DURBAN UNIVERSITY OF TECHNOLOGY
INYUVESI YASETHEKWINI YEZOBUCHWEPHESHE

INVESTIGATION OF POTENTIAL HIGH-YIELDING GROUNDWATER AQUIFER ZONES USING REMOTE SENSING & GIS TECHNOLOGY

By
Tyrone Moodley

Submitted in fulfilment of the academic requirements for the degree of
Masters of Engineering
in the
Department of Civil Engineering and Geomatics
Faculty of Engineering and Built Environment
Durban University of Technology
August 2021

DECLARATION

I, Tyrone Moodley, hereby declare that this dissertation, except where indicated in the text, is my work and has not been submitted in part, or in whole, at any other University or University of Technology.

This research on the investigation of potential high-yielding groundwater aquifer zones using Remote Sensing and GIS technology was conducted in KwaZulu-Natal, South Africa, and registered at the Durban University of Technology under the supervision of Dr Mohammed Seyam and co-supervision of Dr Taher Abunama.

Mr. Tyrone Moodley

APPROVED FOR FINAL SUBMISSION
Dr. Mohammed Seyam

ABSTRACT

Groundwater exploration has been critical in considering groundwater as an alternative freshwater source in basin management. Groundwater exploration simulates the aquifer yield capacity, which is helpful for planning purposes and water resource assessments. However, understanding the dynamic flow conditions of groundwater affected by anthropogenic land cover, water use changes, and uncertain climatic variability, especially in a semi-arid region like South Africa (SA), has called for quantification and quality rating of the resource. The aim of this study was to assess the groundwater potential (GWP) and identify high-yielding groundwater aquifer zones in KwaZulu-Natal (KZN), South Africa. Groundwater potential zones were spatially mapped using Geographic Information Systems (GIS) and remote sensing-based multi-criteria analysis. Spatial thematic layers viz. geology, lineament density, slope, drainage density, rainfall, land use/land cover and evapotranspiration were processed and developed using GIS and weighted using Saaty's Analytical Hierarchy Process (AHP). The thematic layers were subsequently aggregated using the GIS Weighted Overlay Method to develop a groundwater potential index map. Indices from the map were correlated with data from 113 boreholes using the Receiver Operating Characteristic Curve (ROC) and Area Under the Curve (AUC) to validate the results. Due to the widespread domestic use of groundwater in SA and the minimal available groundwater quality data in KZN, the groundwater quality data for parts of SA were analysed regarding concentrations of pollutants, inorganic chemicals and macropollutants. Groundwater quality data was obtained from available literature across SA and was compared with the South African National Standards (SANS) and World Health Organization's (WHO) guidelines for drinking-water quality using the weighted arithmetic Water Quality Index (WQI). A Piper Plot was then used to graphically analyse the chemistry of the groundwater samples to compare their ionic compositions. The groundwater quality results revealed that most parameters were below or slightly above the maximum permissible limit, except fluoride, which exceeded the permissible limit in most studied locations and drastically affected the WQI values. The computed WQI values ranged from 37.92 – 436.06. Therefore, of the eleven groundwater data sets, four are classified as "good", two as "poor", one as "very poor", and four as "unfit for drinking". The results highlight the need to treat fluoride in South African groundwater, as it is a significant factor in categorising areas suitable for groundwater consumption. From the groundwater quality results it was deduced that the water quality data was either clustered as "magnesium-bicarbonate" or "sodium-chloride" type. The results of the groundwater potential mapping revealed that the AHP-based GWP map

exhibited a strong correlation with borehole data (r=0.726, n=113), indicating the accuracy of the AHP as a rating method. The results computed that approximately 47.3 km^2 (2%) of the total area falls under Excellent GWP, 24405.4 km^2 (27.45%) under good GWP, 50950.5 km^2 (57.3%) under moderate GWP, and the poor and very poor GWP zones constitute around 13380.8 km^2 (15.1%) and 135.6 km^2 (1%) of KZN respectively.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AHP : Analytical Hierarchy Process
AUC : Area Under the Curve
Ca^{2+} : Calcium
CGS : Council for Geoscience
Cl^- : Chloride
CSIR : Council for Scientific and Industrial research
CO_3^{2-} : Carbonate
DEM : Digital elevation model
DWAF : Department of Water Affairs and Forestry
EC : Electrical Conductivity
F^- : Fluoride
GDWQ : Guideline for Drinking-water Quality
GDEs : Groundwater-dependent ecosystems
GIS : Geographic Information Systems
GLDAS : Global Land Data Assimilation System
GRA2 : Groundwater Resources Assessment 2
GWP : Groundwater Potential
HCO_3^- : Bicarbonate
K+ : Potassium
KZN : KwaZulu-Natal
Mg^{2+} : Magnesium
MODIS : Moderate Resolution Imaging Spectroradiometer
Na^+ : Sodium
NASA : National Aeronautics and Space Administration
NDVI : Normalised Difference Vegetation Index
NO3- : Nitrate
OE : Output-Error non-linear Hammerstein-Wiener
PH : Potential of Hydrogen
NLHW : Non-linear Hammerstein-Wiener
ROC : Receiver Operating Characteristic Curve
RS : Remote sensing
SA : South Africa

SANS : South African National Standards

SANSA : South African National Space Agency

SRTM : Shuttle Radar Topography Mission

SO_4^{2-} : Sulphate

TDS : Total Dissolved Solids

TRMM : Tropical Rainfall Measurement Mission

USGS : United States Geological Survey

UTM : Universal Transverse Mercator

WGS : World Geodetic System

WHO : World Health Organisation

WQI : Water Quality Index

WR2012 : The Water Resources of South Africa, 2012 Study

WWF-SA : World Wildlife Fund - South Africa

LIST OF UNITS

J/kg : Joules per Kilogram
Kg/m^2 : Kilogram per square metre
Kg/m^3 : Kilogram per cubic metre
Km : Kilometre
Km^2 : Square Kilometre
Km/Km^2 : Kilometre per Square Kilometre
l/s : Litre per Second
m : Metre
Ma : Mega-annum
Mm : Millimetres
m/s : Metre per Second
Mg/l : Milligram per litre
Mm^3/a : Cubic Megametre per Annum
mS/m : Millisiemens per Metre
Us/cm : Microsiemens per Centimetre
W/m^2 Watt per Square Metre
$^{\circ}$: Degree
% : Percent

CHAPTER 1: INTRODUCTION

1.1. Introduction

Groundwater has no one generally accepted definition (Abdikadir 2012). The South African National Water Act of 1998 refers to groundwater as "*water found underground*". Groundwater is one of the most valuable and dependable natural resources because of its many intrinsic qualities, such as widespread availability, consistent temperature, drought reliability, etc. (Jha *et al.* 2007). It occupies voids, pores and fissures within geological formations and is a result of percolation from the infiltration of precipitation and surface water bodies such as rivers, streams and dams (Otieno, Olumuyiwa and Ochieng 2012). Groundwater accounts for 30% of the Earths renewable freshwater and is the primary source of clean water for approximately two billion people globally (Adams *et al.* 2012; Khan and Jhariya 2018).

Since the end of apartheid in 1994, South Africa's groundwater resources have undergone a significant change in role from a private water legal status to a source of domestic water to more than 60% of communities to meet basic water needs (DWS 2016b). Groundwater mainly occurs in deep hard rock aquifers in which yields are limited, the over utilisation of the resource has presented serious warning signals that indicate groundwater use is on an unsustainable path (DWS 2016b).

The importance of groundwater studies is essential for monitoring and managing the resource (Gopinathan *et al.* 2020). Groundwater is subject to wide spatio-temporal variation, making the quantitative assessment of groundwater recharge a critical issue in its identification (Nagarajan, Sivaprakasam and Karthikeyan 2019). The identification of groundwater requires a sound understanding of its recharge and discharge process and its interrelationship with various hydrogeological processes such as geology, soil, land cover, land use and climate (Jha *et al.* 2007; Gopinathan *et al.* 2020).

1.2. Problem statement

In many areas of the world, groundwater is over-utilised due to inadequate or non-existent management and governance (Adams *et al.* 2012). The importance of having a sustainable yield of groundwater is becoming more significant (Kaur *et al.* 2020a), especially in South Africa (SA), where water scarcity is rapidly increasing as a result of climate change and urbanisation (van Wyk and Ubomba-Jaswa 2020). A better understanding of the status of groundwater resources is critical for sustainable use as surface water in SA is reaching its upper limit in terms of availability (Lin and Lin 2019).

South Africa is a semi-arid to arid country with an average rainfall of 450 mm/a (Van Vuuren 2013). The northern and western regions receive significantly less precipitation than other parts of the country, resulting in groundwater reliance (Van Vuuren 2013). With the increasing temperature rate, global warming has had detrimental effects on groundwater recharge in these areas (eThekwini 2007; Fallon *et al.* 2019). However, in KwaZulu-Natal (KZN), the surface water resources have satisfied water requirements except for agricultural purposes and water needs for rural areas (Fallon *et al.* 2019). A significant additional amount of water will be needed in the future as it is predicted that SA will experience severe water scarcity by 2025 (Seckler 1996; Naidoo 2018). As water scarcity increases, the lack of knowledge on groundwater in SA has highlighted the importance of understanding where and why it occurs and its quality (de Lange *et al.* 2019).

1.3. Research objectives

This study consolidates South Africa's groundwater quality data, and identifies potential high-yielding aquifer zones in KwaZulu-Natal, South Africa, by assessing various factors that influence recharge rates and groundwater storage such as Rainfall, Lineament density, Land use/Land cover, slope, evapotranspiration, drainage density and geology.

The objectives of this research was to:

1) Analyse the physio-chemical and biological quality of groundwater across South Africa and assess its conformity to South African National Standards (SANS) and World Health Organisation (WHO) guidelines for drinking water.
2) Develop thematic data layers for potential groundwater recharge zone development.
3) Spatially determine high-yielding ground aquifer zones using these thematic data layers.
4) Validate the resultant potential groundwater zones with borehole and existing groundwater data.

1.4. Thesis outline

This dissertation consists of five chapters arranged to make it easy for the reader to understand the goals and scope of the research and have a complete understanding of the methods employed to accomplish the research objectives. A brief description of each chapter is provided as follows. **Chapter One**, the introduction, outlines the research topic and contextualises the study.

Chapter Two discusses various literature to provide a foundation of knowledge regarding the study and gives an overview of South Africa’s groundwater quality, quantification, and management. **Chapter Three** describes the research design adopted in this study and discusses the research methodology. It includes details of data analysis and the modelling procedures followed. **Chapter Four** presents the study results, discusses the results and compares them to existing data. **The Fifth and final Chapter** summarises and concludes the study, proposes solutions to the research problem, and offers future research recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This chapter provides a general overview of the current status of groundwater, identifies the significant natural factors affecting groundwater and consolidates groundwater quality, quantity and management data of SA. The chapter also highlights the methodologies and technologies used in groundwater research in SA and discusses internationally proven technology used in groundwater studies. The chapters' contents and sequence directly correspond to the aim and objectives of the research, and therefore, the quality, quantity and management of groundwater were reviewed in detail.

2.2. Freshwater depletion

Globally, freshwater scarcity is increasingly becoming a threat to society's sustainable development (Mekonnen and Hoekstra 2016). In research undertaken by (Mekonnen and Hoekstra 2016) who investigated surface water and groundwater scarcity globally at a high spatial resolution, it was found that 4 billion people live under conditions of severe water scarcity at least once a month.

Due to the rapid growth of the human population, natural resources suffer severe pressure to yield sufficient raw materials (Gopinathan *et al.* 2020). South Africa is witnessing rapid growth in the human population with 51.7 million in 2011 to 55.66 million in 2016 (Stats 2016). KZN has the second largest population in SA, after Gauteng, with a growth rate of 1.7% between 2011 and 2016 (Stats 2016). This rapid growth rate combined with urbanisation, poor infrastructure, climate change, expansion of irrigated agriculture, and changing water consumption patterns are the causes of freshwater depletion in SA. With the gap between the spatial and temporal variation of water demand and availability set to widen in SA, it is estimated that a potential water deficit of 20% will be reached by the year 2035 (Situma 2019). The poor management of freshwater resources is another primary cause of water scarcity and contamination (Jha *et al.* 2007; Alagha *et al.* 2012). The reckless use of surface water puts pressure on groundwater, resulting in the over-exploitation of this valuable resource (Jha *et al.* 2007; Seyam and Mogheir 2011a). This unsustainable use of groundwater, together with inadequate or non-existent management and governance leads to ecological complications such as lowering water tables, water scarcity, deterioration of water quality, and seawater intrusion

(Adams *et al.* 2012; Yeh *et al.* 2014; Alagha *et al.* 2017; Seyam *et al.* 2017; Gopinathan *et al.* 2020).

2.3. Groundwater use and its importance

Groundwater is a valuable resource intrinsic to economic development and maintaining and augmenting biodiversity (Pasupuleti *et al.* 2018). If aptly managed, groundwater has the potential to provide a continuous supply of freshwater for agricultural, industrial, and domestic use (van Wyk and Ubomba-Jaswa 2020). It has an excellent resilience to drought as it reacts slowly to seasonal weather change; therefore, aquifers can also be used as a large storage facility that can service at a relatively low cost (Elbeih 2015; van Wyk and Ubomba-Jaswa 2020).

In many semi-arid countries worldwide, surface water is scarce or is not available throughout the year (Rajaveni *et al.* 2015; Seyam *et al.* 2020). Due to water scarcity, most of the requirements for agricultural, industrial and domestic purposes are being met by groundwater resources (Rajaveni, Brindha and Elango 2015).

In SA, the majority of groundwater is being utilised by irrigation as the agricultural sector accounts for 60% of the water demand (Situma 2019). The use of groundwater is increasing as it serves as a cheaper option to develop and maintain new surface water infrastructure, and due to the increasing improvement of technologies for groundwater abstraction (Otieno, Olumuyiwa and Ochieng 2012). Many municipalities in SA have utilised groundwater as a poverty reduction tool due to it being distributed to rural communities far more cheaply and effectively than other sources (Ndou, Palamuleni and Ramoelo 2018).

2.4. Groundwater influencing factors

Groundwater is the basis of sustainable development and accounts for 30% of the Earth's renewable freshwater (Yeh *et al.* 2014; Lin and Lin 2019). Saltwater represents approximately 97.2% of the Earth's water, with 2.8% available for freshwater use. Out of the 2.8% of freshwater, 2.2% is available as surface water and 0.6% as groundwater (Elbeih 2015).

Groundwater is naturally replenished by surface water infiltrating into the groundwater system which recharges the water table (de Lange *et al.* 2019). The groundwater system is governed by physical factors such as climate, topography and geology. These factors are divided into components that directly and indirectly affect groundwater occurrence and movement such as rainfall, infiltration, vegetation, evapotranspiration, lithology, lineament density, and land use. (Gopinathan *et al.* 2020).

- **Precipitation**

Precipitation is responsible for freshwater on the planet, making it the most crucial factor in the groundwater system. It comprises water falling onto the Earth's surface in the form of rain, snow and hail (de Lange *et al.* 2019). Precipitation over large areas results in diffuse recharge which is the infiltration and percolation of water into the phreatic zone. (Huang 2020). There have been many studies conducted to investigate the effect of rainfall on groundwater recharge. Jan, Chen and Lo (2007) analysed groundwater levels from well stations and rainfall data from rain-gauges and concluded that groundwater levels were found to depend on the effective accumulated rainfall amount linearly. Li et al. (2019) explored the impact of rainfall infiltration on groundwater level and quality using the water balance method and 2D numerical simulation and concluded that groundwater levels were mainly affected by the concentrated infiltration of rainfall.

- **Infiltration**

Infiltration is the downward flow of water from aboveground entering into the subsurface due to matric and gravitational forces (Kirkham 2014). Two infiltration processes occur in the vadose zone: Piston flow, which causes stable wetting fronts parallel to the surface, and preferential flow, which is irregular wetting. Piston flow delays the recharging rate of aquifers, whereas preferential flow enables rapid recharge which increases the aquifer's contamination vulnerability (Huang 2020). The infiltration rate and pattern vary depending on precipitation, base flow, soil characteristics, soil saturation, land cover, the slope of the land, and evapotranspiration (de Lange *et al.* 2019).

- **Vegetation cover**

Vegetation cover plays a critical role in the overall ecosystem health. It is an essential factor that can alter groundwater occurrence. Areas with a lack of vegetation cover tend to have an accelerated runoff, reducing the infiltration rate and soil moisture content (Choubin *et al.* 2019). Highly dense vegetative areas often have shallow water tables, resulting from significant evapotranspiration rates (Doble *et al.* 2006).

- **Evapotranspiration**

Evapotranspiration is the transfer of water from land to the atmosphere by evaporation from the soil surface and transpiration from vegetation growing on the surface (Britannica 2020). Evapotranspiration plays a vital role in the Earth's ecological and climate systems as it links the water, carbon and energy cycles (Purdy *et al.* 2018). Groundwater loss due to evapotranspiration plays a significant role in the groundwater balance (Doble *et al.* 2006). Accelerated evapotranspiration rates can cause the water table to rise, resulting in decreased groundwater storage and increased salinisation levels in soil moisture (Doble *et al.* 2006). The most crucial parameters that affect evapotranspiration are temperature, relative humidity and wind speed (Valipour 2017). The influence of vegetation type, groundwater salinity, water table depth and flooding frequency also play vital roles in evapotranspiration rates (Doble *et al.* 2006).

- **Geology**

The geology of an area, which includes bedrock, lithologies and tectonic setting is an essential factor in groundwater water systems (Wirth *et al.* 2020). Surface features such as faults, folds, joints and geological contact can be used as surface indicators for sub-surface fracturing which is essential for high-yielding aquifers (Akinluyi, Olorunfemi and Bayowa 2018; Gopinathan *et al.* 2020). The incorporation of surface features and lithology in groundwater assessment is critical as tectonic fault zones lead to the division of bedrock which increases the transfer of water to deeper depths (Wirth *et al.* 2020).

- **Topography/ land use**

An area's topography is the three-dimensional arrangement of physical features such as shape, height, and depth (Bailey 2014). These features are geological and human-made such as mountains, valleys, plains, surface water bodies, roads, railways, cropland etc. (Bailey 2014). Grinevskii (2014) states that the main feature of topography is slope exposure with a subordinate value of its shape and steepness in terms of groundwater recharge and flow. Groundwater is closely connected with the topography and the land use it underlies (Lerner and Harris 2009). Inappropriate land use and management causes chronic groundwater quality problems (Lerner and Harris 2009).

2.5. Overview of South African groundwater: quality, quantity and management

In SA, limited information is available regarding groundwater resources which is evident in the paucity of studies conducted. This section's main objective is to consolidate the available literature on groundwater quality, quantity and management in SA, with a particular interest in the technologies utilised. The technologies will be assessed for their advantages and disadvantages in order to rank SA's groundwater exploration methods.

2.5.1. Groundwater quality

Groundwater is a favoured source of drinking water in several areas of SA due to its natural protection from contamination (Erdogan *et al.* 2019). Due to SA being typified by climate aridity, water from weathered and fractured crystalline aquifers is the primary water source for the domestic, agricultural and industrial sectors in many areas due to low rainfall occurrence (Abiye and Bhattacharya 2019; Ologundudu *et al.* 2020). However, the quality of groundwater subsides due to increasing environmental metamorphosis caused by natural and anthropogenic factors (Dube *et al.* 2020). Groundwater contamination occurs when fractured aquifers allow infiltration at high rates forming a destructive pathway for contaminants (Belle *et al.* 2020).

Groundwater is a high-priority driver in the South African agricultural sector because of its availability at shallow depths (~40m) (Abiye and Bhattacharya 2019), but the salinity levels range from moderate to high which is detrimental to irrigation and consumption for human and animals (Makubalo and Diamond 2020). Therefore, salinisation has become a significant limiting factor for groundwater in SA, with evaporation thought to be the primary influence (Makubalo and Diamond 2020). However, a recent study conducted by (van Gend *et al.* 2020) in the Buffels River catchment concluded that the evaporation of salts is not a controlling factor of groundwater salinisation. The study stated that the key source of groundwater salinisation is the dry deposition of marine aerosols, mineral weathering, and ion exchange.

Groundwater pollution occurs due to natural processes and human activities such as acid mine drainage, agriculture, sanitation, industry, and waste disposal (Mepaiyeda *et al.* 2020). Also, an aquifer's geochemical composition directly affects groundwater quality due to the mineralisation of the rocks that hold groundwater (Abiye and Bhattacharya 2019). These naturally occurring toxic metals that contaminate groundwater pose a significant threat to the health of the consumer, with fluoride being the most prevalent ion in the groundwater system of SA (Abiye and Bhattacharya 2019; Mengistu *et al.* 2019). As stated by the World Health Organisation (WHO) and the Department of Water Affairs and Forestry (DWAF), fluoride consumption above 1.5 mg/l is noxious and could result in dental fluorosis (Ologundudu *et al.* 2020). Ncube (2006) states that six provinces in SA, including KZN, Limpopo, North-West, Northern Cape, Western Cape and Eastern Cape, have a fluoride concentration of greater than 4 mg/l. Due to the human consumption of high fluoride levels from groundwater, many people have permanently mottled teeth in the country's northern and western parts (Abiye *et al.* 2018). The mottled teeth are caused by the Fluorosis disease, resulting from consuming fluoride concentrations of higher than 1.5 mg/l for extensive periods (Coetzee *et al.* 2003). Abiye *et al.* (2018) stated that fluoride in SA's groundwater courses is inherently related to felsic igneous rocks and is further increased by evaporative processes.

Groundwater has received much attention worldwide due to many people in low-income areas consuming untreated groundwater, which pose severe dangers to their health (Enitan-Folami *et al.* 2020a). Many South African areas are labelled as having a low socio-economic status which has led to the consumption of untreated groundwater from wells and boreholes (Ologundudu *et al.* 2020). The Council for Scientific and Industrial Research (CSIR) and the World Wildlife Fund – South Africa (WWF-SA) have reported that water-borne diseases are one of the leading causes of sickness and death in children (Enitan-Folami *et al.* 2020b). Mudzielwana *et al.* (2020) stated that around 75% of people in the Limpopo Province of SA depend on groundwater as a water source for domestic use despite it not being treated. The prevalence of the dependency on groundwater across SA and the health defects caused by fluorosis has led to many studies being undertaken regarding groundwater quality.

2.5.2. Groundwater quantification

South Africa's groundwater resources, amounting to approximately 7500 million m^3/a, are extensively utilised in the agricultural sector and rural areas for domestic use (Palamuleni and Akoth 2015; Enitan-Folami *et al.* 2020b). In 2002, it was recorded that 15% of the total water consumed was supplied by groundwater (Knüppe 2011).

Groundwater quality studies constitute most groundwater articles in SA, with minimal scientific efforts to identify and quantify the resource (Lin and Lin 2019). This low volume of academic outputs may be due to insufficient management policies and limited facilities for identifying and quantifying groundwater. There are many techniques available for quantifying groundwater but settling on the best and most suitable technique based on the study area is very difficult. When choosing a technique, some of the most important considerations include access to the appropriate equipment, space/time scales, range, and reliability of the results (Scanlon, Healy and Cook 2002). Therefore, this section consolidates groundwater quantification studies of SA and reviews the tools and approaches used in these studies. Thereafter, tools and approaches for groundwater identification are recommended.

- **Early groundwater quantification projects**

Early attempts of groundwater quantification for SA was made by (Enslin 1970) and Vegter J.R in 1980. Their studies were primarily based on educated guesses which resulted in sustainable groundwater yields of 2500 and 5400 Mm/a, respectively.

Due to a lack of systematic nationwide groundwater data collection and analysis, the directorate of geohydrology in the Department of Water Affairs (DWAF) launched a project to compile 21 hydrogeological maps of SA in 1990 and was completed in 2003. The maps were at a scale of 1:500 00 and were accompanied by an explanatory booklet (Woodford and Rosewarne 2006; Lin and Lin 2019).

Vegter, Seymour and Simonic (1995) then produced the first visual representation of groundwater resources of SA in the form of seven maps. The maps indicate borehole yield probabilities, depth to groundwater, groundwater quality, groundwater recharge and baseflow on a country-wide scale. The project was a synopsis of data from the DWAF's National Groundwater Data Base. Baron, Seward and Seymour (1998) built-on to the project by producing the Groundwater Harvest Potential map of SA. This map depicts the sustainable groundwater yield, which is calculated using estimates of aquifer storage and recharge. The Groundwater Harvest Potential map was improved by (Haupt 2001) by applying a factor based on country-wide borehole yield data, that accounts for aquifer permeability (Woodford and Rosewarne 2006; Lin and Lin 2019).

In 2003, the DWAF initiated the Phase 2 Groundwater Resources Assessment 2 (GRA2) project, which quantified SA's groundwater resources. The project used GIS-based algorithms to enable easy updating of future groundwater data. A raster grid GIS model was developed to produce outputs viz. aquifer storage, recharge and yield, at a 1 x 1km cell size. Woodford and Rosewarne (2006) summarised the results of the GRA2 project and stated that the project was undertaken by several consultants, with SRK Consulting being the project leaders, and completed in 2005. Several GIS-based maps were created that represents aquifer storativity, aquifer recharge, groundwater resource potential, groundwater exploitation potential, potable groundwater exploitation potential and utilisable groundwater exploitation potential. The project results presented recharge, aquifer storage and extractable groundwater as 30 520, 235 500 and 19 000 Mm^3/a, respectively. Lin and Lin (2019) states that the results from the GRA2 project cannot be directly used on a national scale due to the project using an average aquifer thickness of 154m, which is much deeper than 90% of the boreholes in SA.

– Review of the tools and approaches used in groundwater quantification studies

In recent years GIS in research has proliferated due to the integration of remotely sensed data from the successful launching of various state of the art satellites (Pandit 2020). This integration of remote sensing and GIS have opened the door for a vast range of opportunities in large-scale mapping, project planning and spatial modelling (Pandit 2020). Even in data-scarce developing countries like South Africa, remote sensing and GIS modelling have emerged as being a reliable cost-effective method in research. Münch and Conrad (2007) delineated the probable location of groundwater-dependent ecosystems (GDEs) using ariel photography, satellite imagery, remote sensing techniques and GIS. Remote sensing data was combined with three GIS models to produce groundwater dependent ecosystems probability rating maps of the Sandveld region in SA. The three GIS models used were: the LWP model, which predicted landscape wetness potential based on terrain morphological features; the GglWP model which predicted groundwater generated landscape wetness potential; and a groundwater elevation model which used groundwater level data collected from 159 boreholes. The modelling objective was to determine areas where groundwater would accumulate based on hydrological accumulation and terrain features. The models used the GIS weighted overlay analysis technique to create an integrated analysis by combining various physical parameters with influence factors for each parameter based on its importance to groundwater recharge at GDEs. The output from the spectral image analysis spatial modelling was compared to the wetness potential classes resulting from the three GIS models to determine the best combinations representing probable locations of GDEs. The comparison showed that the LWP model provided the most accurate results for the region. This method could provide an adequate predictive tool for riverine and wetland GDEs but needs to be tested on-site for terrestrial GDEs, and chemically verified. The model can further be improved by including additional input parameters. (Yousaf *et al.* 2021) stated that research done entirely using remote sensing and GIS could provide repetitive and reliable results on a near real-time basis as it allows the integration of data and methodologies in ways that support traditional forms of analysis and new types of analysis and modelling (Pandit 2020).

One of the main constraints of groundwater research in SA, and in many other developing countries, is the lack of hydrogeological and ecological data which restrict the use of comprehensive evolving technologies (Kashaigili, Mccartney and Mahoo 2006). To compensate for the lack of data, the Desktop Reserve Model was developed to quantify flow requirement where rapid appraisal is required and data is limited (Hughes and Hannart 2003). This approach was used in the rivers of SA by Ebrahim and Villholth (2016) who developed and tested an integrated method for assessing allocatable groundwater from streamflow recession and instream flow requirements. The study aimed to propose an alternative method for determining groundwater availability rather than recharge as the upper limit for groundwater abstraction. Using baseflow separation and recession flow analysis through the Desktop Reserve Model, the excess baseflow compared to the ecological flow requirements was assumed to indicate available groundwater in unconfined aquifers. The method proved to be a valuable tool to assess ecological needs for groundwater and determine available groundwater for human needs. However, due to the composite nature of the fractured rock aquifers of SA and limited available hydrogeological information, the interpretation of the results in terms of physical and hydrogeological properties concluded that streamflow recession controls and baseflow separation could be complicated.

In groundwater studies, identification models are increasingly becoming a popular method due to the models being able to compress large amounts of information in a full spatio-temporal description of the groundwater table dynamics without reducing the data quality (von Asmuth and Knotters 2004). Identification models were utilised in SA by Makungo and Odiyo (2018) who tested the ability of the coupled linear polynomial Output-Error (OE) and non-linear Hammerstein-Wiener (NLHW) system identification model for estimating groundwater levels in Nzhelele and Luvuvhu areas in the Limpopo Province, SA. The study utilised daily groundwater levels from four boreholes, rainfall and evaporation data from selected quaternary catchments. The data was used to develop time series models that simulated water table depths for 30 years. The coupled linear polynomial OE and NLHW model was used to estimate groundwater levels in each borehole using the System Identification Toolbox of Matlab. Seventy and thirty per cent of the data was used to calibrate and validate the model, respectively. The correlation coefficient, coefficient of determination, root mean square error, Nash Sutcliffe coefficient of efficiency, per cent bias and graphical fits were used to evaluate the model performance. The comparisons between observed and estimated groundwater levels for calibration and validation runs showed close agreements, although there were over and underestimations of groundwater levels in some boreholes. The model performance varied from satisfactory to excellent, and therefore it can estimate long term groundwater levels based on the graphical fits and model performance measures.

A recently developed GIS-based rainfall-runoff model was developed for engineering methodologies, resulting in automated watershed analysis from watershed delineation to runoff hydrograph calculations (Foda, Awadallah and Gad 2017). The rainfall-runoff model was used in groundwater studies in South Africa by Watson *et al.* (2018) who evaluated how well the percolation output from a J2000 rainfall/runoff model represents actual groundwater recharge and whether it can be used as a recharge input to a groundwater model. The j2000 model is a distributive hydrogeological model that can be used to simulate components of the hydrological cycle using streamflow, rainfall and climate data. The percolation output evaluation was done by comparing it to the natural rainfall and water level data in the Verlorenvlei estuarine lake on the west coast of SA. Daily evaporation, used for the j2000 model, was calculated using the Penman-Monteith equation, which uses precipitation, wind speed, relative humidity, solar radiation and air temperature as inputs. The percolation model was created using the JAM/j2000 hydrogeological modelling package. The model was used to allocate how much rainfall infiltrates based on vegetation cover and precipitation, how much of the infiltration is lost to evapotranspiration and how much becomes modelled groundwater recharge calculated as percolation into the aquifer. The results indicate that the model would likely be transferable to other semi-arid to arid areas. However, it remains to be tested as to whether the model can cope with areas where runoff is high.

Ebrahim, Villholth and Boulos (2019) developed an integrated hydrogeological modelling approach to guide groundwater and agricultural water management and observe groundwater level data and river discharge in semi-arid hard rock terrain in the Hout catchment, Limpopo Province, SA. Remote sensing data, rainfall-runoff modelling and a three-dimensional hydrogeological model, were used in the study due to a lack of available groundwater data. Independent streamflow and recharge estimations were carried out using the Precipitation-Runoff Modelling System, which is a distributed parameter rainfall-runoff model. Irrigation was estimated using the irrigated cropland delineated from the Landsat Normalized Difference Vegetation Index (NDVI) and crop water requirements. The hydrogeological model was calibrated from 2008 to 2012 and validated from 2013 to 2015 using groundwater level data for ten monitoring wells to compute the hydrogeological system’s annual water budget. The study confirmed that modelling is fundamental for understanding spatio-temporal variability in groundwater sustainability management.

Lin and Lin (2019) attempted to propose a suitable method to evaluate groundwater storage at a local scale in the Tugela area of SA. The study defined and calculated the exploitable and sustainable groundwater storage using geological information and borehole data from the National Groundwater Archive. The borehole data was studied in conjunction with the geological formation found within the study area. The results showed that the Natal Group aquifer and Coastal Plain aquifers are the most productive aquifers. The Basement aquifer has a moderate performance, followed by the Ecca and Dwyka aquifers.

Mpofu *et al.* (2020) attempted to evaluate groundwater potential in the Eastern Cape, SA using remote sensing, geological and geophysical approaches. Fracture patterns were investigated by tracing lineaments from a 1:100000 scale black and white Landsat 4-5 TM image. The mapping of lineament was done manually using GIS 10.2. The study also conducted a microscopic (transmitted light and scanning electron microscopy) investigation to depict deformational structures favourable for groundwater flow. Subsurface lithology was investigated by analysing four borehole logs in Sedlog 3.1 software and Microsoft PowerPoint. The study demonstrated the vital contribution of geology in groundwater exploration and the use of remote sensing data to identify promising sites for high groundwater storage.

Stochastic models in groundwater studies are widely used to quantify uncertainty in parameter concentration over space and time (Sreekanth, Lau and Pagendam 2017). Rwanga and Ndambuki (2020) aimed at using the stochastic approach for modelling groundwater flow using recharge as an uncertain parameter in central Limpopo. The study used two models, a groundwater flow model created from MODFLOW 2000 software and a stochastic model. The model provided reliable information on the groundwater aquifer system and the water budget. The model was also used to solve the stochastic solution considering recharge as an uncertain parameter. Stochastic uncertainty analysis was performed by running a series of Monte Carlo simulations.

Many predictive models are utilised worldwide which could benefit groundwater exploration in SA. Chen *et al.* (2020) evaluated the predictive ability of a series of tree-based models (RF-J48, AB-J48, Bag-J48, RS-J48, Dag-J58) in groundwater potential exploration. It was concluded that these methodologies are highly accurate in groundwater potential mapping as these models have high prediction capabilities (AUC of 0.748 – 0.797). Rajabi (2019) highlighted the benefits of using the Gaussian process emulation and polynomial chaos expansion in groundwater applications. The study concluded that these models could provide good probabilistic predictions with a minute computational time. Many studies highlight the benefits of numerical and conceptual modelling in groundwater exploration. However Malakar *et al.* (2021) states that artificial intelligence methods are better suited in the field of groundwater. The use of artificial intelligence in SA can help understand the triggers changing the groundwater dynamics and the influencing factors of groundwater contamination by producing more accurate predictions, especially in recent times, as data availability increases (Malakar *et al.* 2021).

The demand for freshwater in SA has triggered the utilisation of aquifers as water storage facilities (Asano 2016). Research has been conducted on artificial groundwater recharge due to its ability to reduce, stop and reverse declining water table depths, protect groundwater against saltwater intrusion, and store water for future use (Asano 2016).

Jovanovic *et al.* (2017) calibrated a Modflow model for the managed aquifer recharge site of Atlantis, SA. Their study aimed at running realistic scenario simulations for abstraction and recharge conditions, and contaminant travel times using three-dimensional modelling. The model used geology, terrain elevation, borehole data, groundwater level, groundwater abstraction and chemistry data, evapotranspiration data and hydrogeological data. The model was calibrated to run from January 1993 to December 2011 (6 939 days). Three scenarios were constructed and run with VMOD 2011.1. The scenarios described the best and worst-case in terms of contaminant transport and artificial recharge rates, and the third scenario simulated the tracking of potential contaminants. The purpose of different scenarios was to determine the travel time through the aquifer. Ten-year scenario simulations indicated that proper management is needed for the sustainable use of groundwater as managing the volumes of artificial recharge is more important than the abstraction volumes. There was some limitations to the model, such as the hydraulic conductivity values used only applied to the domain of the regional aquifer and the inflow of water into the artificial basins was uncertain. Even though the model predicted long-term trends in groundwater levels very well, it was not set up to predict seasonal fluctuations and short time-scale variation in recharge and abstraction.

