Identification of potential groundwater recharge zones:

A case study of Kwazulu-Natal, South Africa

BY

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DECLARATION

I, Ms Denisha Ponnusamy (201639161) declare that the thesis titled "Identification of potential groundwater recharge zones: A case study of Kwazulu-Natal, South Africa" submitted in fulfilment of the degree of Master of Science (specialising in Hydrology) is my original work duly performed in the Faculty of Science, Agriculture and Engineering at the University of Zululand. This work has not been submitted before by anyone from University of Zululand or any other institution and all the sources I have used have been acknowledged by complete references.

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The results from this research have been accepted in peer-reviewed journals.

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Abstract

Urbanization has accelerated the changes in the uMhlathuze watershed in Kwazulu-Natal resulting in a deterioration in the quantity and stability of water resources, hence calling upon the development of groundwater resources. This study combined the use of GIS and remote sensing to demarcate groundwater potential recharge zones in the uMhlathuze catchment and Maputaland region using various pertinent parameters. The AHP approach and Catastrophe theory were used to determine acceptable zones by assigning weights to the 10 parameters and their sub-criteria for the uMhlathuze catchment, whilst the potential groundwater zones of the Maputaland coastal plain of Kwazulu-Natal is identified by comparing the Analytic hierarchy process (AHP) – Multi-criteria decision-making (MCDM) technique and Boolean logical approach. The map of groundwater potential zones for Maputaland was prepared by assimilating the 8 thematic layers, i.e., geology, geomorphology, lineament density, soils, slope, rainfall, and land use. Each thematic layer were assigned with subjective relative weights under AHP-MCDM technique and Boolean logic and were overlaid in a GIS platform to identify the groundwater potential zones. The groundwater potential zones were delineated under two different GIS techniques to obtain confident results. Weights of thematic layers were allocated using AHP normalized eigen vector methodology and weighted linear combination method was employed to find the groundwater potential index. Whereas in a Boolean approach, AND operator was applied in order to integrate thematic layers to delineate the groundwater potential zones . The AHP and the emerging Catastrophe theory was applied to the drainage density, geology, morphology, lineament density, soil type, rainfall, land use/land cover, transmissivity and aspect parameters and their sub-criteria for the uMhlathuze catchment and then integrated in a GIS environment. The Catastrophe theory consisted of firstly standardization of the parameters and sub-criteria, followed by the normalization of values using the complementary principle according to the model type and mathematical function encompassed by the model. Once they were normalized the highest mean value of the parameters were assigned the highest factor weight, whilst the lowest mean value was assigned the lowest factor weight. The delineated groundwater potential maps using AHP-Boolean-MCDM technique for Maputaland indicates that 6.0% (310.5 km^2) from total area falls under very good; 67% (3467 km^2) good; 25% (1294 km^2) poor and 2% (103.5 km^2) under very poor, whereas in Boolean logic about 70 % of the area (i.e., 3623 km^2) constitutes good and 30 % (1552 km^2) of the areas constitutes poor groundwater potential zone and the for the uMhlathuze catchment it was discovered that, 22.92% and 26.38% of the catchment is encompassed by 'Low' groundwater potential recharge zones, 0.37% and 0.08% by 'Very low' groundwater potential recharge zones, 9.42% and 10.26% by 'Good' groundwater potential recharge zones, 66.87% and 63.19% by 'Moderate', and 0.42% and 0.09% by 'Very good', for the AHP and Catastrophe theory respectively. Further, the obtained results in Maputaland indicate that the geology, geomorphology, land use and slope played a vital role in groundwater recharge. This pioneer study in Maputaland coastal plain explores the baseline data of the potential groundwater zones. Furthermore, in the uMhlathuze catchment, it was deduced that due to the hard rock complexion of the catchment, this attribute significantly limited presence of ‘Good’ and ‘Very good’ zones. The resultant groundwater recharge potential recharge zones maps were validated against TDS and nitrate concentrations, and groundwater level data of boreholes in the study area. It was revealed that the lowest and highest TDS, nitrate, and groundwater levels overlap with the ‘Good and Very good’ and ‘Low and Very low’ groundwater potential recharge zones respectively. The results emanating from this study can be used in further understanding of the available groundwater resources and can be helpful in future to find suitable groundwater exploration sites in the area. It was inferred that the convergence and use of GIS and remote sensing for delineating groundwater potential recharge zones are effective and may be utilized for groundwater planning and governance.

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Abstract

Urbanization has accelerated the changes in the uMhlathuze watershed in Kwazulu-Natal resulting in a deterioration in the quantity and stability of water resources, hence calling upon the development of groundwater resources. This study combined the use of GIS and remote sensing to demarcate groundwater potential recharge zones in the uMhlathuze catchment and Maputaland region using various pertinent parameters. The AHP approach and Catastrophe theory were used to determine acceptable zones by assigning weights to the 10 parameters and their sub-criteria for the uMhlathuze catchment, whilst the potential groundwater zones of the Maputaland coastal plain of Kwazulu-Natal is identified by comparing the Analytic hierarchy process (AHP) – Multi-criteria decision-making (MCDM) technique and Boolean logical approach. The map of groundwater potential zones for Maputaland was prepared by assimilating the 8 thematic layers, i.e., geology, geomorphology, lineament density, soils, slope, rainfall, and land use. Each thematic layer were assigned with subjective relative weights under AHP-MCDM technique and Boolean logic and were overlaid in a GIS platform to identify the groundwater potential zones. The groundwater potential zones were delineated under two different GIS techniques to obtain confident results. Weights of thematic layers were allocated using AHP normalized eigen vector methodology and weighted linear combination method was employed to find the groundwater potential index. Whereas in a Boolean approach, AND operator was applied in order to integrate thematic layers to delineate the groundwater potential zones . The AHP and the emerging Catastrophe theory was applied to the drainage density, geology, morphology, lineament density, soil type, rainfall, land use/land cover, transmissivity and aspect parameters and their sub-criteria for the uMhlathuze catchment and then integrated in a GIS environment. The Catastrophe theory consisted of firstly standardization of the parameters and sub-criteria, followed by the normalization of values using the complementary principle according to the model type and mathematical function encompassed by the model. Once they were normalized the highest mean value of the parameters were assigned the highest factor weight, whilst

the lowest mean value was assigned the lowest factor weight. The delineated groundwater potential maps using AHP-Boolean-MCDM technique for Maputaland indicates that 6.0% (310.5 km2) from total area falls under very good; 67% (3467 km2) good; 25% (1294 km2) poor and 2% (103.5 km2) under very poor, whereas in Boolean logic about 70 % of the area (i.e., 3623 km2) constitutes good and 30 % (1552 km2) of the areas constitutes poor groundwater potential zone and the for the uMhlathuze catchment it was discovered that, 22.92% and 26.38% of the catchment is encompassed by 'Low' groundwater potential recharge zones, 0.37% and 0.08% by 'Very low' groundwater potential recharge zones, 9.42% and 10.26% by 'Good' groundwater potential recharge zones, 66.87% and 63.19% by 'Moderate', and 0.42% and 0.09% by 'Very good', for the AHP and Catastrophe theory respectively. Further, the obtained results in Maputaland indicate that the geology, geomorphology, land use and slope played a vital role in groundwater recharge. This pioneer study in Maputaland coastal plain explores the baseline data of the potential groundwater zones. Furthermore, in the uMhlathuze catchment, it was deduced that due to the hard rock complexion of the catchment, this attribute significantly limited presence of ‘Good’ and ‘Very good’ zones. The resultant groundwater recharge potential recharge zones maps were validated against TDS and nitrate concentrations, and groundwater level data of boreholes in the study area. It was revealed that the lowest and highest TDS, nitrate, and groundwater levels overlap with the ‘Good and Very good’ and ‘Low and Very low’ groundwater potential recharge zones respectively. The results emanating from this study can be used in further understanding of the available groundwater resources and can be helpful in future to find suitable groundwater exploration sites in the area. It was inferred that the convergence and use of GIS and remote sensing for delineating groundwater potential recharge zones are effective and may be utilized for groundwater planning and governance.

CHAPTER 1

1.1 INTRODUCTION

Water shortages has imposed immense impact worldwide, but it is the disadvantaged and underprivileged communities who suffer the most. Some countries do not have access to clean and safe water instead they rely upon other hazardous sources of water to sustain their livelihood. Such regions are classified as 'Poverty-stricken' where development of the country as a whole is hindered (Vapnek et al.,2009). Developing countries are facing many challenges due to the adverse effects of climate change that impede the development of water infrastructures (Southern Africa Water development report, 2006). Climate change causes a decrease in the rainfall intensity and an increase in the water body temperatures. With the increased evaporation rates, the soil moisture content is decreased leading to more serious and recurring droughts (Melaku Melese, 2016) which would negatively impact on the agricultural sector. The effects of climate change can be seen from the changes in soil pore, water pressure, groundwater level fluctuations, alterations in the groundwater flow regime and changes in the volume and quantity of groundwater resources (Apaydin, 2010). The change in temperature and precipitation rate will have impact on aquifer recharge consequently causing shifts in the water table of the unconfined aquifers. Due to climate changes the shallow aquifers are commonly affected in a localised area when compared to deep aquifers affected by regional climatic changes. The sub-region of southern Africa has the highest climatic variations in the world. This region has been affected by droughts and floods that have impacted the economy of countries within the region. The countries of the sub-region of southern Africa have insufficient infrastructure to avoid and alleviate the harmful effects of such events (Southern africa water development report, 2006). To help ease the demand of food and increase food security in the developing countries the strengthening of agricultural sector is an effective solution. However, the increased rate of irrigation in turn could possibly cause water pollution as a result of accumulation of ions (Mettetal, 2019). There is a need for finding safe, sustainable water resources to sustain agricultural activities which has become a major concern. In South Africa, groundwater is highly significant due to its wide occurrence, it occurs in the drier twothirds of the country where there is little or no surface water; groundwater is used by almost two-thirds of South Africa's population for domestic water needs and groundwater can be delivered directly to the people more cheaper and faster than through a piped or canal water. Rainfall gradient ranges from the east to the west, with the west receiving lesser rainfall than the east and causing freshwater resources being unevenly distributed across the country (NWRSS, 2002) further leading to water crisis. Therefore, identification of groundwater potential recharge zones has become vital which can further assists in monitor, protection, management, and conservation of groundwater resources (Mogaji *et al*, 2016).

The Maputaland Coastal Plain falls within the Umkhanyakude local municipality district and the majority of the population rely on water from shallow wells (Grundling, 2014). The region supports multiple land-uses which has reduced the availability for groundwater in the region and many studies has highlighted the need for the development and sustainability of water resources (Mkhwanazi, 2010; Rawlins and Kelbe, 1998). Throughout the years mostly surface water was used to meet the demands of population which kept groundwater levels constant. This was because there was an assumption that due to the amount of rainfall received in KZN, there was no need for the use of groundwater but, recent drought years have urged the use of groundwater (Ndlovu and Demlie, 2018). If groundwater is over exploited, it lowers the water table and in turn the potential of the aquifer is lowered (Mogaji, Omosuyi and Adelusi, 2016). The western boundary of KZN lays on the Indian ocean, which makes coastal aquifers vulnerable to seawater intrusion. In coastal aquifers, seawater intrusion is a common phenomenon and when groundwater is the only source of freshwater in a region, this poses a threat. When aquifers are pumped excessively the water pressure is reduced and encourages the flow of seawater into the aquifer (Abdalla, 2016).

Amongst the methods used in groundwater exploration to detect and map groundwater resources, drilling test and the investigation of stratigraphy are the most popular methods used which are very tedious, laborious and expensive (Patra *et al*, 2018; Singh *et al*, 2018). Hence, an alternative scientific approach has to be identified. Remote sensing can also be used to yield inputs with regards to estimating the total groundwater resources within an area, aid in the selection of suitable sites for artificial recharge and find the depth of the weathering area. Aquifer recharge can occur by rainfall, the return flow from irrigation and seepage from canals and reservoirs and features such as alluvial fans, buried pediments, old stream channels and deep-rooted interwoven fractures indicate the subsurface water accumulation (Das D., 2009). GIS and remote sensing techniques have become a common method used to target groundwater potential zones. GIS have proved to be an excellent tool when it comes to delineation of groundwater potential zones due to its ability to handle larger amount of information provided with synoptic views of areas on a large areal extent and its ability to model complicated features (Behzad *et al*, 2019; Chaudhary & Kumar, 2018; Chenini *et al*, 2015; Hadžić *et al*, 2015; Hussein et al., 2017; Murasingh *et al*, 2018; Sudarsana &

Siddi, 2019; Vishwakarma *et al*, 2014; Yousif *et al*, 2018). There are many methods used for groundwater potential mapping such as subjective overlay or index methods, statistical methods and physically based methods (Oke and Fourie, 2017).The method adopted in this study is the Analytical Hierarchy Process (AHP) (Al-shabeeb, 2016; Arabameri *et al*, 2019; Arulbalaji *et al*, 2019; Aydi, 2018; Chakrabortty *et al*, 2018; Jhariya *et al*, 2016; Kaliraj *et al*, 2014; Kumar *et al*, 2014; Patra et al., 2018; Yin et al., 2018).

The AHP technique (Saaty, 1987) is useful when there is a variety of judgments and where there is a need for processing and characterising the judgments. The AHP is a theory of relative measurement that aids decision making or decision analysis through creation of pairwise comparison matrices using a scale indicating which variable dominates the other. It includes three basic steps: (1) structuring of the problem and defining the hierarchy (2) Derivation of the pairwise comparisons (3) Determining of the priority vectors and their weighted linear combinations (Brunelli, 2015)

This study was carried out to delineate the groundwater potential zones within the 3 regions (Figure 1) using remote sensing and GIS multi-criteria decision-making techniques by studying the geomorphology, geology, land cover, soils, rainfall, lineament density, slope, and drainage density of the area. These parameters govern groundwater flow and movement and are very significant to the study of the storage and transmissivity of water.

1.2 PROBLEM STATEMENT

The demand for freshwater in South Africa is continuously accelerated by multiple factors such as population growth and climate change. These factors affect the quantity and quality of water resources. Being a developing country, it is important to have a sufficient supply of water to meet the demand. But the challenge of finding these water resources to fill the growing gap between supply and demand is still an impeding factor. With an increase in water body temperatures. Rate of evaporation, and recurring droughts agricultural practices are highly affected, it is important to locate alternate sources of water (Melaku Melese, 2016). But the high vulnerability of surface water makes it as an unreliable source of water, especially in the drier parts of the country that have little or no surface water. Groundwater on the other hand has a high significance due to its availability during the dry seasons and the fact that it occurs within an aquifer or underground makes it less prone to contamination (Nsiah, Appiah-Adjei and Adjei, 2018). These study areas survive on groundwater and with an increase in the demand for water, groundwater supplies are being exploited to meet the demand.

Finding groundwater potential zones is quiet challenging and the unsystematic drilling of boreholes to find groundwater potential zones often ends up unsuccessful. Other traditional methods include stratigraphy analysis, ground field surveys and geophysical investigations that involve substantial labours. Groundwater exploration procedures are costly, time-consuming and require a vast amount of resources which can only be useful in areas that contain shallow aquifers (Venkateswaran and Ayyandurai, 2015; Yin *et al.*, 2018; Al-Ruzouq *et al.*, 2019)

The Maputaland Coastal Plain relies primarily on groundwater and it supports multiple landuses such as: forestry, large urban and industrial developments, extensive farming, commercial enterprises and mining industries and rural communities (Mkhwanazi, 2010). These developments have created an increase in the demand and has degraded the water quality while lessening the water table. Employment of remote sensing and GIS techniques to locate groundwater potential zones has become broadly used by many researchers in an attempt to find groundwater. Satellite data can provide information about important hydrological factors that influence the occurrence of groundwater and GIS has the ability to deal with large amounts of information provide synoptic views of areas that cover large areal extent and the ability to model large features, when both are integrated the delineation of groundwater potential zones becomes an easy task.

1.3 Aims and Objectives

The aim of the study is to demarcate the groundwater potential zones and estimate their percentage of distribution in the Northern part of Kwazulu-Natal using GIS and RS techniques for further management and protection of groundwater resources.

- identification of factors affecting the groundwater recharge and preparation of thematic maps.
- assignment and ranking of critical weights using the Multi-Influencing Factor technique to obtain overly analysis and relative consistency ratio
- delineation and validation of the groundwater potential zones for the assessment of the model reliability
- Identification of locations for construction of the artificial recharge structures using Weighted Overlay Index analysis

CHAPTER 2: LITERATURE REVIEW

2.1 Delineation of groundwater recharge potential zones

The integration and modelling tools of GIS combined with remote sensing techniques which can retrieve spatial, spectral, and temporal data from large inaccessible areas, can be used to delineate groundwater potential zones. The satellite data of an area can be used to provide information on parameters that control the occurrence and movement of groundwater on the basis of morphology, geology, lithology, soil type, climate, rainfall, permeability, drainage density, land use and elevation(Behzad *et al*., 2019; Das, 2019; Das & Pardeshi, 2018; Kumar *et al*., 2014; Lee *et al*, 2019; Pinto & Shrestha, 2017; Sudarsana & Siddi, 2019).

When GIS techniques are combined with remotes sensing techniques, they become useful in studies linked to groundwater. They not only efficiently deal with complex system but also provide the option of integrating spatial data with numerous advanced mathematical, statistical and multi-criteria decision-making techniques such as: the weights of evidence model (Nejad et al., 2017), random forest model, logistic model tree, Boolean logic, catastrophe technique, Dempster-Shafer model, decision tree model, fuzzy logic models, index based models, artificial neural network models, the analytical hierarchy process, evidential belief function models and binary logistic regression models (Patra, Mishra and Mahapatra, 2018; Al-Ruzouq *et al.*, 2019; Das, 2019). The majority of these techniques are based on bivariate and multivariate statistical methods that are restricted in simulating results before an investigation and the sensitivity of findings, whereas the AHP technique is considered an easy, transparent, effective and reliable technique (Patra, Mishra and Mahapatra, 2018).

