INVESTIGATING POTENTIAL AQUIFERS FOR MANAGED AQUIFER RECHARGE USING TREATED WASTEWATER AROUND THE GREATER ETHEKWINI DISTRICT MUNICIPALITY

HLENGIWE FORTUNATE MSWELI

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Discipline of Geological Sciences,
School of Agricultural, Earth and Environmental Sciences
University of KwaZulu-Natal

Supervisor: Prof M Demlie

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ABSTRACT

Managed Aquifer Recharge (MAR) can be used as one of the climate variability and change adaptation strategies so as to alleviate problems related to water security such as water quality deterioration, groundwater level decline and impacts on groundwater-dependent ecosystems. This study investigated potential aquifers within the eThekwini District Municipality that have the capacity to store treated wastewater in the form of MAR. The main objectives of this MAR study was to assist in climate change adaptation and the mitigation of potential seawater intrusion. The study employed geological, hydrogeological, and hydrochemical data analyses and interpretation. Additionally, the study examined the amount and quality of treated wastewater generated within the area for use for use as recharge source of MAR.

The geological and hydrogeological data analyses show that three different aquifers occur in the study area, namely; 1) Weathered and fractured aquifers composed of the Pietermaritzburg Formation and rocks of the Natal Metamorphic Province, where the former is characterised by average borehole yield, hydraulic conductivity (K) and transmissivity (T) of 1.2 l/s, 0.56 m/day and 0.28 m^2/day, respectively. While the latter is characterised by mean borehole yield, K and T values of 0.02 l/s, 0.56 m/day and 3.9 m^2/day, respectively; 2) Fractured aquifers made up of the Natal Group sandstone and the Dwyka Group diamictite. The Natal Group sandstone is characterised by average borehole yields, K and T values of 9.1 l/s, 2.87 m/day and 8.32 m^2/day respectively, and the Dwyka Group is characterised by average borehole yields of 0.4 l/s, K value of 0.8 m/day and T value of 1.3 m^2/day; and 3) Intergranular or primary aquifers of the Maputaland Group which consists of the Bluff and Berea Formations and recent alluvium and estuarine deposits. The Bluff Formation is characterised by mean borehole yield, K and T values of 13.05 l/s, 3.2 m/day and 9.6 m^2/day, respectively. The Berea Formation is characterised by average borehole yield, K and T values of 25 l/s, 5 m/day and 7 m^2/day, respectively. The recent alluvium and estuarine deposits have average borehole yields of 24 l/s, K value of 6.5 m/day and T value of up to 32 m^2/day.

The region receives a mean annual groundwater recharge rate of about 12% of the mean annual precipitation (MAP = 935 mm/year). The groundwater level in the primary aquifers range from 0 to 15 m bgl. The groundwater level in the Dwyka Group has median values of 20 m bgl and 21 m bgl, respectively. The greatest percentage of deep (>50 m) groundwater levels are associated with boreholes drilled in the Natal Group and Granitic Basement rocks of the Natal

Metamorphic Province. The regional groundwater flows from west to east, toward the Indian Ocean.

Based on various factors, including the current rate of natural recharge, the need and water source for MAR, the hydraulic characteristics of aquifer, such as K, storage capacity and the infrastructure needed, seven potential MAR sites have been selected within the primary aquifers. These are: i) Site 1 is located between Umhlanga Rocks and Tongaat, which has a maximum storage capacity of 1.28 $x10^8$ m^3 MAR from treated wastewater; ii) Site 2 is located between the uMgeni and uMbilo Rivers, locally known as the Berea Ridge, and can receive a maximum volume of 6.6 $x10^7$ m^3 treated wastewater; iii) Site 3 is located the around Sea View, Woodlands, Mobeni Height, Joe Slovo and Lamont areas and can receive a maximum of 4.6 $x10^7$ m^3 of treated waste water; iv) Site 4 is located around the uMlazi and Isipingo areas, which can receive about 3.00 $x10^7$ m^3 of treated waste water; (v) Site 5 is located around the uMbogintwini and Amanzimtoti areas and has an approximate capacity of receiving 3.9 $x10^7$ m^3 volume of treated waste water; (vi) Site 6 is located within the Harbour Beds, stretching from the uMgeni River mouth in the north through downtown Durban all the way to uMbogintwini in the south. The average available storage capacity is estimated at 1.01 $x10^8$ m^3. Since a considerable amount of groundwater from this aquifer is being exploited for various industrial and domestic purposes, MAR can be suitably applied to mitigate potential seawater intrusion along the Indian Ocean coast induced by pumping; and vii) Site 7 lies on the central uMgeni alluvial deposits along the Springfield graben and has an approximate capacity of receiving 2.0 $x10^6$ m^3 of treated wastewater in the form of MAR.

The greater eThekwini District Municipality generates about 276414 ML/year volume of treated wastewater from a total of 27 wastewater treatment works (WWTW) located across the Metropolitan region. The proposed source of treated wastewater for Site 1 and 6 would be derived from Northern WWTW, and for Sites 2, 3, 4, 5, 7 are from uMbilo WWTW, Southern WWTW, Isipingo WWTW, Amanzimtoti WWTW and New Germany WWTW, respectively. Though this study identified the potential aquifers sites and sources of treated waste waters for MAR as a potential tool for climate change adaptation and mitigation of seawater intrusion within the greater eThekwini District Municipality, a detailed modelling and feasibility study across the area is recommended to come up with the most suitable sites to store the treated waste waters generated across the region.

Keywords/Phrases: Climate change adaptation, Managed Aquifer Recharge (MAR), Primary aquifers, Seawater intrusion mitigation, Treated wastewater, eThekwini District

PREFACE

This dissertation is based on research conducted by the candidate during her tenure at the School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Campus, South Africa.

The contents of this work have not been submitted to another university, and, except where their work is acknowledged in the text, the results reported are the results of investigations conducted by the candidate.

______________________________ 16/02/2022

Sign Date

DECLARATION 1 - PLAGIARISM

I, Hlengiwe Fortunate Msweli, declare that:

i. The research reported in this dissertation, except where otherwise indicated or acknowledged, is my own original work;

ii. This dissertation has not been submitted in full or in part for any degree or examination to any other university;

iii. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledge as being sourced from other persons;

iv. This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced;
    b. Where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

v. Where I have used material for which publications followed, I have indicated my role in the work;

vi. This dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

vii. This dissertation does not contain text, graphics or tables copied from the internet, unless specifically acknowledged, and the source has being detailed in the dissertation and the references sections.

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Signed: Hlengiwe Fortunate Msweli

TABLE OF CONTENTS

List of Figures

List of tables

LIST OF ACRONYMS

AET	Actual evapotranspiration
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage Transfer and Recovery
Amsl	Above mean sea level
AWRMS	Atlantis Water Resource Management Scheme
C	Runoff coefficient
CBF	Canal bed filtration
CGS	Council for Geoscience
Cl_p	Chloride concentration in precipitation (mg/l)
Cl_{sw}	Chloride concentration in soil water (mg/l)
CMB	Chloride Mass Balance
COD	Chemical oxygen demand
DBP	Disinfection by-product
DEM	Digital elevation model
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
DO	Dissolved oxygen (ppm)
EC	Electrical conductivity (µS/m)
ECA	Environmental Conservation Act
Eh	Reduction potential (mV)
EMPs	Environmental Management Plans
ETo	Reference crop evapotranspiration
ETc	Crop evapotranspiration under standard conditions (mm day-1)
EWS	eThekwini Water and Sanitation
FAO	Food and Agriculture Organisation
GCS	Groundwater Consulting Services
GRIP	Groundwater Resource Information Project
HSG	Hydrologic soil group

IDP	Integrated Development Plan
IDW	Inverse Weighed Distance
IAH	International Association of Hydrogeologist
IC	Ion-Chromatography
ICP-AES	Inductively Coupled Plasma Atomic emission spectrometer
ICP-MS	Inductively Coupled Plasma Mass Spectrometer
ISMAR	International Symposium on MAR
ISS	Incremental security of supply
ISO	International Organization for Standardization
K	Hydraulic conductivity
LBF	Lake bed filtration
MAP	Mean annual precipitation
MAR	Managed aquifer recharge
ML	Megalitres
NEMA	National Environmental Management Act
NGA	National Groundwater Archive
NMP	Natal Metamorphic Province
NWA	National Water Act
ORP	Oxygen Reduction Potential (mV)
P	Precipitation (mm/month)
PET	Potential evapotranspiration
pH	Potential hydrogen
RBF	River bed filtration
S	Storatvity
SABS	South African Bureau of Standards
SAT	Soil Aquifer Treatment
SAWS	South African Weather Service
SANAS	South African National Accreditation System
SCA	South Coast Augmentation Pipeline
SCP	South Coast Pipeline

SCS	Soil Conservation System
SMOW	Standard Mean Ocean Water
Sy	Specific yield
T	Transmissivity (m^2/d)
T	Air temperature (˚C)
TDS	Total dissolved solids (mg/l)
TSS	Total suspended solids
WARMS	Water use Authorisation Registration Management Systems
WMA	Water Management Area
WSA’s	Water Services Act
WWTW	Wastewater Treatment Works
UW	Umgeni Water
USA	United State of America
USEPA	United States Environmental Protection Agency

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My first and foremost thanks go to the Almighty God for sustaining me throughout my journey. I am reminded of the Israelites when He promised to bring them to the Promised Land. By day He went ahead of them in a pillar of cloud and by night in a pillar of fire.

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I would like to thank my family. It was not easy at all, but all your understanding, support and prayers sustained me.

To my late brother Mzamo Zungu, thank you for instilling resilience and agility in me if it wasn’t for the skills you taught me I wouldn’t have made it this far. May your sole rest in eternal peace.

CHAPTER ONE: INTRODUCTION

1.1 Background and rationale of the research

South Africa is a semi-arid and drought-prone country characterised by uneven rainfall patterns and surface water and groundwater distributions. This is a result of the climatic, geographical and geological conditions of the region (Molobela and Sinha, 2011). Rainfall is generally low and erratic, with a mean annual precipitation of 500 mm compared to the world average of 860 mm (DWAF, 2002). South Africa is ranked amongst the twenty most water-scarce countries in the world, owing to limited amount of water resources (Cetinkaya and Gunacti, 2018).

The data of water consumption in South Africa show that groundwater contributes only 20% of the total volume of water supply in the country (Mvandaba et al 2019), with about 300 towns representing 65% of the population is entirely dependent on groundwater as their main source of water (DWAF, 2002). Woodford *et al*. (2005) identified that inadequate reliable hydrogeological information contribute to the poor development of groundwater in South Africa. For example, the groundwater resources in Kwa-Zulu Natal have not been efficiently exploited when compared to the drier parts of South Africa that includes the west coast. This is because the available surface water is sufficient for the current demand within the province. The eThekwini District Municipality, which is located within the KwaZulu-Natal Province, relies highly on reticulated water schemes for its supply. The water supply source is primarily from the uMgeni supply systems of the north coast and south coast supply systems.

Based on the eThekwini Municipality’s Integrated Development Plan (IDP, 2019), the population of eThekwini is about 3.85 million. The increase in population and economic activities will put tremendous pressure on the water sector within the Municipality, increasing the challenge of bridging the water supply - demand gap. Therefore, for future water security within the eThekwini Municipality, water use efficiency and water demand management require improvement, and new water sources need to be identified to cater for the city’s growing population (Gleick, 2000). Examples of other options that could be explored include water recycling, desalination, storing water underground such as the treated wastewater. A proper and planned reuse of treated wastewater represent a viable and reliable source of water in a water-scarce region (Baawian and Sana, 2013). Currently, a significant volume of treated wastewater are processed by the eThekwini Municipality’s water treatment works and is being discharged directly or indirectly through coastal rivers into the ocean. This treated wastewater can be stored in suitable aquifers and reused during times of great demand. This artificial recharge or managed aquifers recharge (MAR) may be one of the water supply augmentation options that can be explored for the eThekwini District Municipality.

MAR is a technique/technology whereby excess surface water is channelled into aquifers, either by surface-spreading using recharge pits and basin or by changing some conditions to improve infiltration or by injecting it into aquifer using wells to replenish aquifers (Riad *et al.*, 2012). It is also a way to store water underground for use during any periods of drought. In the case of treated wastewater, MAR improves water quality through the infiltration process. The storage of excess water in aquifers reduces evaporation and help overcome shortage as a result of surface water variability during droughts, provided that MAR applicable and cheap compared to other alternatives (Arshad *et al.*, 2014). Thus, this MSc research envisages investigating potential aquifers that can be used as storage for MAR using treated wastewater generated within the eThekwini District Municipality.

1.2 Research Questions

Are there potential aquifers for MAR around the Greater eThekwini District Municipality?

If so, do these aquifers have sufficient storage capacity to receive artificially recharged treated wastewater?

1.3 Aims and Objectives

This project aim to investigate suitable aquifers within the Greater eThekwini District Municipality that have the capacity to store treated wastewater in the form of MAR. The specific objectives of the research are:

- To characterize the aquifers within the eThekwini District;
- To understand the volume and quality of treated wastewater generated annually from the Municipality;
- To identify aquifers that can be used for MAR; and
- To quantify the maximum possible MAR that can be under in the study area.

1.4 Structure of the Dissertation

There are seven chapters in this dissertation; they are as follows;
Chapter 1 is the introductory chapter in which the background, rationale, aims, and

objectives of the study are described.

Chapter 2 gives a description of the study area's location, climate, topography, drainage, geological as well as hydrogeological settings which are important inputs in understanding and characterizing of the region.

Chapter 3 provides a literature review on the history of the international and Southern African experience of the MAR technology. The chapter provides an account of the challenges of MAR and legislative framework in the country. Additionally, the literature review includes previous geological and hydrogeological studies undertaken in the eThekwini District Municipality.

Chapter 4 encompasses the research methodology and approaches used in the course of the research during including data collection, analyses and presentation of results.

Chapter 5 presents the results and discussion of the hydrogeological characterization of the eThekwini District Municipality. This includes water balance components of the study area, groundwater level and depth to groundwater contour maps and hydrochemistry.

Chapter 6 presents the results on treated wastewater generated within the eThekwini District Municipality and potential aquifers identified for MAR in the eThekwini District Municipality.

Chapter 7 presents the main conclusions and recommendations emanating from the research. It summarizes the results of the project, including some recommendation for future work.

Finally, all references used in the preparation of the dissertation are listed under the list of references. The appendix sections provides tables of the water budget components, maps, geological logs, water quality and treated wastewater data used during the course of the study.

CHAPTER TWO

DESCRIPTION OF THE STUDY AREA

2.1 Location of the study area

The study area, the greater eThekwini District Municipality, is located the KwaZulu-Natal Province east of South Africa (Figure 2.1). The eThekwini District Municipality is bordered by the iLembe Municipality to the north, uGu Municipality to the south and uMgungundlovu Municipality to the west. The eThekwini District Municipality spans an area of about 2555 km^2, with a population of about 3.8 million people. This represents 7% of the total South African population, making the eThekwini District Municipality the second-most populated area in the country (IDP, 2019).

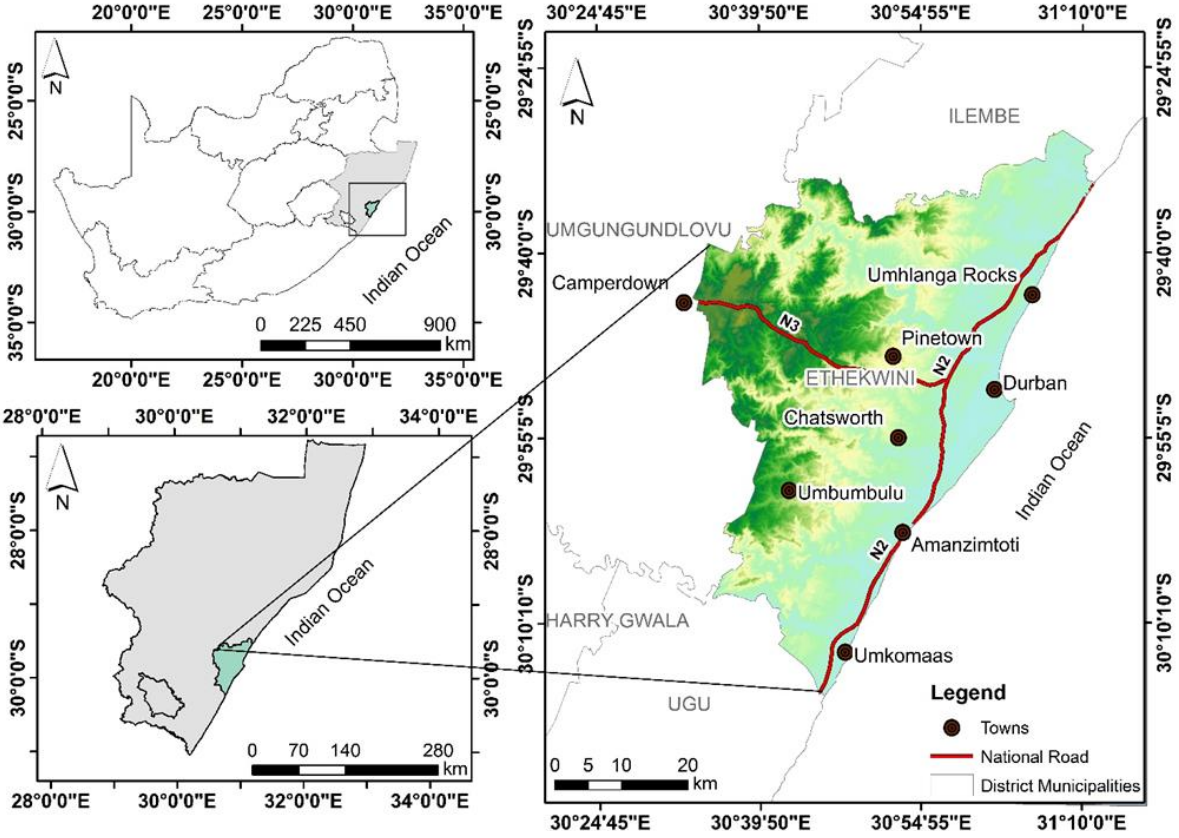


Figure 2.1. Location map showing the eThekwini District Municipality

2.2 Climate

The greater eThekwini District Municipality region is charcaterised by a sub-tropical climate where summer is humid and warm while winter is dry and cold. The mean January temperature is 24°C and the mean July temperature is 13°C (South African Weather Service, SAWS, 2019). Rainfall gradually decreases from about 1140 mm/a near the coast to 800 mm/a in the interior (Figure 2.2).

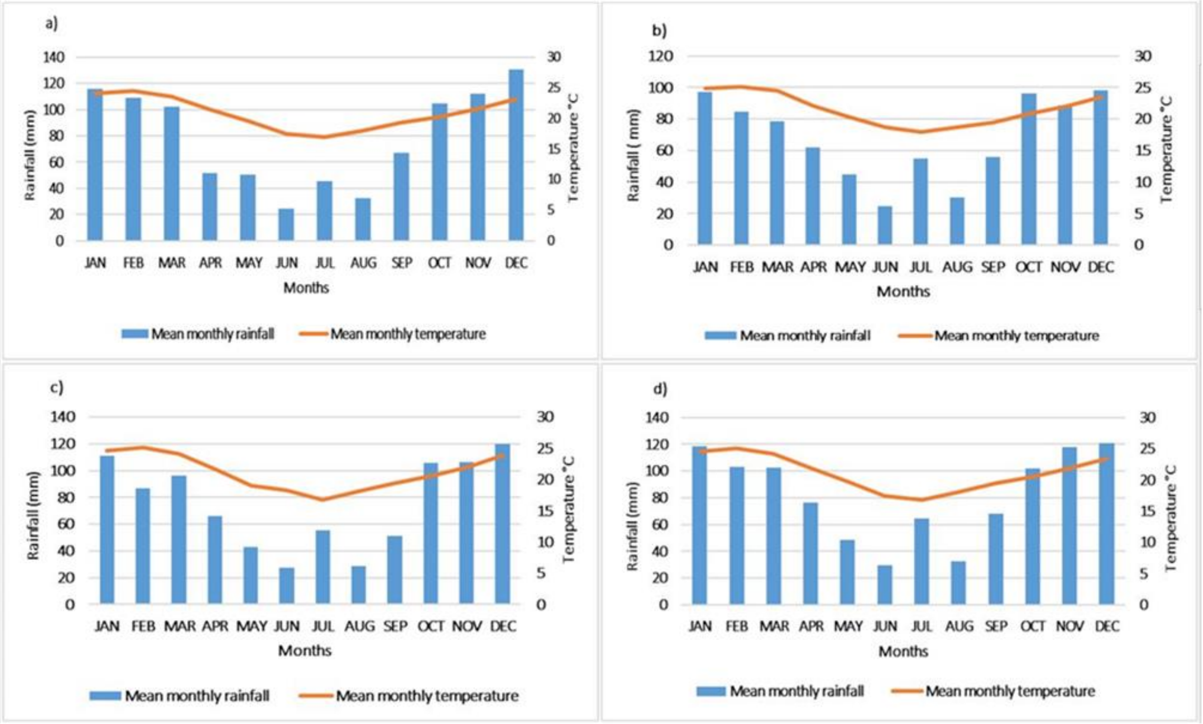


Figure 2.2. Average monthly rainfall and temperature for a) Mount Edgecombe, b) Virginia, c) Botanical gardens and d) Durban South Weather stations located within the study area (data provided by SAWS, 2019).

2.3 Topography and drainage

The topography of the greater eThekwini District Municipality is diverse, including steep, rugged escarpments caused by weathering and faulting in the west. However, the east constitute a narrow and flat coastal plain that hosts relatively recent tertiary deposits (Bell and Maud, 2000). According to King and Maud (1964), the valley sides are steep, where the rivers have cut gorges. Therefore, topography can influence the groundwater such as steep slopes increasing run-off while decreasing potential recharge. According to Bell and Maud (2000), the depth to water table is greater in elevated regions compared to the low-lying areas. Figure 2.3 shows the Digital Elevation Model (DEM) and drainage of the study area. The rivers that drain across the eThekwini District Municipality are the uMgeni, uMlazi and uMkomazi Rivers, with the first two being the main ones (King and Maud, 1964). The study area covers approximately 14 quaternary catchments and includes the Mvoti to Umzimkhulu Water Management Area (WMA 11).

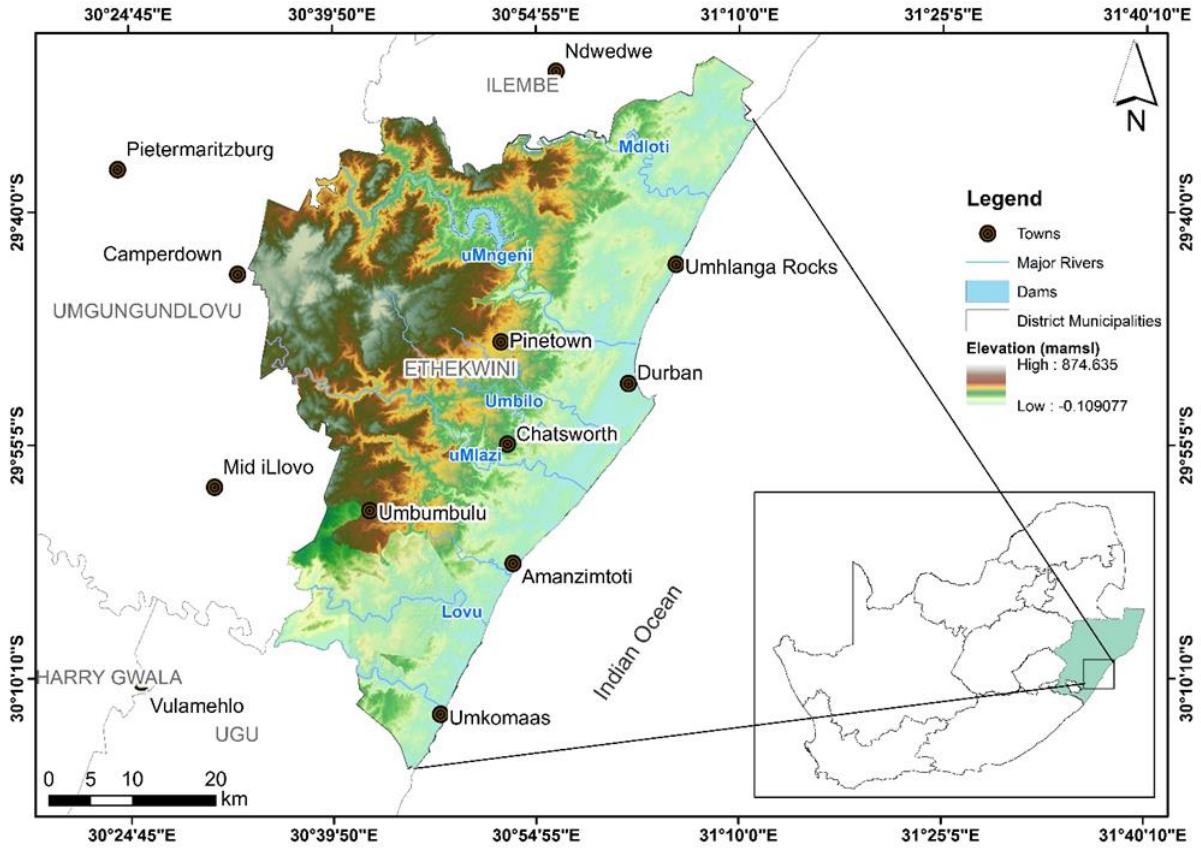


Figure 2.3. Digital Elevation Model (DEM) and drainage map of the eThekwini District Municipality (from eThekwini Water and Sanitation, 2019)

2.4 Land use and land cover

The use of land in the greater eThekwini District Municipality cover a wide spectrum, ranging from urban residential to traditional settlements, informal settlement, industrial (light and heavy industry), mining (quarries) and infrastructure (which includes the King Shaka International Airport) to agriculture (predominantly sugarcane), forestry and conservation areas. A large area of the municipality is also designated to include the Metropolitan open space system. About 45% of the municipality is rural with pockets of dense settlement, while the remainder of 30% is peri-urban and 25% urban (dominated by residential, commercial/office and industrial land uses) (IDP, 2018; 2019). Approximately 10% of the rural areas comprise of privately owned commercial farms whereas about 90% of the rural area are defined by geospatial features such as hilly, rugged terrain; dispersed settlement patterns in traditional dwellings; and communal land holdings under the Ingonyama Trust (IDP, 2019) (Figure 2.4).

The natural vegetation of the greater eThekwini district is evergreen (Ficus natalensis, Calodendrum, Celtis, Erythrina caffra and E. lysistemon), tropical forest, consisting of widely spaced trees (Golder, 2018).

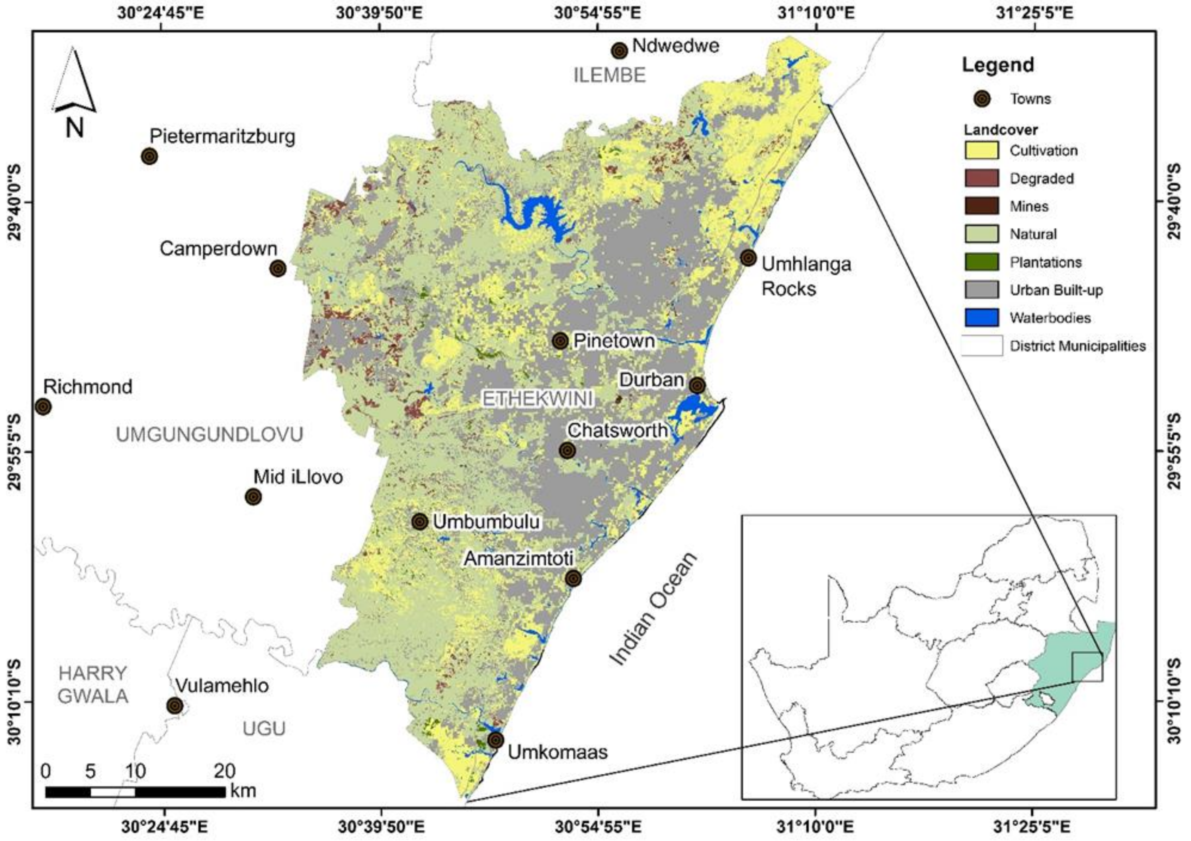


Figure 2.4. Land use distribution of the eThekwini District (data sourced from eThekwini Water and Sanitation, 2019)

2.5 Soils

The different soil types observed exhibit a close association with the underlying geology where the sandstones and granite-gneisses tend to support more free-draining arenosols, while lithosols are derived from shale-mudstones, tillite and dolerite (Bell and Maud, 2000). The eThekwini District Municipality has a very diverse distribution of soils (Figure 2.5). The northern region of the greater eThekwini District Municipality region has soil textures that include sandy loam, clay loam, loam, sandy clay loam and silty loam. The southern region has silty loam, loam, sandy loam and minor clay loam. However, the western region do not show any occurrence of the clay loam, but has large occurrences of sandy loam, loam and silty clay loam soil textures. Finally, the central region is dominated by sandy loam, silty clay loam and silty loam soil textures.

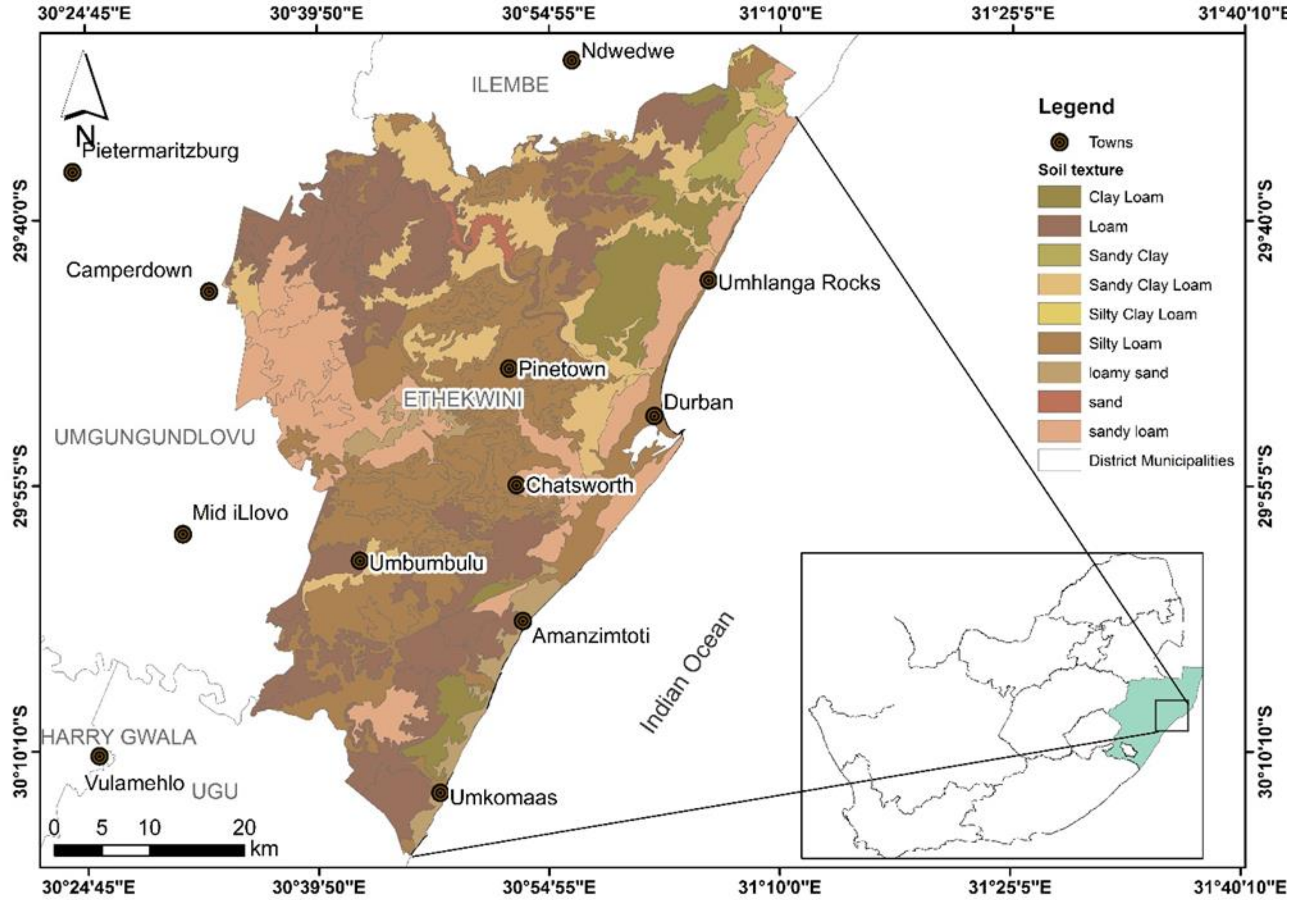


Figure 2.5. Soil map for the eThekwini Municipality

2.6 Geological Settings

2.6.1 Regional Geology

The geological history of the greater eThekwini District Municipality dates back to ~1200 million years (Bell and Maud, 2000). In the west there is the occurrence of granite-gneiss representing the Namaqua-Natal Metamorphic rocks. This granite-gneiss may be presumed to be the basement rocks of the whole of the study area (King and Maud, 1964). The Natal Group unconformably overlies the granite-gneisses, which in turn is overlain by the Karoo Supergroup (Figure 2.6). Structurally, the area consists of fault-bounded blocks inclined towards the east, and exhibiting an average dip of approximately 12° (Bell and Maud, 2000). All other younger geological formations within the greater eThekwini District Municipality formed in the Quaternary Era. These are the Bluff (of consolidated marine and dune rock), the Berea Red Sand and boulder-bed, unconsolidated sand, grit and clay around the harbour and city area, with alluvium along the major river-courses (King and Maud, 1964).

2.6.2 Local geology of the greater eThekwini District Municipality

Granitic Basement rocks of the Natal Metamorphic Province

The granitic basement rocks occur in the far northwest and southwest of the study area. It is typically massive and crystalline, displaying marked foliation (Cornell *et al.*, 2006). The gneisses are composed of quartz, microclineand albite with varying amounts of hornblende, biotite and some muscovite (King and Maud, 1964). The older gneisses of the Mzumbe terrane referred as the Maphumulo Group are subdivided into the Quha and Ndonyane Formations. The Quha Formation comprise of a grey-biotite-hornblende-quartz-plagioclase mineral assemblage, which may include garnet gneisses and migmatite of broadly intermediate composition with interlayered amphibolite (and/or quartz) (Cornell *et al.*, 2006). The Ndonyane Formation constitutes leucocratic gneisses bearing quartz-microcline assemblages (Cornell *et al.*, 1996). Small dyke-like bodies of younger reddish granite have intruded the gneiss. This granite is non-foliated and consists mainly of a deep-red microcline (in which much hematite lies along the crystal planes) with some quartz (King and Maud, 1964).

Natal Group

The Ordovician-Silurian Natal Group lay unconformably above the Archean granite-gneisses of the Natal Metamorphic Province (NMP), but the contact is visible in the far north western part of the study area. The Natal Group consists of reddish grey conglomerates, sandstones, siltstones and mud rocks (Marshall, 2006). Over the central portion of the map, the Natal Group extends from the Mgeni valley, past New Germany, Westville and Pinetown to the southern suburbs of Durban. The outcrops of the Natal Group in the greater Durban area are fault bounded and are frequently jointed which gives rise to a blocky appearance (Bell and Maud, 2000). The eastern margin of the main sandstone is rendered irregular by several strike- slip faults that trend northeast (King and Maud, 1964). The Natal Group is subdivided into a lower Durban Formation and an upper Mariannhill Formation. The Durban Formation is characterised by an upward-fining sequence. This sequence consists of conglomerate at the base followed by arkosic sandstones and ends with quartz arenite (Marshall, 2002). The Durban Formation includes the Ulundi, Eshowe, Kranskloof, Situndu and Dassenhoek Members (Marshall and Van Brunn, 1999). The Ulundi Member is dominated by monomict boulder to pebble conglomerate with minor sandstone and mudrock interbeds (Marshall, 2006). Laying above the Ulundi Member is the unit termed Eshowe Member, comprising interbedds of mudrock and siltstone. The Kranskloof Member is composed dominantly of silicified quartz arenite and subarkose and minor interbedded mudrocks. Overlying the Situndu Member is the Kranskloof Member, which consists of coarse arkosic pebbly sandstone with mudrock interbeds attaining a total thickness of about 84 m (Marshall, 2006). The Dassenhoek Member represents the youngest unit of the Durban Formation, resting conformably on the Situndu Member. The Dassenhoek Member is observed north of Verulam and Wartburg and is comprised of silicified quartz arenite, which attain a thickness of 42 m (Marshall, 2006).

The Mariannhill Formation occurs throughout the Natal Group depositional basin and includes three members: the Tulini, Newspaper and Westville Members. The Tulini Member is visible in the central and northern portion of the basin. The Tulini Member consists of matrix and clast supported conglomerate with interbedded coarse grained to very-coarse grained, subarkosic to arkosic sandstone and granite clast supported conglomerates with minor micaceous shale (Marshall, 2002). Conformably overlying the Tulini Member is the Newspaper Member comprising feldspathic sandstone and subordinate granite clast conglomerate, siltstone and mudrock (Marshall, 2002). According to Bell and Lindsay (1999), the Newspaper Member is the thickest member of the Natal Group. The Westville Member occurs sporadically throughout the basin and forms the youngest unit of the Mariannhill Formation, resting conformably on the Newspaper Member and is overlain by the Dwyka Group. This Member comprises of matrix-supported polymict conglomerate with clasts of quartz, chert and quartzite (Marshall, 2006).

Karoo Supergroup Rocks

The Karoo Supergroup is world famous for its terrestrial vertebrate fossils, distinctive plant assemblages, thick glacial deposits, extensive flood basalts and associated dolerite dykes and sills (Johnson *et al*., 2006). The lower Karoo Supergroup rocks that are found within the eThekwini District are subdivided into the Dwyka and Ecca Groups.

Dwyka Group

The Dwyka Group lies unconformable on the Natal Group and consists wholly of former glacial deposits, tillite with a few occurrences of silicified varved shale and lenses of sandstone (King and Maud, 1964). This rock-type occurrences extensively in the northern half of the study area and generally are bounded by northeast trending faults (King and Maud, 1964). The largest area of the Dwyka Group lies southwest of the study area. Its thickness in the study area have been reported to vary between 250 m and 400 m (King and Maud, 1996).

Ecca Group

The Permian Ecca Group comprises of a total of 16 Formations that reflect the lateral Facies variation. In the case of the Durban area, the Ecca Group comprises the Pietermaritzburg and Vryheid Formations (Figure 2.6). The Pietermaritzburg Formation shale is the lowermost unit of the Ecca Group. It rests conformably on the Dwyka Group, where a sharp contact can be seen. The Ecca Group comprises of dark silty mudrock, which coarsen towards the top of the sequence with the occurrence of bioturbated, deformed sandy and silty beds (Johnson et al., 2006). The Vryheid Formation conformably overlies the Pietermaritzburg Formation shale (Botha *et al*., 1998). This Formation has been subdivided into a lower sandstone, coal zone and upper sandstone (Johnson et al., 2006). The Vryheid Formation consists of altered bioturbated immature sand, dark siltstone and mudstone deposited in anoxic water occurring in moderate depth (Botha *et al*., 1998). The coal seams that are hosted in this formation originate as peat swamps that developed on broad abandoned alluvial plains rather than in interfluves (Van Vuuren, 1981).

Karoo Dolerites

Dolerite intrusions of Stormberg age cut all the Pre-Cretaceous rock types of the Durban area (King and Maud, 1964). The dolerite sills are rare in the basement rocks and occasionally occur in the Natal Group, but are almost entirely absent in the Dwyka Group. However, the dolerite sills are common in the shales of the Pietermaritzburg Formation and abundant in the Vryheid Formation. The sills vary in thickness from a few centimetres to tens of meters in the study area (King and Maud, 1964). The dolerite dyke intrusions represent the last phase of the Karoo igneous activity and their origin is different to that of the sill intrusions (DWAF, 1995). They are regarded as being intruded into the Formation in which tensional stresses existed.

Maputaland Group

The Quaternary deposits are the youngest in the study area (Table 2.1). They are characterised by the Umkwelane, Kosi Bay, Isipingo, Sibayi and Berea Formations (Botha *et al*., 2003). These Neogene and Pleistocene Aeolian sands are now characterised as the weathering products of the Kosi Bay Formations (Botha *et al*., 2003; Botha and Porat, 2007; Porat and Botha, 2008).

Bluff Sandstone Formation

King and Maud (1964) describe the series of Late Pleistocene calcareous sands and sandstone of mainly aeolian origin exposed at intervals and at low levels along the seaward side of the Durban Bluff. This Formation is also known as “Bluff sandstone” or “Bluff Beds”. Some beds and lenses are particularly rich in shell debris. All stages of consolidation are present, from loose and incoherent sand to hard, cemented sandstone. Most of the material is typical “beach rock” or “dune rock” formed by the redistribution of calcite from marine organisms in the original sand (King and Maud, 1964).

The Bluff Sandstone Formation is dominated quartz that are medium to coarse grain and subangular to round. Coarse bands usually have much fresh feldspar in worn crystals which have been derived from the Archean gneiss, other inclusions are derived from the Natal Group, Dwyka Group and Karoo dolerite as well as hornfels shale (King and Maud, 1964). Within the Formation there are several layers or lenses up to 3m in thickness of conglomerate, including a basal conglomerate layer, which represent old beach levels. Weathering of the Bluff Formation resulted in the unit termed the Berea Formation.

Berea Formation

The sandy “Red Beds” of the Berea Formation, which represents a late Pleistocene in-situ weathering of coastal dune deposits, reach a thickness in places of at least 60 to 80m (King and Maud, 1964). The Formation seldom contains feldspar. The quartz grains, which are sub angular to rounded, range in diameter from 0.05 to 0.8mm. The red colour is derived from the coating of quartz grains by goethite or other hydrated iron oxides (King and Maud, 1964). The Formation is characterised by a basal boulder bed of marine origin which rests on a series of submarine-cut benches on the underlying bedrock. The boulder-bed is very distinctive. The boulders are well rounded, percussion marked (King and Maud, 1964), and usually between 7.5cm and 25cm in diameter (King and Maud, 1964).

Quaternary alluvial and estuarine deposits

The shoreline is largely rocky but between the outcrops, bays of medium- to coarse-grained white and cream-coloured beach sands are common (DWAF, 1995). The sands are rich in broken shell debris and contain quartz, feldspar, micas, and amphiboles, derived mainly from the erosion of the weathered bedrock Formations in the interior that have been transported to and along the coast by the rivers and sea currents (DWAF, 1995).

Table 2.1. The lithostratigraphic succession of the greater Durban Metropolitan region (modified from Johnson *et al*., 2006).

