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Assessing effectiveness of groundwater remediation technologies to a coastal aquifer within an urban environment in South Africa

A thesis submitted in fulfilment of the requirements for the degree of Master of Science in Environmental and Water Sciences

By

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Declaration

I, Jessie Mzati Kanyerere, declare that "Assessing effectiveness of groundwater remediation technologies to a coastal aquifer within an urban environment in South Africa": A case study of Cape Flats Aquifer, Western Cape, South Africa" is my work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Jessie Mzati Kanyerere

Signed…......................................

Date…..18/10/2022...........

Dedication

I dedicate this work to my husband and best friend Paschal Ogechukwu Amaechi and our unborn children, my father, Dr. Thokozani Kanyerere, my Mum, Mrs. Joyce Robertson Ng'oma Kanyerere, and my sisters Alice Mwanjiwa Kanyerere and Malumbo Wapulumuka Kanyerere. They have been my strength and support throughout this work.

Contribution to knowledge

In this section, a list of conference presentations that were made during the period of the Master of Science degree in Environmental and Water Sciences are presented below:

1. 21st WaterNet/WARFSA/GWPSA Symposium from 28-30 October 2020
2. 3rd SADC groundwater conference from 24-26 November 2020

Draft Manuscript

- Application of ex-situ remediation technology for groundwater contaminants in unconfirmed aquifer system: the case of Cape Flat Aquifer System, Cape Town, South Africa [Draft paper in progress]

Abstract

The study aimed to assess the effectiveness of Reverse Osmosis technology as an example of ex-situ groundwater remediation technologies. The Cape Flats Aquifer System, an urban coastal system, was used as a case study. Globally, urban groundwater contamination remains a known problem for water users, hence the need to remediate such water. The study argues that effective technologies such as Reverse Osmosis to remediate groundwater contaminants exist. However, the effectiveness of such technologies is not demonstrated to inform the wider application. The question of how effective these technologies are in remediating groundwater contaminants is not fully understood. To answer such a question, the study had three objectives: (1) Determine the concentration levels of selected contaminants, (2) Apply a conceptual model of groundwater flow to explain the transport of contaminants, and (3) Demonstrate the effectiveness of Reverse Osmosis technologies in remediating groundwater contaminants. The groundwater remediation plant at the University of the Western Cape, within Cape Flats Aquifer System, was used to assess the effectiveness of Reverse Osmosis in removing contaminants in groundwater. In general, physical, chemical, and biological parameters were studied from various datasets. However, the focus was on Iron (Fe) and Manganese (Mn) as the reported groundwater contaminants in the studied system. Concentration levels of EC, pH, Fe, and Mn were obtained over 3 months from the Quality filtration systems (QFS) water treatment plant. The average concentration levels of EC, pH, Fe, and Mn before treatment were 146.67mS/m; 6.932µ/l [0.00693mg/L] and 26.3 µg/l [0.026mg/L] respectively. The average concentration levels of EC, pH, Fe, and Mn after treatments were as follows: 44.1mS/m; 7.04,32.1µg/l [0.00704mg/L], and 20.92µg/l [0.0209mg/L] respectively. To assess the effectiveness of the Reverse Osmosis [RO] technology, the formula of Removal rate = (1-A/B) *100% was applied where A is the pollutants after treatment and B is the pollutants before remediation. Results showed that 96% of Fe contaminants were removed from the groundwater, and 78% of Mn contaminants were removed from groundwater. Reverse Osmosis technology was found to be 78% to 96% efficient in removing contaminants from the Cape Flats Aquifer. This study concluded that empirical evidence on the effectiveness of ex-situ groundwater remediation technologies such as RO is critical for rolling out new technologies.

Keywords: Coastal aquifer, contaminants, remediation technologies, Reverse Osmosis, effectiveness

Acknowledgment

I want to thank the following people and organizations who were instrumental to the success of this work: The national research fund (NRF) for the financial support that was provided during my studies. My supervisor Dr. Sumaya Clarke for the help and guidance she provided through my research work. To my Co-supervisor, Dr. Innocent Muchingami, thank you for not getting tired of my messages and emails asking for help. To my husband for the hard work and sleepless nights that you were with me on this journey. You were never tired of my questions and disturbance about my work. Mr. Shawn and Mr. Werner from the Quality Filtration System (QFS) water treatment plant at the University of the Western Cape for their guidance in the process of the Reverse Osmosis plant. To the international Support Network for African Development (ISNAD) fellowship for providing me with a mentor, Dr. David Rutan. To my fellow postgraduate student in the Environmental and Water Science Program, I thank you for being part of the journey. To my family, a word cannot say it all; you encouraged me, pushed me, and trusted me to do this work, it was not easy, but you made it look easy. Thank you so much for everything. Above all, I thank the almighty God for providing me with strength, protection, good health, and guidance throughout my studies.

Abbreviations and Acronyms

CFA:	Cape Flats Aquifer
Fe:	Iron
Mn:	Manganese
NZVI:	Nanoscale Zero valent iron
ZVI:	Zero-valent Iron
SCCMs:	Sustainable compounds carbon source Materials
PRB:	Permeable reactor barrier
AS:	Arsenic
F:	Fluoride
EC:	Electrical Conductivity
TDS:	Total dissolved Solutes
pH:	Power of hydrogen
WHO:	World health organisation
SANS 241:15:	South Africa National Standards
RO:	Reverse Osmosis

Table of content

Contents

List of Figures

List of Tables

CHAPTER 1: GENERAL INTRODUCTION

1.1 Overview of the Study

The present study assesses the application of groundwater remediation technologies to improve water security, especially in drought-prone urban areas. Selected sites within the Cape Flats Aquifer in Cape Town, South Africa, were identified for a case study. This study argues that solutions exist for remediating groundwater contaminants to improve water security. This is usually achieved when appropriate technologies are applied in a phased approach through pilot projects. Also, implementing available remediation technologies for groundwater contaminants on a broader scale beyond pilot projects can help improve groundwater security. Based on this situation, this study believes that concentration levels of contaminants need to be determined and established by comparing them to SANS241:15 and WHO standards. Secondly, contaminants of concern need to be identified. Thirdly, a conceptual model of the groundwater flow system needs to be used to explain groundwater contaminants. This study assumes that groundwater contamination issues can be addressed if the movement of contaminants in the aquifer system is identified, visualized, and explained using a site-specific conceptual model of groundwater flow and contaminant transport. The last part of the present study demonstrates groundwater remediation technologies by identifying contaminants and applying the RO process to remediate them.

In summary, the research uses the Cape Flats Aquifer System as a case study to illustrate the application of remediation technologies for groundwater contaminants to improve water security, especially in drought-prone urban areas. The present study demonstrates how site-specific problems can be addressed by applying available remediation technologies for groundwater contaminants

1.2 Background of the study

Groundwater is a valuable resource and needs to be protected from pollution. This resource serves as the primary source of drinking water in many areas of the world. About 2 billion of the world's population depends on groundwater for their daily source of safe drinking water (Kemper, 2004). Agricultural and industrial sectors also use groundwater for various functions (Farhadian et al., 2008). Activities from different uses threaten groundwater quality, while the increased extreme events such as droughts threaten its quantity (availability). Because of the increased threat to groundwater quality, studies on remediation techniques for groundwater resources have become important. Such studies assess groundwater contaminant sources, transport of such contaminants, and explore the available technologies to clean up contaminants from groundwater. This justifies the need for the current study on remediation technologies. Due to increases in water insecurity and increased pollution challenges, studies on remediation technologies for groundwater have received renewed attention in the groundwater quality sector in recent years. The general concept of groundwater remediation is based on the contamination and pollution in the system because of different natural and anthropogenic activities (Talabi et al., 2019). Thus, the focus of the current study.

In general, groundwater pollution or contamination occurs due to natural or anthropogenic activities on the land surface or subsurface, either accidental or planned (Zhang *et al*., 2017, Li *et al.,* 2021). These pollutants or contaminants move in aquifers under the influence of physical, chemical, and biological factors. The processes involved in the movements of contaminants or pollutants can modify the velocity, direction, and composition of contaminants (Talabi et al., 2019). Such factors include diffusion, dispersion, and absorption, among others. The results of such operations are many, including variations in groundwater velocity. For example, the slow movement of groundwater can result in plumes, where the concentration of such plumes is high. The patterns of contaminated groundwater flow are site-specific and depend on contaminants and groundwater flow characteristics.

Different types of pollution or contaminants occur in aquifers. Therefore, various methods of remediating such pollutants or contaminants are required. This justifies the need to assess the available remediation technologies to identify and apply appropriate ones to remediate pollutants or contaminants in the aquifer system studied. Hence the focus of the current study.

Based on the global reports about pollution and contamination (Skovgaard, 2000; World Health Organisation, 2007; Kirk et al., 2015; Torgerson et al., 2015; Organization, 2017), exploring appropriate groundwater remediation techniques that would be applied to improve water security seems to be a plausible solution in the water sector. Groundwater remediation techniques are broadly categorized into three standard methods, namely: physical, chemical, and biological methods (Hadley and Newell, 2012). Further, these technologies are divided into in-situ and ex-situ remediation technologies. Under each of the technologies, different methods exist for removing contaminants. For example, physical groundwater remediation involves pumping water out of the aquifer, treating such water, and then putting the treated water to desired use (Reddy, 2008; Tack and Bardos, 2020). This method is referred to as the pump and treats procedure, and the associated technology or treatment process is the reverse osmosis (RO) method. The RO method purifies water for drinking and other purposes, whereby the polluted or contaminated water is passed through a semi-permeable membrane and different chambers to remove impurities. The contaminants can have other products such as salts for commercial purposes or manure for agricultural purposes (Hadley and Newell, 2012). The purified water from the RO process can be used for various fit-for-use alternatives after being tested and compared to global standards such as World Health Organisation (WHO) guidelines and national water standards.

Groundwater contamination occurs in many areas and situations. Various sources of pollution exist, and they have been classified according to activities that produce such contaminants in different areas (Talabi et al., 2019; Hadley and Newell, 2012). Adelana and Jovanovic (2010) identified sources associated with groundwater contaminants in the Cape FlatsAquifer [CFA] and characterized those contaminants. This means that contaminants need to be described and their sources identified. Such characterization helps in understanding the behaviour and origin of the contaminants and is an aid in constructing the conceptual model of the groundwater regime, which could explain the vulnerability of such aquifers. (Giljam R 2002) reported that the CFA remains vulnerable to outside influences such as informal settlements, like Philippi agricultural area, and numerous nodal sources of pollution. Therefore, exploring technologies to remediate contaminants from such a vulnerable resource remains an important task that would make the groundwater resource available to many users. Understanding the vulnerability of groundwater in the study area in line with the available groundwater conceptual model helps visualize the use and impact of RO methods in various parts of the aquifer system. Such an understanding improves the development and refining of the fate and transport model of groundwater contamination in the study area for improved water security practice.

Water security is a global problem, and it is due to various causes. For example, (Winter, 2018) cites the 2017 drought as an example of a water security challenge in South Africa that impacted water availability and resulted in water restrictions for various activities. However, poor quality water, including wastewater, was available, but this water could not be used due to its contamination. The availability of poor-quality water justifies the need to explore the available remediation technologies that can be piloted to purify such water for various fit-for-use activities to address water shortages. Although no universal agreement on measuring water security provides operational ways of measuring water security (Winter, 2018), this study argues that exploring technologies for groundwater remediation can improve water security, especially in urban areas and drought-prone regions where demand for freshwater for various activities exists, including in coastal environments.

Groundwater remediation involves the treatment of polluted groundwater by removing the pollutants or converting them into harmless products. Groundwater remediation has goals, missions, and approaches formed in the South African water quality policy for groundwater. The policy goals include remediating groundwater quality where practicable to protect the reserve and ensure at least fitness for the purpose served by the remediation, as per Chapter 3 of the National Water Act of South Africa (DWAF, 2000). Despite the National water Act, there have to be resource-directed measures to manage source-related groundwater contamination to protect the reserve and ensure suitability for beneficial purposes recognized by the Act (Chapter 3 of the National Water Act (DWAF, 2000). These goals are achieved by implementing groundwater principles (DWAF, 2000). This study applies available technologies to remediate contaminants or pollutants in groundwater systems to improve water security. The current study believes that if remediation technologies are not tested, and their effectiveness is not established, scaling up such practices will have no science-based evidence to address water security challenges such as water shortages.

1.3 Problem statement: Research problem, question, and hypothesis

Various sources of groundwater contamination have been reported in the Cape FlatsAquifer [CFA], such as wastewater treatment plants, industrial and agricultural activities, cemeteries, and informal settlements (Ruben Aza-Gnandji et al., 2013; Hay et al., 2016). Though several remediation technologies can be employed in the remediation of contaminated groundwater (Mulligan, Yong, and Gibbs, 2001; Garelick *et al.*, 2005; Bhandari *et al.*, 2007; Hashim *et al.*, 2011), the understanding of the effectiveness of reverse osmosis technology in remediating contaminated groundwater in Cape Flats Aquifer remains limited. There is a need to assess effective remediation technologies to enable such technologies to be rolled out at a larger scale to address water security challenges. Based on such a gap, the present study argues that appropriate groundwater remediation technologies need to be tested and their effectiveness established for scaling up such practices to address water security challenges such as securing fresh, clean water for various activities.

1.4 Research Question

What is the effectiveness of remediation technologies for groundwater contaminants? What is the potential of such technologies in improving water security? In other words, how effective are groundwater remediation technologies in improving the water security of an area?

1.5 Study aim and objectives

Based on the research problem, research question, and hypothesis or argument in sections 1.3 and 1.4, the present study aims to assess suitable technologies for groundwater remediation practices that can improve water security and the effectiveness of such technologies. Such an assessment will enhance the understanding of available feasible technologies for groundwater remediation practice and their efficiency. Furthermore, the improved understanding will inform the basis for scaling up such groundwater remediation practices improving water security for various uses. The Cape FlatsAquifer system is used as a case study for the project.

To achieve the stated aim, three objectives were formulated as follows:

1. To determine concentration levels of selected contaminants
2. To apply a conceptual model of groundwater flow to explain the transport of contaminants
3 To demonstrate the effectiveness of Reverse Osmosis technologies in remediating groundwater

1.6 Significance of the study

The present study is essential for the following reasons: firstly, improving knowledge on assessing the effectiveness of remediation technologies for groundwater contaminants. Such knowledge will be published as a journal article for broader dissemination. Secondly, results from the present study will be used as a case study during the teaching and learning activities, thereby contributing materials on groundwater quality, remediation technologies, and water education. Thirdly, through workshops and conferences, results from the current study will be disseminated to the community of practitioners in the water sector to facilitate wider uptake of the findings to improve the practice. Lastly, the generated results will serve as a knowledge database for various researchers working on groundwater remediation technologies, fate and contaminants transport, and groundwater modeling, thus, the significance of the current study. Furthermore, due to the unconfined and shallow nature of the Cape Flats Aquifer (CFA) system, vulnerability to contaminants of various types is high. Therefore, the study assesses the remediation technologies in CFA that strengthen water security improvement in future urban areas in the South African context. CFA was chosen as a case study because of the presence of various land-use activities and geology. It is known that the area is dominant with a sandy aquifer, which can help infiltrate contaminants at different levels. The study helps compare other research done in regions with the same geologic features. This will help us determine if the technology used in this study has the same effect on contributing to groundwater quality.

1.7 Conceptualisation, Scope, and Nature of the Study

The present study is informed by the groundwater remediation practices explored in South Africa to find appropriate remediation technologies to address water security challenges. South Africans held several talks on desalination initiatives in 2017-2019 during the water crisis period, where several remediation technologies were discussed for the possible adoption of some of these technologies for the South African context. From such discussions and a series of lectures on groundwater remediation technologies in hydro-geochemistry classes, the research problem for the current study was conceived. Although such initiatives are broad, the present study only focuses on groundwater remediation technologies. The present study is also informed by sustainable development goal six, which focuses on clean water to ensure the management of available and sustainable water resources (Mortonet *et al.*, 2017). Hence, the focus is on the purification of contaminated water.

The scope of the study is groundwater contamination/groundwater quality, focusing on groundwater remediation technologies. Such a focus includes sources, characterization, and concentration levels of groundwater contaminants. In addition, groundwater conceptual models are identified, evaluated, and appropriate ones chosen to explain the movements of contaminants in the aquifer system and describe their vulnerability to such contaminants. The present study is not about developing a groundwater model. It is not about conducting aquifer vulnerability assessments. The study's core focus is assessing available technologies for groundwater remediation, identifying and testing the appropriate technologies, and evaluating the effectiveness of the chosen technologies in remediating groundwater contaminants. Therefore, options can be recommended to upscale such technologies to address water security challenges in various hydrogeological settings, including urban and coastal environments.

The current study follows a quantitative approach to studying groundwater contaminants and addresses the three objectives. The first step involves a desktop approach that allows reviewing the records [records review method]. The review process enables selecting standard and current methods for collecting and analysing information for the present study. For example, a record review method identifies available remediation techniques to identify appropriate remediation technologies for testing in the experimental field set-up. A quantitative field experiment research design is chosen for the study where field visits are conducted, and water samples, water levels, and hydrogeological data are collected for various analyses. To a lesser extent, a qualitative observational descriptive study design using hydro-census is used to characterize the groundwater contaminants in the vicinity of the study area. In this approach, sources and types of contaminants are mapped and assessed. The field observational descriptive study design helps provide a context of the study area regarding verification, validation, and ground-truthing of the findings. Such a design or approach remains crucial when explaining the conclusions of the study.

1.8 Research framework at a glance

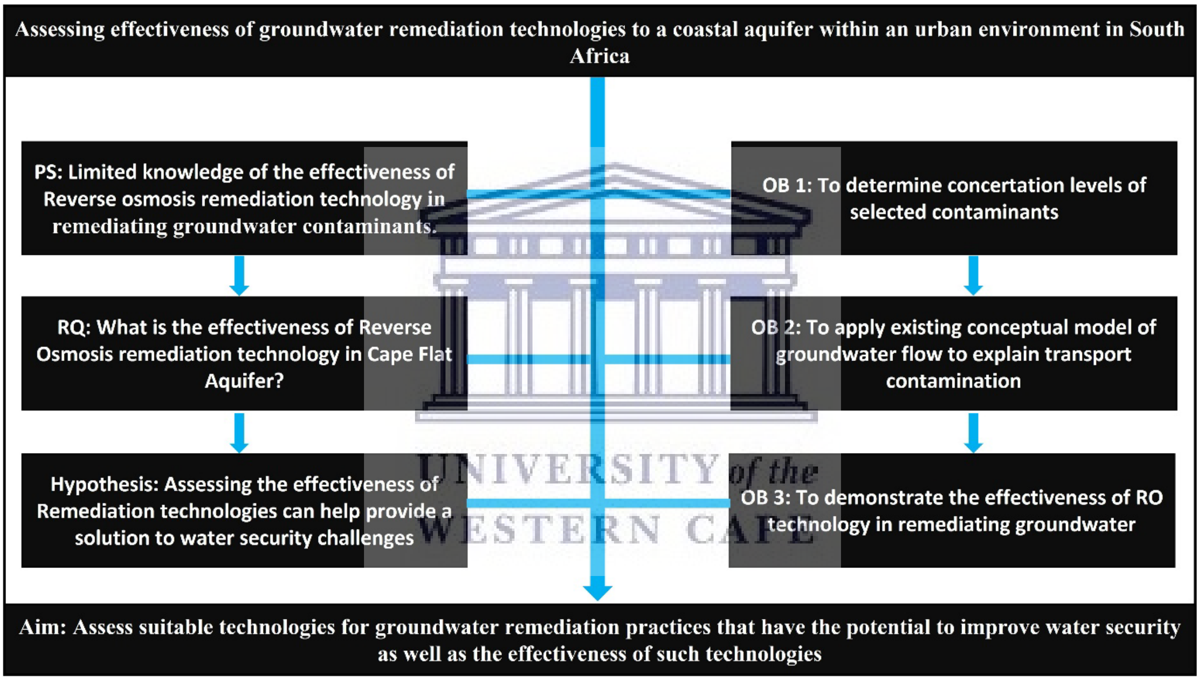

Figure 1: Research Framework at a glance

1.9 Outline of the Thesis Report

Chapter 1 provides the general introductory aspects of the research regarding the contribution, research problem, research question, central argument, objectives, scope, nature, and conceptualization of the present study. Chapter 2 describes the study area regarding the setting or context where the research idea was implemented. Chapter 3 provides the reviewed literature to demonstrate the state-of-the-art knowledge gaps regarding using remediation technologies in groundwater contamination for improved water security. The literature is reviewed systematically and analytically from historical and current literature to highlight the gap in knowledge and practice. The present study narrows the identified knowledge gap with reliable and valid data as evidence for the central argument. Chapter 4 provides the methodological framework for research design and methods to generate and analyse data. It also presents the research integrity and quality assurance aspects for reliable and valid results for interpretation. Chapter 5 provides results and discussion on concentration levels of selected contaminants, transport of contaminants, and effectiveness of reverse osmosis technologies in remediating groundwater. Finally, chapter 6 offers conclusions and recommendations based on the findings.

CHAPTER 2: DESCRIPTION OF THE STUDY AREA: CAPE FLATS AREA

The geology, surface water, groundwater, soil, and geomorphology of the area, climate, and human activities found in the site are described in the context of the study objectives and parameters. The physiography of the area is described to understand how they influence groundwater remediation technologies. The chapter also explores and describes the location of the area and provides justification for the chosen study site. This chapter describes different activities in the study area that can influence the outcome of the study objectives. Therefore, the study provides explanations in the context of such activities.