Zhang, Xu and Kanyerere (2019) presented a two-step method that combines GIS-based analysis with groundwater flow modelling to identify suitable sites for implementing managed aquifer recharge in the West Coast area of SA. The groundwater flow modelling was done to verify and optimise the sites identified by the GIS-based analysis. The data used for both the GIS analysis and groundwater flow modelling were geology, infiltration capacity, measure infiltration and recharge from observational studies, land use, elevation, aquifer thickness, hydraulic conductivity, storativity, residence time, vadose zone thickness, changes in water table elevation and groundwater quality. The data was ranked using the Analytical Hierarchy Process (AHP) to improve the GIS-based analysis accuracy. The GIS weighted linear combination tool was used to create the map of suitable sites for implementing managed aquifer recharge by assigning values of importance for all criteria and sub criteria. The suitable sites were verified and optimised using groundwater flow modelling. The model was created using ModelMuse, together with the MODFLOW and MODPATH packages. The results showed that the area of suitable sites was 2337.2 km^2, which accounts for 50% of the total site area. Spatially, the results were reasonable, but the most suitable sites identified are not necessarily the ideal choices in practice due to the lack of groundwater seepage data. The modelling showed that higher groundwater level, larger storage space, and longer flow path characterise high suitability areas, which covered only 57.1 km^2 of the analysed area.

The technology used in groundwater quantification studies in SA utilises the latest technology such as remote sensing, modelling and the latest data processing software. Geospatial techniques have emerged as one of the most popular and efficient methods of understanding the quantification and spatial distribution of groundwater (Dube *et al.* 2020). Apart from groundwater modelling, countries worldwide are starting to prioritise implementing innovative and cost-effective approaches for utilising groundwater. India has implemented solar-powered groundwater water abstraction by applying solar photovoltaic pumping systems as it offers a cost-effective and sustainable energy solution (Closas and Rap 2017). Morocco and Yemen have also been promoting solar-powered groundwater abstraction for agricultural use (Closas and Rap 2017).

Figure 1 graphically indicates the reviewed distribution of groundwater quantification studies across SA and, Table 1 presents a meta-analysis of the studies and indicates the tools used in the various studies, with their advantages and disadvantages. The meta-analysis consolidates available published groundwater quantity studies of South Africa, highlighting the gabs, in terms of information available and the standard of technology being used. The analysis was used to identify the aim of this research, the study location and the methodology utilised.

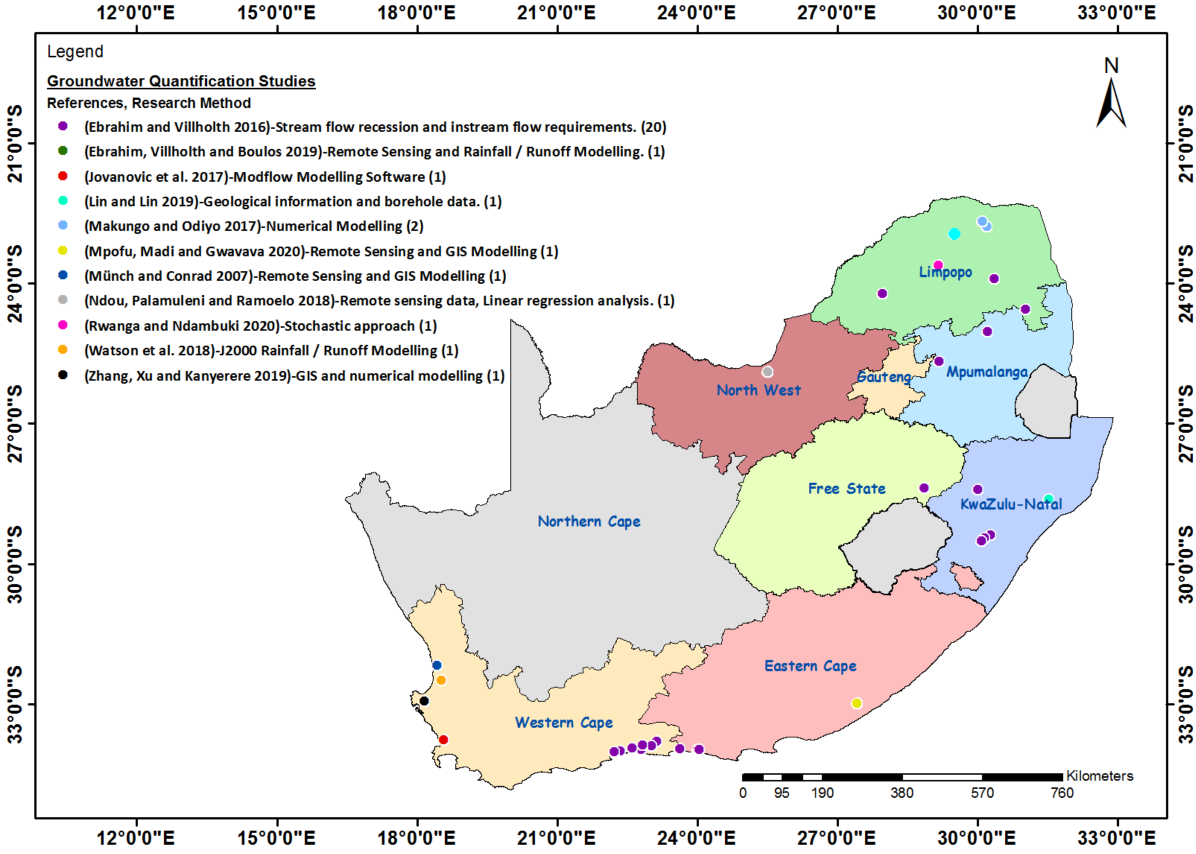


Figure 1: Current groundwater quantification studies in South Africa

Table 1: Current groundwater quantification studies in South Africa

Reference	Province	Location	Aim/Objectives	Applied tools/models/approach	Advantages	Disadvantages
(Ebrahim and Villholth 2016)	Western Cape, Eastern Cape, KwaZulu-Natal, Free State, Mpumalanga, Limpopo	Beaulieu Estate, Farm 508, Kwaai Brand, Lottering, M'Kama, Eastbrook, Karatara Forest, Farm 162, Knoetze Kama, Wolvedans, Mohlabas, Doornspruit, Mohlolobe, Zaaihoek, Elands River Drift, Kleinfontein, Shafton, Mpofana River, Petrus Stroom	To develop a method for assessing groundwater.	Streamflow recession and instream flow requirements.	No prior information on hydrogeology and recharge is required, and it is based on ecological criteria related to the river.	Interpretation of the results proved to be complicated.
(Ebrahim, Villholth and Boulos 2019)	Limpopo	Hout Catchment	To develop a model to support groundwater management solutions.	Remote sensing and rainfall/runoff modelling.	The model is useful in irrigated hard rock and arid areas.	Need to expand data monitoring at a larger scale for proper management.
(Jovanovic *et al.* 2017)	Western Cape	Atlantis	To calibrate a model for managed aquifer recharge.	Modflow Modelling Software	It is a useful prediction tool, depending on the quality of the data used.	Uncertainty of the hydraulic conductivity data used in the model
(Lin and Lin 2019)	KwaZulu-Natal	Tugela Areas	To evaluate groundwater storage at a local scale.	Geological information and borehole data.	Borehole log data was easily assessable.	Impacts of faults, joints and dolerites was not considered.
(Makungo and Odiyo 2017)	Limpopo	Luvuvhu River Catchment, Nzhelele River Catchment	To estimate groundwater levels.	Coupled linear polynomial Output-Error and non-linear Hammerstein-Wiener system identification model.	The model shows better results with more input values.	There were underestimations and overestimations of groundwater levels
(Mpofu, Madi and Gwavava 2020)	Eastern Cape	Ndlambe Municipality	To evaluate groundwater resources	Remote sensing and GIS	The method reduces field verification which is time-consuming and expensive.	Complex geology and hydraulic properties of the study area made it difficult.

(Münch and Conrad 2007)	Western Cape	Northern Sandveld	To delineate probable locations of groundwater-dependent ecosystems (GDEs)	Remote sensing and GIS	The method reduces field verification which is time-consuming and expensive.	The method needs to be field-tested for terrestrial GDEs and chemically verified
(Ndou, Palamuleni and Ramoelo 2018)	Northwest	Upper Molopo River Catchment	To investigate the applicability of dry season evapotranspiration in modelling groundwater depth.	Remote sensing, meteorological data and linear regression analysis.	Remotes sensing proved efficient in estimating evapotranspiration.	Difficult to distinguish between the spectral signature of natural vegetation and irrigated crops.
(Rwanga and Ndambuki 2020)	Limpopo	Central Limpopo	To model groundwater flow	Stochastic approach	Simplifies the more complex reality.	-
(Watson *et al.* 2018)	Western Cape	Verlorenvlei Catchment	To evaluate the recharge output of the j2000 rainfall/runoff model.	J2000 rainfall/runoff model	Can be used in data-scarce areas.	Further modelling is required for yearly recharge estimates.
(Woodford and Rosewarne 2006)	South Africa	South Africa	To highlight the results of the GRA2 project.	GIS	Ease and accuracy of raster modelling	-
(Xu and Beekman 2019)	South Africa	South Africa	To review methods for groundwater recharge.	Chloride mass balance, rainfall infiltration breakthrough, modelling, saturated volume fluctuation, water table fluctuation and aquifer recharge and moisture transport	-	-
(Zhang, Xu and Kanyerere 2019)	Western Cape	Langebaan	To select suitable sites for implementing managed aquifer recharge.	GIS and numerical modelling	The method can be used at other sites.	More factors need to be considered, viz. political, economic etc.

- **Proposed groundwater identification tools**

One of the most prevalent, reliable and cost-effective approaches for assessing groundwater identification, recharge and storage are utilising the combination of remote sensing, GIS and mulita-criteria decision analysis techniques such as AHP. Some of the studies that utilise these approaches are (Jhariya *et al.* 2016; Pinto *et al.* 2017; Rajasekhar *et al.* 2018; Das *et al.* 2019; Nithya *et al.* 2019; Raju, Raju and Rajasekhar 2019; Achu, Thomas and Reghunath 2020; Arefin 2020; Kaur *et al.* 2020b; Lentswe and Molwalefhe 2020; Shao *et al.* 2020).

Due to the problems associated with the sustainable use of groundwater, plans need to be developed and implemented (Jasmin and Mallikarjuna 2011). The monitoring of groundwater conditions and the forecasting of future conditions are crucial processes in every community as it provides reasonable estimates of the state of water and gives an idea of appropriate use for human activities (Jha *et al.* 2007). A method of doing this starts with the physical collection of data and requires extensive sampling and laboratory analysis which is very expensive and time-consuming (Japitana *et al.* 2019). The physical collection of groundwater data are taken from boreholes, which are a critical source of information regarding groundwater recharge, storage and discharge (Sujay Raghavendra and Deka 2015). However, most boreholes drilled in SA are usually used for domestic water supply, which, together with inadequate groundwater monitoring plans results in a lack of continuous long term groundwater level results (Taormina, Chau and Sethi 2012). Due to the lack of borehole monitoring, the data required for groundwater initiatives are rarely available or are expensive to produce. This lack of data leads to approximations being made in the physical methods for groundwater studies, resulting in errors and uncertainty in the outputs (Makungo and Odiyo 2017).

The use of modelling techniques using remote sensing, GIS and AHP can be implemented to make the collection and processing of data inexpensive and straightforward without compromising the data (Elbeih 2015). This collaboration can potentially result in many techniques such as analysing groundwater resources, locating groundwater zones, selecting sites for artificial recharge, GIS-based subsurface flow modelling, groundwater pollution assessment, estimation of natural recharge distribution, and hydrogeological data analysis (Jha *et al.* 2007).

- **Remote Sensing**

Remote sensing is the science of collect data on a specific phenomenon, pattern, or region without direct physical contact with the study area (Nasr *et al.* 2020). Remote sensing aids in procuring spatio-temporal data of large areas within a short period (Pasupuleti *et al.* 2018). The images produced can be beneficial as it provides fast and repeated observations in environmental monitoring as it can derive valuable information on geology, geomorphology, structural patterns and recharge conditions which is beneficial to understanding groundwater systems (Nagarajan, Sivaprakasam and Karthikeyan 2019).

- **Geographic Information Systems**

Geographic Information Systems is a tool that has widely been used in groundwater studies due to its ability to accurately predict and visualise complex data sets. It can explore hydrogeological data and provide spatially explicit information for management and policymaking, making it a popular tool in all research fields (Dube *et al.* 2020). Ricker *et al.* (2020) presented three case studies regarding interdisciplinary research involving GIS. The technical challenges and successful outcomes were shared and it was concluded that GIS is becoming increasingly utilised in multidisciplinary research that generally addresses multifaceted problems.

The GIS Weighted Overlay Analysis tool is a crucial technique in delineating groundwater (Pasupuleti *et al.* 2018). This tool plays a vital role in groundwater site selection as it produces criteria, constraints and suitability maps according to the outcomes from multi-criteria decision analysis and valued judgements (Rikalovic, Cosic and Lazarevic 2014). The Weighted Overlay Analysis is a widely utilised approach globally as it integrates information on several environmental features and results in potential groundwater zones systematically (Jasmin and Mallikarjuna 2011). Jasmin and Mallikarjuna (2011) evaluated the use of remote sensing, GIS, and fieldwork to explore groundwater potential in consolidated and unconsolidated formations. The study concluded that the preparation of thematic maps, assigning appropriate weights and integrating them in GIS ensured and enhanced the accuracy of locating potential groundwater zones. Furthermore, remote sensing and GIS methods have proven efficient and cost-effective in identifying groundwater zones. Pasupuleti *et al.* (2018) used freely available remote sensing data and GIS to do a weighted overlay analysis in their study of identifying groundwater prospect zones in India. The investigation resulted in five potential groundwater zones ranging from very poor to very good.

These methods can prove beneficial in SA, with groundwater monitoring being weak, as there is a lack of modelling (Pietersen *et al.* 2012). In SA, the weighted overlay analysis approach has rarely been used to identify groundwater zones. Münch and Conrad (2007) used GIS and remote sensing to locate groundwater-dependent ecosystems in the Western Cape. The results showed that applying the weighted overlay analysis and GIS modelling, can be a powerful predictive tool for managing ecologically stressed areas. Magaia *et al.* (2018) utilised remote sensing data to identify potential high-yielding aquifer zones in Mozambique. The study used several water-related factors and identified excellent potential zones. The use of remote sensing in the study proved to be a rapid and cost-effective technique.

The weighted overlay analysis approach can also be used for other aspects of groundwater. Pietersen (2006) used it in an approach to model several sustainable groundwater management plans in Namaqualand, SA. Musekiwa and Majola (2013); Makonto and Dippenaar (2014) used the weighted overlay analysis approach to create groundwater vulnerability maps of which different factors such as groundwater recharge, aquifer type, soil, etc. were scored, weighted and combined to create the final maps. The studies showed similarities with other data sources. Makonto and Dippenaar (2014) stated that the benefits of the approach are easy quantification of factors and the exclusion of arbitrary index values.

- **Analytical Hierarchy Process**

GIS-based AHP methods are increasingly becoming a popular tool in the scientific community to determine weights for processed thematic layers (Rahmati *et al.* 2015). The thematic layers, which are processed on GIS, are ranked according to its percentage importance to the research's desired outcome using AHP. Rahmati *et al.* (2015) mapped groundwater potential using GIS-based AHP methods. It was established that AHP is beneficial in areas suffering from data scarcity as planners would have accurate knowledge based on geospatial data analysis.

Even though the combination of these tools has proved to be beneficial in many studies worldwide, some disadvantages could be highlighted when utilised in groundwater studies in SA, such as remote sensing combined with spatial GIS-based modelling only yields adequate results at a regional scale as hydrogeology remote sensing imagery of SA has a high spatial resolution (0.25° x 025°) (Münch and Conrad 2007; Li and Rodell 2018). In terms of spatial resolution, this infers that remote sensing imagery is inappropriate for detailed mapping in groundwater studies at a local scale.

2.5.3. Groundwater management

Due to inadequate or non-existent management and governance, the over-exploitation of groundwater resources will lead to ecological problems such as the lowering of water tables, water scarcity, deterioration of water quality and seawater intrusion (Adams *et al.* 2012; Yeh *et al.* 2014; Gopinathan *et al.* 2020). The over-exploitation of groundwater is also related to economic and social aspects, which should be addressed extensively to support sustainable water supply (Saqr *et al.* 2021).

In SA, groundwater management and monitoring in terms of quality and quantity are weak due to the non-existent management of aquifers and a lack of groundwater modelling (Pietersen *et al.* 2012). According to (DWS 2016a), the continuous pressure on groundwater results in the resource being a critical issue that requires technical, economic, judicial, social, institutional and administrative structures to ensure responsible use and maintenance of groundwater. Recent research conducted by the University of the Free State's Institute for Groundwater Studies (IGS) showed that all municipalities rated groundwater as a crucial resource, but there is no planning or capacity to do actual groundwater-related work. (van Wyk and Ubomba-Jaswa 2020). Proper management is critical in groundwater utilisation as socio-economic development and climate change make the management process complex and unpredictable (van Wyk and Ubomba-Jaswa 2020).

Water is a valuable natural resource that we depend on for life, well-being and economic growth (Palmer, Berold and Muller 2004). It is a resource used in many ways, and if over-used, can cause detrimental effects to life on Earth (Palmer, Berold and Muller 2004). The Bill of Rights of The Constitution of SA Act (1996) section 27(1)(b), states that "Everyone has the right to have access to sufficient food and water…" and section 24(a) states that "Everyone has the right to an environment that is not harmful to their health or well-being…". Therefore, it is essential to manage groundwater resources due to the fundamental change in water resource management in SA, from a riparian system based on land ownership to a system that distributes water fairly (Murray *et al.* 2006).

The subsurface nature of groundwater creates misunderstanding which results in poor management of the resource (Mepaiyeda *et al.* 2020). In SA, policies and strategies related to groundwater management are poorly developed due to a lack of knowledge on the occurrence, quantity and quality of groundwater, resulting in poor resource management (Mepaiyeda *et al.* 2020). Although many municipalities rely on groundwater, the management of the resource has been given little attention as it is not seen as a sustainable water resource for bulk supply in the country (de Lange *et al.* 2019).

Knüppe (2011) identified challenges impeding sustainable groundwater use and presented the results of a qualitative assessment of interviews conducted with experts regarding sustainable groundwater management and current water legislation in SA. The research was centred on semi-structured interviews with experts from the fields of groundwater resources and ecosystems. They have identified four key challenges that represent the main issues SA must overcome to achieve sustainable management of groundwater. These challenges are (1) Undervaluation of the importance of groundwater, which might stem from the private status of the resource in the past (Roma common law) and the invisible nature of aquifers, (2) shortage of expertise and quality groundwater data, (3) centralisation of power, as the management by national and regional offices of the Department of Water Affairs lack cooperation between the various political agencies, administrative levels and stakeholders, and (4) the disregard of groundwater ecosystems and associated goods and services. The study concluded that water managers and decision-makers need to make groundwater management a high priority to overcome groundwater challenges and improve existing policies.

Seward, Xu and Turton (2015) used backcasting to explore ways to improve the government's contribution to groundwater governance in SA. Backcasting was used towards institutional processes for determining desired groundwater scenarios. The first step was to define good groundwater governance, the second was to investigate the needs to link the definition to a detailed governance process, and the third step considers the implementation of the interventions concluded in the previous steps. The investigation uses data, knowledge and judgement from existing literature and a practitioner's experience (principal author). The analysis results show that specific groundwater governance and implementation strategies are needed before the Department of Water and Sanitation (DWS) can improve groundwater governance. The article states that the DWS is plagued with staff shortages, lack of institutional capacity and good service delivery. The findings indicate that the reason groundwater governance is weak in SA is not legislation but the delay in granting authorisation for the use of groundwater. One limitation of the investigation was the use of one person's experience in the backcasting process, which creates subjectivity and bias. In terms of the backcasting method, it can be a valuable tool in improving good groundwater governance in SA.

Table 2 presents the meta-analysis of the groundwater management studies of South Africa and indicates the tools and methodologies used. The meta-analysis consolidates available published groundwater management studies of South Africa, highlighting the groundwater management framework gabs which can be used to identify future management research methodologies.

Table 2: Groundwater management studies in South Africa

Reference/Study	**Location**	**Aim/Objectives**	**Applied tools/models/approach**
(Conrad, Nel and Wentzel 2004)	Western Cape	To discuss the main challenges associated with determining vertical groundwater recharge.	Published literature.

(Knüppe 2011)	South Africa	To present the outcomes of interviews conducted with experts.	Qualitative assessment of interviews.
(Knüppe, Pahl-Wostl and Vinke-de Kruijf 2016)	South Africa	Determining the drivers behind policy change and the integration of ecosystems services into groundwater policies	Intensive document reviews viz. legal documents, government reports, peer-reviewed articles and expert interviews.
(Oke, Alowo and Masinde 2019)	Free State	Solving challenges in groundwater management	Internet of things and GIS.
(Kelbe and Rawlins 2016)	South Africa	Evaluating groundwater management.	Published literature.
(Pietersen 2006)	Northern Cape	Investigating the applicability of MCDA as a tool for groundwater management.	Multi-criteria decision analysis (MCDA)
(Riemann, Chimboza and Fubesi 2012)	South Africa	To improve the management of groundwater by equipping authorities with the required tools.	Published literature.
(Seward, Xu and Turton 2015)	South Africa	Investigating the use of backcasting to improve groundwater governance	Published literature and practitioner experience.
(Tewari and Kushwaha 2008)	Limpopo	Reviewing the socio-economic issues in groundwater management.	Published literature.
(Wright 2000)	South Africa	Applying the water balance approach to sustainable groundwater management.	Water Balance approach

2.6. Overview of the study area

The section describes KZN in terms of regional location, regional physiographic factors and its characteristics that affect groundwater.

- **Locality**

The study is based in KwaZulu-Natal (KZN) (28.5306 S and 30.8958 E), a province in South Africa (SA) located in the south-eastern part of the country, presented in Figure 2. The province is approximately 94.361 km^2 in area and constitutes 7.7% of the land area in SA (Lehohla 2012). KwaZulu-Natal is a coastal province, having a shoreline beside the Indian Ocean. It stretches from Port Edward in the south to the border of Mozambique in the north and shares borders with Swaziland and Lesotho as well as the Free State province and Mpumalanga province (Britannica 2019).

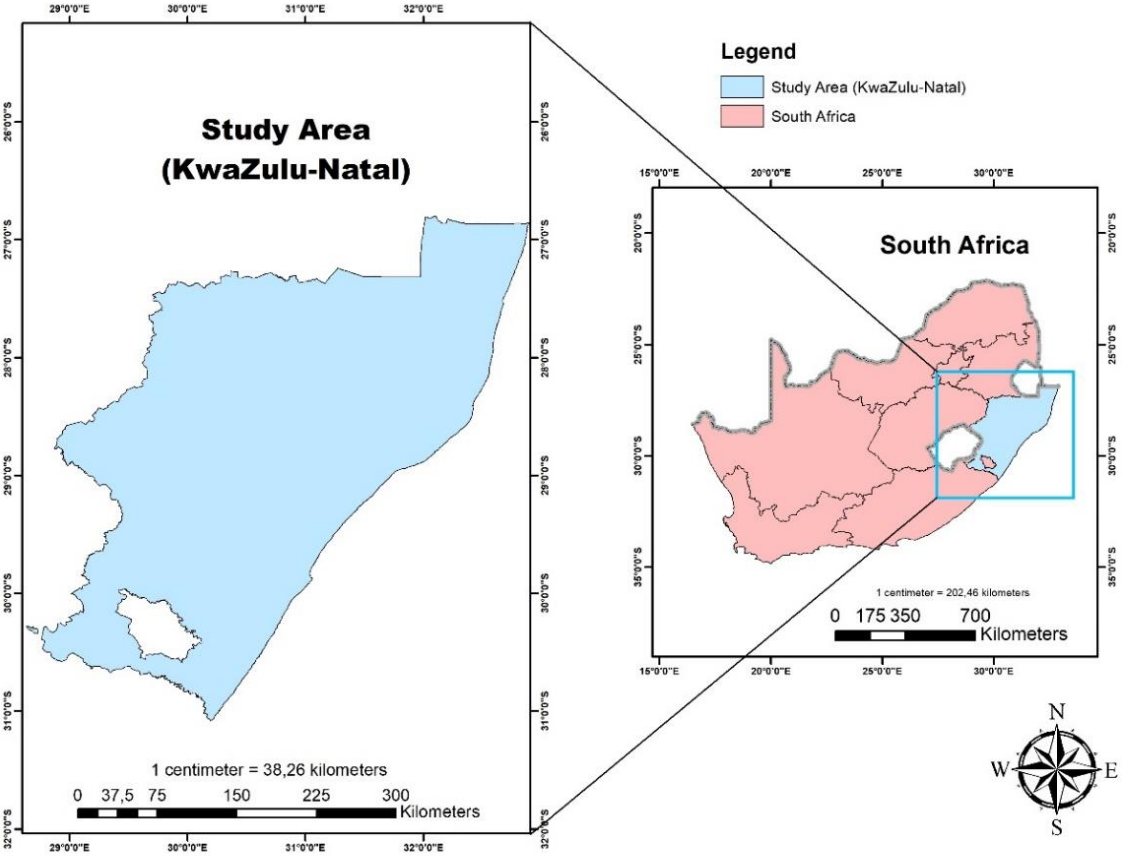


Figure 2: Site Locality Map

- **Topography of KwaZulu-Natal**

KwaZulu-Natal displays a diversity of topographic features. It has five dominant terrain units being high land elevations along its western border which is shared with Lesotho, smooth plains and low mountains spread over the length of the province, highly dissected low undulating mountains, irregular undulating lowlands with hills and valleys (Schulze 1997). The land rises from the relatively flat coastal plain to more than 3300m at the Drakensburg Escarpment (Mabaso *et al.* 2003). The Drakensberg escarpment bordering Lesotho has the highest elevations in the province and the steepest mountain ranges. The Mafadi Peak, 3540m above sea level, is located at the Drakensburg escarpment and is the highest peak in SA (Schaller 2016). The province's terrain creates steps of ascending land elevation, 150m at the coast to 1200m in the centre of the province to its highest elevation along the Drakensburg Escarpment (Britannica 2019), as shown in Figure 3.

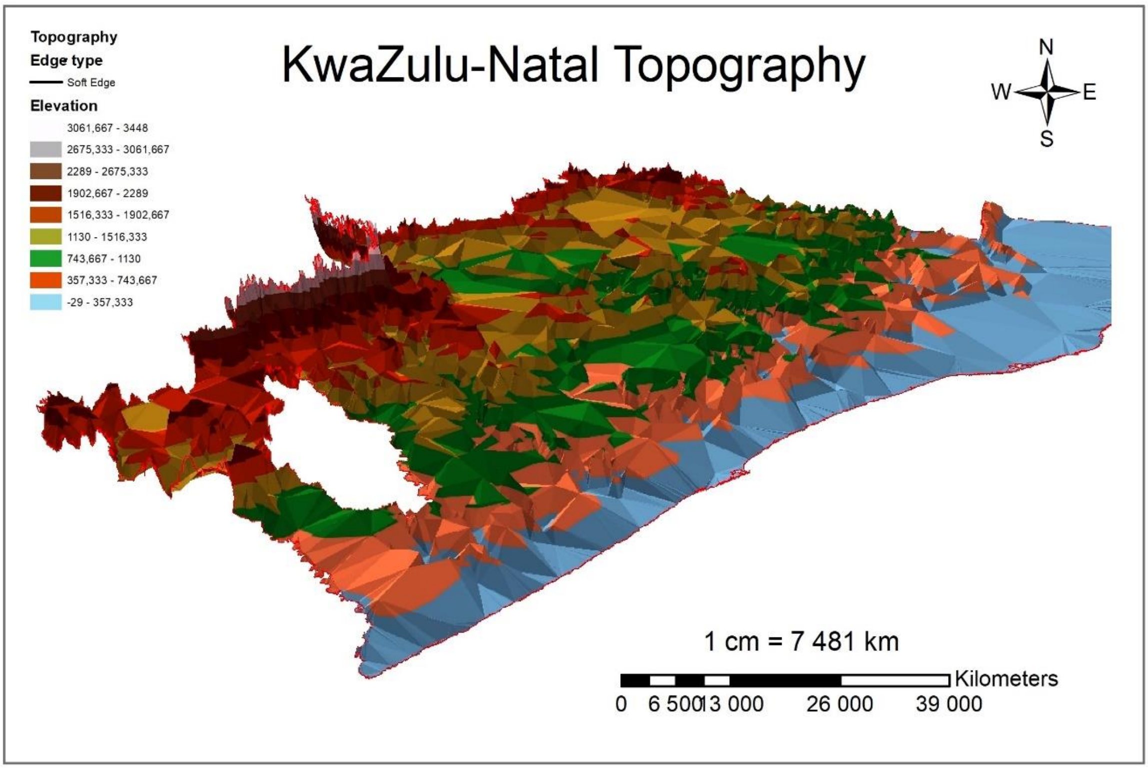


Figure 3: 3-dimensional representation of KwaZulu-Natal’s topography

- **Climate of KwaZulu-Natal**

The climate of KZN is influenced by the Indian Ocean’s warm Agulhas current, which results in the coastal region having high humidity and high temperatures (Fairbanks, Reyers and van Jaarsveld 2001). The climate varies throughout the province from subtropical to temperate, with the temperature and rainfall decreasing from the coast (Britannica 2019). There is variability in climate from the warm coastal regions to the cool interior highlands towards the western border, as well as from south to north (Naidoo 2018). KwaZulu-Natal has the highest annual rainfall as well as the most tropical climate throughout SA.

- **Geology of KwaZulu-Natal**

The geology and lithology of KZN comprises the Karoo Supergroup, which also covers approximately 50% of SA. The Supergroup comprises thick successions of sedimentary strata deposited in an intracratonic basin on Gondwanaland, 300 to 160 million years ago (Woodford and Chevallier 2002). The sediment of the Supergroup is divided into the Beaufort, Ecca, Dwyka and the Stormberg groups, of which the Beaufort and Ecca groups dominate KZN’s geology in terms of cover. The Beaufort Group consists of mudstone, siltstone and sandstone, and overlies the Ecca Group, consisting of clastic mudstone, sandstone, siltstone, minor conglomerate and coal outcrops (Catuneanu *et al.* 2005). The multi-layered beds of the Beaufort group exhibit different hydraulic conductivity, with the medium-grained sandstone having a higher permeability than the finer sandstone and mudstone. (Botha *et al.*, 1998). The very dense shales of the Ecca formation have a very low hydraulic conductivity, but fractures and weathering in the shales and sandstone enhance their potential for storing water (Gomo, 2011). Figure 4 represents the geological map of KZN and Figure 5 represents the cross-section of KZN..

- **Stormberg Group**

The Stormberg Group is the uppermost group of the Karoo Supergroup and represents the final phase of preserved sedimentation (Broom 1947). The Stormberg Group is divided into three geological formations, which were deposited in the Triassic and Jurassic period, which are the Molteno, Elliot and Clarens Formations (Woodford and Chevallier 2002). The sandstone of the Molteno formation is the lowermost formation in the group and is an ideal aquifer as it consists of medium to coarse-grained sandstone beds. It is overlain by red mudstone and fine to medium-grained yellowish sandstone of the Elliot Formation. The dense red mudstone of the Elliot formation causes it to act as more of an aquitard (Woodford and Chevallier 2002). The overhanging, white to cream in colour, cliffs of the Drakensburg Escarpment is composed of Clarens formation sandstone (*Geology Education Museum* No Date). The Clarens formation is the youngest of the Karoo sedimentation and was formed in the middle of the Jurassic age (Catuneanu *et al.* 2005; Mazibuko 2019). The formation has high porosities of the orders of 8% and very low permeability due to it being poorly fractured (Mazibuko 2019).

According to (Domenico and Schwartz 1990), the sandstone in the Molteno formation has an approximate hydraulic conductivity of 6×10^{-6} m/s as the sandstone is medium to coarse-grained, which is an ideal aquifer. The Elliot formation has an approximate hydraulic conductivity of 2×10^{-9} m/s as the mudstone dominates the composition. The Clarens formation has an approximate hydraulic conductivity of 3×10^{-10} m/s due to it being poorly fractured.

- **Beaufort Group**

The Beaufort Group is a subdivision of the Karoo Supergroup. The rocks were deposited through fluvial processes by large meandering rivers (Mazibuko 2019). Course-grained sediments are found alongside the stream environment and fine-grained sediments away from river basins (Woodford and Chevallier 2002). The subgroups are the lower Adelaide and the upper Tarkastad Subgroup (Rutherford, Rubidge and Hancox 2015). The group overlies the Ecca Group and underlies the Stormberg Group (Hancox and Rubidge 1997). The Adelaide

Subgroup consists of mudstones and fine to medium-grained sandstone, with the Tarkastad Subgroup having and higher sandstone-to-mudstone ratio (Rutherford, Rubidge and Hancox 2015; *Geology Education Museum* No Date). The sandstone in the Adelaide Subgroup comprises 20 to 30% of its thickness (Mazibuko 2019).

The multi-layered beds of the group exhibit different hydraulic conductivity, with the coarse-grained sandstone having a higher permeability than the finer sandstone and mudstone. The upper formation of the group exhibit parallel, orthogonal and diagonal fractures which increases the groundwater storage (Botha *et al.* 1998). According to (Domenico and Schwartz 1990), the Adelaide group has an approximate hydraulic conductivity of 2 x 10^{-9} m/s due to it having fractures and being mixed with mudstone and sandstone. The Tarkastad has an approximate hydraulic conductivity of 1 x 10^{-8} m/s due to it having a higher sandstone to mudstone ratio.

- **Ecca Group**

The Ecca Group is a subdivision of the Karoo Supergroup. It was formed over the Dwyka Group, approximately 286-248 Ma, and underlies the Beaufort group (Visser 1978; Mazibuko 2019). The Ecca group consists of shale, typically dark-coloured, and sandstones, which overlay the shale (*Geology Education Museum* No Date).

The very dense shales in the formation have a very low hydraulic conductivity, but fractures and weathering in the shales and sandstone enhance their potential of storing water (Gomo 2011). Even though the porosity is very low due to diagenesis, the groundwater potential in the formation increases as groundwater flow paths form at the contacts between the sedimentary beds (Mazibuko 2019). According to (Domenico and Schwartz 1990), the Ecca formation has an approximate hydraulic conductivity of 2 x 10^{-9} m/s.

- **Dwyka Group**

The Dwyka Group is the lowermost and oldest geological formation within the Karoo Supergroup. It formed when the Gondwanaland migrated over the South pole, approximately 350 Ma (Mazibuko 2019). The group consists of tillite, which is angular to rounded fine-grained clasts of the basement rocks. The tillite in KZN is a very fine-grained yellowish colour and overlies the Natal group (Visser 1986; *Geology Education Museum* No Date).

The Dwyka formation is not ideal for large-scale groundwater storage as the sediments in the group have very low hydraulic properties, which form aquitards (Woodford and Chevallier 2002). The groundwater quality is often saline due to the influence of the marine depositional environments (Mazibuko 2019). According to (Domenico and Schwartz 1990), the Dwyka formation has an approximate hydraulic conductivity of 1 x 10^{-12} m/s.

– Drakensburg Group

The Drakensburg Group is named after the Drakensburg escarpment and was formed approximately 182 million years ago (Erlank 1984; Fitch and Miller 1984). The group consists of basalt and dolerite (*Geology Education Museum* No Date).

According to (Domenico and Schwartz 1990), the Drakensburg formation has an approximate hydraulic conductivity of 4.2×10^{-7} m/s. The porosity of the formations in the Karoo Supergroup decreases with depth. The highest porosities are found in the top 30m of the earth's surface due to weathering of the rocks (Mazibuko 2019). The aquifers within the Supergroup are multi-layered and multi-porosity and store a considerable amount of water. There are two significant flows in the Karoo aquifers when stressed, vertical matrix and horizontal bedding-parallel fracture flow (Woodford and Chevallier 2002).

– Kaapvaal Craton

The Kaapvaal Craton is one of the only remaining areas of pristine crust on Earth (Wit 1998). It was formed by the intrusion of granite on the Earth's basaltic crust between 3.7 and 2.6 billion years ago (Nguuri *et al.* 2001; *Geology Education Museum* No Date). This craton consists of basement granite and greenstone. According to (Domenico and Schwartz 1990), the hydraulic conductivity of the craton is approximately 3.3×10^{-6} m/s.

– Natal group

The Natal Group, found in the northern parts of KZN, consists mainly of a thick accumulation of boulders and pebbles, and further south the sediment is finer-grained (*Geology Education Museum* No Date). According to (Domenico and Schwartz 1990), the Natal group has an approximate hydraulic conductivity of 3×10^{-2} m/s.