Lithostratigraphic unit		Era	Formation	Lithology
Maputaland Group		Quaternary	Harbour Beds	Alluvium, beach sand, alluvium grit, sand, clay, mud
			Berea Red Sands	Red sand, boulders
			Bluff beds	Consolidated sand, grit, conglomerate
		Cretaceous system	Upper division	Consolidated sand, grit, conglomerate
Karoo Supergroup	Ecca Group	Permian	Vryheid Formation	Feldspathic sandstone, grit, shale
			Pietermaritzburg Formation	Shale
	Dwyka Group	Late Carboniferous to Early Permian	Elandsvlei	Tillite, varved shale, sandstone
Natal Group		Cambrian to Ordovician	Mariannhill	Conglomerate and Sandstone
			Durban	Flat/cross bedded, coarse grained arkosic sandstone and granulestone
			Ndonyane	Quartzofeldspathic gneiss

Namaqua Natal Province	Namibian	Quha	Biotite gniess, biotite-hornblende gniess and amphibolite

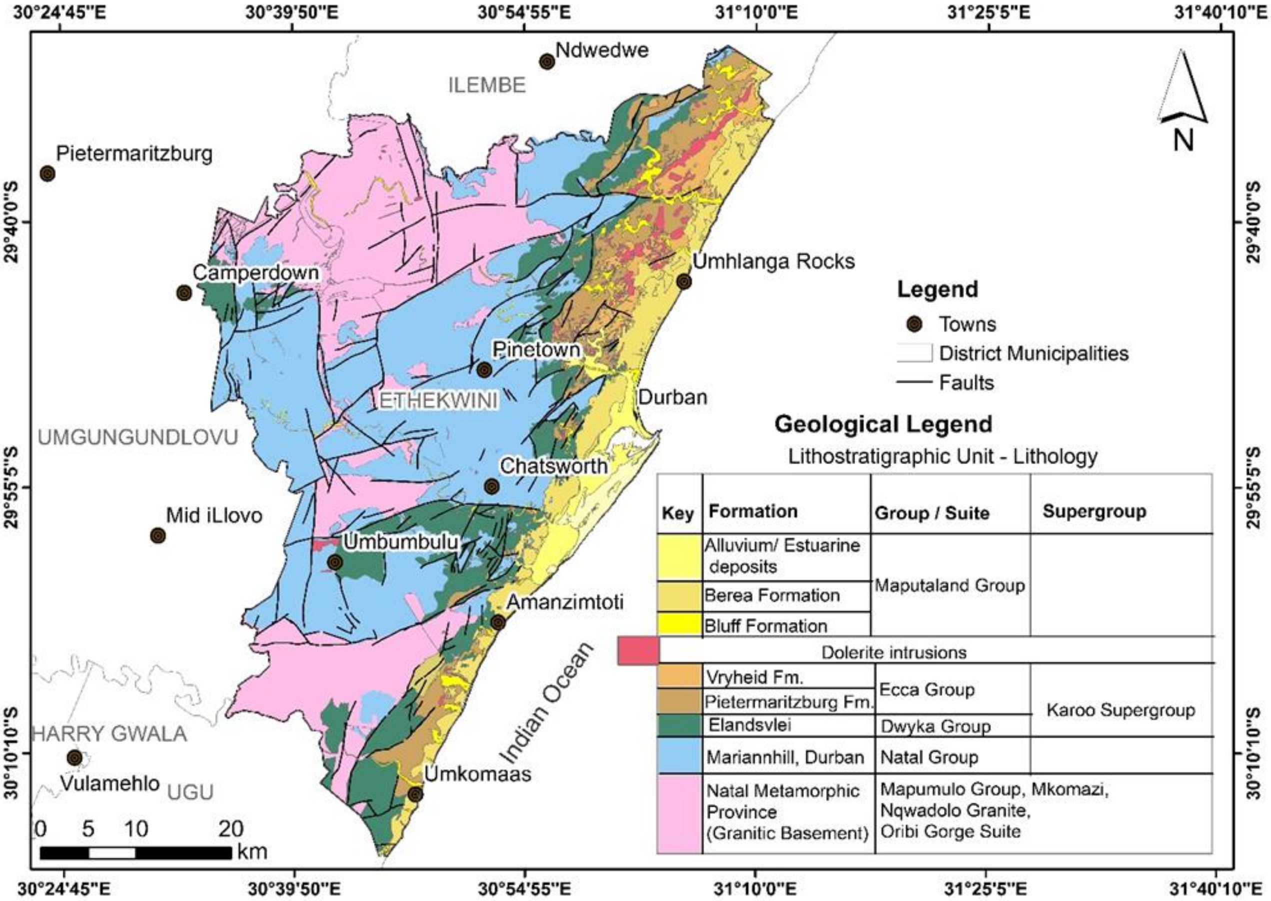


Figure 2.6. Simplified geological map of the eThekwini District (modified from the Council for Geoscience, 2016)

2.7 General Hydrogeological Setting

2.7.1 Aquifer types

Six hydrogeologically relevant lithologies occur in the greater eThekwini region (Table 2.1andFigure 2.7). In order of their importance, these are sand dunes, alluvial and estuarine deposits, sandstone, dolerite, tillite, granite-gneiss and mudstone-shale. These hydrostratigraphic units constitute intergranular, intergranular and fractured or fractured aquifer modes of groundwater occurrence, representing either primary or secondary aquifers.

2.7.2 Intergranular aquifers

These aquifers principally occur along the coastline and major rivers and have textures ranging from sandy to silty clays (King, 2002). It is interstratified and the texture varies both vertically and horizontally (Bell and Maud, 2000; DWA, 2012). Intergranular aquifers have a high degree of permeability and typically are recharged from rainfall and streams (DWA, 2014). Groundwater levels are shallow, ranging from 2 m to 7 m, and the borehole yields can be in excess of 50 l/s, average hydraulic conductivity of 5 m^2/day, average specific yield of 0.18 and electrical conductivities (EC) averaging about 100 mS/m (King, 2002). The groundwater quality is affected by the depositional environment, as well as the proximity to the coast and industrial activities (DWA, 2014). In the immediate hinterland of the coastal area, the sandy Berea Formation occurs as a weathered coastal dune (i.e. weathering product of the Bluff Formation) (Bell and Maud, 2000). The Berea Red sands are not considered true aquifers as groundwater is only intercepted at the base along the contact with the underlying bedrock (DWA, 2014). The Maputaland Formation can reach up to 100 m in thickness (Bell and Maud, 2000). Groundwater derived from alluvial aquifers usually takes on chemical signature of the associated surface water body that drain the area (King, 2002).

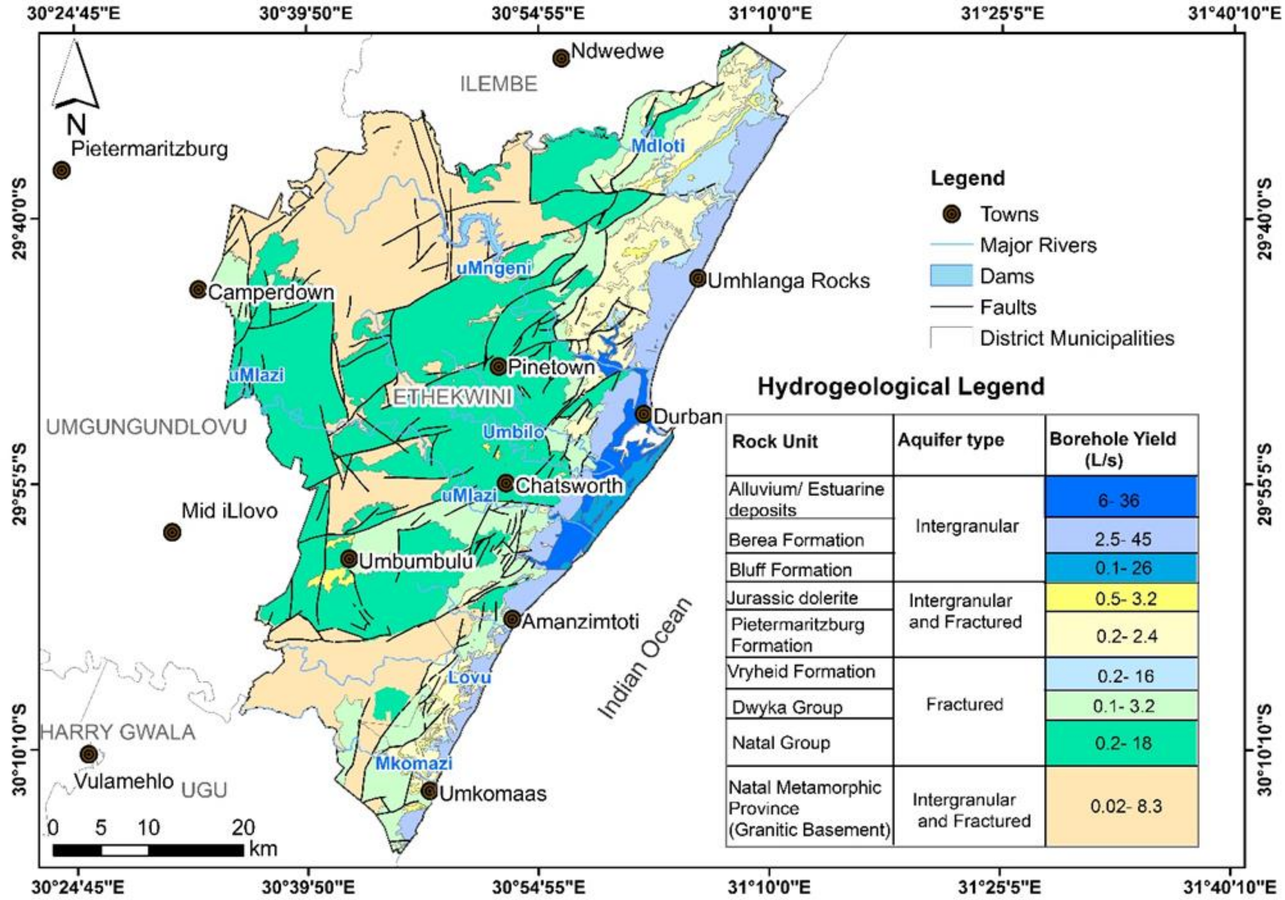
2.7.3 Intergranular and fractured aquifers

The sedimentary deposits of the Karoo Supergroup (mudstone/shale) and the metamorphic rocks of the Namaqua Natal Metamorphic Province give rise to intergranular and fractured aquifers (DWA, 2014). The groundwater in these rock units is observed in the interstices of the saturated weathered zone, as well as in joints and fractures in the hard rocks (King, 2002). Median borehole yields vary between 0.5 and 2 l/s in the Karoo rocks and between 0.1 and 0.5 l/s in the rocks of the Natal Metamorphic Province (King, 2002) (Figure 2.7). Hydraulic conductivities in the Karoo rocks range between 0.05 and 0.5 m/day and storatvity vary between 0.0001 and 0.001 (King, 2002). In areas of more massive granites and gneiss (massive and coarsely crystalline rocks), weathered rocks can provide good groundwater reservoirs (Bell and Maud, 2000).

2.7.4 Fractured aquifers

Fractured aquifers in the study area comprise of the sandstone of the Natal Group and diamictite of the Dwyka Group (Figure 2.7). The Natal Group varies in thickness between 200 and 400 m. The texture of the Natal Group ranges from fine- to medium-grained, exhibiting moderately wide to narrow jointing (Bell and Lindsay, 1999). The Dwyka Group also exhibit variable thickness from 250 to 400 m and is composed of silicified varved shale and thin sandstone lenses, which occur within the main body of the tillite (Bell and Maud, 2000). These aquifers are characterised by faults, fractures, dykes and lithological contacts. Shallow weathering occurs at the surface and the fractures are saturated with groundwater (King, 2002). The dimensions of the fractures are highly variable and therefore influences the borehole yield which ranges from 0.5-2.0 l/s (DWA, 2014). Hydraulic conductivities in the fractured aquifers range between 0.4 and 7.7 m/day while storatvity values between 0.0005 and 0.005 can be expected (King, 2002). It should be noted that the Dwyka Group is the poorest secondary groundwater aquifer in the greater Durban area (Bell and Maud, 2000). Dolerite intrusions, notably sills are common compared to dykes in the study area. These sills vary in thickness from a few centimetres to about 10 meters (King and Maud, 1964). Dolerite dykes, which rarely exceed about 6 m in width, often represent barriers to the flow of groundwater and their contact zones serve as important targets when siting boreholes (Bell and Maud, 2000; DWA, 2014).

The estimated rate of groundwater recharge in the study area ranges from 3% to 7% in mean annual precipitation (MAP) (DWAF, 1995). The sandstone of the Natal Group represents the most productive groundwater-bearing lithology in secondary aquifers, which are followed by mudstone/shale lithologies of the Karoo Supergroup, the granite/gneiss lithologies of the Natal Structural and Metamorphic Province and the diamictite of the Dwyka Tillite Formation (DWAF, 1995).



Rock Unit	Aquifer type	Borehole Yield (L/s)
Alluvium/ Estuarine deposits	Intergranular	6- 36
Berea Formation		2.5- 45
Bluff Formation		0.1- 26
Jurassic dolerite	Intergranular and Fractured	0.5- 3.2
Pietermaritzburg Formation		0.2- 2.4
Vryheid Formation	Fractured	0.2- 16
Dwyka Group		0.1- 3.2
Natal Group		0.2- 18
Natal Metamorphic Province (Granitic Basement)	Intergranular and Fractured	0.02- 8.3

Figure 2.7. Simplified hydrogeological map of the eThekwini District (modified from the DWAF, 1998)

2.8 Water demand and supply in the greater eThekwini District Municipality

According to IDP (2019), the third largest metropolitan administration in South Africa is the greater eThekwini District Municipality. The Metropolitan district is the largest in the KwaZulu-Natal Province with a population of 3.09 million in 2001, which grew at an average annual rate of 1.13% per annum to reach 3.44 million in 2011 (Statistics South Africa, 2011). The short term demographic forecast in (Table 2.2indicates that the population of eThekwini District Municipality increased by 175 000 between 2016 and 2020 and the population would be about 3.85 million (IDP, 2019).

Table 2.2. Population projection for the eThekwini District Municipality (IDP, 2019)

	2016	2017	2018	2019	2020	2030
Population Total	3.677.575	3.723.435	3.767.939	3.811.167	3.853.278	~ 4.400.000

Two thirds of the population living in the eThekwini Municipality region have water in their homes (Statistics South Africa, 2019). The source of water for the Municipality originates primarily from regional and local water supply schemes. These schemes acquire majority (90.5%) of its water from Umgeni Water (UW), while a small portion is being supplied from water treatment works owned and operated by eThekwini Water and Sanitation (EWS). The UW water system that supplies eThekwini Municipality has three schemes, which are Mgeni supply system, north coast supply system and south coast supply system (IDP, 2019). The Mgeni supply system comprises of the Spring Grove, Midmar, Albert Falls, Nagle and Inanda dams (including Mearns Weir). The North coast supply system comprises of the Hazelmere Dam, Northern Aqueduct and south coast system comprising of the Nungwane Dam, couth coast Pipeline (SCP) and the south coast Augmentation Pipeline (SCA) (IDP, 2019). Water supplies also supporting the eThekwni Municipality include boreholes (1.5%), spring (0.3%), rain water tank (0.3%), water vendors (1.5%), water tankers (2.1%) and other 2.8% (Statistics South Africa, 2019).

CHAPTER THREE

LITERATURE REVIEW

3.1 Review of managed aquifer recharge

Managed Aquifer Recharge (MAR), also known as groundwater banking, can be undertaken using two broad approaches. These are the non-infrastructure based and infrastructure based methods (Arshad, 2015). The infrastructure based MAR require transfer of water from surface sources to aquifers. They are primarily based on physical infrastructure for recharge, storage and recovery of water, such as infiltration basins or injection wells method (Arshad, 2015). Groundwater recharge with reclaimed water, the focus of this dissertation, is an approach which involves identifying potential aquifers that can be used for MAR using treated wastewater (Bouwer, 1978; Todd, 1980; Asano, 1985). The main functions of MAR are:

i. To reduce, stop, or even reverse the decline of groundwater levels in order to control land subsidence or to reduce the cost of groundwater pumping,
ii. To protect underground freshwater in coastal aquifers against saltwater intrusion and to store surface water. This includes flood or other surplus water such as reclaimed (treated) wastewater for future use.

This literature review provides a review of the basic understanding on investigating potential aquifer for MAR using treated wastewater.

3.1.1 Artificial aquifer recharge techniques

There are two primary types of artificial groundwater recharge methods. These are surface spreading and direct injection. These two methods are illustrated in Figure 3.1 and a schematic for different types of management of aquifer recharge is shown in Figure 3.2Direct injection wells may also be used as a dual-purpose aquifer storage and recovery (ASR) well for both recharging and recovering stored water (Pyne, 1995). The recharge method depend on the aquifer type and depth, as well as the aquifer characteristics, which impact the ability to recharge and later recover water in the storage zone (USEPA, 2012).

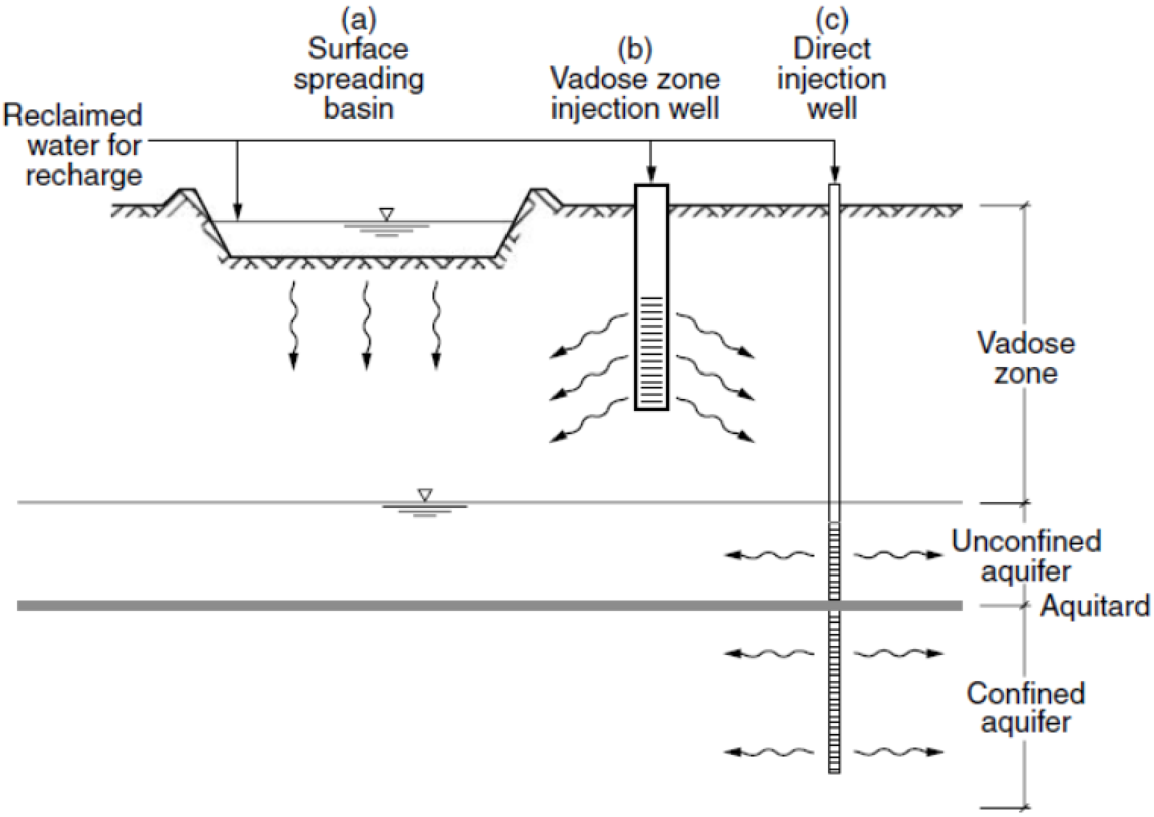


Figure 3.1. Principal methods for groundwater recharge: (a) surface spreading using recharge basins, (b) injection wells in vadose zone, and (c) direct injection wells into an aquifer (Source: adapted from USEPA, 2004)

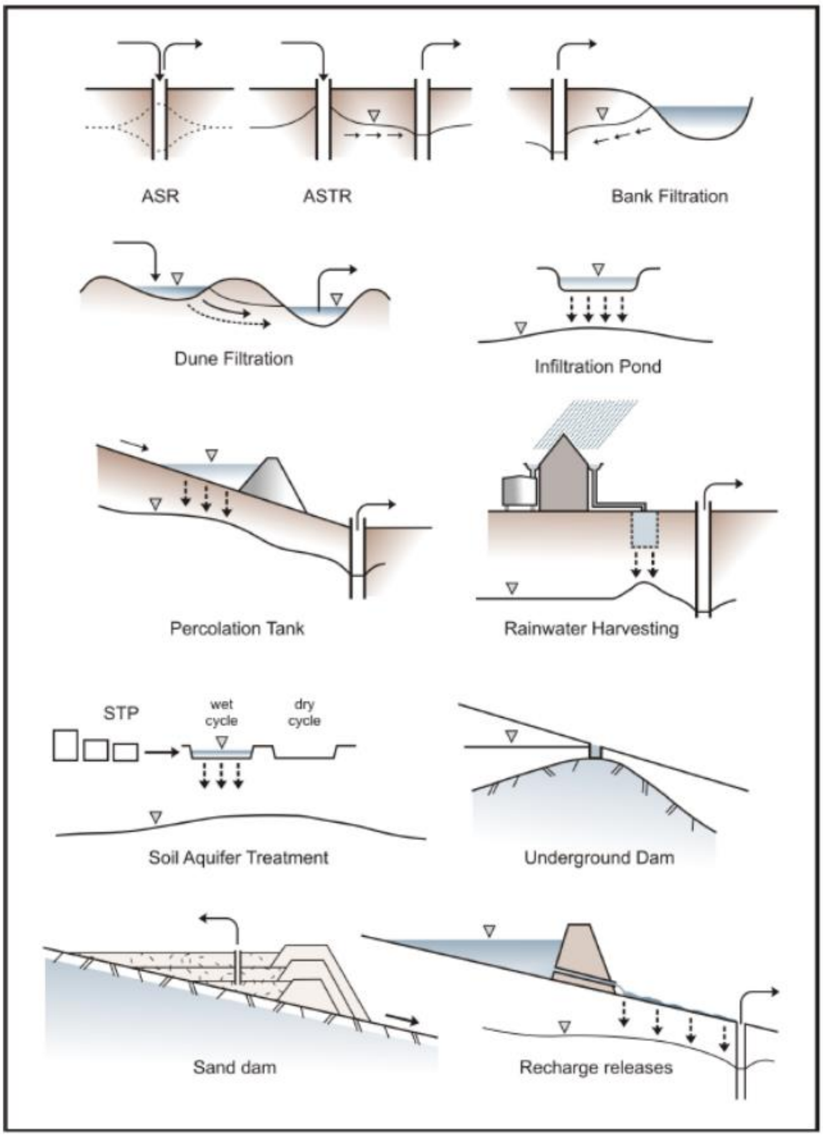


Figure 3.2. Types of managed aquifer recharge (source from Dillion, 2005): ASR-Aquifer Storage and Recovery; ASTR- Aquifer Storage Transfer and Recovery; STP-Sewage Treatment Plant

Surface Spreading Basins: These systems are probably the most used technique throughout the world because of their high loading rates with relatively low maintenance requirements (Todd, 1980; Pérez-Paricio, 1998). Construction requirements are minimal, although land availability and costs may be high (Pérez-Paricio, 1998). These basins are suitable for phreatic aquifers with low permeable layers. The reclaimed water percolates into the soil that consists of layers of loam, sand, gravel, silt and clay. As the reclaimed water filters through the layers of soil, it is exposed to further physical, biological and chemical purification through a process called Soil Aquifer Treatment (SAT). This water eventually becomes part of the groundwater supply. The three main engineering factors that affect the performance of surface spreading systems are reclaimed water pre-treatment, site characteristics and operating conditions (Fox, 2002).

Injection wells: These involve injection into the zone of saturation. Each injection method has its unique applicability and requirements, which vary with location, quantity and quality of source water, as well as hydrogeology of the vadose zone and target aquifers (USEPA, 2012). While direct injection wells are more expensive than vadose zone wells, the control of where the water is injected minimizes the risks associated with water loss, but have a limited life and must be replaced periodically (USEPA, 2012). Direct injection wells can also be cleaned and redeveloped, which reduces fouling and lengthens the life of the wells. Direct injection wells can be maintained for a longer life and allow water recharge directly and quickly into the targeted aquifer.

Other Methods used for MAR

Other methods that have been used for groundwater recharge internationally are; (i) aquifer storage and recovery, (ii) aquifer storage transfer and recovery, (iii) bank filtration, (iv) infiltration basins, (v) percolation tanks or recharge weirs, (vi) sand dams and (vii) underground dams and recharge releases. Each of these methods are described below:

Aquifer Storage and Recovery (ASR) may be defined as the storage of water in a suitable aquifer through a well during times when water is available, and the recovery of water from the same well during times when it is scarce (Pyne, 1995). This is suitable in both confined and unconfined aquifers where water treatment is usually high. However, sediment load and debris must be removed to minimise borehole clogging (DWA, 2010). As a recent technological development, ASR resolves the inherent operational drawbacks of single-purpose injection wells by equipping each well with a pump and operating it in a dual-purpose mode for both recharge and recovery (Pyne, 1995). The pump used for recovery of the stored water is also used periodically to redevelop the well, thereby maintaining its capacity (Pyne, 1995). In the case of recovery of stored water, no additional facilities are required. The ASR approach to aquifer recharge overcomes the plugging associated with most injection wells, hydraulic limitations of many surface recharge sites, and large land area requirements of these sites (Pyne, 1995). Another advantage of the ASR systems is that they can be used to store water in non-portable aquifers such as brackish aquifers (Pyne, 1995; Dillon *et al.*, 2006). The method is optimal in areas where groundwater exhibits a shallow hydraulic gradient such as the Kharkams in Namaqualand (DWA, 2010).

The water quality required for recharge in ASR must rather be good. Since 1994, all operational ASR systems only store water that meets potable standards. However, it is important to distinguish between regulatory requirements for potable water quality and technical requirements for ASR well recharge (Pyne, 1995). While meeting regulatory potable standards is probably suitable for ASR recharge, experience suggests that in some cases additional treatment may be necessary, such as the reduction of total suspended solids or pH adjustment (Pyne, 1995). Potable water standards provide a reasonable reference point against which to evaluate recharge and recovered water quality from ASR wells (Pyne, 1995).

The use of ASR wells also presents several unique problems with respect to water quality. The first issue is the travel path which requires that the first water recovered has the shortest travel time and vice-versa (Pyne, 1995). Therefore, water quality transformations can vary significantly between the time recovery starts and ends. The effect can be especially problematic for disinfection by-products as a chlorine residual is often required to prevent biological clogging during injection (Pyne, 1995). Disinfection by-product (DBP) formation can continue in the aquifer near the well, and if the water is not stored for a long time, the DBPs will be present in the initial water recovered (Pyne, 1995; Dillon *et al*., 2006). The use of ASR wells with reclaimed water has been limited primarily to recovery for irrigation. As a result, serious concerns over water quality variation during aquifer storage have not been expressed (Pyne, 1995; Dillon *et al*., 2006). Due to the flow paths associated with ASR systems, their use for indirect potable reuse is limited to the injection of very high quality water such as treated water (Pyne, 1995). Many water quality changes observed in ASR wells are associated with geochemical interactions from the introduction of aerated water into an anoxic aquifer. To avoid problems with these geochemical interactions, a large quantity of water should be injected initially to create a buffer zone where geochemical interactions will not affect the quality of recovered water (Pyne, 1995).

Aquifer storage transfer and recovery (ASTR): This involves the injection of water into a well for storage and recovery from a different well, generally to provide additional water treatment (Dillon, 2005). This is suitable in both confined and unconfined aquifers (DWA, 2010). It provides additional water treatment in the aquifer by extending the residence time in the aquifer beyond that of a single well, such as the Parafield Gardens, South Africa (Dillion et al., 2009).

Bank filtration: Bank filtration (BF) is the process of extraction of groundwater from a borehole, well or caisson near or under a river or lake to include infiltration from the surface water body. This process consistently improves the quality of recovered water (Dillion, 2005). The term river “bank” filtration is often replaced by the term river “bed” filtration to describe it more specifically (Milczarek *et al*., 2010) or not used at all if the abstraction scheme (e.g. drain pipe) is embedded in the riverbed. As bank filtration at most sites was and is a combination of bank and bed filtration, the term BF should be seen as a general term. The BF could be further subdivided into river (RBF), lake (LBF) and canal (CBF) bank (and/or bed) filtration, with RBF currently being the most commonly practised method (Dillion *et al*., 2019).

Dune filtration: This is the infiltration of water from ponds constructed in dunes and extraction from wells or ponds at lower elevation for water quality improvement (Dillion, 2005). The source water should be reasonably clear to avoid clogging which results to minimal required pre-treatment (DWA, 2010). Dune infiltration is effective for the removal of sediments and microorganisms (DWA, 2010) (e.g. Sedgefield and Amsterdam, The Netherlands).

Infiltration basins: An infiltration basin is essentially a shallow impoundment, generally with a deliberately designed flood event overflow (to prevent uncontrolled over-topping, which could cause erosion and bank failure). This basin is designed to infiltrate water through the soil into the aquifer (GWP Consultants LLP, 2010). These basins are often constructed on sand or gravel aquifers. Infiltration basins are designed to manage storm water runoff and prevent flooding; however, their use in artificial recharge of aquifers is also significant (DWA, 2010; GWP Consultants LLP, 2010). Infiltration basins involve diverting surface water into off-stream basins and channels to allow water through an unsaturated zone to the underlying unconfined aquifer (e.g. Atlantis) (Dillion, 2009). Infiltration basins are believed to have high pollutant removal efficiency, particularly if the depth to the water table beneath the basin is significant. As a result, infiltration basins are more rapid with clean water than turbid water, and the cleaner the water, the longer the infiltration “runs” before having to scrape the basin to remove fine material (DWA, 2010; GWP Consultants LLP, 2010). Natural treatment is achieved by filtering through the unsaturated zone (DWA, 2010). Clogging or silting of the surface, due to deposition of suspended solids can reduce efficiency, however, due to their design de-silting is relatively straightforward. Removal by scraping or digging with anything from a spade to a bulldozer, depending on size of the clogging layer in the system, will restore infiltration rates (GWP Consultants LLP, 2010). They are also subject to evaporation and their effectiveness as recharge structures primarily depends on the infiltration potential of the underlying soil/strata.

Percolation tanks or recharge weirs: Dams built in ephemeral streams detain water, which infiltrates through the bed to enhance storage in unconfined aquifers and is extracted down valley (Dillion et al., 2009). Silt traps may help to prevent surface clogging and siltation of the percolation tank (e.g. Loeriesfontein, Northern Cape) (DWA, 2010).

Rainwater harvesting: Roof runoff is diverted into a borehole, well or a caisson filled with sand or gravel and allowed to percolate to the water table where it is collected by pumping from a borehole or well (e.g. Herman's) (Dillion, 2005).

Sand dams: These types of dams are built in ephemeral streams in arid areas with low permeability lithology (Dillion et al., 2009). They trap sediment when there are flows or successive floods. The sand dam is raised to create an "aquifer" (DWA, 2010). Vertical boreholes or horizontal outlets that face of the dam are used to extract water in dry seasons (e.g. in Namibia) (DWA, 2010).

Underground dams: These types of dams are built in ephemeral streams where basement highs constrict flows. Here a trench is constructed across the stream, keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use (e.g. in Kenya) (Dillion et al., 2009).

Recharge releases: These types of dams are built in ephemeral streams and are used to detain flood water. Their uses may include slow release of water into the downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge (e.g. Little Para River, SA) (Dillion et al., 2009).

The selection of suitable sites for MAR and choice of method depend on the hydrogeology, topography, hydrology and land uses within a given area (Page et al., 2018). Furthermore, it is common to find similar types of MAR projects clustered in the same geographic area due to shared physical attributes (Page et al., 2018).

Substitution of groundwater for surface water (or vice- versa) has been extensively practised by individual water entitlement holders in Australia and other countries to maintain water supplies when water is scarce (Arshad *et al*., 2014). Dillon et al. (2009b) outlined that there are seven major components common to all types of infrastructure based MAR projects. These are shown in Figure 3.3. .

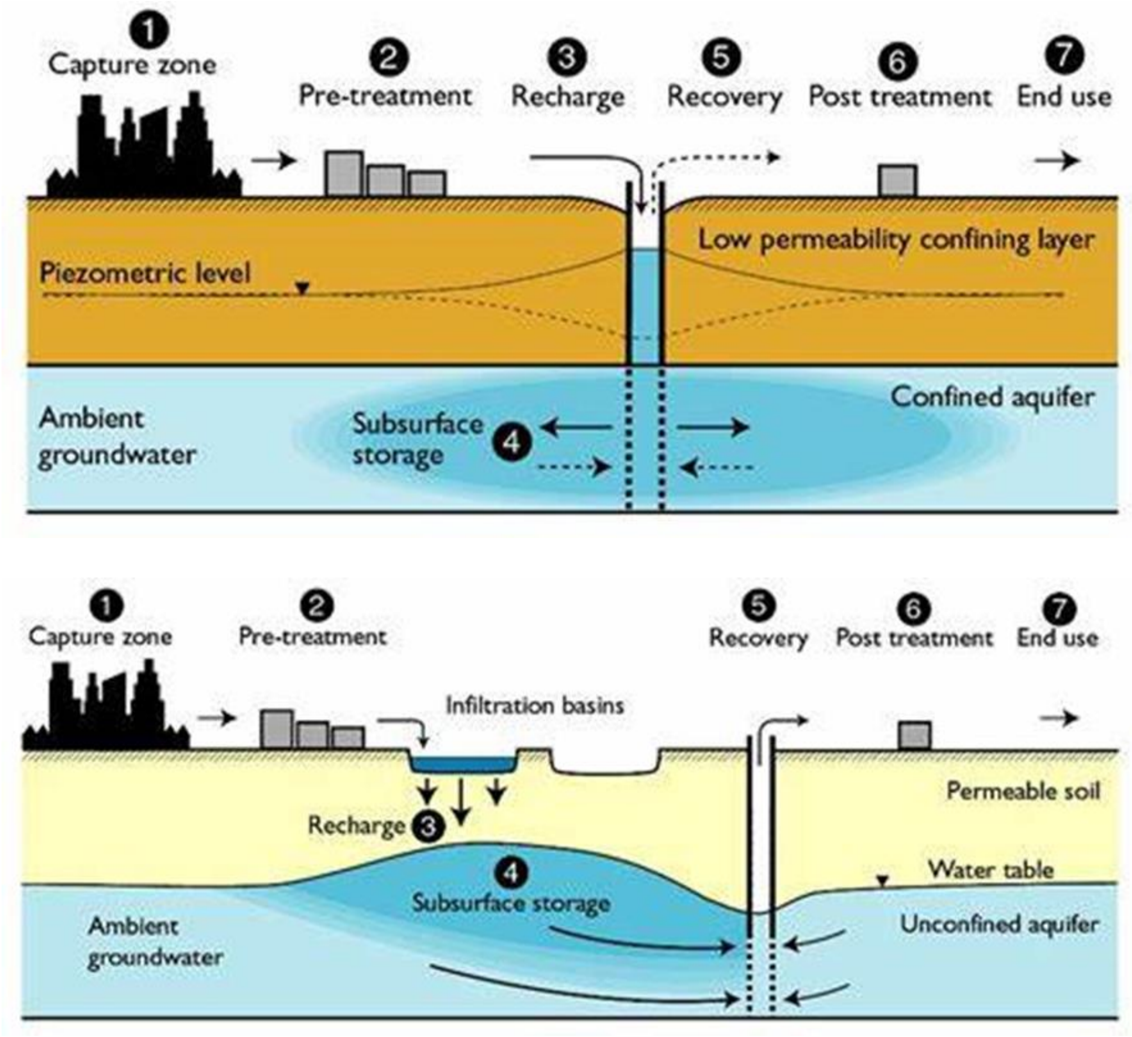


Figure 3.3. (a) Major components of MAR to confined aquifer via well, (b) Major components of MAR to an unconfined aquifer via infiltration basins (Source: Dillion *et al.*, 2009b)

3.2 Feasibility of MAR

A feasibility study for MAR involves assessing appropriate hydrogeologic and other conditions of an aquifer in a given catchment with known or assumed hydraulic properties and defined boundaries (Arshad, 2015). To establish a successful MAR facility, some criteria that need to be followed. Examples of such criteria involves identifying the need for a MAR scheme, the source water, aquifer hydraulic characteristics, water quality (including potential clogging), the MAR method and engineering issues, environmental issues, legal and regulatory issues, economics, management and technical capacity, and institutional arrangements (DWA, 2009a).

DWAF (2007) presented an artificial recharge strategy, where Version 1.3 of the strategy contains wealth of information, including the types of schemes, details on the “success criteria”, authorisation and regulatory issues and the artificial recharge strategy. Tuinhof and Piet-Heederik (2002) documented MAR case studies from six countries where MAR had been used for many years. The International Association of Hydrogeologist (IAH), (http://recharge.iah.org/recharge) through an International Symposium on MAR (ISMAR), provided international experiences of MAR in the thematic areas of modelling, recharge systems, water quality, operation and maintenance, and management of clogging (Arshad, 2015). In the South African context, the Department of Water Affairs (DWA) artificial recharge website (www.artificialrecharge.co.za) contains important information on artificial recharge. All new resources developed under DWA’s roll-out of the artificial recharge strategy were posted on the website (DWA, 2010).

There are two approaches to assessing the feasibility of MAR: i) Hydrogeological, and ii) hydro-economic modelling (Arshad, 2015). There is greater emphasis on integrating the two approaches for assessing the feasibility of MAR, but there are few examples using such a combined approach (Arshad, 2015).

3.2.1 Economic feasibility of MAR

Unused aquifer storage capacity can often be developed at a significantly lower cost than surface storage facilities, and without any adverse environmental consequences (Pyne, 1995). In water treatment, the natural attenuation of wastewater using aquifer media is a cost-effective means of improving water quality. When undertaking economic option analyses, it is important to evaluate all options on the same basis, and include all capital and operational costs.

The Windhoek MAR provides a good example of a comparative cost assessment. In the Windhoek economic assessment, the proposed artificial recharge scheme was compared to alternative water supply options for Windhoek and other recent or planned projects in the central region of Namibia (SWECO, 2002). Windhoek’s priority was to increase the security of supply. To achieve that, the following four factors were evaluated:

1. Present-worth cost, including the following costs and revenues:
    - Initial capital investment cost;
    - Annual depreciation and residual value (discounted to present value);
    - Average incremental annual pumping cost; and

  - Average incremental annual operation and maintenance cost.

2. The incremental security of supply (ISS): This study modelled the supply for each scenario as well as a baseline "do nothing" scenario. The ISS is the difference between the expected annual shortfall of the particular scheme scenario and the "do nothing" scenario during a 10-year planning period. The ISS is measured as volume per year (DWAF, 2007).

3. Water Saving (or scheme efficiency): This is based on evaporation loss for each alternative scheme.

4. Ratio of cost to ISS (in R/annual volume).

Other factors that could be assigned on economic value include:

- The strategic value of drought mitigation measures.
- The efficient use of local resources compared with developing sources in other distant areas.

An economic study should compare the cost per cubic meter of water supplied for each alternative supply option (Pyne, 1995). It is important to use the same method to price water. This is particularly important when water is purchased from a bulk water provider, such as a water board or when compared with existing schemes, as the price of water may be subsidized.

Figure 3.4.describes the different levels of water pricing adopted in the Windhoek economic assessment (SWECO, 2002). In many cases, water is priced on the financial cost; however an accurate comparison should be based on the total water supply cost.

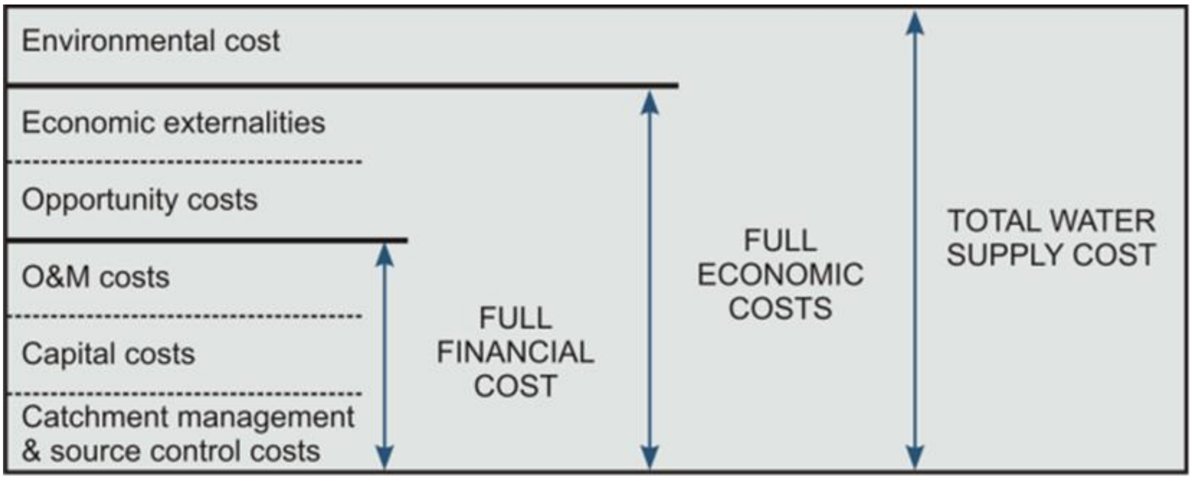


Figure 3.4. Levels of water pricing (after Heyns, 1998)

3.2.2 Legal and regulatory issues

All artificial recharge schemes need to be licensed because storing water underground is defined as a “water use” in the National Water Act (NWA, 1998). The National Water Act (No 36 of 1998) is the principal legal instrument when it comes to water resources management in South Africa. This act contains provisions for the protection, use, development, conservation, management and control of South Africa’s water resources (DWAF, 2007). In addition to the NWA, there are other policies and laws that are directly linked to the development and management of water resources. Some of these that have particular relevance are:

- The Water Services Act (WSA’s) (Act No. 108 of 1997), which relates to the provision of water services by water services institutions, including the safe disposal of effluent. The Water Services Act also requires that WSA produce an annual water audit, including details of water conservation measures.
- The National Environmental Management Act (NEMA) (Act No. 107 of 1998) is relevant to the management of water resources within the context of national environmental principles and legislation.
- The Environmental Conservation Act (ECA) (Act No. 73 of 1989) provides for the effective protection and controlled utilization of the environment, including incidental matters hitherto.
- The National Heritage Resources Act (Act No 25 of 1999) envisages preserving South Africa’s heritage resources for future generations. The act stipulates that the heritage resources of an area need to be mapped, described and preserved when construction projects are undertaken and when the size of those projects are more than certain limits (DWA, 2010).
- The regulations published in terms of the National Environmental Management Act have replaced the ECA Environmental Impact Assessment regulations with effect from 3 July 2006 (DWAF, 2007). However, the ECA remains in force as it relates to waste disposal and the Outeniqua Sensitive Coastal Areas regulations.

The NWA and the NEMA are the two primary laws that govern artificial recharge projects in South Africa. According to DWAF (2007), the other legislation and local bylaws that are key legal issues regarding the assessment and operation of artificial recharge schemes include:

- Water use licensing for artificial recharge schemes;
- Environmental authorization requirements for both testing and implementing the scheme; (e.g. Basic Assessment or Environmental Impact Assessment);

- Environmental Management Plans (EMPs);
- Compliance with regulations (e.g. relating to water reuse);
- Rights associated with the use of artificially recharged water; and
- Compliance with the conditions and reporting requirements of the water use licence and environmental authorisation.

Table 3.1**Error! Reference source not found.** below indicates the water use recognised in s ection 21 of the NWA that may be applied to artificial recharge projects in South Africa.

Table 3.1. Water uses recognised in section 21 of the NWA applicable to artificial recharge projects (DWA, 2010).

Section	**Water uses**
s21(a)	Taking water from a water resource.
s21(b)	Storing water.
s21(c)	Impeding or diverting the flow of water in a watercourse.
s21(d)	Engaging in a stream flow reduction activity (currently only commercial afforestation).
s21(e)	Engaging in controlled activity activities which impact detrimentally on a water resource (activities identified in s37(1) or declared as such under s38(1), namely: • Irrigation of any land with waste or water containing waste which is generated through an industrial activity or a waterwork; • An activity aimed at the modification of atmospheric precipitation; • A power generation activity which alters the flow regime of a water resource; or • Intentional recharge of an aquifer with any waste or water containing waste.
s21(f)	Discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit.

s21(g)	Disposing of waste or water containing waste in a manner which may detrimentally impact on a water resource.
s21(h)	Disposing in any manner of water which contains waste from, or has been heated in, any industrial or power generation process.
s21(i)	Altering the bed, banks, course or characteristics of a watercourse.
s21(j)	Removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or the safety of people.
s21(k)	Using water for recreational purposes.

3.3. Examples of managed aquifer recharge schemes

Artificial recharge is practised throughout the world. Majority of the literature, research and guideline documents are sourced from Europe, the USA, Israel and Australia (Riad *et al*., 2012). Countries such as India, Pakistan, Kuwait, Japan and Namibia, amongst others, have contributed to the international pool of knowledge in various degrees, with well-documented case studies (DWAF, 2007). A summary of artificial recharge schemes from different hydrological setting is provided below.

3.3.1 International Experience with Managed Aquifer Recharge

City of Scottsdale Water Campus, Arizona, USA

The USA has a long history of both infiltration and injection schemes (Riad *et al*., 2012). Textbooks, guideline documents, regulations and many case studies have emerged from the USA, particularly over the past two decades (DWAF, 2007). The implementation of MAR over the past decades has resulted in the supply of an increased proportion of groundwater (>50%) to the Scottsdale municipal system in Arizona (Riad *et al*., 2012). ASR has been a viable approach in the management of both potable and non-potable water supplies (Bloetscher *et al*., 2014). The largest existing ASR operation is located in the Las Vegas Valley Water District (DWAF, 2007). According to Riad *et al*, (2012), one of the main recharge facilities is at the Scottsdale Water Campus where vadose zone wells and ASR wells are used to artificially recharge treated wastewater and surface water harvested during periods of excess water.

The Scottsdale vadose zone recharge system comprises 27 operational wells, which are 100 mm in diameter and up to 55 m deep, within a sequence of alluvial sediments (Riad *et al*., 2012). The combined daily recharge capacity of the scheme is 45 ML, which represents an average recharge rate of approximately 20 l/s per borehole (Merz, 2010). In 1997, a deep ASR well was drilled within the Scottsdale Water Campus to a depth of 497m through a 320 m thick sequence of alluvial sediments and into underlying metamorphic basement (Riad *et al*., 2012). This well is proven to be highly effective, with rates of 114 l/s and 157 l/s achieved for recharge and recovery, respectively (Riad *et al*., 2012). Figure 3.5. graphically shows the concept behind ASR (Bloetscher et al., 2014).

