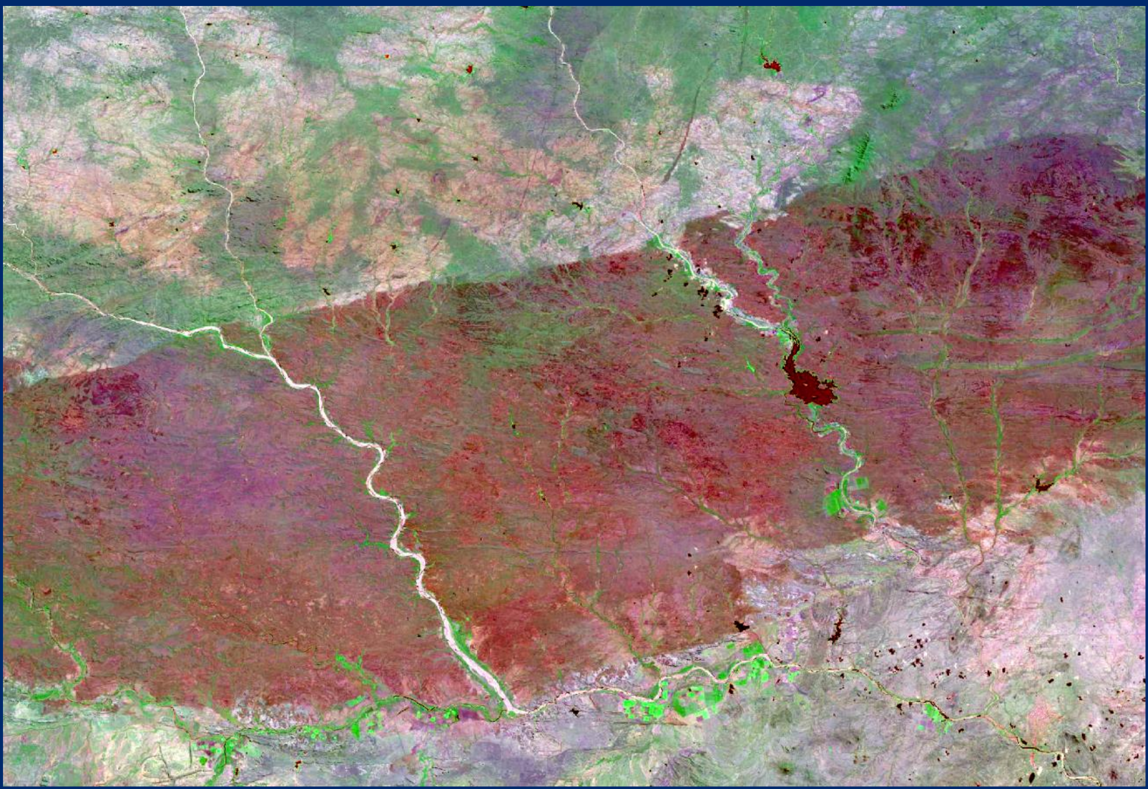
GIS Based Multi-Criteria Decision Analysis to Assess Managed Aquifer Recharge Potential in the Tuli Karoo Transboundary Aquifer



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Executive Summary

Transboundary groundwaters are of growing importance to the Southern Africa Development Community (SADC) region, as an critical means to satisfy the water demands of growing populations and economies. The Tuli Karoo Aquifer – shared among Botswana, South Africa, and Zimbabwe – is one such aquifer. Under-explored and classified as a troublesome, the TBA may benefit from shared management through regional or international co-operation. One way to enhance shared management – which increases availability of water to people, economies and livelihoods – is through the expansion of ground water availability through Managed Aquifer Recharge (MAR). MAR has gained popularity in recent years globally, but in southern Africa uptake is still low. For a MAR scheme to be successful, suitability mapping is an important tool to identify potential sites. The objective of this report is to assess the potential for MAR in the Tuli Karoo Aquifer. The report uses GIS based multi-criteria decision analysis (GIS-MCDA) to identify the areas suitable for MAR in the study area. Based on literature review and availability of data, six criteria (slope, soil, land use/land cover, lithology, lineament density and drainage density) were selected for the GIS-MCDA. Weighted linear combination was used to combine the six thematic maps to produce a spatial MAR suitability map. Results of the suitability assessment show that approximately 57% of the area belongs to the suitable class and while 7% is of high suitability class. The sensitivity analysis shows that land use and land cover is the most sensitive criteria with lineament density being the least. In summary, the area shows good potential for MAR.