– Natal Metamorphic province

These rocks were formed by subduction and collision along the Kaapvaal Craton, which exposed deep mountain roots of granite and gneiss (Clarke 2008; *Geology Education Museum* No Date). According to (Domenico and Schwartz 1990), the hydraulic conductivity of the craton is approximately 3.3×10^{-6} m/s.

– Pongola Supergroup

Pongola Supergroup consists of the Nsuze and the Mozaan Groups. The Nsuze Group consists of basalt, sandstone and minor limestone. The Mozaan Groups, which overlies the Nsuze group, are sedimentary rocks containing conglomerate (Gold *et al.* 2006; *Geology Education Museum* No Date).

– Zululand Group

The Zululand Group consists of silt and sandstone deposited by the Indian Ocean around 145-65 million years ago (*Geology Education Museum* No Date). This group is located in the northern regions of KZN in the uMkhanyakude District.

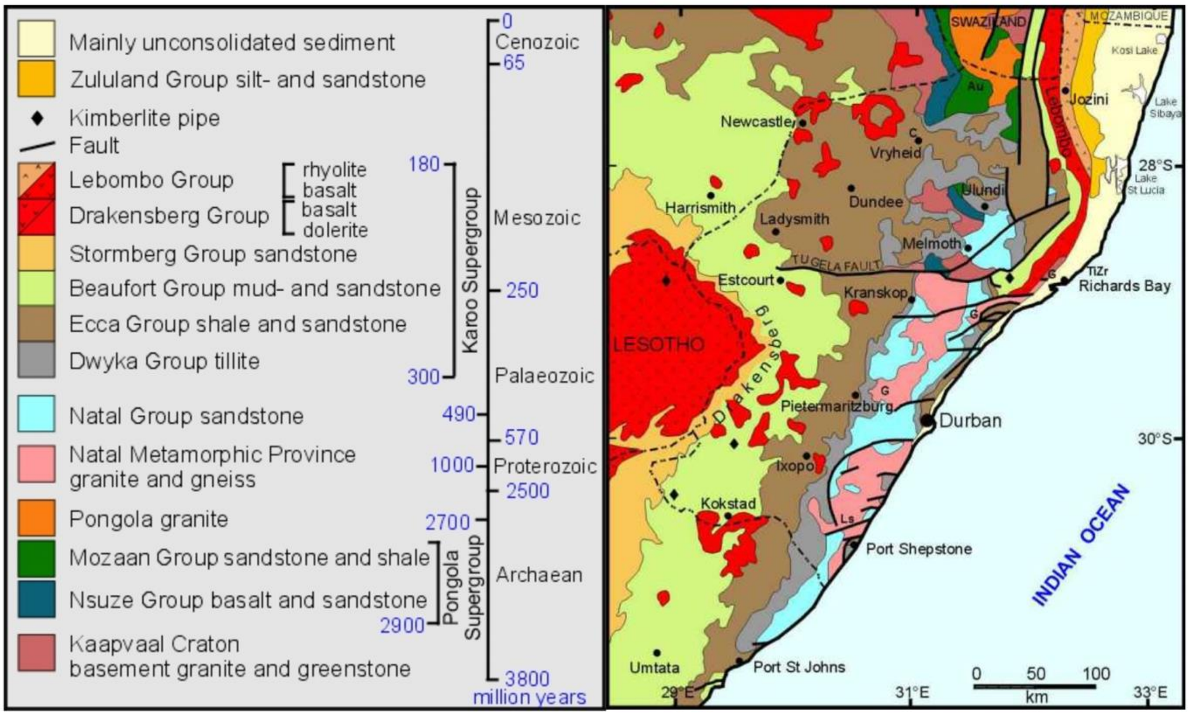


Figure 4: Geological map of KwaZulu-Natal (*Geology Education Museum, No Date)*

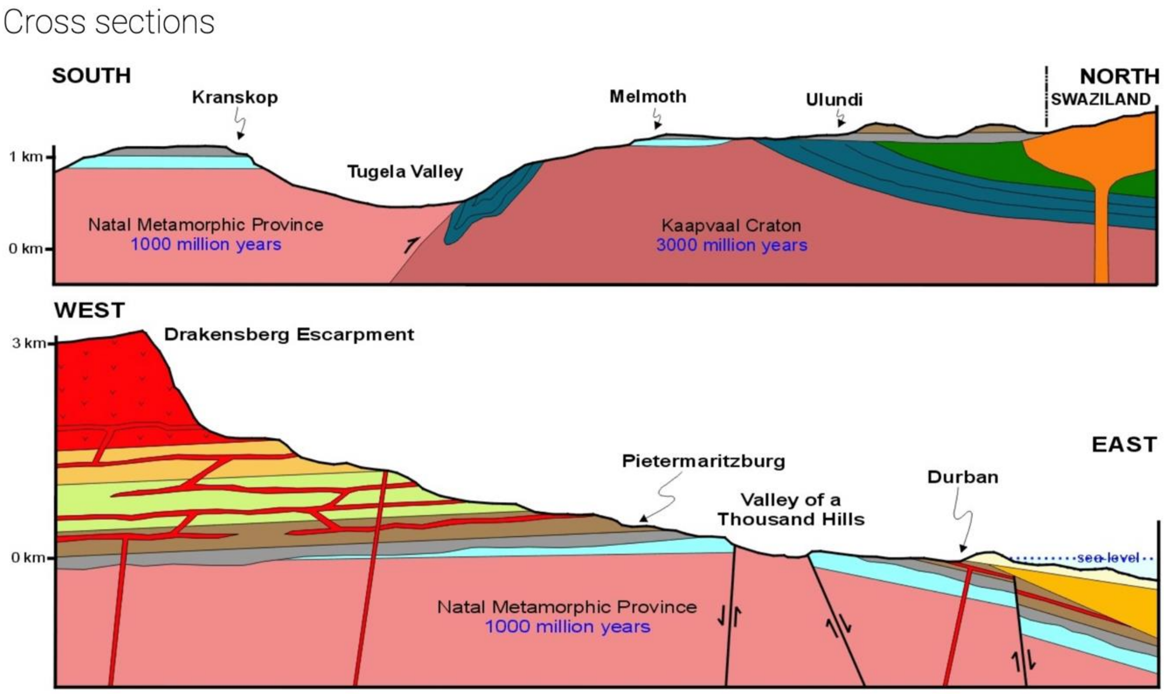


Figure 5: Geological cross-section from Kranskop to Swaziland (top) and from Drakensburg Escarpment to Durban (bottom) (*Geology Education Museum, No Date)*

- **Hydrogeological setting of KwaZulu-Natal**

KwaZulu-Natal has a lot of geological horizontal bending and dips and foliation structures located all around the province. Due to an increase in elevation from east to west, many strike and dip formations have been observed on the eastern side. The flatter regions experience horizontal bending and the Drakensberg escarpment having bending, strike and dips. Takorabt et al. (2018) investigated the role of lineaments on aquifer recharge using remote sensing Landsat 7 ETM+ processing images and concluded that land fractures play a significant role in the recharge of deep aquifers.

There are numerous faults observed in KZN. Most of the faults are located at the coast with the largest being the Tugela Fault (*Geology Education Museum* No Date). These faults and fractures, which were created due to the weakness formed between the Kaapvaal Craton and Natal Metamorphic Province geological groups, act as surface indicators for sub-surface fracturing which increases the transfer of water to deeper depths making them essential for high-yielding aquifers (Akinluyi *et al.*, 2018; Gopinathan *et al.*, 2020; Wirth *et al.*, 2020). The hydrological setting is characterised by the intergranular aquifers of the unconsolidated to semi-consolidated coastal sediments which have shallow groundwater tables (between 2 and 7m below ground level); fractured aquifers of the Natal Group sandstone, Dwyka tillite and sandstone of the Ecca Group; and weathered and fractured granite basement aquifers in which borehole yields in the weathered zones is between 0.1 and 0.5l/s, and yields in the underlying fractures exceeding 0.5 l/s (Ndlovu *et al.*, 2019).

- **Vegetation of KwaZulu-Natal**

KwaZulu-Natal has a complex landscape in terms of biological diversity, ranging from complex in the northeast, becoming less complicated to the south (Naidoo 2018). The vegetation covering the province consists of grasslands, savannas, wetlands and forests, which are species-rich. The province also contains portions of the Maputaland-Pondoland-Albany biodiversity hotspot and the Midlands, Maputland, Pondoland and Drakensburg Alpine centres of endemism (Carbutt and Edwards 2003; Fagan 2007; Perera 2013; Jewitt *et al.* 2015). Agriculture occupies a large portion of the landscape, consisting of orchards, sugar cane, commercial and subsistence crops, and timber agroforestry (Jewitt *et al.* 2015).

There are 101 types of vegetation in KZN and five biomes: Grassland, Savanna, Azonal vegetation, Indian Ocean Coastal Belt, and forests (Jewitt 2018). The Grassland Biome is found on the western side of KZN, covering most of the land (4 583 855ha) (Jewitt 2018). The topography is mainly flat and includes the escarpment at an altitude of 2820m above sea level (Low and Rebelo 1996). The grassland is dominated by a single layer of grass, with very few areas having trees due to fire and grazing (Low and Rebelo 1996). The biome is divided into two bioregions, the Drakensberg grassland bioregion and the sub-escarpment grassland bioregion. The Savanna Biome is found towards the eastern side of KZN and covers 3 259 341 ha of land (Jewitt 2018). The biome is characterised by a grassy ground layer and an upper layer of woody plants. The biome is divided into a Shrubveld and a Bushveld layer. The Shrubveld layer vary from 1 to 20m in height, and the Bushveld layer varies from 3 to 7m (Low and Rebelo 1996). The biome is divided into two bioregions, the sub-escarpment savanna bioregion and the Lowveld bioregion. The Indian Ocean Coastal Belt occurs along the coast of KZN and comprises dominant forest cover. The belt also includes hydrologically controlled areas of grassland and dense savanna vegetation (Mucina, Rutherford and Powrie 2006). The Forest Biome occur in patches no greater than 2km in length. The Forest Biome is the smallest, covering 202 879 ha of KZN (Low and Rebelo 1996; Jewitt 2018). The canopy cover of forests is continuous, which consists of mainly evergreen trees. The ground layer is almost non-existent due to canopy cover (Low and Rebelo 1996). The biome is divided into two bioregions, the zonal and intrazonal forests and azonal forests. The Azonal Biome group is recognised within the forest Biome. The Azonal biome is specialised forests that occur sporadically, such as mangroves, swamps and fringe forests (Low and Rebelo 1996; Jewitt 2018). The biome is further divided into bioregions such as alluvial vegetation, Eastern Strandveld, Estuarine vegetation, freshwater wetlands, inland saline vegetation and seashore vegetation.

- **Land use/Land cover of KwaZulu-Natal**

KwaZulu-Natal has a complex landscape with varied use and ownership of the landscape (Jewitt *et al.* 2015). Much of the province's mining takes place in the northern parts which is predominately coal mining. The coast is the most important agricultural area with the main crop being sugar cane. The midlands area is known for plantations of pine and eucalyptus which provides the raw material for sawmills and paper and rayon pulp mills (Britannica 2019). The land cover of KZN is divided into 47 classes: surface water, cropland, non-natural timber plantations, mines and quarries, settlements, roads and railway, forests, bushland, grassland and bare soil.

Albhaisi, Brendonck and Batelaan (2013) investigated land-use changes on groundwater recharge, using remote sensing Landsat images and simulation, of the Berg catchment in SA. They concluded that rainfall, combined with the change in land use, resulted in a highly increased (278%) predicted mean groundwater recharge. They also confirmed that by clearing non-native hill slope vegetation, the groundwater recharge increased around 8% per year for their 21 year study period.

- **Groundwater of KwaZulu-Natal**

Groundwater levels in KZN are monitored through seventy-two national and regional groundwater monitoring locations (Ndlovu and Demlie 2018). It has been reported that groundwater levels have been declining across the province due to intense pumping resulting from recent droughts (Ndlovu and Demlie 2018). The surface water resources in the province have been able to satisfy requirements except for agricultural purposes and water needs for rural areas (Fallon *et al.* 2019).

2.7. Summa

Based on the available groundwater literature of SA, it is apparent that research outputs are significantly lower than many other countries, which highlights the need for prioritising resources towards groundwater research, and sustainably utilising the resource. Based on the number of groundwater articles, the management and quantification of the resource are the least researched as thirteen articles were found relating to groundwater quantification and ten being based on groundwater management.

A review of the South African literature presented that technologies used in groundwater studies in SA are on par with other countries. The latest modelling and processing software is being utilised to create sustainable groundwater methods, but the problem is the minimal quantity of studies and their distribution across the country. South Africa is a country with many different properties of the lithosphere, hydrosphere, biosphere and atmosphere, making the understanding of groundwater resources very complicated and site-specific. The need for more research in different locations across the country will significantly benefit the water shortage of South Africa.

Combining remote sensing, GIS, and AHP as a tool for groundwater studies is recommended because it is successfully utilised in many countries as an inexpensive tool for groundwater research. Many articles have been published internationally that recommend this method, especially in the identification of groundwater. South Africa and other developing countries can significantly benefit from using these inexpensive and user-friendly tools. The next chapter describes how this study successfully combines these tools to conduct groundwater research entirely through modelling techniques.

CHAPTER 3: METHODOLOGY

3.1. Introduction

The study followed a pragmatic approach using a quantitative method of data collection and analysis. Geographic Information Systems GIS) and remote sensing techniques were used for mapping groundwater potential (GWP) zones and groundwater vulnerability. KwaZulu-Natal (KZN) was chosen as the study area to identify GWP zones. A desktop analysis of groundwater quality data, extracted from past published studies, was also conducted for the whole of SA due to limited available groundwater quality data in KZN.

This chapter is divided into two parts, the materials and methods used in assessing the groundwater quality in areas across South Africa and the identification of GWP zones in the KZN, as shown in Figure 6. This section also describes KZN in terms of regional location, regional physiographic factors and its characteristics.

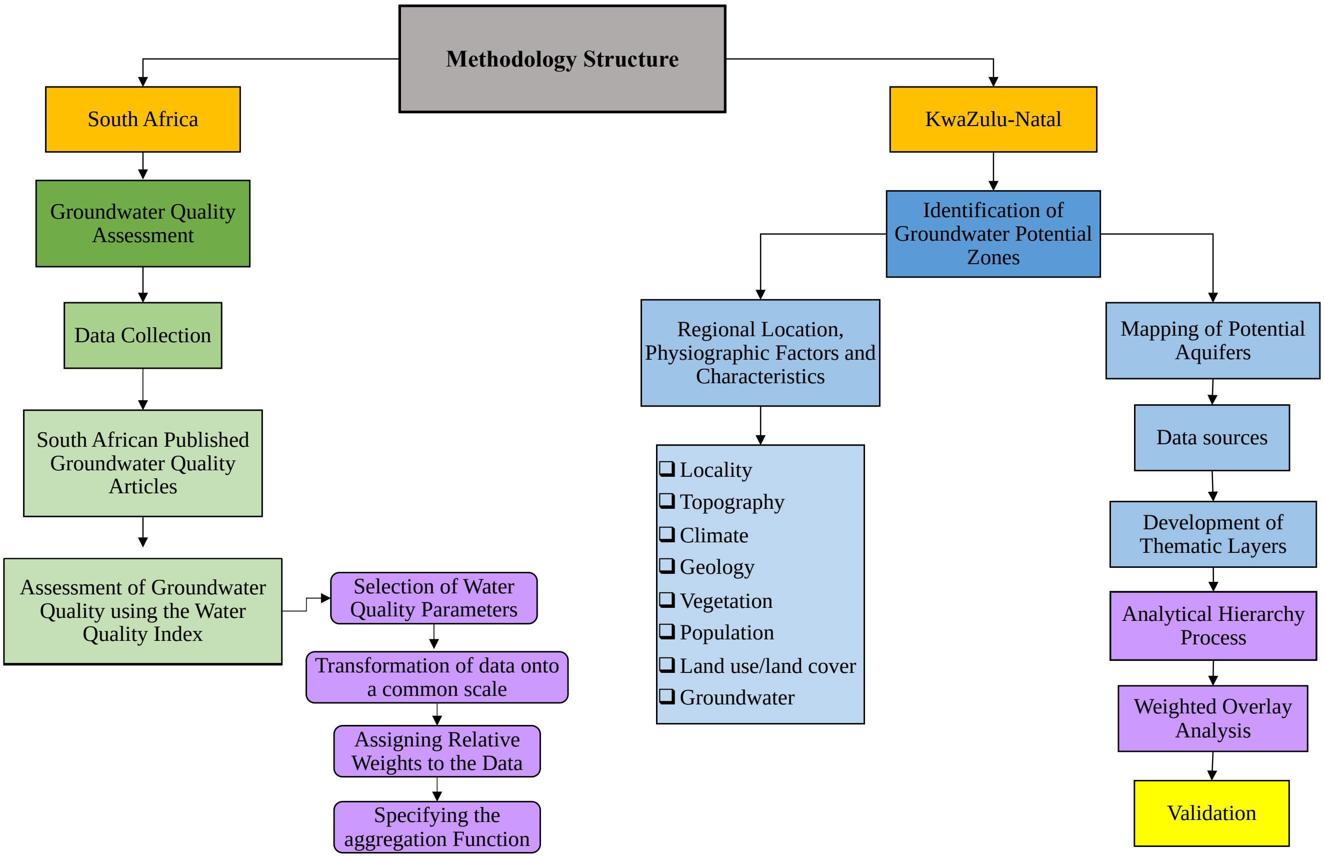


Figure 6: General flow chart of the methodology

3.2. Groundwater quality – a comparison with World Health Organization and South African National Standards for drinking water quality

Groundwater quality assessments range from simple, qualitative and inexpensive approaches to complicated, quantitative and expensive approaches (Sakala *et al.* 2018). The assessments include evaluating the physical, biological and chemical properties of groundwater with recommended allowable limits, depending on its intended use and human effects (El Baba *et al.* 2020). A water quality index (WQI) to score the suitability of water for human consumption was developed by (Horton 1965), which ranks the quality of water from excellent to unsuitable for use (El Baba *et al.* 2020). The WQI index was used to assess groundwater quality data from various areas in SA by consolidating and comparing the groundwater quality parameters to the South African National Standards (SANS) 241:2015 and the World Health Organization (WHO) 2017 guidelines for drinking-water quality and then ranking the groundwater according to possible usages. South Africa's groundwater quality was assessed based on the results of published literature on groundwater quality in various locations across the country. South Africa was chosen as the area to conduct the WQI assessment rather than the KZN province due to groundwater quality data being scarce in many provinces, especially in KZN. However, the WQI method depends on the availability of data and, therefore, can be utilised at any location with access to sufficient water quality data.

3.2.1. Data collection

Water quality data was collected from available published articles on South African groundwater. The data was obtained from standard online resources such as Google Scholar, Web of Science, ScienceDirect, Wiley Online Library etc. Keywords such as "groundwater-quality-South Africa" was used to identify relevant material for studies relating to groundwater quality in SA. Eighteen scientific articles, shown in Table 3, were based on groundwater quality and contamination; however, only ten articles were used to calculate the WQI due to the other articles lacking major chemical parameters.

Table 3: Reviewed groundwater quality articles

Reference/Study	Location (Province)	Aim/Objectives	Applied tools/models/approach
(Abiye and Bhattacharya 2019)	Northern Cape	To estimate Arsenic concentration in groundwater.	Borehole data and laboratory analysis.

(Belle *et al.* 2020)	Free State	To investigate groundwater contamination from gold mine tailings.	Borehole data and laboratory analysis.
(Dube *et al.* 2020)	Limpopo	To model groundwater quality across a land use/land cover gradient.	Field investigations, remote sensing, laboratory analysis and interpolation tools.
(Edokpayi *et al.* 2018)	Limpopo	To evaluate the status of water quality from boreholes and to determine possible health risks.	Borehole data, laboratory analysis and statistical analysis.
(Elumalai *et al.* 2020)	Limpopo	To analyse the spatial variation in chemical constitutes in groundwater.	Borehole data, laboratory analysis and statistical analysis.
(Elumalai, Nwabisa and Rajmohan 2019)	KwaZulu-Natal	To evaluate high fluoride contaminated fractured rock aquifers.	Borehole data and laboratory analysis.
(Enitan-Folami *et al.* 2020b)	Limpopo	To determine if borehole data is safe for consumption.	Borehole data and microbiology methods.
(Erdogan *et al.* 2019)	Northern Cape	To assess the quality of groundwater and to determine its suitability for domestic and irrigation purposes.	Borehole data, laboratory analysis and statistical analysis.
(Esterhuizen, Fossey and Potgieter 2016)	Free State	To assess the compliance of groundwater to the SANS drinking water standard on dairy farms.	Borehole data, laboratory analysis and microbiological analysis.
(Makubalo and Diamond 2020)	Northern Cape	To document groundwater quality and its evolution.	Borehole data, laboratory analysis and hydrochemistry.
(Mengistu *et al.* 2019)	Gauteng	To model groundwater flow.	Hydrogeological and numerical modelling.
(Mepaiyeda *et al.* 2020)	Eastern Cape	To determine the link between groundwater and contaminants.	Borehole and landfill leachate data.
(Molekoa *et al.* 2019)	Limpopo	To assess the water quality status and hydrochemical processes.	Remote sensing, piper plot, speciation modelling and statistical analysis.
(Mpenyana-Monyatsi and Momba 2012)	Northwest	To assess the quality of groundwater.	Borehole data and laboratory analysis.
(Mpenyana-Monyatsi, Onyango and Momba 2012)	Mpumalanga	To determine whether the quality of groundwater poses a threat to humans.	Borehole data and laboratory analysis.
(Mudzielwana *et al.* 2020)	Limpopo	To evaluate hydro-geochemical characteristics of groundwater and their relationship to arsenic concentration.	Borehole data and laboratory analysis viz. Metrohm Ion chromatography, titrimetric method and coupled plasma mass spectrometry.

(Makungo and Odiyo 2018)	Limpopo	To assess the quality of groundwater.	Borehole data and laboratory analysis.
(Ologundudu *et al.* 2020)	Limpopo	Defluoridation of groundwater.	Borehole data and laboratory analysis.

3.2.2. Assessment of South Africa’s groundwater quality using Water Quality Index

Water Quality Index is a method developed by (Horton 1965), which identifies water quality by a single aggregated value and a corresponding scale (Tunc Dede, Telci and Aral 2013). The method consolidates large amounts of water quality parameters and expresses the overall water quality into ranks viz “Excellent”, “Good”, “Fair”, “Poor”, “Very poor” and “Unfit for drinking” (Tunc Dede, Telci and Aral 2013).

The WQI method used in this study was created by (Brown *et al.* 1970), which is similar to Horton’s method but is based on assigning weights to the individual parameters calculated using the weighted arithmetic index method (Paun *et al.* 2016). The following steps describe the WQI method used:

- Selection of water quality parameters to be included.
- Transformation of the parameter data onto a common scale
- Assigning relative weights to the parameter data
- Specifying the aggregation function

- **Selection of water quality parameters**

All hydrochemical data was collected from published articles; however, only potential of hydrogen (pH), electrical conductivity (EC), total dissolved solids (TDS), calcium (Ca^{2+}), potassium (K^{+}), magnesium ($Mg^{2+),}$ sodium (Na^{+}), chloride (Cl^{-}), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO^{3-}), fluoride (F^{-}) and nitrate (NO^{3-}) were used in the water quality index due to these parameters being available in most of the studies. The above-mentioned priority parameters should be considered in any drinking water quality assessment (WHO 2016).

- **Transformation of the parameter data onto a common scale**

The parameter units were converted to the same unit as stated in the SANS 241:2015 for each parameter (mg/l; us/cm). For cases where multiple datasets per parameter per location were available, the dataset's mean was used in the WQI.

- **Assigning relative weights**

The WQI for groundwater was calculated using the weighted arithmetic index method (Brown *et al.* 1972) with respect to the SANS and WHO guidelines for drinking-water quality. The steps used to calculate WQI were:

❖ Step 1: Calculate the unit weight (W_n) factors for each parameters using the formula

$$Wn= \frac{K}{Sn} \qquad \textit{Equation 1}$$

Where $K = \frac{1}{(\Sigma\frac{1}{Sn})}$

Sn = Standard desirable value of the n^{th} parameter.

❖ Step 2: Calculate the Sub-Index (Q_n) value using the formula

$$Qn= \frac{[(Vn\text{-}Vo)]}{[(Sn\text{-}Vo)]} * 100 \qquad \textit{Equation 2}$$

Where V_n = Mean concentration of the n^{th} parameters

S_n = Standard desirable value of the n^{th} parameters

V_o = Actual value of the parameters in pure water. (V_o = 0, for all parameters except for pH)

$$Qph= \frac{[(Vph\text{-}7)]}{[(8.5\text{-}7)]} * 100 \qquad \textit{Equation 3}$$

❖ Step 3: Calculate WQI using the formula

$$\text{Overall WQI}= \frac{\sum WnQn}{\sum Wn} \qquad \textit{Equation 4}$$

- **Specifying the aggregation function**

The overall aggregated WQI value was then ranked using Table 4 to identify the groundwater quality status and to assign possible usages for the groundwater.

Table 4: Water Quality Index range, status and possible usage (Brown et al. 1972)

WQI	**Status/Class**	**Possible usages**
0-25	Excellent	Drinking, irrigation and industrial
25-50	Good	Domestic, irrigation and industrial
51-75	Fair	Irrigation and Industrial
76-100	Poor	Irrigation
101-150	Very poor	Restricted use for irrigation
Above 150	Unfit for drinking	Proper treatment required before use

3.2.3. Groundwater chemistry classification

A Piper Plot was used to graphically analyse the chemistry of the groundwater samples to compare their ionic compositions. According to the location of the samples, the hydrochemical properties were identified and explained using the piper plot. The concentrations of anions and cations were placed in the piper plot triangles, a perpendicular line was then drawn from the sample points in both triangles to the diamond. The point of intersection within the diamond illustrated the groundwater chemistry classification.

3.3. Identification of high yielding groundwater aquifer zones

3.3.1. Mapping of potential groundwater aquifer zones

This section describes the modelling process of identifying GWP zones by using remote sensing, GIS and AHP as recommended by (Pinto *et al.* 2017; Arulbalaji, Padmalal and Sreelash 2019; Das *et al.* 2019; Mohammadi-Behzad *et al.* 2019; Achu, Thomas and Reghunath 2020; Dar, Rai and Bhat 2020). Various datasets viz. rainfall, digital elevation models, land use/land cover, normalised difference vegetation index (NDVI), vegetation cover, lineaments, geology, lithology, evapotranspiration, soil moisture, near-surface temperature, near-surface wind speed and surface water resources were used to analyse groundwater storage in KZN.

The datasets were incorporated into ArcMap 10.8.1 then overlayed and compared with remote sensing groundwater storage data to analyse the influence these factors have on groundwater storage and identify the most influential factors to be incorporated into mapping GWP zones. The thematic layers used in the GWP mapping were geology, lineament density, slope, drainage density, rainfall, land use/land cover and evapotranspiration, which were processed from hydrogeological remote sensing data in ArcMap 10.8.1 environment. The selection of the thematic layers was based on similar studies by; (Pasupuleti *et al.* 2018; Abiye and Bhattacharya 2019; Nagarajan, Sivaprakasam and Karthikeyan 2019; Raju, Raju and Rajasekhar 2019; Lentswe and Molwalefhe 2020).

The thematic layers and their corresponding subclasses were independently weighted using the AHP (Goepel 2013) as described by (Jhariya *et al.* 2016; Nithya *et al.* 2019; Dar, Rai and Bhat 2020; Saranya and Saravanan 2020). The thematic layers were then overlayed in ArcMap 10.8.1 using the weighted overlay analysis tool. The weighted overlay analysis was conducted by assigning a percentage influence on the various parameters, based on its evaluated importance to groundwater recharge. The resultant GWP map was correlated with 113 boreholes using the

Receiver Operating Characteristic Curve (ROC) and Area Under the Curve (AUC) and compared to remote sensing groundwater storage data to validate the results.

The general methodology of mapping of potential groundwater aquifer zones is summarised in Figure 7. It describes the primary processes of data collection, data processing and the reclassification of thematic layers. This completes the process of the identification of GWP zones by integrating the reclassified layers using the weighted overlay analysis method, guided by the AHP technique.

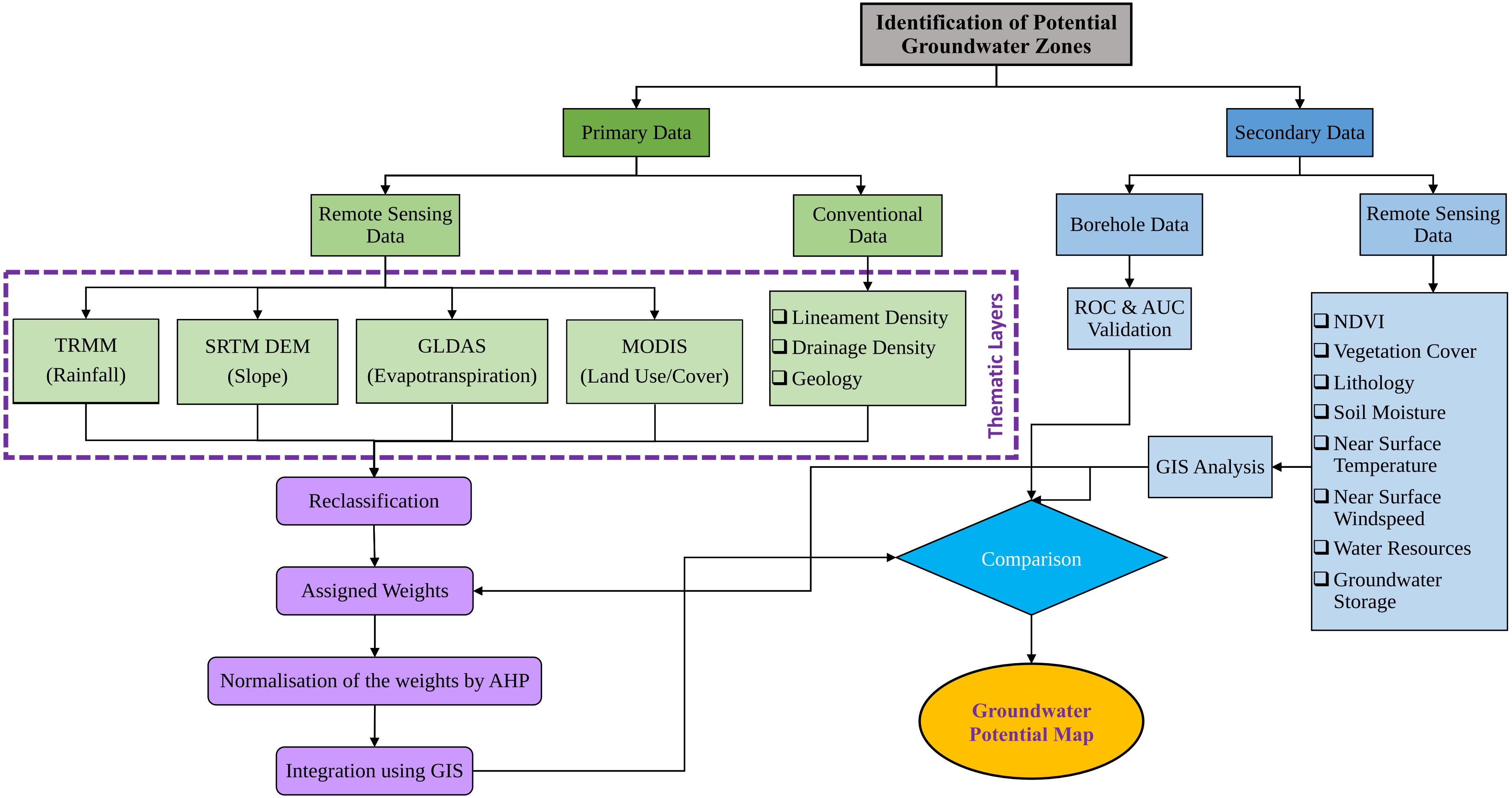


Figure 7: Flow chart of the methodology used for groundwater potential zone mapping.

3.3.2. Data sources

This subsection describes the data sources, formats and processing techniques used for evaluating GWP zones. The data sources used for the study were: the WR2012 website, NASA Giovanni and the Council for Geoscience (CGS).

The Water Resources of South Africa, 2012 Study (WR2012) is a study that began in 2012, intending to build on the previous WR2005 study, which is consolidated on a web-based platform. The website defines the water resources of SA, Lesotho and Swaziland, and results from several water resource studies that have been conducted over the past four decades.

National Aeronautics and Space Administration (NASA) Giovanni is a web-based data centre developed by NASA Goddard Earth Science (GES) Data and Information Services Centre (DISC). The website provides a simple way to visualise, analyse, access, and download earth science remote sensing data. Remote sensing data used in this research was taken from the Giovani website. The data is downloaded as a NetCDF file and was imported into ArcMap 10.8.1 using the multi-dimension tools in the ArcToolbox.

The Council of Geoscience (CGS) is one of the National Science Councils of SA that provides integrated, systematic, and thematic maps of the onshore and offshore geology of SA. Data from this source was utilised to create and analyse the hydrogeology of KZN.

3.3.3. Building the research Geodatabase

The collected, generated, and digitised data was organised into groups based on geology, lineament density, rainfall, drainage density, slope, evapotranspiration, and land use/land cover of KZN. All seven datasets used in the study were converted to raster thematic layers using the conversion, polygon to raster tool, and then to the World Geodetic System (WGS) 1984 Universal Transverse Mercator (UTM) Zone 36 coordinate system, using the Projections and Transformations, Project Tool, in the ArcMap 10.8.1 ArcToolbox. The data was then resampled to have a cell size of 100m x 100m using the Raster Resampling Tool for it to be compatible with the Weighted Overlay Tool for precise results.

3.3.4. Development of thematic layers

The seven GWP conditioning parameters were processed and spatially analysed in ArcMap10.8.1, as described below:

- **Geology**

Geology influences groundwater fluxes and is recommended to be considered in research relating to GWP mapping (Ghorbani Nejad *et al.* 2017; Misi, Gumindoga and Hoko 2018). Geology data, freely downloaded from the CGS, consisted of various geological structures that affect groundwater storage conditions viz. geological bending strikes, dips and foliation, kimberlites hydrovolcanic breccia pipes, dykes, faults, geological contact, and information on the lithology of KZN. These factors are critical in groundwater studies as they provide pathways for water to flow into the subsurface (Pinto *et al.* 2017). All geological data obtained was used in analysing the effect of KZN's geological formations and structures on groundwater storage. However, only data obtained from the WR2012 website was used as an input into the weighted overlay analysis, which included the geological formation groups that make up KZN viz. Ecca, Pongola, Kaapvaal Craton, Lebombo, Zululand, Beaufort, Kalahari, Dwyka, Natal, Stormberg and the Natal Metamorphic Province group. The geological shapefile was clipped for the KZN boundary using the Clip Tool from the ArcMap 10.8.1 ArcToolbox and the KZN provincial boundary shapefile, sourced from the WR2012 website. The clipped shapefile was then converted to a raster layer using the Conversion, Feature to Raster tool and then resampled to a cell size of 100 x 100m. The geological groups were weighted based on their yielding potential of groundwater when analysed by overlaying with remote sensing groundwater storage data and based on the hydraulic conductivity of the material that comprises the groups as described by (Domenico and Schwartz 1990). Hydraulic conductivity is taken from the coefficient of proportionality in Darcy's law, which describes the flow of liquid through a porous media (Shackelford 2013). The equation for calculating hydraulic conductivity is shown as Equation 5.

$$\mathrm{q}= \frac{\mathrm{Q}}{\mathrm{A}} = -\mathrm{ki} \qquad \textit{Equation 3}$$

Where:

- **q** – flow rate (length/time)
- **Q** - Volumetric flow rate of the liquid (length3/time)
- **A** - Cross-section of the soil with voids, perpendicular to the direction of flow (length2)
- **k** - Hydraulic conductivity (length/time)
- **I** - Hydraulic gradient (Shackelford 2013).

Table 5 shows the representative values for hydraulic conductivity for unconsolidated sedimentary materials, sedimentary rocks and crystalline rocks. Figure 8 presents all the lithological groups of KZN.