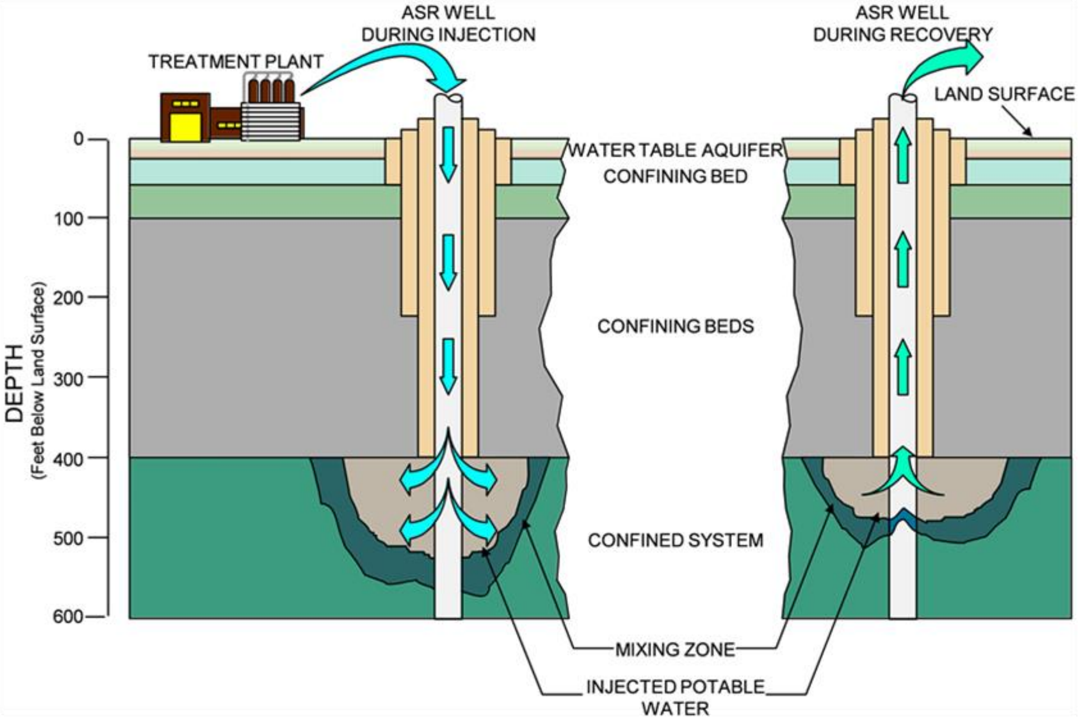


Figure 3.5. Aquifer storage and recovery concept: (Source: Bloetscher et al., 2014)

Australia

Artificial recharge is not a new concept in Australia and has been practised for more than a century at Mt Gambier in Southern Australia (Riad *et al*. 2012; DWAF, 2007). This small city disposes all its storm water into an underlying karst aquifer using more than 300 drainage wells that are dispersed throughout the city (Riad *et al*. 2012). The annual recharge that varies between 3.6 and 6.2 Mm^3 makes its way to a nearby lake from where it is abstracted for reuse (DWAF, 2007). Farmers near Adelaide (Australia) use irrigation supply wells to recharge their brackish aquifer with seasonally available fresh surface water (Pyne, 1995). This water is then recovered to augment irrigation supplies during dry months.

According to Riad *et al*. (2012), considerable research into ASR has recently been undertaken in Australia. This has focussed on water quality and microbiological changes that occur due to blending and sub-surface storage (DWAF, 2007). A major part of this research is related to the use of water with poor quality such as storm water, stream water and reclaimed water (DWAF, 2007). In 2002, 25 ASR projects were, under development, being investigated or in operation, with the intention of using storm water and/or reclaimed water for irrigation (Riad *et al*. 2012). Some deterioration of the aquifer due to the injection of non-potable water appears to be acceptable in Australia. An example of surface infiltration is the Burdekin Delta scheme, which is the oldest and largest infiltration scheme in Australia (DWAF, 2007). The scheme has been operating since the mid-1960s and is largely responsible for supporting the Australian sugarcane area (Riad *et al*., 2012). It is also used to prevent the intrusion of salt-water into the aquifer. The artificial recharge scheme is managed by Water Boards and consists of natural and artificial channels and recharge pits supplied with water drawn from the Burdekin River (DWAF, 2007). The irrigated agricultural land is served by 2000 production boreholes that abstract 210 to 530 Mm^3/a.

Germany

Artificial recharge has been in supply in Germany as early as the 1990s, such as in Berlin 1916, Wiesbaden in 1921 and Hamburg in 1928 (DWAF, 2007). Groundwater in Germany is used as drinking water wherever possible (Riad *et al*., 2012). Most schemes involve bank filtration along the Rhein, Elbe and Ruhr rivers. Approximately 54 percent of Germany’s drinking water is produced through artificial recharge (DWAF, 2007). Figure 3.6. indicates the uses of artificial recharge in Germany.

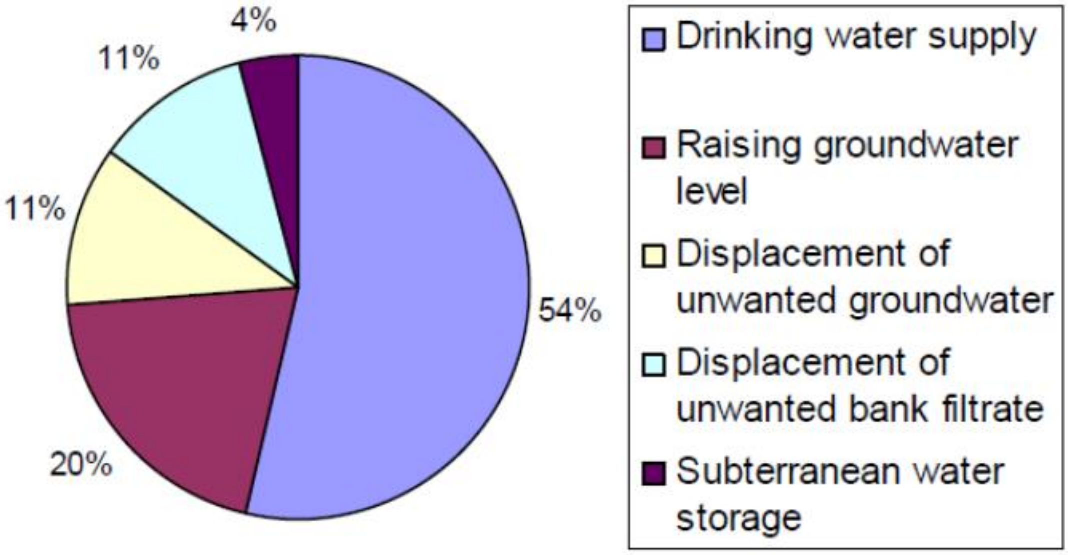


Figure 3.6. Uses of artificial recharge in Germany (Schottler, 1996)

Sweden

In Sweden, infiltration basins are used for artificial recharge. These basins have been operational since 1898 (DWAF, 2007). Recharge is mostly achieved by infiltration basins using partially treated surface water derived from lakes. There are 1800 artificial recharge schemes in the country and 80 of the 284 municipalities employ this technology (Riad *et al*., 2012). Artificial recharge provides about 50% of total groundwater use, which is more than 20% of total water use in the country (DWAF, 2007).

Switzerland

The cities of Zurich, Geneva and Basel rely on sophisticated artificial recharge schemes that use high quality (pre-treated) river water (DWAF, 2007). Artificial recharge was motivated by declining groundwater yields, increasing demands, deteriorating groundwater quality and the need for security of supply (Riad *et al*., 2012). Recharge methods include infiltration basins, ditches and injection boreholes (Connorton and McIntosh, 1994).

United Kingdom

Pilot studies were conducted north of London in the 1890s and 1950s. However, permanent artificial recharge facilities using wells and boreholes were constructed in the 1970s (DWAF, 2007). Surplus winter water from the Lee River is pre-treated to water quality suitable for drinking and injected into the aquifer (Riad *et al*., 2012). A high level of treatment is adopted to avoid clogging and protect the groundwater resource (DWAF, 2007).

The Lee Valley and Enfield-Haringey schemes are currently the only artificial recharge projects operating in the UK. Both make use of surplus potable water (derived from the Thames and Lee Rivers) that is injected into the deeply confined chalk aquifer of the London basin (Figure 3.7.) (DWAF, 2007). When fully developed, the two schemes will provide a strategic drought resource of 60 Mm^3/a for the London area, which experience a water deficit of 10%.

Feasibility studies to develop similar artificial recharge schemes have been undertaken in south London, and projects in the Anglia, Severn-Trent and Yorkshire regions are in the planning stage (Riad *et al*., 2012). All artificial recharge schemes require approval from the National Rivers Authority, which regulates abstraction licences and consent to recharge (quantity and quality) into aquifers (DWAF, 2007).

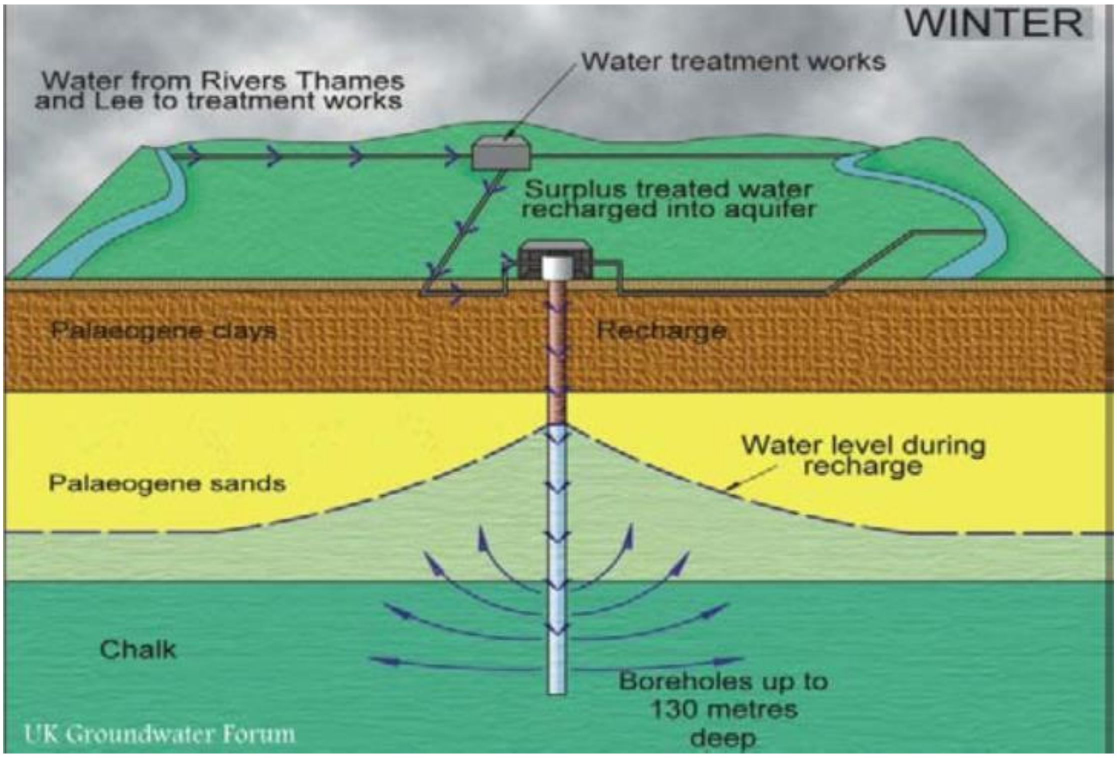


Figure 3.7. Artificial recharge of the Chalky aquifer in the Lee Valley, North London, UK (adapted from the UK Groundwater forum, 2011)

Israel

Since about 1956, artificial recharge through wells has been an important element of the National Water System for Israel (Pyne, 1995). Most of the long-term operating experience has been in the sandstone aquifers of the coastal plain and the limestone-dolomite aquifer of central Israel, although some investigations have also been conducted in the basalt aquifer of lower Galilee (Pyne, 1995). The Yarkon-Taninim Aquifer that is composed of a dolomite-limestone aquifer is one of Israel’s three principal water sources. The others include the Coastal Aquifer and Lake Kinneret (Riad *et al*., 2012). Recharge has occurred primarily through dual-purpose injection/ production wells (ASR wells), although single purpose recharge wells, recharge basins and abandoned quarries are also utilised (Pyne, 1995). The water source is primarily chlorinated water from Lake Kinneret, although storm runoff and groundwater from a limestone aquifer are also recharged (DWAF, 2007; Pyne, 1995). Annual recharge volumes in excess of 80 Mm^3 have been achieved, utilizing over 100 wells and surface recharge facilities (Pyne, 1995). The recovered water was used for unrestricted irrigation and over a five-year period from 1991 to 1996, 400 Mm^3 was supplied for this purpose (Riad *et al*., 2012). There have been some challenges on the recharge boreholes such as clogging which was due to the build-up of silt and algae in the source water. However, this was adequately managed by back-flushing (pumping) the injection boreholes (DWAF, 2007).

There are a number of other artificial recharge schemes in Israel, including the Nahaley Menashe project north of Tel Aviv and Dan Region Project, which is the largest artificial recharge scheme in Israel that uses the aquifer media for treating reclaimed wastewater from Tel Aviv (DWAF, 2007) (Figure 3.8.).

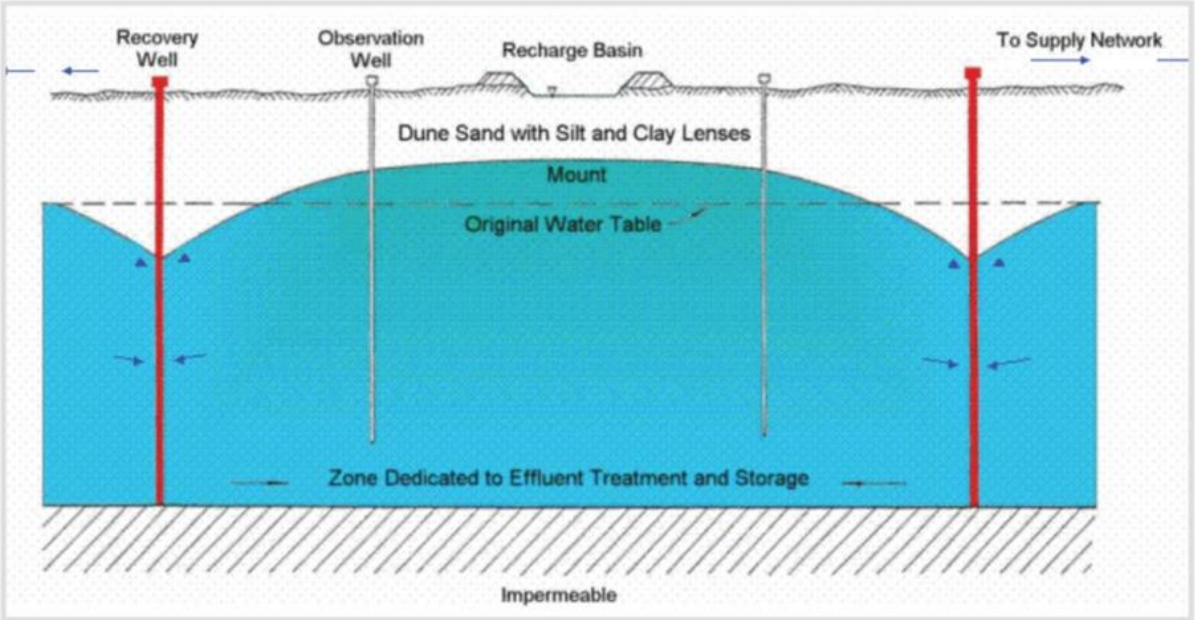


Figure 3.8. Tel Aviv recharge-recovery scheme (adapted from SWITCH Project, 2011)

3.3.2 Southern African experience with Managed Aquifer Recharge

Artificial recharge has been a concept practiced in Southern Africa. For instance, the Atlantis scheme near Cape Town has been operational for over 20 years, and farmers throughout the region built numerous earth dams for the purpose of enhancing groundwater recharge (DWAF, 2007). In Namibia, sand storage dams were constructed in stages for the storage of water in artificial "aquifers" (Wipplinger, 1953). Southern African artificial recharge sites are summarised in **Error! Reference source not found.** and Figure 3.9. .

Table 3.2. Artificial recharge sites in Southern Africa (DWAF, 2007).

Site	**Operational Status**
Atlantis, South Africa	Nearly 30 years of operation
Polokwane, South Africa	Over 20 years of operation
Kharkams, South Africa	Over 5 years of operation
Calvinia, South Africa	Recently tested
Windhoek, Namibia	Recently constructed
Omdel, Namibia	Over 5 years of operation

Figure 3.9. Southern Africa's artificial recharge sites (DWAF, 2007)

Windhoek (Namibia)

The City of Windhoek decided on large-scale artificial recharge before introducing other supply options, such as transferring water from aquifers in the northern parts of the country to the Okavango River (DWAF, 2007). Windhoek water requirement is at 21 million m^3/a. Most of this water comes from three dams, while others are sourced from a quartzite aquifer and reclaimed water (fully treated recycled water) (Tredoux et al., 2012). A major achievement for the city is a reduction in cost through the use of artificial recharge to increase assurance of water supply. Surface water transfer from the Okavango River was estimated at R1.79 billion in comparison to the R242.5 million required for the artificial recharge scheme (Tredoux et al., 2012). The artificial recharge takes the form of water banking, where surface water is “banked” in the aquifer as security against drought. This allows the dams to be used at greater risk levels, where security lies in sub-surface storage and evaporation and aquifer loss are negligible (DWAF, 2007). The main aim of the Windhoek scheme is establishing an aquifer that can meet the entire city’s demand when full, with the ability to rapidly and fully recharge thereafter (Tredoux et al., 2012).

Atlantis (Western Cape)

Atlantis is located along the semi-arid to arid west coast of South Africa. According to DWA (2010b), Atlantis provides an example of wise water usage. The town has a population of 67 491 people (2011 census).The Atlantis Water Resource Management Scheme (AWRMS) was designed to optimise the use of water in the town of Atlantis, situated along the arid west coast of southern Africa (DWAF, 2007). It was initially fully dependent on groundwater; however, the reserves were insufficient, and artificial recharge was introduced to augment local groundwater supplies (Tredoux *et al*., 2002). Treated wastewater and storm water is diverted to large basins where it infiltrates into a sandy aquifer where it is abstracted and reused for municipal supplies (DWA, 2010b).

The primary coastal aquifer system in the Atlantis area is comprised of unconsolidated sediments that are Tertiary to recent in age. These sediments overly Malmesbury Group bedrock composed of greywacke and phyllitic shale (Van der Merwe, 1983). Natural recharge is estimated to be in the order of 15-30% of the annual rainfall (450 mm) (Tredoux et al., 2002). The Atlantis scheme has successfully recharged and recycled water for nearly three decades. Approximately 7500 m^3/d of storm water and wastewater is currently recharged, thereby augmenting the water supply by more than 2.7 million m^3/a (DWA, 2010b). Moreover, 30% of Atlantis's groundwater supply is augmented through artificial recharge.

Managing water quality, especially salinity, has been one of the greatest challenges for the Atlantis Water Scheme (Tredoux et al., 2002). The recent importation of limited quantities of surface water beyond the catchment is an important additional source of low salinity fresh water entering the system (Tredoux et al., 2002). A decline in the yield of the boreholes in the Atlantis aquifer led to the discovery of iron-related clogging problems (DWAF, 2007). The first well clogging occurred in the early 1990s when the boreholes were over-pumped and air filled the screened section of the borehole due to drought conditions (DWA, 2010b).

The Atlantis scheme has proven itself as an innovative and highly successful scheme that has worked extremely well and won various awards (DWA, 2010b). A major component of the scheme has been the separation of the source water into different fractions, which allowed recharge of the good quality water in the areas of importance (Tredoux *et al*., 2002). The Atlantis groundwater scheme provides a cost-effective water supply option when coupled with the careful management of the water sources and aquifer (Tredoux et al., 2002).

Polokwane (Limpopo)

Polokwane grew rapidly over the past decade, with an estimated population of 400,000 and water requirements of about 12 million m^3/a (Tredoux et al., 2002). However, the city has an elaborate groundwater abstraction infrastructure that supplies domestic water to meet daily peak demand, and also serves as a back-up during periods of surface water shortage. For example, during the 1992–1994 drought, groundwater accounted for a large proportion of the city's supply (3.7 Mm^3/a) (DWA, 2010b). The reliability of this source is largely due to the infiltration of Polokwane municipal treated wastewater into the alluvial and gneissic aquifers (Tredoux et al., 2002). Treated wastewater is discharged into the ephemeral Sand River, which flows over a 20 m thick layer of alluvium that is 300 m wide (DWAF, 2007). Underlying the alluvium are granite-gneiss rocks that are weathered and fractured to depths of 60 m (Tredoux et al., 2002).

The reliability of groundwater for Polokwane is largely due to the artificial recharge of 3-4 million m^3/a of treated municipal wastewater infiltrated into the alluvial and gneissic aquifers (DWAF, 2007). This water is used by both the municipality and farmers for large-scale irrigation. To recycle as much water as possible, Polokwane municipality need to continuously abstract groundwater from the gneissic aquifer (Tredoux et al., 2002).

Kharkams (Northern Cape)

Kharkams is a small village in the semi-arid Namaqualand region that depends solely on groundwater from a granitic aquifer. Surface runoff, whenever it rains, is directed into the aquifer through the lowest yielding borehole of the village's three production boreholes (Tredoux et al., 2002). This has had the effect of tripling the borehole's yield and bringing the salinity of the water from virtually undrinkable (EC of 300 mS/m) to an acceptable quality (EC < 100 mS/m) (Tredoux et al., 2002). This method ensures that the surface runoff water used for this artificial recharge is not lost to evaporation and evapotranspiration.

This scheme demonstrated the value of opportunistic artificial recharge in semi-arid areas, even if it is practised on a small scale (DWAF, 2007). Unfortunately, inadequate maintenance of the sand filter resulted to poor operation of the scheme over the past few seasons (Tredoux et al., 2002).

Prince Albert

The demand for water in Prince Albert, located in the Karoo region of South Africa, increased threefold over the summer months from about 1000 to 3000 m^3/day (DWAF, 2007). Water is sourced from untreated river water that runs off from the Swartberg Mountains and enters the furrow and from boreholes in a sandstone aquifer. These boreholes are used to bridge the summer months' supply shortfall. The mountain water is supplied via a furrow and the aim is to divert this water into the aquifer during winter when the furrow is being cleaned (DWAF, 2007). This would add 4000 m^3 to the aquifer for use during summer.

3.4 Challenges of MAR

3.4.1 Clogging

Clogging or "plugging" refers to the reduction of permeability of the filtration surface of the recharge facility, or the reduction in available pore volume and permeability in the aquifer (Pyne, 1995). Aquifer clogging is more difficult to detect because it occurs as a gradual process. In the case of injection boreholes, the surface area is relatively small and the phenomenon of clogging could be rapid and irreversible (Riad *et al*., 2012). It is generally easier to manage in basin recharge. Various forms of clogging, each of which could be a combination of physical, biological and chemical processes, have been identified (Dillon and Pavelic, 1996; Pyne, 1995):

- Filtration of suspended solids;
- Microbial growth;
- Chemical precipitation;
- Clay swelling and dispersion;
- Air entrapment (or entrainment);
- Gas binding (release of dissolved or generated gases); and
- Mechanical jamming and mobilisation of aquifer sediments.

Techniques of clogging mitigation

Several mitigation measures and technologies exist, which can be used to reduce the clogging potential of suspended particles in recharge water. The two general type of preventative methods are pre-treatment before recharge and in-situ techniques (Pérez-Paricio, 1998). Table 3.3.Table 3.3 shows a summary of preventative methods according to the main clogging source.

Table 3.3. Summary of preventative methods according to the main clogging source (Perez-Paricio, 1998)

Physical Clogging	Biological Clogging	Chemical Clogging	Air/Gas Generation	Compaction	Corrosion
Flocculants Prior filtration Reverse osmosis Backwashing Desiccation (basins) In situ filters Constraints	**Bacteria:** Disinfectants Nutrient reduction Constraints **Algae:** Nutrients limit Filtration Chemicals Prevent light Recharge cycle	Acid dosing Daily pumping Separate groundwater strata Avoid oxygen Aquifer treatment	Special valves $T_{RECHWATER} > T_{GW}$ Optimum design	Limit water height	Not to use stressed parts Avoid high temperatures Avoid high velocity flows Avoid work hardened materials

Uncertainty in aquifer hydraulic characteristics

In the case of new artificial recharge schemes that involve deep-seated aquifers or saline aquifers, knowledge about the aquifers hydraulic properties is limited. As a result, either intensive research would be required on the aquifer prior to implementation or the installation of an extensive monitoring system mandatory. Thereafter, the project would have to be commissioned with an acceptable level of risk.

Recovery of stored water

Where the characteristics and extent of the aquifer are known in sufficient detail, water levels can be managed to prevent loss of recharged water. In borehole injection schemes where the quality of the recharge water and the native groundwater are vastly different, recovery efficiency is a major concern. In the case of ASR systems, recovery efficiency is defined as the percentage of water volume stored and is subsequently recovered, while meeting a target water quality criterion (Pyne, 1995). The water quality criteria typically include the total dissolved solids (TDS), electrical conductivity (EC) or chloride concentration. Most schemes can be developed to 100% recovery efficiency, except those in very transmissive, highly saline aquifers which typically reach 70% to 80% efficiency (Pyne, 1995).

Controlled recovery by different users

The concept of whoever stores the water has the right to recover it is generally accepted throughout the world. It would be highly problematic if there was uncontrolled usage of the stored water.

Regulatory constraints

Storage of water in the sub-surface needs to comply with the country's water and environmental legislation. In certain circumstances, environmental approval of a scheme may take a long time, or even be prevented, since the implementation of new legislation is untested in relation to artificial recharge.

Damage of aquifers

This concern refers to the negative effects of recharge such as the precipitation of minerals, the dissolution of aquifer material and contaminants such as arsenic. Precipitation was observed near ASR boreholes as clogging, but has not been observed as widespread aquifer clogging (Dillion, 2005). The dissolution of arsenic bearing mineral was observed in a number of instances, and needs to be assessed in the feasibility stage of most projects. Aquifer collapse due to large-scale dewatering during the recovery stage of the artificial recharge cycle is a concern for some specific aquifer types (such as unconsolidated aquifers). Most artificial recharge schemes around the world are in unconsolidated or primary aquifers, but this problem has not been widely observed.

High outlay before feasibility of ASR can be established

In certain circumstances (e.g. where there is a poor understanding of the hydraulic properties of the aquifer), there may be a need for a high financial outlay in order to establish the feasibility of the scheme. This will have to be compared with the feasibility studies required for other options.

Operational issues

Lack of experience is an obstacle to artificial recharge development.

Environmental concerns relating to fluctuating groundwater

Artificial recharge and recovery could result in groundwater levels being raised above or below the norm, which can have negative environmental consequences. Examples of negative consequences include effect on groundwater level dependant ecosystems, increased aquifer vulnerability to contamination and sinkhole formation in dolomitic aquifers.

3.4.2 Suitability of aquifers for MAR

Aquifers exhibiting high hydraulic conductivities and high storage capacities are more suitable for receiving additional recharge water than those with low hydraulic conductivities and low storage capacities (Murray and Tredoux, 1998). However, if the aquifer has a high hydraulic conductivity and high gradient, water will flow rapidly away from the point of recharge and may be difficult to recover (Murray and Tredoux, 1998). Table 3.4Table 3.4. represents a simpler matrix used in assessing the suitability of aquifers to receive artificially recharged water in terms of aquifer hydraulic characteristics.

Table 3.4. Factors for identifying potential areas for MAR application (modified from DWA, 2007)

Factor	**Description**	**Comment**
Hydraulic conductivity	The rate at which the aquifer can receive and supply artificially recharged water.	Aquifers with moderate to high hydraulic conductivity is the most suitable whereas, those with low hydraulic conductivity is least suitable for MAR.

Aquifer storage	The volume of aquifer storage available for MAR.	Aquifers with high storativity are the most suitable whereas, those with low storativity they are the least suitable for MAR.
Need	The need for artificial recharge should relate to all groundwater users, including reserves.	
Water source	Availability of a source water for MAR.	Water sources include surplus surface water which cannot be used or reused directly. For example, municipal wastewaters, storm runoff, rainfall harvesting, river flows, water released from dams, etc.
Infrastructure	The location of major dams, water transfer infrastructure and water treatment facilities.	Major dams, water and wastewater treatment facilities.

CHAPTER FOUR

METHODOLOGY AND APPROACHES

The methods applied and the approaches followed in analysing the various data and information collected in this project are described in the following sections.

4.1 Study approach

A case study using the eThekwini District Municipality was employed in this study. An integrated hydrogeological approach was adopted to understand the hydrogeological setting as well as to assess potential sites for MAR in this project. Firstly, a broad literature review was undertaken to capture the extensive knowledge pertinent to MAR and the aquifer systems in the eThekwini District Municipality. Literature search and review on MAR were undertaken in terms of identifying suitable sites and how schemes are implemented. Secondly, the intergranular aquifer system that occur in the eThekwini District Municipality was conceptualized based on the analysis of the data and information compiled.

4.2 Research methods

The following main research methods are followed: Desktop study, data collection and collation, GIS analysis and interpretation.

The desktop study involved the research of any available information, including literature review, on MAR, focusing on the research pertinent to potential sites assessments. Literature review of previous studies on eThekwini District Municipality including geological and hydrogeological maps and reports, and groundwater monitoring data. The collected data were collated. The most important data and information collected included geological, landforms, drainage, topographical, hydrometeorological, hydrogeological, location of wastewater treatment works, and quantity and quality of treated wastewater. GIS analysis involved pre-processing data sets including geological, hydrological, hydrogeological, and treated wastewater information of the study area.

4.3 Data types and sources

The following data sources of information and publications were used during the desktop study:

- The 1: 250 000 Geological Map Series titled “2930- Durban”, compiled by the Council for Geosciences (CGS, 1988a);
- The 1: 50 000 Geological Map Series titled “2930 & 2931CC Durban” compiled by the Council for Geoscience (2015);
- The 1: 500 000 Hydrogeological Map titled “3030 Durban” as compiled by DWAF (1998);
- Groundwater abstraction data from the Water use Authorisation Registration Management Systems (WARMS) database;
- Department of Water and Sanitation (DWS) KwaZulu-Natal Groundwater Resource Information Database (GRIP); (DWS, 2019);
- DWS National Groundwater Archive (NGA) (DWS, 2019);
- Meteorological data from the South African Weather Service (SAWS, 2019); and
- Geological and hydrogeological reports from consultants.

The literature review showed that ideal aquifers where MAR can be practised are intergranular and intergranular and fractured aquifers where borehole yields are greater than 0.5 l/s (Murray and Tredoux, 1998). The phased approach for identifying aquifers for MAR are undertaken, consisting of the following three stages:

Phase one: examination of the geological and hydrogeological map, topography and aerial photography of the study area. The examination procedure involved a zoomed-in study in order to map all geological units present within the greater Durban Metropolitan District using existing geological maps (at the scale of 1: 50 000 and 1: 250 000). Examination of aerial photographs and topography of the area. The reason for studying the topography of the area was to eliminate steep terrains, as they would not favour infiltration and storage. This implies that steep areas are not favourable for MAR. Moreover, map the types of aquifers which occur within the study area. Noting that priority will be given to primary aquifers yielding more than 0.5 l/s and intergranular and fractured aquifers that produce more than 5 l/s and those with yield more than 10 l/s on the 1: 500 000 scale hydrogeological map.

Phase two: involved an in-depth literature review on areas identified in Phase One. Phase two looked at previous studies. These studies include borehole logs, pump testing, hydrogeological studies, groundwater-monitoring data and reports. In Phase two, secondary hydrogeological data are scrutinized and a detailed study of potential aquifer hydraulic properties (hydraulic conductivity, transmissivity, storage capacity and specific yield), groundwater contour map, hydraulic gradient, groundwater flow direction, and groundwater quality were undertaken.

Phase three: the elimination phase where examination of information from Phase two was undertaken in order to determine which sites had more information compared to the others and to recommend further studies in sites that lack data. In Phase three, aquifers that have intergranular (a3) (0.5- 2.0 l/s) and upwards yields were given high priority.

4.4. Data analysis, interpretation and conceptualization

All the data gathered in this work that include literature review and field assessment were integrated and analysed using designated approved software's. For example, Aquachem was employed to analyse the hydrochemistry data while Aquitesolv was utilized to obtain pump test data. The method of data interpretation at each step of the investigation is presented below:

Hydrometeorology

The rainfall, temperature, humidity and wind speed recorded from four weather stations, namely, Mount Edgecombe, Virginia, Botanical gardens and Durban South recorded for 31 years (1987-2018) were prepared for estimating the potential and actual evapotranspiration. The monthly potential evapotranspiration (PET) were calculated using the FAO56 Penman-Monteith method which determines the reference evapotranspiration for a standard reference crop (Allen et al., 1998). Additionally, the actual evapotranspiration (AET) was estimated using the Turc method. The monthly runoff were calculated using the SCS Runoff Curve Number method. The SCS Runoff Curve Number method is as follows (SCS, 1986);

$$Q = \frac{(\mathrm{P}-0.1\ \mathrm{S})2}{(\mathrm{P}-0.8\mathrm{S})} \qquad (4.1)$$

Where; Q is the runoff (mm), P is the rainfall (mm), S is the potential maximum retention after runoff being (mm) and Ia is the initial abstraction. Initial abstraction (Ia) is all losses before runoff begins, It includes water retained in surface depression, water intercepted by vegetation and infiltration where S is related to the soil and cover conditions of the water shed through CN. With CN ranging from 0 to 100 and is related to CN by:

$$S = \frac{25400}{CN} - 245 \qquad (4.2)$$

The major factors used to establish the runoff curve numbers include the hydrologic soil group (HSG), type of land cover, hydrologic condition and antecedent moisture condition.

Water budget analysis

A water budget is a vital requirement in the development of a conceptual model (Anderson and Woessner, 2002). In the endeavour of calculating the recharge, it was required to quantitatively assess the water budget components. During the analysis of the water budget, the Thiessen polygon tool available on ArcGIS 10.6 software was used to determine within which surrounding weather station's proximity zone, eThekwini District Municipality occurs. The weather stations considered included the Mount Edgecombe, Virginia, Stanger, Durban Botanical Gardens, Durban South, Pietermaritzburg, Richmond and Allerton station. This tool facilitates the division of the area covered by the weather stations into proximal zones. Based on the result, the rainfall, temperature, humidity and wind speed recorded between the years 1995 and 2018 were prepared for the calculation of the potential and actual evapotranspiration. The potential evapotranspiration was calculated for each month of the year using the FAO Penman-Monteith Method that determines the reference evapotranspiration for a standard reference crop, i.e. short grass as described by Allen *et al*. (1998). Allen *et al*.(1998) used parameters such as precipitation, temperature, relative humidity and wind speed to calculate the potential evapotranspiration, and this require quantification as shown below:

$$Eto = (0.408\Delta\ (Rn - G) + \gamma * (900/T = 273) * U_2\ (es - ea)) / (\Delta + \gamma\ (1 + 0.34U_2) \qquad (4.3)$$

Where, ETo is the reference evapotranspiration (mm/day), R_n is the net retardation at the crop surface ($MJ/m^2/day$), G is the soil heat flux density ($MJ/m^2/day$), T is the mean daily air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa/ ° C) and γ is the psychrometric constant (kPa/ °C).

The actual evapotranspiration was estimated using the Turc method, which shows the precipitation and temperature as the dominant factors controlling evapotranspiration (Shaw, 2005).

The fraction of the rainfall that is lost to overland flow both as sheet flow or within rivers and streams towards the ocean, is referred to as runoff that forms part of components of the hydrological cycle (Beven, 2011; Fetter, 2014). The SCS Runoff curve number was used to decipher runoff.

Groundwater level and hydrochemical data analyses

The data that was sourced from GRIP, NGA and private consultants was combined into an excel spread sheet with a corresponding data ID. Parameters that are relevant for obtaining information for the research objectives were saved (depth to water or water level, water strikes, borehole yields, hydraulic properties, etc.) and the water level calculated. Once the data was prepared, it was then loaded on to ArcGIS 10.6 as X and Y data, and exported into a shapefile, clipped onto the boundary of the study area and then analysed.

Groundwater level contour maps were established using the secondary and primary data obtained from the Surfer 14 software. The depth to groundwater data was compiled by using the water level data (in meters below ground level) in a table. Thereafter, the data was analysed using the Inverse Weighed Distance (IDW) method to produce a surface that accurately describes the distribution of the depth to groundwater of the eThekwini District Municipality. Depth to groundwater measurements obtained from the National Groundwater Archive (NGA, 2019), Groundwater Resources Information Project (GRIP, 2019) and consultant reports were utilized in constructing a regional groundwater level contour map for the eThekwini District Municipality. Hydrochemical data shown include the Piper-trilinear plots, Durov and Stiff diagrams.

Aquifer characterization for MAR

The hydraulic conductivity and storage capacity, and the hydraulic gradient of groundwater in the aquifer determine if an aquifer meets the standard for accepting, storing and allowing for the recovery of artificially recharged water (Murray and Tredoux, 1998).

Hydraulic conductivity of aquifers

The hydraulic conductivity of a soil or rock is controlled by physical factors such as porosity, particle size and distribution, shape of particles, arrangement of particles, etc. (Todd, 1980). The hydraulic conductivity of the fractured aquifers was determined by a calculation that uses transmissivity and aquifer thickness. The transmissivity of the aquifer was determined in the analysis using pumping test data on the FC program (Van Tonder *et al.*, 2013). For unconsolidated sediments where there is no transmissivity value, the hydraulic conductivity was assigned based on literature including Bouwer (1978) and Kruseman and Ridder (1994).

Aquifer thickness, Transmissivity, Storatvity and Specific yield

The aquifer thickness of the study area was estimated after studying borehole logs. The analysis involved the identification of the depth of the borehole and the static water level. Thereafter, the static water level value was subtracted from the depth of the borehole value in order to get the saturated thickness of the aquifer.

According to Kruseman and De Ridder (1990), transmissivity can be calculated by pump testing while applying the appropriate groundwater flow equation. The transmissivity values can be obtained from the data analyses of pumped and observation boreholes (Murray and Tredoux, 1998). In confined aquifers with unsteady-state flow conditions, the transmissivity of the aquifers will be determined by analysing pump testing data using the Cooper-Jacob's or Theis method on the FC program (Van Tonder et al., 2013). Whereas in unconfined aquifers with unsteady-state flow, the Neuman's curve-fitting method and in steady-state flow, the Thiem-Dupuit's method will be used. The equation to determine transmissivity is indicated below:

$$T = K.b\ (m/day).(m) = m^2/day \tag{4.4}$$

The storativity for confined aquifers will be determined analysis of pumping test data. In instances where there is no data, the storativity values will be assigned based on literature (Kruseman and De Ridder, 1994; Vegter, 1995). The specific yield for unconfined aquifers, similar to the storativity, will be determined based on the pumping test data. In instances where there is unconsolidated material, the range of 0.07 - 0.15% suggested by Todd (1980) is adopted.

Estimation of aquifer parameters

In the study, pumping test data for the pumping tests which have previously been conducted within the study area was used. These data were obtained from private consultants. A simple programme called Flow Characteristics (FC) was used to calculate S and T. FC uses several different formulae, including the Theis (1935) and Cooper-Jacob (1946) solutions to calculate hydraulic conductivity, transmissivity and storativity from pumping test data. The programme is in the form of a Microsoft Excel Spreadsheet, which when fed with pumping test data, it automatically/ simultaneously calculates the aquifer parameters. The FC programme was used to estimate aquifers parameters.

Natural groundwater recharge

Groundwater recharge can be defined as the addition of water to a groundwater reservoir (Beekman and Xu, 2003). The estimation of recharge is one of the important components of MAR. Recharge estimation methods are either of physical mass balance, or environmental tracer type (Bean, 2003). Numerous methods are generally used conjunctively (where possible) for a reliable recharge estimation. In this work, the amount of natural groundwater recharge was estimated using the chloride mass balance (CMB).

Chloride Mass Balance Method (CMB)

The CMB method proposed by Bean (2003) is included within the FC Program. The following equation is applied:

$$R = \frac{PClp}{Clgw} \tag{4.5}$$

Where, R = Recharge, P = Precipitation (mm/a), Clp is the Cl content of precipitation (mg/l) and Clgw is the Cl concentration in the groundwater.

Water Budget Method

Water balance is a physical method that has been widely employed to estimate groundwater recharge (Manghi et al., 2009; Zagana et al., 2007). An advantage of the water balance method is its flexibility. This method is not limited by any mechanisms that control the individual components. Hence, water balance can be applied extensively in space and time scales, which vary from centimetres, seconds to global climate models (kilometres, centuries) (Scanlon et al., 2002). The water balance method measured recharge as the residual of other fluxes such as precipitation, runoff, evapotranspiration and change in water storage. The principle is based on the ease of estimation of other fluxes than recharge. The hydrological water balance for the study area was defined using equation (4.6):

$$R = P - (ET + RO + \Delta S) \tag{4.6}$$

Where, R is recharge, P is precipitation, ET is evapotranspiration, RO is runoff and ΔS is change in water storage. All components are calculated in rates (mm/day or mm/year).

The advantage of using the water balance method for this study was the availability of data (rainfall and water levels). This data made it easy compute and account for all water entering a system.

4.5 Hydrogeological conceptual cross-sectional models

Three hydrogeological cross-sections were developed. The cross-sections were developed on the basis of the borehole logs, using two software programs: ArcGIS 10.6 for the construction of the cross-section lines and the derivation of the topographic profiles of the sections and CorelDraw for the development of the cross-sections incorporating the geological and hydrogeological attributes. The cross-section lines were digitized on ArcGIS 10.6, and the topographic profiles were derived from the DEM, along the cross-sectional lines. The topographic profiles were imported into the CorelDraw interface, and the boreholes and their associated geology digitized. The geology between the boreholes were interpolated, and constitute sediment of the Berea and Bluff Formation, sedimentary strata of the Pietermaritzburg and Vryheid Formation and Dwyka Group. The water levels were digitized for each borehole and the water table was subsequently interpolated between the boreholes.

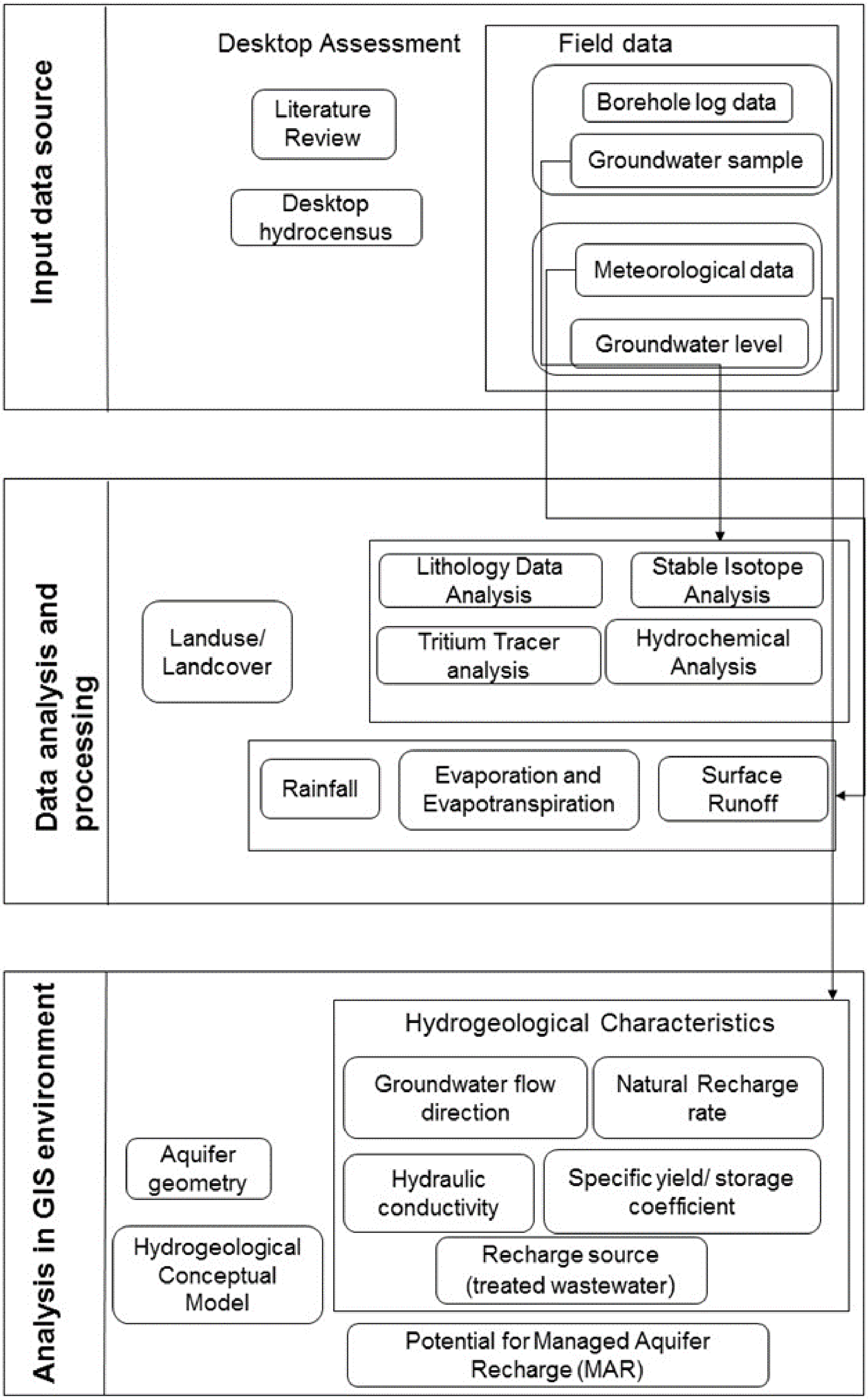


Figure 4.1. Flow chart of the methodology and approach followed in the course of the investigation.

4.6 Study limitation

Although great effort was applied to this study, there are still some study limitations. For instance, data available is limited which constraints the study. There are more than one thousand boreholes in the study area, but most of these boreholes do not have water quality information and corresponding monitoring data with the right aquifer.

