Viability, from a quality perspective on the reuse of wastewater effluents in the Southern Gauteng region, South Africa

by

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DECLARATION

I, Gugulethu Given Skosana, declare that the dissertation, which I hereby submit for the degree Master of Science Water Resource Management at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Signature

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30/09/2015

Date

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SUMMARY

Growing populations, urbanization, environmental awareness with resultant regulations and water scarcity have resulted in a search for alternative water sources. Municipal wastewater reclamation and reuse is a necessity in these conditions because it is a water source that is available throughout the year. It can reduce the demand for source water and could be treated at lower costs to the required water quality requirements of the intended use. South Africa especially the Gauteng Province is subjected to the above mentioned stressors but lacks a holistic approach to wastewater reclamation and reuse as a practical and viable solution. Furthermore, the lack of characterization parameters as well as advanced wastewater treatment methods and the viability assessments of the municipal wastewater generated in the South Gauteng catchment, has led to loss of potential water resource in the province. Therefore the current research was initiated as a baseline study to investigate the feasibility of municipal wastewater reclamation and reuse in the South Gauteng catchment. The specific objectives were to 1) assess the worldwide practices of wastewater reuse, 2) apply influent and effluent data analysis and make recommendations on the type of reuse application available for the Southern Gauteng municipal wastewater treatment effluent and to 3) assess the viability of tertiary

treatment technologies as best fit options available for different reuse options required for the study area.

To achieve the above mentioned objectives a literature review was undertaken to assess worldwide water reuse practices and how they can be used in the study area to utilize the generated wastewater effluent. Influent and effluent data of four wastewater treatment plants (WWTPs) in the Sedibeng district municipality (SDM), three in the Emfuleni local municipality and one in the Midvaal local municipality, was used to assess the viability of water reuse. Available worldwide aggregate, nutrient, ionic and microbiological water reuse standards and criteria for potable, agricultural and industrial use were used to characterize the Sedibeng WWTPs for water reclamation.

Wastewater reclamation and reuse is broadly defined as collecting treated or untreated wastewater and using it for a purpose different from what it was used for previously. Recycling, on the other hand, is using water, for the same purpose repeatedly (DWA, 2013a). Water reuse is practiced in countries such as the Western United States, Australia, Singapore, Namibia, Mediterranean countries and Japan for potable use, irrigation and industrial purposes. South Africa, having laid the foundation of wastewater reuse in Namibia, currently practices direct potable reuse (DPR) in the Beaufort West municipality as well as internal water recycling in the power, steel, petrochemical, paper and pulp industry. Water reuse standards and criteria are set based on regional differences of water availability, public health protection, monitoring feasibility, industry types and the reuse purpose. Risk assessment that includes among others a multi-barrier approach, water quality criteria objectives and acceptance determines treatment technology selection. Tertiary treatment technology such as ultrafiltration, reverse osmosis and advanced oxidation processes especially UV/H_2O_2 are used in water reclamation plants after preliminary treatment of secondary effluent.

The four SDM WWTPs effluent, which was over 220 ML/d, the results show, mostly use activated sludge process and have water quality determinants complying with the design criteria for advanced treatment in water reuse. This effluent meets the Namibian

Goreangab and Beaufort West Water Reclamation Plant (WRP) multi-barrier influent design criteria for DPR in most aggregate, nutrient and ionic parameters except microbiological parameters. Parameters such as chemical oxygen demand (COD), dissolved solids and ammonia and alkalinity were non-compliant for which this could signify incomplete activated sludge process. This shows the importance of secondary treatment as one of the barriers in the multi barrier approach. Even though membrane treatment of this effluent to improve these parameters and microbiological quality is possible effective secondary treatment as one of the barriers is important to prevent downstream membrane fouling. Depending on this water quality the water will be suitable for indirect potable reuse (IPR) with blending, industrial cooling, heat exchange and dust suppression as recommended uses. Municipal effluent, which could reduce potable water demand, is currently not used in the study area's power generation and steel making industries Eskom's Lethabo power station and ArcelorMittal respectively. This is even though, advanced water treatment processes such as reverse osmosis, exist for both organization's internal wastewater recycling. The reclaimed municipal effluent can be introduced to moderate water quality processes such as cooling systems, heat removal, waste handling and washing in both industries in the study area.

Public-private partnerships (PPPs) with water intensive user industries incorporating municipal secondary effluent in current and future infrastructure plans to find viable solutions as part of their water use licensing conditions. These PPPs would include the national Department Water and Sanitation (DWS), Sedibeng district municipality, Eskom, ArcelorMittal and Rand Water the bulk water utility in the study area. An in depth study of water reuse public perception, cost of water reuse, establishing purpose specific reuse guidelines and water quality monitoring and management plan for study area is recommended before implementation. Monitoring, which is one of the barriers in risk abatement, should include for the study area emerging pathogens, inorganic and organic contaminants of concern such as endocrine disrupting chemicals (EDCs).

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LIST OF SYMBOLS

m^3	-	cubic meter
m^3/capita.yr	-	cubic metre per capita per year
^oC	-	degree Celsius
hv	-	Energy photon
K	-	Kelvin
kW.hr/ m^3	-	kilowatt-hour per cubic meter produced
>	-	greater than
λ	-	Lambda
<	-	less than
µ	-	micro
µS/cm	-	microSiemens per centimeter
mS/m	-	milliSiemens per meter
ml	-	milliliter
min	-	minutes
ML	-	Mega liters
mg/l	-	milligrams per liter
mt	-	metric ton
%	-	percent
φ	-	Phi
±	-	plus-minus
µg/l	-	microgram per liter

LIST OF ACRONYMS

AMD	-	Acid mine drainage
AOPs	-	Advanced oxidation processes
APHA	-	American Public Health Association
AR	-	Artificial recharge
AS	-	Activated sludge
BAC	-	Biological activated carbon
BOD	-	Biochemical oxygen demand
BNR	-	Biological nutrient removal
CCT	-	City of Cape Town
CFU	-	Colony forming units
COD	-	Chemical oxygen demand
CSIR	-	Centre for Scientific and Industrial Research
CSIRO	-	Commonwealth Scientific and Industrial Research Organization
DAF	-	Dissolved air flotation
DBSA	-	Development Bank of Southern Africa
DOC	-	Dissolved organic carbon
DPR	-	Direct potable reuse
DWTR	-	Drinking water treatment residue
EC	-	*Escherichia coli*
EDCs	-	Endocrine disrupting chemicals
ELM	-	Emfuleni Local Municipality
ELISA	-	Enzyme Linked Immuno Sorbent Assay
ESKOM	-	Electricity Supply Commission
EWR	-	Environmental water requirement
FAO	-	Food and Agriculture Organization
FC	-	Faecal Coliforms
FOG	-	Fats oil and grease
GWRS	-	Groundwater replenishing scheme

IC	-	Ion Chromatography
ICP-OES	-	Inductively Coupled Plasma-Optical Emission Spectrometry
IPR	-	Indirect potable reuse
ISCOR	-	Iron and Steel Corporation
JHB	-	Johannesburg
LHWS	-	Lesotho Highlands Water Scheme
MAP	-	Mean Annual Precipitation
MAR	-	Mean Annual Rainfall
MAR	-	Mean Annual Run-off
MBR	-	Membrane bioreactor
MBBR	-	Moving bed biofilm reactor
MF	-	Microfiltration
MLM	-	Midvaal Local Municipality
MPN	-	Most probable number
NF	-	Nanofiltration
NTU	-	Nephelometric Turbidity Units
NWRS	-	National Water Resource Strategy
OECD	-	Organization for Economic Cooperation and Development
pH	-	Potential of hydrogen
PhACs	-	Pharmaceutically active chemicals
POC	-	Particulate organic matter
PPCP	-	Pharmaceutical and personal care products
PPP	-	Private-Public-Partnership
RFWW	-	Recovered filter wash water
RO	-	Reverse osmosis
SANS	-	South African National Standard
SAPPI	-	South African Pulp and Paper Industries
SASOL	-	South African Synthetic Oil Limited
SDM	-	Sedibeng District Municipality
SAT	-	Soil Aquifer Treatment
SRB	-	Sulphate reducing bacteria

TDS	-	Total dissolved solids
TOC	-	Total organic carbon
TSS	-	Total suspended solids
UF	-	Ultrafiltration
USEPA	-	United States Environmental Protection Agency
WC/WDM	-	Water Conservation/Water Demand Management
WISA	-	Water Institute of Southern Africa
WRC	-	Water Research Commission
WRP	-	Water reclamation plant
WSI	-	Water Stress Indicator
WWTP	-	Wastewater treatment plant
WWTW	-	Wastewater treatment works
WHO	-	World Health Organization
ZED	-	Zero effluent discharge
ZLED	-	Zero liquid effluent discharge

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CHAPTER 1

Introduction

1.1. Wastewater reuse drivers

Population growth, contamination of both surface and groundwater, uneven distribution of water resources and periodic droughts have forced many countries to search for alternative water supply to supplement their traditional sources (Asano *et al.*, 2007). This population growth and urbanization thus unavoidably result in an increase in the production of treated and/or untreated wastewater effluent that is discharged into surface waters that serve as potable raw water source in some cases. The rate of urbanization in South Africa, as is the case in other developing countries, has increased especially in water stressed Gauteng Province due to population growth and the search for a better life. This has led to a demand for basic services such as electricity, potable water and sanitation which have increased significantly over the past few decades.

South Africa's water resources are inherently limited and, in addition, a dynamic, growing economy and provision of services requires extensive water resources. In some areas this resource can soon become a constraint which will limit economic and social development (DBSA, 2009). Water scarcity in itself does not limit economic and social development but knowledge and recognition of a country's water endowments and living within these means are important (DBSA, 2009). This, unfortunately, is lacking in South Africa. Wastewater reclamation, reuse and recycling are important for this recognition to reduce demand in domestic, agricultural and industrial sectors, in order to close the water scarcity gap in South Africa.

Wastewater recovery which is an old practice that includes reclamation, reuse and recycling has been given different names for marketing purposes (Salgot, 2008). The National Water Resource Strategy (NWRS-2) definitions of water reuse and recycling are heavily inclined towards the change of use or lack thereof (DWA, 2013a). Water reuse is defined as utilization of treated or untreated wastewater for a process other than the one that generated it. In the case of water recycling where there is no change of use the water is used for the same purpose that generated it. Reclaimed water is defined as wastewater treated to a level suitable for sustainable and safe reuse (DWA, 2013a). In this study the term reclamation and reuse are used interchangeable and recycling used in specific cases where the reclaimed product is used for the same process that created it.

Historically, after water was used for societal needs, it was labeled sewage or wastewater and treated for discharge into receiving water or land disposed (Levine and Asano, 2004). This municipal sewage water is viewed as waste in most countries, although it is a potential perennial source of water (as much as 280 litres per capita per day in the United States) (Schroeder *et al.*, 2012). In South Africa Ventilated Improved Pit Latrines (VIPs) which are dry facilities are viewed as basic level of sanitation whereas waterborne sewers are regarded as a high level of sanitation. Hence it is difficult to obtain accurate overall per capita wastewater generation estimates for waterborne sewers (DWA, 2013b). However, 979 wastewater treatment plants in South Africa produce 7 589 ML/per day effluent of which the bulk is from Gauteng province. This is a potential source of water to reduce the demand for high quality potable use by replacing the potable water with reclaimed water (DWA, 2008). Of the total volume of municipal wastewater generated from WWTPs, only a small fraction is reused for example in irrigation of parks, sports fields, golf courses and cooling systems with moderate water quality requirements (DWA, 2013a).

1.2 Water availability, demand and uses

South Africa is semi-arid and the 30th driest country in the world with an annual rainfall ranging from 100mm in the west to 1500mm in the east (DWA, 2013b). It has a mean annual precipitation (MAP) of approximately 500mm/a that is just over half the world average of 800mm/a but this is pressured by high evaporation rates as well as highly sporadic and uneven rainfall patterns in the interior. Historically supply side engineering solutions such as the Lesotho Highlands Transfer Scheme (LHWS) and Tugela-Vaal scheme have met the increasing water demand (King, 2004). The water from the LHWS flows into the Vaal Dam via the Wilge River and the water from the Tugela scheme stored in the Sterkfontein Dam after which it flows into the Vaal Dam (DWA, 2009). Available and imported water resources have to support the country's potable, agricultural and industrial needs especially in the water scarce Gauteng area which benefits most from these schemes and where the study area is located.

The irrigation or agricultural sector according to the NWRS-2 accounts for the most use at 60% of water utilization in South Africa but also experiences losses of between 35-45%. It also states that local government or water services sector, the second highest user, accounts for 23% of South Africa's fresh water resources and has non-revenue water loss of up to 90% in some cases. This water loss includes industrial use supplied by local government and mining use which is varied and accounts for 16% of the use (DWA, 2013a). Wastewater effluent, whether treated or untreated, has a huge potential in managing or reducing demand in the irrigation, industrial and domestic sectors in the short and medium term in South Africa.

1.3 Worldwide existing wastewater reuses

Municipal wastewater reclamation and reuse occurs in, arid and semi-arid countries with high population numbers and subsequent water demand, and other countries with environmental concerns of reducing discharged nutrients (USEPA, 2012). A trust in responsible engineering, increasing water shortages and water pollution are some of the drivers to develop a realistic framework which view wastewater reclamation as a water resource rather than a liability (Asano and Cotruvo, 2004). The main reuse options are for irrigation which accounts for the largest and oldest usage, urban landscaping and other non-potable reuse for flushing, industrial, indirect potable and rarely direct potable reuse.

In the arid west of the United States reclaimed water use occurs where an example is the implementation in the early 1960s in Colorado Springs of a dual distribution system where the reclaimed water line is mostly used for irrigation (Asano *et al*., 2007). Israel has a strategic objective to reuse all of its wastewater for agricultural purposes. The

South African agricultural sector, on the other hand, accounts for 60% of the water use in the country but only a small portion uses treated wastewater (DWA, 2013a). In Windhoek, Namibia, direct potable reuse has been used in domestic water supplies for over 30years using a multi-barrier approach for treatment without any adverse effect detected (Huertas *et al*., 2008).

The reuse of water which is unplanned and indirect, accounts for approximately 14% of total water use in South Africa and it is mostly attributed to return flows mainly through discharged effluent into rivers (DWA, 2013a). Direct potable reuse of wastewater in South Africa is practiced in the Karoo after a recent drought forced the Beaufort West municipality to build a Wastewater reclamation plant (WRP). This plant was designed for 2.1 ML/day to treat water to a potable standard (ATSE, 2013). These unplanned indirect and planned direct reuse examples illustrates steps already taken in wastewater reclamation and reuse in South Africa and it is a building block to entrenched planned use in the future.

1.4 Wastewater reuse options

The most common direct or indirect reuse options are irrigation, residential, urban and recreational uses, groundwater recharge, bathing water, aquaculture, industrial cooling water and drinking water production (Huertas *et al.*, 2008; UKWIR, 2014). The quality requirements for the reclaimed water depend strongly on the application of water, which can include (de Koning *et al.*, 2008):

- Industrial reuse which is varied from ultrapure water in the semi-conductor industry to relatively good quality water for cooling towers in power plants. Functional aspects involved such as clogging, corrosion and sedimentation and health aspects cannot be neglected in this application
- Non potable household reclaimed water for toilet flushing, showering, laundry, car washing and household gardening. Human and animal safety aspects are predominant in this reuse application in relation to functional aspects such as hardness caused by heavy metals

- Irrigation in urban areas including public parks and gardens. In this case human health aspects are also vital
- Restoration of natural water resources where natural waters are replenished or artificial recharged. In this case reclaimed water is used for replenishing in constructed wetlands or boreholes

1.5 Treatment technology

Treatment technologies used for wastewater reclamation, reuse and recycling are called tertiary or advanced treatment processes since, they follow wastewater secondary effluent treatment. The processes can be of a physical, biological or chemical nature in a designed mode or simulated natural processes such as aquifer recharge or wetland systems. The current study focused on chemical processes represented by advanced oxidation, physical processes represented by membrane filtration and natural or biological processes represented by wetlands and aquifer recharge.

This risk assessment and characterisation of reclaimed water influent should guide what treatment regime should be used to reach a particular water quality standard. The reuse option should be chosen based on physical, chemical and biological properties of water. Human health and environmental risks associated with reclamation are determined by the science or typology of risk assessment based on the following variables (UKWIR, 2014):

- Nature of raw wastewater for reclamation such as industrial or domestic source with its associated range of contaminants
- The type of subsequent treatment train and its effectiveness in reducing contaminants
- The reuse options such agricultural or potable and whether this create an exposure route for health and environmental risks

A starting point for the building of a treatment matrix is the definition of the conceivable reuse aims which are linked to water quality objectives achieved through using specific treatment schemes (de Koning *et al.*, 2008). These water quality objectives are based on risk assessment, followed by data collection from monitoring as advocated by the Water Safety Planning (WSP) for risk management and redesign or augmentation of the existing treatment regime (WHO, 2009). The WSP approach also incorporates the fit-for-purpose treatment option selection method which is a cost effective treatment applied to a water source for a specific intended use (USEPA, 2012).

Advanced treatment processes are capable of removing total suspended solids and or trace constituents which include endocrine disrupting chemicals (EDCs) and or pharmaceutically active chemicals (PhACs) (Asano *et al.*, 2007). The main concern against reuse for potable purposes is the presence of pollutants such as pharmaceuticals, health care products, pesticides, industrial chemicals, heavy metals, etc. (DWA, 2013a). Advanced wastewater treatment technologies in addition to secondary conventional wastewater treatment processes may be a possible solution to this concern.

1.6 Problem statement

Characterization of treated and untreated municipal wastewater effluent according to physical, chemical and biological parameters is important to determine the potential and risk of varied reuse options. This, however, is currently not exploited fully in Southern Gauteng.

1.7 Hypothesis

The lack of characterization parameters as well as advanced wastewater treatment methods viability assessments of the municipal wastewater generated in the South Gauteng catchment, has led to loss of potential water resource in the province.

1.8 Aim of the study

The aims of the study were to investigate 1) worldwide reclamation, recycling and reuse of municipal wastewater for potable, agricultural and industrial use and 2) assess viability of incorporation into new and existing South African reuse applications. It was also important to investigate regulation and criteria governing each reuse application based on risk assessment and water quality parameters as well as public acceptance of the reuse of such water. The investigation also included advanced treatment technology needed to reach the required standards as well as parameters for acceptable use and their viability with respect to application in South Africa.

1.9 Research objectives

- **Objective 1:** Evaluate worldwide practices of wastewater reuse for potable use, agriculture and industry through theoretical considerations of existing practices in terms of re-use options, their magnitude and quality criteria thereof
- **Objective 2:** Based on influent and effluent data analysis make recommendations on type of reuse application available for the Southern Gauteng municipal wastewater treatment effluent
- **Objective 3:** To assess viability of tertiary treatment technologies as best fit options available for different reuse options required for the study area based on existing practices and water quality data gathered

1.10 Overview of the report

<u>Chapter1</u>: **Introduction**

Chapter one delved into the theoretical underpinning as an introductory chapter into the study and identified problems to be solved. It also gave an analysis of the gaps available for the research to be conducted. This involved exploring the obvious when looking at the lack of full use of potential of water reuse and exploiting solutions when critically reflecting the problem and identifying gaps. This culminated in the formulation of the problem statement and hypothesis for the gap analysis and resulting definition of research objectives (Figure 1.1).

<u>Chapter 2</u>: **Literature review**

Chapter two uses the established themes and constructs, briefly outlined in Chapter 1, to analyse and integrate them into theoretical problem analysis or give established theoretical consideration. The theoretical foundation of the study was explored and a looked specifically into worldwide reuse practices, water quality parameters of concern and treatment technology are explored. Water quality guidelines, criteria and standards informed by perception, economic consideration and capacity to monitor and control were also considered with benchmarking examples.

Chapter 3: **Study area domain**

Chapter three describes the study area domain in terms of actual size, borders and using established domain descriptors following the integrated water resource management principle of a catchment. The area of study was described in terms of socio-economic, topography, climate, geology, water use, flora and fauna using the broad definition of biophysical and social environment.

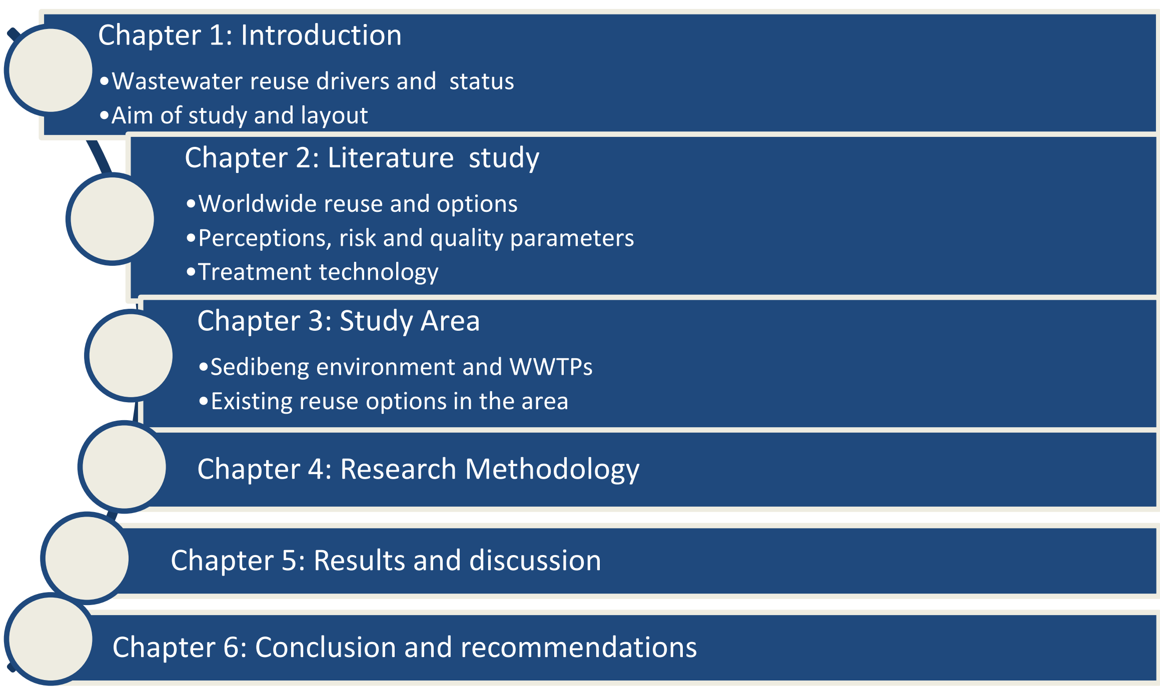

Figure 1.1: Overview of report map summary

Chapter 4: **Research methodology**

Chapter four presented the implementation of the appropriate research design for the study undertaken and throughout the chapter a link to the study was drawn. Research philosophy, approach and strategy adopted highlighted to illustrate the integrated social and scientific nature of the study. Analytical methods, sampling techniques, data collection and analysis strategy all important were used to answer the research questions.

Chapter 5: **Results and discussions**

Chapter five presented all the findings from the study with reference to established constructs from theoretical considerations forming the basis of the discussion. The findings were illustrated in graphs, tables and as comprehensive as possible dealt with contextualization of the research findings unravelled with tools chosen in preceding .chapter 2, 3 and 4. This was aligned and confined to the objectives stipulated in chapter 1.

Chapter 6: **Conclusions and recommendations**

Chapter six outlined the conclusion and recommendations and included a summary of the findings addressing the problem statement and objectives of the research. Future study on the topic that were limited or delimited by, among others, timeframes, scope, resources and data collection are recommended.

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Chapter 2

Literature review

2.1. Introduction

Wastewater recovery which is an old practice that includes reclamation, reuse and recycling has been given different names for marketing purposes (Salgot, 2008). This practice cannot be characterized as unconventional, emerging or alternative only because it still needs to be proven as an effective water supply source. This is because general use of treated wastewater is at least a century old, domestic wastewater has been used for centuries in agriculture. It is wrongly termed “unconventional” because in the last 30 years it has been included in water resource planning (FAO, 2010).

The terms wastewater reuse, wastewater recycling and wastewater reclamation are sometimes used interchangeably but they are not the same (Tassoula, 2011). The South African National Water Resource Strategy NWRS2 definition of water reuse and recycling is heavily inclined towards “change of user” or lack thereof. Wastewater reuse is thus defined as utilization of treated or untreated wastewater for a process other than the one that generated it. In the case of water recycling where there is no change of user the water is used for the same process that generated it. Reclaimed water is defined as wastewater treated to a level suitable for sustainable and safe reuse (DWA, 2013a).

Three other terms that sometimes cause different interpretations in wastewater reclamation are direct reuse, indirect reuse and “de facto” reuse. These are distinguished by planning and existence or nonexistence of an environmental buffer which is absent for direct reuse and present for indirect reuse (Crook, 2010; ATSE, 2013). An environmental buffer is defined as a water body or aquifer, perceived by the public as natural which serves to sever the connection between water and its history and based on its attributes removes and/or dilutes contaminants by providing residence time (NRC, 2012). As an illustration, indirect reuse is when water is discharged from a WWTP to the environment and blends with un-discharged water then re-abstracted and direct reuse is when water is directly transferred to a WRP from a WWTP (UKWIR, 2014). “De facto” reuse or also commonly referred to as unplanned reuse, which is different from indirect reuse, is when reuse of treated wastewater is practiced but not officially recognized (USEPA, 2012; NRC, 2012; ATSE, 2013). This use could be in agricultural and industrial in addition to potable reuse applications.

In South Africa wastewater effluent resource strategy for efficient use, alternative treatment and use, and storage is not available for the large amounts of wastewater generated in the inland catchments and this amount to de facto reuse. According to the National Water Resources Strategy (NWRS2) the key consideration that affect choices related to water reuse as an option for water supply and augmentation are as follows (DWA, 2013a):

- Water quality and security of supply
- Water treatment technology
- Cost relative to other water supply alternatives
- Social and cultural perceptions
- Environmental considerations

Wastewater reclamation reduces the environmental impact of inter-basin transfer which inevitably requires damming, pumping costs, construction of canals and reservoirs (Schroeder *et al.*, 2009). The NWRS2 supports the viewpoint that wastewater reclamation is relatively inexpensive compared to desalination and inter-basin transfer (Figure 2.1). An example of this cost reduction is in the reclamation of the City of Cape Town’s WWTP’s effluent for irrigation of recreational facilities among other uses which cost a third of potable water treatment (CCT, 2006)

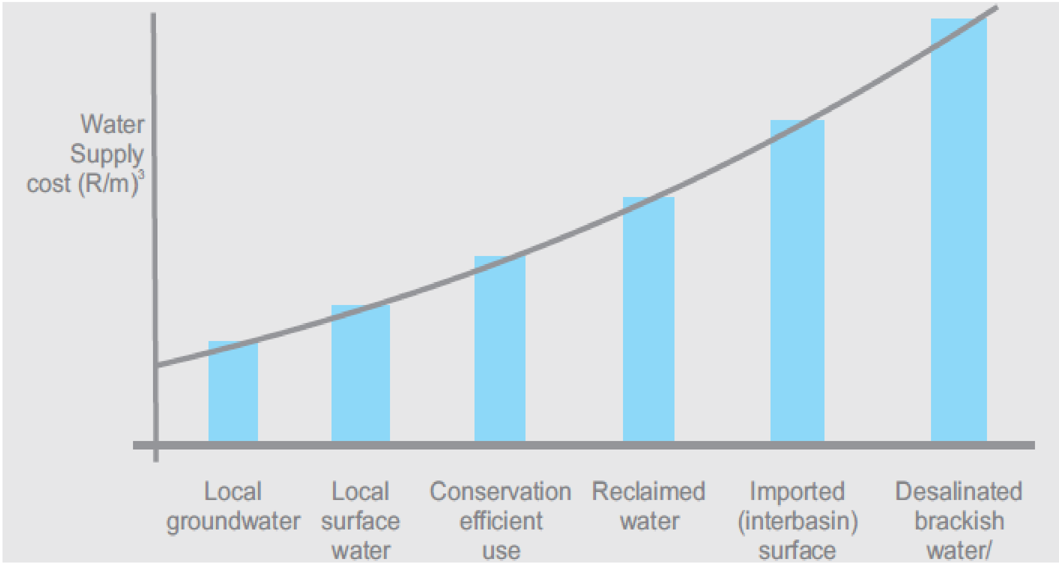

Figure 2.1: Comparative cost of different water sources (DWA, 2013a)

Economics of source water substitution are site specific and cost effective use of reclaimed water use necessitates producing it close to the potential user, for example, agricultural use near urban areas (Levine and Asano, 2004). Furthermore, new industries and housing developments may benefit more compared to existing areas if dual distribution systems are added to new establishments to also carry reclaimed wastewater. A major drawback is thus the additional cost if initial plans of service provision and construction which did not include water reuse and revenues for non-potable water (OECD, 2009). The installation or upgrade of existing wastewater treatment facilities and their recurrent cost of treatment in terms of energy to meet desired standards may also halt or hinder reuse plans (FAO, 2010). As much as wastewater reclamation is a sustainable approach and a cost effective long term alternative the following considerations are important (Asano *et al.*, 2007):

- Costly and energy intensive treatment compared to inter-basin transfer of water beyond secondary treatment
- Installation of reclaimed water distribution systems after treatment which can be costly also compared with inter-basin transfer
- Institutional barriers and varying agencies priorities
- Public awareness of sustainable water resource management is essential

This chapter investigates theoretical considerations with regards to worldwide reuse drivers, extent and water scarcity indices up to regional and country level of leading wastewater reusing states. It then looks into different reuse applications of potable, agricultural and industrial reuse and their drivers which are informed by public perceptions and acceptance, among others, which is the subsequent topic. Risks associated with water reclamation which informs target water quality criteria is then discussed and this is achieved with available treatment technology.

2.2 Worldwide reuse extent and drivers

Increasing pressure on fresh water resources is spurring wastewater reuse in countries such as the United States, Mexico, Mediterranean countries, the Middle East, South Africa, Australia, Japan, China and Singapore (Levine and Asano, 2004). Significant developments in wastewater reclamation and reuse have occurred in arid regions of the world including Australia, Israel, the Middle East, Spain, Tunisia, West and South Western United States (Asano and Bahri, 2011). A need to build resilience against water scarcity is a driver in arid and semi-arid regions but a phase of reuse expansion is occurring despite a moderate water stress classification in countries such as Italy, France and the Netherlands (UKWIR, 2014).

Italy, Spain and Greece account for between 5-12% water reuse and for ease of calculation a median value of 9% is used in (Table 2.1). China, as a large country with various dynamic conditions, reuses 10-15% and 5-10% in the northern and southern cities respectively. An equally misleading statistic based on the vast country is the United States reuse of 2-3% but with the largest volume of 10.7million m^3 per day (Vo *et al*., 2014). Only two states California and Florida have significant reuse extent and in addition the data remain somewhat limited and this skews the statistics on the extent of water reuse in the whole of the United States (Jimenez and Asano, 2008; NRC, 2012). The USEPA estimates water reuse in America at 7-8% better than 2-3% but still low compared to Australia at 8%, Saudi Arabia at 16% and Singapore at 30% (USEPA, 2012). This demonstrates the nascent nature of information on water reclamation in terms of amounts, percentage and type of reuse of reclaimed water worldwide.

Table 2.1: Worldwide water reuse indicator breakdown

Country	% Use[*]	MAP (mm/year)[**]	Population density People/km^2[**]	% Water Intensity Use[***]	WSI[****]
South Africa	14	495	44	47	0.8
Namibia	40	285	3	46	0.9
Australia	17	534	3	27	0.9
United States	8	715	35	62	1
Mexico	41	752	63	58	1
Japan		1668	349	41	0.7
China	10	645	146	38	1
Singapore	30	2497	7713	42	1
Israel	83	435	372	18	1
Saudi Arabia	40	59	13	13	1
Italy	9	832	203	22	0.8
Spain	9	636	94	21	0.9
Greece	9	652	86	26	1
Malta	60	560	1323	20	1
Cyprus	100	500	124	19	1

*EUWI (2007)**World bank (2015)***Jimenez and Asano (2008)****Smakhtin *et al.* (2004)

High population density, which leads to vulnerability of effluent receiving water bodies, has led to a steady increase in water reuse in countries with high rainfall that are expected not to practice water reclamation. These are countries such as Belgium, England and Germany in Europe (Lazarova and Asano, 2005). In Asia a country such as Japan has also adopted wastewater reclamation in spite of its over 1500mm/annum rainfall. Its high population density with a per capita consumption of 900 m^3/yr which is below water scarcity index threshold of 1700 m^3/yr is a reason for adoption of wastewater reclamation (Funamizu *et al.*, 2008). In terms of mean annual precipitation using Figure 2.2 based on Table 2.1 South Africa is comparable to Australia, China and Israel the second largest per percentage wastewater reusing country after Malta. Even though Israel has a larger population density at 372/km^2 compared to Australia and China at 3/km^2 and 146/km^2 respectively the latter two countries are also well established in the wastewater reclamation realm.

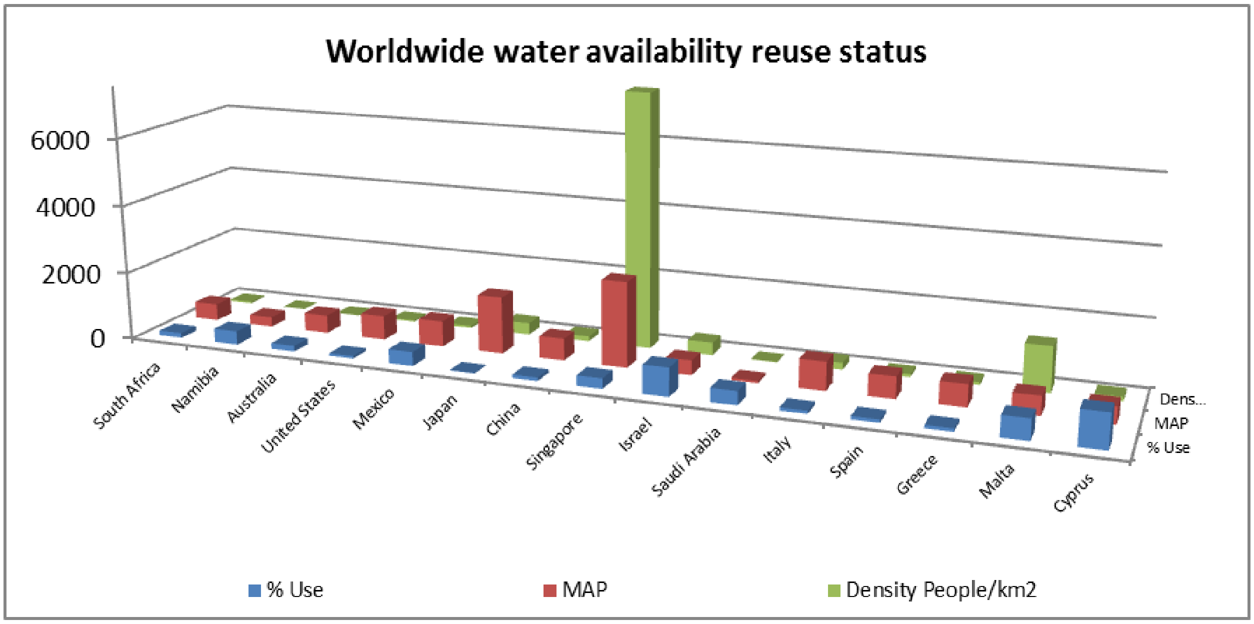

Figure 2.2: Population density, MAP and use of reuse practicing countries

South Africa has one of the lowest population densities because countries such as Singapore, Japan, Israel and Malta dwarf South Africa with a density of 44 people/km^2 (Figure 2.2, Table 2.1). This density is still higher than the United States (35 people/km^2) and Saudi Arabia (13 people/km^2) with established practice in wastewater reuse. In parts of the value could be higher especially for Gauteng where the Sedibeng district municipality is located and where intense urbanization is taking place.

There are established indicators used to express relative water scarcity which illustrate the drivers for reuse such as water scarcity index and water intensity use index (FAO, 2010). Water scarcity index is based on available fresh surface and groundwater representing a per capita threshold of 1700 m^3/yr without regard for existing infrastructure or economic usage. Water intensity use index, also referred to as water stress index expresses the amount of water withdrawals as a percentage of available water resources in the region with threshold of 20% (Bixio *et al.*, 2006; FAO, 2010). The stress index intensity of European countries in relation to wastewater reuse practice is also a good indicator (Figure 2.3).

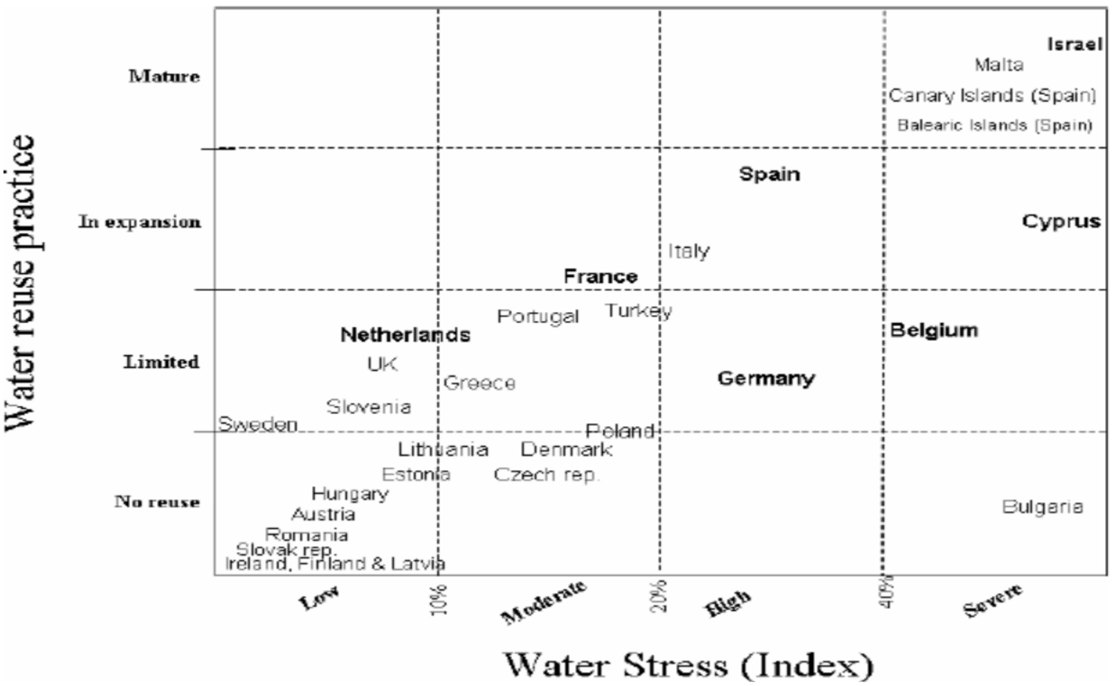

Figure 2.3: European reuse practice in relation to water stress (Bixio *et al.*, 2006)

The water stress indicator displayed in Figure 2.4 also takes into account environmental water requirements (EWR) (Smakhtin, 2004). This can be used to estimate (based on stress index) which countries have or should have current and planned water reuse projects worldwide. South Africa’s semi-arid Gauteng region supplied by the Orange River basin is also highlighted with between 0.8 and 0.9 high WSI which is a high enough index reading to warrant advanced plans on wastewater reuse.

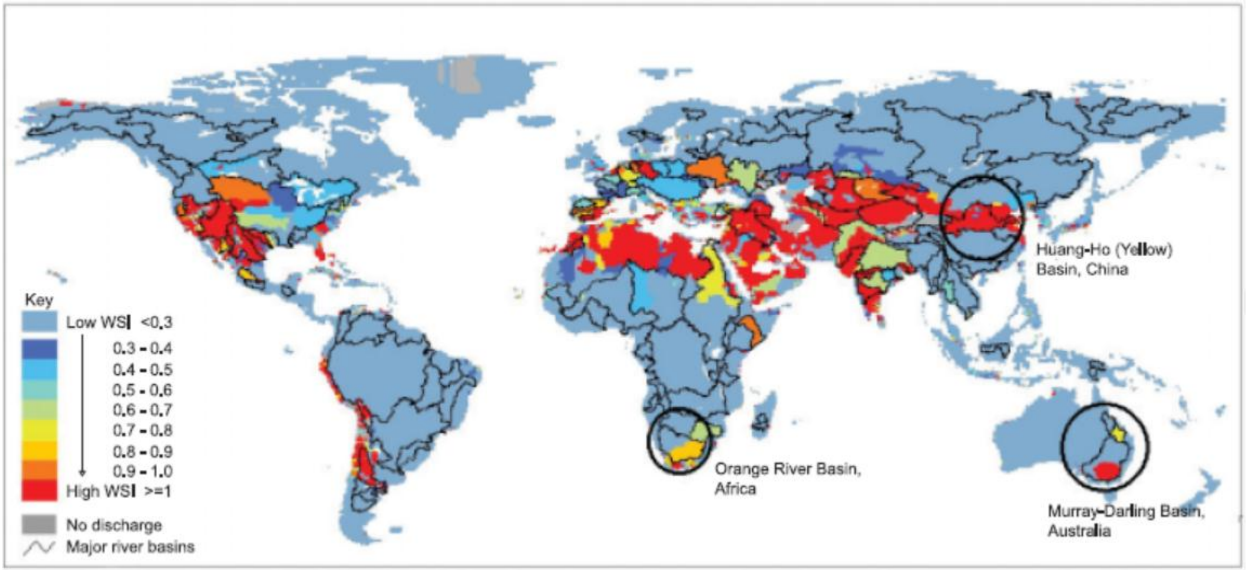

Figure 2.4: Worldwide water stress indicator (Smakhtin *et al.*, 2004)

In the water intensity use index in Table 2.1 South Africa's water intensity use is at 47 greater than Namibia, Singapore and Australia at 46, 42 and 27 respectively. Although this is still lower than the South Western United States and Mexico at approximately 61 and 62, it is still high considering South Africa has no entrenched wastewater reuse plans, policy, guidelines or regulation (Jimenez and Asano, 2008; Jimenez-Cisneros, 2014). South Africa's high water intensity of use, in addition, to population must be as a result of having high water intensity use industries such as power generation, petrochemical, steel, paper and pulp industries and others.

In the Water Stress Index (WSI) in Table 2.1, Namibia has not been classified exclusively since its southern part is part of the Orange River Basin. South Africa is also in the upper end of around 0.8 of their WSI scale with a low of <0.3 and a high of greater than 1. China, South Western United States, Mexico, Mediterranean, Middle East and Southern Australia are highly stressed according to the WSI even though the scale focuses on river basins (Smakhtin *et al.*, 2004). Countries in the Middle East and North Africa are classified by as having absolute water scarcity. By 2025 Pakistan, South Africa, parts of China, Australia, India, Mexico and United States and the

Mediterranean would be added to the list (Lazarova and Asano, 2005; Jimenez and Asano, 2008). South Africa is lagging behind with wastewater reclamation and reuse compared to most of the countries expected to have an increase in water scarcity by 2025.

2.3 Worldwide reuse by region and country

In Europe, most of the reuse schemes are located in highly urbanized coastal areas and islands of the semi-arid Mediterranean (EUWI, 2007; FAO, 2010). The Mediterranean in Southern Europe uses 44% of treated wastewater for agricultural irrigation and 37% for recreational or eco-management. In contrast the temperate Northern Europe uses 51% for eco-management and 31% for industrial purposes in predominantly urban areas (Bixio *et al.*, 2006; USEPA, 2012). Water scarcity is a common constraint in the southern areas with varying precipitation sometimes lower than 300-500 mm per year in southern parts of Spain, Greece, Italy, Malta and Israel (FAO, 2010). These are also the prevailing rainfall conditions in southern Gauteng area under study in semi-arid South Africa as it will be evident from the conclusions of this study.

Israel which was the pioneer of wastewater reuse especially for agricultural purposes collects 92% of wastewater through municipal sewers (Angelakis *et al.*, 1999). A water crisis in this country and low cost of wastewater reuse result in 83% of the wastewater collected to be used for irrigation and groundwater recharge (EUWI, 2007). Israel comparatively treats about 40% of the total amount of reclaimed water used in the European Union in three main water reuse projects namely Dan region, Hakishon and Heifer Valley reclamation schemes (Bixio *et al.*, 2006). Reclaimed water is generated largely in urban areas in Israel and transported to agricultural areas such as the Dan region reclamation plant serving a population of 1.7million including Tel Aviv (Rosenblum, 2005). The Dan region project is the largest water reclamation scheme in Israel in operation since 1977, where 140 Mm^3/yr of domestic and industrial wastewater, is treated for unrestricted agricultural irrigation (Bixio *et al.*, 2006; Asano and Bahri, 2011).

In the United States, California, Florida, Arizona and Texas reuse wastewater effluent in agriculture and ground water recharge in water stressed arid and semi-arid areas to alleviate the impact of rapid growth and urbanization (Sato *et al.*, 2013). Three of the states namely California, Arizona and Texas are in the arid southwest and they have water supply challenges due to variable weather and population growth. Florida, on the other hand, originally launched its reuse program to address nutrient pollution in its lakes, streams and estuaries (NRC, 2012).

