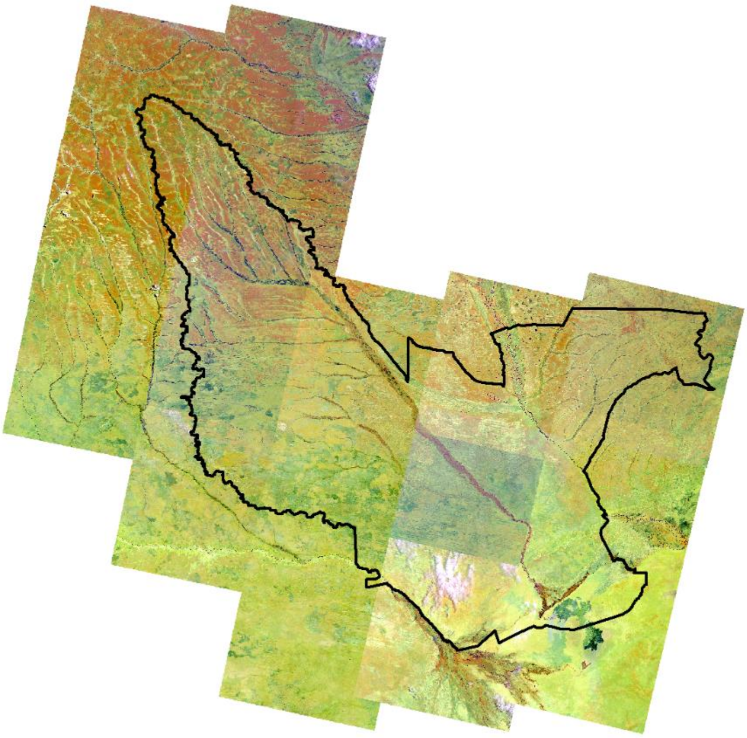

Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area (KAZA-GROW) 2021-2023

Hotspots for Groundwater Development in Kwando River Basin and Wildlife Dispersal Area (Final Report)

October 20, 2022

Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area

KAZA-GROW

Hotspots for Groundwater Development in Kwando River Basin and Wildlife Dispersal Area (Final Report)

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Grant Agreement No.: RWP-G13-IWMI

Cover photo: Landsat 8 [September –November 2021 images] false color combination (5, 6,2) showing healthy vegetation**.**

EXECUTIVE SUMMARY

This report serves as the Final report of the Hotspot for Groundwater Development in the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA) for the ***Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area*** Project – shortly denoted **KAZA-GROW.** The KAZA-GROW flagship project (**Grant Agreement No. RWP-G13-IWMI**) is a project implemented and led by the International Water Management Institute (IWMI) in partnership with the KAZA TFCA Secretariat and Peace Parks Foundation (Peace Parks) and funded by the United States Agency for International Development (USAID) under the Resilient Waters Program. The project runs over two years from **January 18, 2021, to March 2023**.

Groundwater exploration can be very costly due to complex geology, and other factors like recharge spatial variability, cost of test drilling, and technical capacity required for groundwater investigation and drilling. Boreholes that are drilled dry come at a significant financial loss and frustrate local communities and water managers. Groundwater exploration is a two-step process involving surface and subsurface investigations. Surface investigation of groundwater is usually less expensive and less time-consuming than subsurface investigations. Subsurface investigations involve expensive borehole drilling to provide direct access to subsurface formations and groundwater. Though subsurface investigations provide quantitative information concerning aquifers or groundwater they are often expensive and hence, feasibility or desktop studies (e.g. groundwater potential mapping) may be needed to guide or identify where detailed surface and subsurface investigations are to be carried out.

Therefore, the objective of this study is to map groundwater potential zones using Geographic Information System-based Multi-Criteria Decision Analysis (GIS-MCDA). This is to enable an initial assessment of groundwater potential in the Kwando River Basin and Kwando River Wildlife Dispersal Area. Based on the availability of data and literature review, seven criteria, namely geology, soil, slope, land use and land cover, drainage density, lineament density, and rainfall were selected, and used for the groundwater potential mapping. The weights for each thematic map were calculated using the Analytic Hierarchy Process (AHP) technique. The final groundwater potential map was classified into five groundwater potential classes. Results show that nearly 72% of the study area is classified as having moderate potential for groundwater, and about 27.5% is classified as having good potential for groundwater. Only 0.02% of the study area was classified as having very good potential for groundwater.

However, the groundwater at all locations may not be directly used if the quality of water is poor. Therefore, groundwater quality should be determined to establish its potability for humans or livestock and its suitability for irrigation or other agricultural use. To determine the overall groundwater potential in the study that satisfies groundwater quantity and quality, the groundwater potential map was overlaid with the salinity map, which is a major water quality concern in the study area, and a good overall indicator of prevailing groundwater quality. The resulting groundwater potential is 49% and 21.7% of the area is classified as moderate, and good, respectively. Further, 0.45% and 0.02% of the area are classified as having poor and very poor groundwater potential respectively.

The groundwater potential map produced is intended to serve as a baseline upon which further subsurface investigations can be based. The groundwater potential map can serve as a useful means of guiding effective groundwater potential assessment in the study area to increase resilience to climate change for the most vulnerable communities. The maps can also be utilized to analyze and develop key recommendations for policymakers.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
CGIAR	Consultative Group on International Agricultural Research
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
DEM	Digital Elevation Model
GIS	Geographic Information System
GIS-MCDA	Geographic Information System- Multi-Criteria Decision Analysis
ISRIC	International Soil Reference and Information Center
IWMI	International Water Management Institute
LULC	Land Use/Land Cover
KAZA	Kavango Zambezi
KAZA-GROW	The project: Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area
KRB	Kwando River Basin
KRWDA	Kwando River Wildlife Dispersal Area
MCDA-	Multi-Criteria Decision Analysis
TFCA	Transfrontier Conservation Area
SADC	Southern African Development Community
SADC-GMI	Southern African Development Community Groundwater Management Institute
SRTM	Shuttle Radar Topography Mission
USAID	United States Agency for International Development
USDA	U.S. Department of Agriculture
USGS	United States Geological Survey
WHO	World Health Organization
WLC	Weighted Linear Combination
WLE	Water, Land, and Ecosystems

1 INTRODUCTION

This report serves as the Final report of the Hotspot for Groundwater Development in the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA) for the ***Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area*** Project – shortly denoted **KAZA-GROW.** The KAZA-GROW flagship project (**Grant Agreement No. RWP-G13-IWMI**) is a project implemented and led by the International Water Management Institute (IWMI) in partnership with the KAZA TFCA Secretariat and Peace Parks Foundation (Peace Parks) and funded by the United States Agency for International Development (USAID) under the Resilient Waters Program. The project runs over two years from **January 18, 2021, to March 2023**.

1.1 Background

Groundwater is the primary water source for domestic, agricultural, and industrial development in many parts of the world. Moreover, it is vital for supporting ecosystems. It is estimated that between 50 - 75 % of Sub-Saharan Africa's population relies on groundwater, particularly for drinking purposes (Leader and Wijnen, 2018). Approximately 40 % of Sub-Saharan African drylands are underlain either by very shallow (depth < 7 m) or shallow (depth < 25 m) aquifers, and this groundwater is more accessible to people with limited resources and/or human-powered pumps (Leader and Wijnen, 2018). These shallow, small, local aquifers, often linked to alluvial deposits or found in hard-rock areas, are more vulnerable to extended periods of drought. Deeper aquifers that are less sensitive to annual fluctuations in rainfall are less utilized because wells/boreholes require more complex drilling and pump technology and, as a result, are more expensive in construction and operation.

Compared to surface water, groundwater is more slowly impacted by climate change and resilient to climate change impacts. This does not mean that groundwater is immune from climate change impact rather due to the delayed response to below-average or low rainfall groundwater can enable water supply security to the next rain cycle or a wet season. Yet, identifying groundwater availability is difficult due to complex geology, access, and cost. Identifying a good site for groundwater exploration in hard rock terrain is a challenging task (Dar et al., 2010). The first step in identifying areas of high groundwater potential usually involves identifying existing high-yielding boreholes and aquifers (Murray et al., 2012). In cases there is no existing groundwater development in the area, then perhaps the most important types of investigations to be engaged are surface geophysical surveying (if the terrain is suitable) and exploration drilling (Nonner, 2006). Based on these investigations, the optimum sites for production wells/boreholes and the yields and water quality that may be anticipated once these wells/boreholes are installed can be assessed (Nonner, 2006). A lack of precise information on groundwater occurrence has consequences for local well/borehole drilling and regional aquifer management. Similarly, without access to reliable information, government technicians and groundwater consultants face greater difficulties in providing sound advice on groundwater development projects (RTI, 2013). Boreholes that are drilled dry come at a significant financial loss and frustrate local communities. The drilling of an unsuccessful borehole is almost as costly as drilling a successful borehole (Sander, 2007). Groundwater exploration involving the use of geographical information systems (GIS) and remote sensing often provides a rapid and cost-effective means for groundwater exploration.

1.2 Objectives

The main objective of this study was to develop a groundwater potential map for the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA) using Geographical Information

System-based Multi-Criteria Decision Analysis (GIS-MCDA). The groundwater potential map provides a quantitative measure of groundwater potential and supports the identification of suitable areas for detailed investigations, and for drilling production boreholes with adequate water quality. To understand the groundwater potential, a quick and low-expense methodology is needed for preventing the undesirable effects of water resource development.

2 GEOGRAPHIC INFORMATION SYSTEM MULTI-CRITERIA DECISION ANALYSIS

Geographical Information Systems Multi-Criteria Decision Analysis (GIS-MCDA) is a method of combining information from several criteria maps to form a single map that enables identifying the most preferred option (Dodgson et al. (2009)). GIS-MCDA has been used by many researchers for mapping groundwater potential (Agarwal et al., 2013; Arulbalaji et al., 2019; Dar et al., 2010; Gnanachandrasamy et al., 2018; Magesh et al., 2012; Rahmati et al., 2015; Saranya and Saravanan, 2020). One of the advantages of the GIS-MCDA approach is that it often allows the consideration of numerous often conflicting design criteria (Woldt and Bogardi, 1992). The standard GIS-MCDA approach consists of four steps. These include 1) selection of criteria, 2) standardization of criteria, 3) assigning relative weights for each criterion, and 4) combination of criteria to produce the overall map. These steps are briefly described in the subsequent sections.

2.1 Selection of criteria

The selection of criteria involves selecting relevant surface, subsurface, and catchment characteristics. Every selected criterion has to be measurable and non-redundant or not correlated (Bonilla Valverde et al., 2016; Dodgson et al., 2009; Malczewski, 2000).

2.2 Criteria standardization

Standardization involves describing each criterion on a common scale. Usually, each layer of the map is classified into a common scale value between 0 and 1 (the higher the value the most preferred). The step-wise and linear functions are the most common standardization methods (Malczewski, 2000). The values of the resulting suitability layers will no longer have units but a numerical suitability index.

2.3 Assigning Weights

Assigning relative weight is one of the most important steps in the GIS-MCDA approach. This entails assigning relative weight to each criterion based on its importance to the process or objective. The weight assigned to particular criteria reflects the relative preference of that element compared to other criteria.

There are many methods for assigning relative weight. These include rating methods, ranking methods, the Multi-Influencing Factor (MIF) Method, and pairwise comparison. Rating methods involve assigning weight based on expert knowledge. This method is easy and therefore quite popular. It is particularly suitable for problems with a few simple criteria whose relative importance can be estimated with common sense or expertise. However, the distribution of the scores is again subjective and often only poorly justified (GITTA, 2013). The ranking method, on the other hand, involves the ranking of criteria according to their rank order from the most important to the least. Then the weights are calculated by $((N-r+1)/\sum(N-r+1))$, where N is the total number of criteria, and r is rank order. The ranking method is popular because it is easy. The disadvantage of the ranking method is that its explanatory power decreases quickly with an increasing number of criteria (GITTA, 2013).

The MIF method (Magesh et al., 2012; Shaban et al., 2006; Yeh et al., 2009) is another method that involves a graphical representation of cause-and-effect relationships among the selected criteria. Criteria with a major effect on another criterion assign a score of 1 and if criteria have a minor effect would have a score of 0.5 and finally, all major and minor effects for each criterion are summed and divided by the total score to determine the relative criteria weights for each criterion.