CHAPTER FIVE

HYDROGEOLOGICAL CHARACTERISTICS OF THE GREATER DURBAN METROPOLITAN DISTRICT

5. 1. Hydrometeorology of the greater eThekwini District Municipality

5.1.1 Precipitation

Rainfall data is essential in all hydrological studies, amongst others; to estimate runoff and natural groundwater recharge and related water resources quantification. In this study, rainfall data from eight weather stations spanning the period 1988 to 2019 were sourced from SAWS (2019) and analysed to understand the rainfall spatial and temporal distribution and estimate the total annual runoff and annual groundwater recharge in the greater Durban Metropolitan region. These weather stations include the Mount Edgecombe, Virginia, Stanger, Durban Botanical Gardens, Durban South, Pietermaritzburg, Richmond and Allerton. The long term average annual rainfall for the study area is 921 mm, with most of the precipitation occurring from October to March. Based on the isohyet aerial rainfall map (Figure 5.1) from Durban central to the north and south, the spatial variability from the east coast to the western interior show a decrease in rainfall.

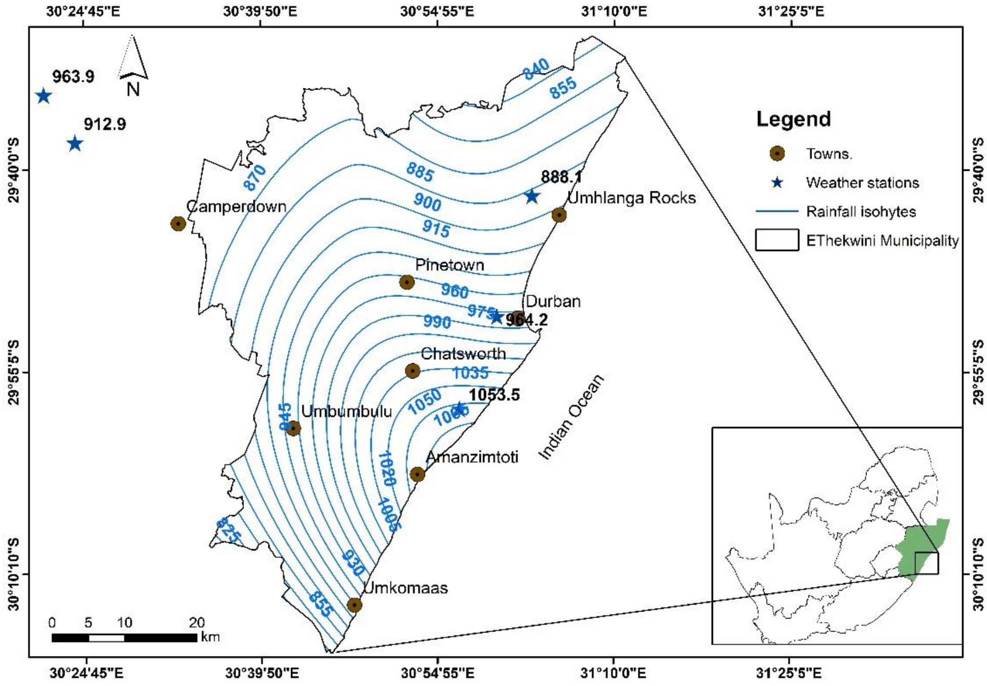


Figure 5.1. The eThekwini District Municipality rainfall distribution.

5.1.2. Evapotranspiration

Several equations have been developed to estimate evapotranspiration using climatic data. The FAO-Penman-Monteith Method (Allen et al., 1998) was used to estimate the monthly evapotranspiration for the study area (Figure 5.2). The estimated potential evapotranspiration (PET) for the year was 987 mm/year and the Turc method based actual evapotranspiration was estimated to be 749 mm/year.

5.1.3 Surface Runoff

Runoff, a component of the hydrological cycle, refers to that fraction of the rainfall which is not lost to infiltration, evaporation or transpiration, but flows across the terrestrial surface in rivers, streams or sheet flow across catchment (Beven, 2011; Fetter, 2014). The monthly and annual runoff for the study area was calculated using the Soil Conservation System (SCS) CN method and Rational formula. According to SCS (1986), the hydraulic condition of each land use can be determined based on the Hydrologic Soil Group (HSG) (Figure 5.3).The HSG, land use type, vegetation cover and hydraulic conditions are the basic parameters used for CN number calculation. Moreover, the rational method’s runoff coefficient was estimated using vegetation density and types; soil texture and slope percentage. Subsequently, the SCS method’s estimated annual runoff was calculated to be 132.73 mm/ year or 14% of mean annual precipitation (MAP), and the rational formula’s estimated annual runoff is 173.9 mm/year or 18.4% of MAP (Table 5.1, Figure 5.3). Comparison of the calculated runoff values using the SCS method and rational formula indicates that the SCS method’s runoff values are representative. This is supported by Smithers (2012) work, where the SCS method was found to be less sensitive to input parameters compared to the rational formula.

Table 5.1. The SCS curve number and rational methods’ estimates for monthly runoff (mm).

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
SCS Runoff (mm)	21.95	10.63	13.45	6.32	0.025	0.015	0.65	0.021	5.895	14.56	29.012	30.20
Rational runoff (mm)	23.59	12.92	16.25	9.37	5.05	2.44	4.57	3.26	9.72	17.49	33.20	36.06

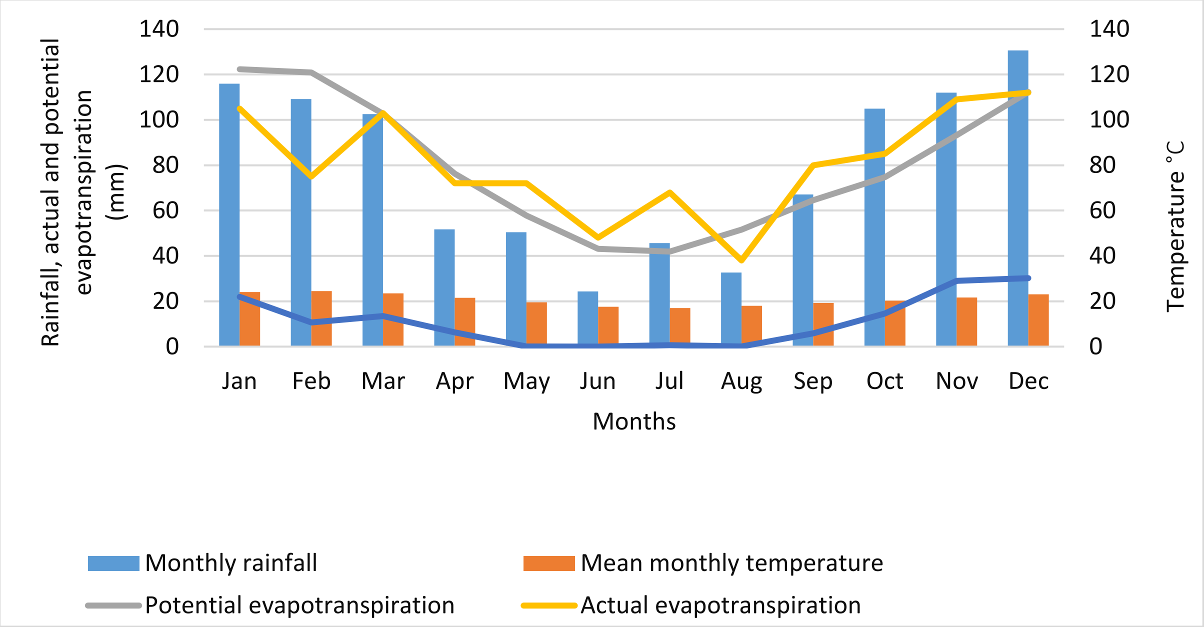


Figure 5.2. Graph exhibiting mean monthly temperature and potential evapotranspiration and runoff.

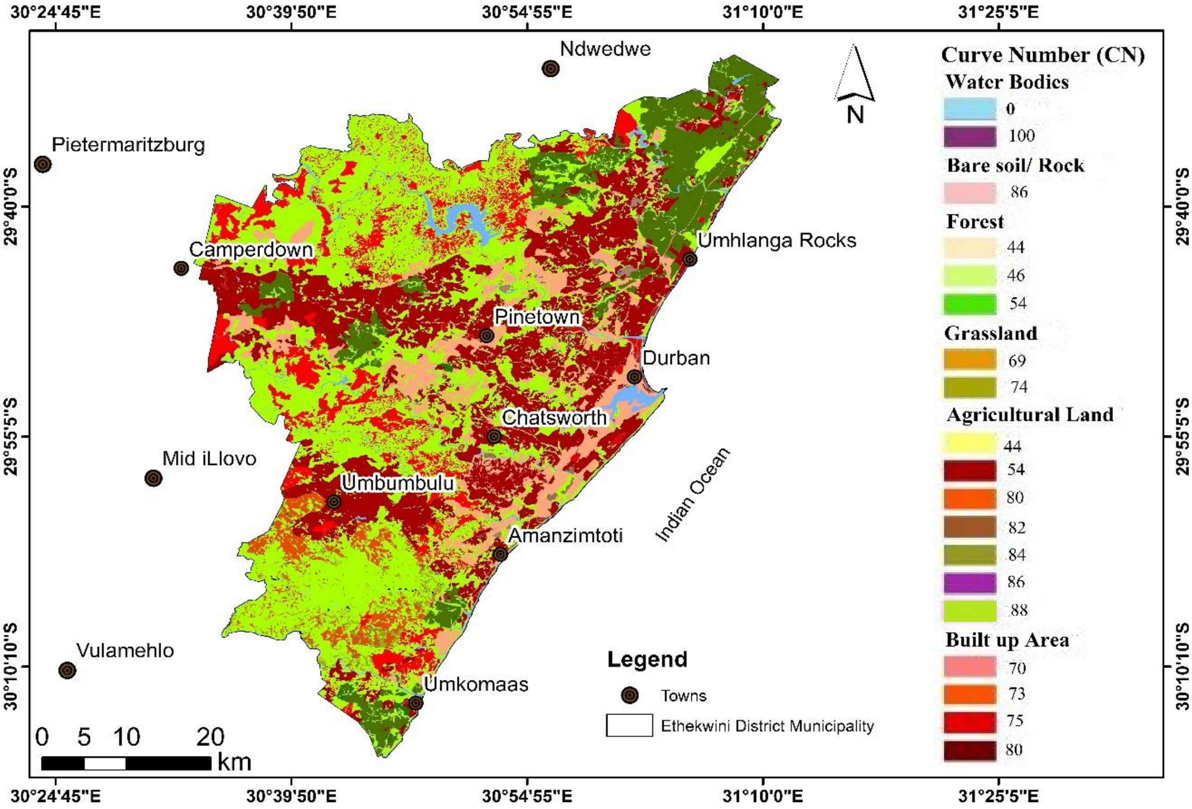


Figure 5.3. Land use map showing runoff CN numbers.

5.1.4 Groundwater abstraction and use

The groundwater use for the greater eThekwini District Municipality is estimated on the basis of registered groundwater uses reported in the Water use Authorization Registration Management Systems (WARMS) database of the Department of Water and Sanitation (DWS). The WARMS groundwater use data shows that industrial (urban), agricultural (irrigation) and industrial (non-urban) groundwater use accounts for the bulk of registered water uses (Table 5.2). The recorded value for urban (excluding industrial and /or domestic) is lower compared to all other water use sectors. Schedule One uses, which refers to private groundwater users and includes, amongst others, small-scale domestic use, gardening and watering of animals (DWA, 2009) accounts for only 3729 m^3/year, indicating that information on private groundwater use is very limited. High groundwater abstraction was observed in fractured aquifers owing to its good quality compared to the other aquifers found in the study area. The distribution of groundwater use within the study area is uneven, as shown in Figure 5.4.

It is to be noted that in the eThekwini District Municipality, surface water provides approximately 98% of all domestic, agricultural and industrial water uses. Only the remaining 2% of water use is supplied from registered and unregistered groundwater supply boreholes and springs.

Table 5.2. WARMS registered Groundwater Use for eThekwini District Municipality (WARMS, 2019)

Sector	**Groundwater use (m^3/year)**	**Percentage (%) of groundwater use**
Schedule 1	3729	0.3
Agriculture (Irrigation)	108632	8.72
Agriculture (Watering and livestock)	32316	2.6
Industry (Urban)	1013283	81.29
Industry (non-urban)	88500	7.1
Urban (excluding industrial and/or domestic)	25	0.002
Total	**1246485**	**100**

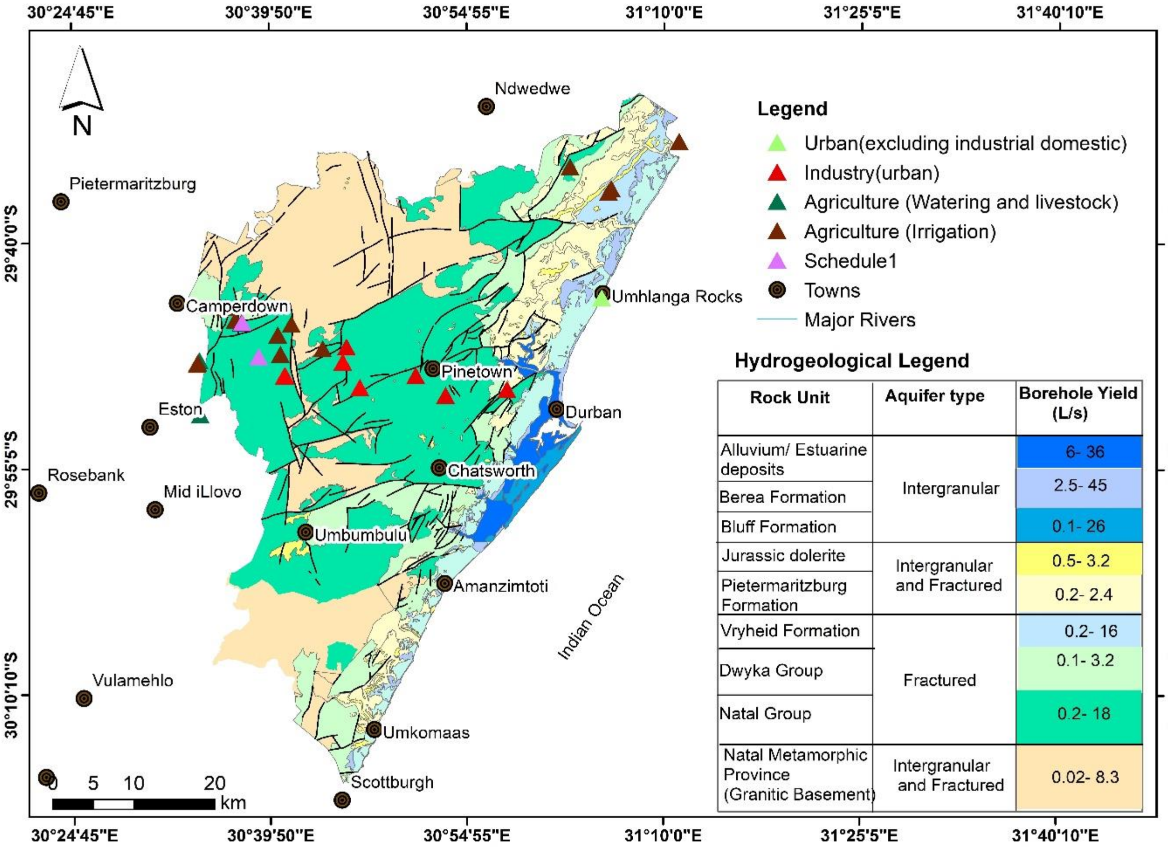


Figure 5.4. Groundwater use distribution map in the eThekwini District Municipality

5.1.5 Groundwater recharge

Groundwater recharge is influenced by meteorological and hydrogeological factors which vary spatially and temporally. Understanding, measuring and quantifying these factors are important to understand and quantify groundwater recharge with some degree of confidence (Tóth, 1963). Recharge estimation for the study area during the course of this research was undertaken using the CMB method. The CMB method assumes that the sole source of chloride is precipitation, and evapotranspiration is the only process that concentrates chloride in groundwater. Furthermore, the method assumes precipitation as the only contributor to groundwater recharge.

The mean rainfall chloride concentrations of 7.38 mg/L sourced from DWAF (2006) are used in the estimation of groundwater recharge in this study. A semi-distributed mean annual precipitation that was used is 985 mm/a, 817 mm/a, 947 mm/a, and 798 mm/a, derived from the isohyet map of Figure 5.1. The estimated recharge rate ranges from a minimum of about 36 mm/a (4% of MAP) to a maximum recharge rate of 236 mm/a (24% of MAP) (Table 5.3). The mean recharge rate based on all point recharge data in this study (Figure 5.5) is about 118 mm/a (12% of MAP), which compares well with previous studies, particularly with the value of 11.78% reported in Ndlovu et al. (2018).

The point recharge distribution (Figure 5.5) indicates that the eastern portion or coastal region of the eThekwini District Municipality, which is characterised by high rainfall, relatively gentle to flat topography and underlain by unconsolidated deposits of the Maputaland Group has the highest recharge rates. The recharge rate decreases gradually to the western regions of the study area relating to decreased rainfall, steep and rugged topography, poor vegetation cover and geology which favours run-off more than infiltration.

Table 5.3. Chloride mass balance recharge estimates.

Site Name	Latitude	Longitude	Ground water Chloride (mg/l)	Recharge (mm/year)	Recharge (% of MAP)
BHKB2S	-30.07513	30.85566	201.00	36.16	3.67
BHAT2S	-30.00839	30.91432	30.80	235.96	23.96
BHUMZ2S	-29.87547	30.88485	82.20	88.41	8.98
BHKWM2S	-29.72888	31.00671	76.00	91.97	9.71
BHTON1S	-29.55885	31.13869	32.10	217.74	22.99
BHHAM2S	-29.79920	30.66368	20.90	281.64	35.31
BHHAM2D	-29.79921	30.66368	35.50	165.81	20.79
BHDT1S	-29.78242	30.64268	98.40	59.82	7.50
BHDT1D	-29.78241	30.64268	52.60	111.91	14.03
ETM1	-29.92000	30.98006	78.32	88.06	9.42
ETM3	-30.00470	30.85111	28.52	241.78	25.87
ETM5	-29.78090	31.05207	44.62	154.56	16.54
ETM6	-29.84600	31.010805	36.45	189.18	20.24
ETM8	-29.97860	30.95503	33.14	208.07	22.27
ETM11	-30.10870	30.82026	108.98	63.28	6.77
ETM15	-29.71690	31.03404	69.47	99.28	10.62
ETM19	-29.59430	30.90064	52.95	130.25	13.94
ETM21	-29.68920	30.90943	54.57	126.38	13.52

ETM25	-29.86840	30.78066	102.90	67.02	7.17
148239	-29.83330	30.78333	40.00	172.41	18.45
171723	-30.22830	30.68472	67.80	101.72	10.88
171725	-30.25810	30.74722	192.60	35.81	3.83
172904	-30.30280	30.73611	192.00	35.92	3.84
184033	-29.94030	30.96777	105.60	65.31	6.99
Mean			**75.32**	**118.57**	**12.01**

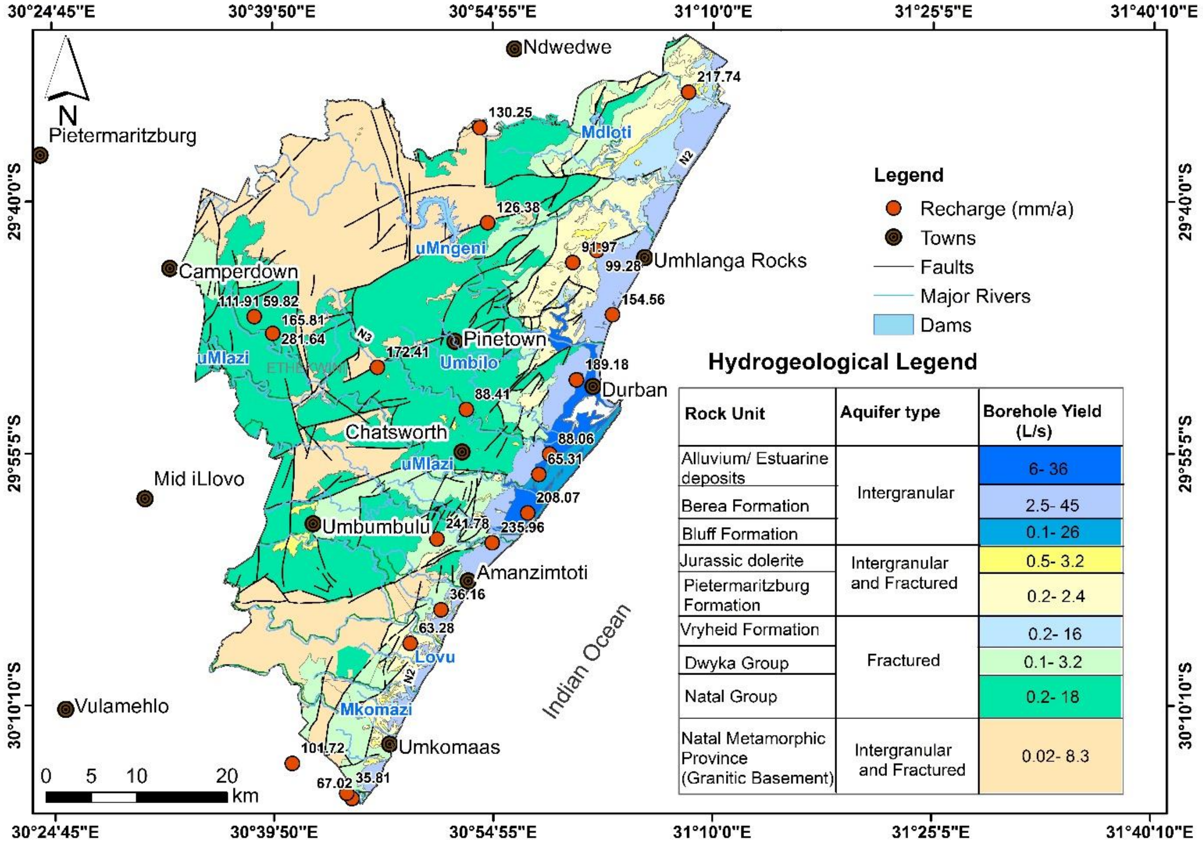


Figure 5.5. Spatial distribution of groundwater recharge, estimated using the CMB method.

The water balance method of groundwater recharge estimation which considers precipitation, evapotranspiration, surface runoff and groundwater abstraction gave recharge volume of 1.35 $x10^8$ m^3/ year or 63 mm/year (6.7% MAP). Thus, the average groundwater recharge, combining both methods, is approximately 87 mm/year or 9% of MAP).

5.2. Hydrogeological properties of the city of Durban

Groundwater occurrence and circulation in the study area is controlled by both geological structures (faults, joints, dykes, geological contacts and weathered zones in secondary aquifer) and the presence of void spaces between particles and openings within primary aquifers. In this regard, the study area comprises seven geological units of hydrogeological significance, namely: alluvial and estuarine deposits (locally called the Harbour Beds Formation), Berea Formation, Bluff Formation, Pietermaritzburg Formation, Vryheid Formation, Dwyka Group, Natal Group and Natal Metamorphic Province (Granitic Basement) (Bell and Maud, 2000). The hydrogeological units are grouped into three types of aquifers of varying thicknesses: intergranular, fractured and fractured and weathered. Intergranular or primary aquifers are made up of the Maputaland Group, comprising the Harbour Beds Formation, Berea Formation and Bluff Formation in this study. The fractured Natal Group sandstones, the Dwyka Group and the Vryheid Formation of the Ecca Group represent the fractured secondary aquifers, whilst the weathered and fractured dolerites, the Pietermaritzburg Formation of the Ecca Group and granite-gneisses are categorized as weathered and fractured aquifers. Three types of groundwater are observed in this project and their detailed descriptions are presented in the following sections.

5.2.1 Intergranular/Primary aquifers

The Harbour Beds Formation, which consists of unconsolidated sediments that varies in texture from medium to coarse grained sands to silty clays (Bell and Maud, 2000), form intergranular aquifers in the eastern side of the study area along the coast. The formation shows thickness that can be up to 60m but with a mean thickness of 15 m. The Harbour Beds Formation borehole yield vary from 6 to 33 l/s. The calculated transmissivity value from boreholes drilled in the alluvial and estuarine deposits has a median value of 0.34 m^2/day. This transmissivity value is not far off from the value Bell and Maud (2000) reported based on pump testing of several boreholes in Mgeni River Springfield flats, Papwa Sewgolum golf course and Windsor Park, which were 0.14, 0.03 and 1.46 m^2/day, respectively. These deposits are characterised by moderate hydraulic conductivity of 4.69 m/day.

The Berea Formation, locally known as the Berea Red Sand, is characterised by a basal boulder bed of marine origin which rests on a series of submarine-cut benches on the underlying bedrock (Bell and Maud, 2000). The boulder bed is distinctive with boulders that are well rounded, percussion marked and usually between 7.5 cm and 25 cm in diameter (King and Maud, 1964). The majority of the depth to groundwater level within this Formation is shallow (<6 m bgl) and borehole yields range from 0.13 to 45 l/. Extensive seepage has historically been reported to emanate from the base of the Berea Formation, just at the back of the shoreline (Bell and Maud, 2000). Based on the available borehole records, the calculated hydraulic conductivity for the Berea Formation ranges from 5 m/day to 6.22 m/day (Table 5.4**Error! Reference source not found.**).

The Bluff Formation is predominantly made up of medium to coarse grained sand which is subangular to rounded (Bell and Maud, 2000). It has an average thickness of between 10 and 53 m and a borehole yield range from 0.13 to 45 l/s. The Bluff Formation shows a mean hydraulic conductivity of 3.2 m/day, while recording transmissivity of about 9.6 m^2/day (Ndlovu *et al*., 2018).

Table 5.4. Aquifer parameters for the Intergranular aquifers in the study area

Reference	**Bell and Maud (2000)**	**King (2002)**	**Ndlovu (2018)**
Geological unit	**Harbour beds (Alluvium and estuarine deposits)**		
Yield (l/s)	33	50	6- 36
Transmissivity (m^2/day)	-	-	32
Hydraulic conductivity (m/day)	-	5	6.5
Storativity	-	0.18	-
Porosity (%)	-	-	-
Thickness (m)	25- 60	-	2- 73
Geological unit	**Berea Formation**		
Yield (l/s)	1.7	50	2.5-45
Transmissivity (m^2/day)	406	-	7
Hydraulic conductivity (m/day)	-	5	5
Storativity	-	0.18	406
Porosity (%)	-	-	-
Thickness (m)	100	-	0.5-45
Geological unit	**Bluff Formation**		
Yield (l/s)	2.3-4	50	0.1-26
Transmissivity (m^2/day)	5.94-51.1	-	9.6

Hydraulic conductivity (m/day)		5	3.2
Storativity		0.18	-
Porosity (%)		-	-
Thickness (m)	0.5- 45	-	10- 75

"-" Denotes no available data

5.2.2 Fractured aquifers

The Natal Group sandstone, Dwyka Group and Vryheid Formation of the Ecca Group are examples of fractured aquifers observed in this study. The sandstones of the Natal Group generally vary from fine-to medium-grained and are commonly moderately wide to narrow jointed (Bell and Lindsay, 1999). The Natal Group exhibits borehole yield range and thickness of 0.2 to 18 l/s and 400 m, respectively. The average calculated storativity, hydraulic conductivity and range of porosity for the Natal Group is 0.001, 2.8 m/day, 9.0 to 16.9%, respectively (van Wyk, 1963; Ndlovu et al., 2018).

The Dwyka Group varies in thickness from 5 to 400 m and its borehole yields are less than 3 l/s, with the average yield being 0.13 l/s (Table 5.5). Its usual hydraulic conductivity is around 0.8 m/day and has virtually no primary porosity, resulting in aquitards instead of aquifers (Ndlovu et al., 2018). The Dwyka Group is the poorest secondary groundwater aquifer in the study, with a mean transmissivity value of 2.09 m^2/day (Jonker, 2016).

The fractured Vryheid Formation sandstone is shows hydraulic conductivity, transmissivity and a mean borehole yield of 0.17 m/day, 6.3 m^2/day and 0.01 to 16 l/s l/s, respectively (Ndlovu et al., 2018). According to van Wyk (1963), the average porosity for the Vryheid Formation ranges between 4.0 and 12.9%.

Table 5.5. Aquifer parameters for the fractured aquifers in the study area

Reference	**Bell and Maud (2000)**	**King (2002)**	**Ndlovu (2018)**
Geological unit	**Vryheid Formation**		
Yield (l/s)	0.1-26	-	0.01- 16
Transmissivity (m^2/day)		-	6.3
Hydraulic conductivity (m/day)	-	0.47-7.7	0.17
Storativity	-	0.0005-0.005	-
Porosity (%)	-	-	-
Thickness (m)	<300	-	15-105

Geological unit	**Dwyka Group**		
Yield (l/s)	0.01-3.2	-	0.1-3.2
Transmissivity (m^2/day)	-	-	1.3
Hydraulic conductivity (m/day)	-	0.4-7.7	0.8
Storativity	-	0.0005-0.005	-
Porosity (%)	-	-	-
Thickness (m)	250-400	-	5-135
Geological unit	**Natal Group**		
Yield (l/s)	0.02-2.7	-	0.2-18
Transmissivity (m^2/day)	-	-	8.32
Hydraulic conductivity (m/day)	-	0.04- 7.7	2.87
Storativity	-	0.0005-0.005	-
Porosity (%)	-	-	-
Thickness (m)	200-400	-	20-350

"-" Denotes no available data

5.2.3 Weathered and fractured aquifers

The weathered and fractured aquifers studied in this project are generally the Jurassic dolerite intrusions, the Pietermaritzburg Formation shale of the Ecca Group and the granitic basement rocks. These units provide evidence that groundwater is present in intergranular interstices in the saturated weathered zone, joints and fractures. The Karoo dolerites hinder groundwater movement, showing a yield that vary from 0.5 to 3.2 l/s and a maximum hydraulic conductivity of 0.5 m/day. The Pietermaritzburg Formation includes shale, exhibiting properties of an aquitard and not an aquifer, with groundwater mainly percolating in fracture zones and bedding planes. It is characterised by very low average hydraulic conductivity and a transmissivity of 0.03 m/day and 0.28 m^2 /day, respectively (Table 5.7). The granitic basement rocks are characterised by average hydraulic conductivity of 0.56 m/day and transmissivity of 0.46 m^2 /day, with borehole yields ranging from 0.02 - 10 l/s. Groundwater in the basement aquifers occur in near surface weathered zones with poor storage capacity, and the clay content produced from weathered feldspars exhibiting high porosity, and poor hydraulic conductivity (Ndlovu et al., 2018).

Table 5.7. Weathered and fractured aquifers' parameters observed in this project.

Reference	**Bell and Maud (2000)**	**King (2002)**	**Ndlovu (2018)**
Geological unit	**Pietermaritzburg Formation**		
Yield (l/s)	0.02-23.2	0.5-2	0.02-2.4
Transmissivity (m^2/d)	-		0.28
Hydraulic conductivity (m/d)	-	0.05-0.5	0.03
Storativity	-	0.0001-0.001	-
Porosity (%)	-	-	-
Thickness (m)	80-100	-	15-105
Geological unit	**Granitic Basement**		
Yield (l/s)	0.2- 4.7	-	0.02-8.3
Transmissivity (m^2/d)	-	-	3.9
Hydraulic conductivity (m/d)	-	-	0.56
Storativity	-	-	-
Porosity (%)	-	-	-
Thickness (m)	-	-	250-350

"-" Denotes no available data

5.3. Groundwater levels and flow direction

Historical water level measurements from 934 boreholes were compiled and integrated to generate a map representing the depth to groundwater for this project (Figure 5.6). The depth to groundwater in the study area varies spatially, controlled by the local geology, topography and the rate of recharge and discharge. The groundwater level for areas close to the coast and alongside major river courses such as the uMgeni, Mkomazi region of the eThekwini Municipality ranges from 0 to 15 m below ground level (bgl) (Figure 5.6). The groundwater levels in the Ecca Group and Dwyka Group have similar median values of 20 m bgl and 21 m bgl. The greatest percentage of deep (>50 m) groundwater level depths are associated with boreholes drilled in the granitic basement.

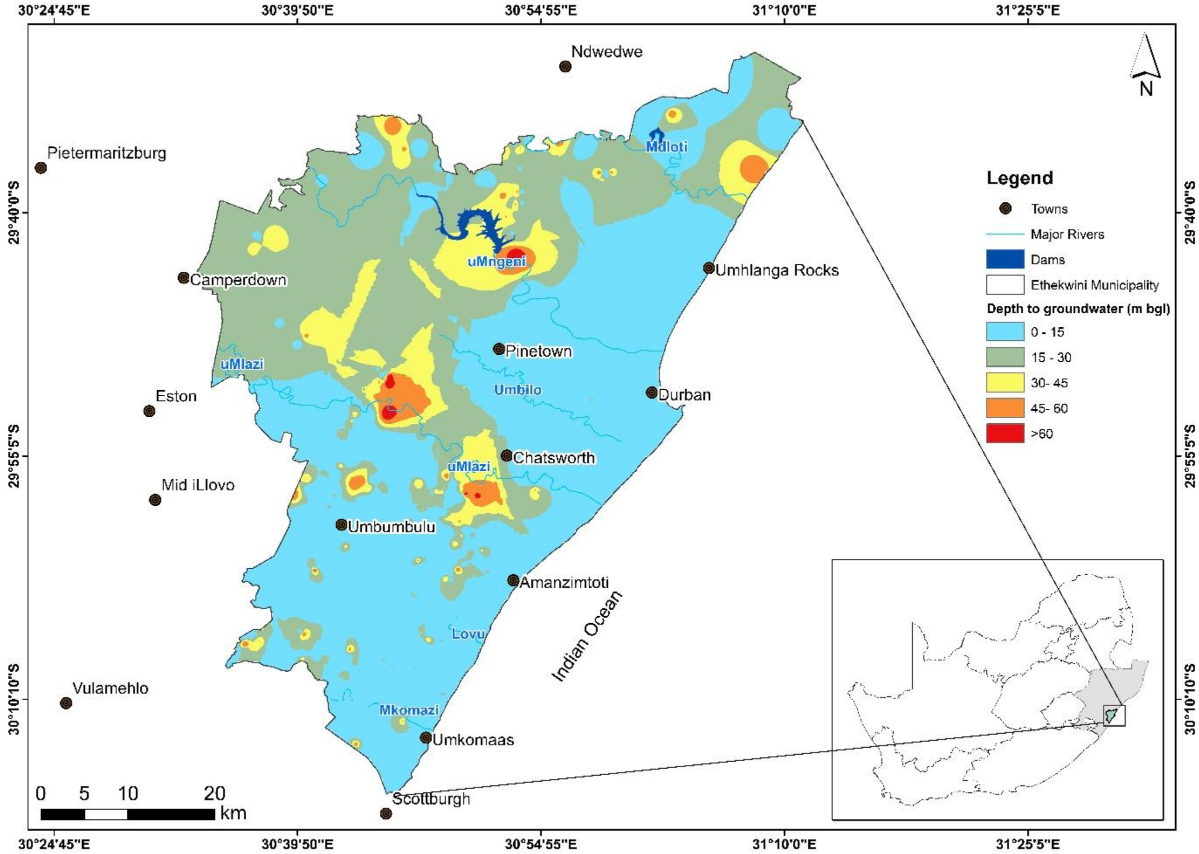


Figure 5.6. Map showing the depth to groundwater level observed in this study

The depth to groundwater level data is used to generate groundwater elevation above mean sea level (amsl). The depth to groundwater level is also interpolated to construct a groundwater level contour map and the direction of groundwater flow. Groundwater level data from 934 boreholes were used in the construction of the groundwater level contour map, with which their longitudes, latitudes and surface elevations were included. The contour map (Figure 5.7) showing the groundwater level supports that groundwater flows from the west to east within the study area. The local groundwater flow vectors indicate complex flow patterns relating to local geological and topographical factors. The groundwater flow gradient is steep in the western granitic basement but gentle in the Maputaland Group. Consequently, the general groundwater flow is from the elevated western areas toward the coastal region.

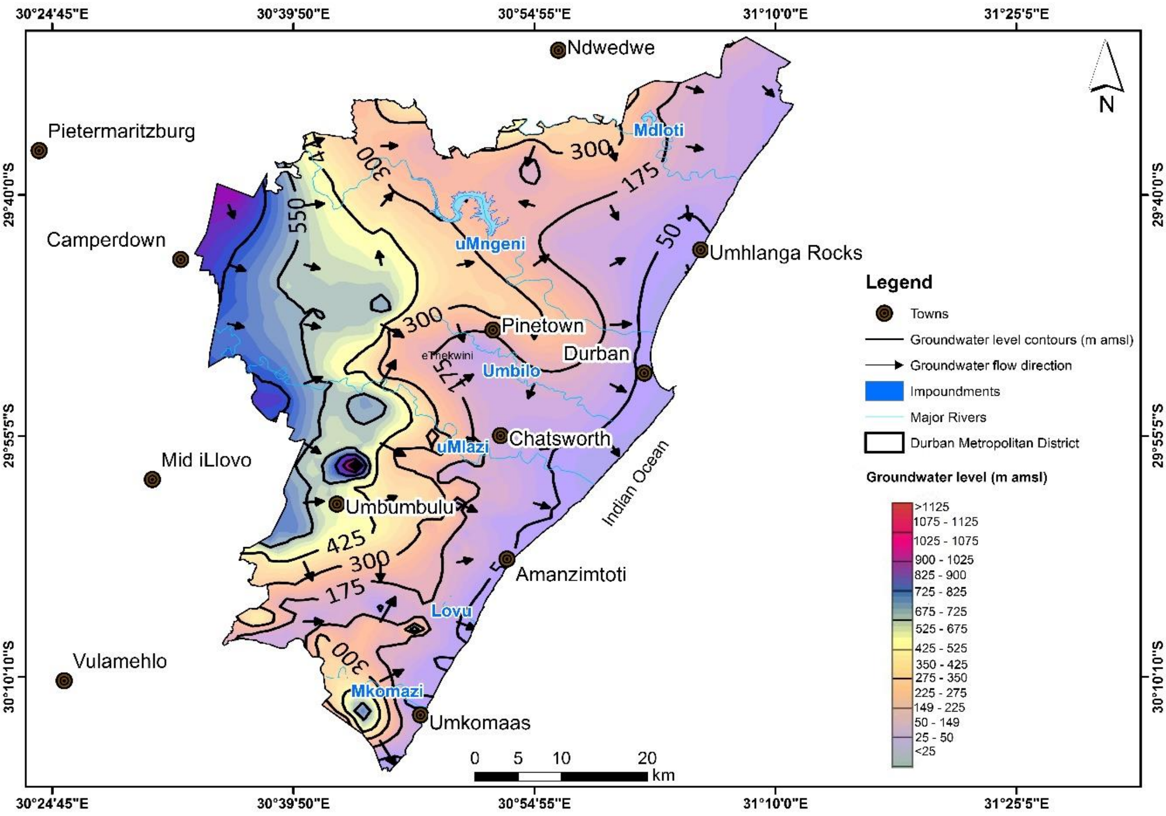


Figure 5.7. Contour map showing groundwater flow directions present in this study.

5.4 Groundwater hydrochemistry

Many studies (DWAF, 1995; Bell and Maud, 2000; Ndlovu et al., 2018) have been conducted and documented on the groundwater hydrochemistry of the greater Durban Metropolitan region. A summary of the groundwater hydrochemistry of the eThekwini District Municipality and the groundwater quality are presented based on aquifer types in the following sections using published literature and additional hydrochemical data from the WARMS, GRIP and NGA.

5.4.1 Intergranular/ primary aquifers

The intergranular aquifer's hydrochemical data that are spread across the aquifers is summarised in Figure 5.8 is shown in Appendix 2.1. Based on the available hydrochemical information, the groundwater pH is near neutral to slightly alkaline (pH 6.3 to 8.5). Adams et al. (2001) stated that groundwater pH ranges between 6.3 and 8.5 is an indication that the dissolved carbonates are predominantly in the HCO_3^- form. The majority of the water samples indicate freshwater (TDS <1000 mg/l). However, one sample (sample ETK7) is brackish (TDS

2534 mg/l).The Electrical Conductivity (EC) of groundwater in the study area varies between 5.5 µS/cm to 119.1 µS/cm, which is within the South African National Standard (SANS) 241: 2015 drinking water quality standards (SABS, 2015). The total dissolved solids (TDS) in the intergranular aquifers are in the range from 252 mg/L to 2534 mg/L. Therefore, ETK7 does not meet the permissible limit for domestic purposes based on the TDS, which is above 1200 mg/L.

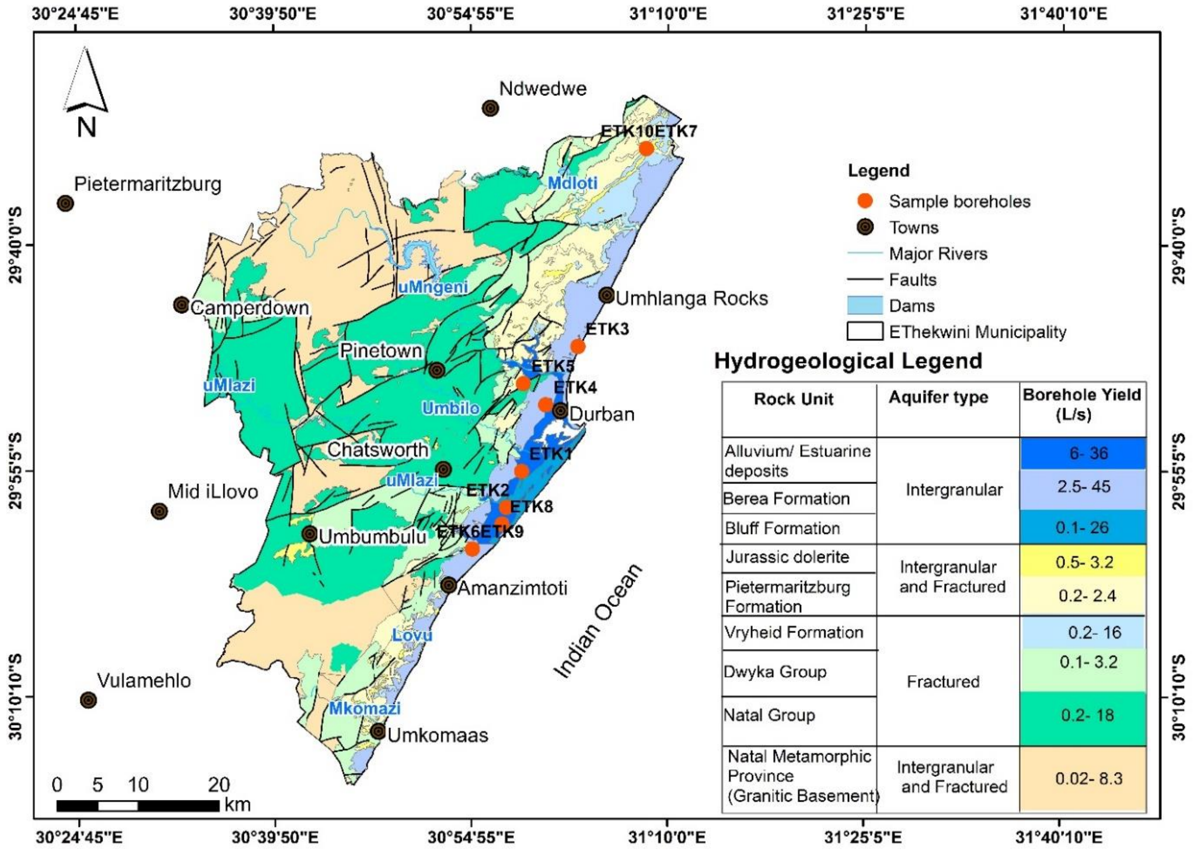


Figure 5.8. Distribution of groundwater samples from intergranular aquifers

All the groundwater hydrochemical data collected for the intergranular aquifer are plotted on the Piper diagram to identify the hydrochemical facies. The geochemical evolution of water in general (groundwater in particular) can be understood by constructing a Piper (1944) trilinear diagram and Durov (1948) plot.

Based on the Piper diagram of Figure 5.9, boreholes ETK7 and ETK10 indicate calcium sulphate waters, which are plotted in the far-right quadrant of the Piper diagram, confirming a relatively saline water type and may suggest pollution. Sample ETK8 is plotted in the left quadrant of the Piper diagram, suggesting recently recharged groundwater. This water sample contains high Ca^{2+} and HCO_3^- concentrations, typical of recharge area groundwater. This is in agreement with Gomo *et al*. (2013), who confirmed that during recharge to the groundwater system, water interacts with the carbonate minerals resulting in high Ca^{2+}, Mg^{2+} and HCO_3^- in the system. Additionally, Jalali (2009) stated that during dissolution of carbonate cement materials in clastic rocks, Ca^{2+} and HCO_3^- are released into solution leading to Ca-HCO_3 water type. Sample ETK9 demonstrates the dominance of alkaline water with prevailing HCO_3^- . The remaining water samples plot in the middle of the piper diagram showing mixing. The order of the abundance of the ions of groundwater in the intergranular aquifers is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-}$.