California in the United States, is the most populous state estimated at 35.9million (2004 population statistics) and two thirds of the population live in semi-arid and desert conditions (Asano *et al.*, 2007). In this state indirect reuse is achieved through aquifer recharge by percolating storm water from streams, imported water or reclaimed water into aquifers and water reclamation has been practiced in California since 1890 for agriculture (Asano *et al*. 2007; Huertas *et al.*, 2008). California and Florida have comparable extents of groundwater recharge but agricultural irrigation makes up a larger percentage of reuse in California compared to Florida (NRC, 2012). In the Irvine Ranch Water District of California reclaimed water makes up 20% of water supply through a separate distribution system with 394 km of pipeline, 8 reservoirs and 12 pumping stations. The reclaimed water is used for landscape irrigation, agricultural irrigation of all crops grown in the area, industrial uses and toilet flushing in dual plumbed buildings (Asano and Bahri, 2011).

Australia with a population of 20million mainly living in urban centres has an average annual rainfall of 455 mm with less than 200 mm in central Australia and is one of the driest countries on earth (Anderson *et al.*, 2008). The northern territory is the only area in Australia not experiencing water shortages and droughts compared to the South-East, South and Western Australia (Dolnicar *et al.*, 2012). In Australia's Murray Darling River basin which provides 50% of the country's use, agriculture uses approximately 70-80% of river flows and 30% is for environmental needs. As a result of this demand in recent years no water from this River has made it to the sea (Anderson *et al.*, 2008; WEF, 2009). This clearly shows a deficit in available water resources which necessitates wastewater reclamation in this country. Australia has wastewater reclamation in regional schemes, new urban developments, agricultural irrigation and industrial recycling (Table 2.2).

Table 2.2: Australian reuse schemes (Adapted from: Anderson, 2008; Apostolidis *et al.*, 2011)

Reclamation scheme	Capacity (ML/day)	Treatment train	Reclamation use
Western Corridor Recycled Water Project, *Brisbane*	180	MF-RO-AOP-Cl_2	Industrial, IPR
Eastern Treatment Plant Water Recycling Scheme, *Melborne*	750	O_3 –BAC-UV- Cl_2	Agricultural, recreational facilities
Rouse Hill, *Sidney*	9	O_3 –MF- Cl_2	Non-potable domestic
Sidney Olympic Park, *Sidney*	5	MF-RO	Non-potable domestic
Pimpama Coomera, *Gold Coast*		Secondary	Rooiwal power station
Caboolture Water Reclamation Scheme, *Caboolture*	10	*MBBR- O_3-C/F-DAF- O_3-BAC- O_3	Industrial, Non-potable domestic, recreational, IPR
Western Treatment Scheme, *Melbourne*	493	Lagoons	Agricultural, Conservation
Lower Molonglo Scheme, *Canberra*	140	Tertiary	Agriculture
Luggage Point Industrial Reuse Scheme, *Brisbane*	10	MF-RO	Boiler feed
Kwinana Industrial Recycling Plant, *Perth*	16	MF-RO	Industrial
Illawara Recycled Water Scheme Stage 1, *Illawara*	20	MF-RO	Steel making
St Mary's Replacement Flows Scheme, *Sidney*	50	UF-RO	IPR

*MBBR= Moving bed biofilm reactor, C/F = Coagulation/flocculation, Cl_2 = Chlorination

The Western Corridor Recycled Water Project is one of the largest water reuse projects in the world using treated wastewater from six WWTPs located throughout Brisbane and Ipswich (Swartz *et al*., 2014). Australia reuses wastewater for industrial and landscape purposes and the cities of Canberra, Perth and Brisbane have considered direct potable reuse schemes (GAA, 2012).

Singapore is a small island city state with a population of 4.5million in an area of 680 km^2 with mean annual rainfall of 2.4 m of which 1.17-1.27 m is lost through evapotranspiration and infiltration among others. It depends on four sources of water supply namely local catchment which formed 60% of the land area in 2011, imported water from Malaysia, reclaimed and desalination water (Seah *et al.*, 2008; Yang *et al*. 2013). As a result of its frequent rains, limited area and high population density there is little irrigation water demand for Singapore. Instead its reuse programs concentrate on industrial and potable water demand (NRC, 2012). Singapore's public utilities board (PUB) has branded reclaimed water as "NEWater" and its four plants producing this water meet 30% of the nation's potable and non-potable water needs. Treated wastewater on a yearly average of 30-40 ML/day and during dry periods 110 ML/day is used to replenish surface water reservoir before drinking water treatment (ATSE, 2013). This reclaimed water in surface reservoirs is blended with capture rainwater and imported raw water or transferred directly to industry for non-potable reuses. Singapore and Australia's Canberra and Brisbane, because of their geology and geography, do not apply aquifer recharge and recovery (NRC, 2012). This illustrates the importance of local conditions in first opting for reuse, then treatment options, storage and transfer guided by context which would also be important for South Africa, specifically the Sedibeng district investigated should reuse be applied.

Japan, with a mean annual precipitation (MAP) of 1714 mm, hundreds of Dams and reservoirs, has not escaped from frequent and severe droughts occurring in several parts of the country. Rapid economic growth and high population density have necessitated development of new water resources such as wastewater reclamation and reuse in major cities (Ogoshi *et al*. 2001). Japan uses one third of recycled water for urban purposes especially toilet flushing, initially the country's reuse program required all new buildings to have on site reclamation plants (Rosenblum, 2005). In-building water recycling installations accounted for 56% of 228 000 m^3/d recycled water produced in 1991, where 61% was used for toilet flushing, 23% for irrigation, 15% for air conditioning and 1% for cleaning purposes (Lazarova and Asano, 2005). In 1997, 1475 on-site individual and block-wide water reclamation and reuse systems provided toilet flushing and landscape water in commercial buildings and apartment complexes (Ogoshi *et al*., 2001). It was determined later though, that municipal reclamation plants were more cost effective compared to individual reclamation facilities (Rosenblum, 2005).

China has a majority of their water resources concentrated in the South leaving the northern and western parts of China in perpetual droughts. To supply the water scares areas the Chinese government has opted for long distance inter-basin transfers as the reuse of wastewater is not readily accepted. Beijing, an 18million plus people megacity, and Tianjin, the second largest, are two northern cities located in a water deficient region which pioneered reclamation of water in the country (Yi *et al.*, 2011). Wastewater reclamation is decentralized at a level of house or commercial building where examples include the Olympic park, Beijing International Airport and Beijing economic technological development area, totaling 45 000 m^3/day (OECD, 2009).

In a study of 181 countries probing generation, treatment and use of wastewater only 62 or 34% had data on reuse, 37% of the data could be categorized as recent (2009-2012) and this data may not reflect the current status. In Sub-Saharan Africa only South Africa, Senegal and Seychelles have complete information on generation, treatment and use of wastewater. High income countries on average treat 70% of generated wastewater and lower income countries treat 8% of their generated wastewater. This disparity results in less data and information generated and available for research and benchmarking. This is compounded by some countries hiding or distorting some information to protect tourism, agricultural produce markets and the reality of water scarcity (Sato *et al.*, 2013).

South Africa has climatic similarities to Australia, Israel, Namibia and the United States and has developmental state characteristics of China and India with high income gaps and high economic growth forecasts. It can learn from leaders of water use and reuse efficiency such as Namibia, Singapore and Israel and advanced environmental policies and legislation such as Australia and the United States (van Niekerk and Schneider, 2013).

2.4 Types of reuse applications

2.4.1 Potable reuse

Direct potable reuse (DPR) and indirect potable reuse (IPR) are distinguished by nonexistence and existence respectively of an environmental buffer which can provide the following (Crook, 2010; NRC, 2012; ATSE, 2013):

- Time for mixing and dilution
- Additional treatment of pathogens and chemical contaminants by natural physical, chemical and biological processes
- Provide “time of response” or “corrective action” to potential water treatment incidents to improve water quality to comply
- Improvement of public perception to wastewater reuse especially for potable purposes

Unplanned IPR or “de facto” reuse is common worldwide and in South Africa for example it is common practice that a treated wastewater stream is discharged into a water body (e.g. river system). Downstream of the point of discharge the water is then abstracted as source water for the treatment to potable use quality (DWA, 2013a). In the US DPR is not common practice and the majority of projects are IPR (Crook, 2010; ATSE, 2013). However the following lists of projects made some inroads in the application of DPR in the US (Tchobanoglous *et al.*, 2011):

- Pure cycle corporation, Colorado (1976-1982)
- Denver potable reuse demonstration project (1985-1992)
- Village of Cloudcroft, New Mexico
- Big Springs, Texas
- Orange County water district Groundwater replenishing scheme (GWRS), California

A majority of reclamation projects are IPR, however, there are four municipal DPR projects operating worldwide namely in Windhoek (Namibia), Beaufort West (South Africa), Cloudcroft NM and Big Springs Texas in the US (ATSE, 2013; UKWIR, 2014). However for the latter project there is blending and a detention period of 40-60 days of treated wastewater and natural water in a covered reservoir which does not have attributes of an environmental buffer (NRC; 2012). Nonetheless, this has allowed health authorities to define the latter as “Indirect Potable Reuse” (Tchobanoglous, 2011; ATSE, 2013).

Windhoek, Namibia was the first city to implement long term DPR without the use of an environmental buffer (USEPA, 2012). It’s Goreangab Water Reclamation Plant (WRP) (Figure 2.5) with current capacity of 21 000 m^3/d has been practicing DPR since 1968, provides 35% of the potable water needs of Windhoek with a population of approximately 250 000 (du Pisani, 2006).

Figure 2.5: The Goreangab Water reclamation plant (Wingoc, 2014)

The research that culminated in the establishment of the Goreangab WRP in Namibia was, conducted by the Council for Scientific and Industrial Research (CSIR) in South

Africa in the 1960s, funded by the Water Research Commission (WRC). The objective of the research was to develop technology such as the multi barrier system for demonstration plants in Pretoria, Cape Town and Port Elizabeth city councils and to promote public acceptance of direct reuse (Schutte, 2008). The only instance of DPR of treated effluent in South Africa currently, is the Beaufort West WRP in the Western Cape (GAA, 2012). DPR of wastewater is practiced in this Karoo town after a recent drought forced the Beaufort West Wastewater reclamation plant designed for 2.1 ML/day to treat water to a potable standard (ATSE, 2013). The municipality has two sources of water, surface runoff captured in the Gamka and Springfontein Dam and borehole water that dried up during the drought. The reclaimed water forms 20% of the town's water in a mixing ratio of 1:4 which can be increased to 25% (Marais and Durckheim, 2012).

2.4.2 Agriculture reuse

Irrigation for agricultural and nonresidential landscape application accounted for 65% of total global water withdrawal for human use (Asano *et al*., 2007). This is the most significant use of the water resources worldwide, in times and regions of water scarcity farmers would turn to domestic or urban wastewater as an alternative (FAO, 2010). Increasing water productivity from wastewater reclamation for irrigation by reducing the demand of potable water is an urgent need. This is especially so in regions with high water vulnerability to preserve water of high quality for drinking water supplies (Asano *et al*., 2007). Agricultural irrigation represents the largest current use of wastewater reclamation and offers significant future opportunities in both industrialized and developing countries (Tassoula, 2011). It is the oldest and most widespread reuse with treated or untreated wastewater effluent, usually of a municipal but also industrial source, and used to grow food, energy and any other industrial crops (Jimenez-Cisneros, 2014).

Wastewater is often a year round reliable source of water and sometimes the only source for agriculture in arid and semi-arid climates and its value has long been recognized by farmers. It contains nutrients necessary for plant growth that can be recycled to reduce downstream health and environmental impact (WHO, 2006). The possibility of selling agricultural produce where the wastewater is produced is an additional benefit that saves transport costs (Jimenez-Cisneros, 2014). The benefits in total with wastewater reclamation for irrigation in agriculture are saving on pumping costs, fertilizers and scarce fresh water resources and result in an increase in income (Norton-Brandao *et al.*, 2013). Secondary treatment typically involving nutrient removal is characteristic of restricted agricultural reuse involving food crops not consumed uncooked (Bixio *et al*., 2005). This is one way of classifying agricultural reuse but may also involve direct reuse by application after treatment, or as is, or intermittent use over short or long term, dilution and blending with surface water (Jimenez-Cisneros, 2014).

Historically South Africa's use of treated effluent for irrigation has been steered towards irrigation of recreational facilities and non-food related plant production (Jagals and Steyn, 2002). This is because unlike other countries, South Africa does not allow disposal of partially or treated effluent by means of irrigation, instead this effluent must be returned to the source from where it was abstracted (Schutte, 2008). This is termed a controlled activity according to the National Water Act 36 of 1998 Section 37(1) and (2) and permission must be sought. This applies to irrigating land with wastewater from a waterworks or industry and intentionally recharging a ground water aquifer with waste or water containing waste (DWAF, 1998). However, in 1978, the Department of Health and Population Development issued a guide to permissible utilization and disposal of treated sewage effluent of domestic origin. This guide divided on primary, secondary and tertiary treatment levels excluded vegetables and crops consumed raw by man and permitted use for industry such as dust control and ore treatment (DHPD, 1978).

Irrigation of sports fields, golf courses, parks and other recreational facilities is an exception especially in the city of Cape Town where 20 ML/day reclaimed from the Potsdam WWTP is for this agricultural use (CCT, 2006; Schutte, 2008). The Gold Fields Driefontein mine located 70 km South West of Johannesburg, contains four WWTPs that treats approximately 10 ML/d of wastewater, where 10% of this effluent is used for toilet flushing and landscape irrigation, among others (Ilemobade *et al.*, 2009). In

Polokwane, SAB Miller's manufacturing plant treats its waste water and uses the effluent for irrigation of adjacent apple orchards (DWA, 2011).

2.4.3 Industrial reuse

Industrial reuse is different from potable and agricultural use since it involves the private sector which is driven by economic forces and has well defined needs and standards. Internal recycling in industrial reuse occurs first, because the gains are immediate. Reuse or reclamation is the second option because it requires investment and negotiation between different parties (Jimenez and Asano, 2008). Some of the negotiations on investment on reuse must include installation of transmission systems from WRP to site of reuse, which might deter industry from reclamation (Asano *et al.*, 2007).

Industrial reuse is varied from, among others, cooling towers in power plants, boiler water semiconductor industry, to textiles, extraction of fossil fuels and food processing (de Koning *et al.*, 2008; USEPA, 2012). Cooling is the most widely applied reuse option in industrial reuse, because of its high water demand, relatively low water quality requirement and application in different industries (Jimenez and Asano, 2008). Industries requiring higher quality water include electronics and fine paper making. The type of industrial reuse that recycled water can be used for are (UKWIR, 2014):

- Material washing and process rinse water
- Crate, pallet, hardstand and car washing
- Industrial fire protection
- pH adjustment
- Boiler or cooling tower water

In the semiconductor industry, which has recently involved wastewater reuse, the use is mainly in rinse operation during circuit board manufacturing which requires ultrapure water (de Koning *et al.*, 2008; USEPA, 2012). The textiles industry is a fragmented and heterogeneous industrial sector dominated by small to medium enterprises (SMMEs) characterized by discharge of organic chemicals and colouring agents with low biodegradability and high salinity. This industry is also one of the greater water consumers even though water reuse in processes such as dyeing, bleaching, printing and washing is largely an uncommon practice (Vajnhandl and Vahl, 2014).

Table 2.3: South African industrial reuse (Adapted from: DWA, 2013a)

Source of reclaimed water			**Reclaimed water user**	
WSA /Municipality	**Facility**	**Level of treatment**	**Institution**	**Category of use**
City of Cape Town	Potsdam WWTP	Tertiary	Chevron Refinery	Process water
City of JHB	Northern WWTP	Secondary	Kelvin power station	Cooling water
Rustenburg	Rustenburg WWTP	Secondary	Platinum mines	Process water
City of Tshwane	Rooiwal WWTP	Secondary	Rooiwal power station	Cooling water
eThekwini	Southern WWTP	Tertiary	Mondi paper	Cooling water
Metsimaholo	SASOL 1	Secondary	Sasol, Sasolburg	Process water
eMalahleni	eMalahleni WRP	Advanced	eMalahleni	Potable use
Steve Tshwete	Optimum WRP	Advanced	Steve Tshwete	Process and potable use
Steve Tshwete	Boskrans WWTP	Secondary	Kanhym feed lots	Agro industry
Polokwane	Pietersburg WWTP	Secondary	Platinum mines	Process water

There are two types of industrial reuses in South Africa namely 1) municipal wastewater reclamation even though limited and 2) internal reuse or recycling with or without treatment. The latter is for reducing intake water and to eliminate problems related to discharge standards (Schutte, 2008). Industrial reuse of water is already practiced (Table 2.3) by water intensive industries and the extent and type of application is industry and process specific. Water intensive industries include power generation, pulp and paper manufacturing, textiles, food processing, ore extraction, chemical manufacturing and oil refineries (Asano *et al.*, 2007).

The type of industrial use is organized according to quality of water required ranging from steam generation, wash water, food processing to final product rinsing and make-up requiring high quality water. Processes requiring moderate water quality are cooling, refrigeration, general washing and rinsing. Processes requiring low water quality are raw material hydraulic transporting, ore washing and milling, dust control and mineral processing (DWA, 2013a).

2.4.3.1 Power generation

Energy resources production goes hand in hand with increasing urbanization and water is always required whether it be energy in nuclear, fossil fuels, waste to energy, hydropower, solar or wind (Levine and Asano, 2004). Water is used in coal fired power stations as ultrapure water in boilers and softened water for cooling, for dust suppression, ash conveyance and handling (SACRM, 2011). Power generation accounts for a sizeable proportion of water use in South Africa (Figure 2.6) and therefore municipal wastewater reclamation and reuse can reduce this demand to release water for other high quality uses.

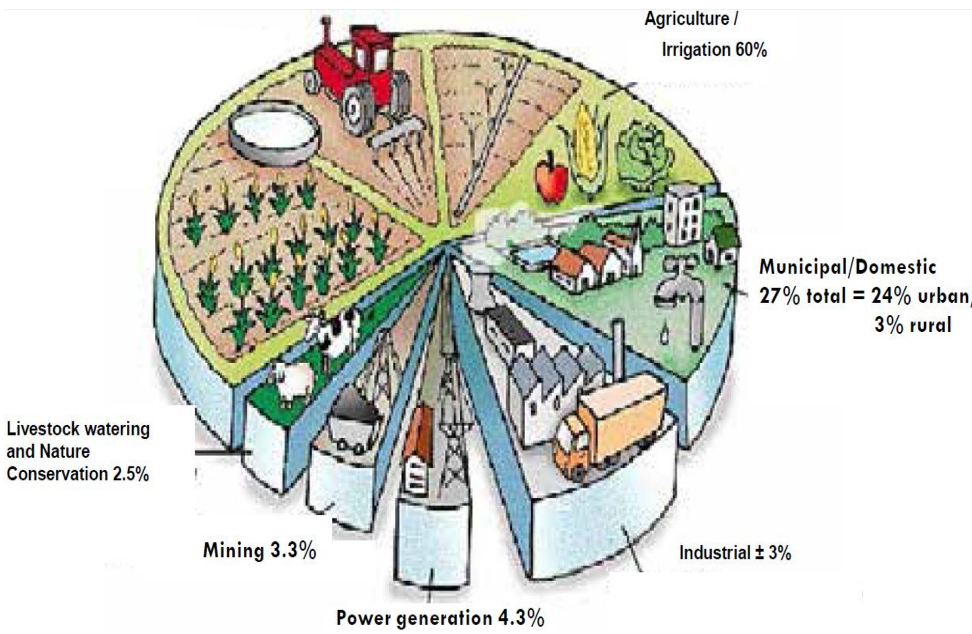

Figure 2.6: Water allocation proportion in South Africa (DWA, 2013b)

There are two approaches to cooling water namely once through cooling water, that takes cool water through the system once, absorbs process heat and transfer the heat through evaporation. The second approach is recirculating evaporative cooling where water goes through the system more than once. In this system cooling water is re-circulated, make up water is required to replace water lost through evaporation and at some point the water must be replaced to prevent dissolved solids build-up (CSIRO, 2008; USEPA, 2012).

All Eskom power plants are on Zero liquid effluent discharge (ZLED) policy, meaning that no polluted water is allowed to leave the site and the only way water leaves the site is through evaporation in the cooling towers (van Zyl and Premlall, 2005). The cooling towers account for approximately 97% of Eskom power generation water usage and ZLED adopted in 1987 advocates cascading water usage from high quality to low quality (Pather, 2004). Cooling water is not the highest quality user especially if used as once through and therefore this can allow for recycling even reclamation and reuse (DWAF, 1996). In addition to the Eskom power stations in South Africa there are five power stations operated by municipalities or private public partnerships (PPP) and three of these are using reclaimed wastewater for their cooling towers. These are, the Rooiwal and Pretoria West power stations operated by city of Tshwane and the Kelvin power station operated by a private conglomerate (AES Sirocco and Global African Power)(van Zyl and Premlall, 2005).

The Northern WWTP-Kelvin power station partnership, which incorporates treated municipal wastewater in power generation to reduce demand, can be used as model for the Sedibeng district WWTPs-Lethabo power station partnership. This WWTP has a capacity of 400 ML/d and treats mainly domestic sewage of Johannesburg's (South Africa) northern areas of Alexandra, Sandton and Randburg and eastern areas of Bedfordview, portions of Edenvale and Germiston. The WWTP supplies 30 ML/d of treated effluent to the Kelvin power station to be used as cooling water (Johannesburg Water, 2014).

The Rooiwal power station receives 7.7million m^3/annum or approximately 21 ML/d from the Rooiwal WWTP and the Pretoria West power station receives approximately 16.4 ML/d of treated effluent from the Daspoort WWTP (Oelofse *et al*. 2012). The latter

WWTP has been supplying the Pretoria West power station since 1952 initially at 12 ML/d and this demonstrates an institutional capacity that can be transferred to other power stations (van Vuuren, 2011).

2.4.3.2 Petrochemical industry

Petroleum refining involves separating and/or transforming components of crude and waste oil feedstock into a range of products. The largest water users in refineries are boilers followed by cooling circuits which together account for over 80% of use. South African refineries do not practice once through cooling compared to their overseas counterparts, this could further reduce potable water demand if they also reclaimed municipal treated effluent (Pearce and Whyte, 2005).

Sasol, a large petroleum and chemical manufacturing company, uses vast amounts of water and has instituted a complex system that employs wastewater reuse and recycling. Its Sasol One plant treats a variety of its industrial wastewater streams and adjacent Sasolburg in Metsimaholo's municipal wastewater with trickling filter technology (Schutte, 2008).

2.4.3.3 Steel making

Metal processing occurs at two levels namely, at a large scale in steel making involving processing and forming and at a small specialty fabrication scale such as in the car parts and metal sheeting industry (CSIRO, 2008). In steel making, steel is an alloy of iron and carbon and the iron exists primarily as an oxide in the earth's crust (Munnik, 2012). This iron ore and carbon primarily in a coke form are heated in blast furnaces in integrated steel mills to convert iron ore into molten or pig iron which is converted into refined steel together with scrap metal in a basic oxygen furnace (BOF). The steel scrap metal, which can constitute up to 30% of refined steel, is sorted to remove non-iron bearing materials and melted in an electric arc furnace (USEPA, 2008). Steel making is energy intensive, requires a lot of raw materials and generates solid, air and water wastes in some of its processes such as coking, furnace blasting, fluxing, sintering and pickling (Munnik, 2012). Wastewater is generated in direct and indirect cooling, gas cleaning, pickling, washing and rinsing operations and runoff from raw material stockpiling (IISI, 2002).

Water use in the metal industry is for material conditioning, dust control and the largest extent is heat exchange (cooling) (CSIRO, 2008). The latter can be in indirect open or closed circuit cooling where water is not in contact with products such as in cooling furnaces and casting machines or in direct open circuit, where water is in contact with products (Panagopoulou *et al.*, 2011). Municipal wastewater can be used in the steel making industry as one of the options to reduce demand (Figure 2.7).

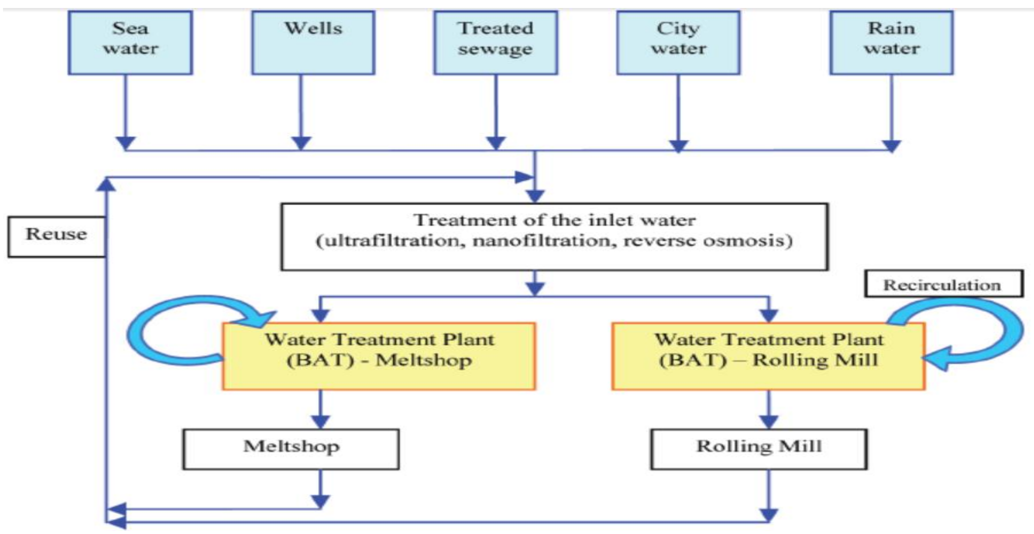

Figure 2.7: Water management in steel industry (Panagopoulou *et al.*, 2011)

BlueScope Steel's Port Kembla Steelworks in Wollongong Australia as, an example, uses reclaimed water from Wollongong WWTP 3km away after under tertiary treatment of microfiltration, reverse osmosis and breakpoint chlorination. The main use of the reclaimed water where specific criteria are set for chlorides, ammonia, hardness and pH is in the following (Figure 2.8):

- Heat removal, cooling of hot coke, metal cooling and cooling towers
- Process use in steam generation for heating purposes, cleaning and rinsing
- Dust suppression, road and truck washing

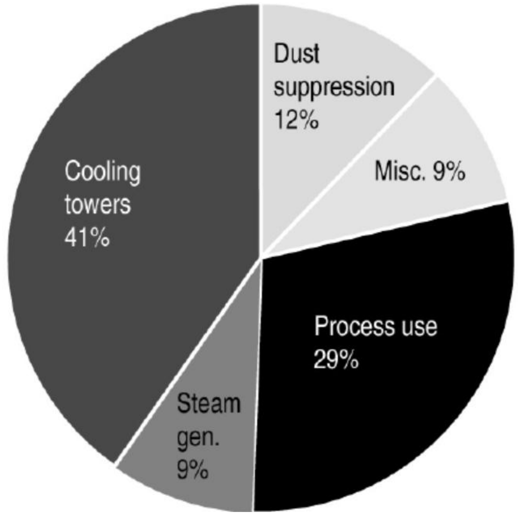

Figure 2.8: Port Kembla steel works water use breakdown (Hird, 2006)

The effect of reclaimed water quality on cooling systems and other industrial processes will depend on materials used in the infrastructure and water quality consideration for processes and final products. This will depend on how heat exchangers, pipework and cooling towers, made generally of carbon steel, copper and copper alloys in cooling systems, reacts with reclaimed water. Typical problems in cooling systems are corrosion caused by high TDS, ammonia and chlorides; scaling caused by calcium, magnesium and iron salts; corrosion inducing biological growth and foaming due to surfactants (CSIRO, 2008).

In the United States approximately 378 ML/d chlorinated wastewater effluent was used since 1942 at the Bethlehem Steel Company in Baltimore, United States for once through cooling systems, metal cooling and processing (USEPA, 2004; Exall *et al.*, 2008). Around the same time in 1941 there was an understanding that ISCOR's (now ArcelorMittal in the study area) Pretoria works would use sewage water when potable water is unavailable (Tempelhoff, 2003). ArcelorMittal, which could follow the US and Australian example on municipal water reuse, implemented a zero effluent discharge policy in 2005 as part of their water license (DWAF, 2006). This strategy which reduce water discharges and demand, expects no water to leave an industrial site except through evaporation. Hence water user industries have to install water treatment technology to recycle and reuse water and ArcelorMittal has introduced advanced treatment technology such reverse osmosis to treat effluent.

2.4.3.4 Paper and pulp industry

Paper and pulp manufacturing by its nature is water intensive even though municipal wastewater reuse is not usually practiced because of quality, instead internal recycling is preferred. It consumes up to 20 to 70 m^3 of water per ton of pulp produced and generates wastewater in pulp processing, bleaching and stock separation. Processes in the manufacture of low quality brown grade paper do not require high water quality and therefore provides an opportunity for water reclamation (Asano *et al.*, 2007).

The Durban Water Recycling Works (DWRW) is designed to treat 47.5 ML/d. The plant is situated in the grounds of the city's Southern Wastewater Treatment Works (SWTW) South of Durban South Africa, which is important for saving pumping costs. It treats predominantly domestic wastewater and 10% by volume and 20% by pollution industrial effluent to meet or exceed 77% of SANS 241:1999 Class 1 potable standard for Mondi's production of fine paper (Gisclon *et al.*, 2002). This is a good example of an effective PPP where two main customers, namely Mondi Paper Mill and Sapref owned by BP and Shell benefit by paying a lower tariff for the reclaimed water compared to potable water. The eThekwini municipality benefits by reducing 7% of its potable water demand through reclamation and reducing of 10% of its wastewater output.

The South African paper and pulp industry has been reusing municipal treated secondary effluent for years with no challenges and this experience can be emulated by other intensive water industries in the study area. This is especially with regards to tertiary treatment and troubleshooting and one of its oldest plants practicing municipal wastewater reclamation is closer to and its effluent discharged ends up in the study area's Vaal Barrage (Grobicki and Cohen, 1999). This is the SAPPI Enstra mill in Ekurhuleni municipality that receives approximately 17.2 ML/d potable water from Rand Water. It reduces its demand by reusing 15.7 ML/d treated municipal sewage effluent and discharges its effluent after use into the Vaal Barrage catchment via the

Blesbokspruit (DWAF, 2006). Less than half a dozen paper mills worldwide use treated wastewater and Sappi Enstra, as one of them, has been using treated municipal sewage effluent since the 1940s (USEPA, 2004).

2.4.3.5 Private-Public partnerships

Industrial reuse is the second option after internal recycling in South Africa and internationally because it requires greater investment needs, PPP and incentive rather than regulation (Jimenez and Asano, 2008; Schutte, 2008). Incentive based philosophies such as industries operated as ZLED facilities are useful since recycling and reusing wastewater to high quality, even suitable for sensitive use such as human consumption, is possible (DWA, 2013a).

Design criteria and treatment technology in terms of who is responsible for primary, secondary and tertiary treatment are also guided by the PPP in place. Usually the local authority will be responsible for the primary and secondary treatment, but if the user agency has total control of the water then it may modify these processes to meet its requirements (Odendaal, 1991). The 25 ML/day eMalahleni WRP, that uses a three stage high precipitate reverse osmosis process, is a multi-agency joint venture between BHP Billiton Coal South Africa (BECSA), the eMalahleni municipality and Anglo American. It supplies 16 ML/day water that meets SANS drinking water standards to the eMalahleni local municipality and the rest of the recycled water re-enters their processes. This is a good example of private-public partnership in water conservation and water demand management that reduces the potable water demand for eMalahleni (SACRM, 2011). This is an interesting project because it involves two competing mining companies jointly collaborating to solve environmental problems and serve communities in their area of operation (Schutte, 2008).

A second example in the private-public partnership also in the Mpumalanga Province, but in this case specific to the municipal wastewater reuse is the Steve Tshwete local municipality in the Nkangala district municipality (DWA, 2010). Municipal sewage effluent from the Boskrans WWTP in the local municipality's Middleburg cluster is reused by Kanhym feedlots, Middleburg ferrochrome and Columbus stainless steel industries (DWA, 2010; DWA, 2013a).

This and the others stated above are examples of integrated water resource management where economic, environmental and equitable aspects of use are integrated holistically. In the study area for example, the Suikerbosrand River catchment contributes substantial amounts of industrial effluent which presents treatment difficulties for downstream users which could further hamper reuse potential. Therefore if industries can have ZLED, such as the eMalahleni example, municipal effluent discharge quality and reuse potential can improve and potable water demand from municipalities to industry may be reduced.

2.5 Perceptions and acceptability of reuse

Economic, scientific and technical soundness do not always translate into support for water reclamation. Trust that lies in the core of understanding, support and acceptance of reuse as an alternative is also important (USEPA, 2012). The most important cornerstone in following the over 40years experience of water reclamation in Windhoek, Namibia is public acceptance and trust by consumers of the water quality (du Pisani, 2006). Perceptions are usually not formulated on a scientific basis, they are sometimes informed by belief and this makes it difficult for positivist scientific research as it is to inform implementation decisions.

The entrenched perceptions to aversion and avoidance of water reuse are illustrated by the example where reclaimed water is subjected to much more rigorous treatment, water quality control and management. It is then rejected for potable use by regulatory agencies and the public, based on perceptions with no scientific basis. Usually surface water is preferred based on the belief that it is clean and often times this is not true since the raw water source is not protected especially in developing countries (Asano and Cotruvo, 2004). In the eThekwini municipality (Durban, South Africa) survey about reclamation, to further illustrate, a respondent said people are willing to drink from untreated, contaminated well water that is considered “natural” rather than reuse water

(Wilson and Pfaff, 2008). This is clearly a psychological issue, which is the most difficult barrier for DPR to overcome in trying to emulate the Goreangab WRP (Namibia) example (du Pisani, 2006).

IPR or DPR raises more public concern because of real or perceived perceptions of aesthetics, long term health concern and the value of water reuse is weighed-in within the context of larger public issues of necessity and opportunity (Asano and Bahri, 2011). This is demonstrated in the reported studies of public attitude and perception to water reuse in the following scales (ATSE, 2013):

- Strong and widespread support for water reuse for recreational facilities irrigation
- Substantial acceptance for irrigation of dairy pastures and edible crops
- Waning support for reuse that involves personal contact such as swimming and bathing
- Lowest levels of support for reuse that involves ingested use such as drinking and cooking

Natural barrier systems that include aquifer recharge or reclaimed water reintroduction into the river, from a public outreach perspective, has been perceived as playing an important role for gaining public acceptance (NRC, 2012; USEPA, 2012).

Terminology, slogans and branding, among them terms such as “constituents of emerging concern”, “toilet to tap” and even “endocrine disruptors” can cause worry, apprehension and confusion in the public (USEPA, 2012). Many water reuse projects have adopted new terminology such as NEWater, processed water, purified water and eco-water to improve the image of reclamation in public (Swartz *et al*., 2014). Singapore produces “NEWater” with the most stringent guidelines for industrial use but finds it difficult to sell extra safe water even in bottled form for potable use (OECD, 2009). Public attitudes and understanding about reuse varies greatly by location and its dynamic therefore it is important to understand and stay current of stakeholder beliefs and attitudes (USEPA, 2012). The above mentioned dynamics are social science aspects of marketing, communication, culture, psychology and belief systems among others and therefore scientific and engineering paradigms alone would not lead to social acceptance of water reclamation.

Internationally research on public perceptions and communication of water reuse has been conducted mainly in Australia, because of the drought around the year 2000, that focused intellectual and policy attention on reuse (NRC, 2012). Australia is one of the countries that rejected potable reuse based on perceptions and extensive perception surveys have been conducted in the country. In a survey about reuse perceptions health concerns, taste and smell, possible contaminants that cannot be scientifically detected at present, were raised as concerns. Interesting enough is that Australians in a survey about reuse admitted lack of information to make informed decisions about wastewater reclamation and reuse. Respondents also stated that in cases where there is no water available such as worsening droughts, presented as a scenario in the survey, they will drink reclaimed water (Dolnicar and Hurlimann, 2009). A statement that says “Only in cases of no viable alternatives would it be possible to introduce DPR” can be seen as evidence of the state of public perceptions in some communities (Du Pisani, 2006).

In the South African survey example, public perceptions was the most intractable implementation barrier to wastewater reuse and this has caused several projects to be abandoned or shelved. This investigation on perception was around the eThekwini (Durban, South Africa) municipality implementation of wastewater for potable reuse and the following among others were noted (Wilson and Pfaff, 2008):

- Potable reuse in Durban is amenable to politicization especially aspects of allocative justice and equity
- There is no justification for rejection of potable reuse on religious grounds
- Concerns over technological, operation and maintenance capacity over time in relation to other experiences in the past such as power cuts and decay of municipal services can erode trust
- People are more comfortable with unplanned reuse rather than planned reuse
- They have not formed comprehensive opinions and entrenched positions.

* Tourism would be affected by the planned water reclamation and reuse scheme (GAA, 2012)

Continuous education involving taste, smell and touch of reclaimed water especially for scholars turned negative perception as much as there was no alternative in Beaufort West WRP's case (Marais and von Durckheim, 2012). On a positive note assessing the USEPA 2012 *Guidelines for Reuse* there is a sharp change in attitude towards DPR, which the public is most averse to, based on significant advances in the following (ATSE, 2013):

* Treatment technology
* Monitoring methodology in the past decade
* Health effects data from IPR projects
* Demonstration facilities of DPR

2.6 Risk associated with wastewater reclamation

The hazard and risk related to reclaimed water use is based on the presence of microbes and chemicals capable of causing harm to humans, animals and the environment (Salgot, 2008). In a clear risk assessment methodological analysis of human and environmental risk to reclaimed water, the following general steps should be involved (Huertas *et al*., 2008):

* Hazard identification
* Dose-response assessment
* Exposure assessment
* Risk characterization

Under hazard identification different sources of wastewater need to be identified with their physical, chemical and microbiological risks and applying risk control measures. These include source control, reclaimed water treatment and quality improvement, critical control point identification, exposure characterization, control and minimization.

Risk characterization, among others, will include risk estimation, quantitative assessment and communication (Chen *et al*., 2013).

The multi-barrier concept loosely equated with a “safety factor” is common in wastewater reuse and can be further interpreted as a risk management strategy. There are three types of barriers applied in wastewater reuse namely non-treatment barriers, treatment barriers and operational barriers which can be distinguished as follows (van der Merwe *et al.*, 2008; du Pisani and Menge, 2013):

- Non-treatment barriers: 1) Separation of industrial effluent from municipal effluent, 2) continuous monitoring of raw and treated water and 3) blending
- Treatment barriers: Measures implemented against specific contaminants such chlorination for bacteria and settling for aggregate parameters (Turbidity, TSS, etc.)
- Operational barriers: Treatment interventions that provide backup or standby for deteriorating quality

Windhoek, Namibia’s New Goreangab, Beaufort West, South Africa and Singapore’s four WRPs apply the multi-barrier safety approach (Seah *et al.*, 2008; van der Merwe *et al*., 2008; Marais and von Durckheim, 2012; du Pisani and Menge, 2013). One of the differences between Singapore and the Southern African examples is that the former uses IPR. Singapore considers transfer of reclaimed water into surface reservoir as an additional safety barrier that allows for natural attenuation or destruction of contaminants (Seah *et al.*, 2008). Preference previously of IPR system over DPR is said to be because real time quality control could not be provided and a number of unknown factors (Leverenz *et al.*, 2011). The epidemiological and toxicology health effects studies have been conducted in the past 30years on recycled water generated at IPR projects and direct potable reuse demonstration facilities. This is not satisfactory because the data is sparse and the inherent limited nature of these types of studies prevents extrapolation (Crook, 2010).

In all potable water supplies the control of pathogenic organisms is fundamental to the protection of public health and a significant initial concentration of pathogens can generally be assumed in reclaimed water (ATSE, 2013). Reclamation for drinking water is the highest level end use in terms of risk with the most stringent water quality requirements because of health and aesthetic concerns (Asano and Cotruvo, 2004). The authors note the irony of drinking water quality though, with an imperfect source with only filtration and disinfection regulated by only the WHO's Guidelines for drinking water quality that assume absence of known and unknown hazardous substances. This is unplanned or "de facto" indirect use where discharged treated wastewater effluent which is then diluted with surface water before being abstracted for potable use downstream (EUWI, 2007). Land use practice and the increasing proportion of treated wastewater discharged into fresh water resource for potable use, has resulted in many of the contaminants of concerns for public health in these sources (Asano *et al.*, 2007).

Sustainable agriculture, human health, soils and groundwater quality might be jeopardized by risks relating to treated effluent used for irrigation that contain, among others, dissolved solids, heavy metals and pesticides (Norton-Brandao *et al.*, 2013). The following concerns with regard to wastewater reclamation for agricultural use are noted (Huertas *et al*., 2008):

- Water quality should be sufficient to protect human health
- Soil, plant and groundwater of the local environment should be protected
- Salinity in most cases will be an important factor that needs monitoring and control
- Bioaccumulation of organic and inorganic contaminants in plants and soils
- Growth inhibition and other deleterious potential of certain chemical species such as boron, chlorides, sodium, potassium and selenium

Industrial use differs from potable and agricultural use in that it involves the private sector, therefore governments can only produce criteria instead of standards and this introduces a different type of risk. In general water parameters that are important for industrial water use are suspended solids, pH, conductivity, dissolved gases and hardness (Jimenez-Cisneros, 2014). Industrial reuse functional aspects related to risk are clogging, corrosion and sedimentation that have to be prevented and health aspects cannot be neglected such as spreading of micro-organisms from cooling towers (de Koning *et al*., 2008). In setting the South African guidelines for water use in industry, related to the latter mentioned functional aspects risk related to the fitness of use was also assessed in terms of the following norms or consideration (DWAF, 1996):

- Potential of water for causing damage to equipment in corrosion and abrasion
- Interferences in the manufacturing process such as causing precipitates and colour change
- Impairment of product quality for example taste and discolouration
- Complexity of waste handling as a result of using water of the quality available

2.7 Water reclamation quality parameters

The overriding operational reliability of the unit process or operation and overall treatment system capability, depends on ability of the system to meet wastewater reclamation quality criteria (Mujeriego and Asano, 1999). The latter with parameters such as EC, turbidity, DOC, phosphorous and nitrogen can give useful information depending on the intended final use of reclaimed water (Huertas *et al.*, 2008). Wastewater treatment consists of a combination of physical, chemical and biological processes to remove the following where water quality parameters can be used to assess efficiency (Mujeriego and Asano, 1999):

- Settle-able, suspended and dissolved solids
- Organic matter
- Metals
- Nutrients
- Pathogens

2.7.1 Aggregate parameters

The organic composition of raw wastewater which becomes part of the sewage stream ending in WWTPs in one way or the other includes the following (USEPA, 2012):

- Naturally occurring humic substances
- Faecal matter
- Kitchen waste

- Liquid detergents
- Oil and grease
- Consumer products
- Industrial waste

Aggregate constituent parameters such as TSS, TOC, COD and BOD are used to characterise the bulk of organic matter in wastewater treatment and reclamation. Aggregate parameters are important because some organic chemicals are not regulated and they are present at extremely low concentrations and might pose a health risk (USEPA, 2012). However, the specific chemical constituents of these parameters are not known thus adding to the risk of indirect potable reuse of waste water (Asano *et al.*, 2007).

Total Suspended Solids (TSS) are important to assess the extent of suspended organic matter in wastewater being reused (USEPA, 2012). Suspended solids include colloidal material, fine particles such as protozoan cysts and oocysts, bacteria and viruses, some, of which may manifest as turbidity (ATSE, 2013). The type and concentration of suspended matter controls turbidity of water which is determined by scattering and absorption of incident light by particles (Chapman, 1996). Organic matter is aesthetically unacceptable (colour and odour), provides a food source for microorganisms, adversely affect disinfection and consume oxygen. Many pathogens, such as viruses and protozoa, are particulate-related. Suspended particulates can shield UV disinfection that is why the TSS measured accounts for both organic and inorganic matter (ATSE, 2013).

Total Organic Carbon (TOC) is a measure of mass of material of organic residual in water and not necessarily an indicator of the abundance of chemical of concern (Huertas *et al.*, 2008). TOC can be subdivided into dissolved organic carbon (DOC) which is a portion of TOC that passes through a 0.45 µm pore size filter and particulate organic carbon (POC) which is a portion of TOC that is retained on the filter (USEPA, 2012). DOC in municipal wastewater comprises of natural organic matter (NOM) from drinking water, soluble microbial products from activated sludge and a large range of organic chemical contaminants including the following (ATSE, 2013):

- Industrial and domestic chemicals (e.g. pesticides, pharmaceutical and personal care products, surfactants, preservatives, flame retardants, perfluorochemicals and nanoparticles
- Chemicals excreted by humans (e.g. pharmaceutical residues and steroidal hormones)
- By-products of drinking water and wastewater treatment processes (e.g. disinfection by-products)

Existence of particulate matter means the microbiological water quality is unstable hence a measure such as biochemical oxygen demand (BOD) is important (USEPA, 2012). BOD a measure of the amount of biochemically degradable organic matter is defined as the amount of oxygen required by microorganisms present in a sample to oxidise the organic matter to a stable inorganic form (Chapman, 1996). A measure of BOD is thus also a measurement that can be used to assess the extent of suspended organic matter in wastewater being reused (USEPA, 2012).