The pairwise comparison involves comparing each criterion to one another and the most common approach is The Analytic Hierarchy Process (AHP) method (Saaty, 2008). The analytical hierarchy process is a structured decision-making process that involves using experts' knowledge to determine the rank and weights by constructing an Eigenvalue pairwise comparison matrix. This method is best-suited for decision-making in a problem involving several parameters influencing the result (GITTA, 2013). This process involves the construction of a pairwise matrix where the weights of each parameter were determined by considering the relative importance of all the other parameters (Saaty, 2008). A pairwise matrix is constructed having criteria arranged in rows and columns. A scale of 1–9 is assigned as a relative scale of importance. Two criteria are evaluated at a time in terms of their relative importance. If criterion A is exactly as important as criterion B, this pair receives an index of 1. If A is much more important than B, the index is 9. if A is much less important than B, the rating is 1/9. This indicates that if A to B was rated with the relative importance of n, B to A has to be rated with 1/n (GITTA, 2013). The diagonal of the matrix contains only values of 1. Table 1 shows the Saaty scale of relative importance. The effort required to compare each criterion with every other one increases rapidly when handling many classes (to be exact: with n criteria, there are n(n-1)/2 comparisons) (GITTA, 2013).

The consistency index (CI) which measures the degree of consistency is calculated using Equation 1. Consistency Ration (CR) is a measure of the consistency of the pairwise comparison matrix and is calculated using Equation 2. If CR value is less than 10%, then the assigned weights are considered consistent, otherwise, the weights need to be re-evaluated. If there is a consistency problem, the decision maker must review his/her comparisons to improve them (de FSM Russo and Camanho, 2015).

$$CI = \frac{\lambda_{max} - n}{n} \qquad (1)$$

$$CR = \frac{CI}{RI} \qquad (2)$$

Where Principal Eigenvalue (λ_{max}) was computed by the Eigenvector technique. n is the number of factors used in the analysis. RI is a random Consistency Index, whose values were obtained from the standard table provided in Table 2.

The AHP method to calculate the weights was chosen for this study. This approach was selected because of less subjectivity and the ability to handle a large number of criteria.

Table 1: The fundamental scale of absolute numbers (Saaty, 2008)

Intensity of Importance	Definition	Explanation

1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Table 2: Satty Random index for different values of n (Saaty, 1994)

n	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.4 Weighted overlay analysis

The final step of the GIS-MCDA is to aggregate the criteria to obtain the groundwater potential map. The groundwater potential map is generated using a linear combination of the seven criteria thematic maps based on their relative importance. Each criteria map is multiplied by its weight and summed to get the groundwater potential map (Equation 3) using map algebra in ArcGis. The groundwater potential map values theoretically range between 0 and 1 (higher values indicate higher groundwater potential).

$$\text{GWP} = \sum w_i x_i \qquad (3)$$

Where GWP= Groundwater potential, w_i= weight for factor i, and x_i= criterion score of factor i

3 STUDY AREA

The Kwando River is one of the major headwater tributaries of the Zambezi River and provides critical water resources to the heart of the Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA), the largest transboundary conservation area on the planet (Figure 1). The Kwando River Basin traverses four countries in south-central Africa (Angola, Namibia, Botswana, and Zambia).

The Kwando River Basin has a total land area of approximately 120,681 km^2 and the Kwando River Wildlife Dispersal Area has an area of 105,288 km^2. The area of the combined Kwando River Basin and Kwando River Wildlife Dispersal Area is about 190,580 Km^2. The Kwando River starts in central Angola and forms the boundary between Angola and Zambia for 225 km. The region is known for its wildlife and biodiversity. Elephants, zebras, and wildebeests use the basin as a migration corridor. Endangered species such as the South African cheetah and the Cape wild dog make their homes along the banks of the river (Carew and Costanzo, 2020). About 35.6% of the Kwando River Basin overlaps with the Kwando River Wildlife Dispersal Area. The percentage area of the Kwando River Basin and the Kwando River Wildlife Dispersal area in each country/ member state is provided in Table 3. The topographic elevation of the Kwando River Basin ranges from 939 to 1596 m above mean sea level, and the Kwando River Wildlife Dispersal Area elevation ranges from 922 to 1229 m above mean sea level.

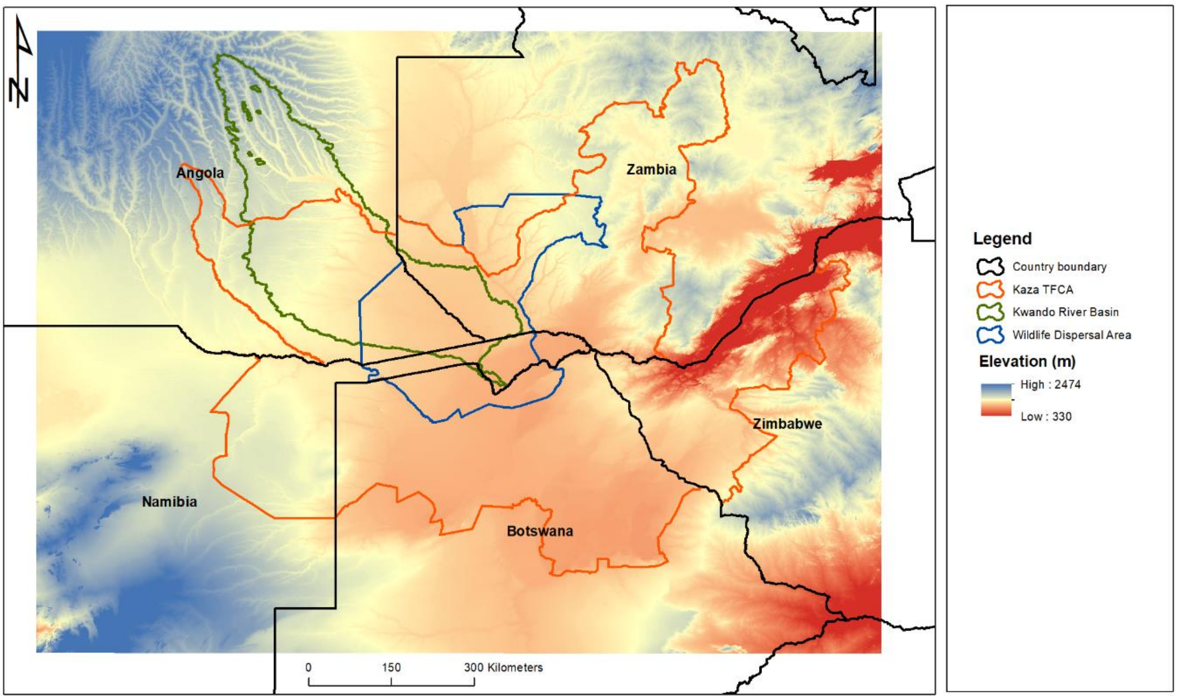

Figure 1: The project focus area of the Kwando River Basin (KRB) and its intersection with the Kwando River Wildlife Dispersal Area (KRWDA) in the north-western corner of the KAZA TFCA

Table 3:Percentage of Kwando River Basin and Kwando Wildlife Dispersal area in each country

Countries	Percentage of Kwando River Basin area (%)	Percentage of Kwando River Wildlife Dispersal area (%)
Angola	85.1	20.6
Botswana	0.2	17.2
Namibia	2.5	13.0
Zambia	12.2	**49.3**
Zimbabwe	0.0	0.0

4 METHODOLOGY

4.1 Common criteria used for groundwater potential mapping

The most common criteria and the weight assignment methods used for groundwater potential mapping are presented in Table 4. The criteria used across the studies are similar. Regarding the weight assignment, the AHP method dominates and was used in this study.

Table 4: Criteria used in previous studies for groundwater potential zone mapping

No	Criteria	Weight assignment method	Reference
1	Geology, Geomorphology, Land use, Drainage density, Slope, Soil, Rainfall, and Lineament	AHP	(Agarwal et al., 2013)
2	Lithology, Land use, Drainage, Slope, Rainfall, Soil, and Lineaments	MIF	(Magesh et al., 2012)
3	Rainfall, lithology, drainage density, lineament density, and slope	AHP	(Rahmati et al., 2015)
4	Topography, geology, drainage density, geomorphology, soil, land use and land cover rainfall, and the lineament density	AHP	(Saranya and Saravanan, 2020)
5	Land use, Slope, Geomorphology, Geology, Lineament density, soil, drainage density, drainage proximity, and Rainfall	AHP	(Fashae et al., 2014)
6	Lithology, land use/land cover, Lineament density, slope, drainage density, Rainfall, and soil	MIF	(Tolche, 2021)
7	Lithology, geomorphology, lineament density, drainage density, soil, slope, rainfall, land use and land cover, and digital elevation model	Ranking	(Mukherjee et al., 2012)
8	Lithology, Lineaments, Geomorphology, curvature, Land use, and soil	Rating	(Dar et al., 2010)
9	Geology, Land use/land cover, Lineament density, drainage density, slope, and Geomorphology	Rank	(Waikar and Nilawar, 2014)
10	Lithology, Slope, Geomorphology, Lineament density, Drainage density, Land cover, and soil type	AHP	(Andualem and Demeke, 2019)

4.2 Selected Criteria and Data Sources

Based on the literature review and data availability we selected seven criteria for groundwater potential zone mapping. These criteria include slope, soil, land use/land cover, geology, rainfall, lineament density, and drainage density. The data source and resolution of these criteria are presented in Table 5. Every selected criterion is measurable and non-redundant.

Table 5: Selected criteria and their data sources

Thematic layers	Source	Resolution

Slope	Derived from Shuttle Radar Topography Mission (SRTM) 30 m by 30 m digital elevation model (https://earthexplorer.usgs.gov/)	30 m
Soil	Soilgrid 250m ISRC-World Soil Information	250 m
Land use/Land cover	European Space Agency (ESA)	20 m
Geology	Southern African Development Community Groundwater Management Institute (SADC-GMI)	3 km
Rainfall	Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)	5.5 km
Lineament density	Southern African Development Community Groundwater Management Institute (SADC-GMI)	
Drainage density	Determined from SRTM 30 m by 30 m digital elevation model	30 m

4.3 Descriptions of selected criteria

4.3.1 Geology

Geology controls groundwater occurrence, storage, and movement. Different geology has different potential for groundwater. For example, the unconsolidated (loosely arranged) sand and gravel, and alluvium have a large volume of interconnected pore space for water storage and have good groundwater potential. Similarly, fractured bedrock's surface greatly increases infiltration rates, whereas layers of un-fractured bedrock have low infiltration and storage. Alluvial aquifers consist of thick sand and gravel deposits that are the primary aquifers and are the sources of most of the water pumped from wells/boreholes in many regions (Aller, 1991). These aquifers are capable of yielding a large quantity of water. In many of the alluvial valleys, groundwater systems and surface water systems are hydraulically interconnected. Rocks that serve primarily as barriers to groundwater movement include clay and shale (Heath, 1984).

Geologically, the study area has been divided into four classes:

i) Unconsolidated to consolidated sand, gravel, and arenites[1]
ii) Unconsolidated sands and gravel,
iii) Sandstone, and
iv) Granite, syenite, gabbro, gneiss, and migmatites.

The Unconsolidated to consolidated sand, gravel, and arenites and unconsolidated sands and gravel are both intergrandular aquifers. The difference being while the unconsolidated to consolidated sand, gravel, and arenites calssfication consists of undifferentiated uncosolidated to consolidated sand the unconsolidated sands and gravel class consist of alluvium, unconsolidated sand ,gravel and calcrete. Sandstone is a fractured rock aquifer while granite, syenite, gabbro, gneiss, and migmatites are

[1] Arenite is a sedimentary clastic rock with sand grain size between 0.0625 mm and 2 mm and contain less than 15% matrix.

aquifers of low permeability aquifers composed of intrusive igneous rock (granite, syenite, and gabbro) and metamorphic rocks (gneiss, and migmatites).

About 87.5% of the study area is covered with unconsolidated to consolidated sand, gravel, and arenites, and about 12% is covered with unconsolidated sands and gravel (Figure 2). Sandstone covers only 0.46% of the study area. Furthermore, Granite, syenite, gabbro, gneiss, and migmatites are not visible due to a small area (less than 0.001% of the area). Unconsolidated sands and gravel, are characterized by intergranular porosity and all contain water primarily under unconfined conditions (USGS, 2021), and has better productivity, and hence, higher preference in determining groundwater potential. Unconsolidated to consolidated sand, gravel, and arenites are also characterized by intergranular porosity, and the hydraulic conductivity of the aquifers is moderate to high and hence given the second preference for groundwater potential. Sandstones are rocks that have been formed by cementing sand gravel in the process of lithification, and the cementing material is mostly where the grain touch, leaving the space between the grains open. Therefore, sandstone is generally porous and well connected, so it can store and transmit a significant volume of water. Hence, sandstone was given the third preference in the groundwater potential. Granite, syenite, gabbro, gneiss, and migmatites on the other hand are low permeability aquifers with very low and limited groundwater potential, and hence assigned low preference.

