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**DIRECTORATE OF RESEARCH AND
GRADUATE TRAINING**

**ASSESSMENT OF VARIATION IN TREATED WATER QUALITY AND
LINKAGE TO POSSIBLE INTRUSION OF CONTAMINANTS IN MAKINDYE
DIVISION, KAMPALA, UGANDA**

BY

PAMELA TWINE

(B. Eng. Civil and Building-KyU)

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OCTOBER 2022

DECLARATION

I, PAMELA TWINE, hereby declare that this dissertation is submitted as my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree of the University or other institute of higher learning, except where due acknowledgement has been made in the text and reference list.

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by Kyambogo University a dissertation titled: **“Assessment of variation in treated water quality and linkage to possible intrusion of contaminants in Makindye division, Kampala, Uganda”**, in partial fulfilment of the requirements for the award of a degree of Master of Science in Water and Sanitation Engineering of Kyambogo University.

Sign.....

Dr. CHARLES ONYUTHA (Supervisor)

Date.....

Sign.....

Eng. Dr. ANNE NAKAGIRI (Supervisor)

Date.....

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LIST OF ACROYNMS

AWWA	American Water Works Association
CAWST	Centre for Affordable Water and Sanitation Technology
CESCR	Committee on Economic Social and Community Rights
DC	Direct connection
DPD	Diethyl-p- Phenylene-Diamine
EPA	Environment Protection Agency
GWTP	Ggaba Water Treatment Plant
IREC	International Resource Centre
NWSC	National Water and Sewerage Corporation
NTU	Nephelometric Turbidity Unit
OECD	Organization for Economic Co-operation and Development
pH	Potential of Hydrogen
PtCo	Platinum-Cobalt Units
PSPs	Public Stand Posts
SDG	Sustainable Development Goals
SPSS	Statistical Package for Social Scientists
ST	Storage Tanks
UIRI	Uganda Industrial Research Institute
WHO	World Health Organization

ABSTRACT

Good drinking water quality is essential for human well-being. However, water quality in the distribution network tends to be affected at points of leakages through intrusion by pathogens. Maintenance of water tanks also tends to be very irregularly undertaken. The study was carried out through field surveys and data collection. This study aimed at assessing the extent to which the variation in treated water quality could be linked to possible intrusion of contaminants. Makindye Division, Kampala, Uganda was selected as the case study.

The study had three specific objectives including: i) assessment of temporal variation in water quality parameters, ii) investigating variation of water quality parameters in space, and iii) determining the possibility of intrusion of contaminants along distribution networks. The research utilised both primary and secondary data for the distribution and storage tanks. With help of the Cochran formula, a sample size was obtained. For primary data, Samples were collected utilizing both Insitu and laboratory measurements for both direct connections and storage tanks. A questionnaire was also used to obtain data from the selected households and direct connections with analysis done in Excel.

In objective 1, Turbidity was found to increase with time from 2015 to 2019 at a rate of 0.145NTU per year. The highest turbidity values were obtained in 2018. Colour increased at a rate of 1.18PtCo per year. Residual chlorine for the period 2015-2018 had an increasing trend at a rate of 0.0247mg/l/yr and was found highest in 2018. The month of March recorded the highest residual chlorine while the month of May recorded the lowest residual chlorine. pH was found to fall within the standard limits of 6.5 – 8.5. However, over the period 2015 to 2019, pH exhibited a decreasing trend at a rate of -0.032 per year.

In objective 2, the mean values of turbidity in water sampled from direct connections and storage tanks were 0.76 ± 0.38 NTU and 5.96 ± 3.8 NTU respectively. The average colour of water from the direct connections was 8 ± 4.1 PtCo while that of the storage tanks had 57 ± 20.5 PtCo. Colour of water from the direct connections and storage tanks showed significant differences with $p = 1.74333E-10$. The mean of residual chlorine in water sampled from direct connections was found to be 0.56 ± 0.16 mg/l while that from storage tanks was 0.25 ± 0.13 mg/l. Using the *t*-test, these mean values were found to be significantly different ($p < 0.05$).

In objective 3, the number of people who do not clean their tanks in the study area was found to be 58% of the study population. Those who clean their water storage tanks after one year or six months was found to constitute 43% of the sampled water users. Water storage tanks

which are not cleaned or regularly maintained can be a potential source of contamination of water at consumer points. There was a significant difference ($p<0.05$) between the water quality in the distribution network and at draw off points for most of the parameters attributed to factors like; approximate of drainage systems (35%), toilets (30%), garbage pits (25%) and main road (48%). The number of leakages in the study area between 2016 and 2019 was found to be 4852 which exhibited a positive trend at a rate of 42 leakages per year. Whereas the significant difference ($p<0.05$) between water in the storage tanks and direct connection draw offs could have been due to leakages, none routine cleaning of storage tanks and the use storage tanks without covers. Kawuku and Soya villages were the most affected areas in terms of water quality distributed to them and this could be attributed to the connection on the dead end of the pipes. Leakage monitoring and management should be prioritized with constant sensitization of water users on how to clean tanks and maintain good water quality.

Key words; Trend, water quality, water pollution, pipe leakages, water contamination.

1 CHAPTER ONE: INTRODUCTION

1.1 Background

Good drinking water quality is essential for human well-being. Therefore, improved water quality is a critical element of the 2030 Sustainable Development Goals (SDGs), fulfilling an essential role in reducing poverty and disease and promoting sustainable growth (Organisation for Economic Co-operation and Development OECD, 2017). Water is a very important resource for humans as it forms 50% to 60% of our body weight and plays a vital role in the body metabolic processes (Abed and Alwakeel, 2007). Generally, safe drinking water is a basic need for good health and a basic right of humans (Muhammad et al., 2013). Furthermore, the importance of water to human health and wellbeing is encapsulated in the Human Right to Water and Sanitation, which entitles everyone to “sufficient, safe, acceptable physically accessible and affordable water for personal and domestic uses” (Committee on Economic, Social and Cultural Rights - CESCR, 2003). Drinking water should be ensured to have good quality to avoid possible infections to consumers. Contaminants may appear in drinking water as a result of failures in the well field, water treatment system or the distribution network (Nygard et al., 2007; Henderson et al., 2009; Richardson et al., 2009).

Efforts to achieve availability of safe water have been frustrated by the recent water pollution trends in most of the water sources all over the world (National Water and Sewerage Corporation - NWSC, 2018). Therefore, to improve the quality of water and make it accessible, there is a need for treatment prior to distribution (Charisiadis et al., 2015). Even after treatment of the water, most domestic and industrial potable water supplies continue to deteriorate in quality before getting to the consumer premises either as a result of pollutants introduced directly into the network from the treatment plant or from bacteria growing on the pipe walls which are later released into the flowing water through joint leakages and breakages (Awopetu et al., 2013). This greatly impacts on the quality of water received by people and could result into hygiene related illnesses. Generally, drinking water distribution systems are vulnerable to external contaminant entry if there is loss of physical integrity like cracking in pipes. This is mainly driven by failure to maintain an adequate pressure in the distribution system. Low and negative pressure events have the potential to result in intrusion of pollutants (Chiara et al., 2015).

Microbiological and physicochemical water qualities can be used to define water quality in a distribution network. These characteristics are often kept within an acceptable range, which is

determined by higher and/or lower bounds. Each water quality characteristic includes several water quality indicators. The overall acceptability of water quality for its intended use is determined by the size of these indicators, which are frequently limited by rules and recommendations. A water quality failure is defined as a breach of one or more water quality indicators' regulations (or recommendations or self-imposed restrictions).(Sadiq et al., 2006).

In Uganda, the NWSC, a government parastatal formed by Decree No. 34 of 1972 and later re-established by the NWSC Act, Cap.317 (1995), is obliged to run and deliver water and sewerage services in regions committed to it by the Water Act, Cap. 152. In order to match the demand, NWSC has broadened its service coverage levels for water and sewerage services currently stand at 71.6% and 6.4%, respectively (NWSC, 2018). However, the corporation continues to face a lot of challenges such as non-revenue water, breakdowns, power outages and many others that all affect service delivery. Most of these challenges come as a result of minimal attention accorded to the distribution systems. In general, the integrity of well-managed distribution networks is one of the most crucial hurdles to contaminant-free drinking water (World Health Organisation-WHO, 2014a). To handle such challenges NWSC has the water quality management department whose mandate is to ensure that customers receive safe water. The staff in that department take samples along the entire water supply chain from the source up to the customer premises including markets and other public places. (NWSC, 2018).

The success of a piped water supply system is generally measured by its ability to provide adequate volumes of safe and portable drinking water to all water users. This can be achieved by carrying out source-to-tap audits most especially the analysis of historical water quality and quantity data, evaluation of treatment system effectiveness, investigation of customer satisfaction, evaluation of monitoring and reporting practices, and an assessment of the future sustainability of the water supply (Vilanova, 2015). In general, water quality metrics can change with time and distance (Caccia and Boyer, 2005). It was therefore imperative to examine the spatial and temporal variation in water quality of already treated (potable) water in the distribution network and also at various consumer points a distance away from the treatment plant within Makindye division, Kampala District since the water treatment plant is in the same area. The study area was prone to high unplanned urbanization and poor solid waste management. This enabled identification of key positions where the quality of water was not desirable and remedial actions recommended.

1.2 Problem statement

The world is covered by 70% water, yet access to safe drinking water is still at bay. According to WHO (2011), more than 780 million people worldwide lacked access to improved drinking water despite the fact that water sources in some areas are improved. This is mainly due to contamination at various stages of water supply such as: abstraction, treatment, transmission, distribution and draw off points. Through five pathways intrusion, regrowth, internal corrosion / leaching and permeation, exceptional of breakthrough, water quality tends to be affected. Furthermore, water quality can also be affected by pipes, either through pipe material type, size, structural condition, hydraulic / operational conditions and/or inner surface degradation (Sadiq et al., 2006).

Water quality in a water distribution system is of concern to water utility operators, public health officials, and populations using the water (MWE, 2018). According to the results of a World Bank survey, about 15 % of treated water is lost annually from the water distribution systems in developed countries, and an average of 35 % and even as high as 60 % of the treated water is lost in developing countries. This is attributed to leakages, bursts from networks' aging and other phenomena causing damage to the network's infrastructure and possibly water losses. Leakages represent an economic, environmental and sustainability issue with consequences to the health safety of the consumers

In Uganda, the situation is not any different. Despite the quality control measures carried out at Ggaba Water Treatment Plant (GWTP) so as to supply safe drinking water, there have been incidences of colored water received in various zones in Kampala District and this could be an indicator of contamination. In addition, NWSC water quality monitoring results over the years show slight variations in the water quality parameters of untreated and piped water at various consumer points in Kampala. These variations could be due to contamination that occurs mainly during distribution stemming from leakages. The situation is worsened as these specific points of contamination cannot be easily traced due to the fact that pipes are under the ground. In addition, variations in colour of water could be even associated to more serious issues such as, presence of residual chlorine and excessive iron.

Exposure and consumption of contaminated water could result into problems like cholera to humans. Understanding the characteristic variation in piped water at selected households would therefore pave way towards providing safe water to residents.

1.3 Study objectives

1.3.1 Main objective

The main objective of the study was to assess the variation in treated water quality and the linkage to possible intrusion of contaminants along the distribution network and at the consumption points in Makindye division, Kampala Uganda

1.3.2 Specific objectives

In order to achieve the main aim, the specific objectives were;

- i). Investigating of temporal variation of treated water characteristics along the distribution network.
- ii). Assessing spatial and temporal variation of treated water characteristics at the draw off points and customer tanks.
- iii). Determining the possibility of intrusion of contaminants along the distribution network and consumer points.

1.4 Research questions

- i). What are the water quality characteristics along the distribution network?
- ii). What are the water quality characteristics at the draw off points?
- iii). Is there a difference in the quality of water from consumer points and that from distribution networks?

1.5 Research justification

Water quality has become a growing concern in Uganda, with human activities such as inadequate wastewater management, open defecation, garbage dumping, chemical spills at industrial sites, and poor agricultural practices, despite the presence of natural contaminants, threatening access to safe water (CAWST, 2013). According to current estimates, the amount of accessible water in emerging countries of South Asia, the Middle East, and Africa is quickly diminishing, while water quality is rapidly degrading owing to increased urbanization, deforestation, and land degradation (Muhammad et al., 2013). This shifting land use from forests and other green uses to developed environments puts strain on the current water delivery infrastructure in a variety of ways. These methods include, among others, inadequate solid waste and faecal sludge management and slum development. As a result, this study is critical for decision makers like NWSC to develop strategies to optimize the distribution network while also maximizing quality for the end customer.

With ever-increasing urbanization, a lack of appropriate water quality monitoring at consumer points will lead to increased consumption of low-quality water. Consumers are at risk of receiving low quality water due to many pipe leaks and an aged pipe network, as well as a lack of effective faecal and solid waste disposal. With this study, NWSC and other relevant authorities will be able to identify pollutant incursion and suggest mitigation measures.

1.6 Significance

The study's relevance was to identify the places with the greatest impact on water quality. Where a damaged region is identified, a course of action to restore water quality can be implemented. To raise awareness about the importance of frequent water storage tank maintenance. If the quality of water in the distribution network differs considerably from that at the consumer locations, suitable corrective steps can be done. SDG 6 seeks to provide universal access to water and sanitation. By 2030, Uganda's Vision 2040 aims to establish universal and equitable access to clean and cheap drinking water for all. This will be monitored through increasing the percentage of safe water supply coverage and increasing the percentage of safe urban water supply. Therefore, through this research Vision 2040 will be achieved through identifying areas that need improvement in water distribution.

The study will be availed to the relevant universities like Kyambogo University in order to add knowledge to the already existing bank full of knowledge. The findings of the study will further help other researchers in coming up with alternative ways of reducing contaminant intrusion in the water supply system ranging from the treatment to end user.

1.7 Project scope

1.7.1 Time

The research was conducted from June to August 2019.

1.7.2 Geographical coverage

The research was carried out in Ggaba parish, Makindye Division Kampala-Uganda because the water treatment plant is in the same area/division. This would give a clear picture of the far areas served by the water treatment plant. This would enabled identification of key positions where the quality of water was not desirable and remedial actions recommended.

1.7.3 Content

The study focused on assessment of the extent to which the variation in treated water quality (Turbidity, Colour, Residual Free Chlorine, pH, Conductivity, E-coli, Faecal coliforms and

Total Suspended Solids) over time could be linked to possible intrusion of contaminants at various points in the network (distribution and consumer drawoff points) in Ggaba parish, Makindye Division Kampala-Uganda. The project area was delineated and mapped using ARCGIS 10.7 (Figure 1-1).

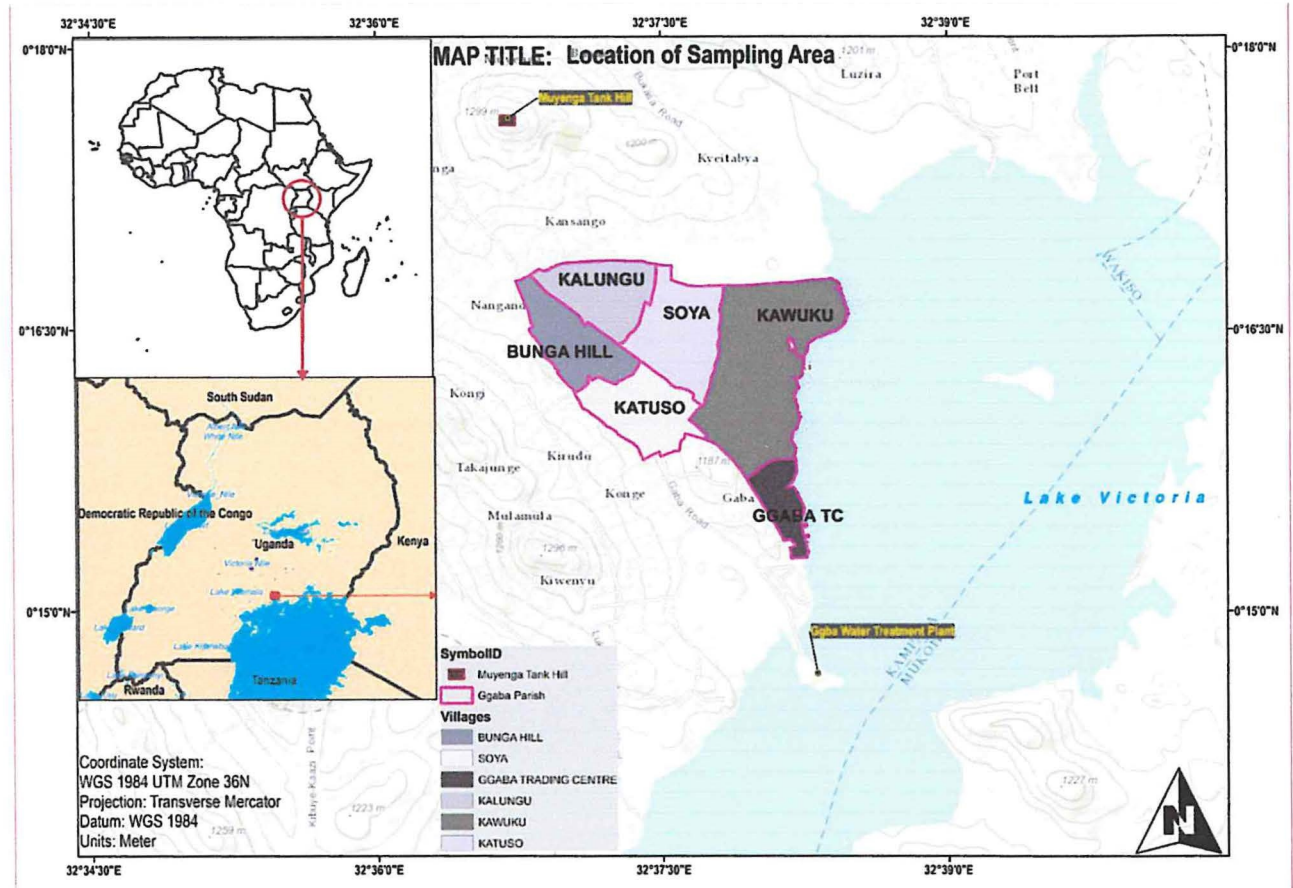


Figure 1-1: Location of project area

1.8 Conceptual model

The conceptual model was designed to aid with showing what we would expect to find in the different sampling points. The model clearly defined the independent variables, dependent variables and intermediate variables. The independent variables are time and location which will determine the temporal and spatial variations respectively. The intermediate variables include: water quality standards, treatment process, distribution network, storage process, Pipe material and aging and contaminant intrusion mechanism. These intermediate variables affect the water quality characteristics received by the consumer over time and distance from the source of water.

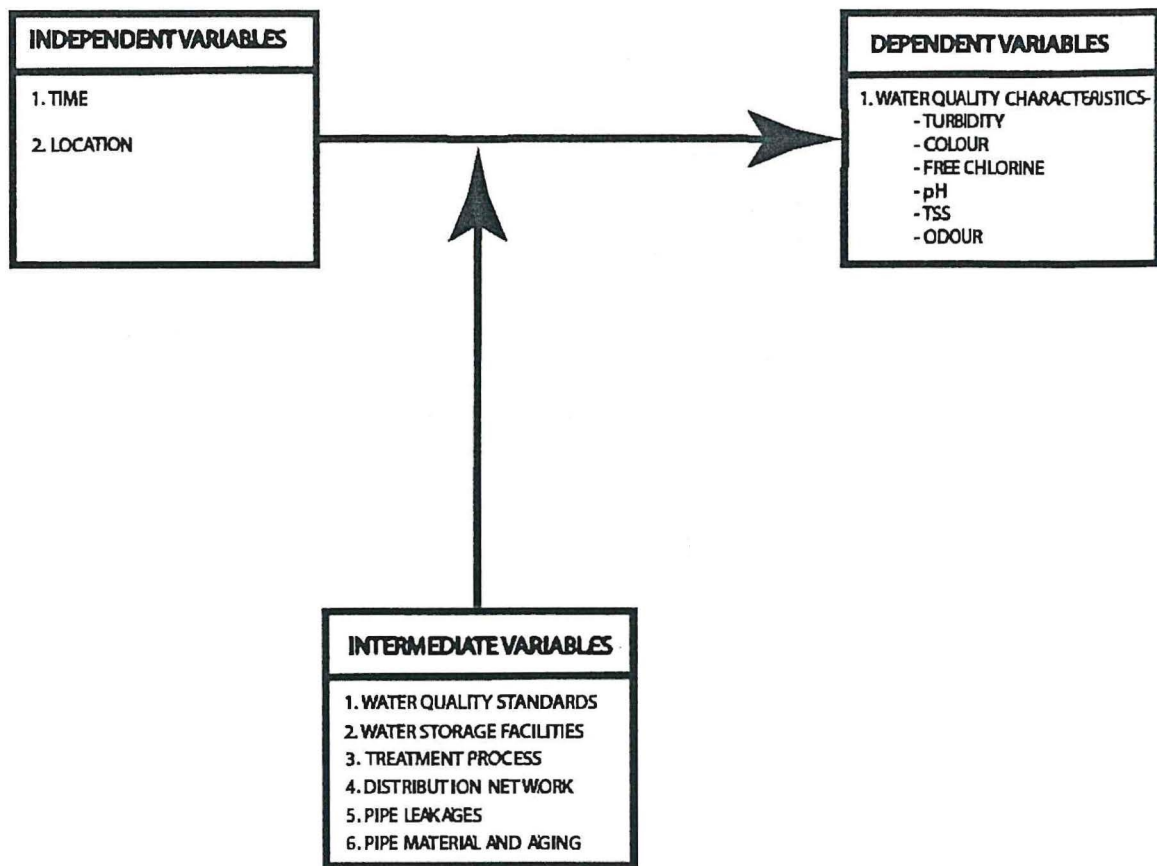


Figure 1-2: Conceptual framework of the study

1.9 Chapter summary

This chapter has provided an overview of water pollution in Kampala- Uganda against the study objective of assessing the extent to which the variation in treated water quality over time in Ggaba parish, could be linked to possible intrusion of contaminants at various points in the network.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Water resource availability and quality are critical to long-term economic development, particularly in developing countries. Where the industrial sector is underdeveloped or weak, water consumption might reach up to 80%. (Shi et al., 2014). This lends credence to water's sociopolitical role in the economic growth of various locations throughout the world. The importance of water to these places is reflected in the water sector's vision in various locations (Meissner and Mampane, 2015).

Water is extremely important to humans, as stated in the Human Rights to Water and Sanitation. This gives everyone the right to "appropriate, economical, safe, physically accessible, and adequate for personal and household usage." (United Nations, 2004). However, a large portion of global water exists in oceans, which are generally not suitable for drinking, and only 3% is fresh water, with 2.97 percent of it in the form of glaciers and ice caps, which are therefore inaccessible, and the remaining 0.3 percent is the only readily available as surface and ground water for human use (Balasubramanian, 2017). This undermines the premise that persons have a right to water by obstructing efforts to provide acceptable, inexpensive, safe, physically accessible, and enough water for personal and household use.

Even the accessible fresh water sources have continuously been threatened by pollution. While water contains natural contaminants, it is becoming more and more polluted by human activities, such as inadequate wastewater management, open defecation, dumping of garbage, chemical spills at industrial sites and poor agricultural practices (CAWST, 2013). According to current estimates, the amount of accessible water in emerging countries of South Asia, the Middle East, and Africa is quickly diminishing, while water quality is rapidly degrading owing to increased urbanization, deforestation, and land degradation. (Manga et al., 2021 cited Muhammad et al., 2013).

Diseases caused by water pollution place a significant strain on public health. Ingestion of water contaminated with bacteria that cause infectious illnesses such as cholera and other diarrheal disorders, dysentery, and enteric fevers poses the greatest danger to health (WHO, 2013). To protect people from infections, there has been a movement away from using unimproved water sources and toward improved water sources such as piped water into a

residence, yard, or allotment, standpipe, borehole, protected excavated well or spring, and rainwater collection (Bain et al., 2014).