Delineation of groundwater recharge potential zones in the upper Marimuktha sub-basin into very low, low, moderate, high, and very categories found that only 34,42% of the rainfall is infiltrated and recharges the aquifers and waterbodies (Venkateswaran et al., 2016). It is found that in hard rock regions, the availability of groundwater is limited and restricted to fractured and weathered zones with secondary porosity. This was mirrored in their results when they found that agricultural land, down-stream areas and hard rock (charnockite) highly influenced the presence of groundwater recharge potential zones in the sub-basin. The groundwater recharge potential zones of the river Vaigai upper basin, India was divided into four categories i.e., high, moderate, low, and unsuitable (Kaliraj et al., 2015). It was found that gullies, fractured valleys, deep buried pediment, and alluvial plains had high to moderate potential for groundwater recharge. Chakrabortty *et al*, 2018 used several factors such as geology, LULC, drainage density, soils, lineament density, rainfall, slope, groundwater fluctuation, infiltration rate, geomorphology and hydrogeology to target groundwater potential zones in Raniganj Block of Paschim Bardhaman District in India and did a comparison between the groundwater depth that was estimated from the model and the actual groundwater depth that was determined from a field investigation and found a 75% consistency between the two. Chenini *et al*, 2010 mapped artificial recharge zones by integrating the watershed limit, drainage, drainage density, lithology, fractured outcrops, lineaments, permeability and piezometry of the Maknassy Basin in Tunisia. They determined suitable recharge structures by overlaying the drainage map over the final map and analysing the lithological structures. It was found that the watershed limits were an important factor in choosing a suitable recharge site. Hammouri *et al*, 2014 established groundwater potential zones in a Jordan valley using the SLUGGER-DQL model, on the basis of eight parameters i.e., slope, LULC, geomorphology, geology, runoff availability, well density, well quality and water levels (summer season). The final map of groundwater recharge potential zones was categorised into three zones viz. high, moderate, and low. The 70,8% of the area achieved high potential owing to the alluvium deposits and high infiltration ability. It was found that the slop factor was the most sensitive parameter and the lowest sensitive parameter was the geology parameter when using the SLUGGER-DQL model.

The AHP techniques are becoming more popular in studies with groundwater potentiality mapping however, the AHP technique assumes that the variables are independent of each other and this is only sometimes correct in the context of environmental variables and the ANP technique (Swetha, et al., 2017) (which is a generalisation of the AHP technique accounts for interdependence among variables rather than independence).

From the results of past studies of groundwater potential zone mapping, the fewer the number of GIS layers used, the lesser the accuracy obtained, whereas the greater the number of GIS layers used, the greater the accuracy obtained (Elea and Qaddah, 2011). Each method has it strengths and weaknesses and it depends on their suitability under a particular set of factors (Oke and Fourie, 2017). The integration of GIS and remote sensing techniques is becoming increasingly popular as the need for a reliable freshwater resource to meet the needs of industrial, agricultural and domestic activities is of a great importance in combating poverty and also aids in the proper management of groundwater resources.

CHAPTER 3: STUDY AREA DESCRIPTION

3.1. Maputaland coast

The study area occurs within the Maputaland Coastal Plain region of Kwazulu-Natal, South Africa. It neighbours the Indian ocean on the left surrounded by the Lebombo mountains on the right and ends at the mouth of the St. Lucia estuary. (Porat and Botha, 2008; Watkeys *et al*, 1993). It is well known for its barrier lakes and highly vegetated coastal sand dunes. Off the coast the local winds and wave refractions create a counter current that moves the sand in a northerly direction and creates sand that can reach elevations of up to 180m. (Weitz and Demlie, 2014; Vaeret *et al*, 2009).

The area has a subtropical, humid climate with mean annual temperatures ranging from 21°C and 23°C (Watkeys *et al*, 1993). The atmosphere of the region is unstable due to the warm air of the Indian ocean converging with the equatorial troughs in the southern part of the country. This results in convective rainfall during summer (Weitz and Demlie, 2014)

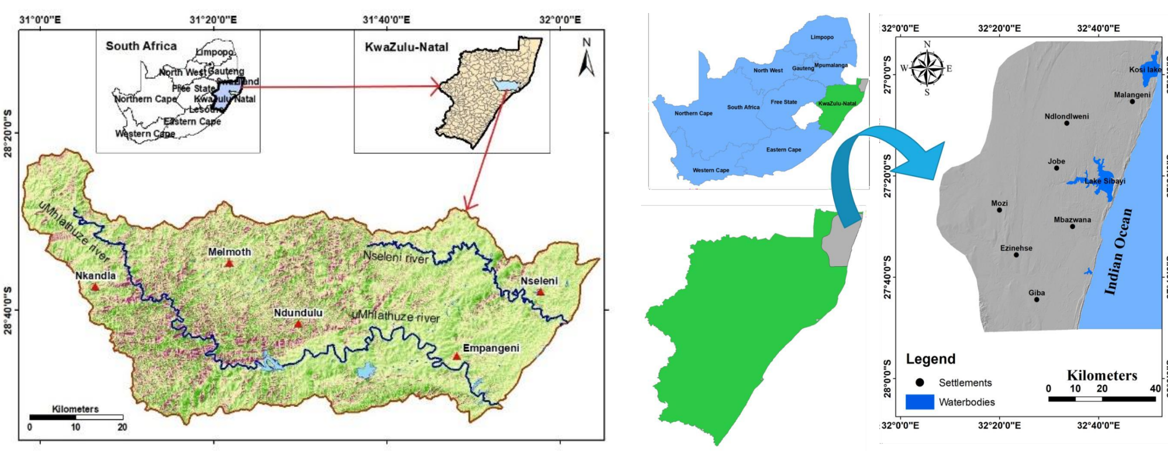

Figure 1: Study Location of Northern part of KwaZulu-Natal

3.1 uMhlathuze catchment

The uMhlathuze catchment falls under Water Management Area (WMA) 6 i.e. Usutu to uMhlathuze and is controlled by uMhlathuze municipality (DWAF, 2002). The climate around the uMhlathuze catchment is subtropical, warm, and humid. Rainfall mostly occurs in summer. The mean maximum temperature is around 20.6 to 31.2° C whilst the mean minimum temperature is around 11.2 to 23° C (Cimanga, 2017).

The land uses occurring in the uMhlathuze catchment are forestry (15.5%), commercial agriculture (14%), other (includes industrial and mining activities), rural settlements (19.5%), urban settlements (2.7%) (Longhurst, 2009). Groundwater is the major source and in some rural areas the only source of water supply and makes up about 65% of the total supply. The uMhlathuze catchment is classified as 'stressed' which would not meet the increasing demand of the eMpangeni and Richard's Bay industrial sectors (DWAF, 2001; Longhurst, 2009). The flow of the uMhlathuze river is regulated by Pongolapoort Dam, and it's three main tributaries include Mhlatazana, Mfule and the Nseleni River (Mkhwanazi, 2010). The coastal lakes occurring in the uMhlathuze catchment consist of Lake Nsezi, Lake Mzingazi, Lake Cubhu and Lake Nhlabane. Lake Cubhu, Mzingazi and Nhlabane are extensions of the groundwater while Lake Nsezi is controlled by the Nseleni River but does not have significant groundwater interaction. The southern part of Lake Mzingazi is at its deepest point which is 14m below sea level, making it more vulnerable to sea water intrusion. An artificial barrier was constructed in the Mzingazi estuary which plays a major role in maintaining the water table elevation between the sea and lake to prevent sea water intrusion (DWAF, 2001; Mathenjwa, 2006; Longhurst, 2009; Cimanga, 2017).

CHAPTER 4: RESEARCH METHODOLOGY

4.1. Thematic layers

A total of 8 thematic layers will be selected for this study viz. geology, geomorphology, lineament density, soils, land cover, slope, rainfall and drainage density, since they are the important factors controlling the groundwater recharge (Samson and Elangovan, 2015; AlRuzouq *et al.*, 2019; Arabameri *et al.*, 2019).

4.2. Data collection and analysis

The maps of geology, geomorphology and land cover will be obtained from the Department of Environmental Affairs (DEA). The map of soils will be obtained from the FAO website (digital soil map of the world). The rainfall data for the past 30 years will be obtained from the South African Weather Services (SAWS) and a rainfall map will be created. The maps of slope and drainage density will be extracted from the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) obtained from the USGS website (https://earthexplorer.usgs.gov/). The SRTM-DEM will then be projected in ArcGIS and merged using the mosaic tool. Once clipped to the boundaries of the study area, the slope tool and flow direction and flow accumulation tool of ArcGIS will be used to create the slope and drainage density respectively. For the lineament of density map, lineaments in the study area will be traced in Google Earth and imported into ArcGIS.

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CHAPTER 5: MAPPING OF POTENTIAL GROUNDWATER RECHARGE ZONES OF MAPUTALAND COASTAL PLAIN

5. 1 Introduction

Water scarcity in South Africa is a reality due to a drastic increase in urbanization and industrialization which has put enormous pressure on the country's water resources. To meet the growing water demand in the country, the surface water resources from rivers, dams, and estuaries are utilized to supply most parts of South Africa's domestic, industrial and agricultural needs (Du Plessis 2017). However, owing to the growing population and industrialization, current surface water resources are under threat (Huizenga 2011; Pitman 2011; Du Plessis 2017; Vetrimurugan et al., 2017a).

Groundwater has become an essential natural resource for the provision of water in many regions and countries of the world (He et al., 2020; Li et al., 2019; Su et al., 2020; Vhonani et al., 2018, Vetrimurugan et al., 2017b, Wu et al., 2020). Groundwater contributes between 13 % and 15 % of the total water need in South Africa (Mpenyana-Monyatsi et al., 2012). It is noted that groundwater is abstracted heavily for industrial, mining and agriculture purposes which have caused a rapid decline in groundwater levels. Hence a comprehensive study should be undertaken to locate and outline the groundwater potential zones before an exploration of groundwater (Fashae et al., 2014; Rahmati et al., 2015; Selvam et al., 2015; Adeyeye et al., 2019; Qadir et al., 2019). This can be achieved using the Geographic Information System (GIS) and remote sensing techniques, which is cost and time effective (Chowdhury et al., 2010; Jha et al., 2010; Deepika et al., 2013; Nampak et al., 2014; Rahimi et al., 2014; Zaidi et al., 2015; Andualem and Demeke 2019). Remote sensing and GIS techniques utilize satellite data along with various thematic maps. Integration of remote sensing and GIS data with assigned weightage in a spatial domain was carried out to prepare various thematic layers such as geology, geomorphology, lineament density, drainage density, land use and land cover, slope gradient, soil texture and rainfall intensity in order to map out the groundwater potential zones. Many researchers around the world have identified the groundwater potential zones using GIS and remote sensing with integrated weighted overlay analysis of AHP and GIS technique, weighted index overlay technique, Frequency ratio (FR) model (Adeyeye et al., 2017; Chaudary and Kumar 2018; Guru et al., 2017; Nsiah et al., 2018; Murasingh et al., 2018)

Analytical Hierarchy Process (AHP) method is a commonly used Multi-Criteria Decision Making (MCDM) technique to delineate groundwater potential zones (Murmu et al., 2019). However, there are considerable research carried out through other methods such as the probabilistic approach of frequency ratio (Manap et al., 2013), weights of evidence (Tahmassebipoor et al., 2016), fuzzy logic (Kumar et al., 2013), Shannon's entropy (Naghibi et al., 2015), machine learning techniques of maximum entropy (Rahmati et al., 2015) and index-based methods to assess the groundwater potential zones (Dar et al., 2010; Elewa and Qaddah 2011 Another beneficial technique for expanding the well-known logically-based GIS model for the integration of thematic layers is the Boolean logical approach. (Robinov 1989; Zaidi et al. 2015). It involves the incorporation of several binary maps, which are the products of the employment of conditional operators (Bonham-Carter 2013).

Identification of groundwater potential zones through the application of remote sensing and GIS has been common among many studies done worldwide, yet there are limited studies carried out so far in South Africa. Local domestic and agricultural water needs in Maputaland coastal plain are supplied from the Mbazwana municipality and local borewells. However, the supply of water through pipelines has been over-extended which has resultant inadequate flow and hence the households receive insubstantial water supply for their daily needs. Lake Sibaya was the main source of freshwater in this area, which is also under stress due to erratic rainfall and over-abstraction (Simonis and Nweze, 2016). Therefore, groundwater has become the only alternative for freshwater, but it is impracticable due to the expensive drilling costs and lack of proper understanding of the aquifer framework. The groundwater in this region is most predominantly abstracted from unconsolidated sedimentary aquifers due to its wide distribution and easy accessibility (Margat and Van der Gun 2013). In an account of this, it is very important to study and explore groundwater resources for present and future demand. The main objectives of this study are identifying and delineating the zones of groundwater potential via the integration of several thematic maps with the use of GIS and remote sensing techniques including various determinant factors of the Analytic hierarchy process (AHP) – Multi-criteria decision-making (MCDM) technique and Boolean logical approach. Delineating the groundwater potential zones will be helpful to the stakeholders and government organisations to locate suitable locations for the exploration of groundwater to supply demands.

5.2 Study area

The study area is situated within the Maputaland coastal plain in northern KwaZulu-Natal, South Africa and lies between 26°89″ to 27°86″ S latitudes and 32°12″ to 32°88″ E longitudes (Figure 2).

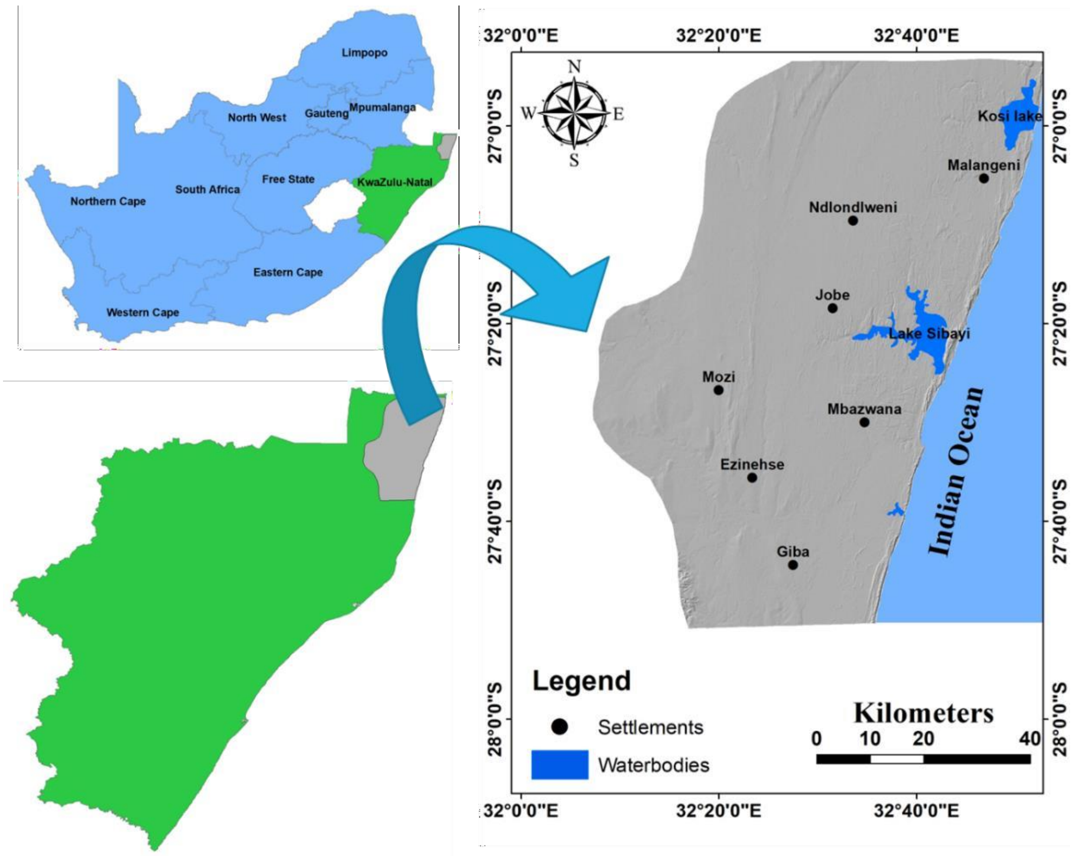

Figure 2: Map of study area

Stretching over 70 km wide beside the border of Mozambique, encompassed by the Lebombo Mountains on the west and its southern border to St. Lucia., The total area ranges about 5175 km^2.The area has a subtropical, humid climate with mean annual temperatures ranging from 21°C and average rainfall in the coastal areas is 1200-1300 mm per annum (Porter and Blackmore, 1998). The geological settings of the study area is Maputaland formation consisting of the Jozini formation, rhyolites from the Lebombo group (Jurassic period) (Watkeys et al, 1993). Lebombo mountain formation are inclined slopes of the Jozini rhyolites which is extended beneath the sea (Ceruti, 1999). The Makathini formation consists of non-marine, riverine coarse sandstone and conglomerate which forms the foundation of this regional aquifer. The formation possesses a very low hydraulic conductivity, porosity and storativity (acts as an aquiclude) and is overlain by the Mzinene Formation consisting of marine silts, clays and sands. The formation is varying with different aquifer types such as confined, unconfined and leaky aquifers. In Port Dunford, formations are laid down on top of the tertiary rocks which have low hydraulic conductivity and storativity and forms a leaky aquifer forming a connection to the Indian Ocean (Kelbe et al, 2016). This formation is overlain by Kosi Bay formations which are porous and more permeable promoting excellent recharge into the aquifers (Weitz & Demlie, 2014). The Maputaland coastal region is known for its barrier lakes, lagoons, swamps and well-vegetated coastal dunes. Further, off the coast, a counter-current exists formed by the local winds and wave refraction pushing the sand northwards and renews the sand on beaches creating the characteristic enormous dunes of the area which have reached the elevations of up to 180 m (Vaeret et al, 2009; Weitz and Demlie, 2014).

