The effectiveness of domestic water treatment processes, North West Province, South Africa

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DECLARATION

I, Nomfundo Gumbi (21606765), declare that this dissertation entitled “The effectiveness of domestic water treatment processes, North West province, South Africa” which I herewith submit to the North West University is in compliance with the requirements set for the Master of Science in Environmental Science degree. This is my own research work, has been language edited, and has not already been submitted to any other university.

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Nomfundo Gumbi **Date**

DEDICATION

This work is dedicated to my parents, Prof. and Mrs. T. Gumbi, the reason for my existence.

The family vacations to the Nature and Game Reserves are the reason I fell in love with the natural environment. I am forever indebted to you, and I will continue to do more work to make you proud while conserving the beauty of nature.

To my brother Siyabonga and family - Nomalungelo and Khanyisa, this humble work is a sign of my love to you.

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ABSTRACT

People are increasingly concerned with the quality of water they drink. Globally, there is still an alarming rate of people who do not have access to basic services such as a supply of clean drinking water from the faucets. This is greatly concerning because our natural water reserves are diminishing exponentially as a result of climate change. Additionally, our water sources are increasingly polluted by anthropogenic activities; which makes the minority of people who are dependent on direct water source consumption at a higher health risk. In the Republic of South Africa, municipalities and independent water boards treat and supply domestic water to urban, semi-urban and some rural areas. This water is mainly for drinking purposes, hence it must meet the specified drinking water quality guidelines according to the South African National Standards (SANS 241) in order to be deemed safe for domestic use. The North West province, in general, is under-resourced, and made of under-privileged communities. Most municipalities in the North West are battling to maintain the aging water infrastructures. Hence, there is a challenge with the water quality, and supply, in places like Mmabatho.

In this study, all parameters are measured and compared to specified drinking water quality limits according to the World Health Organisation (WHO) and the Department of Water Affairs; and then discussed with reference to the national drinking water standards (SANS 241). Current improvements of analytical methods allow for the detection of impurities, even at lower concentrations, and make it easier to ascertain the quality of the water. This study occurred at the water treatment plants of Mmabatho and Klerksdorp. The plant operators from Mmabatho Water Treatment Plant and Midvaal Water Company assisted with the collection of water samples from designated water sampling points; (i) before the treatment process (inlet), and (ii) after the treatment process (outlet). Sterilised and treated water sampling containers that were already labelled accordingly, were used to collect water for microbiological analysis. Sampling containers for chemical analysis were prewashed and oven dried prior to use. Physical parameters were measured *in situ* using various hand-held instruments; while the chemical and microbiological parameters were analysed *ex situ* using various laboratory instruments. Data processing, calculations and statistical analysis of all water quality variables was performed on results using one-way analysis of

variance (ANOVA) at 0.05% level of significance with the objective of evaluating the significant differences among the two study areas as well as the seasonal variations.

At the Midvaal Water Company, in Klerksdorp; the mean values of pH, temperature, electrical conductivity (EC), turbidity, total dissolved solids (TDS) and total suspended solids (TSS) before treatment were 8.86, 20.79 °C, 72.00 mS/cm, 21.09 NTU, 451.00 mg/L and 49.40 mg/L. After treatment, the mean values were 7.96, 23.80 °C, 73.75 mS/cm, 0.46 NTU, 482.00 mg/L and 35.75 mg/L. At the Mmabatho Water Treatment Plant, in Mmabatho; the mean values of the physical parameters: pH, temperature, EC, turbidity, TDS and TSS before treatment were 8.64, 20.88 °C, 222.25 mS/cm, 23.39 NTU, 428.39 mg/L and 284.27 mg/L. After treatment, the mean values were 8.81, 21.34 °C, 193.25 mS/cm, 6.01 NTU, 240.51 mg/L and 151.32 mg/L. All physical parameters from Klerksdorp were within specifications. The physical parameters in Mmabatho were within specifications, except for electrical conductivity and turbidity.

The concentration of major ions nitrate, sulphate, chloride, sodium, magnesium and calcium before treatment in Klerksdorp were 1.51, 129.48, 50.44, 58.85, 21.22 and 58.51 mg/L. After treatment, the mean concentration were 1.77, 163.42, 54.79, 58.10, 23.87 and 63.69 mg/L. In Mmabatho, the concentration of these major ions before treatment were 2.66, 150.13, 222.35, 130.38, 26.72 and 172.60 mg/L. After treatment, ions concentration in Mmabatho were 1.22, 185.51, 226.29, 126.98, 22.67 and 155.67 mg/L. All major ions after treatment were well within specifications at both study areas, except for high levels of calcium concentration in Mmabatho.

The concentration of free chlorine before treatment in Klerksdorp and Mmabatho was 0.00 mg/L. After treatment, the concentration of free chlorine was 1.49 and 3.87 mg/L in Klerksdorp and Mmabatho, respectively. These values fall within specified concentration for free chlorine after treatment. The mean concentration for total hardness for Klerksdorp and Mmabatho before treatment was 228.71 and 356.94 mg/L, respectively. After treatment, the total hardness was 55.19 and 264.79 mg/L, respectively. The hardness concentration was high at both sites before treatment, however, only in Klerksdorp this concentration fell within specifications after treatment. In Mmabatho, the total hardness concentration remained high. The mean values for *Escherichia coli (E. coli)* in Klerksdorp and Mmabatho before treatment were 29.75

and 33.50 CFU/100 mL, respectively. The total coliform detected at both sites before treatment was 38883.90 and 51190.25 CFU/100 mL, respectively. After treatment, both *E. coli* and total coliform were not detected at both study sites.

The overall results for both the study sites after the water treatment process were comparable with the specified domestic water quality standards according to the SANS 241, except for the turbidity, electrical conductivity, total hardness and calcium at the Mmabatho Water Treatment Plant. This suggests that there is more work that needs to be done to investigate and safeguard the water sources in the North West province. This, in turn, will make it easier to mitigate and improve the water treatment processes in Mmabatho.

Keywords: drinking water, physico-chemical, water quality, water treatment processes, source water pollution.

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LIST OF SYMBOLS

%	-	percent
=	-	equal to
>	-	greater than
±	-	plus or minus
≤	-	less than or equal to
µm		micrometers
cm	-	centimetres
cm^3	-	cubic centimetres
g/m^3	-	grams per cubic metres
km	-	kilometres
km^2	-	square kilometres
M	-	molarity
mg/dm^3	-	milligrams per cubic decimetres
Mℓ	-	mega litres
mL	-	millilitres
mm	-	millimetres
mM	-	millimolar
mS	-	millisiemens
N	-	normality

nm	-	nanometres
pg/dm^3	-	picogram per cubic decimetres
ppb	-	parts per billion
ppm	-	parts per million
µg/dm^3	-	microgram per cubic decimetres

LIST OF ACRONYMS

AAS – Atomic Absorption Spectrometry

ACT – Activated carbon treatment

AMD – Acid mine drainage

APHA – American Public Health Association

BDS – Blue Drop System

BOD – Biochemical oxygen demand

Ca^{2+} and Mg^{2+} - Calcium and magnesium ions

CCMLM – City Council of Matlosana Local Municipality

CFU – Colony forming units

COD – Chemical oxygen demand

DAF – Dissolved air flotation

DBPs – Disinfection by-products

DEA – Department of Environmental Affairs

DIW – Distilled/deionised water

DL – Detection limit

DO – Dissolved oxygen

DOC – Dissolved organic carbon

DWA – Department of Water Affairs

DWS – Department of Water and Sanitation

DWTP – Drinking Water Treatment Plant(s)

ECs – Emerging contaminants

EPA – Environmental Protection Agency

EU – European Union

FIB – Faecal indicator bacteria

GAC – Granular activated carbon

HCL – Hollow cathode lamp

HPC – Heterotrophic plate counts

IOCs – Inorganic chemicals

IX – Ion exchange

KCl – Potassium chloride

KOSH – Klerksdorp Orkney Stilfontein Hartebeesfontein

M – Molarity of a solution expressed as moles of solute per litre of solution

MCL – Maximum contaminant level

MPN – Most probable number

MVWMA – Middle Vaal Water Management Area

MWC – Midvaal Water Company

N – Normality of a solution expressed as equivalents per litre of solution

ND – Not detected

NECs – New and emerging contaminant(s)

NEMA – National Environmental Management Act

NOM – Natural organic material

NTU – Nephelometric turbidity unit

NWA – National Water Act

O_3 – Ozone/ozonation

PAC – Powdered activated carbon

POE – Point of entry

POU – Point of use

PPCPs – Pharmaceutical and personal care product(s)

RO – Reverse osmosis

SA – South Africa

SABS – South African Bureau of Standards

SANS – South African National Standards

SD – Standard deviation

TDS – Total dissolved solids

THMs – Trihalomethanes

TOC – Total organic carbon

TSS – Total suspended solids

TTC – Thermo-tolerant coliforms

UK – United Kingdom

UV – Ultra violet

VOCs – Volatile organic compounds

WHO – World Health Organization

WMA – Water Management Area

WSA – Water Service Authority

CHAPTER ONE

INTRODUCTION

1.1 Background

Water is the most vital resource of all living beings (Ali, 2012). The provision of clean and safe water is critical for sustaining human wellbeing as well as improving environmental health and people's livelihoods worldwide (Wanda *et al.*, 2016a). Water may be of good quality for household use according to the SANS 241, a South African national standard for drinking water quality, however it may have characteristics that may give perception that it is of poor quality (DWAF, 1996). For example, tap water may not taste or smell good; or it may produce noticeable stains on laundry and/or appliances; or it may have noticeable suspended particles (Water, 2014). Water assessments tend to emphasise on water quantity, while water quality is equally critical for satisfying human and environmental needs (Gleick, 2014). Good quality drinking water must have an eye and taste appeal before we will drink it with much relish; instinctively we tend to draw back from drinking water that is aesthetically poor (Cheremisinoff, 2001).

The production of potable water has become a worldwide concern. It is said that less than 3 percent of the earth's 330 million cubic miles of water is fresh, and it is very unevenly distributed across the planet (Roy *et al.*, 2015). It is estimated that over one billion people around the world are without clean drinking water and approximately 2.3 billion people live in regions with extreme water shortages. As a result of demographic expansion, many areas in the world face the challenge of meeting the ever-increasing water demands. This is why water has been dubbed the Blue Gold of the 21st century (Barlow & Clarke, 2017).

Water scarcity can be a result of natural or human-made phenomenon, however the latter has become even more prevalent (Liu *et al.*, 2013). Water shortage problems can be addressed through recycling of municipal greywater for reuse in households; a practice which is increasing worldwide. However, reclaimed water may be a major source of biological, chemical, radiological pollutants (Wilcox *et al.*, 2016). Nowadays,

water sectors are also battling with a rise of what has been termed “new and emerging” micropollutants; that include steroid hormones, detergents, personal care products and pharmaceutical waste products; which have been found to be very resistant and often survive the water treatment processes (Richardson & Ternes, 2014). These micropollutants also present an issue of environmental concern when discharged back into the water source owing to their eco-toxicological effects (Wanda *et al.*, 2016b). Different methods have been developed and used for water treatment and purification process over the past decade. The most common and widely used methods are screening, sand filtration, sedimentation and gravity separation, flotation, flocculation and coagulation, reverse osmosis, ion exchange and disinfection (Ali, 2012).

In South Africa, water of sufficient quality and quantity is required to meet the basic human needs as well as the demands of agriculture, industry, conservational, and ecosystem uses (Matthews & Bernard, 2015). However, our fresh water resources are rapidly diminishing as a result of high temporal and spatial variable rainfall. This situation is exacerbated by the increasing water demand, pollution, unsustainable use, and climate change (Sharma *et al.*, 2019). The Constitution, as the mother-body to all South African laws and policies, was promulgated in 1996 to transform all sectors which included political, social, economic and environmental sectors (Monnahela, 2014). In addition to the Constitution, the National Environmental Management Act (NEMA) provided the Water Services Act 108 of 1997 and National Water Act 36 of 1998 with the aim of managing the use of water resources as well as governing the quality of potable water in South Africa (Department of Water Affairs & Forestry, 1998). According to the National Water Act, water must meet certain basic requirements to make it fit for domestic use. However, many people in the rural areas of South Africa are still without the basic services such as indoor tap water, and rely on communal taps for access to clean and safe drinking water. Additionally, Water Service Authorities (WSA), which are either district and/or local municipalities and metropolitans, are required to submit information regarding drinking water quality and management thereof regularly to the national Blue Drop System (BDS).

Since 2009, a trend has emerged in which urban municipalities have shown to consistently improve their water quality and management whilst some of the rural and under-resourced municipalities are falling behind (Rivett *et al.*, 2013). A major concern

has been that the rural/under-resourced municipalities are failing to report the required information, and are not complying with some of the regulator's requirements for water quality monitoring and management (Faust & Aly, 2018). The problem of withholding such information is increasing the potential risks related to ecological and human health impacts (Delpla *et al.*, 2009). Furthermore, to manage and address some of the challenges associated with water shortages of existing water resources in South Africa and all over the world, water treatment and reuse has formed an important component of water management (Hering & Ingold, 2012). The supply of good clean quality water is an important component that can never be overlooked because it poses an increased potential risk to human lives especially in smaller communities across South Africa. Some of the major factors of water management and monitoring efforts are a direct result of improper treatment procedures, broken and/or ageing water infrastructures, poor maintenance of equipment, financial constraints, and a lack of qualified personnel to ensure clean potable water is supplied to communities (Monnahela, 2014).

1.2 Problem statement

The importance of good-quality, potable water for human existence cannot be under-estimated, and life will be practically impossible or difficult without the availability of safe drinking water (Tijani *et al.*, 2013). The primary goal of municipal water treatment is to supply an adequate quantity of safe potable water to the public. A second and most essential goal is to make the water palatable (Davis, 2010). Water is deemed safe to drink when it meets water quality guidelines prescribed by the World Health Organisation (WHO), as well as country-specific guidelines. In South Africa, the Department of Water and Sanitation (formerly known as the Department of Water Affairs) has set water quality guidelines that is fitting to the nature of our water sources. The quality of water in S.A. is measured against, must comply to, the South African National Standards (SANS 241 standards) in order to receive a good Blue Drop Score.

Urban municipalities are capable of utilising different modern and sophisticated water treatment technologies with capacities to treat and remove a variety of contaminants from water. However, such a luxury cannot be afforded by smaller and rural

municipalities (Rivett *et al.*, 2013). The challenge thereof is that rural municipalities will eventually supply water that has not been properly tested, and therefore does not meet all the required specifications. The inconsistency in the level of treatment, water quality and management may be mainly due to a complexity of factors ranging from (1) political influence, (2) economic factors from smaller rates and taxes paid to limited operating funds to run the municipality, (3) lack of state-of-the-art resources to treat and recycle domestic wastewater and raw water from the source, and (4) lack of skilled personnel. The end result is what is typically less sophisticated and robust water treatment plants that needs more and expensive maintenance, and hence the water treatment and monitoring processes are basic and limited (Zanacic *et al.*, 2016).

The community that have experienced palatable water from the cities may be dubious with drinking water that is hard and looks turbid. Hard water would not necessarily pose any threat to human health since it is caused by high levels of dissolved minerals (both calcium and magnesium) in water. In contrast, turbid water may signify the presence of potentially harmful bacteria in water, hence many people would resort to buying bottled water when in doubt. In most cases, turbid water would be noticeable following a water burst in municipal pipes; during or after some extreme weather changes that cause floods; or when there has been some major maintenance works in the water treatment plants. This study seeks to assess the effectiveness of domestic water treatment processes in the North West Province of South Africa.

1.3 Justification

According to the National Water Act No. 36 of 1998, water must meet certain basic requirements to make it fit for domestic use (Department of Water Affairs & Forestry, 1998). Most surface water sources contain harmful micro-organisms and other harmful substances that must be removed from the water, at least, to acceptable levels to make the water fit for drinking and other domestic use. In addition to the requirement that water must be safe to drink, water for domestic use must also have a pleasing appearance, and it must furthermore be chemically stable (Chigor *et al.*, 2013). Effective water treatment processes will not only benefit the end-user/consumers, but has the potential of enhancing the productivity within the water sector and contribute

towards the ecological sustainability and improvement of the entire water environment. The consumption of untreated and/or poorly treated water may result in waterborne diseases such as cholera or dysentery if the water source or point-of-water-use water is contaminated by pathogens (Ngwenya *et al.*, 2013).

Water treatment plants are finding it much harder to treat and remove the different types of pollution contained in domestic water (Hodgson & Manus, 2006). Since this study was focused in the North West province, the state of water quality was studied, and a gap analysis to identify the monitoring needs was undertaken in the province. The analysis of water quality, before and after treatment, was carried out to indicate how effective the treatment processes were in producing water that is of a high drinking quality standard according to WHO, DWA and SANS. The significance of this comparative study is to make WSA aware of the concerns of the public and researchers who have no choice but to rely on other sources of drinking water in order to eliminate potential health risks from drinking poor quality water. This may in turn indicate that there is a gap in the market, especially for the North West province's water treatment plants. The study emphasised the importance of choosing the right treatment method to remove the type of contamination load in a particular town so that the entire process minimises potential negative economic, social and environmental impacts.

1.4 Aim and objectives

The aim of this study is to assess the effectiveness of domestic water treatment processes in the North West province, South Africa.

The specific objectives of carrying this research are as follows:

Objective 1: To analyse the processes used in two water treatment plants in the North West province of South Africa;

Objective 2: To analyse the physico-chemical properties of the water; and

Objective 3: To investigate the microbiological properties of the water, in particular, the *Escherichia coli* and total coliform.

1.5 Hypotheses

Polluted water sources as well as ineffective water treatment works by Mafikeng Local Municipality in the North West province has led to loss of credibility in the quality of potable water supplied by the local municipality to their community.

1.6 Description of the study area

The study was focused on two towns; namely Klerksdorp and Mafikeng as shown in Figure 1, having taken into account the spatial and temporal variations that may influence the hydrochemistry of water and ultimately the choice of water treatment (Pratt & Chang, 2012).

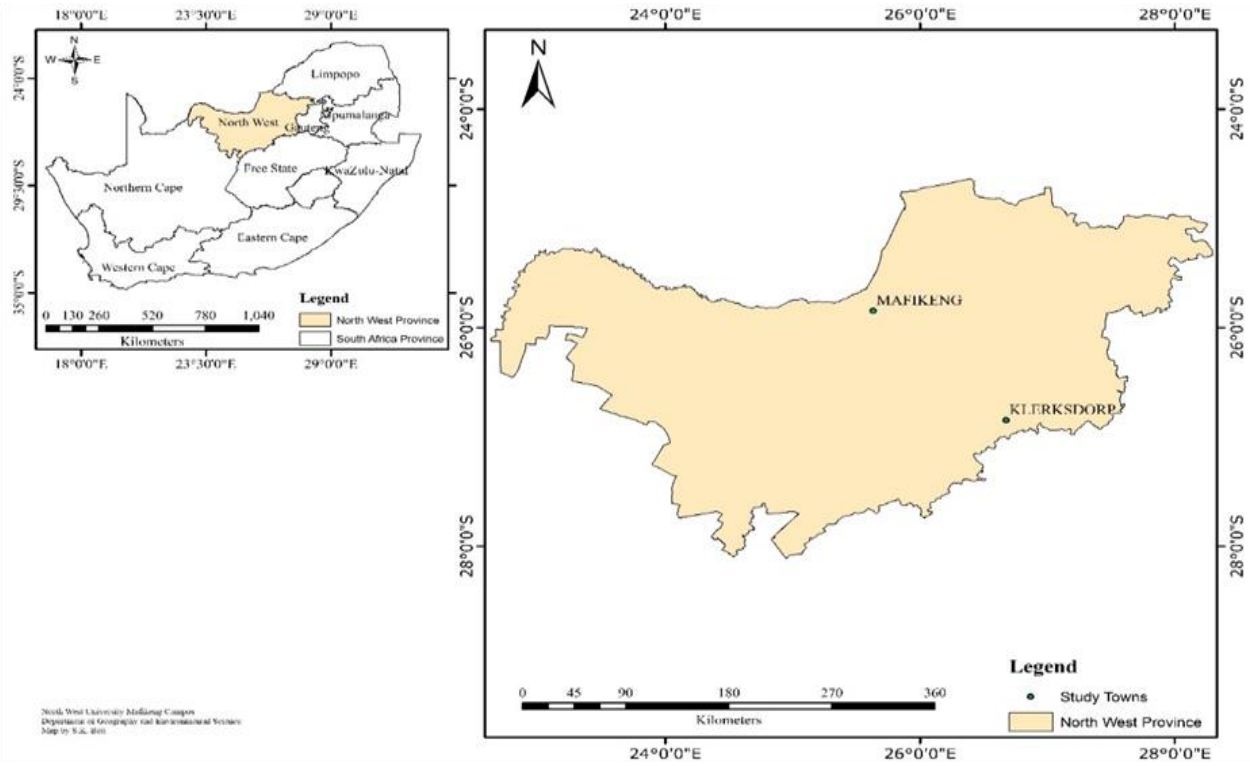

Figure 1: Map of the North West province and locations of the study sites

Location – Mafikeng town

Mafikeng is the capital city of the North West province and has a population of more than 260,000 people (Stats, 2011). It is located within Latitude −25°51′ S and Longitude 25°38′ E, covering a total area of 24.57 km^2 (Palamuleni & Akoth, 2015).