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1. INTRODUCTION

Water Stress in the SADC region Water is a major challenge for sustainable development in Southern Africa and calls for integrated water resources management, including measures to avoid water losses, efficient use of water, introduction of water saving technologies, as well as water re-use and recycling (Villholth, et al., 2011). The region is experiencing low rainfall and high rates of potential evapotranspiration. Furthermore, expected climate change implies risks for rainfall seasons being shorter and less reliable in the future (Zhu & Ringler, 2012). In Limpopo River Basin, water resources is already stressed and this impact is expected to worsen by 2050 due to climate change (Zhu & Ringler, 2012). The effects of climate change are expected to exacerbate water security concerns in Southern Africa (IPCC, 2007).

The role of Managed Aquifer Recharge (MAR) Also known as Artificial groundwater Recharge (AR), MAR is a well-established technique to increase groundwater availability, reduce evaporation losses, and promote conjunctive groundwater and surface water use if carefully implemented (Casanova et al., 2016). Water scarcity in Southern Africa accentuated by urban growth, especially in semi-arid and arid regions, has resulted in a growing interest in MAR as a basis for water supply by collecting surface runoff when it is available or treated wastewater (Wellfield consulting services, 2011). MAR can be achieved through spreading methods, injection wells, in channel modification, and induced bank filtration. The surface spreading method uses constructed infiltration basins to recharge the aquifer system and is often a preferred MAR option to control clogging and to achieve water quality improvement (Bouwer, 2002). However, in areas where evaporation is high or land for construction of surface infiltration system is not available and if there is an impermeable aquifer layer that restrict infiltration, depending on the depth of the impermeable layer, vadose zone wells, trenches or direct injection wells can be used (Bouwer, 2002). In-channel modification involves detaining flood water using dams constructed in non-perennial rivers and allow percolation by slowly releasing water into streambed downstream to match infiltration capacity of the riverbed. Sand dams and subsurface dams also belong to this category. Induced bank filtration involves inducing surface water into aquifer by pumping close to the bank of the surface water bodies, and this process is performed when direct use of surface water is prohibited due to surface water quality issue (i.e., the streambed and the aquifer are used to improve water quality). Details about the different MAR techniques can be found in Dillon (2005) and Gale (2005). Recharged water through MAR may be sourced from rainwater, surface runoff, and treated wastewater. With regard to recharge water not only the quantity but also the quality of recharge water is a determinate for the success of MAR.

MAR experience in SADC region Compared to other regions, MAR in the SADC region and Africa in general is very limited (Ebrahim et al., 2020). According to Dillion (2019), MAR volume growth rate in the SADC region is 5.1% per year and MAR as percentage of groundwater use is as low as 0.2%. In the SADC region MAR is practiced in greatest abundance in South Africa followed by Namibia. The Atlantis cases study in the South Africa is one of the world's notable example of MAR schemes with more than 30 years of services. The Windhoek case study, Namibia provides a very good example that demonstrated the success of a large-scale municipal use MAR scheme in a fractured rock aquifer settings. The Windhoek MAR schemes augment water supply of Windhoek, the capital city of Namibia (Biggs and Williams, 1999). In Botswana, even though there is no single implemented MAR scheme, there have been initial assessments. For example, Fathi (2017) and Ebrahim et al. (2017) conducted a MAR suitability assessment mapping for the Ramotswa Transboundary Aquifer area. Lindhe et al. (2014) carried out a pre-feasibility study of increasing water supply safety by MAR along the North-South Carrier in Botswana. The North-South Carrier connects a number of surface water dams, groundwater aquifers and water treatment facilities along eastern Botswana supplying drinking water to a large portion of the population. Eastern Botswana is where a majority of the country's population resides, thus it supplies water to highly populated urban areas such as Gaborone and Palapye along its route (Lindhe A. et al, 2020). More recently, SWECO (2020) conducted feasibility study of MAR at Pallaroad wellfield, Botswana. The study is currently at an inception stage which includes literature review, reconnaissance work, reports on findings and analysis. The project is being implemented under component 3 of the ongoing World Bank funded ‘Botswana water security and efficiency project’.