5.3 Methodology

The methodology adopted for this study is presented in Figure 2. There are different thematic layers like geology, geomorphology, land use, lineament density, drainage density, soil type, the slope of the area and rainfall of the region which are used to delineate the potential groundwater recharge zones. The data obtained from various organisations were utilized in the ArcGIS 10.5 software and was used for developing the various thematic maps. The maps of geology, land use and geomorphology were derived from data obtained from Council for Geosciences, South Africa and digitized using ArcGIS software. Land use data for the year 2010 was utilized in this study since no significant changes were observed in the last twenty years. Soil type data was obtained from Food and Agricultural Organisations. Rainfall data for the last twenty years (1999-2019) of 8 rain gauge stations were obtained from South African Weather

Service (SAWS). These data were interpolated using Inverse Distance Weighted (IDW) tool in ArcGIS software to obtain the rainfall distribution all over the study area.

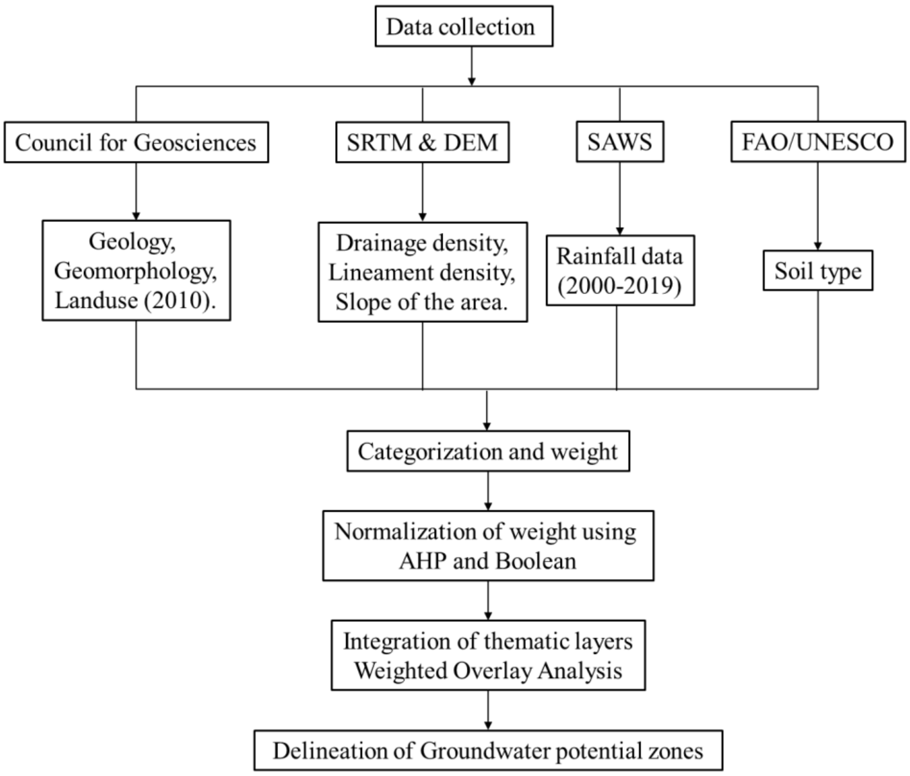

Figure 3: Flowchart of the adopted methodology

Using satellite imageries for Shuttle Radar Topography Machine (SRTM) 30 m resolution and Digital Elevation Model (DEM) 30 m resolution satellite imageries were accessed freely from USGS-Earth Explorer and was utilized to derive the slope, drainage pattern and lineaments of the study area. The drainage density and lineament density of the study area was calculated using line density analysis tool in ArcGIS software.

Satellite imageries and various thematic data were geocoded with Geographic Coordinated System of WGS 1984 and Projected Coordinated System of UTM WGS-84, zone 36 south. Further, the thematic layers were converted into raster format to perform weighted overlay analysis. Groundwater potential map was prepared under weighted overlay analysis using Analytic Hierarchy Process (AHP) and Boolean logic technique. Weighted overlay analysis was performed by assigning ranks for individual parameters.

5.4 Multi-Criteria Decision Making (MCDM) using the AHP technique

AHP technique (Saaty R.W, 1980) was used in this study. The 8 parameters were allocated a weight (1-9) based on their relative importance. The subclasses (sub-criteria) of each thematic layers were also ranked on a scale of 1 to 9 (Table 1), based to their relative influence on the groundwater occurrence. (Al-shabeeb, 2016).

5.5 Weightage calculation

The multi influencing factors such as geology, geomorphology, drainage density, land use, lineament density, drainage density, soil type, the slope of the terrain and rainfall of the area were evaluated and allocated with an appropriate weight as shown in Table 1. All factors were assigned a weightage from 1 to 9 according to Saaty's scale based on the relative importance and its significance. Value 1 denotes the very less importance between other thematic layers and the value 9 denotes very high importance of the thematic layers compared to another (Saaty, 1980).

The weights were normalized with MCDM-AHP techniques with the help of eigen values to remove the bias from assigned weights. To check the consistency of the weights of the different thematic layers and their subclasses, a consistency ratio was computed. The consistency ratio (CR) was calculated using the consistency index (CI) and random consistency index (RCI) using the equation given below (Saaty 1980). The different random consistency index for various criteria used in calculation is given in Table (2). Each pairwise comparison matrix was analysed using the below formulae (Table 3)

$$\text{CR} = \frac{CI}{RCI}$$

The principal eigen value was used to calculate the consistency index (CI) using the following equation (Saaty 1980).

$$\text{CI} = \frac{\lambda\,\text{max} - n}{n - 1}$$

where λ_{max} is consistency vector, n is the number of criteria used

The assigned and normalized weights of various thematic layers and the consistency ratio are shown in Table (4). The value of consistency vector (λ) was 7.84, the normalized weights were found to be consistent according to the consistency ratio (0.02) and found acceptable recommended by Saaty (1980).

5.6 Delineation of groundwater potential zones using Boolean logic

The Boolean logical approach is the most basic type of GIS model to integrate the thematic layers using binary code classification system. Each pixel of various thematic layers was assigned as zero for unsuitable locations and one for suitable locations. (Boole 1854; Freeze and Cherry 1979; Karanth 1987). The Boolean logic consists of its own operators Boolean AND & Boolean OR, which works with two or more datasets. The thematic layers and their subclasses were assigned with suitability limits of 0 and 1 based on their significance when delineating zones of groundwater potential (Table. 1).

Table 1:Random consistency indices for different number of criteria (Sharaf and Choudhury1998)

Thematic layer	**Influencing factor (%)**	**Features**	**Area (sq.km)**	**Area (%)**	**AHP-MCDM Assigned Weight**	**Classes**	**Boolean Binary weight**
Geomorphology	18	Low mountains	36.0	0.7	3	Unsuitable	0
		Moderately undulating plains	248.0	4.8	5	Suitable	1
		Plains	4891.0	94.5	7	Suitable	1
Geology	16	Arenite	2718.0	52.5	4	Suitable	1
		Rhyolite	35.6	0.7	2	Unsuitable	0
		Alluvium	1849.3	35.7	7	Suitable	1
		Siltstone	572.1	11.1	6	Suitable	1
Rainfall (mm)	13	547 - 600	505.0	9.8	4	Suitable	1
		601 - 650	1286.1	24.9	5	Suitable	1
		651 - 700	883.0	17.1	6	Suitable	1
		701 - 750	1382.0	26.7	7	Suitable	1
		751 - 800	1118.9	21.6	8	Suitable	1
Lineament Density (km/km^2)	13	0 - 0.1	4778.0	92.3	1	Unsuitable	0
		0.1 - 0.3	253.6	4.9	5	Unsuitable	0
		0.3 - 0.5	129.1	2.5	7	Suitable	1
		0.5 - 0.7	10.1	0.2	8	Suitable	1
		0.7 - 0.8	4.2	0.1	9	Suitable	1
Land Use	11	Bare land	10.0	0.2	4	Suitable	1
		Agri land	412.0	8.0	5	Suitable	1
		Degraded land	687.0	13.3	3	Unsuitable	0
		Exotic plantations	175.4	3.4	3	Unsuitable	0
		Grassland	872.8	16.9	6	Suitable	1
		Forest	167.5	3.2	4	Suitable	1
		Thicket and bushland	942.7	18.2	4	Suitable	1

		Waterbodies	121.7	2.4	6	Suitable	1
		Wetland	404.5	7.8	7	Suitable	1
		Open land	1381.3	26.7	8	Suitable	1
Soils	11	Lithosols	22.0	0.4	6	Unsuitable	0
		Chromic luvisols	796.0	15.4	5	Suitable	1
		Albic arenosols	4357.0	84.2	8	Suitable	1
Slope (Degree)	11	0 -1,5°	4120.0	79.6	9	Suitable	1
		1,6 - 2,5°	560.0	10.8	8	Suitable	1
		2,6 - 5,5°	375.0	7.2	6	Unsuitable	0
		5,6 - 12°	95.0	1.8	5	Unsuitable	0
		12,1 - 30°	25.0	0.5	4	Unsuitable	0
Drainage density (km/km^2)	7	0 - 0.5	3516.0	67.9	8	Suitable	1
		0.6 - 1	1107.9	21.4	6	Suitable	1
		1.1 - 1.5	370.9	7.2	3	Unsuitable	0
		1.6 - 2	151.0	2.9	2	Unsuitable	0
		2.1 - 2.5	29.0	0.6	1	Unsuitable	0

Table 2: Random consistency indices for the different number of criteria (Sharaf and Choudhury 1998)

No of Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Random Consistency indices (RCI)	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

5.7 Delineation of groundwater potential zones using MCDM approach

Groundwater potential zones were delineated by applying (WLC) method (Malczewski 2000), which helps to integrate criteria and combine the maps to acquire the groundwater potential zone map by AHP-MCDM approach. All the thematic layers were integrated in the ArcGIS environment using weighted overlay tool. The groundwater potential index (GWPI) was calculated using the equation:

$$GWPI = (GM_W \times GM_N) + (GE_W \times GE_N) + (LC_W \times LC_N) + (SO_W \times SO_N) + (RF_W \times RF_N) + (LD_W \times LD_N) + (SL_W \times SL_N) + (DD_W \times DD_N)$$

Where; GWPI=Groundwater Potential Index, GM=Geomorphology, GE=Geology, LC=Land use, SO=Soils, RF=Rainfall, LD=Lineament Density, SL=Slope, DD=Drainage density, w=normalised weight of the thematic layer, n=normalised weight of sub-criteria.

The maps of groundwater potential zones using AHP-MCDM and Boolean logic were verified by superimposing the point maps on raster data set.

Table 3: Pair-wise comparison matrix of thematic layers

Theme	Geomorphology	Geology	Soils	Land use	Rainfall	Lineament density	Drainage density	Slope
Geomorphology	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
Geology	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0
Soils	0.3	0.5	1.0	2.0	3.0	4.0	5.0	6.0
Land use	0.3	0.3	0.5	1.0	2.0	3.0	4.0	5.0
Rainfall	0.2	0.3	0.3	0.5	1.0	2.0	3.0	4.0
Lineament density	0.2	0.2	0.3	0.3	0.5	1.0	2.0	3.0
Drainage density	0.1	0.2	0.2	0.3	0.3	0.5	1.0	2.0
Slope	0.1	0.1	0.2	0.2	0.3	0.3	0.5	1.0
Total	2.7	4.6	7.5	11.3	16.1	21.8	28.5	36.0

Table: 4 Normalized Pair-wise matrix and normalized weight of various thematic layers

Theme	Geomorphology	Geology	Soil	Landuse	Rainfall	Lineament Density	Drainage Density	Slope	Normalized weights	Consistency ratio
Geomorphology	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.2	0.33	0.02%
Geology	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.23	
Soils	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.16	
Landuse	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.11	
Rainfall	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.07	
Lineament Density	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.05	
Drainage Density	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.03	
Slope	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02	

5.8 Results and discussion

5.8.1 Interpretation of the groundwater potential indices

Groundwater potential zone is regulated and influenced by several indices. These indices can be either natural or human-related factors. Geomorphology, lineament density, slope, geology, rainfall, soil type and drainage density ca be considered as natural factors affecting groundwater occurrence, while land use can be considered as a human-related factor as it is significantly affected by human activities. These changes can also significantly affect the groundwater quality (He and Wu 2019; He et al. 2019). The factors are discussed in detail as follows.

5.8.2 Geology

Geology of an area performs a pivotal function when it comes to surface water infiltrating into an aquifer system through the features of porosity and permeability, these features vary for different geological formations. The study area is underlain by pre-Cambrian granitoid basement which is overlain by unconsolidated to partially consolidated sediments derived from alluvium and aeolian deposits of the Late Pleistocene to Holocene (Barath 2015; Weitz and Demlie 2014). The study area comprises of Arenite, Rhyolite, Alluvium and siltstone which acts as aquifer in this region at varying thickness. Majority of the study area consists of sedimentary formations (Figure 4a). These sediments are highly permeable which ease rapid recharge to aquifer system. Geological formations were assigned with weights under AHP-MCDM technique and Boolean logic according to the significance of recharge (Table 1).

The alluvium and siltstone formation were assigned with the highest weight followed by arenite rocks in AHP-MCDM technique, and these formations were considered as suitable for groundwater recharge in Boolean logic (Table 1). Rhyolite formation was assigned with low weight and considered as unsuitable for infiltration since, this formation has very less permeability and are incapable to transmit water.

5.8.3 Geomorphology

Geomorphology of a region is considered as an indicator for identifying groundwater potential zones as it influential on the hydraulic properties of the aquifer system. The prominent geomorphologic features identified in the study area are low mountains, moderately undulating plains and plains. Most of the area is covered by plains (4891 sq.km) and part of south-western region is covered by moderately undulating plains (248 sq.km) and low mountain region (36 sq.km) (Figure 4b).

Plains has significant surface water infiltration potential areas, where the velocity of runoff is very slow and surface water tends to percolate into the aquifer owing to longer resident time. However, the moderately undulating plains and low mountain areas has lesser surface water infiltration when compared to plains having the highest infiltration capacity. Hence the highest weight of 7 was assigned to plains followed by moderately undulating plains with a weight of 5 using AHP-MCDM technique and these features were considered as suitable under Boolean logic, whereas low mountains were assigned AHP-MCDM weight of 3 and considered as unsuitable for groundwater infiltration under (Table 1).

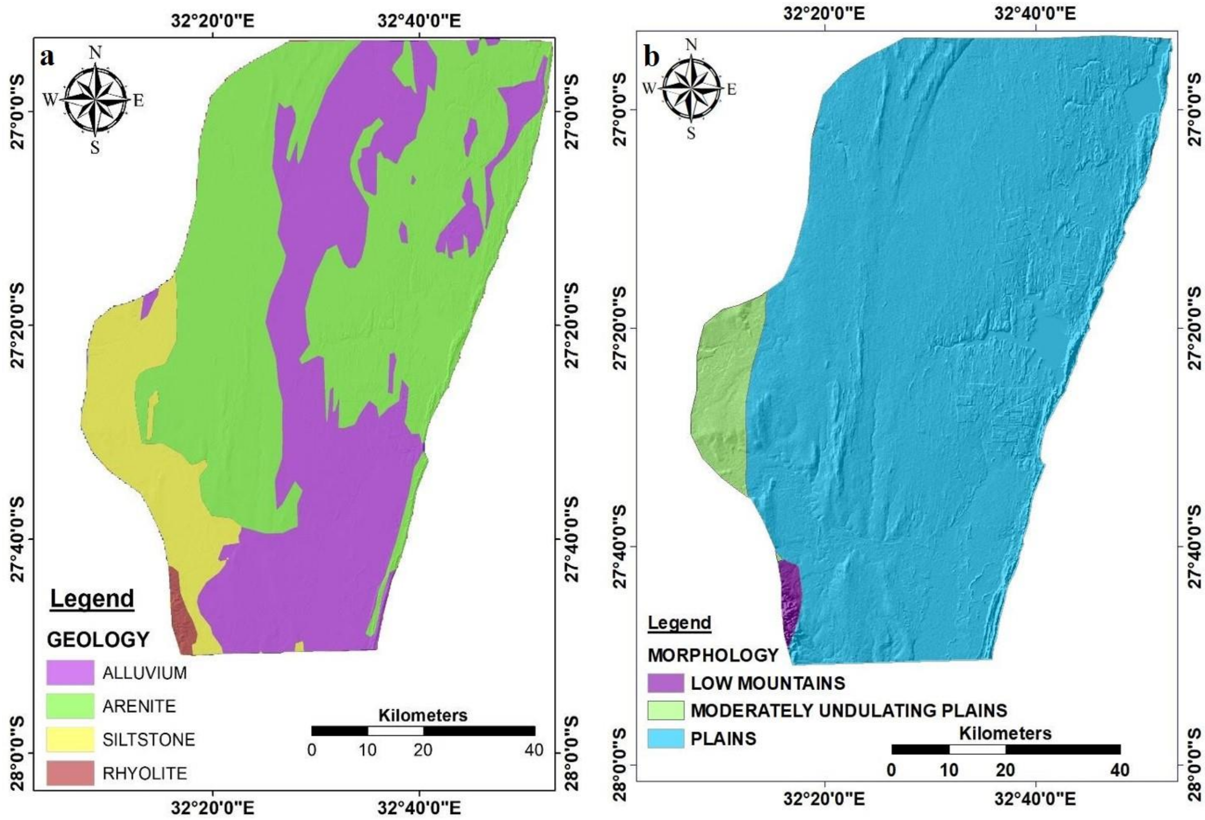

Figure 4: a) Geology and b) Geomorphology of the study area

5.8.4 Land use

A significant factor controlling the recharge of groundwater is the land use pattern. (Ghosh et al., 2016; Murmu et al., 2019). The land use pattern is significantly affected by human activities. Accurate and reliable information on the land-use pattern of an area is necessary to delineate the recharge zone (Singh et al., 2018). In the study area the major land use type is open land with less vegetation followed by agricultural land, degraded land without vegetation and plantation, water bodies and scrub/bushlands (Figure 5a).

Sugarcane cultivation is the major agricultural activity while maize, pineapple, citrus fruits, bananas and vegetables are cultivated in this area. A natural and commercial forest can be seen along the entire coast whereas commercial forest is the major resource for timber industries. Water bodies were given with the highest ranking of 8 due to the significance of continuous surface water recharge (Srivastava and Bhattacharya, 2006). The open land, agricultural land and grassland were provided with an assigned weight of 7 due to its potential surface water infiltration capacity through the roots of plants. Assigned weight of 6 was given to the degraded land and thick bushlands since evaporation rate is higher in these places. The weights assigned to different land-use types are given in Table (1). Other than degraded land and exotic plantations the rest of the regions were considered as suitable for infiltration, since degraded land has compact and very less permeable portions, the exotic plantation regions are dense where the less or no infiltration occurs. Most of the rainfall received in these areas has high runoff.