Sources of water for Mafikeng

The potable water in this city is obtained from three sources. The first source of water is the groundwater. Groundwater from the boreholes is considered safe for drinking purposes because it is abstracted with low microbial load and requires little treatment before use. A number of people from the rural environment of Mafikeng rely on borehole water for domestic use (Palamuleni & Akoth, 2015).

The other two sources that supply the larger part of Mafikeng are; the Molopo Eye and the Setumo dam (Figure 2). The Molopo Eye is a natural spring that is situated 30 km from town. Its water is clear and the total dissolved solids (TDS) is generally very low. For this reason, no sedimentation and filtration is required. The water from this source is only chlorinated and supplied to the Mafikeng Local Municipality (Mulamattathil *et al.*, 2014). The other source is the Setumo dam. The water treatment plant is downstream from the Waste Water Works (Mulamattathil *et al.*, 2014). This water source is thus impacted on by sewage works, human settlements, farming and other anthropogenic activities that are prevalent in this area. However, the Mmabatho Water Treatment Plant (MWTP) is the water works that treats water abstracted from the Setumo dam through the processes of chemical dosing, sedimentation, sand filtration and chlorine sanitation. This water is then stored in reservoirs before being mixed with treated water from the Molopo Eye and supplied to the Mafikeng community by the Local Municipality (Mulamattathil *et al.*, 2014).

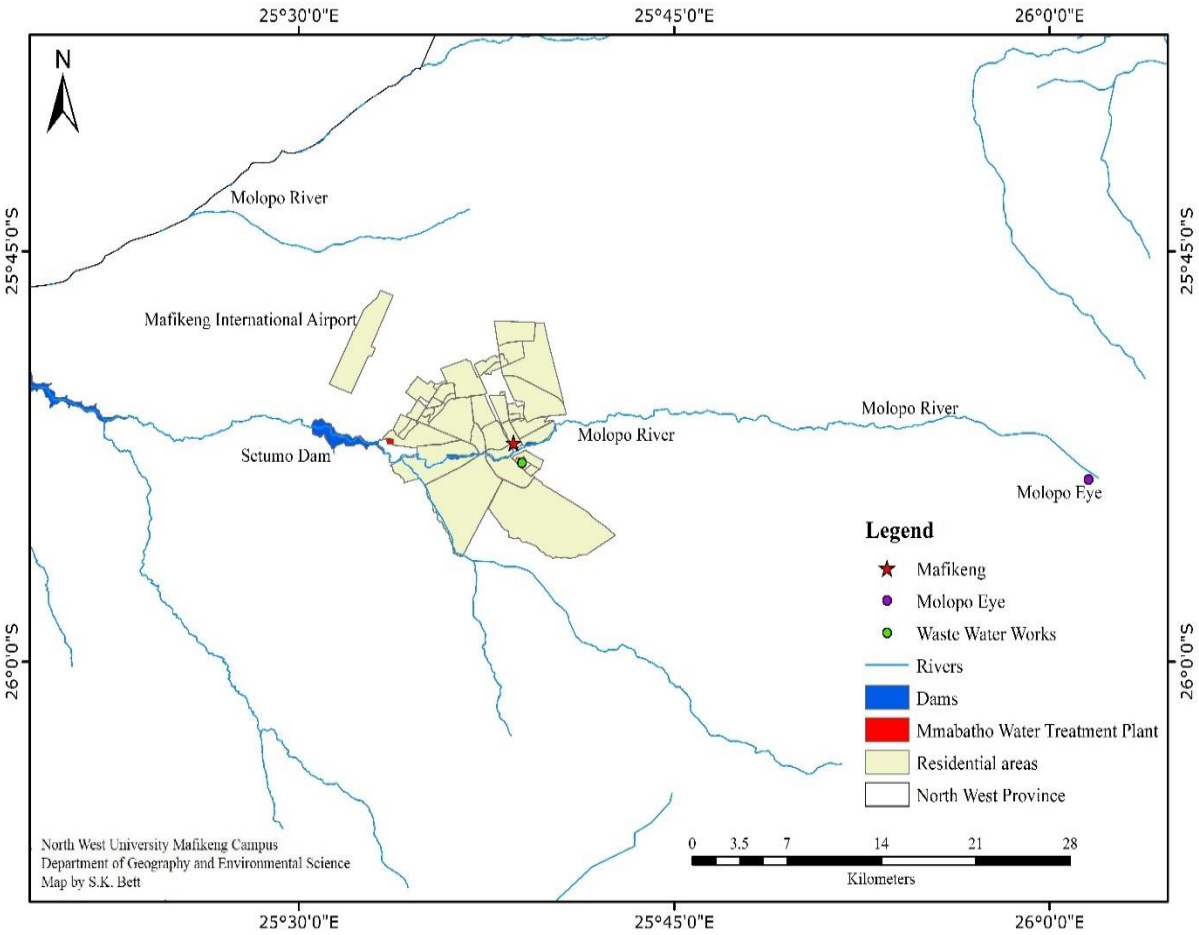

Figure 2: Map of Mafikeng town showing the sources of water

Location – Klerksdorp town

Klerksdorp is a town on the north western area of South Africa (Mamabolo, 2007). It is located within Latitude -26°52′ S and Longitude 26°40′ E, covering a total area of 105.98 km^2. The Midvaal Water Company (MWC), is the water service provider for the treatment and supply of bulk water to the Klerksdorp, Orkney, Stilfontein, and Hartebeesfontein (KOSH) areas.

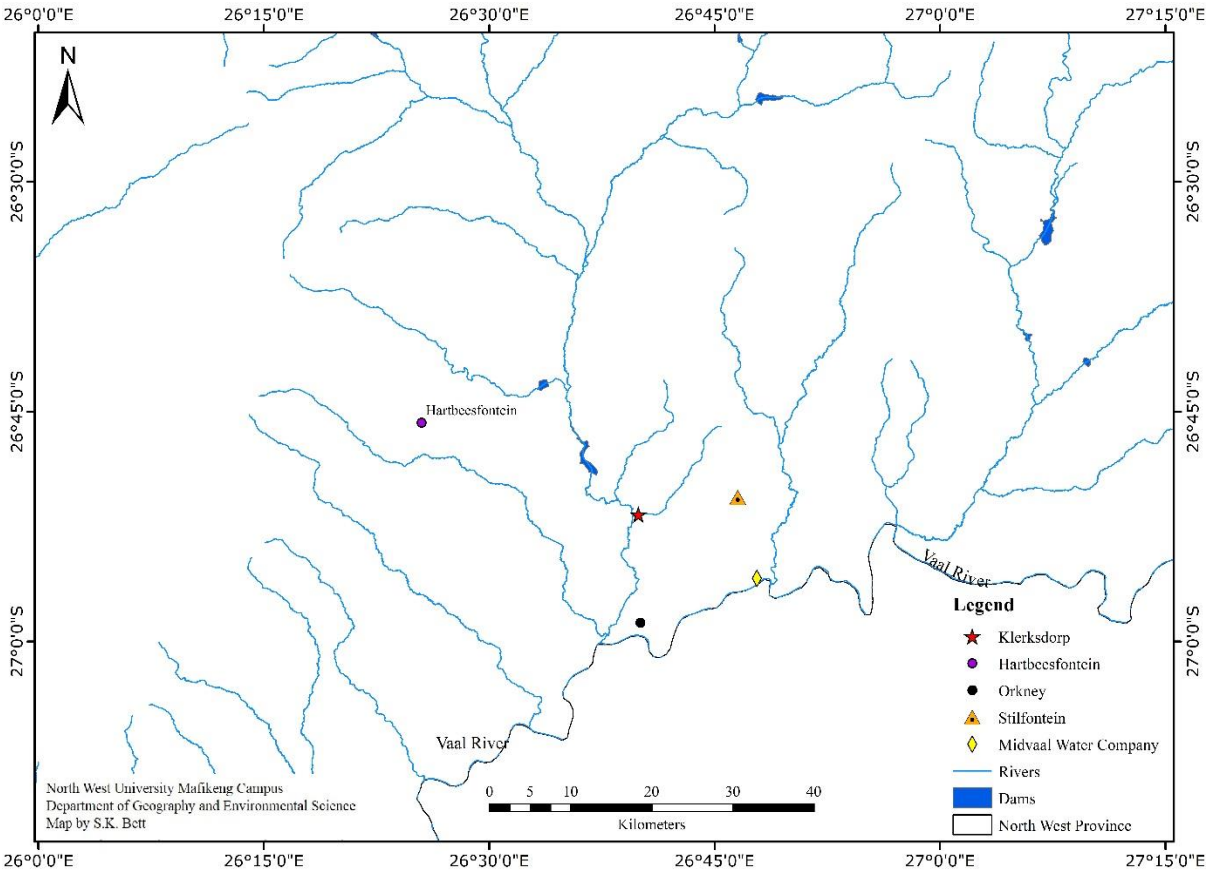

Figure 3: Map of Klerksdorp town showing the Midvaal Water Company and the KOSH areas

The MWC, Figure 3, is situated on the banks of the Vaal River in the North West province town of Klerksdorp, under the City Council of Matlosana Local Municipality (CCMLM) in the Republic of South Africa (Malatji, 2014). MWC abstracts between 95 and 180 Mℓ of water from the Vaal River per day. It has a capacity to treat 320 Mℓ of water daily. The Middle Vaal Water Management Area (MVWMA) is mostly rural, where agriculture, mine dewatering, and the subsequent discharge into the river system, impact on the water quality (Morrison *et al.*, 2012). Tributaries in the catchment of the Vaal River also contribute to the deteriorating water quality of the Middle Vaal system by introducing various pollutants into the system at times (Morrison *et al.*, 2012).

1.7 Research ethics

In order to uphold the various codes of ethics such as honesty, integrity, respect, and confidentiality that govern research, application for ethical clearance was made to the North West University ethical clearance committee. This was a requirement in the fulfilment of a Master's degree with the North West University. Permission to collect water samples from the two treatment plants was granted and the findings from the study are intended for research purposes only.

1.8 Summary

The provision of safe water is critical for sustaining human wellbeing as well as improving the environmental health and livelihoods of people worldwide. Effective water treatment processes will not only benefit the end-users or consumers, but has the potential of enhancing the productivity within the water sector and contribute towards the ecological sustainability and improvement of the entire water environment. The municipalities in South Africa are responsible for the treatment and provision of water services of a specific quality to all respective customers.

1.9 Outline of dissertation chapters

This dissertation is divided into five chapters.

Chapter one outlines a general overview of the research project, study objectives and description of the study area.

Chapter two lays out the general overview of water works, while looking specifically into point and non-point sources of pollution, different treatment processes, and water quality parameters of concern, while also highlighting studies that have demonstrated the use of various (conventional and advanced) treatment technologies to optimally remove pollutants.

Chapter three gives a detailed description of the sampling sites, laboratory procedures undertaken to achieve the main aim of this study.

Chapter four presents the results obtained from the analysis while comparing and discussing the results based on other literature findings.

The conclusions and recommendations from this study are discussed in Chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Water availability and demand

Rapid industrial developments coupled with surging population growth have complicated issues dealing with water scarcity as the quest for clean and sanitised water intensifies globally. The WHO reports that one sixth of the world's population does not have access to safe drinking water (Griggs *et al.*, 2013). Existing fresh water supplies could be contaminated with organic, inorganic and biological matters that have potential harm to the society (Choy *et al.*, 2014). The primary objective of any water supply scheme is to provide clean drinking water to all humans. The earth's renewable supply of water for human consumption and the ecosystem is dependent on the hydrologic cycle (Gleick, 2014). The hydrologic cycle is the system that supplies the earth's natural surface water in the form of wetlands, rivers, dams, wells, lakes, and estuaries. Unfortunately, water quality of most water sources is deteriorating continuously due to overpopulation, civilisation, geological, environmental and global changes (Ali, 2012).

Due to the limited annual rainfall, South Africa is considered a semi-arid, and also the thirtieth driest, country in the world (Duse *et al.*, 2003). The annual rainfall in SA ranges from 100 mm in the west to 1500 mm in the east; with a mean precipitation of 800 mm per annum but this is pressured by high evaporation rates as well as highly sporadic and uneven rainfall patterns in the inland regions (Du Plessis & Schloms, 2017). In addition, a dynamic growing economy and provision of services which requires extensive use of water impacts negatively on the available water supplies. The worst and probably the most devastating is that, no truly large rivers exist in South Africa. The four main rivers SA has are shared with other African countries (Water, 2014). Hence, the water quality of the rivers could also be deteriorating fast due to receiving large quantities of effluent. The major sources of pollution of surface waters are agricultural drainage and runoff; urban runoff and effluent return flows, industries, mining, acid mine drainage and rural settlements with insufficient sanitation services (Khatri & Tyagi, 2015). Moreover, the rate of urbanisation in South African cities has

increased due to population growth and a search for better lives and economic freedom (Stats, 2011). For example, in the Gauteng province, many people from within South Africa as well as other African countries leave their homes in search for jobs, hence Johannesburg city is now water stressed. Cape Town, on the other hand, has experienced minimal rainfall in the recent years, and the city is now in a dire state of drought, coupled with water use restrictions (Ahjum *et al.*, 2015). Although Durban receives enough rain throughout the year, the city's municipality is also water stressed due to over-population by people migrating from other cities to live and/or retire by the coastal region. Water treatment and recycling may be the only alternative for getting and sustaining fresh water sources in the coming decades. For that reason, there is a great need for the development of suitable, inexpensive and efficient wastewater treatment techniques and reuse or conservation methods in this present century (Gupta *et al.*, 2012).

Water treatment plants are the key component of such water supply schemes that transform the raw water into potable water by using the appropriate treatment processes. The selection of the treatment process depends upon the raw water quality as well as the finished water quality objectives (Bonton *et al.*, 2012). Water treatment plants can either be conventional or advanced in design and operation. A conventional water treatment or purification process, which is used by most water companies, will involve the following stages: aeration, coagulation, flocculation, sedimentation, stabilisation, filtration and disinfection (Ewerts *et al.*, 2014). More water industries are realising the need to use alternative water treatment methods such as membrane processes, ozonation and UV disinfection in order to meet the increasing demand for cleaner potable water production (Qu *et al.*, 2013). Similar to domestic water treatment, the treatment processes used for water and wastewater reclamation, reuse and recycling can be of a physical, biological or chemical nature, and they also depend on the type of treatment and reuse options to be achieved in the process (Gadipelly *et al.*, 2014). A detailed discussion of the water treatment processes is found in section 2.3 of this dissertation. Influent and effluent quality of municipal, industrial or mine wastewater treatment plants play significant roles in influencing the overall ecology of receiving water bodies. The importance of wastewater as a resource, and the adoption of advanced treatment solutions and resource utilisation in the long term highlights a step towards sustainable water resource management (Sun *et al.*, 2016). Peng and

Zhang (2012) argued that the worldwide water crisis facing most countries no longer requires new water sources, but rather how to use the available water resources sustainably. This is the reason water treatment and water recycling has become a crucial element in order to make water fit for all domestic use.

2.2 Water pollution

Water is mainly referred to as polluted when it is impaired by both anthropogenic and natural contaminants and becomes unable to support human uses such as drinking, and/or undergoes a marked shift in its ability to support its constituent biotic communities, such as fishes. One major environmental issue affecting the quality of inland and coastal waters is eutrophication caused by excessive presence of dissolved inorganic nutrients (Zamyadi *et al.*, 2013). Algal bloom and oxygen depletion are still reported in many water bodies worldwide. Agricultural activities are responsible for large scale water quality degradation and are estimated to contribute around 55 percent of the nitrogen entering the surface water resources. However, natural phenomena like volcanoes, algae blooms, storms, and earthquakes may also cause major changes in water quality and ecological status of water (Harikumar *et al.*, 2017). Rivers, channels, lakes, oceans, and groundwater are often contaminated by a variety of organic and inorganic substances that can affect aquatic life and threaten human health (Rivera-Utrilla *et al.*, 2013). For instance, water pollution that come from industry, agriculture or households, returns negatively back to the environment. Chemical and mining wastes such as arsenic, fluorides, lead, nitrates, sulphates, pesticides, petro-chemicals and acid mine water have negative effect on living organism in water and subsequently on human health (Alrumman *et al.*, 2016). Acid mine drainage (AMD) is still a huge and most threatening challenge for water sources since it has continued to linger for decades after the closure of gold mines (Humby, 2013). For this reason, groundwater, rivers, lakes, streams and dams in and around the Gauteng province are still fairly affected notwithstanding years of clean-up. This is more evident from the persistent algal growth at Hartbeespoort Dam, Vaal Dam as well as the entire Vaal River, which runs across the Mpumalanga, Gauteng, Free State, North West and Northern Cape provinces, affecting the catchments around it (Paerl & Otten, 2013). The effects of water pollution are varied and depend on the kind

of chemicals dumped and their locations. Pollutants such as lead and cadmium are consumed by tiny animals which cascade to the higher levels of the food chain. Several countries have sought to regulate the discharges of pollutants in the water to minimise the impacts of pollution through various treatments (Alrumman *et al.*, 2016).

Recent research reveals the presence of a multitude of micropollutants, termed new and emerging contaminants (NECs), which affect water resources significantly (Rodriguez-Narvaez *et al.*, 2017). These pollutants can be detected at extremely low concentrations of picogram per litre to microgram per litre range (Mkwate *et al.*, 2017). NECs are natural or synthetically occurring substances not commonly monitored in the environment and having known or suspected undesirable effects on humans and the ecosystem. An example of these type of substances are pharmaceutical and personal care products (PPCPs), pesticides, and hormones that have adverse effects on human and wildlife endocrine systems (Mkwate *et al.*, 2017). Antibiotics are not effectively removed by modern-day water treatment processes, hence they are a growing threat to ecosystem and human health. The emergence, and continual production, of such organic and toxic compounds have become a matter of concern as they may result in the induction and spread of bacterial resistance which may be harmful to humans and/or animals if continually found in aquatic environment (Rivera-Utrilla *et al.*, 2013).

The WHO guidelines for drinking water quality recommend that faecal indicator bacteria (FIB), preferably *Escherichia coli* or thermo-tolerant coliform (TTC), should not be detectable in any 100 mL of drinking water sample (Edition, 2011). However, it is estimated that 1.8 billion people globally use a source of drinking water which suffers from faecal contamination. Drinking water is found to be more often contaminated in rural areas than in urban areas, and contamination is most prevalent in Africa and South East Asia (Bain *et al.*, 2014). Water contamination with coliform bacteria was the main source of waterborne diseases like gastroenteritis, dysentery, diarrhoea and viral hepatitis as complained by most of the respondents during questionnaire survey conducted Charsadda district, Pakistan (Khan *et al.*, 2013).

2.2.1 Point and non-point source pollution

The information age has ushered in a global awareness of complex environmental problems that do not respect political or physical boundaries; such as climate change, ozone layer depletion, deforestation, desertification, and pollution (Axelrod & VanDeveer, 2014). Among these global environmental issues are point and non-point sources of pollution which represent a perfect example of a complex multidisciplinary problem that exists over multiple scales with tremendous spatial and temporal complexity.