It is generally accepted that fats are animal based, oils are vegetable based, greases are petroleum based and the acronym FOG is used to classify them (Buchana, 2014). FOG are listed as soap, oil or grease in the DWAF general and special authorization which is the compliance standard for incoming influent into the Mondi paper and Beaufort West WRPs (DWAF, 1999; Grobicki and Cohen, 1999; WWE, 2012). Surfactants or soaps, which are from industry, algal breakdown products, household cleaning agents and detergents, may cause fouling of membrane processes and foaming in cooling towers and boilers if not biodegradable (CSIRO, 2008).

2.7.2 Inorganic parameters

Inorganic constituents in water include metals, salts, oxy-halides and nutrients, among others, depending on the source of wastewater (NRC, 2012; USEPA, 2012). Generally aggregate parameters of inorganic constituents are total dissolved solids (TDS) and conductivity, even though their measurement may include contributions from organic constituents (NRC, 2012).

TDS, which causes salinity, is highly prevalent in semi-arid areas such as the western United States, Australia and South Africa. It is conservative in that it is difficult to reduce through treatment and therefore salinity loads persist in the environment (Grosskopf, 2004). Salinization in South Africa is mainly a result of industrial activities such as blow down water from cooling systems and mining activities producing underground mine water (Schutte, 2008). In domestic wastewater ions contributing to salinity include cationic species such as sodium, calcium, magnesium, potassium and anionic species such as bicarbonate, carbonate, chloride, fluoride and sulphate (Leverenz and Asano, 2011).

2.7.2.1 Metals and salts

Reclaimed water can introduce a suite of inorganic salts such as sodium chloride and trace elements including heavy metals (Wintgens *et al.*, 2005). Chloride ions are associated with sewage as a possible indication of faecal contamination (Chapman, 1996). Many ions present in reclaimed water are beneficial or harmless at low concentrations but at high concentration ions such as sodium, chloride and boron can cause ion toxicity (Asano *et al*., 2007). Alkalinity of reclaimed water as determined by carbonates, bicarbonates and hydroxyl content is a concern for boiler feed water in industry (USEPA, 2012).

Another important variable in water is pH, which is a measure of acid or alkaline nature of a solution and influences biological and chemical processes. Acidity and alkalinity are the base and acid neutralizing or buffering capacity respectively of water (Chapman, 1996). Typically, pH of reclaimed water ranges from 6.5-8.5 and may vary depending on the source of wastewater (Asano *et al*., 2007). Regularity and consistency of pH to a strict error of ± 1 pH value is required by the BlueScope Steel's Port Kembla Steelworks in Australia because of oil emulsion preparation in rolling operations.

2.7.2.2 Nutrients

Nutrients essential for plant growth are divided into two groups according to USEPA (2012) namely micro-nutrients and macro-nutrients which consist of primary and secondary macro-nutrients (USEPA, 2012). Reclaimed water consists of macronutrients beneficial for irrigation namely nitrogen, phosphorous and potassium (Table 2.4). The first two are mostly in abundance and the last one present in lower concentration but with less significance for plant growth (Asano *et al.*, 2007).

Table 2.4: Micro- and macro-nutrients of importance

Micronutrients	Primary macronutrients	Secondary macronutrients
Boron	Nitrogen	Calcium
Copper	Phosphorous	Magnesium
Iron	Potassium	Sulphur
Chloride		
Manganese		
Molybdenum		
Zinc		

There is a double advantage in using reclaimed water in that first the demand for water can be met and secondly the nitrogen (N) and phosphorous (P) demand beneficial for agricultural production in nutrient reuse can also be met (Norton-Brandao *et al.*, 2013). Nutrients are beneficial to agriculture up to a certain level depending on type of crops, soil and irrigation system but in excess may cause eutrophication in treated wastewater effluent and receiving waters (NRC, 2012).

Nitrogen exists in seven oxidation states or compounds but in water only in four forms namely ammonia, nitrite nitrogen, nitrate nitrogen and organic nitrogen. The latter consists of proteins as examples which have their origin in living material and together with ammonium nitrogen (NH_4OH and NH_3), which all have -3 oxidation state constitutes Total Kjeldahl Nitrogen (TKN). Total nitrogen is the sum of TKN, nitrate and nitrite nitrogen (Ergas and Aponte-Morales, 2014). The only inorganic phosphorous of concern in water are phosphates and their molecular dehydrated form polyphosphates, organically bound phosphates that are usually of minor consideration (Sawyer *et al.*, 2003).

Plants use nitrogen in the exchangeable and soluble form of ammonium (NH_4-N) and nitrate (NO_3-N). Organic nitrogen is not usable unless it's converted to these forms. Ammonium exists in wastewater after secondary treatment without nitrification and nitrates after the latter process (Asano *et al.*, 2007). The Vaal River system has been confirmed to have eutrophication as one of the major water quality issues and the source of nutrients are mainly from irrigation return flows, urban run-off, discharges from industry and municipal WWTP. The latter is due to many municipalities not performing according to specification in terms of nutrient removal and microbiological discharge quality due to poor operation, poor maintenance and management of the WWTPs (DWA, 2009).

2.7.3 Pathogens

Microorganisms or microbes are ubiquitous in nature and most are not pathogenic to humans. They are diverse and critical to nutrient recycling in ecosystems (USEPA, 2012). Microbial contaminants that are pathogenic can be bacterial, viral and protozoan and are by far the most common risk factor when producing reclaimed wastewater for human contact (Asano and Cotruvo, 2004; ATSE, 2013). The diversity and concentrations of pathogens in treated wastewater effluents is highly variable and dependent upon local specific factors. However the most significant human pathogens which are primarily enteric pathogens associated with waterborne diseases in sewage are the following (USEPA, 2012; ATSE, 2013):

- Bacteria (e.g. *Campylobacter*, *Shigella* and *Salmonella*)
- Viruses (e.g. rotoviruses, adenoviruses, noroviruses and Hepatitis)
- Protozoan parasite (*Cryptosporidium* and *Giardia*)

Bacteria are singled celled organisms characterized by a small size (0.2-10 µm), are the most common pathogens found in wastewater and they cause gastrointestinal infections such as diarrhoea, cholera, salmonellosis and dysentery. The most commonly used surrogate or indicator pathogens worldwide are faecal or total coliforms and *Escherichia* *coli* (*E. coli*) which is a member of the faecal bacteria (Paranychianakis *et al*., 2011). Most *E. coli* found in WWTP are non-pathogenic but reduction of their high number during wastewater treatment means the processes is effective (ATSE, 2013). Detection and quantification of *E. coli* is not sufficient to define the microbiological quality of effluent from the WWTP that will be reclaimed or discharge into the environment. This is because some pathogens such as *Giardia and Cryptosporidium* are more resistant to treatment compared to *E. coli* (Huertas *et al*., 2008).

Viruses are host specific obligate intracellular parasites that are small in size (0.01-0.03 µm), have a low infectious dose and are resistant to disinfection hence they require special attention in terms of monitoring and treatment (Asano *et al*., 2007; NRC, 2012). Both bacteria and viruses may be resistant to disinfection but more so for viruses that are resistant to free and combined chlorine. This is because of shielding from suspended matter and therefore removal of TSS and turbidity results in low risk of pathogens and health protection (CSIRO, 2008; NRC, 2012; ATSE, 2013). Pathogenic bacteria and viral indicators in chlorinated effluents of Gauteng's WWTPs have been observed. Rapid sand filtration to reduce turbidity and improve disinfection efficiency and UV disinfection has been recommended for these WWTPs (Dungeni *et al.*, 2010).

Protozoan parasites of the genera *Cryptosporidium* and *Giardia* infect the gastrointestinal tract of vertebrate animals including mammals, reptiles, birds, amphibians and fish. These protozoan parasites are small and infect the micro-villous region of the epithelial cells in the digestive and respiratory tract of their warm blooded vertebrate host and they need a host to be able to multiply (Figure 2.9). There are four main routes of transmission for pathogenic protozoa, namely human-human, animal-human, water and food (Medema *et al.*, 2006).

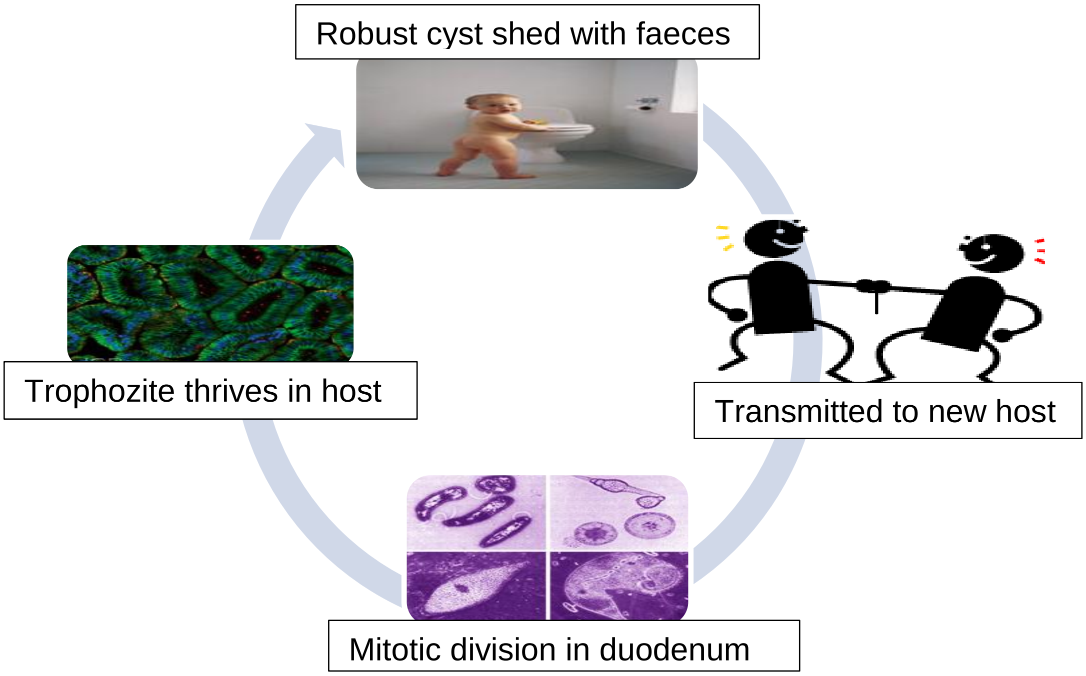

Figure 2.9: Life cycle of *Cryptosporidium* and *Giardia*

A relatively high incidence of *Cryptosporidium* and *Giardia* (C&G) oocysts and cysts in the raw sewage, indicated a potential for prevalence of giardiasis in the South African population with a possibility of high carrier rate. The highest numbers detected in rivers were due to broken sewers or run-off especially during rainfall and high temperature seasons (Bailey *et al.*, 2004). Numbers as high as 400 *Cryptosporidium* oocyts/10L for and as high as 1750 *Giardia* cysts/10L were detected in Gauteng wastewater treatment plant effluent (Dungeni and Momba, 2010; Sigudu *et al.*, 2014). Increasing population numbers, urbanization and overloaded wastewater treatment plants, are some of the reasons given for increased *Cryptosporidium* and *Giardia* counts and subsequent increased risk if mitigation measures are not followed (Sigudu *et al.*, 2014).

2.7.4 Applied reuse guidelines, standards and criteria

Regulations are legally adopted, enforceable and mandatory compared to guidelines which are advisory, voluntary and non-enforceable but can be incorporated in water use permits and become enforceable (Asano *et al.*, 2007; EUWI, 2007). Standards, criteria or guidelines become regulation when adopted by a regulatory body and the first two should not be used interchangeably. Standards usually infer numerical limits whereas criteria may refer to both a narrative statement and numerical limits (Asano *et al.*, 2007). Regulatory framework is an essential step for development and social acceptance of water reuse. The major factor in the choice of regulatory strategy is economic in terms of cost of treatment, monitoring as well as capacity to enforce regulations (Jimenez-Cisneros, 2014). These are some of the considerations that South Africa and the Sedibeng region, which is the focus of this study, have to consider before adopting of guidelines and regulations for water reclamation and reuse.

There are no universal regulations for water reuse because it covers different uses, it is a relatively new human practice and reuse has been developed to suit local conditions for local needs (Jimenez and Asano, 2008). Regulations and guidelines have only been established in countries where reclamation and reuse is well established and widespread, such as the USA and Australia, but also in Israel, Japan and China (UKWIR, 2014). WHO guidelines are universal and mainly orientated to the needs of developing countries compared to the overly strict guidelines such as the California Title 22 guidelines which may not be applicable (Paranychianakis *et al.*, 2011). Even though these were some of the first and some European Union and Mediterranean countries have adopted them for reclamation for irrigation they might be viewed as unachievable under prevailing socio-economic conditions in developing countries (EUWI, 2007).

In the United States there are no federal regulations governing water reclamation and reuse practice, only at state level are these regulations in existence (Asano *et al*., 2007; EUWI, 2007). The primary purpose of the USEPA guidelines is to summarize various water reuse guidelines and in states where guidelines do not exist or under revision, they can assist in developing reuse programs and appropriate criteria (Paranychianakis *et al.*, 2011). Existing South African standards and guidelines on water were not developed specifically to address water reclamation and reuse (Swartz *et al.*, 2014). International and South African regulation, standards and guidelines listed can be used in the interim whilst there is no specific legislation on wastewater reclamation and reuse (Table 2.5).

Table 2.5: Water quality guidelines in wastewater reclamation

Country	Legislation	Type of use
United Nations	WHO Guidelines 2011	Drinking water
United Nations	WHO Guidelines 2006	Agriculture
United States	California Title 17 and 22	Irrigation, Aquifer recharge
United States	USEPA Guidelines 2012	Potable, Agriculture and Industry
South Africa	Water quality guidelines	Domestic, Agriculture, Industry
South Africa	SANS 241:2015	Drinking Water
South Africa	General and Special 1999	Effluent discharge

Quality standards are a broad topic when it comes to irrigation based on water quality parameters, type of crops and irrigation system. Salinity, pathogenicity, nutrients and heavy metals are water quality parameters of concern with regard to regulation because they influence crop yields, soil properties and human health in irrigation with reclaimed water (Norton-Brandao *et al.*, 2013). Economic advantage and perceptions also influence guidelines for instance there are few or no microbial limits for irrigation with surface river water in developed USA and Europe but it does not mean there is no microbial counts. Quoting the UNEP/WHO survey that found that there is a mean faecal coliform count of 1000-10000/100ml in most of the European rivers and this does not justify a 2FC/100ml for reuse water compared to 1000 FC/100ml for surface water (Shuval, 2011).

In South Africa, standards and guidelines in existence were not specifically developed to deal with wastewater reuse even though mention of water reuse might be present. The National Water Act 36 of 1998 Section 22.2(e) states that a user must return seepage, runoff or water containing any waste emanating from that use to a water resource from which the water was taken from. This implies indirect reuse and in Section 26.1(i)(h) further implies reuse regulation through treatment to a certain standard before disposal (DWAF, 1998; Schutte, 2008).

South African Water Quality guidelines for different sector users, SANS 241:2015 drinking water standards, DWAF general and special discharge limits are some of the regulations and guidelines that can be used for water reuse (DWA, 2013a; Swartz *et al*., 2014). Due to the fact that direct potable reuse is worldwide not widely practiced specific water quality guidelines are not readily available. The Namibian Goreangab WRP that treats wastewater for potable reuse uses a combination of the Namibian guideline, USEPA, EU, WHO and Rand Water guidelines for potable use (du Pisani, 2006; Lahnsteiner and Lempert, 2007; du Pisani and Menge, 2013). The SANS 241 (2015) in part 2, states that final drinking water from water reclamation systems shall comply with SANS 241-1 numerical specifications, but in using the limits account shall be taken of the relatively high risk of microbiological contamination. The Durban and eMalahleni WRPs in South Africa use this standard for reclaimed water for potable and industrial use.

Agriculture has the most widespread reuse throughout the world, the oldest standards in existence and was the first reuse option recognized (Jimenez and Asano, 2008; Jimenez-Cisneros, 2014). In the European Union there are no regulations regarding irrigation with reclaimed water. Each country applies its own regulations and directives (Angelakis *et al.*, 1999). The following countries namely Cyprus, France, Israel, Italy, Jordan, Malta, Spain, Tunisia and Turkey in the Mediterranean basin have guidelines for wastewater reuse. They are mainly based on WHO guidelines and some Californian guidelines for irrigation and aquifer recharge (EUWI, 2007; Brissaud and Bahri, 2008). Cyprus for example has guidelines specific for its conditions that are stricter than WHO guidelines for agricultural reuse and way apart to the California philosophy (Angelakis *et al.*, 1999).

2.8. Treatment technology for reclamation

Treatment technologies for wastewater reclamation are for the most part derived from physical, chemical and biological processes used for municipal wastewater and drinking water (Levine and Asano, 2004). Wastewater can be effectively treated to any desired standard but the feasibility of different treatment trains is limited by, among others, the cost of technology, nature of influent wastewater and desired quality for intended use (UKWIR, 2014). Therefore treatment technology needed to meet specific quality objectives should guide the type of reuse option.

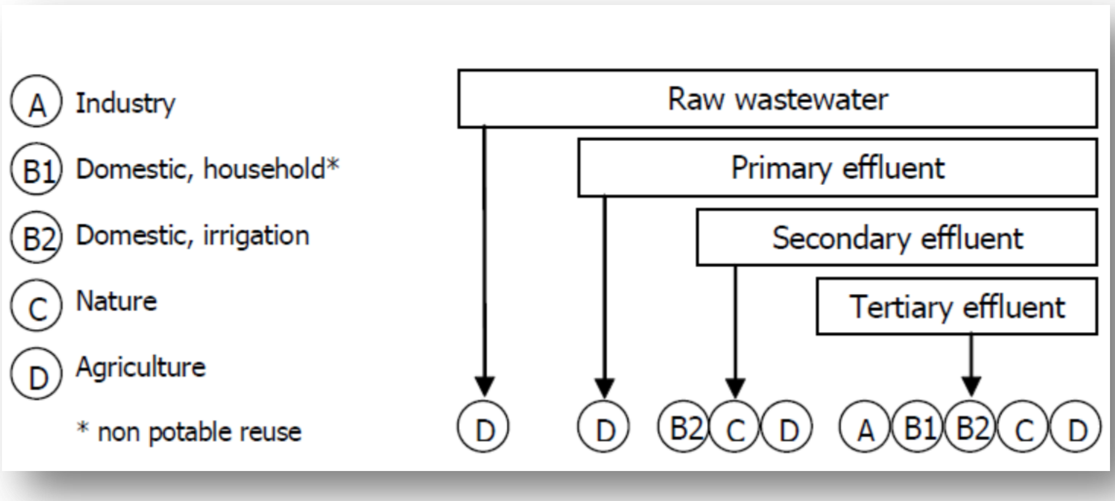

Figure 2.10: Reuse options and treatment levels (de Koning *et al.*, 2008)

Wastewater treatment applications where physical force dominates are unit operations and where contaminant removal is by chemical and biological reactions are termed unit processes. Unit operations are in preliminary and primary treatment, for instance, where gross solids such as rags, sticks, floatables, grit and grease are removed in preliminary and primary treatment removes floating and settleable material by sedimentation (Asano *et al*., 2007). Typical treatment technologies for water reclamation applied after secondary treatment, which mainly remove N and P through biological nutrient removal, are as follows (de Koning *et al.*, 2008; Leverenz and Asano, 2011):

- Dual media filtration (Activated carbon filtration)
- Microfiltration (MF) or ultrafiltration (UF)
- Reverse Osmosis (RO) or nano-filtration (NF)
- Advanced oxidation processes (AOPs)
- Small scale packaged membrane bioreactor (MBR)
- Soil aquifer treatment (SAT)

- Natural polishing step in wetlands
- Lagoon or pond systems followed by chlorination

The above treatment technologies are preceded by biological nutrient removal in secondary treatment and they are usually followed by disinfection through chlorination, UV or chlorine dioxide. Membrane technologies after secondary treatment for biological nutrient removal applied as MF/UF, then followed by RO, followed by advanced oxidation processes (AOP) is the norm in wastewater reclamation (Figure 2.11).

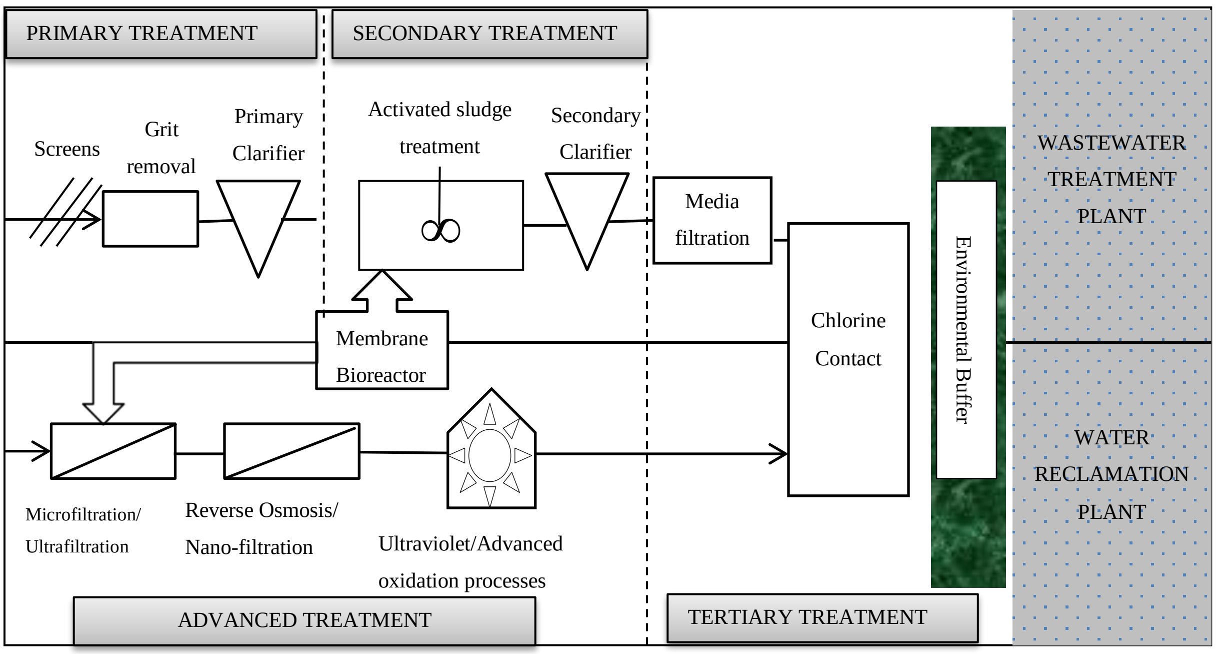

Figure 2.11: Wastewater reclamation treatment processes

Out of 24 operational reclamation plants listed by ATSE (2013) for potable reuse, after secondary treatment, six follow the MF/UF, RO and UV configuration and five follow the MF/UF, RO and UV/AOP with or without chlorination at the end depending on application (ATSE, 2013). Hence the literature review in this study focuses on membrane processes that represent physical filtration processes and advanced oxidation that represent chemical oxidation processes. An environmental buffer separates direct and indirect use in potable and agricultural reuse, hence tertiary natural treatment systems are represented by SAT and wetlands.

2.8.1. Membrane processes

Membrane filtration is defined as a pressure or vacuum driven separation process in which particulate matter larger than 1 µm is rejected by an engineered barrier primarily through a size exclusion mechanism (USEPA, 2005). Membrane technology had been previously limited to desalination and softening, but it is now increasingly been applied to wastewater reclamation. This is due to low cost associated with low pressure membranes that has proliferated the market and treatment trains involving membrane filtration gives the benefit of several reuse options (Leverenz and Asano, 2011). Membrane processes are regarded as a key element of any advanced wastewater reclamation scheme for worldwide reuse options including artificial recharge, potable reuse and industrial process water (Wintgens *et al*., 2005). Membrane processes or systems can be broadly divided into two broad categories based on contaminant removal capacity and size (Figure 2.12). They are basic non-dense systems which include microfiltration (MF) and ultrafiltration (UF) and dense systems which include nanofiltration (NF) and reverse osmosis (RO).

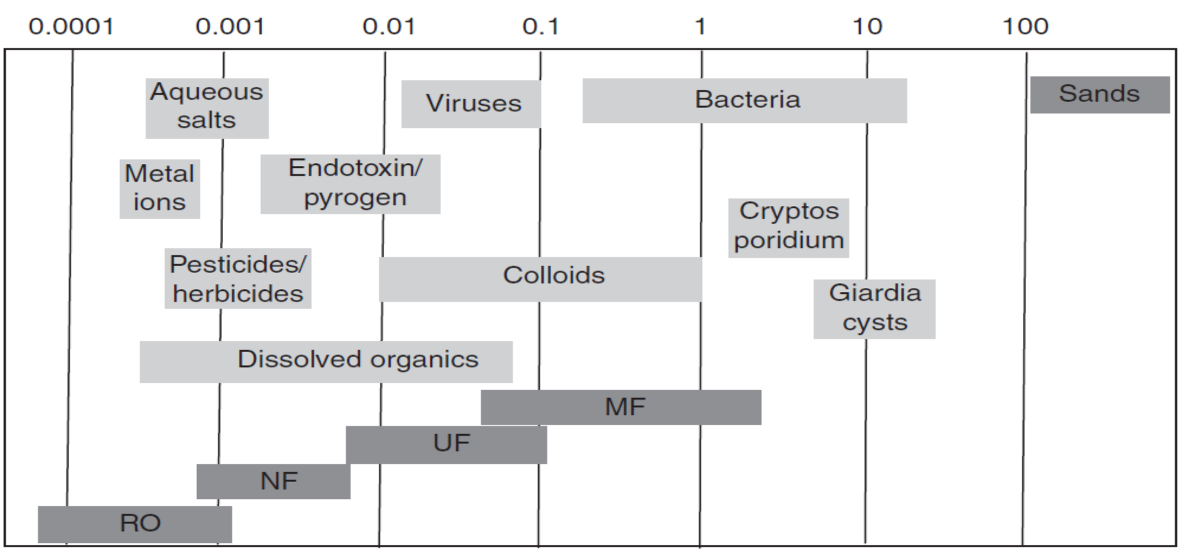

Figure 2.12: Membranes performance capability (Liu, 2014)

Microfiltration (MF) and ultrafiltration (UF), as the most basic membrane filtration systems (Figure 2.12), are pressure driven thin film polymer porous membranes that work primarily on size exclusion. The nominal mean pore size range is from 0.001 µm for the smallest ultrafiltration membrane to 0.4 µm for the largest microfiltration membrane (ATSE, 2013). MF and UF are the two processes commonly associated with the term “Membrane filtration” and they are characterized by removal of suspended and colloidal material (USEPA, 2005).

The difference between MF and UF is that MF can remove suspended solids and large micro-organisms such as bacteria and protozoa whereas UF can remove viruses and organic macromolecules of up to 20 nm. Although MF and UF can eliminate microbial contaminants it is not a complete barrier because of the following (Wintgens *et al*, 2005):

- membrane imperfections
- degradations of membrane by bacterial enzymes and other material
- Re-emergence of a small number of breakthrough bacteria that consume nutrients
- Inferior packaging of membrane modules or elements

Dense membrane processes include nano-filtration (NF) and reverse osmosis (RO), use physicochemical interactions to a greater extent than UF/MF to separate ions and remove dissolved solids (Wintgens *et al.*, 2005). Whereas MF and UF reject constituents based on size and are rated based on pore size and porosity. NF and RO are rated based on salt rejection and flow (Asano *et al.*, 2007). These latter processes are used often in applications that require removal of dissolved contaminants typically softening and desalination (USEPA, 2005). In RO a pump is used to force a liquid through a membrane leaving the salt behind whereas in natural osmosis, water moves towards the high salt concentration (ESKOM, 2013). The key difference between NF and RO is removal of monovalent ions where RO removes these ions at 98 to 99%, while removal in NF varies between 50 and 90% (Asano *et al.*, 2007). Treating wastewater for reclamation with RO and NF achieves 70-85% product water recoveries resulting in loss through brine concentrate that has to be disposed usually to the sea for coastal water reuse projects (NRC, 2012).

Reclaimed wastewater for unrestricted irrigation can be achieved by MF and UF since N and P are retained in the final permeate, conductivity and dissolved oxygen are unaffected by these membrane filtration techniques. UF and MF are employed as preferred processes for microbial retention and as pre-treatment for RO and NF that can generate drinking water quality (Wintgens *et al.*, 2005). Reverse osmosis is vital for removal of excessive nutrients but also removes required nutrients for plant growth and therefore requires optimization (Norton-Brandao *et al.*, 2013). Dissolved solids may include required nutrients for agricultural plant growth and therefore RO may not be required for irrigation, but may be necessary for potable reuse and some industrial purposes (Asano *et al.*, 2007).

Polymeric membranes are well established in the water industry compared to ceramic based membranes. However, they present challenges of membrane fouling as well as low stability against chemical and mechanical stress (Harman *et al.*, 2010; Liu *et al*., 2014). Membrane fouling, such as inorganic scale formation, chemical, organic and biological fouling, occur because of site-specific water quality and this is important for design considerations. This is because membrane fouling can affect pre-treatment needs, cleaning requirements, operating conditions and subsequently cost and performance (Asano *et al.*, 2007).

Ceramic membranes as an alternative, in contrast with polymeric membranes, are constructed from inorganic oxides such as zirconia, alumina and silica, and can be operated at pH 3-11. This allows for long term stability in terms of pH, temperature variability and chemical stress (Harman *et al.*, 2010). Although ceramics are considered non-traditional for MF/UF in terms of size, some manufacturers have experimented with stronger similar sized ceramic membranes (USEPA, 2005). The disadvantage of ceramic membranes, even if the gap is narrowing compared to polymeric membranes, are capital costs (Freeman and Shorney-Darby, 2011). The costs are ten times that of polymeric alternatives (Figure 2.13).

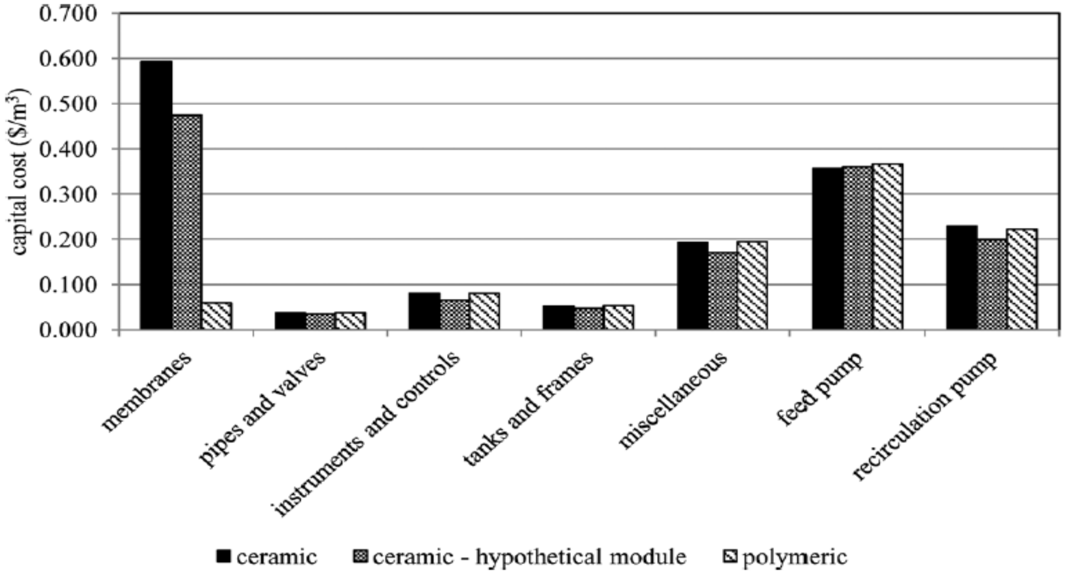

Figure 2.13: Capital costs of membranes (Guerra and Pellegrino, 2013)

The general decreasing cost in membrane technology is also noted in the South African context in that the energy cost for sea water reverse osmosis in kW.hr/m^3 water produced has decreased from the 1970 to currently (Table 2.6). The 2010 figure is compared to the energy cost incurred to deliver Thukela water from the Driel Barrage to Rand Water users in northern Gauteng. Reverse osmosis costs of brackish water and sewage treatment are even lower at 2 kW.hr/m^3 and 06-1.0 kW.hr/m^3 (DWA, 2010a).

Table 2.6: Decreasing cost of reverse osmosis (Adapted from DWA 2010)

Year	Seawater RO costs (kW.hr/m^3)
1970	22
1990	8
2010	4

The membrane bioreactor (MBR) is a combination of an activated sludge process and a micro- or ultrafiltration process, where the membrane filtration system replaces the gravity sedimentation unit. MBR is an alternative to activated sludge treatment that does not require secondary treatment in water reclamation instead raw wastewater can be submerged directly in MF/UF membranes (DEA, 2011). Direct membrane filtration (DMF) with simple mechanical pre-treatment such as screening, sedimentation and dissolved air flotation (DAF) can remove a lot of contaminants. These include suspended solids, protozoan cysts and oocysts as well as bacteria to achieve permeate turbidities of less than 1 NTU, depending on feed water characteristics and membrane pore size (de Koning *et al.*, 2008). It is expected that membrane technology will be integrated into secondary treatment in the future as has been done in decentralized systems in Japan and on ships using MBR (Wintgens *et al.*, 2005). MBR and DMF could be suitable for the South African and Sedibeng district situation where discharge effluent has low compliance, especially microbiological, as evidenced in this study.

2.8.2. Advanced Oxidation

Advanced oxidation processes (AOPs) aim to mineralize contaminants into carbon dioxide, water and halides and are all characterized by the production of a hydroxyl radicals that can oxidize any organic molecule. AOPs are non-selective which makes them ideal for wastewater treatment. Furthermore they are effective against recalcitrant organics (Malato *et al.*, 2009). AOPs are aqueous phase oxidation methods, based primarily and not exclusively, on intermediacy of a highly reactive hydroxyl radical species in a mechanism leading to target pollutant destruction (Comninellis *et al.*, 2008).

The advantage of AOPs compared to RO is that some trace constituents may be found in the RO permeate that can be treated with AOPs and unlike adsorption methods they do not generate a secondary waste stream with further costs (Asano *et al.*, 2007). AOPs in addition, as innovative technologies, have become more important since substances such as pesticides, endocrine disruptors and other emerging trace contaminants are given a priority (de Koning *et al.*, 2008). They have also been used predominantly to treat wastewater containing recalcitrant organics, as evidenced by a majority of research publications dealing with the subject (Suty *et al.*, 2004).

However, it is important to know when in the treatment train AOPs should be applied to get the best results since background organic matter, carbonate, bicarbonate, temperature and pH will affect AOPs. The pH of effluent affects the performance of AOPs, since it determines the distribution of carbonate species and affects charge on organic compounds if they are weak acids or bases. High concentrations of carbonates and bicarbonates in reclaimed water, reacts with (or scavenges), hydroxyl radicals and reduce the rate of organics destruction thereby reducing the efficiency of AOPs (Hernandez *et al.*, 2002; Asano *et al.*, 2007). AOPs in wastewater reclamation are recommended at the beginning, if the effluent is not biodegradable and the TOC is over 100 mg/l. If the effluent is biodegradable, then bio-treatment is recommended prior to AOPs since the former is cost effective (Malato *et al.*, 2009).

2.8.2.1 UV/Hydrogen peroxide

Radiation of wavelength lower than 400 nm is able to photolyse hydrogen peroxide to two hydroxyl radicals (equation 2.1)(Esplugas *et al.*, 2002).

$$H_2O_2 + hv \rightarrow 2OH^{\bullet} \qquad (2.1)$$

The most common UV lamp used in this type of AOPs, is the medium pressure mercury vapour lamp with a major emittance at wavelength between 200-250 nm (Hernandez *et al.*, 2002). This is suitable for hydrogen peroxide because it has favourable and efficient absorption around 250 nm even though photolysis of H_2O_2 at $\lambda < 360$ nm is possible (Momani *et al.*, 2004). The UV/hydrogen peroxide is affected by pH since the rate of photolysis increases with alkaline conditions (Andreozzi *et al.*, 1999), temperature and concentration of H_2O_2 (Hernandez *et al.*, 2002). The quantum yield (φ), which is defined as the number of hydroxyl radicals produced per number of photons adsorbed, is reduced to one because hydroxyl radicals react with H_2O_2 (Andreozzi *et al.*, 1999; Hernandez *et al.*, 2002). Optimum H_2O_2 concentration needs to be maintained to increase yield (equation 2.2 and 2.3).

$$H_2O_2 + OH^{\bullet} \rightarrow H_2O + HO_2^{\bullet} \qquad (2.2)$$

$$2HO_2^{\bullet} \rightarrow H_2O_2 + O_2 \qquad (2.3)$$

The UV/hydrogen peroxide is the most commonly used AOP in wastewater reclamation used in Cloudcroft New Mexico, Orange County GWRS and Beaufort West WRP among others (NRC, 2012; USEPA, 2012; Marais and Durckheim, 2012). Even though H_2O_2 is stable and can be stored on-site, it has poor light absorption capacity which means most of the light input is wasted. The residual H_2O_2, which is added to increase efficiency of hydroxyl radical production, is problematic since it consumes chlorine and interferes with disinfection. UV/hydrogen peroxide process typically includes injection of H_2O_2 and mixing then followed by reactor with UV (Crittenden *et al.*, 2005; Asano *et al*., 2007).

2.8.2.2 UV/O_3 and peroxone (H_2O_2/O_3)

In the UV/O_3 process, ozone reacts with water induced by UV radiation to yield oxygen and hydrogen peroxide that subsequently undergoes homolytic cleavage to produce hydroxyl radicals (equation 2.4 and 2.5).

$$O_3 + H_2O + h\nu \rightarrow O_2 + H_2O_2 \qquad (2.4)$$

$$H_2O_2 + h\nu \rightarrow 2OH^{\bullet} \qquad (2.5)$$

Low-pressure mercury vapour UV lamps are used for this process and other advanced oxidation processes, since they emit most of their radiation at 254 nm and that is the optimal absorption wavelength for ozone. Like the UV/hydrogen peroxide system the UV/ozone is affected by pH, temperature and concentration. The peroxone system is similar to the UV/O_3 system, except that hydrogen peroxide is added instead of being formed from UV-ozone reaction. The added advantage of this process is that it can be used in turbid waters whereas the UV/ozone cannot (Hernandez *et al.*, 2002). Both ozone and UV can degrade specific organic compounds individually, but in combination to form hydroxyl radicals they are non-selective which gives an advantage for water reclamation influent with a plethora of constituents (ATSE, 2013).

2.8.2.3 Fenton's reagent

Fenton's reagent is an oxidative mixture of ferrous Fe (II) and H_2O_2 under acidic conditions produce hydroxyl radicals (equation 2.6 and 2.7). The Fenton's process in its unmodified form is most efficient at pH around 2.8 (Andreozzi *et al*. 1999; Parsons, 2004)

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^{-} + OH^{\bullet} \quad (2.6)$$

$$OH^{\bullet} + R\text{-}H \rightarrow CO_2 + H_2O + X\text{-/ other products} \quad (2.7)$$

Regeneration of Fe^{2+} occurs through the so-called Fenton-like process, (Andreozzi *et al.*, 1999; Martinez *et al.*, 2003; Neyens and Baeyens, 2003; Momani *et al.*, 2004) and the following (equation 2.8 and 2.9) is the reaction of Fe^{3+} and H_2O_2.

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2^{\bullet} + H^{+} \quad (2.8)$$

$$Fe^{3+} + HO_2\bullet \rightarrow Fe^{2+} + H^{+} + O_2 \quad (2.9)$$

The decomposition of hydrogen peroxide is the only way for regeneration of iron (II), and that is a limiting factor and subsequently excessive hydrogen peroxide may also result in hydroxyl radical consumption (equation 2.10 and 2.11) (Maciel *et al*. 2004).

$$OH^{\bullet} + Fe^{2+} \rightarrow Fe^{3+} + OH^{-} \quad (2.10)$$

$$OH^{\bullet} + H_2O_2 \rightarrow H_2O + HO_2^{\bullet} \quad (2.11)$$

Photo-assisted Fenton's reagent is when the above reactions are enhanced by UV radiation (equation 2.12, 2.13 and 2.14). The UV light forms extra hydroxyl radicals and also improves regeneration of iron (II) (Andreozzi *et al.*, 1999; Maciel *et al*., 2004; Momani *et al.*, 2004).

$$H_2O_2 + hv \rightarrow 2OH^{\bullet} \quad (2.12)$$

$$Fe(OH)^{2+} + hv \rightarrow Fe^{2+} + OH^{\bullet} \quad (2.13)$$

$$Fe^{3+}(R\text{-}CO_2)^{2+} + hv \rightarrow Fe^{2+} + OH^{\bullet} \quad (2.14)$$

The quantum yield of the Photo-Fenton reaction can be increased tenfold, for example, if the Fe (II) is complexed with oxalate (equation 2.15 - 2.18). This is called the modified Photo-Fenton reaction (Parsons, 2004), and the resultant oxalate radical can decompose into a carbon dioxide radical and carbon dioxide or it can react with molecular oxygen to produce a superoxide radical (Andreozzi *et al.*, 1999; Parsons, 2004).

$$[Fe^{2+}(C_2O_4)_3]^{3-} + hv \rightarrow [Fe^{2+}(C_2O_4)_2]^{2-} + C_2O_4^{\bullet -} \quad (2.15)$$

$$C_2O_4^{\bullet -} + [Fe^{2+}(C_2O_4)_3]^{3-} \rightarrow [Fe^{2+}(C_2O_4)_2]^{2-} + C_2O_4^{2-} + 2CO_2 \quad (2.16)$$

$$C_2O_4\bullet- + O_2 \rightarrow O_2^{\bullet -} + 2CO_2 \quad (2.17)$$

$$C_2O_4^{\bullet -} \rightarrow CO_2^{\bullet -} + CO_2 \quad (2.18)$$

Fenton's reagent reaction is suitable for water and wastewater with bio-recalcitrant organics because iron, is relatively inexpensive and non-toxic and hydrogen peroxide is easy to handle (Andreozzi *et al*., 1999; Parsons, 2004). It is also effective for high organic load wastewater because the reaction is fast (Martinez *et al*., 2003; Kotsou *et al.*, 2004). Fenton's reagent is superior compared to UV/H_2O_2 and UV/TiO_2 systems in treating 4-chlorophenol but the problem with this system is that pH has to be lowered and this can increase TDS (Crittenden *et al*., 2005). The reaction pH can be raised without chemically converting iron or lowering pH by formation of a complex between the iron (II/III) with a carboxylic acid anion, usually oxalate (Bauer *et al.*, 1999). The problem with increased organic content of the water is that organic matter can also act as a sink to radicals thereby being counterproductive (Parsons, 2004).

2.8.2.4 Photocatalysis

Photo catalyzed, induced, assisted, accelerated, promoted and stimulated reactions are a combination of photochemistry and catalysis (Serpone and Pelizzetti, 1989). In water treatment photocatalysis, is an AOP that makes use of a semiconductor as a catalyst irradiated with UV light from a light source, to produce reactive hydroxyl radicals formed from reaction with H_2O and OH^- (Devipriya and Yesodharan, 2005).

TiO_2, as a semiconductor in photocatalysis, is appealing compared to other semiconductors because of the following (Ray, 1999; Engelbrecht *et al.*, 2000; Devipriya and Yesodharan, 2005):

- It is relatively inexpensive, biologically and chemically inert under most conditions
- It is also photo-stable, non-toxic and environmentally friendly
- Exhibits good recovery and sustainability
- Can be activated by sunlight
- It is commercially available with different allotropic forms with high conductivity
- Its absorption spectrum overlaps with the solar spectrum and that makes using solar energy a realistic possibility

The first step of photo-catalysis involves ejection of an electron from a valence band to the conduction band of the TiO_2 semi-conductor induced by UV light (λ < 390 nm) (Figure 2.14). This irradiation is equal to or greater than the band gap of TiO_2 (3.2 V anatase) (Schiavello, 1997; Engelbrecht *et al.*, 2000; Robert and Malato, 2002). This creates charge carrying conduction band electron and valence band-hole pairs that recombine and stay in the crystal or migrate to the surface to react with available adsorbents (Bauer *et al.*, 1999; Wang and Hong, 1999; Parsons, 2004).