5.8.5 Slope

The slope of an area is the important factor to discriminate the surface morphology of an area (Zaidi et al., 2015) which governs the surface runoff velocity and erosion activity. Slope gradient governs the infiltration of surface water, where there is a lesser degree of slope, the recharge capacity is higher and at places of higher degree of slope, the recharge becomes lesser or negligible due to rapid runoff (Daher et al., 201 1; Magesh et al., 2012; Ghosh et al., 2016).

Degree of slope in the study area was classified into five classes like, 0 – 1.5 ° (very low) 1.5-2.5° (low); 2.5-5.5° (moderate); 5.5-12° (high); 12-30° (very high). Most parts of the study area having the lesser slope gradient (Figure 5b) has enhanced surface water infiltration. Hence the highest weight of 9 was assigned to very low slope gradient areas and were considered suitable for infiltration under Boolean logic approach. The assigned weight for different classes and suitability is shown in Table (1).

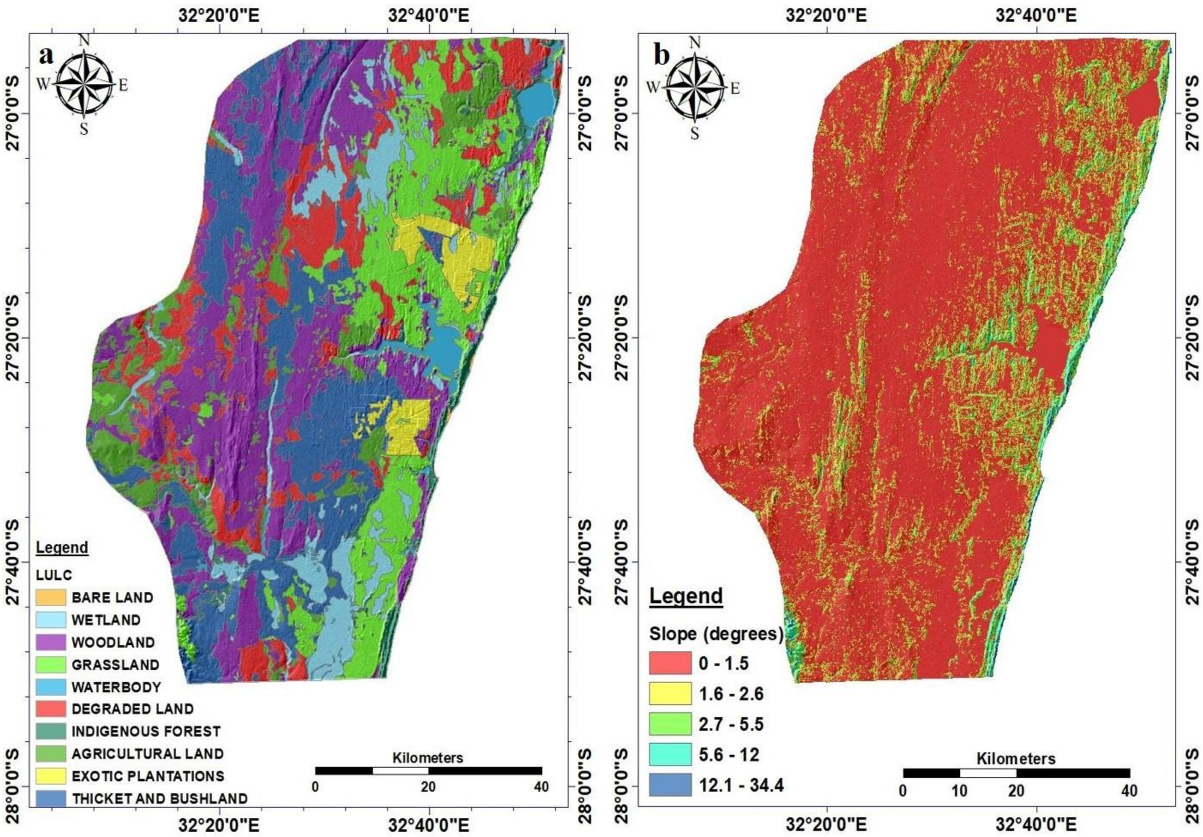

Figure 5: a) Land-use type and b) Slope of the study area

5.8.6 Lineament density

Lineaments are linear features found on the surface of the earth which reflects a superficial expression of subsurface structures like fault, fractures, dykes, etc., (Pradhan and Youssef 2010) which has highest secondary porosity and permeability (Magesh et al., 2012). Lineaments and its density are the important factors having more significance in the delineation of groundwater potential zones since it provides the information on pathways of groundwater flow (Magesh et al., 2012; Rahmati et al., 2015). Lineaments were identified in the northern and central part of the study area, which faces north-south direction extending 5 km – 25 km in length (Figure 6a). The lineament density was calculated from the total length of all lineaments divided by the area being investigated (Edet et al., 1994). It is derived by the following equation.

$$Lineament\ density = \sum_{i-l}^{i=n} \frac{Li}{A}\ (km^{-1})$$

where $\sum Li$ is the sum of the total length of lineaments (km); A is the area (km^2). The observed lineament density of the study area was classified in to 5 classes 0 – 0.1 km^{-1} (very low); 0.1 – 0.3 km^{-1} (low); 0.3 – 0.5 km^{-1} (moderate); 0.5 – 0.7 km^{-1} (high) and 0.7 – 0.8 km^{-1} (very high). Areas consisting of high lineament density are good for prospecting groundwater potential zones (Magesh et al., 2012). Hence highest weight of 9 and 8 were assigned under AHP-MCDM technique to very high and high lineament density zones and these regions were considered suitable under Boolean logic approach (Table 1).

5.8.7 Drainage density

Drainage density of an area is an important indicator to determine the hydrologic features which depicts the attributes of surface and subsurface formations. Drainage density can be defined as the closeness of spacing of streams, which can be measured as the total length of the drainage segment of all stream orders per unit area. Drainage pattern is affected by the qualities and structure of host rock, land use pattern, permeability of soils, vegetation covers and nature of slope gradient (Manap et al., 2013; Rahmati et al., 2015). Dendritic drainage pattern was observed throughout the study area, the drainage density was calculated by the proportion of the sum of lengths of streams to the total area being investigated. The drainage density was calculated by the equation given below.

$$Drainage\ density = \sum_{i-l}^{i=n} \frac{Di}{A}\ (km^{-1})$$

In an area if the drainage density is lesser then a higher infiltration rate and decreased runoff is observed. Hence, the areas having low drainage density are highly considered in delineating the groundwater potential zones. The drainage density of the study area was classified into five classes: 0 – 0.5 (very low); 0.6 – 1.0 (low); 1.1 – 1.5 (moderate); 1.6 – 2.0 (high); 2.1 – 2.5 (very high) as shown in Figure (6b). Most parts of the study area were characterised with very low to low drainage density, which enhances the greater infiltration rate. The highest weight of 8 and 6 were assigned respectively to very low and low drainage density classes under AHP-MCDM technique and were considered as suitable under Boolean logical binary code (Table 1).

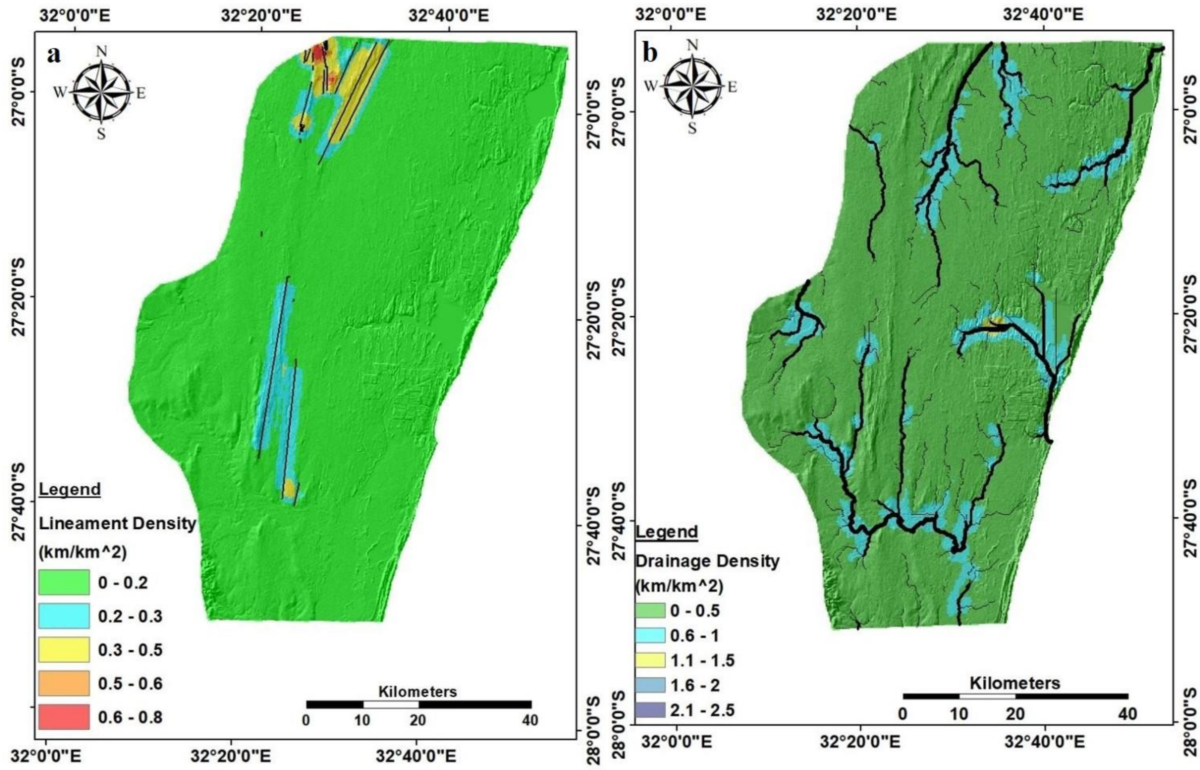

Figure 6: a) Lineament density and b) Drainage density of the study area

5.8.8 Soil type

Soil type is also a major factor that controls the infiltration capacity and governs groundwater recharge (Jang et al., 2013). Different soil types usually possess diverse soil permeability, which is highly dependent on the soil texture, soil structure and land cover of the area. The three main soil types present in the study area are arenosols, chromic luvisols and lithosols, (Figure 7a).

Arenosols are dominant in majority of the study area followed by chromic luvisols (Figure 6a). Arenosols comprises of sandy soils, developed in residual sands with highly siliceous having the highest permeability to infiltrate the surface water. Chromic luvisols are highly enriched with clay materials and lack of abrupt textural change and provide a slower infiltration rate compared with arenosols. Highest weight was assigned to Arenosols followed by chromic luvisols and lithosols (Table 1). Arenosols and chromic luvisols were considered as suitable for infiltration whereas lithosols was considered unsuitable to delineate the groundwater potential zones under Boolean logic approach (Table 1).

5.8.9 Rainfall

A major source of groundwater recharge is rainfall; hence it is considered as a significant input when delineating groundwater potential zones. (Adiat et al., 2012; Shekhar and Pandey, 2015). Rainfall helps to determine the quantity of water that will be recharged into the aquifer system. The maximum rainfall rate in the particular area enhances the possibilities of highest infiltration rate.

Annual average of the last 20 years (1999-2019) rainfall data were used in this study. The results obtained from these data were classified into five classes (Figure 7b) namely; (547-600 mm), (601 – 650mm), (651-700mm), (701-750mm) and (751-800mm). The highest weightage was assigned in the areas of higher rainfall observed (Table 1). However, rainfall has significant contribution in groundwater recharge, all the subclasses in rainfall were considered suitable for infiltration under Boolean logic binary code (Table 1).

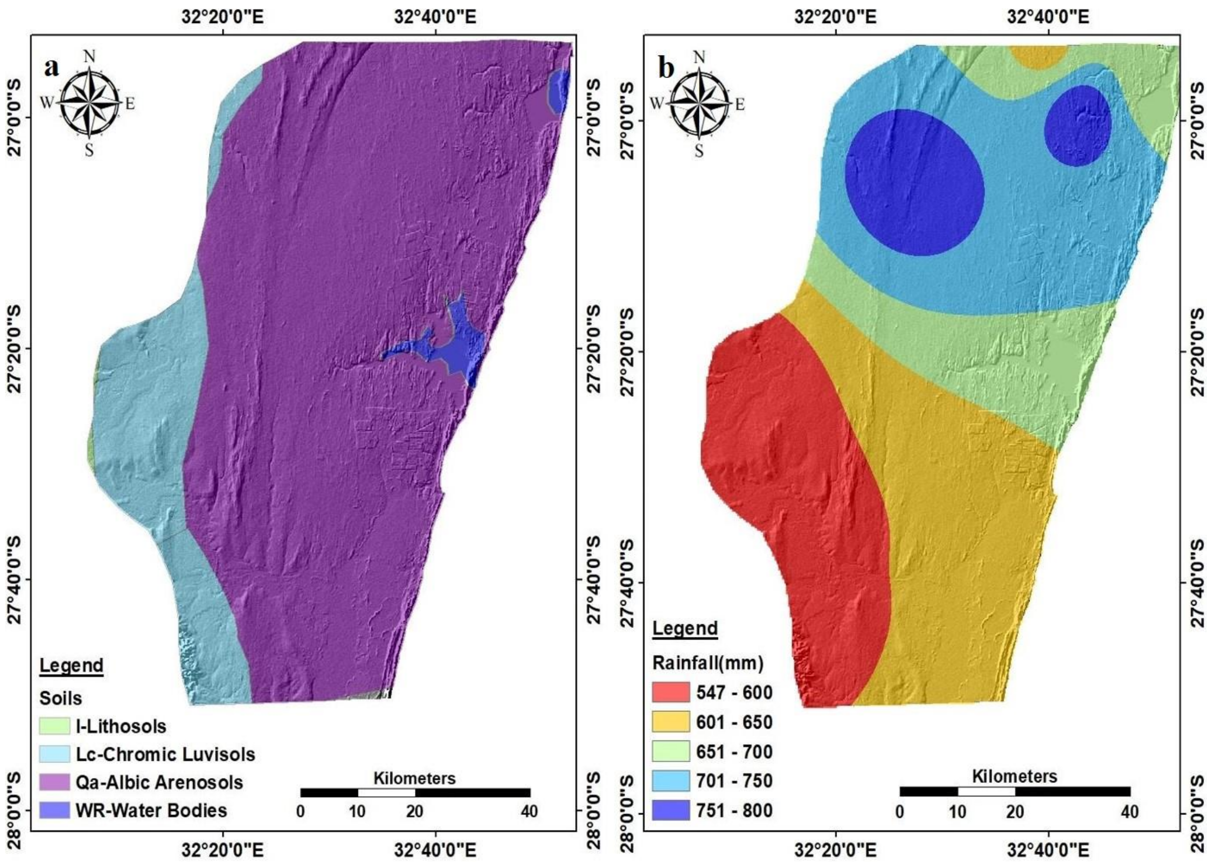

Figure 7: a) Soil type and b) Rainfall distribution map of the study area

5.9 Integration of thematic layers to delineate the groundwater potential zones

The final map of groundwater potential zones was generated through remote sensing and GIS techniques by integrating the various thematic maps viz., geology, geomorphology, Land use type, lineament density, drainage density, type of soil, and slope gradient by employing firstly the AHP technique and secondly, the Boolean logical model. The pictorial explanation of integrated thematic layers as overlay analysis is shown in Figure (8).

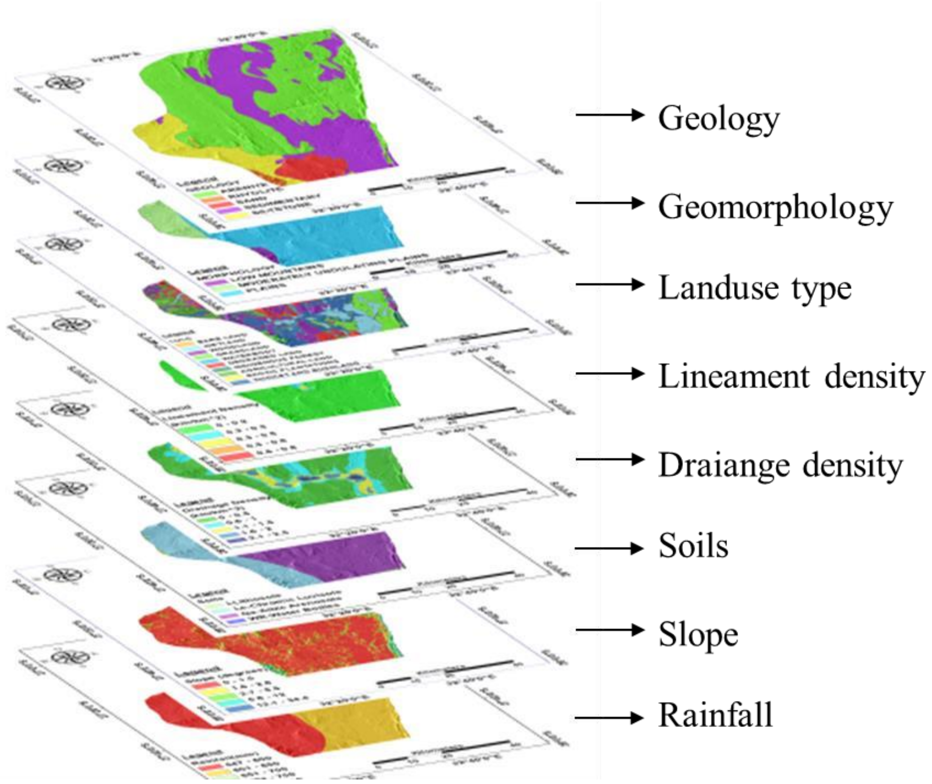

Figure 8: Integration of thematic layers in GIS

The groundwater potential zone prepared using the AHP-MCDM techniques in the study area was categorised into four sub-classes, namely very low, low, good, and very good groundwater potential zones (Figure 9a). the map of groundwater potential developed with Boolean logic was subdivided into two classes viz, poor and good groundwater potential zones (Figure 9b). About 6.0% (310.5 km^2) from the total area falls under very good; 67% (3467 km^2) good; 25% (1294 km^2) poor and 2% (103.5 km^2) very poor. The groundwater potential map developed using the Boolean logic approach have demarcated that about 70 % of the area (i.e. 3623 km^2) constitutes for good and 30 % (1552 km^2) of the area constitutes poor groundwater recharge capacity. In both the AHP and Boolean logic maps these common attributes were present in both maps. Due to high altitude and low mountains in the eastern and south-western part of the study area the potential groundwater recharge is identified as Very poor which makes runoff more rather than recharge. Poor groundwater potential zones are due to the presence of undulating topography, in the eastern and western stretches of the study area. It is observed from the topography that eastern border is dominated by sand dunes of about 180 m, and western part is covered by moderately undulating plain which favours more runoff. The presence of Luvisols in the western part has lesser permeability which is also the major reason for being categorised as a poor groundwater potential zone. The very good groundwater potential zones are identified in the northern part and it is due to geology, geomorphology and especially the cluster of lineament density were observed. Most of the agricultural areas in the study region allows groundwater recharge. This indicates that soil, geology, geomorphology, lineament density, land use and slope plays a vital role in groundwater potential zone mapping. The delineated groundwater potential zones under both AHP and Boolean logic technique give similar kind of results, which confirms the results. However, it is important to delineate the groundwater potential zones with more than one aspect to obtain confident results.