2.2.1.1 Point sources of water pollution

Point sources of pollution are the major causes of degradation of ecosystems, and may have significant effects on human health if they are not properly controlled (Sun *et al.*, 2016). They can be classified in terms of sources, the discharged media, and the pollutants themselves. The sources include municipal and industrial sector activities, and the media include water, air, and solids (Axelrod & VanDeveer, 2014). A point source of pollution discharges to the environment from an identifiable location, whereas a non-point source of pollution enters the environment from a widespread area (Gleick, 2014). The ability to accurately assess present and future point and non-point source pollution impacts on ecosystems ranging from local to global scales provides a powerful tool for environmental stewardship and guiding future human activities (Tietenberg & Lewis, 2016).

Surface water quality, for example river water, is strongly influenced by land use. Most water pollutants such as particles, nutrients and metals show a significantly positive correlation with the percentage of construction land (Gleick, 2014). Crop land cover, however, may have a more complex relationship with water quality. The increase of farm land coverage was found to increase the concentrations of both nitrate and sulphate ion in some case studies, but no influence in others (Gleick, 2014). Other emerging types of land use, such as nursery garden and urban green land, have received relatively little attention in research on water quality and their effects could be underestimated (Tietenberg & Lewis, 2016). Previous studies have shown that land use close to a river was a better predictor of water quality than the spatial pattern of

the entire watershed (Wu & Chen, 2013). In addition, in many regions with flat relief and canals, it is impossible to clearly delineate the watershed boundary (Davis, 2010).

2.2.1.2 Non-point sources of water pollution

Metal pollution from diffuse sources to natural waters is more difficult to control than metals from point-sources (Gleick, 2014). The widespread use of metals in construction materials, batteries, vehicles, personal care products, clothing, and many other materials leads to moderate contamination of watersheds in populated and industrialised areas. Wastewater treatment effluent, combined sewer overflows, and urban runoff all contain elevated concentrations of metals that are very difficult to control. Control of metals in an upstream manufacturing process can reduce metals loads effluent (Davis, 2010).

2.3 Water treatment technology

The basic goal of water treatment is to remove undesired constituents from water (Qu *et al.*, 2013). New and improved treatment technologies are emerging all the time, however their operational cost and maintenance are unsustainable especially for large scale water treatment (Marlow *et al.*, 2013). Water treatment requires physical, chemical and sometimes biological processes to remove contaminants. The various unit processes are critical to the overall process efficiency since each unit has a specific purpose (Gavrilescu *et al.*, 2015). Potable water treatment plants use the physical and chemical processes, while wastewater treatment plants normally use the biological processes (Spellman, 2013).

In a conventional or traditional water treatment, the physical processes used include flocculation, sedimentation, filtration, adsorption, and disinfection by UV light, while the chemical processes for potable water treatment will include oxidation, coagulation and disinfection (Parsons & Jefferson, 2006). The types and order of processes used will depend on the state of the source water, the kind of contaminants that must be removed, the concentrations of contaminants and the water quality standards that must be achieved. Adsorption is the most effective and widely used water treatment

method for the removal of organic and persistent organic pollutants (Ali, 2014). The design for adsorption technology will depend on raw water quality, pollution load and the preliminary treatment results. An example of an adsorbent of choice is the activated carbon which has long been used for water and wastewater treatment due to its good capacity for adsorption (Ali, 2014).

A study by Plappally (2012) explains the stages for water recycling and reuse in relation to energy consumption. The significance of this study is that it emphasises the importance of choosing the right processes in the production of water so that the entire process minimises economic and environmental impacts. It also explains why water treatment processes will differ from one area to another (Plappally, 2012). The water life cycle starts with production or extraction of water from natural sources such as ground water aquifers, lakes, rivers, and oceans. Fresh water from lakes and rivers normally requires treatment for the removal of micro-organisms and suspended solids such as sand or silt. Algae and cyanobacteria (phytoplankton) form part of organic suspended matter in water (Ewerts *et al.*, 2014). Phytoplankton cells such as the dinoflagellate *Ceratim hirundinella* are known to cause major water purification problems, especially during bloom forming periods (Ewerts *et al.*, 2014). In some cases, advanced methods of treatment would be needed to remove organic compounds, dissolved ions, and/or in the case of ground water, absorbed gases. The importance of each stage in the water cycle is distinct and is also significantly affected by variations in the geographical location being served, water availability there, the local climate, the culture and customs of the area, and the economic status of the location (Plappally, 2012).

Treated water is used in different ways by various customers in the residential, commercial, industrial and agricultural sectors (Jensen *et al.*, 2014). For example, residential customers usually pump water for domestic use (washing and cooking), while agricultural consumers pump water to irrigate fields. Treated water may also become polluted at the point-of-use (POU) and thus require some treatment before it can be consumed. There may be a chance that the faucet has accumulated microbiological agents, hence it is always recommended that consumers run the communal taps for at least five minutes before they can draw water for drinking purposes (Harvey *et al.*, 2016). POU treatment processes can be used at home, in the

field, and in emergency situations. The main objective of this kind of treatment is to produce clear and microbiologically safe water. The processes used are relatively simple processes such as boiling water, or adding chlorine in the form of bleach, or exposing the water to sunlight (Sobsey *et al.*, 2008).

2.3.1 Conventional methods of water treatment

Safe drinking water is essential to the health and welfare of a community and water from all sources must have some form of purification before consumption (Saritha *et al.*, 2017). Various methods are used to make water safe and attractive to the consumer. The method employed depends upon balancing a few factors, including intake water characteristics, the volume of water needed, and target water quality. One of the problems with treatment of surface water is the large seasonal variation in turbidity (Padmaja *et al.*, 2014).

Different water treatment processes are used in sequence in order to produce drinking water of a desired quality (Ewerts *et al.*, 2014). A conventional water treatment and purification process includes a series of physical and chemical steps that when applied to raw water sources contribute to the reduction of microorganisms of public health concern (Korotta-Gamage & Sathasivan, 2017). A general example of a purification process would be; an oxidation process followed by sedimentation and filtration process. The oxidation process causes the dissolved contaminants to form a precipitate, which is then removed by filtration (Parsons & Jefferson, 2006).

All raw natural water contains suspended particles which need to be removed. In a conventional water purification works, suspended matter is removed in sedimentation tank and sand filters after coagulation and flocculation (Figure 4). The primary aim of coagulation and flocculation is to remove suspended and dissolved particles that may be undesirable in the final effluent (Ewerts *et al.*, 2014). Very seldom, the water distributed may need further treatment at the POU. This may involve, for example softening of hard water by means of a home ion exchanger, or treatment by some other home treatment device. In some areas, for example in the rural areas, rainwater is collected from rooftops and stored in tanks before use (Visvanathan *et al.*, 2015). The water may be treated by means of a filter or used without any treatment at all.

Provision is often made that the first water collected from the roof is diverted from the tank in order to prevent dirt and debris from entering the tank. In some systems water is supplied without any treatment at all (Padmaja *et al.*, 2014). For example, where water is fetched directly from a source by the individual user or by vendors, the water is often consumed without any treatment (Cheremisinoff, 2001). Consuming surface water without treatment is a dangerous practice that may result in contracting diseases such as cholera if the water source is contaminated by pathogens (Gleick, 2014). Detailed discussions of conventional water treatment processes will be discussed in sections 2.4.1 to 2.4.4.

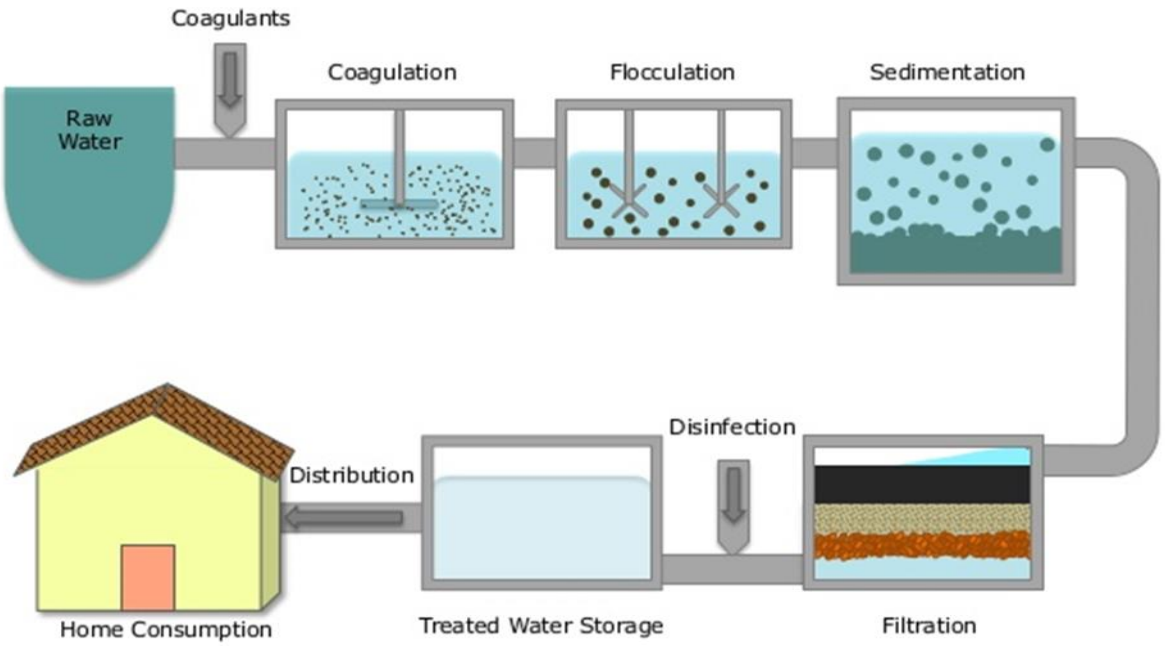

Figure 4: A typical layout of water treatment processes

Source: Karki, 2018.

2.3.2 Advanced methods of water treatment

The intensity of water resource scarcity in South Africa, as well as the rest of the world, is forcing water companies to utilise advanced water treatment processes in order to purify every available water source, even a river, reservoir or wetland with water that looks like pea soup, or one clogged from bank to bank with aquatic plants (Morrison

et al., 2012). Some micropollutants, more especially the emerging contaminants, are particularly more resistant to removal and inactivation by conventional water treatment processes. Therefore, extensive research has been focused on the optimisation of water treatment processes and application of new technologies in order to reduce the concentrations of viable and/or infectious micropollutants to a level that prevents diseases (Betancourt & Rose, 2004). The advanced water treatment processes are discussed in sections 2.4.5 to 2.4.11.

2.4 Water treatment processes

The primary purpose of water treatment is to provide drinking water that is free of biological, chemical and physical contaminants. Since there is no single treatment process that can be expected to completely remove all the different types of contaminants found in water, under all conditions, multiple barriers are desirable. The number of treatment methods required is influenced by the quality of the source water (Benner *et al.*, 2013). For example, groundwater will normally require very minimal treatment, if any, since they are protected from the surface influence. However, low-land surface water will mostly require much more treatment processes because of the poorer source water quality. Hence, selecting an appropriate treatment process is a critical step, influenced by many environmental factors, in providing safe and reliable drinking water quality (Marlow *et al.*, 2013). There is also a need to collect and analyse raw water quality data for an extended period of time, sufficient to show seasonal and extreme events, to make sound decisions on the most appropriate and effective water treatment processes.

Traditionally, there are four stages involved in domestic water treatment. The first stage is called pre-treatment, where screens are used to remove the large debris and objects from the water supply (Faust & Aly, 2018). Aeration can also be used in the pre-treatment phase. This stage also improves colour, taste and odour of drinking water. The second stage in water treatment process involves coagulation and flocculation. A coagulating agent that is added to water will cause the suspended particles to clump together into flocs which can be easily removed as they settle, forming a precipitate, into the sedimentation basins. This step will allow clarified water

to flow through the process, and into the third stage, which is the filtration (Faust & Aly, 2018). Filtration is the process whereby smaller particles not removed by flocculation are removed by running the water through a series of filters. Filter media can include sand, reverse osmosis, adsorbent, ion exchange, granulated carbon, or any activated carbon filter effective enough to remove the salt particles and biological microorganisms in water (Padmaja *et al.*, 2014). Following filtration is the final stage, the disinfection process. Water is finally disinfected to kill, disable or inactivate any microbes or viruses that could potentially make the consumer sick. The most traditional disinfection methods used are chlorination by the use of chlorine gas or chloramines. However, new drinking water disinfection methods are constantly coming into the market. The two disinfection methods that have been gaining traction use ozone and ultra-violet radiation to disinfect the water supply (Cheremisinoff, 2019).

2.4.1 Coagulation-flocculation

Coagulation-flocculation is a solid-liquid chemical process of a conventional water treatment (Zanacic *et al.*, 2016). Coagulation is a primary and most critical processing step used to hasten the agglomeration of fine particles in turbidity, remove the nuisances such as algae, and ultimately aids in the clarification process (Figure 5). In contrast, coagulation causes smaller particles to bind together to form larger suspended particles, known as colloids or flocs, including microorganisms (Saritha *et al.*, 2017).

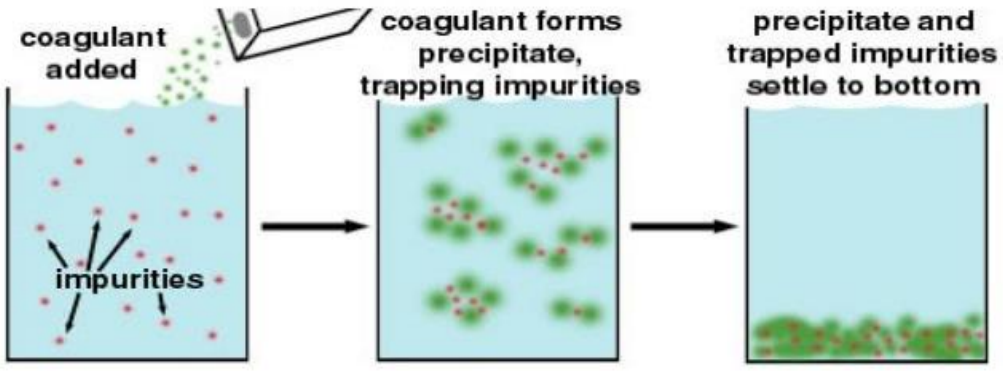

Figure 5: Schematic diagram of a coagulation process

Source: Thakur, 2014.

Flocculation is the process that gathers together the fine particles in water, by the gentle mixing, after the addition of coagulant chemicals (Zanacic *et al.*, 2016). The destabilised suspended particles clump together to form larger flocs. At this stage, the flow rate of water is high enough to discourage the settling of flock within the spiral flocculators, but low enough to encourage flock formation (Figure 6).

Figure 6: Flocculation process in conventional water treatment plants

Source: Chinyama *et al.*, 2014.

The most common coagulants in use throughout the world are aluminium sulphate, ferric sulphate, ferric chloride and poly-aluminium chloride (Javid *et al.*, 2015). The coagulant is mixed with water in order to produce a hydroxide precipitate that is “fluffy” and enmesh particles along with some of the dissolved organic carbon (Marlow *et al.*, 2013). The large floc particles that are formed are subsequently removed by sedimentation or by direct filtration. It is essential that the removal of micro-organisms and particulate matter should be as complete as possible before disinfection such that the need for high disinfectant doses, and the cost of disinfection, is reduced (Haute *et al.*, 2015). This will also limit the formation of disinfection by-products. Factors that influence coagulation–flocculation process are, among others, temperature, pH, effluent quality, dosage and coagulant type (Saritha *et al.*, 2017). Since suspended particles often vary considerably in source, composition charge, particle size, shape and density; the correct application of coagulation-flocculation process, as well as the

selection of the coagulants would normally depend upon understanding the interaction between all these factors. It is therefore imperative for relevant stakeholders to fully comprehend the technicalities involved when considering the coagulants for rural/underprivileged domestic water treatment facilities, where cost limit are a factor (Saritha *et al.*, 2017).

2.4.2 Sedimentation-flotation

Simple sedimentation without the use of coagulants may be used to reduce turbidity and solids in suspension (Khiadani *et al.*, 2014). Sedimentation tanks are designed to reduce the velocity of flow of water so as to permit suspended solids to settle under gravity. An alternative technique to that of sedimentation is flotation. Flotation is achieved by several methods but the most effective form is dissolved air flotation. Dissolved air flotation (DAF) allows for the removal of fragile floc particles found in water treatment via adherence to air bubbles (Betancourt & Rose, 2004). The gas bubbles attach to the particles and make their effective density lower than that of the water. This causes the large particles, or the sludge, to rise and float at the surface (Figure 7). The advantage of flotation over sedimentation are that very small or light particles, particularly fats, oils, and grease, that settle slowly can be removed more efficiently by the use of a skimmer (Cheremisinoff, 2019).

Figure 7: Dissolved air flotation with solid-liquid separation

Source: Khiadani *et al.*, 2014.

2.4.3 Filtration

Filtration is the physical removal of turbidity and microorganisms from water (Shanmuganathan *et al.*, 2017). Filters within a conventional water treatment process are considered as the last barrier to the release of particles into the distribution system. During filtration, water passes through a pore-like structure made up of a variety of bed materials that can be composed of, a bed of sand or gravel also known as sand filtration; a layer of diatomaceous earth also known as diatomaceous earth filtration; or a combination of coarse anthracite coal overlying finer sand, known as dual and tri-media filtration (Zanacic *et al.*, 2016). The water to be treated flows down through the filter bed and, as it does so, a layer a few millimetres thick of algae, plankton and other microscopic plant life forms on the top. The removal of particles in suspension occurs by straining through the pores in the filter bed, by adsorption of the particles to the filter grains, by sedimentation of particles while in the media pores, by coagulation while traveling through the pores, and by biological mechanisms such as slow sand filtration (Zahrim & Hilal, 2013). The latter is accomplished by the filtering action of the schmutzdecke. The schmutzdecke is the top layer, a few centimetres in depth, of sand and particulate materials such as fine soil particles, plant debris, algae, free-living or non-pathogenic protozoa that have been removed from the water as it percolates downward through the sand filter bed (Hoslett *et al.*, 2018).

When the rate of filtration begins to tail off after a month or two, the filter is drained and the top 2 cm of sand is removed to be replaced by fresh sand (Zanacic *et al.*, 2016). Slow sand filters are expensive to build and operate, and require a large amount of space. They cannot be used for coagulated waters because of rapid clogging. Slow sand filters have been largely replaced by rapid gravity sand filters, which are particularly effective for water treated with coagulants and are less expensive than slow sand filters (Divrikli *et al.*, 2007). The filter is cleaned at intervals of 24–48 hours by pumping water and air, to assist in scouring, under pressure backwards through the filter to wash out the trapped impurities. This process is called backwashing. Unlike slow sand filters which tend to produce water with a particularly low bacterial count,

rapid filters produce water with high bacterial counts, increasing the necessity to follow them with disinfection before supplying the water to the public (Boleda *et al.*, 2011).

2.4.4 Disinfection

Before water can be passed into the public supply, it is necessary to remove all potentially pathogenic micro-organisms (Delpla & Rodriguez, 2017). Water suppliers must assume that all surface waters contain *E. coli* and treat the water accordingly. However, by definition disinfection does not usually inactivate every last cell of micro-organisms that are present; it may rather reduce concentrations to acceptable levels for which disease risk is very low (Byrne *et al.*, 2015). Since these micro-organisms are extremely small, it is not possible to guarantee their complete removal by sedimentation and filtration, so the water must be disinfected to ensure its quality. Disinfection is the inactivation of pathogenic organisms and is not to be confused with sterilisation, which is the destruction of all organisms (Momba *et al.*, 2009).

Water disinfection is accomplished with chemical or physical disinfectants (Momba *et al.*, 2009). Worldwide, the most common disinfectant used in water supply is chlorine; as a gas or hypochlorite; but other chemical disinfectants such as chloramine, chlorine dioxide, and ozone are also used. Chlorine acts as a strong oxidising agent which can penetrate microbial cells, killing the micro-organisms. It is known to kill most bacteria but not all viruses. It is relatively cheap and extremely soluble in water, up to 7000 g/m^3 (Zanacic *et al.*, 2016). Unfortunately, chlorine comes with some disadvantages. It can give alter the taste and give odour problems to water. For example, in the presence of organic compounds, chlorine reacts to form carcinogenic disinfection by-products such as trihalomethanes (Betancourt & Rose, 2004). In South Africa, trihalomethanes (THMs) are regulated organic pollutants with a limit of 200 µg/L according to the drinking water quality guidelines by DWA (DWAF, 1996). Thus, there is a need to monitor the presence of these undesirable pollutants in water systems and remove them before they reach the consumers (Betancourt & Rose, 2004). The advanced water treatment process was discussed in the preceding sections.