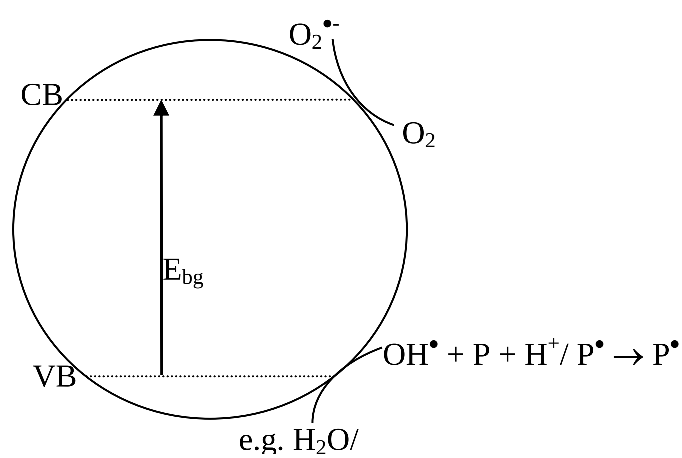

Figure 2.14: Basic mechanism and principle of photocatalysis

Chemical reaction steps for photocatalysis (equation 2.19 - 2.24):

$$TiO_2 + hv \rightarrow TiO_2\,(e^-_{CB} + h^+_{VB}) \qquad (2.19)$$

$$h^+_{VB} + H_2O \rightarrow OH^\bullet + H^+ \qquad (2.20)$$

$$h^+_{VB} + OH^- \rightarrow OH^\bullet \qquad (2.21)$$

$$e^-_{CB} + O_2 \rightarrow {}^\bullet O_2^- \qquad (2.22)$$

$$e^-_{CB} + {}^\bullet O_2^- \rightarrow {}^\bullet O_2^{2-} \qquad (2.23)$$

$${}^\bullet O_2^- + H^+ \rightarrow HO_2^\bullet \qquad (2.24)$$

Adsorbed compounds can be directly oxidized or oxidized through hydroxyl radical reaction by the steps (equation 2.25 and 2.26) below (Bauer *et al.*, 1999).

$$h^+_{VB} + R\text{-}H \rightarrow \text{oxidized products} \qquad (2.25)$$

$$OH^\bullet + R\text{-}H \rightarrow \text{oxidized products} \qquad (2.26)$$

Recombination of conduction band electrons and valence band holes can reduce quantum efficiency of photo-catalysis (Andreozzi *et al*., 1999; Bauer *et al.*, 1999; Wang and Hong, 1999). Adsorbed hydroxyl radicals by conduction band electrons also lowers quantum yield (equation 2.27 and 2.28) (Bauer *et al.*' 1999).

$$TiO_2\,(e^-_{CB} + h^+_{VB}) \rightarrow TiO_2 + \text{heat} \qquad (2.27)$$

$$e^-_{CB} + OH^\bullet + OH^- \qquad (2.28)$$

The reacting solution pH in photocatalysis is important since it significantly affects the charge of the particles, size of aggregates it forms and the position of the conductance and valence bonds (Malato *et al*., 2009).

2.8.3. Soil Aquifer Treatment

Artificial recharge philosophy is the storage of water when in excess and recovery when not available indirectly occurs when there is an oversupply of irrigation water and directly through recharge. Soil Aquifer Treatment (SAT), is defined as a low-technology advanced wastewater treatment system that allows reclaimed water to percolate through layers of loam, sand, gravel, silt and clay. SAT systems require unconfined aquifers, vadose zones free of restricting layers, soils, coarse enough for infiltration and fine enough for filtration (USEPA, 2012). Most removal of chemical and microbiological constituents occur in the top 2m of the vadose zone and removal mechanism include volatilization, biochemical conversions, metals precipitation and sorption with soil matrix (Asano and Levine, 1996).

Traditionally, water utilities use their groundwater or surface water as a source or storage medium compared to wastewater reuse, where there is continued supply of source without storage. Ground water recharge is used the following purposes including the latter (USEPA, 1992):

- To provide for saltwater intrusion in coastal aquifers
- To provide further treatment for future reuse
- To augment potable or non-potable aquifers
- To provide storage of the reclaimed water
- To prevent or control ground subsidence

Groundwater recharge helps provide a loss of identity between reclaimed water and ground water and this psychological impact makes reclaimed water acceptable (du Pisani, 2006). Groundwater recharge has the following advantages which are cost related (Asano and Cotruvo, 2004):

- Cost of AR might be less than the cost of equivalent surface reservoir
- The aquifer serves as a natural distribution system and reduces a need for transmission pipelines
- Water stored in surface reservoirs is subject to evaporation, taste and odour problems due to algae and other pollution as compared to AR
- AR provides psychological and aesthetic benefits if potable reuse is an option

To purposefully recharge groundwater would make it possible to quantify the overuse in irrigation and optimize use. SAT removes essentially all suspended solids, biodegradable material, bacteria, viruses and other microorganisms (USEPA, 2012). Four water quality factors are particularly significant in ground water recharge with reclaimed water (Asano and Cotruvo, 2004):

- Microbiological quality
- Total mineral content in total dissolved solids
- Heavy metals
- Concentration of stable and potentially harmful organic substances

The twin liabilities of abundance of wastewater and AMD water at pH 2.2 and high metal concentration has been successfully bio-remediated (Kumar *et al.*, 2011). This is achieved by stimulating sulphate reducing bacteria (SRB) activity that increase pH and alkalinity, also include decrease in sulphate and heavy metals concentration in the following reactions. Below (equation 2.29 and 2.30) is when using CH_2O as a substrate where the H_2S will form metallic sulphides with heavy metals in acidic water with pH increases (Jamil, 2013):

$$2H^+ + 2CH_2O + SO_4^{2-} \rightarrow H_2S + 2H_2CO_3 \qquad (2.29)$$

$$M^{2+} + HS^- \rightarrow MS\downarrow + H^+ \qquad (2.30)$$

Sewage alone can still neutralize AMD even without SRB and substrate (Kumar *et al.*, 2011). The NWRS2 views the large storage of South African mining workings active and inactive, including their underground space as potential for application of wastewater reuse in AMD affected areas. The underground spaces are devoid of evaporation losses endemic in surface water and the proximity of mines to urban areas in Gauteng is also an advantage (DWA, 2013).

2.8.4. Natural and constructed wetlands

Constructed wetlands are engineered or converted natural systems that use chemical, physical and biological processes to treat contaminated water and they are used in wastewater reclamation (Imfeld *et al.*, 2009). Wetlands can serve the following purpose in general and in water reclamation (USEPA, 2012):

- Flood attenuation
- Wildlife and waterfowl habitat
- Food chain support
- Water quality enhancement
- Regional hydrologic water balance
- Prevention of evapotranspiration
- Treat a wide range of pollution sources

In addition to the above, maintaining appropriate flow regimes by recharging wetlands with reclaimed water, for example, can support and sustain natural and man-made aquatic ecosystems, if receiving water quality objectives are clearly defined (DWA, 2013a).

Constructed wetlands consist of four compartments namely plants, sediments and/or soils, microbial biomass and aqueous phase loaded with chemicals. They can be classified (Figure 2.15) as surface flow, subsurface flow or hybrid systems that treat contaminants through volatilization, photochemical oxidation, sedimentation, sorption and biological degradation (Imfeld *et al.*, 2009).

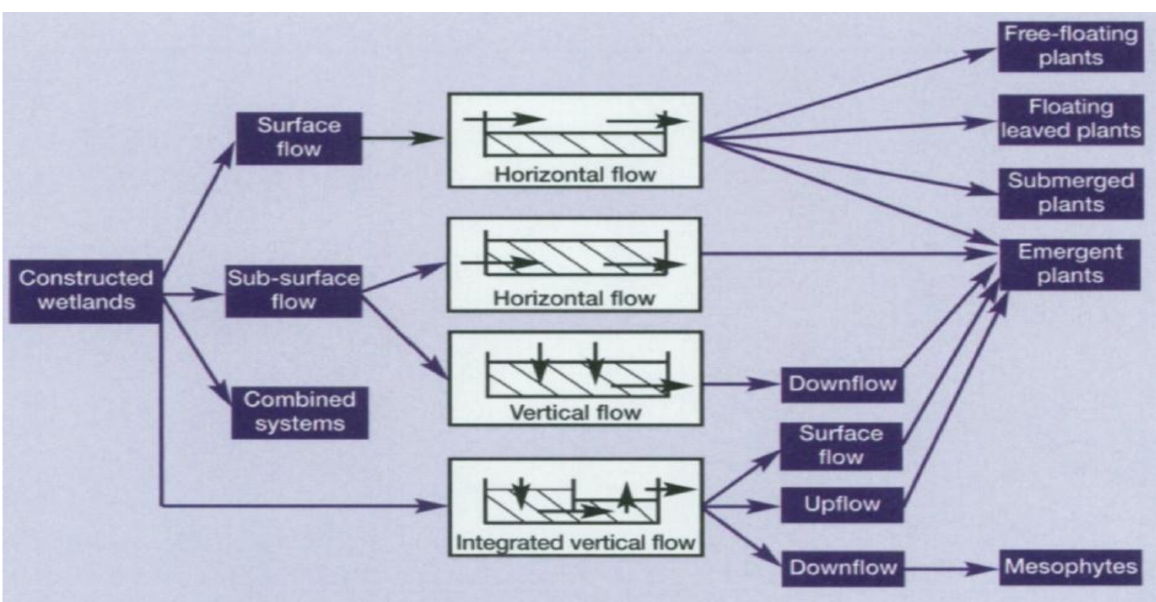

Figure 2.15: Different types of constructed wetlands (Liu *et al.*, 2009)

Wetlands remove pollutants in a number of ways, as an example of sorption, nitrates and phosphates are sequestered directly by wetland vegetation as they are essential for plant growth. In an ideal situation when a wetland is not overdosed with pollutants a wetland such as the Klip River wetland in the study area, would be a site for natural treatment of polluted water. This is achieved by precipitation of heavy metals such as uranium from mining waste after reduction into sulphides and therefore can treat municipal wastewater in reclamation and reuse (McCarthy *et al.*, 2007).

Wetlands require long hydraulic retention time (HRT), available land and factors such as wetland design, source water quality, temperature, vegetation and management practice, that all contribute to their efficiency (Chen *et al*., 2011). The efficacy of a wetland is dependent on resident time of the water in the wetland and pollutant loads. Photocatalysis to convert non-biodegradable organic matter to biodegradable matter can also be used as preliminary step and thus reducing HRT (McCarthy *et al.*, 2007; Chen *et al.*, 2011).

Constructed wetlands in China are used to treat domestic, industrial and agricultural wastewater and are usually constructed in parks in the periphery or within urban living areas, in rural villages and in WWTP effluent receiving areas (Liu *et al.*, 2009). In Europe, specifically in Spain and the Netherlands, wetland effluent is used for nature conservation and agriculture after secondary treatment of wastewater in reclamation (de Koning *et al.*, 2008).

In South Africa this has already been applied in the Klip River wetland, which was initially used, as a water source then a natural treatment site and agricultural water source. It currently serves as a sink of heavy metals and phosphates from acid mine drainage and other mining activities that might enter the Vaal River system if further degradation such as canalization occurs (McCarthy *et al.*, 2007). The multiplicity of treatment capability and capacity, in terms of variability of contaminants, is clearly demonstrated in the changing functions the Klip River catchment has gone through.

Therefore wetlands can be engineered to treat municipal wastewater for reclamation purposes.

2.9 Conclusions

Wastewater reclamation and reuse is a certain option to be exploited in the future as a water source because of a number of drivers. These drivers include among them population growth, environmental awareness, aridity, climate change and security of supply. These factors also determine where and what types of wastewater reclamation and reuse are applicable in each area (e.g. the Western United States, Australia, Israel, Singapore, Japan and Mediterranean countries, among others). The types of reuses outlined in this chapter were indirect and direct potable reuse of which Southern Africa, specifically Namibia and South Africa, are the pioneers. IPR is distinguished from DPR by an existence of a buffer which could be the earth, surface water or stabilization ponds that allows time for dilution or blending and contaminant attenuation through natural processes. Agricultural irrigation reuse, of which Israel is one of the leaders and pioneers, is another reuse option and industrial reuse of which South Africa can easily implement. South Africa has the potential to implement the latter reuse strategy because intensive water user industries are already practicing internal recycling. Therefore their infrastructure can receive and easily be adapted for treated municipal effluent.

Each reuse option has different quality requirements based on risks posed by reclaimed water on health, infrastructure and product quality. Public perceptions, which are most often not based on water quality criteria, are also important for the acceptance of reclaimed water use. Physical, chemical and biological parameters are important to monitor to determine the fitness of use of reclaimed water for different purposes. These parameters include aggregate parameters such as COD, TOC, TDS, TSS, FOG and turbidity. Nutrients such as nitrogen and phosphorous compounds are especially important for agricultural use to reduce the demand of fertilizers among other cost inputs but are detrimental in excess for this option and for industrial use. Treatment technology is important to achieve set guidelines which are presently non-existent in

South Africa for reuse specifically but other water reclamation practicing nations have developed them. Treatment technology can be classified as being physical, chemical and biological or a combination thereof. It can also be natural and or provide an environmental buffer such as in groundwater recharge and wetlands.

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CHAPTER 3

Study area

3.1 Introduction

The Vaal River is the tributary of the Orange River and the latter stretches over parts of Gauteng, North West, Free State and Mpumalanga provinces and two countries Lesotho and Botswana (DWS, 2015). The Vaal River catchment is divided into, the Upper Vaal upstream of the Vaal Dam, Vaal Barrage (Vaal Dam to Barrage wall), Middle Vaal (Vaal Barrage to Bloemhof Dam, Lower Vaal (Bloemhof Dam to Douglas Weir) and Modder-Riet systems (DWA, 2009c). The Upper Vaal Water Management area (WMA), Area 8 using the DWAF (2004) classification, of which the Sedibeng District municipality (SDM) is part of, is located towards the centre of the country. The SDM is the area the study focused on and is part of the southern Johannesburg-Vereeniging-Vanderbijlpark complex north of Area 8 WMA that has strong urban and industrial areas (DWAF, 2004; Hobbs *et al.*, 2013).

The SDM, with three municipalities: Emfuleni, Midvaal and Lesedi, is situated in the southern part of the Gauteng province in the WMA and has a population of 942 373 people with a density of 198 people per km^2. It constitutes 8% of Gauteng's population and has a total land cover area of 4185 km^2; 1728 km^2 is in Midvaal, 1489 km^2 in Lesedi and 968 km^2 in Emfuleni (GPG, 2014; SDM, 2014). Lesedi (Figure 3.1), which will not become part of the envisaged Greater Vaal Metropolitan River City, is functionally linked and will be incorporated into the Ekurhuleni municipality and subsequently did not form part of this study (SDM, 2014).

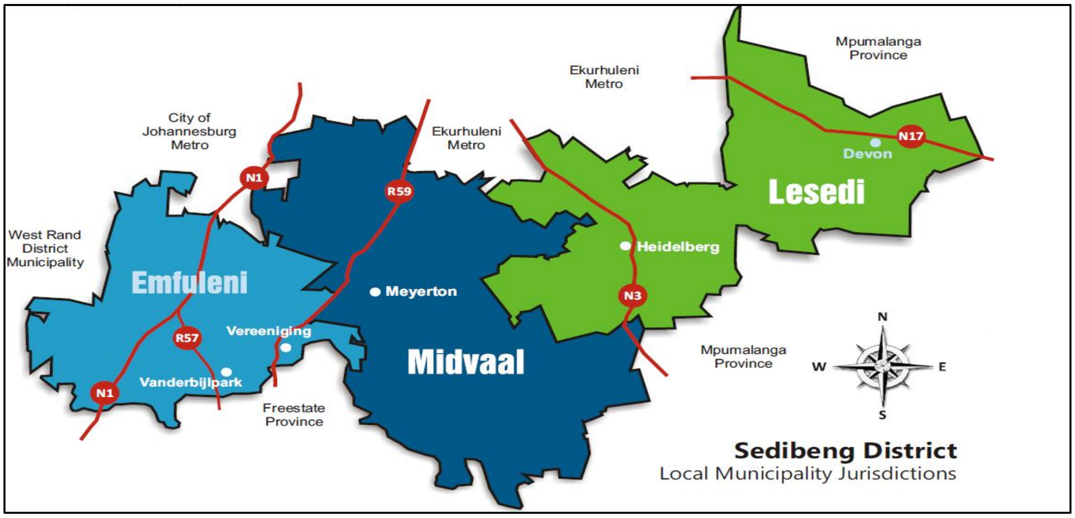

Figure 3.1: Showing the Sedibeng district study area (SDM, 2013)

The 55 565 km^2 Upper Vaal WMA's (Figure 3.2) southern half of the WMA extends towards the Free State, the north east falls mainly in Mpumalanga and the northern and western parts in Gauteng and North West respectively (DWAF, 2004). Major rivers in the Upper Vaal WMA are the Vaal River and its tributary the Wilge and other tributaries are the Klip, Liebenbergsvlei, Suikerbosrand and Mooi Rivers (Figure 3.2). The Upper Vaal WMA catchment supports three major dams namely Vaal Dam, Grootdraai Dam and Sterkfontein Dam (Hobbs *et al.*, 2013).

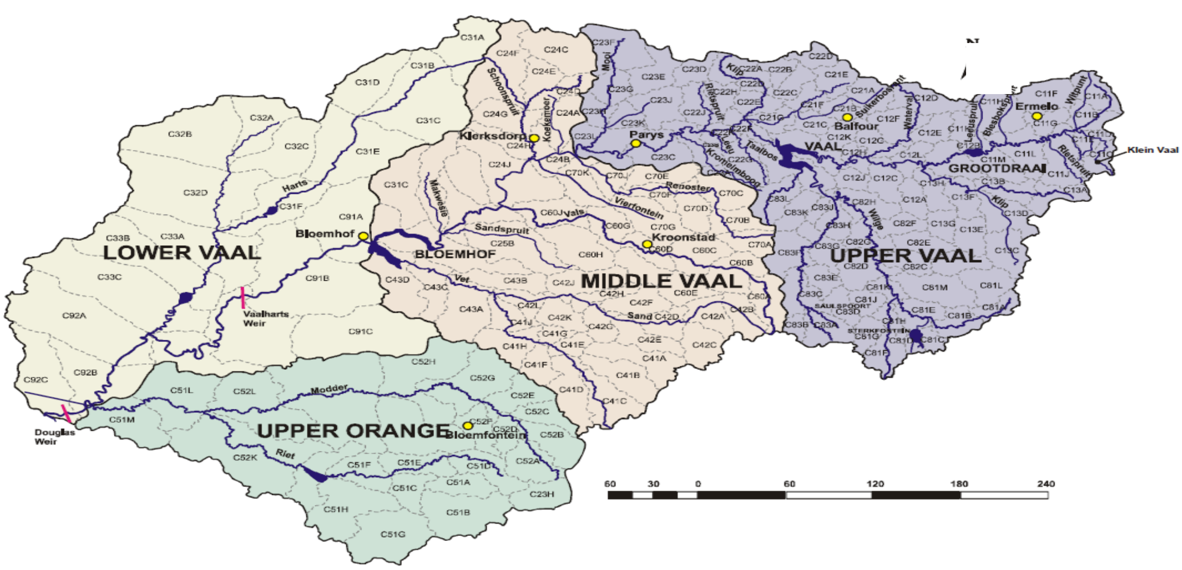

Figure 3.2: Vaal River system with different WMA (DWAF, 2009a)

The local surface water resources have been fully exploited more than three decades ago in the Upper Vaal WMA due to development (DWAF, 2004). This is because spatial migration towards mineral riches, to add, have had a consequence that the requirement of water already far exceeds the natural availability of several river basins in South Africa. The Upper Vaal WMA receives trans-boundary water from KwaZulu-Natal and Lesotho in the Vaal-Tugela scheme and the Lesotho Highlands Transfer Scheme (LHTS) respectively (DWAF, 2003).

Chapter 3 describes the already limited available resource in the study area and shows how wastewater reclamation and reuse can alleviate this shortage with provision from municipal secondary effluent. The Southern Gauteng wastewater treatment plants effluent was used to characterize the water for viability of different reuse options, to alleviate the increasing demand of the scares water resources in this area. The four Waste Water Treatment Plants (WWTPs) are WWTP1 (Sebokeng), WWTP2 (Rietspruit), WWTP3 (Leeukuil) and WWTP4 (Meyerton) in the Sedibeng district. The first three WWTPs are in the Emfuleni local municipality and the last WWTPs in the Midvaal local municipality.

3.2 Natural environment

3.2.1 Climate

Mean daily temperatures in the Upper Vaal WMA, where the Sedibeng district municipality is situated, vary from 16^{o}C in the west to 12^{o}C in the east, with maximums in January and minimums in July (DWAF, 2004; Hobbs *et al.*, 2013). The rainfall occurs as convective thunderstorms and sometimes accompanied by hail. Frost occurs in winter and there is occasional light snow in the high lying areas (DWAF, 2004). It has a temperate and relatively uniform climate with strongly seasonal rainfall most occurring as thunderstorms during summer months. The mean annual rainfall or mean annual precipitation (MAR/MAP) ranges between 600 mm and 800 mm per year (Figure 3.3) and with a potential of 1300 mm to 1700 mm evaporation (DWAF, 2003). The overall feature of the Upper Vaal WMA rainfall is that it decreases fairly uniformly westwards from the eastern escarpment regions across the central plateau area (DWAF, 2004).

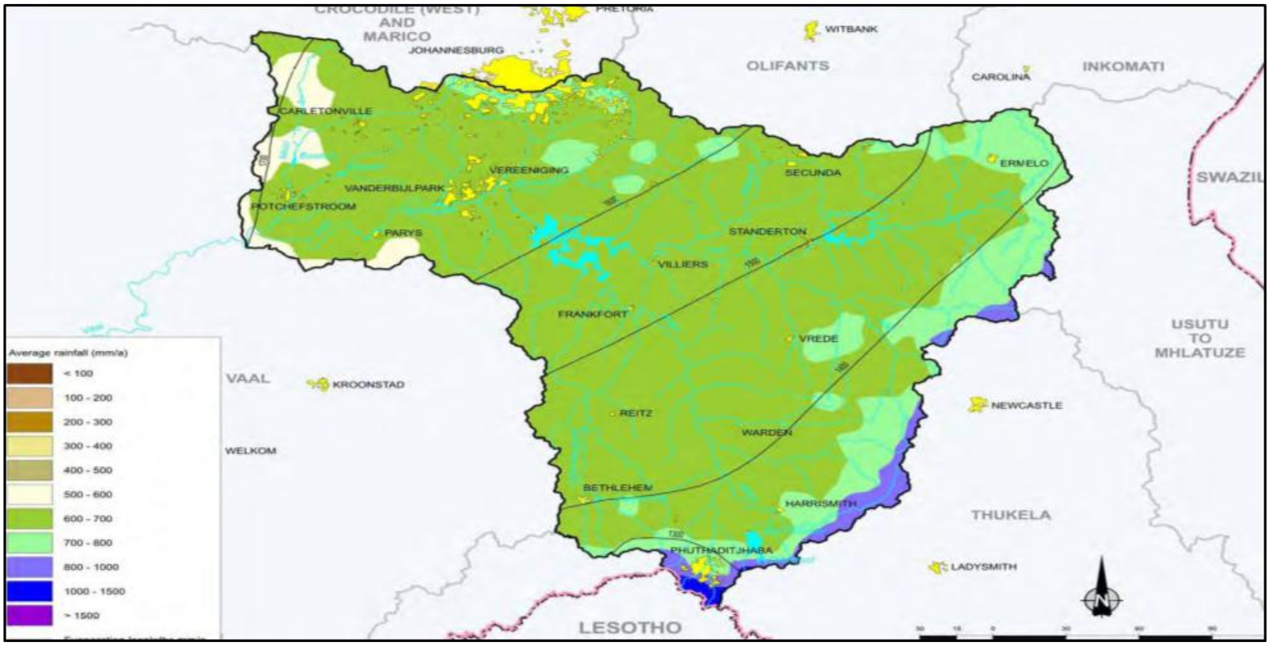

Figure 3.3: Rainfall pattern of the Upper Vaal WMA (DWAF, 2003)

The decrease westwards causes the rainfall for the WMA to range from a high of 1000 mm in the east to a low of 500 mm in the west and an average of approximately 700 mm (DWAF, 2004). The map (Figure 3.3) shows a rainfall range of 300-400 mm surrounded by 600-800 mm in the areas of the study area around Sedibeng district municipality. This is slightly lower than the WMA's mean annual rainfall of 600-800 mm as the south eastern areas increase the average.

3.2.2 Topography and geology

The Vaal catchment slopes gently from about 1800 m in the east to 1450 m in the west around the Vaal Barrage and there are some steep areas in the head waters of the Wilge River tributary (DWAF, 2004). The Sedibeng district municipality is mainly in a flat area ranging between 1440 and 1480 m above mean sea level and the wind direction is primarily north easterly, northerly and north westerly (MSA, 2010).

Southern Africa generally has physiographic and climate limitations, its geological formation mostly hard rock and generally storing insufficient groundwater to take advantage of the run-off (Conley and van Niekerk, 2000). Few ground water aquifers exist that can be utilized in a large scale because of these formation hence groundwater only plays a pivotal role only in rural water supplies (DWAF, 2003). In a geo-hydrological survey undertaken around the Rietspruit River which is the receiving water for two WWTPs under study, it was found that the aquifers were shallow and perched. The deeper aquifer was fractured intergranular, ground water yields were low and the flow followed the topography in a west south west direction (DEA, 2011a). This has consequences for the viability of using ground water recharge as storage or further treatment step as discussed in Chapter 5.

Soil depths are generally moderate-to-deep in the WMA with an undulating relief and there are three main types that dominate namely sandy loam, clay loam and clay soil. The predominant minerals in the Upper Vaal WMA are gold, uranium, base metals, coal, semiprecious stones and industrial minerals (DWAF, 2004). There are numerous shallow and easily accessible coal deposits in the study area and most deposits occur in the lower-lying areas and they meet the demand of local power stations which are intensive water users (DWA, 2010).

3.2.3 Flora and Fauna

The high central plateau of South Africa, of which the study area is part of, falls under the grassland biome and approximately a third of South Africa's mammals occur in the biome (MLM, 2010). The predominant vegetation is pure grassveld in the Upper Vaal WMA, temperate and transitional forest and shrub in the 700-1000 mm rainfall areas and false grassveld in the Mooi catchment (DWAF, 2004). Natural occurring trees and shrubs are limited to special niches such as riverine fringes, rocky hills and ridges. The SDM, especially the western lying area, is located in the Soweto Highveld Grassland vegetation type (MSA, 2010).

A wetland in the Upper Vaal WMA, the Blesbokspruit in the Suikerbosrand sub-catchment, is one of the wetlands of international importance as defined by the RAMSAR Convention (DWAF, 2004). Red data endangered species such as bird, bullfrog and invertebrates species have been identified especially in the protected by law Suikerbosrand nature reserve (MLM, 2010). In the study area there is a relatively large wetland system passing on the western side of two wastewater treatment plants that forms part of the Rietspruit River and provides habitat for a variety of animal species, especially birds (DEA, 2011b; ELM, 2015). A second wetland in the study area is a man-made or artificial wetland system south east of the Meyerton wastewater treatment plant one of four WWTPs in the study area.

3.3 Socio-economic

The single most influential event which impacted on the economic development of the Upper Vaal Water Management Area is the discovery of gold in 1886 which has yielded more than half of the world's gold ever mined. Existence of coal reserves has supported the establishment of six thermal power stations in the WMA and later a petrochemical industry in Sasolburg. However, this has meant that large urban and industrial development zones have been located in areas remote from water courses dictated by mineral riches (DWAF, 2003). The study area has also been impacted by this historic arrangement which has influenced its socio-economic status in terms of urbanization, economic activities, employment and poverty rates which affect water resources utilization.

Emfuleni municipality houses approximately 80% of the Sedibeng district's population and has the largest population of all local municipalities in the Gauteng Province (Figure 3.4). It is the western most local municipality and is largely urbanized, with high population density (ELM, 2007; GPG, 2014). It is comprised of the following towns namely Vanderbijlpark, Vereeniging, Sebokeng, Evaton, Sharpeville, Boipatong and Bophelong (Wegelin *et al.*, 2009). The economic and commercial nodes are Vereeniging and Vanderbijlpark, and the latter was originally built to house workers of Mittal steel previously called ISCOR (AGES, 2008). The manufacturing subsector especially steel and metal products forms the backbone and major share at 27.2% of the SDM's economy even though agriculture and tourism are also important (SDM, 2012; GPG, 2014). In addition to basic metal industries other manufacturing activities in

Southern Gauteng are the manufacturing of chemical, plastic and pharmaceutical products (DWAF, 2003).

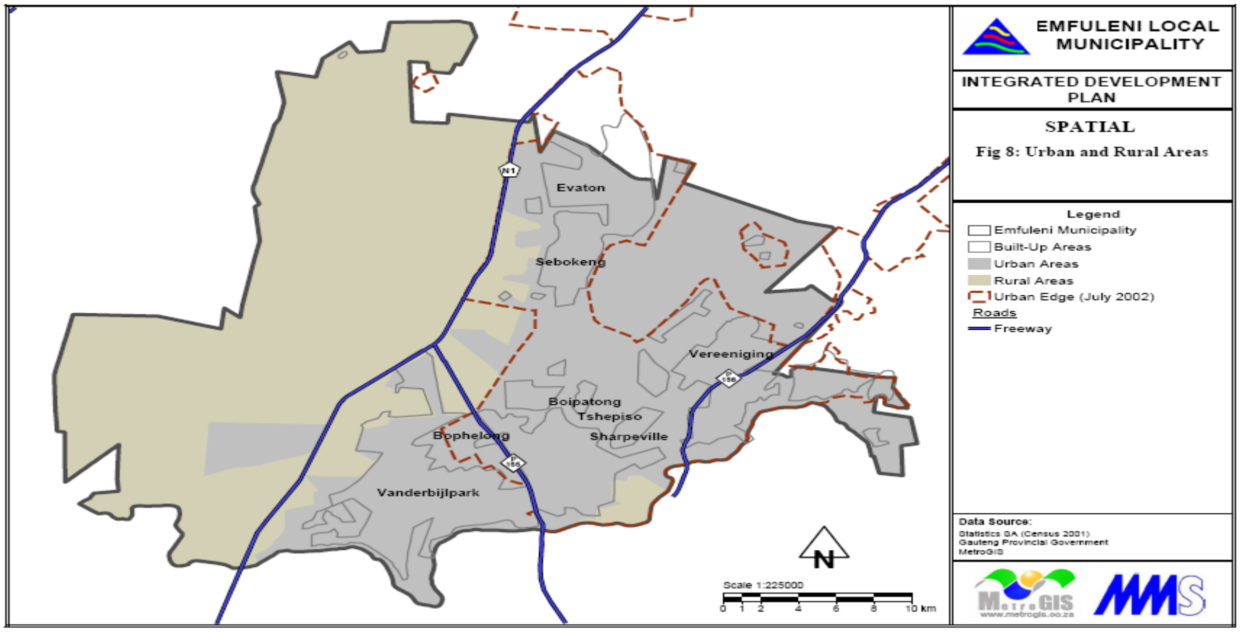

Figure 3.4: Emfuleni local municipality in the study area (ELM, 2007)

The Midvaal local municipality (Figure 3.5) constitutes 8% of Sedibeng district and 0.7% of Gauteng's population and its spatial structure is predominantly rural (MLM, 2011). Its population growth is the largest and density the lowest in the Sedibeng district at 3.94% (55.3 people per km^2), followed by Lesedi at 3.26% (67.1 people per km^2) and Emfuleni at 0.92% (747.1 people per km^2) (MLM, 2014). It is the largest municipality by area size in Gauteng and its urban areas are located in Meyerton and Vaal Marina (AGES, 2008). The rest of the local municipality is situated in predominately agricultural holdings and farmland with 49% of the household having full waterborne sewers and the rest using pit latrines and septic tanks (AGES, 2008).

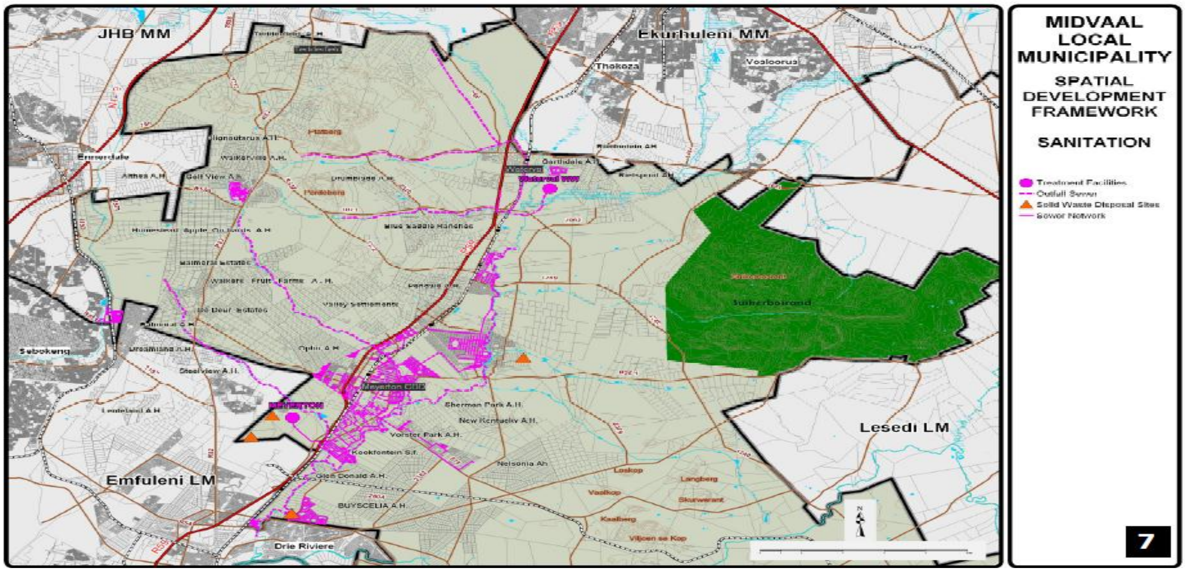

Figure 3.5: Midvaal local municipality (MLM, 2011)

Sedibeng district had the highest number of unemployment and poverty rates in Gauteng in 2010 and 2012 at 41.1% and 47.3% respectively. This was attributed to the declining performance of the manufacturing sector which accounts for the largest proportion of the region’s economic activities (GPG, 2012; GPG, 2014).

3.4 Water use and quality

Treated wastewater forms a substantial portion of available water resource in the Vaal River system and has historically increased and will continue to increase due to development and population growth in the Gauteng province (DWAF, 2009b). A substantial proportion of this treated wastewater in the Upper Vaal WMA’s urban and industrial sectors is used non-consumptively where most or all of the effluent is discharged back into rivers after treatment (DWAF, 2003).

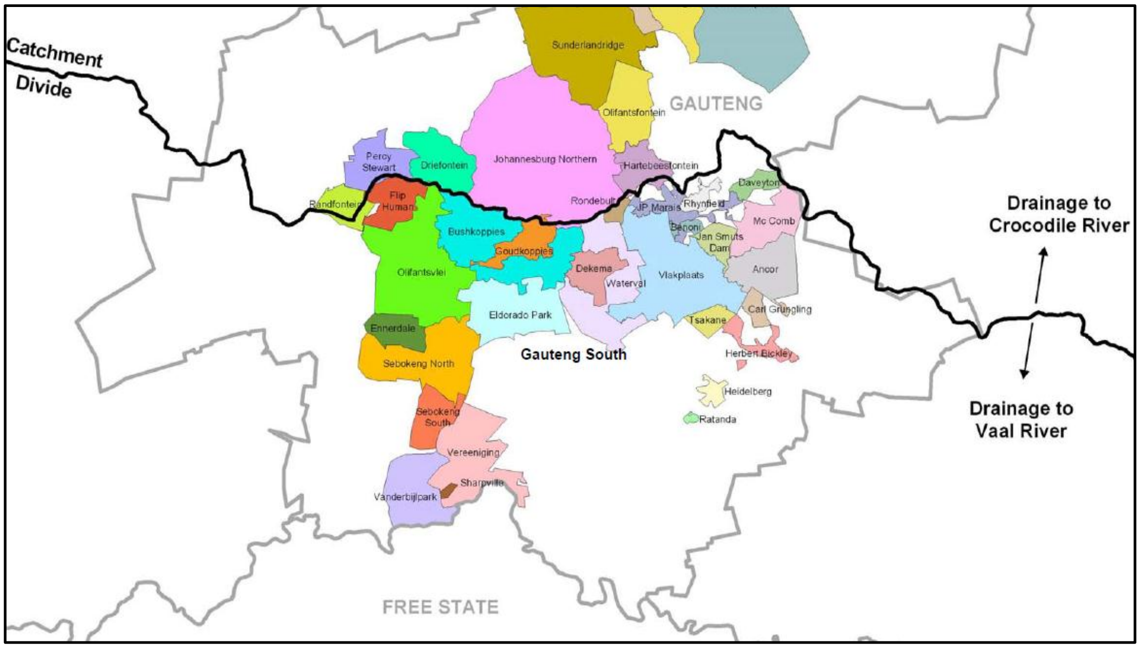

Figure 3.6: Gauteng north and south drainage area (Adapted from: DWAF, 2009b)

The main watershed or divide (Figure 3.6), separates the Gauteng province into two catchments namely the Crocodile River catchment in the north and the Vaal River catchment in the south (Dyson, 2009). The Vaal River Barrage receives domestic and industrial run-off and effluent north from across the Sedibeng region through the Rietspruit, Klip and Suikerbosrand Rivers (Crafford and Avenant-Oldewage, 2011). The water quality in the Vaal River Barrage is impacted by substantial return flows from large WWTPs non-functioning to specification due to poor maintenance and operation (DWAF, 2009a). In addition to impact of wastewater return flows water quality in the Barrage is impacted due to increased point and diffuse discharge pollution input from industries, mine dewatering and irrigation return flows (DWAF, 2004). The sections that follow will assess the main users of water namely domestic, agriculture and industrial users in the Sedibeng district municipality study area.

3.4.1 Potable use

The largest urban users in Gauteng which receives some of its water from outside the boundary in the form of the Thukela-Vaal and LHTS schemes totaled 1186million m^3/annum in 2004. In the Sedibeng district, Emfuleni local municipality (ELM) contributed 79million m^3/annum supplied by Rand Water the bulk water utility of this urban use (DWAF, 2009b). Some of this imported water after treatment and use ends up as waste that cannot be used as it is and therefore treatment to the right condition of use can alleviate some of the demand in the district. A united effort which should involve Rand Water and its generated drinking water treatment residue (DWTR) as well as surrounding industries may reduce this waste.

The ELM, the most populated municipality in the district, is characterized by high water losses and limited cost recovery. Losses are estimated at 34% of the system input volume and up to 53% if non-payment of services is included (Wegelin *et al*., 2009). The municipality had a bulk water usage of 92 976 154 kL or 93million m^3 in the 2012/2013 financial year. It experienced a 2.78% increase in water demand compared to a five year forecast that was estimated at 4% and this saving was attributed to water demand management and conservation initiatives (ELM, 2013). During the pressure management project the municipality saved an estimated 10million m^3 per annum in the worst affected Sebokeng and Evaton areas in terms of water loss (Wegelin *et al.*, 2009). These and other measures such as municipal wastewater treatment and reclamation could further reduce the demand. The example mentioned above shows that reducing demand is possible.

3.4.2 Agriculture

Agriculture is not only the largest water consumer but also impacts heavily on quality of water resources, typically through diffuse run-off of salts and fertilizer causing nutrient enrichment of water resources. Approximately 10% of all water used in irrigation, seeps back into river and stream and the return flow in urban areas is estimated at 50% or higher (DWA, 2010). The Upper Vaal WMA area, despite large areas under cultivation, agriculture only contributes to 2% of the gross geographic product (GGP) but is an important contributor to livelihoods especially in the rural population (DWAF, 2003). In between the years 1998 and 2005, the irrigation water requirements in the WMA increased significantly and this increase is predominantly due to unlawful use. The total irrigation water requirements for the WMA were estimated at 90million m^3/annum in

2005, later validated at 204million m^3/annum and 67million m^3/annum attributed to unlawful use (DWAF, 2009b).

The Sedibeng district municipality is mainly agricultural and rural in the eastern areas. It has large areas of potential agricultural activity to increase rural development and food security but farming activity remains in the main large scale commercial in nature (SDM, 2014). Extensive farming constitutes 50% of the total area of the Midvaal local municipality even though it contributes only 2% to its economy (MLM, 2014). The district is well known for animal production especially towards Lesedi but crop production in the form of maize, grain, ground nuts, dry beans, sunflower seeds, wheat, sorghum, soya and other vegetation are also prevalent (MLM, 2010). It is an important agricultural resource for Gauteng but commercial farming activity has decreased from 33% in 2004 to 32% in 2010 despite the existence of large areas of agricultural potential where it was expected to increase. This decrease in agricultural activity can be attributed to the following among others (SDM, 2014):

- Access to finance and markets
- Water and wastewater sanitation services
- Institutional arrangement, support and strategy
- Agricultural productive land which is protected

3.4.3 Industry

There are three main industries receiving bulk water from the Vaal River system, which are the electrical power utility Eskom, the petrochemical giant Sasol and the large steel industry ArcelorMittal (DWAF, 2009b). The latter is in the ELM in the study area. Eskom's Lethabo power station and Sasol 1 are functionally linked and adjacent to the study area and have abstracted water downstream of the Vaal Dam in the past from the highly impacted Vaal Barrage sub-catchment (DWAF, 2009c). Lethabo power station and Sasol1 in Sasolburg are in the Metsimaholo municipality in the Free State Province which impacts the southern end of the study area. Industrial use of reclaimed wastewater is the second major use worldwide and it can reduce some of the projected increase in demand.

The bulk (twelve) of Eskom's large coal fired power stations are situated in the supply area of the Vaal River system (DWAF, 2009b). They initially used wet-cooled technology with a 3600 MW power station requiring 45million m^3 of water per annum and with dry-cooled station using 10% of wet-cooled water stations even though more expensive to build and operate (DWA, 2010). Some of the power stations were decommissioned but reinstated to increase supply to respond to the growing demand and three more are planned and envisaged to receive water from the Vaal River system. The demand for power and its associated need for water, even municipal effluent, has resulted in proposed power stations projects outside the Vaal River system requiring transfers from this catchment. These are the Olifants and Mokolo/Crocodile catchments which required wastewater return flows from Ekurhuleni and northern Gauteng for planned dry-cooled power stations and coal to liquid fuel plants (DWA, 2010; DWA, 2011). Eskom's 2008 projected water requirements for the Lethabo power station in the study area is projected to stay on average at 48.7million m^3 per annum up to 2030 (DWAF, 2009b).

The large coal-to-liquid petroleum plants, Sasol1 at Sasolburg using 20million m^3 per annum and Sasol 2 and 3 in Secunda using 90million m^3 per annum are all located in the Vaal River system. The Sasol 1 plant in Sasolburg receives water indirectly from the Vaal Dam supported by the trans-boundary schemes and the Sasol Secunda complex receives water from the Grootdraai Dam (DWAF, 2009b). Sasol 1 has two discharge streams, one from the Sasol Midlands plant discharging into the Taaibosspruit, which discharges into the Vaal Barrage. Another stream from Sasol Chemical industries plant discharges by pipeline into the Vaal River downstream of the Barrage. Sasol also treats effluent from industry and domestic sewage from the Sasolburg area and uses some of the treated effluent and mine dewatering water from Mooikraal and Sigma Collieries in their processes (DWAF, 2009c). The projected water requirements for Sasol in Sasolburg close to the study area is expected to gradually increase from 20million m^3 per annum in 2007 to 42.7million m^3 per annum in 2030 (DWAF, 2009b). Water recycling and reclamation which is already practiced but can be increased to include some of the Sedibeng district municipality treated wastewater effluent can reduce some of this demand.

ArcelorMittal South Africa, the largest steel maker in South Africa with 75% market share and two of its steelworks Vanderbijlpark and Vereeniging produced 3.3 and 0.3 mt respectively out of a total of 5.9 mt of steel in 2008 (SACN, 2013). ArcelorMittal also receives its water from the Vaal Dam and it plans to reduce its water use from 17.4million m^3/annum to 16.6million m^3/annum (DWAF, 2009b). This steel operation and metal refineries including Impala platinum, Samancor and Zinkor are potential sources of extreme salinity. This is based on metal migration, nitrates, sulphate and organic chemicals such as polychlorinated biphenyls forming part of their effluent (PCBs) (DWAF, 2004).

3.5 Wastewater treatment plants in the study area

There are four waste water treatment plants (WWTPs) namely WWTP1 (Sebokeng), WWTP2 (Rietspruit), WWTP3 (Leeukuil) and WWTP4 (Meyerton) in the Sedibeng district. They form part of the Sedibeng regional sanitation scheme, three of them WWTP1, WWTP2 and WWTP3 are in the Emfuleni local municipality and WWTP4 in Midvaal. In total the WWTPs servicing the Sedibeng region are six in number with the other two being the minor 1 ML/day each Ohinemuri and Vaal Marina WWTPs (AGES, 2008).

3.5.1 Wastewater treatment plant 1

The Sebokeng WWTP is situated 18 km north west of Vereeniging, bordered by the N1 to the west and the R553 to the East with coordinates 26°34'29.03"S and 27°49'2.64"E and adjacent to the Rietspruit River (DEA, 2011a). It is at an elevation of approximately 1483 m above mean sea level and discharges its final effluent into the adjacent Rietspruit River with wetland characteristics as described previously (Figure 3.7). It is the largest WWTP in the region at a design capacity of 100 ML/day and receives part of its sewer inflows from Emfuleni and across its border from south of Johannesburg and Midvaal (AGES, 2008). The areas that drain into the WWTP1 from Johannesburg metropolitan municipality include Poortje, Palm Springs, Lenasia and Orange farm and accounts for approximately 50% of inflows to the plant (AGES, 2008; DEA, 2011a).