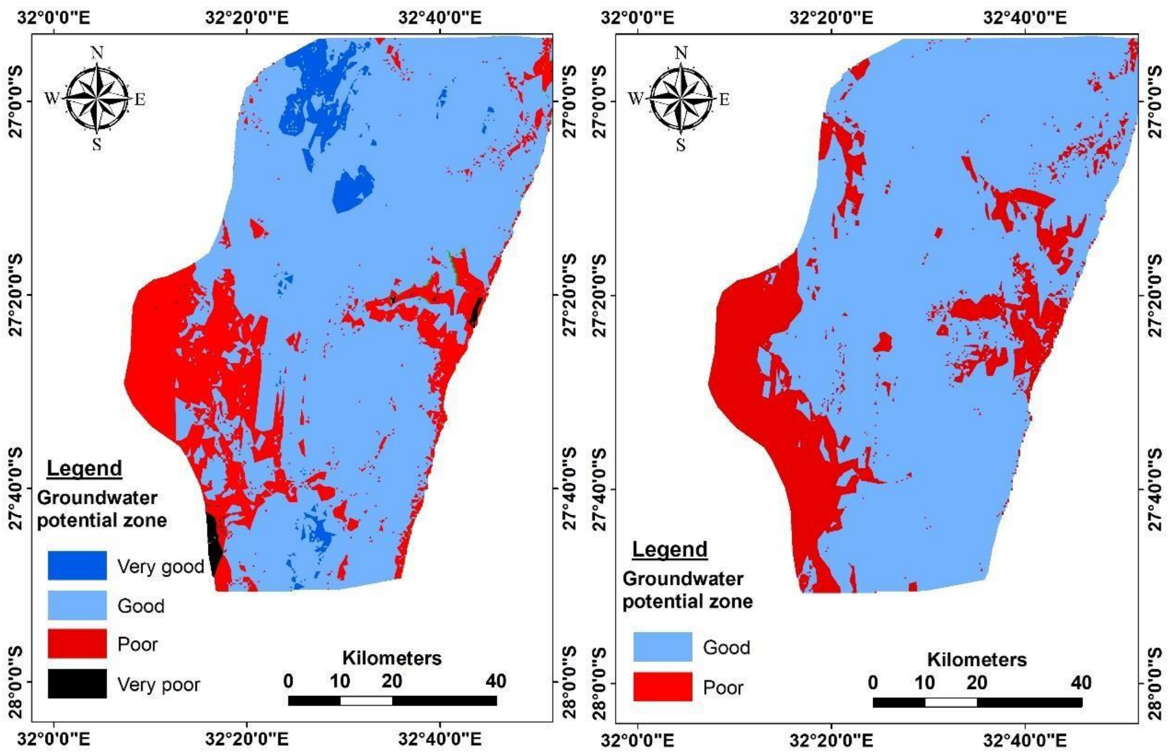

Figure 9: a) Delineated groundwater potential zones using AHP-MCDM technique and b) using Boolean logic

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CHAPTER 6: DETERMINATION OF POTENTIAL GROUNDWATER RECHARGE IN UMHLATHUZE CATCHMENT

6.1 Introduction

Even though water resources are renewable, they are unfortunately limited, with reservoirs that are recharged at varying rates. Surface water is fundamentally limited in arid and semi-arid regions due to periodic rainfall disturbances and rapid return of water into the atmosphere due to increased evaporation (Etikala et al. 2019), hence the human population's reliance on groundwater for commerce, water for drinking, and agriculture has become increasingly important (Shailaja and Kadam 2019; Luo et al. 2021). This makes groundwater one of the most precious natural resources as it is less prone to disturbances such as droughts playing a crucial role in guaranteeing a stable water supply across the world in the face of the changing earth's climate (Mogaji et al. 2016; Singh et al. 2018; Akter et al. 2020). According to the World Water Assessment Programs assessment in 2003, groundwater contributes roughly to nearly half of the water used in global residential water supplies, 40% of the water consumed in industrial operations, and 20% of the water utilized in agriculture (Souissi et al. 2018). However, groundwater is being depleted at alarming rate of 545 km^3 per year (Mussa et al. 2020; Makonyo and Msabi 2021) due to population increase, accelerated urbanization and industrialization, overdraft of groundwater, excessive demand in agricultural activities (Agyemang 2020; Kaur et al. 2020; Verma et al. 2020), overexploitation (Rajesh et al. 2021) widespread deforestation, climate change producing recurrent droughts, and the lack of surface water to meet these problems (Sachdeva and Kumar 2021). As a result groundwater contamination, over extraction of groundwater and even land quality degradation occurs (Arya et al. 2020). The condition and volatility of groundwater availability measurement necessary for efficient groundwater resource use are largely a result of groundwater recharge rate (Mogaji et al. 2015). Furthermore for an appropriate catchment management strategy, the quantifying of groundwater recharge is essential in shielding groundwater resources from the inevitable effects of climate change and other pressures (Goodarzi and Abedi-koupai 2016). There is no systematic strategy for the exploration of groundwater potential in a targeted area (Machiwal and Singh 2015) nor techniques which account for factors that influence groundwater potential, therefore groundwater resources are assessed and selected using traditional approaches such as experimental drilling and strata analysis (Roy et al. 2020) but these methods incur high costs, needs skilled labour, and requires a lot of time (Azma et al. 2021). Groundwater potential zones are influenced by many different hydrogeological parameters such as drainage density, lithology, slope, geomorphology, etc. (Machireddy 2019). Through the application of geoinformatics, different maps of hydrogeological parameters affecting the groundwater potential of a specific area can be produced and superimposed to form one combined layer (Kolandhavel and Ramamoorthy 2019). Many researchers have employed remote sensing and GIS techniques including the popular AHP in the identification of groundwater prospects around the world in different hydrological settings (Nasir 2018; Benjmel et al. 2020; Mukherjee and Singh 2020; Al-djazouli et al. 2021; Hagos and Andualem 2021; Tani and Tayfur 2021; Nugraha et al. 2022). Arshad et al. (2020) used a AHP and frequency ratio model to target groundwater potential recharge zones in Punjab, Pakistan. Various parameters were combined through weighted overlay analysis to produce a DRASTIC-based map and a groundwater potential recharge index map. Based on the final outcomes, both methods were recommended for the identifying of groundwater potential recharge zones. Panda et al. (2020) evaluated the Courtallam region, Tamil Nadu, India. Factors of geology, terrain morphology, hydrology, and hydrometeorology were combined using multi-criteria decision analysis. The results concurred that the model was suitable for targeting groundwater recharge potential zones with one-third of the region being overlapped by moderate groundwater recharge potentiality. Ghosh et al. (2020) developed an MIF approach to discover groundwater potential zones in India's Gandheswari watershed, considering seven factors. Upon validation of the groundwater potential zones map, it was revealed that the MIF technique had a high capability in delineating groundwater potential zones. Apart from the conventional approaches used , The emerging Catastrophe theory (Ahmed et al. 2015; Karimi and Khatibi 2020; Shahinuzzamani et al. 2021; Sun et al. 2021) was also used to analyse groundwater recharge potential. The Catastrophe theory was pioneered by Rene Thom (a French mathematician). Christopher E. Zeeman expanded on his ideas, proposing potential uses in a variety of sectors (Jenifer and Jha 2017). The Catastrophe theory judgment of the decision maker is not relied upon to give weights to elements, but rather ranks the importance of one criteria above the others via its embedded method (Al-abadi and Shahid 2015). The AHP and Catastrophe theory was used in exploring the groundwater potential of the Yamuna basin of India through the combination of eight factors. The validated maps of groundwater prospects revealed that the Catastrophe theory produced better results than the AHP (Kaur et al. 2020). Singh et al. (2020) used a form of a hybrid Catastrophe theory to map groundwater prospects in the Damodar Canal Command of India using eight selected qualitative and quantitative layers. The maps of geomorphology, soil, land use/land cover, and geology followed the principles of the AHP technique whilst maps of drainage density, slope, net recharge, proximity to surface water bodies followed the Catastrophe theory. The results shown in the final hybrid groundwater prospects maps indicated that the hybrid model had good capability in delineating groundwater potential zones with great reliability. The coastal lakes of uMhlathuze catchment include: Lake Nsezi, Lake Cubhu, Lake Mzingazi, and Lake Nhlabane (DWAF 2001) which are affected by ongoing problems of salinization, sewage effluent discharge, and urban runoff which lead to a shortage of water that is further exacerbated by persistent drought (Mkhwanazi 2010; Cimanga 2017). This study proposes the use of groundwater to meet the growing demands in a sustainable manner i.e., through groundwater potential recharge zones. This ensures that degeneration of a groundwater system is prevented and long-term groundwater depletion, reduced river flow, and water quality deterioration (Jakeman et al. 2016; Dalin 2021) is prevented. In South Africa, the number of aquifers investigated for groundwater potential is very limited (Owolabi 2020). Given the increasing shortage of water and environmental concerns caused by changing climatic conditions and an increase in the demand, this study was aimed at identifying prospective groundwater recharge zones by the application of a coupled GIS-remote sensing strategy of the uMhlathuze catchment in the Kwazulu-Natal province of South Africa with the objectives of: (i) the generation of nine thematic maps (geology, transmissivity, aspect, soil type, rainfall, drainage density, slope, land use/land cover, and morphology); (ii) quantification of weights for overlay analysis; (iii) delineation and validation of groundwater and validation of groundwater potential recharge zones.

6.2 Overview of the study region

6.2.1 Physiography and meteorology

The study region, uMhlathuze catchment (Fig. 10), occurs in the KwaZulu-Natal province of South Africa and spans over an aerial extent of 3402.50 km^2. It falls part of water management area six and is controlled by the uMhlathuze municipality (DWAF 2002). The close vicinity of the Indian ocean and its modifying impact on the local climate is a key influence on the weather experienced in the catchment, this is due to warm Mozambique current that offers a consistent heat source throughout the coast (Kelbe 2010). Summers are scorching with highs of more than 35°C, whilst winters are cold mostly across the northern and western portions of the region where temperatures sometimes drop below freezing and frost can develop (DWAF 2009). The rainfall ranges from 800 – 1300 mm along the coast and in the central regions, whilst further inland it ranges from 550 – 700 mm (SAWS 2020). The land uses present in the catchment consist of 15.5% of forestry, 14% of commercial agriculture, 19.5% of rural towns, 2.7% of urban settlements and other (industrial and mining undertakings). Lake Nsezi is surrounded by several enterprises including Mondi Kraft, Richard’s Bay Minerals, Bell Equipment, Tronox, and TATA steel, to mention a few, as well as large scale commercial forests and sugarcane plantations (Cimanga 2017).

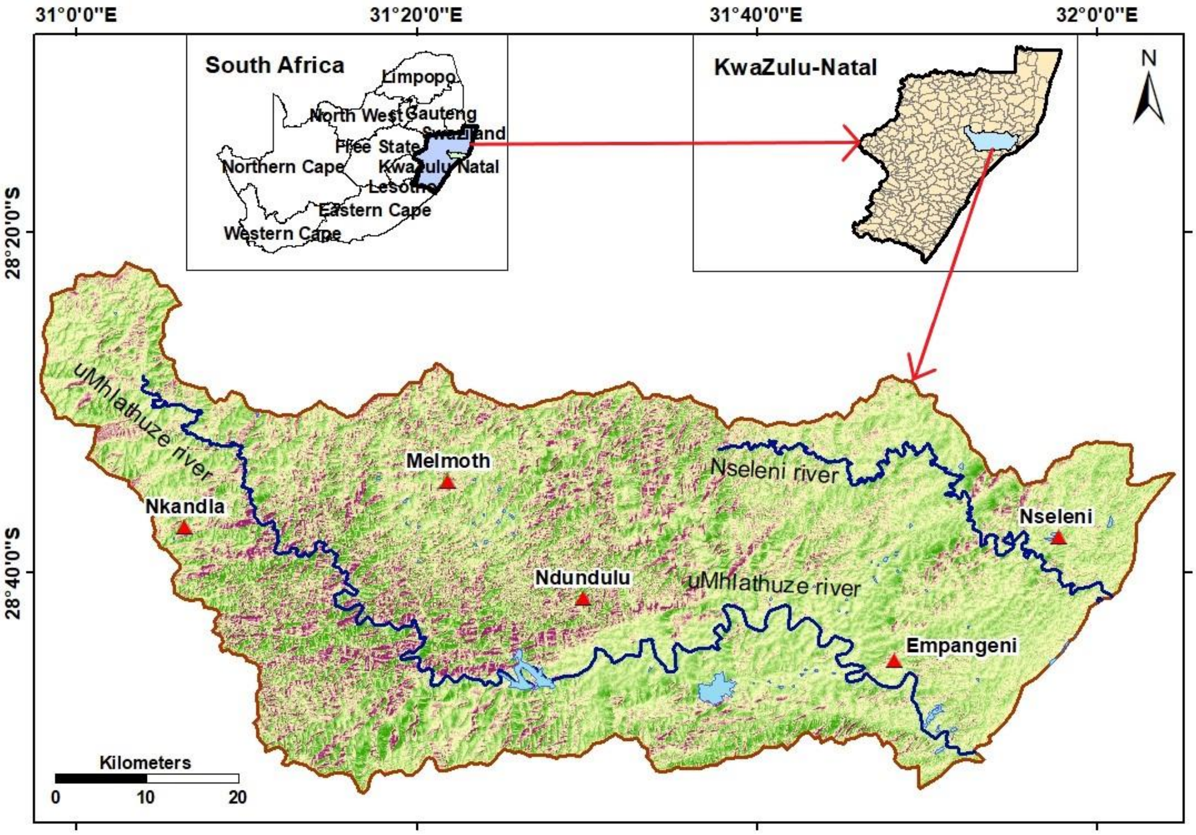

Figure 10: Study Area map of Mhlathuze catchment

6.2.2 Hydrogeology

The fundamental geological formations that make up the uMhlathuze catchment consists of the Karoo supergroup, basement complex, Natal group sandstones, extrusive, and artificial deposits (Omarjee et al. 2021). The Karoo supergroup consists of the Dwyka group followed by the Pietermaritzburg formation shales of the Ecca group overlaid by the Vryheid formation's light grey sandstones (DWAF 2009). The basement complex consists of granites, gneisses, greenstones and rocks of identical make up (Omarjee et al. 2021). The surficial deposits especially near the coastline of Richards Bay is made up of unconsolidated silt that was generated shorter than 55 million years ago by marine deposits of the Cretaceous system, which is mostly composed of siltstones with thin streaks of clay and limestone (Cimanga 2017). The Zululand Coastal Plain (closer to Mtunzini) consists of weathered and fractured secondary porosity aquifers. Faults and joints in the Karoo sedimentary rocks are areas of substantial groundwater presence. Granite and granite-gneiss rocks as well as those of the Vryheid formation and the Natal group, are normally the best aquifers, whereas the Dwyka Tillite formation is the worse. Groundwater yields from hard rock boreholes in the catchment are typically poor ranging from 0.15 to 0.65 ℓ/s, whilst greater yields to an extent of 2.5 ℓ/s can be achieved from boreholes in favourable locations. Yields from cased and screened boreholes in the Zululand Coastal Plain' deep aquifers are typically high ranging from 15 to 25 ℓ/s also featuring strong storativity and transmissivity ratings. Shallow aquifers on the plain often have poor transmissivity and yields of about 0.3 ℓ/s (DWAF 2009).