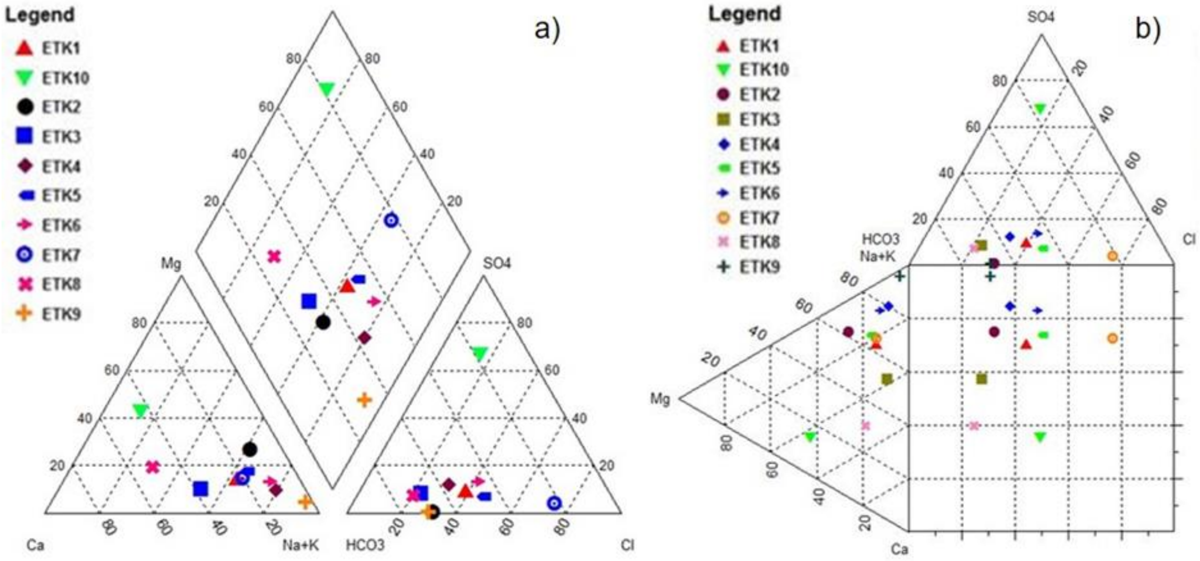


Figure 5.9. Piper diagram of groundwater samples from the intergranular aquifers

The water samples were further plotted in the Stiff Diagram (Figure 5.10) in order to display the dominant ions in the groundwater samples based on the major cations (Ca^{2+}, Mg^{2+} and Na^++K^+) and anions (Cl^-, SO_4^{2-}, and HCO_3^-) concentrations. The plot on Figure 5.10 represents average values of ten water samples (ETK1 to ETK10). Sample ETK7 has a funnel shape, which indicated the relatively high Na and Cl with relatively low Ca concentration. Sample ETK9 indicates the presence of Na, Cl with relatively low Cl and high HCO_3. Sample ETK10 shows a low Na and Cl concentration and high Mg and SO_4 concentration. Samples ETK1, ETK4, ETK5 and ETK6 indicates Na and Cl with relatively lower Ca and HCO_3 concentration and even very low Mg and SO_4.

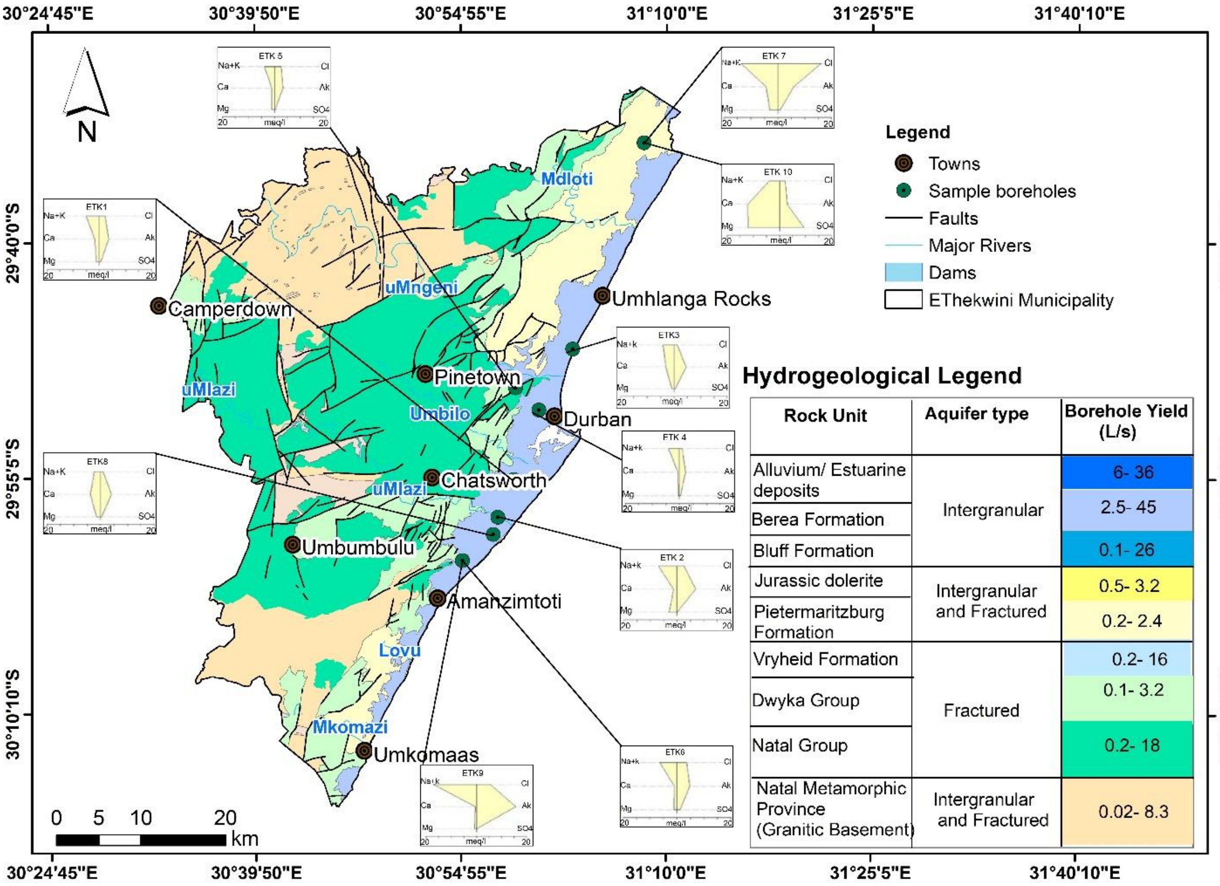


Figure 5.10. Stiff diagram of groundwater samples from the intergranular aquifers.

5.4.2 Fractured aquifers

The hydrochemical database for the fractured aquifers consists of 32 boreholes, which are distributed across the fractured aquifer (Figure 5.11). Appendix 1.2 presents the available data. The pH in the groundwater samples ranged from 5.46 to 7.37 with an average pH value of 6.78. This water meets the SANS 241: 2015 drinking water quality standards of pH, which is 5 to 9.7. The EC values vary between 12 µS/cm to 1267 µS/cm, with an average of 258.76 µS/cm. The highest recorded EC value of 1267 µS/cm is associated with sample ETK 13. All the samples meet the SANS 241:2015 drinking water quality standards with regards to EC less than 1700 µS/cm. TDS ranged from 27.2 mg/l to 588 mg/l (indicating fresh to slightly saline water within the fractured aquifers).

All of the sulphate values comply with SANS 241:2015 drinking water quality standards, as the values are below 500 mg/l. This could be a reflection of the absence of pyritic and gypsum minerals. Concentrations of chloride vary from 20.9 mg/l to 1043 mg/l. The chloride composition from seven samples (ETK 15, ETK16, ETK18, ETK25, ETK27, ETK30 and ETK40) had values exceeding the 300 mg/l SANS 241:2015 drinking water quality standard relating to underlying geology (Appendix 2.2). These samples are associated with the Dwyka Group (samples ETK 15, ETK16, ETK18 and ETK25) and Natal Group (samples ETK27, ETK30 and ETK40). Additionally, the possibility of human influence on groundwater chloride enrichment cannot be ignored. Anthropogenic activities such as the use of fertilizers and septic systems may contribute to elevated chloride and nitrate concentrations, especially because these boreholes are located in the western region of the study area where the land is mostly rural and used for agricultural purposes.

The nitrate concentrations range from 0.01 mg/l to 92.4 mg/l. Elevated nitrate concentrations are observed in sample ETK38 and ETK37 with concentrations of 14.9 mg/l and 92.4 mg/l and may relate to the use of septic tanks and fertilizers in the area. An excessively high concentration of 92.4 mg/l observed in ETK37 could be due to localised contamination from the effluent sourced from septic systems.

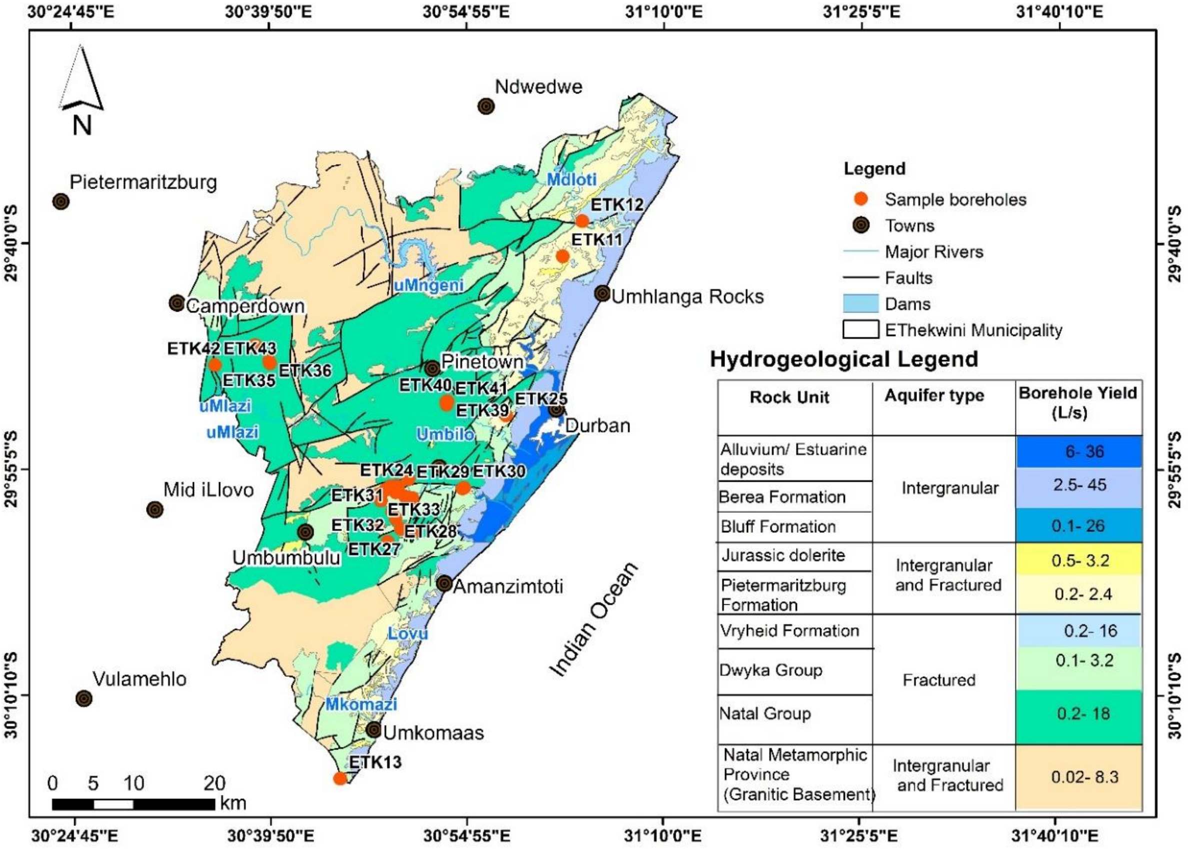


Figure 5.11. Distribution of groundwater samples from fractured aquifer

The piper plot of the fractured aquifer groundwater hydrochemistry dataset is shown in Figure 5.12. Samples ETK35, ETK22, ETK23 and ETK29 are characterised by calcium or magnesium bicarbonate water which indicates recently recharged water. Sodium bicarbonate water types are observed in borehole samples ETK32, ETK17 and ETK13. Samples ETK43, ETK18, ETK15, ETK41, ETK37, ETK39, ETK34 and ETK24 categorises as calcium sulphate waters. The remaining water samples indicate a sodium chloride water type, and this could represent old groundwater. The order of the abundance of ions in the groundwater is Na^+> Ca^{2+}> Mg^{2+}> K^+ and HCO_3^- > Cl^-> SO_4^{2-}.

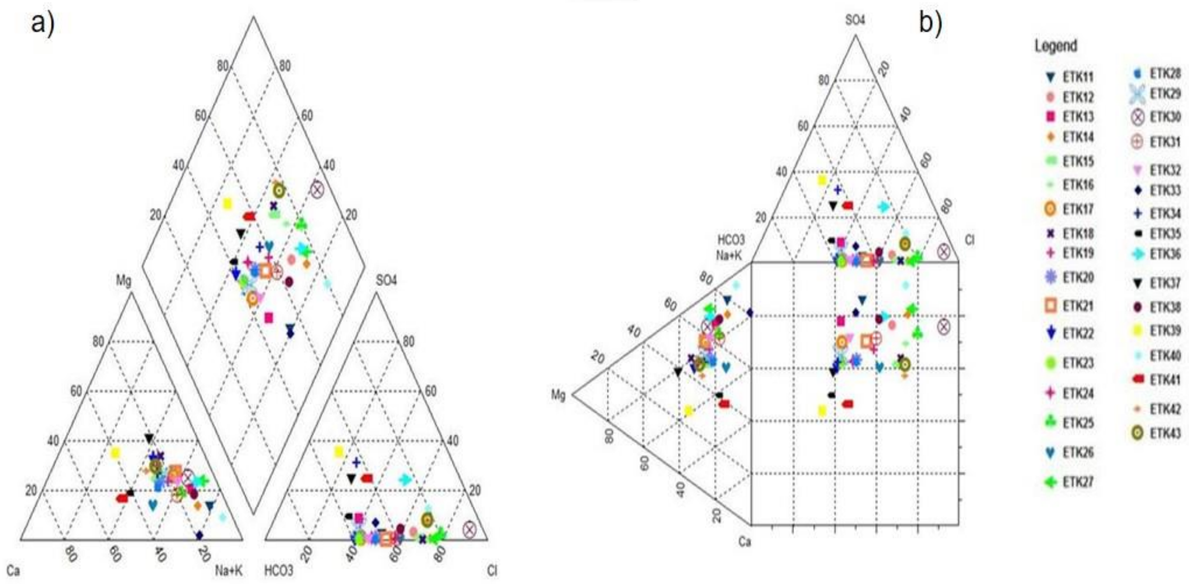


Figure 5.12. Piper diagram of hydrochemical data from the fractured aquifers

The Stiff diagram in Figure 5.13 represents average values of dominating ions in 32 samples. The samples ETK 16, ETK25, ETK30, ETK36, ETK40, ETK42 and ETK43 have funnel shapes, which indicate relatively high Na^+, Cl_- and $Mg^{2+-}HCO_3^-$ SO_4^{2-} with relatively low concentrations. Samples ETK12, ETK14, ETK18, ETK19, ETK26, ETK27 and ETK38 categorize as the Na^+ - Cl^- and Ca^{2+} – Mg^{2+} - HCO_3^- types with a low concentration of HCO_3^-.

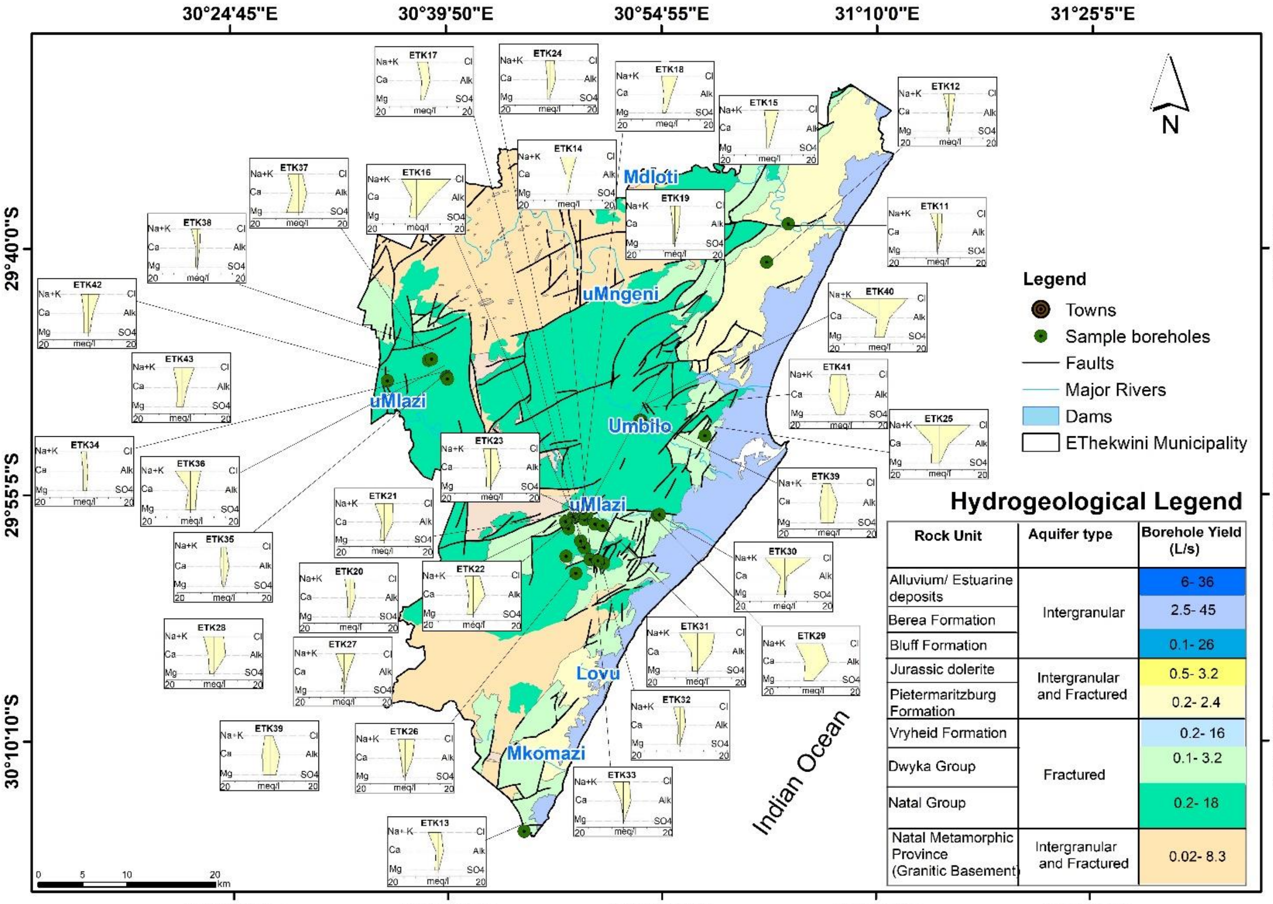


Figure 5.13. Stiff diagram of groundwater samples from the fractured aquifers

5.4.3 Weathered and fractured aquifers

The hydrochemical data for the weathered and fractured aquifers consists of 24 samples, which are distributed across the weathered and fractured aquifers (Figure 5.14). Appendix 2.3 presents the overall available hydrochemical data. The groundwater samples have pH values that vary between 6.23 and 8.55, with an average pH value of 7.23. The water composition meets the SANS 241: 2015 standards for pH. The EC values vary between 10 µS/cm to 1530 µS/cm. The highest recorded EC value is associated with sample ETK 44. All samples meet the SANS 241:2015 standard of less than 1700 µS/cm. TDS ranged from 8.2 mg/l to 765mg/l, with an average of 406.88 mg/l (indicating fresh water).

Sulphate concentrations in all samples are within the SANS 241:2015 drinking water quality limits of 250 to 500 mg/l. Similarly, elevated chloride concentrations exceeding SANS 241:2015 drinking water quality limits were reported for all samples associated with the

Pietermaritzburg Formation (ETK 46, ETK49, ETK51, ETK52 and ETK54), relating to the influence of underlying geology on groundwater quality.

The sodium concentrations ranged from 8.7 mg/l to 233.41 mg/l. The sodium concentrations are in excess of the SANS 241: 2015 drinking water quality standards for sample ETK44 and ETK52. The nitrate concentrations ranged from 0.67 mg/l to 31.83 mg/l. Concentrations of elevated nitrate concentration are within the SANS 241: 2015 drinking water quality standards for sample ETK 48. This could result from agricultural activities in the area.

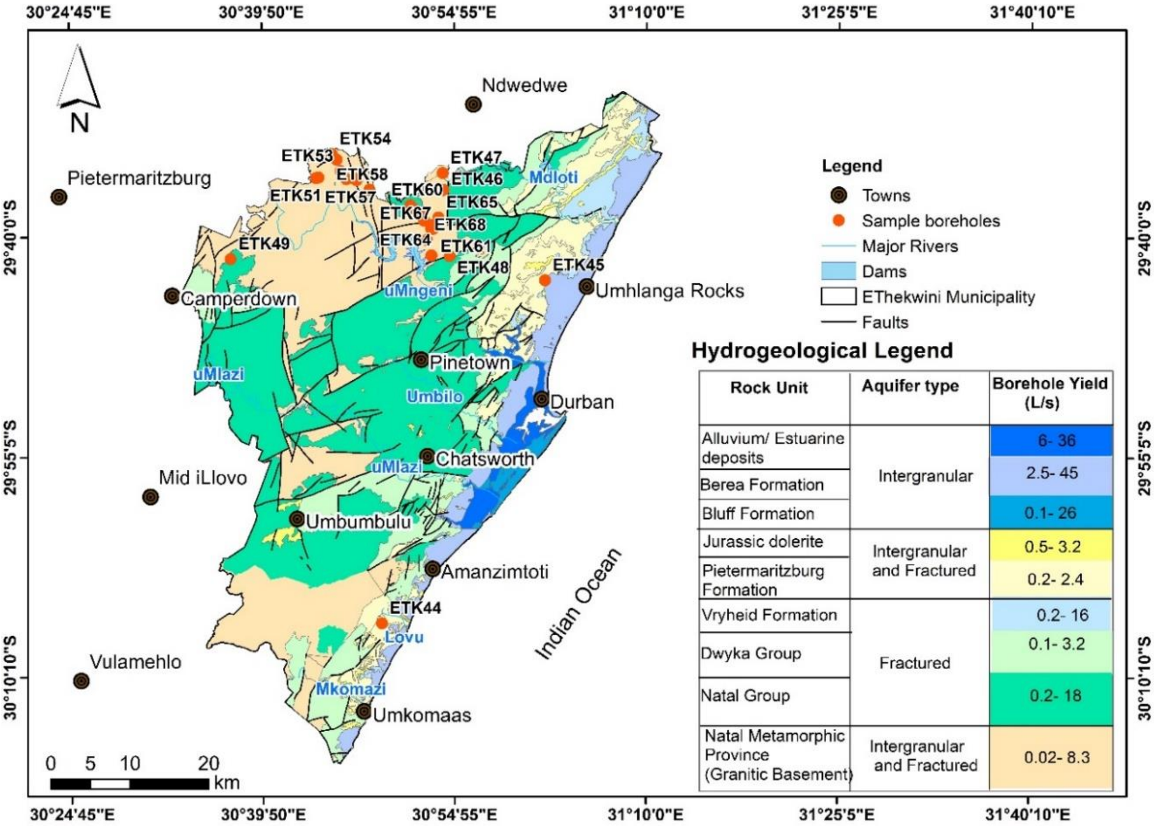


Figure 5.14. Distribution of samples on weathered and fractured aquifer

The Piper plot of hydrochemical data for the weathered and fractured aquifers is shown in Figure 5.15. The samples ETK50, ETK53, ETK64 and ETK66 plot on the Na^+-Cl^- composition, which is a typical of old marine water or deep groundwater. The hydrochemical signature indicates that water has undergone significant ion exchange because of the long residence time in the aquifer. ETK46, ETK47, ETK56, ETK57, ETK58, ETK60 and ETK68 indicate that the water was recently recharged by groundwater rich in calcium and/or magnesium and bicarbonate. The remaining samples indicate sodium bicarbonate water type which is indicative of a dynamic and flushed system as the water is rich in bicarbonate and increasing sodium concentrations. The order of the abundance of the ions in the groundwater is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$.

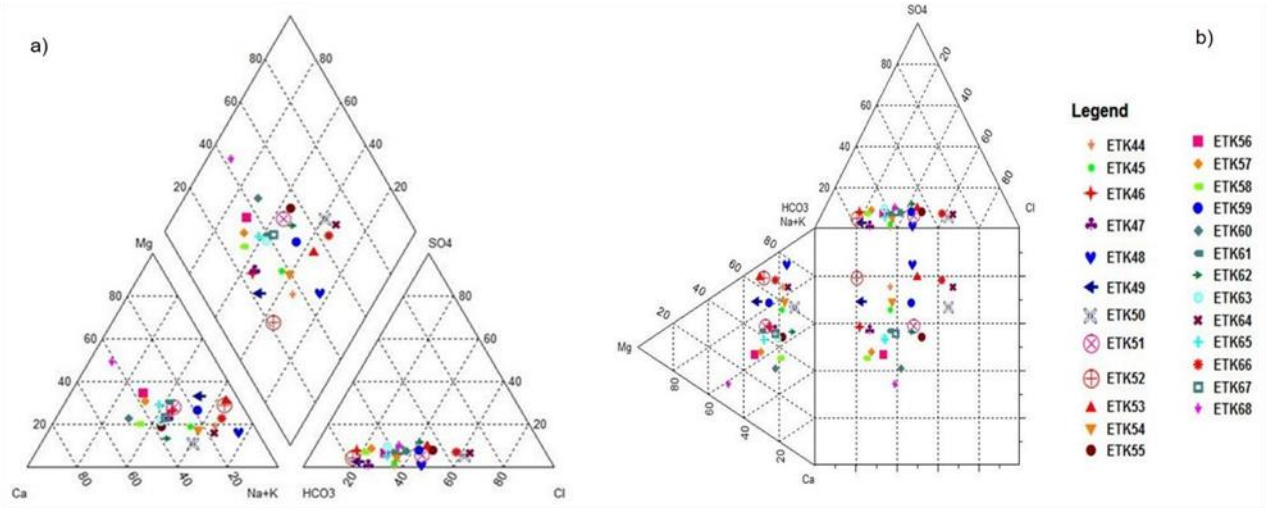


Figure 5.15. Piper diagram of the fractured and weathered aquifers

The stiff plot in Figure 5. 16 represent average values of 24 samples. The ETK 44, ETK45, ETK52, ETK59 and ETK48 water samples indicate presence of Na^+-Cl^- and Ca^{2+} – Mg^{2+} - HCO_3^- with relatively low concentration of SO_4^{2-}. The ETK66, ETK64, ETK51 and ETK50 water samples have funnel shapes, which indicate the relatively high Na^+ - Cl^- and Mg - HCO_3^- - SO_4^2 with relatively low Ca concentration. Samples ETK46, ETK47, ETK49, ETK56, ETK57, ETK58, ETK61, ETK63, ETK65 and ETK67 categorize as Na-Cl with relatively low Ca^{2+}- HCO_3^- and SO_4^{2-} concentrations. ETK53, ETK54, ETK55, ETK60 and ETK62 water samples indicate occurrence of Ca^{2+} - HCO_3^- with a relatively low Na^+ - Cl^- concentration, but a very low concentration of Mg^{2+} - SO_4^{2-}.

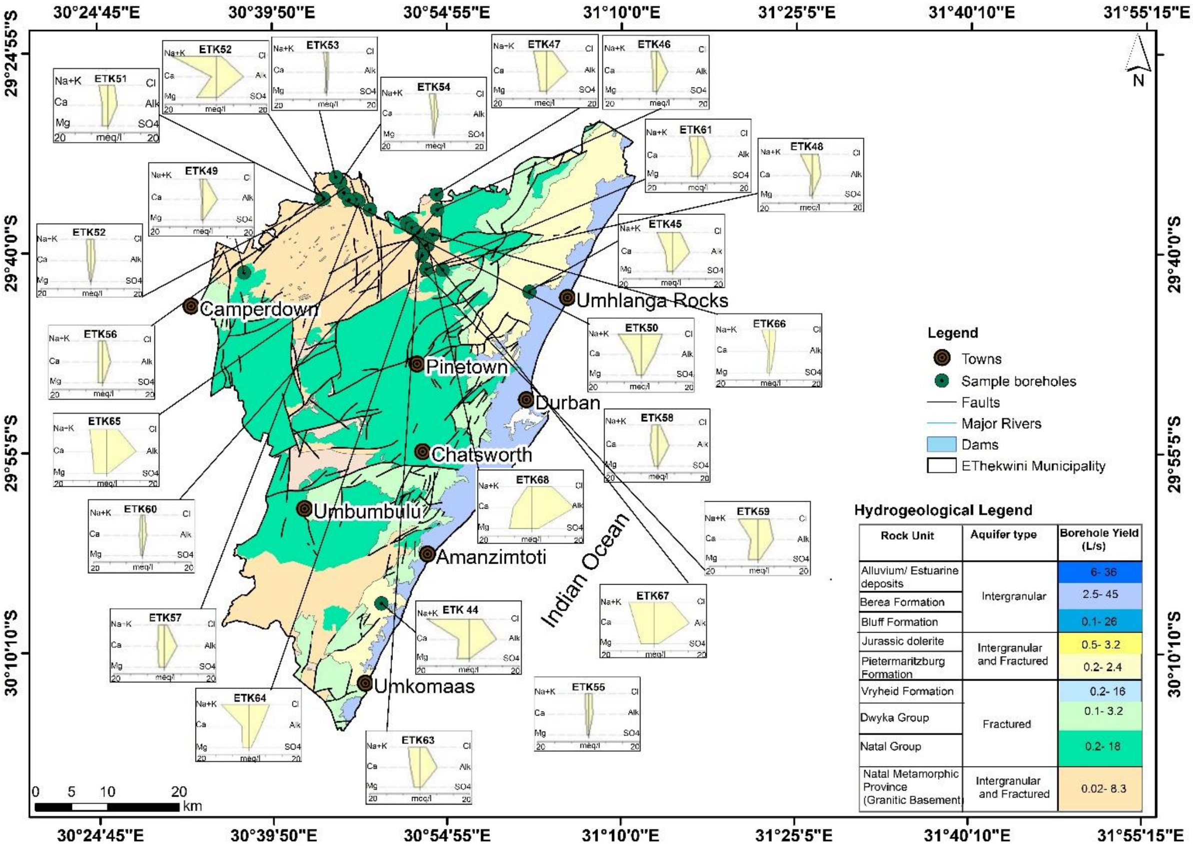


Figure 5.16. Stiff diagrams for weathered and fractured aquifers

5.4.4 Statistical analysis of hydrochemical data

To further illustrate the distinction between the different water types in terms of hydrochemical parameters, a statistical analysis was conducted on data sets collected from 68 boreholes distributed throughout the study area. The statistical analysis showing the minimum, maximum, mean and standard deviation of the parameters in the hydrochemical data as shown in Table 5.7. The pH of the groundwater vary from a slightly acidic (5.46) composition to an alkaline (8.55) one. The EC showed a large variation from 10 µS/cm to 1530 µS/cm. The groundwater in the study area falls into the category of fresh and brackish waters. The TDS reflected a wide range from 8.2 to 2534 mg/l. The water samples observed in this study are exhibit high variations in concentrations of Na^+ (8.70 – 492.00mg/l), Cl^- (15.00 – 1043.00 mg/l), SO_4^{2-} (0.75 – 450.00 mg/l), HCO_3^- (28.00 – 782.74 mg/l) and NO_3^- (0.50 – 220.00mg/l).

Table 5.7. Groundwater hydrochemical parameters (all concentrations in mg/l and EC in µS/cm)

Variables	No of datasets	Minimum	Maximum	Mean	Std Deviation
TDS	68	21.0	2534.0	515.74	432.80
EC	68	10.0	1530.0	297.58	352.20
pH	68	5.46	8.55	7.02	0.50
Na^+	68	8.70	492.00	111.48	92.86
K^+	68	-1.00	24.50	4.23	4.46
Ca^{2+}	68	1.00	243.00	39.29	35.02
Mg^{2+}	68	1.00	146.00	24.61	22.50
Cl^-	68	15.00	1043.00	151.47	186.14
HCO_3^{--}	68	28.00	782.74	210.42	136.23
NO_3^-	10	0.50	220.00	30.06	67.46
$SO4^{2-}$	68	0.75	450.00	24.90	58.24

A bivariate Pearson's correlation matrix of measured variables was computed to understand the relationship between the various hydrochemical parameters (Table 5.8). Pearson’s correlation showed statistical relationships between variables. Pearson’s product-moment correlation (r) is expressed as a measure of linear dependence between two variables that is expressed as the covariance of the two variables divided by the product of their standard deviation. The resultant dimensionless r value ranges between +1 and -1, where 1 is perfect positive linear. Correlations among variables with $r \geq 0.5$ are regarded as meaningful in this study. The correlation strength of variables is described as very strong (r = 0.8 - 1), strong (0.70 - 0.79), moderate (r = 0.5 - 0.69), or weak (r = 0 - 0.49) (Borradaile, 2003).

There is a very strong positive correlation between TDS and Cl^- (r = 0.973); Na^+ and HCO_3^- (r = 0.838); Ca^{2+} and NO_3^- (r = 0.904) & SO_4^{2-} (r = 0.923); Mg^{2+} and NO_3^- (r = 0.936) & SO_4^{2-} (r = 0.959); and between NO_3^- & SO_4^{2-} (r = 0.985). There is a strong positive correlation between EC and K^+ (r = 0.726) and between K^+ and HCO_3^- (r = 0.720).

Table 5.8. Pearson correlation matrices for groundwater hydrochemical data

Variables	TDS	EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_{3-}	NO_3-	$SO4^{2-}$
TDS	1										
EC	.230	1									

pH	-.086	-.037	1								
Na^+	.602	.525	-.158	1							
K^+	-.091	.726	.010	.402	1						
Ca^{2+}	.103	.092	-.053	-.197	-.287	1					
Mg^{2+}	.049	.182	-.228	-.123	-.125	.939	1				
Cl^-	**.973**	.233	-.188	.731	-.054	.055	.030	1			
HCO_3^-	.146	.603	-.018	**.838**	.720	-.290	-.197	.291	1		
NO_3^-	-.188	.042	-.184	-.261	-.273	**.904**	**.936**	-.191	-.281	1	
SO_4^{2-}	-.099	.030	-.262	-.205	-.272	**.923**	**.959**	-.090	-.261	**.985**	1

Table 5.9 shows the factor analysis representing the principal component analysis (PCA) with varimax rotation conducted on the hydrochemical parameters to identify the factors responsible for the groundwater chemistry in this project. Three components representing 84.61% of the hydrochemical data variation were obtained. Hydrochemical variance is greatest in Component 1 (39.15%) and shows a positive loading for Ca^{2+} (0.851), Mg^{2+} (0.827), NO_3^- (0.914) and SO_4^{2-} (0.902). Component 2 accounts for 28.21% of the explained variance, showing a positive loading for TDS (0.627), EC (0.680), Na^+ (0.738), Mg^{2+}(0.526), Cl^- (0.688) and HCO_3^- (0.541). Based on the loading of these hydrochemical parameters with EC, it appears that they are the main contributors to groundwater salinity. Component 3 accounts for 17.25% of the total variance and shows a positive loading of EC (0.680) and K^+ (0.720). The principal component plot (Figure 5.18) signifies the anthropogenic inputs into groundwater as a NO_3^-, SO_4^{2-}, Mg^{2+} and Ca^{2+}cluster together. The plot also shows that groundwater salinity is largely influenced by Na^+, HCO_3^-, Cl^- and K^+.

Table 5.9. Results of principal component factors computed from the hydrochemical data representing all groundwater samples

Variables	Communalities		Components		
	Initials	**Extraction**	**1**	**2**	**3**
TDS	1.000	0.928	-0.270	0.627	-0.681
EC	1.000	0.790	-0.268	0.680	0.505
pH	1.000	0.120	-0.135	-0.303	0.099
Na^+	1.000	0.893	-0.585	0.738	-0.078
K^+	1.000	0.885	-0.508	0.330	0.720
Ca^{2+}	1.000	0.922	0.851	0.445	-0.016
Mg^{2+}	1.000	0.974	0.827	0.526	0.115
Cl^-	1.000	0.993	-0.321	0.688	-0.645
HCO_3^-	1.000	0.850	-0.620	0.541	0.417
NO_3^{--}	1.000	0.971	0.914	0.325	0.175

SO_4^{2-}	1.000	0.980	0.902	0.394	0.105
Eigenvalues	**Total**		4.307	3.103	1.897
	% of Variance		39.153	28.212	17.246
	Cumulative %		39.153	67.365	84.611

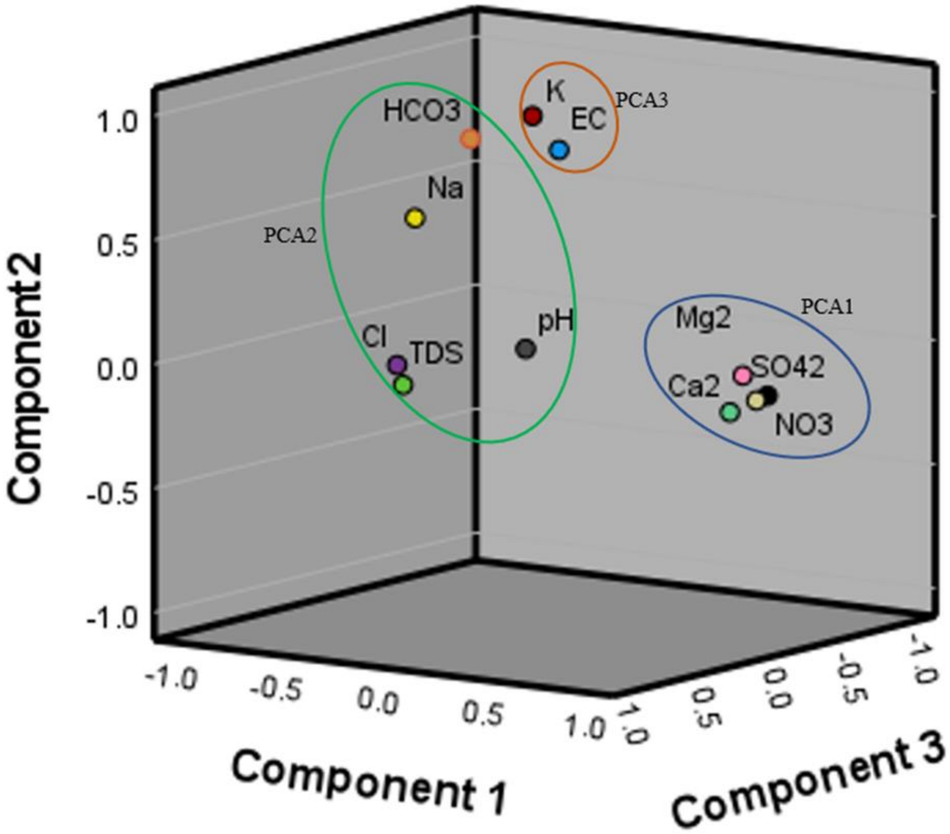


Figure 5.18. Plot showing principal component variables in rotated space

A hierarchical cluster analysis of hydrochemical data was performed using the Ward method. The objective of cluster analysis is the classification of objects or variables into more or less homogeneous groups. The Ward method of cluster analysis is the aggregation of clusters or objects, which causes the least increase in the sum of squared deviations from the arithmetic mean of the cluster. The hydrochemical data were clustered into two distinct groups representing unique hydrochemical systems (Figure 5.19). The first cluster (C-1) shows the similarity between major ions (K^+, Mg^{2+}, NO_3^-, Ca^{2+}, SO_4^{2-}, Na^+, HCO_3^-, and Cl^-), pH and Eh. Group 2 (C2) present the EC and TDS data, and their observed linear relationship. The presence of $NO_3^-$and SO_4^{2-} within the group suggests potential anthropogenic impacts. Group C1-2 indicates that Na^+, Cl^- and HCO_3^- contribute to the salinity of groundwater than other ions.

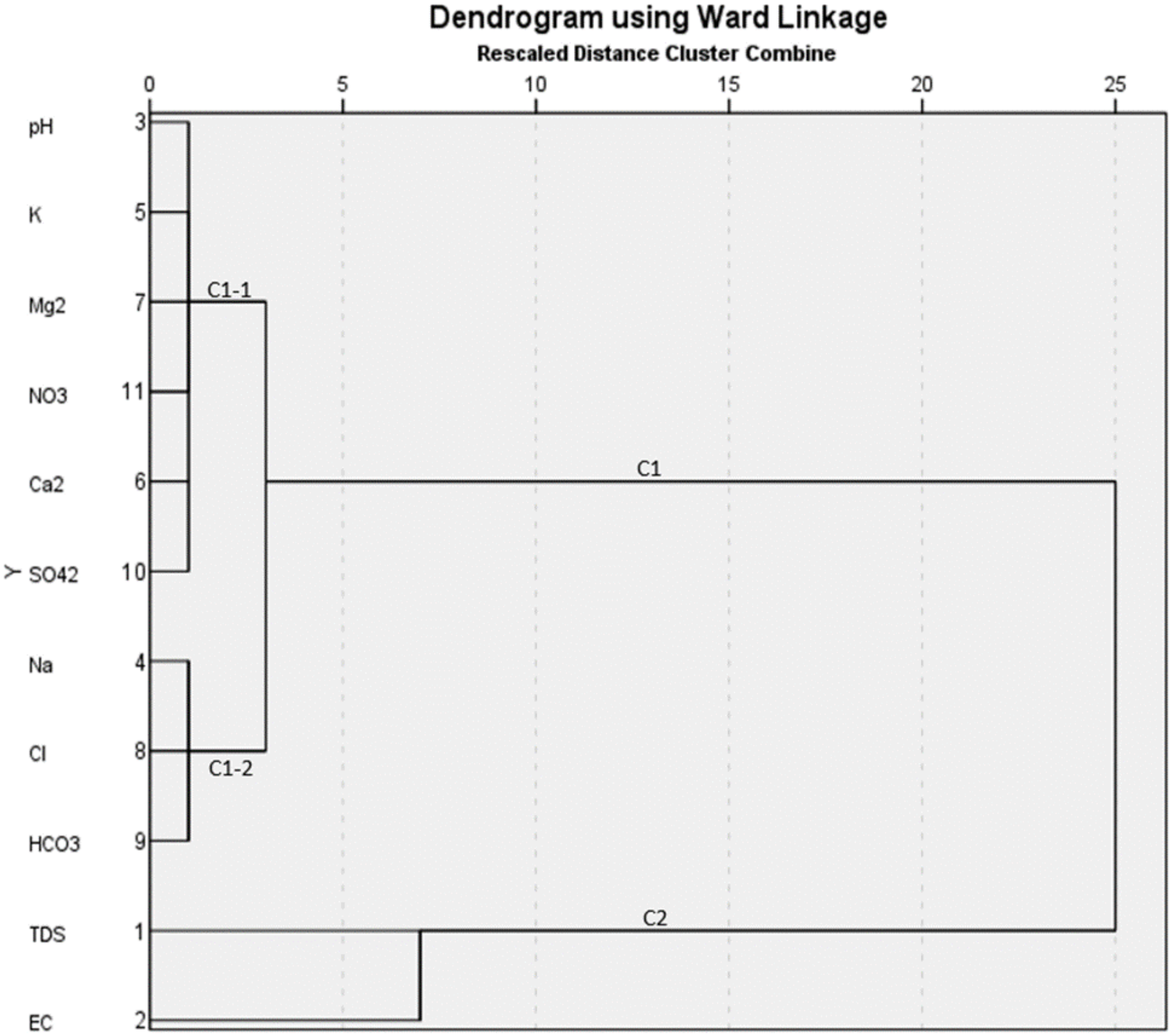


Figure 5.19. Dendogram of seven hydrochemical variables across the intergranular aquifers

5.5 Summary/Synopsis

For a successful implementation of MAR, several criteria that include the availability of aquifer storage volume and the existence of suitable sites need to be considered. Therefore, a detailed characterisation of the hydrogeological situation is a basic requirement of hydrogeological analysis and understanding for MAR application. The geological and hydrogeological data analyses show that three different aquifers occur in the study area, namely: 1) the weathered and fractured aquifers made up of the Pietermaritzburg Formation and rocks of the Natal Metamorphic Province, where the former is characterised by borehole yield with hydraulic conductivity (K) and transmissivity (T) of 0.5 and 2 l/s, 0.05 and 0.5 m/day and 0.28 m^2/day, and the latter is characterised by borehole yield, K and T values of 0.02 and 8.3 l/s, 0.5 m/day and 3.9 m^2/day, respectively; 2) the Fractured aquifers made up of the Natal Group sandstones and the Dwyka Group diamictite. The former is characterised by borehole yields, K and T values of 0.2 and 18 l/s, 2.87 m/day and 8.32 m^2/day, and the latter is characterised by average borehole yields of 0.4 l/s, a K value of 0.8 m/day and a T value of 1.3 m^2/day; 3) the Intergranular or primary aquifers of the Maputaland Group, which consist of the Bluff and Berea Formations and recent alluvium and estuarine deposits. The Bluff Formation is characterised by borehole yield, K and T values of 0.1 and 26 l/s, 3.2 m/day and 9.6 m^2/day. The Berea Formation is characterised by borehole yield, K and T values of 2.5 and 45 l/s, 5 m/day and 7 m^2/day. The recent alluvium and estuarine deposits exhibit borehole yields of 6 and 36 l/s, a K value of 6.5 m/day and a T value that reach 32 m^2/day.

The groundwater level for areas close to the coast and alongside major river courses range from 0 to 15 m bgl. The groundwater levels in the Ecca and Dwyka Group have similar median values of 20 m bgl and 21 m bgl. The greatest percentage of deep (>50 m) groundwater level depths are associated with boreholes drilled into the Natal Metamorphic province granitic basement. The regional groundwater flows from west to east, and into the Indian Ocean. The region receives a mean annual groundwater recharge rate of about 12% of the mean annual precipitation (MAP) of 935 mm/year.

CHAPTER SIX

POTENTIAL AQUIFERS FOR MAR USING TREATED WASTEWATER IN THE GREATER DURBAN METROPOLITAN REGION

6.1. Water Supply Situations in the eThekwini District Municipality

The greater eThekwini District Municipality relies heavily on surface water to meet the water supply requirements. The uMgeni and uMdloti Rivers are the main water supply sources in the study area, with some complement from the Mooi River through a transfer scheme. The Midmar, Albert Falls, Nagle and Inanda dams were constructed on the uMgeni River for water supply purposes. Similarly, the Hazelmere Dam regulates the flow of the uMdloti River. Figure 6.1 shows the current water supply system in the Mooi/uMgeni system, supplying the urban regions (EWS, 2020).