Figure 3.7: Satellite image of the Sebokeng WWTP1

The wastewater streams enter via three main sewer collectors, two from the north and one from the south. This influent is divided into three activated sludge modules each with a design capacity range of 3-35 ML/d. The WWTP treatment train (Figure 3.8) consists of screening, de-gritting, flow balancing, primary sedimentation, reactors, fermentation of raw sludge, final clarification, chlorination, waste sludge thickening and dewatering (DEA, 2011a). The WWTP experienced average daily flows of 145 ML/day in the 2012/2013 financial year and achieved 97% compliance in terms of the Department of Water Affairs (DWA) water use license (ELM, 2013). The Sebokeng WWTP is at a risk, according to the 2012 Green Drop progress report, for operating at 144% over capacity and if the microbiological water quality compliance does not improve (DWA, 2012).

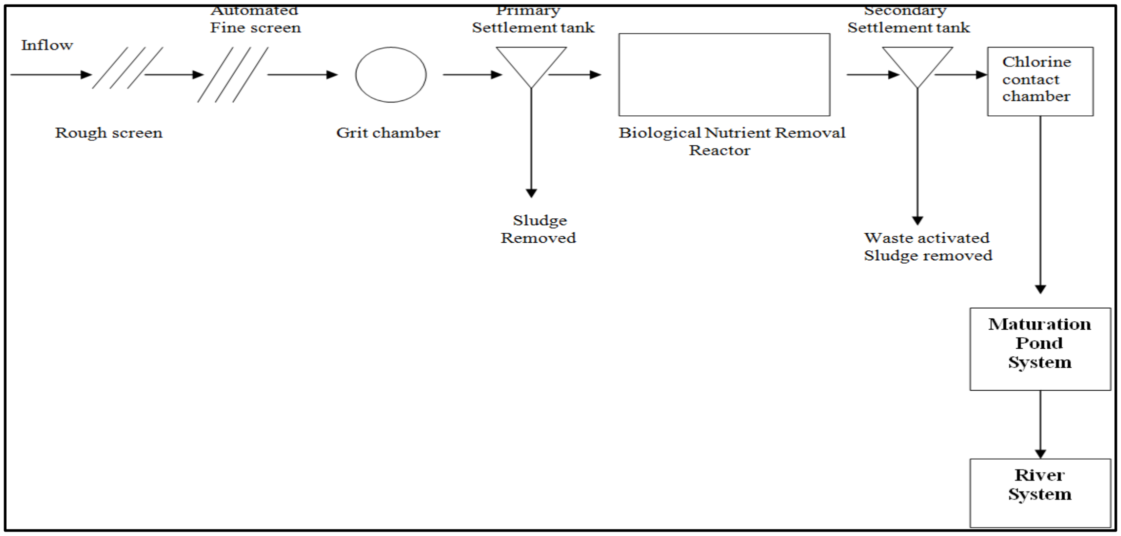

Figure 3.8: Treatment process flow of Sebokeng WWTP1

3.5.2 Wastewater treatment plant 2

Rietspruit is the second WWTP plant in ELM in the Sedibeng region at 36 ML/day design capacity and forms part of portion 70 of the farm Rietspruit. It receives its influent from the Vanderbijlpark area and discharges its final effluent into the Rietspruit River (DEA, 2011b).

Figure 3.9: Satellite image of the Rietspruit WWTP2

It has experienced 32 ML/day average daily flow in 2012/2013 and achieved 92% compliance. Even though the Rietspruit WWTP's operation is running within capacity microbiological compliance is a priority of concern (DWA, 2012). WWTP2 has 16 ML/day biological trickling filter, 20 ML/day activated sludge capacity and the legislated 30 ML storage dam. The process (Figure 3.10) consists of inlet works, screening, de-gritting, primary sedimentation, raw sludge fermentation, sludge thickening and dewatering among others (DEA, 2011b).

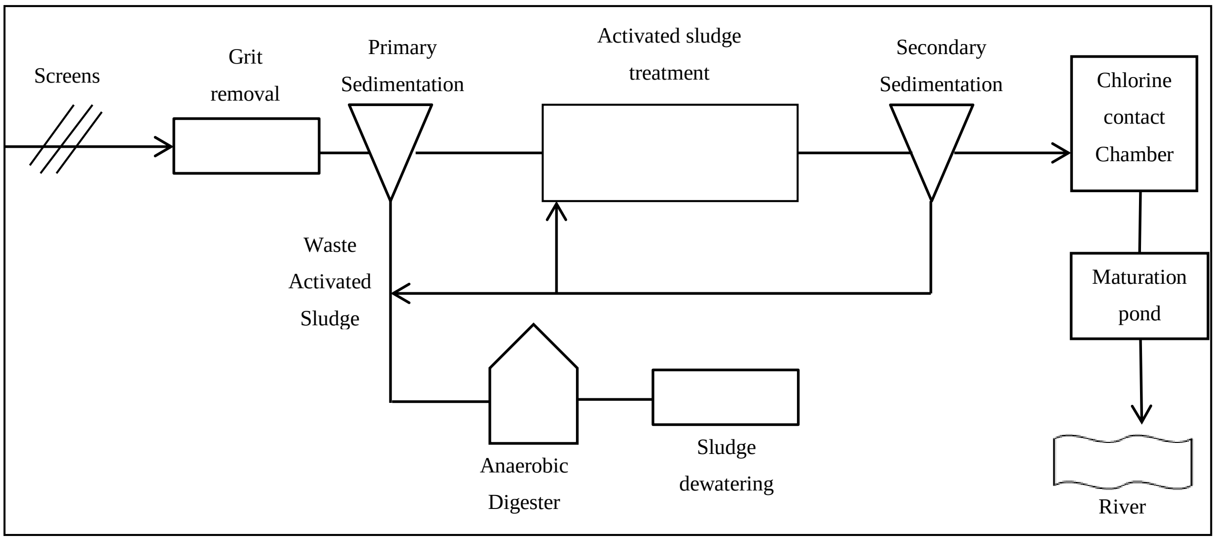

Figure 3.10: Process flow diagram of WWTP2

3.5.3 Wastewater treatment plant 3

Leeukuil, constructed in 1954, is the third WWTP plant in ELM of the Sedibeng district at design capacity of 36 ML/day it treats effluent from Vereeniging, Sharpeville and Kwaggastroom (Figure 3.11). Of the 36 ML/day capacity, 20 ML/day is treated with an activated sludge process and the remaining 16 ML/day (mainly abattoir effluent) is treated using a biological tricking filter process (Rand Water, 2013).

Figure 3.11: Satellite image of the Leeukuil WWTP3

Leeukuil WWTP3 also receives some of its effluent from Risiville, Duncanville Extention 3, Mackay and Uitvlugt, which are areas belonging to MLM (AGES, 2008). Leeukuil WWTP, that discharges its final effluent into the Vaal River Barrage, has experienced average daily flows of 46 ML/day and achieved 91% compliance in the financial year 2012/2013. WWTP3 contains mechanical screens and de-gritters in the inlet works, a primary settling tank for sedimentation of suspended solids, a 5-stage Bardenpho biological nutrient removal system and secondary sedimentation tanks (Figure 3.12). Returned activated sludge is drawn from these settling tanks to sustain activated sludge, final effluent is chlorinated before being discharged into the Vaal River Barrage and anaerobic digesters are used to treat waste activated sludge (Rand Water, 2013)

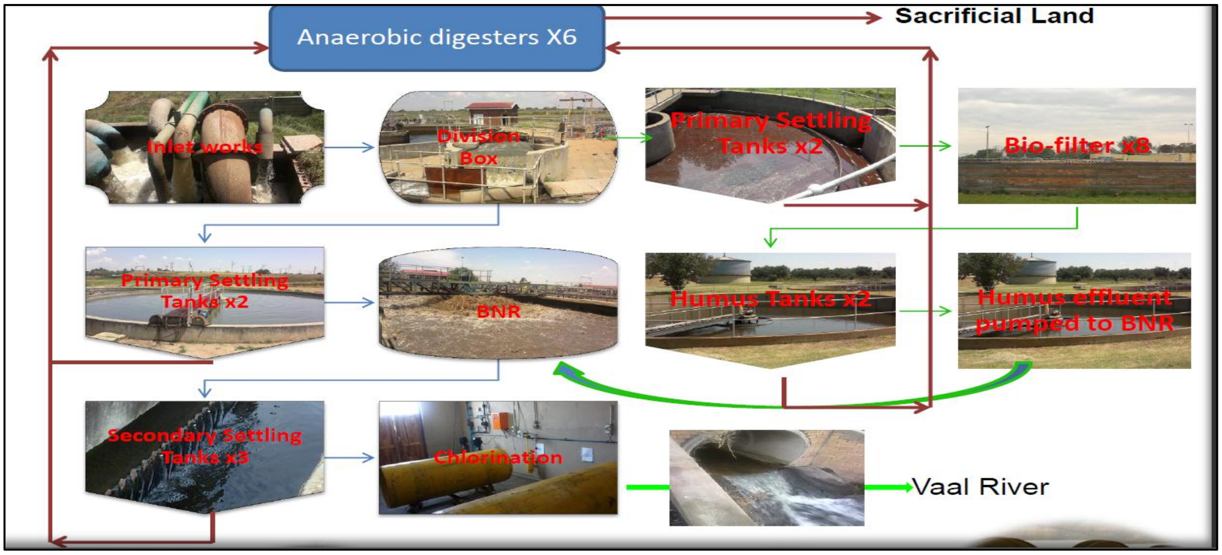

Figure 3.12: Process flow diagram of WWTP3 (Rand Water, 2013)

3.5.4 Wastewater treatment plant 4

The Meyerton WWTP4 one of three in the Midvaal local municipality is at an elevation of 1477 m above mean sea level and the site is level sloping slightly south east towards the Klip River (Figure 3.13). It is about 4 km south west of the town of Meyerton, west of the R59 and south of the R551. Vereeniging Aerodrome and a brickworks site are to the west, a coal mine and Meyerton industrial site to the east (ECO, 2012).

Figure 3.13: Satellite image of the Meyerton WWTP4

Meyerton WWTP is designed for 8 ML/day and is currently running over capacity at 13 ML/day due to Meyerton and Henly-on-Klip effluent (SDM, 2013). The WWTP also receives effluent from Roshnee and Rustervaal which are areas located in the Emfuleni Local Municipality. It is classified as a medium sized plant (2-10 ML/day) that uses activated sludge biological nutrient removal and anaerobic digestion (AGES, 2008). The WWTP was originally commissioned in 1977 with a treatment capacity of 5 ML/day, currently has a theoretical capacity of 10 ML/day and with the proposed expansion (Figure 3.14) will be able to treat 15 ML/day with the following units (MSA, 2012):

- Head of works with screening and de-gritting and a pump station
- Biological treatment reactor
- Waste activated sludge and recycling pump station
- Sludge drying beds and irrigation pump station
- Secondary sedimentation tank
- Chlorine contact tank

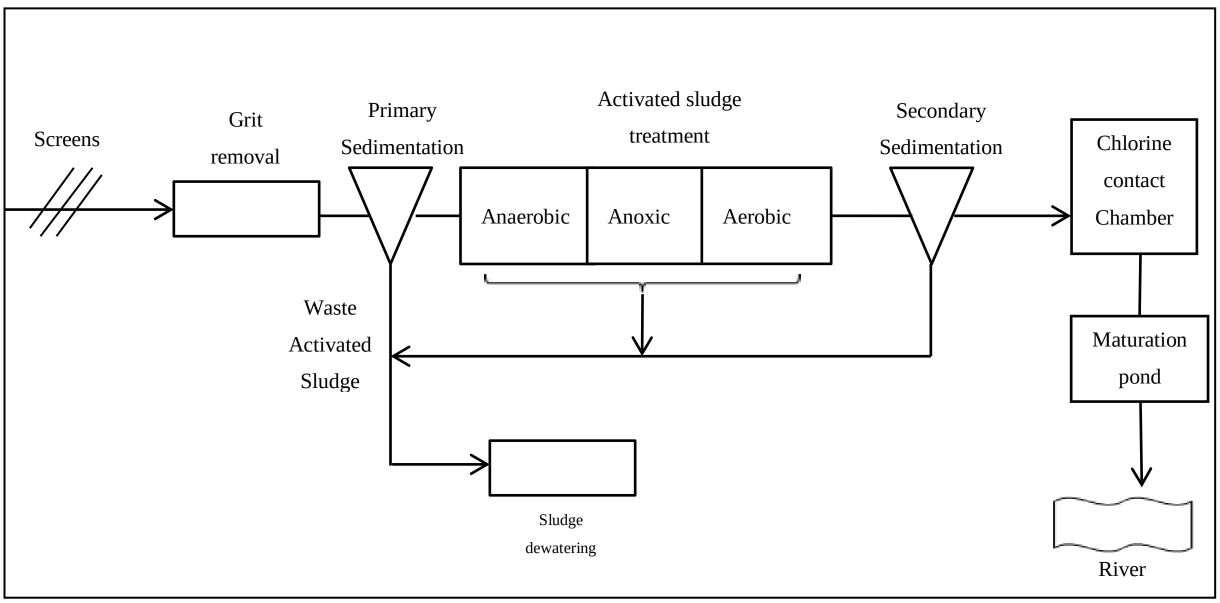

Figure 3.14: Prosed process flow diagram of WWTP4 (Adapted from MSA, 2012)

The Meyerton WWTP has been classified as “high risk” in the area because of running 130% over capacity and the poor quality of effluent discharge in terms of physical, chemical and microbiological compliance (DWA, 2012). Its treatment process involves influent flowing through to bioreactors after screening and grit removal then secondary clarifiers (Teklehaimanot *et al*., 2014). Final effluent is discharged into the Fouriespruit which forms the northern boundary of the WWTP, flows south eastwards, drains into the Klip River 3.5 km south east and the Klip River enters the Vaal River about 10 km south of the WWTP (ECO, 2012).

3.6 Conclusions

The main water users in the study area are: 1) Rand Water, the bulk potable water utility provider, 2) Sasol 1 even though it's in the Free State it still uses the same source and discharge in to the Vaal Barrage. 3) Eskom's Lethabo power station also in the Free State and ArcelorMittal which abstracts water from the Vaal Dam. It is important for all of these water users linked to the Vaal Dam and Vaal Barrage to establish synergistic wastewater management to preserve long term water resources.

A combined total of over 220 ML/d effluent from the four Sedibeng district WWTPs can be used as a year-long water resource for direct and indirect potable water, industrial and even agricultural reuse with appropriate fit for purpose advanced treatment. The discharges secondary effluent projections as detailed in this chapter are that this water resource will increase with population growth and municipal development plans.

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CHAPTER 4

RESEARCH DESIGN AND METHODOLOGY

4.1 Introduction

Sustainability science research, that seeks to answer research questions at a global scale with a local relevance, differs considerably in structure, methods and content from science as we know it (Kates *et al*., 2001). In wastewater reclamation, the challenge is to establish sound, cost effective, scientific, reliable, practical and efficient monitoring tools to reduce risks if there is exposure to reclaimed water (Levine and Asano, 2004). In addition, wastewater reclamation is an evolving discipline that has to answer research questions on public perception, technology, economic feasibility, which sometimes do not require conventional scientific data collection strategies.

The acceptability of a specific reclaimed water application is depended on physical, chemical and microbiological quality of water, which is important where health and the environment are of concern (Leverenz and Asano, 2011). However it is not possible to directly monitor and analyse all trace level organic substance and pathogenic microbial organisms with its species and strains since they are so diverse. The process is usually slow, labour intensive and analyses takes place in carefully controlled and specialized laboratories (Levine and Asano, 2004; ATSE, 2013). Traditional microbial monitoring methods are time consuming, implying that it can take up to four weeks to type and quantify water sample viruses. Rapid on-line monitoring of microbial pathogens that present acute health effects are either unavailable or unreliable (Figure 4.1), and it is essential to remove, destruct and inactivate pathogens (Crook, 2010). Indicator parameters such as coliform bacteria and chlorine residuals are used to counter the cost prohibitive and impractical nature of analyses of all pathogens (Leverenz and Asano, 2011).

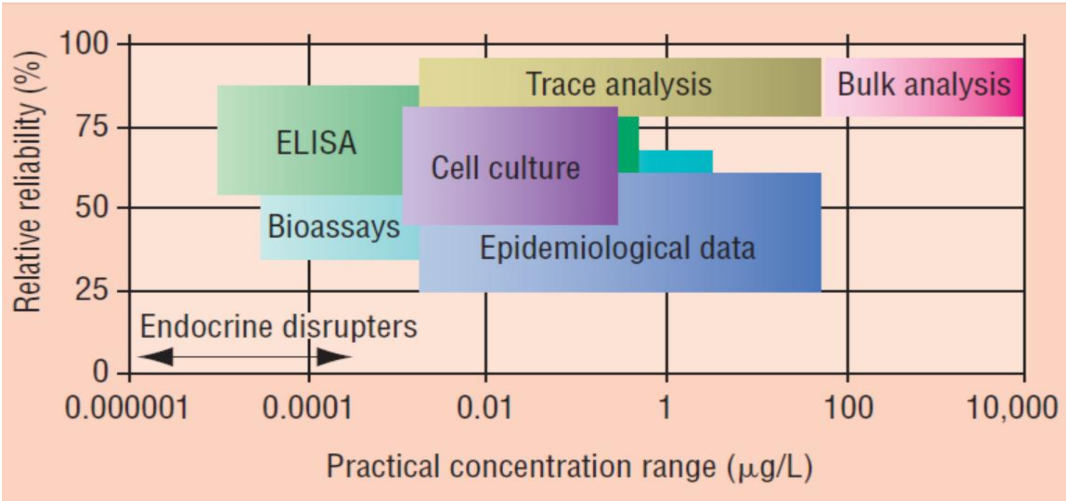

Figure 4.1: Complexity of wastewater reuse analyses (Levine and Asano, 2004)

Current legislation on wastewater reuse is based on physicochemical and microbiological parameters which are not sufficient in the evaluation of biological effects (Kontana *et al.*, 2008). The practical range of biological assays, for example, is at a tenth nanogram/L range and their reliability comparable to ELISA (Enzyme Linked Immuno Sorbent Assay) which is useful if wastewater reclamation for human contact and exposure is applied (Figure 4.1). These two methods can detect low-level effective ranges, which can be as low as parts per trillion, required to detect endocrine disruptors (Levine and Asano, 2004).

The research approach followed was benchmarking through theoretical considerations of existing wastewater reuse philosophies for potable, agricultural and industrial use. To assess the water quality suitability of the chosen study area of Sedibeng district municipality's WWTPs, analyses of chemical, physical and biological parameters were carried out and compared to existing wastewater reclamation standards. The following sections address the procedure carried out in sampling, laboratory and statistical analyses of these parameters.

4.2 Sampling and data collection

The main sampling was conducted in the four Sedibeng district wastewater treatment plants to determine the physical, chemical and microbiological parameters. Appropriate sampling bottles were used for each of these parameters using the Rand Water Analytical Services sampling methods (Rand Water, 2014a). Rand Analytical Services is International Standards Organization (ISO) 17025 accredited which specifies general requirements for the competency to carry out tests and or calibration including sampling. Emphasis on method validation, operator competency, equipment maintenance, credibility of results and procurement of stock, among others, are stressed to achieve accreditation (Balfour *et al.*, 2011).

4.2.1 Sampling sites

A description of each of the WWTP's sampling sites is given in the preceding chapter 3 of the dissertation, but the approximate co-ordinates are given below for each sampling site. Weekly samples on alternate days for each of the four wastewater treatment plants WWTP1, WWTP2, WWTP3 and WWTP4 in the Sedibeng district municipality were taken. The data collected was from January 2012 until December 2013 and this was averaging 104 data points for most parameters.

Table 4.1: Approximate co-ordinates of the four WWTPs sampling sites

Sampling location	Type of sample	Approximate Coordinates
WWTP1	Influent raw water	26^{o}34$^{'}$26.47” S
	Effluent discharge water	27^{o}48$^{'}$52.37” E
WWTP2	Influent raw water	26^{o}41$^{'}$38.67” S
	Effluent discharge water	27^{o}45$^{'}$43.10” E
WWTP3	Influent raw water	26^{o}40$^{'}$20.88” S
	Effluent discharge water	27^{o}53$^{'}$43.96” E
WWTP4	Effluent discharge water	26^{o}34$^{'}$58.60” S 27^{o}58$^{'}$24.62” E

Results for WWTP4 in Midvaal local municipality of the Sedibeng district municipality do not include incoming influent water quality analyses but do include an extensive effluent analysis (Table 4.1). The results for WWTP4 include total organic carbon (TOC) analysis in addition to chemical oxygen demand (COD) and suspended solids analysis for aggregate parameters results. This compared to turbidity analysis results, in addition to COD and suspended solids analyses for aggregate, of WWTP1, WWTP2 and WWTP3.

4.2.2 Sampling procedure

Sampling procedure for WWTP1, WWTP2, WWTP3 and WWTP4 of the Sedibeng district municipality was the Rand Water Analytical Services sampling procedure No. 3.3.1.10.1 (Rand Water, 2014a). Samples, if they were not analysed immediately, after scanning in were stored in a 5 ± 3^{o}C cool room with 30 minute interval temperature data logging (Rand Water, 2013a).

4.2.2.1 Physical and chemical analyses

Organic chemistry analyses sample bottles used were 1 L and 500ml Schott® glass bottles with scheduled barcodes for scanning in and out of the laboratory. Bottles were rinsed with samples then samples were taken 10-15 cm below flowing water surface, filled to the brim and stored in a cooler box with frozen ice bricks (Rand Water, 2014a).

For inorganic chemistry analyses, 1 L and 100 ml polypropylene sample bottles with scheduled barcodes were used. Bottles were also rinsed with samples then samples were taken 10-15 cm below flowing water surface, filled to the brim and stored in a cooler box with frozen ice bricks (Rand Water, 2014a).

4.2.2.2 Microbiological analyses

Bottles used for microbiological samples were sterilized 500 ml polypropylene bottles with scheduled barcode labels for scanning in and out to indicate starting and ending of sampling event. The bottles contained sodium thiosulphate, to neutralize chlorine and after sampling the bottles were stored in a cooler box with frozen ice bricks. No rinsing with sample was performed for the microbiological samples. Samples were filled up to 2 cm below the top of bottle and care was taken not to touch the inside of the bottle and cap (Rand Water, 2014a).

4.2.3 Sampling transportation and reception in laboratory

During transportation of samples to the laboratory samples were prevented from exposure to high temperature, ultraviolet and visible light by storing them in a cooler box with frozen ice bricks. This was to prevent growth or destruction of microorganism and an illustration of packaging of ice bricks and samples in Figure 4.2 that was followed after sampling (Rand Water, 2014a).

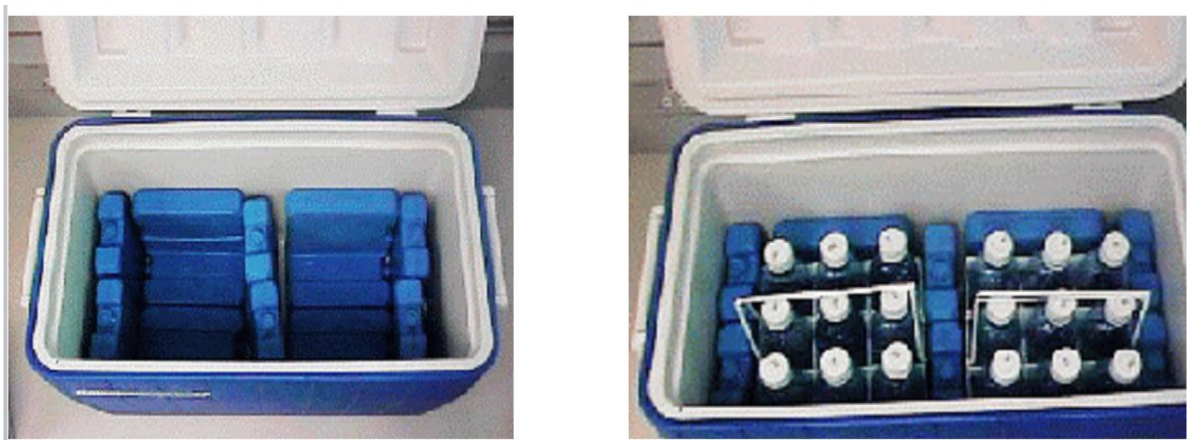

Figure 4.2: Packaging of ice bricks and samples (Rand Water, 2014a)

To indicate safe arrival of samples and to confirm chain of custody scanning of building barcode on arrival was conducted. The bottles were then scanned and stored in the cool room (Rand Water, 2014a).

4.3. Analytical parameters and techniques

Parameters of concern for treated wastewater effluent are classed as physical, chemical and biological. Aggregate parameters which can either be constituted by inorganic or organic components are represented by parameters such as COD, total suspended solids (TSS) and turbidity. Nutrients, salts and trace metals important for plant and animal life can be represented by conductivity, total dissolved solids (TDS). Microbiological water quality can be assessed by indicator pathogens, viruses, protozoa and helminthes.

Table 4.2: Physical, chemical and microbiological analyses conducted

Aggregate Parameter	Analytical method	Salinity parameter	Analytical method
TSS	APHA	Total hardness	APHA cation-aggregate
TOC	TOC Analyzer	Conductivity	Conductivity meter
COD	Dr Lange method	pH	pH meter
Turbidity	Turbidimeter	TDS	APHA
Nutrient parameter	**Analytical method**	**Biological parameter**	**Analytical method**
NH_4-N	APHA	*E. coli*	APHA
NO_3-N	APHA	Total Coliforms	APHA
NO_2-N	APHA	Faecal Coliforms	APHA
TKN	APHA	Helminths eggs	APHA
PO_4-P	APHA	Viruses	APHA
Organic parameter	**Analytical method**	**Inorganic parameter**	**Analytical method**
Oil and grease	APHA-TTHM	Al, B, Ca, Cd, Cr, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Si, V, Zn	ICP-OES
Phenol		Br^-, Cl^-, F^-, NO_3^-, SO_4^{2-}	IC

4.3.1 Chemical oxygen demand

Chemical oxygen demand (COD), gives the oxygen equivalent of the portion of organic matter in a sample, susceptible to oxidation under test conditions, after boiling with acid dichromate solution (Bartram and Ballance, 1996). Most organic compounds are oxidized by potassium dichromate under acid conditions and the dichromate is easy to manipulate, compared to other oxidants. Hence the dichromate method is used as a reference method for COD (Bartram and Ballance, 1996; UNEP, 2014).

The dichromate Rand Water Analytical Services method 2.1.3.0.3.1 was used for COD determination where low and high range COD are determined photometrically at wavelengths 345 and 436 nm respectively (Rand Water, 2014b). A sample is boiled at 150 ± 2^{o}C under reflux with potassium dichromate, silver sulphate catalyst and mercuric sulphate, as masking agent, in a strong sulphuric acid solution. The dichromate is partially reduced by oxidizable organic matter in the sample and the remainder is determined photometrically (Bartram and Ballance, 1996; Rand Water, 2014). COD analysis was carried out for the influent and effluent samples of WWTP1, WWTP2 and WWTP3. It was also carried out for the five years (2010-2014) bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources used by Rand Water. COD analysis of drinking water treatment residues (DWTR) supernatant, as source water with treatment capability, was also carried out for the study sampling period.

4.3.2 Total organic carbon and dissolved organic carbon

Dissolved organic carbon (DOC) is a portion of total organic carbon (TOC) that passes through a 0.45 µm pore size filter and particulate organic carbon (POC) which is a portion of TOC that is retained on the filter (USEPA, 2012; UNEP, 2014). The principle of DOC measurement involves ultraviolet catalysed persulphate oxidation of organics to CO_2 then subsequent infrared analysis. TOC analysis with Rand Water Analytical Services 2.1.1.01.2 was carried out for WWTP4 effluent and for the five years (2010-2014) bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources used by Rand Water (Rand Water, 2011e).

4.3.3 Suspended solids and turbidity

Suspended solids give rise to turbidity in water and the relationship between the amount of suspended solids and turbidity is dependant on particle size distribution. Therefore, following appropriate calibration, turbidity can be an indirect measure of total suspended solids (Chapman, 1996). Suspended solids are dried weight of material removed from measured volume of sample filtered through a standard filter (Bartram and Balance, 1996; Rand Water, 2013b). Turbidity or clarity of water is light scattering properties of a suspension, constituted by, among others clay, silt, finely divided organic and inorganic matter, plankton and microscopic organisms (Rand Water, 2011a)

The Rand Water Analytical Services suspended solids method 2.1.2.05.1 used in this study, is a gravimetric method that involves measurement of retained matter on a glass fibre filter ,after filtration of a well-mixed sample and drying of the filter at 103-105^{o}C. The glass fibre filter is a Whatman GF/C grade or equivalent and the drying is carried out until a constant weight with variability of 0.5 mg/l is obtained (Bartram and Ballance, 1996; DWAF, 1996c, Rand Water, 2013b; UNEP, 2014). The most reliable method for turbidity determination on the other hand is nephelometry or the light scattering by suspended particles measured using a turbidimeter which gives values of nephelometric turbidity units (Chapman, 1996). A strong light beam is sent through a tube containing a shaken sample, light reflected at 90 degrees to the axis is captured by photo cells and its electrical response is proportional to sample turbidity (UNEP, 2014). Rand Water Analytical Services method number 1.1.2.19.1, which follows the principle described above, was used for turbidity measurement in the study (Rand Water, 2011a). Suspended solids determinations for influent and effluent discharge of WWTP1, WWTP2 and WWTP3 and only effluent discharge for WWTP4 were conducted. Turbidity measurements were taken for final discharge effluent on WWTP1 and WWTP3.

4.3.4 Fats, oil and grease

Fats, oil and grease is a gravimetric method that measures n-Hexane extractable materials that are relatively non-volatile hydrocarbons such as vegetable oils, animal fats, waxes, soaps, greases and related materials. The principle of the method is that a sample is acidified to pH less than 2 then serially extracted three times, the extract is dried with sodium sulphate, the solvent is distilled and the product is desiccated and weighed (USEPA, 1999). The Rand Water Analytical Services hexane extractable materials (HEM) method 2.2.1.02.1 for oil and grease was used in this study (Rand Water, 2011b). These analyses were conducted for incoming influent for WWTP1, WWTP2 and WWTP3 and for discharge effluent for WWTP4.

4.3.5 Nutrients and metal salts

Total nitrogen in soils, plants, and any other environmental samples is basically composed of Total Kjeldahl Nitrogen (TKN) and nitrite and nitrate nitrogen (NO_2-N and NO_3-N) (Saha *et al*., 2012). TKN constitute tri-negative oxidation state nitrogen compounds of organic nitrogen, NH_4OH and NH_3 (Ergas and Aponte-Morales, 2014). Nitrite is an unstable, intermediate stage of the nitrogen cycle caused by oxidation of ammonia or reduction of nitrate hence it exists in natural waters at a low concentration (Bartram and Ballance, 1996).

The Rand Water Analytical Services colourimetric TKN method 2.1.8.02.2 was used in this study. It involves a shaken sample being digested for two hours with perchloric acid ($HClO_4$) and sulphuric acid or equivalent solutions at 380^{o}C to convert free ammonia and organic nitrogen to ammonium bisulphate (NH_4HSO_4) (Rand Water, 2011c; UNEP, 2014). The subsequent determination carried out either by the accurate but laborious distillation-titration method or colourimetric method (Saha *et al*., 2012). The latter method was used where the total ammonium nitrogen was determined at 660nm by the reaction of ammonia with salicylate and dichloroisocyanurate solutions in the presence of sodium nitroprusside to form an indophenol blue complex (UNEP, 2014). Total Kjeldahl Nitrogen was determined for WWTP1 influent, WWTP3 influent and effluent and WWTP4 effluent and ammonia was determined for influent and effluent for WWTP1, WWTP2 and WWTP3 and effluent for WWTP4.

There are four major general measures of ionic characteristics of water namely pH, alkalinity, hardness and conductivity which were analysed in this study with conductivity related to aggregate parameter of total dissolved salts (TDS). Salinity is the quantitative measure of soluble salts or TDS in water or soil and electrical conductivity is used as surrogate measure of the TDS concentration. TDS in natural waters can be measured by a gravimetric standard method or by use of conductivity/TDS meters at 25^{o}C (Atekwana *et al.*, 2004). In the case of gravimetric method determination of TDS, the principle is that a well-mixed sample is filtered with a standard glass fibre filter and the filtrate is dried to constant weight at 180^{o}C (Rand Water, 2012a). Conductivity is a measure of the ability of a solution to carry an electrical current and this ability is depended on the number and type of ions in solution (Rand Water, 2012b). Total dissolved solids (mg/l) may be obtained by multiplying the conductivity (µS/cm) by a factor that must be determined for each water body, that is commonly between 0.55 and 0.75 and it is 0.67 for waters dominated by sodium and chloride (Chapman, 1996). When using mS/m as a unit of measurement, the factor is 5.5 to 7.5 and the average conversion factor for most water is 6.5 (DWAF, 1999a). In this investigation, Rand Water Analytical Services conductivity Metrohm method 2.1.3.01.2 was used for influent and effluent of WWTP1, WWTP2, WWTP3 and effluent discharge of WWTP4 (Rand Water, 2012b). It was also used for the five years (2010-2014), bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources for Rand Water. The Rand Water Analytical Services gravimetric TDS method 2.1.2.04.1 was used for WWTP4 final effluent (Rand Water, 2012a).

Alkalinity involves titration of a sample with a standard solution of a strong mineral acid (0.04M H_2SO_4). Two colour indicators are used to determine the end point and for high accuracy electrometric titration is used which was the case with this study. Titration to the end point of pH 8.3, mainly for hydroxides and carbonates, determines the phenolphthalein (p)-alkalinity and the titration to end point pH 4.5 the total alkalinity or methyl-orange (m)-alkalinity (Bartram and Ballance, 1996; Rand Water, 2012b). The Rand Water Analytical Services pH and conductivity determination method 2.1.3.01.2 was used in this study for influent and effluent of WWTP1, WWTP2 and WWTP3. Alkalinity with the same method was used for influent of WWTP1, WWTP2 and WWTP3 and effluent of WWTP4 (Rand Water, 2012b). It was also used for pH, conductivity and alkalinity for the five years (2010-2014), bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources for Rand Water. The pH analysis of DWTR to determine its precipitation potential was also carried out using this method.

Atomic Absorption spectrophotometry (AAS) Rand Water Analytical Services method 2.1.9.01.1 was used for analysis of sodium (Na) for samples collected for WWTP1 and WWTP3. It was also used for the five years (2010-2014) bi-weekly sampling of Vaal

Dam-Canal and A18 Vereeniging raw water sources used by Rand Water (Rand Water, 2010a). Its principle is that while a sample is being aspirated into a flame, a light beam is directed through a flame into a monochromator onto a detector that measures the amount of light absorbed by the atomized element in the flame (Bartram and Ballance, 1996).

Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) is called Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) to distinguish it from Auger Electron Spectrometry (AES) (Boss and Fredeen, 1997). The principle of ICP-AES which is the same as ICP-OES is that an ICP source consists of a flowing stream of argon ionized by an applied radio frequency. A sample aerosol is heated and excited in the high temperature plasma, after it is generated, in a nebulizer and spray chamber and after returning to the ground state excited ions, produce ionic emission spectra (WHO, 2011). A temperature of 4000 to 8000 K which is two or three times hotter than combustion flame temperatures causes molecules to completely dissociate so that little interference between them exists (Sawyer *et al.*, 2003). ICP-OES was used for trace element analyses of sodium (Na) and total hardness for WWTP4 collected samples. The hardness of natural water depends mainly on calcium and magnesium salts and can be divided into carbonate and non-carbonate hardness (Chapman, 1996). The Rand Water Analytical Service multi-element ICP method 2.1.4.01.1 was used to analyse sodium and total hardness (Rand Water, 2011d).

Chromatography is a separation method based on affinity difference between mobile and packed or coated stationary phase, where compounds with less affinity to the stationary phase move more quickly through the column and elute earlier. In ion chromatography an ion exchanger is used as a stationary phase where colorimetric, electrometric and titrimetric detectors can be used for determining individual anions (WHO, 2011). In the study using Rand Water Analytical Services ion chromatography for high range method 2.1.7.01.1, anions in their acid form were measured by conductivity and identified on the basis of their retention times (Rand Water, 2010b). The following anions were determined using this ion chromatography method namely bromide, chloride, fluoride, nitrate and sulphate for WWTP4, for WWTP1 and WWTP3 only chloride, nitrate and sulphate and WWTP2 only nitrate. The anion determination was also used for chloride, nitrate and sulphate for the five years (2010-2014) bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources used by Rand Water.

4.3.5 Microbiological analyses

Due to the inherent constrains associated with pathogen monitoring indicator organisms are employed as surrogates for pathogens. The current monitoring approach, which was also partly used in the study, is to assess the microbial safety of reclaimed water using total and faecal coliform (Harwood *et al.*, 2005). Different methods for pathogen detection measure different properties, culture methods such as broth and agar based bacterial media and cell cultures for viruses and phages detect living organism based on infection or growth. Pathogen detection by microscopy, nucleic acid presence or amplification and immunological assays measure the physical presence of pathogen or its components whether dead, alive or infectious (WHO, 2011).

Faecal coliform (FC) bacteria are thermotolerant bacteria that grow and have the same fermentive and biochemical properties at 44^{o}C as they have at 37^{o}C. Escherichia coli (*E. coli*) inhabit the large intestine of humans and animals and its presence indicates recent faecal pollution. *E. coli* is a faecal thermo-tolerant coliform bacterium that ferments both lactose and mannitol with the production of both acid and gas, that produce indole from tryptophan and that hydrolyse 4-methyl-umbelliferyl-β-D-glucuronide (MUG) (SANS, 2015).

The IDEXX Colilert-18®/Quanty-Tray 2000 most probable number (MPN) test method's chemical reactions is based on Defined Substrate Technology™. A chemical substrate containing MUG is metabolized by the enzyme β-glucuronidase releasing the 4-methyl-umbelliferyl dye which fluoresces at 365 nm and is measured after 18 hours at 35^{o}C incubation (Kinzelmann *et al.*, 2005; Rand Water, 2012c). The Rand Water Analytical Service Colilert method 1.2.2.09.1 was used to enumerate coliform bacteria for

WWTP1, WWTP2 and WWTP3 effluent and *E. coli* for WWTP1, WWTP2, WWTP3 and WWTP4 (Rand Water, 2012c).

4.4. Data and statistical analyses

Methods of data analyses are primarily determined by the hypothesis to be tested and this determines the instrument and the level of data gathering and there is a general confidence and dependence in statistical data analyses in the quantitative research approach (Ashley and Boyd, 2006; Baron, 2010). Laboratory data on the water quality of the incoming influent into the four WWTPs and effluent leaving the WWTPs was collected over a period of two years from January 2012 to December 2013. The data was analyzed to test the viability of different reuse options and technology required for that reuse option based on water quality parameters to test the hypothesis. Which was that the lack of characterization parameters as well as advanced wastewater treatment methods viability assessments of the municipal wastewater generated in the South Gauteng catchment, has led to loss of potential water resource in the province

Spatial or temporal patterns were illustrated using graphical illustrations if the trends were strong then simple time plots or linear regression can revealed trends and in complex situation statistical models and procedures were needed and applied. Complexity arose from overlaying short term and long term trends, cyclical effects such as seasonal and weekly variations, autocorrelations and impulses as well as jumps due to interventions or procedural changes (USEPA, 2006). Graphical representation of trend lines, histograms and boxplots were carried out using Microsoft Excel and R software. Trend lines were used to analyze trends over a period of time and they were used to illustrate maximum and minimum contamination level in wastewater reclamation. Histograms were used to illustrate normality of data and also show maximums and minimum guidelines.

Boxplots are an excellent way of summarizing data, demonstrating normality, dispersion or spread and other descriptive statistics. Some boxplots give the median as 50th percentile and this descriptive statistic is the second most used measure of central tendency after the mean. The median was used in this investigation since it is not influenced by extreme values and non-detects (USEPA, 2006; Dytham, 2011). Measures of central tendency are more meaningful if accompanied by measures of dispersion, and this investigation range and standard deviation were used (USEPA, 2006). Statistical outlier tests give probabilistic evidence that an extreme value does not “fit” in with the remainder of the data and cannot determine if an outlier should be discarded or corrected. Potential outliers may be identified through graphical representations such as box and whiskers, ranked data, normal probability and time plots (USEPA, 2006). The box and whiskers and time plots were used to identify outliers in the study and they were not discarded as they scientifically did not significantly affect data.

Any transformation of data if it is significantly different from normal is allowed as long as every piece of data or datum is treated the same (Dytham, 2011). It is not recommended to transform data for estimation purposes such as transforming, estimating, and then transforming the estimate back to the original domain (USEPA, 2006). Microbiological parameters of faecal coliforms and *E. coli* for the four WWTPs were significantly variable and Log_{10} transformations were carried out to normalize and graphically illustrate them.

Data sets often include measurements of several variables for each sampling point and a level of association between two or more variables and one of the most common measures is association. Pearson correlation may be sensitive to extreme values or what is called non-parametric data especially when sample sizes are small and therefore it is wise to use scatter plots in conjunction with correlation coefficient (USEPA, 2006; Dytham, 2011). This scatter plot was used to correlate total dissolved solids and conductivities in chapter 5.

4.5 Conclusions

Research methodology and subsequent analytical methods must provide data that answers the research questions and make generalizations that are valid, reliable and repeatable. Analytical methods can be time consuming, expensive, inconclusive and require specific technical expertise and hence fit for purpose analytical methods must be chosen with these factors in mind.

Physicochemical and microbiological water quality analyses of four WWTPs for the incoming influent into the WWTP and effluent leaving the WWTP was collected over a period of two years from January 2012 to December 2013. The data was analyzed to test the viability of different reuse options and technology required for that reuse option based on water quality criteria and standards for potable, agricultural and industrial use. Hence physicochemical analyses were carried out for the DWTR supernatant and five years (2010-2014), bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources for Rand Water for comparison.

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CHAPTER 5

Results and discussion

5.1 Introduction

Worldwide, the dynamics of climate change, water availability, population growth and urbanization, industrialization, economic growth and perceptions on wastewater reuse, among others, are important for any study on wastewater reuse. The eventual decision to revert to wastewater reclamation, recycling and reuse for potable, agricultural and industrial purposes can be broadly described as influenced by the following factors which some of them are interpreted in the study:

- Population growth, density and per capita usage
- Climate and geology, including precipitation, evapotranspiration, hydrogeological storage and aridity
- Environmental regulations and degradation
- Intensive industry water requirements such as power generation
- Agricultural practices and perceptions
- Availability of infrastructure to capture, transfer and store available water
- Public perceptions and acceptance

Israel, Australia and Singapore, for example, are influenced by local history, geography and cultural practice that lead to choice of reuse options (NRC, 2012). Countries such as Australia and United States can be emulated by South Africa in their progressive wastewater reclamation regulation and guidelines. Namibia, Israel and Singapore, of which South Africa, can benchmark against are leaders in sustainable municipal wastewater reuse for potable, agricultural and industrial application respectively (van Niekerk and Schneider, 2013). In South Africa, because of economic growth, urban and industrial settlements towards mineral resources and variable rainfall patterns, flow regimes have been altered which has resulted in water resources quality degradation. In urban and industrial areas of Gauteng only, approximately 50% of water is available as return flows, which indicates the existence of indirect unplanned reuse (Schutte, 2008; DWA, 2010).

The first direct potable reuse (DPR) worldwide is the Namibian Goreangap water reclamation plant (WRP) which has been in operation since 1968 and this study uses some of its water quality guidelines (NRC, 2012; ATSE, 2013). In South Africa, DPR without an environmental buffer was the commissioning in 2011 of the Beaufort West WRP which is also benchmarked in this study (Marais and von Durckheim, 2012; GAA, 2012; ATSE, 2013; Swartz, 2014). In 1985, one of the options mooted by DWA was to use, for domestic purposes, Johannesburg Northern and Kempton Park WWTP treated municipal effluent via their tributaries Klip and Blesbokspruit respectively. This signifies institutional memory and capacity that provides scope for this study area to potentially use its treated municipal effluent to augment potable water sources as one option, after tertiary treatment (DWAF, 2006).

Irrigation with reclaimed municipal wastewater is currently practiced mainly for recreational facilities such as sports fields, golf courses and parks. In the study area agriculture has an influence on the water quality of the Vaal River Barrage reservoir but water abstracted for agricultural purposes (e.g. irrigation) is minor in terms of volume compared to the other abstractions (Ochse, 2007). A proposal to supply small scale farmers or resource poor agriculture in the Southern Gauteng with local treated municipal effluent was rejected previously. This was because of the fear that point source salt loading will find its way back into the Vaal River through difficult to monitor and control diffuse source from run-off, hence the results of this study will not focus on agriculture (DWAF, 2006).