Planning for MAR According to Murray & Ravenscroft (2009), implementation of MAR schemes is divided into four stages; Pre-feasibility, feasibility, implementation and operation and maintenance stages (see Annex 1). According to Dillion (2005), one of the critical steps in the implementation of MAR projects is identification of suitable MAR sites. This step is very essential because it influences the MAR technique, operation strategy and maintenance of the MAR project. One of the common approaches for the identification of MAR sites involves suitability mapping. A suitability map that assists the identification of suitable site can be produced based on Geographical Information System (GIS) and Remote Sensing based Multi criteria decision analysis (Lentswe & Molwalefhe, 2020). One advantage of this approach is its ability to produce a spatial map covering a large area and allowing quick analysis which is inexpensive but with an acceptable outcome (Sallwey et al, 2018). This is particularly useful for areas such as transboundary aquifers which cross political boundaries and access to those locales can be costly or time consuming. Suitability maps for MAR sites hold strong potential for integration into sustainable groundwater management plans (Sallwey et al., 2018).

Objective The main objective of this report is to develop a MAR suitability map using GIS based multi-criteria decision analysis for the Tuli Karoo Transboundary Aquifer shared between Botswana, South Africa and Zimbabwe. The suitability provide a quantitative means for assessment of MAR potential in the Transboundary Aquifer and help to guide identification of suitable areas for detail investigations of MAR.

2. STUDY AREA DESCRIPTION

The Tuli Karoo Transboundary Aquifer is shared between Botswana, South Africa and Zimbabwe. The Aquifer area is located in the Upper Limpopo River Basin (Figure 1). It covers an area of around about 12,293 km2. The mean annual precipitation ranges between 200 and 455 mm. The population in the South African and Zimbabwean side of the aquifer is largely rural while being mostly urban in Botswana (Lautze et al, 2019). The areas are also home to heavy agricultural and mining activity. More than half of the Bobirwa sub-district in the Botswana lies within the Tuli Karoo aquifer (Lautze et al, 2019). The population in the area was estimated at around 81, 500 and is said to be steadily growing at an average rate of around 2% per annum in the last decade alone (Statistics Botswana, 2015). The area poverty headcount has noticeably decreased from 32.8% in 2009/10 to 13.9% in 2015/16 and Bobonong is considered an urban village (Statistics Botswana, 2016). The South African portion of the aquifer lies entirely within the Musina local municipality. The Municipality has a total population of 132 009. 84% of residents in the area access water from a regional or local provider (Statistics South Africa, 2016). Musina had a poverty headcount of 24.7 % in 2011 which reduced to 19.1 % in 2016 (Statistics Botswana, 2016). The Tuli Karoo Aquifer has its largest portion in Southern Zimbabwe, known as the Matabeleland South Province (Zimbabwe National Statistics Agency, 2017). The area population has increased from 683 900 to 810 100 in 5 years from 2012 to 2017, a more than 5% increase (Lautze et al, 2019). The area has a 62.8% poverty prevalence and 17.8% extreme poverty prevalence.