2.1 Location of the Cape Flats Area

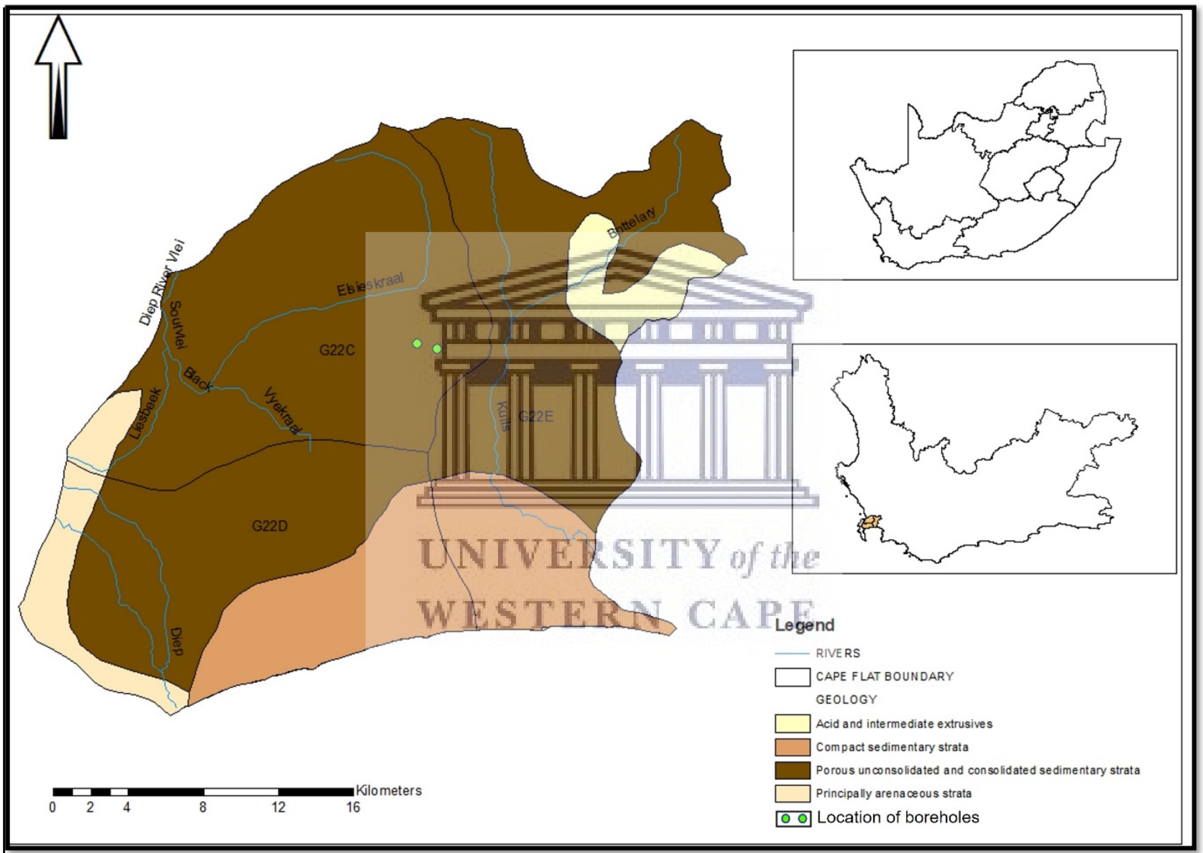

Figure 2: Location area map including production boreholes

Cape Flatsaquifer is located within the City of Cape Town with the coordinates Latitude: -34° 00' 0.00" S and Longitude 18° 39' 59.99". The area is situated in the Cape metropolitan area's central part and covers about 630 km^3 of the Western Cape Province in South Africa (Adelana *et al*. 2010). The Cape Flats Aquifer is bordered by false Bay in the south, Tygerberg Hills in the northeast, and Milnerton in the northwest. The Cape Flats aquifer area is boarded by the Cape Town-Muizenberg, Cape town Bellville-Kraaifontein and Bellville –Eerste river –Strand railway, and the false bay coast with a narrow strip of land along the western coast extending northwards from Cape Town and Bellville through Bloubergstrand up until Atlantis (Adelana *et al*., 2010). The topography of the study area is a low-lying flat with an average elevation of 30m above sea level (Adelana, 2010). The map provides a visual location and identification of the area of the study; this map helps in the demarcation of the Cape FlatsArea and the specific focus of the study. Therefore, it is essential to have a study area map to show the studied location or visualize the study area.

2.2 Justification for the selection of the Cape Flats Area

The Cape Flats Area (CFA) is one area commonly known for excess iron and manganese, making the water unsuitable for drinking. The excess iron and manganese in the CFA are due to natural contamination and anthropogenic activities. Different scholars have studied the problem of iron and manganese in the Cape Flats Area. The concentration of iron and manganese in the Cape Flats area showed to be elevated (Aza-Gnandji *et al.*, 2013). For example, the walls of most houses that use borehole water display a brownish colour to indicate the concentration levels of iron and manganese in the groundwater sources. Such concentration levels of iron and manganese need to be remediated and then monitored to evaluate the effectiveness of the technology used to remediate such pollutants. Purifying such water increases its use for various purposes and mitigates the effects of climate change, reducing the availability of surface water resources. CFA was selected for the present study because of iron and manganese problems in CFA.

Different studies have been done on the CFA on groundwater quality (Adelana and Jovanovic, 2010; Adelana et al., 2010; Gintamo et al., 2021b, 2021a). However, the focus on groundwater remediation studies remains limited, hence the focus of the current study. The University of the Western Cape hired a company to drill boreholes and install a water treatment plant to help supply water on the premises of the University during the 2017 drought period in Cape Town. The groundwater remediation plant was used as a case study to demonstrate the effectiveness of reverse osmosis technology in removing contaminants from groundwater.

2.3 Geology and soils of Cape Flats Area

Cape Flats are large undulating sandy areas connecting the Cape Peninsula's hard rock (Adelana *et al*., 2010, Hay *et al.*, 2015). It is a lowland area that has varied terrain, ranging from low-lying sandy plains (with an average elevation of 30 m.a.m.s. l) to rocky mountains with a series of peaks rising to 1038m on Table Mountain and dropping sharply to the sea in many parts of Peninsula (Adelana *et al*., 2010)). The area comprises late tertiary and recent sand units in the Western Cape overlaying the Malmesbury shale (Adelana, 2010). The oldest rocks in the Western Cape are meta-sediments of the -pre-Cambrian Malmesbury group (Adelana *et al*.,2010). The geology of the aquifer is mainly sand that varies from unconsolidated to semi-consolidated, with clay and peat layers interbedded, causing the aquifer to be semiconfined in some parts (Saayman and Adams, 2002). Understanding the type of geology and the type of contaminants such as iron and manganese helps to recognize the origin of such contaminants in characterizing and determining the movements and behaviour of contaminants in the groundwater systems of such a dominant geological environment.

2.4 Soil type of Cape Flats Area

Soil texture refers to the soil composition of the proportion of small, medium, and large particles (clay, silt, and sand) (Ball, 1997). Cape Flats consist of fine sand soil and are aeolian, meaning they are transported by wind (Norman and Whitfield, 2006). The Cape Flats consists of a narrow strip of land along the western coast, extending northward from cape town (Adelana *et al*., 2010). The undulating sandy area connecting the hard rock of the cape peninsula is called the Malmesbury shale. Silty sand, quartz clay, and peat are some of the soil types found in the area. Sandy soils are composed of large particles, making water move rapidly. These sandy soils influence water chemistry and help the fast recharging mechanism (Ball, 1997). Cape Flats is a flat area that has undulated sand that allows diffuse type and a local type of groundwater recharge. Due to the undulating types of the soils, these areas are vulnerable to contaminants because of the unconsolidated geological environment such as the loose sandy soils type existing in the study area, the Cape Flats area. Hence, the understanding of such unconsolidated geological environment helps in explaining the movement of contaminants or pollutants from the surface to the subsurface or within the subsurface system.

2.4 Geomorphology of the Cape Flats Area

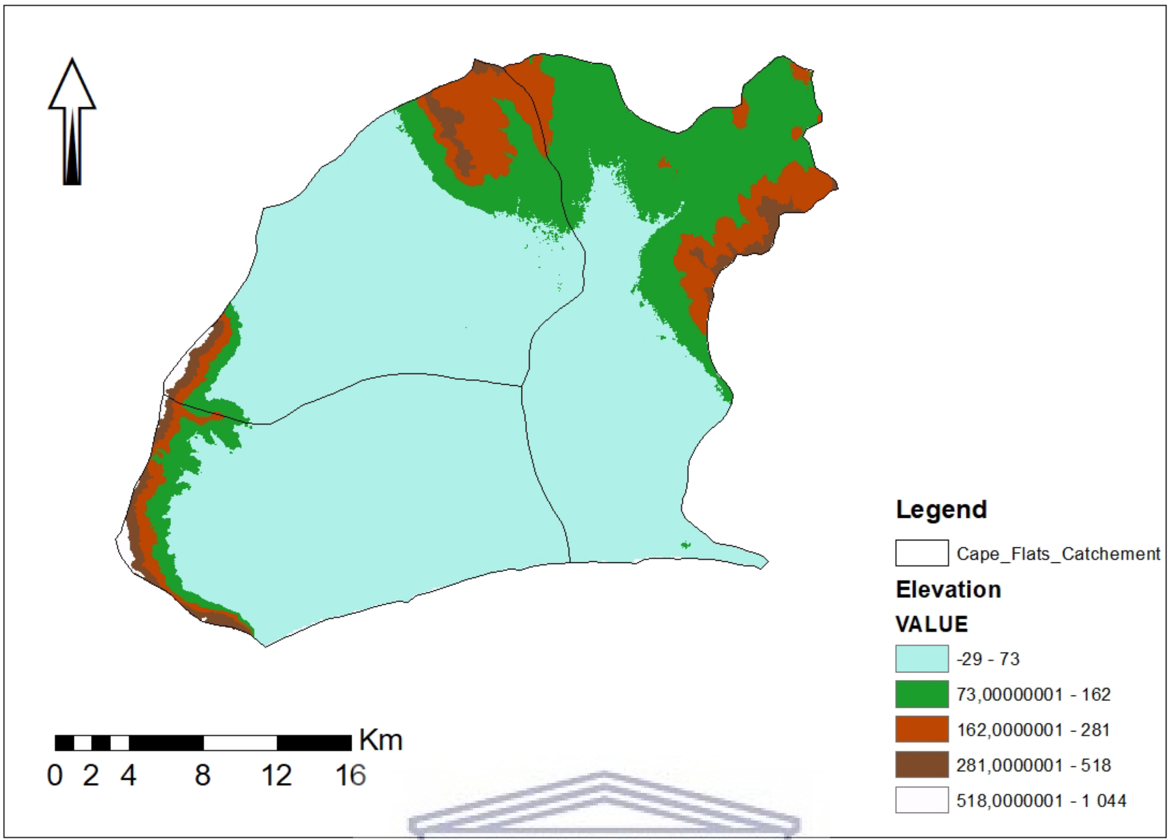

Figure 3: Topography of Cape Flats catchment

Different geomorphological features dominate the Cape Flats area. Cape Flats is a lowland area with varied terrain ranging from low-lying, sandy plains with an average elevation of 30 m (Meters above mean sea level) to the Rocky Mountains with a series of peaks rising to 1038 m on Table Mountain and dropping sharply to the sea; this is shown in many parts of the peninsula. Dunes are frequent with a prevalent south-easterly orientation, and the highest dunes are approximately 65 m.a.m.s.l. Due to the dune in the area, characterized as sandy soil with increased permeability, most areas in Cape Flats are sources of recharging to the groundwater. The topography of the area is varied and includes narrow Flats, kloofs, gorges, cliffs, rocky shores, wave-cut platforms, small bays, and sandy and gravel beaches (Adelana *et al*., 2010, Theron and Siegfried, 1992).

2.5 Climate [Rainfall and temperature] of Cape Flats Area

Climate refers to the long-term change in a particular area (Gxokwe and Xu, 2017). The CFA experiences the Mediterranean climate, which receives rain in the winter. Hence, the winter season is wet and rainy, implying more groundwater recharge and a more significant dilution effect on the contaminants in the subsurface. The summer season in CFA is dry and has no rain, implying a low groundwater level and elevated concentration levels of contaminants. In this way, understanding climatic variables are essential for groundwater quality apart from groundwater quantity, which is usually discussed when the climate is related to groundwater. In short, The Western Cape Province has a Mediterranean climate characterized by dry summer and cold, wet winter because of the Indian and Atlantic oceans. The average temperature for the dry summer ranges is 170C C-290C, while the wet winter ranges between 11^0C-22^0C. However, the generally mountainous nature of the Cape Fold Belt results in the entire region having sharp climate changes (Adelana, 2010). This makes most areas in Western Cape have winter rainfall with relatively few summer rainfalls. The annual rainfall for Cape Town is 788mm per annum (Adelana, 2010). Rain plays an integral part in the vertical and seasonal recharge of the aquifer system. The shallow unconsolidated aquifer of CFA is mainly charged by rainfall.

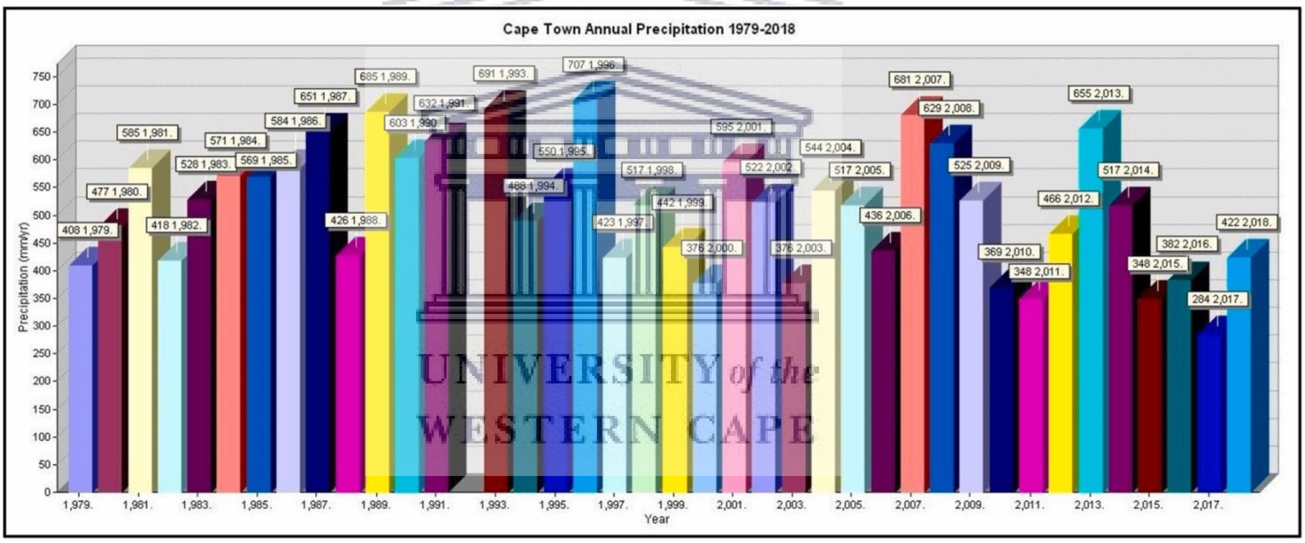

Figure 4: Rainfall chart for Cape Town over 39 Years: Adopted from (Gintamo et al., 2021)

The Cape Flats Aquifer System is an unconsolidated aquifer; therefore, more recharge is expected to occur during the rainy season. In winter, the area receives more rain, making the aquifers recharge water and contaminants in the subsystem. Concentration levels of contaminants increase as the flow to groundwater increases based on the permeability of the vadose zone. Rimon *et al*. (2007) worked on water percolation through the deep vadose zone and groundwater recharge, and the results showed that groundwater increases during the rainy season. In addition, the results confirmed that precipitation increased nutrient and sediment loading to underlying aquifers, lowering groundwater quality. In agreement with Rimon *et al*., 2007, the analysis by Gintamo *et al*. (2021) on Cape Flats Aquifer System showed similar results as those in Israel by Rimon *et al.* (2007). Therefore, rainfall has a two-fold effect, i.e., it increases the volume of water in the subsurface and speeds up the pollutants/contaminants in the subsurface. Cape Flats Aquifer System receives winter rains, and thus lower quality groundwater is expected. During the dry season, due to the shallow aquifer system of the Cape Flats area, more subsurface water evaporates, leading to slightly higher concentration levels of contaminants. In both ways, the climates (rainfall and temperature) influence the quality of groundwater resources, hence the need to remediate such waters.

2.6 Hydrology and hydrogeology of the study area

Figures 5 and 6 below indicate different types of hydrology, main rivers, wetlands, and the hydrogeology of the Cape Flats area, which is the study area:

2.6.1 Hydrology

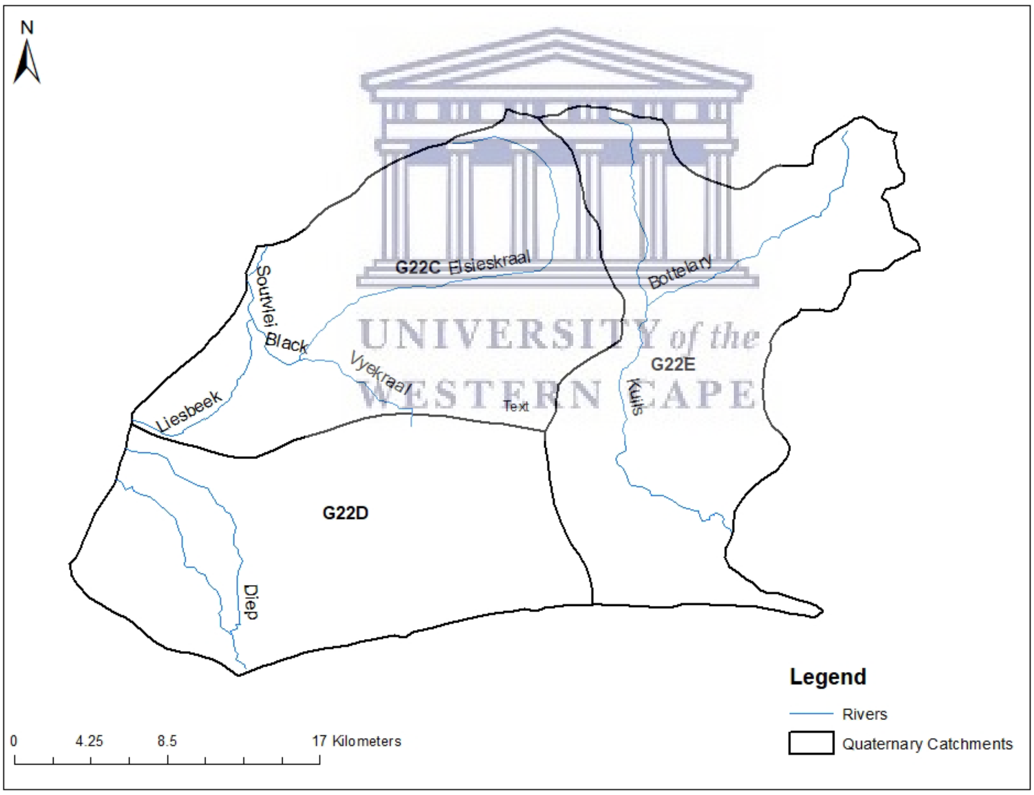

Figure 5: Hydrology of the area

The Cape Flats Aquifer falls under the city of Cape Town Water Management Area (WMA) at an extension of approximately 2159 km^2 (Adelana, 2010). The area is characterized by different wetlands and streams flowing through and interacting with shallow underlying CFA (Gxokwe and Xu, 2017). Rivers in the area include the Elsieskraal River, Vygekraal River, Kuils River, Black River, and the Deep River (Adelana *et al*., 2010). It is essential to know these rivers as one of the significant sources of pollution to groundwater. This is done through the losing and gaining stream process in surface water-groundwater interaction. The pollutants or contaminants in the streams are caused by people dumping wastes in nearby rivers, industrial areas, and many dumpsites. However, these rivers and dumpsites act as groundwater-focused recharge zones. Therefore, it is essential to know that the presence of many surface water bodies in the study area means many sources of focussed recharge zones for the aquifer system and if such water sources contain polluted and contaminated water. Underlying aquifers risk being recharged with polluted surface waters if the geology and soils above such aquifers are porous.

2.6.2 Hydrogeology

The Cape Flats Aquifer hydrogeology is dominated by preferred flow paths from the paleo-channels of the present-day Kuils (Kuils river paleo-channel), Lotus, and other rivers (Hay et al., 2016). The groundwater in the area flows semi-radially from the higher-lying basement in the northeast near Durbanville towards table bay to the northwest and the false bay coast to the South (Hay et al., 2016). The CFA hydrogeology is characterized by large undulating sandy aquifer CFA, which is the central focus of this study. The area forms part of shallow unconfirmed aquifers, also known as the water table aquifers. These aquifers are closer to the earth's surface than confined aquifers. Due to the closeness of the aquifer to the surface, these aquifers are more vulnerable to contamination than confined aquifers.

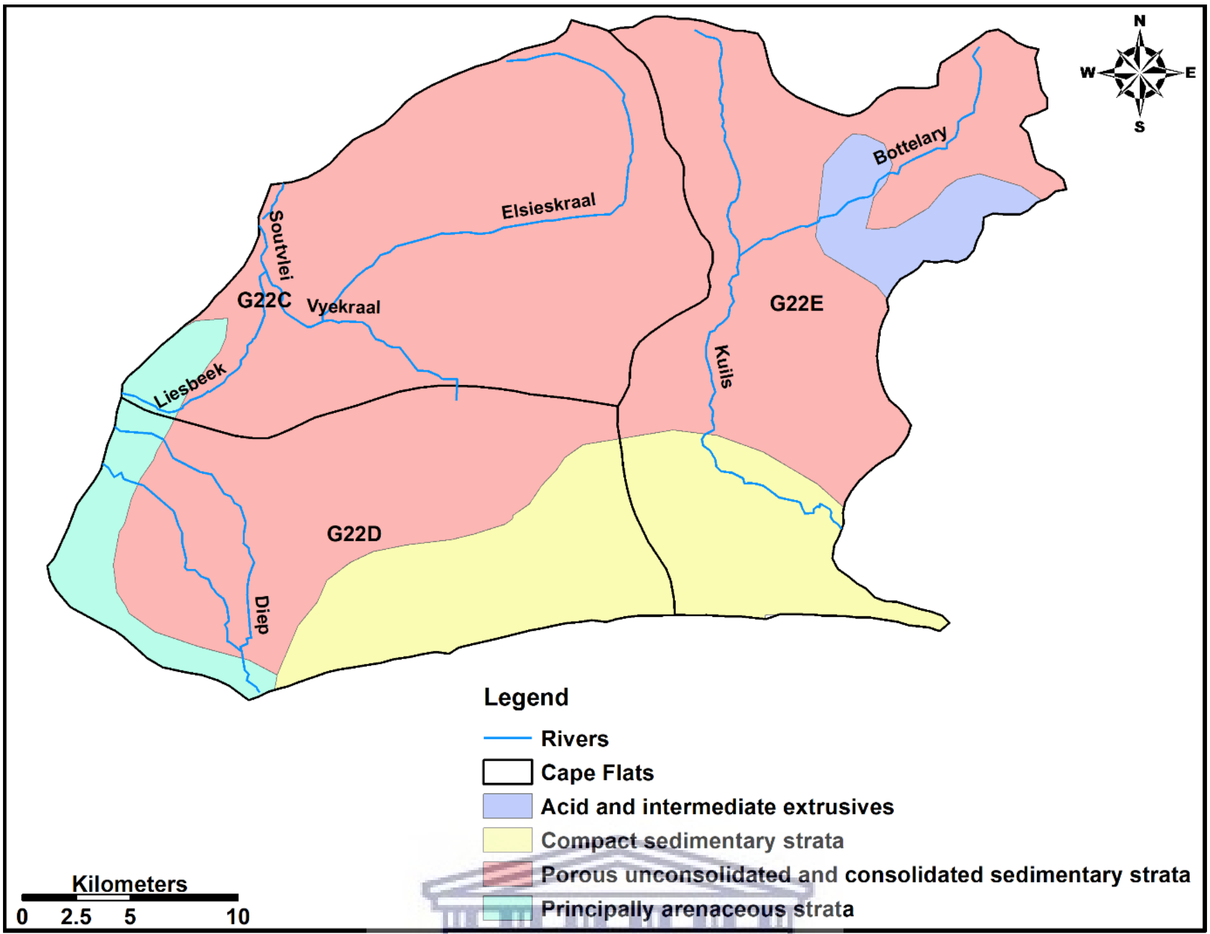

Figure 6: Hydrogeology of the CFA

The area forms part of a shallow unconfined sand aquifer within the central part of the area and pitches out against the impermeable rock forming the eastern, northern, and western boundaries (Adelana, 2010, Gxokwe and Xu, 2017). Loose sands mainly characterize CFA with some clay and peat layer, causing some parts of the aquifer to be semi-confined (Gxokwe and Xu, 2017, Henzen, 1973, & Gerber, 1976). Recharge of the area mainly occurs due to precipitation falling on the aquifer's surface, despite other sources such as sewer leakages, water pipes, and urban irrigation. The groundwater levels are deepest during the dry season and shallow during the wet season. The direction of groundwater flow is from high to lower elevations toward a coastline (Gxokwe and Xu, 2017).