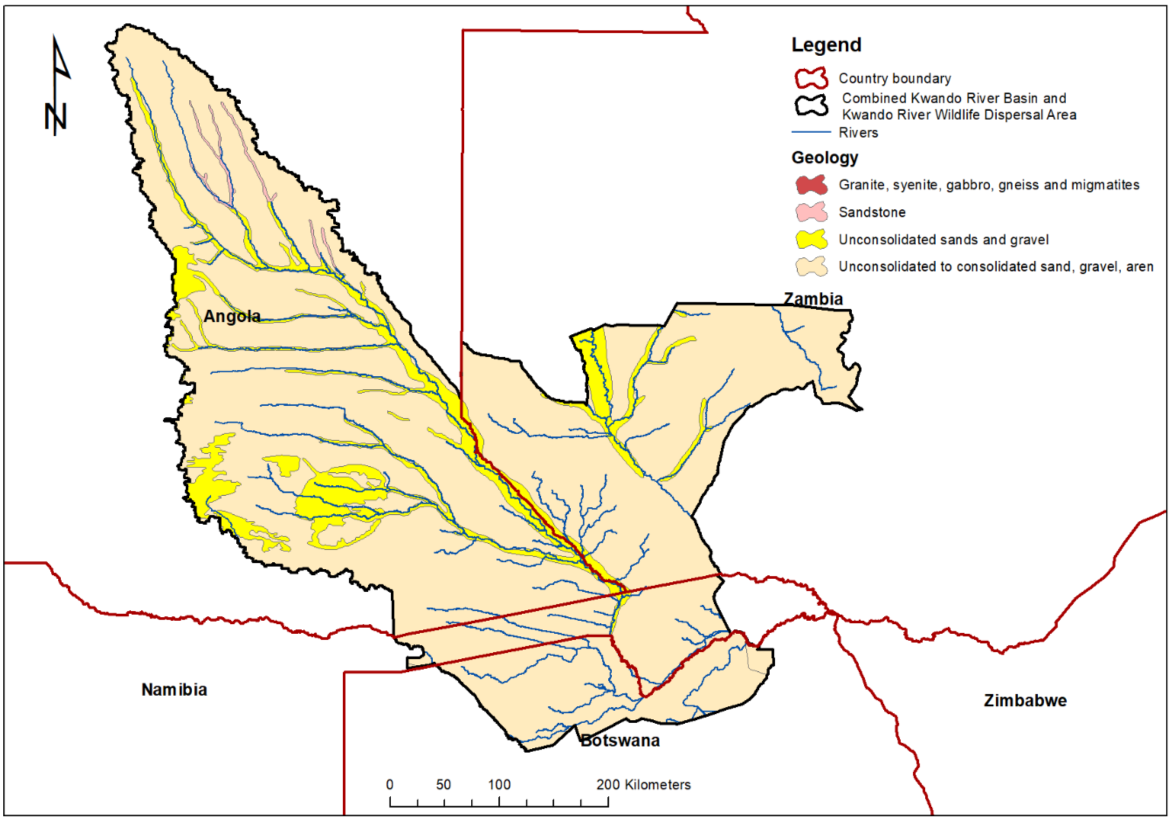

Figure 2: Geology map of the study area

4.3.2 Soil

The Soil type map (Figure 3) was extracted from the global soil texture class map obtained from ISRIC-World Soil Information (https://www.soilgrids.org). The ISRIC-World Soil Information soil classification utilizes the United State Department of Agriculture (USDA) soil texture triangle and divided soils based on their relative amounts of clay, silt, and sand into 12 soil types (Hengl et al., 2017). In general, sandy soils have the highest infiltration capacity, while clay soil has the lowest. In the study area sandy loam, sandy clay loam, and loamy sand respectively cover about 41.4, 31.8, and 24.6% of the study area. Sandy soil covers only 1.8% of the study area.

Soil properties are the most significant factors affecting the infiltration rate. The rate at which water enters the soil cannot exceed the infiltration capacity of the soil. Soil infiltration rate decreases with increasing clay content in the soil. The rank of soils has been assigned based on their infiltration rate (Table 6). In general, sandy soil has a high infiltration rate, hence assigned higher value, while clay soil has the least infiltration rate hence assigned low value.

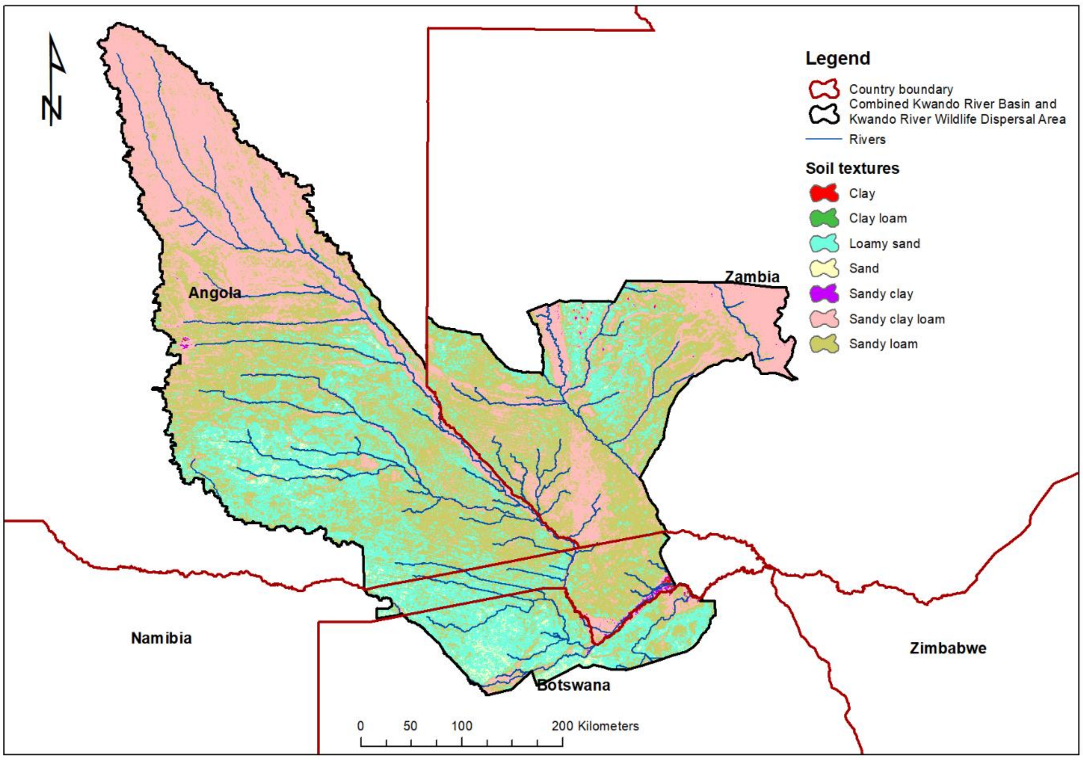

Figure 3: Soil type map of the study area (Source: ISRC global soil map).

Table 6: Infiltration rates for different types of soils as measured by infiltrometer rings in the third hour of a wet run (Johnson, (1963))

Soil type	Porosity (%)	Infiltration rates (cm/hr)
Gravelly silt loam	54.9	12.60
Clay loam	61.1	10.11
Silty loam	57.0	5.31
Sandy loam	49.6	4.90
Clay (eroded)	54.3	4.52
Sandy clay loam	48.8	3.61
Silty clay loam	50.8	1.83
Gravelly silty loam	59.7	1.40
Fine sandy loam	41.5	1.40
Very fine sandy loam	49.6	1.29
Loam	45.7	1.27

Sandy clay	42.9	0.13
Heavy clay	57.8	0.05
Light clay	47.0	0.00
Clayey silt loam	49.4	0.00

4.3.3 Rainfall

Long-term average annual rainfall was extracted from the Climate Hazards Group Infrared Precipitation with Stations version 2 (CHIRPS) (Funk et al., 2014). CHIRPS combines 0.05° x 0.05° resolution satellite imagery with in-situ station measurements. CHIRPS data are available from 1981-present (ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0).

Rainfall is a major source of recharge. Rainfall amount and spatial variability exert significant control of recharge and groundwater potential in space and time. Rainfall distribution along with the slope gradient directly affects the infiltration rate and runoff and groundwater potential. Studies have shown that recharge events are better correlated to the sum of heavy rainfalls, exceeding a threshold of 10 mm/d, than to that of all daily rainfall events (Owor et al., 2009). For the humid climate in Africa (mean rainfall is ~1,200 mm/ year) it was shown that recharge is observed to occur seasonally and linearly in response to rainfall exceeding a threshold of between 140 and 250 mm/year (Kotchoni et al., 2019). The long-term mean annual rainfall across the study area ranges from 474 – 1117 mm/year (Figure 4). The rainfall map was divided into five classes. Higher rainfall areas are preferred for high groundwater potential, hence assigned a higher value.

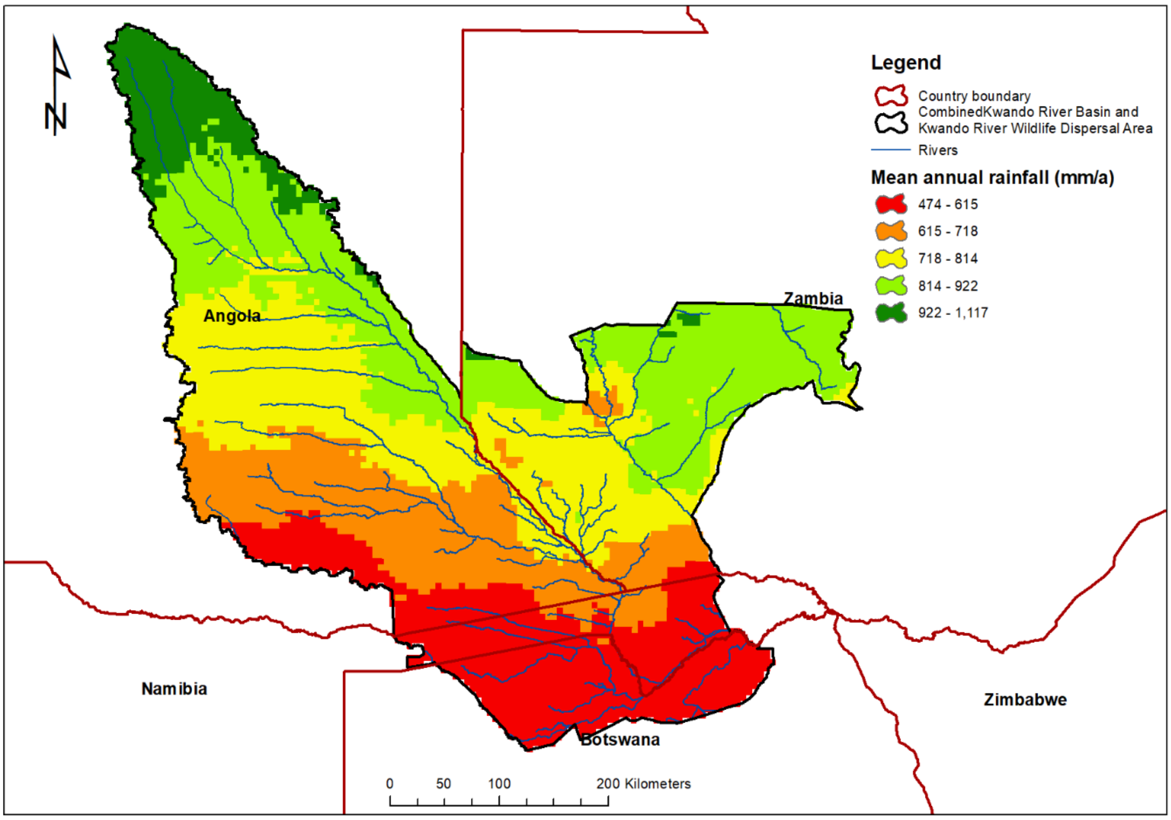

Figure 4: Rainfall map of the study area

4.3.4 Slope

There is an inverse relationship between topographic slope and soil infiltrations. The slope indicates the inclination of the topographic surface and formations contributing to recharge and aquifer geometry. Steep slopes result in more runoff, which will affect the amount of infiltration. Less infiltration will occur on slopes and hills than on flat areas and depressions, where runoff is slow, accumulates in depressions and has more time for infiltration to occur. That means in highly sloping areas, the run-off is more, offering less retention time for runoff to infiltrate, reducing groundwater recharge potential significantly. In contrast, a gentle slope will have a high potential for groundwater recharge.

The slope of the study area is calculated in percentage based on the SRTM 30 m resolution Digital Elevation Model (DEM) (Figure 5). The slope in the study area varies between 0-77%. Nearly 77% of the study area is within the range of 0-4% slope. About 41.5% of the study area has a slope in the range of 0-2% and 35.4% has a slope in the range of 2-4%. The slope class with a lower value is assigned a higher rank as flatter terrain promotes groundwater recharge, while higher slopes are not preferred due to their high runoff.