Table 5: Hydraulic conductivity ranges (Domenico and Schwartz 1990)

Unconsolidated Sedimentary Materials		**Sedimentary Rocks**		**Crystalline Rocks**	
Material	**Hydraulic conductivity (m/s)**	**Rock Type**	**Hydraulic Conductivity (m/s)**	**Material**	**Hydraulic conductivity (m/s)**
Gravel	3 x 10^{-4} to 3 x 10^{-2}	Karst & Reef Limestone	1 x 10^{-6} to 2 x 10^{-2}	Permeable Basalt	4 x 10^{-7} to 2 x 10^{-2}
Coarse Sand	9 x 10^{-7} to 6 x 10^{-3}	Limestone, Dolomite	1 x 10^{-9} to 6 x 10^{-6}	Fractured Igneous & Metamorphic Rock	8 x 10^{-9} to 3 x 10^{-4}
Medium Sand	9 x 10^{-7} to 5 x 10^{-4}	Sandstone	3 x 10^{-10} to 6 x 10^{-6}	Weathered Granite	3.3 x 10^{-6} to 5.2 x 10^{-5}
Fine Sand	2 x 10^{-7} to 3 x 10^{-4}	Siltstone	1 x 10^{-11} to 1.4 x 10^{-8}	Weathered Gabbro	5.5 x 10^{-7} to 3.8 x 10^{-6}
Silt, Loess	1 x 10^{-9} to 2 x 10^{-5}	Anhydrite	4 x 10^{-13} to 2 x 10^{-8}	Basalt	2 x 10^{-11} to 4.2 x 10^{-7}
Till	1 x 10^{-12} to 2 x 10^{-6}	Shale	1 x 10^{-13} to 2 x 10^{-9}	Unfractured Igneous and Metamorphic Rock	3 x 10^{-14} to 2 x 10^{-10}
Clay	1 x 10^{-11} to 4.7 x 10^{-9}	-	-	-	-
Unweathered Marine Clay	8 x 10^{-13} to 2 x 10^{-9}	-	-	-	-

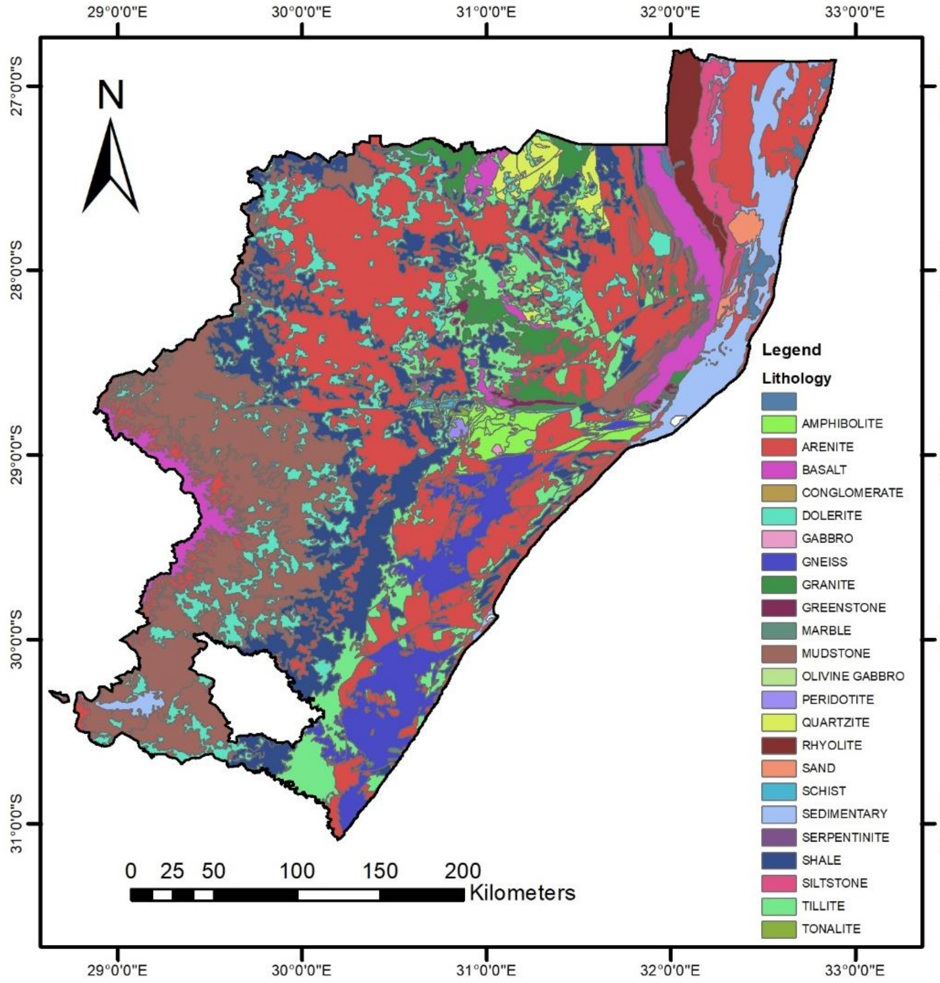


Figure 8:Lithology of KwaZulu-Natal

- **Lineament density**

Lineaments play a vital role in groundwater recharge as faulting and fracturing are responsible for increasing porosity and permeability, and therefore, groundwater potential remains very high closer to lineaments (Dar, Rai and Bhat 2020). Figure 9 presents the geological structures in KZN, which form fault lines and geological contact.

Two separate lineament density raster maps, representing fault lines and geological contact were created using the Spatial Analyst, Line Density Tool from the ArcToolbox, as presented in Figure 10. The maps were reclassified using the Reclassify Tool by natural breaks. The faults and geological contact data was sourced from the CGS and was in the form of GIS shapefiles. The tool divides the length of lineaments by the area of the study location. Areas with a high lineament density are considered to have an excellent groundwater potential as the presence of lineaments usually denotes a permeable zone (Haridas, Aravindan and Girish 1998; Pinto *et al.* 2017).

Remote sensing data was not used to create lineament density maps due to lineament data being freely available in SA and due to the study area being too large to extract lineaments from satellite images manually.

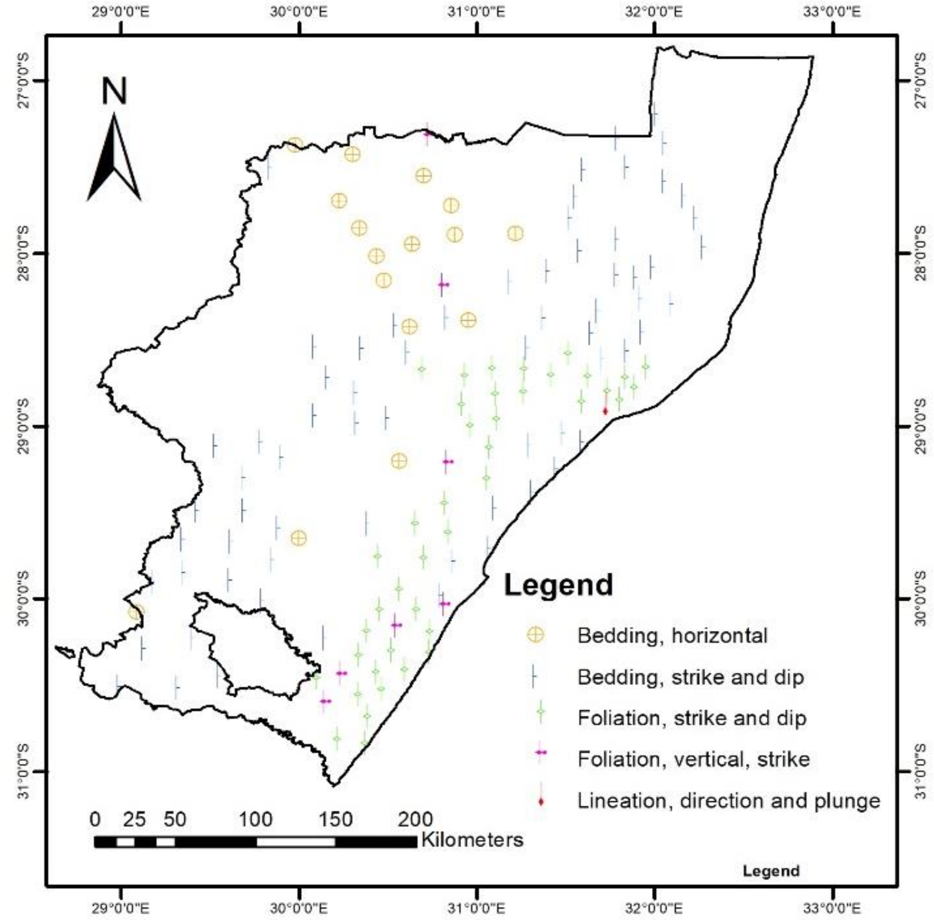


Figure 9: Geological structures in KwaZulu-Natal

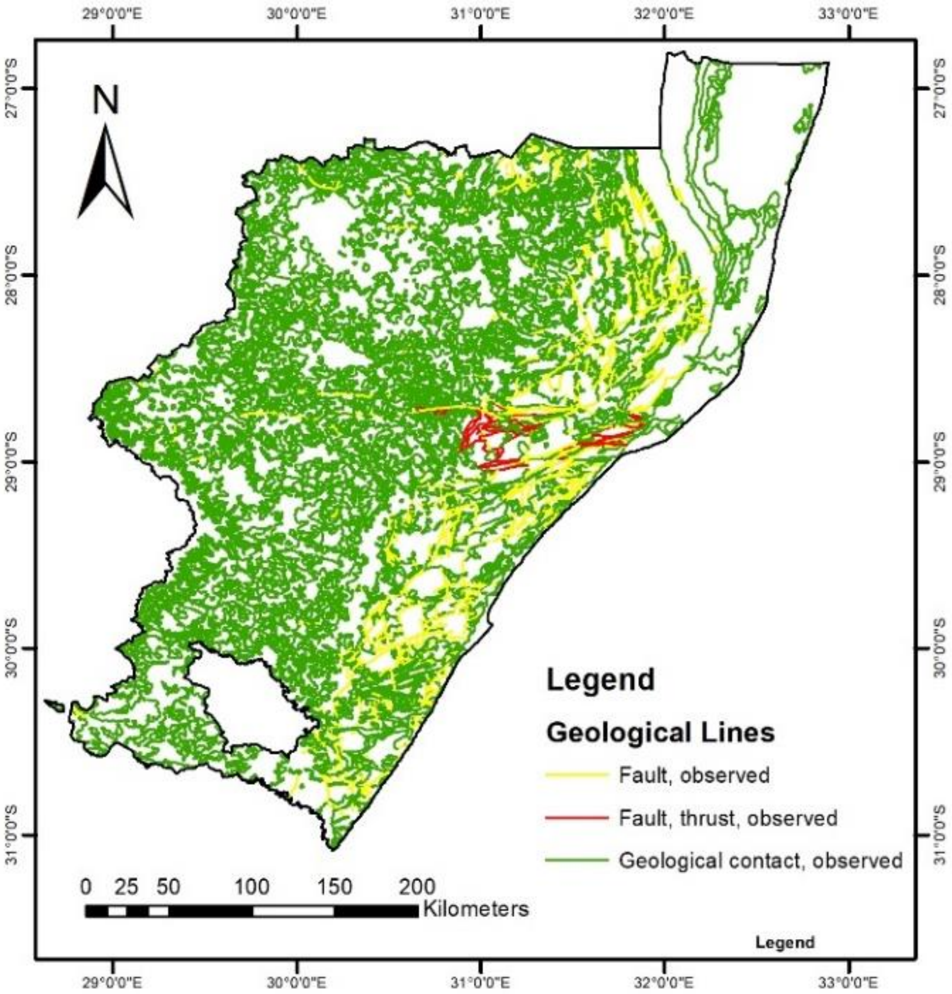


Figure 10: Geological lines of KwaZulu-Natal

- **Slope**

The slope of an area is an essential parameter in identifying GWP zones as it one of the primary groundwater recharge controlling factors (Dar, Rai and Bhat 2020). Steep slopes increase surface runoff and soil erosion rates, which hinder infiltration, whereas gentle slopes increase the residence time of runoff, promoting infiltration, hence high GWP (Misi, Gumindoga and Hoko 2018; Dar, Rai and Bhat 2020).

Digital elevation models play a vital role in geosciences and engineering (Hirt 2016). They can be used to calculate quantities such as volumes, slope, hill shade, contours and drainage (Hirt 2016). The digital elevation model (DEM) used in this study is derived from United States Geological Survey (USGS)/NASA Shuttle Radar Topography Mission (SRTM) data and has a resolution of 90m. The data was sourced in three separate raster maps as KZN is situated in three different SRTM DEM tiles. The raster DEM maps were merged using the ArcMap 10.8.1, Mosaic to New Rastertool, for ease of use. Data sinks and peaks were removed using the Fill function. The merged DEM was used to create a contour layer, presented in Figure 11, slope layer and hillshade layer. These layers were edited to a lower transparency value for assessing them on top of each other for better analysis. The stacking of the layers resulted in a map showing a 3-dimensional representation of the terrain surface with colour coded slope values to show height differences of the land. The contour layer was integrated to show exact height values when assessing the map.

The hillshade layer, presented in Figure 12 represents a greyscale 3-dimensional representation of the surface. The sun's relative position was considered for shading the image. The altitude, which is the sun's angle of elevation above the horizon, was chosen as 45◦, and the azimuth, which is the sun's relative position along the horizon, was taken as 315◦. Vertical exaggeration was added for a visual effect using a Z factor of 0.00001036 due to the latitude position of KZN. The slope layer represented the steepness at each cell and was calculated using the planner method, where the slope is measured as the maximum rate of change in value from a cell to its immediate neighbouring cell. The slope map of KZN was created using the Spatial Analyst Slope tool in ArcMap 10.8.1. The Slope tool calculates the changes in elevations of the surrounding areas.

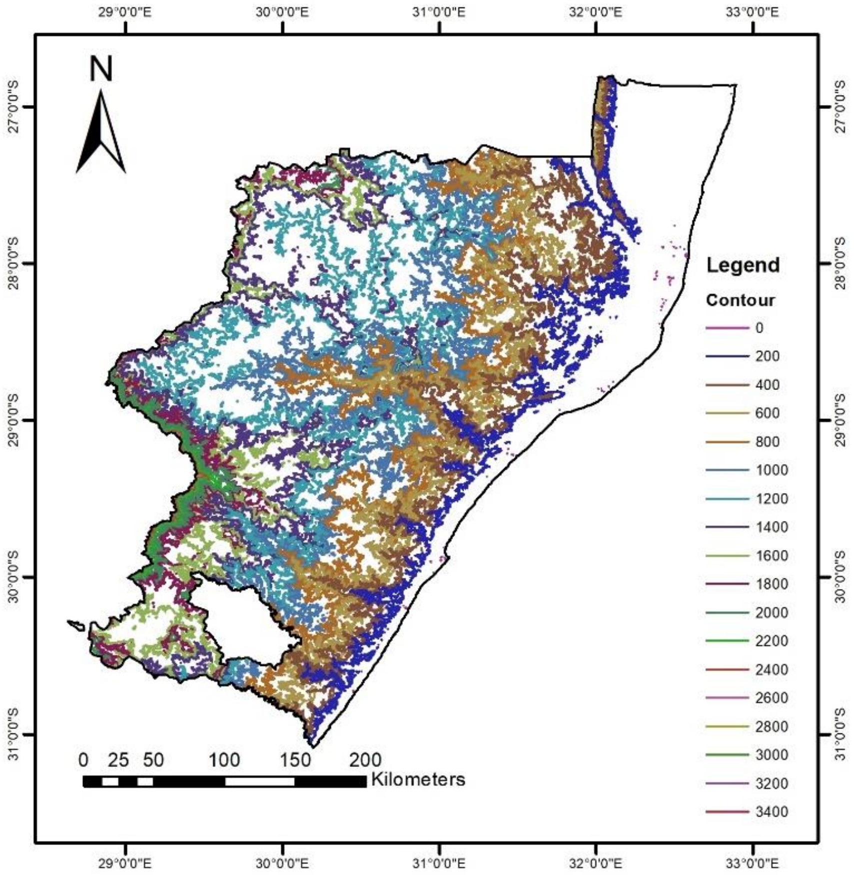


Figure 11: KwaZulu-Natal contour map

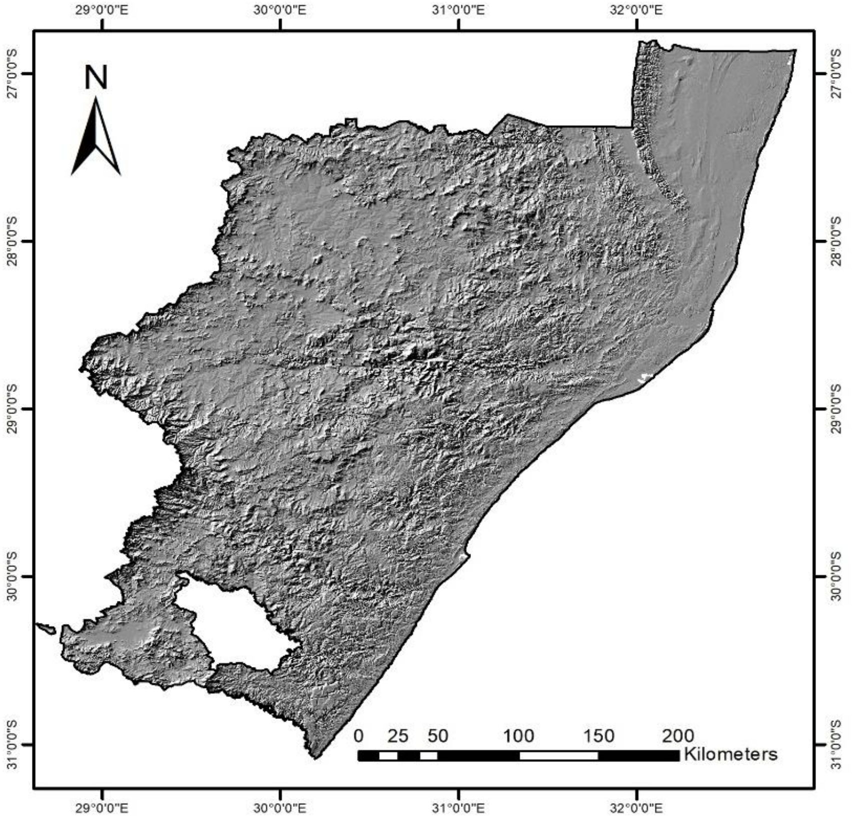


Figure 12: KwaZulu-Natal hillshade map

- **Drainage density**

Drainage density indicates the total length of streams within an area (Km/Km^2) (Lentswe and Molwalefhe 2020). Traditionally, drainage density is used in groundwater studies as an inverse function of permeability, which indicates high drainage density values favouring runoff and therefore indicated low GWP zones, as stated by (Bagyaraj *et al.* 2013; Shekhar and Pandey 2015; Jenifer and Jha 2017; Pinto *et al.* 2017; Thomas and Duraisamy 2017; Arulbalaji, Padmalal and Sreelash 2019; Mohammadi-Behzad *et al.* 2019; Achu, Thomas and Reghunath 2020). However, rainfall follows the slope of an area and accumulates at areas having the lowest elevations irrespective of the lithological setting (Das and Pardeshi 2018). Therefore in this study, high drainage density areas, which represent low elevation areas, favour groundwater recharge as river beds can substantially contribute to groundwater recharge (Das and Pardeshi 2018). In this study, drainage density was extracted from the DEM by using ArcMap 10.8.1. Firstly, the DEM was clipped for the watershed using the Raster Clip tool, then the Hydrology tools in the ArcMap 10.8.1 ArcToolbox were used to calculate flow direction using the DEM as the input; flow accumulation using flow direction as the input; stream order using flow accumulation as the input, and stream to feature using the flow accumulation as the input. These tools visually represent the watershed streams as polylines located at low lying areas where water accumulates. Figure 13 illustrates the model created in ArcMap 10.8.1 to produce the stream map, which presented in Figure 14. The drainage density map was then created by using the Spatial Analyst, Line Density tool which calculates the density of polylines in the area of each output raster cell (Silverman 1986).

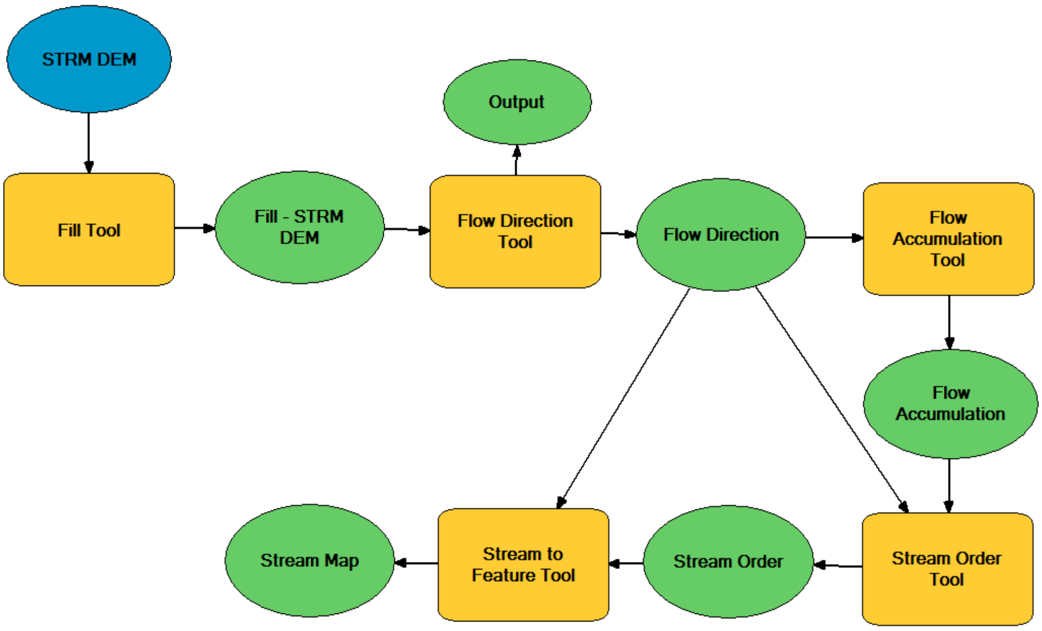


Figure 13: Flow chart representing the conversion from a DEM to a drainage density map

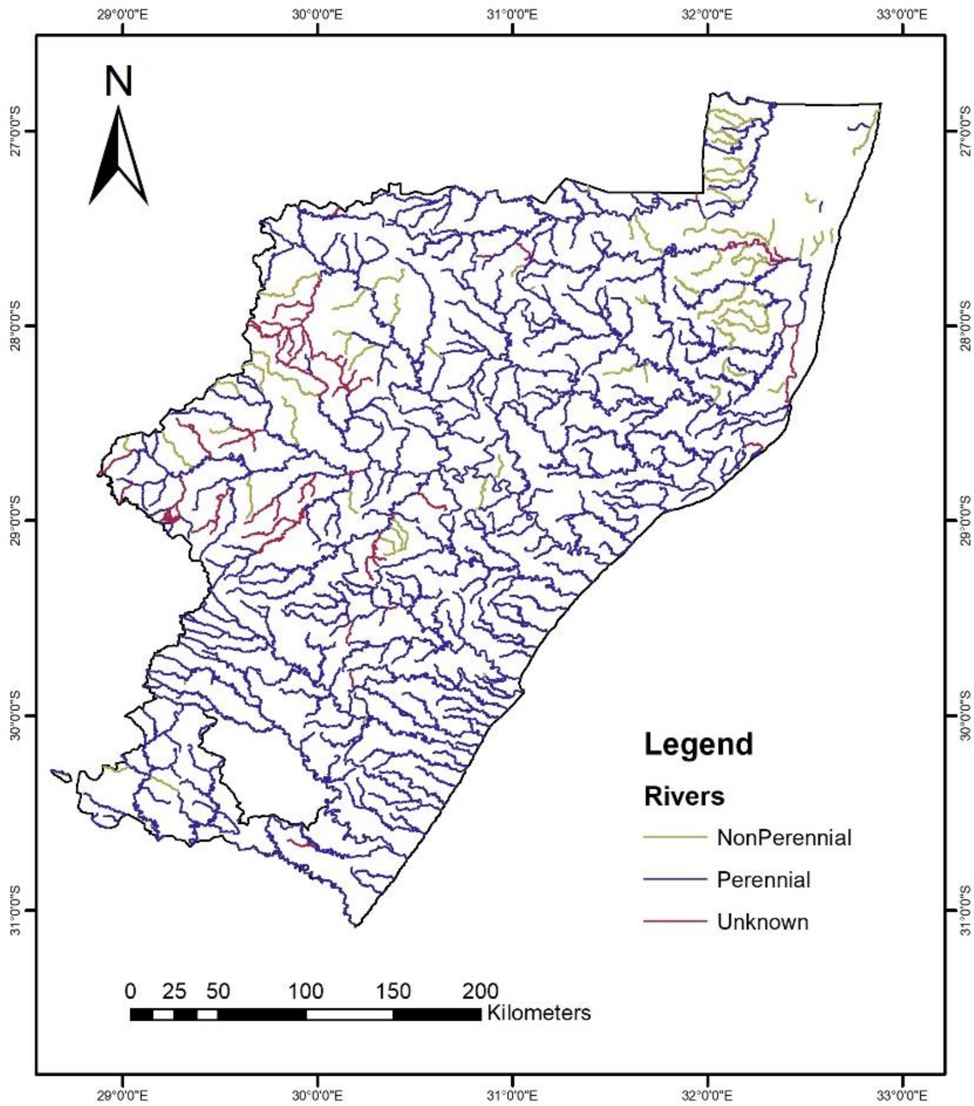


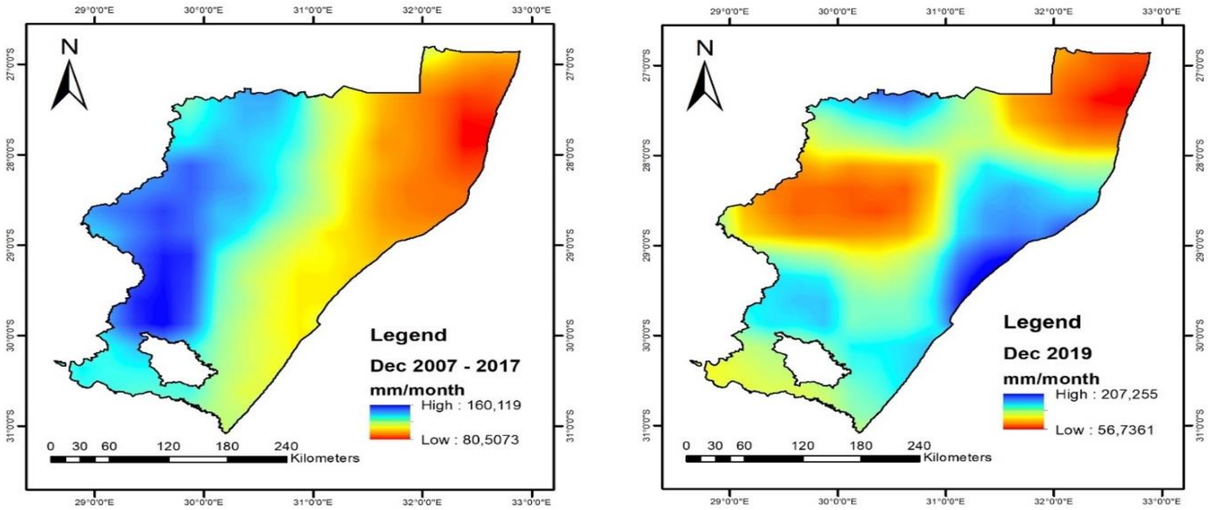
Figure 14: Resultant stream map

- **Rainfall**

Rainfall distribution is considered the most influential parameter in identifying GWP zones (Misi, Gumindoga and Hoko 2018; Dar, Rai and Bhat 2020). Rainfall data used in the study was obtained from the Tropical Rainfall Measurement Mission (TRMM) observatory and its partner satellites. This mission is a joint effort between NASA and the Japanese Aerospace Exploration Agency.

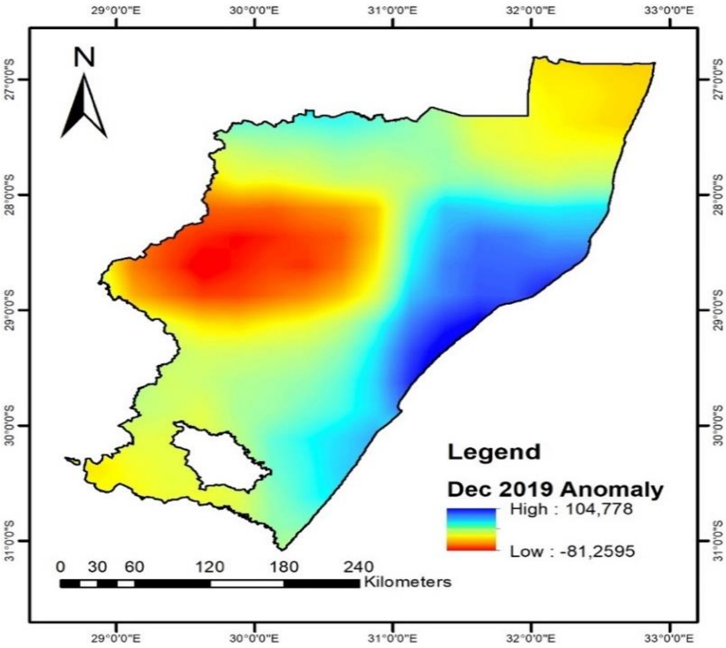
The TRMM Multi-Satellite Precipitation Analysis (TMPA) rainfall estimate product, 3B43 version 7 used in the study combines satellite rainfall estimates with gauge data into gridded estimates on a calendar month temporal resolution and a 0.25 by 0.25 spatial resolution from 50◦ S to 50◦N latitude.

Rainfall anomaly data was created by comparing 2019 monthly average data, Figure 15(b), with the monthly average data for 2007-2017, shown in Figure 15(a). The anomaly data represents how rainfall has changed from 2007-2019, with the negative areas (red) representing a decrease in rainfall and the positive areas (blue) as an increase in rainfall, as shown in Figure 15(c). The rainfall data used in the weighted overlay analysis was monthly accumulated rainfall for the year 2019 and was downloaded from the NASA Giovani website.



(a) Average December rainfall (2007-2017)

(b) Average December rainfall (2019)



(c) December rainfall anomaly data

Figure 15: KwaZulu-Natal rainfall data

- **Land use/Land cover**

Land use/land cover plays a vital role in groundwater recharge as it affects evapotranspiration, surface runoff and infiltration (Mondal 2012; Misi, Gumindoga and Hoko 2018). Land use/land cover data was freely downloaded from the South African National Biodiversity Institute website. The data includes information for the whole of SA but was clipped using the KZN provincial boundary shapefile. The dataset accumulates information from fine-scale municipal land cover data, provincial land cover, Agricultural Research Council cultivation field boundaries and ESKOM Spot 5 building count. The data set is digitised at 30 megapixels and is assumed to have an accuracy of approximately 90% as the two major data sets used, Agricultural Research Council cultivation and ESKOM data, have an accuracy of 90%. The dataset represents land cover/land-use for the year 2008. Data this old was only be used to analyse and investigate land cover/land-use change. Therefore, remote sensing images and GIS was used to create land cover data for 2019 to identify GWP zones.

Remote Sensing land cover data was freely downloaded from the USGS Earth Explorer website. The downloaded data was from the NASA MODIS MCD12Q1 V6 product, which is the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 data product. The product provides data sets that map global land cover at 500m spatial resolution annually. The data is derived using supervised classifications of MODIS Terra and Aqua reflectance data and then undergoes additional processing that incorporates prior knowledge and ancillary information to refine specific classes. Each year five land cover classification schemes are developed by different research organisations. These classifications are:

- Land Cover Type 1: IGBP global vegetation classification scheme
- Land Cover Type 2: University of Maryland scheme
- Land Cover Type 3: MODIS-derived LAI/fPAR scheme
- Land Cover Type 4: MODIS-derived Net Primary Production scheme
- Land Cover Type 5: Plant Functional Type scheme

The five research organisations developed their land cover classification schemes using one year of Terra and Aqua MODIS data. The International Geosphere-Biosphere Programme type 1 land cover scheme was used to classify land use/land cover data for KZN and is shown in Table 6.

Table 6: Landcover categories (Adapted from Friedl *et al*. 2010)

	Landcover types (1 through 4 classification schemes)			
Class	**IGBP (Type 1)**	**UMD (Type 2)**	**LAI/fPAR (Type 3)**	**NPP (Type 4)**
0	Water	Water	Water	Water
1	Evergreen needleleaf forest	Evergreen needleleaf forest.	Grasses/cereal crops.	Evergreen needleleaf vegetation
2	Evergreen broadleaf forest	Evergreen broadleaf forest	Shrubs	Evergreen broadleaf vegetation
3	Deciduous needleleaf forest	Deciduous needleleaf forest	Broadleaf crops	Deciduous needleleaf vegetation
4	Deciduous broadleaf forest	Deciduous broadleaf forest	Savanna	Deciduous broadleaf vegetation
5	Mixed forest	Mixed forest	Evergreen broadleaf forest	Annual broadleaf vegetation
6	Closed shrublands	Closed shrublands	Deciduous broadleaf forest	Annual grass vegetation
7	Open shrublands	Open shrublands	Evergreen needleleaf forest	Non-vegetated land
8	Woody savannas	Woody savannas	Deciduous needleleaf forest	Urban
9	Savannas	Savannas	Non-vegetated	-
12	Grasslands	Grasslands	Urban	-
11	Permanent wetlands		-	-
12	Croplands	Croplands	-	-
13	Urban and built-up	Urban and built-up	-	-
14	Cropland/natural vegetation mosaic	-	-	-
15	Snow and ice	-	-	-
16	Barren or sparsely vegetated	Barren or sparsely vegetated	-	-
254	Unclassified	Unclassified	Unclassified	Unclassified
255	Fill value	Fill value	Fill value	Fill value

Two map tiles covering KZN were downloaded in Hierarchical Data Format (HDF) for 2019. The data sets were imported into ArcMap 10.8.1 using the type 1 classification. The two tiles were then merged, using the Mosaic tool, and changed to Tag Image File Format (TIFF) for ease and efficiency of further processing. Data for KZN was extracted using the Extract tool and converted to a feature class polygon using the Raster to Polygon tool. The data was then classified using the grid codes, representing the land cover classification codes shown in Table 6. The landcover of KZN by the type 1 grid code classification scheme is represented Figure 16.

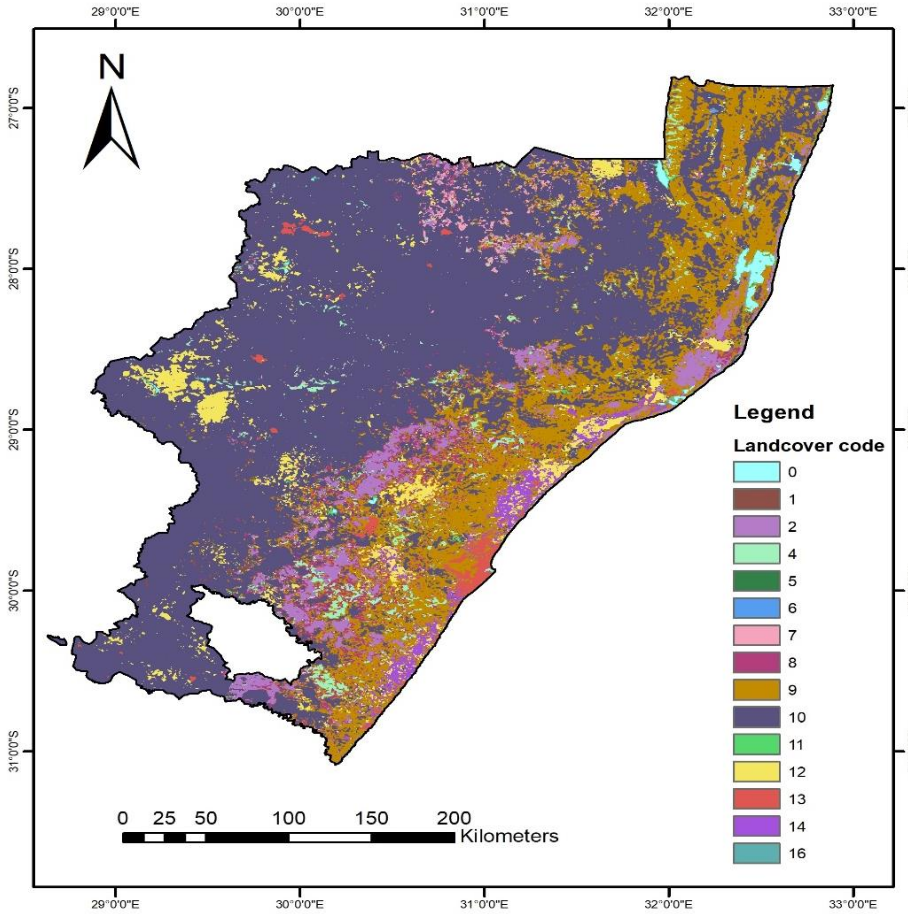


Figure 16: IGBP type 1 Landcover map of KwaZulu-Natal

Vegetation data was used in conjunction with the land use/land cover data for an in-depth analysis. Vegetation data was taken from the WR2012 website in the form of a GIS shapefile. The data contains information on vegetation cover types in SA. The shapefile was converted to a raster layer using the Conversion, Feature to Raster tool. The raster layer was then reclassified to represent the different biomes in KZN. There are 101 types of vegetation in KZN and five biomes: Grassland, Savanna, Azonal vegetation, Indian Ocean Coastal Belt, and forests, as shown in Figure 17.