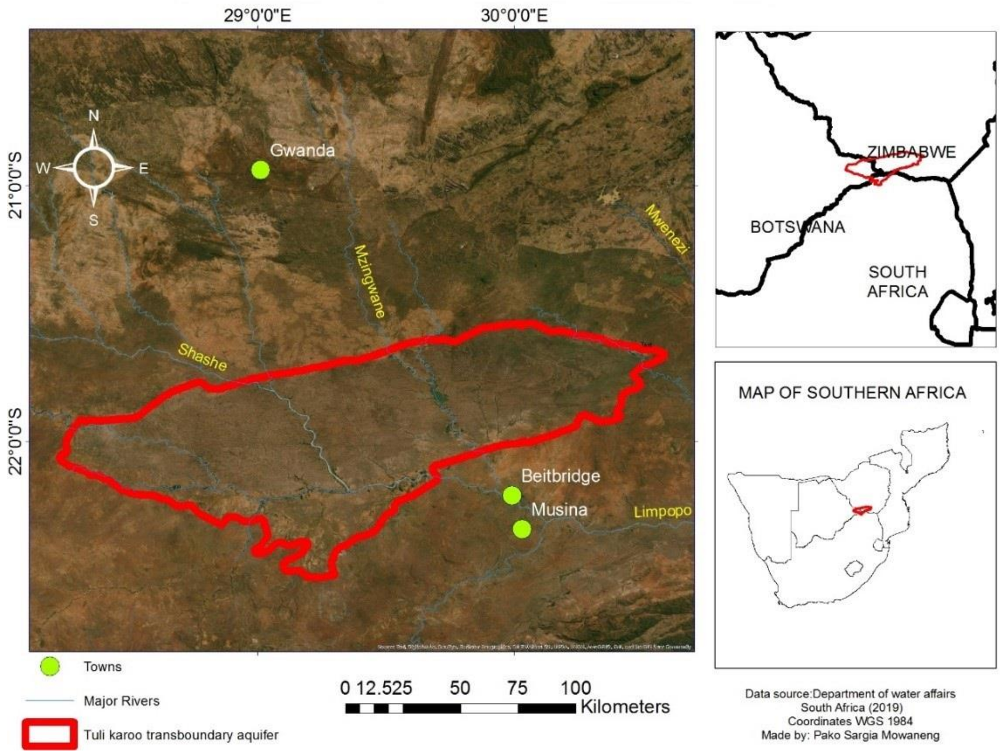

Figure 1: Tuli Karoo Aquifer

3. METHODOLOGY

This report uses both a quantitative and qualitative approach. The qualitative approach includes use of literature to determine the most suitable method of MAR for the study area. A quantitative approach involved ranking and giving weight to the thematic maps and using a determination of overlay analysis to identify suitable areas for MAR. The data collection and analysis methods detailed in the next section was used for ultimately identifying those areas suitable for MAR.

Selected MAR type The present report assumes that the preferred method of MAR in the Tuli Karoo Transboundary Aquifer is the spreading method, for at least three reasons. First, the spreading method is low cost and practically simple to apply. Second, data are easily available for suitability assessment according to this method. Third, the spreading method allows a natural treatment process. A previous study by Ebrahim et al. (2017) used these criteria to choose MAR techniques applied in the Ramotswa Transboundary Aquifer Area. Spreading method consists of all kinds of measures that enhance natural recharge (e.g., infiltration basins, controlled flooding).

3.1 GIS MULTI-CRITERIA DECISION ANALYSIS STEPS

Multi-Criteria Evaluation is a method of combining information from several criteria to form a single index of evaluation (Ebrahim et al., 2017). Geographic information systems based multi criteria decision analysis (GIS-MCDA) is a method that contains a collection of methods and tools in order to combine and transform spatial data based on their value judgements to gain unit information and ultimately make a judgmental decision (Malczweski, 1999). GIS-MCDA involves several steps that include: problem definition, constraint mapping, criteria selection, standardization of criteria, assigning relative weights, map overlay analysis and sensitively analysis. Problem definition consists of defining and characterizing the problem and the required datasets. Constraint mapping comparises of excluding restricted areas deemed non feasible for MAR application (Figure 2). Selection of criteria involves selecting relevant surface, subsurface and catchment characteristics used for suitability analysis. It is important that every selected criteria has to be measurable and non-redundant or should not be correlated. The standardization step involves describing each criteria in a common scale. Since map units used for overlay analysis are different, it is important that each map is described in a common scale usually between 0 and 1. Assigning relative weight involves ascribing different weights to each criterion based on their importance to the process. Map overlay involves multiplying each standardized map with assigned weight. The Weighed Linear combination (WLC) method (Equation 1) is the most common approach for weighted overlay analysis from (Rahman, Rusteberg, Gogu, Ferreira, & Sauter, 2012). Sensitivity analysis is carried out to check the sensitivity of each criteria for change in assigned weights. Sensitivity analysis is performed to determine the rate of change in MAR suitability classes by varying the weights, thus giving an understanding of how change in criteria weight influence the output of the suitability mapping.