2.4.5 Membrane filtration

Membrane filtration is becoming popular in water treatment processes for the removal of micropollutants such as trace organic compounds, trace heavy metals, and microbiological compounds such as pesticides. Pesticides, which are often carcinogenic, are not at all desirable in potable water. According to the SANS 241, an allowable limit for individual pesticides is less than, or equal to 0.1 micrograms per litre of water (DWAF, 1996).

Membrane filtration is an important enrichment technique for separating trace metal ions and microbiological components in water (Divrikli *et al.*, 2007). The formation of hydrophobic species is necessary for the quantitative extraction of the desired trace elements on the membrane filter. The collection of trace metal ions is performed very quickly by filtration under suction with the aid of a vacuum aspirator (Divrikli *et al.*, 2007). The collected trace elements are dissolved together with the membrane in a small amount of mineral acid. The trace ions in the final solution are determined by analytical laboratory instruments. The most attractive features of membrane filtration technique are the simplicity and rapidity of the procedure, an easily attainable high concentration factor and determination with high-precision (Divrikli *et al.*, 2007). Pressure-driven membrane processes are also used in water treatment processes to control and remove disinfection by-products (DBPs), pathogens, inorganic and synthetic organic chemicals, respectively (Holloway *et al.*, 2016).

2.4.6 Reverse osmosis

Reverse osmosis (RO) is another technique that has become popular in water treatment for the removal of pollutants such as trace organics and salts; and it is worth considering for nitrate removal (Holloway *et al.*, 2016). When a solution of a salt is separated from pure water by a semi-permeable membrane that permits the passage of pure water but prevents that of the salt, water will tend to diffuse through the membrane into the salt solution, continuously diluting it. This phenomenon is called osmosis (Holloway *et al.*, 2016). If the salt solution is in an enclosed vessel, a pressure will be developed. This pressure in a particular solution is known as the osmotic

pressure of that solution. Reverse osmosis is therefore a process in which water is separated from dissolved salts in a solution by filtering through a semi-permeable membrane at a pressure greater than the osmotic pressure caused by the dissolved salts in the water (Holloway *et al.*, 2016). The salts to be eliminated could be in any form, including nitrates. The removal rates in excess of 93 percent for nitrates have been reported for RO technology (Holloway *et al.*, 2016). Furthermore, operating costs and space requirements for RO are said to be much less than of an equivalent ion exchange (IX) water treatment plant.

2.4.7 Adsorption and ion exchange

Ion exchange (IX) is used in some water treatment plants to remove nitrates from drinking water (Ali, 2014). In this process, water is passed through an IX resin which removes the undesired ions and replaces them with ions which do not affect the water quality. This technology for nitrate removal was developed from water softening systems which were used to remove the hardness conferring ions, Ca^{2+} and Mg^{2+} (Ali, 2014). For example, the Vaal Dam in South Africa has a high concentration of blue-green algae during the summer months. This type of algae produces an odorous substance called “geosmin” which causes an unpleasant taste to linger on in water even after coagulation and the entire treatment process. An imported and expensive chemical called powdered activated carbon (PAC) is added to the water to adjust the taste and smell of the finished product (Korotta-Gamage & Sathasivan, 2017).

2.4.8 Granular activated carbon

After conventional treatment, water may still contain trace concentrations of synthetic organic compounds, which, if left in the water, can lead to taste and odour problems (Ang *et al.*, 2015). The problem is most likely to arise where the raw water source has been badly polluted. The problem can be solved by including the process of granular activated carbon adsorption after the filtration process (Ang *et al.*, 2015). Activated carbon is treatment by carbon which has been activated by heating in the absence of oxygen. This results in the formation of many pores within each carbon particle, which

has more adsorbent characteristics. Charcoal is a form of activated carbon but with fewer pores. Granular activated carbon (GAC) is known to be an effective adsorbent material of organic compounds. Its effectiveness can be measured by the reduction in the chemical oxygen demand (COD), which is the oxygen needed to chemically oxidise all carbonaceous material present, and the total organic carbon (TOC) of water (Ang *et al.*, 2015). GAC can be used in a water treatment process for the removal of soluble phenols which produce strong smelling and tasting chlorophenols upon reaction with chlorine in the disinfection stage. In the event that trihalomethanes (THMs) are formed after disinfection by chlorine, GAC can be used to eliminate these toxic compounds. GAC, once exhausted, can be regenerated by heat treatment (Ang *et al.*, 2015).

Another method of removing trace organics is to oxidise them to harmless products such as carbon dioxide by using ozone (Ang *et al.*, 2015). Ozone oxidation and activated carbon are capable of removing trace quantities of organic pollutants, such as pesticides, present in water supplies to comply with the limit specified by the EU and WHO (Ang *et al.*, 2015). Powdered activated carbon (PAC) can also be added to water for the adsorption of trace organic contaminants. It has also been used to eliminate tastes and odours in drinking water brought about by algae, actinomycetes and fungi. It is usually added in the coagulation stage prior to sand filtration. Unlike GAC, the regeneration of PAC is not practicable, so it is only used when intermittent water quality problems occur (Ang *et al.*, 2015).

2.4.9 Ozonation

The ozone, (O_3), used in water treatment plants is usually generated by passing dry air or oxygen between plates, across which a high voltage is imposed (Rivera-Utrilla *et al.*, 2013). Ozonation is an expensive technology; and the necessary equipment to produce the method is complex. However, ozone which is a blue gas; and a very strong oxidising agent, has recently become a popular disinfecting agent as it is particularly more effective against viruses and spores (Rivera-Utrilla *et al.*, 2013). In the United Kingdom (UK), it is often used to oxidise any pesticide residuals present in water treatment. Also, the ozonation process does not produce the toxic by-products

such as THMs which can occur with chlorine. It can, however, form toxic bromates if bromine is present in the water (Rivera-Utrilla *et al.*, 2013). Ozonation is particularly popular in European water treatment plants because many water suppliers in Europe source water from rivers that contain organic substances that can be destroyed by ozone without forming the toxic organochlorines. The only drawback with ozone is that it is not possible to have a residual level, as there is for chlorine, to confer protection in the supply and distribution system. Ozone will break down to oxygen very rapidly when any particles are present in water. However, if water is ultra-clean, it will remain as O_3. Hence, after ozonation, the water is chlorinated before it goes into the supply system (Rivera-Utrilla *et al.*, 2013).

2.4.10 UV radiation

Ultraviolet radiation is also a powerful disinfecting agent, and is becoming increasingly popular in New Zealand and other countries, particularly for inactivating protozoa, again in part because organochlorine by-products are avoided (Stanfield *et al*., 2003). There is also increasing interest in natural solar disinfection of water, particularly in developing countries where infrastructure for water disinfection is unavailable or has been damaged, but sunlight is abundant (Rivera-Utrilla *et al.*, 2013). Although UV radiation can be used to disinfect water, care must be taken to ensure that no suspended solids are present which could shield the micro-organisms and prevent them from being destroyed. UV systems are generally only used in small-scale water treatment units. Similar to ozonation, UV radiation do not give a residual for protection in the distribution system (Lee & Park, 2013).

2.4.11 Chemical stabilisation

Post-treatment stabilisation is an important process for aesthetic quality of water and public health and cost-effective operation of the treatment plant. Priority issues relating to post-treatment stabilisation are scaling and corrosion control, as well as water quality goals (Jensen *et al.*, 2014). Corrosion is one of the most apparent problems in the drinking water industry. Corrosive pipes are in the exposure of microbial

contamination and elevated water metal concentrations such as iron, zinc, copper, manganese, lead, selenium, and arsenic that in addition to endangering the health of people, cause consumer complaints due to the smell, taste and colour of the water (Asghari *et al.*, 2018). In water distribution networks, corrosion causes entrance of various substances into the water body; and the occurrence of the toxic metals such as lead (Pb) and cadmium (Cd) is attributable almost entirely to leaching caused by corrosion of plumbing materials (Tchounwou *et al.*, 2012). Copper, iron, and zinc may cause staining of plumbing fixtures and sometimes a metallic taste on water.

Plant operators use three parameters to control and generate more stable water, which is: pH, alkalinity and hardness. Each of these parameters possess unique properties that can enhance the quality and stability of the water as it travels from the treatment plant through the distribution system (Gitis & Hankins, 2018). Proper stabilisation of aggressive water can also extend the life of the plumbing fixtures and distribution system, hence lowering operating cost by reducing excessive scaling, corrosion and its damaging effects. Ineffective chemical stabilisation may also increase the risk of bacterial or viral regrowth in water (Faust & Aly, 2018).

2.5 Threats to water treatment

The rapid changes in human lifestyles over the years have consistently added different notorious anthropogenic pollutants in the aquatic systems (Das *et al.*, 2014). Eradication of these newly emerging deleterious pollutants is either impossible or difficult using the classical water treatment systems. Major threats to common water purification systems are summarised in Figure 8. This clearly reflects that a single method is insufficient to remove all pollutants from water (Das *et al.*, 2014). For instance, the pathogen removal processes of conventional water treatment plants may affect the effluent water quality parameters, such as turbidity, pH and temperature, and further decrease pathogen sensing ability (Das *et al.*, 2014). Certain bacteria in treated water may release toxins, which may seriously affect the overall quality of water during the treatment process. For example, cyanobacteria release microcystin toxin in water while undergoing the treatment process. Low concentration and small dimensions of pollutants are difficult to sense and mitigate (Das *et al.*, 2014).

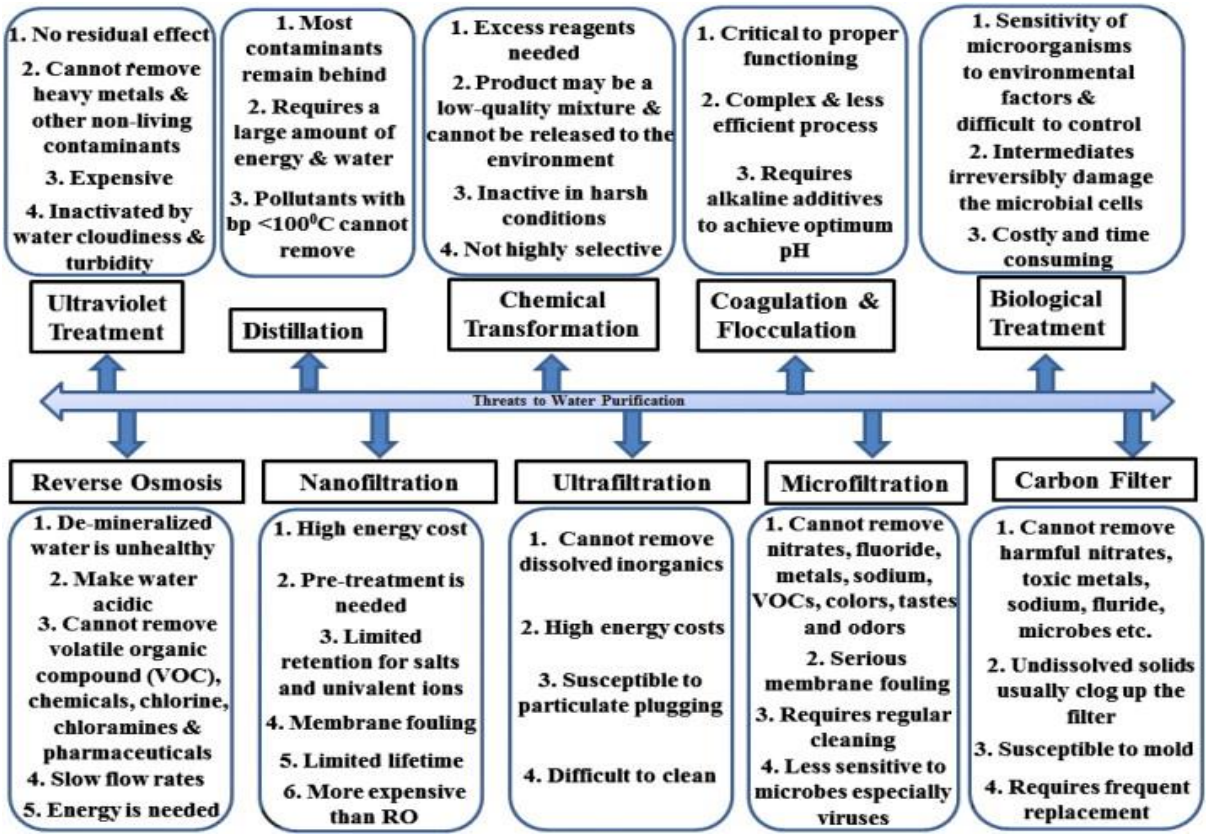

Figure 8: Major threats to water treatment systems

Source: Das *et al.*, 2014.

2.6 Summary

There are various processes and technologies used to remove contaminants from water and to improve the quality of water in many parts of the world. The major and most crucial steps are common to both conventional and non-conventional (advanced) processes; which are the coagulation-flocculation, filtration and disinfection stages. There have been studies to find cost-effective and efficient ways to remove contaminants in drinking water, for example, the development of effective membrane filters, as well as the use of environmental catalysts in water treatment. The most critical stage is the final, in which most water treatment plants need to be aware of the possibility for the formation of carcinogenic by-products as a result of the chlorination process if organics are present in the water being disinfected. However, if the water has been previously treated by coagulation-flocculation and pre-ozonation, the

chances of organic pollutants being present to form these harmful by-products are remote. Hence the additional use of filters is more preferred for the effective removal of trace organics. There is evidence that the choice of a water treatment process depends upon the type of the raw water source and the cost of the treatment method.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

In water-scarce environments, surface water bodies serve both as water sources and waste disposal channels. The Molopo River that drains through Mafikeng, South Africa, has been dammed for agricultural and municipal water supply, resulting in four reservoirs near Mafikeng. It receives municipal waste water discharges from point pollution source sewage processing plants. Molopo River is the main water source for Mafikeng Municipal water supply, having been purified through Mmabatho Water Treatment Plant. A spatial variation analysis conducted by Munyati (2015) revealed a manifestation of eutrophic and hypertrophic in the reservoir water around July, the dry season where river flow is at its lowest. The Matlosana Municipality, in Klerksdorp, gets water supply through the Midvaal Water Company. The Midvaal, as the name suggests, is situated at the middle of the stretch of the Vaal River. The quality of the river water varies seasonally as the river is affected by extensive activities upstream, hence it contains numerous types of algae and other nuisance water plants as a result of the high levels of phosphates and nitrates. This study is aimed at assessing the effectiveness of the drinking water treatment processes at the Mmabatho and Midvaal water plants. This was done by analysing the different treatment processes used by the two facilities, and lastly by determining the water quality produced by the two plants by analysing the physico-chemical and microbiological constituents of water samples at specific points of the treatment process. Table 1 summarises the water quality variables that were measured, and the analytical methods used to determine the water quality at each site.

Table 1: Water quality parameters and analytical methods for water source evaluation

Parameter	Analytical method	Instrument
pH	Instrumental, analyse on site	pH meter, HACH SENS Ion
Temperature	Instrumental, analyse on site	Thermometer, glass thermometer
Conductivity and total dissolved solids	Instrumental, analyse on site	Conductivity meter, HACH Model
Turbidity	Nephelometric method, analyse on site	Turbidimeter
Residual chlorine	DPD method	Free chlorine test kit
Total hardness	EDTA titrimetric method	Titration apparatus
Total suspended solids	Gravimetric method	Filtration apparatus
Chlorides	Photometric method	Spectroquant prove 300, Merck
Sulphates	Photometric method	Spectroquant prove 300, Merck
Nitrates as nitrogen	Photometric method	Spectroquant prove 300, Merck
Calcium and magnesium	Photometric method	Flame spectrophotometer
Sodium	Photometric method	Flame spectrophotometer
E. coli	Culture-based method	Membrane filtration technique
Total coliform	Culture-based method	

Source: Hounslow, 2018.

Refer to sections 3.3, 3.4, 3.5 and 3.6 for an overview of the sampling regime that was followed as well as materials and methods that were used to determine the water quality variables.

3.2 Research design

The research process most suited for the study was a quantitative experimental approach. Most water quality analyses cannot be done on site, i.e. *in situ*. Therefore, a representative volume of water, at specific points of interest, were collected for analysis in the laboratory, i.e. *ex situ* (Schutte, 2001*)*. The research design followed is illustrated in Figure 9.

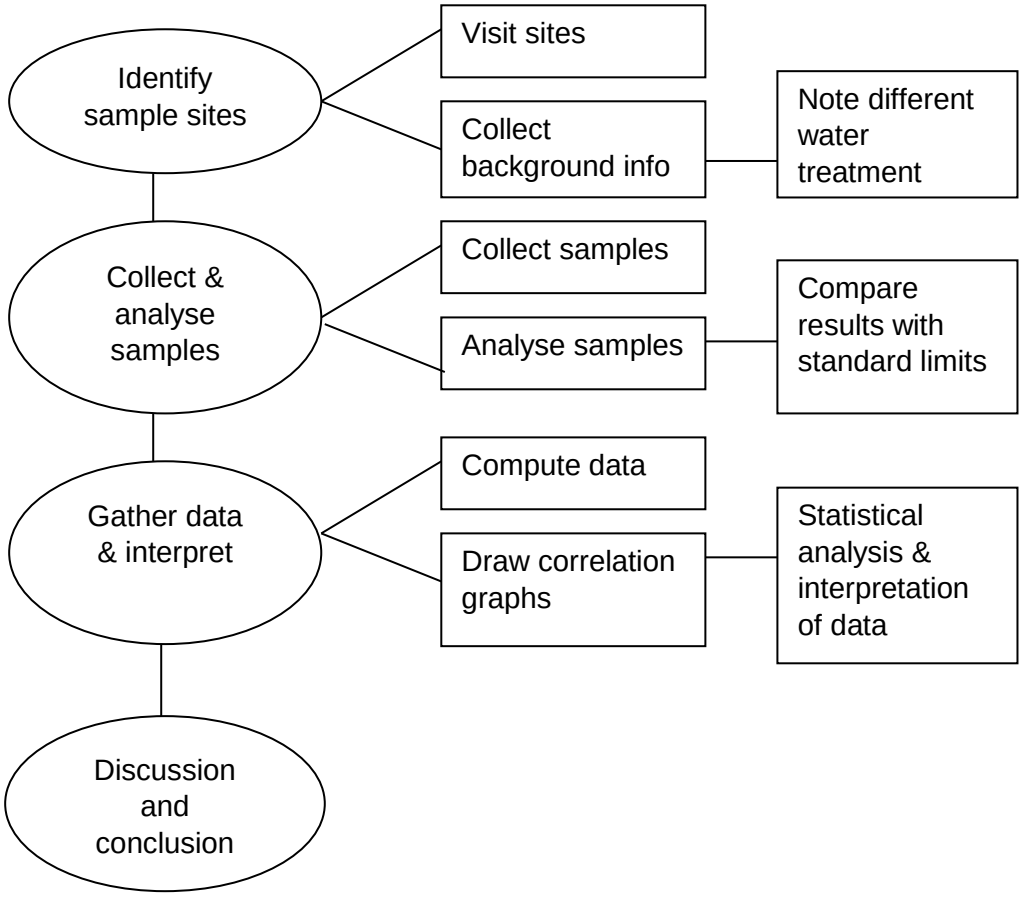

Figure 9: Flow chart showing the research design

3.3 Sampling sites and points

The points sampled at the Midvaal Water Company are illustrated in Figure 10; (1) the inlet – to determine the quality of water before the treatment process; and (2) the outlet – to determine the quality of water after the treatment process. The results were compared to the WHO, DWA and SANS 241 guidelines for drinking water quality.

Similarly, a flow diagram for the conventional water treatment process as used by the Mmabatho Water Treatment Plant is illustrated in Figure 11. The sampling points are also indicated in the diagram.