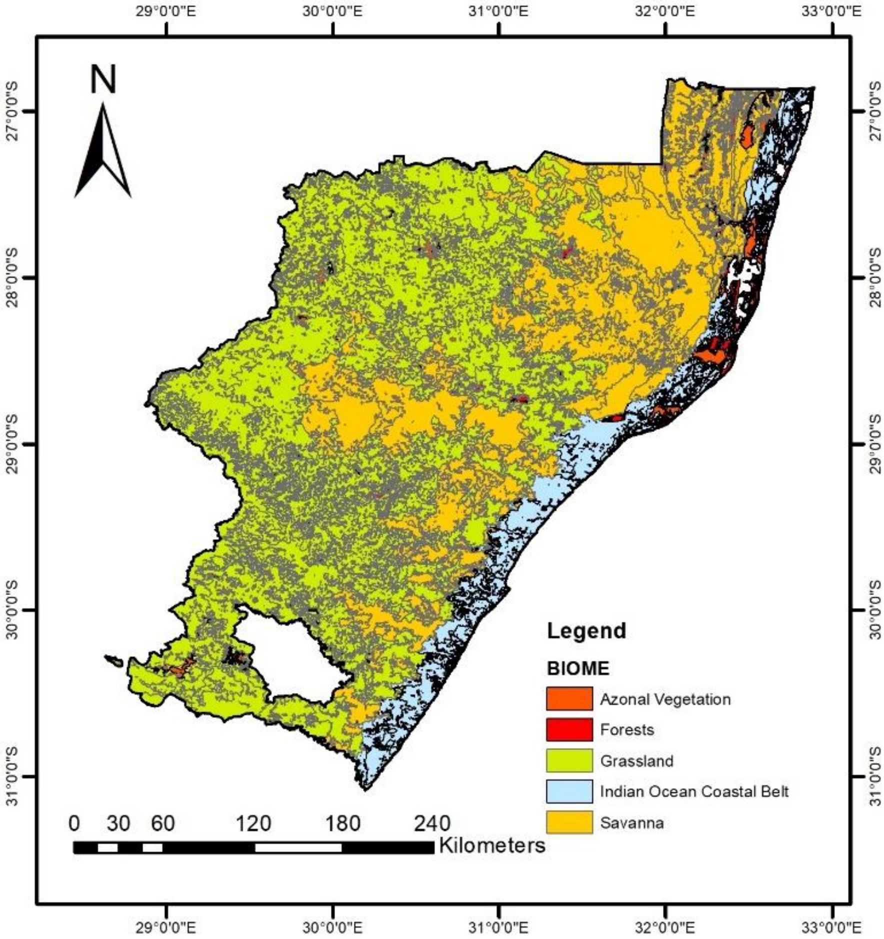
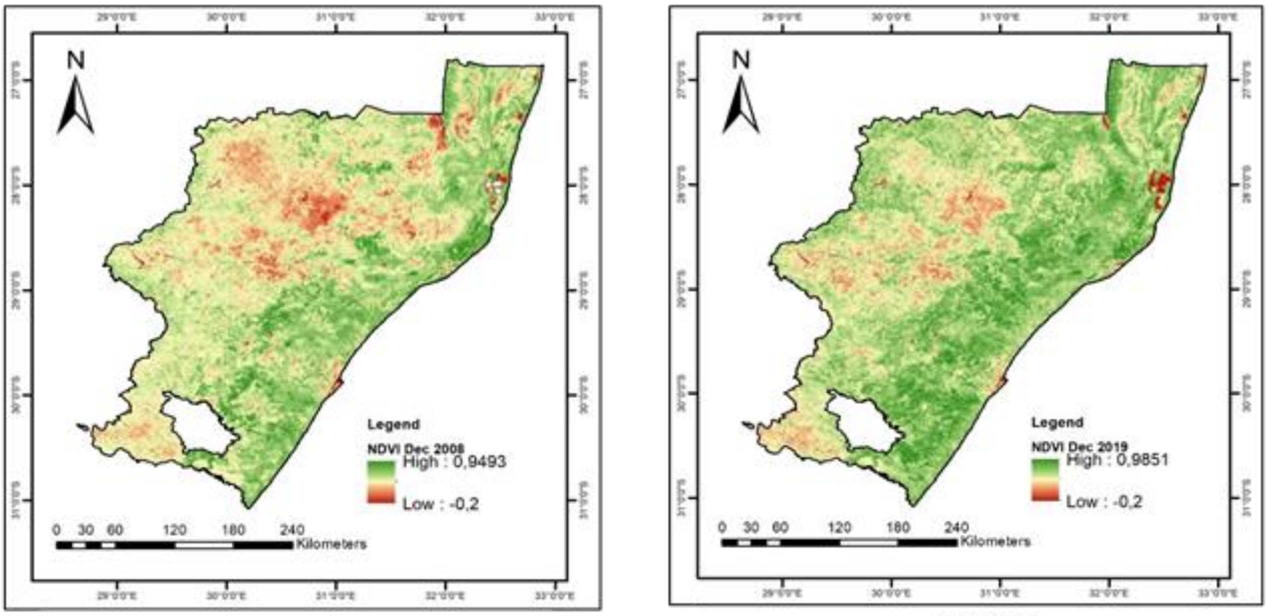


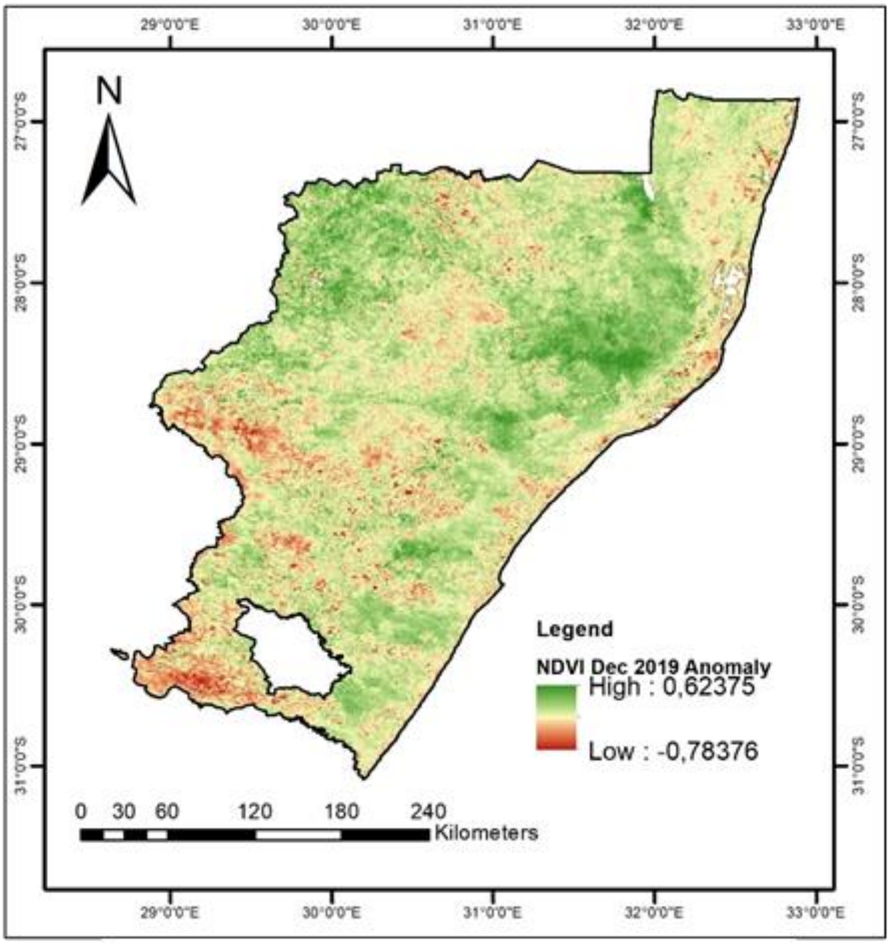
Figure 17: Vegetation biomes of KwaZulu-Natal

Remotely Sensed Normalised Difference Vegetation Index (NDVI) data was used to investigate the density of green on KZN land. The data set is a product of the MODIS 13 satellite and measures NDVI based on how plants reflect light at specific frequencies (Weier and Herring 2000). The MODIS 13 satellite provides consistent spatial and temporal time-series comparisons of global vegetation conditions that can be used to monitor the Earth's vegetation activity. The product offers Vegetation Index values at 500-meter spatial resolution. Two vegetation layers are provided, NDVI and Enhanced Vegetation Index (EVI), of which NDVI is used in the study. One image for each month, from December 2017 to December 2019, was used. Anomaly data was created using NDVI data from 2008 – 2019, represented in Figures 18 (a) & (b), to show the deficit in vegetation up to December 2019. The negative values indicated in Figure 18 (c) represent a decrease in green vegetation, and the positive values indicate an increase. Both vegetation data and land cover data were used to analyse how vegetation affects groundwater recharge. The analysis was based on the type of cover, canopy cover and infiltration and was used as a guide in the weighted overlay analysis.



(a) 2008

(b) 2019



(c) Deficit from 2009 - 2019

Figure 18: KwaZulu-Natal NDVI deficit from 2009 - 2019

- **Evapotranspiration**

The relationship between evapotranspiration and groundwater is globally known. When groundwater storage increases, evapotranspiration decreases and vice versa (Ndou, Palamuleni and Ramoelo 2018). Remote sensing data has been used in evapotranspiration and groundwater studies due to it resulting in valuable information regarding the behaviour of groundwater resources (Ndou, Palamuleni and Ramoelo 2018).

Global Land Data Assimilation System (GLDAS) is used to retrieve data of land surface states and fluxes by using advanced modelling and data assimilation techniques with satellite and ground-based observation products. GLDAS drives four land surface models, NOAH, Catchment, Community Land Model and the Variable Infiltration Capacity.

Evapotranspiration data averaged over the year 2019, with a spatial resolution of 0.25 degrees, was sourced from the GLDAS model and clipped for KZN. The GIS raster calculator was used to convert the data into mm/month by assuming the heat of vaporisation of water at zero degree Celsius is 2.5 x 10^6 J/Kg, and water density is 1000 Kg/m^3. Evapotranspiration data given in Watts/meter^2 was converted to a more functional unit, mm/day, using Equation 6. The evapotranspiration data was used in the weighted overlay analysis as an inverse function of groundwater recharge.

$$\frac{\mathrm{W}}{\mathrm{m}^2} \times \frac{\mathrm{kg}}{2.5\times10^6\mathrm{J}} \times \frac{\mathrm{J}}{\mathrm{W(sec)}} \times \frac{\mathrm{m}^3}{1000(\mathrm{kg})} \times \frac{1000(\mathrm{m})}{1(\mathrm{m})} \times \frac{86400(\mathrm{sec})}{\mathrm{day}} = \frac{\mathrm{mm}}{\mathrm{day}}$$

Equation 4: W/m^2 conversion to mm/day

3.3.5. Computation of weights using the Analytical Hierarchy Process

The AHP is a GIS-based spatial multi-criteria structured technique for organising and analysing complex decisions based on mathematics and psychology. The AHP pairwise matrix method is suitable for separating large amounts of complex data into a series of pairwise comparisons (Lentswe and Molwalefhe 2020).

The AHP method was used to determine the percentage importance of the thematic layers used to identify GWP zones by computing weights of the thematic layers and their corresponding attributes. The AHP was implemented in four phases: (1) Selection of factors influencing groundwater storage, (2) pairwise comparison matrix, (3) estimating relative weights and, (4) assessing matrix consistency.

- **Selection of factors influencing groundwater storage**

The first stage in the AHP method is the selection of groundwater influencing factors and their corresponding attributes. This allows for the research problem to be classified into a pyramid structure, with the aim as the apex, followed by the factor attributes and then the solutions as the base (Lentswe and Molwalefhe 2020). Given the study's objective, the influencing factors used were rainfall, lineament density, land use/land cover, slope, evapotranspiration, drainage density and geology. Table 7 presents the hydrogeological influencing factors and their description, type and the source of the data.

Table 7: Hydrogeological factors in relation to groundwater productivity

Category	Hydrogeological factors (unit)	Description	Data type	Source
Topology	Lineament density	Lineament, geological bending strikes, dips and foliation, kimberlites, hydrovolcanic breccia pipes, dykes, faults, and geological contact are essential features for increasing the permeability of the bedrock	Line	CGS
	Drainage density	Drainage density is a function of permeability. The drainage density map represents topographic lows that correspond to higher drainage density, and therefore high drainage density values are favourable for infiltration, which indicates a high groundwater potential.	Line	WR2012
RS images	Rainfall (mm)	Rainfall is the primary source of recharge. The rainfall map was grouped into five classes which are 598–688; 688–764; 764–829; 829–912, and 912-1058 mm/year. High rainfall is favourable for high groundwater potential and hence assigned a higher priority.	Grid	TRMM
	Slope	The slope of KZN ranges from 0-72 degrees in steepness. A steeper slope angle results in rapid runoff zones, which decreases groundwater recharge potential.	Grid	SRTM
	Evapotranspiration	Evapotranspiration and groundwater are closely linked. When groundwater storage	Grid	GLDAS_NOAH025_M_v2.1

		increases, evapotranspiration decreases and vice versa.		
	Land use/land cover	Landcover, vegetation cover and NDVI data were combined and analysed in terms of cover type, canopy cover and infiltration.	Grid	MODIS MCD12Q1 V6
Geology	Hydrogeological (unitless)	Geologically, the area has been divided into various geological groups, viz. Ecca, Pongola, Kaapvaal Craton, Lebombo, Zululand, Beaufort, Kalahari, Dwyka, Natal, Stormberg and the Natal Metamorphic Province group.	Polygon	WR2012/SA NSA/CGS

A standard method for deriving weights for different factors is constructing a schematic map of the interrelationship between the factors. The stronger the influence of a factor on others, the greater its importance and, therefore, its weight (Dar, Rai and Bhat 2020).

The relationship between the factors used and their influence on delineating groundwater aquifer zones is shown in Figure 19. The straight lines represent the factor having a significant effect on the receiving factor, and the dashed line representing a minor effect.

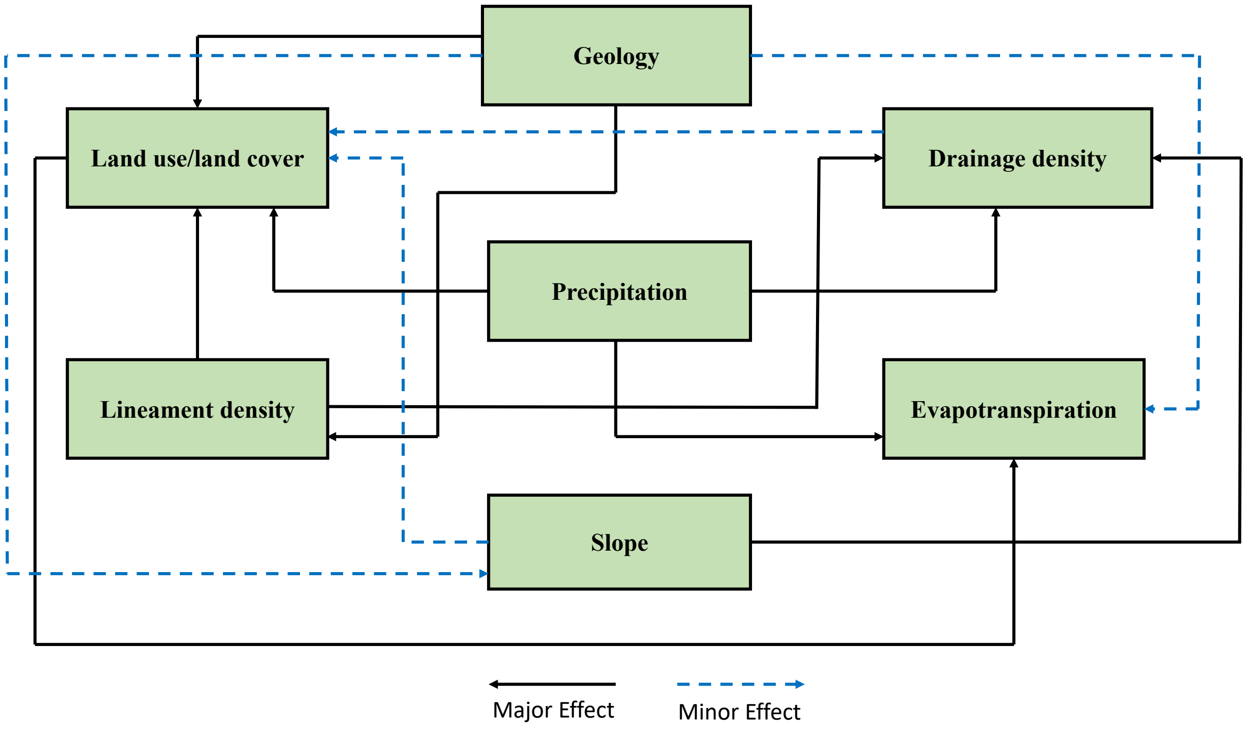


Figure 19: Interrelationship between the multi influencing parameters controlling GWP zones. Adapted from (Das and Pardeshi 2018)

- **Pairwise comparison matrix**

Based on the thematic layers used to identify GWP zones, a pairwise comparison matrix $(A(m \times m))$ was constructed. Each input of the matrix represents the row factor relative to the column factor. The relative importance of the factors influencing groundwater storage was assigned based on the nine-point scale shown in Table 8, where 1 represents equal importance between factors, and 9 representing the substantial significance of one parameter over another (Saaty 1988; Dar, Rai and Bhat 2020).

Table 8: The relative importance of the factors (Saaty 1988)

Intensity of importance	**Definition**	**Explanation**
1	Equal Importance	Two criteria/sub-criteria contribute equally to the level immediately above.
3	Moderate Importance	Judgement slightly favours one criterion / sub-criterion over another.
5	Strong Importance	Judgement strongly favours one criterion / sub-criterion
7	Very Strong Importance	One criterion/sub-criterion is favoured strongly over another.
9	Absolute/ Extreme Importance	There is evidence affirming that one criterion / sub-criterion is favoured over another.
2,4,6,8	Immediate values between the above scale values	Absolute judgement cannot be given, and a compromise is required.

- **Estimating relative weights**

Analytical Hierarchy Process utilises experts' opinions and the principal eigenvectors to assign weights to the parameters and eigenvalues to rank the parameters. There is no record of expert opinions being used in studies to assign weights to factors influencing groundwater storage in South Africa (Lentswe and Molwalefhe 2020). Therefore, expert opinions was not used in this research; instead, published literature and desktop investigations were carefully analysed before assigning weights. Weights were assigned to the seven thematic layers and their equivalent classes, which form the basis of mapping GWP zones.

- **Assessing matrix consistency**

Due to uncertainty in judgements, AHP captures uncertainty through the principal eigenvalue and the consistency index (Saaty 2004). The consistency index (CI) was calculated to assess the evaluations made when creating the pairwise comparison matrices. Inconsistencies in the matrices increase with the increasing number of comparisons (Lentswe and Molwalefhe 2020). The measure of consistency was calculated using equation 7:

$$CI = \frac{(\lambda max - n)}{(n-1)} \qquad \textit{Equation 7}$$

Where λ_{max} is the largest eigenvalue of the matrix and n is the number of classes.

The Consistency Ratio (CR) was then calculated to measure the consistency of the pairwise comparison matrix. CR is the ratio of the consistency index to the Ratio Index (RI), which is calculated using:

$$CR = \frac{CI}{RI} \qquad \textit{Equation 8}$$

RI is Saaty's ratio index for a matrix of order n. The RI values are shown in Table 9.

Table 9: Saaty's Ratio Index for various values of n

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

AHP accepts a CR value of 0 - 10%. If the CR is equal to 0%, the comparison matrix is perfectly consistent, and anything greater than 10% calls for the revision of the comparisons (Saaty 1988; Dar, Rai and Bhat 2020).

By using AHP, the weights given to each thematic layer and their corresponding classes were normalised. Table 10 presents the matrix of the thematic layer comparison.

Table 10: Pair-wise comparison matrix

Criteria	**Rainfall**	**Land use/Land cover**	**Lineament density**	**Stream density**	**Slope**	**Evapotranspiration**	**Geology**	**Weights**
Rainfall	0.26	0.35	0.36	0.19	0.36	0.21	0.43	0.32
Land use/ Land cover	0.04	0.06	0.04	0.10	0.04	0.15	0.04	0.06
Lineament density	0.05	0.12	0.07	0.10	0.07	0.13	0.04	0.08
Stream density	0.51	0.23	0.29	0.38	0.29	0.21	0.34	0.33
Slope	0.05	0.12	0.07	0.1	0.07	0.13	0.04	0.08

Evapotranspiration	0.03	0.01	0.01	0.05	0.01	0.03	0.01	0.02
Geology	0.05	0.12	0.15	0.10	0.15	0.15	0.09	0.11

3.3.6. Weighted Overlay Analysis

Firstly, the data was classified into five classes to produce the five groundwater potential zones using ArcMap 10.8.1. The data classes were then reclassified and ranked on a common preference scale of 1-5, with 5 being the most favourable in terms of groundwater recharge potential. The ranks was determined by in-depth analysis of the spatial data collected and information from published articles relating to KZN. The reclassification is based on natural breaks in the data, using the reclassify tool in ArcMap 10.8.1. The weighted overlay analysis tool was then used to identify GWP zones in KZN using feature class and raster data. The analysis aimed to categorise zones of GWP, shown in Table 11, by assigned weights and ranks to the parameters controlling the potential groundwater recharge of the area.

Table 11: Groundwater potential categories

Groundwater Potential Categories	
1	Very poor (least important)
2	Poor (not very important)
3	Moderate
4	Good (important)
5	Excellent (most important zone - high groundwater potential)

The weights obtained from the AHP was assigned to each thematic layer to generate a cumulative weight, shown in Table 12 as normalised principal eigenvectors, and then imported into the Weighted Overlay Analysis tool in ArcMap 10.8.1. The overlay analysis used Equation 9, which incorporates all thematic layers, to calculate the groundwater potential index (GWPI).

$$\sum_{j=1}^{m}\sum_{i=1}^{n}(Wj \text{ x } Xi)$$ *Equation 5*

Where

- W_j is the normalised weight/percentage influence of the j thematic layer
- X_i is the scale value of each class with respect to the j layer
- m is the total number of thematic layers
- n is the total number of classes

Table 12: Normalised Principal Eigenvector and assigned weights of respective thematic classes

Thematic Layer	Normalised Principal Eigenvector	Classes	Rank
Rainfall	31.75%	598 – 688 mm	1
		688 – 764 mm	2
		764 – 829 mm	3
		829 – 912 mm	4
		912 – 1058 mm	5
Land use/Land cover	6.19%	Water	5
		Evergreen needleleaf forest	4
		Evergreen broadleaf forest	4
		Deciduous broadleaf forest	4
		Mixed forest	4
		Closed shrublands	3
		Open shrublands	2
		Woody savannas	2
		Savannas	2
		Grasslands	2
		Permanent wetlands	5
		Croplands	3
		Urban and built-up	1
		Cropland/natural vegetation mosaic	3
		Barren or sparsely vegetated	1
Lineament density	7.93%	0 - 0.21 km/km^2 (Very Low)	1
		0.21 – 0.39 km/km^2 (Low)	2
		0.39 – 0.53 km/km^2 (Moderate)	3
		0.53 – 0.65 km/km^2 (High)	4
		0.65 – 1.02 km/km^2 (Very High)	5
Drainage density	32.95%	0 – 0.08 km/km^2 (Very Low)	1
		0.08 – 0.15 km/km^2 (Low)	2
		0.15 – 0.19 km/km^2 (Moderate)	3
		0.19 – 0.24 km/km^2 (High)	4
		0.24 – 0.37 km/km^2 (Very High)	5
Slope	7.93%	0 – 3.94º (Flat)	5
		3.94 – 8.45º (Gentle)	4
		8.45 – 14.37º (Moderate)	3
		14.37 – 22.25º (Steep)	2
		22.25 – 71.83º (Very Steep)	1
Evapotranspiration	2.18%	28.16 – 37.62 mm	5
		37.62 – 48.24 mm	4
		48.24 – 56.54 mm	3
		56.54 – 62.84 mm	2
		62.84 – 70.48 mm	1
Geology	11.08%	Ecca	5
		Pongolo	3
		Kaapvaal Craton	4
		Lebombo	2
		Zululand	2
		Beaufort	3
		Kalahari	2
		Dwyka	2
		Natal	4
		Stormberg	2
		Natal Metamorphic Province	3

3.3.7. Validation of the groundwater potential zones

The resulted map of GWP zones was validated using remote sensing data and known groundwater research outputs of SA. The remote sensing and existing groundwater data were overlaid on the GWP map to determine the accuracy of the map. The ROC and AUC were also used to validate the accuracy of the GWP map using borehole location and yield data by correlating them with the GWP index values from the map. The ROC and AUC plot evaluates the accuracy of models. The AUC ranges from 0.5 to 1.0; if the model results in a 0.5 AUC, then the model does not predict the occurrence of GWP zones.

3.4. Summary

The methodology to analyse groundwater quality and quantity was based on a multivariate analysis and modelling techniques. The WQI method was chosen to analyse groundwater quality due to it being able to transform large quantities of groundwater quality data into a single value which represents the water quality level. Determining groundwater quality using the WQI method is a fundamental process in water resource management as it consolidates large amounts of quality data at a relatively low cost compared to other in-situ methods.

In SA, identifying and quantifying groundwater is entirely based on in-situ methods which are very expensive, time consuming and do not have a high strike rate. The use of remote sensing, GIS and AHP proved to work coherently, eliminating the need for in-situ methods. However these methods rely on the availability of data, and therefore will not be successful in data-scarce areas. These desktop-based methods however do need to be validated using available in-situ results.

These methods were used in this study to gain further information on implementing desktop-based analysis in groundwater exploration in SA, which is dominated by out-dated technological in-situ methods.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Introduction

This chapter describes the results of the water quality assessment conducted across SA and presents the identified groundwater potential zones in KZN. The groundwater quality of SA was compared to the drinking water standards of the WHO and SANS by using the WQI method. The results were incorporated into a piper plot diagram in order to classify and understand the sources of the dissolved constituents in the groundwater.

Groundwater pertaining to KZN was quantified by modelling remotely sensed data through GIS, aided by AHP. The results were validated using borehole data in order to identify the success rate of the model.

4.2. Groundwater quality - a comparison with the World Health Organization and South African National Standards for drinking water quality

An assessment of SA's groundwater was conducted using published groundwater quality results from various areas of the country, presented in Figure 20. A water quality index was created to compare the results to the WHO and SANS drinking water standards.

All analysed groundwater quality data is found in Annexure 1, presented as ranges. The recorded potential of hydrogen (pH) values was all within the SANS limit of 9.7. Most of the TDS levels were within the SANS limit of 1.200 mg/l. However, in some groundwater samples, relatively high average levels of TDS were reported viz. 1.378 mg/l in (Elumalai *et al.* 2019); 1.793 in (Erdogan *et al.* 2019) and 2.450 in (Makubalo and Diamond 2020). Even though there are no major health concerns from TDS or major ions in drinking water, excessive salinity can affect the water's odour and taste, and high levels of magnesium and calcium can lead to scaling (El Baba et al. 2020).

The concentration levels of the reported water cations, Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}) and Potassium (K^{+}) indicate that majority of the levels were below the SANS maximum permissible drinking limit for Ca^{2+} (150 mg/l), Mg^{2+} (70 mg/l), Na^{+} (200 mg/l) and K^{+} (50 mg/l). However, high averaged Ca^{2+} levels of 184 mg/l, and 256 mg/l were found in Namaqualand (Northern Cape) by (Erdogan *et al.* 2019; Makubalo and Diamond 2020). Belle *et al.* (2020) recorded an average Ca^{2+} level of 164.52 mg/l in Welkom and Virginia (Free State). High Mg^{2+} levels were recorded in the Giyani (Limpopo), with an average of 83.06 mg/l, recorded by (Mudzielwana *et al.* 2020). Further, high Na^{+} values of 243, 333, 446 and 911 mg/l were reported in O'kiep-Namaqualand (Northern Cape), Jozini (KZN), Waterberg (Limpopo) and the whole of Namaqualand by (Erdogan et al. 2019; Elumalai *et al.* 2019; Abiye *et al.* 2018; Makubalo and Diamond 2020) respectively.

Similarly, the concentrations of most water anions, Chloride (Cl^-), Sulfate (SO_4^{2-}), Carbonate (CO_3^{2-}) and Bicarbonate (HCO_3^-) were below the SANS maximum permissible drinking limits of 300 and 500 mg/l for Cl^- and SO_4^{2-}, and below the WHO's maximum permissible drinking limits of 180 and 500 mg/l for CO_3^{2-} and HCO_3^-. However, high Cl^- levels averaged at 618, 470, 921.3 and 1300 mg/l were recorded in Jozini, O'Kiep-Namaqualand, Waterberg and Namaqualand. Only one area had SO_4^{2-} levels exceeding the limit, with an average concentration of 608 mg/l in the Namaqualand area (Makubalo and Diamond 2020). Two studies (Erdogan *et al.* 2019) and (Mengistu *et al.* 2019) reported high CO_3^2 concentrations exceeding the limit with average concentrations of 192 and 275.3 mg/l, respectively. However, all reported HCO^{3-} concentrations were below the WHO limit of 500mg/l.

The major contributor to SA's poor groundwater quality is high fluoride (F^-) levels. The SANS maximum permissible drinking limit for F^- is 1.5mg/l, which is exceeded in most of the collected groundwater samples reported in the various studies. For example, the average F^- concentrations are 4.02, 10.7, 6 and 5.26 mg/l in the Siloam Village of Limpopo, rural areas of Mpumalanga, Waterberg, and Namaqualand of the Northern Cape, reported by (Odiyo and Makungo 2018; Mpenyana-Monyatsi and Momba 2012; Abiye *et al.* 2018) respectively. Most reported heavy metal levels were below the SANS and WHO maximum permissible drinking limits, viz. Boron, Copper, Zinc, Nickle, Lithium and Manganese. However, some heavy metals exceeded the SANS maximum permissible drinking limits. For example, Belle *et al.* (2020) investigated groundwater contamination from gold mine tailings in the Welkom and Virginia area. The study concluded that Iron, Lead, Arsenic and Calcium exceeded the permissible limits which are directly associated with gold ores from mining activities and therefore the study's groundwater quality is not found suitable for consumption. The groundwater quality of Arsenic in Namaqualand, Welkom and Virginia, as reported by (Odiyo and Makungo 2018) and (Belle *et al.* 2020) was 0.08 and 0.02 mg/l, respectively, which is higher than the SANS limit of 0.01mg/l. Furthermore, the iron limit of 2 mg/l was exceeded in Namaqualand with an average concentration of 5.65mg/l (Odiyo and Makungo 2018) and in Welkom and Virginia with an average concentration of 3.59 mg/l (Belle *et al.* 2020). Lead exceeded the SANS limit of 0.01 mg/l in Welkom and Virginia, with an average concentration of 0.82 mg/l (Belle *et al.* 2020). Mepaiyeda *et al.* (2020) tested Mercury concentrations in the groundwater of Buffalo City, Eastern Cape and reported an average concentration of 0.061mg/l which exceeded the SANS limit of 0.006 mg/l. All analysed concentrations and their corresponding limits are presented in Figure 21.

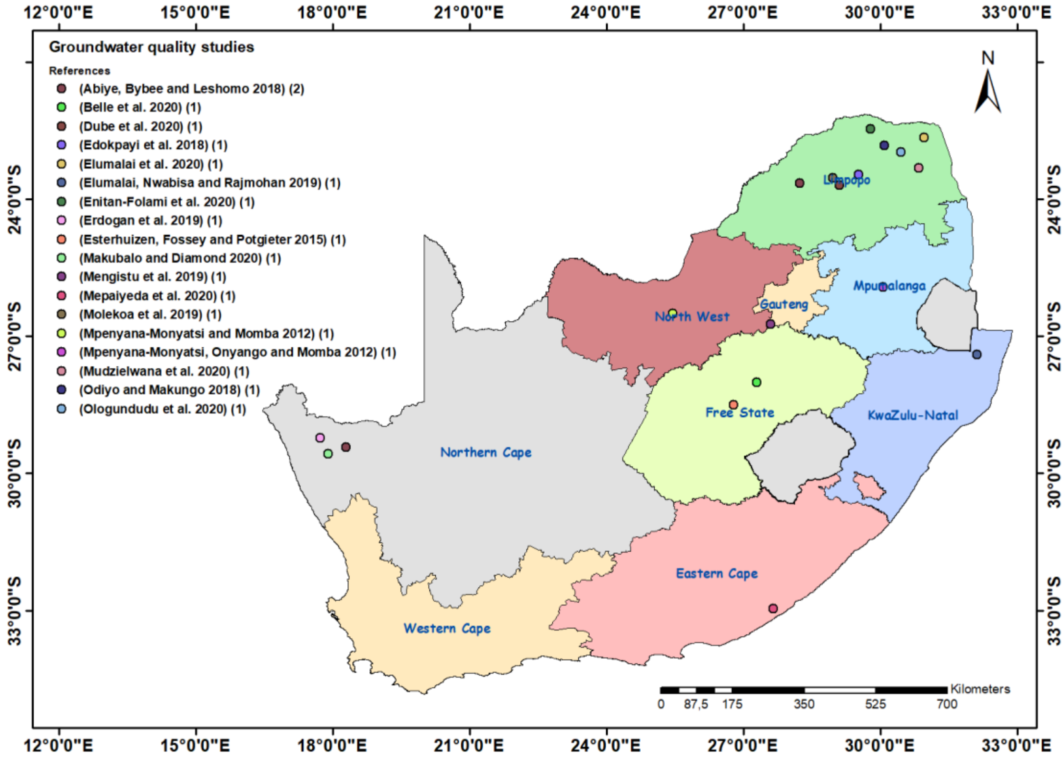


Figure 20: Locations of the studied boreholes in the reviewed groundwater quality articles.