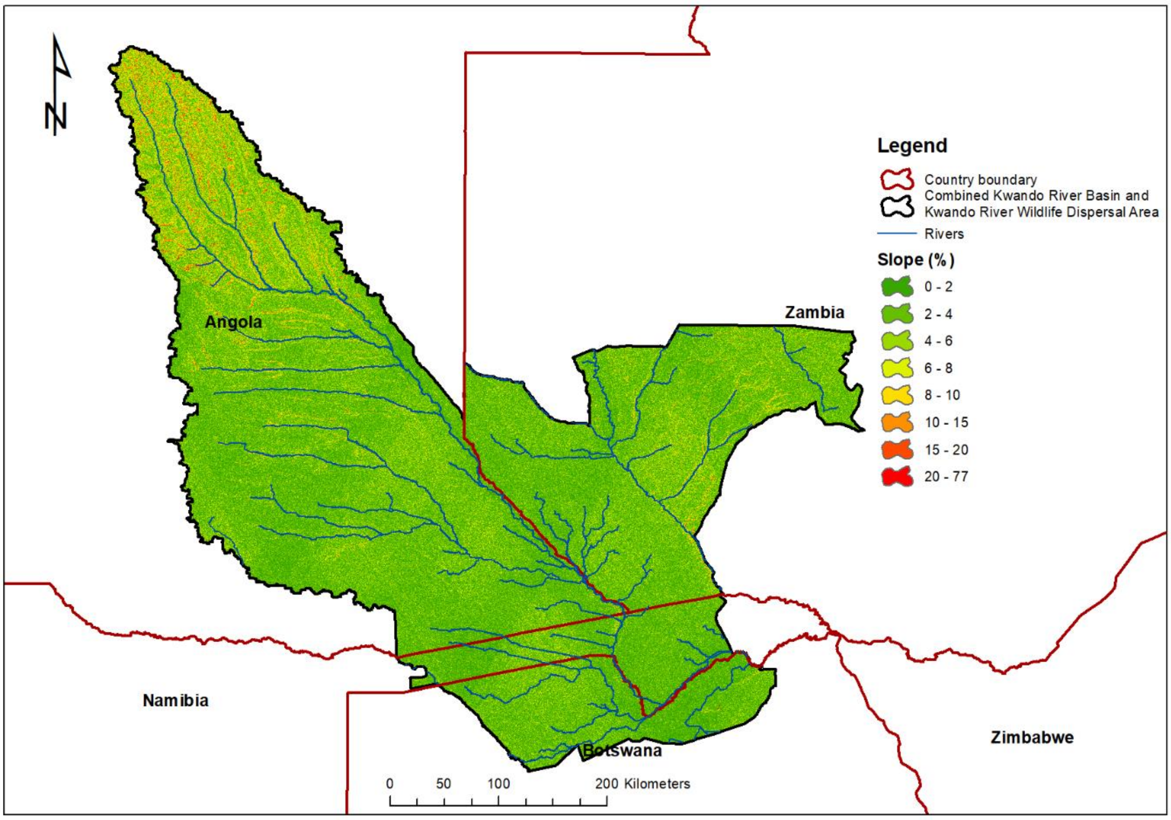

Figure 5: Slope map of the study area

4.3.5 Land use/Land cover

Land use refers to how land is utilized for different activities while land cover represents natural and human features that cover the earth's surface. Examples include natural vegetation, forest, wetlands, and human construction such as buildings, roads, and other infrastructures. The land cover map for the study area was extracted from European Space Agency (ESA, 2016). The land cover map was produced from Sentinel-2A observations from December 2015-December 2016. The Sentinel-based Africa land use and land cover map (20 m resolution) consists of 10 classes. Figure 6 shows the land use/land cover types in the study area. The dominant land cover in the study area is a shrub (44%) and followed by Tree cover (34.4%). About 19% of the study area is covered with grassland. Cropland covers only 2.2% of the study area.

Land use/Land cover plays an important role in controlling groundwater recharge. Built-up areas generally decrease infiltration rate and increase surface runoff as a result of the increasing presence of various impervious surfaces. If forests are cleared for rangelands, groundwater recharge increases. Conversion of natural forests to cultivated crops reduces evapotranspiration losses and the excess water available for increasing groundwater recharge and or/streamflow (Scanlon et al., 2005). Forest systems have higher evapotranspiration rates than managed land use; therefore, any gains in recharge are often offset by evapotranspiration losses (Owuor et al., 2016). A high interception under forest systems therefore further limits groundwater recharge.

The impact of forests on groundwater recharge is somewhat controversial. Adams et al. (2004) argue that vegetation has the potential to increase infiltration in three ways: by retarding runoff, reducing raindrop compaction, and by increasing organic matter content, bulk density, and surface horizon depth. Root systems of vegetation increase soil porosity and permeability while the increase in organic matter increases pore size and pore size distribution. Table 7 presents the impact of land use/Land cover on groundwater recharge. As seen in Table 7 groundwater recharge rate is higher for bare land than for forests. Therefore, in this study land use/land cover type of bare land was prioritized, followed by rangeland, grassland, cropland, and forest, while urban areas and water bodies are considered poor for groundwater potential. Contrary to other studies, Agarwal et al. (2013) assigned the highest rank for vegetation class for groundwater potential mapping.

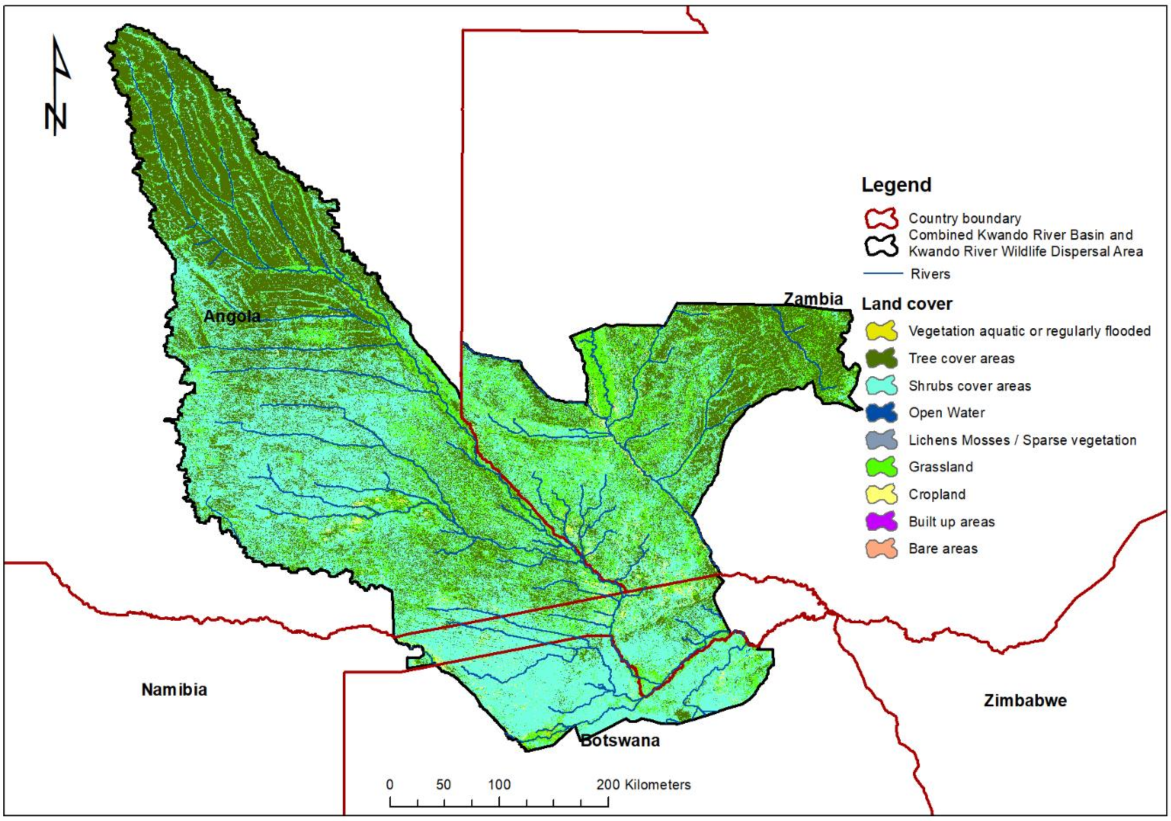

Figure 6: Land cover map of the study area

Table 7: Groundwater recharge as a percentage of precipitation of different land use/Land cover types (Source Owuor et al.(2016))

Land use/Land cover type	Description	Groundwater recharge rate (% of precipitation)
Forest	Forest vegetation consists of woodland, eucalyptus plantation, and bushland	0.13-0.18
Cropland	Cropland includes annual crops and perennial crops	3.4-8.6
Grassland	Grassland refers to natural vegetation with no livestock grazing	4.4-14
Rangeland	Rangeland comprises pasture used for livestock grazing	0.64-10.7
Bare land	Bare lands are an artificial scenario created through a clearing of natural vegetation and avoidance of regrowth	36 - 50

4.3.6 Lineament density

Lineaments, faults, and fractures are important Preferential flow paths (Agarwal et al., 2013). According to Agarwal et al. (2013), lineaments play an important role in determining groundwater potential as it directly provides information about the movement and storage of groundwater. According to Murray et al. (2012), dolerite dyke intrusions can produce baking, deforming, and fracturing of the sedimentary host rocks thereby allowing transmissive zones to develop along these geological contacts. The dykes and faults that are present in the study area are shown in Figure 7. Lineament density (Figure 8) was calculated using the line density technique in Arc GIS as demonstrated by Magesh et al (2012). The presence of lineaments generally indicates a permeable zone and high lineament density shows good potential for groundwater hence priority was given to higher lineament densities and vice-versa.