Industrial wastewater reclamation from treated municipal wastewater is not widespread in South Africa. Only internal on-site generated wastewater recycling following the zero liquid effluent discharge (ZED) philosophy occurs at certain industrial sites (van Leeuwen, 1996; Grobicki and Cohen, 1999; Schutte, 2008). Few cases of water reuse from treated municipal wastewater are in the pulp and paper (e.g. Durban Mondi and

Sappi Enstra Paper Mill) and oil (e.g. Durban Sapref and Sasol Sasolburg) industries as an example (Gisclon *et al*., 2002; USEPA, 2004; Schutte, 2008). The other two industries in the study area, namely power and steel, with the potential to reuse municipal wastewater are Eskom's Lethabo power station and Arcelor Mittal which have also adopted the ZED philosophy in 1987 and 2005 respectively. This has necessitated installation of costly reverse osmosis water treatment processes for example to meet their recycling water quality requirements (Pather, 2004; Wilson, 2008).The two local power and steel industries form the focus of the results in this study and the petrochemical giant Sasol in Sasolburg does not form part of the results. This is because, as much as the petrochemical giant abstracts and discharges into the Vaal River, it is situated in the Free State and already uses the municipal wastewater from the Metsimaholo municipality for its process water (Schutte, 2008; DWA, 2013).

5.2 Data analyses parameters and reuse applications

Table 5.1 and 5.2 present a summary of results for the four sampled Sedibeng district WWTPs, which are designated WWTP1, WWTP2, WWTP3 and WWTP4 as described in Chapter 3. Table 5.1 gives the calculated averages, recoveries and standard deviation of aggregate, nutrients, ionic and microbiological parameters for the four sampled WWTPs over two years between January 2012 and December 2013. Table 5.2 compares these averages with local and international established operating standard and guidelines.

Table 5.1: Two years averages of analytical determinants of Sedibeng WWTPs influent, effluent and recoveries

Constituents (Average)		WWTP1 Means				WWTP2 Means				WWTP3 Means				WWTP4 Means	
		Influent	Effluent	%Change	SD_{eff}	Influent	Effluent	%Change	SD_{eff}	Influent	Effluent	%Change	SD_{eff}	Effluent	SD_{eff}
Aggregate Parameters	COD (mg/l)	199.9	19.7	90.1	5.8	93.5	21.3	90.8	7.3	224.2	26.9	85.3	6.4	101.0	84.6
	TSS (mg/l)	82.0	0.6	99.2	7.2	232.7	29.7	67.0	20.2	97.5	3.0	96.3	6.4	28.2	33.3
	Turbidity (NTU)		3.3		2.4						4.1		2.4		
	TOC (mg/l)													12.3	10.6
	FOG (mg/l)	16.0				19.3				16.1				4.62	3.8
Nutrients	NH_4^+ (mg/l)	14.7	0.5	96.6	2.1	23.6	1.0	94.4	1.6	26.7	3.2	88	3.9	25	10.9
	NO_3^- (mg/l)	2.8	3.7	-34.0	2.5	0.6	4.6	-651.1	1.6	0.8	3.5	-354.7	2.5	2.6	2.3
	TKN (mg/l)	23.1								31.1	6.0	80.7	7.40	25.0	17
	PO_4^{2-} (mg/l)	2.2	0.3	85.0	0.4	3.0	1.0	67.8	0.5	2.8	0.9	66	0.7	4.1	3.4
Ionic parameters	pH (pH units)	7.06	7.07	0.09	0.3	7.06	7.12	-0.75	0.3	7.06	7.11	0.79	0.3	7.6	0.3
	Conductivity (mS/m)	52.5	40.8	22.4	4.2	69.4	57.4	17.3	9.9	86.2	60.4	29.9	8.7	92.8	16.9
	TDS													470.1	
	M-Alkalinity (mg/l as $CaCO_3$)	182				241.6				293				419.3	275
	SO_4^{2-} (mg/l)		37.9		14.7						55.6		20.7	33.3	19.0
	Na^+ (mg/l)		33.8		3.4						41.7		4.0	84.8	24.9
	Cl^- (mg/l)		30.2		11						75.0		22.4	65.2	16.3
Microbiological	FC (FC/100ml)		4776		18188		15979		36725		1443		3487		
	E. coli (MPN/100ml)		5259		21006		12783		28850		1589		4090	$1.4x 10^6$	$2x10^6$

NOTES: SD_{eff} = Standard Deviation of effluent, % Change = Change in water quality after WWTP treatment process

Table 5.2: Four Sedibeng district WWTPs effluent quality compared with water quality criteria for different reuses

Worldwide standard Parameters	Sedibeng District WWTPs means				Potable Water Reuse			Agriculture		Industrial Reuse		
	WWTP1	WWTP2	WWTP3	WWTP4	SANS 241:2015	Beaufort West 2^0 Effluent[+]	Namibia Final[++]	WHO 2006	DWAF General limit[#]	[*]Eskom Cooling	[**]Durban Mondi 2^0 Effluent	Bluescope 2^0 Effluent[***]
COD (mg/l)	19.7	21.3	26.9	130.8	-	47	15	-	75	75	19	-
TSS (mg/l)	0.6	29.7	3.0	28.2	-	20		100	25	-	4	1
NH_4^+ (mg/l)	0.5	1.0	3.2	25	1.5	4.9	0.1	30	3	15	0.5	1
NO_3^- (mg/l)	3.7	4.6	3.5	2.6	11	16	10	30	15	15	12	4
PO_4^{2-} (mg/l)	0.3	1.0	0.9	4.1	-	5.1		20	10	-	8	1
SO_4^{2-} (mg/l)	37.9	-	55.6	33.3	500	-	200	-	-	100	17	1
Cl^- (mg/l)	30.2	-	75	65.2	300	-	250	140	-	180	64	20
pH (pH units)	7.07	7.06	7.11	7.6	5 - 9.7	7.5	-	6-9	5.5-9.5	9	7	7.5
Conductivity (mS/m)	40.8	63	60.4	92.8	170	122	-	300	150	400	44	-
M-Alk(mg/l as $CaCO_3$)	182	241.6	293	419.3	-	-	-	500	-	150	51	-
FC (CFU/100ml)	4776	15979	1443		0	-	0	-	1000	10^6	-	1
E. coli (MPN/100ml)	5259	12783	1589	248900	0	-	0	-	-	-	-	-

NOTES: [+](WWE, 2012; 2^0= Secondary effluent from WWTP)[++] (du Pisani and Menge, 2013) [#](DWAF, 1999) [*](van Zyl and Premlall, 2005; Asano *et al.* 2007) [**](Grobicki and Cohen, 1999) [***](Hird, 2006)

5.2.1 Aggregate parameters

The treatment goal in reclaimed water is to achieve less than 1-10 mg/l in terms of five day biochemical oxygen demand (BOD_5), total organic carbon (TOC) and total suspended solids (TSS). This is from an approximate range in treated wastewater that is the influent of the WRP, which varies at 10-30 mg/l for BOD_5, 1-20 mg/l for TOC and less than 1-30 mg/l for TSS (Levine and Asano, 2004). Worldwide COD is not used as a primary aggregate parameter, but in South Africa and neighbouring Namibia is used extensively. Secondary treatment effluent from the Gammams municipal WWTP in Windhoek that supplies the WRP has COD concentrations of approximately 60 mg/l. It is discharged into maturation ponds where the COD is reduced to 30-40 mg/l after 2-4 days to meet the design capacity of 43 mg/l. This effluent serves as raw water for the New Goreangab WRP for direct potable reuse (DPR) and, as shown in Figure 5.1, the limit is set at 40 mg/l for this investigation (Lahnsteiner and Lempert, 2007). The Beaufort West WRP for potable drinking water purposes COD maximum concentration requirement from the WWTP is the DWAF general limit of 75 mg/l which is less stringent (DWAF, 1999; WWE, 2012).

The COD averages for the four WWTPs are 19.7, 21.3, 26.9 and 130.8 mg/l respectively for WWTP1, WWTP2, WWTP3 and WWTP4 (Table 5.1 and 5.2). For WWTP1 it is below 20 mg/l as shown in Figure 5.1, which is over 50% below the design capacity of the New Goreangab WRP of 43 mg/l and only in one incident during the week of 14 August 2012 was the COD over this limit at 57 mg/l. The same week, also recorded the highest value of turbidity with two other incidences over the 5 mg/l recommended by the USEPA (USEPA, 2012). The COD for WWTP2 was only above 43 mg/l less than 5% of the time during the sampling period (Figure 5.3). The COD average for WWTP3 over the two years sampling period is slightly higher than WWTP1 and WWTP2 but below the maturation ponds effluent quality design criteria of 30-40 mg/l (Lahnsteiner and Lempert, 2007). The COD of the secondary effluent of WWTP4 is above the 60 mg/l over 50% of the time during the two year study period and the average is at 101 mg/l with a standard deviation of ±84.6 mg/l (Table 5.1). The 60 mg/l is the typical secondary effluent COD before maturation ponds for COD Namibia WRP

(Figure 5.4) even though the dispersion as measured by the standard deviation is very high for WWTP4 (Lahnsteiner and Lempert, 2007).

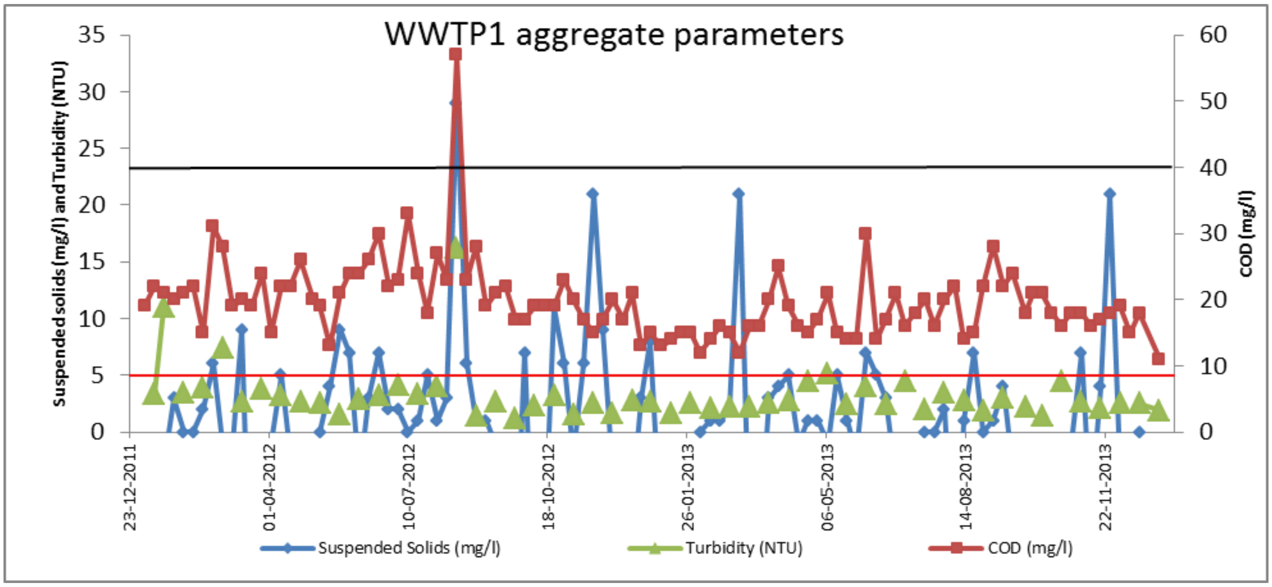

Figure 5.1: WWTP1 effluent aggregate parameters over two year sampling period

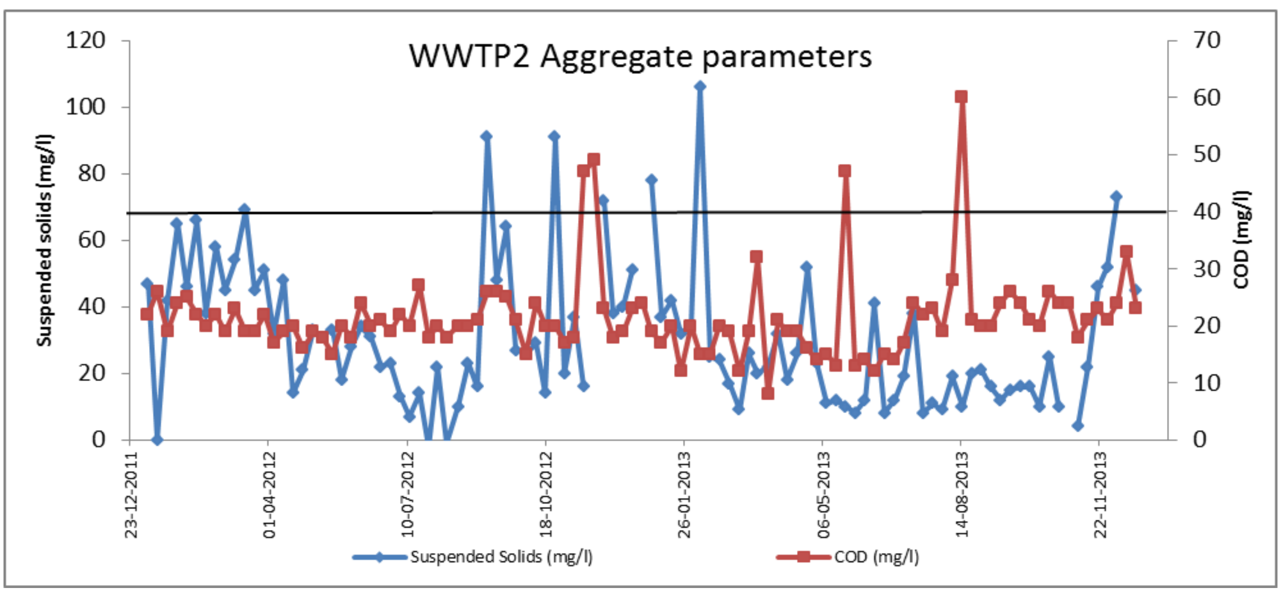

Figure 5.2: WWTP2 effluent aggregate parameters over two year sampling period

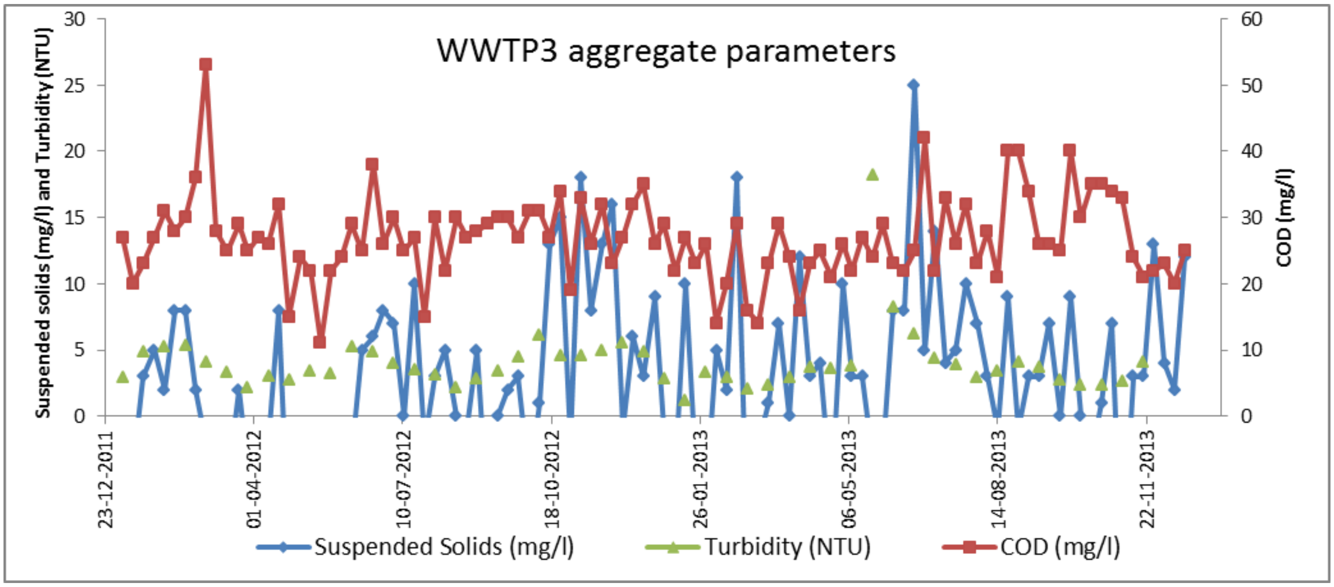

Figure 5.3: WWTP3 effluent aggregate parameters for two years sampling period

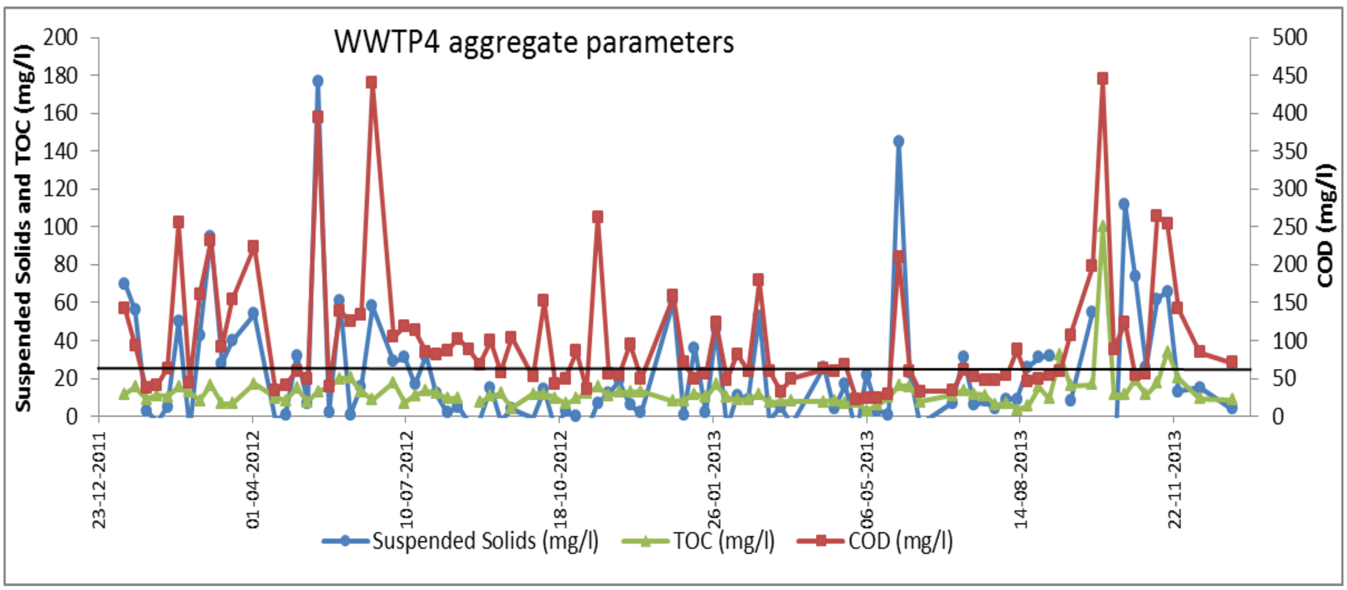

Figure 5.4: WWTP4 aggregate parameters for the two year sampling period

The South African National Standard (SANS) 241-1:2015 for drinking water distinguish between operational and aesthetic quality limits for turbidity and specifies them at 1 NTU and 5 NTU respectively. Turbidity, related to suspended solids, can be noticed by the naked eye, which is aesthetic, at approximately 4 NTU and to ensure effective disinfection for operational quality it should be no more than 1 NTU (SANS, 2015). It should be, even lower, in large well run water supply utilities to save disinfection cost and to maintain disinfection residual among others. For small water supply and usually rural utilities 5 NTU, which is the limit curve set for this investigation in Figure 5.1, is still acceptable based on affordability of turbidity measuring systems (WHO, 2011).

WWTP1's turbidity is within specification of aesthetic water quality 95% of the time during the two years study period using SANS 241-1 classification. The suspended solids for WWTP1 are below 10 mg/l for more than 95% of the time and below 30 mg/l for 100% of the time which is acceptable for secondary treated effluent used as influent for wastewater reclamation (Levine and Asano, 2004). There were no turbidity measurements for WWTP2 and the total suspended solids (Figure 5.2) for WWTP2 fluctuated considerably at an average of 29.66 mg/l and a standard deviation of ±20.20 mg/l. The turbidity measurements of WWTP3 discharge effluent (Figure 5.3) shows levels of more than 5 NTU less than 10% of the time which is the maximum at any time for the above mentioned reclaimed water uses (USEPA, 2012). The suspended solids results for WWTP3 were approximately 4 mg/l and over 65% of the time below 5 mg/l (Figure 5.3). The WWTP3 discharge effluent meets the design requirement over 95% of the time for a Namibia WRP influent of turbidity at 53 NTU and COD at 43 mg/l. Suspended solids for WWTP4 (Figure 5.4) are inconsistent and fluctuating for the most part in the two year study period. It is over the 30 mg/l 25% of the time and 50 mg/l 15% of the time respectively for water reclamation recommendation.

TOC measured only for WWTP4 is for the most part stable at approximately <20 mg/l for the sampling period increasing to over 250 mg/l around October 2013 (Figure 5.4). The average is 12.3 mg/l and this is twice the five years (2010-2014) bi-weekly Vaal Dam-Canal and A18 Vereeniging raw water sources used by Rand Water at average 6.0 and 6.4 mg/l respectively (Table 5.1 and 5.4). This is consistent and complies with target range of 1-20 mg/l as a requirement for wastewater treatment effluent used for WRP influent (Levine and Asano, 2004).

Typical suspended solids tolerable concentration required for the petrochemical, textiles, paper and pulp industries processes are 10 mg/l and they are even less stringent for cooling tower water (CSIRO, 2008). Fats, oil and grease (FOG) as part of the aggregate parameters, even though not listed in potable water standards such as SANS 241-1 (2015), are very important for industrial processes involving heat exchange for example. FOGs are listed as soap, oil or grease in the general and special authorization and the limits are 2.5 mg/l and zero respectively (DWAF, 1999). The FOG analysis in the investigation was carried out only for WWTP4 effluent of which its average was 4.62 mg/l (Table 5.1) and for the other three WWTPs only the influent was analysed (Figure 5.5). FOG, which causes foaming, in paper manufacturing processes, typical values of treated effluent from the Southern WWTP supplying Mondi paper were 12.6 mg/l in 1997 (Grobicki and Cohen, 1998).

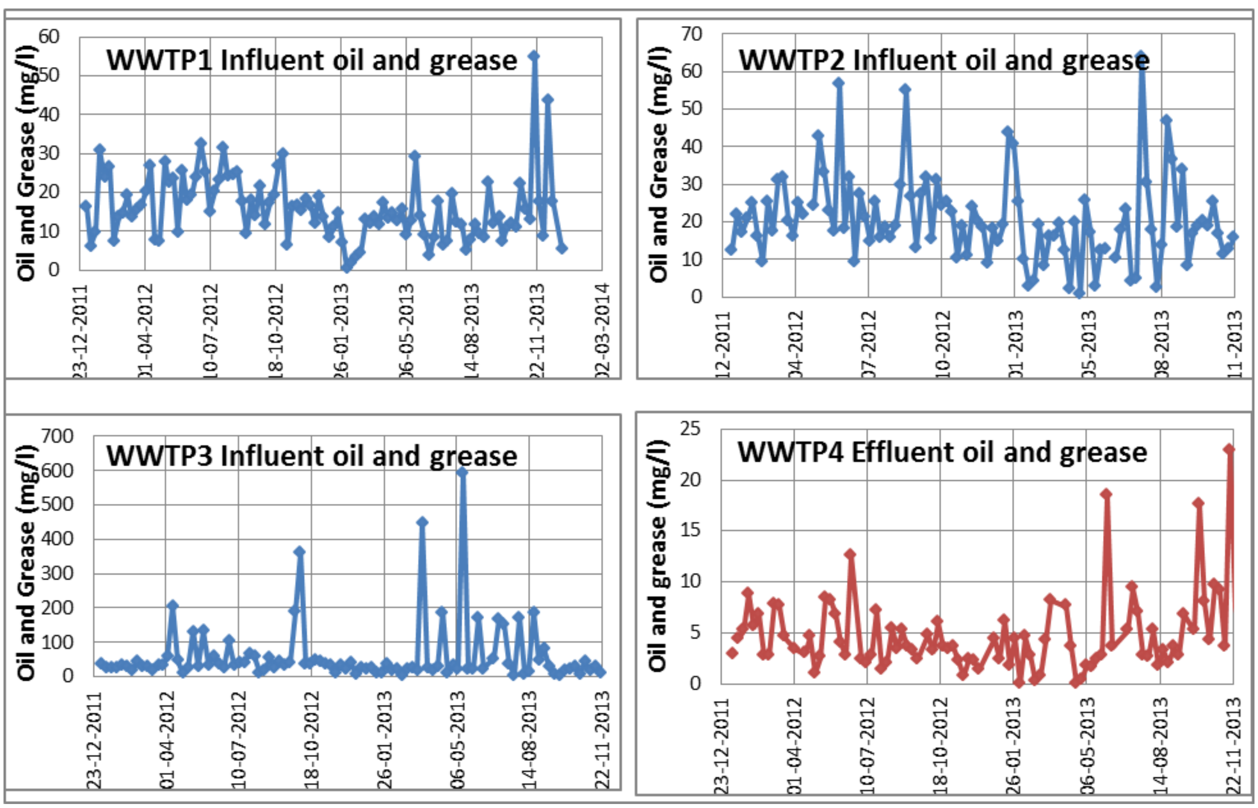

Figure 5.5: FOG analysis for Sedibeng WWTPs over the sampling period

The South African water quality guidelines on industrial use have four categories of industrial water based on deteriorating water quality. Category 1 has COD TWQR of 0-10 mg/l with no effect for high recycle cooling water, high pressure demineralized boiler feed water, product and process water in pharmaceutical and petrochemicals and wash water for electronics (DWAF, 1996a). Category 2 and 3's water with TWQR with no effect at 0-15 mg/l and 0-30 mg/l respectively can still be used for high recycle and once through boiler feed water, moderate high pressure and low pressure cooling water and other miscellaneous process functions. These include water used for solvents, lubrication, transport and dilution agents, gas scrubbing, descaling as well as gland and vacuum seal. In the set TWQR there should be no damage to equipment, no interference with processes, no effect on product quality and no problems in waste handling (DWAF, 1996a). WWTP1, WWTP2 and WWTP3 effluents are suitable for Category 3 industrial waters. The first two are at an average COD of approximately 20 mg/l and the last at 26 mg/l. WWTP4 at an average of over 60 mg/l is not suitable for Category 3 industrial water (Figure 5.6).

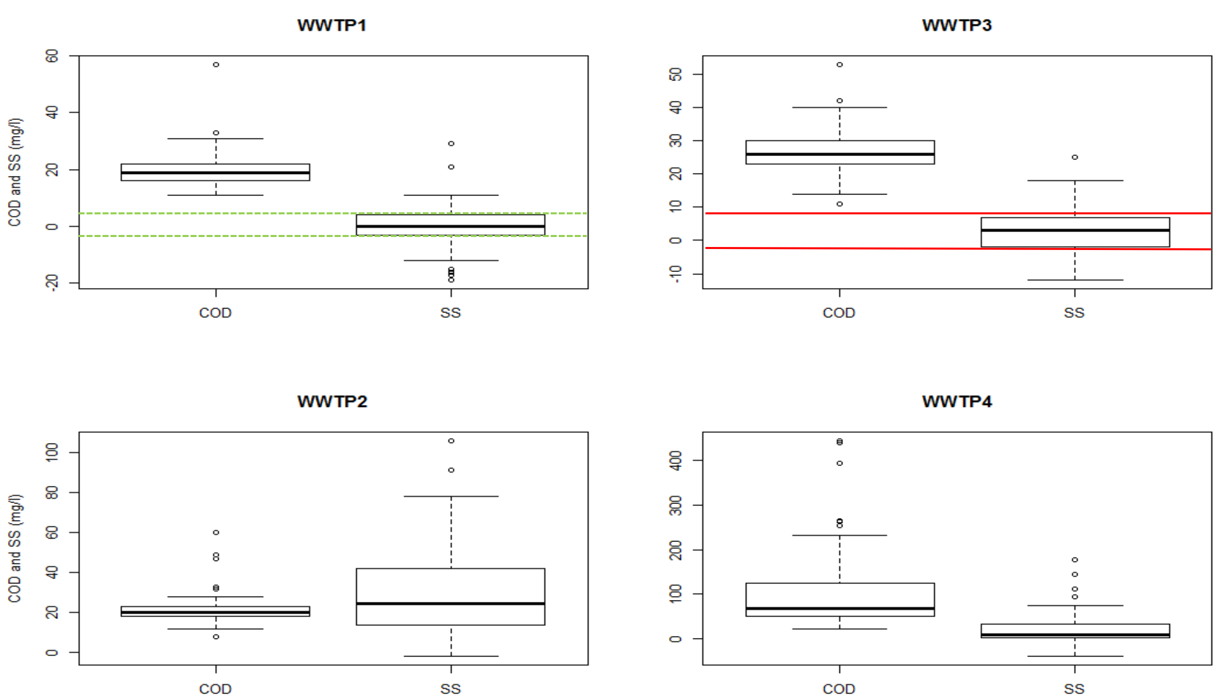

Figure 5.6: COD and suspended solids for over two year weekly samples

Suspended solids are undesirable in industrial processes and this is demonstrated by a TWQR of 0-3 mg/l for category 1 and 0-5 mg/l for category 2 and 3 water (DWAF, 1996a). There is generally a high degree of dispersion in the results obtained for the study in terms of total suspended solids with WWTP2 and WWTP4 giving the most dispersion and WWTP1 and WWTP3 with the least. WWTP1 is within specification for category 1 when using the median and with specification for category 2 and 3 industrial water when using the interquartile range. WWTP2 will qualify for category 2 and 3 when using the median and category 4 when using the interquartile range or 50% of the values (Figure 5.6).

5.2.2 Nutrients

Total nitrogen is composed of tri-negative oxidation state Total kjeldahl nitrogen (TKN) compounds (Org-N, NH_4OH, NH_3), nitrite and nitrate (Saha *et al*., 2012; Ergas and Aponte-Morales, 2014). The approximate range after secondary wastewater treatment is 10 to 30 mg/l for total nitrogen and 0.1 mg/l to 30 mg/l for phosphorous. The Namibian WRP for DPR philosophy is that nutrient removal should be completed in the secondary treatment stage of biological nutrient removal (du Pisani and Menge, 2013).

The SANS 241-1:2015 sets limits for nitrate and nitrite for acute health effect at less than 11 mg/l and 0.9 mg/l respectively and ammonia for aesthetic reasons at <1.5 mg/l. There is no set limit for TKN in this drinking water standard even though it is very important for secondary treated effluent from WWTPs (SANS, 2015). WHO drinking water guidelines do not have guidelines for ammonia since it occurs in water at levels well below health concern. Nitrate and nitrite are set at <50 mg/l and <3 mg/l respectively for short time exposure (WHO, 2011). When ammonia decreases then nitrate should increase and this pattern is observed only for WWTP1 and WWTP2 in the study (Figure 5.7). This is because nitrate generally increases after nitrification in biological nutrient removal. The averages for nitrate were 3.7, 4.6, 3.5 and 2.6 mg/l for WWTP1, WWTP2, WWTP3 and WWTP4 respectively. This compared to ammonia at

0.5, 1.0, 3.2 and 25 mg/l for WWTP1, WWTP2, WWTP3 and WWTP4 respectively which should generally decrease after the activated sludge process (Table 5.1).

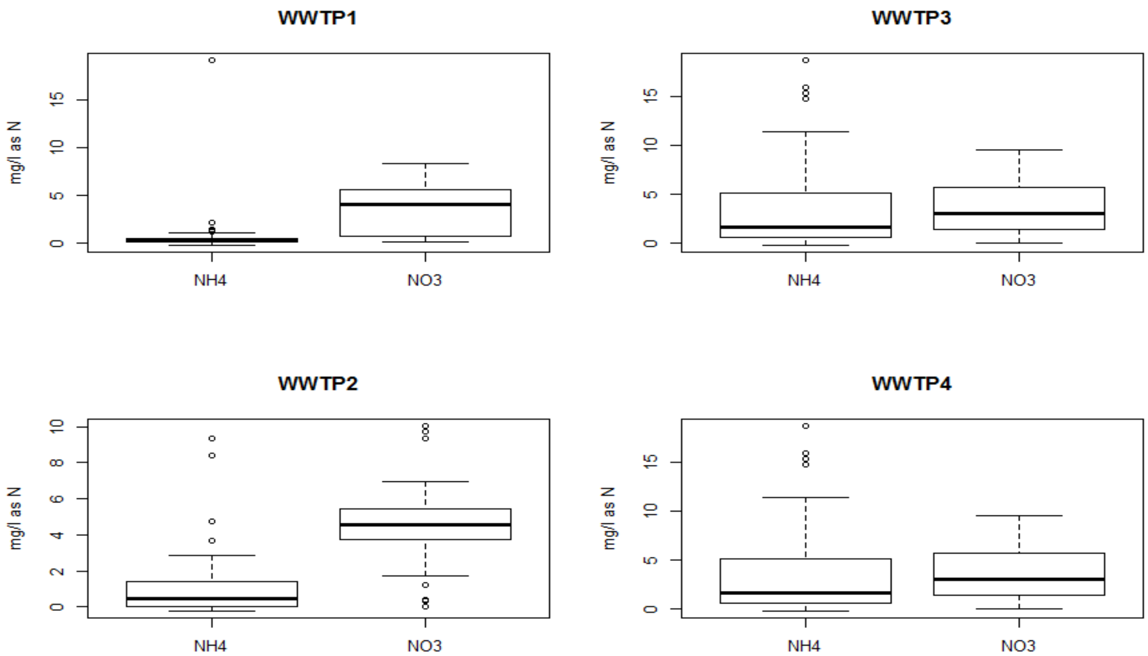

Figure 5.7: WWTPs ammonia and nitrate levels for the two years weekly samples

WWTP1 and WWTP2 comply and WWTP3 and WWTP4 do not comply with regard to ammonia at <1.5 mg/l using the SANS 241:2015 class 1 drinking water standard (SANS, 2015). Ammonia levels at median value of 25 mg/l and interquartile range or 50% of values between 18 and 30 mg/l in WWTP4 are higher than nitrate levels over the two years of sampling from January 2012 to December 2013 (Figure 5.7). Reclaimed water that has not been nitrified or denitrified can contain ammonia-nitrogen concentrations of >20 mg/l which is the case with WWTP4 and can exert a nitrogenous oxygen demand of up to 100 mg/l (USEPA, 2012). The nitrate levels for acute health as set by SANS 241-1 (2015), complies for all WWTPs of the Sedibeng district municipality, since they are all below 5mg/l for the two year study period. The nitrite parameter recorded for WWTP4 does not comply with the SANS 241-1(2015) acute health effect of 0.9 mg/l.

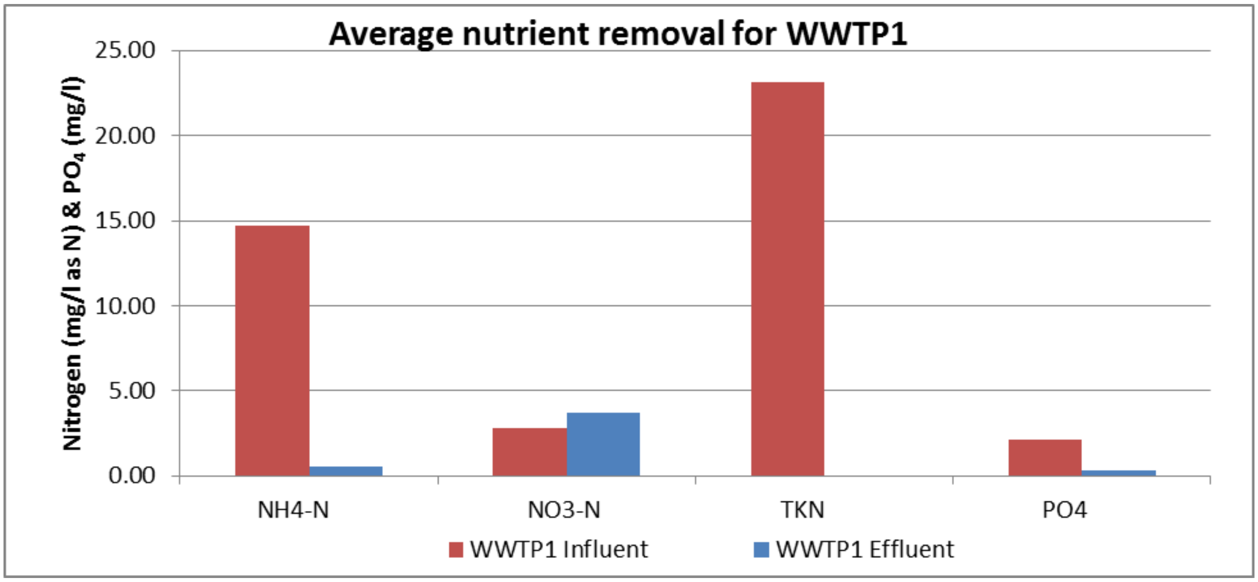

Figure 5.8: WWTP1 two years average nitrogen and phosphate nutrients removal

Total Kjeldahl nitrogen (TKN) was very high at an average of 23.1 mg/l (Table 5.1) in the influent for WWTP1. Even though the effluent for WWTP1 TKN was not measured the effluent nitrate and ammonia combined were below 5 mg/l which indicates effluent TKN was low as well. Average phosphate levels for WWTP1 during the study period were approximately 2 mg/l before biological nutrient removal and <1 mg/l for discharged effluent (Figure 5.8).

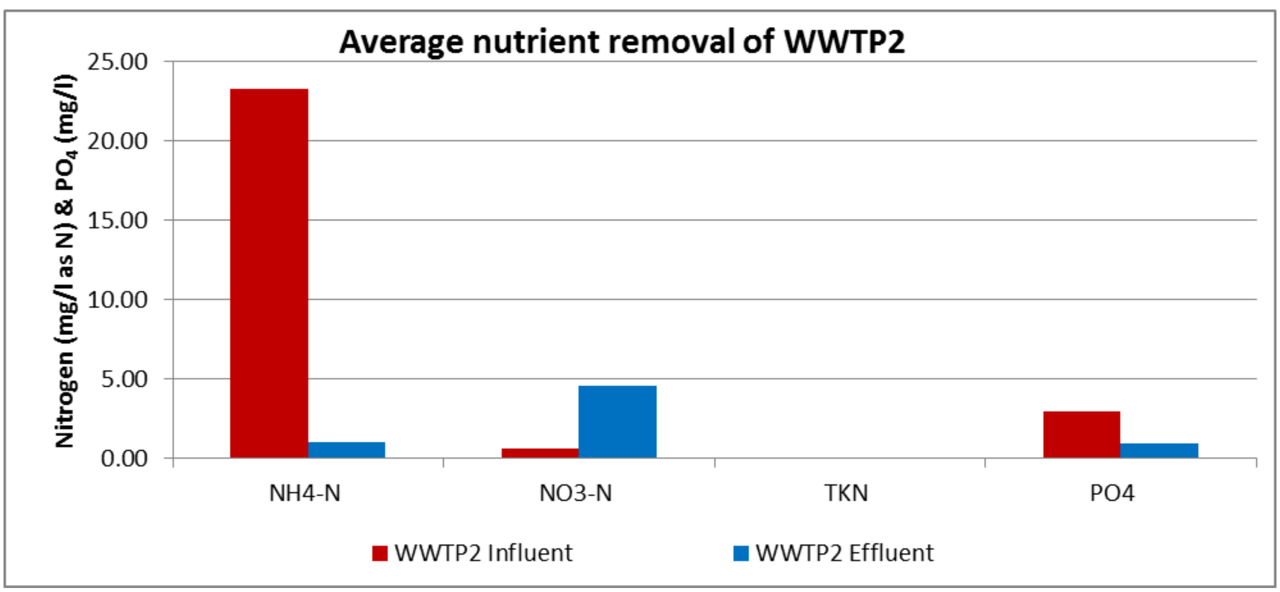

Figure 5.9: WWTP2 two years average nitrogen and phosphate nutrients removal

Although TKN is not measured for secondary treatment influent and effluent for WWTP2 ammonia and nitrate were below 5 mg/l the TKN should not be expected to be significant in a well-functioning biological nitrogen removal (BNR) system. WWTP2 has an effective BNR system since there is over 90% removal of ammonia (Figure 5.9). Since the ammonia and nitrate form part of TKN it can be deduced that the latter will also be low. Phosphate levels for WWTP2 in the effluent were below 1 mg/l.

Effluent ammonia, nitrate and TKN for WWTP3 were approximately 3, 4 and 6 mg/l respectively and this is well below the SANS 241-1 limit for nitrate for acute health effect. Even though the WWTP3 effluent ammonia at 3 mg/l does not comply with the <1.5 mg/l SANS 241-1 for aesthetic reasons and the DWAF general limit of 3 mg/l, further tertiary treatment could improve the quality (DWAF, 1999; SANS, 2015).

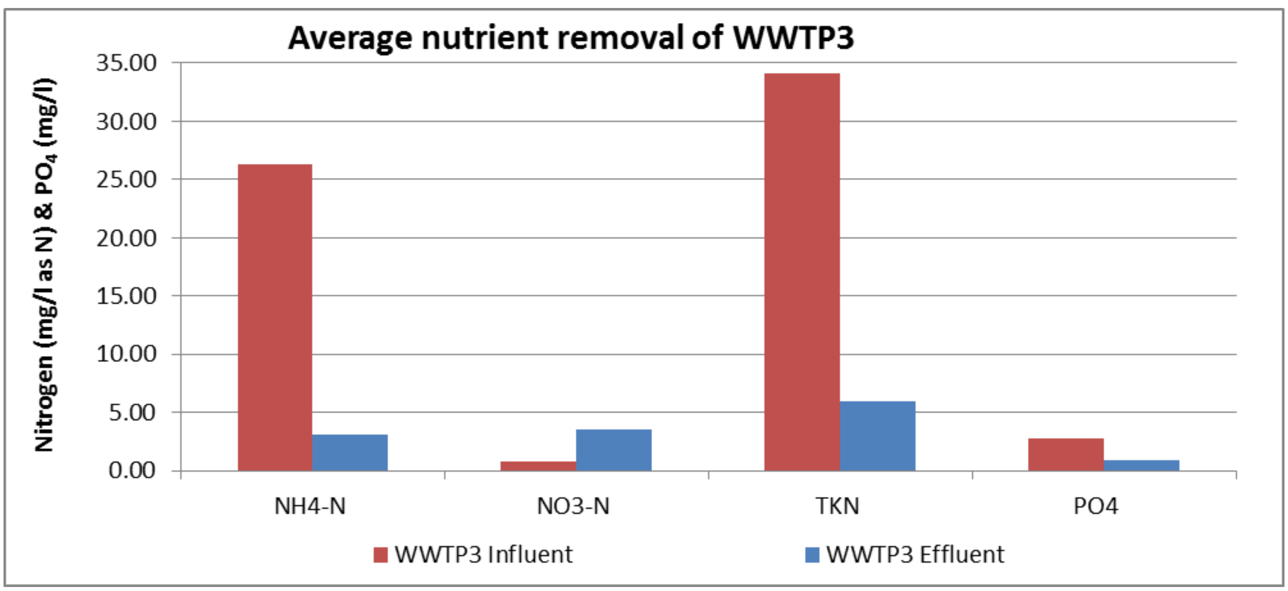

Figure 5.10: WWTP3 two years average nitrogen and phosphate nutrients removal

Total nitrogen that exceeds the 30 mg/l stipulated was observed for WWTP4 (Figure 5.11) which had the highest effluent TKN at >25 mg/l and ammonia at 25 mg/l in the treated effluent (Asano *et al*., 2007). The high level of ammonia could be attributed to the incomplete activated sludge process and this is plausible for WWTP4, since its original design capacity was 5 ML/day and now it is receiving 15 ML/day (MSA, 2012).

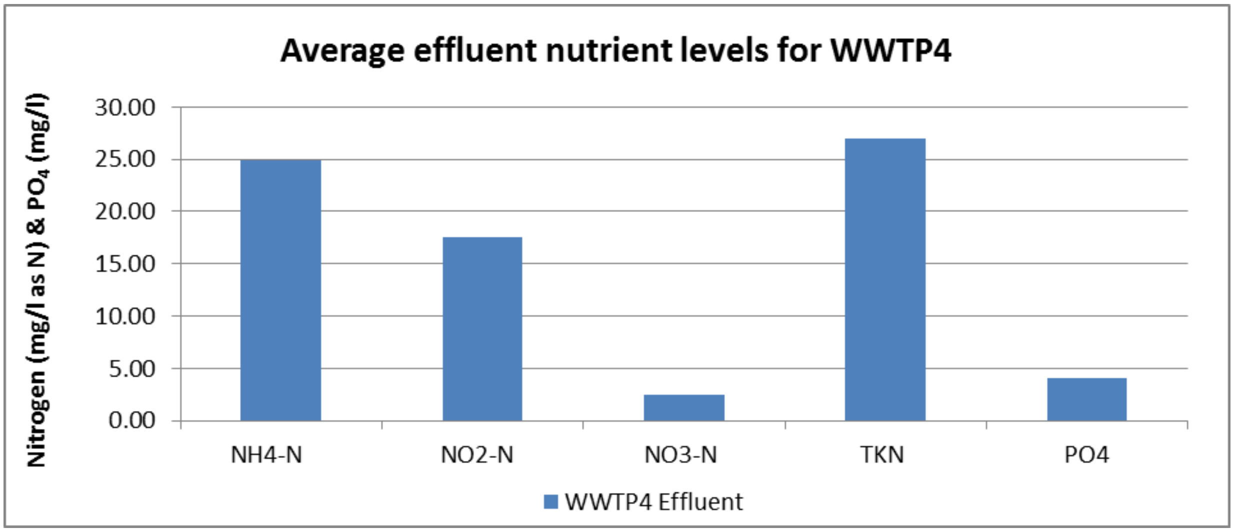

Figure 5.11: WWTP4 two years average nitrogen and phosphate nutrients levels

Typical levels of phosphorous in effluent receiving conventional activated sludge treatment processes, are between 4-10 mg/l and can be as low as 1-2 mg/l (NRC, 2012). Phosphate levels for WWTP1 were approximately 2 mg/l before biological nutrient removal and <1 mg/l for discharged effluent as shown (Figure 5.8). Nitrate levels and phosphate levels for WWTP2 in the effluent were below 1 mg/l.

