M. J. (2004). *Disinfection By-Products (DBPs) in Drinking Water and Predictive Models for their Occurrence: A Review.* Science of the Total Environment, 321, (1 – 3): 21 – 46.

Sarbar, M. A. (1992). *Carbon Dioxide and Weak Acid Content of Wasia Water:* Proceedings of the International Conference on Chemistry in Industry, Bahrain, Nov. 3(2), 14-16.

Sharp, W. W., Pfeffer, J. and Morgan, M. (1991). *Insitu chlorine decay rate testing. In Water Quality Modeling in Distribution Systems*, 311 – 321, Cincinnati, Ohio, American Water Works Association.

Singer, P.C. (2003). *"Formation and Fate of DBPs in Distribution Systems".* Presented at the 2003 Water Quality Technology Conference- Workshop 2: Preparing for the.-Initial Distribution System Evaluation (IDSE). A WW A, 2003.

Sudeshna Banerjee, Vivien, F., Yvonne Y., Healther S, and Quentin W. (2008). *"Cost of Recovery, Equity and Efficiency in Water Tariffs: Evidence from African Utlities".* African Infrastructure Country Diagnostic. World Bank. P.5

Ohwo, O. (2014). *The Impact of Pipe Distribution Network on the Quality of Tap Water in Ojota, Lagos State, Nigeria*. A Seminar Paper presented at the Department of Geography and Environmental Management, Faculty of Social Sciences, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria.

The MathWorks, Inc. (2015). *Simulink® User's Guide*, 3 Apple Hill Drive Natick, MA 01760-2098.

United Nations Development Programme (2003). *A Strategy for Water Sector Capacity Building Proceedings of the UNDP Symposium*, Delft, (IHE Report Series 24). New York.

US Environmental Protection Agency (2005). Water Distribution System Analysis: Field Studies, Modeling and Management EPA/600/R-06/028 December 2005

USAID, 2007: *Nigeria Water and Sanitation Profile*, ca.

Vanguard Newspaper. *"Lagos: Water everywhere but none to drink*: pp. 3 April 2012. Accessed 18 November 2017

Wable, O., Dumoutier, N., Duguet, J. P., Jarrige, P. A., Gelas, G. and Depierre, J. F. (1991). *Modelling chlorine concentrations in a network and applications to Paris distribution system.* In Water Quality Modeling in Distribution Systems, pages 77 – 87, Cincinnati, Ohio, Feb. American Water Works Association.

Walski, T. M. (1983). *Technique for calibrating network models*. J. Water Res. Pl.-ASCE, 109(4), 360-372

Water Utility Partnership (WUP) Africa (2003). *Better water and sanitation for the Urban Poor- Good Practice from Sub – Sharan Africa*, WSP and WUP, Cote d'Ivoire.

WHO (1997). *Guidelines for drinking-water quality*, 2nd Edition, Volume 3.

WHO (2003) *Guidelines for drinking water quality,* 3rd ed., WHO, Geneva.

WHO (2004) *Guidelines for drinking water quality,* 4th ed., WHO, Geneva.

WHO and UNICEF Joint Monitoring Programme (JMP) (2006). *Water Supply and Sanitation:* 2006 Update, WHO, Geneva. ISBN 978 92 3124395 6.

WHO and UNICEF Joint Monitoring Programme (JMP) (2010a). *Progress on Sanitation and Drinking Water:* 2010 Update, WHO, Geneva. ISBN 978 92 4156395 6.

WHO and UNICEF Joint Monitoring Programme (JMP) (2010b). *Water Supply and Sanitation*, WHO, Geneva. ISBN 978 92 4156395 6.

WHO and UNICEF Joint Monitoring Programme (JMP) (2015). *Water Supply and Sanitation:* 2015 Update, WHO, Geneva. ISBN 978 92 4176834 5.

World Bank (2010). *New Project to Bring Clean Water to 50,000 Households*. 22 April 2010.

World Bank/Federal Republic of Nigeria, (2012). *Water Supply and Sanitation Interim Strategy Note*, November 2000, retrieved on April 11, 2012.