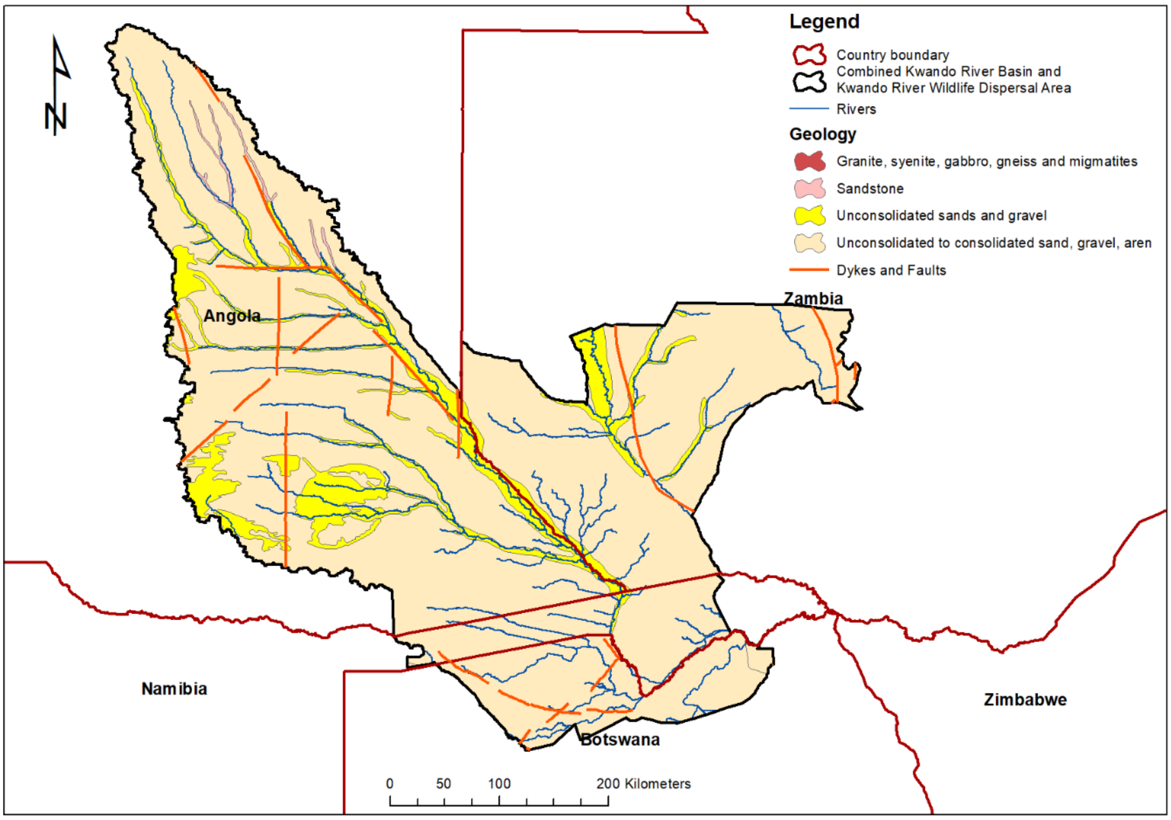

Figure 7: Dyke and faults map of the study area

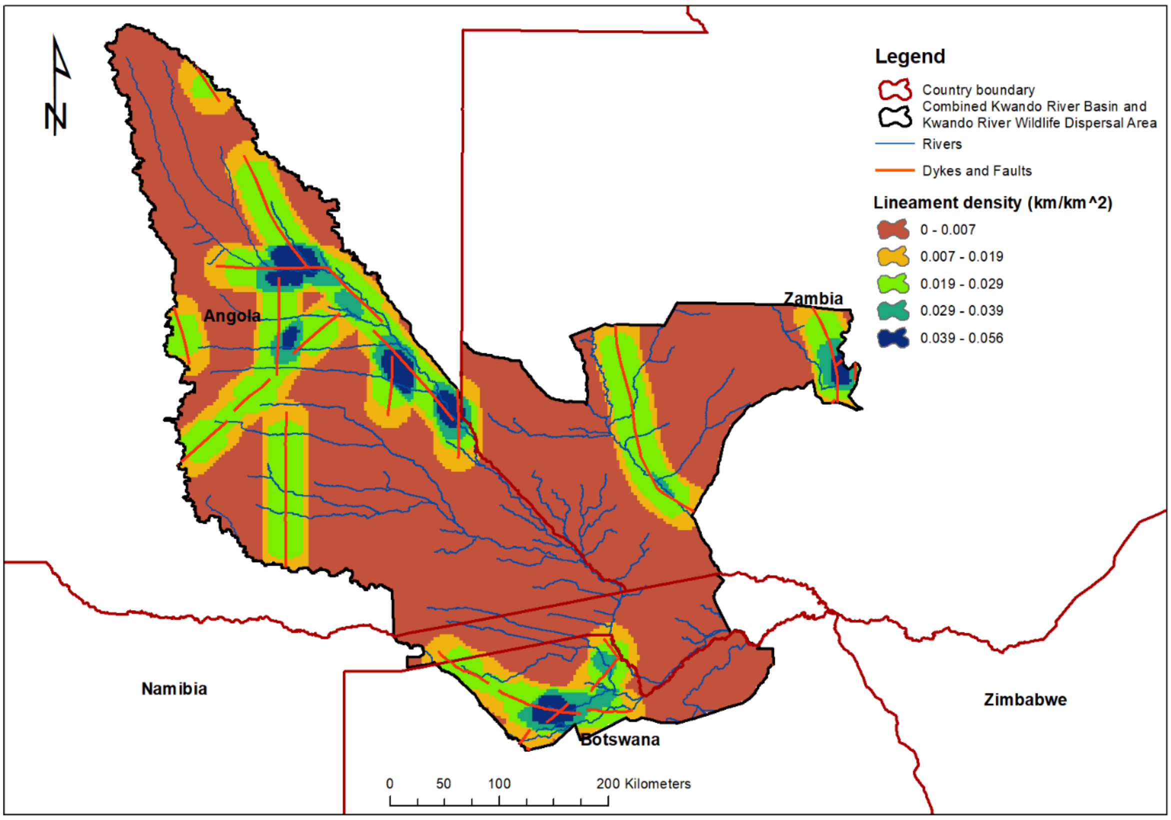

Figure 8: Lineament density map of the study area

4.3.7 Drainage Density

Drainage density is calculated as the total length of all streams in a basin divided by the total drainage area. The stream order map shown in Figure 9 was developed based on SRTM 30 in ArcGIS and is used for drainage density calculation. Only stream orders greater than or equal to 3 are considered for drainage density calculation. Drainage density was calculated using the Line density method in ArcGIS. Figure 10 shows the computed drainage density map. There is an inverse relationship between drainage density and permeability and hence drainage density is an important parameter in evaluating groundwater potential (Agarwal et al., 2013). The higher the drainage density, the higher the run-off, and less infiltration, hence, not preferred as groundwater potential zones. The drainage density map is reclassified with areas having less density designated with a higher rank. It is also important to note that even if less drainage density is preferred as it has high potential in terms of decreasing surface runoff and promoting infiltration from rainfall, higher drainage density areas (e.g. alluvial streambed) may promote focused recharge from the riverbed. In this study high ranks are assigned to low drainage density areas and vice versa.

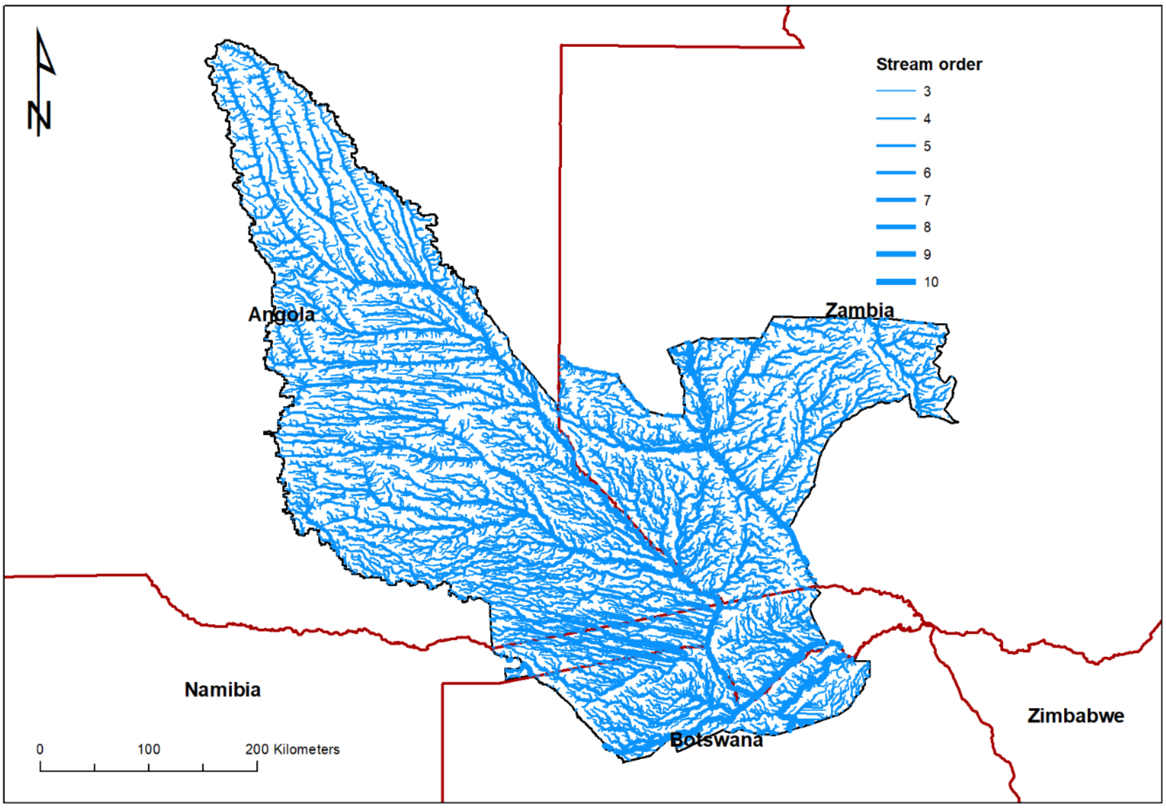

Figure 9: Stream order of the study area

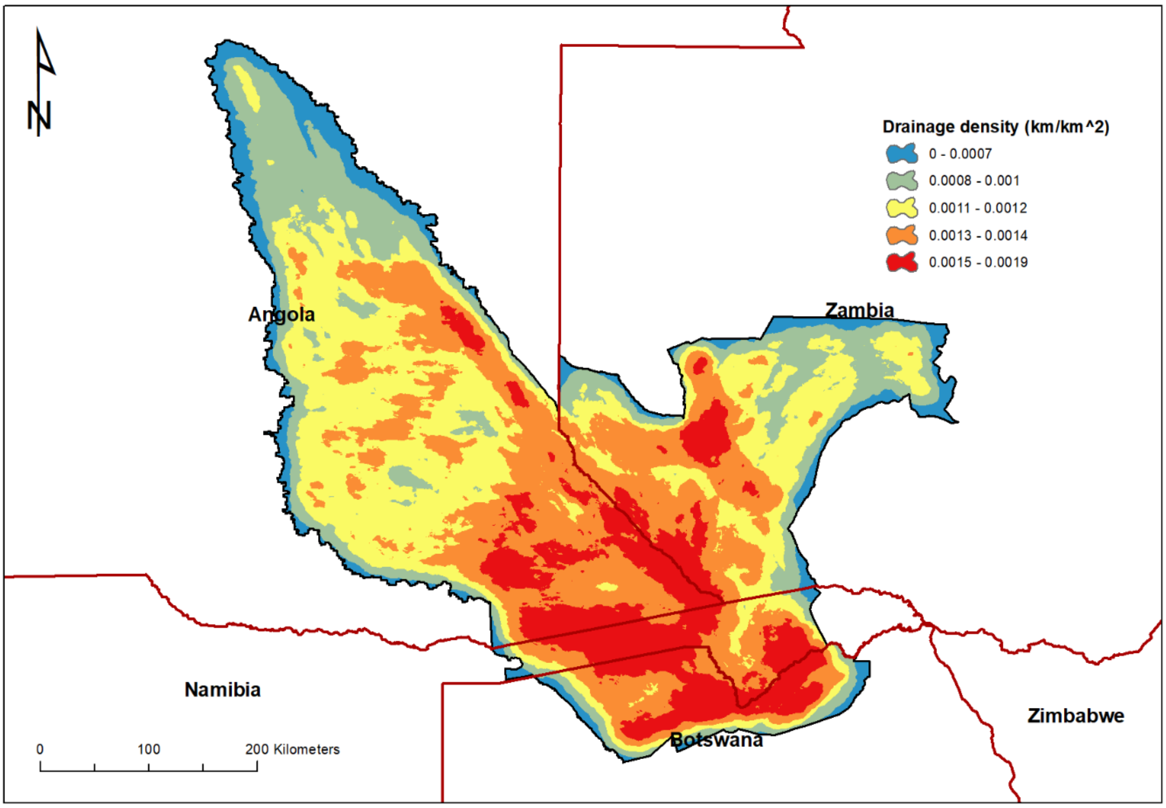

Figure 10: Drainage density map of the study area

4.4 Reclassification and standardization

In the present study, step-wise standardization is used. Table 8 presents classification and standardized values for the seven criteria described in the previous section. The standardized value ranges from 0 to 1. The higher the value the most preferred.

Table 8: Criteria classification and standard values

Criteria	Classification	Standardize value	Reference
Lineament density (km/km^2)	0 – 0.007	0.125	(Arulbalaji et al., 2019)
	0.007 – 0.019	0.25	
	0.019– 0.029	0.50	
	0.029 – 0.039	0.75	
	0.039 – 0.056	1.00	
Land use	Cropland	1.00	(Saranya and Saravanan, 2020)
	Grassland, Bare areas, Lichens Mosses / Sparse vegetation	0.75	
	Shrubs cover areas	0.50	
	Tree cover areas	0.25	
	Built up areas	0.125	

	Open Water, Vegetation aquatic, or regularly flooded	0.03	
Geology	Unconsolidated sand and gravel	1.0	(Saranya and Saravanan, 2020)
	Unconsolidated to consolidated sand, gravel, arenites	0.75	
	Sandstone	0.5	
	Granite, syneite, gabbro, gneiss	0.25	
Drainage density (km/km^2)	0.0 – 0.0007	1.00	(Singh et al., 2018)
	0.0008 – 0.001	0.75	
	0.0011 – 0.0012	0.5	
	0.013 -0.0014	0.25	
	0.0015 – 0.0019	0.125	
Slope (%)	0-1.5	1.00	(Saranya and Saravanan, 2020)
	1.6-3.8	0.75	
	3.9-8.8	0.50	
	8.9-17	0.25	
	18-25	0.125	
	>25	0	
Rainfall (mm/a)	922-1,117	1.00	(Saranya and Saravanan, 2020)
	814-922	0.75	
	718-814	0.50	
	615-718	0.25	
	474-615	0.125	
Soil	Sand	1.00	(Machiwal et al., 2011)
	Loamy sand	0.75	
	Sandy loam	0.50	
	Sandy clay loam	0.25	
	Sandy clay	0.125	
	Clay loam	0.04	
	Clay	0.0	

4.5 Assigning weights for the selected criteria

The Analytical Hierarchy Process (AHP) method (http://bpmsg.com) was used to calculate the weight for each criteria map. The pairwise comparison was assigned based on Agarwal et al. (2013), as per the comparison matrix is presented in Table 9. The calculated criteria weights based on the AHP method are presented in Table 10.

The computed consistency ratio (CR) is 2.4% which is less than 10%. Hence, the assigned weights and pairwise comparison matrix were consistent and acceptable. Geology was found to be the most important criterion (35.4%) followed by drainage density (24.0%) and lineament density (15.9%).