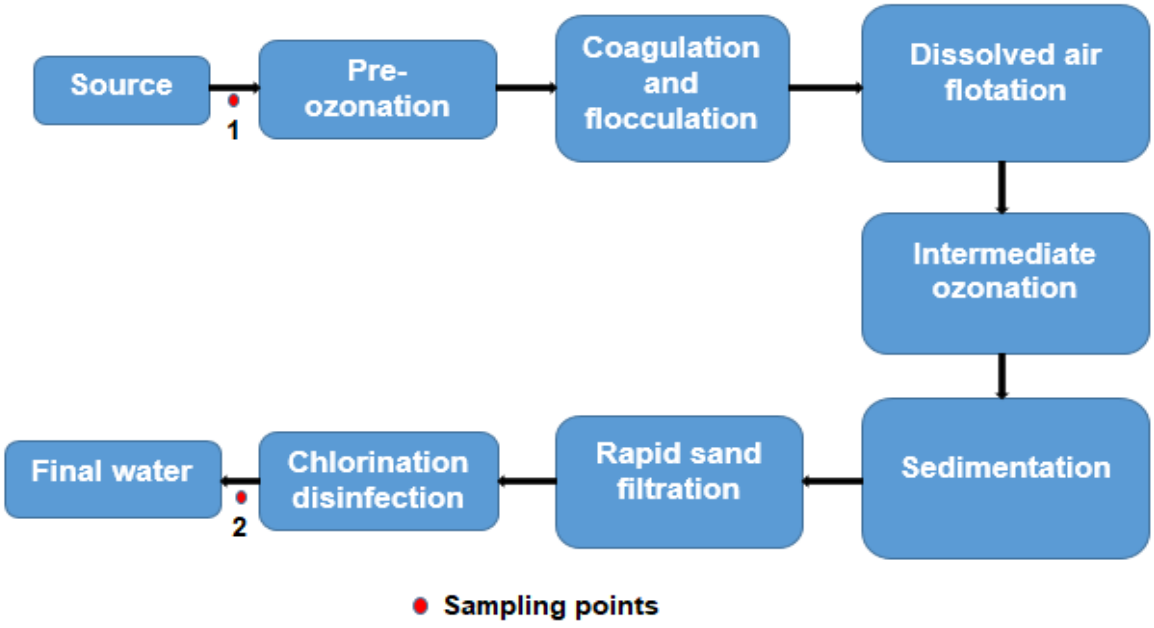

Figure 10: Flow chart showing the sequence of the water treatment steps, plus the sampling points, at Midvaal Water Company

Source: van Rensburg *et al.,* 2016.

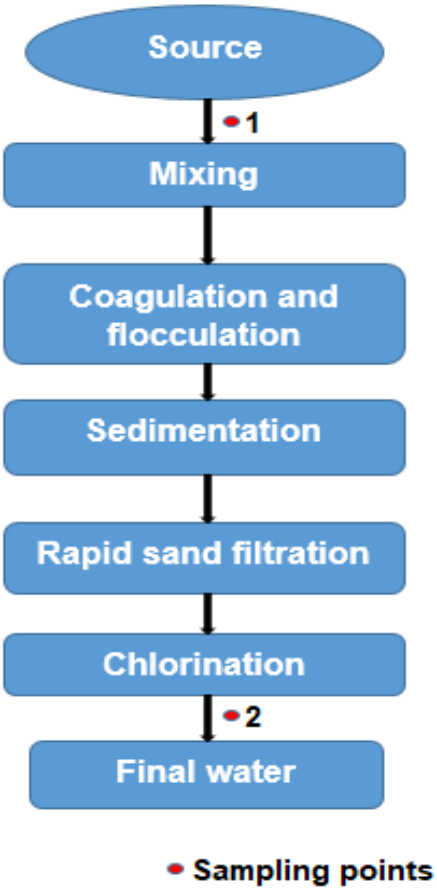

Figure 11*:* Flow chart showing the sequence of the conventional water treatment steps, and the sampling points used at Mmabatho Water Treatment Plant

Source: Kawamura, 2000.

3.4 Data collection

3.4.1 Materials and methods

Analytical grade reagents and standards were used throughout this study, according to the methods of water analysis in the preceding section 3.5; and were obtained from Merck Chemicals (South Africa). Unless otherwise indicated by the DWA analysis guide, ultra-pure or type 1 deionised water was used to prepare and dilute all standards and water samples. All field apparatus and laboratory instruments used were calibrated according to manufacturer's instructions. Furthermore, the glassware

were of A-grade and were washed and treated according to the standard guide (Schutte, 2001).

3.4.2 Preliminary data collection

The first step involved a field trip to the sites to learn the different water treatment processes employed at the two study areas and the motivation towards the selection of their treatment processes. Furthermore, the baseline information pertaining the source water; the general characteristics of the water source; as well as the quality of the water was obtained before gathering individual site data. The sample locations were also identified with the assistance of plant operators. Sampling and analysis using environmental analytical instrumentation were scheduled for the months between December 2017 and November 2018 to cover the different seasonal variables.

3.4.3 Preparation of sampling equipment

Sampling equipment checklist was obtained and checked before every sampling trip to ensure that all necessary equipment was brought along. Specific hand-held equipment used to determine the physical constituents such as pH, electrical conductivity, temperature, turbidity and free chlorine were calibrated in advance. Twelve new polypropylene bottles (1000 cm^3) and their caps were washed in warm soapy water, and rinsed three times with distilled water. Only the six bottles for microbiological sampling were further sterilised, and treated with 10% sodium thiosulfate solution (i.e. 0.1 cm^3/100 cm^3 sample), which is a preservation method used to neutralise further disinfection process of the water sample. All bottles were tightly sealed with caps, to prevent contamination, and labelled accordingly to indicate sample location, sample number, and date of sampling (Keith, 2017).

3.4.4 Collection of water samples

The collection of samples for various analysis was performed with the assistance of plant operators at designated points. Six batches of 1000 cubic centimetres (cm^3) per site were collected, labelled, preserved and analysed according to the relevant guides outlined in the Quality of Domestic Water Supplies, Volume 3, Analysis Guide by the Department of Water Affairs (DWA) and Water Research Commission (WRC).

3.4.4.1 Sample collection and preservation – microbiological analysis

Samples for microbiological analysis were collected first. The faucets were sterilised by wiping with a disinfecting wipe. The taps were then allowed to run water fully for at least 5 minutes to remove any stagnant water from the system. The water flow was adjusted to a normal flow before the collection of each sample. As a precautionary measure, the sample containers were handled at the base to prevent contamination of the sample. With the free hand, the cap of the sample container was carefully removed, and water filled to the line, ensuring that water does not overflow from the container. The container cap was replaced tightly, and the sample placed in the cooler box filled with ice to maintain the temperature at 4 °C until delivery to the lab for further analysis of faecal and total coliforms within 24 hours (Keith, 2017).

3.4.4.2 Sample collection and preservation – chemical analysis

For chemical analysis, the sample containers and their caps were rinsed 3 times before the water flow was reduced to allow for the collection of the sample at reasonable flow. No preservation was necessary for samples for chemical analysis, therefore the sample containers were filled to the top, and caps put tightly with no air gap (Keith, 2017). Samples were immediately put in the cooler box filled with ice to maintain the temperature of 4 °C until delivery to the Chemistry lab for further analysis of selected chemicals. These included the most abundant anions and cations in water such as nitrates (NO_3^-), sulphates (SO_4^{2-}), chlorides (Cl^-), calcium (Ca^+), magnesium

(Mg^{2+}), and sodium (Na^{+}); as well as other important determinants in domestic water quality like free chlorine, total suspended solids (TSS), and total hardness (TH).

3.5 Physico-chemical analysis

A range of different analytical methods were used to gather data on physical and chemical determinants of the various sampling points. Laboratory instruments and hand held apparatus were used to measure and compare the related water parameters. It should also be noted that calibration of equipment was done to ensure accuracy and reliability of test results.

3.5.1 *In situ*

The parameters that were measured *in situ* included temperature, pH, conductivity, total dissolved solids (TDS), turbidity and residual chlorine (as free chlorine). The equipment, as mentioned in section 3.4.1, were first calibrated following the manufacturers' guidelines before analysis took place.

3.5.1.1 Temperature measurement

Approximately 100 cm^3 of water was obtained. A small A-grade beaker and the glass thermometer were rinsed three times using a portion of distilled water, followed by the water sample. A glass thermometer was immersed into a sufficient volume of the representative water sample, and held 1 centimetre (cm) away from the sides and the bottom of the beaker, for approximately 1 minute. The readings were recorded to the nearest 0.1 °C.

3.5.1.2 pH measurement

The meter was switched on and allowed to warm for 5 minutes. It was then standardised with a buffer solution. The tip of an electrode was immersed into the water sample and a constant pH value was read and recorded as it appeared on the dial of the meter. The electrode was rinsed out with deionised water and blotted dry with an adsorbent paper. The next measurement was read in the same manner until all the samples were recorded.

3.5.1.3 Electrical conductivity measurement

The meter was switched on and standardised using 0.1 N KCl at 25 °C. The electrode was then immersed into the water sample and conductivity reading of each sample was recorded.

3.5.1.4 Turbidity measurement

The meter was calibrated using 4 standards; <0.1, 20, 200, and 800 NTU. It was then immersed into each sample bottle filled to just below the shoulder of the container. The meter was kept steadily, and a few minutes allowed for a stable reading to be taken. After each reading was recorded, the meter was rinsed with deionised water and blotted dry. The meter was finally rinsed and blotted dry after the last sample was measured and recorded, and kept away.

3.5.1.5 Determination of residual chlorine

5 drops of Reagent 1 plus 3 drops of Reagent 2 were added to the colour comparator cube. The colour comparator cube was filled with water sample to the 5 mL mark. The cap was replaced, and the solution mixed by carefully swirling the cube in tight circles and inverting it several times. Free chlorine was determined by matching the sample solution with the colour bands in the vessel. The concentration corresponding to the

best match read in the vessel was recorded as a result in mg/dm^3 (ppm) free chlorine Keith (2017).

3.5.2 Cation and anion analysis

Calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) were carried out based on the relevant standard test procedures as per Analysis Guide, Volume 3 (Schutte, 2001).

3.5.2.1 Preparation of calcium, magnesium, and sodium stock solutions

Primary standards of calcium carbonate ($CaCO_3$, FW = 100.087), magnesium oxide (MgO, FW = 40.304) and sodium chloride (NaCl, FW = 58.442), were weighed to be 1.26, 0.05, and 1.28 (± 0.001g) respectively, into 500 cm^3 volumetric flasks, to make the standard solutions for calcium, magnesium and sodium.

The standards for calcium and magnesium were rinsed with a few cubic centimetres of deionised water and 6 M hydrochloric acid, and mixed thoroughly, before they were further diluted to a 500 cm^3 mark with deionised water. The salt to make a sodium standard was transferred into a 500 cm^3 volumetric flask, and mixed gradually with a little deionised water until all the solid was thoroughly dissolved. It was then diluted to a 500 cm^3 mark with deionised water. A series of dilutions were prepared from above standard solutions to make the calibration standards for calcium, magnesium and sodium (Keith, 2017).

Chloride (Cl^{-}), sulphate (SO_4^{2-}), and nitrate (NO_3^{-}) were carried out based on the standard test procedures as per Analysis Guide, Volume 3 (Schutte, 2001).

3.5.2.2 Preparation and analysis of chloride, sulphate, and nitrate

Working standard solutions for anions of interest were prepared following sequential dilutions method. Mixed standard solutions with concentrations of 1, 5, 25 and 50 ppm of each of the three desired anions were used to plot the calibration curve. The linear relationship between the peak area and concentration was confirmed experimentally (Keith, 2017).

3.5.2.3 Determination of cations

The determination of cations in water was done using a flame spectrophotometer (iCE 3300 series, Thermo Fisher Scientific Inc). For analysis of calcium and magnesium, a combination hollow cathode lamp (HCL) was used; while sodium required a separate lamp as well as different operating wavelengths (Helaluddin *et al.*, 2016). The instrument is standardised with the known concentration of each cation (1 to 100 mg/L). The absorbance was measured for each standard using a respective HCL and plotted against the concentrations in excel, thus confirming the linear relationship. These graphs became the calibration curves for the measurements of specific elements in the water samples.

The hollow cathode lamps for specific elements to be measured were used, and the AA instrument was set to the desired wavelength, slit width and line source before the emission intensities for standards and water samples were measured. The deionised water was used as a blank before each standard was measured. The samples having higher concentration are suitably diluted with distilled water and the dilution factor is applied to the observed values (Keith, 2017).

3.5.2.4 Determination of anions

Anions were measured using the Spectroquant prove 300 (Merck, Germany). The corresponding method numbers were used to operate the photometer. Measurements could be made without any further adjustments to the instrument.

3.5.2.4.1 Chloride

Chlorides were determined by iron (III) thiocyanate method. A pre-programmed method number 63, with a total measurement range of 10 – 250 mg/L, was used for the determination of chlorides in raw and processed water. No further adjustments were required to the instrument. The concentration was recorded as displayed in the photometer.

3.5.2.4.2 Sulphate

Sulphates were first determined by nephelometric method in which the concentration of turbidity was measured against the known concentration of synthetically prepared sulphate solution. Barium chloride was used for the production of a turbid solution as a result of barium sulphate and a mixture of glycerol and sodium chloride is used to prevent the settling of turbidity. The results obtained using this method corresponded well with the recordings from the photometer. The photometer also measures sulphates using a pre-programmed method 82, with a total measurement range of 100 – 1000 mg/L.

3.5.2.4.3 Nitrate

Nitrates were determined by nitrospectral method, with corresponding method number 59. A total measurement range of 0.5 – 18.0 mg/L nitrate-nitrogen was used for the determination of nitrates in raw and processed water. The concentration was recorded as displayed in the photometer.

3.5.2.5 Determination of total suspended solid

A fixed volume (100 cm^3) of the water samples were poured onto pre-weighed glass fibre filter papers (Whatman GF/F circles, 47 mm diameter and 1.5 µm nominal pore size) before starting the vacuum filtration process. After the completion of the filtration process, the filters were removed and placed in an aluminium dish in an oven at 103 °C for 2-3 hours until all the remaining water was completely dried off. Thereafter, the

filters were removed from the oven and placed into the desiccator until cooled to balance temperature; and then weighed. The mass was recorded in mg/dm^3 (this is the tarred weight of the filter). Total suspended solids were obtained using the formula below.

$$Total\ suspended\ solids, as\ TSS \frac{mg}{L} = \frac{(A-F)\ X\ 1000}{S}$$

Where,

A = final 103 °C weight of the dried residue + the tarred filter (in mg),

F = tarred filter weight (in mg), and

S = sample volume (in mL)

Source: Keith, 2017.

3.5.2.6 Determination of total hardness

10 cm^3 of Water sample was pipetted into a conical flask. 1 cm^3 of the buffer solution (NH_4Cl) of pH = 10 and 3 drops of Eriochrome Black T (EBT) indicator were added to the flask. The mixture was then titrated with 0.01 M EDTA (ethyl diamine tetra acetic acid) until the colour changed from wine red to blue. The procedure was repeated two more times to obtain the average litre value. Calculation of total hardness was as equations 1 and 2 below.

$Total\ hardness\ (ppm) : M_1V_1 = M_2V_2$ .....Equation 1

$M_1 = \frac{M_2V_2}{V_1}$.....Equation 2

Where,

M_1 = Total hardness of sample water (in ppm)

V_1 = volume of sample hard water titrated (in mL)

$M_2 = \text{Molarity of EDTA (in ppm)}$

$V_2 = \text{Volume of EDTA consumed (in mL)}$

Source: Keith, 2017.

3.6 Microbiological analysis

3.6.1 Determination of *Escherichia coli* and total coliforms (TC)

Aliquots of 50 mL from each samples were filtered using 0.45 μm paper filters. The filters were placed on mFC and mEndo agar, and plates incubated aerobically at 45 and 37 °C respectively for 24 hours. Blue and metallic sheen colonies on mFC and mEndo agar plates were purified and used for bacteria identification tests. The isolates were subjected to preliminary gram staining; oxidase, citrate utilisation; triple sugar iron tests and confirmatory biochemical identification tests (EnteroPluri-Test, Ref: 78618-78619) to screen for characteristics of bacteria belonging to the family *Enterobacteriaceae* (Palamuleni & Akoth, 2015).

3.7 Data processing, calculations and statistical analysis

The quality of drinking water and the pollution status were evaluated according to the standards suggested by WHO, DWA, and SANS. Analytical methods used for the determination of total suspended solids, total hardness, *E. coli* and total coliforms required the final values to be calculated using the formulas in equations 3 to 6 below.

$$Total\ suspended\ solids, as\ TSS \frac{mg}{L} = \frac{(A-F)\ X\ 1000}{S} \quad \text{.....Equation 3}$$

$$Total\ hardness\ (ppm) : M_1V_1 = M_2V_2 \quad \text{.....Equation 4}$$

$$E.coli \frac{mL}{100} = \frac{Number\ of\ blue\ colonies}{Volume\ of\ sample\ filtered\ (mL)}\ X\ 100 \quad \text{.....Equation 5}$$

$$TC \frac{mL}{100} = \frac{Number\ of\ fluorescent\ colonies + Number\ of\ blue\ colonies}{Volume\ of\ sample\ filtered\ (mL)}\ X\ 100 \quad \text{.....Equation 6}$$

Statistical conclusions and tests were made on the basis of a multi-parametric model. The data for physico-chemical parameters of water samples were presented as mean values of water sampled at different study areas. Pearson's correlation product of the moment was used to determine the correlation between conductivity, TDS, pH and temperature. A coefficient of correlation (CV) and student's t-test was used to describe the temporal variations of the observed water quality parameters. Prior to investigating the seasonal effect on water quality parameters, the observation period was divided into two major seasons: summer season (December, January and February) and the winter season (June, July, and August). The data was analysed using one-way analysis of variance (ANOVA) at 0.05% level of significance with the objective of evaluating the significant differences among the sites for all water quality variables. The two-tailed test of significance ($p < 0.05$) was used to determine the significance of the result (Momba *et al.*, 2009). All statistical analyses were performed using Microsoft Excel 2013, SPSS Version 24, and PAST Version 1.93 software applications.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

Sampling and analysis for fourteen physico-chemical and two microbiological parameters was done between December 2017 and November 2018. The sampling periods were strategically selected in order to observe the seasonal variations of water quality. The mean and standard deviation of the samples were calculated, and results are presented in Tables 4, 5, 6, 7, 8 and 9, respectively. The results obtained show the overall characteristics of drinking water quality. Each parameter is discussed in relation to the drinking water quality limits stipulated by World Health Organisation (WHO), Department of Water Affairs (DWA) and the South African National Standards (SANS).

4.1.1 Water treatment processes

The significance of water quality variables are not only to characterise a water source, but also to provide information on the likely water quality related problems that can lead to health, aesthetic and economic impacts (Spellman, 2017). The most applicable water treatment options are ascertained by determining the water quality of the source as this often influences the variables for the entire treatment process. For example, the water treatment processes at the Midvaal Water Company (MWC) have changed over the years to adapt to the varying water quality of the Vaal River as illustrated in Table 2 (van Rensburg *et al.*, 2016). Unfortunately, no data was available to illustrate the same trend, or any continuous improvement plans to improve the quality systems, at Mmabatho Water Treatment Plant (MWTP).

Table 2: A summary of the water treatment process at Midvaal Water Company from 1954-2015

Process	Plant 1954	Plant 1978	Plant 1980	Plant 1985	Plant 1992	Plant 1997	Plant 2007-2015	Treatment objective
Abstraction	✓	✓	✓	✓	✓	✓	✓	
Pre-chlorination		✓	✓	✓				Removal of algal related problems e.g. colour and filter capacity
Pre-ozonation				✓	✓		✓	Improve colour & oxidise manganese, iron and total chlorophyll (1985–1997) Enhance algal removal by DAF (2007)
Primary addition of chemicals	✓	✓	✓	✓	✓	✓	✓	Coagulation and flocculation to remove turbidity/suspended matter
$KMnO_4$ oxidation			✓	✓				Manganese removal
Dissolved air flotation						✓	✓	Separation and removal of light particulate matter and algae
Intermediate ozonation						✓	✓	Manganese & iron removal, colour, taste and odour improvement
Secondary addition of chemicals						✓	✓	Flocculation of particulate matter/solids after the oxidation step
Sedimentation	✓	✓	✓	✓	✓	✓	✓	Separation of solids from water
Filtration	✓	✓	✓	✓	✓	✓	✓	Removal of remaining particulate matter and removal of micro-organisms which might pose a health risk
Disinfection	✓	✓	✓	✓	✓	✓	✓	Pathogen removal

Source: van Rensburg *et al.*, 2016.