2.7 Land use activities and Land cover in the study area

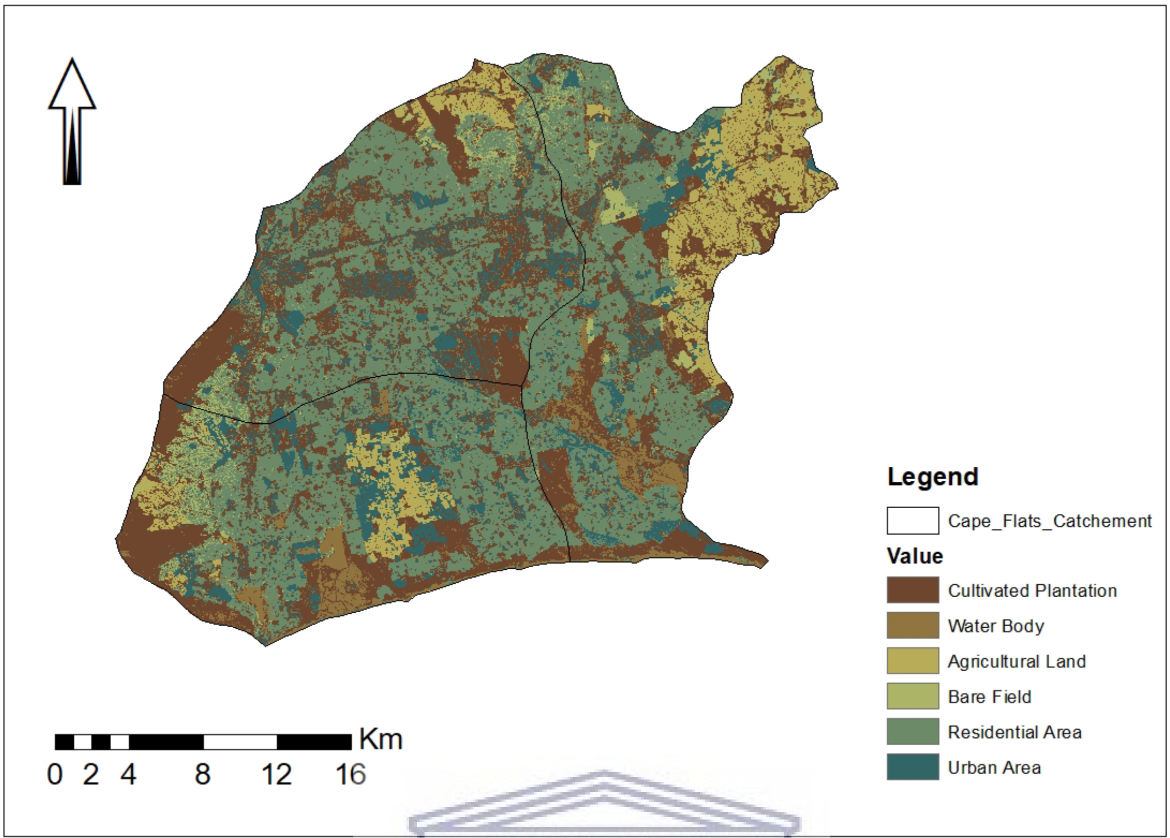

Figure 7: Landover and land use map

Various land-use activities exist on the surface of the aquifer. These include agricultural activities, formal and informal settlements, open spaces, and sand mines (Maclear L.G.A, 1995, Gxokwe and Xu, 2017). Hay *et al.* (2015) reported that lands in the Cape Flats Aquifer include formal-(primary land use) and informal townships. Residential land occurs on a small fringe of Cape Flats. The land has industrial activities in the center, north, and northeast areas. The informal townships are seen adjacent to these industrial areas. Lastly, many smallholdings are present in the southeast of the Phillipi farm area land used for agriculture.

In most cases, the by-products of land-use activities produce contaminants that threaten groundwater systems, thereby making water quality in the aquifer system susceptible to contaminants. For example, in the Philip area, where agriculture activities occur, fertilizers contribute to the poor quality of groundwater, which is a concern. The Cape Flats area has an unconfined aquifer and confined aquifer systems. The current study focuses on the unconfined aquifer system prone to contamination and extreme climate variability. The improved knowledge of geomorphology enhances the interpretation of the conceptual model of groundwater flow systems, including contaminants' movement.

These activities may cause a threat to the quality of groundwater. Furthermore, these threats can result from chemicals from agricultural activities such as applying fertilizers that seep into the system, pollutants from septic systems, and solid waste that can be collected through landfills. Some of these landfills allow chemicals to leach into the groundwater system resulting in groundwater contamination. Therefore, it is crucial to understand the type of activities in the area as it helps determine the types of contaminants commonly found.

2.8 Chapter Summary

Chapter two gives an overview of the study area, the location, and the justification for the current study in the Cape Flats Area. The geology, soil type, geomorphology, climate, hydrology, hydrogeology, and land use activities were described in relation to the study topic, i.e., groundwater contamination.

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction

The first chapter provided a general introduction to the present study regarding the problem statement, study aim, and study objectives. The second chapter described the study area. This chapter reviews previous studies to show a gap analysis of what is known and unknown about groundwater remediation for water supply purposes. This chapter argues that improved understanding is essential for groundwater remediation in terms of the technologies to remediate groundwater contaminants. Therefore, making groundwater a reliable source of water supply to supplement surface water supply sources, especially in urban environments where demand for water supply is ever-increasing due to natural hazards and human activities. Principles and concepts that guide groundwater remediation practices are reviewed and analysed to guide the present study. The chapter reviews groundwater pollution/contaminants and groundwater remediation practices/studies towards achieving Sustainable Development Goals on water in general and groundwater remediation technologies for improved water supply.

This review will highlight the gap and the need to review current research to contribute to the body of knowledge on applying groundwater remediation technologies in the water sector. The review is structured from global, regional, and national perspectives to contextualize the present study. The review is also presented systematically and analytically based on each objective of the current research: concentration levels of groundwater contaminants, application of conceptual models on transport contaminants, and demonstration of the effectiveness of reverse osmosis in remediating groundwater. The focus is on demonstrating the effectiveness of the chosen remediation technology in making groundwater available and fit for different purposes. This chapter highlights the known and unknown aspects of applying groundwater remediation technologies in the water sector using a selected site/plant in Cape Town as a case study.

3.2 Groundwater Contaminants

(Thesaurus Merriam-Webster, 2020) explains that contaminants are substances that are not needed or required or that make a resource impure for use. Groundwater contamination occurs naturally or anthropogenically when contaminants migrate into porous media into the aquifer system (Idrees et al., 2018). Different mechanisms influence pollutants' transport into the subsurface, including diffusion, adsorption, and precipitation. Groundwater pollution levels refer to specific contaminants above the expected norm or the water standards of a particular country or standard by the World Health Organisation (WHO). High concentration levels concern human and environmental/ecological health (Idrees *et al.*, 2018)). Therefore, concentration levels of contaminants in a water system such as aquifers need to be known through monitoring. This study assessed the concentration levels of selected contaminants to ascertain abundance, distribution, and concentration levels. The contaminants of concern in this study include Iron and Manganese as stated in chapter 2. The source of iron and manganese in groundwater is usually naturally occurring. However, land-use activities and infrastructures like sewage, landfill leachate, acid mine drainage, and industrial effluents can also contribute to the presence of iron and manganese in groundwater (Rusydi et al., 2021)

3.2.1 Remediation in groundwater

The increasing demand for water due to various causes has encouraged the innovation and implementation of multiple technologies in purifying polluted water for more freshwater. As a result, polluted or contaminated water sources have become alternative or augmented water supply sources when such water has been purified. Water remediation involves removing contaminants from water or converting the pollutants into harmless products (Hashim et al., 2011b; Sharma et al., 2018). Chen *et al.* (2019) showed that remediation technologies had improved water quality, and such water treatment increases the portable water quantity.

In the physical method of groundwater remediation, water is pumped out of the system and treated on-site(pump and treat method) (Farhadian et al., 2008; Reddy, 2008; An et al., 2016; Chen et al., 2019), or it can be done underground using air sparging (Chen *et al.*, 2019). Chemical treatment methods can be achieved using different methods: carbon absorption, ion exchange, oxidation, and chemical precipitation (Reddy, 2008; Saleh et al., 2020). The chemical method is mainly used alongside physical water treatment. Chemical treatments involve removing contaminants from water and producing a liquid effluent suitable for the natural environment's disposal. Finally, biological treatment technologies remove dissolved and suspended organic chemicals through biodegradation and suspended matter through physical separation (Hunter and Shaner, 2010; Saleh et al., 2020).

Remediation technologies can also be described as in situ or ex-situ. Insitu remediation technology involves using chemical, biological, or physical remediation methods to remove contaminants without bringing the water to the surface. In contrast, ex-situ methods generally involve bringing the groundwater to the surface before the application of either chemical, biological or physical method of remediation (Carberry and Wik, 2001a, 2001b; Hatzinger et al., 2002; Concetta Tomei and Daugulis, 2013; Gomes et al., 2013; Kuppusamy et al., 2016; Paul et al., 2021).

This research used physical treatment technologies such as pump and treat. Pump and treat refer to water being pumped from the aquifer system into a tank where such water goes under chemicals or the membrane filtration treatment process such as Reverse Osmosis, Nano-filtration, and ultrafiltration. These details are provided in chapter 4 under the experimental design of pump and treat remediation technology).

3.3 Previous studies on groundwater remediation

This section presents the reviewed work following three themes or levels to contextualize the present study properly. Such levels include global, regional, and national levels, where the global level refers to research work outside Africa, and the regional refers to Sub-Saharan countries. National refers to South Africa, where the present study was implemented. The focus is to present the status of the work on groundwater remediation technologies at different levels nationally (in South Africa) and internationally. This will allow the contextualization of the findings in the study area in comparison to global scales and acceptable practices

3.3.1 Groundwater remediation work from a global perspective

Liu et al. (2022) reviewed the global problem of polluted water in Europe and the use of the Nanoscale Zero Valent Iron (NZVI) application for groundwater remediation. NZVI was used as the new emerging remediation for treating groundwater contaminated and soil. The technology was applied to chlorinated organic contaminants such as solvents, pesticides, and inorganic anions or metals. Different types of aquifers were used, and the use of the NZVI was effective in removing contaminants. In addition, the use of NZVI showed no adverse impact on the environment. Although the current study did not use NZVI technology, assessing the effectiveness of the technology in removing contaminants is similar to the NZVI study. The review from various sources showed that improving groundwater remediation technologies in Europe remains an ongoing task (Mueller et al., 2012).

Mueller et al. (2012) applied a multi-level groundwater method to reduce groundwater contamination and pollution with oil in the Saskatchewan area in Canada. The argument for using multi-level non-linear simulation optimization (ML-NSO) was that, for groundwater remediation management, objectives should satisfy multiple levels to reduce the environmental standard of concentration levels after reuse. The integration framework of health risk assessment, energy assessment, and contamination assessment was used to collect data. They used the method to pump and treat to optimize the model. Statistical analyses were used, and the results showed that the concentration of toluene, ethylbenzene, and xylene decreased below their respective environment standard once benzene concentration satisfied the designated limits (Mueller et al., 2012). The removal rate of total Cr, Cu(II), Cd(II), and Pb(II) from actual electroplating wastewater treatment was 89.4%, 98.9%, 94.9%, and 99.4%, respectively. These results demonstrated the effectiveness of remediating groundwater contaminants when multi-level methods combined with the pump and treat method were used.

In China, a study was carried out on biological denitrification coupled with chemical reduction for groundwater nitrate using permeable reactor barrier (PRB) filter sustainable compound carbon source materials (SCCMs) as a carbon source Zhang *et al.*, (2019). Four PRBs were set up to respond to groundwater temperature under 24-day hydraulic residence time. DNA extraction from samples for microbial using a soil DNA isolation kit was used alongside quantitative PCR and high throughput sequencing. This was used to determine the aerobic ammonia oxidation functional gene (h20) and denitrification functional gene (n1r5). The experiment showed that NO-3 removal efficiency in Zero-Valent iron SCCMs was higher than in the ZVI-free SCCMs. Furthermore, the NO-3 removal reaction began quickly in the early stage, owing to ZVI chemical reduction, whereas biological denitrification was lower and incomplete with NO-2 concertation of 0.8mgl-1 in the ZVI system (Zhang et al., 2019).

In Latin America, (Alarcón-Herrera et al., 2013) studied the co-occurrence of arsenic and fluoride in groundwater of semi-arid regions in genesis, mobility, and remediation. Results showed that AS and F's co-occurrences in drinking water were linked to volcanoclastic particles in the loess or alluvium, alkaline pH, and limited recharge. The use of chemical precipitation, filtration, and reverse osmosis were used to remove AS and F (Alarcón-Herrera et al., 2013).

In Mexico and Argentina, (Alarcón-Herrera et al., 2013) showed that reverse osmosis removed 92% of AS (V) and AS (III) and 85-95% of F from groundwater as contaminants. While scholars observed that chemical precipitation /filtration was the most expansive spread process used in Argentina and Chile to remove As and F, in Latin America, activated alumina adsorption was successfully tested in the laboratory and pilot-level tests. However, reports on applying such field-tested and lab methods in the community were unavailable (Alarcón-Herrera et al., 2013).

Johnston (2016) worked on the Middle East's Bulk Petroleum terminal remediation strategy. The author used a vacuum-enhanced dual-phase extraction/air spurge groundwater to clean the system. The aim was to eliminate and prevent further migration of free and dissolved phase contaminant plumes and vapor intrusion beneath the off-site building located northwest and down the gradient of the terminal property lines. Data were collected on the following geochemical parameters: temperature, specific conductivity, total dissolved solutes, salinity, and dissolved oxygen. Statistical analyses were used. The study showed the effectiveness of the technology by comparing the untreated and treated effluent samples (Johnston, 2016).

3.3.2 Groundwater remediation work at the regional level [Sub-Saharan Africa]

Onipe *et al*. (2020) and Kut *et al.* (2016) reviewed fluoride in African groundwater and local remediation methods focusing on groundwater contamination in most African countries. Results showed that groundwater in most countries had fluoride concentration levels that exceeded the 1.5mg/l permissible limit established by the World health organization (WHO). Remediation methods such as Nano-filtration and Reverse Osmosis were recommended as successful, although they remain expensive in most African countries. However, a cost-benefit analysis showed that despite the cost aspect, Nano-filtration and Reverse Osmosis were expected and easily accessible (Onipe,*et al*., 2020).

Exploring environment-friendly technologies to remediate groundwater contaminants is still being developed. For example, Medjor et al. (2018) used silica encapsulation technologies to remove hydrocarbons in groundwater in Nigeria. The study used optimum pH, contact time, and the treatment solution's concentration for each contaminant. In addition, the study used regression coefficient analysis, and the range was between 0.9964-0.9988. This was demonstrated by the percentage reduction in petroleum hydrocarbon, ranging from 51.97-to 90.68% (Medjor et al., 2018). Results showed that such a technique proved to be an effective remediation technology for cleaning up and restoring hydrocarbons from contaminated groundwater with an efficiency of 51.97–90.68% (Table 1).

Furthermore, when such technology was compared with chemical methods such as Fenton Oxidation, the environmental technology was a better remediation technology. It does not emit greenhouse gases, has minimal environmental disturbance, and enables the remediation process to be completed within a short period.

Table 1: Comparison of percentage remediation of hydrocarbons in Water by silica encapsulation obtained by other authors Medjor *et al*. (2018)

S/N	Authors	Type of work	% Remediation of Hydrocarbons as TPH
1	Mbhele (2017)	Remediation of soil and water contaminated by heavy metals and hydrocarbons using silica encapsulation	>70%
2	Obielumani et al., 2017	Kinetics study of remediation of crude oil contaminated surface water by silica encapsulation	92.78%
3	Medjor et al. (2018)	Remediation of hydrocarbons contaminated groundwater by a silica encapsulation technique	51.97–90.68%

(Ofomola *et al*., 2017), worked on contamination assessment of dumpsites using the leachate pollution index method Ugheli area, in Nigeria. The collection of water samples from boreholes around four dumpsites for laboratory analysis and estimation of the leachate pollution index was done. The study showed that the groundwater was at a high risk of being contaminated by the dumpsite through leachate percolation (Ofomola *et al*., 2017). The leachate parameters were computed according to the standard approach for examining contaminated water by American Public Health Association (APHA). Descriptive statistics like correlation analysis were used to determine or assess the degree of association among various variables. The author recommended implementing remediation procedures to prevent groundwater from being contaminated by percolation from leachates from the dumpsite.

3.3.3 Groundwater remediation work at the national level [South Africa studies]

Pietersen et al. (2012) evaluated groundwater governance and showed that other governance provisions across all thematic areas are weak or non-existent. The groundwater monitoring is inadequate, and the quantity and quality of groundwater resource assessment are flawed. Besides, the evaluation showed that provisions to control groundwater abstraction and pollution are weak (Pietersen et al., 2012). These findings informed the basis for the current study to assess groundwater remediation techniques that would improve groundwater quality in South Africa from a case study perspective, thereby improving water security in urban areas.

A study by Raleru (2005) showed that remediation techniques were mainly conducted for soils. This study focussed on geo-hydrological remediation of hydrocarbon-contaminated soil in South Africa (Raleru, 2005) Johannesburg international airport area. Appropriate remediation technologies were evaluated to rehabilitate the hydrocarbon-affected zones. Costs associated with implementing, such as preventive and corrective measures, were determined. When Raleru (2005) applied a carbon detection method to assess groundwater contamination, results showed no carbon in groundwater. From such a study, the current study argues that different approaches need to be reviewed in line with land-based activities at a particular site to apply the most appropriate detective and remediation technologies. Alternatively, one method is insufficient for remediation studies; many methods are required.

Chen *et al.* (2019) studied groundwater remediation from the past to the future: A bibliometric analysis was used to provide statistics showing emerging groundwater remediation technologies to improve groundwater systems. In agreement with Chen *et al.* (2019), Bruesseau (2019) observed that the public concern with polluted soil and groundwater encouraged the government to design programs to control and remedy the reported contamination and prevent further contamination. Such studies agreed with the study by Mulligan *et al*. (2001). They proposed that remediation technologies can reduce groundwater contamination and effectively remove contaminants, improving the water supply.

Shabalala (2013) carried out a study in Krugersdorp, South Africa, on managing and treating contaminated mine water through permeable reactive barriers (PRBS), which were put in place to help clean the acid mine drainage, which is a problem in the area. Results showed that the fly ash was a suitable reactive material to clean or remediate the groundwater of the acid mine. These results were based on the method used to clean the system (Shabalala, 2013).

Israel (2015) studied in situ denitrifications of nitrate-rich groundwater in South Africa at Somerset west. The study conducted laboratory experiments to compare the denitrification efficiency, reaction rate, and reaction mechanism between woodchips, biochar, and a mixture of woodchips and biochar. The study showed that groundwater is mainly contaminated with nitrate by anthropogenic activities; the study found that nitrate exceeds the SANS limitations. According to DWA water quality standards, these nitrates exceeded 40mg/L NO3 as N, which falls in the category of dangerous drinking water quality (1998, 1999, and 2015). Furthermore, the study results showed that combined biochar and woodchips were more effective than wood chips in denitrifying groundwater.

3.4 Evaluating concentration levels in groundwater contaminants

It remains a fundamental issue to measure concentration levels in groundwater contaminants to establish whether the levels are permissible according to national standards or global guidelines by World Health Organisation (WHO, 2008) to determine if the water can be classified as fit-for-use. For this reason, it was crucial to review the literature on concentration levels of contaminants in groundwater from different physiographic settings, methods used, and results obtained from such locations. The cause of contaminants in groundwater varies from place to place due to natural or anthropogenic activities. Concentration levels of contaminants in groundwater become a problem when they surpass a specific country's water standards or international drinking guidelines (WHO, 2008). Contaminants in shallow groundwater from microbial sources are becoming common, and sources have been linked to human activities.

In Uganda, Howard et al. (2003) assessed risk factors contributing to the microbiological contamination of shallow groundwater aquifers. Results showed a significant relationship between the median level of contamination and rainfall to short-term rainfall events. It was concluded that the rapid recharge of springs after rain leads to microbiological contamination (Howard et al., 2003). Although the Uganda study did not measure concentration levels of microbial contaminants in shallow groundwater systems, the focus on shallow aquifers and the relationship between rainfall and concentration levels of contaminants in aquifers remain essential; such a relationship was provided in chapter 2.

In Telangana state of South India, Narsimha and Sudarshan (2018) studied elevated fluoride concentration levels and assessed fluoride concentration levels in the groundwater using the electrochemical method. In this study, the Thermo Scientific Orion Star A214 Benchtop pH/ISE meter uses the USEPA ion-selective electrode method to determine the fluoride concentration. The titration method was used in analysing the Calcium, chloride, magnesium carbonate, and bicarbonate. The pH, EC, and TDS meters were used for measuring physicochemical parameters. Descriptive statistics for Fluorine and other physicochemical parameters were used for analysis.