WLC $s(x_i) = \sum w_i \, . \, s_i(x_i)$ Equation 1

Where w_i=normalized weight; $\sum w_i = 1$; $s_i(x_i) = \text{standardised criteria function/map}$

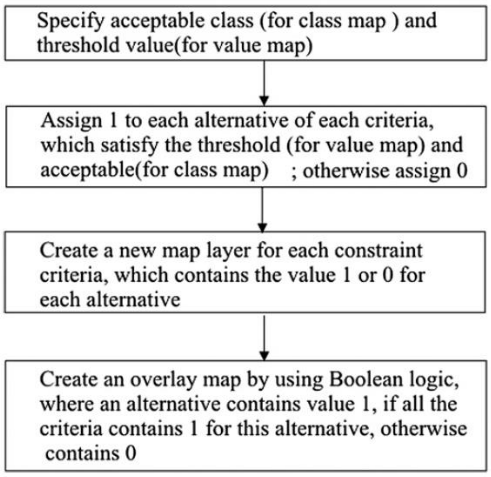

Figure 2: Flow chart for constraint mapping (Rahman, Rusteberg, Gogu, Ferreira, & Sauter, 2012)

3.2 CRITERIA SELECTION

The selection of the criteria is based on literature review study based on similar studies such as Valverde et al (2016) and Malczewski (1999). The main thematic layers identified that was used include: slope, soil, land use/land cover, lithology, and drainage density and lineament density. Table 1 presents the six criteria and their data sources;

Table 1: Selected criteria and data source

CRITERIA	DESCRIPTION	SOURCE	RESOLUTION
SLOPE	The runoff is directly related to slope angle thus flat areas prove to be more suitable for surface infiltration and was given a higher weight	SRTM 1ARC-Second Global https://earthexplorer.usgs.gov/	30x30 m

SOIL	Soil properties determine penetration as the first contact of water through surface infiltration. Low permeability soils are unsuitable for surface infiltration. The highest weight was assigned to soils with high water infiltration rates. In the present study, Harmonized World Soil Database (HWSD) (Nachtergaele, van Velthuizen, Verelst, & Batjes, Harmonized world soil database (version 1.0):, 2008) and Soil Atlas of Africa (Dewitte, Jones, & Spaargaren, Harmonisation of the soil map of Africa at the continental scale, 2013) was used to classify and standardize soil classes. HWSD contains information for top and sub-soil layers.	International Soil Reference and Information Centre (ISRIC) Data Hub https://data.isric.org/geonetwork/srv/eng/catalog.search;jsessionid=CEAF36FC8B9C51EC4BB1F19986823DC4#/metadata/3571c1f3-159d-442c-b324-0af53d03f12e	1 km Vector file
LAND COVER/LAND USE	Highly Vegetated areas are unsuitable for MAR since land has to be cleared for surface infiltration. Urban areas have many impermeable surfaces thus are not viable The land use and land cover classification was carried out based on the European Space Agency (ESA) Climate Change Initiative (CCI) 2015 land use and land cover classes (European Space Agency (ESA) Climate Change Initiative (CCI), 2020). European Space Agency (ESA) Climate Change Initiative (CCI) – Land cover map 2015 land use and land cover map consists of 22 land use classes;	European Space Agency (ESA) Climate Change Initiative (CCI) – Land cover map 2015 http://maps.elie.ucl.ac.be/CCI/viewer/download.php	300 x 300 m
LITHOLOGY	The lithology determines the main aquifer storage and permeability. The higher the permeability the higher the recharge rates. Low transmissivity can inhibit lateral flow from recharge area resulting in groundwater mounds. The highest weight was given to rocks that have high porosity. Geological maps developed using airborne electromagnetic survey was used for the analysis.	Simplified geology map IGRAC-GGIS Global Portal https://apps.geodan.nl/igrac/gGIS-viewer/viewer/sadcgip/public/default	1 km
DRAINAGE DENSITY AND RIVER NETWORK	Areas with high drainage density provide more runoff and less permeability; hence, areas considered as favourable, can trap excessive runoff. Drainage plays a key role as hydrogeological indicators, because underlying lithological and geological aspects control drainage density.	SRTM 1ARC-Second Global https://earthexplorer.usgs.gov/	30x30 m
LINEAMENTS DENSITY	Highly fractured rock zones have higher percolation rates and can hold more water in. In addition, lineament analysis can help find the water flows and groundwater storage.	SADC-GMI	Vector

3.3 CONSTRAINT MAPPING

A global review of GIS-based MAR suitability by Sallwey et al (2018) indicated that agricultural land use, surface water bodies, urban areas, forests, traffic routes and vulnerable areas in most case studies. In the present study three maps were used for constraint mapping. These include: Slope, soil, and land use/land cover (Table 2), combining the three restriction maps resulted in the constraint map below. Figure 3 shows constraint map produced using the three criteria