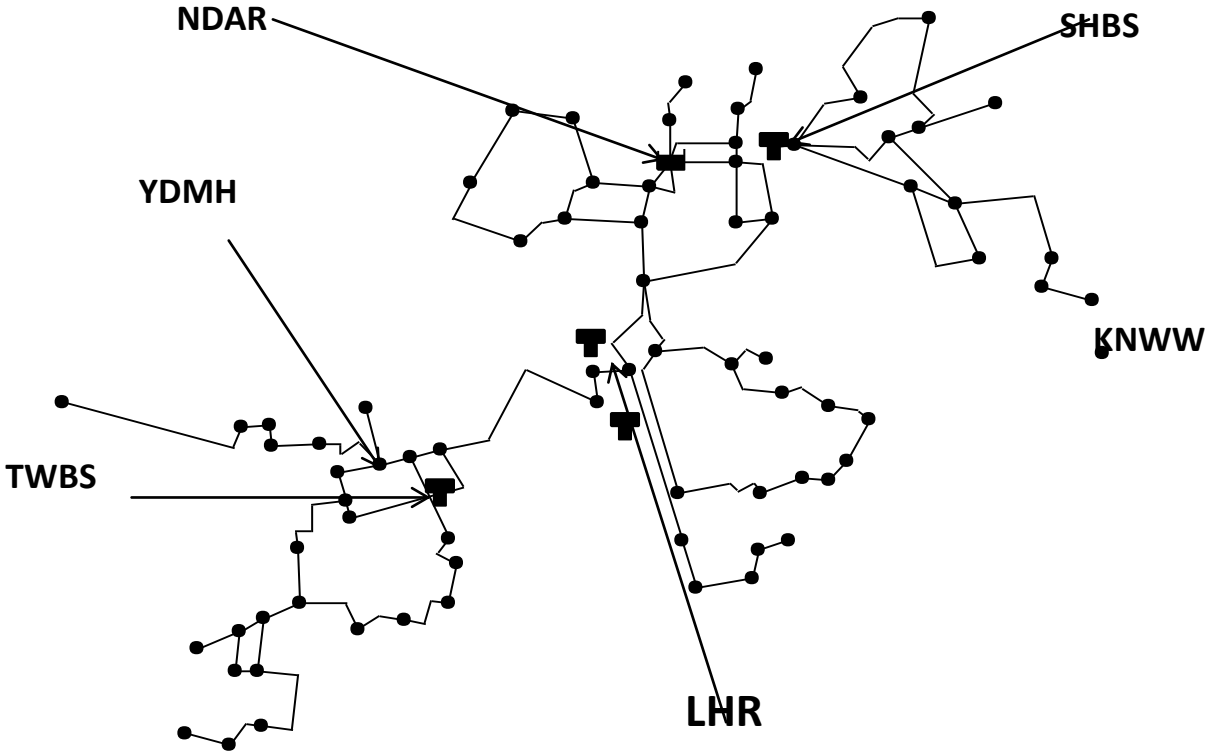
World Water Council, "Water supply and sanitation" 2005 [Online] Available: http://www.worldwatercouncil.org/index.php?id [Accessed 13 November, 2007].

Daily Trust Newspaper. *Yobe charges least water tariff in Nigeria*. 7 October 2010. Accessed 18 November 2017.

APPENDICES

Appendix 1

Schematic of Kaduna Metropolis Water Distribution Network (showing sampling points)



LEGEND:

KNWW – Kaduna North Water Works

LHR – Lugard Hall reservoir

SHBS – State House Boosting Station

NDAR – NDA Reservoir

TWBS – Tudun Wada Boosting Station

YDMH – Yusuf Dantsoho memorial Hospital

Appendix 2

Pump Capacities of KNWW

Pump Capacity for Old Treatment Plant

Low lift pumps (for abstraction)

50 MLD Section (Pre-settling Pumps)

Pump 1 – 1051cm^3/hr (B3)

Pump 2 – 1174 cm^3/hr (B2)

Pump 3 – 1150 cm^3/hr (B1)

40 MLD Section (Balancing Pumps)

Pump 4 and 5 (Meregalli) - 1800 cm^3/hr

Pump 6 and 7 - 936 cm^3/hr (B4 and B5)

Pump Capacity for New Treatment Plant

Low lift pumps (for abstraction)

4 pumps of 75 MLD

2 pumps of 50 MLD

1 pump of 25 MLD

High lift pumps (for distribution)

4 pumps of 1190 cm^3/hr

2 pumps of 566 cm^3/hr

2 pumps of 1400 cm^3/hr

Appendix 3

Average Water Quality Data for KNWW Final Water (2011)