Critical water quality parameters of concern for industrial use are selected based on their effect on health, corrosion, scaling, fouling and process issues (CSIRO, 2008). Water quality requirements are specific for each industrial process, however key variables include pH, alkalinity, organics, nutrients and those that affect corrosion and scaling (Asano *et al*., 2007). Brass fittings, common in industrial plants, can become brittle if exposed to high ammonia concentration water (USEPA, 2012). Copper or copper alloys are susceptible to corrosion by ammonia since it forms complexes with metals resulting in solubility and metal releases. High ammonia concentrations can also promote biological growth and microbiologically induced corrosion (Asano *et al.*, 2007). Phosphorous compounds form complexes with copper and calcium for instance and that can result in scale formation in industrial processes. Nitrogen and phosphorous compounds are required for biological growth and can form biofilms that can interfere with industrial processes (CSIRO, 2008).

In the Australian Eraring power generating plant a maximum of 15 mg/l for phosphorous, total oxidized nitrogen and ammonia respectively, is required for municipal wastewater secondary effluent, before used in reclamation (Masson and Deans, 1996). This is also consistent with the Beaufort West WRP secondary effluent quality requirement which is the same as DWAF general limit (Table 5.2) of 15 mg/l for nitrate or nitrite and 10 mg/l for phosphorous (DWAF, 1999; WWE, 2012). WWTP1, WWTP2 and WWTP3 from the Sedibeng district all comply with these nutrient specifications and WWTP4 only comply for phosphorous.

5.2.3 Ionic parameters

The South African National Standard, SANS 241-1 (2015), prescribes conductivity and TDS concentration of less than 170 mS/m and 1200 mg/l respectively for Class 1 drinking water for aesthetic reasons. The palatability of water at TDS <600mg/l is considered good and it becomes unpalatable at >1000 mg/l. Chloride concentrations of up to 250 mg/l may affect the taste of water but are influenced by associate cat-ions and there is no health based guideline value for drinking water. Presence of sulphates in water can have noticeable change in taste at thresholds of 250 mg/l for sodium sulphate and 1000 mg/l for calcium sulphate and have laxative effects at higher concentration (WHO, 2011). The SANS 241 divides acute health effects and aesthetic effects for sulphates at 250 mg/l and 500 mg/l respectively (SANS, 2015). All wastewater treatment plants studied (WWTP1, WWTP2, WWTP3 and WWTP4) are within specification for conductivity of <170 mS/m as prescribed by SANS 241-1 (2015) for drinking water (Figure 5.12).

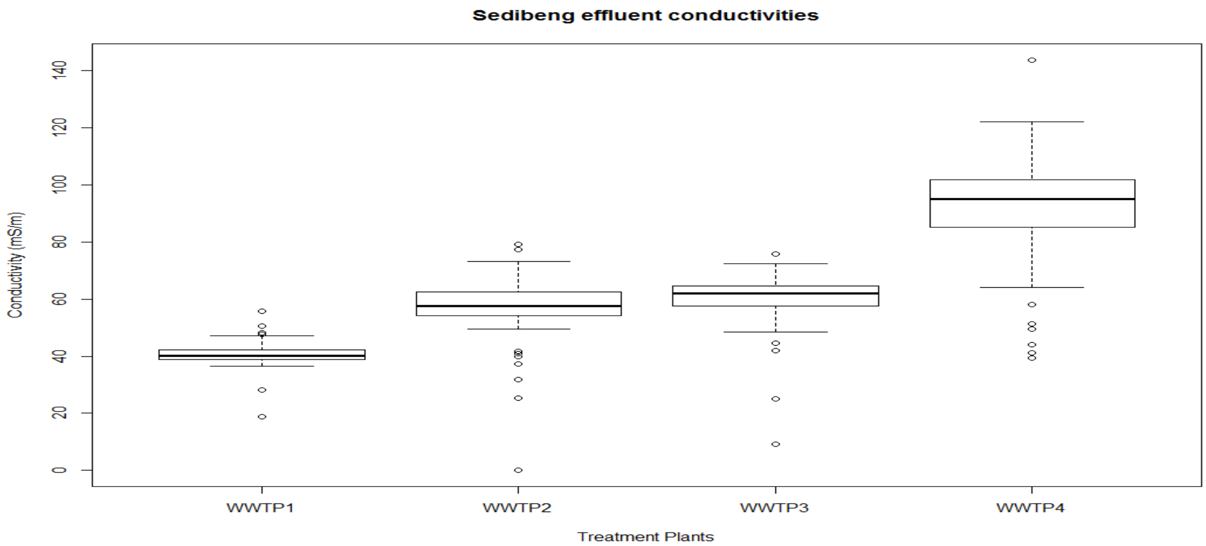

Figure 5.12: Sedibeng WWTPs recorded conductivities

WWTP1 has the lowest median conductivity at 40 mS/m which is lower than the highest (50 mS/m) recorded Vaal Dam water used as raw water source for Rand Water and this shows that the WWTPs are not polluters in terms of salinity (Table 5.4). This is corroborated by the DWA salinity balance study of the Vaal Barrage where this reservoir had a salinity catchment average of 636 mg/l TDS higher than WWTPs average. The study found that the average TDS concentration contribution of the WWTP and mine effluent, between 1995 and 2004, were 497 and 2505 mg/l with volumes of 405 and 51.3million m^3/annum respectively (DWAF, 2009b). WWTP2 and WWTP3 have similar medians at approximately 60 mS/m and WWTP4 has the highest at 100 mS/m which is still within SANS 241 specifications. The averages for the WWTPs are 40.8, 57.4, 60.4 and 92.8 mS/m and these are similar value ranges to the median ranges (Table 5.1).

Salinity in the Department of Water Affairs water quality management strategy is measured in TDS and the study used mainly conductivities and hence a correlation assessment was important (DWAF, 2009b). A strong positive association of conductivity and TDS for WWTP4, the only WWTP with both results, was demonstrated by the Spearman's rho (ρ) or r_s of 0.68 with a correlation graphical illustration (Figure 5.13).

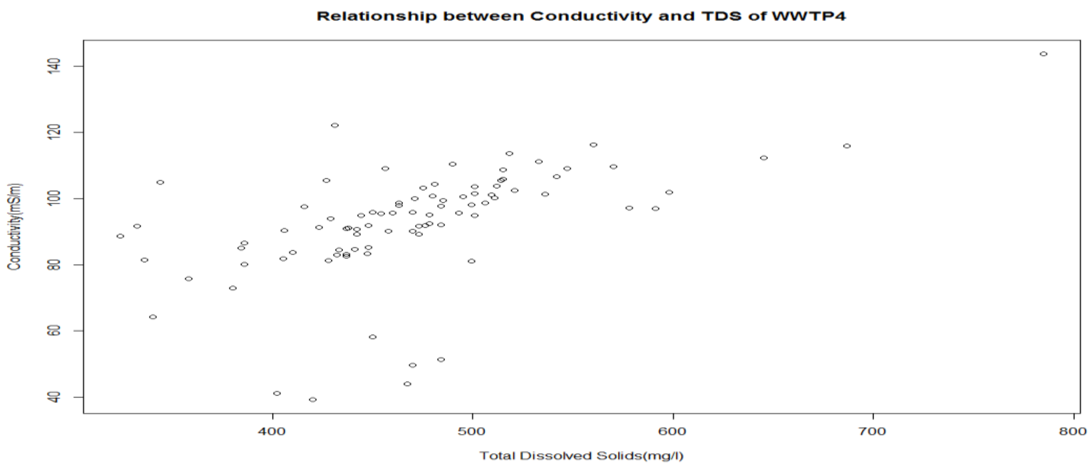

Figure 5.13: WWTP4 correlation of conductivity and TDS

Salinity is measured indirectly by a set of parameters such as conductivities, total dissolved solids, sodium adsorption ratio, sodium and chloride concentration analysed in the study (Figure 5.14). Water with a salinity of <450 mg/l TDS, conductivity of <70 mS/m and chlorides <140 mg/l can be used to irrigate any plants including salt sensitive plants (WHO, 2006). Having three different parameters is helpful to correlate to obtain the absent information if one or two analysis data is available or has to be conducted.

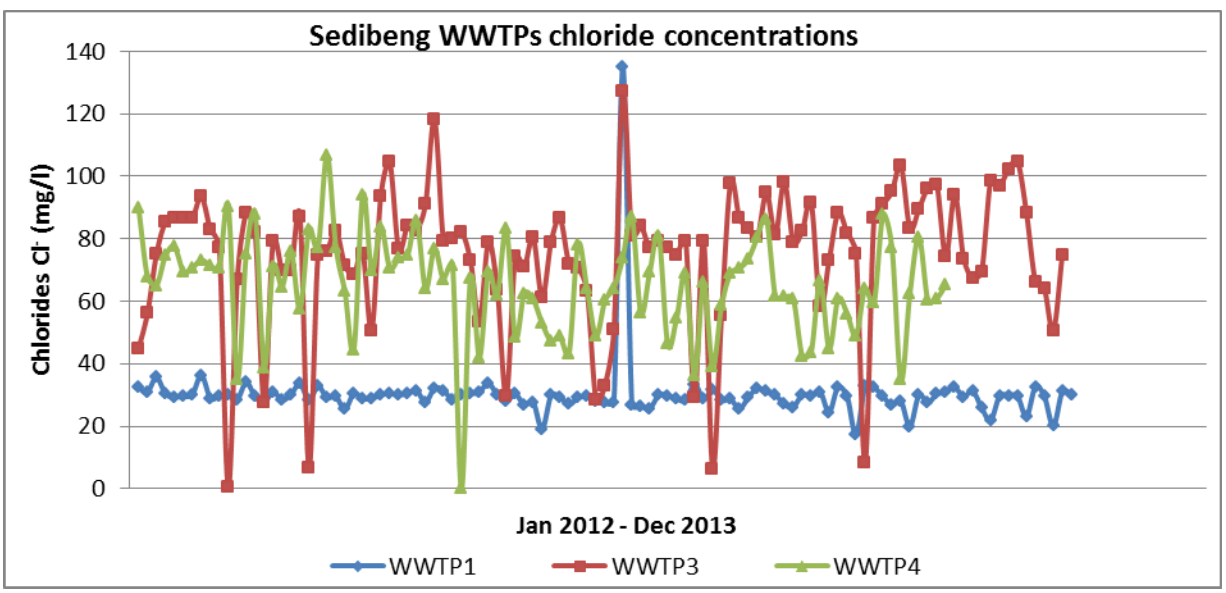

Figure 5.14: Chloride concentration of three WWTPs effluent for 2012-2013

All four Sedibeng district's WWTPs chloride concentrations were below 140 mg/l (Figure 5.14) and are within the specification of WHO guidelines for agricultural irrigation. The normal pH range for irrigation water is 6.5-8.4, pH values outside this range, can be corrosive to pipelines, sprinklers and control valves. However pH is seldom a problem on its own as it might be indicative of the presence of toxic ions (Lazarova *et al.*, 2005).

The effect of reclaimed water quality on cooling systems and other industrial processes will depend on materials used in the infrastructure and water quality consideration for processes and final products. This will depend on how heat exchangers, pipework and cooling towers (generally made of carbon steel, copper and copper alloys in cooling systems) reacts with reclaimed water. Typical problems in cooling systems are corrosion caused by high TDS, ammonia and chlorides; scaling caused by calcium, magnesium and iron salts; corrosion inducing biological growth as well as foaming due to surfactants (CSIRO, 2008).

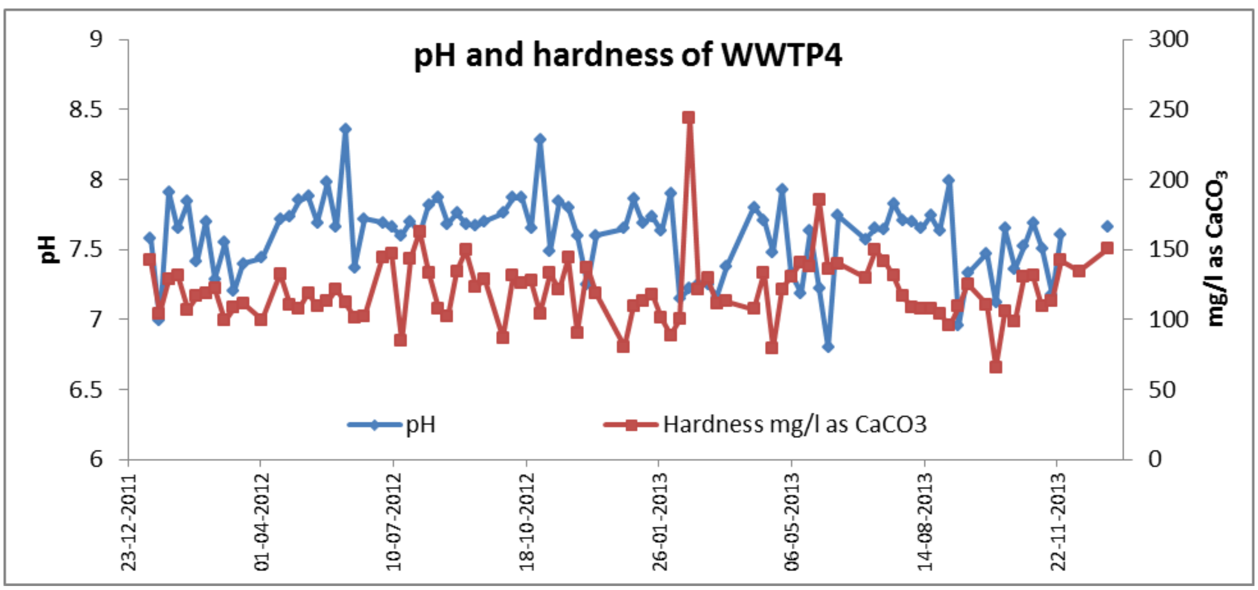

Figure 5.15: Comparison of WWTP4 pH and hardness

General corrosion is mostly associated with soft and acidic waters with pH below 6.5 and hardness of less than 60 mg/l of calcium carbonate per litre are aggressive to copper for instance. The only hardness measured in the investigation was for WWTP4 at an average of above 150 mg/l (Figure 5.15) and it complies with this recommendation (WHO, 2011). High alkalinity in cooling and other industrial systems provide carbonate and bicarbonate ions that can lead to scaling in the presence of calcium ions. Alkalinity as low as 20 mg/l as $CaCO_3$ for recirculating cooling water and as high as 500 mg/l as $CaCO_3$ for once through water, 125 mg/l and 500 mg/l for chemical and petroleum products respectively is recommended (Asano *et al.*, 2007).

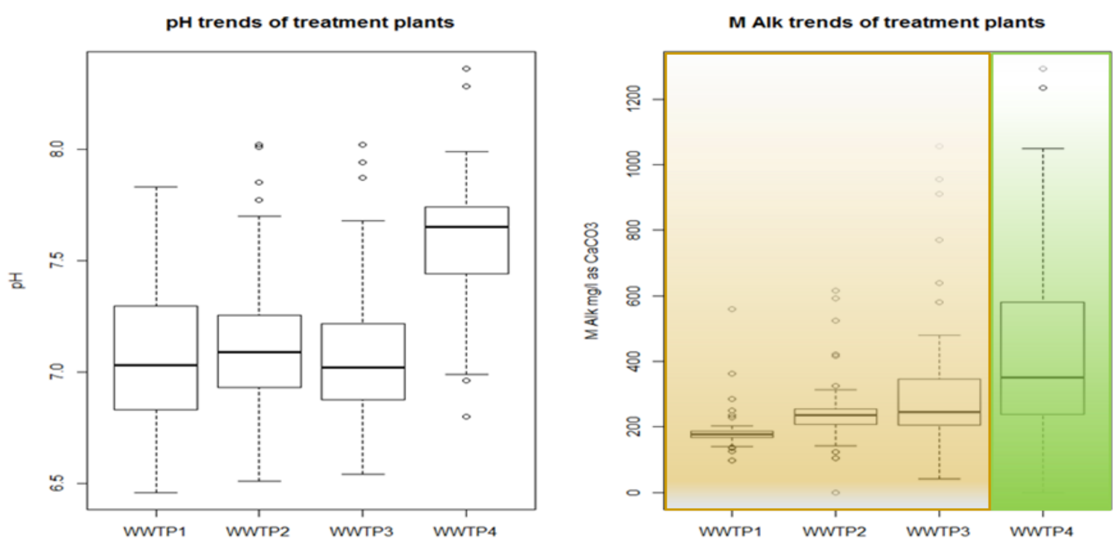

Figure 5.16: M-Alkalinity and pH for the four WWTPs

WWTP1, WWTP2 and WWTP3 influent M-alkalinity measurements were 182, 241.6 and 293 mg/l respectively and WWTP4 effluent measurement was 419.3 mg/l (Table 5.1) WWTP1 has a median value <200 mg/l, WWTP2 and WWTP3 have M-alkalinity median values of just >200 mg/l and WWTP4's median value is >300 mg/l. The pH medians of WWTP1, WWTP2 and WWTP3 were close to neutral and that of WWTP4 was above 7.5. The range and interquartile range or 50% of the data are over 1 and 0.5 pH value respectively excluding outliers for the two year study period for the four WWTPs (Figure 5.16). Biological processes release or take up hydrogen ions resulting in buffering where nitrification consumes alkalinity and denitrification recovers alkalinity. Therefore alkalinity and pH affect activated sludge process and effluent alkalinity can be calculated from pH and expected nitrate concentration (Ekama, 2011).

Dispersion in pH compromises the regularity and consistency required in oil emulsion water in rolling mills for the BlueScope Port Kembla Steelworks in Australia (Hird, 2006). In the South African context, where pH range is also important, the stated parameters (Table 5.3) are recommended for cooling tower use in coal fossil fuel power generation which guides target water quality of reclaimed effluent (van Zyl and Premlall, 2005).

Table 5.3: Cooling tower water allowable limits for impurities (van Zyl and Premlall, 2005)

PARAMETER	ALLOWABLE LEVEL
pH @ 25 ^oC	8 – 8.7
Turbidity (NTU)	< 100
P-Alk (as mg/l $CaCO_3$)	< 15
M-Alk (as mg/l $CaCO_3$)	80 - 180
Sulphates (as mg/l SO_4)	< 1000

All four of Sedibeng district's WWTPs comply in terms of the power plant cooling tower turbidity and pH maximum criteria (Figure 5.17) with a turbidity of <20 NTU for over 99% of the time for WWTP1, WWTP3, and WWTP4. In terms of M-alkalinity, where effluent alkalinity was estimated from nitrate produced and pH (Ekama, 2011), only influent WWTP1 is close to compliance for cooling tower water and all WWTPs measured P-alkalinity was on average zero. The measured sulphates for the Sedibeng district's three WWTPs (WWTP1, WWTP3 and WWTP4) were all <1000 mg/l as SO_4^{2-} recommended for cooling water (Figure 5.17).

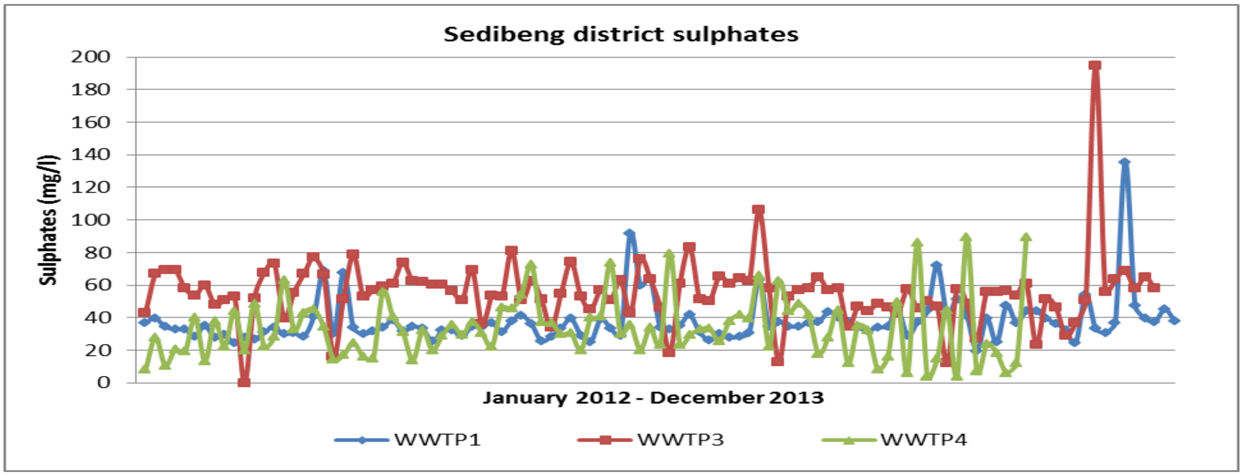

Figure 5.17: Sulphate levels for three Sedibeng WWTPs over sampling period

5.2.4 Microbiological parameters

There is no perfect indicator organism for wastewater especially for non-faecal bacterial pathogens, helminthes, viruses and protozoa (WHO, 2006). In addition pathogenic organisms, such as *Cryptosporidium* and *Giardia*, which may originate from human source invalidates the accuracy of using indicator pathogens (Asano *et al.*, 2007). The use of microbial indicators and use of effective barriers such as disinfection are important in this regard (ATSE, 2013). A different view presented with respect to disinfection is that chlorination inactivates the number of bacteria significantly but does not inactivate viruses, protozoa and helminthes (WHO, 2006). In the multi-barrier approach used by the New Goreangab WRP in Windhoek barriers include ozonation, enhanced coagulation, dissolved air flotation (DAF), dual media filtration and chlorination for *Cryptosporidium*. The raw water design value for *Cryptosporidium* and *Giardia* for this WRP is 334 oocysts and 214 cysts per 100 ml respectively (Lahnsteiner and Lempert, 2007).

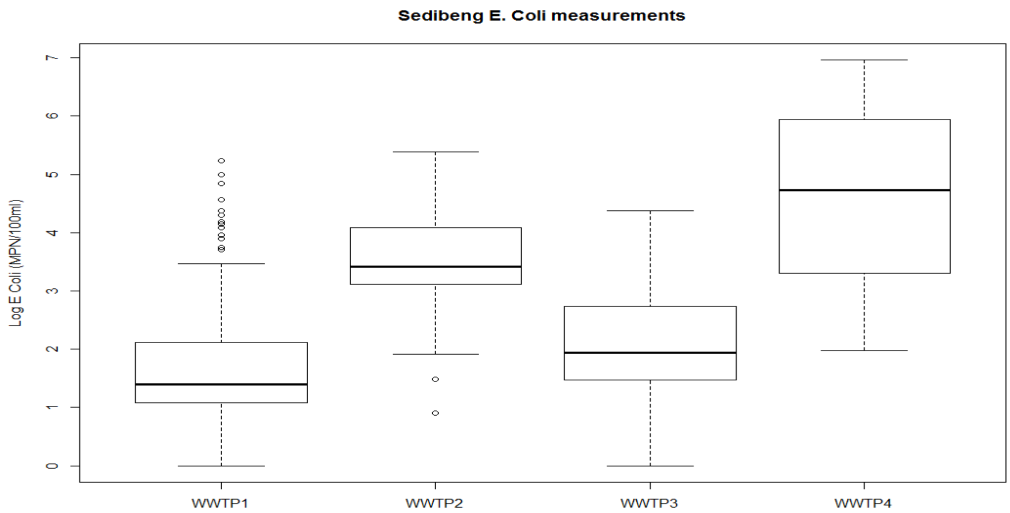

Figure 5.18: *E. coli* counts variation over sampling period for Sedibeng WWTPs

The recommendation from the Green Drop progress report was that urgent attention was required in terms of microbiological compliance of WWTP1 and WWTP2 (DWA, 2012). WWTP1 performed better compared to WWTP2 in terms of *E. coli* measurements during the two year sampling period, based on median and interquartile ranges even though there are more outliers for WWTP1 compared to WWTP2 (Figure 5.18). WWTP3 and WWTP4 do not have outliers but their median values are higher than WWTP2 and WWTP4 has the highest interquartile range and median value.

In quoting the limits set by Colarado State it is said that total coliform count should not exceed 2.2/100ml for reclaimed irrigation water for food eaten raw. Reclaimed irrigation water for processed food should not exceed 23/100ml (both 7day median) (Norton-Brandao *et al.*, 2013). In the Israeli standard coliform counts for irrigation water should not exceed 12/100ml over 80% or 2.2/100ml over 50% of the time (Angelakis *et al.*, 1999). Total coliforms are used as indicator organisms in the California regulation, they must be monitored daily and compliance is based on a running seven day median number. Irrigation for high risk uses such as crops eaten raw and open access areas this number must not exceed 2.2/100ml and 23/100ml in 30 days (Paranychianakis *et al.*, 2011).

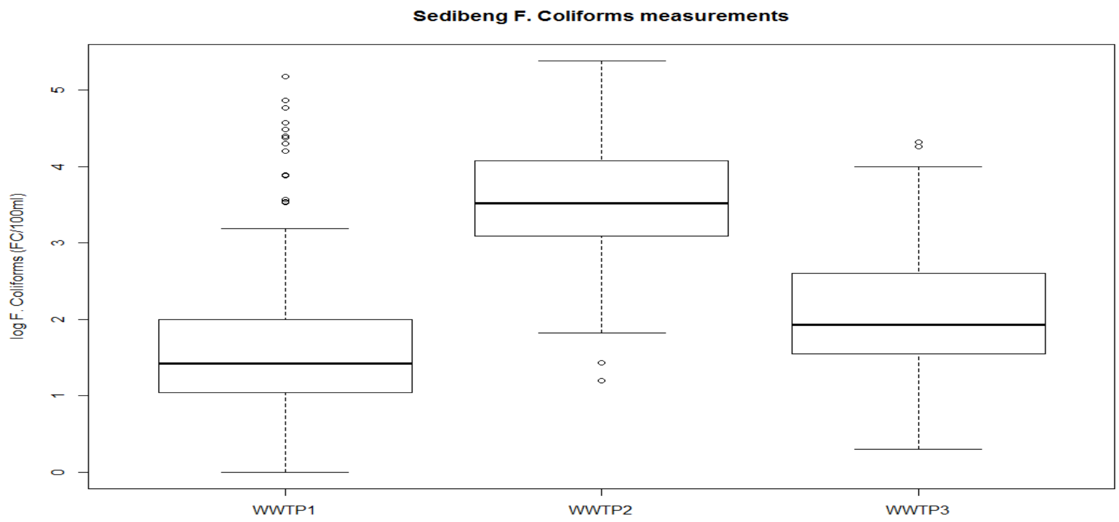

Figure 5.19: Faecal coliforms for WWTP1, WWTP2 and WWTP3

The faecal coliform measurement patterns for WWTP1, WWTP2 and WWTP3 (Figure 5.19) with the Log_{10} values approximately 1.4, 3.5 and 2 respectively and are similar to *E. coli* measurement patterns and values. This means that *E. coli* which is a subset of faecal coliforms dominates and it can be concluded that the effluent is predominantly of a domestic source or human faecal pollution (DWAF, 1996b, Teklehaimanot *et al.*, 2014). This is in terms of WWTP1 being the lowest followed by WWTP3, then WWTP2 and from this it can be deduced that WWTP4 will also have the highest faecal coliform values.

Reclaimed water with a microbiological content can harm workers and affect processes by bio-corrosion and bio-fouling and the easily measured microbiological parameter in industry is faecal coliforms (CSIRO, 2008). The recommended secondary effluent microbiological quality for faecal coliforms is 1 x 10^6 for the Australian Eraring power plant, which mainly uses reclaimed water for cooling systems. The faecal coliform mean values for WWTP1, WWTP2 and WWTP3 were 4776, 15979 and 1443 CFU/100ml respectively. This complies with the 1 x 10^6 Australian maximum even though there is non-compliance with the 1000 CFU/100ml DWAF general limit (Masson and Deans, 1996; DWAF, 1999). Faecal coliform was not measured for WWTP4 and *E. coli* mean value for this plant was over the 1×10^6 limit at 1.4×10^6 CFU/100ml (Table 5.1).

5.3 Treatment technology

Over the 50 years of wastewater reclamation in the United States there has been a shift from the reliance on lime clarification and activated carbon adsorption of contaminants to membrane filtration and advanced oxidation (NRC, 2012). Out of the 24 operational plants listed by ATSE for potable reuse, six follow the MF/UF, RO and UV configuration and five follow the MF/UF, RO and UV/AOP with or without chlorination at the end depending on application (ATSE, 2013). This shows that membrane technology followed by advanced oxidation seems to be the consistently applied technology. The following section discusses possible treatment barriers, technology options and trains with emphasis on the latter which can be applied in the study area.

All water reclamation systems require a minimum of secondary treatment since untreated municipal wastewater contains a range of pollutants. These are from dissolved trace metals and trace organic compounds to large solids such as rags, sticks, floating objects grit and grease (USEPA, 2012). As a result, most water reclamation plants receive their influent after secondary treatment in conventional wastewater treatment plants.

Primary and secondary conventional wastewater treatment processes are still important even with the use of advanced tertiary treatment processes. This is demonstrated in the Goreangab, Windhoek case where nitrification and denitrification are still depended on biological nutrient removal in secondary treatment (du Pisani and Menge, 2013). Almost all large wastewater reclamation schemes have been designed as add-on technology to conventional secondary wastewater schemes (Wintgens *et al.*, 2005). In the Beaufort West WRP's case, ferric chloride is added in the activated sludge stage to remove ortho-phosphates and to aid settling of suspended solids as a flocculent in the secondary settling tank.

Namibia's New Goreangab WRP considers three types of barriers in its philosophy of multi-barrier approach namely non-treatment barriers such as diversion of industrial effluent, treatment and operational barriers (du Pisani and Menge, 2013). Singapore uses an eight multi-barrier safety approach from source to tap for water reclamation with aspects such as enforcement, water quality monitoring, plant design, operation and maintenance and these can be adopted in the Southern Gauteng context. The Singapore approach includes (Seah *et al.*, 2008):

1. Source control at industries through regulations and legislation, site surveillance, monitoring, awareness and engagements
2. Source of WRPs is 85% domestic
3. Comprehensive secondary wastewater treatment to prevent membrane fouling among others
4. Microfiltration, reverse osmosis and UV disinfection in NEWater production
5. Natural attenuation in surface reservoir to allow natural buffering, photo and or biotransformation of emerging contaminants, among others
6. Conventional water treatment processes of coagulation/flocculation, sand filtration and disinfection
7. Comprehensive water quality monitoring of more than 290 parameters, research and development of more sensitive analytical tools and biannual external audits
8. Strict operating philosophy with a pool of competent, highly trained and experienced operators with operating with reference to plants baseline performance

The Beaufort West WRP follows the same multi-barrier concept similar to the successful Goreangab WRP in Windhoek (Figure 5.24), Pimpamaon, the Gold Coast and Kranji in Singapore (Marais and von Durckheim, 2012). Natural systems provide environmental buffering and may fulfil one or all of the following 1) provision of retention time, 2) contaminant attenuation and 3) blending or dilution (NRC, 2012). Physical treatment processes directly or indirectly such as settling tanks and stabilization ponds for suspended solids act as a buffer in the Beaufort West and New Goreangab WRPs (Marais and von Durckheim, 2012; du Pisani and Menge, 2013). The latter retains secondary effluent for 2-4 days compared to the US example of Cloudcroft (Figure 5.20) of 40-60 days. It is small hence authorities have designated the US example as IPR (Lahnsteiner and Lempert, 2007; NRC, 2012).

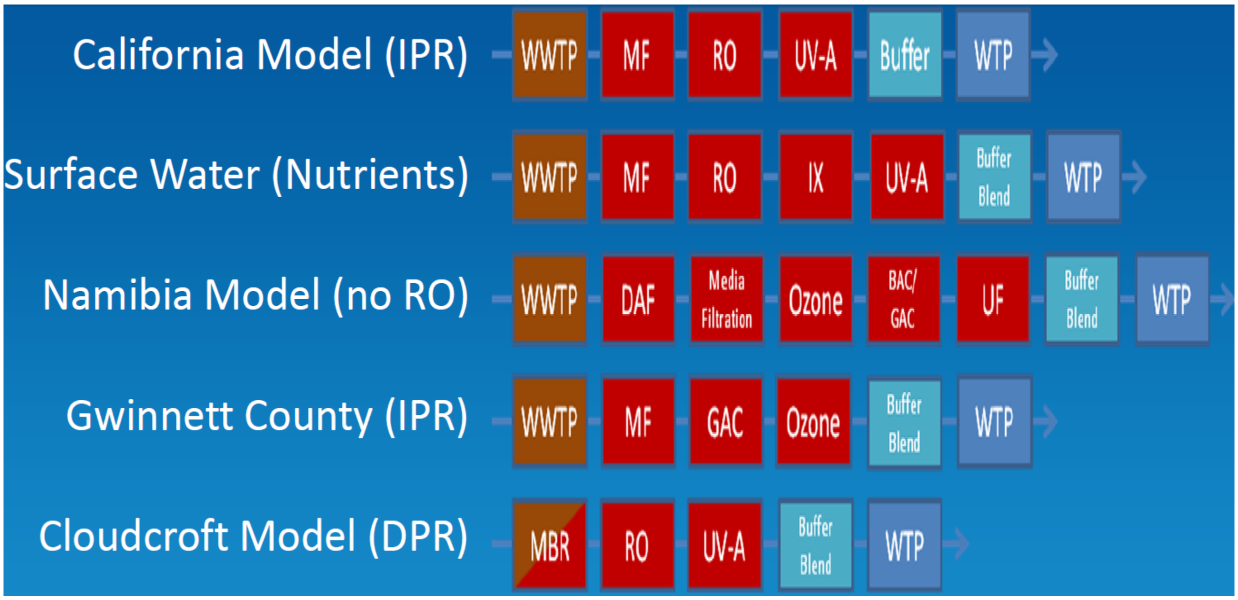

Figure 5.20: Typical treatment process trains (Chalmers *et al.*, 2011)

Singapore's four NEWater treatment plants use micro or ultrafiltration (MF/UF), reverse osmosis (RO) and UV. The Beaufort West WRP in addition instead of UV adds UV/H_2O_2 AOP and a final disinfection (Wintgens *et al*., 2005; USEPA, 2012; ATSE, 2013). In the case of Orange County district in the US also applies MF, RO and UV/H_2O_2 AOP where half the near distilled water quality is used to prevent saline intrusion and another half is applied in deep water aquifers of the ground water basin (UKWIR, 2014).

Benefits from extended residence time in an environmental buffer are minor for wastewater treated with reverse osmosis and advanced oxidation processes or any other advanced processes (Tchobanoglous *et al.*, 2011). The following section focuses on reuse options available for Southern Gauteng starting with DPR and IPR then moving on to the most viable reuse option for the region in industrial uses of power generation and steel making.

5.4 Southern Gauteng reuse options

The CSIR has been researching the treatment technology and pathology, among others, of water reclamation from secondary effluent since the 1960s, which demonstrates South African institutional memory capacity. The Stander WRP, of which some of its process developments were incorporated into the Windhoek plant in the 1970s, contain basic barriers such as lime coagulation, granular activated carbon (GAC), sand filtration and chlorine disinfection (van Leeuwen, 1996). These are some of the standard conventional drinking water treatment processes employed currently with no full guarantee on the pollution impact on raw water sources and therefore direct potable water treatment is a psychological rather than technological barrier.

Most of Sedibeng district's WWTPs comply with respect to aggregate, nutrient and ionic as feed for advanced treatment for potable, agricultural and industrial reuse (Figure 5.21). The only non-compliances are COD for WWTP4, TSS for WWTP 2 and WWTP4, ammonia for WWTP3 and WWTP4 and m-alkalinity for all WWTPs. Microbiological water quality as faecal coliform does not comply as design feed for the Beaufort West WRP for DPR which is the same as the DWAF general limit of 1000 CFU/100ml for all WWTPs (DWAF, 1999; WWE, 2012).

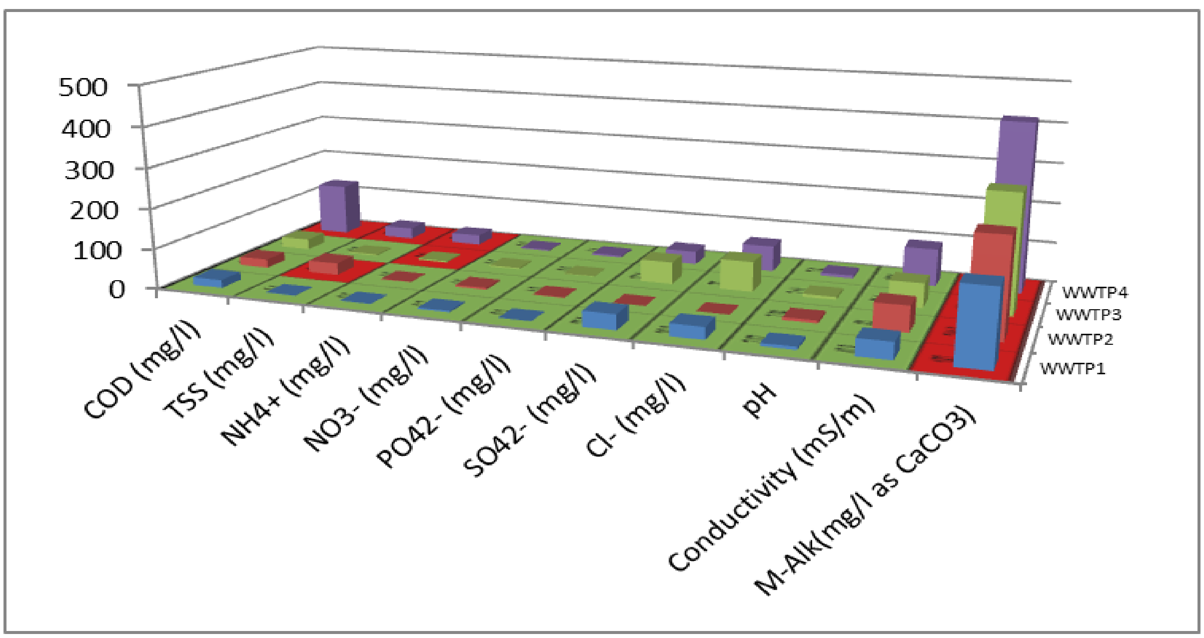

Figure 5.21: Four Sedibeng WWTPs reuse water quality parameters compliance

Rand Water's potable water treatment plants, situated in the study area, currently abstract raw water from the Vaal Dam via a canal and a gravity pipeline. The Vaal River Barrage reservoir and Zuurbekom groundwater are two other alternative sources which are currently not in use (Rand Water, 2015). These sources present opportunities for the Sedibeng WWTPs secondary effluent to be reclaimed for DPR via the Vaal Dam or at the potable water works and IPR in the Barrage reservoir and Zuurbekom wells (not in study area). Centralized or regional wastewater collection WRPs are used extensively in urbanized or developed areas and will be well suited when there is no suitable IPR or ground water recharge system such as in the study area (Leverenz and Asano, 2011). The possible scenarios for the Sedibeng districts are that preliminary reclamation or discharge quality improvement can be performed on site the four WWTPs or a central WRP can collect effluent, reclaim and distribute to users (Figure 5.22).

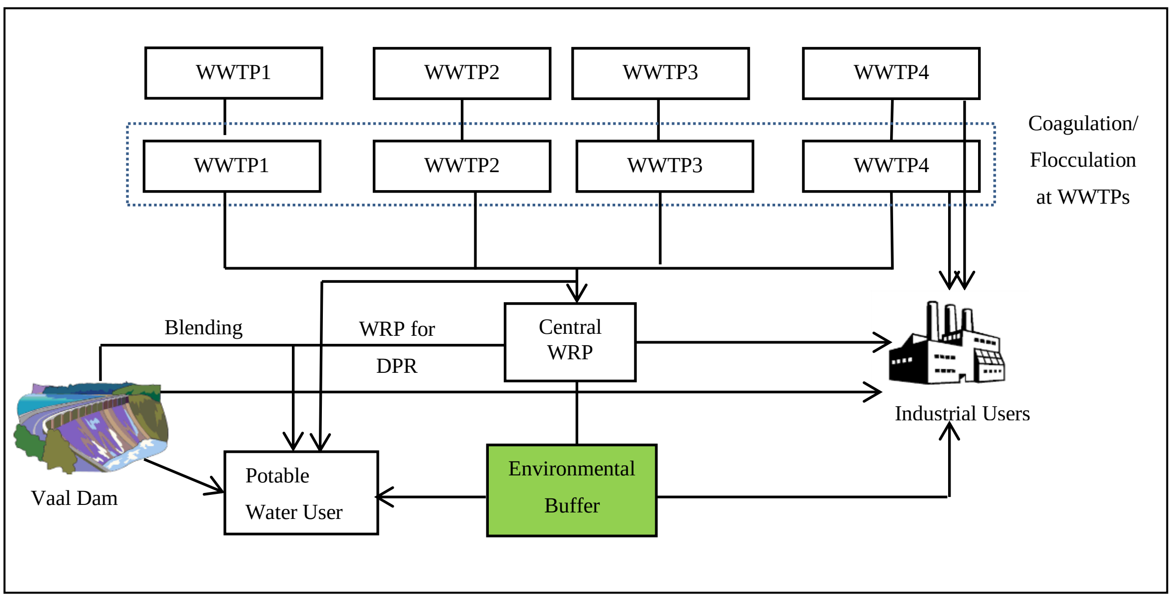

Figure 5.22: Potential water reuse scenarios for the Sedibeng district

Rand Water the bulk potable water utility in the area could use the WRP water to add to its capacity either by blending directly at its head of works or indirectly by blending the water with the Vaal Dam water. Alternatively the bulk water utility can build and own a separate WRP and use some of its distribution capacity extending trans-provincial borders to sell reclaimed water at a reduced tariff. The Vaal Barrage reservoir for IPR could only be used if point source discharges improve their quality and an increase in monitoring to include water reuse parameters of concern is implemented. For the existing water intensive industrial users Eskom's Lethabo power station and ArcelorMittal the secondary effluent could be used for their cooling and heat exchange processes among others after tertiary treatment.

5.4.1 Direct potable reuse

For direct potable reuse (DPR) in the study area to be a success, it has to involve Rand Water as the main water utility in the area, with upgrading or changing its existing potable water treatment processes. Rand Water, the largest water utility in Africa, supplied in the 2013-2014 financial year on average 4183million litres of water per day to metropolitan and local municipalities, mines and industries through a 3056 km pipeline over an estimated area of 18000 km^2 (Rand Water, 2014). Rand Water in the Vereeniging and Zuikerbosch purification plants use the conventional treatment processes of coagulation/flocculation, sand filtration and disinfection where waste is generated and recycled in the first two processes (Figure 5.23). This is recovered filter wash water from backwashing sand filters, which is returned to the head of works at Vereeniging or treated at the 35 ML/d filter wash water recovery plant at Zuikerbosch. The sludge or drinking water treatment residue (DWTR) supernatant from coagulation/flocculation is thickened, dried and the supernatant recycled (Rand Water, 2013). This DWTR can be recovered and used to improve the Sedibeng district WWTPs discharged secondary effluent quality with further membrane and AOPs or disposed of in IPR.