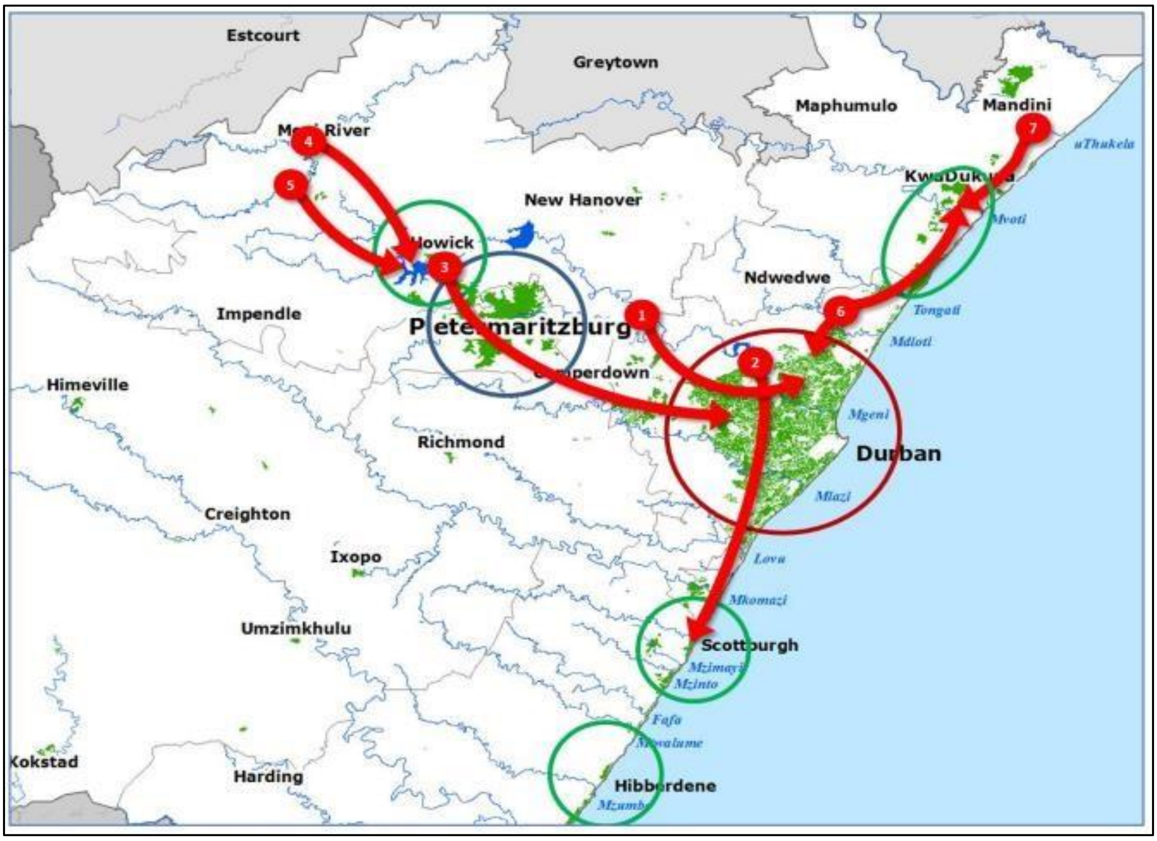


Figure 6.1. Mooi/uMgeni current bulk water supply scheme (EWS, 2020)

The eThekwini Water and Sanitation Unit (EWS), the water services provider of the eThekwini Metropolitan Municipality, purchases water from the uMgeni and uMdloti Rivers scheme through the a state-owned Umgeni Water Board. Through its large network, EWS distributes the water to its various customers. Figure 6.2 shows the overall water balance of the uMgeni River system, including water demand projections. With the newly constructed Spring Grove dam, the total supply of water is just over 1100 ML/day, while demand is estimated to be around 1230 ML/day, implying a current water supply gap of about 120 ML/day. Furthermore, the demand is projected to increase to about 1750 to 1900 ML/day by 2050, implying a potential future water gap of 700 ML/day without new infrastructure (EWS, 2020). The current and future water supply demand for the eThekwini District Municipality is presented in Table 6.1.

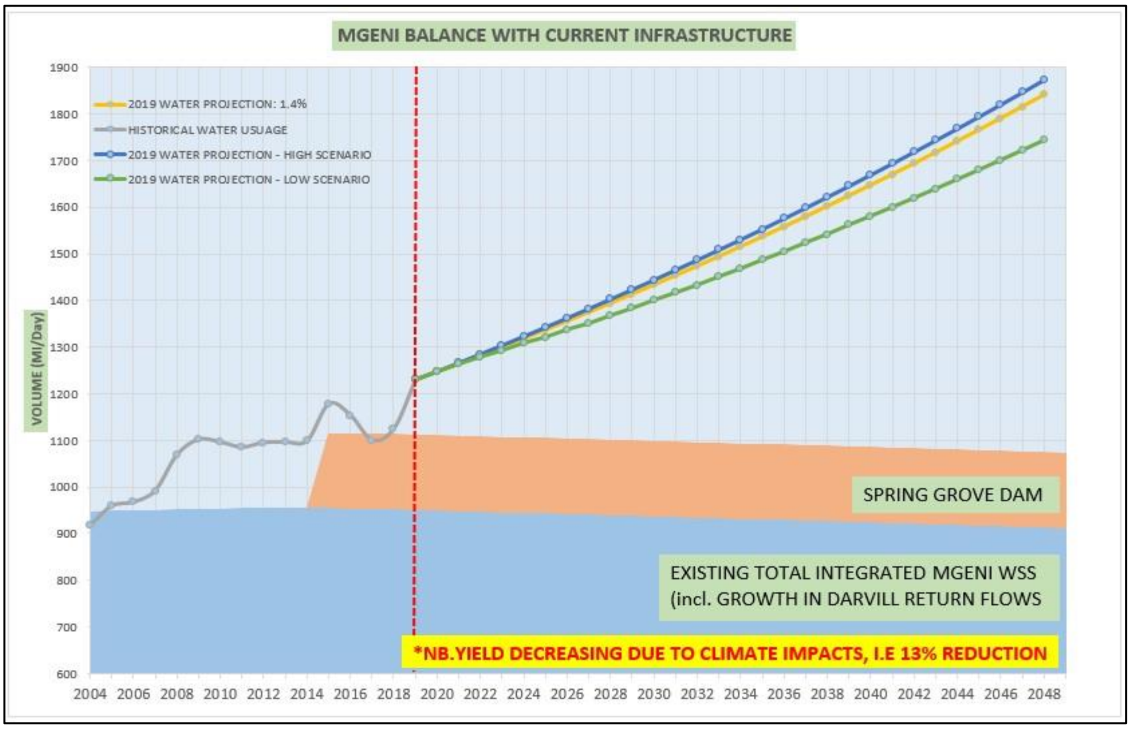


Figure 6.2. Water balance in the uMgeni river system (EWS, 2020)

Table 6.1. Current and Future water supply and demand for the region, including population (EWS, 2017)

Year	2016	2017	2018	2019	2020	2021	2022	2023
Population	3677575	3723435	3767939	3811167	3853278	4295316	4371277	4444516
Supply (ML/day)	838	880	951	990	1010	1040	1050	1060
Demand (ML/day)	875	896	900	973	1022	1073	1126	1183

6.2. Volume of treated wastewater generated annually in the eThekwini Municipality

eThekwini Water and Sanitation (EWS) is responsible for the operation and management of various Wastewater Treatment Works (WWTW) in the greater eThekwini Metropolitan Municipality. Table 6.2 lists the WWTW under the responsibility of EWS and Figure 6.3 shows the relative locations of the WWTW across the area. The bulk infrastructure for sanitation for EWS comprises the following eleven wastewater treatment works catchments (Tongaat catchment, Mdloti catchment, Mhlanga catchment, uMgeni catchment, Umhlatuzana catchment, Umlaas catchment, Isipingo catchment, Mbokodweni catchment, Little Manzimtoti catchment, outer west catchments and Lovu to Mkomazi catchment).

- The Tongaat catchment comprises the Tongaat WWTW that has a design capacity of 11 ML/day. The treated effluent generated at the Tongaat WWTW is discharged into the Tongati River.
- The Mdloti catchment comprises the Genazzano, Umhloti Regional, Mhloti and Verulam WWTW. The treated effluent generated from these works is discharged into the Mdloti River.
- The uMhlanga catchment comprises the Phoenix and Umhlanga Works. The treated effluent generated from these WWTW is discharged into the Mhlanga estuary.
- The uMgeni catchment comprises the KwaMashu, New Germany and Northern WWTW. The treated effluent generated from this catchment is discharged into the uMgeni River.
- The Umhlatuzana catchment comprises the Hillcrest, Umbilo and Umhlatuzana WWTW and the treated effluent generated from these Works is discharged into the Umbilo and Umhlatuzana rivers.
- The Umlaas catchment comprises the Dassenhoek, Central, Southern and Kwandengezi WWTW. The treated effluent generated from the Central and Southern Works is discharged into the sea whilst the treated effluent generated at Dassenhoek and KwaNdengezi WWTW is discharged into the rivers adjacent to the works.
- The Ispingo, Mbokodweni and Little Manzimtoti Catchment comprises of the Isipingo, Amanzimtoti and Kingsburgh WWTW and the treated effluent generated in these works is discharged into the Isipingo, Mbokodweni and Little aManzimtoti rivers.
- The outer west catchments comprise the Fredville, Hammarsdale, Cato Ridge and Mpumalanga WWTW and the treated effluent is discharged into the uMgeni, Sterkspruit and UMlazi Rivers.

- The Lovu to Mkomazi catchments comprises of the Magabeni, Umkomaas and Craigieburn WWTW and the treated effluent is discharged into the Umkhomazi River.

The total treated wastewater generated within the study area is about 23034.54 ML/month or 276414.50 ML/year (Table 6.2).

Table 6.2. Total daily, monthly and annual treated wastewater generated within the eThekwini District Municipality (EWS, 2019)

No.	Name of WWTW	Status	Catchment	Designed Capacity ML/day	Designed Capacity ML/month	Designed Capacity ML/year
1	Tongaat Works	Active	Tongaat Catchment	11	334.58	4015
2	Genazzano Works	Active	Mdloti Catchment	1.5	45.63	547.5
3	Umhloti Regional Works	Active		66	2007.50	24090
4	Umdloti Works	Active		1.5	45.63	547,5
5	Verulam Works	Active		12.5	380.21	4562,5
6	Umhlanga Works	Active	Mhlanga Catchment	7	212.92	2555
7	Phoenix Works	Active		25	760.42	9125
8	Northern Works	Active	uMgeni Catchment	58	1764.17	21170
9	KwaMashu Works	Active		59	1794.58	21535
10	New Germany Works	Active		7	212.92	2555
11	Hillcrest Works	Active	Umhlatuzana Catchment	1.2	36.50	438
12	Umbilo Works	Active		23	699.58	8395
13	Umhlatuzana Works	Active		15	456.25	5475
14	Dassenhoek Works	Active	Umlaas Catchment	5	152.08	1825
15	Central Works	Active		135	4106.25	49275
16	KwaNdengezi Works	Active		2.4	73	876
17	Southern Works	Active		230	6995.83	83950
18	Isipingo Works	Active	Isipingo, Mbokodweni, Little Manzimtoti Catchments	18	547.5	6570
19	Amanzimtoti Works	Active		30	912.5	10950
20	Kingsburgh Works	Active		7.5	228.13	2737.50
21	Fredville Works	Active	Outer West Catchments	5	152.08	1825
22	Cato Ridge Works	Active		0.5	15.21	182.5
23	Hammarsdale Works	Active		27	82.25	9855
24	Mpumalanga Works	Active		6.4	194.67	2336
25	Magabeni Works	Active		0.8	24.33	292
26	Umkomaas Works	Active		1	30.42	365

27	Craigieburn Works	Active	Lovu to Mkomazi Catchments	1	30.42	365
Total				**757.3**	**23034.54**	**276414.5**

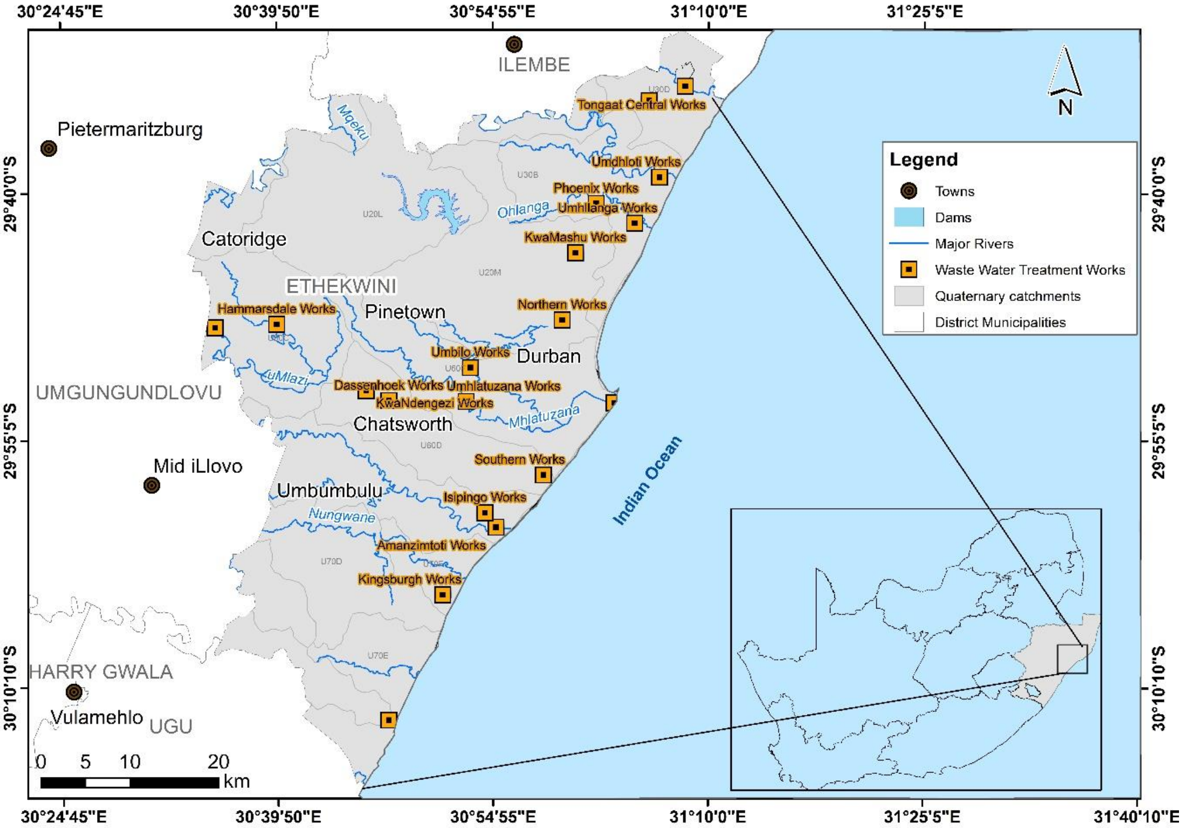


Figure 6.3. Location of WWTW under the responsibility of EWS (modified from EWS, 2019)

6.3. Quality of treated wastewater discharged into the receiving environment per bulk wastewater treatment catchment

The Department of Water and Sanitation (DWS) regulates the discharge of wastewaters to the natural environment (EWS, 2020). As such, each WWTW is required by DWS to treat the wastewater and achieve the water quality required as per the authorised standards laid out in its discharge permit, before discharging into the environment. The scientific service branch of eThekwini Water and Sanitation (EWS) samples each of the works to ensure that these standards are met (EWS, 2020). Analytical results of Wastewater samples (sourced from the eThekwini Water and Sanitation Monitoring Database, 2020 are shown in Table 6.3 and are based on the physiochemical characteristics of pH, ammonia (NH_3), chemical oxygen demand

(COD), electrical conductivity (EC) and total suspended solids (TSS). The observed physiochemical composition of the various treated wastewaters are presented in Table 6.3 and are discussed below.

6.3.1. pH

The mean pH values in the treated wastewaters that are discharged into the receiving environment from the eThekwini WWTW range from 5.5 - 8. The South African National Standard (SANS) 241:2015 drinking water quality standards (SABS, 2015) for pH with respect to domestic use is $5.0 \leq pH \leq 9.7$. The pH reported in all treated wastewater falls within this range (Table 6.3), suggesting that the impact of the treated wastewater on the receiving water bodies (rivers and estuaries) would not adversely affect their use for domestic purposes, recreational and aquatic ecosystem functioning. The average pH at each wastewater treatment works meet the general requirements for treated wastewater regulation (pH of between 5.5 and 9.5) as specified in the National Water Act, 1998 (Act 36 of 1998) (NWA).

6.3.2. Ammonia (NH_3)

The National Water Act (Act 36 of 1998) (NWA) specifies that the general NH_3 concentration requirement of off-site marine disposal is 10 mg/l NH_3 as N. The observed Ammonia (NH_3) concentration in Tongaat, Genazzano, uMdloti, uMhlanga, Phoenix, New Germany, uMbilo, uMhlathuzana, Kingsburgh, Hammarsdale and Craigeburn WWTW exceeded the general limits stipulated in the National Water Act (Act 36 of 1998), as shown in Table 6.3. Sewage effluent and industrial waste discharge are examples of sources that generate ammonia from the use of ammonium salts or ammonia-containing compounds. In the surface or groundwater, ammonium is produced by the decomposition of nitrogenous organic matter, which represents a component of the nitrogen cycle (Day and Dallas, 2011). Ammonia is hazardous and contributor to eutrophication (Naidoo, 2013). Eutrophication could adversely affect the use of rivers and dams for recreation purpose as the covering of large areas by macrophytes could prevent access to waterways and could cause unsightly and malodours scum, which could lead to the growth of blue-green algae or cause the release of toxic substances (cyanotoxins) into the water systems, resulting in death of farm livestock (Holdsworth, 1991). Even though there may not be of high concern in the eThekwini Metropolitan Region, farms which are located in the western and southern regions of the eThekwini District Municipality must be cautious as these receiving water bodies might be used for livestock farming. In addition, since eutrophication increases the treatment cost of drinking water through filter clogging in water treatment works (Murray *et al.*, 2000), the WWTW which produce effluent that exceed the general limits of SANS 241:2015 need to address the problem of nutrient removal in these sewage treatment works in order to avoid the incidences of eutrophication in receiving water bodies.

6.3.3. Chemical Oxygen Demand (COD)

Chemical oxygen demand is a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant (Naidoo, 2013). The National Water Act (Act 36 of 1998) specifies that the COD of treated wastewater should not exceed 75 mg/l. However, the Tongaat, Genazzano, Verulam, Umhlanga, KwaMashu, New Germany, Hillcrest, uMbilo, uMhlatuzana, KwaNdengezi, Southern, Amanzimtoti, Kingsburgh and Hammarsdale WWTW produce treated waste water with COD that exceeds the 75 mg/l requirements (Table 6.3). Treated wastewater with COD greater than 75 mg/l indicates the level of organic contaminants after treatment of the wastewater at the treatment plants. This could possibly indicate the inefficiency of the wastewater treatment plants in lowering the chemical oxygen demand in the treated water and should be rectified to improve the quality of water discharged into the receiving environment.

6.3.4. Electrical Conductivity (EC)

According to the National Water Act (Act 36 of 1998), the general requirements for the purification of wastewater specify that the treated water EC should not to exceed 75 mS/m (DWAF, 1998). The average EC of treated wastewater in Table 6.3 exceeds the minimum requirement of 75 mS/m at Tongaat, Genazzano, uMdloti, Verulam, uMhlanga, Northern, uMbilo, uMhlatuzana, Dassenhoek, Southern, Kingsburgh, Hammarsdale, Maghabeni and uMkomaas wastewater treatment plants, highlighting the need for an improvement in the non-complying WWTW. Only 9 WWTW (Phoenix, KwaMashu, New Germany, Hillcrest, KwaNdengezi, Isipingo, Fredville, Mpumalanga and Craigeburn) complied with the general standards related to EC levels.

6.3.5. Total Suspended Solids (TSS)

Suspended solids refer relatively large particles that settle under quiescent conditions (WRC, 2006). Total suspended solids measure the amount of sediments suspended in water. The mean suspended solids of the treated wastewater in the various WWTW in the study area range from 2 mg/l to 666.3 mg/l (Table 6.3). Except for the Southern WWTW, all wastewater treatment works have a good total suspended solids removal capacity since the suspended solids load in the final effluent is within the standard limits of 0 to 450 mg/l of DWAF (1996d). The observed suspended solids in the Southern Works WWTW treated effluent was 666.3 mg/l, exceeding the limits. These suspended solids concentrations will influence the quality of the receiving water bodies. Excess suspended solids may block sufficient sunlight from reaching underwater plant life, thus preventing normal growth and productivity (National Sewage Report Card, 1999). This can affect aquatic organisms feeding underwater plant life. Furthermore, trace metals and organic contaminants harmful to human health and the environment can attach to suspended solids and enter receiving water bodies through effluents (Nantel, 1996). Therefore, the Southern Works WWTW needs to improve the suspended solids level of the treated waste water to acceptable levels of 450 mg/l or below.

6.3.6. Residual chlorine

The free chlorine residual concentrations in the final treated effluents of the various WWTW plants are indicated in Table 6.3. The residual chlorine concentrations range from 0.1 to 0.5 mg/l. In terms of the general requirements of effluent from the treatment of wastewater, the National Water Act (Act 36 of 1998) (NWA) specifies concentrations not to exceed 0.25 mg/l (DWAF, 1998). The majority of the treatment plants have residual chorine concentrations below 0.25 mg/l, except in Tongaat, Genazzano, Verulam, Phoenix, Kingsburgh, Mpumalanga and uMkomaas wastewater treatment plants. The average residual chlorine of the treated wastewater in Table 6.3 were not recorded for uMhlanga, Dassenhoek, Central, kwaNdengezi, Southern and Cato Ridge. Total residual chloride is the total amount of chlorine present in a sample. This is the sum of the free chlorine residual and the combined available chlorine residual. Whereas, chlorine residual is the amount available for chlorine present in wastewater after a given contact time (20 minutes at peak flow; 30 minutes at average flow) under specific environmental conditions (USEPA, 2017). A free chlorine residual concentration less than 0.25 mg/l was observed at uMdloti, Northern, KwaMashu, New Germany, Hillcrest, uMmbilo, uMhlatuzana, Isipingo, Amanzimtoti, Fredville, Hammarsdale, Maghabeni and Craigeburn wastewater treatment plants. Also, free chlorine residual concentration less than 0.25 mg/l was observed at Tongaat, Genazzano, Verulam, Phoenix, Kingsburg, Mpumalanga and uMkomaas wastewater treatment plants. Therefore, it is suggested that the residual chlorine levels for the treated effluent be improved at non-complying WWWT before it is discharged into the receiving environment.

Table 6.3. Treated wastewater quality for the eThekwini District Municipality (Data from EWS, 2020)

Sample ID	pH	Free Ammonia mg/l	COD mg/l	EC mS/m	E.coli	Suspended solids mg/l	Residual chlorine mg/l
Tongaat Works	7.2	25	106.2	76	16.8	21.6	0.3
Genazzano Works	7.3	26.2	127.6	79.5	>4851.8	57.2	0.3
Umdloti Works	7.4	8.7	59.2	85.3	>4845.4	7.2	0.2
Verulam Works	7.5	3.1	145	146	>12098	65	0.3
Umhlanga Works	7.4	20.6	84.2	75.7	>12334	11.2	-
Phoenix Works	7.3	18.3	52.3	72.5	0	8.3	0.3
Northern Works	6.9	6.2	62	77.9	0	15.5	0.2
KwaMashu Works	7.5	6.2	86.8	73.7	1221	33	0.1
New Germany Works	7.3	23.3	154.8	68.5	5602	25.4	0.2
Hillcrest Works	7.4	6.5	142.8	57.1	492	54.3	0.2
Umbilo Works	7.4	19.5	243.8	76.1	140.5	118.5	0.2
uMhlatuzana Works	7.5	21.5	85.3	86.5	81.3	6	0.2
Dassenhoek Works	6.6	0.1	23	82.2	0	16.5	-
KwaNdengezi Works	6.9	7.1	125.3	58.7	-	44.5	-
Southern Works	5.5	8.9	4985	325.5	-	666.3	-
Isipingo Works	6.8	3.7	44.5	56.1	589.8	15	0.2
Amanzimtoti Works	7.6	6.3	133.3	-	41	86	0.2
Kingsburgh Works	7.6	16.5	97.3	83.9	>12098	22	0.3
Fredville Works	7.5	6.1	44.8	40.9	>6270	2.5	0.2
Cato Ridge Works	-	-	-	-	164.5	-	-
Hammarsdale Works	7.8	25.3	79.8	248	40.3	18.3	0.1
Mpumalanga Works	7.2	6	50.8	55.9	0	7.8	0.3
Magabheni Works	8	7.3	49.5	90.8	7.5	4.8	0.1
uMkomaas Works	7.2	0.5	38	98.5	2.5	2.5	0.5
Craigeburn	7.5	8.7	34.8	68.5	>6049	2	0.1

6.4. Treated Water Quality requirements for MAR and implications on using treated waste water effluent for MAR in the study area

Hydrogeochemical processes between injected water, native groundwater and the subsoil occur when treated wastewater is injected into an aquifer (Willemsen, 2020). Under normal circumstances, the recharge water (treated wastewater) should not degrade the quality of the groundwater, nor impose any additional treatment requirement after pumping (Brissaud, 1999). Apart from those in Australia (NWQMS, 1995), regulations concerning aquifer recharge do not rely on the capability of the aquifer to remove pollutants to meet the water quality required within the aquifer (Brissaud, 1999). In practice, the recharge water reaching the saturated zone of the aquifer should have previously acquired the quality acceptable for drinking water (Brissaud, 1999).

If the aquifer recharge is direct, then the injected water should be potable and should, as a minimum requirement, meet the standards required by SANS 241:2015 or contained in the WHO guidelines for drinking water quality (WHO, 1996). Moreover, the injected water should be treated to prevent clogging around the injection wells; long-term health risks linked to mineral and organic trace elements; and the degradation of the aquifer (Brissaud, 1999). Clogging is an operational problem largely related to the quality of the recharge water. The capacity of the aquifer to remove pollutants provides an additional barrier protecting the abstracted water quality (Brissaud, 1999).

According to Murray (2009), provisional recharge water guidelines for MAR are DOC = 4 mg/l, EC = 70 mS/m, chloride = 100 mg/l, sulphate = 50 mg/l and Nitrate & Nitrite as N, 5 mg/l. All the WWTW treated wastewater effluent in the greater Durban region except for the Craigeburn and Fredville works do not meet the SANS 241:2015 drinking water quality criteria for public water supply for free ammonia, COD and EC.

EC for all WWTWs except New Germany, Hillcrest, KwaNdengezi, Isipingo, Fredville, Mpumalanga and Craigeburn have an EC value of more than 70 mS/m. COD for Genazzano, Phoenix, Northern, Dassenhoek, Isipingo, Fredville, Mpumalanga, Magabheni, uMkomaas and Craigeburn do not exceed 75 mg/l. However, for the remaining WWTWs, it exceeded 75 mg/l. Trace organic solutes, such as trihalomethanes and compounds containing two carbon atoms such as trichloroethylene, tetrachloroethylene and trichloroethane are attenuated by the aquifer material in approximate accord with the order of elution of these compounds in gas chromatography (Treweek, 1985). Following adsorption, these species are often biodegraded, as evidence by decreasing concentrations of COD and single carbon compounds are degraded at a rate ten times greater than the two carbon atoms (Treweek, 1985).

The wastewater effluent concentrations for free ammonia for Tongaat, Genazzano, Umhlanga, Phoenix, New Germany, Umbilo, Umhlatuzana, Kingsburgh and Hammarsdale exceed the 10 mg/l limit of the SANS 241:2015 standards. Through the proper operation of recharge basins, the ammonia concentration can be reduced to negligible levels, with some increase in the nitrate level. The needs for drinking and industrial process water can often be achieved by a well-run secondary treatment plant. With respect to surface spreading, both bacteria and viruses are removed in the soil column by filtration, adsorption and other natural means. In surface spreading, disinfection is not recommended since the danger from the formation of chlorinated organics may be greater than the changes from viruses and pathogens which might pass through the soil column.

The suitability of the treated wastewater generated at the various WWTWs suggests that further treatment is required before the treated wastewater is injected into the aquifers. As it stands, only the Craigeburn and Fredville works are compliant with the guidelines for drinking-water quality SANS 241:2015. The Craigeburn works has a volume of 1Ml/day of treated wastewater, while the Fredville produces 5 ML/day of treated waste water which complies for MAR application.

6.4 Identification of potential aquifers in the greater Durban Metropolitan region for MAR using treated wastewater

6.4.1 MAR site identification

Before identifying potential aquifers that can be used for MAR in the study area, a number of factors that are generally considered for the feasibility and decision for MAR are identified. These factors include the current rate of groundwater recharge, need and water source for MAR, aquifer hydraulic characteristics including hydraulic conductivity, storage capacity, and infrastructure required for the entire process. Aquifers showing high hydraulic conductivities and high storage capacities are more suitable for additional recharge water than those with low hydraulic conductivities and low storage capacities (Murray and Tredoux, 1998). Table 6.4 represents a simple matrix for assessing the aquifer quality to receive artificially recharged water in terms of aquifer hydraulic characteristics.

Table 6.4. Potential of an aquifer to receive artificial recharge water (Murray and Tredoux, 1998)

Storativity (S) or Specific yield (Sy)	**Hydraulic conductivity (K)**	**Aquifer Potential**
High	Moderate- High K	High Potential ↓ No Potential
High	Low K	
Low	High K	
Low	Low K	

According to DWA (2009), MAR is generally more successfully achieved in intergranular/primary aquifers than in weathered or fractured aquifers. In the present study area, intergranular aquifers occur along the coast, including the area where the city of Durban is located. These aquifers are the Bluff Formation, Berea Formation and alluvial/estuarine deposits. Amongst these aquifers, the Berea Formation shows the highest potential for MAR because of its high values of K, T, borehole yields and thickness (Table 6.5). Moreover, the extent of the Berea Formation is relatively well-defined. The properties of the primary aquifers that occur in the greater Durban Metropolitan Region are presented in Table 6.5. Based on their hydrogeological assessments, the potentials of different aquifers in the study area classified as:

- High potential;
- Intermediate potential;
- Low potential; and
- Negligible potential

Figure 6.4 displays different potential MAR sites identified in the eastern sector of the eThekwini District Municipality.

Table 6.5. Characteristics of the two intergranular aquifers Targeted for MAR in the study area.

Aquifer unit	**Borehole Yield (l/s)**	**Aquifer thickness (m)**	**Hydraulic conductivity (m/day)**	**Transmissivity (m^2/day)**	**MAR Potential Sites**
uMgeni alluvium and estuarine deposits	6 - 36	25-60	5-6.5	32	Intermediate Potential
Berea Formation	2.5 - 45	0.5 - 45	5	7 - 406	High Potential

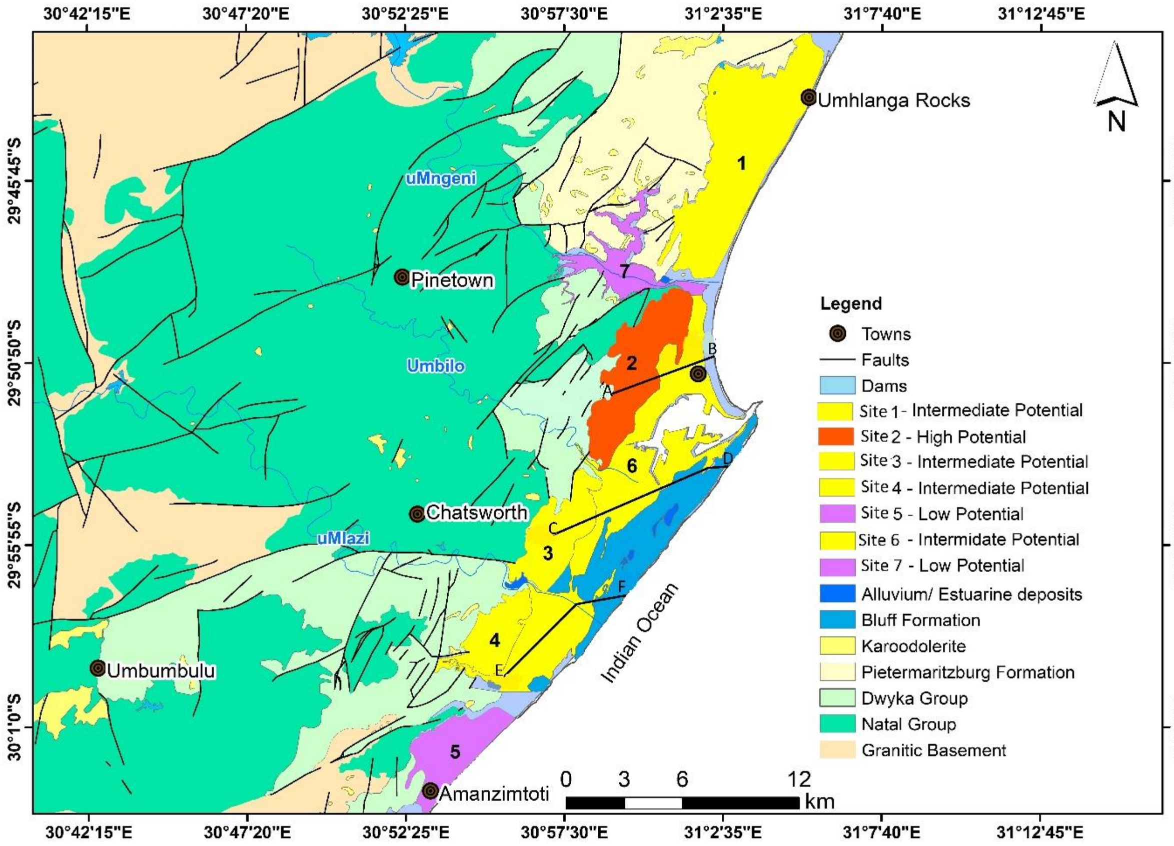


Figure 6.4. MAR potential sites along the eThekwini District Municipality. The black lines indicate cross section directions.

6.4.2 Potential sites for MAR in the Berea Formation

The Berea Formation is characterised by fine to medium, red decalcified dune sand and boulders, as described in Chapter 5. The major component is the fine sand, which limits infiltration, as opposed to coarse sand which offers the ideal aquifers. According to DWAF (1998), ferricrete layers have been observed in the Berea Formation, although not widespread to possibly restriction flow or create clogging. The Berea Formation in the study area occurs as a few separated dune deposits, stretching in a northeast to southwest direction along the coast and separated by the incision of the uMgeni River, uMbilo River and uMlazi River (Figure 6.5).

Aquifer volume is calculated as the relationship between aquifer thickness, area and porosity as illustrated in equation (6.1)

$$VT = A*d*n \tag{6.1}$$

Where, VT is the total pore volume (m^3), A is the area or areal extent of the aquifer (m^2), d is the unsaturated thickness and n is the average total porosity, which is equal to the ration of void space within a total volume of material.

Available information suggests that the thickness of the Berea Formation is around 23 m in the south central part of the eThekwini District Municipality, but thickness as high as 77 m is reported. This site comprises red to yellowish silty, fine and medium sands, having an area of about 42.84 km^2 .The average depth to water level is 10 m bgl. Assuming a water level recovery of 3 m will be allowed during MAR, using equation (6.1), the volume of 0.128 km^3.is calculated for the unsaturated sand without inducing water decanting. Making the Berea Formation potentially conducive for MAR. In areas, where deeper groundwater levels were recorded (vicinity of Borehole BH 421) 15 m bgl, large volumes of the unsaturated material is available for MAR. It is however understood that due to slightly different depth to water level, the thickness of unsaturated material differs from one area to the next and accurate groundwater monitoring data (recorded during both dry and wet season) is required to calculate the volumes in each section of the study area. The Berea Formation is bordered almost directly by the ocean in the north (uMhlanga Rocks) and south (Amanzimtoti) and separated from the ocean by the estuarine deposits and the Bluff Formation around central Durban. Table 6.5 depicts the characteristics of the Berea Formation, which are favourable aquifer characteristics for potential MAR. According to the best-practice guideline for MAR (Murray, 2004), the properties of the five sites of the Berea Formation, stretching from northeast to southwest in the eThekwini District Municipality, are listed in Table 6.3.

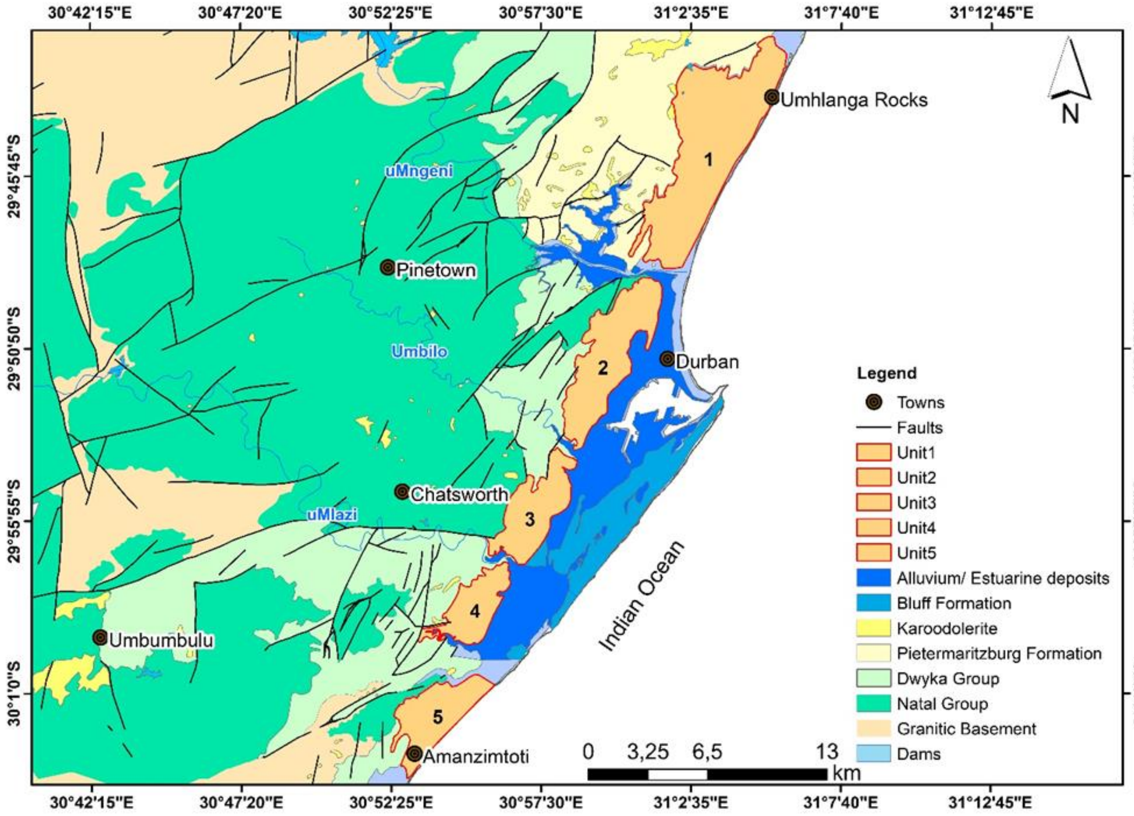


Figure 6.5. Berea Formation potential MAR location

Table 6.3: Properties of the Berea Formation MAR potential sites in the eThekwini District Municipality

MAR Sites	**Aquifer thickness (m)**	**Static water level (m bgl)**	**Aquifer area (km^2)**	**Hydraulic conductivity (m/day)**	**Transmissivity (m^2/day)**	**Potential recharge water storage capacity (km^3)**	**Natural Recharge (mm/year)**	**MAR Potential Sites**
Berea Formation Site 1	23	10	42.84	5	7- 406	0.128	93	Intermediate Potential
Berea Formation Site 2	23	10	21.85	5	7- 406	0.066	105.5	High Potential
Berea Formation Site 3	23	10	13.87	5	7- 406	0.046	88	Intermediate Potential
Berea Formation Site 4	23	10	9.89	5	7- 406	0.03	88	Intermediate Potential
Berea Formation Site 5	23	10	13.01	5	7- 406	0.039	80	Low Potential

Berea Formation Site 1

The site 1 in the Berea Formation (denoted as 1 in Figure 6.4) is located between Umhlanga Rocks and Tongaat. This site comprises red to yellowish silty, fine and medium sands having an area of about 42 km^2, which makes it the largest of the potential sites identified. The current natural recharge is 93 mm/year. The groundwater in this site occurs at average depth of 10 m bgl. Information on current groundwater use within this aquifer suggests that groundwater abstraction in the aquifer is limited. According to Geomeasure Group (2018), the average effective porosity is 30%. Targeting a rise in water levels of 3 m, this will give a potential storage capacity of 0.128 km^3. This potential storage capacity is more than adequate for the purpose of MAR. The aquifer hydraulic characteristics of the potential Site 1 is shown in Table 6.3. The aquifer around Site 1 tends to yield fresh to slightly saline groundwater.

The source of recharge water for the MAR (i.e. treated wastewater) for this site would be derived from the Northern Works WWTW, which is located approximately 2 km from the area. However, the Northern Works treated wastewater is of substandard quality as described in preceding sections, which means that the facility needs to improve its treated wastewater quality to a level required for MAR. If the treated water quality is improved, the overall rating of the Berea Formation at Site 1 is intermediate potential for MAR. However, there are two additional challenges for undertaking a MAR project at this site, namely:

i. Since the area is highly developed (residential area) and mainly private land, it creates difficulty in locating recharge areas. Therefore, MAR sites will be limited to public spaces (parks/ recreational land owned by the municipality).
ii. The application of MAR in highly developed residential areas may bring about issues of flooding and related engineering problems to infrastructure and as such, the feasibility study must consider all negative consequences.

Berea Formation Site 2

The Berea Formation Site 2 is located between the uMgeni and uMbilo Rivers and is locally known as the Berea Ridge (Figures 6.4 and 6.5). The Site lithology can be described as red to yellowish silty, fine and medium sands, with land surface area of 21.85 km^2 (second largest of the five sites). The current natural recharge is 105.5 mm/year. The groundwater within this unit occurs at average depth of 10 m bgl and tends to flow towards the eastern central part of the site. Information on current groundwater use within this aquifer suggests that groundwater abstraction in the aquifer is limited. The average effective porosity of the sand is 30% and the storage capacity is 0.066 km^3. This storage capacity is more than adequate for the purpose of MAR. The closest source of treated wastewater feasible for use for Site 2 is the uMbilo WWTW. The uMbilo works has a design capacity of 23 Ml/day.

Based on the lithological log of borehole BH415 drilled at Westridge, the Berea Formation is 21 m deep in this vicinity. The thickness increases to 72.5 m in the south (around the University of KwaZulu-Natal, Howard College Campus) (Figure 6.6). As a result of the hydraulic conductivity (5 m/ day) and Transmissivity (7 to 406 m^2/ day), the area around Westridge and Bulwer (where Berea FM is thickest) will be conducive for MAR. Infiltration into the aquifer will have a tendency to move following the groundwater flow direction towards the eastern central part of the Site.

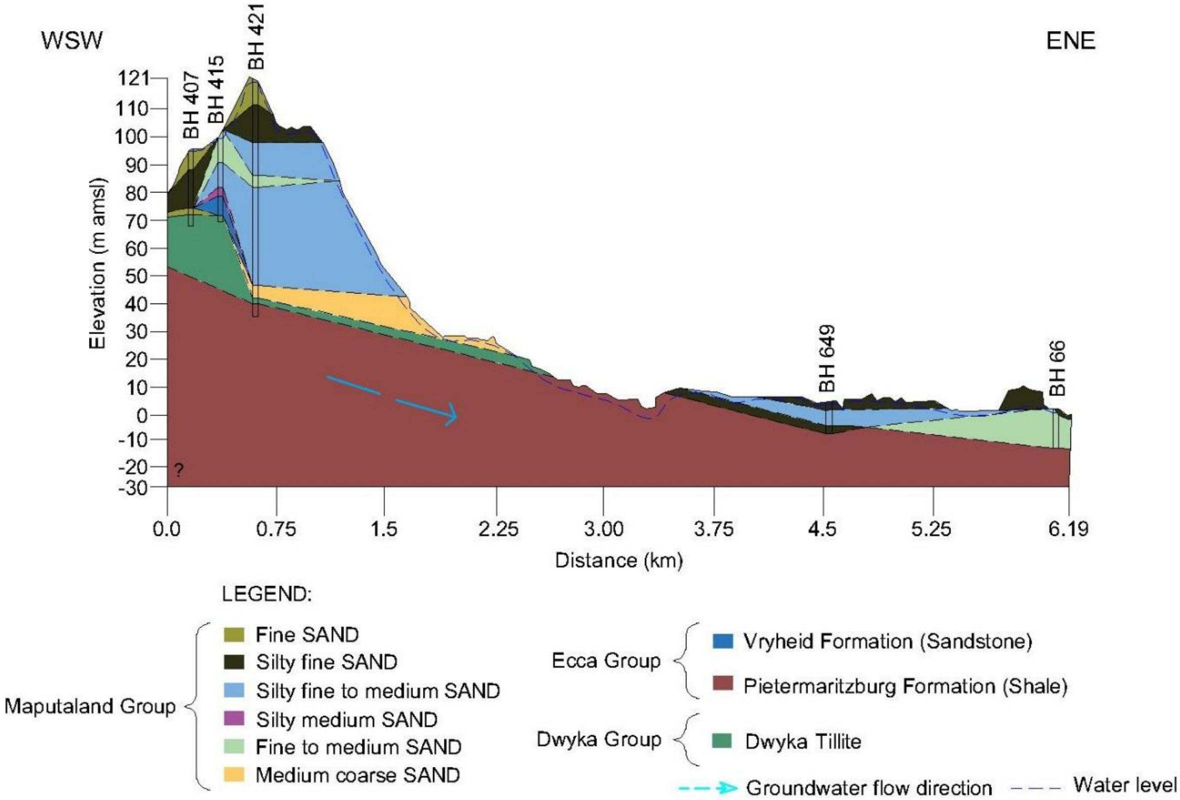


Figure 6.6. Cross section of WSW - ENE (A to B in Figure 6.4)

The recharge water sources are close to the Site, including uMbilo WWTW 2 km away, Northern WWTW about 5 km away.