Due to intermittent water supply issues in underdeveloped nations, households typically utilize water storage tanks as well as small containers such as jerry-cans to conserve water for usage throughout the day (Manga et al., 2021). Rural populations utilize tiny containers that can be readily moved from water sources to dwellings, whereas urban communities use water storage tanks to conserve water because they have piped water. In impoverished nations, there is widespread worry about in-house microbial contamination during water handling and storage. Water storage tanks are one of the most common sources of pollution in residences (Manga et al., 2021).

2.2 Water supply system

Many individuals overlook the importance of water. Rapidly rising populations and migration to urban areas in emerging nations have necessitated the creation of centralized water systems to provide citizens with safe drinking water. The process of getting water from source to tap is a complex one with multiple components and possible issue places (Stathis, 1998). A water supply system's key components are the source/abstraction point, water treatment facility, transmission network, storage tanks, distribution network, and consumer draw off points.

2.2.1 Abstraction

Water abstraction is the process of obtaining or extracting water from natural sources such as rivers, lakes, and groundwater aquifers for a variety of purposes ranging from drinking to irrigation, treatment, and industrial applications (Wiek and Larson, 2012). The success of an abstraction point is based on the optimal separation of water and other particulate materials in the natural source, such as silt or organics.

2.2.2 Water treatment

Water extracted from a natural source is subjected to a number of physical and chemical treatment operations in order to fulfill the requirements for drinking and domestic use. This might be conventional treatment, non-traditional treatment, or compact treatment to give clean and safe potable drinking water to populations. Screening (using coarse and fine screens), coagulation and flocculation, sedimentation/clarification, filtration, and disinfection are all phases of the water treatment process. Contaminant intrusion in water is often caused by

backwashing of tanks, extended water retention time at the treatment plant, and old pipelines, among other things (Stathis, 1998).

2.2.3 Transmission

The transfer of water from the treatment plant to a storage reservoir or the conveyance of raw water from the abstraction point to the treatment plant is referred to as transmission (Colombo and Karney, 2002). Transmission or trunk mains often transport significant volumes of water across long distances, such as from a treatment plant to a distribution system storage tank. Transmission mains transport large amounts of water, either by gravity or under pumping pressure, to the highest point in the distribution region under concern.

2.2.4 Storage

Storage tanks and reservoirs are used to provide storage capacity to meet fluctuating demand (or to reduce peaks), to provide reserve supply for fire-fighting use and emergency needs, to stabilize distribution system pressures, to increase operating convenience and flexibility in pumping, to provide water during source or pump failures, and to blend different water sources. A storage tank should be placed slightly outside the service area's center of demand. Elevated tanks are the most common form of tank and reservoir, although other types of tanks and reservoirs include in-ground tanks and open or closed reservoirs (Novo et al., 2010).

2.2.5 Distribution network

A water utility's main asset is often its distribution system infrastructure. The American Water Works Association (AWWA) defines a water distribution system as "all water utility components for the distribution of treated or potable water to customers or other users via gravity storage feed or pumps through distribution pumping networks, including distribution equalizing storage" (AWWA, 2003). The purpose of a water distribution system is to provide potable water to a community in order to fulfill home, industrial, commercial, and fire flow demands. Under typical working conditions, the system must provide an appropriate flow of high-quality water at a suitable pressure to consumers. Most water distribution systems have three main configurations: branch, grid/loop, and ring (MWE, 2013).

- i. **A branch system** is comparable to a tree branch in that tiny pipes branch off bigger pipes across the service area, allowing water to travel just one path from source to consumer. This approach is most commonly found in rural regions.

- ii. The most common configuration in big municipal areas is a **grid/looped system**, which consists of linked pipe loops throughout the region to be serviced. There are various paths that water may go from the source to the customer in this sort of system. If a line break occurs, a looped system provides a high level of dependability since the break may be isolated with little impact on users outside the surrounding region (NRC, 2007). Looping also decreases some of the difficulties associated with water stagnation, such as unpleasant interactions with pipe walls, and boosts fire-fighting capacity by keeping water circulating. However, loops can be dead ends, particularly in suburban settings, with related water quality issues.
- iii. **Hybrid systems** are a combination of both looped and branched portions.

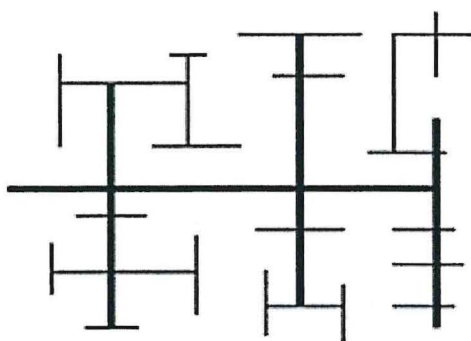


Figure 2-1: Branched system

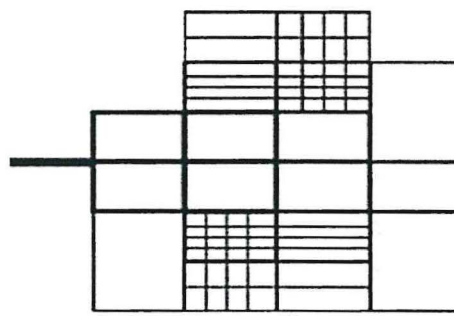


Figure 2-2: Looped system

Source: MWE 2013

2.2.6 Consumer draw off points

These are the end users of the water abstracted, treated, transmitted and distributed for domestic, agricultural and industrial use. These include Public stand posts (PSPs), Taps, and storage tanks.

2.3 Rainwater harvesting

The collecting, storage, and utilization of rainwater is known as rainwater harvesting. It is the act of collecting rainwater from catchment surfaces such as iron sheets, grass thatched roofs, tarpaulins, trees, and rocks (MWE, 2015). This water can be utilised for domestic use, irrigation and even industrial use. Rainwater harvesting is advantageous since it is cheap, affordable,

provides improved water quality but storage depends on seasons, contaminant intrusion source and if not well protected can be a mosquito breeding point.

According to MWE (2015), water quality management in rainwater harvesting tanks and storages is key as the roof is one of the entry points for contaminants both physical and microbial. Requirements for better water quality management as set by MWE (2015) are;

- Fitting of tank with first flush system;
- Covering of tank;
- Regular cleaning of tank at least 2 times a year;
- Regular cleaning of the catchment and gutters;
- Trimming of tree branches hanging above the roof to reduce bird droppings and leaves;
- Correct installation of gutters;
- Avoid light penetration in the tanks to avoid growth of algae and;
- Water disinfection.

2.4 Contaminant intrusion

Contaminants can enter the water distribution network through pipelines and storage tanks. Intrusion can occur through deteriorating water mains during maintenance and repair operations, as well as through broken pipes and gaskets and cross-connections (Kirmeyer et al., 2001). In addition to infections, intrusion can bring chemicals such as insecticides, herbicides, hydrocarbons (gasoline spills), and physical pollutants like as plant debris and soil particles into the pipeline. Intrusion into water mains necessitates the simultaneous presence of three elements: a channel, a driving force (the differential in pressure between the pipe and its surroundings), and a contamination source. The sub-sections that follow offer a brief summary of various aspects.

2.4.1 Leakages – path way

Unaccounted-for water, often known as nonrevenue water, is a significant issue in many poor nations. Unaccounted-for water is the discrepancy between the amount of water delivered to the system and the amount of water sold to users (Lee and Schwab, 2018). Leaks are an economic, environmental, and sustainability concern, with implications for consumer health and safety. Due to the presence of pipe fractures, holes, poor gaskets, and/or faulty appurtenances that might serve as intrusion paths, a water distribution network can never be totally water tight. A pressure differential is often necessary to drive incursion. Therefore, it is

improbable that intrusion will occur as long as the water pressure inside the network is greater than the pressure outside although movement of microbial or viral contaminants against the pressure gradient is possible (Sadiq et al., 2006). When segments of the distribution network are depressurized, pressure differentials can arise during maintenance activities such as break repairs and flushing.

Contaminants can enter by sewage water exfiltrated from nearby damaged sewers, polluted groundwater/soil, or backflow through unprotected cross-connections. The actual exposure of a damaged pipe to polluted soil or water during repair is another direct channel of incursion. If correct flushing and disinfection protocols are not followed prior to re-commissioning, contamination may result. Clearly, the frequency of pipe breaking, the duration of repair tasks, and the size of the network section that may be separated during maintenance are all factors that influence incursion risk.

However, due to a variety of factors such as pressure changes in pipes caused by power outages, even upgraded water systems such as piped water supply systems undergo incursions through pipe breaches, resulting in water contamination and modification of piped water characteristics (Sadiq et al., 2006). Many other factors, such as rainfall, distance traveled, pipe age, and the level of internal deposition in mains and conduits, contribute to piped water pollution and, as a result, differences in features.

Water losses along the water supply system are a key factor in determination of contaminant intrusion. Table 2-1 shows the different ways water is lost in a water supply system with emphasis put on both distribution networks and users as it is our point of interest in determination of contaminant intrusion.

Table 2-1: Examples of real losses in a water supply system

Water Supply component	Real losses from each component
Source	Leaks in mains running from the source to the treatment plant
Treatment plant	1. Excessive backwashing of the filters 2. Leaks in the reservoirs 3. Reservoir overflows
Transmission	Leaks in Transmission lines

Storage	1. Leaks from storage tanks 2. Storage tank overflows
Distribution Network	1. Leaks in service connections 2. Leaks or breaks in water mains
End User Points	1. Excessive uses 2. Inappropriate uses 3. Plumbing leaks (toilets, faucets, etc.) 4. Illegal water connections and water theft

Source: NWSC 2019

2.4.1.1 Causes of Leakages

Leaks in pipe networks can occur in a variety of ways. To be able to repair leaks, one must first understand the causes of leaks so that they can be avoided in the future and fixed appropriately in the present. Leaks can happen at joints, valves, service connections, or even within the pipe itself (Stathis, 1998). Service connections are a major source of leaks as well.

Leaks at valves are not a substantial cause of network leakage. Water main leaks can be produced by cracking, crushing, or longitudinal splitting, as well as pipe corrosion.

2.4.1.2 Open leakages

These are leaks and bursts that occur to pipes passing near the surface (Clayton et al., 2010). These are usually noticeable as they create a nuisance to the community. Open leakages happen more often than not and usually the response time from the utility operators is instant as a lot of unaccounted for water is majorly lost here.

2.4.1.3 Background leakages

These are leakages that occur in pipes that are buried deep in the soil (Clayton et al., 2010). These leakages occur due to corrosion of pipes, high pressures and distortion during excavation or compaction. These are most lethal leakages as they are hard to detect and mitigate. These

can be regarded as the most contributor to the intrusion of both physical and microbial contaminants in a distribution system although they occur on small scale.

2.4.2 Transient pressures – driving force

Extreme transient pressures in a water supply system can occur as a result of a pumping station's power failure, quick valve closing, fire flows, pipe breakage, and other factors. These transients can result in negative pressures in pipes, which can be amplified by unusual topographical circumstances. Contaminants may be pushed through damaged pipe walls and joint gaskets as a result of these negative pressures. Extreme transient pressures are more common in lengthy transmission mains than in an urban distribution network where consumers' faucets function as widely dispersed pressure relief valves. An exemption may be made during fire flows or near a wet industrial plant. Because transient pressures last just a few seconds, the volume of polluted solute input is often fairly modest (less than 1% of the flow in the pipe) (Kirmeyer et al., 2001).

2.4.3 Contaminant source

Chemical (pesticides, herbicides, petroleum products, fertilizers, solvents, detergents, medicines, etc.) or microbiological contamination sources exist (microbes, viruses, bacteria). Karim et al. found total coliform, faecal coliforms, clostridium, bacillus, and viruses in soil and water samples collected near water mains (2003). Total and faecal coliforms were identified in over 60% and 40% of the samples, respectively. Bacillus was discovered in the majority of the samples, as predicted given that it is a natural soil bacterium. Enteroviruses, Norwalk, and Hepatitis A viruses were also discovered near the pipe, indicating that human and animal contamination was present.

Intrusion is a complicated phenomenon that is dependent on the three aspects listed above, yet the evidence on these elements is often insufficient, non-specific, and unclear (Wiek and Larson, 2012). Evidential reasoning provides a relevant technique to combine / aggregate these facts in order to draw conclusions about the danger of contaminant entry.

2.5 Water quality analysis

Analyzing water quality is one approach to determine whether or not the water quality is capable of ensuring compliance with water quality objectives. Water age is another element that can cause variations in water quality and degradation within the distribution system. Interactions between the pipe wall and the water, as well as reactions within the bulk water

itself, are the two primary processes for water quality degradation. As bulk water flows through the distribution system, it experiences a variety of chemical, physical, and aesthetic modifications, influencing water quality (Environment Protection Agency - EPA, 2002). Furthermore, if the storage facilities are not adequately maintained and sufficient disinfection residual is not maintained, all of this might lead to water pollution (Coelho et al., 2003).

As a result, while the presence of a public water distribution network is frequently a sign of better water supply in a developing nation, it should not be assumed that the resulting water quality is always suitable for human consumption (Lee and Schwab, 2005).

Most of the time, the chemical criteria of drinking water quality indicate water acceptability for human consumption, which might include industrial, household, and agricultural usage (Chatwell et al., 1989). As a result, such chemical criteria as source protection, treatment efficiency and dependability, and distribution network protection must be included in the assessment of water quality (CAWST, 2013).

2.5.1 Physical tests

Most physical qualities, such as taste, smell, and color, are easily seen. Turbidity is the most significant physical characteristic to assess since high turbidity levels are usually associated with high levels of microbial contamination. Furthermore, excessive levels of turbidity might limit the efficacy of various water treatment systems (Kusuma et al., 2019).

2.5.2 Chemical tests

It is not practical nor required to test water for all of the substances that may cause health concerns. Most chemicals are seldom found, and many are the consequence of human pollution in a small region, affecting just a few water sources. However, three compounds have the potential to cause major health concerns and are found in large quantities. These are arsenic and fluoride, all of which exist naturally, and nitrate, which is extensively used in agricultural fertilizer. These three pollutants should be prioritized for testing when developing new water supply infrastructure.

A second priority for water quality testing should be for chemical characteristics that frequently cause water to be rejected for aesthetic reasons, such as metals, particularly iron and manganese, and total dissolved solids (salinity). When chlorine is used to disinfect water, it is critical to evaluate the drinking water quality for pH and free residual chlorine as markers of

adequate and successful treatment. It may also be necessary to test for substances known to be present nearby, such as copper or lead from industrial contamination.

2.5.3 Microbiological tests

Microbiological pollution is by far the most significant public health issue connected with drinking water, making it the top priority for water quality assessment. Water pathogens such as bacteria, viruses, protozoa, and helminths can cause a variety of health issues, but the principal worry is infectious diarrheal illness, which is spread by individuals drinking contaminated water. Most drinking water projects prioritize testing for microbiological contaminants. The criteria for testing for microbiological contamination include *Escherichia coli* (*E. coli*) and/or thermo-tolerant coliforms (TTC) (Kusuma et al., 2019)

Supply of pipe treated water faces a lot of challenges all over the world such as power black outs that lead to intermittence in the systems; this lowers pressure in the pipes therefore possibility of external materials entering into the water in pipes. Other challenges include vandalism and improper waste handling. A piped water supply system's performance is often assessed by its capacity to provide appropriate amounts of safe and tasty drinking water to all water consumers. This can be accomplished by conducting source-to-tap audits, which include an analysis of historical water quality and quantity data, an evaluation of treatment system effectiveness, an investigation of customer satisfaction, an evaluation of monitoring and reporting practices, and an assessment of the water supply's future sustainability (Ediriweera and Marshall, 2010).

However, whereas drinking water quality is a major problem in the industrialized world, it receives little attention in the developing world. People continue to drink contaminated water, despite the fact that it is occasionally cleaned before delivery. While assessing the quality of water in public elementary schools in Ankara's Metropolitan Area, Bilal et al. (2015) discovered that cadmium and lead levels were much beyond the permitted limits. Similarly, Napacho and Manyele conducted a research in 2010 and discovered that the chemical characteristics of water sources did not exceed WHO guidelines. This means that there's somewhere along the distribution / transmission lines where the pollutants enter the system.

2.5.4 Water quality standards

The water quality tests will be checked in accordance to the Uganda and East African standards for Potable water that is also being used by National Water and Sewerage Corporation (Table 2-2).

Table 2-2: National standards for potable water

Parameter	Units	National Standards for Potable Water (Maximum Permissible)
pH	-	6.5-8.5
Electrical Conductivity	µS/cm	1,500
Colour: apparent	PtCo	15
Turbidity	NTU	5.0
Total Dissolved Solids	mg/l	700
Total Suspended Solids	mg/l	0
Alkalinity: total as CaCO ₃	mg/l	500
Hardness: total as CaCO ₃	mg/l	300
Calcium: Ca ²⁺	mg/l	Not Specified
Magnesium: Mg ²⁺	mg/l	100
Bi-Carbonate: as CaCO ₃	mg/l	500
Chloride: Cl ⁻	mg/l	500
Fluoride: F ⁻	mg/l	1.5
Iron: total	mg/l	0.3
Sulphate: SO ₄ ²⁻	mg/l	200
Nitrate: N	mg/l	5.0

Source: UNBS (2014)

2.6 Conceptual review

The Joint Monitoring Programme for Water Supply and Sanitation (JMP) of WHO/UNICEF classifies a drinking-water source type as enhanced if it is "protected from outside contamination, particularly faecal matter pollution, by nature of its construction or via active intervention." (WHO, 2011).

Improved sources include piped water into a home, yard, or plot, a standpipe, a borehole, a protected excavated well or spring, and rainfall (Bain et al., 2014). Unimproved source types

are ones that do not safeguard water from outside pollution (unprotected wells, unprotected springs, surface waters, and tanker trucks). While the classification reflects well-established sanitary protection standards, when the objective was announced as reached in 2010, the JMP emphasized that the MDG indicator did not take water quality measures into consideration (WHO, 2014). The indicator has been chastised for failing to accurately reflect safety, with some estimates implying that claimed access to safe water may be exaggerated by billions of people due to a failure to account for microbiological water safety or a failure to account for sanitary status (Onda et al., 2012).

Water quality is a relative phrase that refers to the relationship between the composition of water and the impact of natural processes and human actions. As a result, its degradation is caused by the entry of chemical compounds into the water supply system via leaks and cross connections. (2010) (Napacho and Manyel). This implies that the quality of treated water will always vary based on where you are. The more from the place of testing, the greater the danger of contamination and the more susceptible the water will be to contamination.

2.7 Empirical review

Over the years, many authors have carried research on piped water contamination and some of their findings are highlighted in this section. According to the experimental study by Chiara et al. (2015) while analyzing contaminant intrusion through leaks in water distribution system at the University of Enna, results showed that intermittent distribution is the main cause. It allows large number of contaminants inside the pipes through infiltration especially when the pipes are empty.

According to Bain et al. (2014), in a research on faecal contamination of drinking water in low- and middle-income countries, 38 percent of 191 investigations revealed that more than a quarter of samples from improved sources included faecal contamination. Water sources were more likely to be polluted in low-income nations and rural locations. As a result, it was established that access to a "improved source" provides some sanitary protection but does not guarantee that water is free of faecal contamination, nor is it consistent across source types or contexts. As a result, international estimates vastly overestimate the consumption of clean drinking water and fail to account for inequalities in access. An improved monitoring technique would integrate indications of sanitary protection with water quality measurements.

Napacho and Manyel (2010) discovered that the chemical characteristics of water sources did not satisfy the permitted World Health Organization (WHO) and Tanzania Bureau of Standards (TBS) thresholds while analyzing drinking water in Temeke District, Tanzania. When exceeding the WHO requirements was examined, it was shown that the majority of the samples contained chloride levels that exceeded the permissible WHO limits. It was later advised that home drinking water supplies be protected from polluting sources. Furthermore, leakage in the transmission or distribution system adds to the intrusion of sediments and pollutants into Dar es Salaam's piped water. When sewage and piped water systems collide, the situation gets much worse. The important variables leading to drinking water pollution were the distance traveled, the age of the pipes, and the level of internal deposits in mains and conduits.

According to Lee and Schwab (2005), while investigating deficiencies in drinking water distribution systems in developing countries, it was discovered that these deficiencies are caused by inadequate disinfection residual, low pressure, intermittent service, leaks, and corrosion, which frequently interact with one another and result in a decrease in both the quantity and quality of water arriving at the consumer. As a result, distribution networks serve as pathogen transmission vectors.

2.8 Chapter Summary

Chapter 2 mainly summarized material pertinent to the research subjects of the study. The chapter described the extraction, processing, and distribution of water. The chapter then went into depth on the numerous causes of intrusion or pollution that can only be evaluated or identified in the laboratory using water quality tests that comply with East African potable water laws and WHO standards.

3 CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction

The study took a hybrid strategy, using both qualitative and quantitative methodologies to gather, present, and evaluate data. To gather, present, and analyze verbal, descriptive data such as water color and turbidity, qualitative approaches were utilized. For numerical data such as total coliforms in water, quantitative methodologies were applied.

3.2 Description of study area

Ggaba is located on the northern banks of Lake Victoria, near the city of Kampala's southern edge (Figure 3-1). It is bordered by the Murchison Bay of Lake Victoria to the south and East, the village of Kawuku to the northeast, Bunga to the North, Buziga to the Northwest and Munyonyo to the south west. In terms of administration, it is under Makindye division of Kampala with villages such as Ggaba, Kalungu, Katuso, Soya, Kawuku and Bunga.

The area is served by National Water and Sewerage Corporation (NWSC) whose area branch office is located at Bunga market. In this area, NWSC provides various tariff plans such as domestic connections, commercial, public standpipe and institution depending on the water demand. However, a large percentage is under domestic connection which is the reason why this study entirely focused on domestic connections (NWSC, 2019).