S/N	Parameters	Average Value	NSDWQ Standard
1	Turbidity (NTU)	9.41	0 – 5.0
2	pH Value	6.60	6.5 – 8.5
3	Conductivity µS/cm at 25^0C	22.20	1000 (Max.)
4	Chlorides as Cl mg/L	15.99	250
5	Nitrates as N mg/L	Nil	10
6	Bicarbonate Alkalinity as $CaCO_3$ mg/L	22.00	
7	Carbonate alkalinity as $CaCO_3$ mg/L	0	
8	Total alkalinity as $CaCO_3$ mg/L	22.00	
9	Total hardness as $CaCO_3$ mg/L	42.00	150
10	Total Iron as Fe mg/L	0.13	0.5
11	Silica as SiO_2 mg/L	0.10	
12	Sulphate as SO_4	3.0	250
`13	Free CO_2 mg/L	26.00	
14	Calcium mg/L	30.00	100
15	Total dissolved solid mg/L	13.05	250
16	Ammonium (NH_4^+)	0	0.5

Average Water Quality Data for KNWW Final Water (2012)

S/N	Parameters	Average Value	NSDWQ Standard
1	Turbidity (NTU)	9.5	0 – 5.0
2	pH Value	5.3	6.5 – 8.5
3	Conductivity µS/cm at 25^0C	59.04	1000 (Max.)
4	Chlorides as Cl mg/L	19.99	250
5	Nitrates as N mg/L	0.01	10
6	Bicarbonate Alkalinity as $CaCO_3$ mg/L	14	
7	Carbonate alkalinity as $CaCO_3$ mg/L	0	
8	Total alkalinity as $CaCO_3$ mg/L	14	
9	Total hardness as $CaCO_3$ mg/L	14	150
10	Total Iron as Fe mg/L	0.08	0.5
11	Silica as SiO_2 mg/L	0.8	
12	Sulphate as SO_4	11	250
`13	Free CO_2 mg/L	12.0	
14	Calcium mg/L	10.0	100
15	Total dissolved solid mg/L	20.16	250
16	Ammonium (NH_4^+)	0	0.5

Average Water Quality Data for KNWW Final Water (2013)

S/N	Parameters	Average Value	NSDWQ Standard
1	Turbidity (NTU)	9.47	0 – 5.0
2	pH Value	5.6	6.5 – 8.5
3	Conductivity µS/cm at 25^0C	49.004	1000 (Max.)
4	Chlorides as Cl mg/L	21.99	250
5	Nitrates as N mg/L	0.01	10
6	Bicarbonate Alkalinity as $CaCO_3$ mg/L	24	
7	Carbonate alkalinity as $CaCO_3$ mg/L	0	
8	Total alkalinity as $CaCO_3$ mg/L	25	
9	Total hardness as $CaCO_3$ mg/L	21.4	150
10	Total Iron as Fe mg/L	0.134	0.5
11	Silica as SiO_2 mg/L	0.672	
12	Sulphate as SO_4	13.7	250
`13	Free CO_2 mg/L	25.7	
14	Calcium mg/L	19.9	100
15	Total dissolved solid mg/L	30.1	250
16	Ammonium (NH_4^+)	0	0.5

Average Water Quality Data for KNWW Final Water (2014)

S/N	Parameters	Average Value	NSDWQ Standard
1	Turbidity (NTU)	10.4	0 – 5.0
2	pH Value	6.64	6.5 – 8.5
3	Conductivity µS/cm at 25^0C	89.004	1000 (Max.)
4	Chlorides as Cl mg/L	30.99	250
5	Nitrates as N mg/L	0.01	10
6	Bicarbonate Alkalinity as $CaCO_3$ mg/L	32	
7	Carbonate alkalinity as $CaCO_3$ mg/L	0	
8	Total alkalinity as $CaCO_3$ mg/L	28	
9	Total hardness as $CaCO_3$ mg/L	27.4	150
10	Total Iron as Fe mg/L	0.13	0.5
11	Silica as SiO_2 mg/L	0.62	
12	Sulphate as SO_4	14.2	250
`13	Free CO_2 mg/L	27.7	
14	Calcium mg/L	20.6	100
15	Total dissolved solid mg/L	29.16	250
16	Ammonium (NH_4^+)	0	0.5