Table 2: Defined thresholds and selected criteria for Constraint mapping

CRITERIA	Excluding criteria description
SLOPE	Areas with a slope of more than 30% are considered too steep ,since the sites needs to be relatively flat to allow water to infiltrate the surface and not runoff
SOIL	Clay has a very low infiltration rate thus will not transmit water to aquifer
LAND COVER/ LANDUSE	Urban areas and water bodies have no potential for MAR since the already being used for other important activities

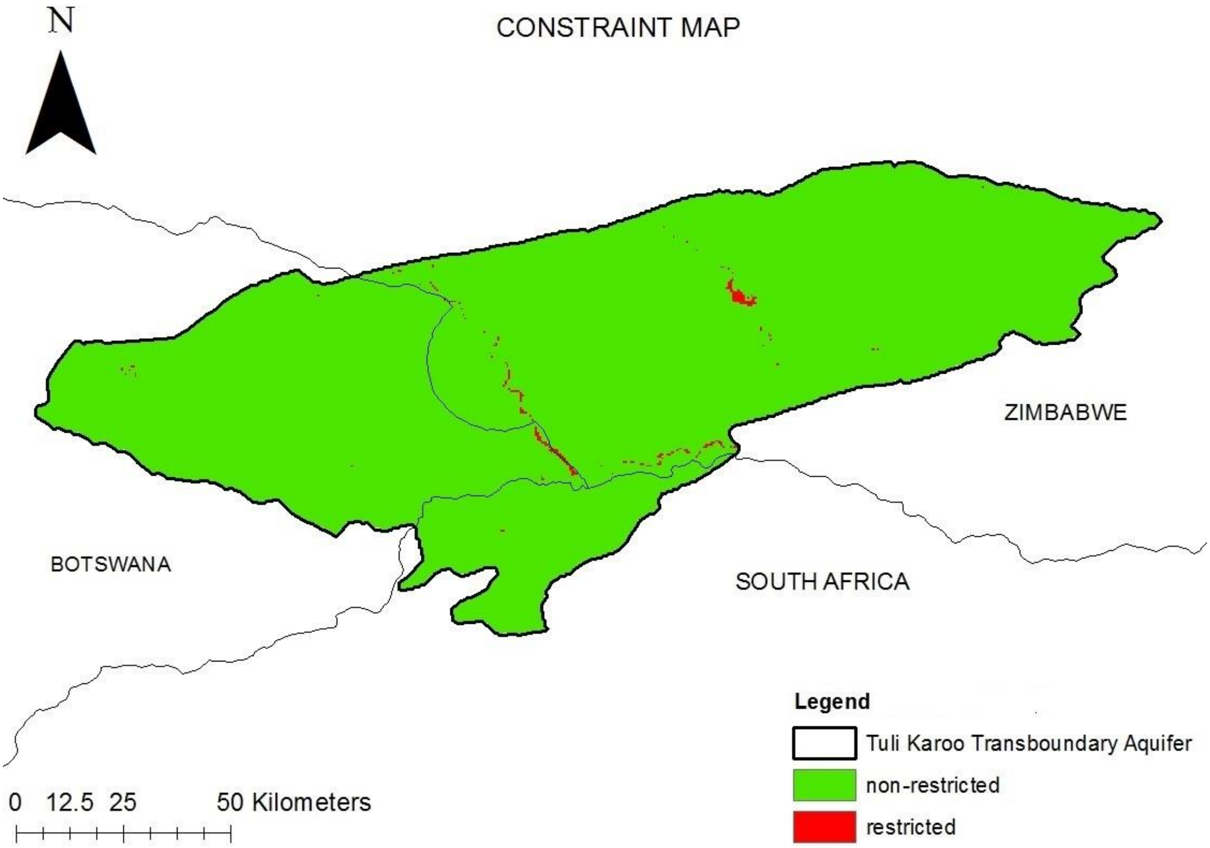

Figure 3: Constraint mapping for the Tuli Karoo Aquifer

3.4 RECLASSIFICATION AND STANDARDIZATION

CRITERIA 1: SLOPE

The slope gradient directly influences groundwater infiltration and, as such, it is one of the main criteria that control natural recharge in a basin (Yeh et al, 2009). The steeper the slope, the less the recharge because water runs rapidly off the surface without sufficient time to infiltrate. Furthermore, on steep slopes runoff is more erosive thus removes and transports