6.3 Materials and Methods

6.3.1 Data collection and software employed

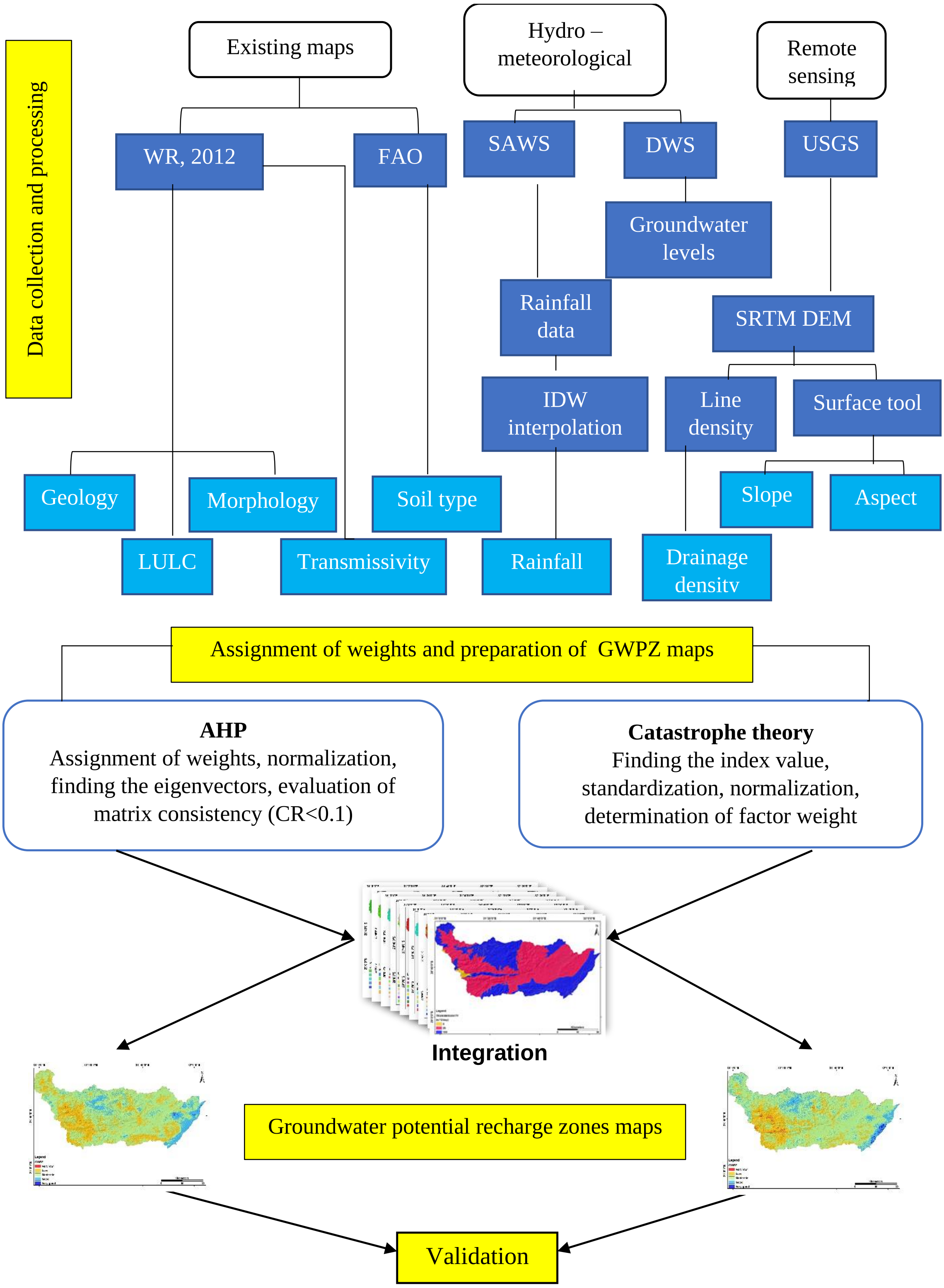

Figure 11: Flowchart of methodology adopted in this study

Shapefiles of geology, transmissivity, morphology, and land use/land cover were retrieved from the Water Resources Commission, 2012 and the Digital Soil Map of the World was used to create the soil type map (Fig. 11). The maps of drainage density was created by applying the surface and line density tools available in ArcGIS 10.5 to the SRTM DEM (The Shuttle Radar Topography Mission Digital Elevation Model) (USGS, 2020), whilst the maps of aspect and slope was produced by applying the aspect and slope tool, respectively to the SRTM DEM. To create the map of rainfall the mean annual rainfall data from 2010 to 2019 from different weather stations, provided by the South African Weather Services, occurring within the study area were plotted on the study area map in ArcGIS and then interpolated using the inverse distance weighting (IDW) interpolation tool of ArcGIS. For validation of the research, groundwater levels, total dissolved solids, and nitrate concentrations were retrieved from the Department of Water and Sanitation.

6.4 Assignment of weights using multi-criteria decision-making (MCDM) techniques

6.4.1 The Analytical Hierarchy Process (AHP)

The AHP technique is focused on building a series of matrices that apply comparative assessment of criteria against one another to decide which one is more significant (Al-shabeeb 2016). The AHP was created by Thomas L. Saaty who suggested that a comparative scale of 1 to 9 be used where 1 denotes equal importance and 9 signifies extreme importance (Saaty 1980) (Table 4).

Table 4: Saaty's scale of relative importance (Saaty, 1980)

Scale	**Degree of performances**	**Explanation**
1	Equally important	The contribution of the two factors is equally important
3	Slightly important	Experiences and judgment slightly tend to a certain factor
5	Quite important	Experiences and judgment strongly tend to a certain factor

7	Extremely important	Experiences and judgment extremely tend to a certain factor
9	Absolutely important	There is sufficient evidence for absolutely tending to a certain factor
2, 4, 6, 8	Intermediate value	In between two judgements

In this study, a total of ten factors affecting groundwater availability and occurrence namely lineament density, transmissivity, geology, morphology, land use/land cover, rainfall, aspect, drainage density, soil type, and slope were chosen. After a pertinent literature review and based on the comparative significance of factors and their elements to the presence of groundwater, appropriate weights according to Saaty's AHP scale then allocated to the factors and the sub-criteria. (Table 4 and Table 5).

Table 1: Weight of thematic layerand sub-criteriaby AHP

Thematic layer	**Weigh t**	**Sub-criteria**	**Weight s**
Geology	8	Sedimentary	8
		Amphibolite	2
		Arenite	4
		Basalt	3
		Dolerite	2
		Gneiss	2
		Granite	1
		Greenstone	4
		Mudstone	5
		Olivine gabbro	3
		Schist	6
		Shale	4
		Tillite	4
LULC	7	Built-up land	4
		Cultivated land	7
		Exotic plantations	7
		Grassland	8

		Indigenous forest	5
		Mines and quarries	2
		Shrubland/Fynbos	6
		Thicket and bushland	6
		Waterbodies	9
		Wetland	8
		Woodland	6
		Degraded land	3
Morphology	8	Escarpments	3
		Highly dissected hills	3
		Highly dissected low undulating mountains	2
		Low mountains	4
		Plains	8
		Undulating hills	4
		Undulating mountains and lowlands	5
Slope(degrees)	8	0 – 5	9
		6 – 10	6
		11 – 15	5
		16 – 20	3
		21 - 60	2
Rainfall(mm)	6	674 – 765	4
		766 – 855	5
		856 - 945	6
		946 – 1040	7
		1041 - 1135	9
Aspect	4	Flat	5
		North	1
		Northeast	3
		East	5
		Southeast	7
		South	9
		Southwest	7
		West	5
		Northwest	3
Transmissivity(m2/day)	6	5	1
		25	3
		100	6
Soil type	6	Eutric cambisols	3
		Rhodic ferralsols	5

		Chromic luvisols	6
		Orthic luvisols	6
		Albic arenosols	7
Drainage density(km/km2)	5	0 – 0.3	9
		0.4 – 0.5	8
		0.6 - 0.8	7
		0.9 – 1.1	6
		1.2 – 1.3	5
Lineament density(km/km2)	9	0 - 0.6	1
		0.7 - 1.1	3
		1.2 - 1.7	5
		1.8 - 2.3	6
		2.4 - 2.9	8

Table 6: Pairwise comparison matrix (PCM) of thematic layers

THEME	LD	MO	GEO	SL	LULC	TRANS	RF	ST	DD	ASP
LD	9/9	9/8	9/8	9/8	9/7	9/6	9/6	9/6	9/5	9/4
MO	8/9	8/8	8/8	8/8	8/7	8/6	8/6	8/6	8/5	8/4
GEO	8/9	8/8	8/8	8/8	8/7	8/6	8/6	8/6	8/5	8/4
SL	8/9	8/8	8/8	8/8	8/7	8/6	8/6	8/6	8/5	8/4
LULC	7/9	7/8	7/8	7/8	7/7	7/6	7/6	7/6	7/5	7/4
TRANS	6/9	6/8	6/8	6/8	6/7	6/6	6/6	6/6	6/5	6/4
RF	6/9	6/8	6/8	6/8	6/7	6/6	6/6	6/6	6/5	6/4
ST	6/9	6/8	6/8	6/8	6/7	6/6	6/6	6/6	6/5	6/4
DD	5/9	5/8	5/8	5/8	5/7	5/6	5/6	5/6	5/5	5/4
ASP	4/9	4/8	4/8	4/8	4/7	4/6	4/6	4/6	4/5	4/4
Totals	7.444	8.375	8.375	8.375	9.500	11.167	11.167	11.167	13.400	16.750

The eigenvector was then calculated to demonstrate the relative weight of each parameter with regards to recharge. The principal eigenvalue (λmax), which represents the addition of eigenvalues, is an indicator of the divergence of a matrix from general consistency (Lentswe and Molwalefhe 2020). The summing of products of column sums and eigen vectors in the matrix yields the result of a principal eigenvalue (λmax). Because inconsistencies in paired comparisons grow as the number of comparisons grows, AHP includes a consistency index for evaluating the assessments done in a matrix (Lentswe and Molwalefhe 2020). The principal eigenvalue calculated in the previous step is used to first find the consistency index by using the equation $CI = \frac{\lambda_{max}-n}{n-1}$ (Equation 1)(Brunelli 2015). Thereafter to assess the ultimate consistency of the matrix, a consistency ratio is calculated by using the consistency index and random consistency index (Table 4) as shown in the equation $CR = \frac{CI}{RCI}$ (Equation 2)(Brunelli 2015).

Table 2: Random consistency index (Saaty, 1980)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.56	1.57

AHP allows CR values between 0 to 0.1 or 10%, however anything more than 10% necessitates a re-evaluation of the comparisons (Lentswe and Molwalefhe 2020). The consistency ratio was found to be 0.08, hence the maps and their respective weights could be used to evaluate groundwater potential recharge zones.

6.4.2 The catastrophe theory

According to the Catastrophe theory, the reliance of conditioning parameters (variables) on the control parameters is established using fuzzy membership functions of the Catastrophe theory opposed to user-allocated weights. . The sub-criteria (of lineament density, transmissivity, geology, morphology, land use/land cover, rainfall, aspect, drainage density, soil type, and slope) class ranges are normalised from 0 to 1 using the logic of the Catastrophe theory in order to remove the influences of scales and units with different baseline data sets (Ahmed et al. 2015; Al-abadi and Shahid 2015; Jenifer and Jha 2017). By averaging each sub-criteria's class range, we can obtain the index value (X_i) (Table 8).

Table 3: Weights of thematic layers and sub-criteria by the Catastrophe theory where; Xi=Index value, Yi=Standardized value, Wi=normalized value, Mi=mean, and FWi=Factor weight

Factor	**Sub-criteria**	**Model type**	**X_i**	**Y_i**	**W_i**	**M_i**	**FW_i**
Drainage Density	0 – 0.3	Wigwam	0.15	1.00000	1.00000	0.6969	7
(km/km²)	0.4 – 0.5		0.45	0.72727	0.90024		
	0.6 - 0.8		0.7	0.50000	0.84090		
	0.9 - 1.1		1	0.22727	0.74355		
	1.2 - 1.3		1.25	0.00000	0.00000		
Geology (Sy)	1	Butterfly	1	1.00000	1.00000	0.53947	2
	0.26 - 0.33		0.295	0.25397	0.63618		
	0.05 - 0.2		0.125	0.07407	0.52169		
	0.015 - 0.04		0.055	0.00000	0.00000		
Aspect	157.5 - 202.5	Wigwam	180	1.00000	1.00000	0.73657	8
	202.5 - 247.5		225	0.73333	0.90271		
	247.5 - 292.5		270	0.46667	0.82652		
	292.5 - 337.5		315	0.20000	0.72478		
	337.5 - 360		348.75	0.00000	0.00000		
Land use/Land	Class 1= 1	Wigwam	1	0.00000	0.00000	0.68357	6
cover	Class 2= 2		2	0.25000	0.63288		
	Class 3= 3		3	0.50000	0.84090		
	Class 4= 4		4	0.75000	0.94409		
	Class 5= 5		5	1.00000	1.00000		
Morphology	Class F= 1	Butterfly	1	0.00000	0.00000	0.61844	4
(Terrain division)	Class E= 2		2	0.25000	0.63288		
	Class D = 3		3	0.50000	0.84090		
	Class A= 5		5	1.00000	1.00000		
Rainfall	674 – 766	Wigwam	720	0.00000	0.00000	0.6838	6
	767 – 857		812	0.25102	0.63373		
	858 - 949		903.5	0.50068	0.84118		
	950 – 1040		995	0.75034	0.94417		
	1041 - 1132		1086.5	1.00000	1.00000		
Soil Infiltration	Group D= 1.3 - 3.25	Butterfly	2.275	0.00000	0.00000	0.56398	3

	Group C/D= 4 - 7		5.5	0.09855	0.46549		
	Group C= 5.1 - 25		15.05	0.39037	0.79044		
	Group A= 30 - 40		35	1.00000	1.00000		
Slope(°)	0 – 6	Wigwam	3	1.00000	1.00000	0.75	9
	7– 11		9	0.84810	0.94708		
	12 – 17		14.5	0.70886	0.91757		
	18 – 24		21	0.54430	0.88546		
	25 - 60		42.5	0.00000	0.00000		
Transmissivity	5	Dovetail	5	0.00000	0.00000	0.53266	1
(m^2/day)	25		25	0.21053	0.59799		
	100		100	1.00000	1.00000		
Lineament	0 - 0.6	Wigwam	0.3	0.00000	0.00000	0.68328	5
Density	0.7 - 1.1		0.9	0.25532	0.63729		
(km/km^2)	1.2 - 1.7		1.45	0.48936	0.83639		
	1.8 - 2.3		2.05	0.74468	0.94274		
	2.4 - 2.9		2.65	1.00000	1.00000		

Thereafter, to eradicate discrepancies in the index value's scales and units the index values are then standardized (Jenifer and Jha 2017) using the following equations:

Bigger the better/Directly proportional: $Y_i = \frac{x_i - x_{i(min)}}{x_{i(max)} - x_{i(min)}}$ (Equation 3)(Singh et al. 2020)

Smaller the better/Inversely proportional: $Y_i = \frac{x_{i(max)} - x_i}{x_{i(max)} - x_{i(min)}}$ (Equation 4)(Singh et al. 2020)

Depending on the type of catastrophe model (Table 9), standardization is succeeded by a normalization procedure. Analysis of all control variables may be approximated from initial fuzzy subordinate functions using the normalizing formulae of the Catastrophe theory using the normalizing formulae (Table 10). There are two concepts that may be used to derive normalized values of data: the complementary and the non-complementary (Zhang et al. 2009; Cheng et al. 1996). Under the complementary principle, it states that the state parameters (a, b, c, d) of a scheme balance each other.

Table 4: Seven types of Catastrophe models (Singh et al., 2020)

Catastrophe model	Control parameters	State variables	Potential function
1. Fold	1	1	$1/3x^{3+}ax$
2. Cusp	2	1	$1/4x^4 + 1/2bx^2 + ax$
3. Dovetail	3	1	$1/5x^5 + 1/3cx^3 + 1/2bx^2 +ax$
4. Butterfly	4	1	$1/6x^6 + 1/4dx^4 + 1/3cx^3 + 1/2bx^2 + ax$
5. Oval Umbilici Point	3	2	$X^3 - y^3 + ax + by + cxy$
6. Elliptic Umbilici Point	3	2	$X^3 - xy^2 + ax + by + cx^2 + cy^2$
7. Parabolic Umbilici Point	4	2	$X^2y + y^4 + ax + by + cx^2 + dy^2$

Table 5: Catastrophe models and their normalization formulas (Jenifer and Jha, 2017)

Model	Control variables	State variables	Function
Cusp	2	1	$X_a = x^{1/2}$, $x_b = x^{1/3}$
Swallowtail	3	1	$X_a = x^{1/2}$, $x_b = x^{1/3}$, $x_c = x^{1/4}$
Butterfly	4	1	$X_a = x^{1/2}$, $x_b = x^{1/3}$, $x_c = x^{1/4}$, $x_d = x^{1/5}$
Wigwam	5	1	$X_a = x^{1/2}$, $x_b= x^{1/3}$, $x_c = x^{1/4}$, $x_d = x^{1/5}$, $x_e= x^{1/6}$

Therefore, the average value is the system's parameter $\mathcal{X} = (\mathcal{X}_a + \mathcal{X}_b + \mathcal{X}_c + \mathcal{X}_d)/4$whereas, under the rules of a non-complementary principle the control variables cannot be balanced by one another hence, the state parameter of a system is identical to the system's lowest value $\mathcal{X} = \min(\mathcal{X}_a, \mathcal{X}_b, \mathcal{X}_c, \mathcal{X}_d)$ (Zhang et al. 2009; Cheng et al. 1996). For this study, the complementary principle was used to deduce the mean weights in this study.

6.5 Computation of the groundwater potential index (GWPI) and weighted overlay analysis through the AHP and Catastrophe theories

The nine thematic layers consisting of geology, soil type, transmissivity, morphology, Land use/land cover, drainage density, aspect, rainfall, and slope were reclassified into their respective weights for both the factors and the sub-criteria. Weighted linear combination was applied to obtain the GWPI for both the AHP and Catastrophe theory i.e., $GWPI = (GE_W \times GE_R) + (ST_W \times ST_R) + (TR_W \times TR_R) + (MO_W \times MO_R) + (LULC_W \times LULC_R) + (DD_W \times DD_R) + (AS_W \times AS_R) + (RF_W \times RF_R) + (SL_W \times SL_R) + (LD_W \times LD_R)$ (Equation

5), where GWPI= groundwater potential index, GE= geology, ST= soil type, TR= transmissivity, MO= morphology, LULC= land use/land cover, DD= drainage density, AS= aspect, RF= rainfall, SL= slope, LD= lineament density, W= weight of factor, and R= weight of sub-criteria. The GWPI was used to integrate all thematic layers in ArcGIS by applying the weighted overlay tool in order to produce the maps of potential groundwater recharge zones for both the AHP and Catastrophe theory.

6.5.1 Validation

In order to validate the outputs of both the AHP and Catastrophe theory total dissolved solids, nitrate concentration, and groundwater levels were employed for validation. The Department of Water Affairs provided data for 79 boreholes available in the catchment for the year 2005. These values were superimposed onto the map of the study region and then the values interpolated using IDW interpolation in ArcGIS.