4.2 Water quality analysis

The physicochemical and microbiological water quality variables of MWC and MWTP were analysed. Results were compared with the WHO (1993), DWA (1996) and SANS 241 (2015) domestic water quality guidelines, to ascertain whether the quality of drinking water from the study sites was in accordance with appropriate drinking water quality standards. In SA, the quality of the domestic water supply is assured by monitoring for compliance with the South African National Standard (SANS 241:2015). Analysis for water quality in this study was performed using the standard test methods for domestic water analysis as prescribed by the Department of Water Affairs – Analysis Guide, Volume 3 of 2001. The standard guide also provided a great criteria for the selection of important parameters for testing domestic water quality. For

instance, substances listed in Table 3 provide an indication of general water quality, hence it was important to include them in this study.

Table 3: Substances which are general indicators of water quality

Electrical conductivity (total dissolved salts)	Conductivity is an indicator of total dissolved salts (TDS), and also establishes if the water is drinkable and capable of slaking thirst.
Faecal coliforms	This is an indicator of the possible presence of disease-causing organisms. It establishes if water is polluted with faecal matter.
pH value	This has a marked effect on the taste of the water and also indicates possible corrosion problems resulting from dissolution of metals such copper, zinc and cadmium that can be very toxic.
Turbidity	This affects the appearance, and thus the aesthetic acceptability, of the water. Turbidity is commonly high in surface waters.
Free available chlorine (Residual chlorine)	This is a measure of the effectiveness of the disinfection of the water. Residual chlorine is the chlorine concentration remaining at least 30 minutes after disinfection. There should be residual chlorine in the water, but if concentrations are too high it may impart an unpleasant taste and smell to the water.

Source: DWA, 2003.

4.2.1 Physical properties

Some physical parameters of water were performed *in situ* according to the methods outlined in Chapter 3, Section 3.5.1. Tables 4 and 5 summarise the average physical properties of water; that is, temperature; pH; conductivity; turbidity; total dissolved solids (TDS) and total suspended/settle-able solids (TSS); sampled at two specific sampling points of the two study areas between December 2017 and November 2018.

4.2.1.1 Temperature

The highest temperature measured and recorded was in the summer season, and the lowest in the winter season. Temperature values ranged from 15.58 to 26 °C (Table 4). Both the maximum and minimum temperature values were recorded in the raw water for Klerksdorp. The maximum temperature (26 °C) was recorded during the summer season, and the minimum (15.58 °C) during the winter. Generally, water temperature corresponds with air temperature regardless of where sampling was done. Temperature recording for inlet water followed a typical seasonal pattern whereby higher water temperatures were measured during the summer season and lower temperatures were measured in the winter season. In Klerksdorp, the temperature of water measured at the inlet was 26.00±0.14 and 15.58±2.56 °C for summer and winter, respectively. After the treatment process, the temperature of water was 25.65±1.48 and 21.94±2.50 °C for summer and winter, respectively. There was no significant difference between the temperature measurements before and after treatment with the p value equal to 0.43. In Mmabatho, the temperature of water before treatment measured 22.86±3.51 and 18.90±0.88 °C for summer and winter, respectively. After treatment the temperature of water was 21.88±0.54 and 20.79±1.88 °C for summer and winter, respectively. Similarly, there was no significant difference in the temperature values before and after treatment in Mmabatho, the p value was 0.85. The overall results revealed that water temperature was significantly different between the sampled seasons with $p = 0.04$, but insignificant between the two study areas at p value = 0.80.

The temperature of water is an important parameter to measure and monitor in a water treatment process. Water temperature will influence the rate of biochemical reactions in a water treatment process and also affect most water quality parameters (Barnes *et al.*, 2014). For instance, the efficiency of coagulation; one of the key steps in the water treatment process is greatly dependent on temperature. As water temperature increases, the optimal pH will decrease during coagulation. Additionally, as temperature decreases, the viscosity of water increases causing the rate of

sedimentation to decrease (Tetteh & Rathilal, 2019). However, effective water treatment plants and processes tend to defeat this problem.

Water temperature can also affect the disinfection process. When water has a pH value higher than 8.5, higher temperatures multiply the bactericidal effectiveness of chlorine, as well as its effectiveness in killing some viruses (Haydar *et al.*, 2016). It has also been found that water temperature influences the seasonal variation in trihalomethane (THM) concentrations. Furthermore, without corrosion inhibitors, the corrosion rate will greatly increase when water temperature is higher (Gough *et al.*, 2014). This study observed that water temperature influenced most parameters. There was a significant variation ($p \leq 0.05$) in the pH, conductivity, TDS, turbidity, and calcium of water with p values between the water temperature and the mentioned parameters less than 0.001. However, water temperature was insignificantly different to magnesium and total coliforms, the p values were 0.49 and 0.29, respectively.

In RSA, the North West province is known to be very hot and dry during the summer seasons. High water temperatures are big contributors to the growth of cyanobacterial (algal) blooms in water sources. Cyanobacterial blooms have aesthetic impacts on the overall quality of potable water hence they are a nuisance to water treatment plants (van Rensburg *et al.*, 2016).

Table 4: Seasonal mean values of electrical conductivity (EC), pH, temperature and TDS

	Temperature (°C)		**pH**		**EC (mS/cm)**		**TDS (mg/L)**	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
MWC 1	26.00±0.14	15.58±2.56	9.32±0.11	8.39±0.47	83.50±7.78	60.50±26.16	525.50±51.62	376.50±143.54
MWC 2	25.65±1.48	21.94±2.50	7.68±0.15	8.24±0.16	69.50±2.12	78.00±7.07	491.50±54.45	472.50±50.20
MWTP 1	22.86±3.51	18.90±0.88	8.91±0.05	8.36±0.08	**240.00±76.37**	**204.50±36.06**	530.53±11.43	326.24±53.97
MWTP 2	21.88±0.54	20.79±1.88	9.33±0.01	8.29±0.06	**203.00±16.97**	**183.50±2.12**	266.64±9.50	214.37±16.92
DWA	**No guideline**		**6.0 ≥ to ≤ 9.0**		**≤170**		**≤1200**	
WHO	**No guideline**		**6.5 ≥ to ≤ 8.5**		**≤150**		**≤1000**	
SANS	**No guideline**		**5.0 ≥ to ≤ 9.7**		**≤170**		**≤1200**	

Note: 1 represent inlet values and 2 represent outlet values.

4.2.1.2 pH

The pH of water is a reflection of the degree of acidity (pH ≤ 7) or alkalinity (pH ≥ 7) hence it is the most important operational parameter in the water treatment processes (Mulamattathil *et al.*, 2015). The pH values higher than 8 are not suitable for effective disinfection of water, while values less than 6.5 enhance the corrosion in galvanised or copper pipes and household plumbing system (Haydar *et al.*, 2016). The taste of water, its corrosiveness and solubility and speciation of metal ions are all influenced by the pH. At low pH, water may taste sour while at high pH water tastes bitter or soapy (Mulamattathil *et al.*, 2015).

The pH of most unpolluted water lies between 6.5 and 8.5. As shown in Table 4, the pH of water from the 2 water treatment systems (MWC and MWTP) ranged from 7.68 to 9.33. The lowest overall mean pH value of 7.68±0.15 was measured at Klerksdorp outlet during the summer season while the highest overall annual mean pH of 9.32±0.11 was measured at the inlet. Although the pH of 9.32 was above the specified drinking water quality limits by WHO and DWA; the SANS 241 guideline still provides for pH limits of 5.0 to 9.7 for potable water quality. Hence, the overall mean values of 8.29 and 9.33, at the Klerksdorp outlet measured in winter and summer, respectively are acceptable and within the SANS limits.

In Klerksdorp, the value of pH measured at the inlet was 9.32±0.11 and 8.39±0.47 during summer and winter, respectively. After treatment, the value of pH was 7.68±0.15 and 8.24±0.16 during summer and winter, respectively. There was no significant difference in the pH values before and after the treatment process, the p value was 0.24. In Mmabatho, the value of pH measured at the inlet was 8.91±0.05 and 8.36±0.08 for summer and winter, respectively. After treatment, the pH of water was 9.33±0.01 and 8.29±0.06 measured in summer and winter, respectively. Similarly, there was no significant difference between the pH of water before and after treatment in Mmabatho, the p value was 0.82. The student t-test revealed an insignificant difference in pH values between the seasons measured, at $p = 0.44$; however, there was an inverse correlation in the p value of the sampled areas at $p = 0.02$. All pH values of water before and after the treatment process were within specified acceptable limits, making water marginal for irrigation and drinking purposes.

4.2.1.3 Total dissolved solids

Total dissolved solids (TDS) is a measure of the chemical constituents dissolved in water. Salts and minerals such as calcium, potassium, sodium, bicarbonates, chlorides, magnesium and sulphates produce an unwanted taste, and discolour the appearance of water. High TDS concentrations in water indicate mineralised water. According to the WHO water quality guidelines, the acceptable TDS limit is between 500 and 1000 mg/L. DWA and SANS has a prescribed maximum limit of 1200 mg/L, even though; according to WHO; the TDS higher than 1000 mg/L imparts the taste of drinking water. Furthermore, a value higher than 1000 mg/L results in excessive scaling in water pipes, heaters, boilers and other household appliances (Haydar *et al.*, 2016).

Table 4 shows the concentration of TDS recorded in this study which ranged between 214.37 and 530.53 mg/L. The mean TDS at the Mmabatho inlet were 326.24±53.97 mg/L and 530.53±11.43 mg/L during the winter and summer seasons, respectively. At the outlet, the lowest mean TDS of 214.37±16.92 mg/L and 266.64±9.50 mg/L during the winter and summer seasons, respectively. The same trend of differences was also reflected in their respective electrical conductivity values. However, there was no significant difference in the TDS measurements before and after water treatment in Mmabatho, the p value was 0.22. For Klerksdorp, the highest TDS mean of 525.50±51.62 mg/L was recorded at the inlet during the summer season while the lowest TDS mean of 376.50±143.54 mg/L was recorded in the winter season. After the water treatment process, the mean TDS values of 491.50±54.45 mg/L and 472.50±50.20 mg/L were measured during the summer and winter seasons, respectively. Similarly, there was no significant difference in the TDS measurements before and after water treatment in Klerksdorp, with the p value equal to 0.72. The highest mean concentration of TDS in drinking water is due to the highest availability of CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} in water (Nawab *et al.*, 2016). Overall, there was no significant difference in the mean concentrations of TDS between the study areas as well as between the seasons measured, at p values = 0.13 and 0.25, respectively. High TDS values have been shown to be more prevalent in groundwater than in surface waters.

4.2.1.4 Electrical conductivity

Electrical conductivity (EC) is an important tool to assess the degree of water purity (Shigut *et al.*, 2017). It measures the ability of water to conduct an electric current, and is mostly dependent upon the number of ions or charged particles in the water. Determining electrical conductivity in water quality studies is useful because they provide a direct measurement of dissolved ionic matter in the water. Low EC values are characteristic of high-quality, low-nutrient waters. The high values of conductivity can be indicative of salinity problems, while very high values are good indicators of possible polluted sites (Suratman *et al.*, 2019). Based on the WHO guidelines, the electrical conductivity for domestic water quality should be between 75 and 150 mS/cm; while in RSA, DWA and SANS 241 permissible limits are both at 150 mS/cm.

Table 4 shows that the overall mean electrical conductivity levels between the two study sites ranged from 60.50 to 240.00 mS/cm. The mean EC levels recorded in Klerksdorp inlet were 83.50±7.78 mS/cm and 60.50±26.16 mS/cm for summer and winter, respectively. After the water treatment process, the conductivity values were 69.50±2.12 mS/cm and 78.00±7.07 mS/cm for summer and winter, respectively. There was no significant difference between the EC measurements before and after water treatment in Klerksdorp, the p value was 0.90. Moreover, the overall EC means for Klerksdorp at both the inlet and outlet were within the specified drinking water quality standards throughout the seasons of assessment.

In Mmabatho, the mean EC levels at the inlet were high and above specific limits, at 240.00±76.37 mS/cm and 204.50±36.06 mS/cm, for summer and winter, respectively. After treatment, the EC levels in Mmabatho were 203.00±16.97 and 183.50±2.12 mS/cm during summer and winter, respectively. There was no significant difference in the EC measurements before and after water treatment, at p value equal to 0.29. Overall, there was no significant difference ($p = 0.77$) in electrical conductivities of both Klerksdorp and Mmabatho between the seasons of measure. On the contrary, there was a significant difference ($p < 0.01$) between the two study sites.

4.2.1.5 Turbidity

Turbidity is a measure of the clarity of a water body and is routinely used to indicate drinking water quality (Robert *et al.*, 2016). Turbidity; which is caused by suspended chemical and biological particles such as silt, organic matter and microbiological contamination; can have both safety and aesthetical implications for drinking water supplies (Zaman *et al.*, 2016). Turbidity does not always represent a direct health risk; however, it is alarming for raw water and treated water to have high turbidity. For example, high turbidity in source waters can harbour microbial pathogens, which can be attached to particles and impair disinfection; high turbidity in filtered water can indicate poor removal of pathogens; and an increase in turbidity in distribution systems can indicate sloughing of biofilms and oxide scales or ingress of contaminants through faults such as mains breaks (Robert *et al.*, 2016). Therefore, it is always vital to perform water quality assessments in turbid waters as it may be indicative of the presence of harmful pathogenic microorganisms (Uyttendaele *et al.*, 2015).

The turbidity was measured in all sampled water as shown in Table 5. The results indicated very high levels of turbidity at the water inlet that exceeded the permissible limits (1≥ NTU ≤5). The highest overall mean turbidity of 23.43±100.37 NTU was measured at Mmabatho inlet during summer season, followed by the measurement of 23.34±34.97 NTU in winter. Following the water treatment process, the turbidity levels at Mmabatho measured 5.37±16.92 NTU and 6.64±9.50 NTU during summer and winter seasons, respectively. Although there was a notable decline in the turbidity levels after the water treatment process, but these turbidity levels are very high and unacceptable according to specific domestic water quality guidelines. This suggests the chlorination process was not efficient in reducing the pathogens in the water system. The presence of pathogens in drinking water is a serious health concern, while on the other hand, over-chlorination increases the possibility of trihalomethanes formation in drinking water (Allard *et al.*, 2015). There was a significant difference in the turbidity levels in Mmabatho before and after the treatment process, the p value was 0.008.

In Klerksdorp, the highest turbidity levels were recorded at the inlet, and ranged between 21.50±1.65 NTU to 20.67±0.94 NTU during the summer and winter seasons,

respectively. After treatment, the turbidity at Klerksdorp measured 0.53±0.03 NTU and 0.39±0.12 NTU during the summer and winter seasons, respectively. Similarly, there was a significant difference in the turbidity levels before and after treatment in Kleksdorp, the p value was less than 0.001. Overall, the student t-test showed that there was no significant difference in the overall means of turbidity between the study areas as well as between the sampled seasons, with p values equal to 0.53 and 0.91, respectively.

Table 5: Seasonal mean values of turbidity and total suspended solids (TSS)

	Turbidity (NTU)		**TSS (mg/L)**	
	Summer	Winter	Summer	Winter
MWC 1	**21.50±1.65**	**20.67±0.94**	56.00±55.83	42.80±14.99
MWC 2	0.53±0.03	0.39±0.12	26.50±7.78	45.00±24.04
MWTP 1	**23.43±100.37**	**23.34±34.97**	290.54±116.95	278.00±28.79
MWTP 2	**5.37±16.92**	**6.64±9.50**	141.40±11.48	161.23±13.85
DWA	**1≥ to ≤5**		**No guideline**	
WHO	**1≥ to ≤5**		**No guideline**	
SANS	**1≥ to ≤5**		**No guideline**	

Note: 1 represent inlet values and 2 represent outlet values.

4.2.1.6 Total suspended solids

Total suspended solids (TSS) is the turbidity caused due to silt and organic matter in water. The overall mean TSS of water at the inlets ranged from 42.80±14.99 mg/L to 290.54±116.95 mg/L; and at the water outlets, the mean TSS ranged from 26.50±7.78 mg/L to 161.23±13.85 mg/L, as shown in Table 5.

The highest mean TSS concentration of 290.54±116.95 mg/L was found in Mmabatho inlet during the summer season. This was followed by a decline to 141.40±11.48 mg/L at the outlet. In winter, the mean TSS concentration at Mmabatho inlet was 278.00±28.79 mg/L and decreased to 161.23±13.85 mg/L at the outlet. Although the water quality guidelines have not yet established the standard measure for total suspended solids in water, it makes sense that the parameter is included in water

quality assessments. High TDS and TSS in drinking water are aesthetically unpleasant and the accumulation of total solids in the water system reveals the overall ineffectiveness of the current treatment process. Most minerals in drinking water are undesirable at high concentrations. Moreover, there was a significant difference in the TSS concentration of Mmabatho before and after the treatment process, the p value was equal to 0.08. Similarly, as shown in Table 5, the same trend is observed for Klerksdorp with a high TSS mean concentration of 56.00±55.83 mg/L measured in summer at the inlet and decreased to 26.50±7.78 mg/L at the outlet. Inversely, the mean TSS concentration at Klerksdorp inlet measured 42.80±14.99 mg/L in winter, and then increased to 45.00±24.04 mg/L after at the outlet. Where a certain parameter increases instead of the expected decrease after the water treatment process, this could be attributed to the failure to dissolve the chemicals used during the treatment process. There was no significant difference in the TSS concentration of Klerksdorp before and after the treatment process, with the p value equal to 0.35. Overall, the TSS mean concentrations showed a significant difference between the study areas, however, there was no significant difference between the sampled seasons at p values equal to 0.004 and 0.97, respectively.

In summary, the physical parameters of water give the general indication of the water quality. Furthermore, an assessment of the physical water quality parameters before and after the water treatment process is important to provide the baseline information on the critical chemical and biological constituents that will need further analysis, for example, nutrient load, pathogens, heavy metal ions, and disinfection by products in resultant water. The results of the physical water parameters show that the conventional water treatment processes used in Mmabatho is not effective in removing contaminants from the water specifically conductivity and turbidity levels which were still above the water quality ranges after the treatment process. However, all the other parameters, especially in Klerksdorp, were reasonably within the permissible water quality limits after water treatment even though the inlet water quality had been above the water quality standards. Therefore, from the physical parameters, the Klerksdorp water treatment processes have shown to be the most effective drinking water treatment method.

4.2.2 Chemical properties

Water contamination with anions, cations and other organic and inorganic chemicals is a concerning issue for human health and the environment (Nawab *et al.*, 2016). The concentrations of the major anions (chloride, nitrate, sulphate); cations (calcium, magnesium, sodium); and other important chemical constituents were measured. The results are summarised in Tables 6, 7 and 8. The mean concentrations of anions in Mmabatho were found in the order of $Cl^- > SO_4^{2-} > NO_3^-$ and $SO_4^{2-} > Cl^- > NO_3^-$ for Klerksdorp. Cations followed this order $Ca^{2+} > Na^+ > Mg^{2+}$ for both study areas. Taste properties of drinking water are largely determined by cations (K^+, Na^+, Ca^{2+}, Mg^{2+}), whereas anions (Cl^-, NO_3^-, SO_4^{2-}) tend to modify its taste intensity (Vingerhoeds *et al.*, 2016).

4.2.2.1 Calcium and magnesium

Calcium and magnesium are the two main ions, or rather dissolved minerals that are naturally occurring in surface and ground water that contribute to the total hardness (TH) in water, which were discussed as a separate parameter before the end of this section. These two minerals mainly originate from carbonate, such as calcite and dolomite, as water moves through sedimentary environments such as rocks and stones (Vingerhoeds *et al.*, 2016).