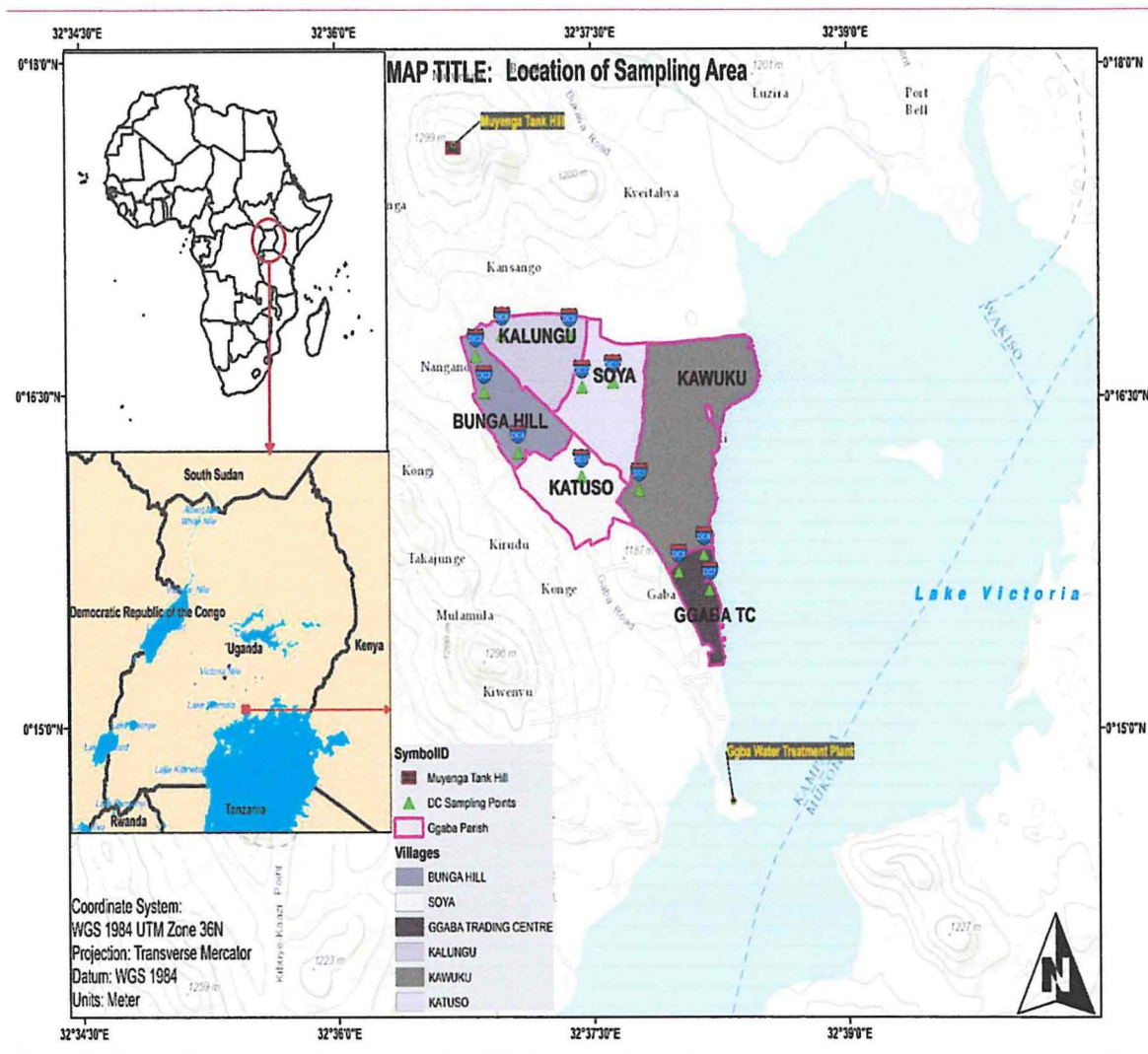


Figure 3-1: Location of direct connection and storage tanks

3.3 Research design

The study followed both descriptive-comparative/correlational and longitudinal research designs. It was hinged on water quality characteristics/parameters of water along the distribution network and the selected consumer points. These included; Turbidity, Colour, Residual free Chlorine, pH, TSS, Faecal Coliforms. In particular, it followed descriptive comparative/correlational because there was a need to identify the characteristics of water from different sources and later compare/establish the relationship between them. It followed a longitudinal research design because water was collected from each of the randomly selected domestic connection more than once during the study.

3.4 Sources of data

Both secondary and primary data were utilized. NSWSC provided secondary data, including; the population that the distribution network serves, pipe network specifications, Water quality data from NSWSC monitoring stations specifically Ggaba station over a period of 5 years. This data was of great importance during determination of the spatial and temporal variation of contaminants. The primary source of data for this study were sample units of the different water quality tests, field observations, key-informant interviews of water consumers and questionnaires.

3.5 Sample size determination

To establish a representative sample, the study used both random and non-random sampling procedures. Each individual was picked purely by chance in random sampling, providing each member of the population an equal chance of being included in the sample, but in non-random sampling, samples are not given an equal chance of being selected (Amin, 2005). Stratified random sampling technique was preferred since sampling was categorized on the basis of whether they possessed water storage tanks or not. Observation, interviews and transect walks together with questionnaires were used to collect the relevant data for this research. The sampling methodology was done by; defining the target connections in Ggaba Parish, delineating main connection links and sample collection and analysis.

3.6 Data collection methods

3.6.1 Qualitative data

Data were obtained from the NSWSC website and the NSWSC offices. Semi structured interviews were conducted at each of the sampling locations. This enabled the study to obtain data on the quality of water consumed at the various sampling locations, the water availability, the age of the pipes and tanks. Different observations at each of the locations and in the different villages were assessed and noted down.

3.6.2 Quantitative data

Quantitative data was collected from six villages at different sampling points. Some of the parameters were analysed onsite (in-situ measurements) to avoid any errors or alteration of the samples and other parameters were collected and analysed from laboratory. Residual chlorine was analysed onsite using a HACH colorimeter. The collected sample was used as the blank to zero the machine and later on Diethyl-p- Phenylene-Diamine was added to the sample to allow

a reaction of chlorine to take place. The sample was then placed in the meter and read to obtain results for each different sampling point at the premises.

A clean acid washed HDPE plastic bottle was used to collect the physiochemical sample that was analysed in the laboratory. The collected samples were stored in a cool box that had ice packs at a temperature of 15-18°C for proper preservation. The bacteriological samples were collected in sterilised bottles to minimise any cross contamination.

Samples for testing physiochemical parameters were collected and different parameters were analysed for example pH and Electrical Conductivity using a pH/EC multimeter (HACH Smm374). Colour and total suspended solids were analysed using DR 6000 (HACH). Turbidity was also analysed using a Turbidimeter. The bacteriological samples were analysed for Faecal coliforms using the membrane filtration method. All the laboratory analysis was conducted according to the laboratory Standard Operating Procedures in line with the "Standard Methods for the Examination of Water and Wastewater (APHA, 2005)".

3.6.3 Target connections

According to NWSC, there are 757 domestic connections in Ggaba parish of six villages, where 231 were served by storage tanks (NWSC, 2018). The Cochran formula was used to determine the village average sample points benchmarked on desirable confidence level using equation 3-1

$$n = \frac{Z^2 pq}{d^2}$$

Where
n - Sample Direct Connections (DC)
z - Standard Deviation (95% confidence level-1.96)
p - Proportion of target DC/ sample points (7%, 6%, 5%, 4%, 3%, 2%, 1%)
q - (1 - P) = 95%
d - Absolute precision (0.05)

Equation 3-1: Cochran's sample size formula

The sample size was 44 household stratified under the 6 villages categorizing both DC and ST.

3.6.4 Connection links

According to Ggaba NWSC network layout, links serving more than 3 DC lines were ordered and delineated as the major service lines which led to the proposed sample points.

3.6.5 Sample collection and analysis

In-situ water parameters were measured using a multi-parameter water quality meter (HANNA HI 9828; Figure 3-2) while samples collected were sent to the Public health Laboratory at Makerere University and Uganda Industrial Research Institute (UIRI), accredited laboratories for testing and analysis of water samples. Laboratory analysis was done for the following parameters; Faecal Coliforms, colour and turbidity.



Figure 3-2: Hanna Meter HI 9828

3.7 Data analysis and presentation

Data obtained from NWSC and the laboratory were statistically analysed. Results were presented in both tabular and graphical forms as seen in chapter four.

3.7.1 Statistical testing for differences between means of samples

Procedure for statistical *t*-test

Step 1: Set up a hypothesis: The null hypothesis (H_0) was set up as "the mean of parameter (such as, pH, TDS) from DC (X_1) is the same as that for ST (X_2) "

Step 2: Select the appropriate test statistic. If the sample size is less than 30, *t*-test is selected to test the hypothesis

Step 3: Compute the test statistic using:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

Equation 3-2: *t*-test statistics

where

$$S_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

Equation 3-3: Explanation of S_p in Equation 3-2

S_1 : Standard deviation of the parameter (such as, pH, TDS) from bottled water samples;

S_2 : Standard deviation of the parameter (such as, pH, TDS) from tap water samples;

X_1 : Mean of the parameter (such as, pH, TDS) from tank water samples;

X_2 : Mean of the parameter (such as, pH, TDS) from tap water samples;

n_1 : Sample size of tank water samples;

n_2 : Sample size of tap water samples;

t : t -statistic;

α : nominal significance level;

Step 4: Select the nominal level α

In this study, α was set as 0.05.

Step 5: Compute the probability (p) value.

The p -value was computed using Student's t -distribution. Here, the researcher made use of in-built function within Ms Excel. This function is called T.INV

Step 6: Decision on the hypothesis

If the p -value is less than the selected α (or 0.05), the H_0 was rejected; otherwise, H_0 was not rejected.

3.8 Ethical Considerations

Permission was obtained from the selected families with domestic connections inside Bunga village to participate in the study. To emphasize ethical values even further, each member of the research team was given an identification card that would be presented upon arrival at each household of concern during the research process in order to eliminate any possibility of impersonation with the intent of accessing people's residents without permission.

3.9 Chapter summary

Chapter 3 was a summary of the description of the study area where the research was carried out. The chapter further explained how the research was carried out and how data was collected. The number of samples to be collected was determined by the Cochran's equation. The collected data was then analysed using Microsoft excel.

4 CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the analysis of the results obtained from the primary and secondary data coupled with field surveys in line with the stated methodologies. A discussion of the results follows immediately after the results.

4.2 Objective 1: Investigating temporal variation of treated water characteristics along the distribution network

The secondary data was obtained from NWSC and the raw data comprised of data from Ggaba, Bunga and Muyenga distribution areas. The averages of each area were obtained into one per month and later generated yearly data from 2015 to 2019.

4.2.1 Temporal variations in colour

Colour of sampled water ranged from 0 – 18 PtCo with a percentage compliance of 90% for the standard of 15 PtCo (UNBS, 2014). Colour had the widest deviations from the mean (Figure 4-1; 4-2; 4-3; 4-4). The average indicator of colour was highest in 2018 while 2016 displayed the lowest value. May and August had the highest average colours. January to August had averages above the required UNBS (2014) standards.

Over the period considered for analysis, colour had an increasing trend for most of the months apart from October to November that had negative trends. The months of January to September and December had positive increasing trends ranging from 0.5 to 2.5. However, October to November had negative trends of -0.1 and -0.7, respectively. Linear trend fitted through results for colour showed that the increase was at a rate of 1.18PtCo per year with R^2 of 0.756.

When the colour levels are low, the water is assumed to be clean and aesthetically good looking to drink. Very low colours in the pipe network indicate good treatment, good pipe network and lack of bursts and leakages. When the colour of water is high it indicates poor quality of water. Colour may not be very harmful to human health but in a way not attractive to drink (USGS, 2014). The colour of drinking water in the pipe network largely depends on the quality of water being treated, efficiency in the water treatment process, the quality, type and age of the pipes (Gilca et al., 2020; Matilainen, 2007). If the organics in water are not fully removed may continue reacting thus causing high colour levels. The presence of iron in water may also lead to high colours (USGS, 2014). The type and age of the pipe determines the colour of water for

example cast iron pipes tend to deposit some particle in the water that may lead to colour changes. Pipes that are prone to frequent bursts are likely to increase the colour of water very often due to intrusion and contamination.

The colour of water may also depend on the different climatic seasons. The lake water tends to have higher amounts of algae in the dry seasons. January and July are reported as the hottest months around this study area while May and April are the most wet months (Weather and Climate). This complies to our study where January had some of the highest colours. The months with the highest values are an indication of a transition from the rainy season into the dry season (Ling et al., 2017; Niene et al., 2017).

Figure 4-1 shows box plots where the x indicates the mean colour for that month while the line in the middle indicates the median colour for each month. Colour showed the highest variation in the month of January which is closely related to the season. (Figure 4-1). All the months from January to December, the box plots showed no normal distribution as some box plots were skewed to the left and others skewed to the right. There were no outliers identified in any of the months.

Figure 4-3 shows colour variations in years where 2017 had outliers while 2019 had the widest variation. This indicates that through the years the colour variations keep increasing which may be as a result of water quality changes brought about by the increasing pollution over the years.

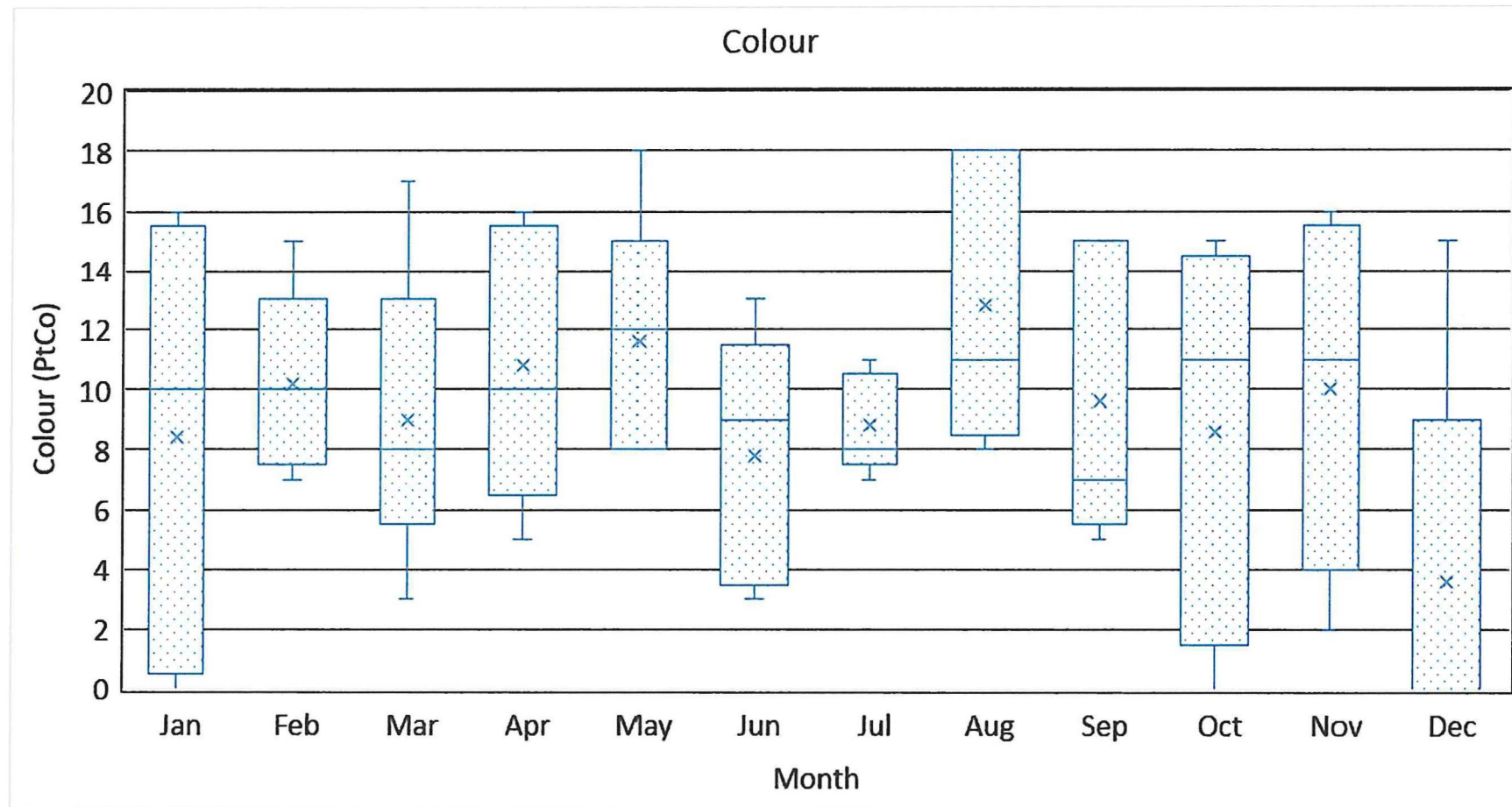


Figure 4-1: Colour variations in months

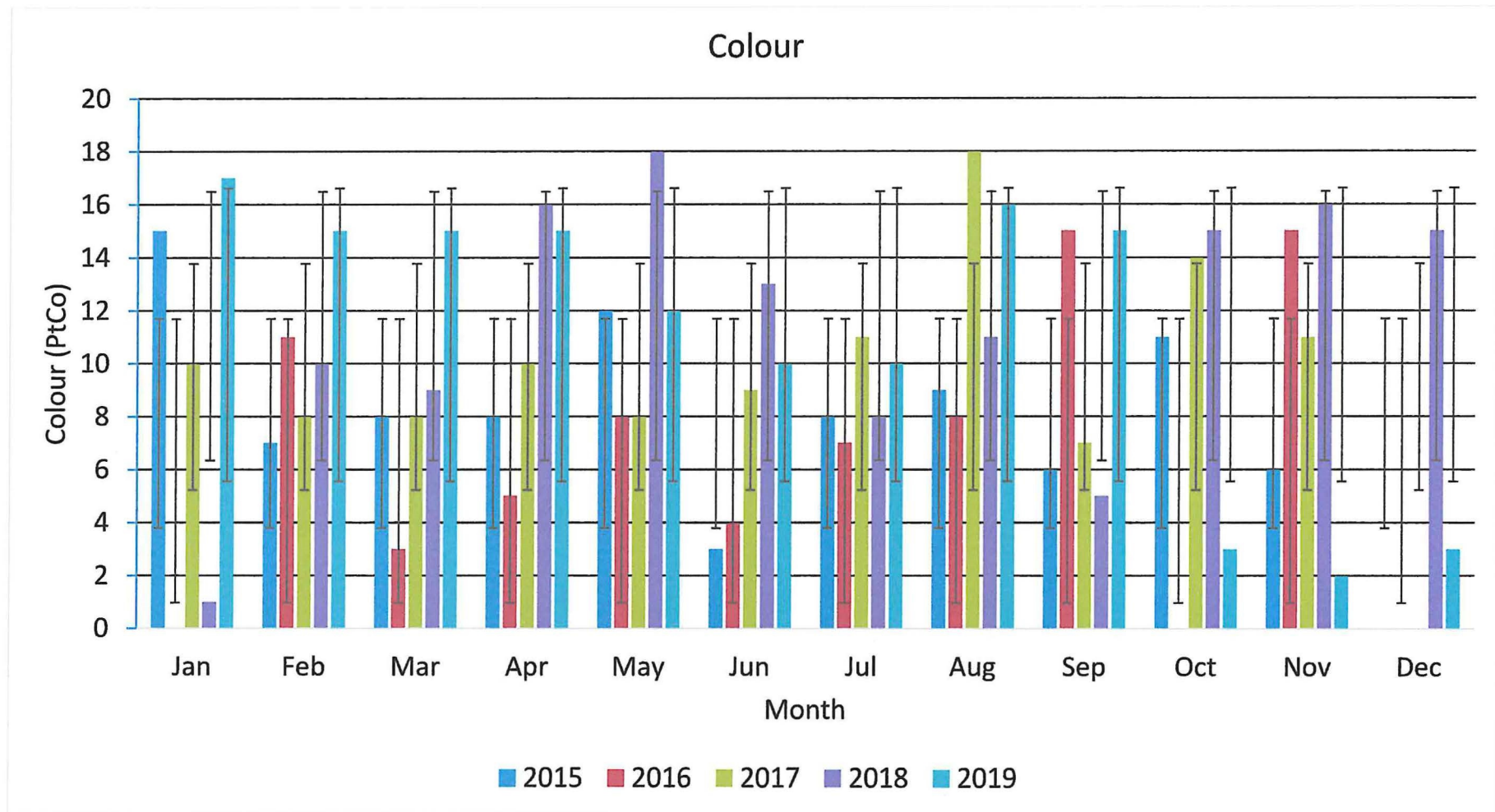


Figure 4-2: Average colour variations along the distribution network in different years

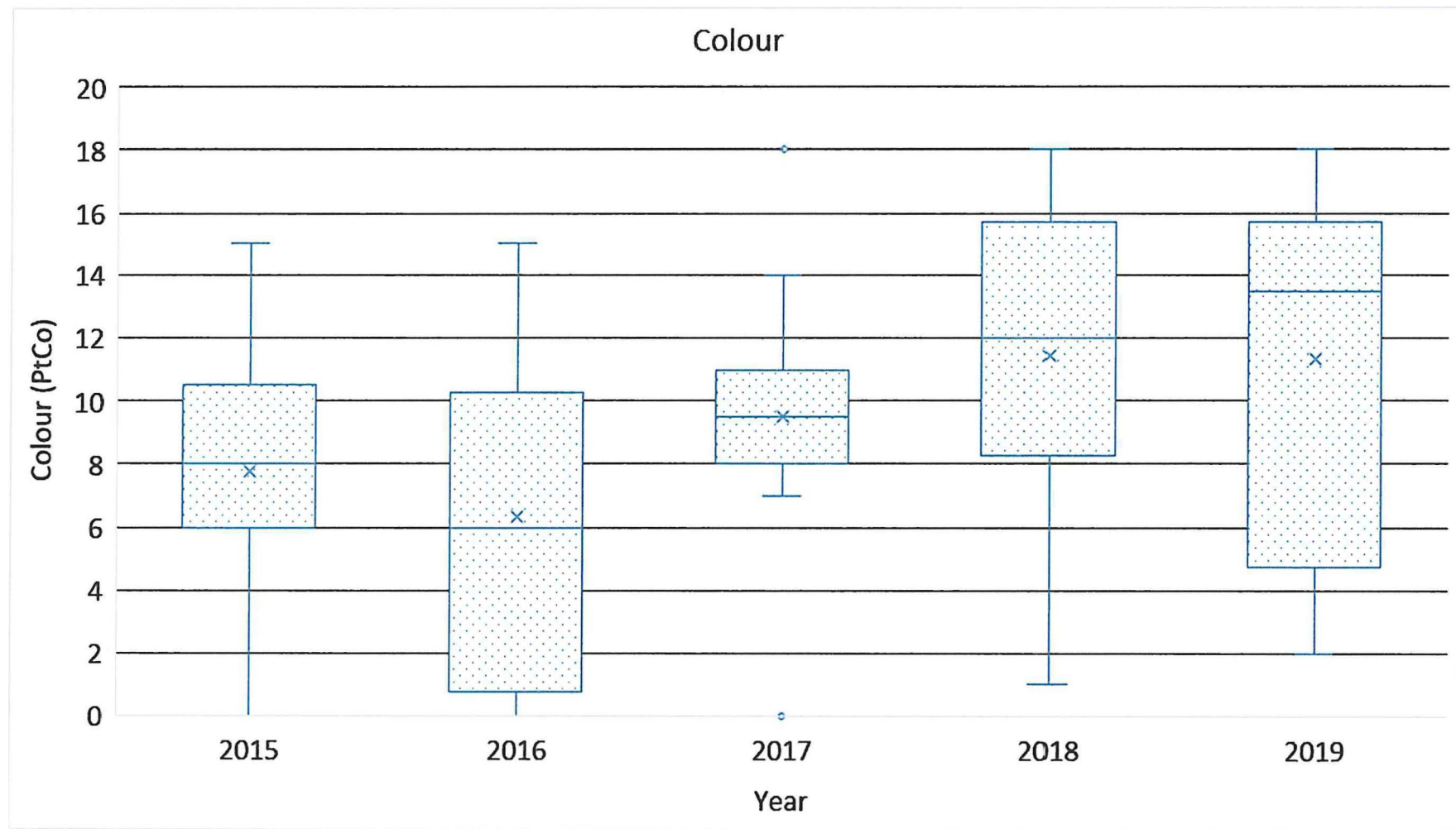


Figure 4-3: Colour variations with time

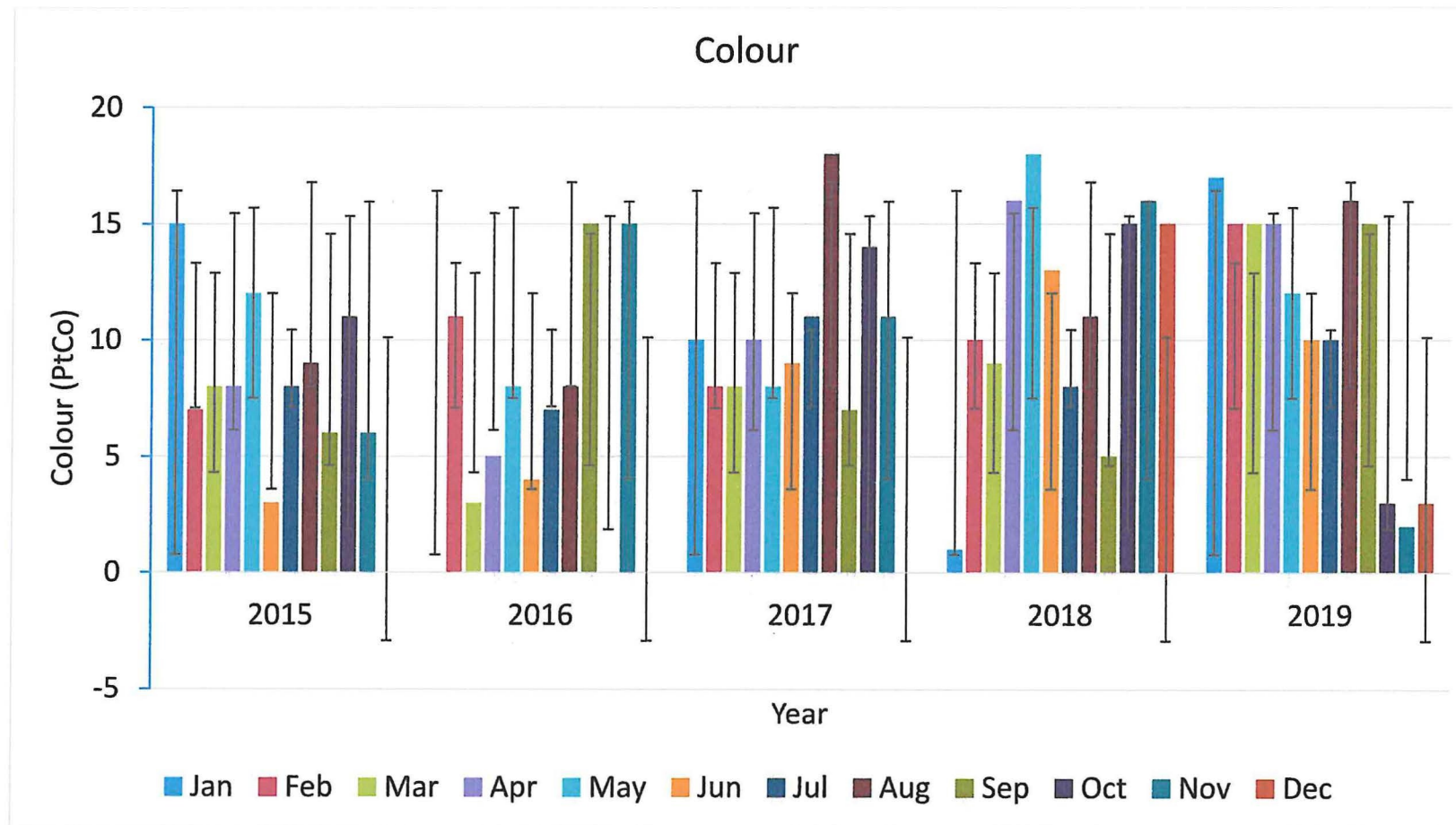


Figure 4-4: Average colour variations along the distribution network in different months

4.2.2 Temporal variations in turbidity

Turbidity in simple terms is the cloudiness of water which in most cases is a combination of suspended solids and the colour of water. The turbidity of this study ranged from 0.10 to 1.9 NTU below the standard of 5 NTU (UNBS, 2014) thus a percentage compliance of 100 (Figure 4-5; 4-6; 4-7; 4-8).