6.7 Results and discussion

6.7.1 Lineament Density

Any joint, fracture or fault occurring on the surface of the earth is referred to as a lineament. They create conduits for groundwater flow and secondary porosity in hard rock environments (Pani et al., 2016) and play an extremely important role in groundwater recharge, as high rates of infiltration are experienced in groundwater regions with lineaments and junctions of lineaments provide suitable locations for groundwater recharge and storage (Samson and Elangovan, 2015; Murmu et al., 2019). The lineament density of the uMhlathuze watershed (Fig. 12a) is relatively high with the highest-class range of '2.4 – 2.9 km/km^2' covering an area of 5.30 km^2. The lowest lineament density range of '0 – 0.6 km/km^2' covers an area of 1899.06 km^2. The highest concentration of lineaments occur under the 'Amphibolite', 'Arenite', Basalt', 'Dolerite', and 'Granite' geology (hard rock regions) making these areas more susceptible to groundwater recharge, whilst the lowest concentration of lineaments fall under areas covered by sedimentary type rocks. For the AHP, the lineament density layer was assigned a weight of 9 and the highest and lowest range were assigned weights of 8 and 1 respectively. For the Catastrophe theory, the lineaments density layer weight was evaluated as 5 whilst the highest and lowest range weights were evaluated as 9 and 1 respectively.

6..7.2 Drainage density

The distance of all orders of flow segments per unit of area can be defined by drainage density; drainage density shares an inverse relationship with permeability (Ramachandra et al. 2021). Drainage density is affected by bedrock, soil infiltration capacity, vegetation, and slope angle, and drainage patterns depict the pattern of rivers and streams throughout geological formations (Mogaji et al. 2016). The lower the drainage density the greater the infiltration hence more recharge will occur and vice versa (Saranya and Saravanan 2020). For AHP, the drainage density layer (Fig. 12b) was allocated a weight of 5 and greatest range (with the lowest possibility of recharge occurring), '1.2 – 1.3', was given the lowest rating of 5, but the lowest range, '0 – 0.3', which is most appropriate for GRPZ, was assigned the highest rating of 9 takes up 2124.13 km^2 of the catchment, an excellent signal that recharge is taking place. Whereas for the Catastrophe theory, the drainage density layer factor weight was calculated as 5 and greatest range, '1.2 – 1.3', was given a rating of 1, but the lowest range, '0 – 0.3', was given the highest rating of 9.

6.7.3 Rainfall

The catchment's rainfall was plotted over a 10-year span using an average of 9 gauges (Fig. 12c). Rainfall is a critical component of groundwater recharge since it is one of the principal recharge sources. The higher the quantity of rainfall, the greater the likelihood of recharging. For the AHP the rainfall layer was given a rating of 6, whilst for the catastrophe theory the factor weight was evaluated as 6. The watershed receives the most rainfall in the east and north-west, whereas the catchment receives the least rainfall in the extreme west. Rainfall falls in the range of '858 – 949mm' for 1616,2 km^2 of the catchment, with the maximum rainfall falling in the range of '1041 – 1132mm' for 298.57 km^2 of the watershed and the smallest falling in the range of '674 – 766mm' for 206.02 km^2 of the catchment.

6.7.4 Slope

The slope element is extremely relevant since it controls the reaction rate with water. The steeper the slope, the greater the runoff and, thus, the shorter the period for water collection, infiltration, and recharging into the saturated zone. The higher the gentleness of the slope, the longer water has to enter and hence the bigger the groundwater recharge (Karami et al. 2016).

The general slope of the region is relatively flat (Fig. 12d). For the AHP, the slope layer was assigned a weight of 8 and the lowest slope class was determined to be '0 - 6°' (1045.10 km^2) and was assigned a weight of 9, while the greatest slope class was determined to be '25 - 60°' (164.62 km^2) and was assigned a weight of 2. For the Catastrophe theory, the slope layer's factor weight was determined as 9 and the lowest class range '0 - 6°' and highest-class range '25 - 60°' weights were evaluated as 9 and 1 respectively.

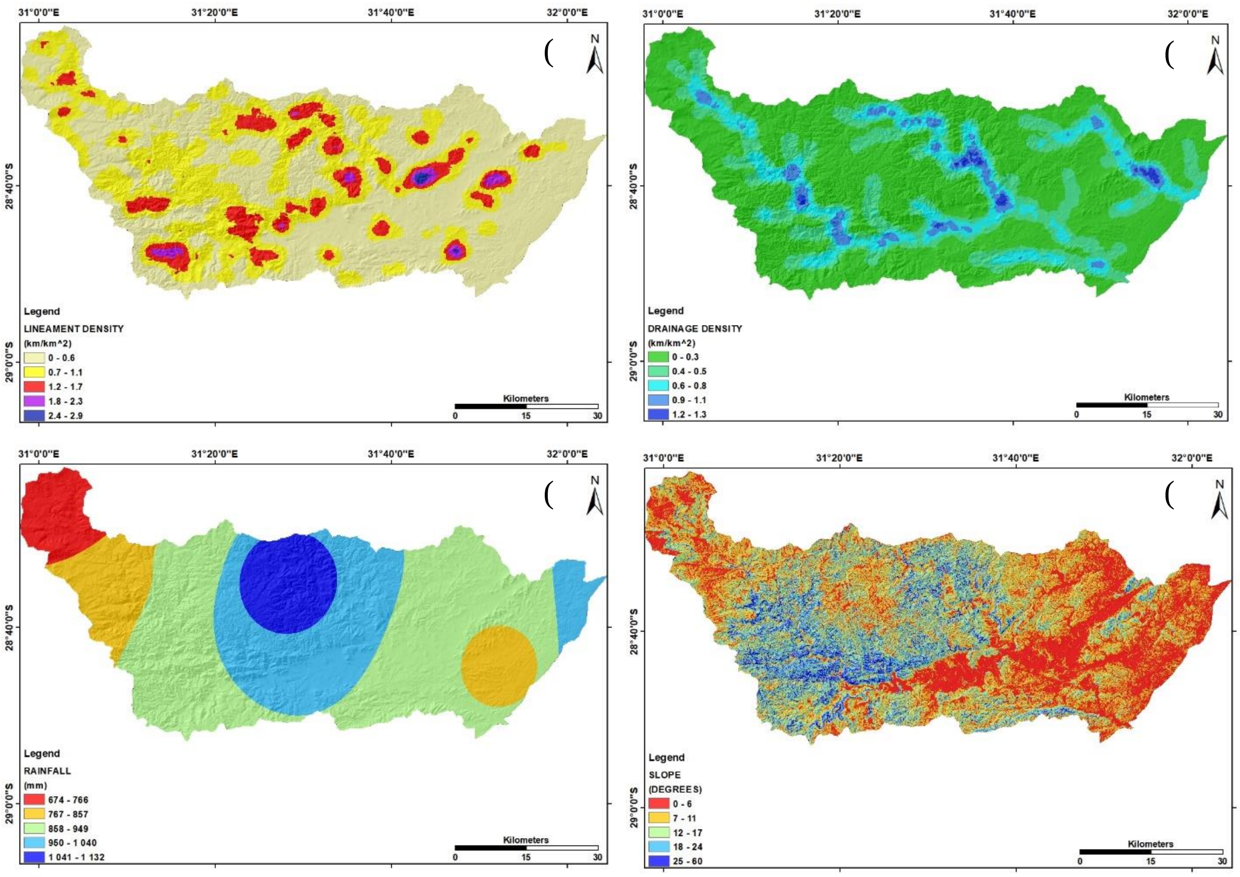

Figure 12: Thematic maps of the study area; a) Lineament density, b) Drainage density, c) Rainfall, and d) Slope

6.7.5 Transmissivity

The rate of movement of groundwater horizontally across an aquifer is defined as transmissivity (Kanagaraj et al. 2019). Transmissivity is a critical aquifer parameter that varies from hydraulic conductivity because it applies to the full thickness of an aquifer under saturation, while hydraulic conductivity is defined for unit thickness of a saturated aquifer (Şen 2015). The transmissivity attributes for the research region are rather low and fall into three separate classes (Fig. 13a), namely 5 m^2/day (33.35 km^2), 25 m^2/day (1941.16 km^2), and 100 m^2/day (1427.99 km^2). For AHP these classes were assigned with weights of 1, 3, and 6 respectively, whereas for the Catastrophe theory these classes weights were determined as 1, 3, and 9. The bulk of the research area was encroached upon by 100 m^2/day transmissivity.

6.7.5 Aspect

Aspect is a factor that determines amount of solar energy, which is linked to evapotranspiration (Singh et al. 2019). The sun's angle varies in two ways i.e., between the southern and northern hemispheres, and between the northern and southern facing slopes. Because the sun rises in the northern section of the skies in the southern hemisphere, a slope oriented facing north will be warmer. The northern hemisphere's south-facing slopes are the warmest because the sun remains mostly in the southern half of the sky (Bennie et al. 2006). Flat ground receives less solar energy than slopes facing north and greater solar energy than slopes facing south. As a result, flat land receives the equivalent amount of solar radiation as slopes pointing east and west (Singh et al. 2019).The northern slopes of an area contribute the least amount of water to the recharge of groundwater because northern slopes experience a greater amount of evapotranspiration which significantly reduces the amount of water accessible to percolate and become groundwater. The best percolation occurs on a slope that faces south. The aspect of the region can be seen in (Fig. 13b). For the AHP, the aspect parameter was given a weight of 4 and the nine classes were assigned weights relative to their influence i.e., 'flat'=5, 'north'=1, 'northeast'=3, 'east'=5, 'southeast'=7, 'south'=9, 'southwest'=7, 'west'= 5, and 'west'=5, but for the Catastrophe theory as the maximum number of parameters or criteria that can be used in the model is 5, therefore criteria were grouped according to similar influences i.e., 'flat, east, west'=5, 'northeast, northwest'=3, 'southeast, southwest'=7, 'north'=1, and 'south'=9. The factor weight was estimated as 8.

6.7.6 Geology

The in situ presence and flow of groundwater is determined by the underlying rocks' distinctive permeability and porosity abilities and the surface rocks have a significant influence in groundwater recharge, infiltration rate, and runoff rate (Yeh et al. 2016), hence we can gather information about the subterranean dispersal of groundwater (Gyeltshen et al. 2020). By mapping the lithology of the region (Fig. 13c) it was revealed that the catchment's eastern section is dominated by 'Sedimentary' (46.08 km^2) while the western portion is studded with

'Shale' (286.29 km^2), 'Tillite' (471.96 km^2), 'Arenite' (913.36 km^2), 'Granite' (519.42 km^2), and 'Greenstone' (228.23 km^2). For AHP, the geology layer was given a weight of 8, and because of its coarse texture and increased penetration rate, 'Sedimentary' was given the highest weight of 8, the lowest weight of 1 was assigned to 'Granite'. When geology was evaluated for the Catastrophe theory, due to the model only accepting a maximum of five values, the geology of the area was grouped according to their specific yields (S_y). 'Basalt' S_y=1, 'Sedimentary, Arenite, Mudstone, Schist' S_y=0.26 – 0.33, 'Greenstone, Shale, Tillite' S_y=0.05 – 0.2, and 'Gneiss, Dolerite, Granite, Olivine gabbro, Amphibolite' S_y=0.015 – 0.04 (Morris and Johnson, 1967; Heath, 1983).

6.7.7 Land use/Land cover

The LULC map (Fig. 13d) depicts the impact of different types of land use/land cover on percolation and groundwater storage.

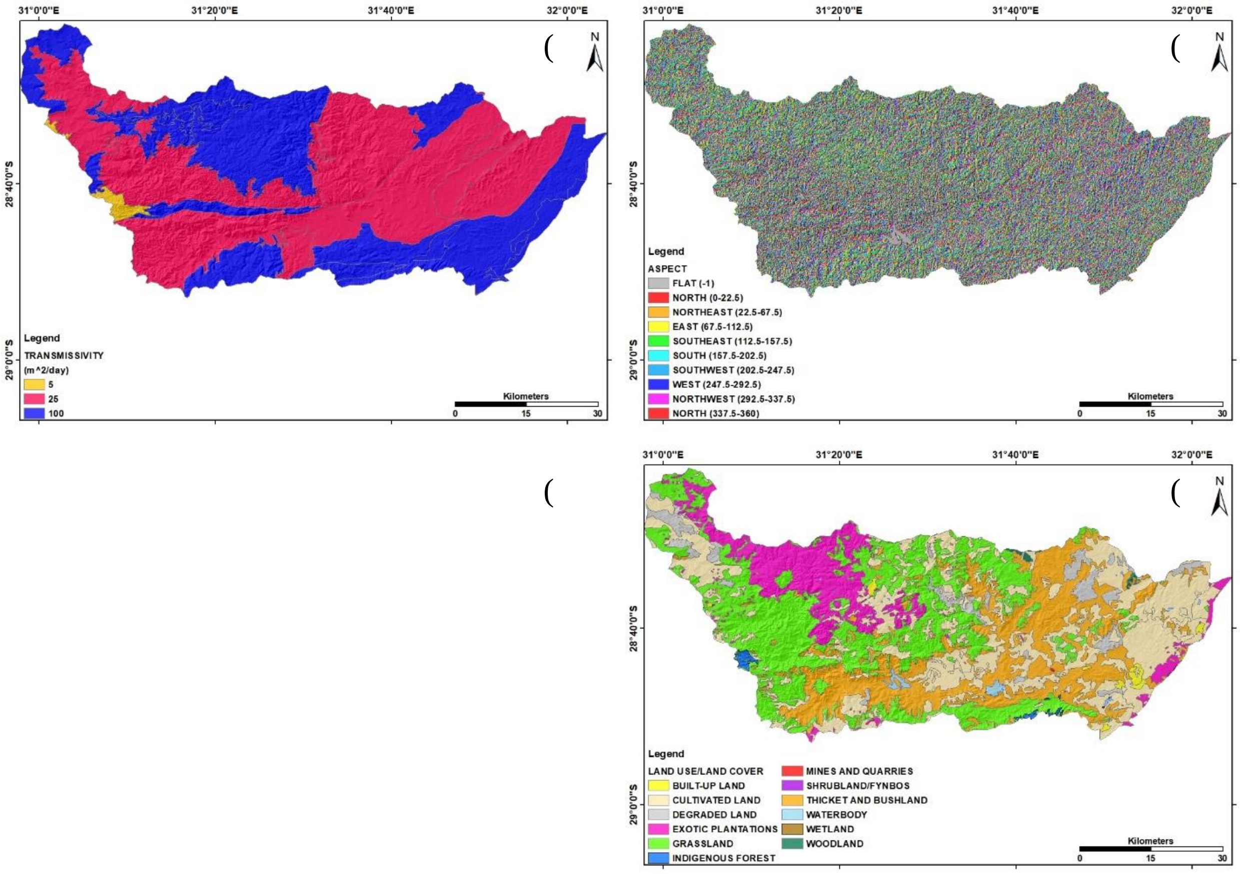

Figure 13: Thematic maps of the study area; a) Transmissivity, b) Aspect, c) Geology, and d) Land use/ Land cover

For example, built-up land (business and residential) has a high rate of runoff, leaving little water to infiltrate; therefore, it is classified as low potential, whereas cultivated land, thicket, bushland, and grassland promote water infiltration in an area and are affiliated with good and very good groundwater probability (Rajasekhar et al. 2020). The speed of infiltration, however, is not the only element influencing groundwater prospects; the kind of vegetation also has an impact on percolation. This has to deal with the rate of evapotranspiration. The more the vegetation, the higher the rate of evapotranspiration (Pani et al. 2016) and, as a result, the lesser the chances of infiltration and percolation to the subterranean and groundwater storage. For AHP, the LULC layer was assigned a weight of 7. The preponderance of 'Shrubland and Fynbos' (0.19 km^2) 'Thicket and Bushland' (815.38 km^2), and 'Woodland' (7.67 km^2) reveals a high chance of groundwater and was assigned a rating of 6, while 'mines and quarries' and 'built-up land' were assigned a rating of 2. The catchment's major land use was discovered to be Grassland,' which spans an area of 1042.47 km^2 followed by 'Cultivated land' (956.39 km^2). For the Catastrophe theory the LULC classes were grouped according to their effect on infiltration and the effects of evapotranspiration on the type of LULC. Class I/Very poor= 'Built-up land, Mines and quarries', Class II/Poor= ', Degraded land', Class III/Moderate= 'Grassland, Shrubs, Thicket and Bushland, Cultivated land', Class IV/Good= 'Indigenous forest, Exotic plantations, Cultivated land', and Class V/Excellent= 'Waterbodies, Wetlands'. The factor weight was determined as 7.

6.7.8 Morphology

The underlying rocks and geology have a significant impact on an area's shape. It connects bathymetry and terrain to show how characteristics of the surface of the earth evolve (Deepa et al. 2016). Plains have the highest water retention capabilities; hence they are given the highest ranking since groundwater prospects are better. They are made of a porous and permeable substance (Samson and Elangovan 2015). Because hills and mountains have minimal capability for infiltration and a high runoff rate, the groundwater prospects are limited .For AHP, the morphology layer (Fig. 14a) was assigned a weight of 8 and 'Plains' had the maximum rating of 8 and covered an area of 222.23 km^2, 'Highly dissected low undulating mountains', was given the lowest weight of 2 and overlapped an area of 2608.28 km^2. For the Catastrophe theory, the morphology was classified according to the terrain morphology divisions by Schulze and Kruger (2007) i.e., Class F= 'Escarpments', Class E= 'Highly dissected low undulating mountains, Highly dissected hills, Low mountains, Undulating hills', Class D= ‘Undulating mountains and lowlands’, and Class A= ‘Plains’ and the factor weight was calculated as 4.