A study by Lalumbe and Kanyerere (2021) showed how the groundwater could be sampled and analysed. The groundwater is sampled and sent to the lab to analyse the concertation of contaminants found in the water. The common concentrations analysed are the physio-chemical parameters, major anions and cations, and some trace metals. These parameters include pH, TDS, EC, alkalinity, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, $SO_4{}^{2-}$, $HCO_3{}^{-}$, $NO_3{}^{-}$, and metals such as Fe and Mn. Concentrations of constituents dissolved in groundwater can be analysed using different analytical techniques and data processing methods. One of those methods will include statistical analyses using Microsoft excel to determine the concentration levels of contaminants through the use of graphs and tables and software to determine the type of groundwater (e.g., groundwater chart, aqua chem). The statistical analysis tool excel was used to determine the descriptive statistics and these variables included the mean, minimum maximum, and standard deviation of various contaminants. These methods by Lalumbe and Kanyerere (2021) will be adopted for this study to determine the statistical distribution of concentrations of chemical species in the water.

Bretzler *et al.* (2017) studied groundwater arsenic contamination in Burkina Faso in West Africa. In this study, risk regions were predicted and verified, and the distribution and magnitude of geogenic groundwater concentration were investigated to identify better-affected areas and populations. The arsenic concentration levels were measured from boreholes and calibrated and validated by the arsenic prediction model. On-site parameters such as temperature, pH, EC, O_2 concentration, and redox potential were also measured (Bretzler et al., 2017). The results showed that out of the 1498 collected samples, only 14.6% contained arsenic concentration above the national and WHO guideline value of 10ug/L and 2.3% above 50ug/L.

In South Africa, Aza-Gnandji et al. (2013) studied the salinity of irrigation water in the Philippi farming area of the Cape Flats. The research investigated the nature, source, and spatial variation of the salinity of the water used for irrigation in Philippi's urban area. The results showed that groundwater and pond water in the study were generally suitable for irrigation purposes with some caution. According to DWA irrigation water guidelines, the vegetables are sensitive and moderately sensitive to salt. The research indicated that the concentration of ions such as chloride, nitrate, potassium, and sodium exceeded in places compared with the department of water affairs and forestry.

In South Africa, (Abiye and Bhattacharya, 2019) assessed the concentration levels of arsenic in groundwater. Groundwater samples from granite and granitic gneiss aquifer were analysed for nine metals. Results showed that groundwater's arsenic concentration levels reached up to 253ug/L in Namaqualand, 6150ug/L in west Johannesburg, and about 500ug/L in the Karroo aquifers than the WHO value, which is 10ug/L (Abiye and Bhattacharya, 2019). The analysis showed that Acid mine drainage from coal and gold mining was the source of arsenic and other toxic metals in groundwater.

Land use activities such as industrial, household, and agricultural activities are associated with by-products contaminating groundwater systems. For example, various studies show that agricultural chemicals and pesticides produce adverse groundwater system outcomes. (Kulabako et al., 2007) evaluated the impact of land use and hydrogeological settings on the shallow groundwater quality in Uganda. The results showed that concentration levels of nitrates in groundwater increased during the rainy season as the system received high loads of organic nitrogen through leaching from agricultural activities (Kulabako *et al.,* 2007). A study assessing nitrate contamination in groundwater in Italy found that 80% of the area had a high degree of potential nitrate contamination from biological, organic, or inorganic contaminants (Ducci, 2018).

Hu et al. (2005) conducted a study in China on spatial variability of shallow groundwater level, electrical conductivity, nitrate concentration, and risk assessment of nitrate contamination in the North China Plain. The study's objective was to evaluate groundwater quality and the risk of nitrate pollution in groundwater. The current study followed some methods of how the concentration-level analysis of contaminants was carried out. The kriging method was used to analyse the spatial variability of shallow groundwater levels and NO3-N concentrations. The randomization approach method was used in selecting the water sampling points; shallow groundwater levels were measured from the soil surface to the water surface using a measuring ruler. Groundwater EC was measured using the DDS-11. PMA biomass inhibitor was added to the groundwater at the electrical conductivity meter to calculate NO3 -N concertation. The NO3-N was analyzed using the TRAACS2000 nitrogen auto-analyzer (Hu et al., 2005). Results showed the distribution of groundwater level, EC, and NO3-N ranging from 2.55 to 18.97m with a decrease in groundwater by an average of 140% compared to 1990 (Table 2). However, the study focused on assessing remediation technology. Therefore, descriptive statistics also helped understand the type of distribution portrayed in the three observed items. The table below shows the results.

Table 2: Descriptive statistics of groundwater level, EC, and NO_3–N concentrations measured in 139 underground wells across Quzhou County in the North China Plain (Hu et al., 2005).

Observed items	**Skewness**	**Kurtosis**	**Type of distribution**	**Mean**	**STD**	**Min**	**Max**	**CV**
Groundwater level (m)	0.40	2.46	Normal	9.81	4.07	2.55	18.97	0.414
EC (dS m^{-1})	0.056	2.63	Lognormal	2.94	1.43	0.76	6.64	0.486
Nitrate (mg L^{-1})	4.51	26.04	Positive skewness	2.39	5.37	0.01	36.28	2.25

Presentation of results as shown in table 2 was adopted in the current study

A study was done by (Thakur et al., 2010)on the Arsenic contamination of groundwater in Nepal. The study aimed at determining arsenic concertation levels in groundwater. Different testing methods were available to measure arsenic concentration in environmental and biological samples. Methods included laboratory-based and field-based approaches. The field-based method used hydrochloric acid and zinc metal. This method relies on the inorganic reaction of converting arsenic to arsine gas (Thakur et al., 2010). The gas passes through the mercury bromide paper, and the intensity of the colour indicates the concentration of arsenic. The study results showed that 89.8% of arsenic concentration cases were lower than 10ug/l in the 7.5% concentration of 10-50 Ug/l and larger than 50ug/l in the samples' 2.3 %.

3.5 Groundwater flow systems concept

Groundwater flow deals with understanding the movement of water in the subsurface. The groundwater flow is governed by Darcy's law ($q = Q/A = -K*dh/dl$), which says that the discharge rate q is proportional to the gradient in the hydraulic head and the hydraulic conductivity.

This section reviews a couple of the existing groundwater flow models used in groundwater studies to explain the transport of contaminants in the subsurface within the current study area. Gxokwe et al. (2020) applied a three-dimensional steady-state groundwater flow model on the Cape Flats aquifer to predict scenarios for the water-sensitive urban design (WSUD).

Gintamo et al. (2021) evaluated climate conditions affecting groundwater quality using a hydrological model with GIS in the Cape flats aquifer.

3.5.1 Transmissivity and Storativity

Transmissivity refers to the rate at which water passes through a cross-section width of the aquifer's whole saturated thickness under a unit hydraulic gradient (Guo, 1997, Kruseman, 1994, Valero, 2016). Storativity refers to the volume of water released from the aquifer's storage per unit surface area or aquitard per unit decline in the hydraulic head. The unconfined aquifer included a specific yield (Valero, 2016). It is essential to understand the storage and movement of water as these will help guide the direction of contaminants in the area. Storrativity and transmissivity can vary across different geologic settings and aquifers. In confined aquifers, Storativity is the specific storage multiplied by the aquifer thickness. In an unconfined aquifer, it is determined by multiplying the specific storage by the aquifer thickness plus the specific yield (Medina et al., 2011; Gleeson et al., 2016). Geologic parameters like permeability, porosity, and lithology can affect the rate of transmissivity at different locations. A more porous and permeable aquifer will have higher transmissivity, while a less porous and permeable aquifer will have a lower transmissivity (Koltermann et al., 1996; Library et al., 2011; Holland and Witthüser, 2011; Achtziger-Zupančič et al., 2017).

Zone characterization is vital in the study of contaminant transport; the study by Gxokwe and Xu (2017) in the Cape Flats aquifer used the Theis equation to calculate the aquifer parameters. The parameters involved include static water levels, flow rates depth to water level and well diameters for pumping and observation. These data were then analyzed using the Theis analytical flow solution, incorporating the aqua test graphical interface software and semi-log plots spreadsheet.

3.5.2 Contaminants Transport

Amirabdollahian and Datta (2013) used the monitoring network design to identify and characterize the contaminants. The literature showed different methods to describe the contaminants in the groundwater systems. Such procedures included monitoring network design, vulnerability assessment of the area, and sampling (Ducci, 2018, Abiye and Bhattacharya, 2019). One of the standard methods used to characterize contaminants in the groundwater system was the traditional sampling method, checking the concentration levels of contaminants and comparing them to a particular country's water standard or WHO guidelines. Different groundwater contaminants exist as inorganic, organic, chemical, physical, microbial, and biological contaminants. Contaminants reach groundwater systems through point sources or diffused sources as pathways. Point sources refer to discrete locations or well-defined locations or sites, whereas diffuse sources occur over broad geographical scales or not well-defined areas or sites (Lapworth et al., 2012). In this study, groundwater contaminants were characterised using the sampling method and assessing the land use activities found in the study area. Details on land use activities in the study area were presented in chapter 2 under section 2.7.

3.6 Current and common technologies for groundwater remediation

Groundwater remediation involves removing impurities or pollution from the groundwater system to enable water fit-for-purpose. The common remediation methods are physical, chemical, and biological. Classification of these remediation methods is based on the operation, type of aquifer, and the type of contaminants being treated. Groundwater technologies are categorized into four types: in-situ, ex-situ, passive, and active remediation technologies.

In-situ and ex-situ remediation are standard methods used to treat groundwater. An example of an in-situ remediation method is the permeable reactive barrier (PRB), while ex-situ remediation is Reverse Osmosis. The PRB is composed of the material that degrades or immobilizes contaminants as groundwater passes through the barrier (Hunter and Shaner, 2010). Although the study did not focus on in-situ remediation, this section briefly illustrates in-situ and ex-situ remediation technology.

Ex-situ remediation treatment involves the treating of contaminated groundwater. The contaminants are extracted from the ground via wells, and the water is treated above the ground (Stein et al., 2021). This process involves air stripping, reverse osmosis, Nano-filtration, and chemical precipitation. Reverse osmosis is a widely applied technology that has been used to supply portable water worldwide (Stein et al., 2021).

Sharma and Reddy (2001) highlighted that site characterization, risk assessment, and selection of effective remedial action need to be considered before a contaminated site is set for remediation. They described Site characterization as one of the first steps that need to be considered before the remediation process; this helps understand the types of contaminants found in the area and select a suitable technology. The study also highlighted that remediation technology for a particular area is determined based on site-specific hydrogeological, and contaminant conditions, desired clean-up levels, remedial time, and cost.

A physical or ex-situ remediation method can be applied when water is in storage facilities. An example used for such a method is Reverse Osmosis (RO). The technique involves treating water on the surface by passing it through different membranes; the water is pumped from the ground and is kept in storage tanks where chemicals are added (for pre-treatment). This is an example of an ex-situ remediation method, as the water is pumped out from the sub-surface and treated above ground. This method is commonly used in the coastal aquifer where desalination plants are used; South Africa and Israel are some examples of countries where these methods are used.

Physical methods are common types of remediation technologies. Air sparging and pump and treat methods are common examples that fall under physical methods. In air sparging, the air is used to strip water, whereas in the pump and treat method, groundwater is removed from the aquifer and is treated on the surface, not underground or in situ, and this can be in tanks or storage facilities. A study by Reddy and Adams (2000) on the effect of groundwater flow on the remediation of dissolved–phase Volatile Organic Compounds (VOC) contamination using air sparging. The study aimed to understand how groundwater flow may affect the injected air zone of influence and remedial performance. The result showed that the groundwater flow's size and shape of the zone of influence were negligibly affected. As a result, similar contaminant removal rates were realized within the zone of influence with and without groundwater flow. The study concluded that air sparging was effectively implemented to intercept and treat a migrating contaminant plume.

Bradl and Xenidis (2005) did a general overview of different remediation technologies; they divided them into physical, chemical, and biological categories. Under the chemical, the focus is mostly on using chemicals in the process, and the following methods exist Carbon absorption, Adsorption, Ion exchange, chemical precipitation, and Oxidation. The literature has shown that these general methods take longer to execute and remain costly for implementation in the field (Bradl and Xenidis, 2005). Despite such challenges, Ion exchange is used in water to remove nitrates from drinking water; this process removes the undesired ions and replaces them with ions that do not affect water quality. A study was done by Mondal *et al.* (2013) on the remediation of organic arsenic in groundwater for safe water supply; a critical assessment of technological solutions in Belgium is an example. They highlighted some of the technologies that have been used to remediate the water system and the advantages and disadvantages of the technologies. The technology of removing nitrates was developed from water softening systems to remove the hardness-conferring ions, Ca^{+2} and Mg^{+2} (Velizarov *et al.*,2004). Major cations and anions are studied to improve understanding of water behaviour and movement in the aquifer.

3.6.1 Reverse Osmosis Remediation technology

In Reverse osmosis (RO), the solvent is passed through a porous membrane in the opposite direction as natural osmosis when subjected to a hydrostatic pressure greater than the osmotic pressure. This is done by transferring water through a series of semi-permeable membranes. This technology removes common chemical contaminants such as metal ions and aqueous salts, including sodium, chloride, copper chromium, and lead. The technology also reduces arsenic, fluoride, radium sulphate, calcium, magnesium, potassium, nitrate, and phosphorus, making the groundwater fit for various purposes. The current study applied RO technology in purifying groundwater in the CFA system using BHs at UWC as a case study.

Stein *et al.* (2021) studied the redox condition of saline groundwater from coastal aquifers and how it influences the reverse osmosis (RO) desalination process. Their study aimed to investigate how the redox stages of the saline groundwater (SGW) and chemistry affect the desalination process's performance in permeate flux and fouling properties. Three samples were sampled from different coastal aquifers and characterized chemically. The results showed that all three samples had anoxic saline groundwater, and two were found to be intensive anaerobic oxidation of organic matter. This showed that the natural redox stages of SGWs from coastal aquifers affect the RO desalination performance. Although this study did not focus on the RO performance, it showed the disadvantages of the RO when used under the natural redox performance, which need to be avoided.

The removal efficiency of different remediation technologies used in the groundwater system is presented. Table 3 below shows some examples and highlights of technologies for treating contaminated groundwater.

Table 3: Examples of remediation technologies and their efficiency rates in removing groundwater contaminants

S/N	*REMEDIATION TECHNOLOGY*	*CONTAMINANT*	*EFFICIENCY*	*REFERENCE*
1	Ion exchange	Perchlorate	92-97%	(Gu et al., 2007)
2	Reverse Osmosis	Brackish groundwater and TDS	99%	(Srivastava et al., 2022)
3	Reverse osmosis and Nanofiltration	EC, Total hardness, Fluoride	95%	(Ketharani et al., 2022)
4	Reverse Osmosis + Microdegradation	Pesticide residue	97%	(Schostag et al., 2022)
5	Supercritical Water Oxidation	Contaminants of Emerging concerns (carbamazepine/17β-Estradiol)	99%	(Aviezer and Lahav, 2022)
6	Permeable Reactive Barriers	Cu(II), Co(II), Cr(VI) and As(III)	87.10% - 99.11%	(Zhu et al., 2022)
7	Bioremediation	Heavy Metals (Zinc, Nickel, and Chromium)	55% - 80%	(Znad et al., 2022)
8	Electrodialysis	Nitrates	99%	(Turki and Hamdouni, 2022)

3.7 Studies on the effectiveness of remediation technologies

The use of reverse osmosis has been demonstrated to be one of the technologies that can remove most emerging contaminants in Waste Water treatment plants (WWTP). These include prescription drugs, perchlorate, and other contaminants such as arsenic, cyanide, and fluoride that are difficult to remove by other treatment methods (Joo and Tansel, 2015; Corbacho *et al.*, 2019; Lan *et al.*, 2019). In the USA, (Song *et al.*, 2017) evaluated methods for assessing the effectiveness of in situ remediations of soil and sediment contaminated with organic pollutants and heavy metals. A systematic review method for remediation of factors for contaminants was used. In addition, measurements of pollutants concentration before and after remediation were also used to assess the effectiveness. This was divided into two groups of measures: removal rate % = (1-A/B) *100, where A referred to the residual fraction of pollutant after remediation and B was the total amount of contaminants before remediation. This formula enabled the calculation of the effective rate of the technology.

In Australia, Al-Rifai *et al*. (2011) worked on removing pharmaceuticals and endocrine-disrupting compounds in a water recycling process using reverse osmosis systems. The concentration of 11 pharmaceutical contaminants from various therapeutic categories and two endocrine chemicals were examined in full-scale microfiltration and reverse osmosis membrane facilities. Micro-pollutants' occurrence, persistence, and fate range at different processing points were evaluated. The overall removal efficiencies in the final recycled water were above 97%, resulting in product water concentrations lower than 0.1µg/L for most compounds. The Removal Efficiency was calculated using the formula below:

$R=\frac{ci-ce}{ci}$ *100% where Ci and Ce are the concentrations measured in the influent and effluent of the Wastewater Treatment Plant (WWTP), respectively.

Microfiltration and reverse osmosis were found to lower the concentration of the pollutant by order of magnitude, and the overall removal efficiency was 97%, resulting in a water concentration of 0.1 µg/L. This means RO/Mf removed 97% concentration in the wastewater treatment.

Liu *et al.* (2015) conducted a study on the effectiveness of remediation technology and environmental factors when Cr (VI) contaminated groundwater remediation was purified with natural permeable reactive barriers (PRB) filled with natural pyrite as reactive materials. (Liu et al., 2015) used characterization and measurements of the pH and dissolved oxygen (DO) methods, batch effect experiments of environmental factors, and PRB simulation tests. The results showed that the technology effectively removed contaminants when pH on Cr (VI) removal efficiency was assessed. Cr (VI) removal decreased with increasing initial (Cr) concentration because the Cr (VI) absorbed on the pyrite surface prevented the FeS_2 from dissolving into the water solution (Liu et al., 2015).

(Mishra et al., 2014) researched the effectiveness of the reverse osmosis (RO) plant in the Rairu Gwalior area of India. In this research, they used two software, theoretically and experimentally, to analyse the effectiveness of RO. The samples used in the first effluent plant software for analysis using the KOCH software include pH, TDS, Cl, and SiO_2. The second software was ROSA, and similar parameters were used to analyze the water. The theoretical results of ROSA and KOCH software and the experimental results were then compared at the end of the experiment to determine the effective one. The results also showed that the experimental results of the KOCH-type membrane show more recovery, high TDS reduction, and low investment cost than the ROSA membrane (Mishra *et al*., 2014). Experimental data showed that direct filtration is a process that demands excessive monitoring because even slight variations in the quality of raw water may result in increased maintenance of the machine. Following membranes, RO stage 1 and RO stage 2, theoretical and experimental studies were more effective in improving the boiler sector. It is also found that approximately 75% of treated water was used for recycling purposes in houses, the remaining 25% of rejected waste could be sent to air dust, and 40% of steam was recycled into the boiler water.

3.8 Theoretical and conceptual Framework

This section covers the theories guiding the study. These include Darcy law, the effectiveness concept, and the rock-water interaction. These are explained in detail and relation to their use in the study. The understanding of these theories for the current work is essential.

3.8.1 Theoretical framework

Darcy law is a standard theory explaining the flow in groundwater systems and guides the present study. Darcy's law describes the fluid flow in porous media and rock water interaction, demonstrating the exchange of chemical and thermal aspects in the aquifer system. In Darcy's Law, the flow is assumed to be laminar in saturated porous media. Such a flow occurs under steady-state conditions; the fluid is water and homogenous, and the kinetic energy is not considered [neglected]. In Darcy's Law, the specific discharge rate (q) is proportional to the hydraulic head gradient and hydraulic conductivity (Verruijt, 1982). If there is a pressure gradient, flow occurs from high pressure towards low pressure opposite the increasing gradient direction, hence the negative sign in Darcy's Law. In Darcy's law, the greater the pressure gradient through the same formation material, the greater the discharge rate. Darcy's law works because the medium's viscous resistance balances the fluid's driving forces (gravity and pressure). If inertial forces become necessary, the head drop is no longer linear. Darcy law is applied to describe water movement in the aquifer system (Freeze and Cherry, 1979). The aquifer geometry and geology mainly control the flow in aquifer systems. Understanding principles and assumptions in Darcy Law will help interpret results from contaminants' movement in the aquifer system.

Principles and assumptions made by Darcy explain that the flow of a fluid with constant viscosity across a rock is only a function of its pressure difference. Five principles were made based on this assumption. These include (i) flow will not occur if there is no pressure gradient over a distance, (ii) if there is a pressure gradient, the flow will occur from high pressure towards low pressure (iii) the greater the pressure gradient through the same material, the greater the discharge rate (iv) the discharge rate will be different through different formations even if the pressure gradient is the same in such differing formations (Freeze and Cherry, 1979). Darcy argued that in fractured rock aquifers, the law of Darcy is valid if an assumption is made that the fracture spacing is sufficiently dense and that the fractured media hydraulically acts in the same way as granular porous media (Freeze and Cherry, 1979). The water represents the porous medium in the study area, and the pressure gradient flows from high to low.

The theis equation, first published in 1935 by C.V Theis explains the relationship between the lowering of the piezometric surface and the rate and duration of well-using groundwater storage.

$$S(r,t) = \frac{Q}{4\pi T} W(U)$$

Where $S(r,t) =$ drawdown at distance(**r**) at time (**t**) after the start of pumping [L]

Q = discharge rate $[L^3T^{-1}]$

$W(U)$ = well function of Theis

The theis equation introduced an analytic solution for the drawdown for a non-steady flow in a confined aquifer (Turki and Hamdouni, 2022)

3.8.2 Conceptual Framework

Effectiveness is the unit of analysis/degree to which some things successfully produce the desired result (Mishra et al., 2014). In this study, the concept of effectiveness for remediation technology in groundwater has an operation definition because it provides conceptual guidance in establishing the performance of the technology in reducing (remediating) contaminants in the groundwater system. The study aims to measure Reverse Osmosis technology's effectiveness in removing/remediating contaminants in the area. Song *et al.* (2017) used different methods to identify various elements of effectiveness. These elements produced an operational definition of effectiveness as a technique or tool for reducing pollutants less disturbingly to the natural environment. Such a tool is applicable only when the remediation goals meet environmental criteria. This definition informs the basis of a conceptual meaning of the term effectiveness used in this study. In other words, the study adopted the operational definition of effectiveness (Song et al., 2017). This study measured the effectiveness of RO technology in removing or remediating groundwater contaminants.

Rock-water interaction is known for the chemical and thermal exchange between groundwater and rocks (Ghassemi Dehnavi et al., 2011). This concept is vital in explaining the effects of water chemistry and the rocks' weathering. During weathering, chemical processes such as dissolution, ion exchange, oxidation, and reduction occur (Dehnavi *et al.*, 2011). During these processes, concentration levels of ions and pH values in groundwater change, including the mobility of dissolved constituents. The concept of rock-water-interaction explains the formation of hydrolysis of aluminosilicate minerals and dissolution of carbonates, including releasing chemical elements in solution and secondary mineral precipitation.