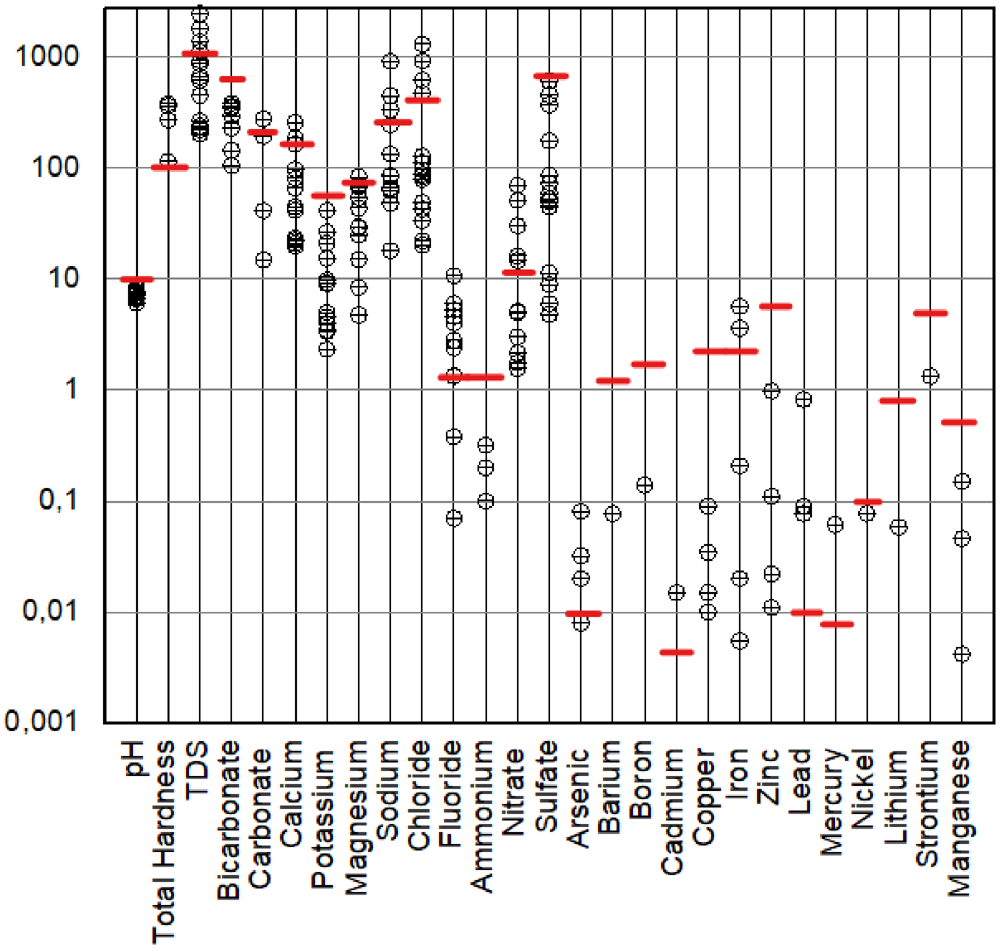


Figure 21: Observed concentrations of inorganic chemicals and macro pollutants in groundwater from the reviewed studies referring to South Africa and their corresponding limits (red dashes) set by SANS and WHO for drinking water. All concentrations are in mg/L, except pH.

4.2.1. Assessment of groundwater quality using Water Quality Index

The mean values for each groundwater quality parameter used in the WQI are presented in Table 13, with the maximum permissible limits for drinking water, average, standard deviation and WQI values. The areas investigated were: O'Kiep in Namaqualand (Northern Cape), south Johannesburg (Gauteng), Namaqualand (Northern Cape), Waterberg (Free State), Northwest Province, Jozini (KZN), Luvuvhu Catchment (Limpopo), Mokopane and Giyani district (Limpopo Province).

The pH values averaged at 7.63, which indicates the slight alkaline nature of groundwater across the studied locations, but all values fall below the SANS maximum limit of 9.7. HCO^{3-} also contributes to groundwater's alkaline nature (Ibrahim 2019), and one study (Mengistu *et al.* 2019) recorded an average of 765 mg/l, which exceeds the maximum limit. High TDS values in water may impair its taste and according to (SANS 2015), the maximum permissible limit is

1200 mg/l which is exceeded in the samples from Namaqualand and Jozini, as reported by (Abiye *et al.* 2018; Elumalai *et al.* 2019; Erdogan *et al.* 2019; Makubalo and Diamond 2020). Though SO_4^{2-} is not a significant concern in drinking water, high levels can induce a laxative effect. Makubalo and Diamond (2020) recorded a high SO_4^{2-} level of 608 mg/l in Namaqualand which exceeds the maximum limit of 500 mg/l.

The main cations and anions that averaged above the SANS maximum drinking water limit are Cl^-, Na^+, and F^-. High chloride levels of 921, 618, 470 and 1300 mg/l, and high sodium levels of 446, 333, 243 and 911 mg/l were reported in Namaqualand and Jozini by (Abiye *et al.* 2018; Elumalai *et al.* 2019; Erdogan *et al.* 2019; Makubalo and Diamond 2020) respectively. Levels of Cl^- above 250 mg/l increases the metal concentrations in drinking water and gives it a salty taste (Ibrahim 2019). Sodium levels higher than 200 mg/l can cause water to taste salty and harmfully affect people with high blood pressure (Ibrahim 2019). The significant contributor to many areas in SA having poor groundwater quality is high fluoride levels. Fluoride concentrations were higher than the maximum limit of 1.5 mg/l for most studies which drastically affected the drinking water quality. Studies by (Mpenyana-Monyatsi and Momba 2012; Abiye *et al.* 2018; Elumalai *et al.* 2019; Molekoa *et al.* 2019; Makubalo and Diamond 2020) all found fluoride concentrations much higher than the maximum limit, ranging from 2,4 -10,7 mg/l. The ionic dominance pattern show is in the order of $Na^+ > Ca^{2+} > Mg^{2+} > k^+$ and $Cl^- > HCO_3^- > CO_3^{2-} > NO_3^- > F^-$.

The computed WQI values ranged from 37.92 – 436.06 and were ranked to a class using Table 4. The results revealed in Table 13 indicate that four areas out of eleven resulted in good groundwater quality, being south of Johannesburg, central Free State, Luvuvhu Catchment and the Giyani district. Areas towards the north of the country viz. Namaqualand, Waterberg and the Northwest province, resulted in having groundwater quality, “unfit for drinking”. This groundwater quality is due to Waterberg having a F^- concentration of 6 mg/l (Abiye *et al.* 2018) L1, Namaqualand having F^- concentrations of 5.26 and 2.4 mg/l, reported by (Abiye *et al.* 2018) L2 and (Makubalo and Diamond 2020) respectively, as well as Namaqualand having a very high nitrate concentration of 51 mg/l compared to the SANS standard of 11 mg/l which is due to mining and the use of pesticides and fertilisers to boost subsistence farming productivity in the area (Makubalo and Diamond 2020).

The results of the WQI indicate that the high levels of fluoride are the main contributor to groundwater quality being “unfit for drinking”. However, when fluoride is excluded from the WQI calculation of groundwater for each sample location, most of the computed WQI values are categorised into the “excellent” class. High levels of fluoride in SA are caused by a high evaporative concentration, long resistance time, groundwater having a high electrical conductivity of 750-1750 mS/m and the weathering of felsic igneous rocks (Makubalo and Diamond 2020).

Table 13: Physio-chemical analysis of groundwater samples taken from various groundwater literature of South Africa; also given are the WQI score, the water quality classification, and the mean and standard deviation (SD).

Study	**pH**	**EC**	**TDS**	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Na^+**	**Cl^-**	**F^-**	**NO_3^-**	**SO_2^{4-}**	**Co_3^{2-}**	**HCo_3^-**	**WQI**	**Water Quality**
Reference		**(us/cm)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(mg/L)**	**Score**	**Class**
(Erdogan et al. 2019)	8,10	2410	1793	184	15,3	67	243	470	1,3	2,2	455	129	358	79,89	Poor
(Mengistu et al. 2019)	7,80	1287	1121	45	3,4	25	86	112	0,8	5,5	86	275	765	50,11	Good
(Abiye, Bybee and Leshomo 2018) L1	8,36	421	455	22	5,0	5	63	43	6,0	5,5	175	52	144	306,88	Unfit for drinking
(Abiye, Bybee and Leshomo 2018) L2	6,78	3852	2084	23	26,6	69	446	921	5,3	5,5	369	82	228	267,41	Unfit for drinking
(Makubalo and Diamond 2020)	7,70	3500	2450	256	21,0	70	911	1300	2,4	51,0	608	106	294	176,40	Unfit for drinking
(Esterhuizen, Fossey and Potgieter 2015)	7,49	955	620	81	4,6	44	66	87	0,4	14,7	59	101	279	37,92	Good
(Mpenyana-Monyatsi and Momba 2012)	7,68	850	639	42	9,3	30	48	79	10,7	5,0	53	136	379	436,06	Unfit for drinking
(Elumalai, Nwabisa and Rajmohan 2019)	7,60	2152	1378	97	4,0	29	333	618	2,8	5,1	73	82	227	148,28	Very Poor
(Elumalai et al. 2020)	6,70	344	220	21	9,0	15	18	49	0,8	3,0	6	38	105	42,43	Good
(Molekoa *et al.* 2019)	8,30	1022	664	20	3,5	54	134	83	1,4	5,0	45	41	347	81,66	Poor
(Mudzielwana et al. 2020)	7,43	1446	867	66	9,8	83	84	20	0,8	1,6	9	137	381	44,56	Good
Standard	9,7	1700	1200	150	50	70	200	300	1,5	11	500	180	500	-	-
Mean	7,63	1658	1118	78	10,1	45	221	344	3,0	9,5	176	107	319	151,66	-
SD	0,54	1183	723	77	7,8	26	265	433	3,2	14,2	206	66	174	132,59	-

4.2.2. Groundwater chemistry classification

A Piper Plot, shown in Figure 22, was used to graphically analyse the chemistry of the groundwater samples taken from literature across SA to compare their ionic compositions. The Piper Plot shows the major water constituents, cations (left ternary) and anions (right ternary), while the upper diamond projects the matrix transformation of these ions.

Based on the cation analysis, half of the groundwater samples from the reported locations were classified as $Na^+ + K^+$ type, such as the Waterberg and Namaqualand areas reported by (Abiye *et al.* 2018) L1 and L2, Jozini reported by (Elumalai *et al.* 2019) and the whole of Namaqualand reported by (Makubalo and Diamond 2020). The groundwater quality of these locations presented relatively low concentrations of Mg^+ and Ca^+. Studies conducted by (Elumalai *et al.* 2020) in the Limpopo province and (Mpenyana-Monyatsi and Momba 2012) in the Northwest province reported that the collected groundwater samples had no dominant cation type. However, based on the anion analysis, five groundwater sampled locations were classified as $CO_3^{2-} + HCO_3^-$ type. These water samples were reported south of Johannesburg by (Mengistu *et al.* 2019), central Free State by (Esterhuizen *et al.* 2016), Luvuvhu catchment (Limpopo) by (Elumalai *et al.* 2020), Mokopane (Limpopo) by (Dube *et al.* 2020), and in the Giyani district (Limpopo) by (Mudzielwana *et al.* 2020). The groundwater quality of these locations showed low Cl^- and high SO_2^{4-} concentrations. Three locations were classified as Cl^- type, namely areas in Namaqualand reported by (Makubalo and Diamond 2020) and (Abiye *et al.* 2018) L2, and in Jozini reported by (Elumalai *et al.* 2019). The groundwater quality data from these locations showed high TDS values of 2,450 mg/l (Makubalo and Diamond 2020), 2,084 mg/l (Abiye *et al.* 2018) L2, and 1,378 mg/l (Elumalai *et al.* 2019).

Based on the Piper plot, it can be deduced that the water quality data was either clustered as “magnesium-bicarbonate” or “sodium-chloride” type. In general, high TDS concentrations directly relate to the sodium-chloride type.

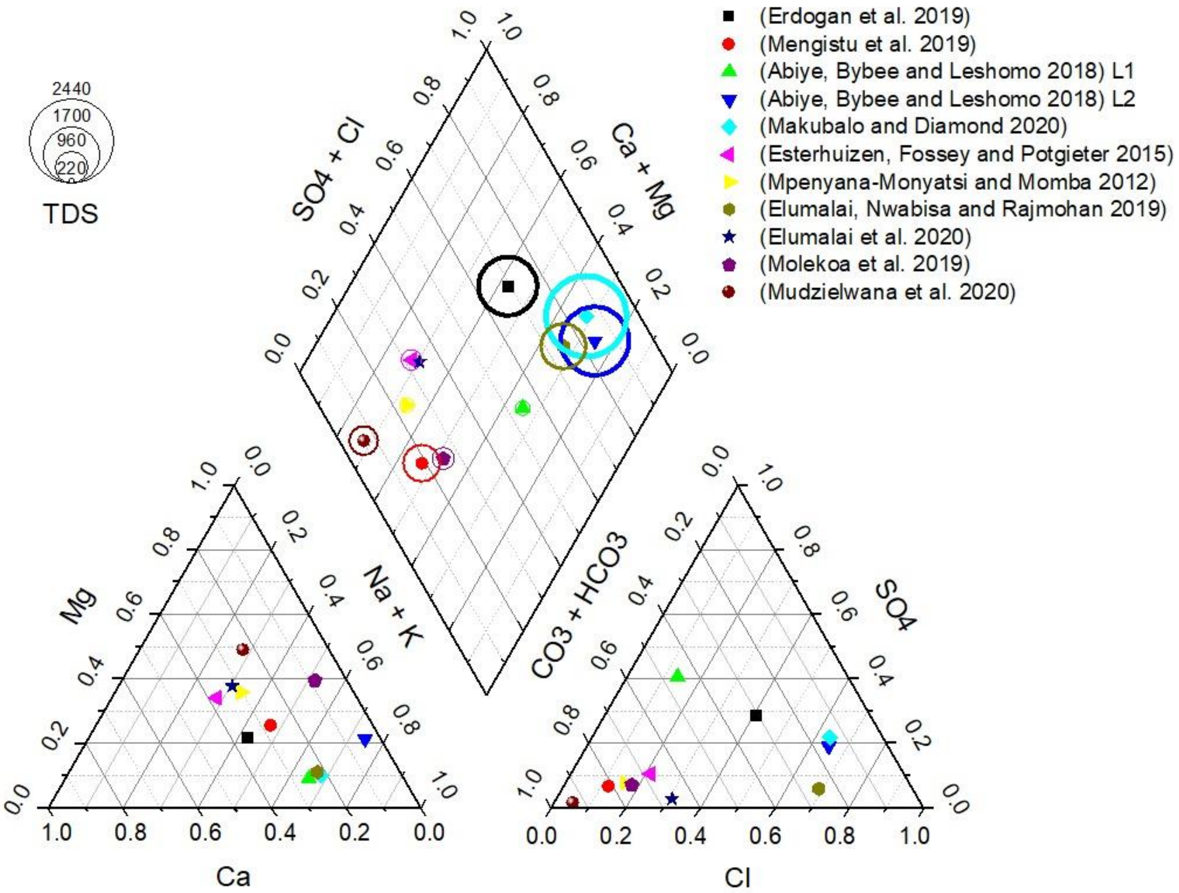


Figure 22. Piper plot showing the major ion composition of the groundwater samples

4.3. Identification of groundwater potential zones in KwaZulu-Natal

The seven parameters used to spatially identify GWP zones in KZN were firstly analysed on GIS against previous research results and remote sensing groundwater storage data. The spatial variations of groundwater recharge parameters used for mapping GWP zones are presented in Figure 24. The resultant groundwater potential map was developed by aggregating groundwater recharge parameters using the Weighted Overlay Analysis method and is presented in Figure 25. The resultant groundwater potential map was validated with borehole data using the ROC and AUC curve, which exhibited a strong positive correlation (AUC = 0,726), as shown in Figure 27.

4.3.1. Geology

Eleven geological groups make up KZN which are shown in Figure 24(a).

- **Geological analysis of KwaZulu-Natal using remotely sensed groundwater storage data**

– **Stormberg Group**

The group covers a small area of KZN, with approximately a 9 km width band surrounding the Drakensberg Escarpment along the Lesotho and KZN border. The groundwater storage depth within the group is low, ranging from 700-900mm.

- **Beaufort Group**

The group is mainly located along the western border of KZN with the majority of the group surrounding the Drakensberg Escarpment. The groundwater storage located within this group is relatively high, having more than 1000mm in most locations. The storage depth decreases towards the Drakensberg Escarpment and the north-eastern coastal regions with groundwater storage ranging from 600-800mm.

- **Ecca Group**

The Ecca Group spans across the western part of KZN from the Ugu District to the Zululand District. The majority of the group has a high groundwater storage depth reaching 1600mm. The storage decrease closer to the coast, with areas having a low of 440mm. However, these areas cover a small portion of KZN.

- **Drakensburg Group**

This group is scattered all over KZN with the majority located in the outer regions. The groundwater storage depth at these areas vary from 550 -1350mm, with the lower values found at the Drakensberg escarpment and the northern coastal areas.

- **Kaapvaal Craton**

The Kaapvaal Craton covers a small region of KZN. It is found in the central parts of the province and towards the north, along the Swaziland and Mpumalanga borders. The depth of groundwater storage in the group ranges from 600-1500mm, with the lower values located along the Swaziland border.

- **Natal group**

The group is found in the eastern part of the province spanning from the Ugu District to the Zululand District. The majority of the formation is located around the eThekwini and Pietermaritzburg regions which have high groundwater storage depths ranging from 1000-1600mm. The groundwater storage decreases further from these areas and reaches a low of 440mm at areas close to the coast.

- **Natal Metamorphic province**

This group is located in the southern coastal regions of KZN spanning from the uGu District to the King Cetshwayo District. The depth of groundwater storage ranges from 300mm at

Richard's bay to 1500mm at Pietermaritzburg. The coastal areas within the Ugu District have a groundwater storage depth of 700mm which is the second-highest coastal region groundwater storage after Durban.

- **Pongola Supergroup**

The group covers a small area in KZN with the majority located in the Zululand District, at the border of Mpumalanga. The groundwater storage depth at these regions varies from 800-1400mm.

- **Zululand Group**

This group is located in the northern regions of KZN in the uMkhanyakude District. The groundwater storage depth ranges from 450-650mm.

- **Spatial variation of geology**

In terms of geological conditions, the Ecca group occupy 31% (28 340 Km^2) of KZN, followed by the Beaufort group (16 974Km^2) and Dwyka group (88 759 Km^2), which cover the majority of the province.

4.3.2. Lineament

- **Lineament analysis of KwaZulu-Natal**

The area alongside the Tugela fault has high groundwater storage ranging from 1100-1500mm. There are also fault thrusts observed between Durban and Richard's Bay. The coastal region from Durban to Jozini has the lowest daily average of groundwater storage, 400 – 500mm, compared to the rest of the province. As the density of geological faults increases inland, the groundwater storage gradually increases. Fault line density is high on the east coast of KZN, ranging from 0-0.43 sq. Km. The groundwater storage depth at highly dense fault areas, 0.28-0.43 sq. km, ranges from 700mm-1400mm, except the coastal area within the King Cetshwayo District which has a groundwater storage depth of 430-750mm. Areas that have a contact density value of 0.8 sq. Km and above, which are highly dense areas, have groundwater depths ranging from 900-1300mm. There is a rapid increase in groundwater storage, reaching a high of 1596.44mm, between Pietermaritzburg and Kranskop as this is the densest area of geological contact in the province.

- **Spatial variation of lineament density**

Figure 24(b) represents the classified lineament density map of KZN. The density range of 0.53-0.65 is dominant, which accounts for 32% of KZN. Lineament density ranges; 0-0.21, 0.21-0.39, 0.39-0.53 and 0.65-1.02 account for 11%, 16%, 28% and 14% of KZN respectively.

4.3.3 Slope

- **Slope analysis of KwaZulu-Natal**

The slope layer indicates that KZN is a very mountainous region with slopes reaching an angle of 72º in steepness. Areas at the coastline are relativity flat, but further inland the land gets very hilly with central KZN being the most mountainous area. It can be seen that flat low lying land have a high groundwater storage depth.

Slope inclination and elevation play a significant factor in groundwater storage. Data analysis shows that steep slopes increase surface water runoff which reduces the infiltration rate. Areas that have steep slopes have low groundwater storage due to there being less time for precipitation to infiltrate (Kakish and Katimbo 2017). The highest groundwater storage areas are situated at relatively flat plains between ranges of hills and mountains and gentle slopes.

- **Spatial variation of slopes**

Figure 24(c) shows the classified slope map of KZN. A slope range of 0-4º is dominant, which accounts for 41% of KZN. Slope ranges; 4-9º, 9-14º, 14-22º, and 22-72º account for 29%, 18%, 9% and 3% of KZN, respectively. Moderately flat slopes up to 14º account for 89% of KZN. Fenta *et al.* (2015) stated that slopes with a range of 0-15º have greater groundwater storage as it is characterised by high infiltration and low runoff generation.

4.3.3. Drainage density

- **Drainage density analysis of KwaZulu-Natal**

Drainage density shows how well an area is drained by stream channels. KZN has a mountainous terrain that causes high drainage density areas which have high groundwater potentials. It can be seen that areas in KZN with high drainage density have a high groundwater storage depth, except the northern coastal areas. Water drains from high to low elevation regions which creates a drainage area. These high-density drainage areas have high groundwater storage due to the infiltration rate increasing as surface water increases. Baseflow also follows elevation and slope, which increase groundwater storage at these low-lying drainage areas.

- **Spatial variation of drainage density**

Figure 24(d) presents the classified drainage density map of KZN. The density range of 0.19-0.24 Km/Km^2 is dominant, accounting for 33% of KZN. Drainage density ranges; 0-0.08, 0.08-0.15, 0.15-0.19 and 0.24-0.37 Km/Km^2 account for 6%, 16%, 29% and 17% of KZN respectively.

4.3.4. Rainfall

- **Analyses of rainfall in KwaZulu-Natal**

Rainfall anomaly data was created by comparing 2019 monthly average data with the monthly average data for 2007-2017, as shown in Figure 15. The anomaly data represents how the rainfall pattern has changed from 2007-2019 by indicating areas that have gained or decreased in monthly rainfall rates compared to the average rainfall rate. The analysed anomaly data indicated that between 2007 and 2017 most of KZN's rainfall fell in the summer months. The western side of the province, at the Drakensburg escarpment, received most of the provinces' rainfall reaching a high of 180mm/month. The rest of the province received an average rainfall rate of 100mm/month. In the autumn months of April and May the rainfall rate decreased, with the entire province receiving an average rainfall of 30-60mm/month. In winter the rainfall pattern changes, with the coastal regions experiencing most of the rainfall. The rainfall rates continued to decrease following autumn, with the coastal areas receiving 22-55mm/month and the northern and inland areas receiving 8-26mm/month. The rainfall rate started to increase in spring, with the coastal areas receiving a high of 130mm/month and inland areas a high of 100mm/month.

The anomaly data shown in Figure 15(c) indicate that in 2019, the months of February, March, and April, rainfall has increased for the whole of KZN. For January, May, June, July, August, September and October, the rainfall has decreased for the whole of KZN. In November and December, the rainfall has increased for the coastal areas and decreased for areas on the western side. It can be seen that the seasons of KZN are changing over time with the dry months getting dryer and the wet months getting wetter.

Rainfall data averaged over the year 2019 indicates that KZN receives an average monthly high of 82 mm/month and a low of 51 mm/month. The coastal regions and areas at the Mpumalanga and Eastern Cape borders receive high rainfall ranging from 70-82mm/month. KwaZulu-Natal has a high rainfall rate compared to the rest of the country, with only the region at the KZN and Eastern Cape border receiving a higher rainfall rate.

- **Spatial variation of rainfall**

Figure 24(e) shows the classified rainfall map, and Figure 23 shows the groundwater storage of KZN. Even though rainfall is the most crucial factor in groundwater occurrence, data shows that high rainfall rates and high yielding aquifer zones do not follow the exact pattern as many other factors can affect groundwater occurrence. The northern coastal regions receive some of the provinces highest rainfall rates, except parts of the uMkhanyakude and Zululand districts, but have low groundwater storage. Further inland, the patterns start to align as there are areas with high rainfall rates and high groundwater storage like the region surrounding the Mpumalanga border.

Based on the classified map in Figure 24(e), the majority of KZN, 26 494 Km^2, receives 764 – 829 mm of rainfall, followed by 19 041 Km^2 receiving 688-764 mm of rainfall, 19 084 Km^2 receiving 829 – 912 mm, 17 858 Km^2 receiving 598 – 688 and 9 884 km^2 receiving 912-1058 mm of rainfall.

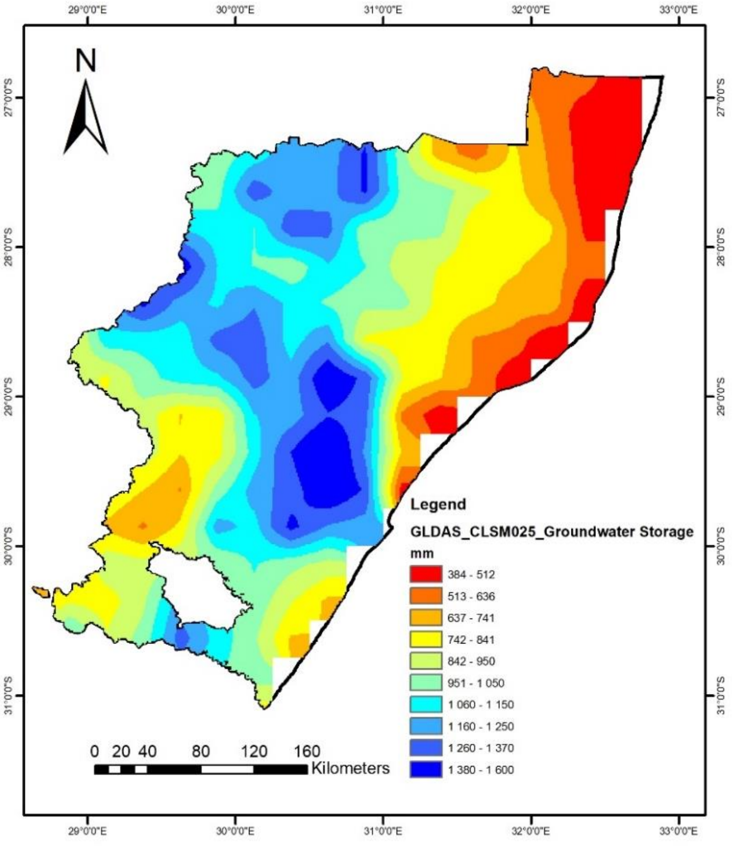


Figure 23: Remotely sensed groundwater storage (GLDAS CLSM025)

4.3.5. Land use/Land cover

- **Land use/Land cover analysis of KwaZulu-Natal**

KwaZulu-Natal is covered by many factors that affect groundwater recharge.
Areas with high groundwater storage, ranging from 1250-1600mm, mainly have the same land cover types. These types include:

- Non-natural timber plantation and temporary clear-felled stands awaiting replanting.
- Commercial sugarcane cultivation which includes both irrigated and dryland crops.
- Low-density rural settlements that do not belong to a denser built-up settlement. These settlements practice subsistence farming and include subsistence-level dryland sugarcane farming.
- Medium to tall, dense trees and shrubs with a 40-100% canopy closure.
- Grassland dominated areas with scattered bush and thicket clumps.
- Degraded grassland that has significant loss of grass canopy cover, compared to surrounding areas of grassland.

– **Vegetation cover**

High yielding groundwater regions are situated under the Savanna and Grassland biomes. The highest yielding aquifers are located at the centre of the province and are covered by mainly the Savanna Biome. The high yielding aquifers towards the north, at the Mpumalanga border, are covered by the Grassland Biome. The majority of the Indian Ocean Coastal Belt does not have high groundwater storage except the Durban and Pietermaritzburg areas. The Forest Biome accounts for a small portion of KZN's vegetation situated on areas with high groundwater storage, except for the coastal areas.

– **NDVI**

Anomaly data was created using NDVI data from 2008 to 2019, which show the deficit in vegetation up to December 2019, as shown in Figure 18. The NDVI for December 2019 shows that the eastern half of KZN has a very thick vegetation cover with NDVI values ranging from 0.6-1. The vegetation cover is less in the western and central regions of the province. The anomaly data indicates that the majority of KZN has increased vegetation cover from the year 2008, except for small areas along the coast and towards the Eastern Cape and Lesotho borders. High yielding groundwater regions are located under areas with an NDVI index value ranging from 0.5-0.8. The regions with low NDVI values have low groundwater storage. KwaZulu-Natal has very dense vegetation at the coast, but groundwater storage is minimal except for Durban, which has groundwater storage of 1200mm.

- **Spatial variation of land use/land cover**

The land use/land cover map shown in Figure 24(f) shows dominance of grassland and savannas within KZN, occupying 55758,94 Km^2 and 18525,92 Km^2 respectively, which accounts for 80% of the landcover.

4.3.6. Evapotranspiration

- **Evapotranspiration analysis of KwaZulu-Natal**

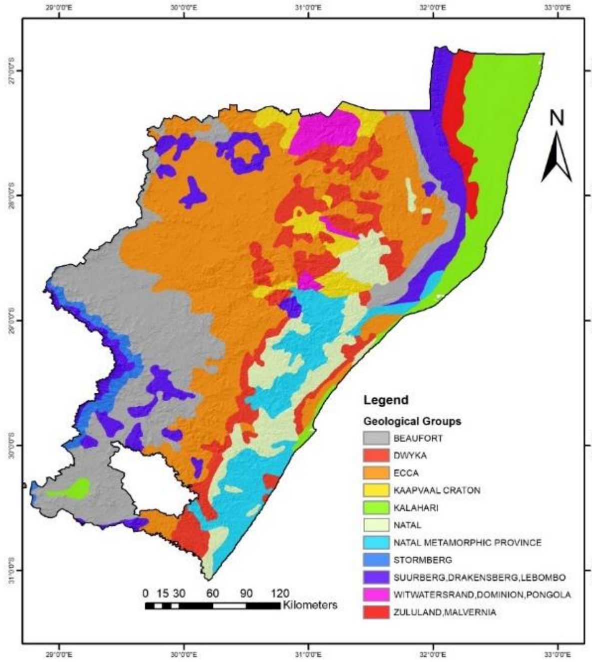
The evaporation rates from bare soil are low, ranging from 4-24 mm/month. Areas with the highest evaporation rates are found towards the centre of the province. KwaZulu-Natal has high potential evaporation, which is substantially more significant than the rainfall rate, categorising KZN as a dry land.

The transpiration rates range from 14-41 mm/month, with the highest values found towards the south of the province at the Eastern Cape border and areas towards the Mpumalanga border. Transpiration contributes the most towards the evapotranspiration rates, as it exceeds evaporation for all regions in the province. The high transpiration rates indicate that KZN has dense vegetation cover and very few areas of bare soil that will significantly affect the evapotranspiration rate.

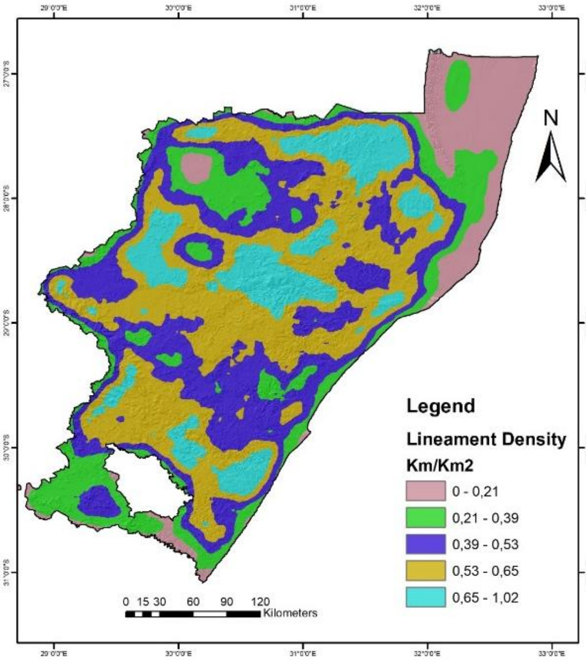
The evapotranspiration rates for the KZN range from 28-71 mm/month. The majority of the province has high evapotranspiration rates, ranging from 55-77 mm/month, except for Durban and Pietermaritzburg, which have rates of 28 and 53mm/month, respectively. The evapotranspiration rates do not drastically change within the province, but they decrease closer towards the northern and western boundaries due to a lack of rainfall in these areas. KwaZulu-Natal has deep-lying water tables, with high yielding aquifers located within 22m below ground level. High evapotranspiration regions are located above deep-lying water tables, greater than 22m below ground level. It can then be concluded that evapotranspiration has a negative effect on groundwater storage, but not significantly, as KZN has high evapotranspiration rates and high groundwater storage compared to other regions in SA.

- **Spatial variation of evapotranspiration**

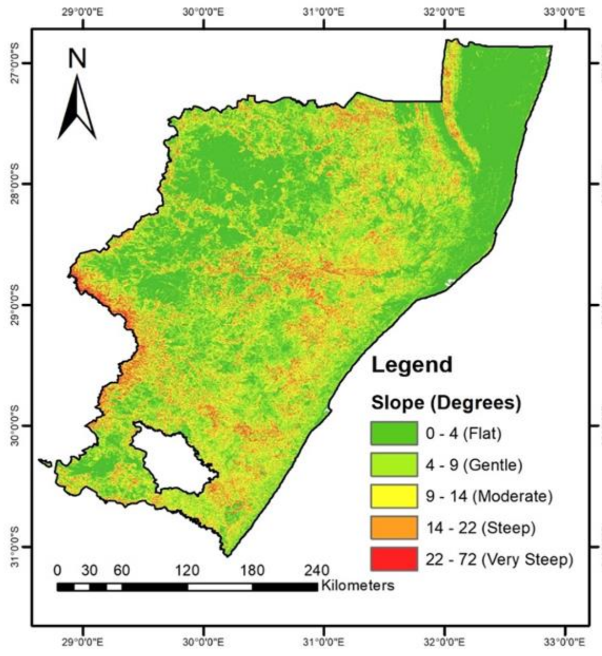
In terms of evapotranspiration across the province, as shown in Figure 24(g), 56 29,93 Km^2 (62%) has an evapotranspiration range of 63-70mm, followed by 28 182,33 Km^2 (31%) with a range of 57-63mm. The low ranges are found in the Durban and Pietermaritzburg areas due these areas being the most built-up areas in the province.