6.7.9 Soil type

The soil type of a region is a significant aspect in determining groundwater potential recharge zones. The water retention capacities of a region is determined by the types of soils and their permeability. Soil primarily influences infiltration and percolation processes, which in turn affect groundwater recharge and, ultimately, groundwater potential in a specific location.(Berhanu and Hatiye 2020). The soil type map (Fig. 14b) shows four primary soil types: 'Cambisols,' 'Ferralsols,' 'Luvisols,' and 'Arenosols.' The major soil group is 'Luvisols' (1335.79 km^2), with 'Cambisols' (788.16 km^2) being the least prominent. For AHP, the soil type layer was allocated a weight of 6 and since ‘Arenosols’ are highly sandy (coarse grained) soils with high permeability and limited water storage capacity, and this soil group received a value of 9. ‘Cambisols’ are moderate to fine grained and were assigned a value of 3, ‘Ferralsols’ are heavily weathered and contain significant levels of clay, however they are well drained, therefore they were assigned a rating of 5, and ‘Luvisols’ were assigned a rating of 6 because they are well drained. For the Catastrophe theory soils were categorized into their hydrological soil group: Group A= ‘Arenosols’, Group C= ‘Luvisols’, Group C/D= ‘Ferralsols’, and Group D= ‘Cambisols’, and standardization and normalization were evaluated using the infiltration rates of the respective hydrological soil groups.

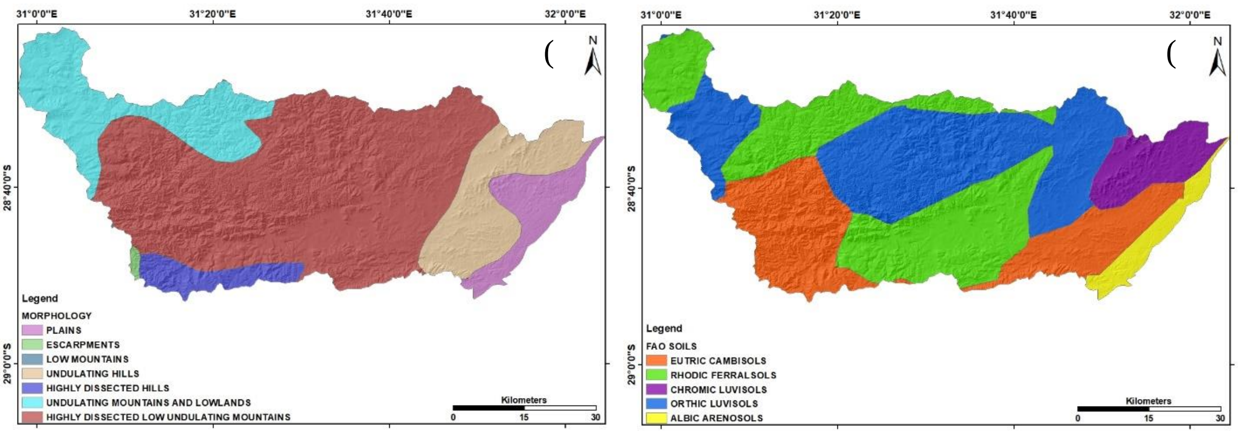

Figure 14: Thematic maps of the study area; a) Morphology and b) Soil type

6.8 Groundwater potential recharge zones map: AHP

After weights were assigned to all thematic layers and their features using Saaty's scale of relative importance the respective weights were converted into normalized weights by means of the eigenvector method of AHP. With regards to consistency of the weights, the consistency ratios of all the thematic layers and their attributes were rigorously evaluated and determined to be below the specified threshold limit of 10%. The GWPI was derived through Equation 5 and once the weighted linear combination was complete, the resultant groundwater potential recharge zones map was distributed into five zones (Fig. 15a) i.e., 'very low' (11.64 km^2), 'low' (780.81 km^2), 'moderate' (2275.32 km^2), 'good' (320.59 km^2), and 'very good' (14.14 km^2). The eastern extent of the study area (near the coastline) is predominated by 'very good' groundwater potential recharge zones. The 'good' groundwater potential zones occupy the eastern, northwest, and southwest regions of the study, whilst the western regions are dominated by 'very low' and 'low' groundwater potential recharge zones with small patches of 'low' in the northern and central portions. The 'moderate', 'good', and 'very good' groundwater potential recharge zones are recommended for the judicious exploitation of groundwater.

6.9 Groundwater potential recharge zones map: Catastrophe theory

The feature analysis using the Catastrophe approach is simple and straightforward it involved finding the index value, standardization, and normalization of the data to find the feature weights. This technique did not need the judgment of experts when assigning weights to theme characteristics. The GWPI was computed using Equation 5 and superimposed using weighted linear combination in ArcGIS. The resultant groundwater potential recharge zones map was classified into five classes (Fig. 15b) i.e., 'very low' (2.76 km^2), 'low' (897.55 km^2), 'moderate' (2149.99 km^2), 'good' (349.09 km^2), and 'very good' (3.11 km^2). In the study area, the entire region is speckled with zones of 'good' groundwater recharge prospects, whilst the eastern portion is predominated by zones of 'very good' groundwater recharge prospects.

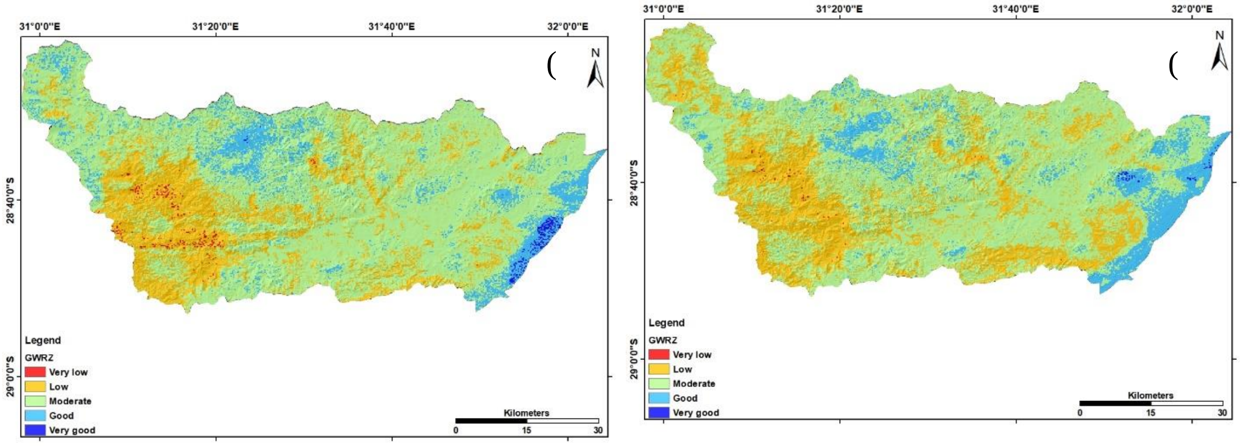

Figure 15: Groupwater potential recharge zones maps a)AHP and b) Catastrophe

Across the central and western regions of the area under study minor patches of the zone ‘low’ groundwater recharge prospects occur. Zones of ‘moderate’, ‘good’, and ‘very good’ groundwater recharge potential are recommended for the cautious exploitation of groundwater.

6.10 Validation

6.10.1 Groundwater levels

Boreholes with low levels of groundwater (where the water table is close to the surface) indicate a better chance of groundwater recharge occurring, whereas boreholes with higher groundwater levels (water table is far from the surface) indicate a lower chance of recharge occurring. The highest groundwater levels of ’19 – 24 mbgl’, ’25 – 50 mbgl’, and ’51 – 81 mbgl’ occurs in the western portion of the study area (Fig. 7a) which coincided with the ‘Low’ and ‘Very low’ groundwater recharge zones of both the AHP and the Catastrophe theory maps, and there is a patch of ’13 – 18 mbgl’ occurring on the western border which overlaps the ‘Good’ groundwater recharge zones of the AHP and Catastrophe theory maps thereby validating the model. On the eastern portion of the study area, the lowest groundwater levels are experienced, on the AHP and Catastrophe theory maps these groundwater levels of ‘3 – 6 mbgl’, ‘7 – 12 mbgl’, and ’13 – 18 mbgl’ overlap the ‘Good’ and ‘Very good’ groundwater recharge zones further validating the models.

6.11 Total dissolved solids (TDS) and Nitrate (NO32-) concentrations

The concentrations of TDS (Fig. 16b) and nitrates (Fig. 16c) vary across the study area. The nitrate concentrations ranged from 0.02 to 43.57 mg/l throughout the region. The highest nitrate value of 43.57 mg/l is predominant in the north-eastern part of study area indicating either contamination due to agricultural runoff/waste, municipal waste, or sewage leaching (Khan et al., 2022; Mallick et al., 2018). Agricultural runoff can be confirmed when overlapped due with the map LULC which depicts the presence of 'Cultivated land' in the same vicinity of the highest nitrate value. Closer to this point is another borehole with a nitrate value of 38.03 mg/l and a TDS value of 9560 mg/l further validating the presence of agricultural fertilizers and the high presence of minerals which indicates rock dissolution (Abboud, 2018; Khan et al.,2022). Both these boreholes fall under the 'Low' category for groundwater potential recharge zones on both the AHP and Catastrophe theory final maps, validating the models. When the groundwater potential recharge zones of 'Very good'

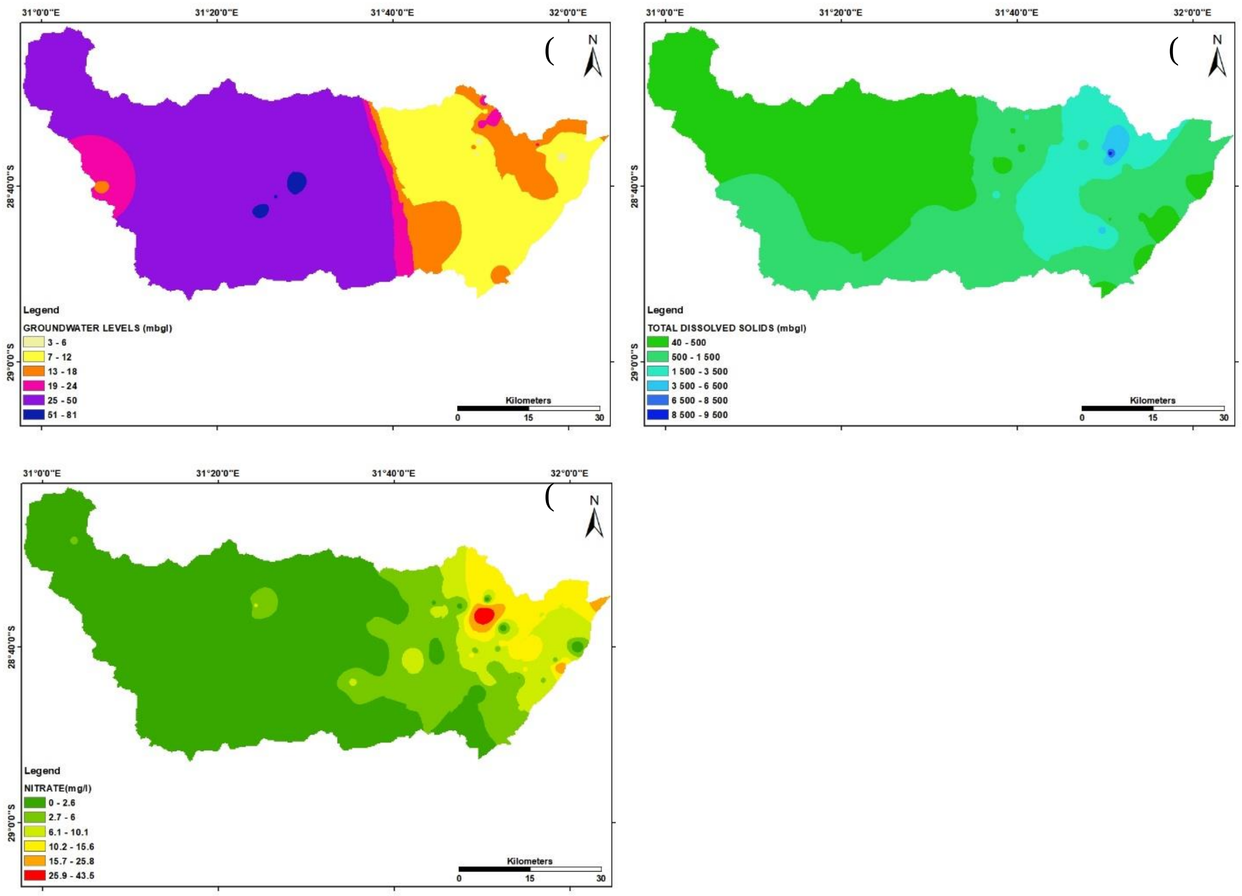

Figure 1: Thematic maps of a) Groundwater levels, b) Total dissolved solids, and c) Nitrates of the study area

for both maps were validated, it was found that for the AHP model, in the north-western portion of the ‘Very good’ groundwater potential recharge zones, the borehole TDS value was found to be 284 mg/l and the nitrate value was 1.19 mg/l indicating suitability of the model. In the eastern central portion of the study area, the ‘Good’ and ‘Very good’ groundwater potential zones occur on both the AHP and Catastrophe theory final maps, a reference to the borehole values show TDS and nitrate values of 1212 and 729 mg/l and 0.22 and 3.38 mg/l respectively, thus validating the accuracy of both models. On the AHP map, the presence of ‘Very good’ groundwater potential recharge zones and on the Catastrophe theory map, the presence of ‘Good’ groundwater potential recharge zones can be seen along the eastern border of the study area with boreholes TDS values ranging from 370 to 643 mg/l indicative of high aquifer potentiality and nitrate values ranging from 0.04 to 6 mg/l, validating both the models output, except for one of the boreholes which has a nitrate value of 23.31 mg/l. This illustrates that even though this point overlaps ‘very good’ groundwater potential recharge zones and the TDS value is low, since this point also overlaps ‘Cultivated land’ on the LULC map, that there is an excessive utilisation of nitrate fertilizers occurring due to agriculture (Chidambaram et al., 2018). In the western half portion of the study region, the aquifers are suitable for both drinking and irrigation uses, whereas on the eastern portion even though some nitrate and TDS values are high, they are still with the permissible limits of DWAF (1996) and WHO (2011) for drinking and irrigation (Table 11) indicating good groundwater potential.

Table 6: Permissible limits of TDS and nitrates

Permissible limits		
	DWAF (1996)	**WHO (2011)**
TDS	1500	1000
NO_3^-	<6	45

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CONCLUSION

Integration of thematic layers of the various parameters such as geology, geomorphology, land use, lineament density, drainage density, soil type, slope and rainfall of the study area using the AHP-MCDM approach and Boolean logic to delineate the groundwater potential zones in Maputaland coastal region was carried out. The study reveals that 73 % and 70 % of areas falls under good groundwater potential zone based on AHP-MCDM and Boolean logic respectively. The generated maps of 10 influencing parameters were processed to evaluate groundwater potential recharge zones in the uMhlathuze catchment. The AHP consisted of the assignment of weights using Saaty's scale of relative importance through the decision makers judgment, whilst the Catastrophe theory involved the assignment of weights based on index values, standardization, and normalization outside the decision makers judgment. The resultant maps were then validated against the water levels of boreholes present in the study area. The succeeding conclusions were reached from the two study's findings:

i. In the Maputaland region for the AHP: 6.0% (310.5 km^2) of the total area was covered by very good groundwater potential recharge zones, 67% (3467 km^2) good, 25% (1294 km^2) poor, and 2% (103.5 km^2) very poor, whilst for Boolean logic: 70 % of the area (3623 km^2) consisted of suitable zones groundwater recharge potential and 30 % (1552 km^2) of the area consisted of unsuitable zones.
ii. In the catchment for the AHP the resultant groundwater potential zones were deduced as: 'very low' 0.37 % (11.64 km2), 'low'22.92 % (780.81 km2), 'moderate' 66.87 % (2275.32 km2), 'good' 9.42 % (320.59 km2), and 'very good' 0.42 % (14.14 km2), whilst for the Catastrophe theory the resultant groundwater potential zones comprised of 'very low' 0.08 % (2.76 km2), 'low' 26.38 % (897.55 km2), 'moderate' 63.19 % (2149.99 km2), 'good' 10.26 % (349.09 km2), and 'very good' 0.09 % (3.11 km2).
iii. The groundwater recharge potential zones for the Maputaland region were highly influenced by soils, geology, geomorphology, lineament density, land use, and slope, whilst the probabilistic recharge zones of uMhlathuze was significantly influenced by soils, geology, transmissivity, drainage density, lineament density, slope, rainfall, and morphology.
iv. The similarity between the AHP (73%) and Boolean (70%) models concluded that the Maputaland region possessed good capability for groundwater recharge and was recommended for utilization in other various topologies.

v. The validation of the AHP and Catastrophe approaches through TDS concentrations, nitrate concentrations, and groundwater levels revealed that the 'Low' and 'Very low' groundwater potential recharge zones overlapped with both high TDS and nitrate concentrations and the 'good' and 'Very good' groundwater potential zones overlapped with low TDS and nitrate concentrations. Based upon this finding, it was concluded that both models were accurate in predicting the potential of recharge occurring within the catchment.

vi. The overall results for Maputaland conclude that geospatial techniques like, GIS, remote sensing, AHP-MCDM and Boolean logic can provide the platform to delineate the groundwater potential zones.

vii. Ultimately, it was concluded that both the capabilities of GIS and remote sensing paired with focused MCDM techniques are suitable for the mapping of zones of groundwater recharge prospects with sufficient and reliable accuracy.

viii. Lastly, the results proved that the integrated multi criteria decision making – GIS – remote sensing techniques are suitable for mapping groundwater potential recharge zones with high capability.

The study shows the importance of studying the two different integration methods, it is essential to delineate the groundwater potential zones with a different approach to obtain the accuracy of results. The merging of GIS – Remote sensing – MCDM strategies, conventional data, and the use of data from boreholes demonstrates that it is possible to establish areas with a greater occurrence of groundwater without using traditional methods that take time, money, and labor - intensive efforts. The results emanated from this study could be useful for sustainable groundwater pumping and in identifying the suitable location for implementation of groundwater exploration wells. Obtained results have proven that integration of GIS techniques under AHP-MCDM, Catastrophe theory and Boolean logic are efficient to enable decision-making tool for sustainable groundwater resources management, as it provides the preliminary information on groundwater recharge.