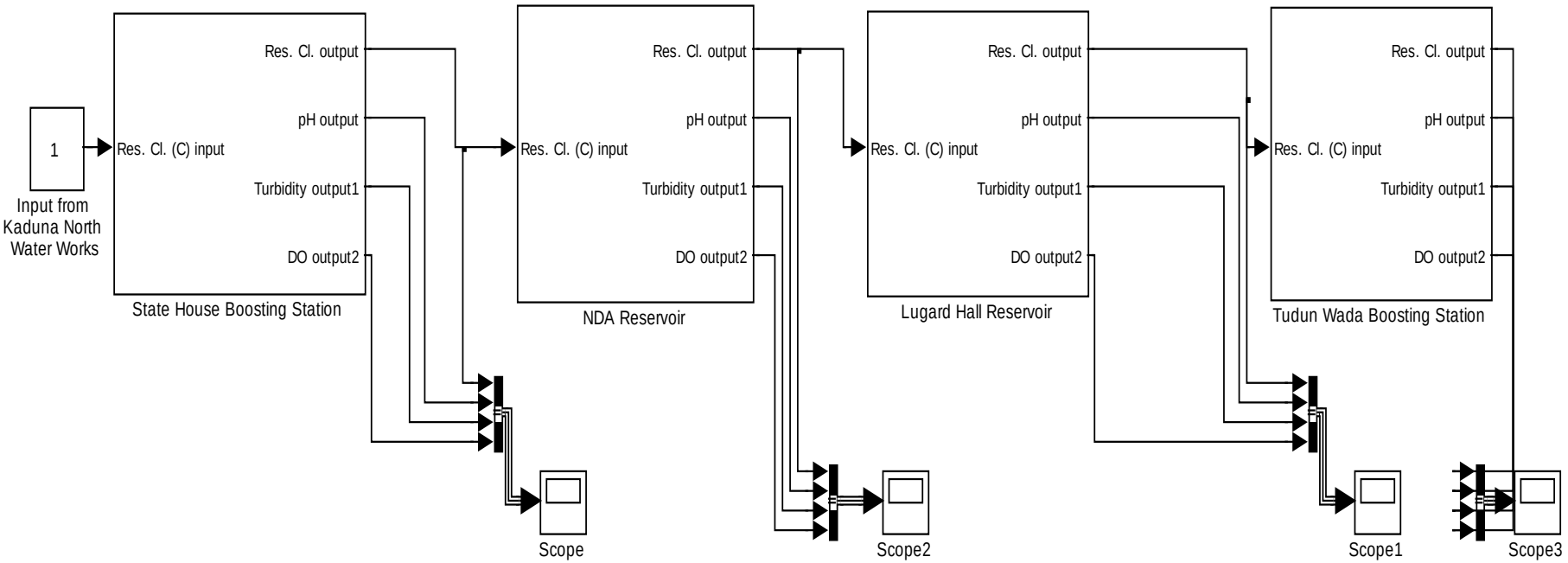
Average Water Quality Data for KNWW Final Water (2015)

S/N	Parameters	Average Value	NSDWQ Standard
1	Turbidity (NTU)	9.4	0 – 5.0
2	pH Value	5.60	6.5 – 8.5
3	Conductivity µS/cm at 25^0C	59.0	1000 (Max.)
4	Chlorides as Cl mg/L	20.0	250
5	Nitrates as N mg/L	0.02	10
6	Bicarbonate Alkalinity as $CaCO_3$ mg/L	28	
7	Carbonate alkalinity as $CaCO_3$ mg/L	0	
8	Total alkalinity as $CaCO_3$ mg/L	26	
9	Total hardness as $CaCO_3$ mg/L	25.4	150
10	Total Iron as Fe mg/L	0.14	0.5
11	Silica as SiO_2 mg/L	0.52	
12	Sulphate as SO_4	15.2	250
`13	Free CO_2 mg/L	25.78	
14	Calcium mg/L	19.9	100
15	Total dissolved solid mg/L	29.16	250
16	Ammonium (NH_4^+)	0	0.5