The concept of rock-water-interaction helped explain the chemical composition of water when the rock is identified and described. Understanding the weathering process helps enhance the sub-surface's visual penetration ability to describe how contaminants move through rock openings (weathered material) as natural pathways for groundwater and contaminants. In addition, rock structures helped understand the attenuation capacity of geological materials for anthropogenic contaminants, thereby describing whether such geological materials can effectively remediate the contaminated aquifer system. The operationalized concept of rock-water-interaction was a geological cross-section of the study site presented in chapter 5. The subsurface's spatial visualization and visual penetration ability are enhanced to describe the movement of contaminants from the surface to the subsurface. Spatial visualization on the cross-section helped trace the pollutants' sources in the subsurface and the flow direction. The cross-section enhanced the visualization of the recharge mechanism of contaminants, the flow direction of pollutants, and the source of contaminants in the subsurface.

3.9 Chapter summary

This chapter reviewed the literature on groundwater remediation worldwide, in Africa and South Africa, and the effectiveness of such work in the country. The aim was to identify standard and appropriate groundwater remediation methods, as achieved in chapter 2. Finally, the standard and current methods used in collecting data and analysing results about groundwater remediation technologies were presented, discussed, and summarised to inform methods for the study.

Chapter 4 Research design and methodology

4.1 Introduction

The previous chapter highlighted some previous studies that have been done on groundwater remediation, concentration levels, and the effectiveness of reverse osmosis. This chapter describes and explains the research design, methodological approach, and methods used to collect and analyze data to answer the research question and objectives set in the first chapter. Furthermore, this chapter argues that a detailed description of the research design, methods for data collection and analysis, and research integrity are essential for providing the basis for the reliability and validity of the results of the study, thereby providing reliable and valid interpretation and implication of the results from the research for uptake in other areas of similar characteristics. The chapter covers the following aspects: the research design approach, data collection and analysis methods, quality assurance and quality control, and research integrity and research limitation.

The general approach to this study was a case study approach whereby the Cape Flats Aquifer in the Western Cape of South Africa was used. This aquifer system remains an essential water source for the ecosystem and socio-economic utilization. Therefore, a comprehensive approach to understanding the groundwater system, groundwater quality, and associated tools for water purification was adopted, focusing on determining concentration levels of contaminants in the groundwater system, evaluating existing conceptual models of the groundwater flow system, and the movement of contaminants in groundwater system among others. First, a desktop study was carried out for gap analysis. Then, the research design was reviewed and adapted. Finally, data were collected from various sources for analysis before interpreting the results.

4.2 Research design

4.2.1 Research design approach

The study is designed to follow an experimental and observational approach by assessing different parameters in the area that influence groundwater flow and groundwater treatment through the technology used. A qualitative methodology was adopted, whereby the qualitative approach uses the induction approach to emphasize meaning interpretation and try to understand other perspectives. This approach relies on a few case studies, highlighting the context's depth and details (Morgan, 2017). The approach was applied to objective 2, where a conceptual model of groundwater flow was applied to explain transport contaminants.

Secondly, a quantitative methodology was used where this approach tests theories through observations. It emphasizes things that can be measured, and results depend on numerical calculations. It also emphasizes generalization and replication; it uses experimental and statistical controls, which work across many cases (Morgan, 2017). This approach was used on objectives 1 and 3, where the determination of concentration levels of selected contaminants and the demonstration of the effectiveness of Reverse Osmosis technologies on remediating groundwater, respectively, were used to determine the water quality from the treatment plant. Historical data were used to assess the behaviour of different parameters and concentration levels of such parameters. The results were later used to compare the current data in terms of validation found in the vicinity area to understand the quality of the water and the data available in the area.

4.2.2 Sampling design methods

There are two sampling designs: random or probability and non-random or non-probability sampling designs. Probability sampling involves the researcher selecting a few criteria and randomly choosing population members. In contrast, non-probability sampling consists of the researcher choosing a research member at random; the sampling method is not fixed. This study followed quota sampling, which is a non-random approach. This approach helps researchers select members based on a pre-set standard; this research method is used to determine samples based on previous work on the Cape Flats Aquifer. The strength of this method is that it allows researchers to create a hypothesis for the research. In our study, the hypothesis was developed in chapter 1.3, and it helped in the immediate return of data and built a base for further analysis. The weakness of the approach is that it requires more funds and is time-consuming. This study used this design to provide evidence for the formulated hypothesis.

Purposive sampling design is a non-random approach. Simple Random sampling was used in the research; this method is used to obtain information where a member of a population is chosen randomly as everyone has the same probability of being chosen to be part of the sample. This study used the purposive sampling design to select the sampling borehole. The wastewater treatment plant at the University of the Western Cape was used during the study; this plant was selected based on the area's characteristics and the study type. The advantage of this approach is that it reduces sample bias and creates an accurate sample. The results found in this study can be used for other remediation technology found in a similar area with similar characteristics. The disadvantage of the approach is that there is no way to ensure that the sample is representative of the population (Showkat and Parveen, 2017). This approach helped select the samples that were most representative of the study. Therefore, water samples from the treatment plants and the concentrations of contaminants before and after were observed and analysed, and the interpretation was provided on such results.

4.2.3 Data types and data sources

Data from published papers, peer-reviewed literature, grey literature, project reports, and previous theses were collected and analysed to answer the research question. Primary, secondary, qualitative, and quantitative datasets were accessed from sources of datasets outlined above through records, reports, and databases. The preliminary data for the study were obtained from the field visit of the study area at the water treatment plant and lab reports, while the secondary data were obtained from literature, records, and previous studies, as stated above. The study area has a commercial water treatment plant used for treating water in the vicinity area. The water is used on the University of the Western Cape (UWC) Campus. Water samples were collected from the water treatment plant pump using polythene bottles, the water was then kept in a cooler box before it was transferred to the lab 4 water bottles were collected every fortnight. The concentration levels of contaminants were determined from the water pumped and treated at the plant at the UWC campus. The effectiveness of Reverse Osmosis technology was determined based on the before and after the remediation process.

4.3 Methodological approach

4.3.1 Determining concentration levels of contaminants

Data were collected through direct measurements. During field work, groundwater was sampled using a polyethylene bottle to test the concentration levels, and pH and DO meters were used to measure the physical parameters. Before sampling the water, groundwater was purged to remove any impurities even though the pump constantly pumped water to the tank. Before water was collected in the bottle, the bottle was rinsed using the groundwater to control or ensure no contamination occurred. Water was sampled and put in the cooler box to maintain the temperature. Later water samples were sent to the laboratory to analyse contaminants concentration levels for selected elements. This method is common in most reviewed literature where contaminants concentrations are determined, and the concentration levels are compared with the national or global water standards. We compared the sampled water to selected parameters (Fe and Mn) of the South African National Standards (SANS 241) and World Health Organisation (WHO) guidelines.

4.3.2 Evaluating conceptual *groundwater* flow model.

Historical data, literature review, and previous studies on groundwater flow and contaminants were used to understand flows in the Cape Flats Aquifer (CFA) system. The conceptual model by (Gxokwe and Xu, 2017) on the urban water-sensitive design was used to understand groundwater flow in the CFA. The use of surfer software was also used to develop a conceptual model of the CFA with some of the borehole water levels at UWC. This was done to understand the groundwater flow system of the area, which helped understand the groundwater flow direction, groundwater flow rate, and transport flow. The contaminants' type, movements, and groundwater in the area were determined from such flow assessment. The understanding of contaminant transport was also used in the study through the literature reviews and conceptual model. The Darcy law, which governs law in understanding groundwater flow, was used in the area. This helped in explaining the movement of contaminants in porous media. Conceptual models of groundwater flow in different environments explain the basis for the movement of contaminants in the aquifer system. The aquifer parameters of the CFA were used to describe the flow direction of groundwater and contaminates. Previous studies on groundwater flow on CFA were reviewed and adapted.

4.3.3 Assessing the effectiveness of groundwater remediation technologies.

Figure 8 below shows the Reverse Osmosis remediation plant process at the University of the Western Cape, which was used to understand the operation of groundwater remediation technology in the area.

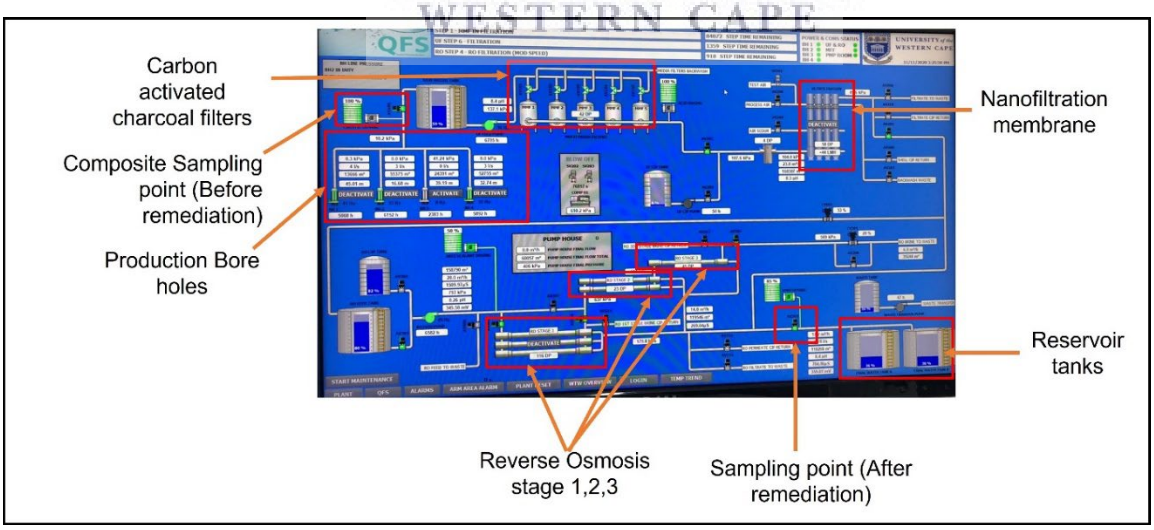

Figure 8: Showing process of Reverse Osmosis plant at University of the Western Cape

The observation method was also used to observe various processing stages and activities at the plant site. The plant has four boreholes used to pump water from the aquifer; after water is pumped, it is sent to the first tank where raw water is collected; in this first tank, acid is added to break down iron and manganese. After that, water is sent to tank 1 for filtration; in this tank, there is carbon-activated charcoal that helps sieve the water. The water passes through the four tanks with the same processes before it is sent to ultra-filtration; this is where some of the water's bacteria, salinity, and viruses are treated. The water is then sent to tank 2, dosed with sulphuric acid. Dosing is the process of stabilizing pH in the water. After this tank, water is sent into the Reverse Osmosis (RO) membrane, where water is purified. Once the water enters the RO membrane, which has different fabric backing that helps purify the water, pure water enters the permeate tube, and impurities are washed away in the brine. Grooves in the tricot create a spiral flow of desalted water that exits in the centre of the vessel; the RO Membrane is sealed on the three sides to form an envelope that helps filter different elements based on the size. This membrane shell helps encase the membrane; once the purification process is complete, clean water is sent to tanks 3 and 4, and the impurities are sent out to a wetland nearby as debris.

The water is then sent to RO stage 1, stage 2, and stage 3. There is continuous filtration as the water passes through all these stages. Water samples are collected from sampling points after stage 3 to test for contaminant concentrations water is now sent to tank number 4 for the addition of chlorine and checks for the concertation. After this stage, water is collected into the reservoir tanks that store the water, and later the water is sent out for use at the University of the Western Cape. Before the water is sent out, water samples are collected at an outlet to test the concentration of contaminants and compare the water with the SANS241 and WHO standards. This observation and learning of the system were done on a monthly routine visit to the plant for familiarisation field visits and the remediation process at the UWC campus. Figure 9 shows where the Water Treatment Plant (WTP) is located, with the purple arrow showing the wetland/lake of the area.

Figure 9: Water Treatment Plant location at the University of the Western Cape

In Figure 9, the yellow stars show the locations of the boreholes. The red line shows pipes bringing water from the bore holes into the plant marked with a blue circle. The blue lines show pipes distributing treated water to the whole campus, while the purple line shows the direction of the wetland used as a waste disposal area for the wastewater. The wastewater containing the contaminants in the wetland is purified by bioremediation and phytoremediation technologies. These methods were not further explored because it is not the focus of this study. The reviewed literature has shown various remediation technologies, but the current research focused on RO remediation technology. The pictures (Figure 10) below show the water treatment plant used for the current study.

Photos of the Water Treatment Plant at the University of the Western Cape

Figure 10:Photos of the Water treatment plant

4.4 Research methods

4.4.1 Methods for determining concentration levels of groundwater contaminants

Different sampling methods can be used to determine concentration levels of groundwater contamination. Such methods include low-flow sampling, positive displacement pumps, submersible pumps, bailer sampling, and peristaltic pump sampling. However, this study used submersible pumps and routine sampling to collect the groundwater samples, and later, they were sent to an accredited laboratory. The collected groundwater samples were sent to A.L Abbott and associates (Pty) Ltd, an accredited laboratory by SANAS, to assess the concentration levels. Using the certified laboratory ensured the quality assurance of the sampled water, and reliable and valid results were obtained in that manner.

In addition, the observation method was used to validate the remediation process at the plant. For example, the researcher observed how the plant purifies the water. The researcher was shown all the plant sections, and all the remediation steps were explained to the researcher. In this way, the researcher/student validated the results, which enabled the interpretation of the results obtained. For analysis, the collected groundwater samples were sent to A.L Abbott and associates Lab. Physical parameters determined included pH, DO, Temperature, and EC. Hach equipment (Model number: DR900) was used to measure these physical parameters before the water was sent to the lab for further analysis. Water was sampled from the four boreholes at

UWC, as depicted in figure 9. A pump inside the water treatment plant was used to get samples from the bore holes through the red pipes shown in figure 9. There was a collection point before the water was sent into the first tanks, and the water was sampled at the last point before it was sent out for use.

Before the water was sent into the first tanks, the collection point was used to assess water quality before treatment. The water sampled at the last point before the water was sent out for use was used to establish the effectiveness of the treatment plant. Concentration levels of contaminants were determined at the point before treatment. The concentration levels of contaminants before and after treatment were compared to ascertain which contaminants were removed entirely from groundwater, which contaminants were reduced, and which contaminants were not removed by the treatment plan or after passing through the treatment plant. The difference in concentration levels of groundwater contaminants before and after the treatment/remediation process enabled the researcher to compute or calculate the effectiveness of the remediation technology in removing or reducing impurities.

Note that the water sampled before and after the treatment was sent to A.L Abbott and associates laboratory to analyse concentration levels of different groundwater contaminants. The sampled and analysed contaminants were iron, magnesium, manganese, potassium, fluoride, nitrate, calcium, chloride, bicarbonate, and sulphites.

During field visits and discussions with plant operators at the UWC campus, it was observed and reported that contaminants and parameters shown in the table below were routinely sampled from the groundwater resources and UWC Treatment plant for various uses.

Table 4: Parameters measured at the University of Western Cape Treatment Plant after treatment

Parameters that the UWC treatment plant routinely sampled for analysis
pH (at 25ºC)
Conductivity(mS/m) (at 25ºC)
Turbidity (NTU)
Iron (Ug/l as Fe)
Manganese(Ug/l as Mn)
Calcium (Mg/l as Ca)
Total Alkalinity (Mg/l as CaCO3)
Hydrogen Sulphide (Mg/l)
Sulphide (Mg/l as S)
Free Chlorine (Mg/l)
Aluminium (Ug/l as Al)
Chloride (Mg/l as Cl)
Combined Trihalomethanes (Ug/l)
Trihalomethane (Bromodichloromethane) (Ug/l)
Trihalomothane (Bromoform)(Ug/l)
Trihalomethane (Chloroform) (Ug/l)
Trihalomethane (Dibromochloromethane) (Ug/l)
Faecal coliforms (count per 100 ml)
Heterotrophic plate count (count per ml)
Langelier Saturation Index (at 25 °C)
Colour (Mg/l as Pt)
CaCO3 Precipitation Potential (Mg/l)
Total Hardness (Mg/l as CaCO3)
Calcium Hardness (Mg/l as CaCO3)
Magnesium Hardness (Mg/l as CaCO3)
Magnesium (Mg/l as Mg)
Sodium (Mg/l as Na)
Potassium (Mg/l as K)
Zinc (Mg/l as Zn)
Fluoride (Mg/l as F)

Sulphate (Mg/l as SO4)
Total Dissolved Solids (Mg/l)
Ammonia Nitrogen (Mg/l as N)
Nitrate & Nitrite Nitrogen (Mg/l as N)
Combined Nitrate plus Nitrite (Mg/l as N)
Nitrate Nitrogen (Mg/l as N)
Arsenic (Ug/l as As)
Cadmium (Ug/l as Cd)
Copper (Ug/l as Cu)
Dissolved Organic Carbon (Mg/l as C)
Lead (Ug/l as Pb)
Odour
Selenium (Ug/l as Se)
Vanadium (Ug/l as V)
Faecal Coliform Bacteria (count per 100ml)

Descriptive statistics were used to analyse the concentration of the groundwater sample. The analysis provided the background condition of the groundwater quality in the study aquifer system. Results from such analyses were presented in tables and graphs for interpretation.

Descriptive statistics: This process describes the number of contaminants in the area. The mean, mode, and median values were calculated. The analysis summarized the quantitative aspects of the datasets. The advantage of using descriptive statistics is well explained by Trochim (2020), who said that 1) The analysis helps to describe the features and patterns, and trends in the datasets; 2) The analysis provides a simple summary (Maximum, minimum, and average/mean, and measures of the data. In the current study, this method helped to summarise the results, visualize the trend of the data, and provide a clear understanding of different concentration levels of groundwater contaminants in the sampled groundwater in the studied aquifer system.

Correlation analysis was done to show how variables are linearly related. The analysis showed if contaminants depend on other variables such as Temp, EC, and DO. The focus was on the linear relationship and correlation coefficients which are scaled to range from -1 to +1, where 0 indicated that there was no linear association (Schober *et al.*, 2018). Microsoft Excel was used to tabulate concentration levels compared to the SANS 241:15 and WHO guidelines. Using the correlation coefficient in groundwater pollution helps assess how parameters relate. Correlation revealed the relationship of parameters and measured the degree of association between two variables to describe how the parameters relate to each other. Results from the analysis help water quality managers implement strategies (Kumar and Sinha, 2010). Correlation can be described in three ways small correlation $-0.010 \leq r \leq 0.29$, medium $-0.30 \leq r \leq 0.49$, and significant correlation $-0.50 \leq r \leq 1.0$ (Schober *et al.*, 2018). The positive and negative points in the direction of the relationship, positive indicates an increase in one variable associated with an increase in the other. In comparison, the negative correlation means an increase in one variable relates to a decrease in the other, while 0 indicates no relationship (Schober *et al.*, 2018; Kumar and Sinha, 2010) about the analysis hence informing robust interpretation of the results.

4.4.2 Methods used for evaluating groundwater flow

4.4.2.1 Conceptual model

The borehole mapping in the area was done to evaluate the groundwater flow conceptual model. ArcGIS software was used to map boreholes, and an overlay analysis was used to assess and understand the groundwater flow. Google Earth image collection was used, and GPS was also used to validate the borehole coordinates used with google earth. The groundwater flow direction in the study area was determined using the water table elevation using the surfer software. The borehole logs were used to identify the geology of the study area and the depths of the boreholes; the secondary data, such as log data, were collected using records reviewed from various reports and dissertations. This helped explain the flow direction of contaminants in the study aquifer system based on the type of geology found in the boreholes drilled. Previous literature and flow models also showed a similar flow direction. Three scenarios were created to evaluate and understand the cause of groundwater contamination in the area. The use of google earth, excel, and surfer software was used to produce cross-sections, lithology, and a conceptual model of groundwater flow dynamics. The use of historical data and previous models helped use the regional groundwater conceptual model and the site-specific model of the study area to explain the flow direction of groundwater and contaminants in the subsurface environment of Cape Town.

4.4.3 Methods for assessing the effectiveness of groundwater remediation techniques

Different methods for calculating effectiveness were reviewed from the literature, and the appropriate method was selected and used as shown below:

Removal Rate %= (1-A/B) *100 where;

A referred to the residual fraction of pollutants after remediation.

B is the total amount of pollutants before remediation.

Removal Efficiency

$R=\frac{ci-ce}{ci}$ *100% $R=\frac{c_i-c_e}{c_i}$

Where c_i is the concentration before

c_e are the concentrations measured after the remediation, and R is the removal efficiency

The water balance calculation determined the water quantity removed during borehole water filtration and how much was left in the system. This calculation helped identify how much water was produced from the aquifer system and how much water was distributed or supplied to various users in the study area. In this case, the UWC campus was used as the study site.

Water balance = water out – water in. As explained before, the groundwater samples collected were sent for analysis at the accredited Lab, making results reliable and valid for interpretation. The Koch and Rosa software was used to check the effectiveness of the Reverse Osmosis technology in remediating groundwater contaminants. The before and after results of the remediation process were compared using the software. Such validating procedure made the results from the current study more reliable and valid for interpretation, thereby achieving the quality control or assurance criteria of results.

Objective 3 focussed on demonstrating the effectiveness of reverse osmosis technology for remediating contaminants in the groundwater system. Based on the reviewed literature, appropriate descriptive statistics were selected and used in analysing the secondary and primary datasets. Results were presented in tables and graphs to show the significant difference between the before and after experimental results from the reverse osmosis technology. The concentrations of contaminants obtained before and after the experiment were calculated and presented in tables and graphs as a percentage for the analysis. Results showed that the RO plant effectively removed contaminants such as TDS, salts, iron, and other substances in the water, which was in line with the study by Song et al. (2017), where similar methods were followed to obtain identical results.

4.5 Quality assurance of the study

Standard methods for data collection and analysis were used in the study. Statistical methods were used to check for the normality of the data, among others. Cation-anion charge balance was not used to test the reliability of the result before interpretation. However, the accredited Lab, A.L abbot, and associates (pty) Ltd provided the required reliability and validity of the results obtained for science-based interpretation. Nevertheless, the charge balance error from previous studies in the same Cape Flats Aquifer system was used because it was conceived that geochemical aspects of groundwater quality would not have dramatically changed since the last study in 2018. Note that instruments used to collect water samples were calibrated, and the standard sampling procedures according to Weaver et al. 2007 were followed. Ground truthing or validation was carried out to verify the coordinates of the sampled boreholes. The GPS and google earth were used to locate the boreholes in the study area and validate such locations. Primary data sets were used to validate secondary data from peer-reviewed journals, previous theses, and reports. Sampling methods were followed as per previous authors such as (Gxokwe and Xu, 2017) and (Adelana, 2010), who worked in the same study area. Results were processed and cleaned up before a comparative analysis was carried out.