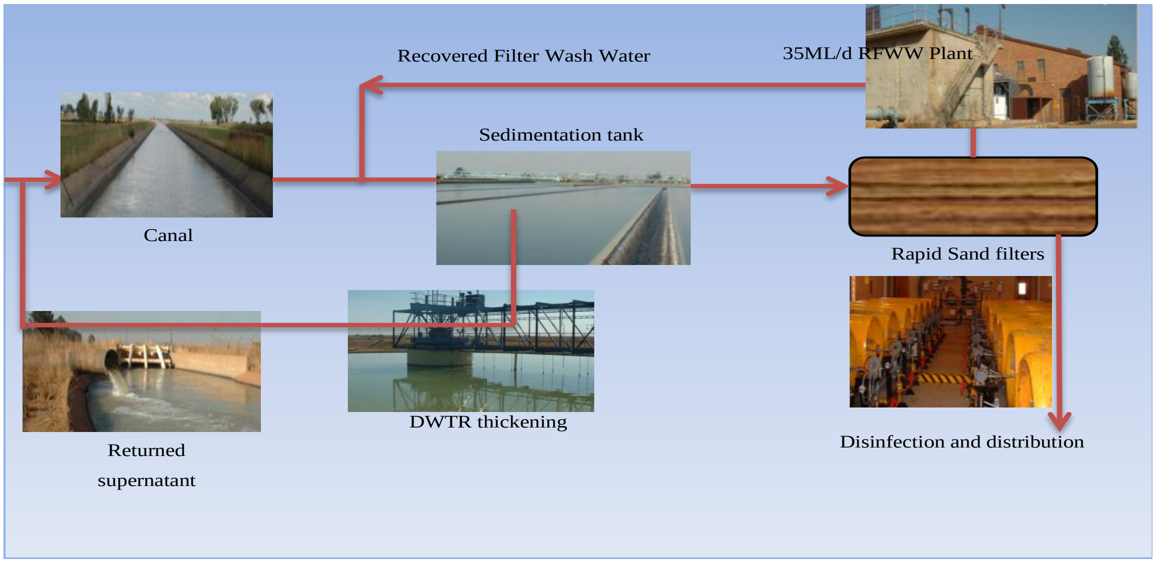

Figure 5.23: Rand Water drinking water treatment residues

Much research has been devoted to coagulation/flocculation in relation to potable water treatment process and the recovery and reuse of water from DWTR involving substantial coagulants is no exception. However this process can be used in wastewater treatment even though there are much greater proportion of particulates that would require and result in a different coagulant demand and flocculation behaviour (Adin and Asano, 1998). DWTR because of its coagulation/flocculation constituents can be recycled and used in treating municipal secondary treated effluent for wastewater reclamation purposes. It occurs as gelatinous or particulate form consisting of, among others, organic and suspended matter, coagulants and suspended matter depending on raw characteristics, coagulant used and its dosage (Babatunde and Zhao, 2007).

Activated silica is a coagulant aid that increases the weight and size of flocs and it is formed by acidification of the viscous sodium silicate (SiO_2Na_2O). Quicklime, which can be purchased and slaked on-site, raises the pH to between 10-11.5 forming the initial magnesium hydroxide floc, then when carbonated, reduces the pH and then removes heavy metals and suspended matter (Freese *et al.*, 2003). Rand Water's preferred chemical treatment regimen is a combination of lime and sodium silicate but alternative combinations involving polyelectrolytes and ferric chloride are also used (Rand Water, 2013). Therefore the DWTR sludge and supernatant in addition to the raw water quality characteristics would reflect the floc forming pH as shown (Figure 5.24) and flocculent aid used.

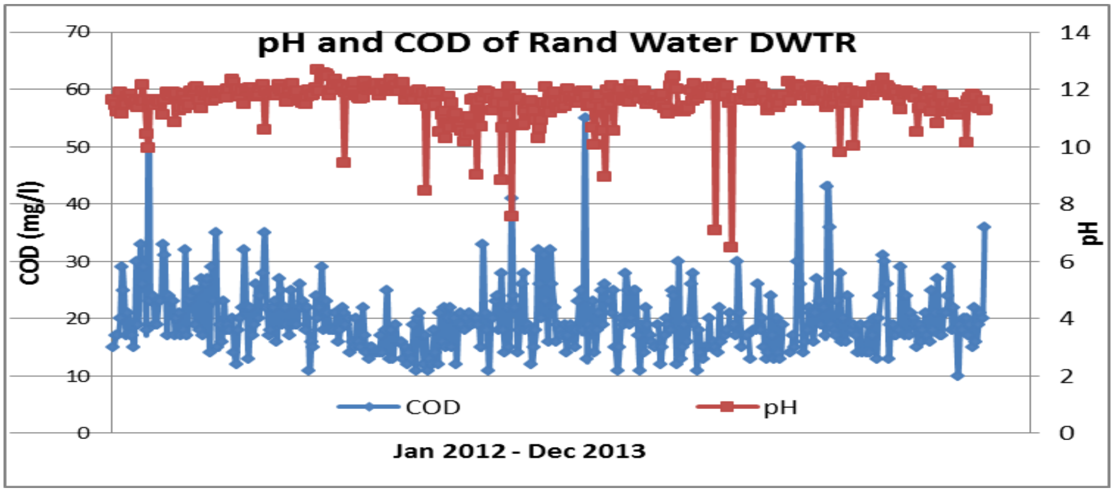

Figure 5.24: Rand Water DWTRs pH and COD concentration

Rand Water produces between 500 and 1500 tonnes of dry sludge at 3% (m/v) of raw water treated depending on the treatment regimen used and this amounts to approximately 120 ML/d sludge produced if 4183 ML/d is treated (Rand Water, 2015). This DWTR is lime based and lime at high pH is capable of significant removal of suspended and colloidal matter, inorganic and organic matter including phosphates and heavy metals and inactivate most microorganisms (Odendaal, 1991).

Ferric chloride in the DPR Beaufort West WRP is dosed in the activated sludge to treat ortho-phosphates and as flocculent to clarify suspended solids in the secondary settling tank (Marais and von Durckheim, 2012). This could also be applied in the study area as separate units or in activated sludge process in WWTPs (Figure 5.25) in combination with lime or existing recovered coagulant from DWTR. Phosphates levels at Beaufort West are comparable to WWTP4 in the study area at 5.1 and 4.1 mg/l respectively which is way below the other three WWTPs at average 0.3, 1.0 and 0.9 mg/l for WWTP1, WWTP2 and WWTP3 respectively (Table 5.2). Breakpoint chlorination that further reduces nutrients applied in the Beaufort West case is not necessary in the study area with these low levels of nutrients and lime clarification from DWTR (NRC, 2012).

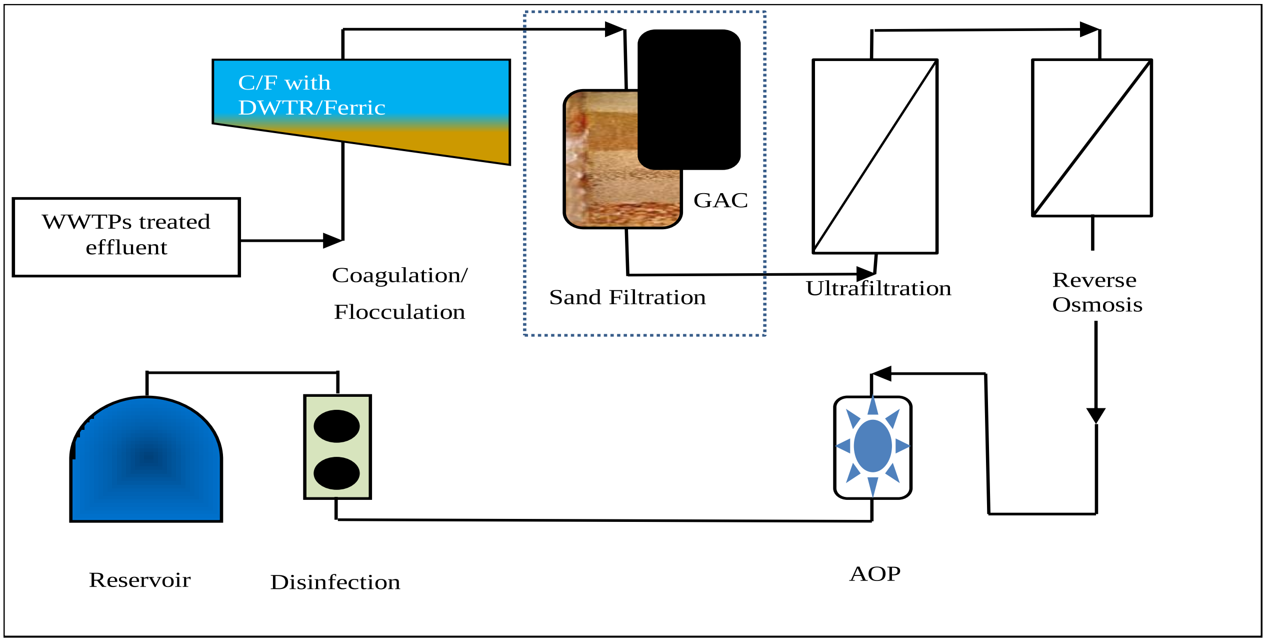

Figure 5.25: Proposed treatment train for DPR of Sedibeng WWTPs effluent

Sand filtration which reduces the load by removing macro organic matter and suspended solids to prevent fouling for subsequent membrane processes of ultrafiltration (UF) and microfiltration (MF) could be optional in the study area. This is because the organic matter represented by COD and suspended solids of Beaufort West secondary effluent are on average 47 and 20 mg/l respectively (WWE, 2012), higher than those of the Sedibeng WWTPs (Table 5.2). Alternatively sand filtration can be included to reduce membrane operational costs and increase their longevity. UF removes viruses in addition to removal of suspended solids compared to MF hence it is preferable. The suspended solids are variable for the results of the study which are at the lowest 0.6mg/l for WWTP1 compared to 29.7 mg/l for WWTP2 the highest (Table 5.1). Bacteria, *Cryptosporidium* and *Giardia* prevalent in the study area are removed by both UF and MF (Marais and von Durckheim, 2012).

Pressure driven dense membrane process (NF/RO) will remove the remaining organics, hormones, pesticides, contaminants of emerging concern (CEC), aqueous salts and metal ions (Marais and von Durckheim, 2012). Reverse osmosis typically removes 95 to

99.5% of the total dissolved solids and 95 to 97% dissolved organic matter (Asano *et al*., 2007). RO efficiency is demonstrated in the Beaufort West WRP where the RO system operates at 80% recovery with feed water of TDS 1200-1520 mg/l and final water quality of <30 mg/l. This represents a 97.5% TDS removal rate using the lower limit and significantly exceeds the SANS 241 (2015) drinking water standard in terms of acceptable health, palatability and aesthetics. What is noteworthy is that in the Sedibeng district WWTPs investigated, WWTP4 which had the highest conductivities compared to the other three WWTPs, has the highest TDS at 800 mg/l (Figure 5.26) and it is still 30% lower than the Beaufort West WRP's feed.

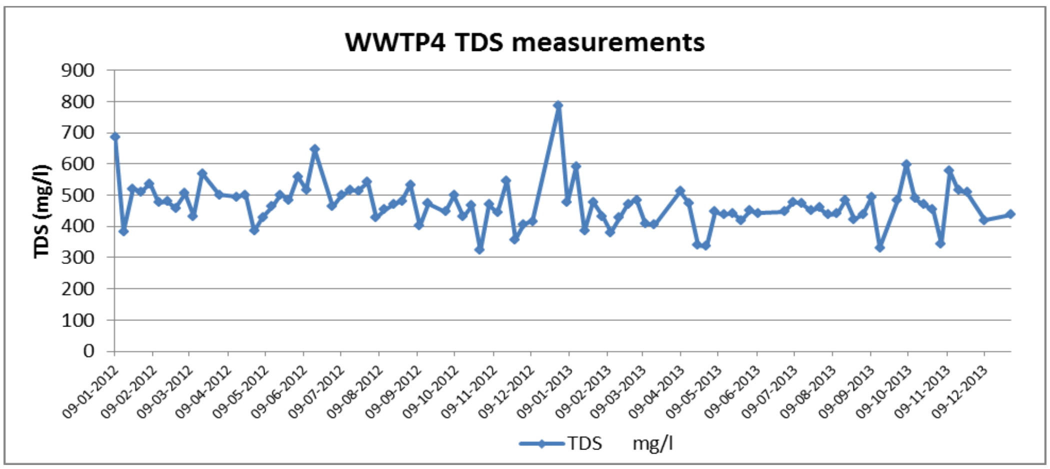

Figure 5.26: WWTP4 TDS two years sampling period measurements

In the Beaufort West WRP for DPR the activated carbon step is not present but the RO step is present and in the Namibia WRP the RO step is absent but the activated carbon step is present (Figure 5.26). RO/NF, activated carbon and advanced oxidation processes are technologies used to reduce TOC concentrations, hence in the study area, either RO or activated carbon can be used depending on costs (ATSE, 2013).

Typically photocatalysis is applied after RO to reduce the effects of suspended material shielding light transmission and applied after scavenging carbonate, bicarbonate, reduced metals, COD and TOC are removed (Asano *et al.*, 2007). TOC is also used as an indicator parameter in assessing the progress of photocatalysis, for instance, because the treatment technology is non-selective and must also destroy all other intermediates. The only TOC measured for the Sedibeng district municipality is less than 20 mg/l over 95% (Figure 5.27) of the time for WWTP4 which implies that AOPs can be applied after secondary treatment in reclamation.

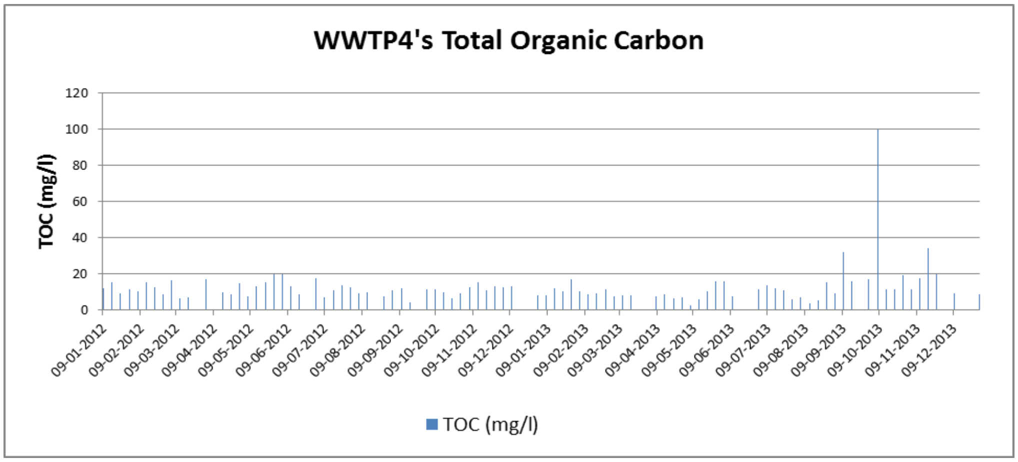

Figure 5.27: WWTP4 Total organic carbon measurement over sampling period

An AOP step of UV/H_2O_2 after reverse osmosis and before disinfection residual protection chlorination is used in the Beaufort West WRP to destroy the remaining dissolved organic carbons, remove all EDCs and add to the safety of the water (Marais and von Durckheim, 2012). The objective of inclusion of AOPs and other oxidative processes in the treatment train is to degrade biologically recalcitrant organic constituents that are poorly retained by membranes (ATSE, 2013). The efficiency of destruction of trace organics, viruses, bacteria and protozoa is high for this AOP even though associated energy costs are high (NRC, 2012).

5.4.2 Indirect reuse

Most inland cities effluent run into impoundments used as a raw water source for conventional drinking water treatment plants and the Rietvlei Dam in Pretoria and the Vaal Barrage are such impoundments (van Leeuwen, 1996). The Vaal River Barrage Reservoir in the study area is fed by the polluted Suikerbosrand, Klip and Rietspruit, it is 64 km long (Figure 5.28), and has a storage capacity of 63million litres (Rand Water, 2015). Indirect potable reuse can be achieved in the study area by additional tertiary treatment of effluent from the four Sedibeng WWTPs and subsequent disposal of improved quality effluent. Alternatively selective disposal of effluents that can work together to treat by natural processes and time in River buffer systems, which has an effect of reducing COD for instance from 60 mg/l to 30-40 mg/l in the Namibia case, can be modelled.

Public perceptions and acceptance are partially addressed by environmental buffers which are considered to sever the connection between wastewater and potable water (du Pisani, 2006). Singapore's NEWater, which undergoes UF/MF-RO-UV treatment and is at WHO and USEPA drinking water standards, is still discharged into existing surface water reservoirs for dilution and biotransformation (Seah *et al.*, 2008). These buffers could be blending of reclaimed water with surface water and groundwater recharge. In the case of the study area surface water recharge or blending has to be in the Vaal Barrage catchment which is polluted and can expose the purified water to contamination (Figure 5.28). Blending the reclaimed water from a proven performing and reliable WRP with quality validated by an extensive monitoring system, with Vaal Dam water which is less polluted, can be an alternative solution (Leverenz *et al.*, 2011).

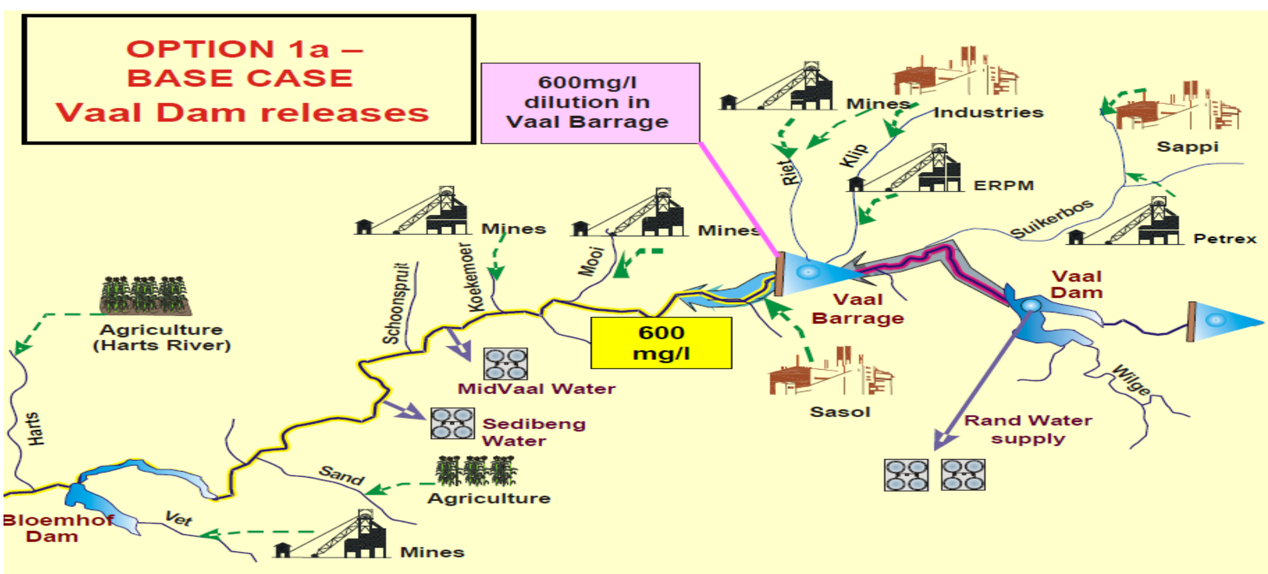

Figure 5.28: Vaal Barrage Reservoir map with industrial discharges (DWAF 2008)

The two most important water quality issues to be managed based on Rand Water Vaal Barrage catchment sampling points are biological impacts represented by faecal coliforms and chemical impact through manganese, sodium and sulphates. It is important to know the contamination components and their sources in the Vaal Barrage catchment if it is to be used for IPR (Rand Water, 2014). In the study area it is recommended the secondary effluent should undergo coagulation flocculation, UF and RO then be introduced into an environmental buffer. This could be discharge into a surface water reservoir such as the Vaal Dam or the Vaal Barrage with improved water quality. Alternatively water users Rand Water, Lethabo power station and ArcelorMittal in the study area could blend this water into their treatment processes. This would require in addition to conventional treatment processes GAC and UV or advanced oxidation processes but all of this requires the receiving environmental buffer quality to improve (Figure 5.29).

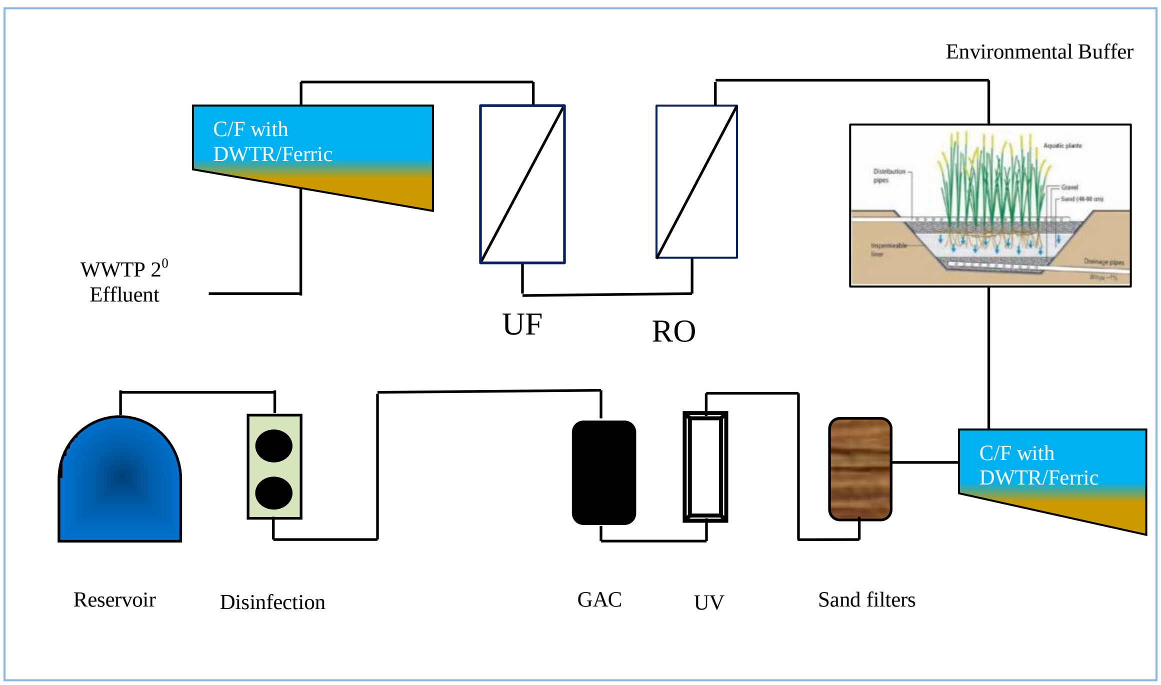

Figure 5.29: Proposed treatment train for Sedibeng WWTPs effluent use in IPR

Different combinations of soil, sand and gravel as a medium, enhance the treatment characteristics of wetlands. DWTR to enhance this media has been proposed as a good adsorbent of wastewater contaminants especially phosphorous (Babatunde and Zhao, 2007). The south drainage area into the Vaal River could have been worse off, in terms of pollution, compared to the north drainage area into the Crocodile River as evidenced by the chronic eutrophication of the Hartbeespoort Dam. This is because the south drainage area where most of the development occurred has the Klip River wetland which lessens the impact of sewage run-off with elevated residual phosphates and nitrate, acid mine drainage and industrial pollution. This is a form of natural wastewater reclamation through wetlands, in practice for decades and needs to be enhanced for future impacts (McCarthy *et al.*, 2007).

The Vaal Barrage feeding Rietspruit and Klip River where WWTP1 and WWTP3, and WWTP4 discharge their effluent respectively have wetland characteristics. If DWTR are introduced in this medium, with reduction of industrial point discharges, they can improve its treatment characteristics. There is no water quality and retention times determination for these WWTPs beyond effluent discharge points and these have natural and artificial wetland characteristics in the Rietspruit and Fouriespruit.

5.4.3 Power generation

Wet cooling coal fired power station use up to 90% of water in some cases in cooling towers which do not require high quality water, especially once through systems, used mostly in municipal power plants in South Africa (van Zyl and Premlall, 2005). Municipal power plants currently use treated municipal wastewater and Eskom power plants use in-house domestic treated wastewater. The latter can be extended to include municipal wastewater. Of the four Sedibeng WWTPs only WWTP4 does not meet the requirements for cooling water systems even before tertiary treatment.

Eskom's Lethabo power station in the study area is projected to continue using 48.7million m^3 of water per annum or approximately 133 ML/d up to 2030 (DWAF, 2009a). It has been stated previously that Eskom power stations are not using treated municipal wastewater because their plants are mainly located in small towns away from metropolitan areas near coal mines. The small towns could not provide up to 120 ML/d water for example required by cooling systems of large power stations and costly long pipelines would have been required to transport municipal effluent (van Leeuwen, 1996; Grobicki and Cohen, 1999). An increase of treated effluent from the Sedibeng district's WWTPs is expected which has an estimated total projected generated flow of up to 390 ML/d by 2025, based on Emfuleni and Midvaal population growth rates of 2.6 and 6.7% respectively (AGES, 2008).

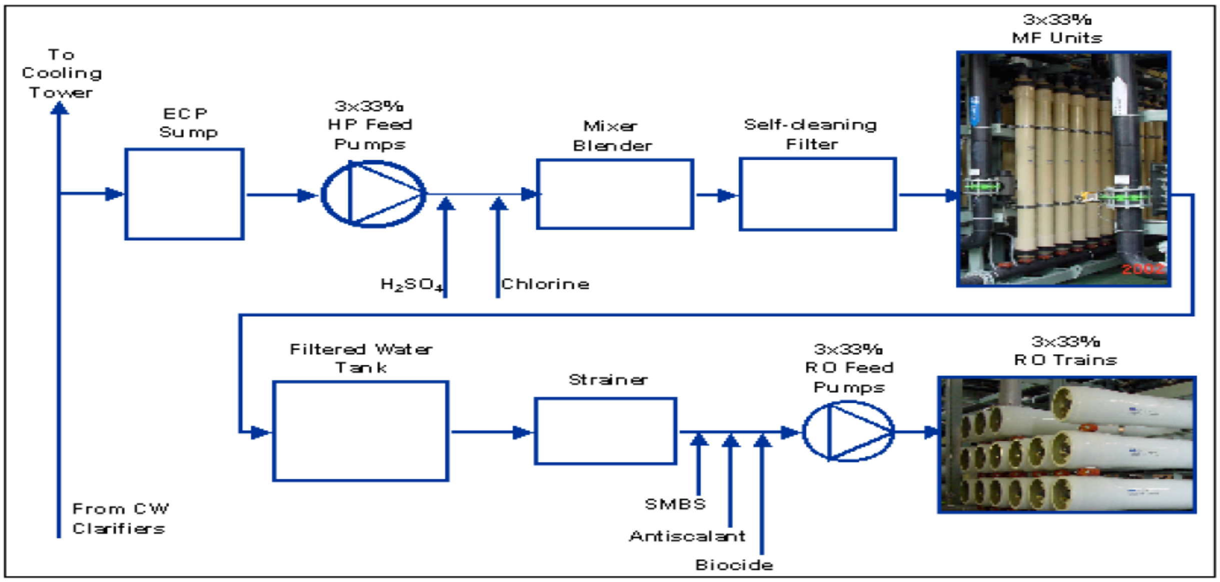

Figure 5.30: Lethabo power station reverse osmosis plant (Pather, 2004)

Lethabo power station uses approximately 1 ML/day of its on-site treated sewage effluent, raw water from the Vaal River and the New Vaal colliery mine wastewater to feed its 12 ML/day reverse osmosis plant (Figure 5.30). The permeate from this plant is used as "make up water" for cooling tower water and for boiler feed water after it has undergone further processes such as ion exchange (ESKOM, 2013). This potential water source from Sedibeng WWTPs can increase the capacity to the on-site generated treated effluent and can reduce the demand of the power utility's cooling tower water.

5.4.4 Steel making

The ArcelorMittal Vanderbijlpark integrated steel works is one of the world's largest inland plant and the largest flat steel products supplier from raw materials in sub-Saharan Africa. It uses up to 65 ML/d of water of which 1250 m^3/h or 30 ML/d is from the Vaal Dam and 1460 m^3/h or 35 ML/d is from the Vaal River which demonstrates cascading and tolerance of variable water quality requirements in its processes. The steel works implemented a ZED philosophy in 2005 where before implementation its dry weather discharge into the Rietspruit was 1300 m^3/h or approximately 31 ML/d which is close to half of the total abstracted volume (Wilson, 2008). After attaining the ZED status, which was part of the water license condition, there was approximately 50% reduction in raw water abstraction. There has been a loss of the ZED status notably in 2011 until 2012 due to the need to discharge excess low quality water in its process. The following schematic diagram (Figure 5.31) shows the steel works water balance with water consumption and generation in cooling towers, cold rolling and treatment plants processes (ZECS, 2015).

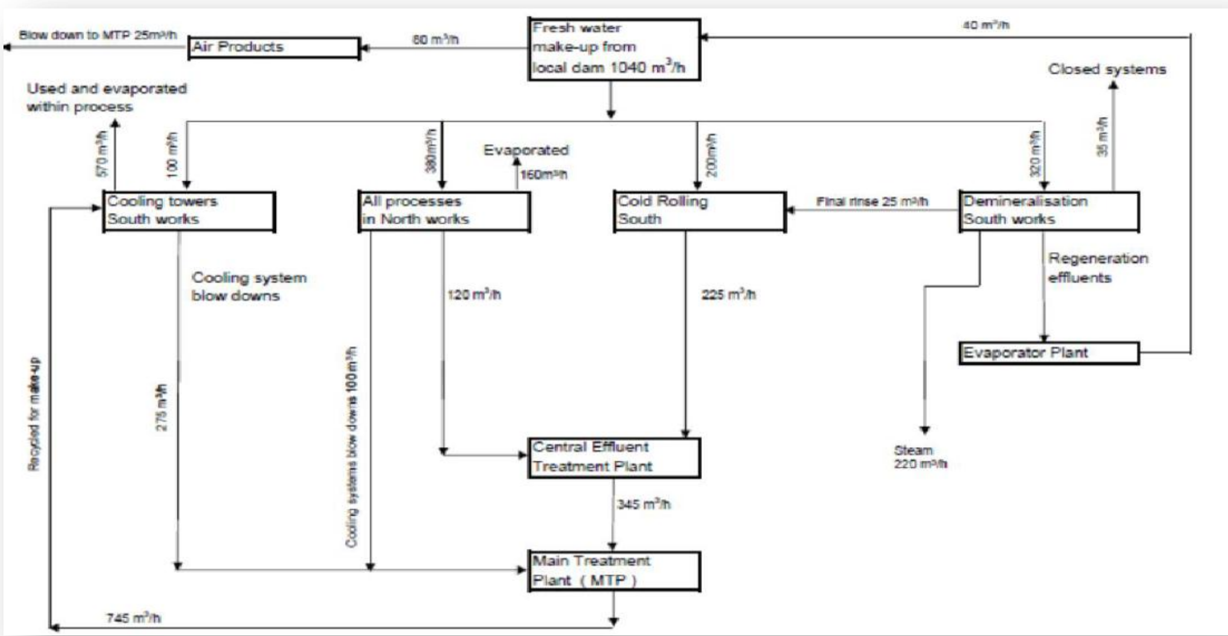

Figure 5.31: Water balance in steel works processes (ZECS, 2015)

Table 5.4 gives the five year (2010-2014) bi-weekly Vaal Dam quality determinants used by two of Rand Water's purification stations namely Vereeniging and Zuikerbosch as raw water source for potable treatment. This Vaal Dam water is a similar source used by ArcelorMittal Vanderbijlpark which gives an indication of water quality requirements for the steel works. The Sedibeng WWTPs effluent is comparable to the Vaal Dam water and both are not complying with BlueScope Port Kembla Steelworks in Australia's water quality requirements in terms of limit to pH range of ±1. The chlorides which are other important specification for the steelworks complies for the Vaal Dam water but does not comply for the Sedibeng WWTPs at less than 20 mg/l.

Table 5.4: Rand Water's stations five years bi-weekly average raw water quality

	A18 Vereeniging Raw water						Raw Water Zuikerbosch (VD and Canal)					
	Mean	Median	Mode	Min	Max	*SD*	Mean	Median	Mode	Min	Max	*SD*
COD (mg/l)	15	13	11	10	36	4.2	15	15	12	10	32	3.9
DOC (mg/l)	5.8	5.5	6.0	3.6	10	1.27	5.7	5.7	5.7	3	8.8	1.3
Turbidity (NTU)	69	73	92	25	110	21.3	61	64	71	15	100	20.5
TOC (mg/l)	6.4	6.2	6.5	2	10	1.64	6.0	6.0	5.1	2.2	19	2.3
NH_4^+ (mg/l)	-	-	-	-	-	-	-	-	-	-	-	-
NO_3^- (mg/l)	0.42	0.39	0.43	0.05	2.6	0.35	0.40	0.38	0.38	0.1	1.6	0.2
PO_4^{2-} (mg/l)	-	-	-	-	-	-	-	-	-	-		
pH	7.58	7.63	7.78	6.43	8.86	0.54	7.72	7.85	8.06	6.4	8.8	0.5
Conductivity (mS/m)	20	19	18	10	30	2.9	20	19	18	9.9	50	4.5
TDS	-	-	-	-	-	-	-	-	-	-	-	-
M-Alkalinity(mg/l as $CaCO_3$)	68	65	60	54	99	8.9	72	68.5	65	55	115	10.8
SO_4^{2-} (mg/l)	15	15	15	8.3	47	4.7	16	15	14	6.7	88	8.3
Na^+ (mg/l)	8.6	8.5	11	3.7	16	2.0	9.0	8.4	10	4.7	46	4.6
Cl^- (mg/l)	6.7	6.4	6.3	2.7	23	2.14	6.9	6.3	6.7	4.5	47	4.6

The ArcelorMittal ZED plant in Vanderbijlpark treats in total 2000 m^3/h or approximately 48 ML/d of its generated wastewater from internal processes, which are reused within the plant as general utility water. Some of the technologies used to treat separate waste streams such as blow-down and storm water, include lime and soda ash softening, clarification, sand filtration, granular activated carbon and brackish water RO (Water Wheel, 2006). The targeted contaminants in the waste streams in this plant, just like power plants are suspended solids and hardness from process water circuits and dissolved salts in blow down water (Water Wheel, 2006; CSIRO, 2008). Suspended solids give rise to turbidity and the turbidity of the Vaal Dam water used by ArcerlorMittal is high and variable (15-110 NTU) just like the Sedibeng WWTPs secondary effluent's suspended solids 0.6-29.7 mg/l during the sampling period. The turbidity of the WWTPs is low and stable as demonstrated by WWTP1 and WWTP3 averages of 3.3 and 4.1mg/l (Table 5.1 and 5.4). Due to macro-ion content, high salt load and eutrophication intensive water user industries such as Sasol (Sasolburg), Mittal and Eskom's Lethabo power station have stopped using the Vaal Barrage water. Cost of desalination treatment technology, such as RO, is decreasing and these water users have already installed this technology as part of their ZED requirements (Pather, 2004; Water Wheel, 2006; Schutte, 2008). Therefore there is no technical reason why they should not also add tertiary treated Sedibeng WWTPs water even for low quality uses such as dust suppression, fire-fighting and even some heat exchange processes after tertiary treatment. The treatment train is recommended for treatment of Sedibeng WWTPs effluent based on cascading water quality use (Figure 5.32).

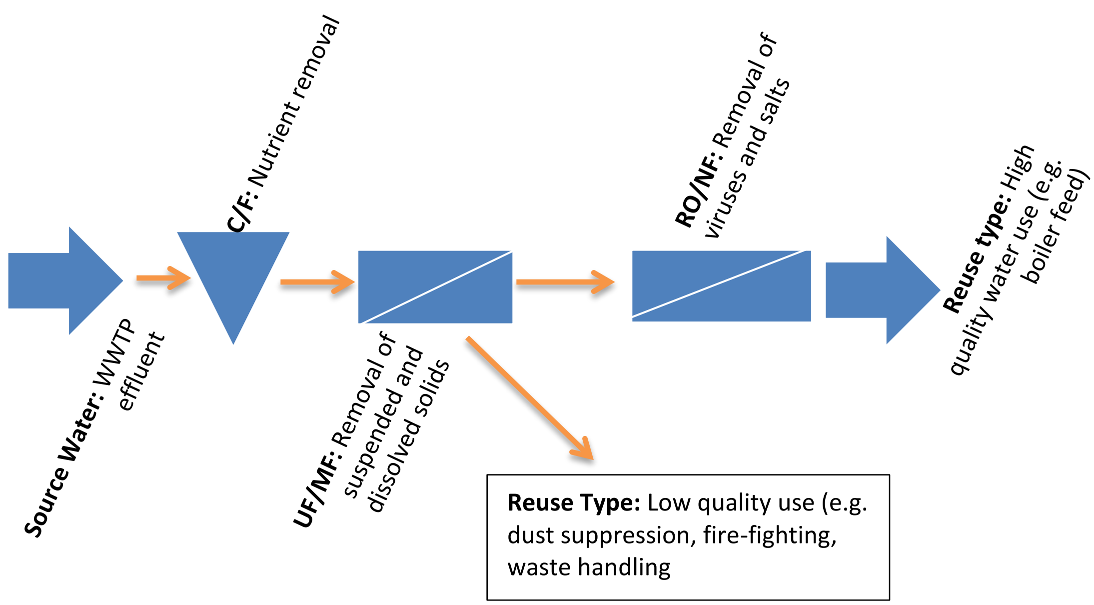

Figure 5.32: Proposed treatment train for WWTPs effluent use in steel works

The private sector threshold capacity and competence as demonstrated by several mining and industrial reuse projects including steel industry must be leveraged for water reuse projects to include municipal treated effluent (Swartz *et al.*, 2014). The water user industries in addition, in PPP, can provide capital investment, operation and maintenance cost, of water reuse infrastructure lacking in municipalities. They could in turn benefit by utilizing the excess water generated and comply with their license conditions (DWA, 2011). In the US approximately 378 ML/d chlorinated wastewater effluent was used since 1942 at the Bethlehem Steel Company in Baltimore, United States for once through cooling systems, metal cooling and processing (USEPA, 2004; Exall *et al.*, 2008). BlueScope Port Kembla Steelworks in Australia, as an example of this, has been using 20 ML/d of reclaimed municipal wastewater in its steel making processes such as cooling and dust suppression since 2006 (Sidney Water, 2009). This steelworks is an integrated steel works just like ArcelorMittal steelworks in Vanderbijlpark in the study area. It uses reclaimed municipal wastewater that undergoes the primary and secondary treatment of screening, degritting, activated sludge process and secondary settling. The effluent then undergoes the tertiary treatment of MF-RO, with hollow fibres and fine barrier membranes respectively and ultimately disinfection of treated water takes place (Hird, 2006; Sidney Water, 2009).

However safety and public perception and acceptance concerns have to be addressed in consultation before implementation. This was the case with the Port Kembla Steelworks in Australia where the New South Wales fire brigade refused to control fires at this site using reclaimed water (ABC, 2006; CSIRO, 2008). This is, despite health of workers and community due to exposure being the number one concern in terms of quality adherence of the works, hence the importance of open communication between stakeholders is stressed (Hird, 2006).

In order to use treated effluent from sewage plants, steel industries must assess its quality and install appropriate treatment technology such as UF-RO (Panagopoulou *et al.*, 2011). Vanderbijlpark ArcelorMittal works, an integrated steel works as well, has no process related reason why they should not use treated municipal effluent from the

Sedibeng and Gauteng south district. This is because the steel works already has the advanced tertiary treatment process of reverse osmosis that can treat the Barrage water.

5.5 Conclusions

South Africa has institutional memory capacity, having been part of the plans for the Goreangab WRP in Windhoek and having already installed and run the Beaufort West WRP. Rand Water which is the bulk water supplier can be involved in water reclamation as well to manage its waste and increase its supply capacity. Water intensive user industries in the study area, Arcelormittal and Eskom's Lethabo power station are practicing internal recycling and there is no reason why the Sedibeng district secondary effluent cannot be incorporated into their processes. SDM municipal wastewater effluent can be reclaimed at a lower cost compared to currently used processes and reused for the above mentioned industries in the study area and thereby reducing demand of freshwater. This is based on comparative costs of different water sources and declining costs of membrane technology as outline in the Literature Review Chapter 2 (DWA, 2010; DWA, 2013). The water can be introduced to moderate water quality processes such as cooling systems, heat removal, waste handling and washing in industries in the study area.

The water quality of the four WWTPs in the district, meets most requirements for reuse feed water into tertiary treatment processes of the water user industries. Aggregate parameters such as COD, suspended solids, turbidity and TOC comply with influent design criteria for DPR for WWTP1, WWTP2 and WWTP3 except for WWTP4. These parameters should be kept low to prevent membrane fouling in further tertiary treatment and prevent damage to equipment in industrial processes. Nutrients and ionic parameters, which comply for all WWTPs except ammonia in WWTP3 and WWTP4, should be removed to prevent eutrophication in receiving water bodies and corrosion or scaling in industrial processes. Microbiological quality is of great concern for all Sedibeng WWTPs as it is not complying with the DWAF general limit which is the influent design criteria for the Beaufort West WRP. This microbiological quality can also overload membrane processes and if the effluent is used with limited tertiary treat, it can compromise the health of workers in industry and result in negative perceptions.

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CHAPTER 6

Conclusions and recommendations

6.1 Conclusions

South Africa does not have water reuse guidelines even though there is a strong reuse practice in direct potable reuse (DPR) such as in the Beaufort West Water reclamation plant (WRP) case and "de facto" reuse through downstream abstractions. These guidelines could assist in the design strategy of water reclamation plants and urban infrastructure planning for future incorporation, reclamation and reuse of municipal secondary effluent. This could reduce demand in potable water especially imported water, water for agricultural and industrial processes with high water demand.

Industrial reuse and recycling is practised in power generation, steel making, mining, chemical and paper manufacturing industries in South Africa. A good public-private partnership is that of eThekwini municipality and Mondi paper/Sapref, which the study area could learn from in the reclamation of municipal secondary effluent. Agricultural reuse, which is the oldest and accounts for the largest reclamation and reuse worldwide is not fully exploited in South Africa and the study area. This could be partly due to declining agricultural activity in the study area, non-existent current guidelines and standards and concerns of irrigation return flows.

For water reclamation, reuse and recycling to be a success for the study area there has to be a paradigm shift from supply side to demand side solutions in combination with alternative supply. This was evident in countries practicing wastewater reclamation in the study, which the Sedibeng district can adopt, which had the following characteristics:

- They were arid and semiarid, water scarce with variable and low rainfall patterns and they have exhausted their infrastructure capacity to retain the precipitation

- They have large population numbers, increasing population growth and urbanization with associated industrial activity
- Water quality regulations are developed to protect the public and the environment against the accompanying risk of wastewater reclamation
- Even though statistics of water reclamation and reuse are not up to date they are advanced in some countries such as Singapore to determine reuse status quo, forecasts and projections
- Perceptions on acceptability of wastewater reclamation is influenced positively by water education, trust in technology, standards and authorities, among others and are continuously negotiated with changing conditions

Australia among the leading wastewater reuse countries is similar to South Africa, in water scarcity, annual rainfall, mineral resource and wastewater quality challenges such as salinization and only differs in population density. South Africa has a high water intensity usage similar to Australia in industries such as power generation and steel industry but the latter is advanced in specific guidelines for wastewater reuse.

Aggregate, nutrient, ionic and microbiological water quality parameters were analysed for the four WWTPs in the Sedibeng district municipality situated in the Southern Gauteng study area. All four WWTPs comply with respect to most aggregate, nutrient and ionic parameters except for microbiological parameters and this shows the importance of secondary treatment as one of the barriers in water reclamation. These were measured against worldwide water quality criteria as feed and final effluent for advanced treatment for potable, agricultural and industrial reuse with emphasis on the study areas potential water reuse areas. Water quality guidelines, criteria and regulations are based on parameters that can be measured with affordable and dependable analytical monitoring tools and continuous technology improvement is required.

Water reclamation of Sedibeng municipal effluent either through direct (DPR) or indirect potable (IPR) water reuse, power generation and steel making industry has a potential in the study area. This could be either in a centralized WRP where all effluent is advanced treated after collection as secondary effluent or in a decentralized WRP format where each WWTP would improve quality of effluent and supply to nearest user. Advanced oxidation processes (AOPs) and membrane treatment technology with preliminary treatment such as coagulation flocculation and sand filtration such as in Namibia and Beaufort West WRPs. These two cases were benchmarks for DPR without an environmental buffer and other international IPR schemes such the ones in Australia, US and Singapore were benchmarks for IPR and quality criteria in the study.

Eskom's Lethabo power station and ArcelorMittal are existing intensive water user industries in the study area where potable water demand can be reduced with reuse of Sedibeng WWTPs effluent. They could incorporate this year round readily available source for further tertiary treatment which already exists for zero effluent discharge (ZED) internal recycling processes as part of their water license conditions. ArcelorMittal, as an integrated steel works, requires water of different quality in its cooling, heat exchange, dust suppression, etc. processes and this could reduce the demand for higher quality water extracted from the Vaal Dam. Eskom's Lethabo power station, as any coal fired power station, uses most of its water in cooling towers which do not require high quality water especially for once through cooling systems.

6.2 Recommendations

The following recommendations can be drawn from the study results for direct and indirect potable, agricultural and industrial reuse utilizing wastewater generated from the Sedibeng district's WWTPs as a viable water source:

- Water quality guidelines to be formulated to address health concerns with monitoring protocol and risk assessment among others specific for water reuse
- Future studies in the study area can focus on industry or site specific inorganic metals analysis and monitoring emerging compounds such as personal care and pharmaceutical compounds (PPCPs) and endocrine disrupting chemicals (EDCs)
- Bio-toxicity test that can act as surrogate for complex analysis for feed effluent and reclaimed water for acute and chronic exposure in risk assessment

- Public perception and acceptance investigation in the study area on reuse based on among others exposure through working with reclaimed water and reuse for domestic purposes
- Economic feasibility of infrastructure implementation geared towards water reuse in terms of the central WRP, pumping costs, potable and WWTPs treatment technology upgrades
- Feasibility of the formation of private-private partnerships in water reuse for the study area involving the municipality, Rand Water bulk water utility and water intensive user industries such as Eskom and ArcelorMittal