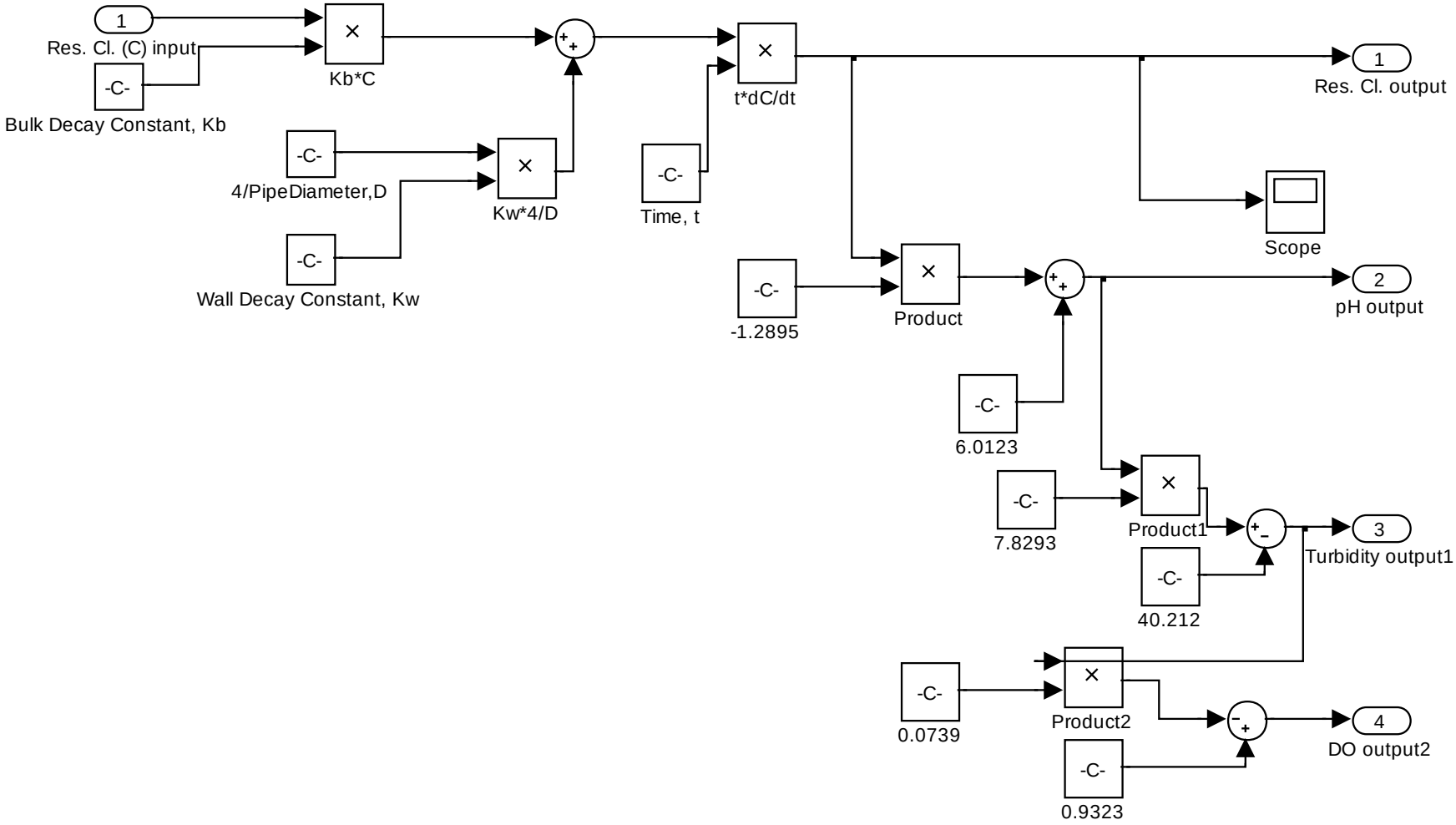
Appendix 4

Model Structure

Subsystems



Model Substructure



Appendix 5

Tabular Comparison of Average Observed Water Quality Parameter Measurements and SIMULINK Model Results

Residual Chlorine (mg/L)

Sampling points	Observed	Modelled
KNWW	0.23	0.23
SHBS	0.17	0.15
NDAR	0.11	0.12
LHR	0.05	0.03
TWBS	0.04	0.02
YDMH	0	0

pH

Sampling points	Observed	Modelled
KNWW	5.7	5.4
SHBS	5.8	5.6
NDAR	5.9	5.6
LHR	5.9	5.7
TWBS	6	5.8
YDMH	6	5.9

Turbidity

Sampling points	Observed	Modelled
KNWW	4.9	4.6
SHBS	5.2	4.7
NDAR	5.7	5.4
LHR	4.8	4.5
TWBS	7	6.5
YDMH	7.5	7

Dissolved Oxygen

Sampling points	Observed	Modelled
KNWW	0.6	0.3
SHBS	0.5	0.2
NDAR	0.5	0.3
LHR	0.6	0.3
TWBS	0.4	0.1
YDMH	0.4	0.1

Appendix 6

LEAKAGE SITES AND GPS LOCATIONS



Plate II: Leakage at Kawo ($10^0$19’23.5” N and $7^0$13’12.2”E)



Plate III: Leakage at Tudun wada ($10^0$29’13.5” N and $7^0$13’11.2”E)