The Berea Formation Site 2 possesses high potential for MAR, but any potential MAR feasibility study project at this Site must overcome the following three challenges:

i. The area is mostly residential and landownership issues may arise during drilling.

ii. The Site is located in a relatively high elevated area and thus the recharge wells will have to be drilled deep.
iii. The groundwater level must be monitored to avoid flood, seepage and related damage to residential areas and infrastructure.

Berea Formation Site 3

Berea Formation Site 3 (denoted as 3 in Figures 6.4 and 6.5) is located around the Sea View, Woodlands, Mobeni Heights, Joe Slovo, Mobeni and Lamont residential areas. This Site has an area of 13 km^2 and an aquifer thickness of 23 m, which makes it the third largest of the five Berea Formation Sites identified. Site 3 comprises silty, fine and medium sands. This formation shows borehole yields that vary from 2.5 to 45 l/s; average K of 5 m/day; and T values ranging from 7 to 406 m^2/day and the average porosity of 30%, with a storage space of 0.046 km^3. The closest source of treated wastewater feasible for use in Site 3 is the Southern WWTW, which is located within 2 km from the Site. The Southern works has a design capacity of 230 Ml/day.

The overall potential of Site 3 shows that that MAR has intermediate potential. The following challenges may need to be resolved during the MAR feasibility study stage:

i. The treated wastewater from the Southern WWTW has poor quality as the Total suspended solids and electrical conductivity exceeds (DWA, 1998). Therefore, the efficiency of the Southern Works Treatment Plant must be improved to ensure that good quality water is produced for the MAR.
ii. Groundwater levels must be monitored to avoid flooding and infrastructure damage.

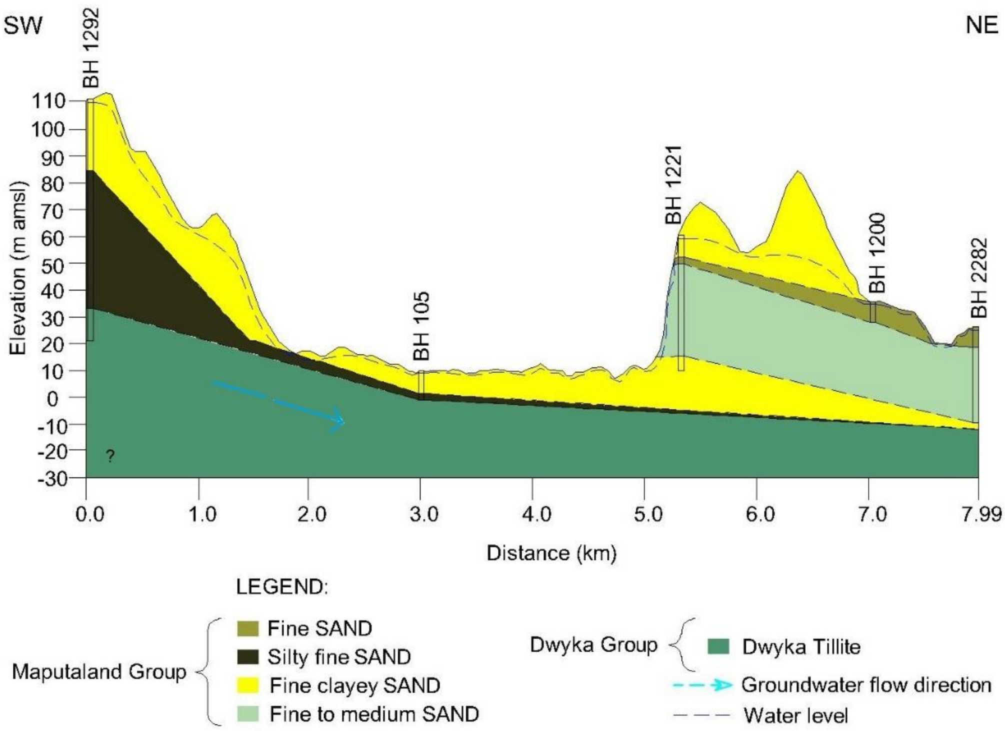


Figure 6.7. Cross section of SW – NE (C to D in Figure 6.4)

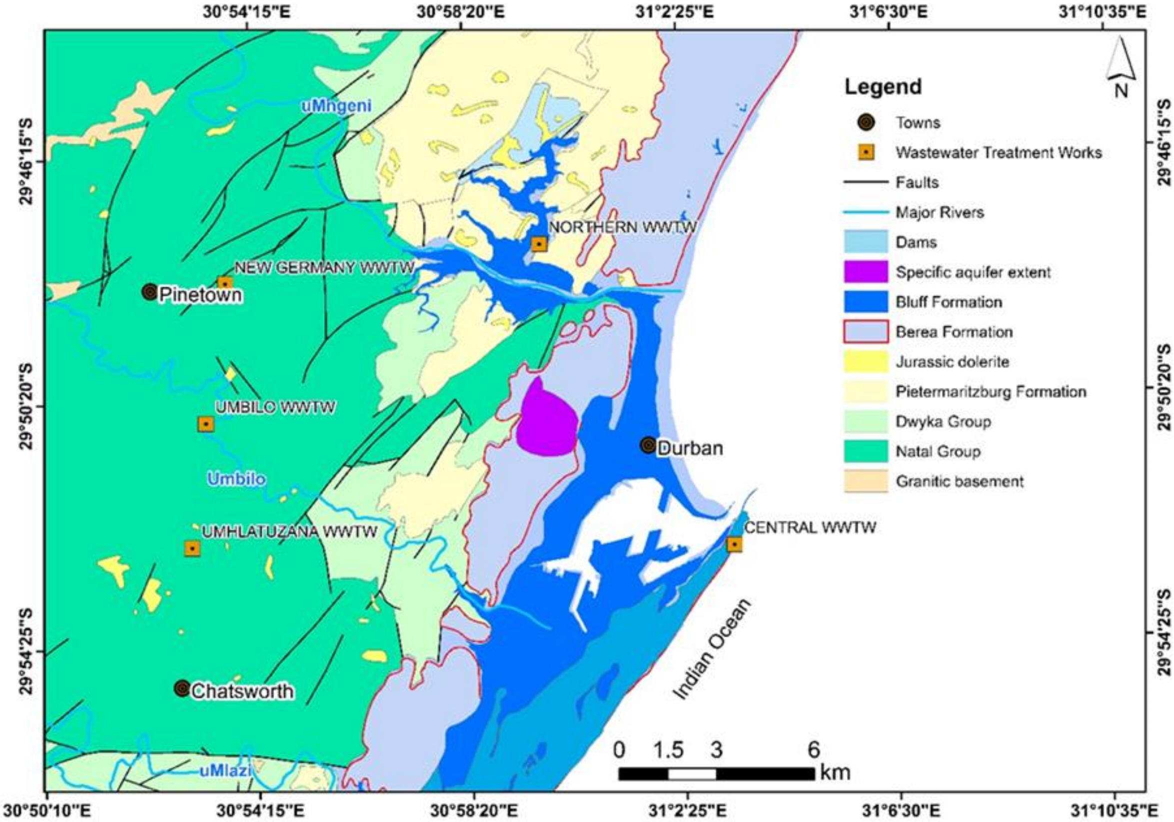


Figure 6.8. Berea Ridge specific aquifer unit for MAR (Site 3)

Berea Formation Site 4

Berea Formation Site 4 (denoted as 4 in Figures 6.2 and 6.5) covers the area around the uMlazi and Isipingo residential areas. The site comprises silty, fine and medium sands with borehole yields ranging from 2.5 to 45 l/s. This Site has an aquifer area of about 10 km^2; average K of 5 m/day; and T values ranging from 7 to 406 m^2/day, a natural recharge rate of 88 mm/year and the average porosity of 30% and the storage capacity of 0.03 km^3. The Isipingo WWTW is located less than a kilometre south of the Site and can be used as a source of recharge water for the MAR.

Site 4 is rated to have an intermediate potential for MAR. Since the area is covered with urban settlements (formal), commercial/ retail and informal settlements, potential issues related to groundwater level rise and consequent problems of flooding and related infrastructure damage will be an issue. The feasibility study must consider all these and related challenges of applying MAR in the area.

Berea Formation Site 5

Berea Formation Site 5 (denoted as 5 in Figure 6.4, 6.5) covers the area around uMbogintwini and Amanzimtoti. The area is underlain by silty, fine and medium sands with borehole producing 2.5 to 45 l/s. The surface area of Site 5 is about 13 km^2, average K of 5 m/day, and T values ranging from 7 to 406 m^2/day, natural recharge rate of 80 mm/year, and average porosity of 30% and storage space of 0.039 km^3. The Amanzimtoti WWTW is located within a kilometre north of the aquifer unit and can be used to source water for the MAR in this vicinity. An advantage of Site 5 is its location along the coast. In this region, MAR can essentially be used as a buffer for sea water intrusion. The Site is rated to have high potential for MAR.

6.4.3 Potential MAR in the alluvium and Harbour Beds Formation

The alluvium/estuarine deposits (the Harbour Beds Formation) are characterised by beach sand, alluvial grit, sand, silt and clay. The clay content in the alluvium/estuarine deposits potentially restricts flow in some parts of the aquifer, forming confining layers. The alluvial/estuarine deposits are characterised by high K, T and borehole yields (higher than the Berea Formation), but are thinner and more widespread compared to the Berea Formation. Additionally, shallow groundwater levels and groundwater quality issues have been associated with these deposits because of its proximity to the coast.

Site 6: Harbour Beds Formation aquifer

The Harbour beds occur from the uMgeni River mouth in the north through downtown Durban all the way to the Umbongitwini area in the south (Figure 6.9). The Harbour Beds underlie the lowest lying parts of the Durban area and are located at a high flooding potential zone. Large rivers drain across the area, including the uMbilo, uMhlatuzana, uMlazi and Amanzimtoti Rivers. In fact, one specific part of this area (Isipingo) was previously known to be a wetland and with regular flooding (EWS, 2018). Site 6 has an area of approximately 48 km^2 and underlain by sand dune, beach sand, alluvial grit, silt and clay. Based on the lithological log of BH1220 drilled in the Merebank East area, the harbour beds is about 37 m deep. Its thickness increases to about 39 m to the south (around Prospection Industrial area) (Figure 6.10). The Harbour beds aquifer is characterised by K values from 5 to 6.5 m/day; borehole yields ranging from 6 to 36 l/s; and T-values of about 32 m^2/day. The average effective porosity of fine sand is 30%. Average depth to water in this aquifer is 8 m bgl and the thickness of unsaturated material is 7 m. Therefore, using equation 6.1, the calculated volume of the unsaturated material is 0.101 km^3

The natural rainfall recharge rate over this area is about 105 mm/year. Information regarding groundwater use within the aquifer is limited. The groundwater flow direction within this aquifer is towards the coast. The various properties of the Harbour Beds Formation aquifer are indicated in Table 6.4.

Table 6.4. Properties of the Harbour Beds Formation for a potential MAR site in the study area

Site 6	**Aquifer thickness (m)**	**Static water level (m bgl)**	**Aquifer area (km^2)**	**Hydraulic conductivity (m/day)**	**Transmissivity (m^2/day)**	**Potential recharge water storage capacity (km^3)**	**Natural Recharge (mm/year)**	**MAR Potential Sites**
Harbour Beds	37.5	8	48	5- 6.5	32	0.101	105.5	Intermediate Potential

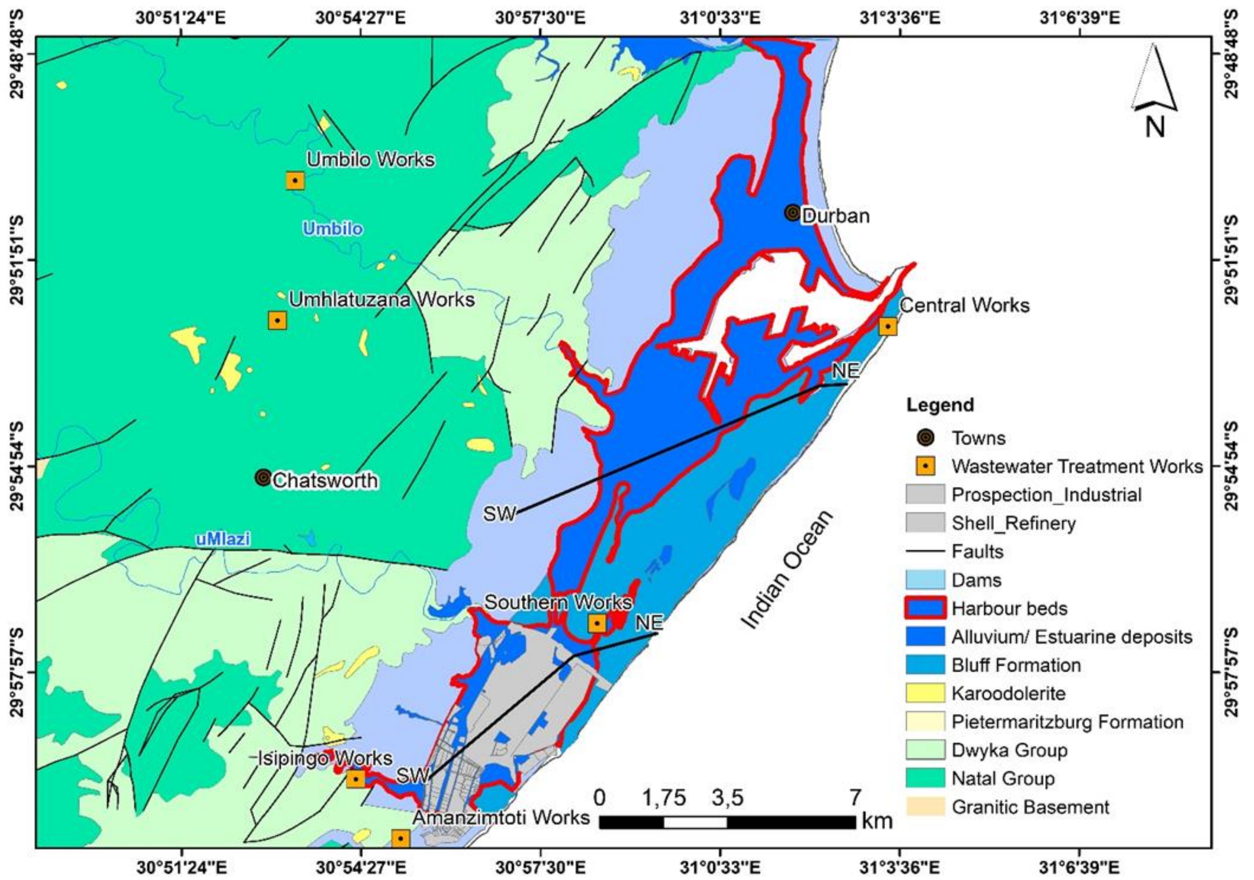


Figure 6.9. The potential areas for MAR where a Harbour Beds aquifer occurs

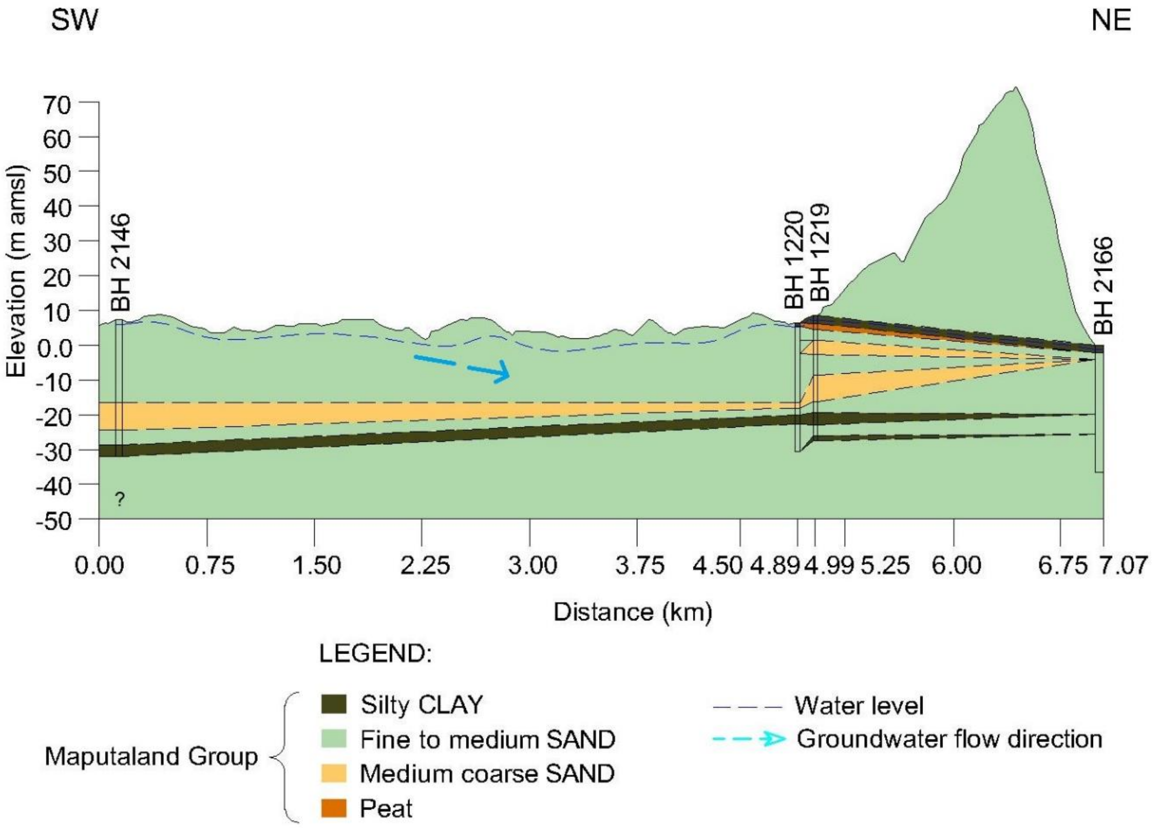


Figure 6.10. SW - NE Cross section (A1 to A2) through the Harbour Beds Formation

This site possesses intermediate potential for MAR. Some advantages of undertaking MAR in this Site is the fact that it augments groundwater pumped for industrial use and it also mitigates potential seawater intrusion. The challenges for MAR in this area are related to shallow groundwater level conditions in which the aquifer may not receive substantial artificial recharge because of potential flooding.

Site 7: uMgeni alluvial deposits

The Umgeni alluvial deposits consist of unconsolidated clay, silt and sand. The alluvial deposits extend from the Indian Ocean, further inland along the main river floodplain and its tributaries. Site 7 mainly lies on the central Umgeni alluvial deposits, as indicated in Figure 6.11. Some of the properties of Site 7 is indicated in Table 6.5.

Table 6.5. Properties of the uMgeni alluvial deposits and Site 7 for potential MAR in the study area

Site 7	**Aquifer thickness (m)**	**Static water level (m bgl)**	**Aquifer area (km^2)**	**Hydraulic conductivity (m/day)**	**Transmissivity (m^2/day)**	**Potential recharge water storage capacity (km^3)**	**Recharge (mm/year)**	**MAR Potential Sites**
uMgeni alluvial deposits	30	8	0.979	5- 6.5	32	0.002	93	Low Potential

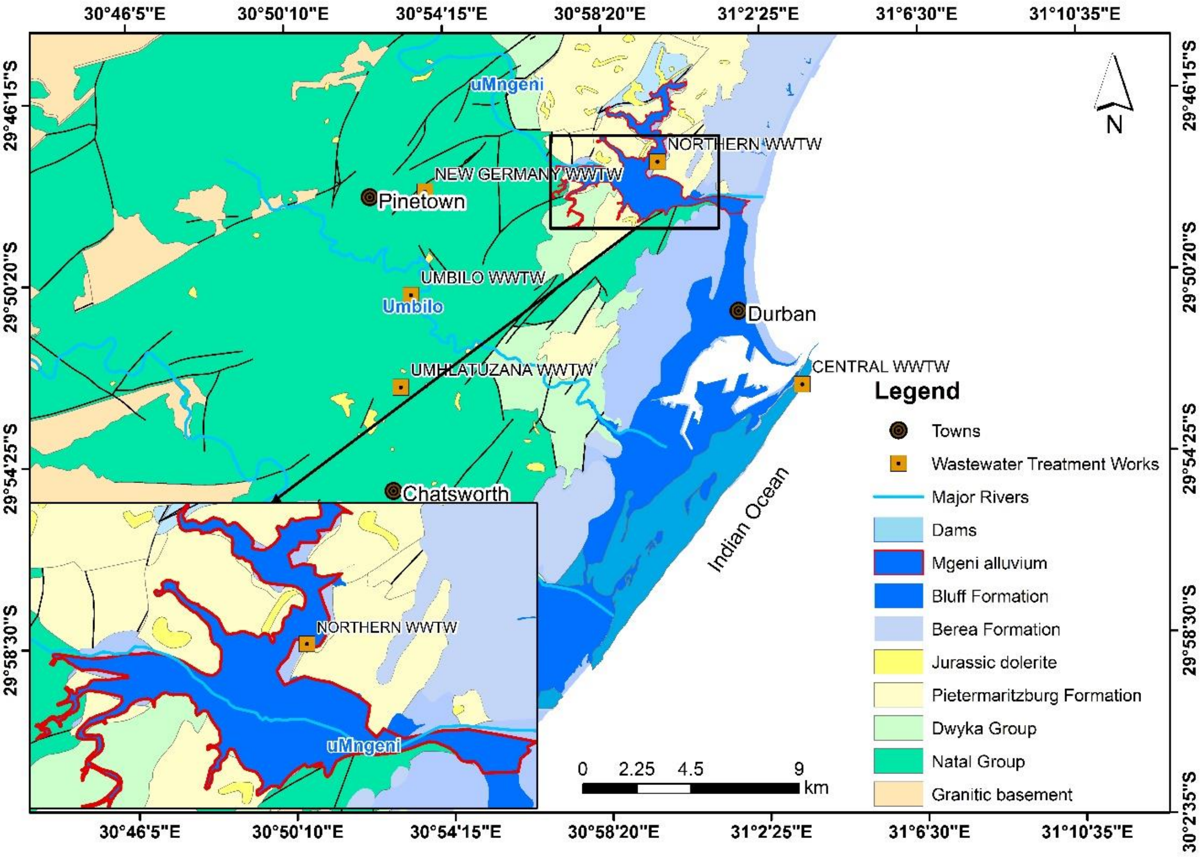


Figure 6.11. Potential MAR site in uMgeni alluvium aquifer

The area covered by the alluvium deposits in Site 7 is approximately 5 km^2 (Figure 6.11). The uMgeni alluvial aquifer is up to 40 m thick within its central, southern and eastern areas, but can be thinner along its borders, especially towards the west. Its average thickness is approximately 30 m. The uMgeni alluvial sediments include sand and silt with clay intercalations. Multiple sand layers of the uMgeni sediments can be identified in the borehole logs, although data is too sparse to delineate a specific sand layer aquifer. However, based on available geological logs of borehole drilled into the uMgeni alluvial aquifer, the average thickness of sand layer is 10 m.

This alluvial deposit has an average K of about 5.5 m, borehole yields ranging from 2.5 to 45 l/s and T values of 32 m^2/day. The aquifer has an estimated porosity of 30% (Geomeasure Group, 2018). Two wastewater treatment works boarder the aquifer, namely, the Northern WWTW and the New Germany WWTW which can contribute 58 and 7 Ml/day of treated water, respectively. However, based on the treated wastewater quality assessment, the Northern and New Germany WWTWs treated wastewater quality do not have the required standard for MAR unless the plants' treatment efficiency is improved.

Based on an assessment of the hydraulic properties and related factors, the aquifer has low potential for MAR. Furthermore, the following possible challenges need to be addressed during feasibility study stages:

i. The Bisasar Road landfill site is located upstream to the uMgeni alluvium aquifer. According to Ndlovu *et al*. (2018), the groundwater downstream of the Bisasar landfill are impacted by leachate leakage. Therefore there is high groundwater pollution potential.
ii. Shallow groundwater levels in the alluvial aquifer mean that additional MAR may induce unnecessary groundwater level rise and flooding.

6.5 The primary challenges for implementation of MAR in the study area

The primary challenge for the implementation of a MAR project in eThekwini District Municipality is to obtain land for MAR infrastructure. Being a Metropolitan municipality in KwaZulu-Natal, the value of land in the city is high. The quality of the treated wastewater for MAR is a big concern as outlined in preceding sections. Improperly treated wastewater requires further treatment before infiltration or injection, which might raise the investment costs for MAR.

The formation of a clogging layer at the bottom of the infiltration ponds and clogging of injection wells or recharge trenches is a potential problem. According to Brown (2005), in the United States 28 out of 50 ASR projects had faced well clogging problems to some extent. In the greater eThekwini District Municipality, clogging of wells and recharge will be a challenge as well. In addition, the occurrence and position of fault zones may pose difficulties for the construction of an optimal aquifer storage and recovery system. Aquifer pollution is another key concern for MAR implementation in the eThekwini District Municipality. In some places such as the Bluff, Wentworth and Springfield areas, the aquifer is already showing some indication of pollution with industrial hydrocarbons, waste and leachate from landfill sites, which may compromise the use of the injected water for later use.

6.6 Synopsis

Nowadays, a number of countries are using treated waste water from wastewater treatment plants (WWTP) for MAR (e.g., Namibia (Windhoek), Israel). The eThekwini Water and Sanitation manages 27 wastewater treatment plants where the treated effluent is directly discharged into the nearby or adjacent rivers. This treated wastewater could be a suitable source of water for MAR as the volume available is high, presently estimated to be 276414 ML/year. After reviewing a number of scientific papers and studies (e.g., Murray et al., 1998; Amin *et al*. 1998, Haq, 2006; Hanson *et al*. 2006, Water Reclaim, 2009; Arias-Barreiro *et al,* 2010) it can be summarised that two principal factors are of concern with respect to the reuse of wastewater; 1) the treatment process and efficiency of the WWTP, and 2) huge pollution loads from the industry. Hence, the reuse of treated wastewater will require intensive investigation for implementing low-cost water treatment technology in the eThekwini District Municipality to improve the treated waste water to the standard required for MAR.

Seven potential aquifer sites are identified in the Berea Formation and more recently in the alluvium and estuarine deposits. These sites exhibit varying storage sizes and suitability for MAR. However, detailed feasibility study is required at each site to reach to a final decision for MAR implementation both for use as water security and mitigation of potential seawater intrusion.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

One of the major goals for eThekwini District Municipality is to provide safe drinking water for each household. Integrated and innovative water-management concepts considering conventional and non-conventional water resources are required to achieve this goal. This study investigated the potential application of MAR in the Municipality using treated wastewater. The investigation indicates that the greater eThekwini District Municipality has the prospect of using MAR techniques to conserve excess treated wastewater for reuse and as potential seawater intrusion mitigation strategy. The hydrometeorological data analysis indicates that the region receives a mean precipitation of 92 mm/year of which 79% is lost to evapotranspiration, 14% runs of through surface water drainage channels to the Indian Ocean. The average CMB and water balance method based estimated groundwater recharge is 118 mm/year or 12% MAP. The hydrogeological and hydrochemical characterisation identified five main hydrostratigraphic units that very in their hydraulic and hydrochemical characteristics. According to stratigraphic order, these are: 1) weathered and fractured granitic basement aquifers is characterized by average borehole yield and transmissivity (T) of 1.2 l/s and 3.9 m2 /day, respectively and Ca-Mg-HCO3 hydrochemical water type; 2) fractured Natal Group sandstone aquifer characterized by average borehole yield and hydraulic conductivity (K) of 5.6 l/s and 2.8 m/day, respectively and Na-Mg-HCO3-Cl dominant hydrochemical water type; 3) fractured aquifers of the Dwyka Group diamictite and tillite that are characterized by average borehole yield of 0.4 l/s and T of 1.3 m2 /day and Na-Cl-HCO3 dominant hydrochemical water type; 4) the Vryheid Formation sandstone of the Ecca Group, which is characterized by average borehole yield of 2.5 l/s, T of 4.9 m2 /day, K of 0.17 m/day and Na-Cl-HCO3 hydrochemical water type; 5) the intergranular primary aquifers of the Maputaland Group which consists the Bluff, Berea Formations and recent alluvium and estuarine deposits. These primary aquifers have average borehole yield of 14.8 l/s and transmissivity of up to 406 m2 /day with a mainly Na-Cl-HCO3 hydrochemical signature.

Measured depth to groundwater varies across the aquifers of study area are mainly controlled by the surface topography and geology. In the granitic basement aquifers, depth to groundwater can be as deep as 45 m bgl, whereas in the Natal, Dywka and, Ecca Groups, groundwater is encountered at average depth of 20 m. Groundwater in the Maputaland Group primary aquifers, along the coast, occurs at an average depth of about 6 m. The groundwater flow in the area is from west to the eastern side following the topographic gradient and discharges along the coastline into the Indian Ocean.

All the WWTW treated wastewater effluent in the greater Durban region except for the Craigeburn and Fredville works do not meet the SANS 241:2015 drinking water quality criteria for public water supply for free ammonia, COD and EC. The suitability of the treated wastewater generated at the various WWTWs suggests that further treatment is required before the treated wastewater is injected into the aquifers. As it stands, only the Craigeburn and Fredville works are compliant with the guidelines for drinking-water quality SANS 241:2015. The Craigeburn works has a volume of 1Ml/day of treated wastewater, while the Fredville produces 5 ML/day of treated waste water which complies for MAR application.

MAR is generally more successfully achieved in intergranular/primary aquifers than in weathered or fractured aquifers. In the present study area, intergranular aquifers occur along the coast, including the area where the city of Durban is located. These aquifers are the Bluff Formation, Berea Formation and alluvial/estuarine deposits. Amongst these aquifers, the Berea Formation shows the highest potential for MAR because of its high values of K, T, borehole yields and thickness

Seven potential MAR Sites (Berea Formation Sites 1 to 5, the Harbour Beds and the uMgeni alluvial deposits) have been identified within the greater eThekwini District Municipality. The Berea Formation, Harbour Beds and uMgeni alluvial deposits provide suitable characteristics and storage capacities for a MAR implementation. The most beneficial results are obtained when MAR is coupled with long term underground storage and with a water recovery system to supply individual households and industries. In general, the basic MAR technique such as ASR/ASTR (aquifer storage, transfer and recovery) can be suitable for eThekwini District Municipality. Some modification may be required to adjust the techniques with respect to water sources and locations to reduce cost. A minimum separation distance between the injection well and the recovery well is required to get the advantage of natural attenuation for improving groundwater quality. As there is limited space within the greater eThekwini District Municipality, this might be problematic. In this case, the installation of injection wells in the unsaturated zone will allow sufficient time for the recharge water to reach the regional water table.

The sedimentology and hydrochemistry of aquifers identified are conclusively understood. Therefore, intensive survey accompanied by hydrogeochemical modelling is recommended for a better understanding of the consequences of potential hydrogeochemical processes in the region's aquifers under MAR conditions. As the type, scale, and feasibility of MAR depends on a number of site-specific conditions, detailed scientific research combined with flow and reactive transport modelling are required to select the proper MAR technology, and to explore the mixing of recharge water and groundwater to ascertain the expected MAR project benefits.

Thus, the following recommendations drawn from the present study:

- Improve the efficiency of the various WWTW to improve the quality of treated wastewater;
- The impacts of treated wastewater on aquifers is required. This include water uses after recharge, the probable water- rock interactions and the environmental impacts;
- Investigation of infrastructural options for both implementation of MAR and recovery and use of the stored water;
- Identify and map pollution sources and the extent of pollution in the area
- Identify potential areas susceptible for seawater intrusion and potential use of MAR for its mitigation.

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APPENDICES

Appendix 1. Hydrometeorological Data

Appendix 1.1. Monthly rainfall (mm) recorded at different weather station (SAWS, 2019)

Mount Edgecombe

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1995	88	22,8	289	173	49	43	9.8	4.4	9.2	106.4	90.8	311.6
1996	314.2	222.6	127.6	34.6	12.4	12.4	216.6	12	6.4	106.2	54.8	62.2
1997	209.2	163.2	52.4	59	35.8	80.4	121	27.8	63.2	163.2	258.4	85.6
1998	76.4	190.8	64.4	65.4	33.4	0.2	14.4	72.4	20.8	64	95	152.8
1999	47.2	263.2	37.8	11.6	46.8	45.6	0.6	20.6	79.8	387.8	61.2	396.2
2000	212.8	245	69	52	117.6	8	4.2	15.4	26.2	49.2	143	174.2
2001	108.6	91.2	28.2	122.2	15.6	0.4	8.4	0.6	46.4	158.2	131.8	257.4
2002	203	98.6	36.8	124	0.8	9	158.4	46.8	37.6	29	49	76.6
2003	100.2	16.2	72	28.2	21.8	23	0.4	10.8	67.8	8.2	64.4	71
2004	171.6	96.4	41.6	25.2	0.8	0.2	57	24.6	39.4	39	79.4	33.4
2005	84.4	50.8	57.2	13	1.4	21.4	0.4	26.6	39.4	52.6	103	78.4
2006	83.4	122.4	55.6	60.2	99.6	1.4	0	65.2	66.4	96.4	87.8	176.6
2007	54.2	53.6	167	26.4	1.2	59.2	7.2	9.6	43.4	110.6	176.4	53.4
2008	111.8	112	36.8	75	6.2	31.4	0.6	1.4	64.6	49.8	64.8	98.6
2009	95.4	84.8	24	29.2	34.4	0.4	0.2	32.8	36.4	72.6	104	155.8
2010	119.2	47.2	17.4	10.6	7.4	12.8	1.8	3.2	16.8	61.4	95	180
2011	193	7	74.6	116.8	63.6	73.2	138.4	71.2	39.6	98.8	280.4	60.2
2012	56.2	22.6	162.6	25.6	11	12.4	4	55	232.8	202.2	154.6	137.2
2013	136	76.4	121.6	80	85.8	60.6	23.4	16.4	41.4	160.8	78.8	90.6
2014	112.8	49.8	99	23	11.6	12	5.2	3.2	33.4	104.4	53.2	82.8
2015	105.2	116.2	100	13.4	0	5	147.2	2.8	45.2	25.8	42	95.8

2016	124.2	47	109.6	21.4	118.8	3.6	263.2	46.4	84	106	82.4	45.2
2017	65.4	167.2	37	51.6	165.8	0.6	20.4	28.8	65.6	112	195	205.2
2018	30.6	64	168	36	44	2.8	14.6	21	79.2	64.8	39.4	104.8

Durban South

Year	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1993	73.5	58.4	38.6	43.8	16.2	8.8	33.2	44.8	58.9	117	84.6	169.5
1994	69.6	37	165	16.2	2	13.6	91.6	49	15.3	112.3	24.7	79.6
1995	73.6	32.8	211.2	172.6	44.1	44.4	16.1	11.1	16.2	102.9	82.6	224
1996	448.2	247.5	106.4	36.9	18.7	1.1	261.4	12.7	22.9	120.8	72.7	72.7
1997	187.1	99.5	59.6	167.9	40.5	89.4	159.2	16.6	71.2	151.3	277.2	71.3
1998	93.3	158.3	83.8	237.4	52.2	33	22.9	69.4	25.5	64.5	106.4	132.6
1999	94	239.3	44.2	36.7	36.5	74.4	3.5	12.2	74.1	195.9	59.1	291.8
2000	181.7	157.3	148.8	63.2	167.5	3.8	20.2	17.7	62.8	60.2	142	124.5
2001	65.5	77.4	43.4	89.5	12.5	5.6	45.3	0.3	145.4	171.3	191.2	142.9
2002	155.8	154.7	21.3	162.6	3.3	23.8	151.5	53.9	43.6	32.4	64.2	113.3
2003	102.1	15.7	96.3	121.8	36.3	61.5	1.9	58.4	121.5	48.5	61.3	93.8
2004	231.7	126	39.5	23.7	2.1	5.3	111.3	12.6	56.4	64.6	51.7	74.2
2005	66.6	128.8	120.7	38.9	3.4	48.3	2.8	20.6	25	44.2	95.1	90
2006	110.8	188.8	77.5	81.6	110.4	5.4	8.2	71.9	67.4	109.1	178.8	201.9
2007	68.2	80.1	245.4	156	0.8	58.7	21.3	22.7	98.1	139.5	301.2	57.3
2008	133.8	78.7	196.2	122.1	28.4	171.2	3.5	1.8	99.3	81.6	80.5	184.9
2009	159.8	121.7	52	51.5	25	8.9	12.9	54	72.6	94.2	126.8	145
2010	94.3	104.2	28.4	8.5	54	24.6	1.6	0.4	18.2	82.8	100	169.8
2011	124.8	12.2	75	67.8	73.2	47.4	98.4	62.4	47.4	65.4	276.2	55.4
2012	50.6	33.4	282.4	17	18.2	28.4	5.8	80.8	265	209.8	125.6	124.2
2013	165.8	57.2	115.4	87	52.6	28	33.4	13.2	50.6	156.8	83.2	79
2014	69	89.2	65.2	35	17.8	10.4	4.4	5.2	33.6	86.2	119.6	83.8

2015	56	96.8	79.4	25.8	8.8	6.6	199.4	10.8	75.8	39.2	61.4	102
2016	103.2	69.4	129.4	30.8	212.6	6.8	281.2	67.2	85.8	116.6	84.4	55.2
2017	62.4	137	47.8	60.6	217.4	6.3	34.4	40.8	77.6	166.6	129	119.6
2018	34.4	82.4	98.8	36.2	17.6	6	25.3	41.2	77.3	167.1	123	123

Virginia

Year	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1995	50.4	24.2	158.,8	130.2	36	46	15.2	5.6	4.8	63	59.2	168
1996	118.8	113.2	100.6	32	18	5.8	242.8	13.8	7.4	96.6	47.8	73
1997	164.8	114.8	45.2	75.8	30.6	79.6	108.6	25	55	141.4	227.8	66
1998	67.6	159.2	59.4	99.8	49.2	3.4	19.4	80.2	18	66.6	101.6	97.4
1999	54.8	208.8	30.6	15.2	24.6	50	1	27.4	62.6	474.2	32	221.6
2000	184.8	211.6	62.8	57.2	164.6	7	9.2	22.4	36.4	6.2	13	149.2
2001	88.2	90.6	26	121	7	0	22.2	1.6	139.6	153.6	139.2	180
2002	157.4	96.8	39.6	171.8	2.6	23.4	178	59.2	49	35.4	87.8	62.8
2003	100.8	9.8	95	43.8	12.2	41.6	7.6	29.2	90.6	16.8	86.4	5.2
2004	212.6	115.4	52.8	19.6	3.4	1.6	59.8	23.4	43.8	57	39.6	34.2
2005	73	104.2	91.8	16.6	3.6	47	1.8	23.6	27.8	47.4	93.2	65
2006	84.6	86.8	44.4	76.8	57.4	3	0	70.4	66.4	81.6	78	141.2
2007	54.4	56.4	122.2	118.8	0.8	59.8	24.6	12.4	53.4	128.6	136.8	49.8
2008	98.6	103.8	53.6	80.4	8.4	34.4	1.4	5	71	42.4	71.8	127.8
2009	123.2	59.4	27	32.8	36.6	0.2	0.4	46.2	19.4	54.6	87.2	109.4
2010	69.6	67	18.4	23.6	10.8	7.2	1.6	0.4	10	55.8	81.2	160.6
2011	148.6	5	60.2	109.8	49.4	75.8	97	50	37.8	59.4	262.2	54
2012	28	34	263.8	12.6	14	40.6	5.4	82.2	231.8	145.8	100.4	107.6
2013	99.2	50.4	135.2	82	69	52.4	34.8	3	41.6	113.6	85	93
2014	75.4	35.2	69	28.6	20.2	8	4.2	8.8	32.4	105.4	45	80
2015	80.2	58.2	75	28	0.6	0	159.4	0	11,8	17,2	43	64

2016	130	57.4	55.8	26	211.8	2	281.2	46.8	82.4	87	88	44.2
2017	56.8	105	41	71.6	193.6	0	24.6	62.4	67.8	189	169.6	130.8
2018	33	67.8	116.2	43.2	54	5.4	22.2	30.4	84.6	68.6	43.4	91.8
2019	72	81	116.4	30.8								

Appendix 1.2. Daily monthly mean temperature recorded at different stations (SAWS, 2019)

Mount Edgecombe

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1993				27.1	25.1	24.4	24.6	23.9	24.7	24.5	26.5	27
1994	28	29	27.7	25.8	24.9	24.4	23	22.8	24.4	23.3	25.9	27.5
1995	27.9	29.5	27.7	24.5	24.7	22.9	22.5	24.1	24.2	24.6	25.4	25.5
1996	27.6	28	26.3	24.7	24.6	23.7	20.5	22	23.8	24.4	26.3	28.3
1997	28	27.9	27	25	23.8	23.6	21.8	23.6	23.1	24.7	24.3	26.6
1998	28.3	28.3	27.5	26.6	25	23.7	23.6	23.2	23.9	24.4	26.6	27
1999	29.4	28.8	28.7	27.7	25.5	24.2	24	24.6	24.2	24.4	26.9	27.8
2000	27.2	28.9	28.3	25.4	23.6	24.2	22.8	23.7	23.9	23.2	25.3	26.9
2001	27	27.4	28.3	25.5	24.7	24.1	22.8	23.9	22.9	24.7	26.3	26.8
2002	28.4	26.9	27.6	26.7	25	22.5	22.4	22.7	23.4	25	24.8	27.4
2003	28	29.4	28.8	27	24.2	22.3	22.7	22.5	22.8	24.4	25.5	25.4
2004	27.4	26.4	25.8	24.8	23.6	21.5	19.7	22.2	21.6	23	25.8	27.3
2005	26.8	27.6	26.2	24.4	24	22.5	21.5	22.8	22.8	23.3	24.3	24.7
2006	265	27.7	25.5	24.5	21.7	21.1	22.7	21.8	22.4	23.1	23.7	25.5
2007	26.7	27.9	25.7	25.3	26.7	23.7	23.7	23.9	24.8	24.3	25.4	26.8
2008	28	29	27.9	25.7	25.6	23.5	24.2	24.3	24.4	24	25.5	27.6
2009	27.7	28.4	27.8	26.4	25.4	24.8	23.4	23.4	23.8	24.1	24.7	25.9
2010	27.7	29.4	28.5	27.9	26.9	23.8	24.2	24.7	25.3	24.9	26.3	26.5
2011	27.6	28.7	29.5	25.5	24.3	22.4	20.5	22.2	24.1	24.1	25	27

2012	29.1	29.1	28.1	25.3	25.6	24.4	23.5	25.2	23.4	24.1	25.8	28.1
2013	28.1	28.3	27.2	25.5	249	244	23.4	24.4	25.3	24,2	26	25.7
2014	28.4	29.2	28.2	26.4	25.4	24.7	23.7	24,5	25.2	23.8	25.2	27.6
2015	28.7	27.9	28	25.8	27.3	25.4	22.7	24.4	23.5	26.5	26.3	28.1
2016	29.1	29.2	28.8	27.5	25.7	24.4	22.6	24.6	23.7	23.7	25.6	28.3
2017	28.4	28.8	29.2	27.2	26.3	25.5	24.3	24.1	24.8	25.7	26.5	27.7
2018	30.3	30	29.2	29.3	27.8	27.1	26	24.8	25.7	25.8	26.4	29.3

Durban South

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1993	28.6	28.4	28.8	27.1	25.4	24.3	24.5	23.7	24	24.2	25.8	26.6
1994	27,7	28,7	28	26,4	25,2	24,4	22,9	22,1	23,5	23	25,5	27,3
1995	27.6	29.1	27	24.1	23.9	22.2	21.7	23.6	23.8	24.3	25.1	25
1996	27.2	28.1	26.4	25.1	24.8	23.9	20.7	21.9	233	23.8	25.8	27.7
1997	27.9	27.6	27.1	24.9	23.2	22.7	21.6	23.6	23.1	24.3	23.6	26.1
1998	27.6	28.2	27.1	26.4	24.5	23.1	23.2	23	23.5	24.3	26.4	26.5
1999	29	28.8	29.1	27.8	24.8	24.3	23.6	24.3	24	24.3	26.5	27.5
2000	27.2	28.7	28.1	25.3	23.4	23.7	22.8	24.1	23.6	23.4	25.7	27.1
2001	27.9	28.3	28.9	25.6	25.5	25	23.5	24	23.5	24.8	26.2	27
2002	28.4	27.4	28.4	27.2	25.2	23.3	23	22.8	23.6	25.3	25.3	27.5
2003	28	29.9	29.1	27.1	24.3	22.2	22.5	22.2	22.4	23.8	25.5	27
2004	27.5	28	27.3	27	25.6	23.8	21.6	23.8	22.7	24.3	26.6	28.7
2005	27.8	28.5	27.1	25.6	25	23.9	22.9	23.6	23.9	24.9	25.6	26
2006	27.4	28.5	26.6	26.1	23.4	23	24.3	23.6	24.2	24.9	25.6	26.9
2007	28.3	29.2	27.2	26.5	25.9	23.4	23.3	23	23.9	23.6	24.6	25.9
2008	27.5	28.4	27.5	25.2	24.8	22.4	23.1	23.3	23.6	23.1	24.7	26.5
2009	26.6	27.7	27	25.9	24.4	24.3	22.9	22.7	22.8	23.5	24.2	25.5
2010	27.8	29.2	28.2	27.6	26.7	23.5	24.1	24.5	25.7	25.1	26.3	26.9

2011	28.6	29.9	30.3	25.9	24.6	23.3	21.3	22.4	24.1	24.9	25.6	27.6
2012	30.4	30.5	29.5	26.3	26.2	24.1	23.1	24.2	22.9	23.5	24.4	28
2013	28.4	29.1	28.1	26.2	25.8	24.5	22.8	24	24.4	23.6	25.6	25.8
2014	28.9	29.7	28	26.4	25.1	24.6	23.5	24.1				

Virginia

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1995	26.5	27.3	26.1	23.7	23	21.4	20.8	22.2	22.6	24	24.3	24.5
1996	26.8	27.3	25.4	24	23.3	22.6	19.8	20.9	21	25.3	26.9	28.3
1997	28.2	28.9	27.2	24.5	23.1	22.5	21.2	22.3	20.1	22.5	23	24.9
1998	26.3	26.1	25.9	25.6	21.3	24.2	23.7	23.5	24.2	25	26.6	27.6
1999	29.9		29.2	27.6	25.7	25	24.2	24.4	24.2	24.8	27.3	26.8
2000	26.3	27.7	27.5	24.4	22.9	22.7	21.8	22.5	22.5	22.7	24.8	26
2001	26.4	26.9	27.3	24.8	24	23.5	22.3	22.6	22.3	23.6	25.4	26.3
2002	27.2	26.5	27.1	25.9	24.8	22.8	22	22.1	22.8	23.9	24.2	26.3
2003	26.9	28.9	28.4	26.6	23.7	21.5	21.3	20.8	21.1	22.8	24	24.4
2004	26.7	27.4	26.7	25.9	24.1	22.1	20.9	22.6	22	23.3	25.8	27.3
2005	27.2	28	26.8	24.6	24	23.4	22.3	22.8	23	23.8	24.9	25.6
2006	27	28.1	26.6	25.4	23.3	22.6	23.3	23.1	23.1	24.3	25	26.6
2007	27.7	28.7	27.5	25.9	25.4	22.8	22.6	22.5	23.5	23.3	24.8	26.3
2008	27.6	28.6	26.9	24.5	24.1	22.2	22.2	22.8	23.1	22.9	24.2	26.2
2009	26.6	27.1	26.7	24.9	24.1	23.4	21.4	21.3	21.6	21.8	21.9	23
2010	26.8	28.7	27.5	26.7	25.5	23.1	23	22.9	24.4	24.2	25.3	25.9
2011	27.4	27.8	28	25.3	23.8	22.1	20.4	21.2	233	232	243	26.1
2012	28.2	28.1	27.3	24.7	24.5	23.2	21.9	22.3	22	22.6	23.9	26.6
2013	27.4	28	27	25.1	24,6	24.2	22.2	22.9	23.3	23	25.5	26.5
2014	29.1	29,5	28,8	26,6	25,4	24,7	23,4	24,4	24,9	24	25,4	27,3
2015	28.9	28.6	28.1	26.6	26.4	24.7	23.3	24	23.5	26.2	26	28.3

2016	28.9	28.8	29.1	25.3	23.6	23.1	21.9	23.7		31.6		
2017	31.3	29.1	29.9	26.3	26.4	22.8	22.8	22,7	24.2	22.4		
2018			29.0			23.8	22.6	22.4	22.9			

Appendix 2. Groundwater physical and chemical parameters

Appendix 2.1. Groundwater physical and chemical parameters for intergranular aquifers sourced from Ndlovu et al (2018), Geomeasure Group (2018) and WARMS (2019). Concentrations is in mg/L, EC is in µS/ cm.