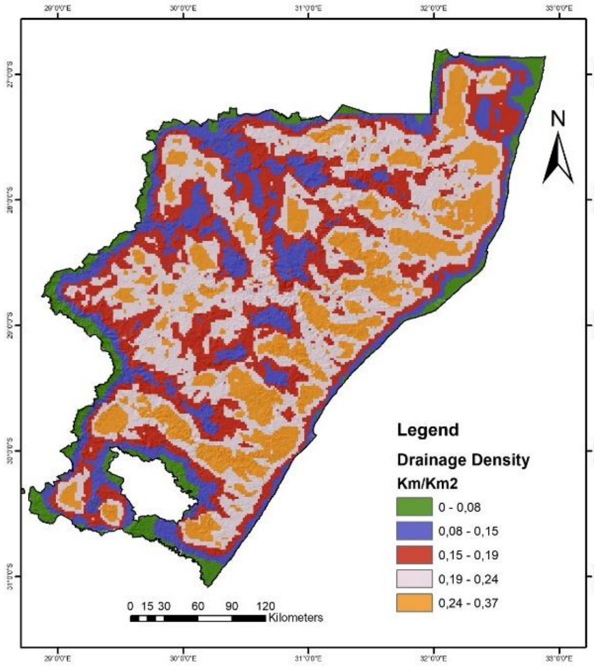
(a) Spatial variation of geological groups



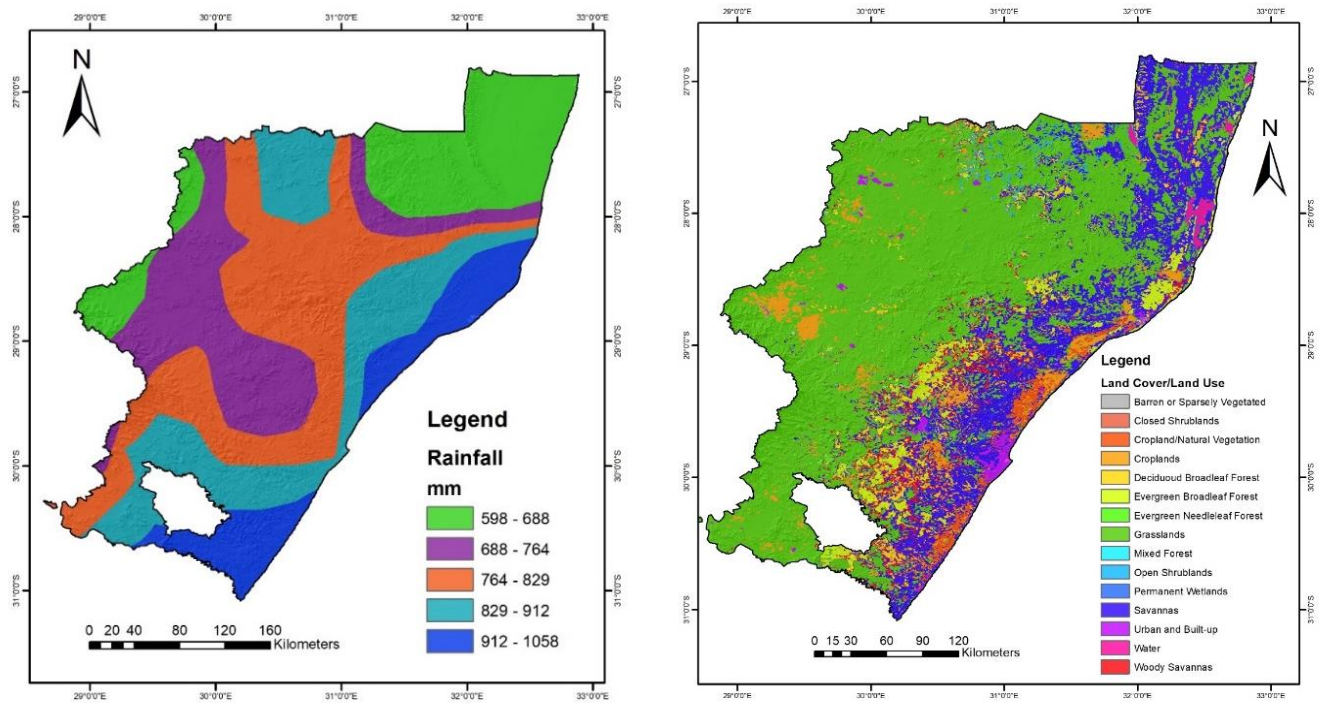
(b) Spatial variation of lineament density



(c) Spatial variation of slopes

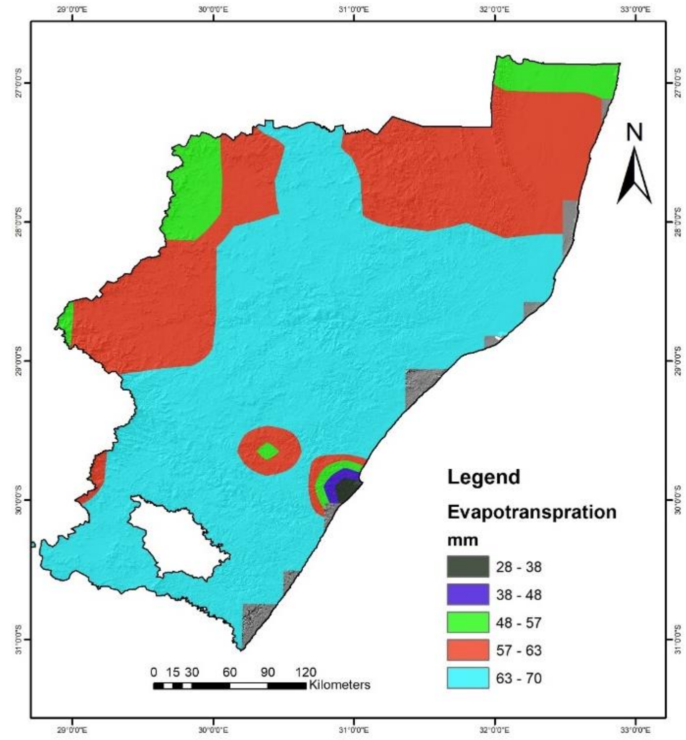


(d) Spatial variation of drainage density



(e) Spatial variation of rainfall

(f) Spatial variation in land use/land cover



(g) Spatial variation of evapotranspiration

Figure 24: Spatial variation of groundwater parameters in KwaZulu-Natal

4.3.7. Soil moisture

Soil moisture content was examined in 4 layers, 0-10cm, 10-40cm, 40-100cm and 100-200cm. Soil moisture data is an instantaneous average derived from 3 hourly data over 2019. It can be seen that soil moisture content ranges from 15 kg/m2 to 362 kg/m2 in a 2m depth. The soil moisture content rises as the depth increases. Durban has the highest soil moisture content in the province, with Richards Bay having the least. The majority of the province has a relatively high soil moisture content, and it can be seen that high yielding groundwater regions are located under and relatively close to high soil moisture regions, with the exception to the Drakensburg Escarpment and the Ulundi area, as these places have a high soil moisture content but low groundwater yield.

4.3.8. Groundwater storage analysis

KwaZulu-Natal is divided into four water management areas. These are the Usutu to Mhlatuze, Thukela, Mvoti to uMzimkhulu and the Mzimvubu to Keiskamma Water Management Areas. The Usutu to uMhlatuze Water Management area is located to the north of KZN. It covers the areas of Zululand, uMkhanyakude and King Cetshwayo municipalities and a portion of the Mpumalanga province. The main rivers in the area are the Usutu, Pongola, uMhlatuze and Mkuze rivers. The management area has the least groundwater storage compared to the other water management areas, with the coastal regions having storage ranging from 370-600mm. Groundwater storage gradually increases inland, reaching a high of 1400mm at the region approaching the Mpumalanga border.

The Thukela Water Management Area is located in the centre of the province, and it covers the area of the uMzinyathi, uThukela and Amajuba Municipalities. Part of the iLembe Municipality falls in the management area because the Tugela River flows through it. The Tugela River is the main river in the management area. The majority of the management area has high groundwater levels, ranging from 900-1500mm, but decreases towards the coast and the Lesotho border.

The Mvoti to uMzimkhulu Water Management Area is located south of the province and covers iLembe, eThekwini, Ugu, uMgungundlovu and Harry Gwala municipalities. The main rivers are the Mvoti, Umgeni, Umkomazi and the uMzimkhulu rivers. The area has relatively high groundwater levels, with the central region having up to 1600mm, which is the maximum in KZN. The groundwater levels reduce closer to the Lesotho border and towards the coast. The coastal areas in the management area have higher groundwater levels compared to the other coastal regions in the province.

The area between Durban and Pietermaritzburg has the highest groundwater storage in the province. This area is known as the valley of a 1000 hills, which is a valley where the Umgeni and Msunduzi rivers meet. The second and third high storage areas are situated along the Tugela valley. The areas alongside the valley up to the Drakensberg escarpment have high groundwater storage. The storage is greater at areas where the Buffels, Mooi, Sundays, Boesmans, Bloukrans and Klip rivers meet the Tugela river.

4.3.9. Identification of potential high yielding aquifer groundwater zones

The seven layers presented were used within the AHP method to compare each factor in a pairwise way to determine the percentage weights of each factor contributing to groundwater potential. The factors were compared with each other, and a scale value was assigned, depending on its importance to groundwater potential. A matrix of the thematic layer comparison was developed in pairs, and the normalized weight for each layer was calculated by each variable in a row by variables in columns (Table 14). The calculated consistency ratio (CR) of the 7x7 matrix when assigning scale values resulted in a 6% CR, which is lower than the maximum of 10% and hence show the level of consistency of the matrix.

Table 14: 7x7 pairwise comparison matrix of all thematic layers used and their weight

Matrix	**Rainfall**	**land use/ Land cover**	**Lineament Density**	**Drainage Density**	**Slope**	**Evapotranspiration**	**Geology**	**Normalized Weights**
Rainfall	1	5	2	4	4	7	3	33.70%
Land use/ Land cover	1/5	1	1/5	1/3	1/3	4	1/5	4.88%
Lineament Density	1/2	5	1	3	3	7	2	23.43%
Drainage Density	1/4	3	1/3	1	1	6	1/2	9.95%
Slope	1/4	3	1/3	1	1	6	1/2	9.95%
Evapotranspiration	1/7	1/4	1/7	1/6	1/6	1	1/5	2.48%
Geology	1/3	5	1/2	2	2	5	1	15.60%

After obtaining the normalised weights of each of the seven layers, they were integrated within ArcMap 10.8.1 using the weighted overlay method combined on a pixel base using Equation 3 for identifying groundwater potential zones. Based on the analysis of weighing the different thematic layers and their parameters, KZN was classified into five distinct groundwater zones, namely excellent, good, moderate, poor and very poor. The results computed that approximately 47.3 Km^2 (2%) of the total area falls under Excellent, 24405.4 Km^2 (27.45%) under good, 50950.5 Km^2 (57.3%) under moderate potential zones, and the poor and very poor zones constitute around 13380.8 Km^2 (15.1%) and 135.6 Km^2 (1%) of KZN (Visually presented in Figure 25 and tabulated in Table 15). Due to KZN having high groundwater storage compared to the other provinces in SA, it can be concluded that regions categorised as Excellent and Good are potential high-yielding groundwater aquifers. KwaZulu-Natal has medium to high-yielding potential groundwater aquifers in the southern, central and coastal regions, while the northern and western boundary regions have poor groundwater potential aquifers. The assessment of the groundwater potential map revealed that the distribution of groundwater is highly influenced by rainfall and lineament density. The hydrogeological setting of KZN reveals that potential high-yielding aquifer zones are present within the Ecca formation, which consists of clastic mudstone, sandstone, siltstone, minor conglomerate and coal outcrops; having flat topography; lower slopes (0-3.94°); high permeability and porosity; and high infiltration capacity. Agricultural fields and forests show a strong influence of holding groundwater capacity, as evapotranspiration in KZN has a low influence on GWP. The water bodies have a high groundwater potential influence as the concentration of drainage of KZN and its rivers help the streamflow to recharge the groundwater aquifers. Poor and very poor GWP zones are located in mountainous areas with steep slopes with high runoff potential. The poor and very poor GWP zones occur at the geological formations of Zululand, Dwyka and Lebombo, due to their lower permeability and porosity.

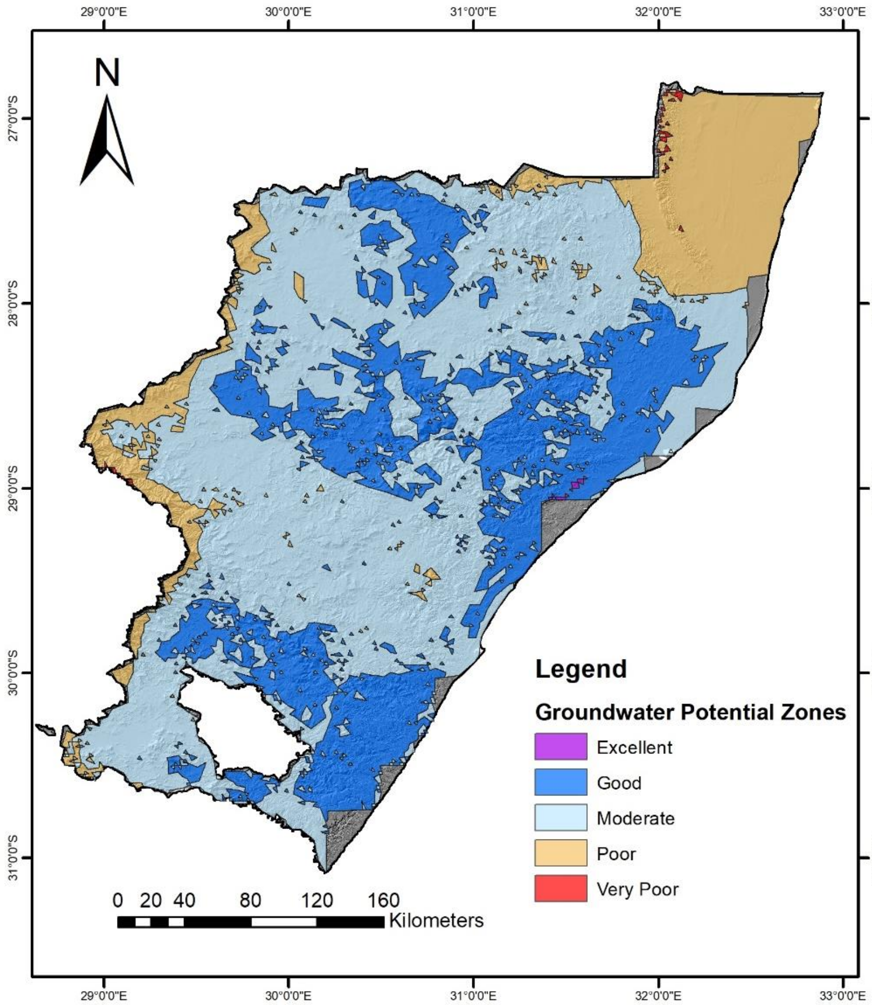
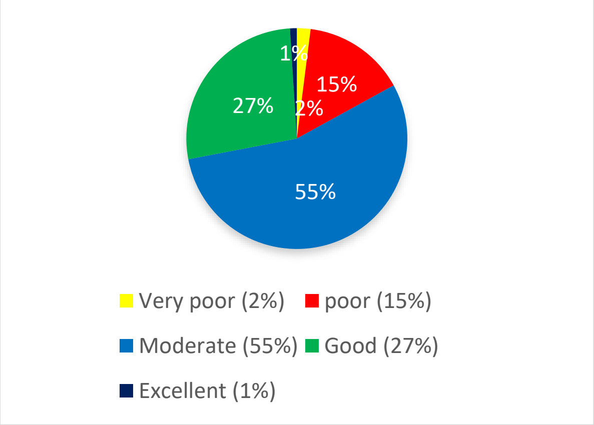


Figure 25: Groundwater potential zone map of KwaZulu-Natal

Table 15: Classification of groundwater potential zones

Percentage Area Coverage	Groundwater Potential	Area (km²)
 	Excellent	42,3
	Good	24406,4
	Moderate	50950,5
	Poor	13360,8
	Very Poor	135,6

4.3.10. Validation of the identified groundwater potential zones

Validation of data is a crucial step, post designing any model to validate its proficiency of the predicted results (Das and Pardeshi 2018). The groundwater potential map was validated by performing correlation analysis using borehole data in KZN. Boreholes are generally used as a proxy for high yielding aquifers, as many boreholes can be found in regions with high groundwater yield (Das et al. 2019). Data of existing boreholes was collated to validate the groundwater potential zone map based on remote sensing, GIS, and AHP analysis. The borehole data used is from the National Groundwater Database of South Africa. The borehole locations and their yields are displayed in Figure 26**.** The yields of the boreholes varied from 0 to 5 l/s and are classified as moderate to good if it ranges from 2 to 5 l/s and poor yield if it is <2 l/s. The borehole coordinates, the actual borehole yields obtained from pumping tests, the expected borehole yields from the GWP zone map and the agreement/disagreement between the expected/actual yield descriptions are presented in the supplementary data.

.

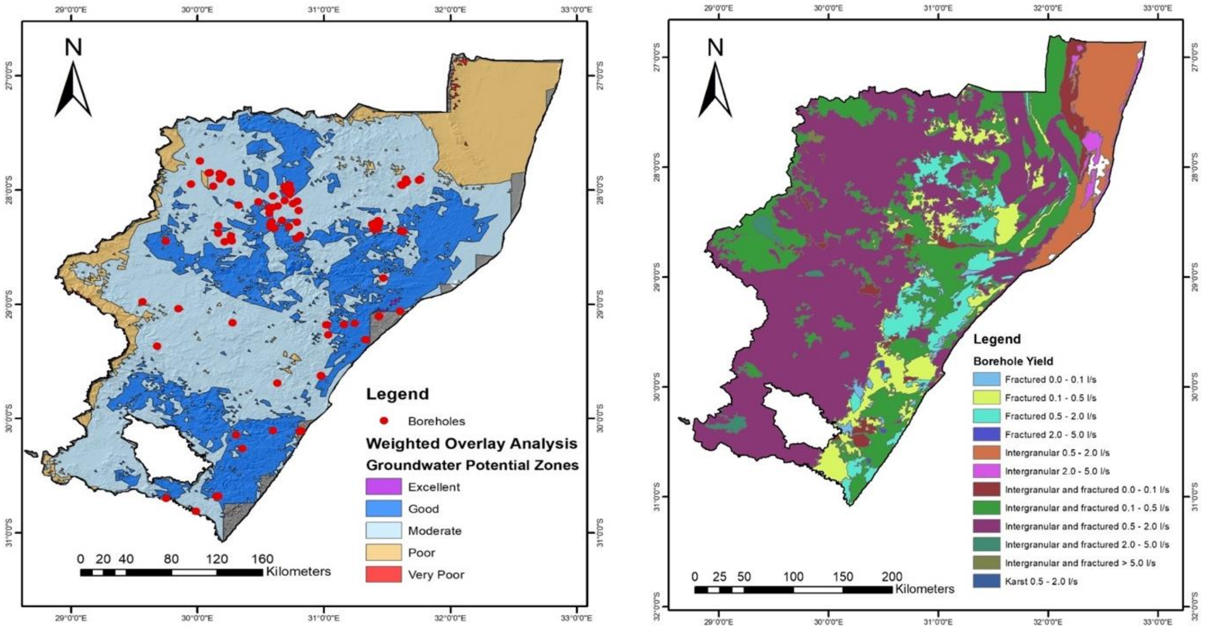


Figure 26: Borehole locations and their respective yield capacity from the different rock fracture zones of KZN

Figure 27 presents the ROC plot for KZN. Out of the 113 boreholes, 2 fall in the excellent category, 29 within good and 82 within the moderate GWP category, with 0 in the poor and very poor category. It was found that the yield of 9 boreholes did coincide with the expected potential yield, as the GWP map indicate good groundwater potential, but the actual yield indicated poor groundwater potential. Hence, the AUC was found to be 72,6%, indicating moderate to high predictability groundwater storage zones by the AHP and weighted overlay method.

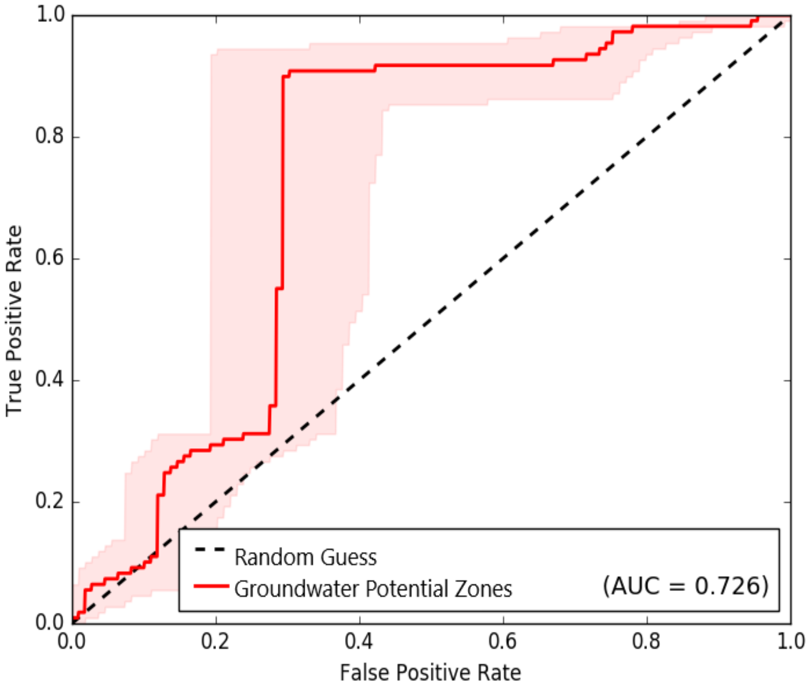


Figure 27: Receiver operating characteristic curve for validation of groundwater potential map

The GWP map was also validated by overlaying it with the storage volume for the weathered zones map, as shown in Figure 28 and the remote sensing groundwater storage map, shown in Figure 29. The comparison with the weathered zones map indicates that the zones of good to excellent groundwater zones of the GWP map follow a similar pattern as the storage volumes of the weathered zones of 66 000 – 140 000 m^3/km^3, which are located at the northern coastal areas, south of KZN and towards the north-western regions. The moderate to very poor zones of the GWP map follow a similar pattern as the storage volumes of the weathered zones of 55 000 – 0 m^3/km^3, which are located in the northern regions of KZN. Comparing the GWP map and the remotely sensed groundwater storage map indicated that both maps follow a similar pattern of groundwater storage volumes. The majority of the good to excellent GWP zones fall with the remotely sensed groundwater storage zones of 1160 – 1600 mm, except for the northern coastal region with good GWP zones within the 513 to 841 mm. The overall validation results are in good agreement with the GWP map, which indicates that utilising remote sensing, AHP, and GIS can be used in groundwater studies and physical methods for precise results.

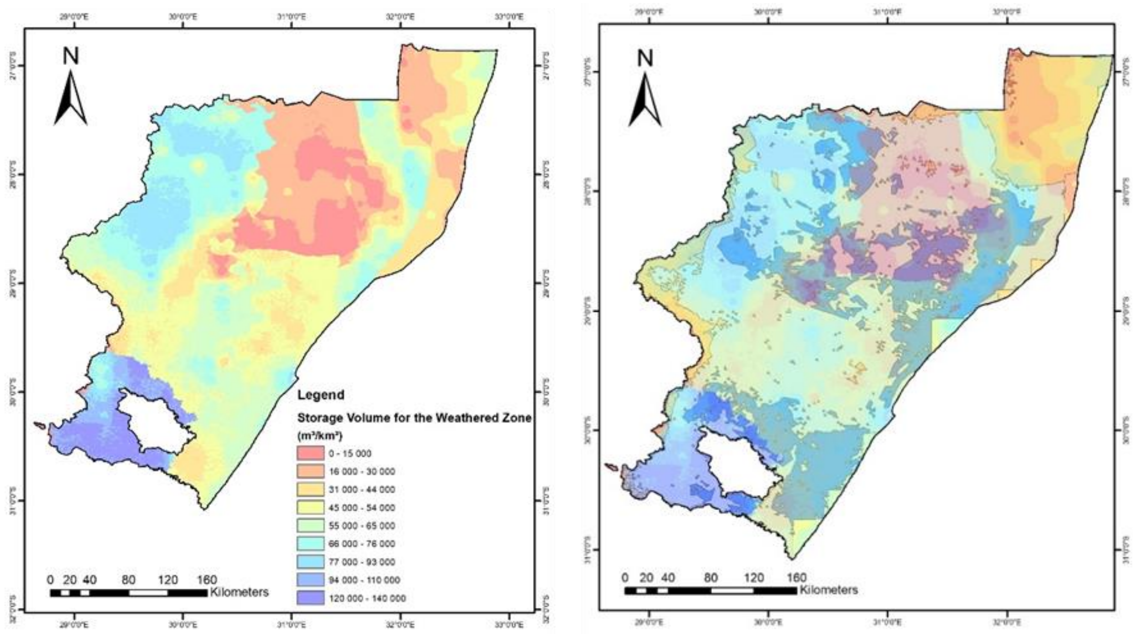


Figure 28: Storage volume for weathered zones overlayed with the GWP map

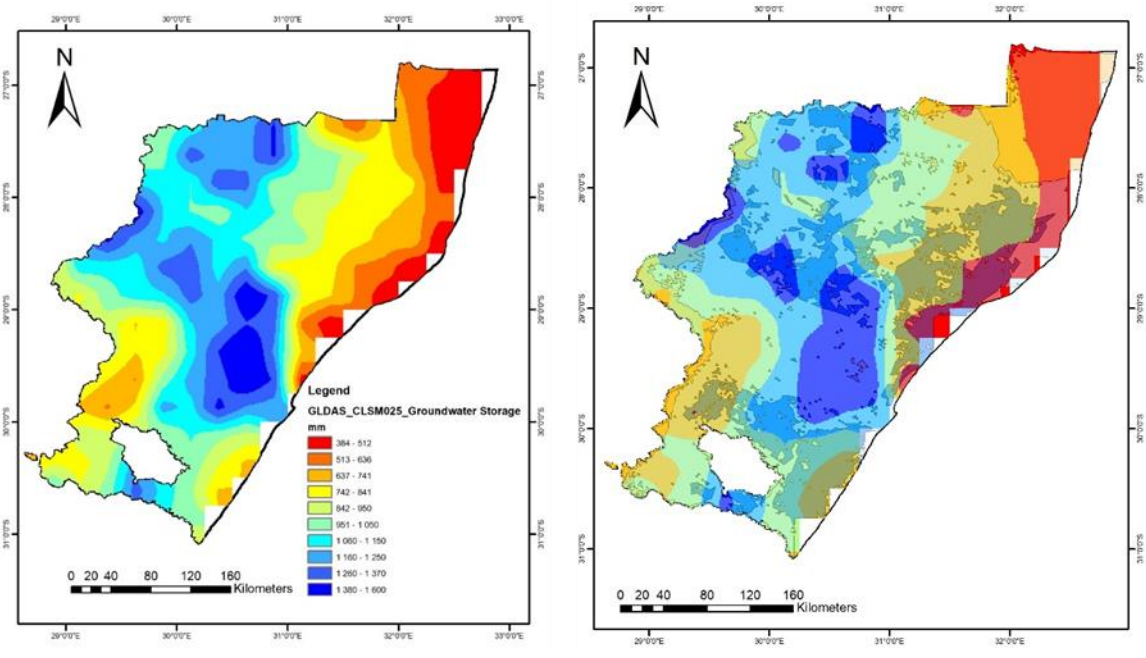


Figure 29: Remotely sensed groundwater storage overlayed with the GWP map

4.3.11 Model comparison to other published methodologies

In recent years GIS in research has proliferated due to the integration of remotely sensed data from the successful launching of various state of the art satellites (Pandit, 2020). This integration of remote sensing and GIS have opened the door for a vast range of opportunities in large-scale mapping, project planning and spatial modelling (Pandit, 2020). Even in data-scarce developing countries like South Africa, remote sensing and GIS modelling have emerged as being a reliable cost-effective method in research. The modeling techniques used in this study to identify groundwater in KZN proved to have a 72.6% correlation to borehole location data. This proved that modeling techniques can be used in data scarce regions as a method to accurately conduct groundwater exploration at a relatively low cost. Data scarcity in groundwater studies has been an ongoing setback, especially in SA, as this was proved in a study by Ebrahim and Villholth, (2016) who aimed to propose an alternative method for determining groundwater availability using baseflow separation and recession flow analysis through the Desktop Reserve Model. The method proved to be a valuable tool to assess ecological needs for groundwater and determine available groundwater for human needs. However, limited available hydrogeological information, the interpretation of the results in terms of physical and hydrogeological properties concluded that streamflow recession controls and baseflow separation could be complicated. There are other models that can accurately map groundwater potential like Chen *et al.,* (2020) who evaluated the predictive ability of a series of tree-based models (RF-J48, AB-J48, Bag-J48, RS-J48, Dag-J58) in groundwater potential exploration. It was concluded that these methodologies are highly accurate in groundwater potential mapping as these models have high prediction capabilities (AUC of 0.748 – 0.797). However, Malakar *et al.,* (2021) states that artificial intelligence methods are better suited in the field of groundwater. The use of artificial intelligence in SA can help understand the triggers changing the groundwater dynamics and the influencing factors of groundwater contamination by producing more accurate predictions, especially in recent times, as data availability increases (Malakar *et al.,* 2021).

4.4. Summary

The use of the WQI to analyse and compare groundwater quality amongst different regions in SA proved to be successful as the method allowed for easy computation of minimal data to compare groundwater constituents to the SANS and WHO maximum allowable drinking limits. Based on the comparative study, the index method indicated that high levels of fluoride are the main contributor to groundwater quality being “unfit for drinking”. The use of a Piper Plot diagram indicated that the groundwater quality across SA were either clustered as “magnesium-bicarbonate” or “sodium-chloride” type.

The modeling techniques used to identify groundwater in KZN proved to have a 72.6% correlation to borehole location data. This proved that modeling techniques can be used in data scarce regions, however the use of modeling techniques together with in-situ methods can results in accurate groundwater exploration at a relatively low cost.

CHAPTER 5: CONCLUSION AND RECOMENDATIONS

5.1. Conclusion

The suitability of groundwater for drinking purposes in various locations in South Africa (SA) based on published data was investigated. A Water Quality Index (WQI) concerning the South African National Standards (SANS) and World Health Organization (WHO) maximum allowable drinking limits was used for a quality assessment. Thirteen macro-pollutants and inorganic chemical parameters, was used to calculate WQI. The conclusion of this method can be summarised as follows:

- Most parameters was almost below or not too high off the maximum allowable limits based on SANS and WHO, except fluoride, which was very high in most data sets.
- The computed WQI values ranged from 37.92 – 436.06. Therefore, out of the eleven data sets, four classified as “good”, two as “poor”, one as “very poor” and four as “unfit for drinking”.
- Fluoride was considered the most influential parameter in the WQI of this study, which was confirmed by comparing the WQI values without including the fluoride parameter, which resulted in most datasets falling into the “excellent” class.

Based on the cation analysis using a piper plot, four locations was classified as having Na^+ + K^+ groundwater type, and two had no dominant cation type. Based on the anion analysis, five locations were classed as CO_3^{2-} + HCO_3^- groundwater type. The Piper plot diamond matrix presented the data to either be clustered as “magnesium-bicarbonate” or “sodium-chloride” type.

Groundwater is an essential resource in semi-arid drought-prone areas like KZN. However, groundwater in KZN is not utilised as a primary source of clean drinking water due to insufficient scientific research and data pertaining to the resource. Hence the present study also dealt with the identification of GWP zones in KZN using GIS, remote sensing and the AHP technique. The thematic layers of geology, lineament density, slope, drainage density, rainfall, land use/land cover and evapotranspiration was prepared and assigned weights, along with their respective subclasses using the AHP technique. The following conclusions were drawn from the results obtained:

- The study concluded that the majority of KZN is covered by moderate groundwater potential zones (57.3%).

- Due to KZN having high groundwater storage compared to the other provinces in SA, it was concluded that regions categorised as Excellent and Good are potential high-yielding groundwater aquifers (29.45%) which are located in the southern, central and coastal regions.
- The study confirms that all groundwater influencing parameters used are significant but the most effective parameters in KZN are rainfall (33.7%), lineament density (23.4%) and geology with a (15.6%) influence.
- The combination of GIS, remote sensing and the AHP techniques as a tool to identify potential high-yielding groundwater aquifer zones is a very useful and cost-effective tool. The use of modelling techniques with remote sensing data has made it possible to conduct groundwater exploration without in-situ results, however validation of the results with in-situ data is important as it provides a degree of accuracy.
- The use of GIS and remote sensing data aided by the AHP techniques proved to be a reasonably accurate tool as it had a 72.6% correlation with 113 borehole logs.

5.2. Recommendations

Based on the findings, the following recommendations were proposed:

- Latest borehole log data should be freely available to allow for precise quantification and quality analysis of groundwater resources within KZN rather than having arbitrary values in water demand management.
- Rigorous groundwater monitoring should be done across South Africa to prevent further degradation of groundwater quality and to avoid indiscriminate use of the resource.
- Human development patterns should be monitored to ensure that direct interaction of the water table and sanitation facilities are restricted.
- Further research should be undertaken on the high fluoride concentration in groundwater across South Africa as it is the most influential parameter negatively affecting the drinking quality of the resource.
- The groundwater potential (GWP) map and the thematic layers that were created to identify high-yielding groundwater aquifer zones, serves as a resource information data base that can be updated from time to time or edited based on a particular objective or location.
- The GWP zone information will be helpful in the identification of suitable locations for extraction of water for different purposes.

- It is recommended that government, water resource planners and policy makers need to develop strategies considering the results of the study to address water scarcity in KZN. Efforts should be made to augment the sustainability of aquifer management in the 57.3% moderate GWP zones, in order to meet the water requirements for domestic and agricultural purposes.
- The use of GIS, remote sensing and AHP in the present study were helpful and cost effectives tools for identifying GWP zones. Therefore, these tools as well as the methodology utilised in the study can be used as a timeous, cost-effective, and accurate method in groundwater exploration.
- The GWP map will serve as a useful guideline for planners, engineers and decision makers for preliminary decision making in groundwater exploration and the management of the resource.
- It is recommended that more groundwater research to be undertaken across South Africa by incorporating additional modeling techniques and borehole log data, as SA is a country with many different properties of the lithosphere, hydrosphere, biosphere and atmosphere, making the understanding of groundwater resources very complicated and site-specific. The need for more research in different locations across the country is something that will significantly benefit the water shortage of SA.
- Combining GIS, remote sensing and AHP as a tool for groundwater studies are recommended due to it being successfully utilised in many countries as an inexpensive tool for groundwater research. Many articles have been published internationally, that recommend this method, especially in the identification of groundwater. SA and other developing countries can significantly benefit from using these inexpensive and user-friendly tools.
- In order improve the results of the methodology to identify GWP, more input parameters should be used based on the study area characteristics. Both positive and negative influencing GWP factors should be used for accurate and realist results. The latest borehole data should be used to validate the results, as groundwater volumes constantly change.

LIST OF PUBLICATIONS

- Tyrone Moodley[1], Mohammed Seyam[1*], Taher Abunama[2], Sheena Kumari[2], Faizal Bux[2] / Prevailing technologies in groundwater exploration in South Africa – A situational review / WaterSA / under review

- Tyrone Moodley, Mohammed Seyam[*], Taher Abunama, Faizal Bux / Delineation of groundwater potential zones in KwaZulu-Natal , South Africa using remote sensing, GIS and AHP / Journal of African Earth Science / accepted

REFERENCES

Abdikadir, H. A. 2012. Groundwater policy and law in South Africa and mainland Tanzania: a comparative study.

Abiye, T., Masindi, K., Mengistu, H. and Demlie, M. 2018. Understanding the groundwater-level fluctuations for better management of groundwater resource: A case in the Johannesburg region. *Groundwater for Sustainable Development*, 7: 1-7.

Abiye, T. A. and Bhattacharya, P. 2019. Arsenic concentration in groundwater: Archetypal study from South Africa. *Groundwater for Sustainable Development*, 9: 100246.

Achu, A., Thomas, J. and Reghunath, R. 2020. Multi-criteria decision analysis for delineation of groundwater potential zones in a tropical river basin using remote sensing, GIS and analytical hierarchy process (AHP). *Groundwater for Sustainable Development*: 100365.

Adams, S., Cobbing, J., Dennis, I. and Riemann, K. 2012. Groundwater: our source of security in an uncertain future. *Water SA*, 38 (3): 357-358.

Akinluyi, F. O., Olorunfemi, M. O. and Bayowa, O. G. 2018. Investigation of the influence of lineaments, lineament intersections and geology on groundwater yield in the basement complex terrain of Ondo State, Southwestern Nigeria. *Applied Water Science*, 8 (1): 49.

Albhaisi, M., Brendonck, L. and Batelaan, O. 2013. Predicted impacts of land use change on groundwater recharge of the upper Berg catchment, South Africa. *Water SA*, 39: 211-220.

Arefin, R. 2020. GIS and remote sensing based weighted linear combination (WLC) of thematic layers for groundwater potentiality study at Plio-Pleistocene elevated tract in Bangladesh. *Groundwater for Sustainable Development*: 100340.

Arulbalaji, P., Padmalal, D. and Sreelash, K. 2019. GIS and AHP techniques based delineation of groundwater potential zones: a case study from southern Western Ghats, India. *Scientific Reports*, 9 (1): 1-17

Asano, T. e. 2016. Artificial recharge of groundwater. *Elsevier*,

Bagyaraj, M., Ramkumar, T., Venkatramanan, S. and Gurugnanam, B. 2013. Application of remote sensing and GIS analysis for identifying groundwater potential zone in parts of Kodaikanal Taluk, South India. *Frontiers of Earth Science*, 7 (1): 65-75.

Bailey, G. B. 2014. Land Surface Topography. In: Njoku, E. G. ed. *Encyclopedia of Remote Sensing*. New York, NY: Springer New York, 320-325. Available: https://doi.org/10.1007/978-0-387-36699-9_80 (Accessed

Baron, J., Seward, P. and Seymour, A. 1998. The groundwater harvest potential map of the Republic of South Africa. *Department of Water Affairs and Forestry, Pretoria, South Africa, Gh*, 3917

Belle, G., Fossey, A., Esterhuizen, L. and Moodley, R. 2020. Contamination of groundwater by potential harmful elements from gold mine tailings and the implications to human health: A case study in Welkom and Virginia, Free State Province, South Africa. *Groundwater for Sustainable Development*, 12: 100507.

Botha, J., Verwey, J., Van der Voort, I., Vivier, J., Buys, J., Colliston, W. and Loock, J. 1998. Karoo aquifers: Their geology, geometry and physical properties. *Water Research Commission*, 487 (1): 98.

KwaZulu-Natal (online). 2019. Encyclopædia Britannica: Encyclopædia Britannica, inc. Available: https://www.britannica.com/place/KwaZulu-Natal (Accessed May 12, 2020).

Britannica, T. E. o. E. 2020. Evapotranspiration. *ENCYCLOPÆDIA BRITANNICA*. Available: https://www.britannica.com/science/evapotranspiration (Accessed 2020-05-24).

Broom, R. 1947. XXI.—A Contribution to our Knowledge of the Vertebrates of the Karroo Beds of South Africa. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh*, 61 (2): 577-629.