4.6 Research integrity

In this study, verbal and written permission to access the UWC water treatment plant and use the data were granted by the University of the Western Cape officers and the Quality Filter System (QFS) management. The visit to the plant to collect data and become familiar with the processes at the plant was monthly. Apart from the data from the plant, secondary data were collected from previous researchers who worked on Cape FlatsAquifer Systems. Permission was granted to use the data for the current research from the earlier researchers. Technical assistance was acquired on the collected datasets, and assistance for the plant supervisor on the water sampling process, parameters used, Lab process, the purpose of the plant at UWC campus, and maintenance of the water treatment plant was provided. Such interaction between the researchers and the Plant Operator or supervisor of the plant gave the researcher an improved understanding of the water treatment plant at the UWC campus. All the relevant precautions were adhered to to ensure that requirements were met per the consideration of the ethics for the QFS and from the student's perspective during the study period.

4.7 Limitations of the study

The study encountered some limitations in different ways. For example, due to the 2019 COVID- pandemic, many institutions closed down, and access to such institutions for data collection was problematic as employees working for such institutions were working from their homes. South Africa implemented a national lockdown from April to early November, which delayed data collection. In other words, fieldwork activities become difficult due to restrictions. However, arrangements were made with one plant operator who agreed to a monthly meeting at the UWC water treatment plant for data collection. This led to collecting few datasets compared to standard data collection protocols. Such erratic data collection led to gaps in the lab reports after analysing the water samples, as few parameters were analysed.

The second challenge is the availability of grey literature and the non-wide application of remediation technologies, especially in the groundwater sector. Although reverse osmosis technology shows potential in removing contaminants from water, the broader application on the commercial scale of such technology remains a challenge, i.e., few case studies exist to demonstrate its wider application. For example, several pilot studies exist where remediation technologies have been applied; however, such applications remain at the pilot or academic research scales. Few applications exist in peer-review journals to showcase the effectiveness of such technologies. This led to the limited comparative analysis in the literature review and the discussion section to compare results from previous studies with results from the current study. In other words, there were limited data/results from earlier studies for comparison. However, the current study provided the insights obtained for a broader study.

The third challenge was the limited studies about ex-situ groundwater remediation in urban and coastal environments, especially those focusing on the pump and treat methods. The current study was conceived to demonstrate the effectiveness of reverse osmosis remediation technology to showcase how fresh water can be made available from contaminated water to address the water shortage problem in urban areas. The limited case studies on such a topic prevented the generalisation of applying reverse osmosis remediation technology in urban coastal environments to solve the water shortage challenges in ever-changing climates. However, a demonstration provided critical insight.

Chapter 5 Results and discussion

5.1 Introduction

The previous chapter described and explained the research design, methodological approach, and methods used to collect and analyze data to answer the research question and objectives set in the first chapter. This chapter presents the results found in the study. The effectiveness of groundwater remediation was assessed using the Water Treatment Plant (WTP) at the University of the Western Cape. The chapter argues that unless the assessment of the remediation technology is done, we cannot improve our understanding of how the remediation plant works. The research question for the current study is, what is the effectiveness of remediation technologies for groundwater contaminants? What is the potential of such technologies in improving water security in ever-changing climates? The concentration levels of selected contaminants in the study area were determined to answer this question. Movements of contaminants in the groundwater system were explained based on the conceptual model of the groundwater flow system that was adopted and used. In other words, the focus of the study hinged on determining how effective groundwater remediation technologies are and their role in improving water security. Statistical methods and a comparison approach were used to help interpret the results. Detailed data analysis is presented in this chapter. The chapter has been thematized as follows: description of and interpretation of results, comparative analysis and implications of the results, evaluation of the study, and summary chapter.

5.2. Concentration levels of groundwater contaminants

Objective 1 assessed the concentration levels of groundwater contaminants. Cape Flats aquifer is dominated by the Ca-HCO3 type of water, shown in figure 12 below. General concentration levels of different parameters in the Cape Flats were recorded. From table 7, Iron and Mg exceeded the water standards, leading to the selection of the two parameters to be analysed in the area current study.

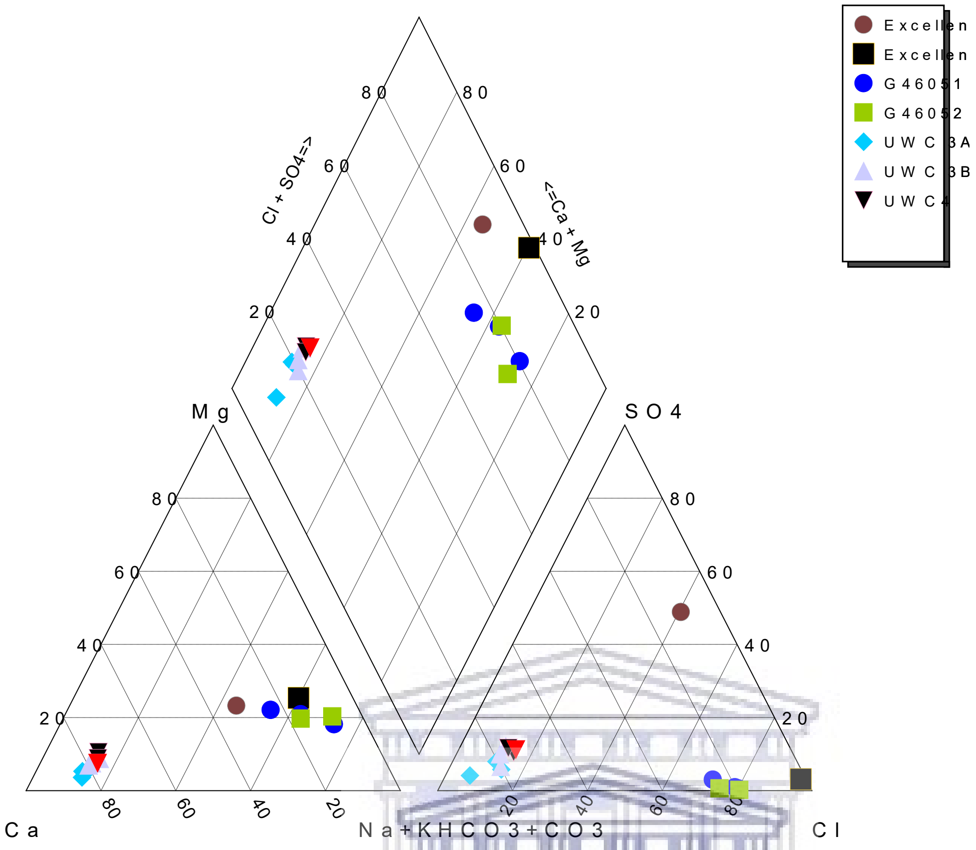

Figure 11: shows the results of boreholes that fall within the general area of investigation

Figure 11 showed three distinct groups of water quality, a Ca-HCO3 dominated composition (UWC boreholes) and a Na-Cl dominated composition (Bellville), and the samples collected at Excellent Meat Facility within Cape Flats Aquifer System on two occasions analyzed by BEMLAB and CSIR, plotting in a different section of the piper plot. The water can best be described as Na-Mg-Cl type water, slightly salty. Therefore we can conclude that the study area has three dominant water types.

Table 5: Parameter comparisons on concentration ranges of selected parameters

Parameter	Unit	SANS 241:2015	RAW water requirements	Min	Max	Mean	Standard deviation
pH (field)		>5.0 to <9.7	>5.0 to <9.7	6.5	8.4	7.62	0.509
Ca	mg/l		<90	22	198,7	70,4	53,6
Mg	mg/l		<100	1,4	209	29,5	52,7
Na	mg/l	<200	<480	7,2	933	140,5	234,9
K	mg/l		<10	1	10	2,994	2,325
Cl	mg/l	<300	<1400	13	2330	288,9	569
EC	mS/m	≤170 Aesthetic	<400	26,5	680	120,5	164,5
HCO3	mg/l			57,3	330	191,5	66,3
SO4	mg/l	<500	<250	1	710	63,7	174
Fe	mg/L	<2	<6.5	0,04	15,2	1,65	4,38
Mn	mg/l	<0.05	<0.24	0	0,88	0,1888	0,292

Table 5 shows that the concentration of Cl within the Cape Flats Aquifer System exceeds the Cl concentration range for the surrounding boreholes. As included in previous analyses, EC's field measurement showed even higher electrical conductivity at the site. Results also showed sulphate enrichment of the sample at Excellent meat Facility for 2017 results, while 2019 results showed a reduction of the sulphate levels. Table 5 showed that dissolved iron and manganese fell outside the SANS241:2015 guideline values and exceeded the maximum concentration requirements of effluent for the Reverse Osmosis Technology or RO plant at the site. The total iron levels of the unfiltered sample collected, shown in the bottle below, were 10mg/L, while the dissolved iron levels (filtered sample) were below detection limits, as shown in the bottle below Figure 12.

Figure 12: Excellent meat water sample collected by UWC and analyzed by CSIR.

Note that the picture on the left represents the sample after shaking, while the image on the right represents an unshaken sample.

On collection of the sample, the water was clear. This demonstrated how iron reacts to exposure to the atmosphere or the introduction of oxygen. The dissolved portion had precipitated out into the sample bottle. This alluded to the fact that water pumped from the borehole, collected in tanks or filtered through a system, may clog filters or lead to tank deposition before or during treatment. This result provided a basis for exploring techniques for remedial action if the situation persists for ex-situ remediation. High iron content in groundwater within Cape Flats Aquifer System has been reported in several parts, but no comprehensive study has been carried out on such parameters. Therefore, the findings on the concentration levels of Manganese are not surprising. The current study found high iron and manganese in the UWC groundwater remediation plan. Table8 shows some additional parameters in samples from boreholes surrounding the site. These are compared to SANS241 concentration limits and requirements for the treatment plant to assess whether or not these parameters were suitable concentrations for optimal treatment.

This objective measured physical parameters such as EC, pH, temperature, and chemical parameters such as Iron and Manganese (chosen from table 4). Composite sampling was done for groundwater at the sampling point before the water entered the collection tanks and routine sampling was to measure chemical constituents. Results went through quality control, where the 95% Confidence Interval with a Coverage Factor K = 2 was used. Physical parameters in the Cape Flats Aquifer System were determined by the concentration levels. To understand the concentration levels of parameters, the concentration levels of parameters in the Cape Flats were measured. Then the concentration levels before treatment in the vicinity area were also measured.

Table 6: Concentration levels of Fe and Mn before treatment with RO technology n=11

Variables	**Skewness**	**Kurtosis**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
pH	2.30	6.70	6.93	0.55	6.25	8.50
EC	2.01	4.19	146.67	15.26	132.00	187.00
Fe (μg/l)	2.28	5.20	2452.50	392.97	2152.00	3526.00
Mn (μg/l)	1.31	0.11	20.92	2.54	19.00	26.00

Using descriptive statistics, values of concentration levels before treatment in the area for Fe and Mn indicated that Fe had higher values for concentration levels compared with Mn as per table 6 above. This means that iron is a major contaminant of manganese. Figure 13 shows groundwater monitoring points and pH levels in South Africa.

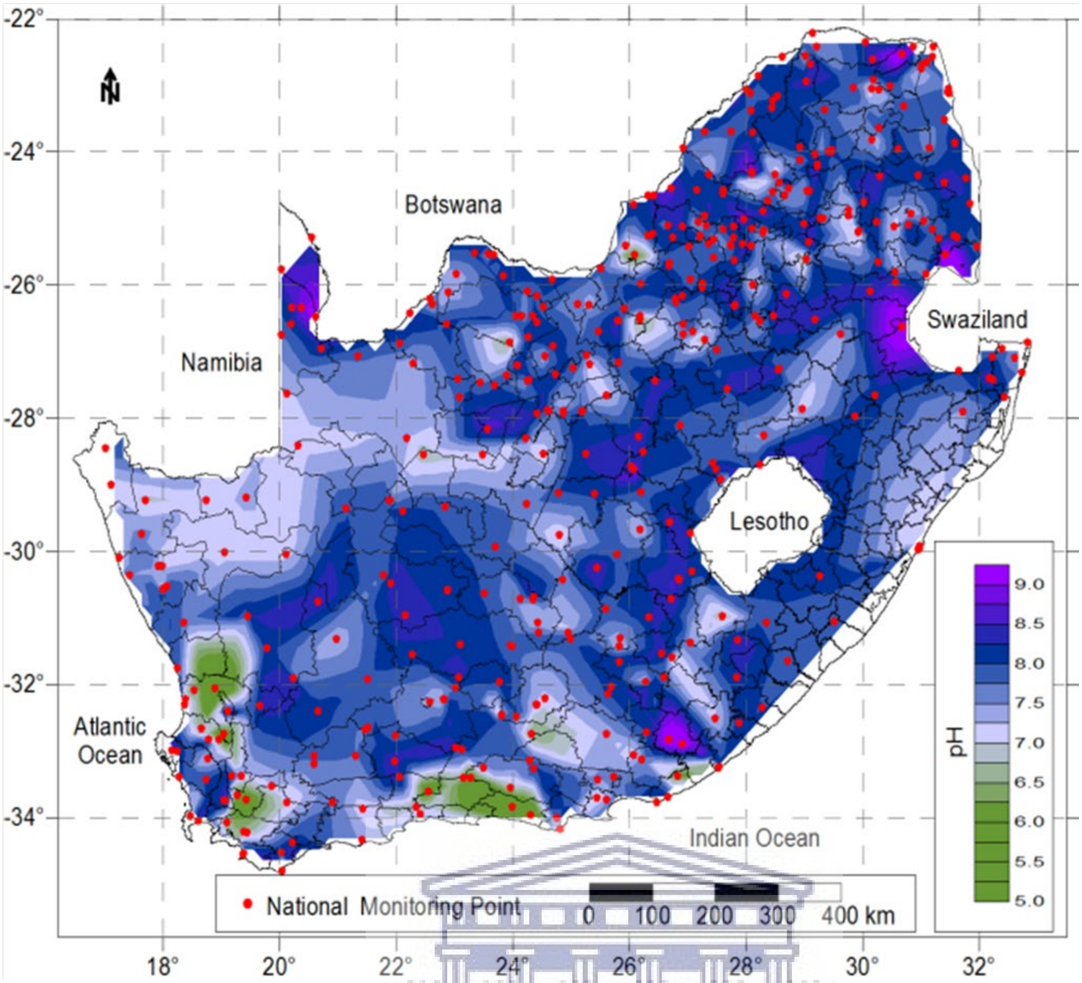

Figure 13: Map showing the pH distribution in South Africa.

The maps show that some groundwater in the Western Cape is acidic (5.0-6.5), and some water is alkaline (7.5-9.0). The CFA boreholes in the national monitoring points had acidic and alkaline waters. The sampled water had a minimum pH value of 6.25 and a maximum pH of 8.50, as shown in Table 6. This pH was expected in CFA as per Fig. 13.

Table 7: Contaminants Levels in Cape Flats Aquifer compared with the SANS 241: 15 (after treatment)

Variables	Concentration levels (Averages)	SANS 241:15
pH (at 25ºC)	7,04	≥5.0≤9.7
EC (mS/m)	44,1	170
Mn (µg/l)	26,3	400
Fe(µg/l)	32,1	2000

When concentration levels of contaminants after treatment on the studied parameters were compared with SANS 241:15, results showed that groundwater quality from the Cape Flats Aquifer System is suitable for drinking. In other words, the Cape Flats Aquifer System had fresh groundwater, as the comparative assessment showed in Table 7. Note that the study was not about whether the Cape Flats Aquifer System had poorer drinking water quality but about demonstrating the effectiveness of remediation technology in removing contaminants in groundwater resources. For this study, reverse osmosis was a selected remediation technology. Reviewed studies show that reverse osmosis as a remediation technology effectively removes contaminants in water resources. However, the research question for the current study was how much such technology removes contaminants. Therefore, the effectiveness of reverse osmosis technology in removing contaminants was demonstrated as an evidence-based intervention or as a case study to show how the technology can remediate contaminated water.

5.2.1 Discussion

The pH values from the Cape Flats Aquifer system ranged from 7.4-to 8; table 4 shows that groundwater was slightly alkaline. CFA system being in the coastal system, the findings were expected. The dissolution of carbonate minerals is believed to cause such poor quality. For example, the Electrical Conductivity (EC) value from the Cape Flats Aquifer System from UWC boreholes was 49.91mS/m with maximum and minimum values of 155.6mS/m and 26.5mS/m, respectively. Such EC values that proxy salinity showed that the groundwater was fresh when results were compared to (Freeze and Cherry, 1979) simplified classification of groundwater salinization where a value less than 1000 mg/L refers to fresh water. These results suggested that such water was suitable for drinking. However, since microbial tests and other chemical parameters were not assessed, the recommendation for drinks remains cautious. The Cape Flats Aquifer System is known for its high manganese and iron concentration. Results from the current study confirmed such findings. Such results mean that natural or atherogenic conditions/factors resulting in such an increasing need to be well understood for the status and compliance monitoring of the groundwater resources in the study area.

5.2.2 Comparative analysis of concentration levels of groundwater contaminants

A study by Haricombe (2016) at the UWC research boreholes on the Cape Flats Aquifer System worked on microbial contaminants in the groundwater system. Among other findings, she linked the salinity with the adsorption in the study area and explained the high Iron and Manganese in the area, which occurred through the adsorption process. The Ph in the water was as well linked to the study findings

The standard method of characterizing contaminants in groundwater through sampling, sending the samples to the lab, and comparing them to the SANS as well as WHO guidelines was used. Different groundwater contaminants exist as inorganic, organic, chemical, physical, microbial, and biological; the results and method used in this study were similar to that of (Ducci, 2018b) and Abiye and Bhattacharya, (2019).

The results on the concentration levels are similar to that of Ruben Aza-Gnandji et al. (2013), who did a similar study on the Cape Flats. His study found that the concentration of ions such as chloride, nitrate, potassium, and sodium exceeded in places compared with the department of water affairs and forestry. These results are similar to the result of the current study summarised in section 5.2.

5.3 Conceptual model of groundwater flow

Conceptual models played an essential role in the CFA's visual representation and helped understand the movements of contaminants on the sub-surface. This section presents the discussion of the data used to explain how the conceptual model of the groundwater flow system improved understanding of the movements of contaminants in the subsurface. Objective 2 of the current study focused on applying the conceptual model of groundwater to explain the transport of contaminants. Records were reviewed, and primary data were used. Results showed that different contaminants in groundwater behaved differently in other aquifer systems. The focus was on shallow and unconfined aquifer systems. Iron (Fe) and Manganese (Mn) were the contaminants of concern; previous studies showed that iron and manganese are problematic in the Cape Flats Aquifer System. The studied depth of the boreholes was about 34 meters deep. This depth is of sandy and gravel; the aquifer is easily recharged in the rainy season and can easily be contaminated with various contaminants or pollutants that are natural and anthropogenic. The diagram below shows the cross-section of the geological environment when the studied boreholes exist for visualization.

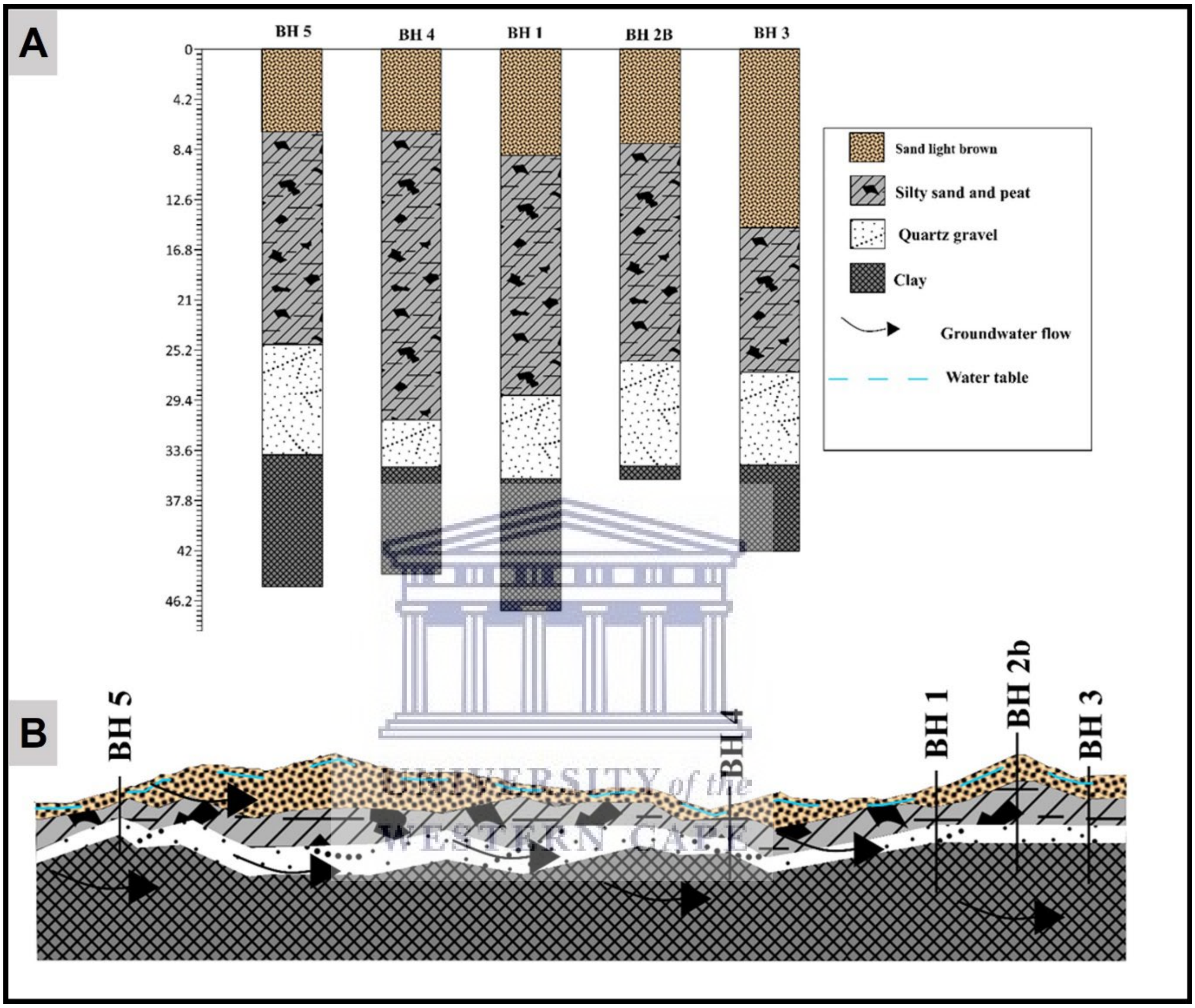

Figure 14 (A): Boreholes 1-5 in the lithological units of the Cape Flats Aquifer System (B): Conceptual model of groundwater flow system in Cape Flats Aquifer(drawn not to scale)

Figure 14a shows boreholes 1-5 drilled in the lithological units of the Cape Flats Aquifer System. The studied boreholes were drilled in the sandy and gravel geological environment. Such a geological environment helped to understand the fast flow of groundwater in such porous media and the transport of contaminants in such sandy and gravel environments. Also, the conceptual model of the groundwater flow system of the Cape Flats Aquifer, where the study was conducted, is shown in Figure 14b. The model shows the boreholes' location and the groundwater's flow direction in the geological formation, which is sandy and gravel. The conceptual model enhanced the visualization of water movement in the subsurface and the movement of contaminants in the subsurface.