Table 9: Pairwise comparison matrix (Agarwal et al. (2013))

Criteria	Geology	Soil	Slope	Land cover	Rainfall	Lineament density	Drainage density
Geology	1	4	6	7	5	3	2
Soil	1/4	1	3	4	2	1/2	1/3
Slope	1/6	1/3	1	2	1/2	1/4	1/5
Land cover	1/7	1/4	1/2	1	1/3	1/5	1/6
Rainfall	1/5	1/2	2	3	1	1/3	1/4
Lineament density	1/3	2	4	5	3	1	1/2
Drainage density	1/2	3	5	6	4	2	1

Table 10: Criteria weight based on the AHP method

Criteria	Weight (%)
Geology	35.4
Soil	10.4
Slope	4.5
Land cover	3.1
Rainfall	6.8
Lineament density	15.9
Drainage density	24.0

4.6 Groundwater potential zone mapping

A groundwater potential map for the study area was produced using map overlay analysis based on the weights calculated using the AHP method. Using raster calculator tools in ArcGIS, a composite groundwater potential map for the study area was generated. The weight reflects the relative importance of each layer. The largest weight is assigned to the most important layer. The resulting map was validated using an aquifer productivity map and well/borehole yield data obtained from SADC-GMI. However, the resultant map does not take into account groundwater quality constraints. Hence, the groundwater potential map was further analyzed together with the spatial map of water quality (i.e. salinity map) to delineate groundwater potential zones satisfying the quantity as well as the quality aspects.

4.7 Groundwater potential areas considering groundwater quality

A groundwater quality spatial map was used as a constraint for the groundwater potential map. The groundwater quality spatial map was used to exclude part of the area where water quality is exceeding the permissible limit for drinking water standards set by WHO. Using Boolean, areas exceeding the WHO drinking water standard for salinity were assigned a value of zero, and those areas having water quality within WHO permissible limits were assigned a value of one (which means areas with zero values are those areas that are excluded from the groundwater potential map). After this, the groundwater potential map obtained using GIS-MCDA, which is primarily focused on the groundwater quantity aspect is multiplied by the groundwater quality constraint map to obtain the spatial map of groundwater potential with good potential groundwater quality. Figure 11 shows the salinity sampling site during the dry period and interpolated values using the Inverse Distance Weighted (IDW) interpolation method. As can be seen in Figure 11 the sampling sites are concentrated in one location, hence the interpolated spatial values are associated with large uncertainties. Furthermore, natural salinity in groundwater may increase at depth owing to chemical reactions with aquifer material, residence time, and mixing of different waters (Monjerezi, 2012), however, no distinction is made in the present salinity mapping.

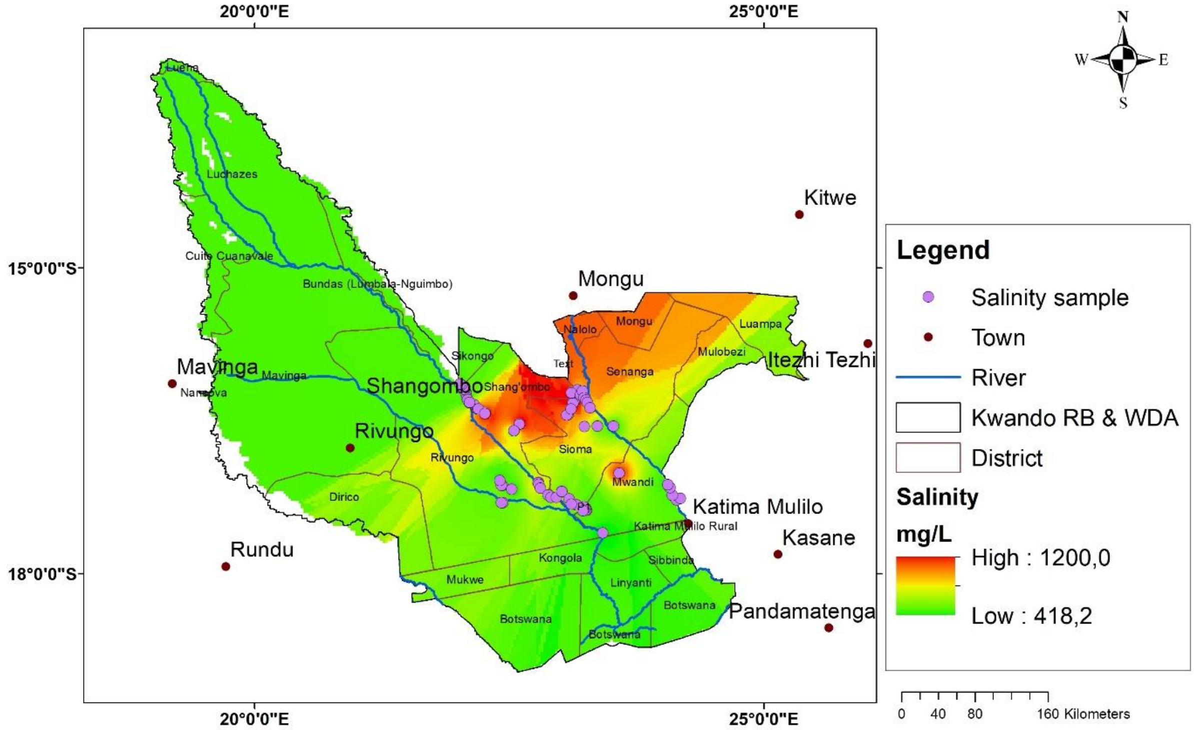

Figure 11: Salinity spatial values interpolated using Inverse Distance Weight based on combined wet and dry season sampling sites

5 RESULTS

Following the Gnanachandrasamy et al. (2018) approach, the groundwater potential map was classified into five classes (Table 12) from which the area in each groundwater potential class is calculated. The percentage area of each groundwater potential class calculated as the area in each groundwater potential class divided by the total area results in a computed groundwater potential index, which ranges between 0.34 and 0.82 (Figure 12). The computed groundwater potential index per district in the Kwando River Basin and Kwando River Wildlife Dispersal Area is given in Table 12. In terms of the mean groundwater potential index, Moxico and Lumbala-Nguimbo districts from Angola are ranked first and second respectively and Kaoma and Mongu districts are ranked third and fourth respectively.

Using the map values and the groundwater potential classes in Table 12, the groundwater potential map for the combined Kawando River Basin and Kwando River Wildlife Dispersal Area is shown in Figure 13. As shown in Figure 13, the groundwater potential is relatively good in the Angolan part of the study area.

Considering groundwater potential (quantity only), results show that only 0.02% of the area was classified as having very good groundwater potential and 27.57% of the area was classified as having good groundwater potential, with over 71.95% being moderate and 0.47% of the area being poor. 0% of the area is of very poor groundwater potential. Also including the consideration of groundwater quality, nearly 49 % and 21. 7% of the area is classified as moderate, and good groundwater potential, respectively. About 0.45% and 0.02% of the area are classified as having poor and very poor groundwater potential respectively. The moderate groundwater potential is reduced by 31% due to water quality (salinity) problems. Eleven out of the twenty districts (Dirico, Mavinga, Rivungo, Mukwe, Kongola, Kalabo, Kaoma, Mongu, Senanga, Sesheke, and Shangombo) are having salinity levels greater than 500 mg/L

Due to the high drainage density and low rainfall in the low land areas (flat topography), the groundwater potential seems low. This is contrary to what is expected in reality because shallow groundwater is more likely to occur in larger quantities under valleys than under hills because groundwater obeys the law of gravity and flows downward just as surface water does (Nonner, 2006).

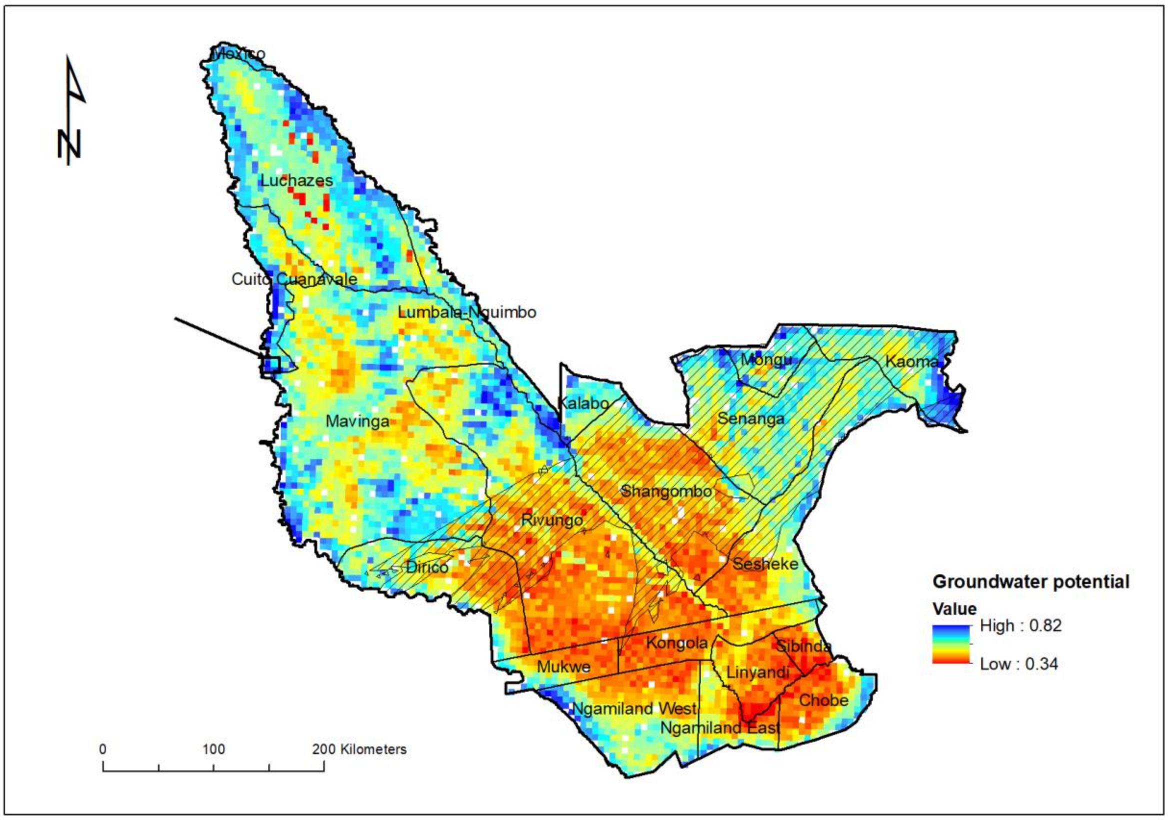

Figure 12: Groundwater potential map of the study area overlaid with districts. Salinity greater than 500 mg/l is shown in the hash polygon. The arrow shows the only single grid with very good groundwater potential (Cuito Cuanavale district, Angola).

Table 11: Groundwater potential index per district in the combined Kwando River Basin and Kwando River Wildlife Dispersal Area

SN.	District Name	Percentage area of the KRB and KRWDA	Country	Min	Max	Mean	Std
1	Cuito Cuanavale	2.345	Angola	0.453	0.820	0.611	0.079
2	Dirico	5.090	Angola	0.406	0.697	0.530	0.066
3	Mavinga	19.876	Angola	0.419	0.763	0.574	0.059
4	Rivungo	15.379	Angola	0.388	0.785	0.510	0.075

5	Luchazes	11.120	Angola	0.336	0.747	0.605	0.061
6	Lumbala-Nguimbo	2.059	Angola	0.495	0.782	0.621	0.052
7	Moxico	0.262	Angola	0.638	0.680	0.656	0.011
8	Chobe	2.510	Botswana	0.388	0.687	0.500	0.079
9	Ngamiland East	1.926	Botswana	0.373	0.687	0.510	0.064
10	Ngamiland West	5.135	Botswana	0.403	0.748	0.540	0.075
11	Mukwe	1.691	Namibia	0.414	0.687	0.500	0.071
12	Kongola	2.597	Namibia	0.414	0.653	0.472	0.046
13	Linyandi	1.988	Namibia	0.391	0.552	0.457	0.036
14	Sibinda	0.803	Namibia	0.396	0.579	0.448	0.040
15	Kalabo	1.210	Zambia	0.529	0.722	0.615	0.044
16	Kaoma	3.298	Zambia	0.501	0.794	0.618	0.061
17	Mongu	1.600	Zambia	0.460	0.800	0.617	0.064
18	Senanga	6.733	Zambia	0.434	0.766	0.579	0.048
19	Sesheke	6.120	Zambia	0.419	0.685	0.549	0.066
20	Shangombo	8.258	Zambia	0.413	0.715	0.497	0.052