Brown, R. M., McClelland, N. I., Deininger, R. A. and Tozer, R. G. 1970. A WATER QUALITY INDEX- DO WE DARE.

Carbutt, C. and Edwards, T. J. 2003. THE FLORA OF THE DRAKENSBERG ALPINE CENTRE. *Edinburgh Journal of Botany*, 60 (3): 581-607.

Catuneanu, O., Wopfner, H., Eriksson, P., Cairncross, B., Rubidge, B., Smith, R. and Hancox, P. 2005. The Karoo basins of south-central Africa. *Journal of African Earth Sciences*, 43 (1-3): 211-253.

Chen, W., Zhao, X., Tsangaratos, P., Shahabi, H., Ilia, I., Xue, W., Wang, X. and Ahmad, B. B. 2020. Evaluating the usage of tree-based ensemble methods in groundwater spring potential mapping. *Journal of Hydrology*, 583: 124602.

Choubin, B., Soleimani, F., Pirnia, A., Sajedi-Hosseini, F., Alilou, H., Rahmati, O., Melesse, A. M., Singh, V. P. and Shahabi, H. 2019. Chapter 17 - Effects of drought on vegetative cover changes: Investigating spatiotemporal patterns. In: Melesse, A. M., Abtew, W. and Senay, G. eds. *Extreme Hydrology and Climate Variability*. Elsevier, 213-222. Available: http://www.sciencedirect.com/science/article/pii/B9780128159989000178 (Accessed 2020-05-24).

Clarke, B. 2008. The geology of the Natal Metamorphic Province in the Durban area. *South African Journal of Geology - S AFR J GEOL*, 111: 1-20.

Closas, A. and Rap, E. 2017. Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy*, 104: 33-37.

Conrad, J., Nel, J. and Wentzel, J. 2004. The challenges and implications of assessing groundwater recharge: A case study–northern Sandveld, Western Cape, South Africa. *Water SA*, 30 (5): 75-81.

Dar, T., Rai, N. and Bhat, A. 2020. Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP). *Geology, Ecology, and Landscapes*: 1-16.

Das, B., Pal, S. C., Malik, S. and Chakrabortty, R. 2019. Modeling groundwater potential zones of Puruliya district, West Bengal, India using remote sensing and GIS techniques. *Geology, Ecology, and Landscapes*, 3 (3): 223-237.

Das, S. and Pardeshi, S. D. 2018. Integration of different influencing factors in GIS to delineate groundwater potential areas using IF and FR techniques: a study of Pravara basin, Maharashtra, India. *Applied Water Science*, 8 (7): 1-16.

de Lange, J., Molaolwa, G., Kotzé, Y., van der Merwe, J., Esterhuizen, L. and Mantyeane, A. 2019. *Training Manual for Groundwater Resource Management and Groundwater Governance for Municipalities in South Africa*. Water SA. Available: www.wrc.org.za (Accessed 2020-05-23).

Doble, R., Simmons, C., Jolly, I. and Walker, G. 2006. Spatial relationships between vegetation cover and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. *Journal of Hydrology*, 329 (1-2): 75-97.

Domenico, P. A. and Schwartz, F. W. 1990. Physical and chemical hydrogeology, John Wiely and Sons. *New York*: 824.

Dube, T., Shoko, C., Sibanda, M., Baloyi, M. M., Molekoa, M., Nkuna, D., Rafapa, B. and Rampheri, B. M. 2020. Spatial modelling of groundwater quality across a land use and land cover gradient in Limpopo Province, South Africa. *Physics and chemistry of the earth. Parts A/B/C*, 115: 102820.

DWS. 2016a. National Groundwater Strategy. Department of Water and Sanitation, Pretoria.

DWS. Sanitation, D. o. W. a. 2016b. *National Groundwater Stratergy*. South Africa: Department of Water and Sanitation. Available: www.dws.org.za (Accessed

Ebrahim, G. Y. and Villholth, K. G. 2016. Estimating shallow groundwater availability in small catchments using streamflow recession and instream flow requirements of rivers in South Africa. *Journal of Hydrology*, 541: 754-765.

Ebrahim, G. Y., Villholth, K. G. and Boulos, M. 2019. Integrated hydrogeological modelling of hard-rock semi-arid terrain: supporting sustainable agricultural groundwater use in Hout catchment, Limpopo Province, South Africa. *Hydrogeology Journal*, 27 (3): 965-981.

Edokpayi, J. N., Enitan, A. M., Mutileni, N. and Odiyo, J. O. 2018. Evaluation of water quality and human risk assessment due to heavy metals in groundwater around Muledane area of Vhembe District, Limpopo Province, South Africa. *Chemistry Central Journal*, 12 (1): 1-16.

El Baba, M., Kayastha, P., Huysmans, M. and De Smedt, F. 2020. Evaluation of the Groundwater Quality Using the Water Quality Index and Geostatistical Analysis in the Dier al-Balah Governorate, Gaza Strip, Palestine. *Water*, 12 (1): 262.

Elbeih, S. F. 2015. An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. *Ain Shams Engineering Journal*, 6 (1): 1-15.

Elumalai, V., Nethononda, V. G., Manivannan, V., Rajmohan, N., Li, P. and Elango, L. 2020. Groundwater quality assessment and application of multivariate statistical analysis in Luvuvhu catchment, Limpopo, South Africa. *Journal of African Earth Sciences*, 171: 103967.

Elumalai, V., Nwabisa, D. P. and Rajmohan, N. 2019. Evaluation of high fluoride contaminated fractured rock aquifer in South Africa – Geochemical and chemometric approaches. *Chemosphere (Oxford)*, 235: 1-11.

Enitan-Folami, A., Mutileni, N., Odiyo, J., Swalaha, F. and Edokpayi, J. 2020a. Hydrochemical, bacteriological assessment, and classification of groundwater quality in Thulamela Municipality, South Africa: potential health risk. *Human and Ecological Risk Assessment: An International Journal*, 26 (8): 2044-2058.

Enitan-Folami, A. M., Mutileni, N., Odiyo, J. O., Swalaha, F. M. and Edokpayi, J. N. 2020b. Hydrochemical, bacteriological assessment, and classification of groundwater quality in Thulamela Municipality, South Africa: potential health risk. *Human and ecological risk assessment*, 26 (8): 2044-2058.

Enslin, J. 1970. Die grondwaterpotensiaal van Suid-Afrika. In: Proceedings of *Convention: Water for the future*.

Erdogan, I., Fosso-Kankeu, E., Ntwampe, S., Waanders, F., Hoth, N. and Rand, A. 2019. Groundwater as an alternative source to irregular surface water in the O'Kiep area, Namaqualand, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 114: 102801.

Erlank, A. 1984. Petrogenesis of the volcanic rocks on the Karoo Province. National geodynamics programme sponsored by the South African Council for scientific industrial research.

Esterhuizen, L., Fossey, A. and Potgieter, E. 2016. Groundwater quality on dairy farms in central South Africa. *Water S. A.*, 41 (2): 194.

eThekwini. 2007. Sustainability Best Practice Special Edition Water.

Fagan, B. M. 2007. The Story Of Earth And Life: A Southern African Perspective on a 4.6-Billion-Year Journey. *African Studies Review*, 50 (3): 198-199.

Fairbanks, D. H., Reyers, B. and van Jaarsveld, A. S. 2001. Species and environment representation: selecting reserves for the retention of avian diversity in KwaZulu-Natal, South Africa. *Biological Conservation*, 98 (3): 365-379.

Fallon, A., Villholth, K., Conway, D., Lankford, B. and Ebrahim, G. 2019. Agricultural groundwater management strategies and seasonal climate forecasting: perceptions from Mogwadi (Dendron), Limpopo, South Africa. *Journal of Water and Climate Change*, 10 (1): 142-157.

Fenta, A. A., Kifle, A., Gebreyohannes, T. and Hailu, G. 2015. Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. *Hydrogeology Journal*, 23 (1): 195-206.

Fitch, F. and Miller, J. 1984. Dating Karoo igneous rocks by the conventional K-Ar and 40Ar/39Ar age spectrum methods.

Foda, R. F., Awadallah, A. G. and Gad, M. A. 2017. A fast semi distributed rainfall runoff model for engineering applications in arid and semi-arid regions. *Water Resources Management*, 31 (15): 4941-4955.

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A. and Huang, X., 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote sensing of Environment*, *114*(1), pp.168-182.

Geology Education Museum. No Date. Available: http://www.stec.ukzn.ac.za/GeologyEducationMuseum/KZNGeology/Introduction.aspx (Accessed 09-06-2020).

Ghorbani Nejad, S., Falah, F., Daneshfar, M., Haghizadeh, A. and Rahmati, O. 2017. Delineation of groundwater potential zones using remote sensing and GIS-based data-driven models. *Geocarto International*, 32 (2): 167-187.

Goepel, K. D. 2013. Implementing the Analytic Hierarchy Process as a Standard Method for Multi-Criteria Decision Making In Corporate Enterprises – A New AHP Excel Template with Multiple Inputs (computer software).

Gold, D., Johnson, M. R., Anhaeusser, C. R. and Thomas, B. 2006. The Pongola Supergroup. *The geology of South Africa. Geol Soc South Afr*: 135-148.

Gomo, M. 2011. A groundwater-surface water interaction study of an alluvial channel aquifer. University of the Free State.

Gopinathan, P., Nandini, C. V., Parthiban, S., Sathish, S., Singh, A. K. and Singh, P. K. 2020. A geo-spatial approach to perceive the groundwater regime of hard rock terrain- a case study from Morappur area, Dharmapuri district, South India. *Groundwater for Sustainable Development*, 10

Grinevskii, S. O. 2014. The effect of topography on the formation of groundwater recharge. *Moscow University Geology Bulletin*, 69 (1): 47-52.

Hancox, P. and Rubidge, B. S. 1997. The role of fossils in interpreting the development of the Karoo Basin.

Haridas, V., Aravindan, S. and Girish, G. 1998. Remote sensing and its applications for groundwater favourable area identification. *Quarterly Journal of GARC*, 6 (6): 18-22.

Haupt, C. 2001. Water resources situation assessment. *Directorate of Water Resource Planning. Dept of Water Affairs and Forestry. Groundwater Resources of South Africa. Compiled by WSM Engineers*,

Hirt, C. 2016. Digital terrain models.

Horton, R. K. 1965. An index number system for rating water quality. *Journal of Water Pollution Control Federation*, 37 (3): 300-306.

Huang, T. 2020. How does precipitation recharge groundwater in loess aquifers? Evidence from multiple environmental tracers. *Journal of hydrology (Amsterdam)*, 583: 124532.

Hughes, D. A. and Hannart, P. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology*, 270 (3-4): 167-181.

Jan, C.-D., Chen, T.-H. and Lo, W.-C. 2007. Effect of rainfall intensity and distribution on groundwater level fluctuations. *Journal of Hydrology*, 332 (3): 348-360.

Japitana, M. V., Demetillo, A. T., Burce, M. E. C. and B. Taboada, E. 2019. Catchment characterization to support water monitoring and management decisions using remote sensing. *Sustainable Environment Research*, 29 (1)

Jasmin, I. and Mallikarjuna, P. 2011. Review: Satellite-based remote sensing and geographic information systems and their application in the assessment of groundwater potential, with particular reference to India. *Hydrogeology Journal*, 19 (4): 729-740.

Jenifer, M. A. and Jha, M. K. 2017. Comparison of analytic hierarchy process, catastrophe and entropy techniques for evaluating groundwater prospect of hard-rock aquifer systems. *Journal of Hydrology*, 548: 605-624.

Jewitt, D. 2018. Vegetation type conservation targets, status and level of protection in KwaZulu-Natal in 2016. *Bothalia*, 48

Jewitt, D., Goodman, P. S., Erasmus, B. F., O'Connor, T. G. and Witkowski, E. T. 2015. Systematic land-cover change in KwaZulu-Natal, South Africa: Implications for biodiversity. *South African Journal of Science*, 111 (9-10): 01-09.

Jha, M. K., Chowdhury, A., Chowdary, V. and Peiffer, S. 2007. Groundwater management and development by integrated remote sensing and geographic information systems: prospects and constraints. *Water Resources Management*, 21 (2): 427-467.

Jhariya, D. C., Kumar, T., Gobinath, M., Diwan, P. and Kishore, N. 2016. Assessment of Groundwater Potential Zone Using Remote Sensing,

GIS and Multi Criteria Decision Analysis Techniques. *GEOLOGICAL SOCIETY OF INDIA*, 88: 481-492.

Jovanovic, N., Bugan, R. D., Tredoux, G., Israel, S., Bishop, R. and Marinus, V. 2017. Hydrogeological modelling of the Atlantis aquifer for management support to the Atlantis Water Supply Scheme. *Water SA*, 43 (1): 122-138.

Kakish, K. and Katimbo, A. 2017. Evaluation of Groundwater Recharge Potential Using GIS – Case study at the Salmon River Watershed. Available: http://blogs.ubc.ca/kamalabia/ (Accessed 2020-07-16).

Kashaigili, J. J., Mccartney, M. and Mahoo, H. F. 2006. Estimation of environmental flows in the Great Ruaha River Catchment, Tanzania: use of the desktop reserve model.

Kaur, L., Rishi, M. S., Singh, G. and Nath Thakur, S. 2020a. Groundwater potential assessment of an alluvial aquifer in Yamuna sub-basin (Panipat region) using remote sensing and GIS techniques in conjunction with analytical hierarchy process (AHP) and catastrophe theory (CT). *Ecological Indicators*, 110

Kaur, L., Rishi, M. S., Singh, G. and Thakur, S. N. 2020b. Groundwater potential assessment of an alluvial aquifer in Yamuna sub-basin (Panipat region) using remote sensing and GIS techniques in conjunction with analytical hierarchy process (AHP) and catastrophe theory (CT). *Ecological Indicators*, 110: 105850.

Kelbe, B. and Rawlins, B. 2016. South Africa: Groundwater Management.

Khan, R. and Jhariya, D. C. 2018. Assessment of Land-use and Land-cover Change and its Impact on Groundwater Quality Using Remote Sensing and GIS Techniques in Raipur City, Chhattisgarh, India. *Journal of the Geological Society of India*, 92 (1): 59-66.

Kirkham, M. B. 2014. Chapter 13 - Infiltration. In: Kirkham, M. B. ed. *Principles of Soil and Plant Water Relations (Second Edition)*. Boston: Academic Press, 201-227. Available: http://www.sciencedirect.com/science/article/pii/B9780124200227000136 (Accessed 2020-05-23).

Knüppe, K. 2011. The challenges facing sustainable and adaptive groundwater management in South Africa. *Water S.A.*, 37 (1): 67-79.

Knüppe, K., Pahl-Wostl, C. and Vinke-de Kruijf, J. 2016. Sustainable Groundwater Management: A Comparative Study of Local Policy Changes and Ecosystem Services in South Africa and Germany. *Environmental Policy and Governance*, 26 (1): 59-72.

Lehohla, P. 2012. Census in brief 2011. *Statistics South Africa*,

Lentswe, G. B. and Molwalefhe, L. 2020. Delineation of potential groundwater recharge zones using analytic hierarchy process-guided GIS in the semi-arid Motloutse watershed, eastern Botswana. *Journal of Hydrology: Regional Studies*, 28: 100674.

Lerner, D. and Harris, R. 2009. The relationship between land use and groundwater resources and quality. *Land Use Policy*, 26: S265–S273.

Li, B. and Rodell, M. 2018. *GLDAS Catchment Land Surface Model L4 daily 0.25 x 0.25 degree GRACE-DA1 V2.2* 2.2 ed. Goddard Earth Sciences Data and Information Services Center (GES DISC). Available: https://disc.gsfc.nasa.gov/datacollection/GLDAS_CLSM025_DA1_D_2.2.html (Accessed 2021/01/31).

Li, J., Li, F., Li, H., Guo, C. and Dong, W. 2019. Analysis of rainfall infiltration and its influence on groundwater in rain gardens. *Environmental Science and Pollution Research*, 26 (22): 22641-22655.

Lin, H. and Lin, L. 2019. A typical groundwater storage assessment in the Tugela area, South Africa. *Hydrogeology Journal*, 27 (3): 827-840.

Low, A. and Rebelo, A. 1996. Vegetation of South Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism, Pretoria. *South Africa*,

Mabaso, M., Appleton, C., Hughes, J. and Gouws, E. 2003. The effect of soil type and climate on hookworm (Necator americanus) distribution in KwaZulu-Natal, South Africa. *Tropical Medicine & International Health*, 8 (8): 722-727.

Magaia, L. A., Goto, T.-n., Masoud, A. A. and Koike, K. 2018. Identifying groundwater potential in crystalline basement rocks using remote sensing and electromagnetic sounding techniques in central western Mozambique. *Natural Resources Research*, 27 (3): 275-298.

Makonto, O. T. and Dippenaar, M. A. 2014. Aquifer vulnerability using recharge, depth to groundwater, soil type and slope to classify the vadose zone (Molototsi and Middle Letaba quaternary catchments, Limpopo Province, South Africa). *Environmental Earth Sciences*, 72 (5): 1615-1623.

Makubalo, S. S. and Diamond, R. E. 2020. Hydrochemical evolution of high uranium, fluoride and nitrate groundwaters of Namakwaland, South Africa. *Journal of African Earth Sciences*, 172: 104002.

Makungo, R. and Odiyo, J. O. 2017. Estimating groundwater levels using system identification models in Nzhelele and Luvuvhu areas, Limpopo Province, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 100: 44-50.

Makungo, R. and Odiyo, J. O. 2018. Groundwater quality and its distribution in Siloam Village, Limpopo Province, South Africa. *WIT Transactions on Ecology and the Environment*, 228: 35-44.

Malakar, P., Sarkar, S., Mukherjee, A., Bhanja, S. and Sun, A. Y. 2021. Chapter 40 - Use of machine learning and deep learning methods in groundwater. In: Mukherjee, A., Scanlon, B. R., Aureli, A., Langan, S., Guo, H. and McKenzie, A. A. eds. *Global Groundwater*. Elsevier, 545-557. Available: https://www.sciencedirect.com/science/article/pii/B9780128181720000402 (Accessed

Mazibuko, J. C. 2019. Estimating hydraulic conductivities through the measurement of streaming potentials. University of the Free State.

Mekonnen, M. M. and Hoekstra, A. Y. 2016. Four billion people facing severe water scarcity. *Science advances*, 2 (2): e1500323-e1500323.

Mengistu, H. A., Demlie, M. B., Abiye, T. A., Xu, Y. and Kanyerere, T. 2019. Conceptual hydrogeological and numerical groundwater flow modelling around the Moab Khutsong deep gold mine, South Africa. *Groundwater for Sustainable Development*, 9: 100266.

Mepaiyeda, S., Madi, K., Gwavava, O. and Baiyegunhi, C. 2020. Geological and geophysical assessment of groundwater contamination at the Roundhill landfill site, Berlin, Eastern Cape, South Africa. *Heliyon*, 6 (7): e04249.

Misi, A., Gumindoga, W. and Hoko, Z. 2018. An assessment of groundwater potential and vulnerability in the Upper Manyame Sub-Catchment of Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 105: 72-83.

Mohammadi-Behzad, H., Charchi, A., Kalantari, N., Nejad, A. M. and Vardanjani, H. K. 2019. Delineation of groundwater potential zones using remote sensing (RS), geographical information system (GIS) and analytic hierarchy process (AHP) techniques: a case study in the Leylia–Keynow watershed, southwest of Iran. *Carbonates and Evaporites*, 34 (4): 1307-1319.

Molekoa, M. D., Avtar, R., Kumar, P., Minh, H. V. T. and Kurniawan, T. A. 2019. Hydrogeochemical assessment of groundwater quality of mokopane area, Limpopo, South Africa using statistical approach. *Water*, 11 (9): 1891.

Mondal, S. 2012. Remote Sensing and GIS Based Ground Water Potential Mapping of Kangshabati Irrigation Command Area, West Benga. *Geography & Natural Disasters*,,

Mpenyana-Monyatsi, L. and Momba, M. 2012. Assessment of groundwater quality in the rural areas of the North West Province, South Africa. *Scientific Research and Essays*, 7 (8): 903-914.

Mpenyana-Monyatsi, L., Onyango, M. S. and Momba, M. N. B. 2012. Groundwater quality in a South African rural community: A possible threat to public health. *Pol J Environ Stud*, 21 (5): 1349-1358.

Mpofu, M., Madi, K. and Gwavava, O. 2020. Remote sensing, geological, and geophysical investigation in the area of Ndlambe Municipality, Eastern Cape Province, South Africa: Implications for groundwater potential. *Groundwater for Sustainable Development*, 11: 100431.

Mucina, L., Rutherford, M. C. and Powrie, L. W. 2006. Vegetation Atlas of South Africa, Lesotho and Swaziland. *The Vegetation of South Africa, Lesotho and Swaziland'.(Eds L. Mucina and MC Rutherford.) pp*: 748-789.

Mudzielwana, R., Gitari, M. W., Akinyemi, S. A., Talabi, A. O. and Ndungu, P. 2020. Hydrogeochemical characteristics of arsenic rich groundwater in Greater Giyani Municipality, Limpopo Province, South Africa. *Groundwater for Sustainable Development*, 10: 100336.

Münch, Z. and Conrad, J. 2007. Remote sensing and GIS based determination of groundwater dependent ecosystems in the Western Cape, South Africa. *Hydrogeology Journal*, 15 (1): 19-28.

Murray, R., Cobbing, J., Woodford, A., Ravenscroft, L. and Chevallier, L. 2006. Groundwater research needs in the Eastern Karoo basin of South Africa. *Pretoria: Water Research Commission*,

Musekiwa, C. and Majola, K. 2013. Groundwater vulnerability map for South Africa. *South African Journal of Geomatics*, 2 (2): 152-162.

Nagarajan, N., Sivaprakasam, S. and Karthikeyan, K. 2019. Delineation of Groundwater Recharge Potential Zones of Varaha Watershed, Villupuram District, Tamilnadu, India. *i-Manager's Journal on Civil Engineering*, 9 (4): 38.

Naidoo, N. 2018. The ecological and functional assessment of wetlands: case study of a constructed wetland, Dundee, KwaZulu-Natal.

Nasr, M., Elbeih, S.F., Negm, A.M. and Kostianoy, A., 2020. Overview for Recent Applications of Remote Sensing in Egypt. In Environmental Remote Sensing in Egypt (pp. 13-22). Springer, Cham.

Ncube, E. J. 2006. The distribution of fluoride in South African groundwater and the impact thereof on dental health. University of Pretoria.

Ndlovu, M. S. and Demlie, M. 2018. Statistical analysis of groundwater level variability across KwaZulu-Natal Province, South Africa. *Environmental Earth Sciences*, 77 (21): 1-15.

, M., Demlie, M. and Butler, M. 2019. Hydrogeological setting and hydrogeochemical characteristics of the Durban Metropolitan District, eastern South Africa. *South African Journal of Geology 2019*, 122 (3): 299-316.

Ndou, N. N., Palamuleni, L. G. and Ramoelo, A. 2018. Modelling depth to groundwater level using SEBAL-based dry season potential evapotranspiration in the upper Molopo River Catchment, South Africa. *The Egyptian Journal of Remote Sensing and Space Science*, 21 (3): 237-248.

Nguuri, T., Gore, J., James, D., Webb, S., Wright, C., Zengeni, T., Gwavava, O., Snoke, J. and Group, K. S. 2001. Crustal structure beneath southern Africa and its implications for the formation and evolution of the Kaapvaal and Zimbabwe cratons. *Geophysical Research Letters*, 28 (13): 2501-2504.

Nithya, C. N., Srinivas, Y., Magesh, N. and Kaliraj, S. 2019. Assessment of groundwater potential zones in Chittar basin, Southern India using GIS based AHP technique. *Remote Sensing Applications: Society and Environment*, 15: 100248.

Oke, S. A., Alowo, R. and Masinde, M. 2019. Using Internet of Things for sustainable groundwater drought management in the Modder River catchment of South Africa. In: Proceedings of. 2019. IEEE, 63-70.

Ologundudu, T. O., Durowoju, O. S., Odiyo, J. O. and Ekosse, G.-I. E. 2020. Defluoridation of groundwater from Siloam Village, Limpopo Province, South Africa, using vermiculite modified with hexadecyltrimethylammonium. *Cogent Engineering*, 7 (1)

Otieno, F. A. O., Olumuyiwa, I. O. and Ochieng, G. M. 2012. Groundwater: Characteristics, qualities, pollutions and treatments: An overview. *African journal of agricultural research*,

Palamuleni, L. and Akoth, M. 2015. Physico-chemical and microbial analysis of selected borehole water in Mahikeng, South Africa. *International journal of environmental research and public health*, 12 (8): 8619-8630.

Palmer, C., Berold, R. and Muller, W. 2004. Water Research Commission TT No 217/04.

Pandit, A. P. 2020. Topic No. 15. Integration of RS and GIS data:-The Integration of Remote Sensing and GIS Technology for Geographical Study.

Pasupuleti, S., Sandilya, D. K., Singha, S., Singha, S. S. and Saha, S. 2018. Delineation of groundwater potential zones utilising geospacial techniques in Kadiri watershed of Anantapur district, Andhra Pradesh, India. *Journal of Environmetal Biology*,

Paun, I., Cruceru, L., Chiriac, F. L., Niculescu, M., Vasile, G. and Marin, N. 2016. *WATER QUALITY INDICES - METHODS FOR EVALUATING THE QUALITY OF DRINKING WATER*.

Perera, S. 2013. Patterns of animal endemism in the Maputaland-Pondoland-Albany biodiversity hotspot.

Pietersen, K. 2006. Multiple criteria decision analysis (MCDA): A tool to support sustainable management of groundwater resources in South Africa. *Water SA*, 32 (2): 119-128.

Pietersen, K., Beekman, H. E., Holland, M. and Adams, S. 2012. Groundwater governance in South Africa: A status assessment. *Water SA,* 38 (3)

Pinto, D., Shrestha, S., Babel, M. S. and Ninsawat, S. 2017. Delineation of groundwater potential zones in the Comoro watershed, Timor Leste using GIS, remote sensing and analytic hierarchy process (AHP) technique. *Applied Water Science*, 7 (1): 503-519.

Purdy, A. J., Fisher, J. B., Goulden, M. L., Colliander, A., Halverson, G., Tu, K. and Famiglietti, J. S. 2018. SMAP soil moisture improves global evapotranspiration. *Remote Sensing of Environment*, 219: 1-14.

Rahmati, O., Samani, A. N., Mahdavi, M., Pourghasemi, H. R. and Zeinivand, H. 2015. Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. *Arabian Journal of Geosciences,* 8 (9): 7059-7071.

Rajabi, M. M. 2019. Review and comparison of two meta-model-based uncertainty propagation analysis methods in groundwater applications: polynomial chaos expansion and Gaussian process emulation. *Stochastic Environmental Research and Risk Assessment*, 33 (2): 607-631.

Rajasekhar, M., Sudarsana Raju, G., Bramaiah, C., Deepthi, P., Amaravathi, Y. and Siddi Raju, R. 2018. Delineation of groundwater potential zones of semi-arid region of YSR Kadapa District, Andhra Pradesh, India using RS, GIS and analytic hierarchy process. *Remote Sensing of Land*, 2 (2): 76-86.

Rajaveni, S. P., Brindha, K. and Elango, L. 2015. Geological and geomorphological controls on groundwater occurrence in a hard rock region. *Applied Water Science,* 7 (3): 1377-1389.

Raju, R. S., Raju, G. S. and Rajasekhar, M. 2019. Identification of groundwater potential zones in Mandavi River basin, Andhra Pradesh, India using remote sensing, GIS and MIF techniques. *HydroResearch,* 2: 1-11.

Ricker, B., Rickles, P., Fagg, G. and Haklay, M. 2020. Tool, toolmaker, and scientist: case study experiences using GIS in interdisciplinary research. *Cartography and Geographic Information Science*: 1-17.

Riemann, K., Chimboza, N. and Fubesi, M. 2012. A proposed groundwater management framework for municipalities in South Africa. *Water SA*, 38 (3): 445-452.

Rikalovic, A., Cosic, I. and Lazarevic, D. 2014. GIS based multi-criteria analysis for industrial site selection. *Procedia Engineering*, 69 (12): 1054-1063.

Rutherford, A. B., Rubidge, B. and Hancox, J. 2015. Sedimentology and Palaeontology of the Beaufort Group in the Free State Province Supports A Reciprocal Foreland Basin Model for the Karoo Supergroup, South Africa. *South African Journal of Geology*, 118: 355-372.

Rwanga, S. and Ndambuki, J. 2020. Solving groundwater problems fraught with uncertain recharge: An application to Central Limpopo, South Africa. *Groundwater for Sustainable Development*, 10: 100305.

Saaty, T. L. 1988. What is the analytic hierarchy process? In: *Mathematical models for decision support*. Springer, 109-121.

Saaty, T. L. 2004. Fundamentals of the analytic network process—multiple networks with benefits, costs, opportunities and risks. *journal of systems science and systems engineering*, 13 (3): 348-379.

Sakala, E., Fourie, F., Gomo, M. and Coetzee, H. 2018. GIS-based groundwater vulnerability modelling: A case study of the Witbank, Ermelo and Highveld Coalfields in South Africa. *Journal of African Earth Sciences*, 137: 46-60.

Saqr, A.M., Ibrahim, M.G., Fujii, M. and Nasr, M., 2021. Sustainable Development Goals (SDGs) Associated with Groundwater Over-Exploitation Vulnerability: Geographic Information System-Based Multi-criteria Decision Analysis. Natural Resources Research, 30(6), pp.4255-4276.

Saranya, T. and Saravanan, S. 2020. Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. *Modeling Earth Systems and Environment*: 1-18.

Scanlon, B. R., Healy, R. W. and Cook, P. G. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 10 (1): 18-39.

Schaller, L. 2016. Reaching new heights. *TAXtalk*, 2016 (60): 88-93.

Schulze, R. E. 1997. *South African Atlas of Agrohydrology and Climatology: Contribution Towards a Final Report to the Water Research Commission on Project 492: Modelling Impacts of the Agricultural Environment on Water Resources: TT82-96*. Water Research Commission (WRC).

Seckler, D. W. 1996. *The new era of water resources management: from" dry" to" wet" water savings*. Iwmi.

Seward, P., Xu, Y. and Turton, A. 2015. Using backcasting to explore ways to improve the national water department’s contribution to good groundwater governance in South Africa. *Water International*, 40 (3): 446-462.

Shackelford, C. D. 2013. Geoenvironmental Engineering☆. In: *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. Available: http://www.sciencedirect.com/science/article/pii/B9780124095489054245

Shao, Z., Huq, M. E., Cai, B., Altan, O. and Li, Y. 2020. Integrated Remote Sensing and GIS Approach using Fuzzy-AHP to Delineate and Identify Groundwater Potential Zones in Semi-Arid Shanxi Province, China. *Environmental Modelling & Software*: 104868.

Shekhar, S. and Pandey, A. C. 2015. Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. *Geocarto International*, 30 (4): 402-421.

Silverman, B. W. 1986. Density Estimation for Statistics and Data Analysis. New York: Chapman and Hall.

Situma, E. 2019. IFC, SECO Partner to Address Water Scarcity in South Africa. *Newspaper Article*

Sreekanth, J., Lau, H. and Pagendam, D. 2017. Design of optimal groundwater monitoring well network using stochastic modeling and reduced-rank spatial prediction. *Water Resources Research*, 53 (8): 6821-6840.

Stats, S. 2016. Community survey 2016, statistical release P0301. *Statistics South Africa*,

Sujay Raghavendra, N. and Deka, P. C. 2015. Forecasting monthly groundwater level fluctuations in coastal aquifers using hybrid Wavelet packet–Support vector regression. *Cogent Engineering*, 2 (1): 999414.

Takorabt, M., Toubal, A. C., Haddoum, H. and Zerrouk, S. 2018. Determining the role of lineaments in underground hydrodynamics using Landsat 7 ETM+ data, case of the Chott El Gharbi Basin (western Algeria). *Arabian Journal of Geosciences*, 11 (4): 76.

Taormina, R., Chau, K.-W. and Sethi, R. 2012. Artificial neural network simulation of hourly groundwater levels in a coastal aquifer system of the Venice lagoon. *Engineering Applications of Artificial Intelligence*, 25 (8): 1670-1676.

Tewari, D. D. and Kushwaha, R. L. 2008. Socio-economics of groundwater management in Limpopo, South Africa: poverty reduction potential and resource management challenges. *Water International*, 33 (1): 69-85.

Thomas, R. and Duraisamy, V. 2017. *Hydrological delineation of groundwater vulnerability of droughts in semi-arid areas of western Ahmednagar district. Egypt J Remote Sens Space Sci*.

Tunc Dede, O., Telci, I. T. and Aral, M. M. 2013. The Use of Water Quality Index Models for the Evaluation of Surface Water Quality: A Case Study for Kirmir Basin, Ankara, Turkey. *Water Quality, Exposure and Health*, 5 (1): 41-56.

Valipour, M. 2017. Analysis of potential evapotranspiration using limited weather data. *Applied Water Science*, 7 (1): 187-197.

van Gend, J., Francis, M., Watson, A., Palcsu, L., Horváth, A., Macey, P., le Roux, P., Clarke, C. and Miller, J. 2020. Saline groundwater in the Buffels River catchment, Namaqualand, South Africa: A new look at an old problem. *Science of the Total Environment*: 143140.

Van Vuuren, L. 2013. Institutional conundrum sinking groundwater supply in North West town: municipal water supply. *Water Wheel*, 12 (6): 17-19.

van Wyk, Y. and Ubomba-Jaswa, E. 2020. IDEAS FOR MAINSTREAMING GROUNDWATER *Water Research Commission*,

Vegter, J., Seymour, A. and Simonic, M. 1995. Groundwater resources of the Republic of South Africa. A set of 7 maps. *Water Research Commission and Dept of Water Affairs and Forestry*,

Visser, J. 1978. Water depth in the main Karoo basin, South Africa, during Ecca (Permian) sedimentation. *South African Journal of Geology*, 81 (2): 185-191.

Visser, J. 1986. Lateral lithofacies relationships in the glacigene Dwyka Formation in the western and central parts of the Karoo Basin. *Transactions of the Geological Society of South Africa*, 89: 373-383.

von Asmuth, J. R. and Knotters, M. 2004. Characterising groundwater dynamics based on a system identification approach. *Journal of Hydrology*, 296 (1-4): 118-134.

Watson, A., Miller, J., Fleischer, M. and de Clercq, W. 2018. Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology*, 558: 238-254.

Weier, J. and Herring, D. 2000. Measuring vegetation (ndvi & evi). *NASA Earth Observatory*, 20

Wirth, S. B., Carlier, C., Cochand, F., Hunkeler, D. and Brunner, P. 2020. Lithological and Tectonic Control on Groundwater Contribution to Stream Discharge During Low-Flow Conditions. *Water*, 12 (3): 821.

Wit, D. 1998. Vaalbara, Earth's oldest assembled continent? A combined structural, geochronological, and palaeomagnetic test. *Terra Nova*, 10 (5): 250-259.

Woodford, A. and Chevallier, L. 2002. Hydrogeology of the Main Karoo Basin: Current knowledge and future research needs. WRC Report No. TT 179/02. *Water Research Commission, Pretoria*,

Woodford, A. and Rosewarne, P. 2006. 1 HOW MUCH GROUNDWATER DOES SOUTH AFRICA HAVE?

Wright, Y. 2000. A water balance approach to the sustainable management of groundwater in South Africa. *Water SA*, 26 (2): 167-170.

Xu, Y. and Beekman, H. E. 2019. Review: Groundwater recharge estimation in arid and semi-arid southern Africa. *Hydrogeology Journal*, 27 (3): 929-943.

Yeh, H.-F., Lin, H.-I., Lee, S.-T., Chang, M.-H., Hsu, K.-C. and Lee, C.-H. 2014. GIS and SBF for estimating groundwater recharge of a mountainous basin in the Wu River watershed, Taiwan. *Journal of Earth System Science*, 123 (3): 503-516.

Yousaf, W., Awan, W. K., Kamran, M., Ahmad, S. R., Bodla, H. U., Riaz, M., Umar, M. and Chohan, K. 2021. A paradigm of GIS and remote sensing for crop water deficit assessment in near real time to improve irrigation distribution plan. *Agricultural Water Management*, 243: 106443.

Zhang, H., Xu, Y. and Kanyerere, T. 2019. Site Assessment for MAR through GIS and Modeling in West Coast, South Africa. *Water*, 11 (8): 1646.