Turbidity was seen to increase over the years (2015 to 2019) with an increasing rate of 0.145NTU per year (Figure 4-7; 4-8). Over the years 2018 had the highest average turbidity. The strong R^2 indicates a good model for predicting turbidity over the next years. The turbidity for each month over the years generally had a positive increasing trend ranging from 0.023 to 0.366 NTU per year. The month of April was seen to have the highest increasing trend while November had the lowest increasing trend (Figure 4-5; 4-6).

High amounts of turbidity make the water less aesthetic to drink as it in the end gives it a colour. Turbidity may easily be caused by water treatment chemicals that are used, inorganic and organic matter, algae and dissolved colour (USGS, 2014). The causes of turbidity confirm the fact that seasons play a great role in determining turbidity amounts in water. The months with the highest values are an indication of a transition from the rainy season into the dry season (Ling et al., 2017; Niene et al., 2017).

Figure 4-7 of the box plots indicated that turbidity was increasing over time thus being dependent on time. The years 2018 and 2019 showed the highest variations and tremendous increase.

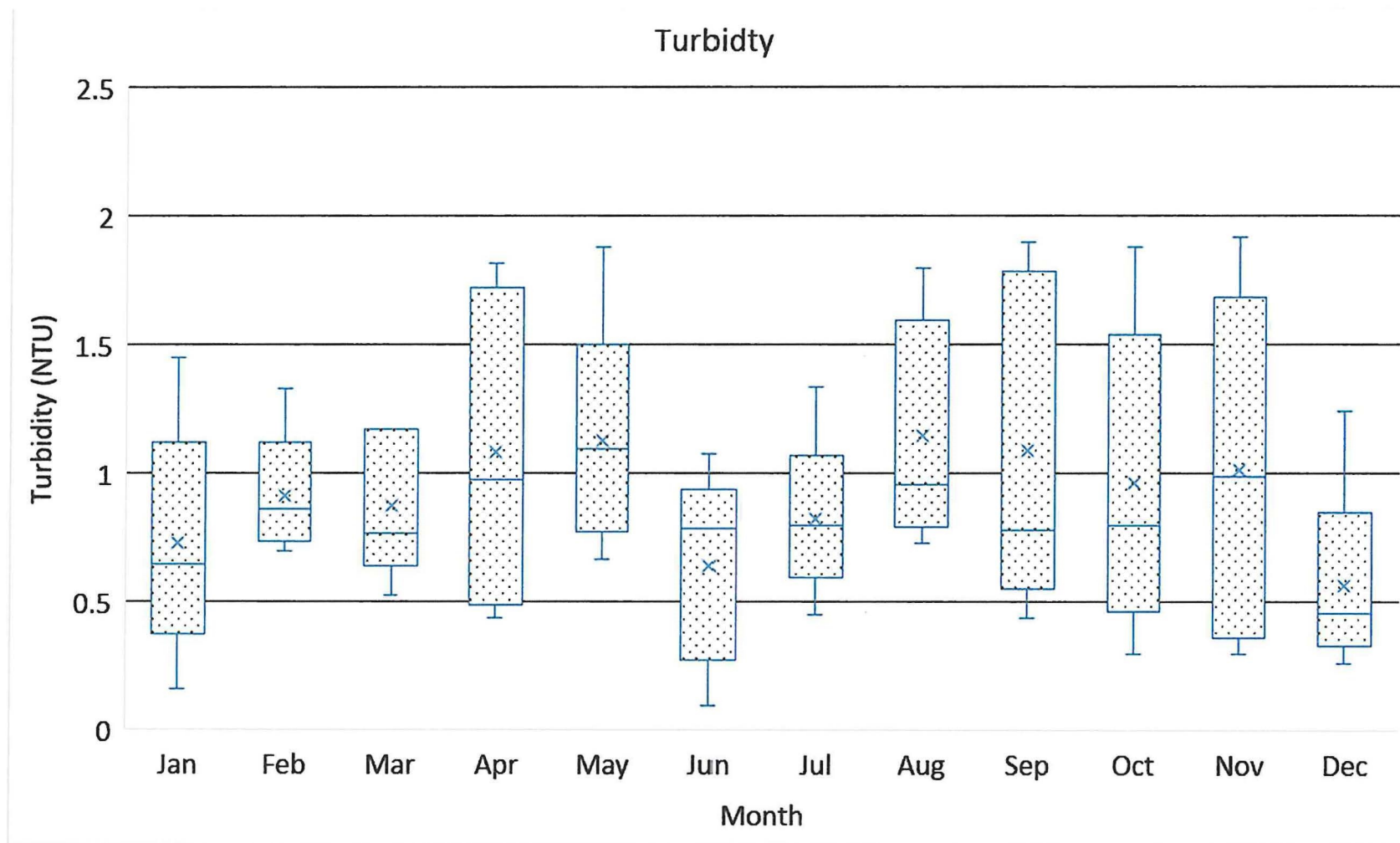


Figure 4-5: Turbidity variations in months

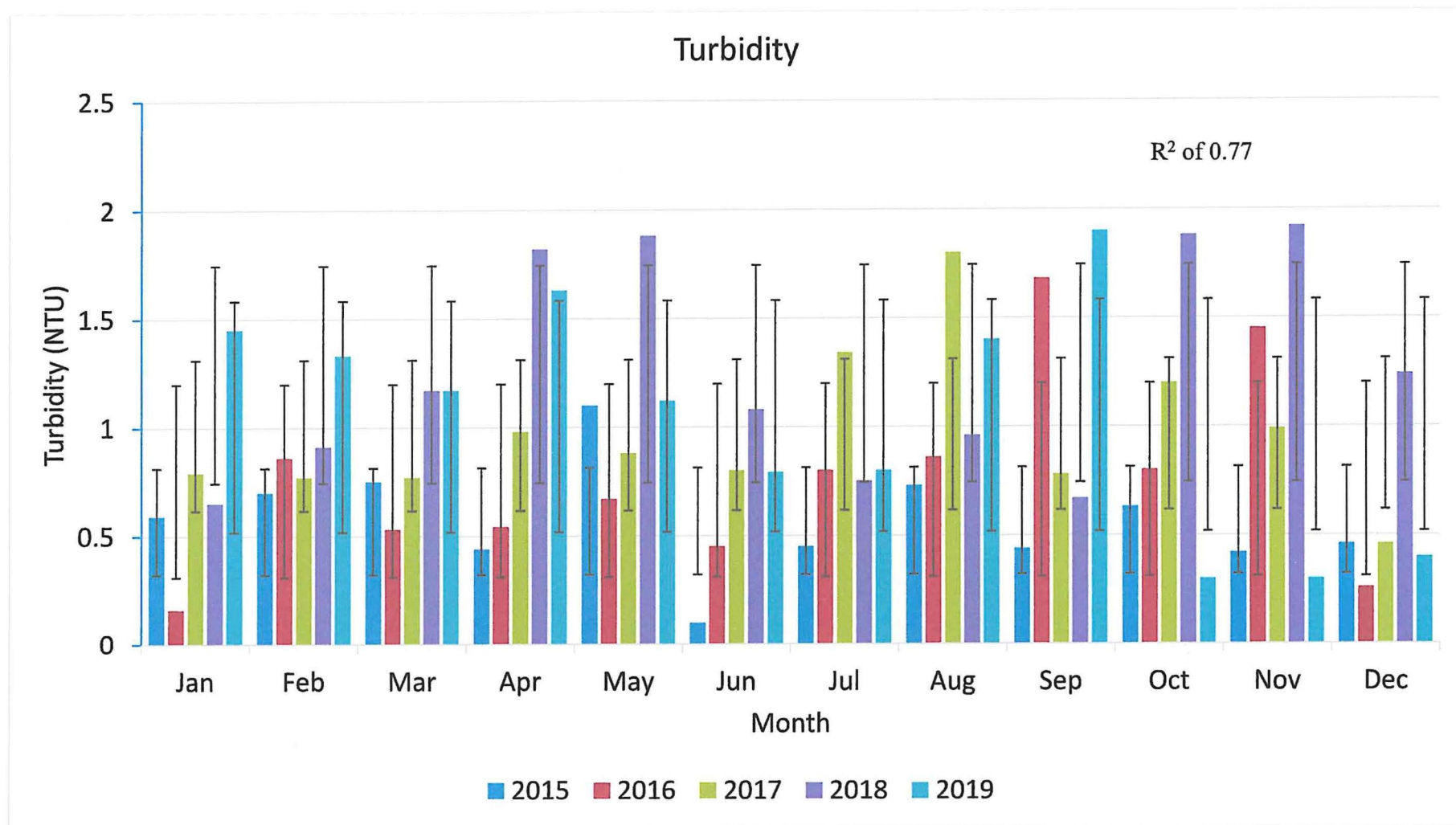


Figure 4-6: Average turbidity variations along the distribution network in different months

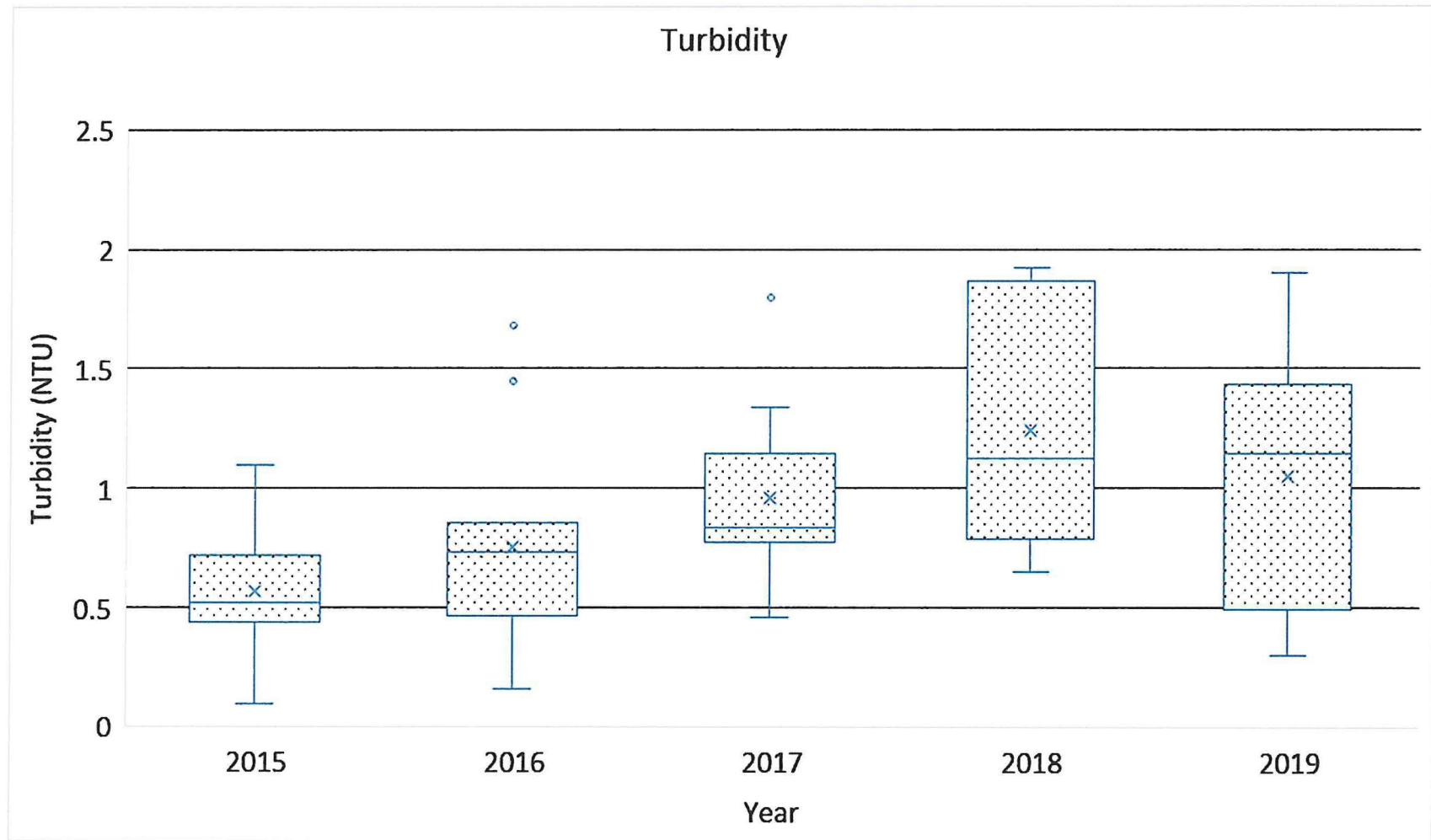


Figure 4-7: Turbidity variations in years

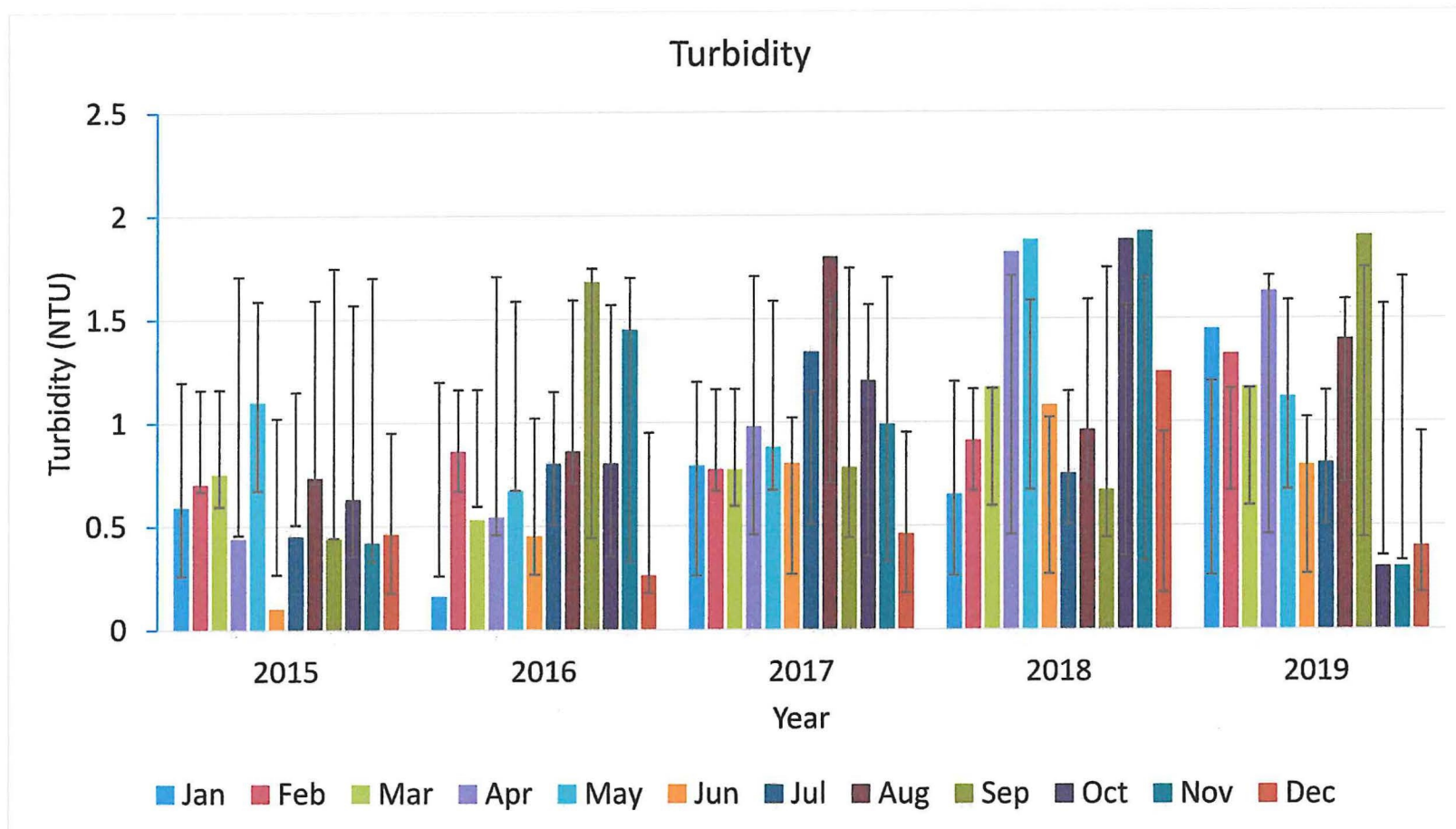


Figure 4-8: Average turbidity variations along the distribution network in different years

4.2.3 Temporal variations in free chlorine

Residual chlorine is the chlorine readily available in water for disinfection. Residual chlorine ranged from 0.15 to 1.00 mg/l all through from 2015 to 2019. On average all the months from 2015 to 2019 were within the acceptable residual chlorine standards of 0.2 to 0.5 mg/l (Figure 4-9; 4-10; UNBS, 2014; NWSC, 2020). The month of May 2015 had the lowest residual chlorine of 0.15 mg/l which is below the set UNBS (2014) and NWSC (2020) standards. The highest average residual chlorine was recorded in March 2018 (Figure 4-9; 4-10). In this month the water quality parameters of colour and turbidity were below the standards which could have enabled the applied disinfectant to work efficiently. The residual chlorine on average per year had a positive increasing trend until 2018 and decreased again in 2019 (Figure 4-9; 4-10). The residual chlorine was increasing at a rate of 0.0247 mg/l per year. Over the years (2015 to 2019) linear trend line fitted to residual chlorine had a an R^2 of 0.1994 which indicated that there was no relationship between the years and residual chlorine (Figure 4-9 to 4-13).

The boxplots in Figure 4-9 showed no outliers but the months of September to December showed minimal variations showing a decreasing trend towards December to January. However, the boxplot in figure 4-12 showed an outlier in 2016 which was the same year with minimal variation.

The months of February to July to September had a positive increasing trend ranging from 0.027 to 0.1380 mg/l per year. However, the months of January to December had a negative trend ranging from -0.027 to -0.005 mg/l per year.

Low values of residual chlorine indicate that the water may not be of good quality and not completely safe for drinking. Low residual chlorine is a result of different key indicators which include: recontamination in the network that consumes the chlorine with time. This may also be as a result of total organics in the water consuming all the chlorine present in the water. This is very realistic as seasons play a major role in the variability of the water quality and thus residual chlorine (Dyck et al., 2015).

The presence of chlorine in water is very important for killing bacteria and viruses that are sources of several disease like cholera and diarrheal (CDC, 2014). Therefore, the presence of

chlorine is correlated with disease free water and safety of water for consumption. Residual chlorine should be in specific amounts for human consumption (0.2 to 0.5 mg/l) but if the values exceed these limits may not be very dangerous but may cause other effects with time that develop from chlorine by products. Trihalomethane (THMs) release in the water are a byproduct of chlorine which may be cancerous in the long run (WHO, 2015).