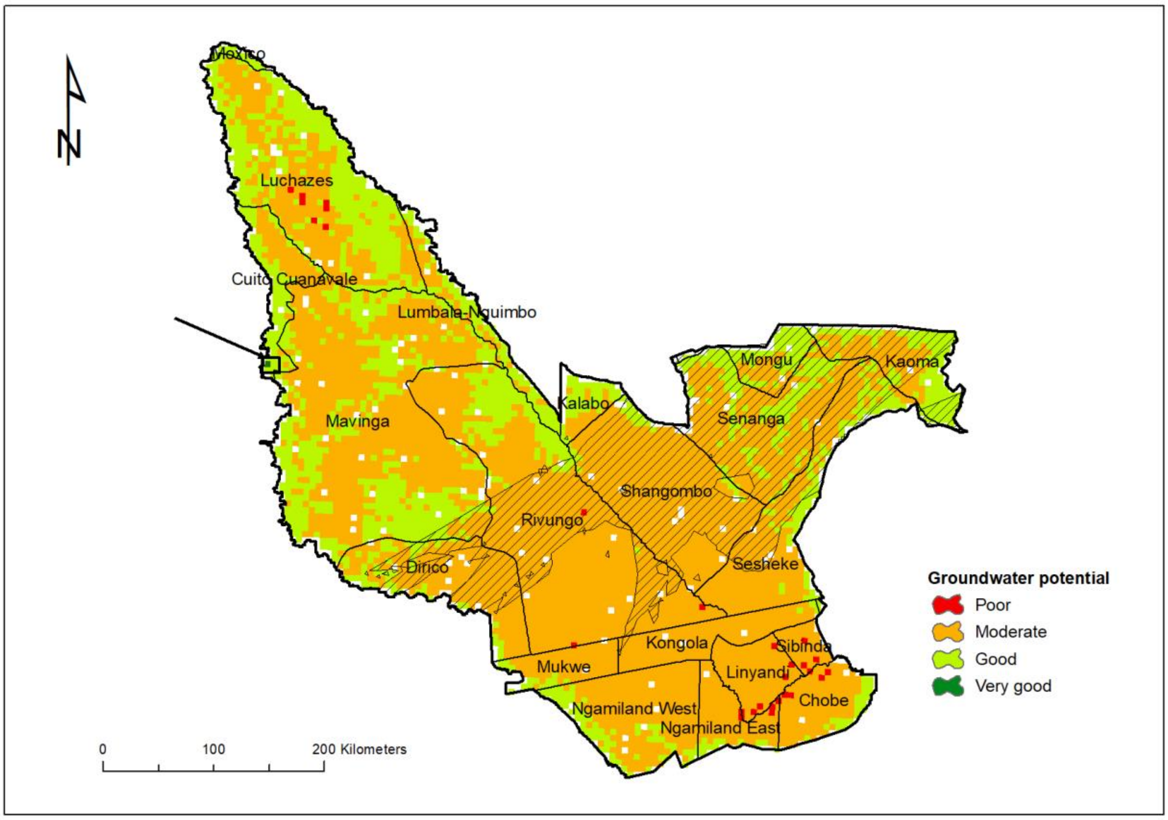

Figure 13: Groundwater potential zone map of the study area overlaid with districts (the white pixels are no data points and the box with the arrow shows the only pixel with very good groundwater potential). Salinity greater than 500 mg/l is shown in the hash polygon

Table 12: Percentage area of groundwater potential classes in the KRB and KRWDA

Map values	Groundwater potential classes	Percentage areas in each class considering groundwater quantity potential (%)	Percentage areas in each class considering groundwater quantity and salnity potential (%)
0-0.2	Very poor	0.0	0.0
0.2-0.4	Poor	0.47	0.45
0.4-0.6	Moderate	71.95	49.3
0.6-0.8	Good	27.57	21.65
0.8-1.0	Very good	0.02	0.02

6 DISCUSSION

Based on data availability and literature review, seven criteria including geology, lineament density, soil, slope, land use and land cover, rainfall, and drainage density were selected and used for groundwater potential mapping using GIS-MCDA. The AHP method was used to calculate the weight for each criterion map. The computed groundwater potential index ranges between 0.34 and 0.82. The final groundwater potential zone map was categorized into five classes: very good (0.02%), good (27.57%), moderate (71.95%), poor (0.47%) and very poor (0%). Results showed that the majority of the area is classified as moderate potential followed by good. The groundwater potential map developed in this study is in agreement with the aquifer productivity map (SADC, 2009) developed for the SADC region (Figure 14). Consideration of groundwater quality results in nearly 49 % and 21. 7% of the area is classified as moderate, and good groundwater potential, respectively. The moderate groundwater potential is reduced by 31% due to water quality (salinity) problems. The very good potential zone of the groundwater occurred just in one pixel (Figure 13). The good groundwater potential zones occurred in patches in the northern part and at the boundary of the study area.

The aquifer productivity map (~2.7 km x 2.7 km) produced by MacDonald et al. (2012) classified most of the KRB and KRWDA as highly productive areas, while most of the alluvial aquifer along the river channels are regarded as very highly productive area. MacDonald et al. (2012) classified aquifer productivity into six classes: very high (> 20 l/s), high (5-20 l/s), medium (1-5 l/s), low medium (0.5-1.0 l/s), low (0.1-0.5 l/s) and very low (<0.1 l/s). Of the 669 borehole yield data compiled from the SADC-GMI portal, mainly for Botswana and Namibia, covering the lower portion of the KRB and KRWDA study area show that only 0.7% of boreholes have yields of >20 l/s, 16% have borehole yields between 5-20 l/s and 55% have borehole yields between 1-5 l/s. This indicates that the study area should rather be classified as a moderate productive aquifer as opposed to high yielding aquifer as mapped by MacDonald et al. (2012).

A comparison of the groundwater potential map and the water scarcity vulnerability map shown in Figure 15 (IWMI, 2021) shows areas of moderate groundwater potential (in Angola, Botswana, Namibia, and Zambia) are appearing as areas of moderate to very high water scarcity vulnerability. This is expected as the water scarcity map considered both physical (e.g. rainfall, wetland, and protected areas) and socio-economic factors (e.g., distance from the river, population density, poverty levels, frequency of veld fire outbreaks, distance from wildlife corridors, boreholes and roads) that affected water access. An area might have a high physical potential for water supply but if the community does not have the capacity or infrastructure to harness the water, then they are vulnerable to water scarcity. The water scarcity vulnerability map shows vulnerability to water scarcity in the southern part (in Angola, Botswana, and Namibia) and less vulnerability due to high rainfall in the upper part of the study area in Angola (Figure 15). More importantly, the nuances that make the water scarcity vulnerability map provide an added value, showing an integrated human vulnerability, influenced by a host of biotic and abiotic, including human and wildlife, factors. The mapping of water scarcity vulnerable areas is important for the identification of livelihood vulnerability and investments needed to enhance adaptation and resilience building of communities under climate change, considering both current and potential future impacts in the KRB and KRWDA.

The resolution of the groundwater potential map developed in this study is approximately 5.5 Km by 5.5 km. This is due to the very coarse (~5.5 km x 5.5 km) global CHIRPS rainfall data resolution which limits the overall usability of the groundwater potential map at a scale less than the grid size (~5.5 km). Hence, it is important to update the groundwater potential map whenever better resolution rainfall, as well as geology and lineament density data, becomes available.

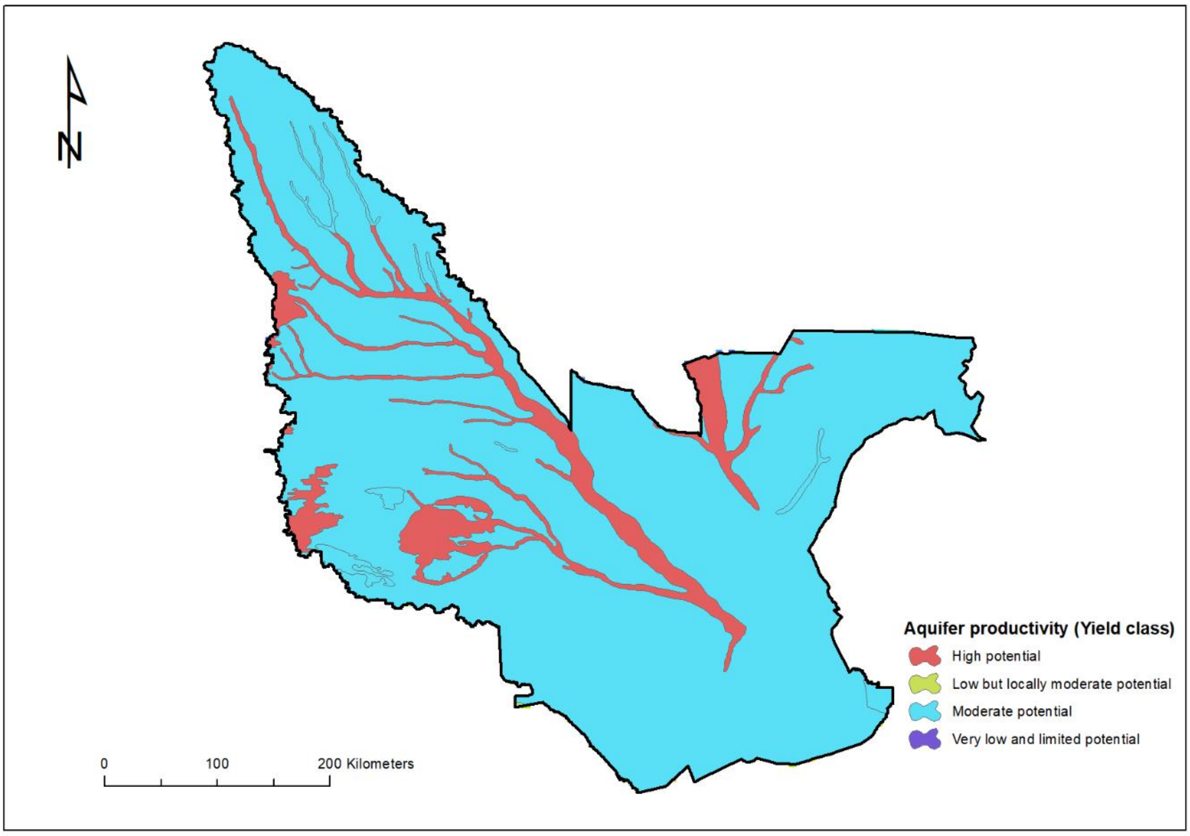

Figure 14: Aquifer productivity map from SADC hydrogeology map scale of 1:2,500 000 obtained from SADC-GMI (SADC, 2009)

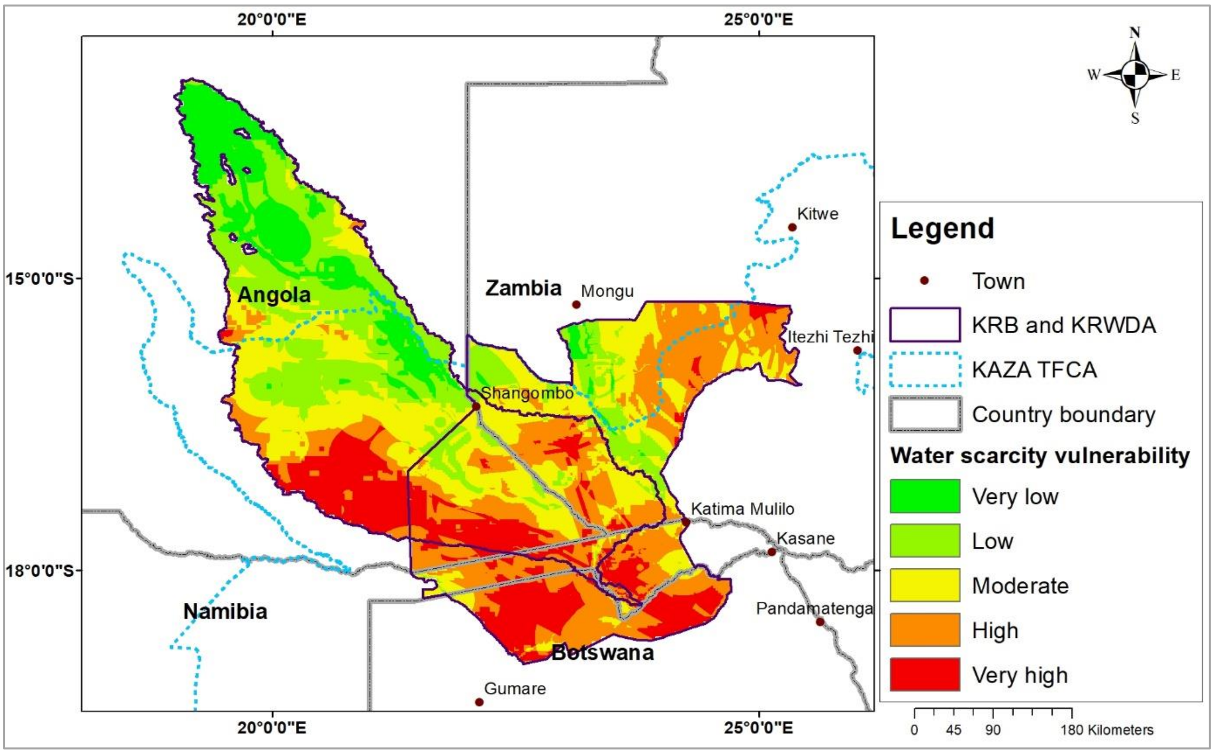

Figure 15:Water scarcity vulnerability map for the KRB and KRWDA (IWMI, 2021)

7 CONCLUSIONS

Groundwater investigations are costly and often involve the drilling of exploration boreholes. GIS-MCDA is a rapid and cost-effective method for groundwater potential mapping. GIS provides a robust technique for managing spatial data. The technique is useful for integrating geological, hydrogeological, topographic, and climatic information into a single map. Hence, it is a rapid and cost-effective tool for producing valuable groundwater potential maps.