4.2.2.1.1 Calcium

The desirable limit of calcium content in drinking water is 75 mg/L according to WHO, 80 mg/L for DWA and 150 mg/L for SANS (Table 6). Calcium is a naturally occurring mineral found in abundance as a result of the environmental cycle. It is an essential component of limestone and commonly found in hydrothermal environments. The concentration of calcium in water resources is greatly influenced by high temperatures. Table 6 shows that the concentration of calcium was higher at the inlets during the summer season. This is because water temperature is higher in summer thus aiding the solubility of the mineral in water (Cheremisinoff, 2019).

The concentration of calcium at Klerksdorp inlet was 69.40±6.51 mg/L in summer and 47.61±26.01 mg/L in winter. After water treatment, the mean concentration recorded in Klerksdorp was 62.47±9.14 mg/L in summer and 64.90±0.99 mg/L in winter. The concentrations were all within the acceptable limits for calcium according to the drinking water standards, however, the slight increase in the concentration noted in winter may be due to other steps in the water treatment process. For example, lime is often used in the water treatment process to adjust the pH of water, or as a softening agent. This increase was not significant in the overall calcium concentration between the sampled points, with the p value = 0.68.

In Mmabatho, the concentration of calcium recorded at the inlet was 178.37±0.80 mg/L and 166.83±11.69 mg/L during summer and winter, respectively. Again, after the water treatment process the concentration of calcium was 149.19±22.78 mg/L and 162.15±7.85 mg/L during summer and winter, respectively. Although both measurements at the inlet were above the recommended limits, the most concerning deviations for the study are the concentrations that exceed the drinking water standard limits after the treatment process. These are the deviations that may be detrimental to human health in the long term, and hence form a basis for rendering the water treatment process as ineffective. The student t-test showed no significant differences in calcium concentration between sampled points and sites, at p = 0.51 and 0.76, as well as between the seasons of measure, at p = 0.48.

4.2.2.1.2 Magnesium

Similarly, as Table 6 shows, the same trend is observed for magnesium ion (Mg^{2+}). The overall magnesium in water ranged from the highest mean concentration of 29.44±8.72 mg/L to the lowest overall mean magnesium content of 18.79±8.78 mg/L. All sampled water revealed that magnesium concentrations were within the permissible specified levels of 150 mg/L and 70 mg/L according to the WHO, DWA and SANS drinking water standards. The highest overall mean Mg^{2+} concentration of 29.44±8.72 mg/L was measured in Mmabatho inlet during the winter season. Inversely, the lowest overall mean Mg^{2+} concentration of 18.79±8.78 mg/L was measured in Klerksdorp inlet during the winter season. The concentration made a steep increase to 25.50±0.57 mg/L after water treatment. Many factors could have

played a role in this notable increase in magnesium concentration after treatment. However, all magnesium concentration from both study areas were still within the specified acceptable drinking water limits after the treatment process. There was no significant difference in the values of magnesium between the sampled points and study sites, at p = 0.46 and 0.76; as well as between the sampled seasons at p = 0.68.

4.2.2.2 Sodium

A cation can evoke different taste qualities such as astringent, bitter, salty, sweet, sour, metallic, and/or irritation depending on concentration and the mean level at which the specific taste can be detected. For sodium, a salty taste has been acknowledged between 30 and 60 mg Na/L, and taste recognition thresholds of 0.59–0.67 g Na/L, have been reported (Boateng *et al.*, 2016). However, consumers have different taste or sensory recognition thresholds which leads to many people being particular to a brand of bottled mineral water they drink.

In this study, all raw water samples had relatively high sodium concentrations ranging from 42.69 mg/L to 133.05 mg/L. Treated water had sodium concentrations ranging from 56.89 mg/L to 129.40 mg/L, as illustrated in Table 6. The maximum permissible limits of sodium concentration in drinking water according to the WHO, DWA and SANS is 200 mg/L. This means that the overall mean concentrations of sodium of all sampled water were well within the maximum allowable concentration. According to Hua *et al.* (2015), a high percentage of municipal water supplies obtained from lakes and rivers are low in sodium content. However, some surface water sources may absorb a considerable amount of salt from alkali soils. Raw water in Mmabatho has slightly higher sodium concentrations than Klerksdorp water which could be attributed to leaching out of alkaline salts of sodium, calcium and magnesium (Edition, 2011). In addition, the bicarbonates and sulphates of calcium and magnesium along with some iron salts may be the cause of the water hardness in Mmabatho. The lowest mean concentration of sodium ion in water of 42.69±24.48 mg/L was measured in Klerksdorp inlet during the winter season, however it increased to 59.30±5.94 mg/L at the outlet which could be as a result of the mixing with other salts during the treatment process. However, this increase was not significant (p = 0.97). During the summer season, the

concentration of sodium at Klerksdorp inlet was 75.00±6.36 mg/L and decreased to 56.89±1.97 mg/L at the outlet.

In Mmabatho, the highest mean concentration of sodium in water of 133.05±3.48 mg/L was measured in the inlet during the summer season, and decreased to 129.40±0.14 mg/L at the outlet. Similarly, the mean concentration of sodium in Mmabatho inlet was 127.71±1.31 mg/L, and decreased to 124.56±5.76 mg/L at the outlet. Again, the differences between the inlet and outlet concentration were not significant with $p = 0.96$.

The overall concentration of sodium between the study sites was insignificant ($p \leq 0.05$); however, the concentration between the sampled seasons were significant, with p value = 0.74.

4.2.2.3 Chloride

The permissible limit of chloride (Cl^-) content in water is 250 mg/L for WHO and 200 mg/L for both DWA and SANS standard guidelines. The chloride content of water of all sampling sites were within these permissible limits. As shown in Table 7, the overall mean concentration of chloride in water ranged from 39.14 to 242.41 mg/L. The lowest chloride content was measured at the Klerksdorp inlet during the winter season, while the highest chloride content was measured at Mmabatho outlet in summer (Table 7). In Klerksdorp, the chloride concentration before treatment was 61.73±3.78 and 39.14±18.42 mg/L during the summer and winter, respectively. But after treatment, the concentration of chloride was 51.95±1.73 and 57.62±6.51 mg/L during summer and winter, respectively. The differences in concentration of chloride between the inlet and outlet were not significant, with $p = 0.74$. In Mmabatho, the concentration of chloride at the inlet was 226.86±4.79 and 217.83±9.71 mg/L during the summer and winter seasons, respectively. After treatment, the chloride concentration was 242.41±1.17 and 210.16±0.08 mg/L during summer and winter, respectively. Again, the differences in concentration between the inlet and outlet were not significant, with $p = 0.84$.

Table 6: Seasonal mean values of calcium, magnesium and sodium in mg/L

	Calcium		**Magnesium**		**Sodium**	
	Summer	Winter	Summer	Winter	Summer	Winter
MWC 1	69.40±6.51	47.61±26.01	23.65±3.46	18.79±8.78	75.00±6.36	42.69±24.48
MWC 2	62.47±9.14	64.90±0.99	22.24±2.45	25.50±0.57	56.89±1.97	59.30±5.94
MWTP 1	**178.37±0.80**	**166.83±11.69**	24.00±1.98	29.44±8.72	133.05±3.48	127.71±1.31
MWTP 2	149.19±22.78	**162.15±7.85**	21.13±4.02	24.20±0.99	129.40±0.14	124.56±5.76
DWA	**≤80**		**≤70**		**≤200**	
WHO	**75 ≥ to ≤ 200**		**≤150**		**≤200**	
SANS	**≤150**		**≤70**		**≤200**	

Note: 1 represent inlet values and 2 represent outlet values.

Generally, the high concentration of chloride ion in natural source waters is due to dissolution of salts, soil erosion and discharge effluents into the water sources (Cheremisinoff, 2019). Conversely, the high chloride content in treated drinking water is most likely a result of the chlorination process. Chlorides may get into surface water from several sources including rocks containing chlorides, agricultural runoff, waste water from nearby industries, and effluent waste water from wastewater treatment plants. Furthermore, high chloride concentration in water can corrode metal piping of the water distribution system, which will then affect the taste of drinking water. Hence, it is vital for water treatment plants to monitor and limit high chloride levels in treated water. The resulting salty taste in drinking water may also result in hypertension, osteoporosis, renal stones and asthma problems (Boateng *et al.*, 2016). Overall, the student t-test revealed a significant difference ($p \leq 0.05$) in the overall means of chloride concentration between the study areas, however, there was no significant difference ($p \geq 0.05$) between the sampled seasons with p value = 0.84.

4.2.2.4 Sulphate

Drinking water is susceptible to high levels of sulphate (SO_4^{2-}). This is mainly because surface water sources are polluted by sulphur dioxide emissions from anthropogenic sources such as oil refineries, mine dumps, etc. In addition, the mean sulphate level in municipal drinking water supplies may be increased by water treatment processes (Hounslow, 2018). Interestingly, the increase in sulphate ion concentration is also observed in the analytical results as shown in Table 7. However, the levels of sulphate were all within the acceptable limits of ≤ 500 mg SO_4^{2-}/L of drinking water.

Table 7 shows the overall mean concentration of sulphate in analysed water ranged from 123.42 to 187.97 mg/L. At Klerksdorp inlet, the sulphate content recorded during the summer and winter seasons were 135.53±16.01 and 123.42±83.76 mg/L, respectively. The concentration of sulphate increased at after treatment and measured 152.23±23.29 and 174.60±23.31 mg/L for summer and winter seasons, respectively. This increase in concentration of sulphate before treatment and after treatment was not significant, at p = 0.12. Similarly, with Mmabatho, the concentration of sulphate at

the inlet was 168.51±24.61 and 131.75±83.44 mg/L during the summer and winter seasons, respectively. The concentration of sulphate at the outlet increased to 187.97±29.32 and 183.05±6.99 mg/L during summer and winter seasons, respectively. Again, this increase was not significant as the p value was 0.20.

Aluminium sulphate or alum may be responsible for the increase of sulphate ion concentration in the treatment processes. Aluminium sulphate aids in the removal of suspended particles, as well as clear unwanted colour and turbidity from water supplies. However, it is still critical for water treatment plants to neutralise the aluminium and sulphate ions to within acceptable drinking water levels so that they do not cause adverse health effects to consumers (Choy *et al.*, 2014). The overall student t-test showed that there was no significant difference ($p \geq 0.05$) in the concentration of sulphate between the study sites as well as between the sampled seasons, with p values = 0.25 and 0.69, respectively.

4.2.2.5 Nitrate

Water quality monitoring shows that nitrate ion (NO_3^-) exists naturally in the environment and changes forms as it moves through the nitrogen cycle (Leip *et al.*, 2015). However, excessive concentrations of nitrate-nitrogen in drinking water can be hazardous to health, especially for infants and pregnant women (Jensen *et al.*, 2014). The permissible limit of the nitrate ion in drinking water is ≤11 mg/L for WHO, DWA and SANS 241. The highest nitrate-nitrogen contents were found at the inlets, the raw water reservoirs, for both study sites (Table 7). Mmabatho has the highest nitrate concentration, especially in summer. The high levels of nitrate-nitrogen water pollution are likely a result of the many agricultural and farming activities dominating the towns, domestic effluents, leachates from refuse dumps, sewage disposal and some industrial discharges. The nitrate content measured at the inlet during summer was 3.07±0.23 mg/L, while in winter it was 2.24±1.37 mg/L. In Klerksdorp, the nitrate concentration at the inlet was higher in winter than in summer, measuring 2.31±0.96 and 0.71±0.66 mg/L respectively. There was no significant difference ($p \geq 0.05$) in the overall means of nitrate-nitrogen between the study areas and between the seasons, with p values equal to 0.21 and 0.69, respectively.

Table 7: Seasonal mean values of the most prevalent anions in mg/L

	Chloride		**Nitrate**		**Sulphate**	
	Summer	Winter	Summer	Winter	Summer	Winter
MWC 1	61.73±3.78	39.14±18.52	0.71±0.66	2.31±0.96	135.53±16.01	123.42±83.76
MWC 2	51.95±1.73	57.62±6.51	0.82±0.81	2.72±0.25	152.23±23.29	174.60±23.31
MWTP 1	226.86±4.79	217.83±9.71	3.07±0.23	2.24±1.37	168.51±24.61	131.75±83.44
MWTP 2	242.41±1.17	210.16±0.08	0.83±0.82	1.61±0.88	187.97±29.32	183.05±6.99
DWA	**≤250**		**≤11**		**≤500**	
WHO	**≤250**		**≤11**		**≤500**	
SANS	**≤300**		**≤11**		**≤500**	

Note: 1 represent inlet values and 2 represent outlet values.

4.2.2.6 Total hardness

The total hardness (TH) of water is not known to cause any potential health risks to human health. However, WHO has a recommendation that the TH of drinking water should not exceed 500 mg/L (Edition, 2011). The challenge with water hardness above 500 mg/L is that an excess use of soap is needed to achieve effective cleaning. Again, hard potable water may modify the chemical forms of fluoride and other trace elements; therefore, it may act as a secondary factor in the overall toxicity of drinking water (Haydar *et al.*, 2016).

Total hardness represents the concentration of calcium and magnesium in water (Krishnan *et al.*, 2007). Drinking water with a hardness of <61 mg/L is considered soft; 61–120 mg/L is moderately hard; 121–180 mg/L is hard; and more than 180 mg/L is considered very hard (Edition, 2011). The desirable upper limit of TH in drinking water is 200 mg/L according to DWA and SANS 241, while the WHO has a range of between 100 and 500 mg/L.

Table 8 shows that the total hardness (TH) of water at the inlets of the two study sites ranged from 216.58 mg/L to 360.52 mg/L. At the water outlets of the sites, the TH ranged from 42.56 mg/L to 267.64 mg/L. The acceptable limits of total hardness in drinking water according to the WHO, DWA and SANS are ≥20 to ≤200, ≥100 to ≤500, and ≥20 to ≤200, respectively. This means the TH of water was above the acceptable limits at all the water inlets. After the treatment process, only the TH of water from Klerksdorp fell to within the specified acceptable limits, but in Mmabatho, the total hardness was still above specified TH standards after water treatment. In Klerksdorp, the total hardness of water before treatment was 240.83±46.22 and 216.58±76.09 mg/L during summer and winter, respectively. After treatment, the TH was 67.81±20.98 and 42.56±11.76 mg/L for summer and winter, respectively. There was a significant difference ($p \leq 0.05$) in the concentration of TH of water at the inlet and outlet in Klerksdorp, with the p value equal to 0.01. In Mmabatho, the concentration of TH of water before treatment was 360.52±4.88 and 352.36±19.76 mg/L during summer and winter seasons, respectively. After treatment, the concentration of TH of water was 267.64±13.56 and 261.94±15.27 mg/L during summer and winter seasons, respectively. Again, there was a significant difference between the inlet and outlet

concentration of total hardness of water in Mmabatho, with p value equal to 0.003. The overall student t-test also showed a significant difference in the TH concentration between the study areas, with the p value equal to 0.03; however, there was no significant difference in the TH of water between the sampled seasons, with the p value equal to 0.86.

The high levels of total hardness in raw water is mainly due to the mixing of waste effluents into the rivers; conversely, permanent or natural hardness in water is caused by elevated concentrations of chloride and sulphate (Khosravi *et al.*, 2017).

Table 8: Seasonal mean values of free (residual) chlorine and total hardness (TH) in mg/L

	Free chlorine		**TH**	
	Summer	Winter	Summer	Winter
MWC 1	0	0	**240.83±46.22**	**216.58±76.09**
MWC 2	1.47±0.01	1.50±0.37	67.81±20.98	42.56±11.76
MWTP 1	0	0	**360.52±4.88**	**352.36±19.76**
MWTP 2	3.60±0.18	4.14±0.33	**267.64±13.56**	**261.94±15.27**
DWA	**0.2≥ to ≤5**		**≥20 to ≤200**	
WHO	**0.2≥ to ≤5**		**≥100 to ≤500**	
SANS	**0.2≥ to ≤5**		**≥20 to ≤200**	

Note: 1 represent inlet values and 2 represent outlet values.

4.2.2.7 Free (residual) chlorine

The disinfection step of the water treatment process involves application of chlorine to water; in the form of chlorine gas, granular form, or solution (bleach); to form a solution of hypochlorous acid and hypochlorite ion. The disinfectant solution contains chlorine species termed free chlorine or residual chlorine.

The acceptable limits of free chlorine (free Cl_2) in drinking water range between 0.2 mg/L to 5 mg/L for WHO, DWA and SANS 241. As can be noted in Table 8 that there was no residual chlorine measured and recorded at both inlets (before treatment) of the study sites, but a recording was taken at the outlets (after treatment) when chlorination had taken place. It should be noted that residual chlorine is taken as an

index of pollution in treated water. This is because an optimal point of disinfection happens when there is a balance between the chlorine demanded and consumed by the treatment process. Therefore, any chlorine species remaining after the disinfection process has taken place is unfavourable for human consumption.

Table 8 shows that the residual chlorine content measured at both Klerksdorp and Mmabatho was within the permissible drinking water quality limits. In Klerksdorp, the mean residual chlorine concentration was 1.47±0.01 mg/L during summer season and 1.50±0.37 mg/L during the winter season. In Mmabatho, the mean residual chlorine was within the permissible limit though a bit higher, and measured 3.60±0.18 mg/L in summer, and 4.14±0.33 mg/L in winter. There was a clear significant difference in the free chlorine measurements before and after the treatment processes, with the p values of 0.0001 and 0.005 in Klerksdorp and Mmabatho, respectively. Furthermore, the high and low concentrations of free chlorine in drinking water may lead to health, aesthetic and operational risks. A free chlorine content that is less than 0.2 mg/L may increase the turbidity of water as a result of microbial recontamination at the point of distribution; and a residual chlorine content of >5 mg/L is aesthetically unacceptable. There was no significant difference ($p \geq 0.05$) in the overall means of free chlorine between the study areas as well as between the seasons measured, with $p = 0.92$ and 0.36, respectively.

In summary, both the conventional and non-conventional (advanced) water treatment processes employed at the two study areas in the North West province were effective in treating the chemical pollutants in the water sources. The exception was the effective removal of total hardness and calcium in Mmabatho's processed water. Although the chemical parameters measured are not known to cause any adverse or long health impacts, it is however imperative to control them for aesthetic quality of drinking water. Calcium, in the form of carbonates, is naturally occurring in sedimentary environments, hence the mineral may be dissolved by the water sources influenced by high temperatures. The chemical parameters that were measured are total hardness, magnesium, calcium, sodium, chloride, sulphate, nitrate and the residual chlorine. Another parameter that raised concern, even though the concentration of outlet water was within the acceptable level, was the sulphate. The

sulphate ion in the form of aluminium sulphate is used in one of the stages in treatment process hence it needs close monitoring.

4.2.3 Microbiological properties

An important source of microbial contamination of surface and/or groundwater is runoff water from agricultural, pasture lands, and urban areas (Meffe & de Bustamante, 2014). Faecal bacteria enter surface water by direct deposit of animal faeces and by overland runoff. The movement of faecal wastes into water sources is the major factor contributing to the detection of *E. coli* and total coliform (TC) bacteria in domestic water.

4.2.3.1 *E. coli* and total coliforms

The ability of faecal bacteria to survive in environmental waters generally increases as the temperature decreases. Coliforms have no taste, smell, or colour. They can only be detected through a laboratory test. The guideline value for *E. coli* and total coliforms in drinking water as prescribed by WHO, DWA, and SANS 241 is “none detectable colony forming unit (CFU) in any 100 mL sample of water” (Affairs & Services, 2005; Edition, 2011)

The mean microbial counts for *E. coli* and TC were counted for sampled water, at the inlets (before chlorination) and outlets (after chlorination) from the study areas and recorded as the number of colony forming units (CFU) per 100mL (Table 9). The results obtained indicate that the sources that supply Klerksdorp and Mmabatho are highly contaminated with bacteria. The total coliforms recorded at Klerksdorp during the summer and winter seasons were 74855±3047.63 and 2912.80±2493.05 CFU/ 100 mL, respectively.