Free chlorine also varies with seasons. During the dry season the algae levels keep rising and consumes more chlorine, in the same way the organics keep increasing and at the start of the rainy seasons the lake mixes and releases organics in the water to be treated (Dyck et al., 2015)

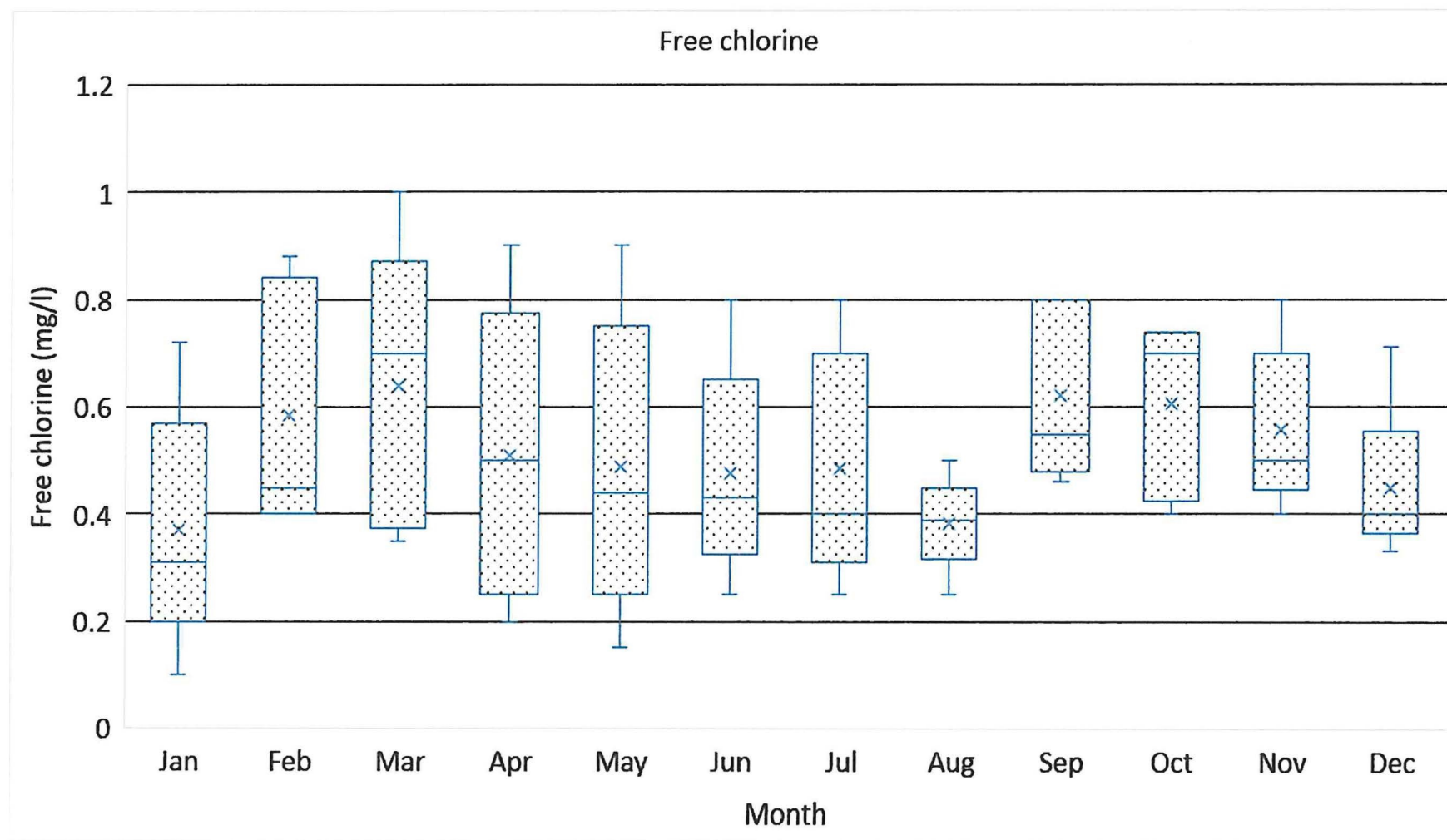


Figure 4-9: Residual chlorine variations along the distribution network in different months

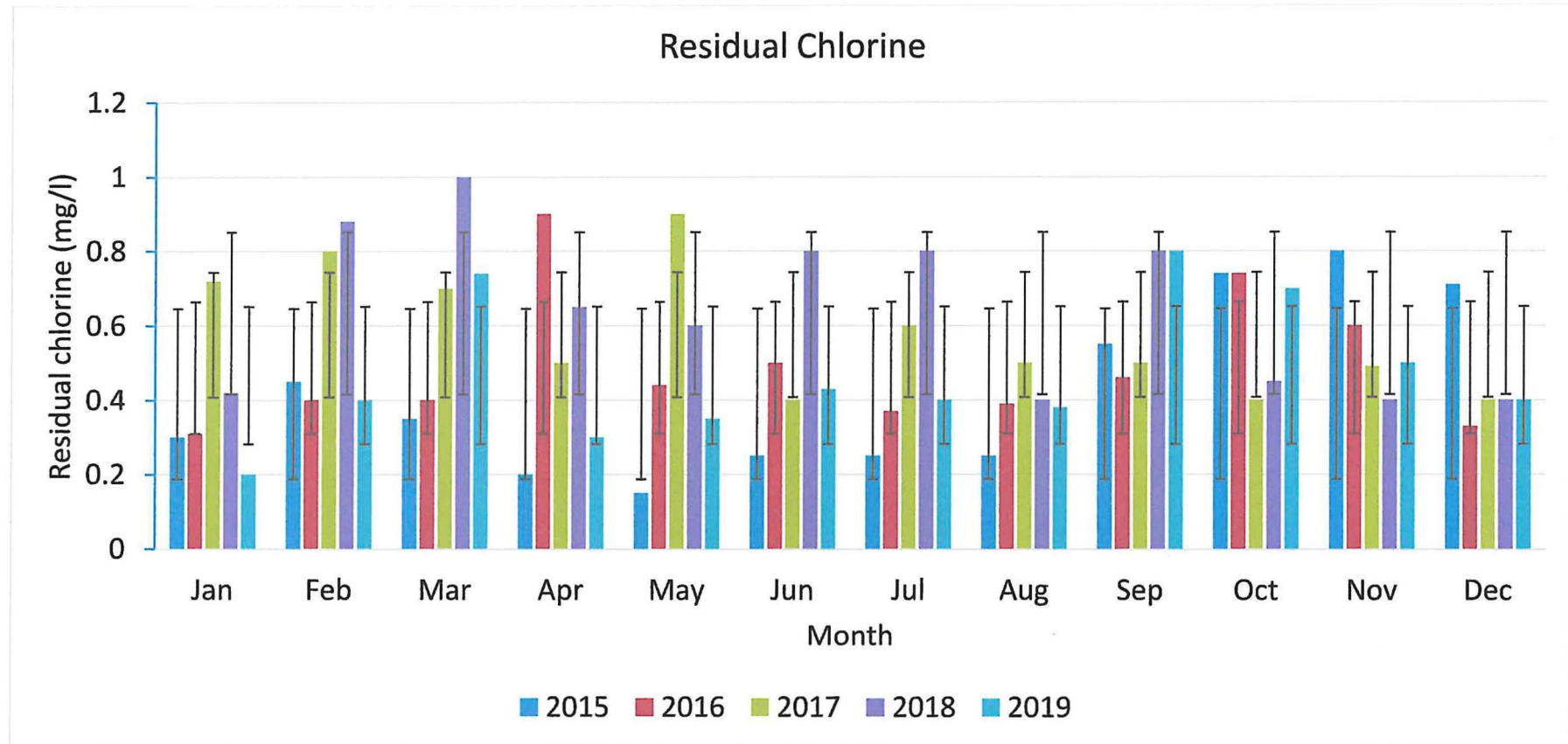


Figure 4-11: Residual chlorine variations along the distribution network in different years and months

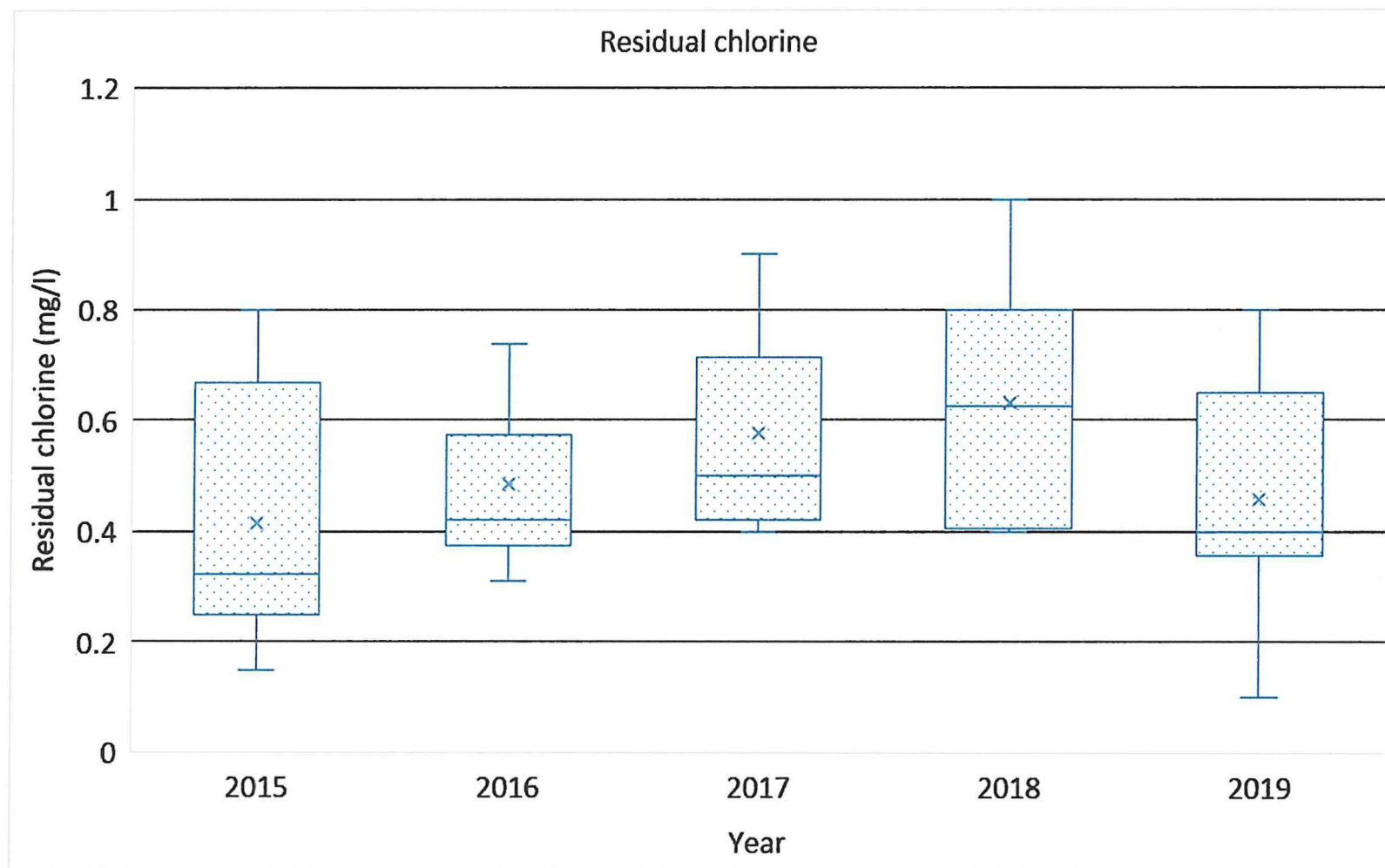


Figure 4-12: Residual chlorine variations along the distribution network in different years

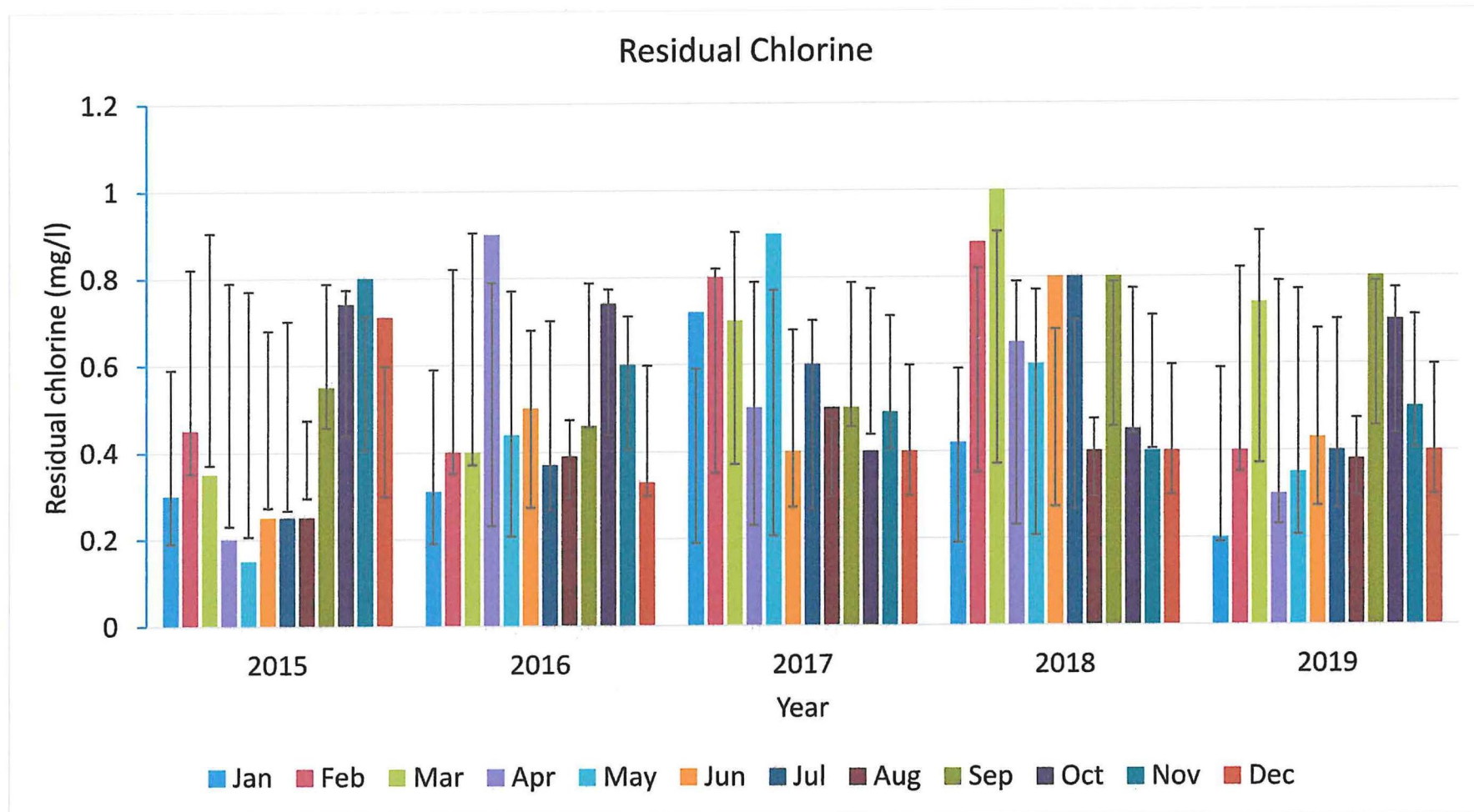


Figure 4-13: Residual chlorine variations along the distribution network in different years

4.2.4 Temporal variations in pH

The analysis discovered that water quality in the distribution line has been declining over the previous five years (2015 to 2019). pH range of 6.3 to 7.8 which were within the set standards of 6.5 - 8.5 (UNBS, 2014). In the month of October 2016, the pH was below the UNBS (2014) standard.

In general, the average pH was decreasing between the years 2015 to 2019 at a rate of -0.032. However, considering each month over the years didn't show any systematic pattern but most of the months showed a decrease over the years. The months of March to December showed a decreasing trend over the years with a decreasing trend range of -0.120 to -0.020 (Figure 4-15; 4-16). In the same way some months showed an increasing trend ranging from 0.0010 to 0.070 mainly in the months of January to August (Figure 4-15; 4-16).

Figure 4-15 shows boxplots varying with months where no outliers were found. The month of October showed the highest variation while December showed the highest results. The graph showed no specific pattern with the months. Figure 4-17 showed outliers in 2016 but the data was normally distributed. pH was decreasing over the years.

An increase in pH in water quality indicates alkaline water that is normally caused by different effects. Water with high pH tends to taste bitter but has no side effects to humans. Increase in temperature leads to increased pH which may also be as a result of increased carbonates in water (Ole et al., 2013), (Figure 4-14). The other factor that causes pH increase is when chlorine reduces or is degraded. The age and type of the pipe may also affect the pH.

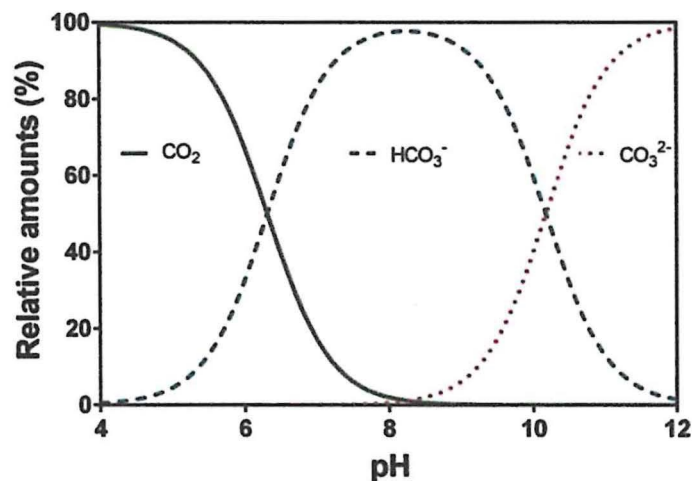


Figure 4-14: PH variations with carbonates

(Source: Adapted from Ole et al., 2013)

When the pH in water decreases then the water is termed acidic which may have a few side effects like corrosion and wearing away of pipes thus leading to leakages. This effect goes further and affects home appliances like saucepans, kettles and boilers. The major causes of decreased pH include presence of gases in water like carbon dioxide that tend to decrease the pH (Figure 4-15; 4-16; 4-17; 4-18). High residual chlorine is another factor that may lower the pH levels and the use of aluminium sulphate for water treatment that tends to suppress the water thus lower pH levels (NWSC, 2020). This was evident in 2018 and 2019 where it is reported that aluminium sulphate was the major coagulant used at the water treatment plant (NWSC, 2020). The pH trends are closely related to the weather patterns and seasons.