In this study, the groundwater potential was identified using GIS–MCDA techniques. To delineate groundwater potential, seven thematic maps were systematically integrated using the weighted overlay analysis. The AHP method was used to determine the weights of the seven thematic maps. These weights are applied in a linear combination method for identifying the groundwater potential. The final groundwater potential map shows five levels of groundwater potential: very good, good, moderate, poor, and very poor groundwater potential classes. Results show that nearly 72% of the study area is classified as having moderate potential for groundwater but this value is reduced to 49% when salinity is considered (31% reduction in moderate groundwater potential classes). The low potential in low-lying areas is due to high drainage densities accompanied by low rainfall that promotes less groundwater recharge. Groundwater development should target areas with a high groundwater potential index.

As an overarching tool for planning, the map provides a powerful means of communicating results with stakeholders and policymakers on the overall situation and potential of groundwater in a spatial context in the KRB and KRWDA. The map will guide groundwater experts on the best areas for groundwater investigation, so they can drill new productive wells more rapidly and minimize the loss of time and resources associated with drilling unproductive wells, and prioritize aquifer and site investigations; inform planning decisions, and improve awareness of groundwater. The study and the map produced is intended to serve as a baseline upon which further investigations can be based and referred because it does not provide quantitative information on how much groundwater is in the aquifer. The groundwater potential map should be viewed as a dynamic system that is responsive to changing information needs. The methodology used in this study can be easily applied to the larger KAZA TFCA.

8 RECOMMENDATIONS

A detailed and comprehensive site investigation of groundwater and the conditions under which it occurs still need to be made by subsurface investigations. Furthermore, exploratory drilling provides the actual information regarding subsurface formations and direct access to subsurface formations and groundwater. Therefore, further refinement of this approach is necessary through geophysical investigations, exploratory drilling, and groundwater modeling. For sustainable development of groundwater in the study area understanding the groundwater system as a whole is important. Furthermore, promoting enhanced groundwater recharge is key to improving groundwater sustainability. Groundwater should also be protected from pollution. Environmental protection is central to maintaining the quantity and quality of water in an aquifer.

Effective groundwater development programs should comprise the following key components:

- Exploration of groundwater using geophysical and exploration drilling.
- Identify borehole sites that offer the greatest chance of success.
- Choosing the appropriate drilling technique.
- Borehole drilling and construction –the borehole must be constructed and completed to certain minimum standards to secure the long-term viability and serviceability of the installation. During borehole drilling, borehole-log information needs to be documented properly.
- Borehole testing- which includes borehole yield, and determining aquifer parameters through pumping tests and water quality testing.
- Water quality testing should be conducted before the water source is developed and, if the source is suitable, at regular intervals thereafter.
- Evaluation of the sustainability of groundwater yield and use. This is important to protect groundwater resources from over-exploitation.
- Wellhead protection measures to eliminate or mitigate human-induced contaminations
- Proper operation, maintenance, and repair of existing boreholes.
- Groundwater level monitoring should be an integral part of groundwater development. *You cannot manage what you can't measure.*
- It is important to undertake measures to increase groundwater recharge. For example, increasing aquifer recharge through watershed management best practices is key for groundwater sustainability.
- Capacity building. It is important to increase the awareness of the local community regarding the importance of groundwater. This is important to develop a sense of ownership for the operation, maintenance, and protection of groundwater supplies. It is also important to increase institutional capacity.

REFERENCES

Adams, S., Titus, R., and Xu, Y., 2004, Groundwater Recharge Assessment of the Basement Aquifers of Central Namaqualand: Report to the Water Research Commission, WRC.

Agarwal, E., Agarwal, R., Garg, R. D., and Garg, P. K., 2013, Delineation of groundwater potential zone: an AHP/ANP approach: Journal of earth system science, v. 122, no. 3, p. 887-898.
Aller, L., 1991, Handbook of suggested practices for the design and installation of ground-water monitoring wells, Environmental Monitoring Systems Laboratory, Office of Research and ….
Andualem, T. G., and Demeke, G. G., 2019, Groundwater potential assessment using GIS and remote sensing: A case study of Guna tana landscape, upper blue Nile Basin, Ethiopia: Journal of Hydrology: Regional Studies, v. 24, p. 100610.
Arulbalaji, P., Padmalal, D., and Sreelash, K., 2019, GIS and AHP techniques based delineation of groundwater potential zones: a case study from southern Western Ghats, India: Scientific reports, v. 9, no. 1, p. 1-17.
Bonilla Valverde, J. P., Blank, C., Roidt, M., Schneider, L., and Stefan, C., 2016, Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods: Water, v. 8, no. 9, p. 391.
Carew, A., and Costanzo, S., 2020, Kwando River Basin Report Card Stakeholder Workshop Summary 9–11 March 2020, Kasane, Botswana.
Dar, I. A., Sankar, K., and Dar, M. A., 2010, Remote sensing technology and geographic information system modeling: an integrated approach towards the mapping of groundwater potential zones in Hardrock terrain, Mamundiyar basin: Journal of Hydrology, v. 394, no. 3-4, p. 285-295.
de FSM Russo, R., and Camanho, R., 2015, Criteria in AHP: a systematic review of literature: Procedia Computer Science, v. 55, p. 1123-1132.
Dodgson, J., Spackman, M., Pearman, A., and Phillips, L., 2009, Multi-criteria analysis: a manual.
ESA, 2016, CCI Land cover –S2 Prototype land cover 20 m map of Africa 2016, http://2016africalandcover20m.esrin.esa.int/.
Fashae, O. A., Tijani, M. N., Talabi, A. O., and Adedeji, O. I., 2014, Delineation of groundwater potential zones in the crystalline basement terrain of SW-Nigeria: an integrated GIS and remote sensing approach: Applied Water Science, v. 4, no. 1, p. 19-38.
Funk, C. C., Peterson, P. J., Landsfeld, M. F., Pedreros, D. H., Verdin, J. P., Rowland, J. D., Romero, B. E., Husak, G. J., Michaelsen, J. C., and Verdin, A. P., 2014, A quasi-global precipitation time series for drought monitoring: US Geological Survey, 2327-638X.
GITTA, 2013, Suitability analyis by Geographic Information Technology Training Alliance (GITTA) http://www.gitta.info/Suitability/en/text/Suitability.pdf [Accessed on August 2022].
Gnanachandrasamy, G., Zhou, Y., Bagyaraj, M., Venkatramanan, S., Ramkumar, T., and Wang, S., 2018, Remote sensing and GIS based groundwater potential zone mapping in Ariyalur District, Tamil Nadu: Journal of the Geological Society of India, v. 92, no. 4, p. 484-490.
Heath, R. C., 1984, Ground-water regions of the United States, US Department of the Interior, Geological Survey.
Hengl, T., de Jesus, J. M., Heuvelink, G. B., Gonzalez, M. R., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., and Bauer-Marschallinger, B., 2017, SoilGrids250m: Global gridded soil information based on machine learning: PLoS one, v. 12, no. 2, p. e0169748.
IWMI, 2021, Water Scarcity Vulnerability Map of the Kwando River Basin and Kwando River Wildlife Dispersal Area. Deliverable submitted by International Water Management Institute (IWMI) to Resilient Waters for the project: Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area KAZA-GROW. Pretoria, South Africa.
Johnson, A. I., 1963, A field method for measurement of infiltration, US Government Printing Office Washington.
Kotchoni, D., Vouillamoz, J.-M., Lawson, F., Adjomayi, P., Boukari, M., and Taylor, R. G., 2019, Relationships between rainfall and groundwater recharge in seasonally humid Benin: a

comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers: Hydrogeology Journal, v. 27, no. 2, p. 447-457.
Leader, T. T., and Wijnen, M., 2018, Assessment of Groundwater Challenges & Opportunities in Support of Sustainable Development in Sub-Saharan Africa.
MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., and Taylor, R. G., 2012, Quantitative maps of groundwater resources in Africa: Environmental Research Letters, v. 7, no. 2, p. 024009.
Machiwal, D., Jha, M. K., and Mal, B. C., 2011, Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques: Water resources management, v. 25, no. 5, p. 1359-1386.
Magesh, N., Chandrasekar, N., and Soundranayagam, J. P., 2012, Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques: Geoscience frontiers, v. 3, no. 2, p. 189-196.
Malczewski, J., 2000, On the use of weighted linear combination method in GIS: common and best practice approaches: Transactions in GIS, v. 4, no. 1, p. 5-22.
Monjerezi, M., 2012, Groundwater salinity in lower shire river valley (Malawi) hydro-geochemical and isotope constraints on sources and evolution: University of Oslo (June), v. 188.
Mukherjee, P., Singh, C. K., and Mukherjee, S., 2012, Delineation of groundwater potential zones in arid region of India—a remote sensing and GIS approach: Water resources management, v. 26, no. 9, p. 2643-2672.
Murray, R., Baker, K., Ravenscroft, P., Musekiwa, C., and Dennis, R., 2012, A groundwater-planning toolkit for the main Karoo basin: identifying and quantifying groundwater-development options incorporating the concept of wellfield yields and aquifer firm yields: Water SA, v. 38, no. 3, p. 407-416.
Nonner, J. C., 2006, Groundwater Exploration, UNESCO-IHE, Lecture Notes.
Owor, M., Taylor, R., Tindimugaya, C., and Mwesigwa, D., 2009, Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin: Environmental Research Letters, v. 4, no. 3, p. 035009.
Owuor, S. O., Butterbach-Bahl, K., Guzha, A. C., Rufino, M. C., Pelster, D. E., Díaz-Pinés, E., and Breuer, L., 2016, Groundwater recharge rates and surface runoff response to land use and land cover changes in semi-arid environments: Ecological Processes, v. 5, no. 1, p. 1-21.
Rahmati, O., Nazari Samani, A., Mahdavi, M., Pourghasemi, H. R., and Zeinivand, H., 2015, Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS: Arabian Journal of Geosciences, v. 8, no. 9, p. 7059-7071.
RTI, 2013, Advanced Survey of Groundwater Resources of Northern and Central Turkana County, Kenya FINAL TECHNICAL REPORT.
Saaty, T. L., 1994, How to make a decision: the analytic hierarchy process: Interfaces, v. 24, no. 6, p. 19-43.
-, 2008, Decision making with the analytic hierarchy process: International journal of services sciences, v. 1, no. 1, p. 83-98.
SADC, 2009, Explanatory Brochure for the South African Development Community (SADC) Hydrogeological Map & Atlas.
Sander, P., 2007, Lineaments in groundwater exploration: a review of applications and limitations: Hydrogeology journal, v. 15, no. 1, p. 71-74.
Saranya, T., and Saravanan, S., 2020, Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India: Modeling Earth Systems and Environment, v. 6, no. 2, p. 1105-1122.
Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., and Dennehy, K. F., 2005, Impact of land use and land cover change on groundwater recharge and quality in the southwestern US: Global Change Biology, v. 11, no. 10, p. 1577-1593.

Shaban, A., Khawlie, M., and Abdallah, C., 2006, Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon: Hydrogeology Journal, v. 14, no. 4, p. 433-443.
Singh, L. K., Jha, M. K., and Chowdary, V., 2018, Assessing the accuracy of GIS-based multi-criteria decision analysis approaches for mapping groundwater potential: Ecological Indicators, v. 91, p. 24-37.
Tolche, A. D., 2021, Groundwater potential mapping using geospatial techniques: a case study of Dhungeta-Ramis sub-basin, Ethiopia: Geology, Ecology, and Landscapes, v. 5, no. 1, p. 65-80.
USGS, 2021, Unconsolidated and semiconsolidated sand and gravel aquifers https://www.usgs.gov/mission-areas/water-resources/science/unconsolidated-and-semiconsolidated-sand-and-gravel-aquifers [Accessed on August 2022].
Waikar, M., and Nilawar, A. P., 2014, Identification of groundwater potential zone using remote sensing and GIS technique: International Journal of Innovative Research in Science, Engineering and Technology, v. 3, no. 5, p. 12163-12174.
Woldt, W., and Bogardi, I., 1992, Groundwater Monitoring Network Design Using Multiple Criteria Decision Making and Geostatistics JAWRA Journal of the American Water Resources Association, v. 28, no. 1, p. 45-62.
Yeh, H.-F., Lee, C.-H., Hsu, K.-C., and Chang, P.-H., 2009, GIS for the assessment of the groundwater recharge potential zone: Environmental geology, v. 58, no. 1, p. 185-195.