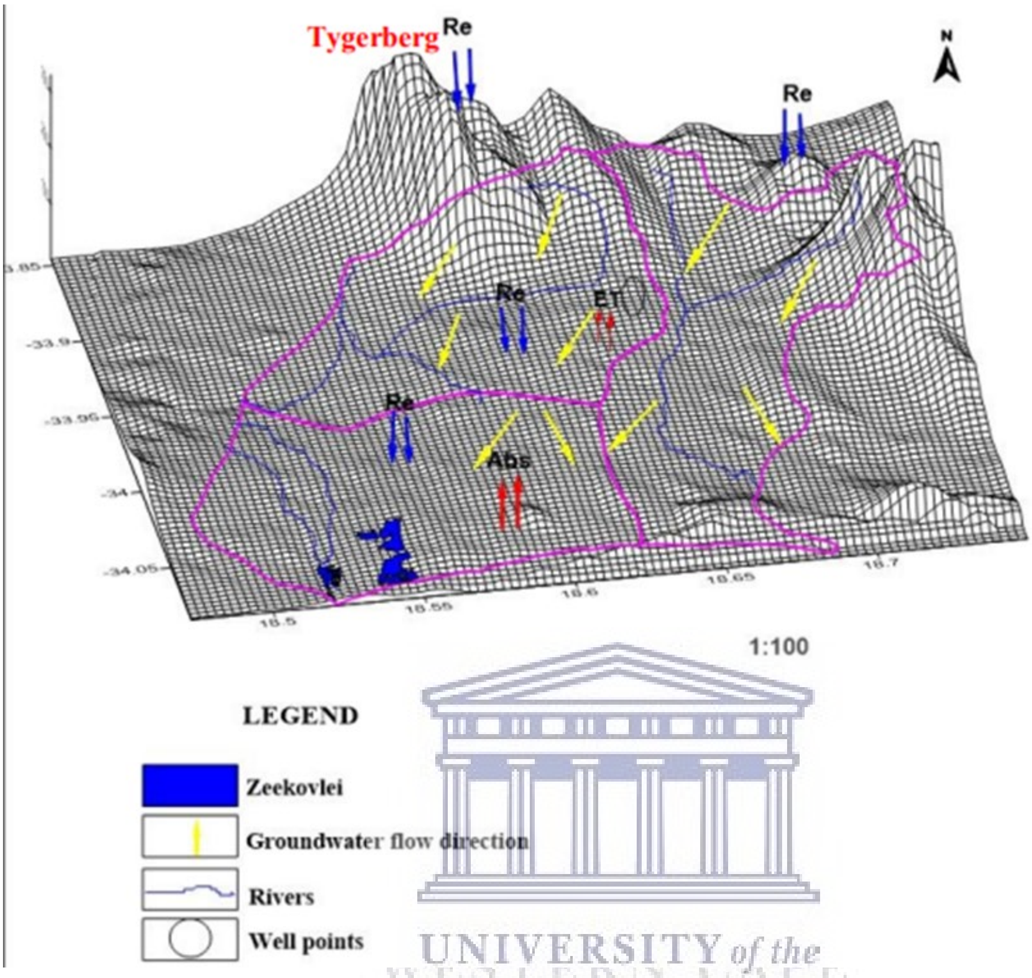

Figure 15: The flow directions of the groundwater in the CFA (Gxokwe et al., 2020)

Figure 15 shows the wetlands, rivers, well points, and the flow direction from higher to low areas. In addition, recharge and discharge points of the Cape Flats Aquifer System have also been shown in the improved conceptual model of the study area. Three scenarios were formulated for the movement of the selected contaminants in the study area as follows: Scenario1: Fe and Mn were found in groundwater due to the natural movement of water through the geological formation in the Cape Flats aquifer System (Natural occurrence of Fe and Mn); Scenario 2: based on the activities in the urban area, Fe and Mn in groundwater was due to urban contamination from human activities; due to the farming activities in the Cape Flats Aquifer System, the third scenario is that Fe and Mn in groundwater are due to agriculture activities. These scenarios suggest that the application of the remediation technology of groundwater contaminants should consider the occurrences of such contaminants to provide a lasting solution if a cost-effective or sustainable solution is to be achieved in the water purification sector.

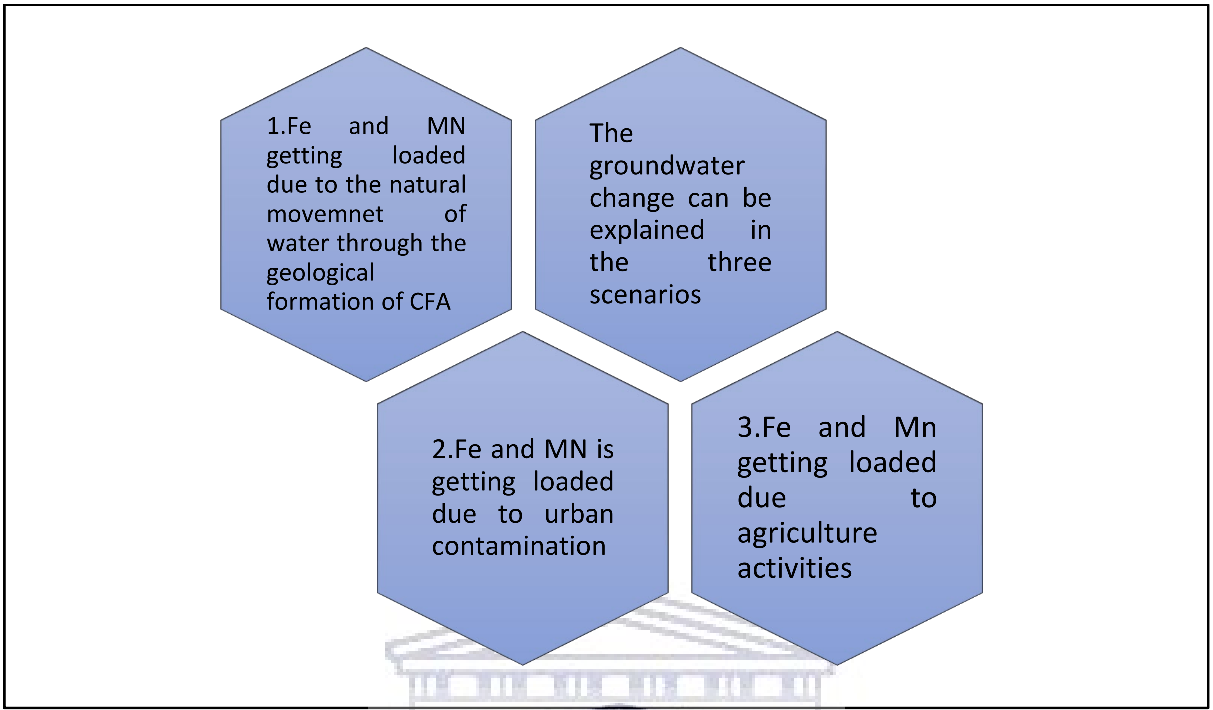

Figure 16: Possible scenarios for groundwater contamination in the Cape Flats Aquifer by Iron and Manganese

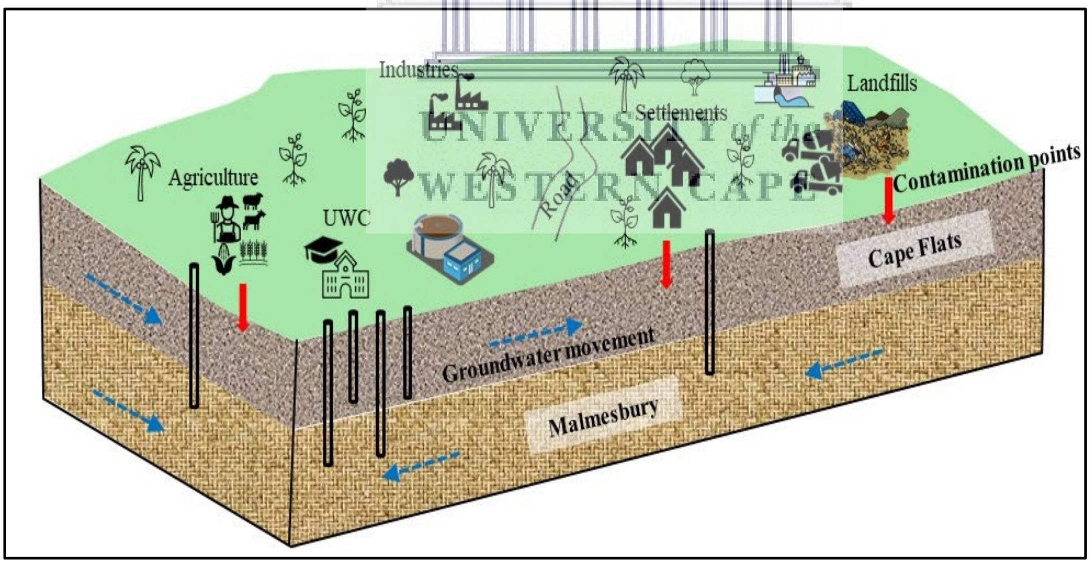

Figure 17: Potential sources of groundwater contaminants in the Cape FlatsAquifer(drawn not to scale)

Figure 17 shows potential sources of groundwater contaminants in the Cape Flats Aquifer System. Red arrows represent the recharge direction of water and contaminants; blue arrows represent groundwater flow direction; black lines represent boreholes where samples are collected for analyses of various parameters depending on the purposes of the research project. For this project, the samples were selected for groundwater contaminants, especially iron and manganese; UWC represents the location of the University of the Western Cape, where the actual study site is located this is where the ex-situ remediation plant is set up; In addition, Figure 17 shows human activities that take place in the CFA area that are potential of groundwater contaminants. These include agricultural activities, settlements, industrial activities, and landfill activities. Lastly, Figure 17 shows the Cape Flats and Malmesbury geological formations, which produce natural contaminants in the aquifer system. The figure shows potential sources of groundwater contaminants that need to be considered when using remediation technology to achieve sustainable water purification for improved water security.

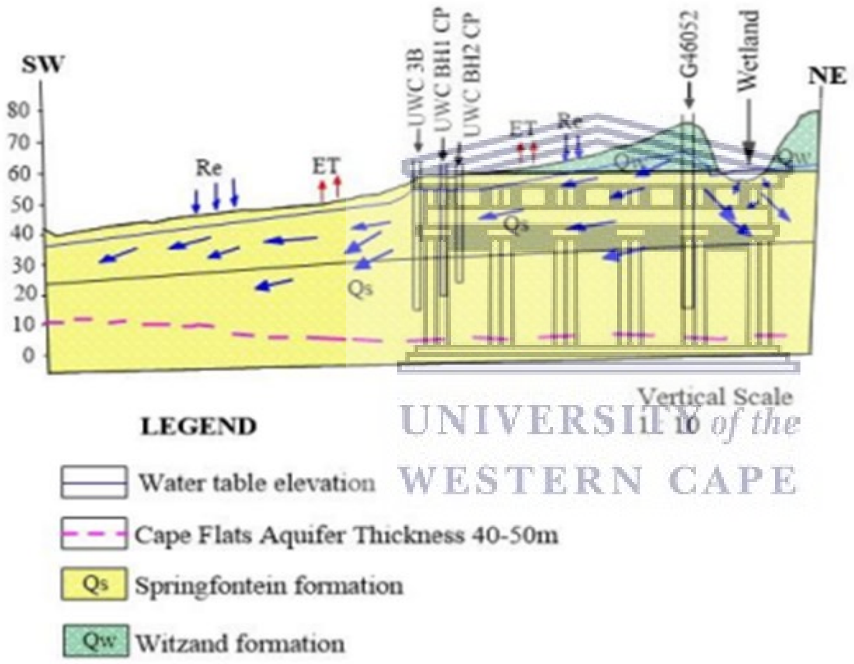

Figure 18: Conceptual model of groundwater flow in Cape FlatsAquifer System (Gxokwe et al., 2017)

Figure 18 presents the conceptual model of groundwater flow in the Cape Flats Aquifer System by Gxokwe et al. (2017). The model shows that the groundwater in the CFA System flows from Northeast to Southwest. Such a flow has implications for the movement of contaminants in the groundwater system. In other words, from the model, one can visualize the flow direction of contaminants in the groundwater. Such visualization has implications for the type of remediation that can be effective in the system because the contaminants constantly move in the subsurface from Northeast to Southwest, following the groundwater flow direction. Boreholes at UWC are shown to exemplify the site where the ex-situ remediation plant is located. In addition, the model shows the recharge and discharge zones in the study area for broader visualization of groundwater processes. The model shows that the Cape Flats aquifer thickness is from 40-50 m (Adelana and Jovanovic, 2010; Gxokwe et al., 2020) The knowledge about the aquifer thickness is essential because it shows the attenuation capacity of the aquifer to filter some contaminants before they arrive at the water table.

The water table elevation shown by the model enables readers to visualize how shallow the CFA System is and hence how vulnerable such a system is to contaminants and thus how vital remediation is for water from such a system. In short, the model enables the visualization of the CFA System and shows how activities in the area can impact the groundwater system, thereby causing the reported contamination of the aquifer. The conceptual model reader helps to understand the site and the water movement in the subsurface, as demonstrated in figure 18. The table below shows the borehole water treatment plant at the University of the Western Cape, where the current study was carried out using the pump and treat remediation method. Reverse osmosis as the ex-situ remediation technology was used to assess the effectiveness of such a technology.

5.3.1 Discussion

Understanding the conceptual model of the groundwater flow system helped provide the meaning of the developed three scenarios: Scenario1 was that the increased concentration of Fe and Mn reported and measured in the study aquifer was due to natural occurrences from the geological formation of the Cape Flats Aquifer System as described in chapter 3. Scenario 2 was that the increased concentration of Fe and Mn reported and measured in the study aquifer was due to urban contamination on top of the Cape Flats Aquifer System in the City of Cape Town, as described in the description of the study area chapter (Chapter 3). Scenario 3 was that the increased concentration of Fe and Mn reported and measured in the study aquifer was due to agricultural activities on top of the Cape Flats Aquifer System, as described in chapter 3.

The scenarios provided the potential sources of the increased concentration of Fe and Mn reported and measured. The conceptual model of the groundwater flow system provided a visualization of the flow direction of such increased concentration of Fe and Mn in the aquifer system. The conceptual model of Gxokwe and Xu (2017) was used to explain the fate and transport of contaminants in the study aquifer system. The elevated concentrations of Fe and Mn were the selected groundwater contaminants for the current study because of their historical abundance in the study area. The results showed that the combined influence of reduced recharge and variable abstraction rates showed a substantial decline in water levels when withdrawal rates were higher and recharge rates lower; when recharge rates were decreased, groundwater levels, outflows, and fluxes also dropped. When increased, all three components also increased, indicating that groundwater levels, outflows, and fluxes were directly proportional to the varying groundwater recharge rate within the area. Therefore, the area could expect varying recharge and abstraction rates, fluctuations in outflows, fluxes, and groundwater levels. The understating from such a model was necessary for the three scenarios set for the current study when assessing the fate and transport of contaminants of concern in the study area, i.e., increased/elevated concentrations of Fe and Mn.

5.3.2 Comparative analysis of results on the conceptual model of groundwater flow

Using groundwater models in the Cape Flats Aquifer System is not new because researchers have developed and refined different flow models of groundwater systems for various purposes. For example, Gxokwe *et al.* (2017) used a site-specific groundwater flow model for urban water-sensitive design research to model flow in the Cape Flats Aquifer System. The DWS 2008 used the groundwater numerical model and developed scenarios to develop the conceptual model for simulating the effects on informal settlements and agricultures activities of the quality of groundwater resources. The current study also used scenario analysis to explain the fate and transport of groundwater contaminants. Results from the DWS study were similar to the current study on the movement of contaminants in groundwater.

A study by Aza-Gnandji *et al.* (2013) produced the conceptual model of the groundwater flow system to explain the movement of natural and anthropogenic contaminants in the groundwater system. His work's results and scenario were similar to the current study.

The study by Bugan *et al.* (2018) on the hydrological model to support the scheme in Atlantis confirmed that aquifer recharge is a critical factor in determining groundwater flow and mass transport besides the hydraulic properties. Jovanovic et al. (2017) found that particle tracking from pollution sources indicated that particles move at a speed of about 100 m per 10 years from the old landfill due to the low hydraulic conductivity in that aquifer zone. Both studies focus on the movement of contaminants in groundwater systems, similar to the focus of the current research on the fate and transport of the contaminants in groundwater resources.

Hydraulics of groundwater systems is critical to groundwater flow systems. Pumping tests are one of the most valuable tools for evaluating groundwater resources. They assess a borehole's performance, yield, zone of influence, and aquifer characteristics (i.e., the aquifer's ability to store and transmit water, aquifer extent, presence of boundary conditions, and possible hydraulic connection to surface water). The water levels that respond to the pumping are analysed to determine the aquifer system's borehole efficiency and hydraulic characteristics. Three types of pumping tests are typically carried out: (i) step drawdown test (SDT), constant discharge test (CDT), and recovery test (RT). The SDT is designed to establish the short-term relationship between yield and drawdown for the tested borehole. This test is carried out to determine the optimum abstraction rate for the CDT. The CDT is performed to (i) gather hydraulic information about the aquifer and determine the borehole's long-term optimum production yield. The pumping test is crucial as it helps in understanding contaminant transportation.

The RT involves recording the water level recovery towards the original water level and provides information on aquifer hydraulics. Due to the infrastructure, SDT was not conducted at UWC Groundwater Treatment Plant. The CDT was limited to the existing boreholes at the experimental wellfield, which provided proxy measurements on the same UWC institution/campus. Recovery was for 1 hour. The shorter duration than normal was due to security concerns at the site. Pumping test data (pump rate of 0.9ℓ/s for 10 hours and recovery data for 1 hour were analysed as proxy values from Cape Flats Aquifer System) from the Excellent Meat Facility using graphical type-curve matching techniques.

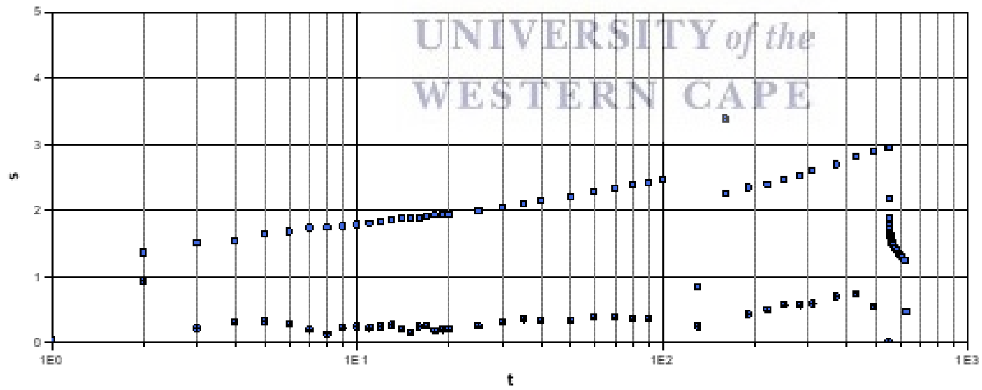

Figure 19: Semi-log plot of time-drawdown and drawdown derivative data: Time vs change in drawdown

The static water level at the start of the CDT was 4.26 meters below ground level (mbgl), and the graph of drawdown and derivative vs. time in semi-log is given in Figure 27. Using derivative analysis on pumping test data improves the understanding of aquifer types and curve matching in hydrogeologic settings. The graph in Figure 27 suggests that groundwater flow to the wells is from a confined aquifer. This means abstraction was from the underlying Malmesbury aquifer rather than the Cape Flats aquifer. Data on the borehole depth would have supported this assumption that was not available. The Theis method was used to interpret the pumping test per the semi-log plot of time drawdown, with the fitted line in Figure 19. The transmissivity for the pumped borehole was calculated as 1.98 x 101. A yield of 0.9ℓ/s can be maintained as per pump specifications. A higher yield of 1.43ℓ/s is possible based on available drawdown and no boundary conditions. However, the current study focused on Cape Flats Aquifer System, a shallow and unconfined sandy aquifer. Thus, discussions on other aquifer systems in the study area were beyond the conceptualization of the current study. However, two aquifer types underlay the current study, confined and unconfined.

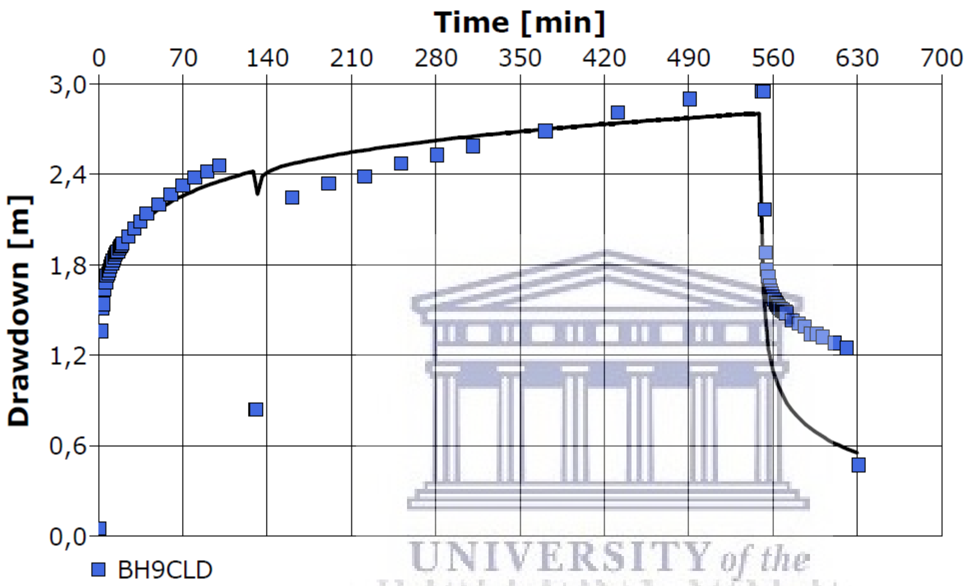

Figure 20: Theis plot for solving the drawdown equation, with a fitted line

5.4 Effectiveness of Reverse Osmosis remediation technology

This section describes results obtained from the water treatment plant on the effectiveness of the remediation plant in removing the contaminants from groundwater following the pump and treat method using reverse osmosis technology. Lab reports before and after the treatment process were analyzed.