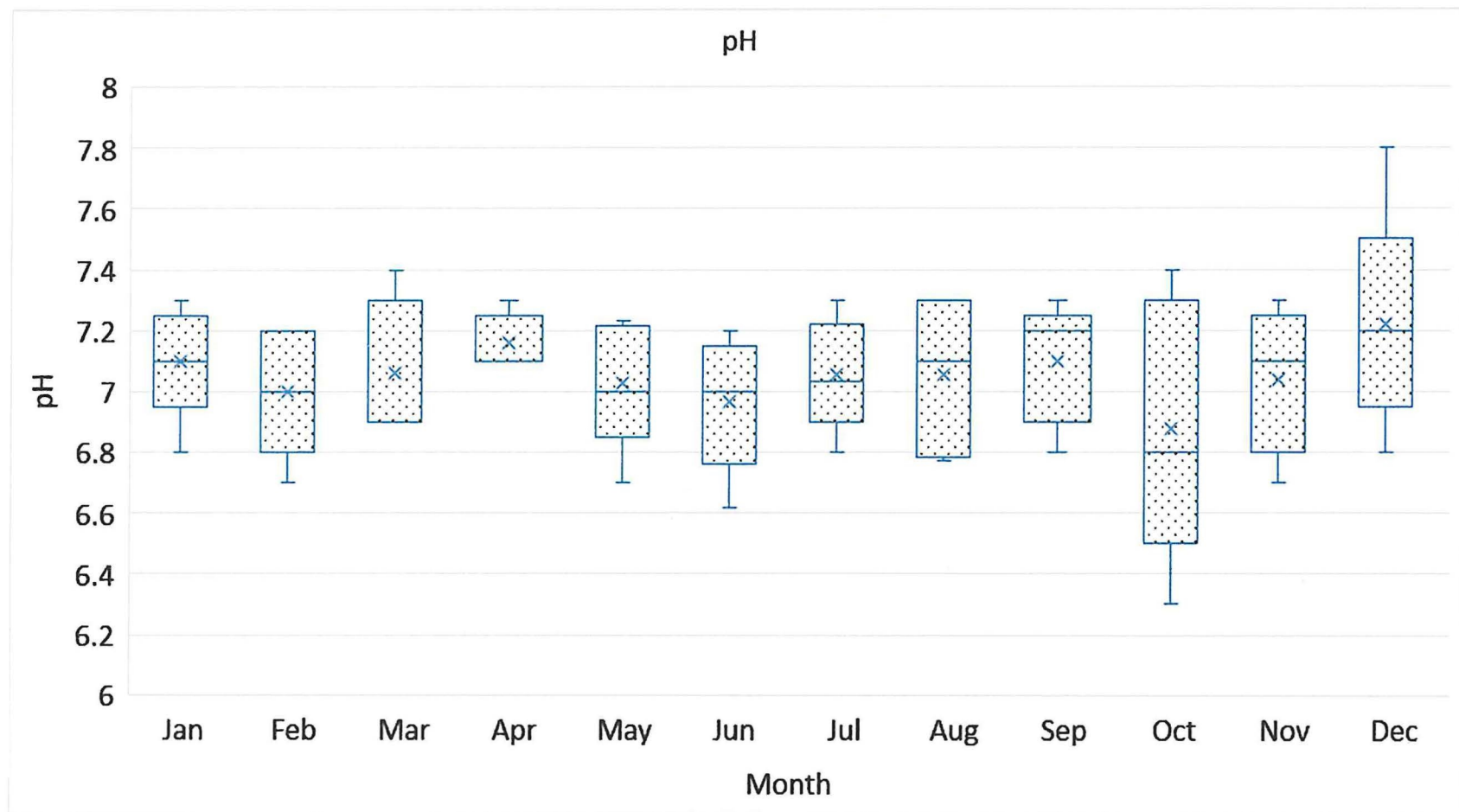


Figure 4-15: pH variations along the distribution network in different months

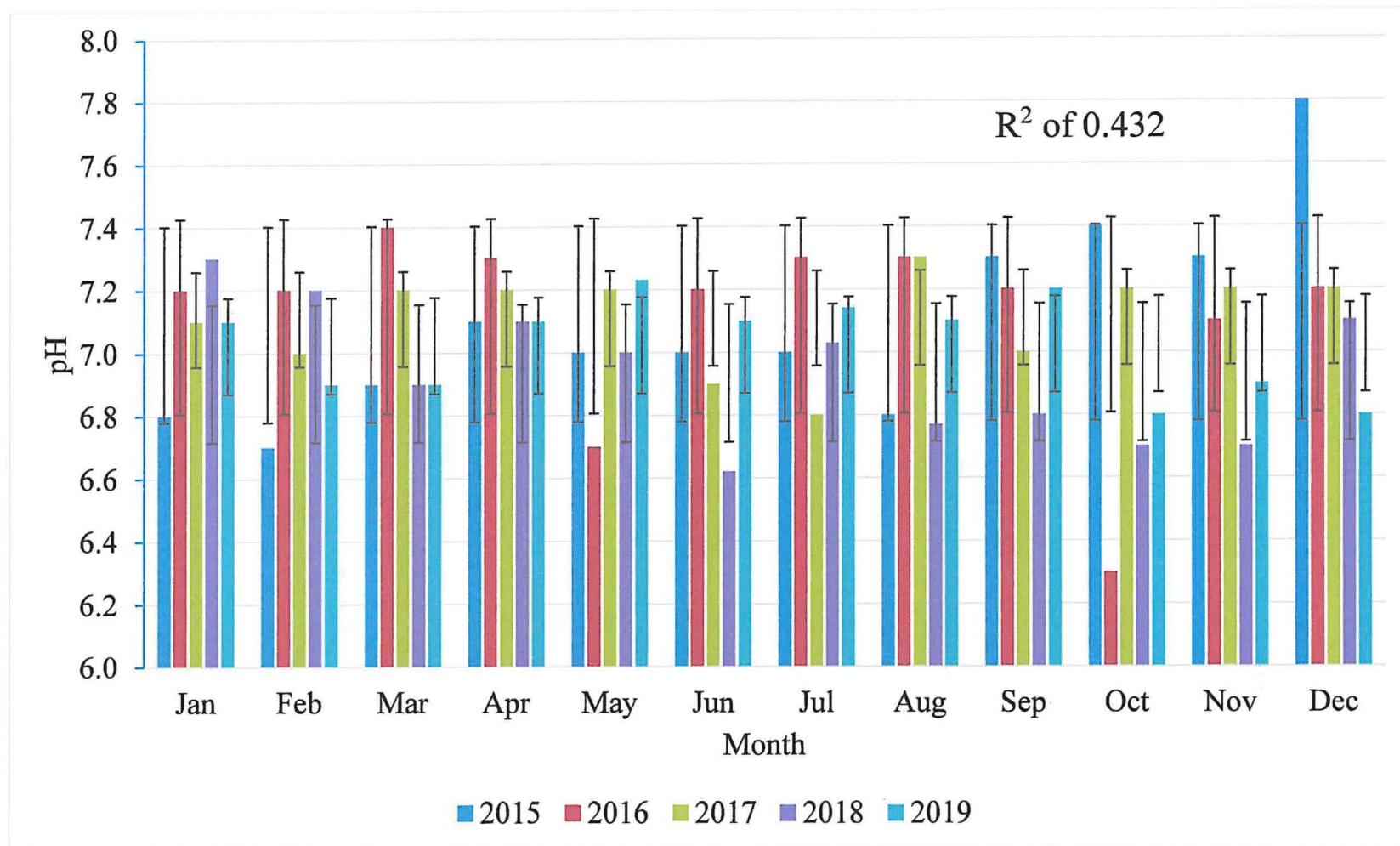


Figure 4-16: Average physical parameters of pH on consumer point

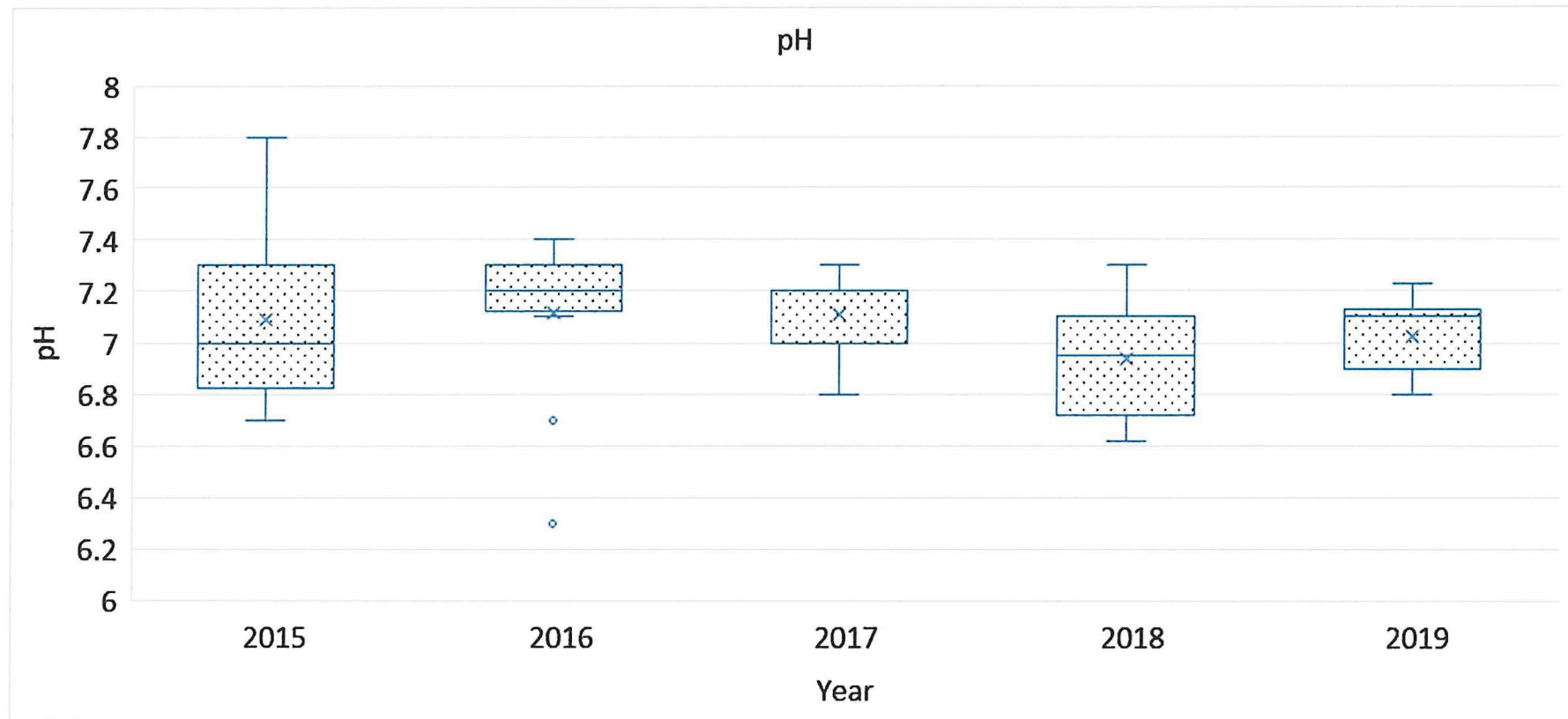


Figure 4-17: pH variations along the distribution network in different years

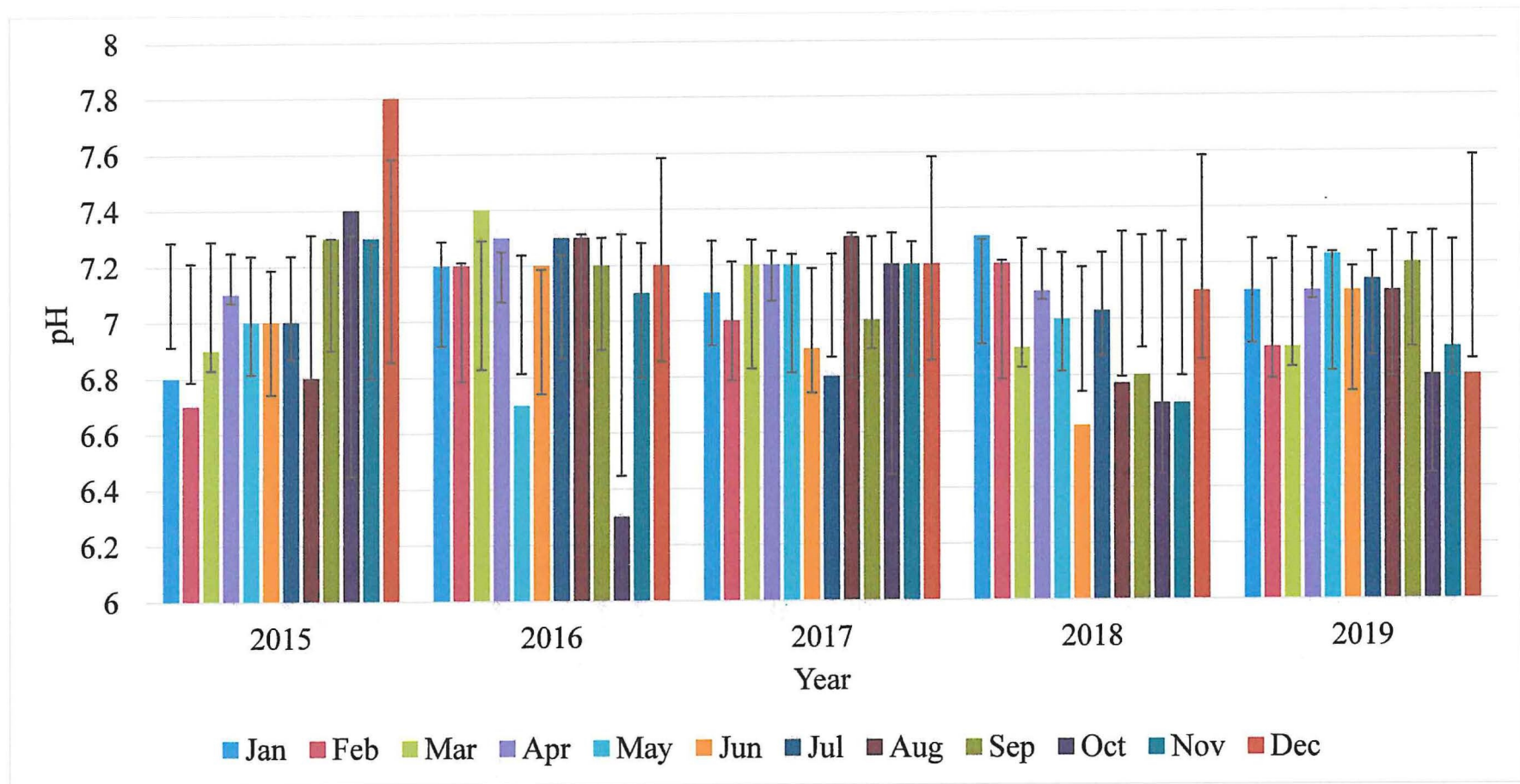


Figure 4-18: Average physical parameters of pH on consumer point

4.3 Objective 2: Assessing the spatial and temporal variation of treated water characteristics at the consumer points

Variations along the service lines in Ggaba parish were described by water quality data sampled at draw off points and storage tanks for home use from June to August, 2019 as presented in subsequent sections. Six sampling points were used to fulfil this objective and they were distributed with some distance from the main source of distribution as shown in Figure 3-1.

4.4 Correlations

A linear regression model was run for colour and turbidity on the samples collected from the direct connections (DC) and the storage tanks (ST). Both DC and ST showed high correlations between turbidity and colour. This has been found in other studies (Amfo-Out et al., 2011). The linear relationship between turbidity and colour for storage tanks yielded R^2 values of 0.8797 while the power trendline yielded R^2 of 0.9293 (Figure 4-20). The power trendline showed a better fit as compared to the linear relationship. The linear relationship between turbidity and colour for direct connection yielded R^2 values of 0.8328 while the power trendline yielded R^2 of 0.8303. The linear trendline showed a better fit compared to the power (Figure 4-20). This is simply because when samples were collected from the DC there was high pressure that may lead to agitation of the particles present in the water. The residual errors on the fitted model describing the linear relationship between turbidity and colour were larger for DC than ST. In other words, the plotted points were more scattered along the fitted model for DC than that of ST. This is because the samples were collected from tanks where water has been allowed to settle out. The dissolved organic matter in the water tends to increase when the water is left to settle thus the results being close to each other (Nasrabadi et al., 2016)

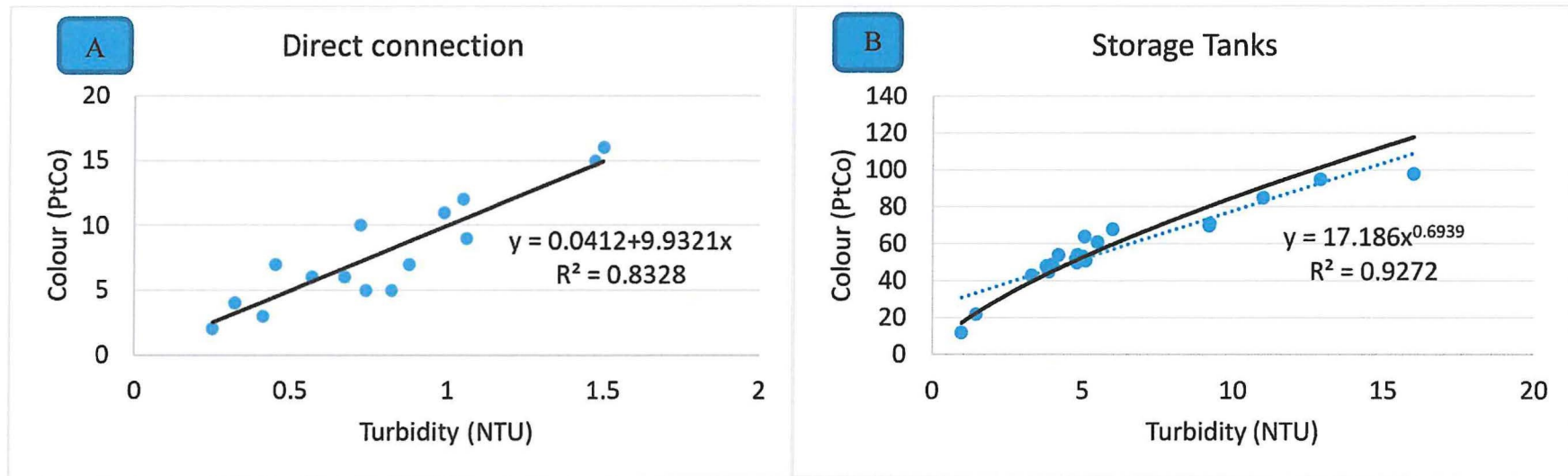


Figure 4-20: Scatter plots of turbidity and colour for A) direct connection and B) storage tanks

4.5 Direct connections (DC) and storage tanks (ST)

4.5.1 Turbidity

In general, the turbidity of water at the DC points were within the drinking water standards (UNBS, 2014) and lower than the ST points. The average turbidity for the DC points ranged from 0.3-1.2 NTU meeting the drinking water standards (UNBS, 2014) with Bunga recording the highest value and Kalungu having the lowest value. The average turbidity for the ST points ranged from 3.7-6.8 NTU with Katuso recording the highest value which didn't meet the drinking water standards and Kalungu having the lowest value (Figure 4-21). The mean of turbidity for the samples collected from DC was 0.76 ± 0.38 NTU while the mean of turbidity for the ST samples was 5.96 ± 3.7 NTU. The *t*-test results revealed that the DC points were statistically significantly different from the ST points with $p = 1.2579\text{E-}06 < 0.05$ (Table 4-1).

Table 4-1: Turbidity *t*-test results

	<i>Storage tanks</i>	<i>Direct connection</i>
Sample Size	33	11
Mean	5.955238095	0.7635625
Variance	13.70774619	0.147316396
Observations	21	16
Hypothesized Mean Difference	0	
<i>df</i>	21	
<i>t</i> Stat	6.381057048	
<i>p</i> ($T \leq t$) one-tail	1.2579E-06	
<i>t</i> Critical one-tail	1.720742903	
<i>p</i> ($T \leq t$) two-tail	2.5158E-06	
<i>t</i> Critical two-tail	2.079613845	

The quantity of light scattered by any foreign item in the water is measured as turbidity. When the intensity of the dispersed light increases, so does the turbidity. This is in line with the correlation of the total suspended solids (USGS, 2014). The main reason why the turbidity is higher in the Storage Tanks compared to the Direct Connections was because of the following reasons;

- i). Silt accumulation in the storage tanks due to lack of proper storage covers
- ii). Algae growth / Bloom due to contamination from bird and animal faeces
- iii). High resident time of water in ST as compared to DC

These reasons among others tend to change the appearance of water and in turn deteriorate the quality of water.

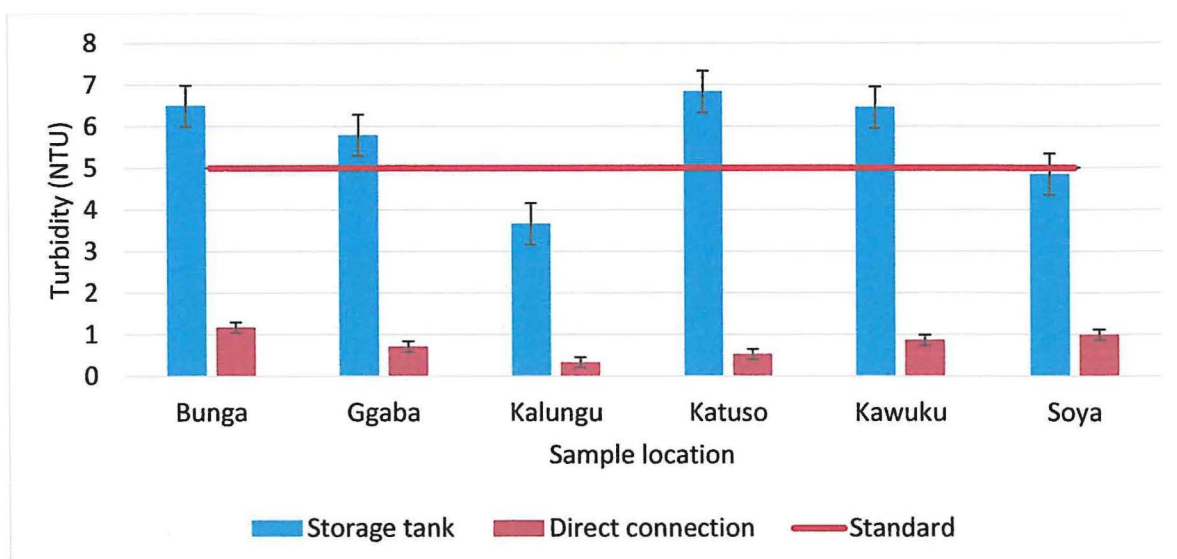


Figure 4-21: Average turbidity along with WHO standard

4.5.2 Colour

Colour is organic matter that has dissolved in solution, the colour of water from the DC points was within the drinking water standards (UNBS, 2014) unlike the ST points where none of them met the standards. The average colour for the DC points ranged from 3 to 11 PtCo with Soya and Bunga recording the highest values and Kalungu having the lowest value but all meeting the drinking water standards (Figure 4-22). The average colour for the ST points ranged from 46 to 61 PtCo above the UNBS (2014) standard with Kawuku recording the highest value and Kalungu having the lowest value. The samples collected from storage tanks didn't meet the standards of 15 PtCo (Figure 4-22). The mean colour for the samples collected from DC was 8 ± 4.1 while the mean colour for the ST samples was 57 ± 20.5 PtCo. The *t*-test results revealed that the DC points were statistically significantly different from the ST points with $p = 1.74333\text{E-}10 < 0.05$ (Table 4-2).

Table 4-2: Colour *t*-test results

	<i>Storage tanks</i>	<i>Direct connection</i>
Sample Size	33	11
Mean	56.80952381	7.625
Variance	420.9619048	17.45
Observations	21	16

Hypothesized Mean Difference	0	
<i>df</i>	22	
<i>t</i> Stat	10.69824781	
<i>p</i> ($T \leq t$) one-tail	1.74333E-10	
<i>t</i> Critical one-tail	1.717144374	
<i>p</i> ($T \leq t$) two-tail	3.48666E-10	
<i>t</i> Critical two-tail	2.073873068	

The dirt in the water tends to settle at the bottom of the tank and samples were collected from the bottom after mixing the water. This then depicts the high colours in the water. The algae growth and die off also tends to increase the colour and turbidity of water. When the algae dies off, it increases on the organics thus increasing the colour of the water thus affecting the pH either upwards or downwards.

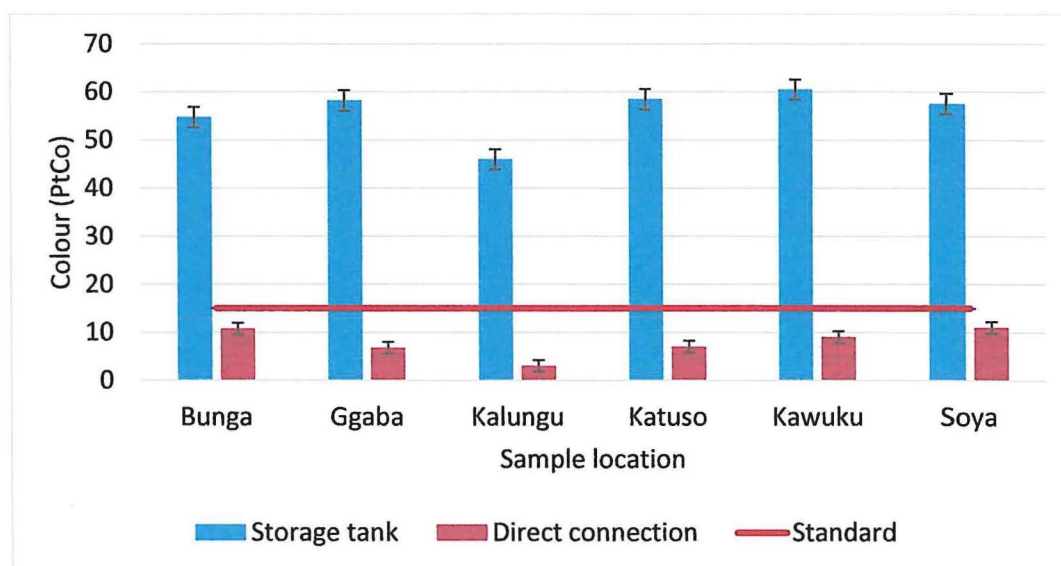


Figure 4-22: Average colour along with WHO standard

4.5.3 Free chlorine

The recommended free chlorine range for potable water is 0.2-0.5 mg/l (UNBS, 2014). The ST ranged from 0.02-0.37 mg/l with four sampling points meeting the standards and two not meeting the standards. Katuso had the highest values while Soya had the lowest (Figure 4-23). The DC points all met the standards ranging from 0.24-0.73 mg/l. Ggaba had the highest and Kawuku had the lowest. The mean free chlorine for the samples collected from DC was 0.56 ± 0.16 while the mean free chlorine for the ST samples was 0.25 ± 0.13 . The *t*-test results revealed that the DC points were statistically significantly different from the ST points with $p = 6.06599E-07 < 0.05$ (Table 4-3).

Table 4-3: Free chlorine *t*-test results

	<i>Storage tanks</i>	<i>Direct connection</i>
Sample Size	33	11
Mean	0.254761905	0.56125
Variance	0.01659619	0.027051667
Observations	21	16
Hypothesized Mean Difference	0	
<i>df</i>	28	
<i>t</i> Stat	-6.153158916	
<i>p</i> ($T \leq t$) one-tail	6.06599E-07	
<i>t</i> Critical one-tail	1.701130934	
<i>p</i> ($T \leq t$) two-tail	1.2132E-06	
<i>t</i> Critical two-tail	2.048407142	

Because of the distance between the water treatment plant and reservoir tank, free chlorine was highest in Ggaba parish and lowest in Soya parish. The Ggaba sample station receives water directly from the treatment plant, whereas Soya receives water from the reservoir tank and is positioned near the distribution network's dead end. The chlorine is also highest in the DC compared to the ST because in the tanks, the organic matter tends to accumulate with time during which the water is stored in the tank thus consuming all the available chlorine. Furthermore, chlorine decay is a function of time. In other words, the concentration of chlorine reduces exponentially with time. Because DC has freshly dosed chlorine still available to disinfect water, water in the DC is expected to have higher concentration of chlorine than the ST. The regrowth of microorganisms also consumes the available chlorine in the water (Karikari and Ampofo, 2013).

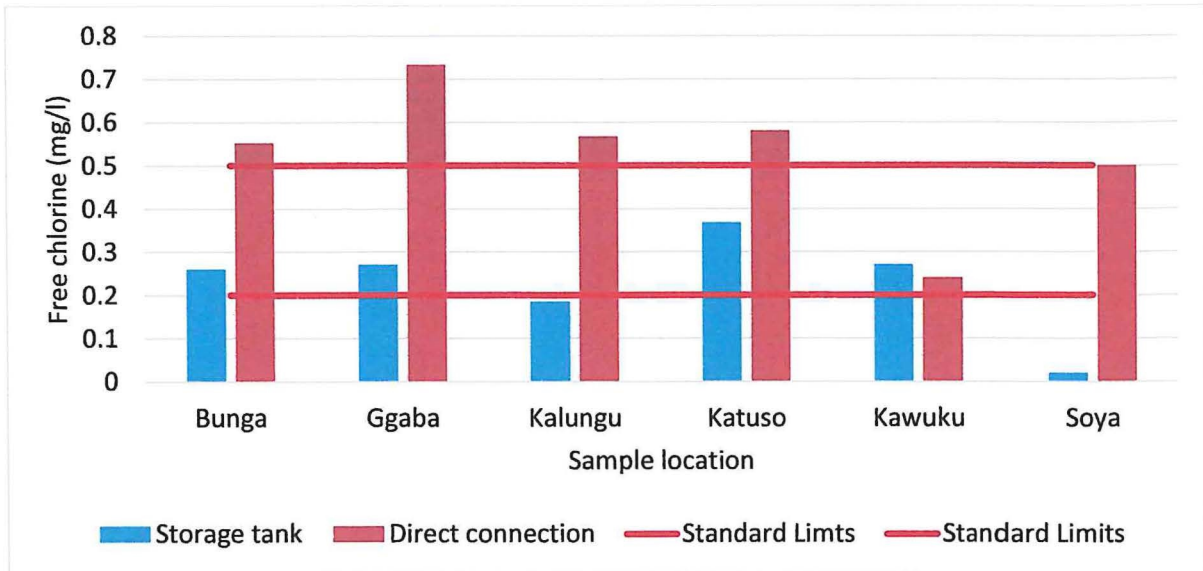


Figure 4-23: Average free chlorine along with WHO standard

4.5.4 Faecal coliforms (FC)

The DC sampling points showed no contamination with faecal coliforms of 0 CFU/100mls while the STs showed contamination in all parishes with Soya giving the highest value and Ggaba showing the lowest (Figure 4-24). The values that Soya presented are attributed to a number of reasons one being the low chlorine values all through the study period. This increases the chances of bacterial regrowth thus contamination (Karikari and Ampofo, 2013). The factor of distance is very important and plays a special role in this case. The Soya sampling point is at the dead end of the distribution line (NWSC) and storage of water in tanks is very common. The mean Faecal coliforms for the samples collected from DC was 0 ± 0 while the mean of Faecal coliforms for the ST samples was 5 ± 8 . The *t*-test results revealed that the DC points were statistically significantly different from the ST points with $p = 0.004824461 < 0.05$ (Table 4-4).