Table 9: Seasonal mean values of *E. coli* and Total coliform (TC) in CFU/100 mL

	E. coli		**Total coliform**	
	Summer	Winter	Summer	Winter
MWC 1	**14.50±4.95**	**45.00±49.50**	**74855.00 ± 3047.63**	**2912.80±2493.05**
MWC 2	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
MWTP 1	**41.50±44.55**	**25.50±34.65**	**920356.00±56.57**	**10024.50±21.93**
MWTP 2	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
DWA	**0**		**0 - 5**	
WHO	**0**		**0**	
SANS	**0**		**0**	

Note: 1 represent inlet values and 2 represent outlet values.

In the great majority of studies, microbial contamination is more often detected and found at higher concentrations during the wet seasons (Rochelle-Newall *et al.*, 2015). This trend is observed in the data for Mmabatho. In Mmabatho, the total coliform measured before treatment was 920356±56.57 and 10024.50±21.93 CFU/100 mL for summer and winter, respectively. Again, this trend coincides with seasonal patterns in health outcomes, such as diarrheal diseases, that are associated with drinking faecal-contaminated water. These diseases are known to be more prevalent during periods of heavy rainfall and floods (Kostyla *et al.*, 2015). After treatment, no total coliform bacteria were detected at both study areas, and for all sampled seasons. There was no significant difference in the total coliform measurement between the inlet and the outlet at both study areas, with the p values equal to 0.39 and 0.41, respectively. Again, the student t-test showed no significant differences in the measurements between both study areas, as well as between the sampled seasons, with the p values equal to 0.39 and 0.32, respectively.

Similarly, the *E. coli* detected at the inlets of Klerksdorp and Mmabatho ranged from 14.50 to 45.00 CFU/100 mL. In Klerksdorp, the *E. coli* measured at before water treatment was 14.50±4.95 and 45.00±49.50 CFU/100 mL during summer and winter, respectively. In Mmabatho, the *E. coli* was 41.50±44.55 and 25.50±34.65 CFU/100 mL for summer and winter, respectively. There was no significant difference at the *E. coli* measurements in Klerksdorp, with the p value equal to 0.19. However, there was a significant difference in the *E. coli* measurements for Mmabatho, with the p value equal to 0.05. Overall, the student t-test show that there was no significant differences in measurements for *E. coli* between the study areas, as well as between the sampled seasons with p values equal to 0.90 and 0.81, respectively.

In summary, microbial contaminants were well treated and eliminated by the two water treatment processes, rendering the two water treatment processes effective. The sources of microbial pollution are the mixing of water from the municipal wastewater treatment systems as well as runoff of faecal matter into surface water sources.

4.3 Summary

Overall, the water quality parameters from the outlets (post-treated water), except for temperature and pH, were significantly different from the inlets (pre-treated water). This means Klerksdorp and Mmabatho water treatment systems have, and are able to produce, fairly good potable. The contamination of outlet water (post-treatment) is the most concerning in all water quality studies because it has a greater potential to cause adverse effects to human health in the long run. This is the reason water quality studies, assessments and monitoring continue to be important and relevant at municipal, governmental, provincial and national level. The majority of the physico-chemical and microbial properties of water were found to be within permissible limits according to the World Health Organisation, Department of Water Affairs and the South African National Standard guidelines for drinking water quality.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study aimed to assess the effectiveness of domestic water treatment processes in the North West province, South Africa. This was achieved by analysing the physico-chemical and microbial properties of water from the water treatment plants of the two study areas. In addition, a major objective was formulated to achieve the aim of this study. The overall conclusions from the study are presented in the sections that follow.

I. Analysing the processes used in the two water treatment plants in the North West province of South Africa

The conventional treatment process by filtration, alum treatment, and disinfection by chlorination is, and has been, relied upon by many water treatment plants; and offers the most sustainable way to eliminate health risks as a result of consuming contaminated water (Gitis & Hankins, 2018). This study revealed that a conventional water treatment process with rapid-sand filtration and chlorination can treat the most widespread source of municipal and agricultural pollution and/or runoff in the Setumo Dam, the water source feeding the Mafikeng Local Municipality, in the North West province. The exception were parameters such as conductivity, turbidity, hardness, and calcium that were still present in the water after the treatment process at the levels exceeding the standard limits as specified by the SANS 241 for drinking water quality.

The non-conventional (advanced) water treatment process used by the Midvaal Water Company, in Klerksdorp, is the most effective water treatment process for domestic water treatment and purification. The advantages of the pre- and intermediate ozonation step in the purification process of the Middle Vaal River, which is known to be affected with the major algal species, cannot be understated (Morrison *et al.*, 2012). The intermediate ozonation step plays a crucial role in the elimination of unwanted species and contaminants that vary the physico-chemical characteristics of the output

water; while the pre-ozonation step removed most of the trivial algal species very early into the treatment process. Additionally, the combination of the intermediate ozonation and the dissolved air flotation steps were very crucial in the effective removal and elimination of: organic and inorganic matter, including natural organic matters (NOM); micro-pollutants such as pesticides; disinfection by-products (DBP's) such as trihalomethanes (THMs); and odour and taste.

II. Analysing the physico-chemical properties of water from the selected sample points of the water treatment plants in the North West province

The quality of water in Mafikeng and Klerksdorp, which are both situated the North West province, were successfully analysed to determine their physico-chemical properties. The 14 physico-chemical parameters measured were compared to the drinking water quality guidelines as set out by the WHO, DWA, and SANS (DWAF, 1996d). Their comparison to these standards yielded results of whether or not the water is suitable for domestic purposes after the treatment process.

Most physico-chemical parameters analysed at the study sites were within the permissible limits according to the drinking water quality guidelines (DWAF, 1996b) except few parameters such as electrical conductivity, total hardness, turbidity and calcium; particularly in Mmabatho; which exceeded the total water quality ranges (TWQRs) after the treatment process. The excessive levels in these physico-chemical parameters is most likely the cause of the aesthetic, taste and scaling problems, amongst the many challenges that have been reported in Mmabatho. Furthermore, a seasonal variation was notable from both study sites, with higher levels measured during the wet-summer seasons.

Overall, Mmabatho Water Treatment Plant produces and supplies fairly good domestic water despite the poor status in the Blue Drop Score rating. The only concern for Mmabatho is the long term impacts for failure to meet all the water quality guidelines. Some more work needs to be done to investigate further the core problems and their long term effect on the operational and health risk of the consumers. Klerksdorp, on the other hand, has continually maintained their excellent Blue Drop Score status over

the past years according to the statistics by the Department of Water and Sanitation (DWS website, 2019).

III. Investigating the microbiological properties of water, in particular, the *Escherichia coli* and total coliform from the selected sample points of the water treatment plants in the North West province

The microbial properties of water samples, particularly *E. coli* and total coliform, from Klerksdorp and Mmabatho Water Treatment Plant in the North West province were investigated. The results clearly indicate significant differences in individual levels of bacterial pollutants (total coliform and *E. coli*) at the inlet. However, statistically there were insignificant differences in *E. coli* and total coliforms levels during the wet-summer and dry-winter seasons. The presence of *E. coli* in concentrations above the SANS 241 (2015) and WHO Guidelines for Drinking Water Quality specifications is unacceptable in drinking water. From this study, no bacterial pollutants were detected at the outlet of all sampled water which means the WTPs of the study areas were able to eliminate the major health risks from domestic water distribution systems.

5.2 Recommendations

With reference to this study, the following recommendations are suggested:

- Parameters such as pH, conductivity, turbidity, faecal coliform and residual chlorine (for water treated with chlorine-based disinfectants) should be tested and closely monitored at all points in the water treatment system. These substances are indicators of potential problems in the water system, and give an indication of the general water quality (DWAF, 1996).

- The present study did not analyse for chemical oxygen demand (COD) and biological oxygen demand (BOD). It is recommended that future studies should analyse and monitor for COD and BOD from the study areas because of the major agricultural activities. These parameters provide vital information that

indicate the presence of toxic organic pollutants in the water system (Organization, 1993).

- The study recommends adherence to strict environmental policies and procedures that do not allow any treated or untreated effluent into open channels without prior authorisation. Additionally, all waste or effluent water generating industries, including the municipal wastewater, are required to pre-treat the effluent to conform with required wastewater quality guidelines before discharging to the centralised wastewater treatment plant. The Department of Water and Sanitation has a set of guidelines that should be adhered to ensure protection of the receiving water bodies. Poorly treated wastewater effluent is the major cause for the eutrophication of fresh water bodies, and create environmental conditions that favour proliferation of waterborne pathogens (Ahmad *et al.*, 2008).

- The physico-chemical and microbiological levels should be correlated to rainfall patterns as well as the river flow conditions. This correlation will help explain seasonal variations and trends observed in the surface water systems and their respective treatment plants (Bezuidenhout, 2013).

- *E. coli* species confirmed by biochemical techniques (such as API, EnteroPluri-Test) and the identification should be further confirmed by molecular methods. A polymerase chain reaction (PCR) amplification procedure that uses *E. coli* and coliform detection genes such as *lacZ* and *uidA* could be used for this purpose (Deshmukh *et al.*, 2016).

This study presented the baseline data on the current state of potable water quality in the North West province of South Africa. With the rise in industrialisation and global warming, more environmental challenges, especially those that will affect the surface water quality, are imminent. Therefore, there is still a gap in the market to look at other practical but effective ways to improve water treatment of domestic water, especially at the point-of-use. Some POU technologies have emerged as a way to empower people and communities without an access to safe water to improve their water quality by treating it at their homes by using readily available material, such as ceramic and

bio-sand, as household water filters. These materials have been identified by Rosa *et al.* (2016) as simple, effective and sustainable methods that may reduce waterborne diseases in drinking water. However, attention still needs to be drawn into continual monitoring of natural water resources, and upgrade the existing water treatment infrastructures according to the changes in the physico-chemical and biological properties of the natural waters. Furthermore, a detailed study into the presence of new and emerging pollutants such as pharmaceutical and personal care products in natural waters in the North West province needs to be looked at as it is an emerging source of water quality concern.

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APPENDICES

Appendix 1: Ethical clearance

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ETHICAL CLEARANCE LETTER OF STUDY

Based on approval by the **Health Science Ethics Committee (FAST-HSEC) on 26/05/2018** after being reviewed at the meeting held on **21/05/2018**, the North-West University Research Ethics Regulatory Committee (NWU-RERC) hereby **approves** your project as indicated below. This implies that the NWU-RERC grants its permission that, provided the special conditions specified below are met and pending any other authorisation that may be necessary, the project may be initiated, using the ethics number below.

Project title: The effectiveness of domestic water treatment processes, North West Province, South Africa.

Project Leader/Supervisor: Prof L.G. Palamuleni
Student: N. Gumbi

Ethics number: N W U - 0 0 2 8 7 - 1 8 - A 9
(Institution / Year / Status)
Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single study
Commencement date: 2017-03-01 **Expiry date**: 2021-03-31 **Risk:** Minimal

Special conditions of the approval (if applicable):

- Translation of the informed consent document to the languages applicable to the study participants should be submitted to the HSEC (if applicable).
- Any research at governmental or private institutions, permission must still be obtained from relevant authorities and provided to the HSEC. Ethics approval is required BEFORE approval can be obtained from these authorities.

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following:

- *The project leader (principle investigator) must report in the prescribed format to the NWU-RERC via HSEC:*
  - *annually (or as otherwise requested) on the progress of the project, and upon completion of the project*
  - *without any delay in case of any adverse event (or any matter that interrupts sound ethical principles) during the course of the project.*
  - *Annually a number of projects may be randomly selected for an external audit.*
- *The approval applies strictly to the protocol as stipulated in the application form. Would any changes to the protocol be deemed necessary during the course of the project, the project leader must apply for approval of these changes at the HSEC. Would there be deviated from the project protocol without the necessary approval of such changes, the ethics approval is immediately and automatically forfeited.*
- *The date of approval indicates the first date that the project may be started. Would the project have to continue after the expiry date, a new application must be made to the NWU-RERC via HSEC and new approval received before or on the expiry date.*
- *In the interest of ethical responsibility the NWU-RERC and HSEC retains the right to:*
  - *request access to any information or data at any time during the course or after completion of the project;*
  - *to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process.*
  - *withdraw or postpone approval if:*
    - *any unethical principles or practices of the project are revealed or suspected,*
    - *it becomes apparent that any relevant information was withheld from the HSEC or that information has been false or misrepresented,*
    - *the required annual report and reporting of adverse events was not done timely and accurately,*
    - *new institutional rules, national legislation or international conventions deem it necessary.*
- *HSEC can be contacted for further information via Lesetja.Motadi@nwu.ac.za or 018 289 2598.*

The RERC would like to remain at your service as scientist and researcher, and wishes you well with your project. Please do not hesitate to contact the RERC or HSEC for any further enquiries or requests for assistance.

Yours sincerely

Prof Lesetja Motadi
Chair NWU Health Science Research Ethics Committee (FAST-HSEC)

Appendix 2: Raw data

	ph	temp	ec	tds	free cl2	ca2+	cl-	mg2+	no3-	so42-	th	tss	na+	e.coli	tc	turbidity
Klerksdorp inlet Summer	9,32	23,45	83,50	525,50	0,00	69,40	61,73	23,65	0,71	185,53	271,70	56,00	75,00	14,50	74855,00	22,67
Klerksdorp inlet Winter	8,385	15,80	60,50	376,50	0,00	47,61	39,14	18,79	2,31	123,42	197,06	42,80	42,69	45,00	3483,50	20,33
Klerksdorp outle Summer	7,675	25,65	69,50	491,50	1,47	62,47	51,95	22,24	0,82	152,23	67,81	45,00	56,89	0,00	0,00	0,55
Klerksdorp outle Winter	8,235	21,94	78,00	472,50	1,50	64,90	57,91	25,50	2,72	174,60	42,56	26,50	59,30	0,00	0,00	0,51

	ph	temp	ec	tds	free cl2	ca2+	cl-	mg2+	no3-	so42-	th	tss	na+	e.coli	total coli	turbidity
Mmabatho inlet Summer	7,26	22,86	240,00	230,53	0,00	68,37	126,86	24,00	3,07	168,51	60,52	478,10	133,05	41,50	920356,00	288,07
Mmabatho inlet Winter	6,55	18,90	274,50	326,24	0,00	56,83	117,83	19,44	2,24	131,75	72,36	290,54	124,56	25,50	10024,50	238,61
Mmabatho outl Summer	7,415	21,88	83,00	166,64	1,60	49,19	142,41	21,13	0,83	147,97	67,64	61,23	129,40	0,00	0,00	173,35
Mmabatho outl Winter	5,995	20,79	83,50	214,37	2,14	62,15	110,16	24,20	1,61	183,05	61,94	41,40	127,71	0,00	0,00	159,92

Seasonal t-tes Study area t-tes t-test t t-test be inlet vs outlet

pH	**Summer**	**Winter**	**SANS 241**				t-test	0,444	t-test	0,015	2E-04	7E-09				
Klerksdorp inlet	9,32	8,39	5	9,7									0,2413			
Klerksdorp outle	7,68	8,24	DWA													
Mmabatho inlet	7,26	6,55	6	9									0,8246			
Mmabatho outl	7,42	6,00	WHO													
temp	**Summer**	**Winter**	6,5	8,5			t-test	0,039	t-test	0,799	5E-04					
Klerksdorp inlet	23,45	15,80											0,4301			
Klerksdorp outle	25,65	21,94														
Mmabatho inlet	22,86	18,90											0,8454			
Mmabatho outl	21,88	20,79														
ec	**Summer**	**Winter**	**SANS 241/DWA**				t-test	0,767	t-test	4E-05	0,05	0,0005				
Klerksdorp inlet	83,50	60,50	0	170									0,8996			
Klerksdorp outle	69,50	78,00	DWA													
Mmabatho inlet	240,00	204,50	0	150									0,2885			
Mmabatho outl	203,00	183,50														
tds	**Summer**	**Winter**	**SANS 241/DWA**				t-test	0,247	t-test	0,134	1E-04	5E-07				
Klerksdorp inlet	525,50	376,50	**0**	**1200**									0,7198			
Klerksdorp outle	491,50	472,50	**WHO**													

Mmabatho inlet	530,53	326,24	0	1000							0,2167
Mmabatho outl	266,64	214,37									
free cl2	**Summer**	**Winter**	**SANS 241/DWA/WHO**		t-test	0,916	t-test	0,359			
Klerksdorp inlet	0,00	0,00	0,2	5							0,0001
Klerksdorp outle	1,47	1,50									
Mmabatho inlet	0,00	0,00									0,0048
Mmabatho outl	3,60	4,14									
ca	**Summer**	**Winter**	**SANS 241**		t-test	0,484	t-test	0,764	0,009	5E-09	inlet vs outlet
Klerksdorp inlet	69,40	47,61	0	150							0,6829
Klerksdorp outle	62,47	64,90	DWA	0 80							
Mmabatho inlet	68,37	56,83	WHO	75 200							0,5081
Mmabatho outl	49,19	62,15									
cl-	**Summer**	**Winter**	**SANS 241**		t-test	0,844	t-test	1E-06	0,966		inlet vs outlet
Klerksdorp inlet	61,73	39,14	0	300							0,7374
Klerksdorp outle	51,95	57,91	DWA/WHO								
Mmabatho inlet	226,86	217,83	0	250							0,8359
Mmabatho outl	242,41	210,16									
mg	**Summer**	**Winter**	**SANS 241/DWA**		t-test	0,684	t-test	0,853		0,491	inlet vs outlet
Klerksdorp inlet	23,65	18,79	0	70							0,4605
Klerksdorp outle	22,24	25,50	WHO								
Mmabatho inlet	24,00	19,44	0	150							0,7635
Mmabatho outl	21,13	24,20									
no3-	**Summer**	**Winter**	**SANS 241/DWA/WHO**		t-test	0,211	t-test	0,686			inlet vs outlet
Klerksdorp inlet	0,71	2,31	0	11							0,8548
Klerksdorp outle	0,82	2,72									
Mmabatho inlet	3,07	2,24									0,128
Mmabatho outl	0,83	1,61									
so42-	**Summer**	**Winter**	**SANS 241/DWA/WHO**		t-test	0,689	t-test	0,252			
Klerksdorp inlet	135,53	123,42	0	500							0,1164
Klerksdorp outle	152,23	174,60									
Mmabatho inlet	168,51	131,75									0,1967
Mmabatho outl	187,97	183,05									
th	**Summer**	**Winter**	**SANS 241/DWA**		t-test	0,865	t-test	0,026	0,101		

Klerksdorp inlet	240,83	216,58	20	200							0,01
Klerksdorp outle	67,81	42,56	WHO								
Mmabatho inlet	360,52	352,36	100	500							0,0029
Mmabatho outl	267,64	261,94									
tss	**Summer**	**Winter**	t-test	0,97	**turb**	**Summ**	**Winter**	**SANS 241/DWA**	t-test	0,9062	inlet vs outlet
Klerksdorp inlet	56,00	42,80			Klerksdo	21,5	20,67	1	5		0,0004
Klerksdorp outle	26,50	45,00	t-test	0,004	Klerksdo	0,53	0,39		t-test	0,5333	
Mmabatho inlet	290,54	278,00	0,353	in vs ou	Mmabat	23,43	23,34				0,0078
Mmabatho outl	141,40	161,23	0,008	in vs ou	Mmabat	9,37	6,64		t-test	0,0456	
na	**Summer**	**Winter**	**SANS 241/DWA/WHO**		t-test	0,743	t-test	5E-05			inlet vs outlet
Klerksdorp inlet	75,00	42,69	0	200							0,9672
Klerksdorp outle	56,89	59,30									
Mmabatho inlet	133,05	124,56									0,9588
Mmabatho outl	129,40	127,71									
ecoli	**Summer**	**Winter**	**SANS 241/DWA/WHO**		t-test	0,813	t-test	0,903			inlet vs outlet
Klerksdorp inlet	14,50	45,00	0	0							0,1904
Klerksdorp outle	0,00	0,00									
Mmabatho inlet	41,50	25,50									0,0526
Mmabatho outl	0,00	0,00									
tcoli	**Summer**	**Winter**	**SANS 241/WHO**		t-test	0,316	t-test	0,39		0,287	inlet vs outlet
Klerksdorp inlet	74855,00	2912,80	0	0							0,3927
Klerksdorp outle	0,00	0,00	DWA								
Mmabatho inlet	920356,00	10024,50	0	5							0,4143
Mmabatho outl	0	0									