Sample No	Sample date	pH	EC	TDS	Ca^{2+}	Mg^{+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-
SANS 241 (2015)		≥5.0 to≤9.7	1700	1200	ns	ns	200	ns	ns	300	500	11
ETK1	7/1/2018	6.78	807	403	36.12	14.04	113.46	2.72	179.23	78.32	25.79	**19.63**
ETK2	7/1/2018	7.2	1191	594	27.22	36.32	148.54	20.74	348.37	93.25	0.75	0.68
ETK3	7/1/2018	7.65	736	369	59.56	9.45	90.01	7.71	229.55	44.62	20.59	**22.86**
ETK4	7/1/2018	8.07	501	252	11.32	5.91	92.99	1.66	113.35	36.45	18.54	**24.46**
ETK5	1/1/1986	7	55	366	21	12	86	2	161	92	18	-
ETK6	7/9/2018	6.3	649	400	18.2	13	140	7.97	199	129	55.5	8.7
ETK7	5/1/2016	7.24	847	**2534**	87	36.8	314	3.25	241	**571**	38	0.69
ETK8	7/1/2018	8.47	644	323	77.42	17.63	47.87	7.21	101.95	33.14	15.04	2.39
ETK9	7/9/2018	7.41	1096	534	9.89	9.16	382	16.9	241	**751**	2.72	<0.50
ETK10	5/1/2016	6.94	790	350	43	20	88.4	3.38	124	**600**	85	**220**

ns- not stated

Appendix 2.2. Groundwater physical and chemical parameters for fractured aquifers sourced from Ndlovu et al (2018), Geomeasure Group (2018) and WARMS (2019). Concentrations is in mg/L, EC is in µS/ cm.

Sample No	Sample date	pH	EC	TDS	Ca^{2+}	Mg^{+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-
SANS 241: 2015		≥5.0 to≤9.7	1700	1200	ns	ns	200	ns	ns	300	500	11
ETK11	5/16/2006	7.37	81.1	55.2	11.5	12.5	137	0.14	201.6	131	8.23	0.01
ETK12	5/16/2006	6.76	88.9	62.23	21.2	19.3	115	2.6	150	180	10.6	0.1
ETK13	7/1/2018	7.36	1267	634	32.64	31.99	199.82	2.71	247.09	102.9	30.26	1.06
ETK14	1/1/1986	6.6	131	72.5	24	15	153	1.9	152	258	1	-
ETK15	1/1/1986	7.2	143	80.6	41	22	83	2.7	236	**310**	1	-
ETK16	1/1/1986	6.8	246	145.6	87	75	**306**	5.2	645	**1043**	1	-
ETK17	1/1/1986	7	80	47.5	37	32	132	2.4	273	121	1	-
ETK18	1/1/1986	7	159	91.6	31	32	82	3	257	**366**	1	-
ETK19	1/1/1986	6.9	77	44.9	30	20	87	2.7	194	159	1	-
ETK20	1/1/1986	7.1	100	59.7	41	22	92	2.5	236	135	1	-
ETK21	1/1/1986	7	142	78.7	48	46	180	4.8	381	264	1	-
ETK22	1/1/1986	7.2	106	59.3	73	59	150	2.7	520	204	1	-

ETK23	1/1/1986	6.8	129	78.2	64	43	144	2	413	176	1	-
ETK24	1/1/1986	7.1	81	47.7	38	29	86	2.3	259	140	1	-
ETK25	6/16/2006	7.12	362	253.4	123	76.4	**492**	4.83	410	**939**	30.7	-
ETK26	7/17/1994	6.4	121	74.4	73	19	130	7.2	318	290	-	-
ETK27	1/1/1986	5.9	12	69.4	12	29	157	8.9	181	**343**	1	-
ETK28	1/1/1986	6.9	90	52.5	46	22	99	4.1	255	147	1	-
ETK29	3/23/2009	6.88	124	64.2	61.7	43.3	164	2.87	372	157	26.8	-
ETK30	3/23/2009	5.46	158	91.2	32.7	40.9	189	12.9	46.2	**411**	26.3	-
ETK31	1/1/1986	7	120	27.2	52	28	181	3.7	313	268	1	-
ETK32	1/1/1986	6.7	52	31.4	16	13	62	2.1	117	60	1	-
ETK33	1/1/1986	7	55	36.6	21	1	104	-1	161	92	18	-
ETK34	10/1/2018	6.19	175	31.4	16.1	10.5	34.2	3.86	60.7	20.9	34.5	4.31
ETK35	10/1/2018	6.61	197	47.7	28.8	7.81	30.1	3.21	107	35.5	13.3	<0.50
ETK36	10/1/2018	6.34	578	44.9	17.7	27	146	3.74	138	163	104	<0.50
ETK37	10/1/2018	6.82	652	90.23	55.5	64.5	106	12.5	166	52.6	65.9	**92.4**
ETK38	10/1/2018	6.54	273	60.9	9.31	8.06	55.9	3.25	53.6	49.5	4.62	**14.9**
ETK39	10/1/2018	6.45	305	322	68.6	36.8	47.8	7.08	199	38	114	5.38
ETK40	10/1/2018	6.77	928	314	16.7	19.6	**356**	5.75	234	**445**	110	<0.50
ETK41	7/01/2018	7.1	458	366	97	20.2	85	9.38	197	89.8	87.7	8.52

ETK42	7/01/2018	6.85	654	434	41.2	23.4	67.3	3.71	95.9	168	25.5	<0.50
ETK43	7/01/2018	6.52	394	588	38.6	28	81.6	4.1	107	187	27.9	<0.50

ns- not stated

Appendix 2.1. Groundwater physical and chemical parameters for weathered and fractured aquifers sourced from Ndlovu et al (2018), Geomeasure Group (2018) and WARMS (2019). Concentrations is in mg/L, EC is in µS/ cm.

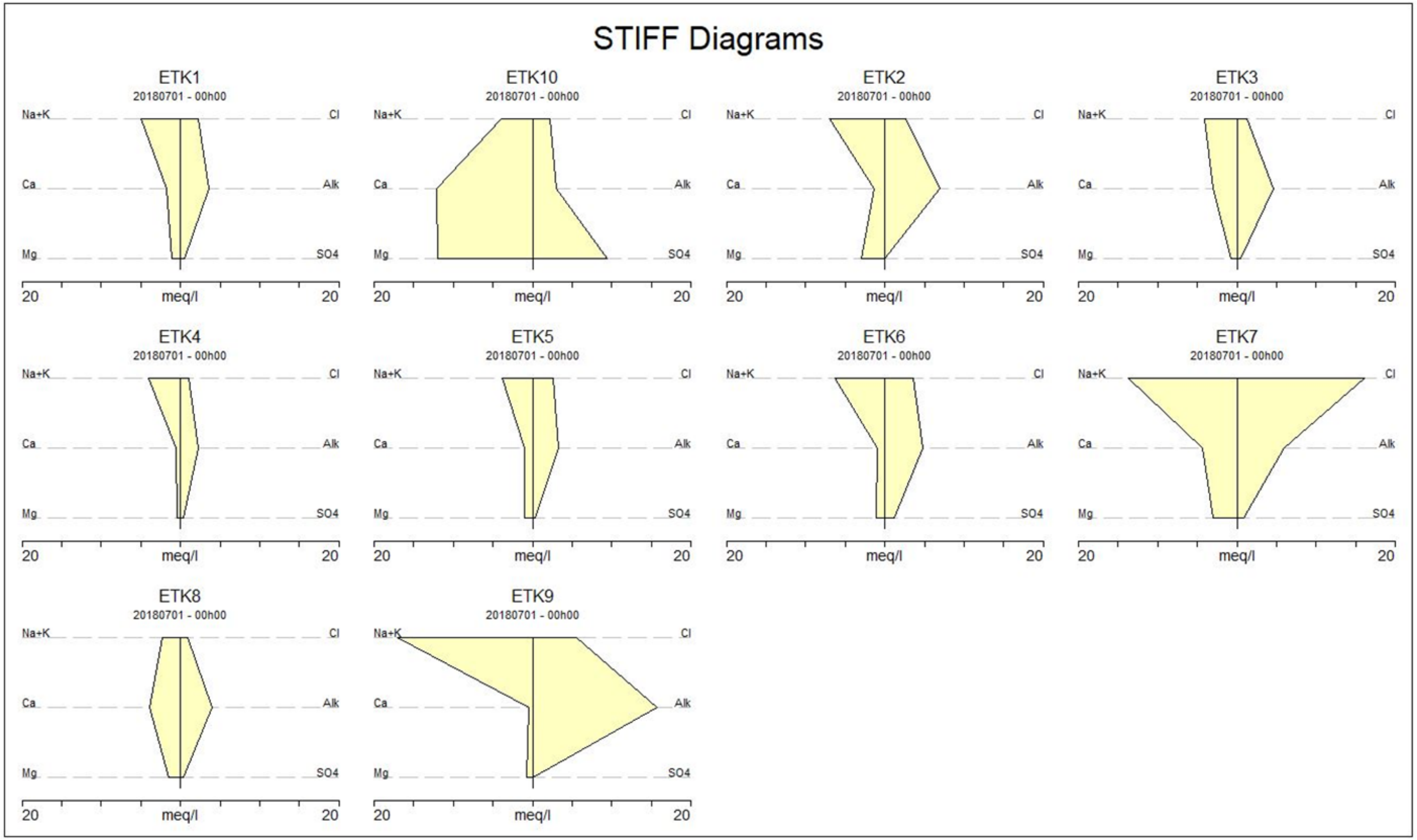
Sample No	Sample date	pH	EC	TDS	Ca^{2+}	Mg^{+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}
SANS 241:2015		≥5.0 to≤9.7	1700	1200	ns	ns	200	ns	ns	300	500	11
ETK44	7/1/2018	8.55	1530	765	49.2	34.79	**233.41**	2.04	331.05	108.98	1.15	0.7
ETK45	7/1/2018	6.89	661	331	34.82	15.6	85.3	3.56	213.33	69.47	4.56	1.05
ETK46	7/1/2018	6.88	226	114	15.93	8.66	26.94	2.44	132.88	18.47	10.11	4.36
ETK47	7/1/2018	7.75	618	312	42.14	17.98	66.28	3.03	255.98	52.95	1.19	0.67
ETK48	7/1/2018	6.23	356	180	5.6	7.25	63.93	1.67	104.9	54.57	-	**31.83**
ETK49	7/1/2018	6.95	107	57	3.79	5.05	14.71	0.71	175.52	27.91	3.64	3.71
ETK50	1/26/1998	7.2	90	52.8	49	12	123	1.6	156	173	20	-
ETK51	1/24/1998	7.1	47	30.8	26	16	47	2	114	60	10	
ETK52	11/4/2003	6.58	31.5	10	22	56.5	**225.5**	24.5	323	43	14	-
ETK53	12/12/1997	6.9	10	8.2	-1	4	15	0.77	28	16	5	-
ETK54	1/19/1998	7.1	14	11.6	9	4	24	4.7	44	15	2.5	-

ETK55	2/1/1998	7.2	24	18.0	13	4	17	1.7	48	30	6.5	-
ETK56	2/1/1998	7.1	29	21.2	21	12	19	0.86	100	27	8	-
ETK57	1/21/1998	7.2	44	25.6	30	15	29	0.86	154	30	15	-
ETK58	1/29/1998	7.4	36	23.0	34	9	29	1.8	140	24	10	-
ETK59	12/15/1997	7.4	80	51.2	34	29	113	1.4	198	98	23	-
ETK60	1/27/1998	7.2	17	13.4	14	4	8.7	1.9	50	20	5	-
ETK61	1/13/1998	7.4	48	30.7	28	18	46	1.1	158	50	14	-
ETK62	1/10/1998	7.3	20	12.8	14	3	20	2	54	27	10	-
ETK63	1/12/1998	7.2	66	42.2	45	16	59	3.6	210	57	25	-
ETK64	12/15/1997	7.5	63	40.3	22	12	95	2.6	90	110	15	-
ETK65	12/4/1997	7.5	56	35.8	43	23	57	1.5	220	62	14	-
ETK66	12/6/1997	7.5	21	21	4	5	26	2.9	34	32	5	-
ETK67	12/8/1997	7.4	80	51.2	58	24	86	2	260	91	27	-
ETK68	1/16/1998	7.2	106	65.6	56	40	13	2.8	316	108	43	-

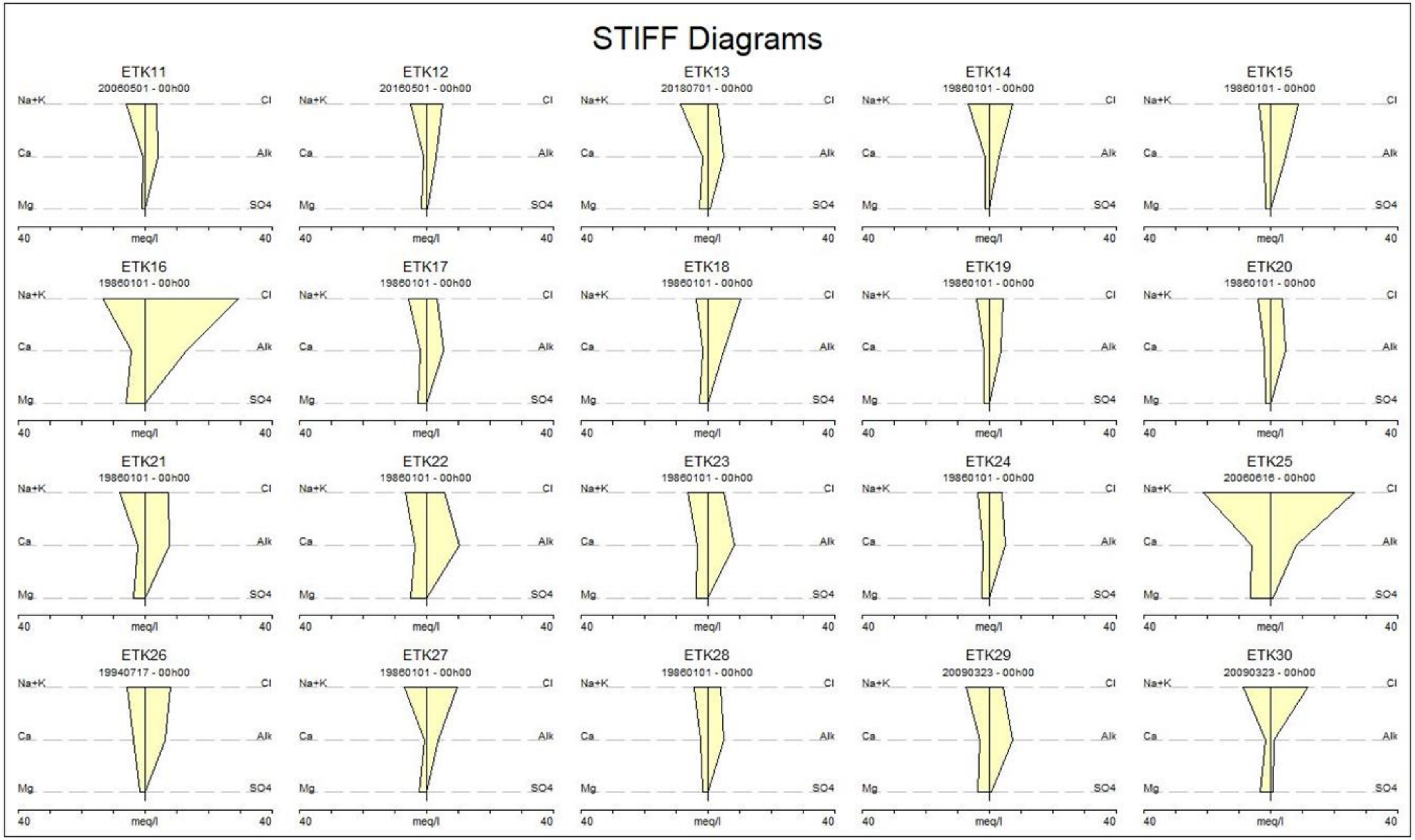
ns- not stated

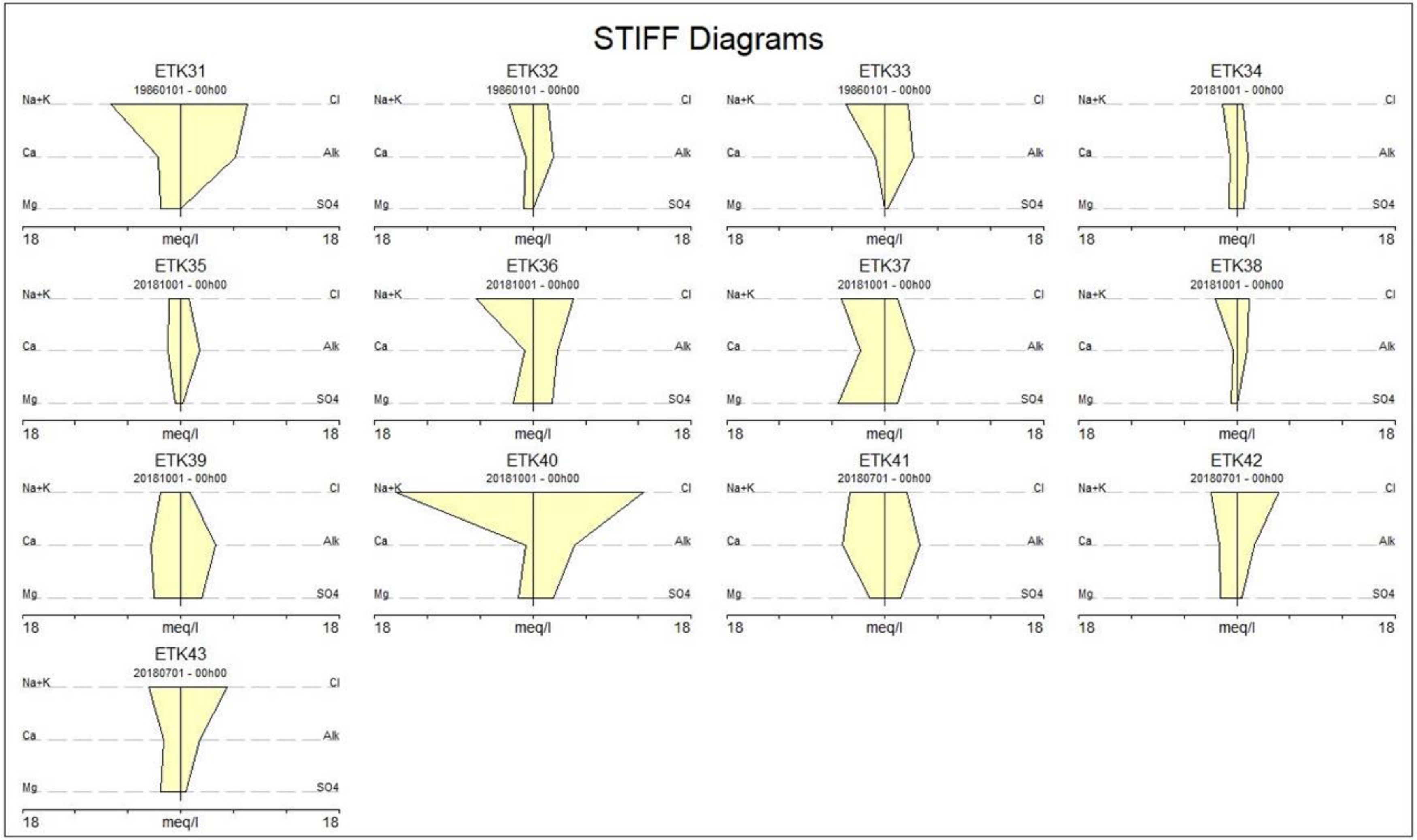
Appendix 3. Stiff Diagrams

Appendix 3.1. Intergranular aquifer hydrochemical data stiff diagrams

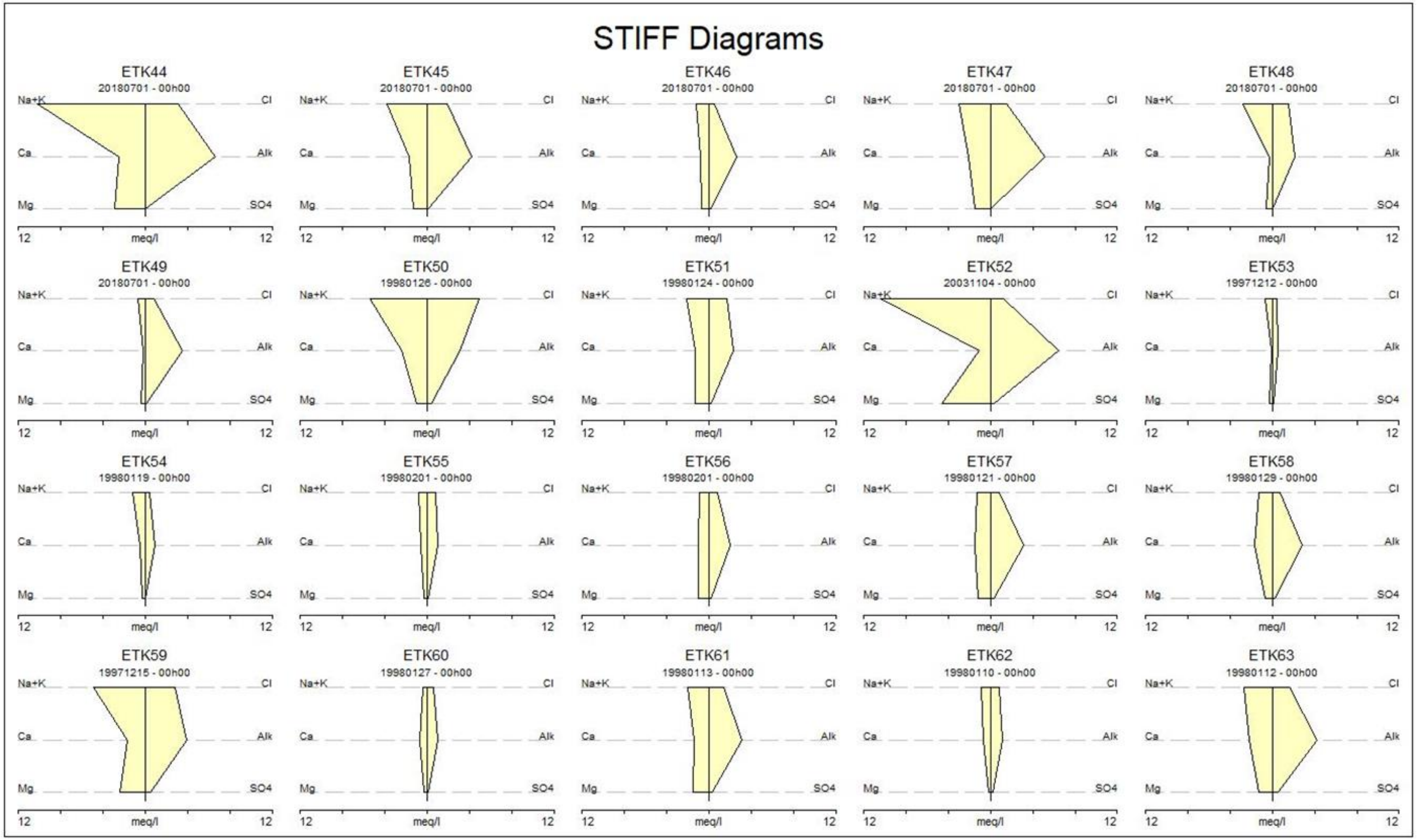


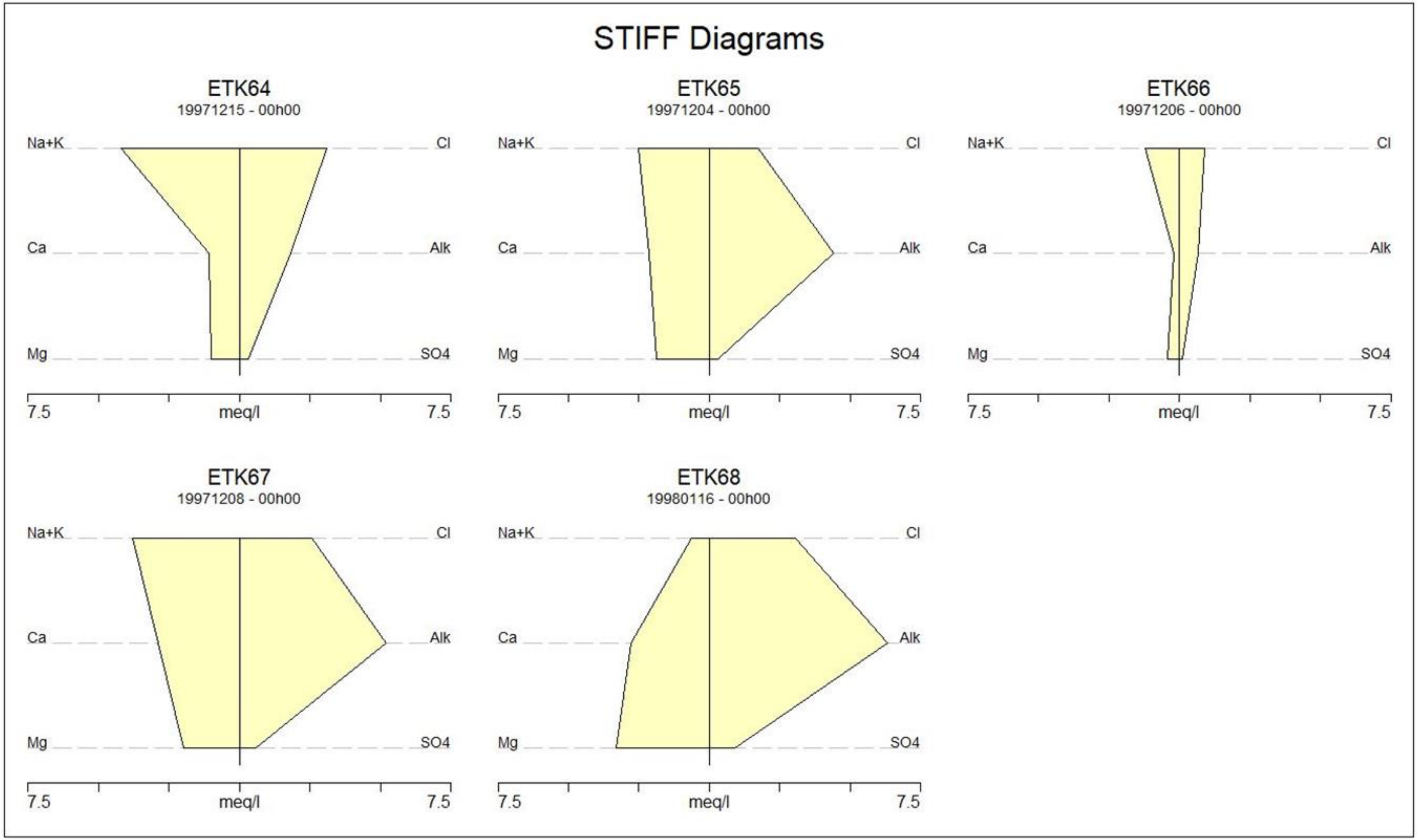
Appendix 4.2. Fractured and weathered aquifer hydrochemical data stiff diagrams



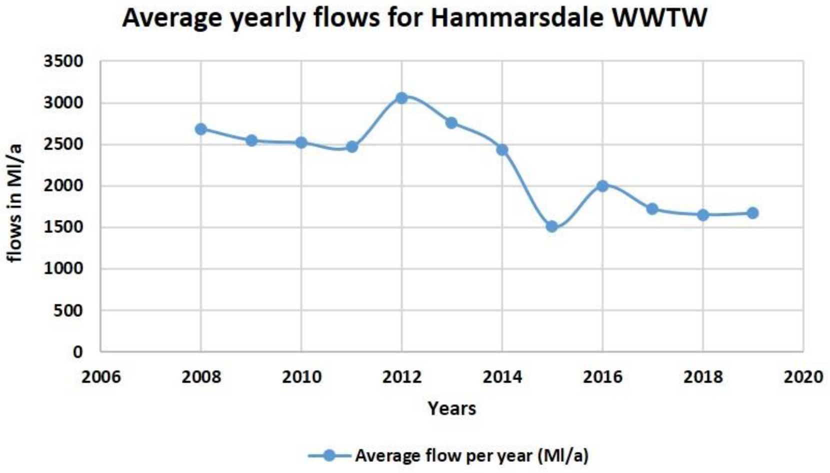

STIFF Diagrams
ETK31
19860101 - 00h00
ETK32
19860101 - 00h00
ETK33
19860101 - 00h00
ETK34
20181001 - 00h00
ETK35
20181001 - 00h00
ETK36
20181001 - 00h00
ETK37
20181001 - 00h00
ETK38
20181001 - 00h00
ETK39
20181001 - 00h00
ETK40
20181001 - 00h00
ETK41
20180701 - 00h00
ETK42
20180701 - 00h00
ETK43
20180701 - 00h00
Na+K
Ca
Mg
Cl
Alk
SO4
18
meq/l
18

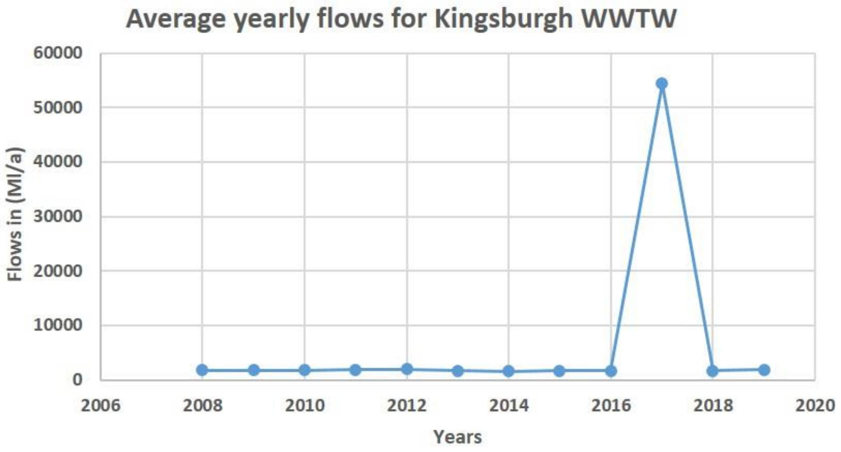
Appendix 4.3. Weathered and fractured aquifer water quality stiff diagrams

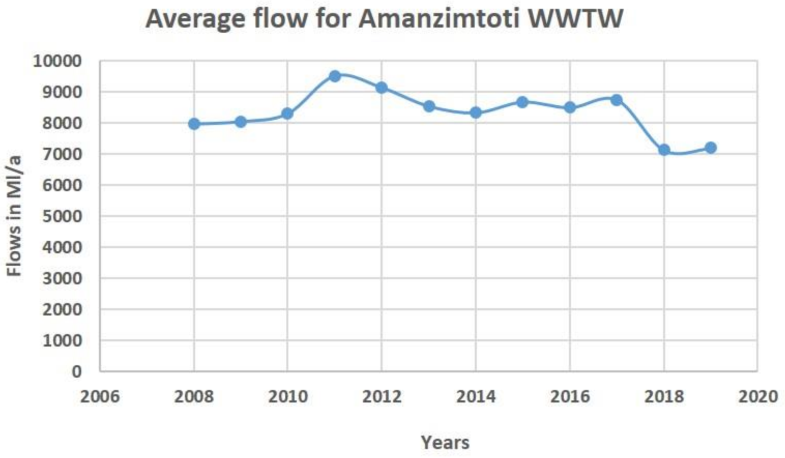


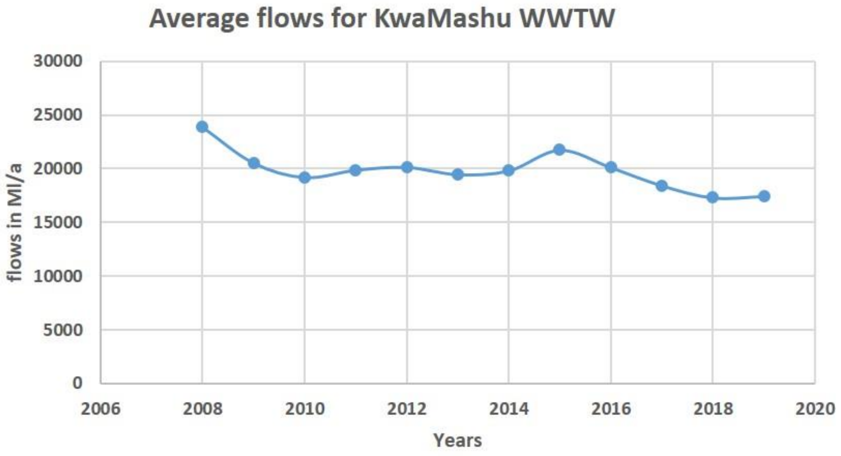

STIFF Diagrams
ETK64
19971215 - 00h00
ETK65
19971204 - 00h00
ETK66
19971206 - 00h00
ETK67
19971208 - 00h00
ETK68
19980116 - 00h00
Na+K
Ca
Mg
Cl
Alk
SO4
7.5
meq/l
7.5

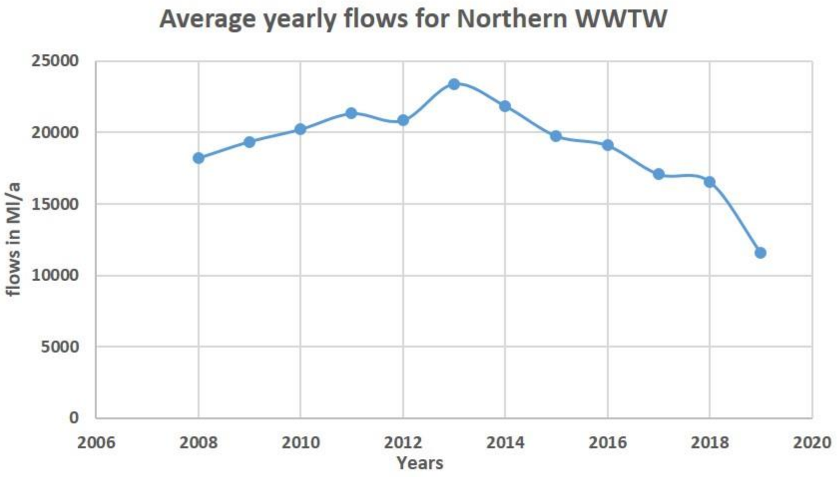
Appendix 5. Trends of annual treated wastewater flows

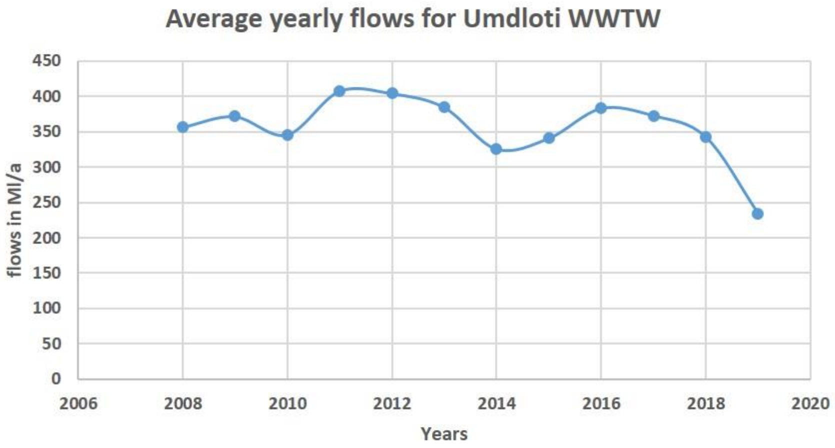


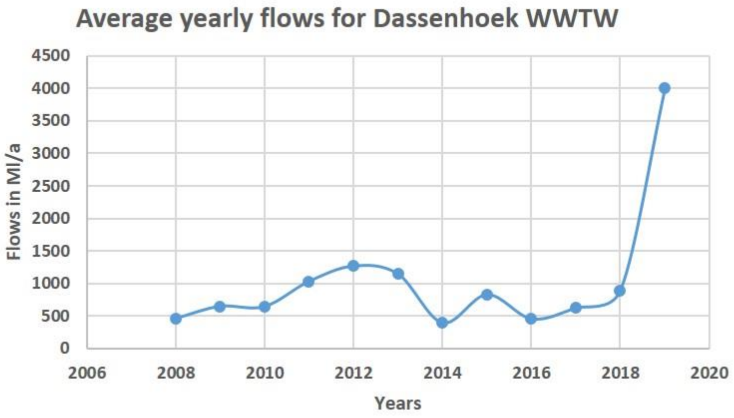


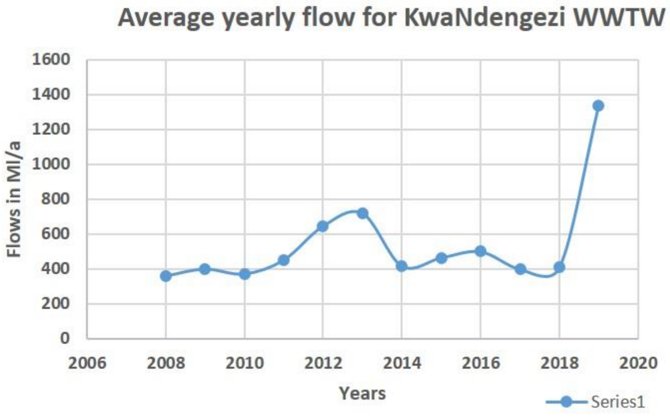


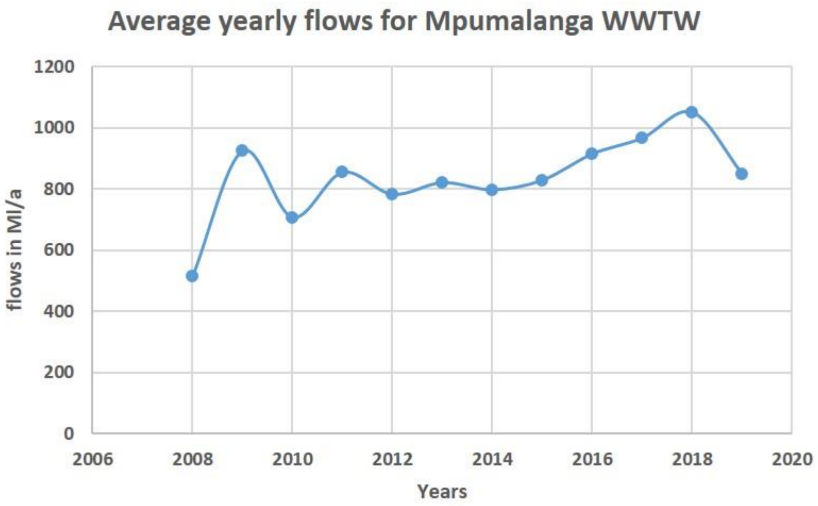


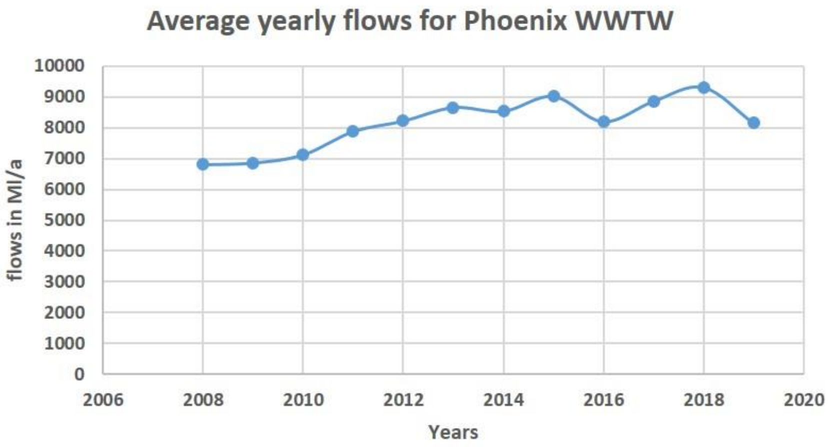

Average yearly flows for Northern WWTW

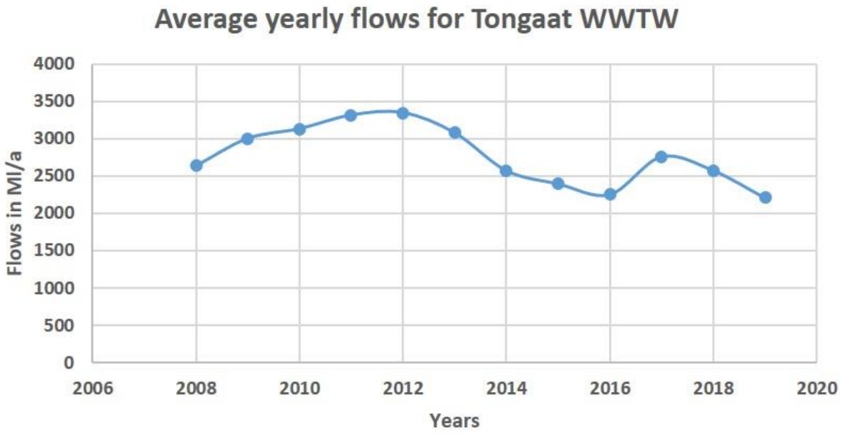

Average yearly flows for Umdloti WWTW

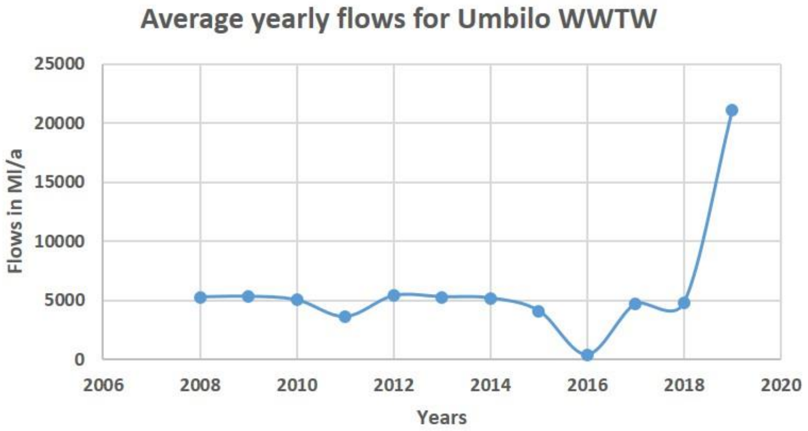

Average yearly flows for Dassenhoek WWTW


Average yearly flow for KwaNdengezi WWTW


Average yearly flows for Mpumalanga WWTW
flows in Ml/a
0
200
400
600
800
1000
1200
2006
2008
2010
2012
2014
2016
2018
2020
Years


Average yearly flows for Phoenix WWTW
flows in Ml/a
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
2006
2008
2010
2012
2014
2016
2018
2020
Years


Average yearly flows for Tongaat WWTW
Flows in Ml/a
0
500
1000
1500
2000
2500
3000
3500
4000
2006
2008
2010
2012
2014
2016
2018
2020
Years


Average yearly flows for Umbilo WWTW
Flows in Ml/a
0
5000
10000
15000
20000
25000
2006
2008
2010
2012
2014
2016
2018
2020
Years