Table 4-4: Faecal coliforms *t*-test results

	<i>Storage tanks</i>	<i>Direct connection</i>
Sample size	33	11
Mean	5.047619048	0
Variance	65.34761905	0
Observations	21	16
Hypothesized Mean Difference	0	
<i>df</i>	20	
<i>t</i> Stat	2.86141819	

$p(T \leq t)$ one-tail	0.004824461	
t Critical one-tail	1.724718243	
$p(T \leq t)$ two-tail	0.009648922	
t Critical two-tail	2.085963447	

The increase in FC is related to the seasonal changes since the study was done from a rainy season to a dry season of August (Tripathi and Sharma, 2011). The high faecal contamination is also related to untimely cleaning of storage tanks (NWSC, 2020), regrowth of microorganisms due to low residual chlorine present in the water (Karikari and Ampofo, 2013), lack of covers on the tanks that expose the tanks to contaminations from birds and other factors. The low FC at the Ggaba point was as a result of the residual chlorine that is present in the water and is able to continue killing all microorganisms (Karikari and Ampofo, 2013).

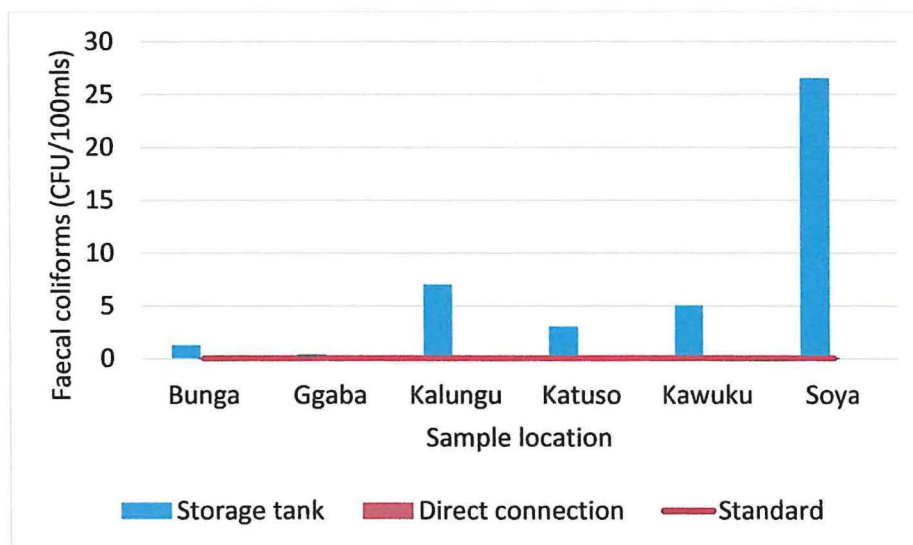


Figure 4-24: Average faecal along with WHO standard

4.5.5 pH variations

pH for both DC and ST were in the range of acceptable drinking water standards of 6.5 to 8.5 (UNBS, 2014). Soya had the highest pH for the ST while Ggaba had the lowest. For the DC Ggaba had the highest and Soya had the lowest (Figure 4-25). pH was in very close range for the ST sampling points with minimal deviations as indicated by the error bars. However, the DC points varied about which may be due to the incoming water on the different days (Figure 4-16). The mean pH of the DC samples was 7.20.299, while the mean pH of the ST samples was 7.30.45. With $p = 0.147807382 > 0.05$, the t-test findings demonstrated that the DC points were not statistically significantly different from the ST values (Table 4-5).

Table 4-5: pH *t*-test results

	<i>Storage tanks</i>	<i>Direct connection</i>
Sample size	33	11
Mean	7.336190476	7.205
Variance	0.203434762	0.089053333
Observations	21	16
Hypothesized Mean Difference	0	
Df	34	
<i>t</i> Stat	1.062237879	
<i>p</i> ($T \leq t$) one-tail	0.147807382	
<i>t</i> Critical one-tail	1.690924255	
<i>p</i> ($T \leq t$) two-tail	0.295614764	
<i>t</i> Critical two-tail	2.032244509	

As explained in objective 1, pH may increase is when chlorine reduces or is degraded which is the case in point for the storage tanks where the chlorine levels were low thus low pH. The age and type of the pipe may also affect the pH.

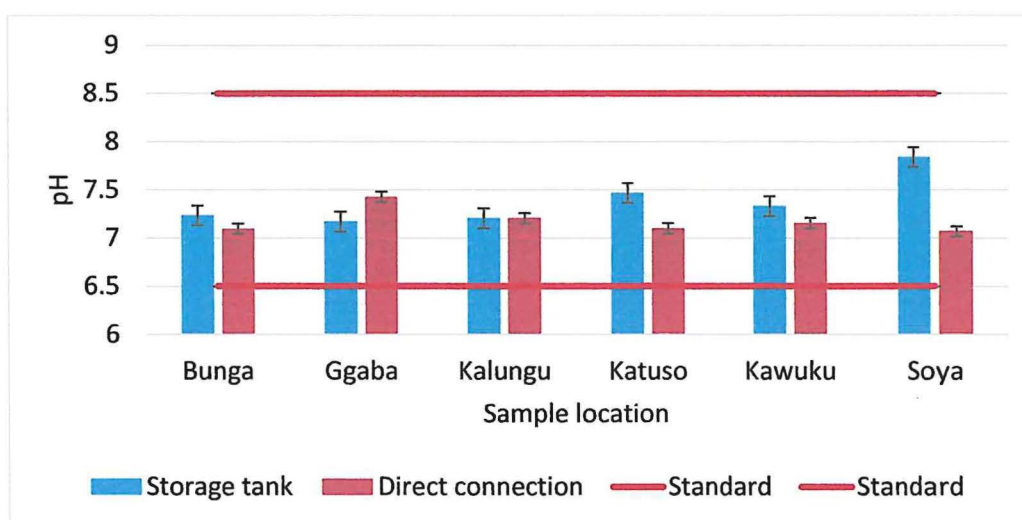


Figure 4-25: Average pH for storage along with WHO standard limits

4.6 Objective 3: Determining the possibility of intrusion of contaminants along the distribution network and consumer points

Under this section, possible sources of contaminants and their pathways into both the distribution network and consumer draw off points are presented and discussed. This information was obtained from the sampling campaigns carried out and with the help of a checklist and questionnaire administered at the consumer draw off points. This helped to give an understanding in regards to contaminant sources and their pathways into the distribution

network, consumer draw off points and storage tanks. The possible routes of contamination are explained below which include: pipe material, storage tanks, pipe leakages on the main lines and at home premises.

4.6.1 Pipe Material and age

The examined consumer points were mostly made up of High-density polyethylene (HDPE) pipes and Galvanized Iron (GI) pipes of 15 mm diameter average sized pipes (26), which were subject to leaks. Despite the benefits of HDPE pipes, such as their low cost and lack of corrosion, they are also very susceptible to fast fracture propagation, making them more vulnerable to pollutant infiltration at distribution and consumer points. GI is supposed to be the most efficient, although it has a high accident rate (Saghi and Aval, 2015). The age of the pipe is a very big factor that is considered in detecting the causes of leakages (Saghi and Aval, 2015). GI are said to last 15 years while HDPE is said to be 16 years (Tabesh and Karimi, 2006; Saghi and Aval, 2015). The loss of water is said to increase with increase in the age of the pipe (Saghi and Aval, 2015; Schouten and Halim, 2010).

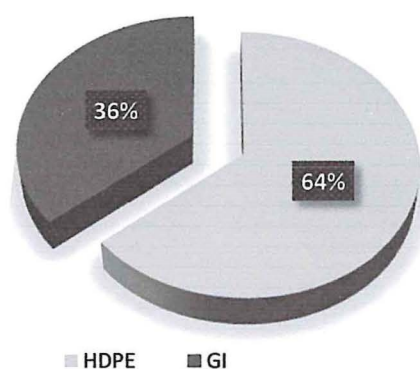


Figure 4-26: Pipe material

4.6.2 Pipe Leakages

Along with the water quality analysis of the distribution network through its monitoring stations data provided, further analysis was done concerning the leakages and bursts happening in the study area. The data was obtained from both NWSC data at the branch and interviews done during the study. The data on bursts and leakages indicated that 2019 recorded the highest number of bursts (Figure 4-27). This may be attributed to the so many road constructions and repairs taking place in the area. These leakages may be a source of intrusion

and later contamination. However, the data from the distribution network indicated that the colour levels were higher in 2019. This shows that in between the tank and the network has something leading to a change in the colour levels. This leads us to point out one of the causes being the leakages and bursts in the distribution network.

Leakages and bursts are mainly caused by intentional cutting of pipes, accidental cutting of pipes during excavation and road construction, high water pressure on the line, drastic changes in temperature which affects the pipe type, pipe corrosion and seal damages (Rooter, 2018; Saghi and Aval, 2015).

These leakages are observed and reported by different people. Some are observed and repaired by the branch personnel and others are reported directly to the call centre office (NWSC, 2019).

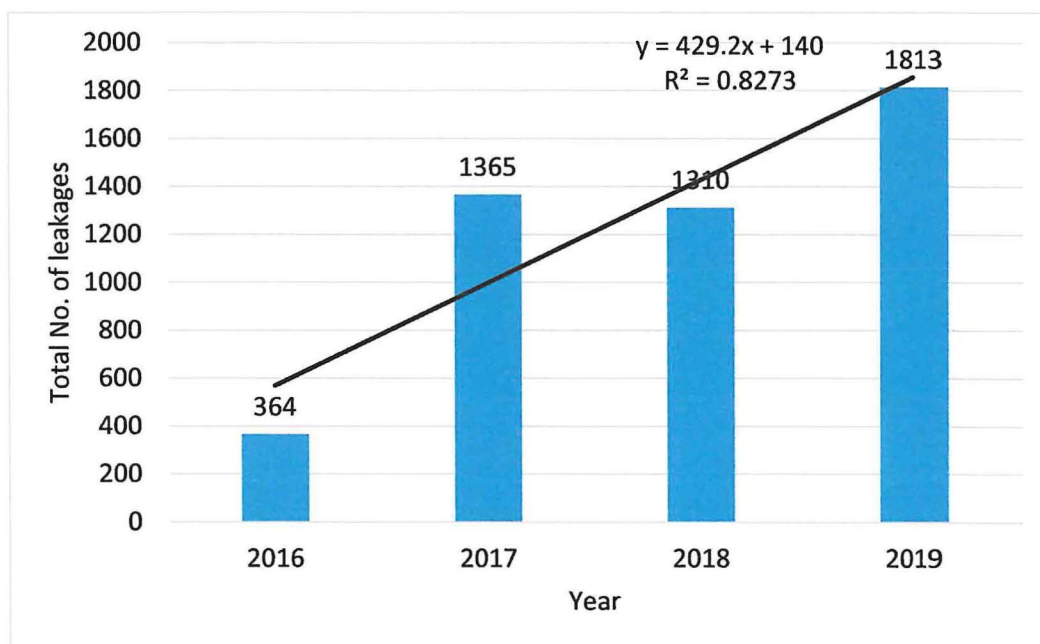


Figure 4-27: Total number of leakages from 2016 to 2019

The study established a significant variation in the number of leakages between 2016 and 2019 as per the assumed level of significance (3.7.1 Statistical testing for differences between means of samples). The data showed that 60% of the leakages were burst leakages which were reported and detected. The background leakages that seem to be low tend to have higher impact as they aren't detected easily by the public or operators hence deteriorate the water quality in terms of colour and turbidity (Clayton et al., 2010).

All the materials used in joining pipes end up leaching some substances into the water leading to more contamination in the water (NRC, 2006). Depending on the material of the pipe, the quality of water may cause corrosion in the pipes. Residual chlorine was highest in the direct connections which may be a high source of corrosion.

4.6.3 Storage tank facilities

The major water storage alternatives for these residential areas are storage tanks which obtain water directly from the water supply distribution network and rainwater. From the data collected, it was noted that storage tanks (ST) had the highest level of contamination (Figure 4-24).

The plastic material of storage tanks comprised 81% of all the total number of tanks sampled followed by metallic tanks (19%) (Figure 4-28). The high turbidity at draw off points was due to the ST that tended to combine both rainwater and treated water from the distribution lines. The dust and other organic content on the roof are drained straight into the tank hence contaminating the water.

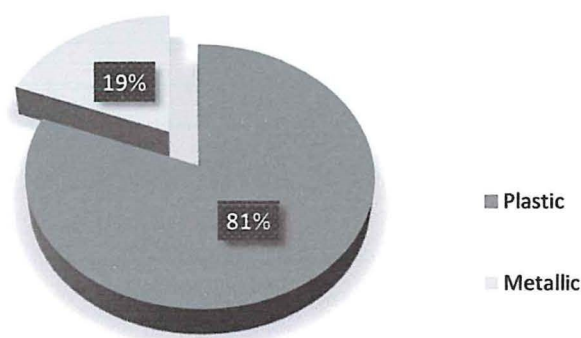


Figure 4-28: Storage tank material

Storage tanks have helped in combatting water shortages in dry spells but this also comes with the principle of cleanliness and hygiene. Contaminants have utilized the roofs as an entry point into these storage tanks and if not cleaned regularly, water quality tends to go bad. Data showed that 58% of the water consumers washed their tanks (Figure 4-29) of which 43% washed their tanks in 1 year and 6 months while 14% washed every 3 months (Figure 4-30). 10% washed the tanks with water only 60% and 40% used detergent coupled with sponges and brushes (Figure 4-31).

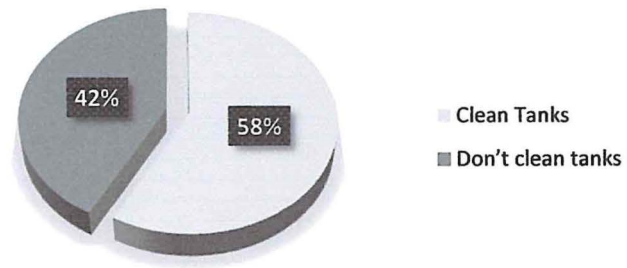


Figure 4-29: Consistency in washing Tanks

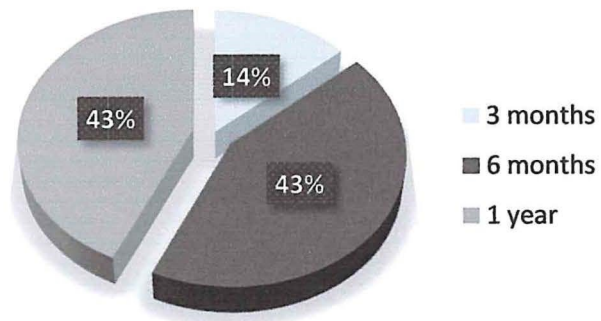


Figure 4-30: Duration of washing tanks

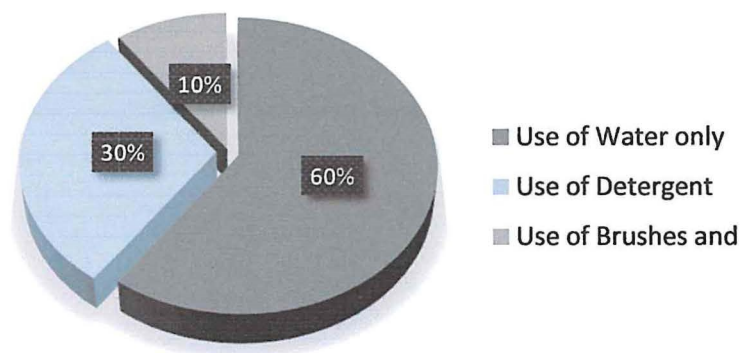


Figure 4-31: Tank washing mechanism

In the field study pH was recorded highest in the storage tanks (Figure 4-25) and depending on the type of tank used especially metallic may have a higher rate of corrosion. The end products of corrosion may then alter the quality of the water in turn causing an increase in colour and turbidity (NRC, 2006).

From the survey the data generated was presented graphically as indicated in Figure 4-32. The results indicated that most of the sampling points had a storage tank at their premises (Appendix1).

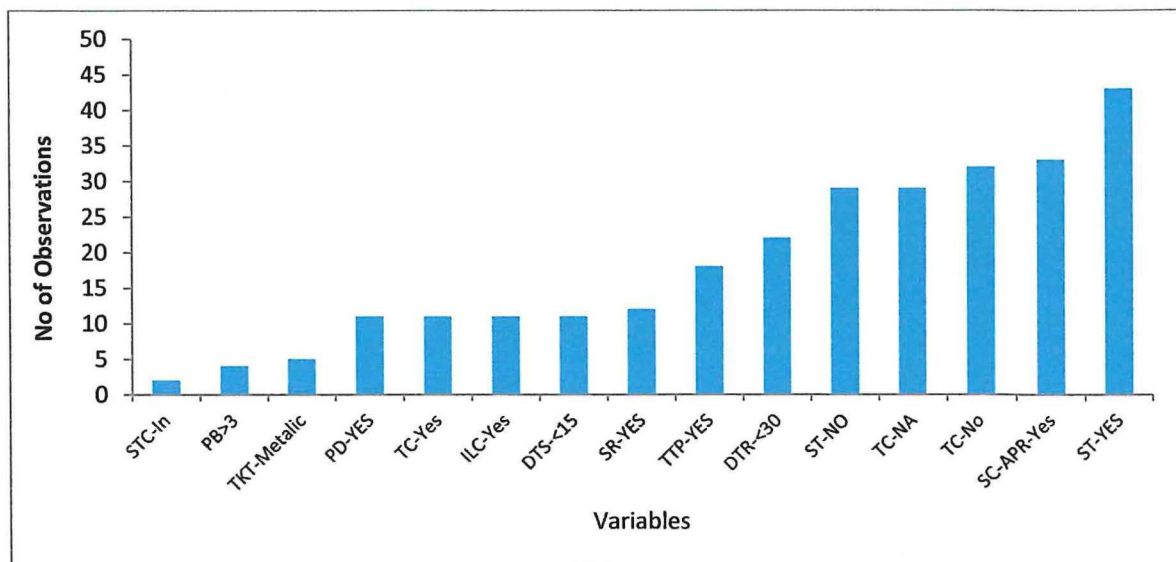


Figure 4-32: Number of observations from qualitative data.

Site of connection	STC-In
Pipe burst < 3 months	PB<3
Tank Type Metallic	TKT-Metallic
Poor drainage	PD-Yes
Tank cleaning	TC-Yes
Illegal connections	ILC-Yes
Distance from Sanitation Facility <15m	DTS<15
Sign of rust	SR-Yes
Tank Type Plastic	TTP-Yes
Distance from road	DTR<30
Don't have a Storage Tank	ST-No
No Tank cleaning	TC-No
Surface/ Apperance of pipes	SC-APR-Yes
Storage Tank	ST-Yes

4.6.4 Contaminant area of influence

Assertion to the surrounding of the draw off points, area of influence was analysed with possibility of contamination intrusion. The proximity of sampled areas to the closed access road and activities carried out close to the consumer points. Proximity of the sampled points was analysed and data showed that majority of the sampled points (Figure 4-33) were in a proximity of 10 – 20 metres (48%) from the closest main road, followed by 20 – 40 metres (32%), hence justifying the 33% cause of damage of the service lines.

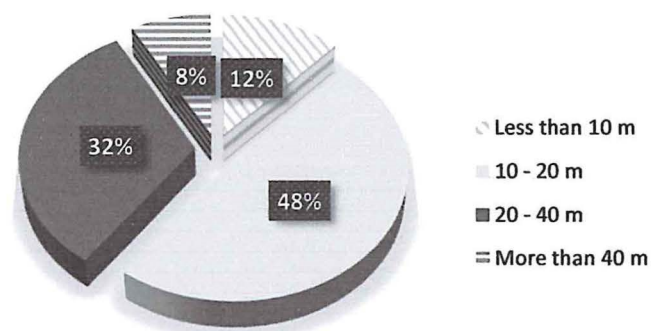


Figure 4-33: Distance of sampled points from main road

Considering an average of 15 metre zone of influence, surrounding areas were analysed to understand the activities carried out in close proximity to the sampling points. Within the 15 m diameter, data showed that 35% of the sampled areas were surrounded by drainage systems (Figure 4-34), toilets (30%) followed by garbage pits (25%), this justified the presence of E.coli and faecal matter in Soya village water samples.

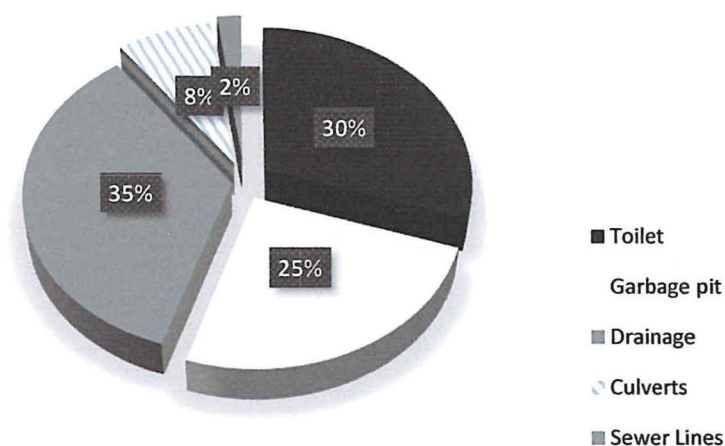


Figure 4-34: Surrounding of the sampling points

Contamination may be secondary, internal or external (Jachimowski, 2017). The external factors include intrusion from leakages and bursts while internal may be as a result of reactions and transformations (Figure 4-35). Water quality may be degraded due to different factors and transformations that take place within the pipe network, the service tanks, residential storage tanks and premise plumbing (NRC, 2006).



Figure 4-35: Pipe network in Soya

Seasonal changes may also be another factor leading to variations in water quality. High temperatures may lead to chlorine decay and changes in organic matter. However, in the rainy season several leakages and bursts are seen which may act as sources of intrusion for contamination (from interviews).

Growth of bacteria on surfaces as biofilms may also increase and lead to contamination. Precipitation of residual aluminum may cause scaling. Sarin et al. (2004) discovered that when flow standstill occurs, iron scales and releases iron, increasing the levels of color and turbidity. iron scales release iron during flow stagnation, resulting in murky and colored water

4.7 Chapter summary

Chapter 4 was a summary of results obtained from the data obtained both primarily and secondary. The chapter went on to discuss how the research combined the three objectives with the data collected. The data was then analyzed with Microsoft Excel and SPSS. Conclusions were written in Chapter 5 based on the findings in Chapter 4.

5 CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS.

5.1 Conclusion

Objective 1: Investigating of temporal variation of treated water characteristics along the distribution network.

Analysis of data obtained from NWSC indicated that all the physio-chemical parameters were increasing over the years studied apart from pH. The free chlorine levels were high which is directly correlated with the levels of contamination. The water quality varied through the years.

Turbidity was found to increase with time from 2015 to 2019 at a rate of 0.145 NTU per year. The highest turbidity values were obtained in 2018. Colour increased at a rate of 1.18 PtCo per year with 2018 giving the highest reading and 2016 giving the lowest. The months of May and August had the highest colours. Residual chlorine for the period 2015-2018 had an increasing trend at a rate of 0.0247 and was found highest in 2018. The month of March recorded the highest residual chlorine while the month of May recorded the lowest residual chlorine. The pH was within the standards all through the years with December recording the highest results and October recording the lowest result. However, all through the years pH has a decreasing trend at a rate of -0.032 per year.