Table 8: Contaminants levels in Cape Flats Aquifer System before and after remediation

Variables/Parameters	Concentration before treatment	Concentration after treatment
pH (at 25°C)	6,93	7,04
EC (mS/m)	146,67	44,1
Mn (µg/l)	26,03	20,92
Fe(µg/l)	2452,50	32,1

Results in Table 8 showed that concentration levels before treatment in the area for Fe were significantly reduced from 2452.5 to 32.1, and values for Mn reduced from 26.03 to 20.92. However, the remediation process made groundwater more alkaline, from a pH of 6.93 to 7.04 after treatment. More salts were removed from the groundwater after remediation, i.e., from 146.67 EC (mS/m) to 44.1 EC (mS/m). This shows that the technology has the potential to purify contaminated groundwater and make more fresh water available for various uses, thereby improving water security by addressing the challenge of water shortage.

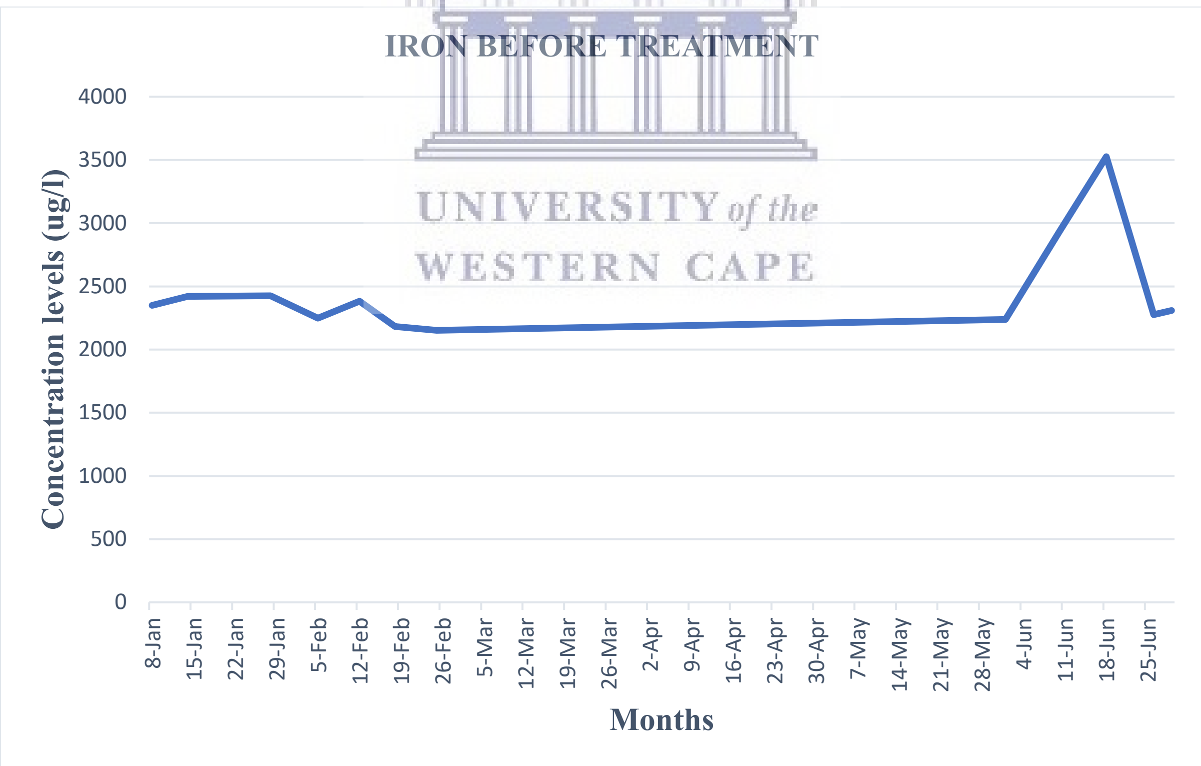

Figure 21 Concentration levels of iron before treatment

Figure 21 shows the readings on iron concentration levels before the remediation process. In general, the readings or values were constant, but the months of January and February had fluctuated readings, and the month of June had the highest concentration level of iron as a contaminant before commencing the remediation process

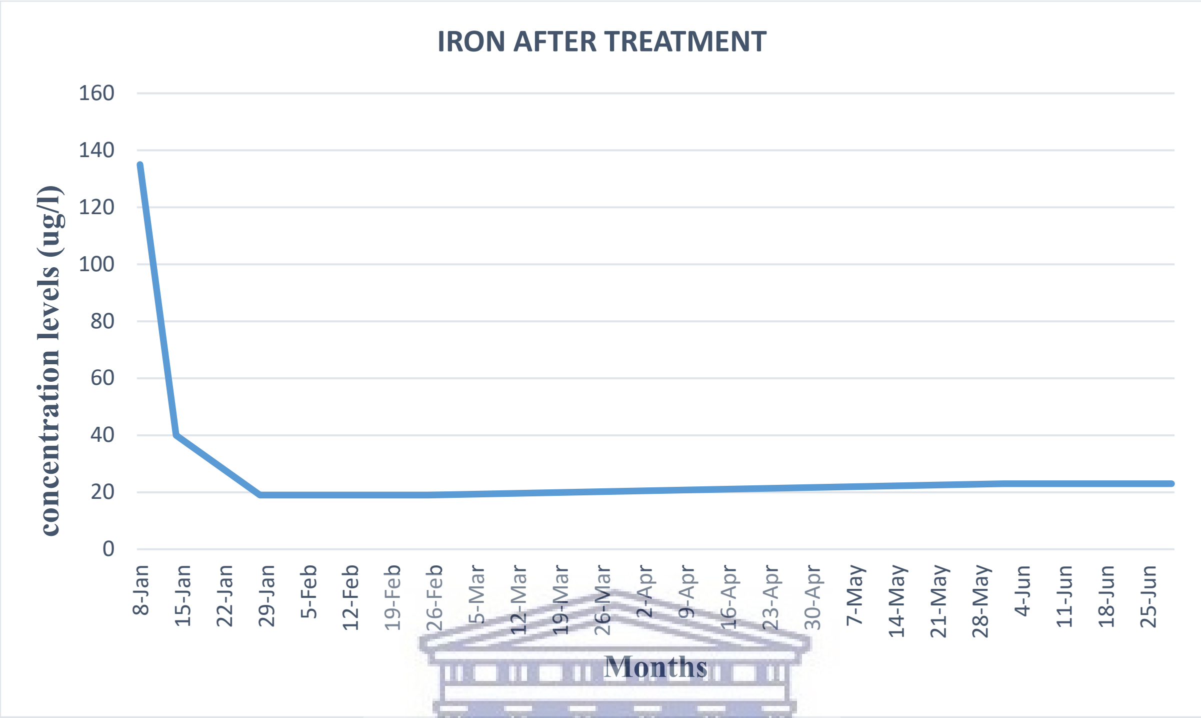

Figure 22: Concentration levels of Iron after treatment

The above graph showed the decrease in the concentration levels from January; concentration levels dropped, making the month of June have low concentration levels after the treatment.

Figure 22 shows readings on concentration levels of iron after the remediation process. There was a decrease from 140 ug/L to 20ug/L. In other words, the remediation technology (reverse osmosis technology) removed or filtered out 120 ug/L of contaminants from 140 ug/L and left only 20ug/L, representing about 96%. The figure also showed that the high values in June in Figure 21 were lowered, meaning that the after-treatment process showed that the technology could remove 96% of impurities.

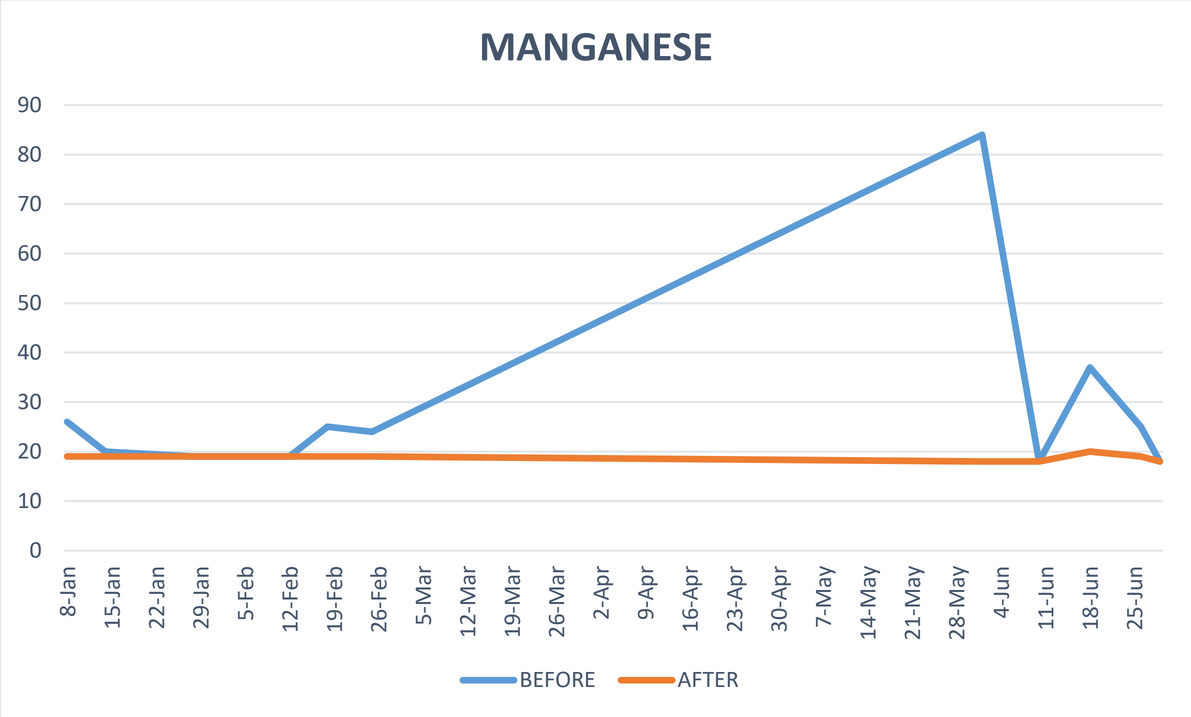

Figure 23: Concentration levels of manganese before and after treatment

Figure 23 showed that the remediation technology could remove manganese as contaminants from the groundwater. There was an increase of manganese from February to June before treatment, but after treatment, such an increase came down to 20% for 84% [84%-18% = 66%], meaning 78% [66/84x100 = 78%] were removed from the water. Results showed that reverse osmosis technology could remove 78% of manganese concentration from groundwater after treatment. A meeting with plant operators proved confirmed the effectiveness of the remediation technology.

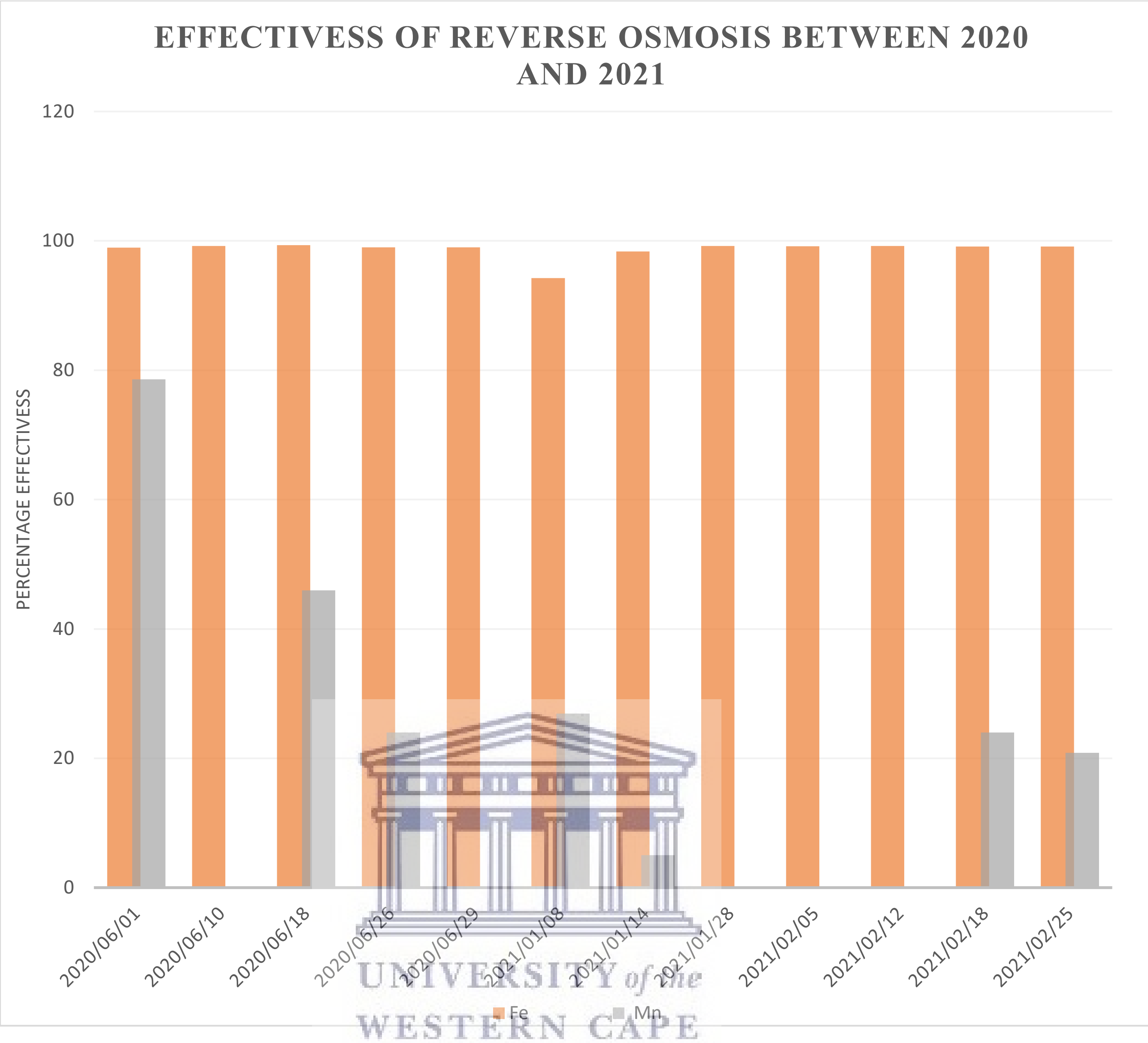

Figure 24: Effectiveness of reverse osmosis technology for groundwater remediation

The effectiveness of the reverse osmosis technology in remediating groundwater contaminants was assessed based on two parameters, namely, iron and manganese. The effectiveness of the technology for iron was very high (96%). The figure above also shows that Mn in June, January, and February was not detected due to the low concentration of Mn. However, it was not possible to assess the efficacy of the technology in removing manganese from groundwater because the dataset obtained seems erroneous; hence a statement cannot be made on the effectiveness of the technology.

5.4.1 Discussion

The current study's research question was to determine the effectiveness of the available remediation technologies for groundwater contaminants. For the present study, reverse osmosis

(RO) was selected as one of the promising technologies in removing or reducing impurities from groundwater resources to make such water fit for different uses, thereby improving water security by making more fresh water available after being treated. To see the effectiveness of reverse osmosis technology, we used the formula adopted below (Song et al., 2017) to calculate and find the percentage of contaminants removed by reverse osmosis was later used as the effectiveness of the technology.

$$Removal\ rate = \left(1 - \frac{A}{B}\right) * 100\%$$

The calculations showed that the RO technology was 96% and 78% effective in removing iron and manganese contaminants from groundwater resources at the UWC water treatment plant. Demonstrating such a high effective rate was essential for showcasing the available technology in purifying contaminated water. That demonstration was crucial to provide evidence for the technology for scaling up the application of such technology in the water treatment sector, thus, addressing the water shortage problem to improve the water security challenge.

5.4.2 Comparative analysis of results on the effectiveness of groundwater remediation

Several studies have shown the effectiveness of remediation technologies in remediating groundwater contaminants, including using Reverse osmosis as provided in the Literature review chapter of the current thesis [Chapter 3]. For example, in Europe (Mueller et al., 2012), NZVI effectively removed contaminants. In the Saskatchewan area in Canada, (Mueller et al., 2012) used the pump and treat method; the results demonstrated the effectiveness of remediating groundwater contaminants. In China, Zhang et al. (2019) experimented and showed that NO-3 removal efficiency in Zero-Valent iron SCCMs was higher than in the ZVI-free SCCMs. In Latin America, (Herrera et al., 2013) applied reverse osmosis as a remediation technology to remove AS and F. In Mexico and Argentina, (Herrera et al., 2013) showed that reverse osmosis removed 92% of AS (V) and AS (III) and 85-95% of F from groundwater as contaminants. The study by Israel (2015) guided the current work on software and analysis methods, including the improved understanding of differentiating the in-situ and ex-situ remediation in groundwater.

5.5 Implication of results

Objective 1 focused on the determination of concentration levels of selected contaminants. Findings from such objectives benefit scientists, practitioners, educators, researchers, and industries interested in the Cape Flats Aquifer in Cape Town but who also want to use such results for various purposes. The implication of the results on objective two on the groundwater flow model is more relevant to educators/academics, researchers, and learners who want to improve their knowledge of the movement of the groundwater in the subsurface so that they can design interventions, model future scenarios, and teach the learners as part of the training program or capacity building. The implication of objective 3, which focuses on showcasing the effectiveness of remediation technology, is relevant to practitioners in the commercial sector who want to do business with public and private institutions, researchers who want to publish such results, and academics who wish to teach the working technologies. The other stakeholders in objectives one and two would also like to benefit from objective three if such technology is rolled out at a broader scale.

5.6 Evaluation of the study

The analysis and interpretation of the results from the current study and the comparative analysis showed an adequate basis to rate the study as good. For example, the quantitative assessment of the effectiveness of the remediation technology showcased how one of the available technologies could remove impurities from groundwater, thereby making more fresh water available for various purposes. Such a demonstration showed the feasibility of turning contaminated water into fresh water to address the water shortage problem, the desired solution for water security, and adaptation measures of climate change impact. Secondly, the comparative assessment of iron and manganese was based on the real problem. The current study compared its findings with findings on the same parameters and the same RO technology in the same study area. Such an approach broadens the evidence on the application of RO technology in solving practical problems in the study area. Such analysis requires implementable technology recommendations on a broader scale for practical issues. Thirdly, the use of the UWC Water Treatment Plant on the University Campus and the experimental design of the study demonstrated how contamination problems need to be approached, i.e., the involvement of private companies operating at public institutions training university students at the postgraduate level provided the practical skills that are required at workplace environment which was unique in the current study. Despite the above strengths of the study, the lack of long-term data, lack of comprehensive datasets, restrictions to publicize company datasets, and COVID restrictions which led to fewer contacts and practical tasks at the plant than desired and planned, prevented the application of some robust statistical tools on the company datasets. Accessing long-term monitoring datasets on iron and manganese would have allowed the application of inferential statistics such as regression analysis and fate and transport contaminant model, which was not possible.

5.7 Chapter Summary

Chapter 5 described and discussed the results of the current study. The conceptual model was used to understand the flow of groundwater contaminants. Statistical methods were used to understand the concentration levels of groundwater contaminants and the effectiveness of remediation technology on groundwater contamination. The interpretation of results on each objective was provided. The implication and comparative assessments were carried out.

Chapter 6: Conclusion and recommendations

6.1 Introduction

This study aimed to assess suitable technologies for groundwater remediation practices that can improve water security and the effectiveness of such technologies. The study argues that appropriate groundwater remediation technologies need to be tested and their effectiveness established for scaling up such practices to address water security challenges. The two main objectives of this study were to i) determine concentration levels of selected contaminants, ii) explain transport contaminants in groundwater systems, and iii) demonstrate the effectiveness of Reverse Osmosis technologies in remediating groundwater. A case study approach was followed where Cape Flats Aquifer System was used to showcase the effectiveness of the reverse osmosis remediation technology in South Africa. This chapter presents conclusions from the analysis of the results obtained for each study's objective contribution to scientific research. It further proposes recommendations from the findings of the study.

6.2 Concentration levels of contaminants

The analysis of concentration levels of iron [Fe(µg/l)] and manganese [Mn (µg/l)] showed that before remediation, both were higher 2452.5 (µg/l)] for Fe and 26.3 (µg/l)] for Mn and after remediation values for Fe and Mn were 31(µg/l) and 20.92 (µg/l)] respectively. Based on such findings, the analysis in the current study determined the concentration levels of selected contaminants (Iron and Manganese, Table 6). Therefore, the first objective of this study was to determine the concentration levels of selected contaminants (Iron and Manganese). The current research recommends assessing different types of contaminants for an extended period (5-20 years) and from different parts of the aquifer system for a representative spatiotemporal variation of such contaminants in the groundwater system to inform a broader application of remediation technology for such contaminants of concern. However, the current study provided a basis for designing and implementing such research work at the aquifer scale.

6.3 Contaminant Transport

The second objective of the current study was to explain the transport of contaminants or the fate and transport in the groundwater system using a conceptual model of groundwater flow. Different groundwater flow models were reviewed and compared. The appropriate site-specific groundwater model from the Cape Flats Aquifer System was used. Scenarios on potential sources of the increased concentration of Fe and Mn reported and measured were explained using a conceptual model of a groundwater flow system which provided a visualization of the flow direction of such increased concentration of Fe and Mn in the aquifer system. Therefore, the second objective of this study, using the groundwater flow model to explain the movement of contaminants in the groundwater system in the study area, was fulfilled. The conceptual model of groundwater was good, but more work needs to build on such initial work to model contaminants. The current study recommends the application of fate and transport contaminant modeling in such work to improve understanding of the movement of different kinds of contaminants in groundwater under different conditions.

6.4 Effectiveness of remediation technologies

The third objective of the current study was to demonstrate the effectiveness of Reverse Osmosis technologies in remediating groundwater. Statistical tools were applied to compute the effectiveness rate. Results showed that the remediation technology could remove iron and manganese as contaminants from the groundwater. After treatment, reverse osmosis technology had a 78% removal efficiency for manganese from groundwater. In addition, a 96% removal efficiency was achieved for iron contaminants from groundwater resources. Such results were compared with previous studies, which confirmed or validated the findings from the current study. Based on the findings and interpretation of the current study alongside the comparative assessment of such results, the current study demonstrates the effectiveness of Reverse Osmosis technologies in remediating groundwater, thereby achieving the third objective. The current study recommends more detailed studies or rolling out studies on applying the Reverse Osmosis technology in remediating groundwater contaminants in different places.

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