Objective 2: Quantification of the Spatial and temporal variation of treated water characteristics at the draw off points and customer tanks.

The results from objective two indicated levels of intrusion in the distribution network which was as a result of the pipe leakages, and pipes going through stagnant water points. This was also evident with the contamination experienced at consumer points. The pollution was caused by the distribution system's aged ductile iron/steel pipes. Water quality indicators change throughout time and space, independent of proximity to the main distribution.

The mean values of turbidity in water sampled from direct connections and storage tanks were 0.76 ± 0.38 NTU and 5.96 ± 3.8 NTU respectively. The average colour for the direct connections was 8 ± 4.1 PtCo while the storage tanks had 57 ± 20.5 PtCo. The direct connections and storage tanks showed significant differences where $p = 1.74333E-10$. The residual chlorine recorded for the direct connections was found to be 0.56 ± 0.16 mg/l while the storage tanks recorded 0.25 ± 0.13 mg/l. The t-test revealed that these mean values were substantially different ($p < 0.05$).

The water quality from direct connections was clearly better than that from storage tanks. However, given the city's inconsistency in water delivery, storage tanks may be a viable choice for storing water in Kampala if adequately covered and maintained (regular cleaning).

Objective 3: Investigating the possibility of intrusion of contaminants along the distribution network and consumer points.

Drinking water contamination was caused mostly by external and internal sources. Pipe material, storage tanks, pipe leakages on main lines, and cross contamination at home premises were all potential sources of contamination. The number of people who don't clean their tanks was 58% of the study area, the percentage of those who clean tanks after one year or six months was 43% for each while the sampling points that had pipes running through drainages was 35%. All these are major sources of contamination of the drinking water.

In spite the fact that water, a critical resource for human and environmental livelihood is abundant, on a closer inspection today, contamination characterization is on the rise. In reality of water pollution, NWSC, Uganda's public utility company has sustainably and equitably provided cost effective quality water through its networks as affirmed by the significant water quality sustained levels. This study established that in spite the fact that water in the service network is of significant ($p < 0.05$) quality (bench marked on STD), there was a significant variation ($p < 0.05$) from its quality in between water direct connections and storage tanks attributed to increased leakages along the lines and draw points. Kawuku had the highest deviation whereas Soya was characterised to be most contaminated village in the project area basing on storage tanks sampled.

5.2 Recommendation

Unaccounted-for water is significantly more prevalent in underdeveloped nations than in rich countries. It has been demonstrated that when distribution system operations and maintenance diminish, unaccounted-for water levels rise fast. Understanding the site of incursion as primarily being roof catchment to storage tanks, then polluted consumer pull off points, and finally leakages in the distribution network, research suggestions included:

- i. Provision of multiple point source strategies including multiple monitoring stations on the distribution network to help test the varying water quality as it reaches the end

users. Furthermore, provide more chlorination points to further improve on the final quality of the water received by the user communities.

- ii. Provision of leak detection mechanism coupled with swift repairs so as to avoid possible contaminant intrusion into the system. This also involves prompt checking and rehabilitation of aging pipes and valves. This will help keep the distribution network fully functional and efficient.
- iii. Sensitization of communities on regards to rainwater harvesting and usage. This will involve but not limited to workshops and training sessions on how to care for tanks and any other apparatus used to collect and harvest water. Prompt cleaning is to be emphasised with post chlorination being the ideal way of disinfecting.
- iv. Provision of guidelines and laws for proximity of sanitation facilities and drainage systems from distribution networks so as to avoid contaminant intrusion.
- v. Using a model-based technique to assess pollutant penetration at various locations throughout the water supply system.

Pipe and tank materials are among the elements contributing to degradation of water quality in the distribution network, which requires additional attention. All materials used in the pipe and distribution system must be standardized and capable of handling the water quality provided. More research may be required to maintain an effective water distribution system. More sensitization is required in residential areas in order to lower pollution levels.

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APPENDICES

Appendix I: Self-Administered Questionnaire

Dear Respondent, I am a student of Kyambogo University pursuing a Master's degree in Water and Sanitation Engineering. I am conducting a study on the **assessment of the extent to which the variation in treated water quality can be linked to possible intrusion of contaminants in Makindye division, Kampala**. I would be grateful if you avail me with the information relating to the above topic for research purposes. Be assured that the information you provide will be used for this study and will be treated with maximum confidentiality.

GENERAL INFORMATION:

- 1) District: 2) Division:
3) Parish: 4) Village:

HOUSEHOLD DATA

- 5) Respondent name:
6) Household Identification/sample Number.....
7) What is the highest level education of the head of family? *(Tick or circle from the options)*
- i) No formal education
 - ii) Primary education
 - iii) Secondary Education
 - iv) Above secondary level

8) Do you have a water storage tank?

- i) Yes
- ii) No (*Circle the relevant option*)

If yes,

a) What material is it made of?

- i) Concrete
- ii) Plastic
- iii) Any other material (*Circle the relevant option*)

b) How often do you clean it?

.....

c) What do you use to clean?

.....

d) Is the water connected directly to a water storage tank? *Tick or circle from the options*)

i) Yes

ii) No

Appendix II:

QUALITATIVE DATA RESULTS SHEET

Variable	Bunga															
Tap No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Storage Tank	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Pipe Type SC	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE
Pipe Type plub	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI
Meter Type	3	2	2	1	2	1	2	2	2	3	2	2	1	2	2	2
Sign of rust	No	No	No	Yes	No	No	No	Yes	No	No	No	No	Yes	No	Yes	No
Poor drainage	No	No	No	Yes	No	No	No	Yes	No	No	No	Yes	No	No	No	No
Pipe burst < 3 months	No	No	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	No
Type of tap/ Funal	Yes	No	Yes	Yes	No	No	No	No	Yes	No	No	No	Yes	No	Yes	No
Site of connection	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out
Tank cleaning	No	Yes	No		Yes			No	No		No	No		Yes	Yes	
Tank Type	Plastic	Plastic	Plastic		Plastic			Plastic	Plastic		Plastic	Plastic		Plastic	Plastic	
Illegal connections	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Distance from road	<30	30<	30<	30<	<30	<30	<30	30<	30<	<30	30<	<30	<30	30<	30<	30<
Surface/ Apperance -SC	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Distance from Sanitation F	>15	>15	>15	<15	>15	>15	>15	<15	>15	>15	<15	>15	>15	>15	>15	<15

Variable	Ggaba															
Tap No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Storage Tank	No	No	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Pipe Type SC	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE
Pipe Type plub	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI
Meter Type	3	3	2	3	2	2	3	2	2	3	2	3	2	3	2	3
Sign of rust	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No
Poor drainage	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No
Pipe burst < 3 months	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Type of tap/ Funal	No	No	No	No	No	Yes	No	No	No	Yes	No	No	No	No	No	No
Site of connection	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out
Tank cleaning			No				Yes	No		No	No	No		No	No	Yes
Tank Type			Plastic				Plastic	Plastic		Metalic	Plastic	Plastic		Plastic	Plastic	Plastic
Illegal connections	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Distance from road	<30	<30	>30	<30	<30	<30	<30	>30	<30	>30	>30	<30	<30	<30	<30	<30
Surface/ Apperance -SC	No	No	Yes	No	Yes	No	No	Yes	Yes	Yes	No	No	No	Yes	No	No
Distance from Sanitation F	>15	>15	<15	>15	>15	>15	>15	<15	>15	>15	>15	>15	>15	>15	>15	>15

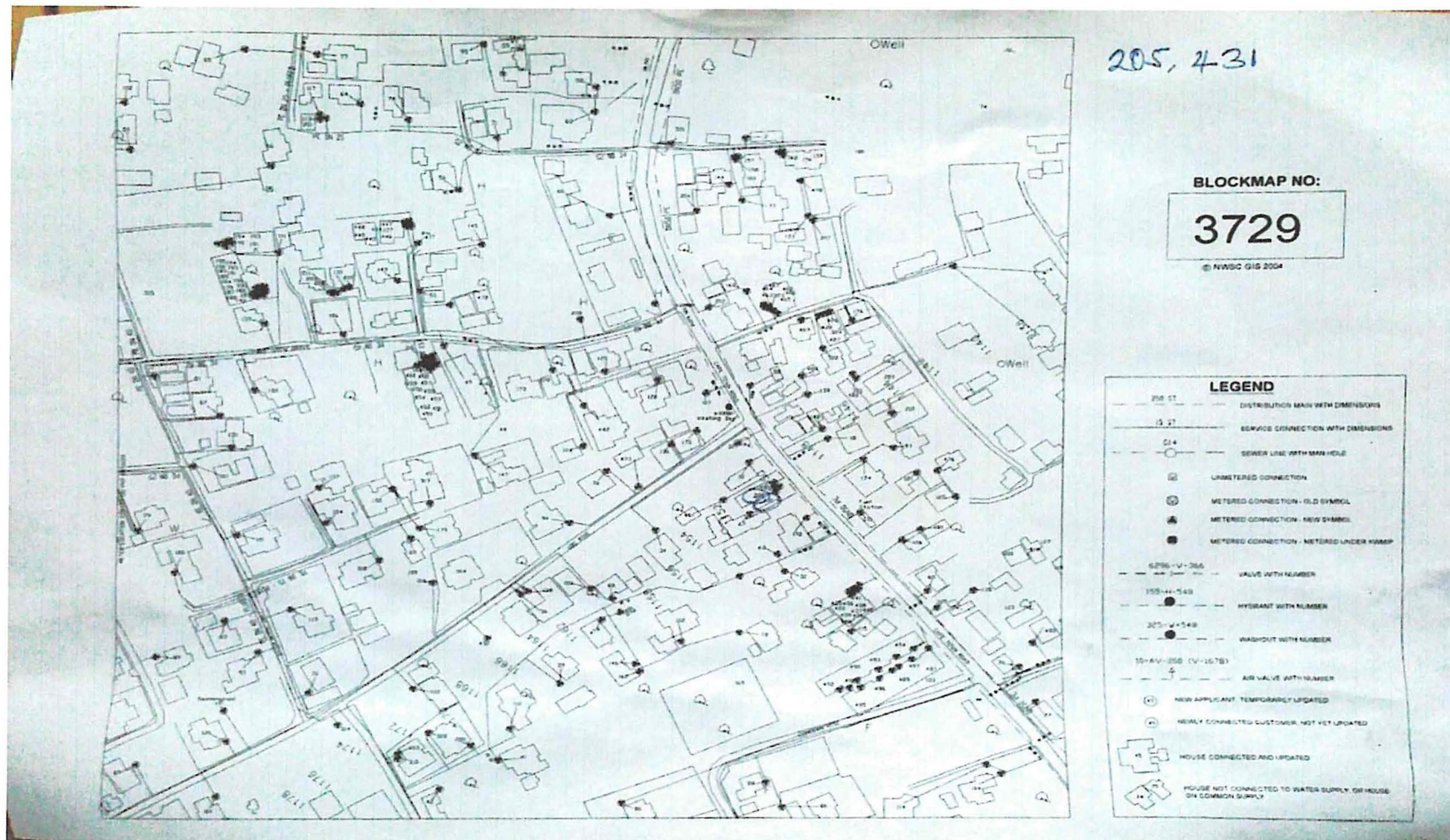
Variable	Kakungu									
Tap No	1	2	3	4	5	6	7	8	9	10
Storage Tank	No	No	No	Yes	No	No	No	Yes	No	No
Pipe Type SC	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE
Pipe Type plub	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI
Meter Type	2	2	2	3	2	2	2	3	2	2
Sign of rust	No	No	Yes	No	No	No	No	No	No	No
Poor drainage	No	No	No	No	Yes	No	No	No	No	No
Pipe burst < 3 months	No	No	No	No	No	No	No	No	No	No
Type of tap/ Funal	Yes	Yes	No	Yes	Yes	No	Yes	No	No	No
Site of connection	Out	Out	In	Out	Out	In	Out	Out	Out	Out
Tank cleaning				Yes				Yes		
Tank Type				Plastic				Plastic		
Illegal connections	No	No	No	No	No	No	No	No	No	No
Distance from road	30<	30<	30>	30<	30<	30<	30<	30<	30>	30<
Surface/ Apperance -SC	Yes	No	No	No	Yes	No	No	No	Yes	No
Distance from Sanitation F	15<	15<	15<	15<	15<	15<	15<	15<	15<	15<

Variable	Katuso									
Tap No	1	2	3	4	5	6	7	8	9	10
Storage Tank	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No
Pipe Type SC	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE
Pipe Type plub	GI	GI	GI	GI	GI	GI	GI	GI	GI	GI
Meter Type	3	3	2	2	3	2	3	2	3	3
Sign of rust	No	No	No	No	No	No	Yes	No	No	No
Poor drainage	Yes	No	No	No	No	No	Yes	No	No	No
Pipe burst < 3 months	No	No	Yes	No	No	No	No	No	No	No
Type of tap/ Funal	No	Yes	No	No	Yes	No	No	No	No	No
Site of connection	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out
Tank cleaning	Yes	No	No	No		Yes	No	Yes		
Tank Type	Plastic	Plastic	Plastic	Plastic		Plastic	Plastic	Plastic		
Illegal connections	No	No	No	No	No	No	No	No	No	No
Distance from road	30<	30>	30>	30<	30>	30>	30>	30>	30>	30>
Surface/ Apperance -SC	No	No	Yes	No	No	Yes	No	Yes	No	No
Distance from Sanitation F	15<	15<	15<	15<	15<	15<	<15	15<	15<	15<

Variable	Kawuku							
Tap No	1	2	3	4	5	6	7	8
Storage Tank	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Pipe Type SC	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE
Pipe Type plub	GI	GI	GI	GI	GI	GI	GI	GI
Meter Type	1	2	2	2	2	3	2	2
Sign of rust	Yes	Yes	No	Yes	Yes	No	Yes	No
Poor drainage	Yes	Yes	No	No	Yes	Yes	Yes	No
Pipe burst < 3 months	Yes	No	No	Yes	No	No	No	No
Type of tap/ Funal	Yes	Yes	No	Yes	Yes	Yes	No	Yes
Site of connection	In	Out	Out	In	Out	Out	Out	Out
Tank cleaning			No	No	No	Yes	No	No
Tank Type			Plastic	Metalic	Plastic	Metalic		Plastic
Illegal connections	Yes	No	No	No	No	No	No	No
Distance from road	<30	<30	30<	30<	30<	<30	30<	30<
Distance from Sanitation F	<15	>15	>15	>15	>15	>15	>15	>15

Variable	Soya					
Tap No	1	2	3	4	5	6
Storage Tank	No	No	Yes	Yes	Yes	Yes
Pipe Type SC	HDPE	HDPE	HDPE	HDPE	HDPE	HDPE
Pipe Type plub	GI	GI	GI	GI	GI	GI
Meter Type	2	2	2	2	2	3
Sign of rust	No	No	No	No	No	No
Poor drainage	No	Yes	No	No	No	No
Pipe burst < 3 months	No	No	No	No	No	No
Type of tap/ Funal	No	Yes	No	No	Yes	Yes
Site of connection	Out	In	Out	Out	Out	Out
Tank cleaning			No	Yes	No	No
Tank Type			Plastic	Plastic	Plastic	Plastic
Illegal connections	No	No	No	No	No	No
Distance from road	30<	30<	<30	30<	30<	30<
Distance from Sanitation F	<15	15<	15<	15<	15<	<15

Appendix III: Sample Map for the Distribution network



Appendix IV: Insitu Water Quality Data

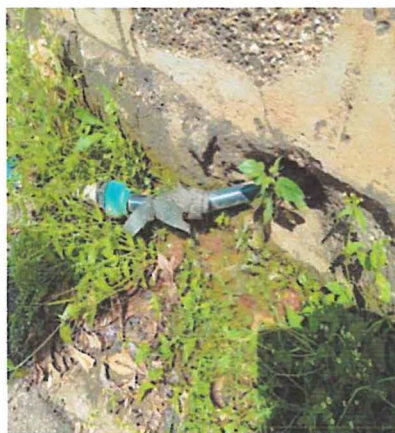
Location	AVR	DO %	DO (mg/L)	pH	Temp	Atmospheric Pressure (mbar)	Resistivity (Ω .cm)	Conductivity (μ S/cm)	Total Dissolved Solids (tds)	Salinity	Oxidation Reduction Potential
Village											
Ggaba TC	DC 1	34.3	2.45	6.65	14.96	755	15800	63	32	0.03	-138.8
	DC 2	38.6	2.65	7.10	15.6	734	16200	56	31	0.03	-133.4
	DC 3	32.9	2.25	7.55	16.24	753	17600	43	30	0.02	-143.9
	DC 4	37.2	3.65	6.80	14.88	792	15200	46	37	0.02	-124.4
	DC 5	31.5	3.25	7.45	15.52	771	15400	51	30	0.02	-164.9
	ST 1	35.8	3.45	6.90	15.16	750	16800	43.6	32	0.03	-175.4
	ST 2	40.1	3.65	6.75	14.8	730	14200	54.2	35	0.03	-185.9
	ST 3	34.4	3.45	6.60	14.44	709	15600	48.8	40	0.01	-156.4
	ST 4	38.7	2.85	6.45	15.08	788	16000	51.4	41	0.03	-136.9
	ST 5	33	3.25	6.80	14.72	767	17400	60	43	0.03	-117.4
	AVG	35.65	3.09	6.905	15.14	755	16020	51.7	35.1	0.03	-147.74
BUNGA	DC 1	9.5	0.74	6.4	13.43	755	48400	21	10	0.01	-122.9
	DC 2	11.0	0.65	7.2	13.5	715	41200	24	15	0.01	-133.4
	DC 3	10.8	0.99	7.7	15.1	780	45200	19	12	0.02	-143.9
	DC 4	11.7	0.81	7.3	16.2	775	41700	22	13	0.01	-124.4
	DC 5	12.4	0.85	6.9	14.7	788	40100	18	11	0.01	-164.9
	ST 1	9.6	0.99	7.5	14.8	790	38500	21	15	0.02	-175.4
	ST 2	10.5	1.00	7.1	14.3	705	46900	24	14	0.01	-185.9
	ST 3	11.4	1.06	6.7	16.0	720	35000	22	15	0.01	-156.4
	ST 4	10.5	0.91	6.3	14.4	735	43700	23	10	0.03	-136.9
	ST 5	10.3	0.96	7.0	15.0	749	42100	24	13	0.01	-117.4
	AVG	10.76	0.90	7.01	14.71	751	42280	21.82	12.80	0.01	-146.15

Location	AVR	DO %	DO (mg/L)	pH	Temp	Atmospheric Pressure (mbar)	Resistivity (Ω.cm)	Conductivity (µS/cm)	Total Dissolved Solids (tds)	Salinity	Oxidizer Reducizer Potential
Village											
Katusu	DC 1	11.7	0.87	6.45	14.8	748	40300	23	12	0.01	-124.3
	DC 2	12.1	0.85	7.25	15.1	715	41400	25	15	0.01	-135.5
	DC 3	11.4	0.92	6.85	15.4	782	39500	26	19	0.01	-129.6
	DC 4	12.6	0.90	6.45	14.7	740	43250	29	30	0.02	135.1
	DC 5	12.2	1.05	6.05	16.0	762	47000	31	24	0.01	-137.8
	ST 1	11.9	0.99	6.45	14.5	754	40750	21	19	0.01	-140.4
	ST 2	10.3	1.00	6.85	12.6	744	45600	32	29	0.03	-129.6
	ST 3	13.2	1.06	7.25	14.4	741	36500	28	14	0.01	-135.1
	ST 4	12.6	0.91	7.65	16.2	734	45400	22	16	0.01	-140.6
	ST 5	13.0	1.16	7.89	16.0	727	31162	26	20	0.01	126.1
	AVG	12.1	0.96	6.91	14.91	745	41386	26.3	19.8	0.01	-133.41
Kawukwu	DC 1	12.1	0.88	8.65	16.9	767	29040	48	24	0.02	-120.4
	DC 2	15.3	0.95	8.45	15.2	747	30245	52	32	0.01	-130.7
	DC 3	14.6	1.02	7.65	16.5	762	22514	56	30	0.03	-141
	DC 4	12.2	0.90	6.90	15.8	754	20740	50	34	0.03	151.3
	DC 5	14.7	1.02	7.10	15.6	751	17477	51	37	0.04	161.6
	ST 1	12.3	0.93	7.25	15.4	749	14214	50	40	0.02	-111.9
	ST 2	13.2	1.00	7.50	15.2	746	20951	49	43	0.01	-132.2
	ST 3	12.6	1.01	7.14	15.0	744	21688	48	45	0.01	-122.5
	ST 4	13.0	0.96	8.10	14.8	741	24425	47	48	0.01	-132.8
	ST 5	14.1	1.06	8.00	14.6	739	31162	46	51	0.02	-113.1
	AVG	13.41	0.97	7.65	15.5	750	23246	49.5	38.4	0.02	131.75

Appendix V: Microbial Analysis

E.COLI								
	Bunga	Ggaba	Kalungu	Katuuso	Kawuku	Soya	RainWater	Control
0.9	2	15	3	0	85	250	5	300
0.09	0	3	0	0	12	24	0	101
0.001	0	0	0	0	0	0	0	5
Total	2	18	3	0	97	274	5	406
Conc	1000	9000	1500	0	48500	137000	2500	203000
CFC/100ml	10	90	15	0	485	1370	25	2030
0.9	1	7	2	0	14	14	2	30
0.09	0	3	0	0	4	3	0	12
0.001	0	0	0	0	0	0	0	5
Total	1	10	2	0	18	17	2	47
Conc	500	5000	1000	0	9000	8500	1000	23500
CFC/100ml	5	50	10	0	90	85	10	235
Average	7.5	70	12.5	0	287.5	727.5	17.5	1132.5
Faecal Coliforms								
	Bunga	Ggaba	Kalungu	Katuuso	Kawuku	Soya	RainWater	Control
0.9	0	0	0	0	31	3	1	50
0.09	0	0	0	0	0	0	0	17
0.001	0	0	0	0	0	1	1	1
Total	0	0	0	0	31	4	2	68
Conc	0	0	0	0	15500	2000	1000	34000
CFC/100ml	0	0	0	0	155	20	10	340
0.9	1	0	0	0	12	1	1	22
0.09	0	0	0	1	0	0	0	5
0.001	0	0	0	0	0	0	1	1
Total	1	0	0	1	12	1	2	28
Conc	500	0	0	500	6000	500	1000	14000
CFC/100ml	5	0	0	5	60	5	10	140
Average	2.5	0	0	2.5	107.5	12.5	10	240

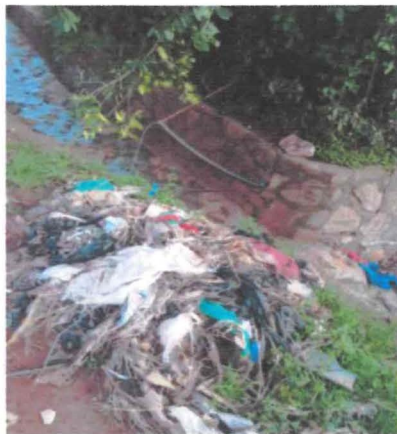
Appendix VI: Pictorial



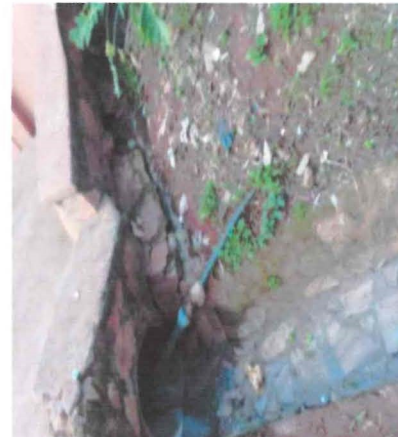
Distribution Mains in Soya Village



Distribution Mains in Ggaba TC Village



Distribution Mains in Kawuku Village



Distribution Mains in Bunga Village