detached sediments down the slope which could be a risk to an infiltration pond (Valverde et al, 2016). Figure 4 shows the land surface slope of the Tuli Karoo Aquifer. Based on its suitability for MAR using the spreading method, slope is normalized to a scale from 0 to 1. Gentle slopes (<5%) increase infiltration rates and are very suitable and hence assigned a value of '1' (very suitable). For the areas with a slope between 5 and 30%, a continuous criteria as shown in Figure 5 was used with the following linear function: y= - 0.04 x+1.2 based on Ebrahim et al. (2017) approach. Areas with more than 30% slope are deemed unsuitable due to poor groundwater infiltration conditions thus given a value of '0'. The standardized slope map based on the above criteria was re-classified into MAR suitability class based on slope classes presented in Table 3. The resulting slope suitability for MAR map is shown in Figure 6.

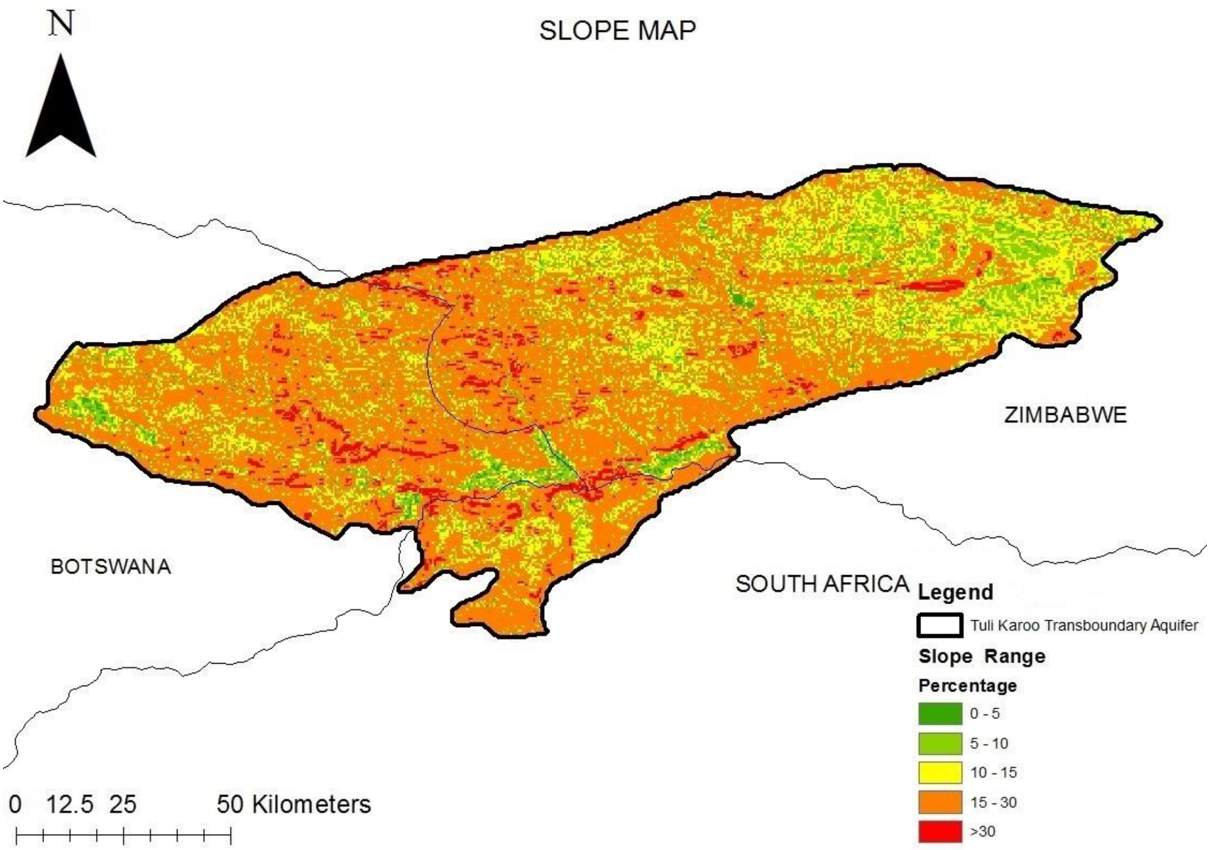

Figure 4: Land surface slope classes of the Tuli Karoo Aquifer

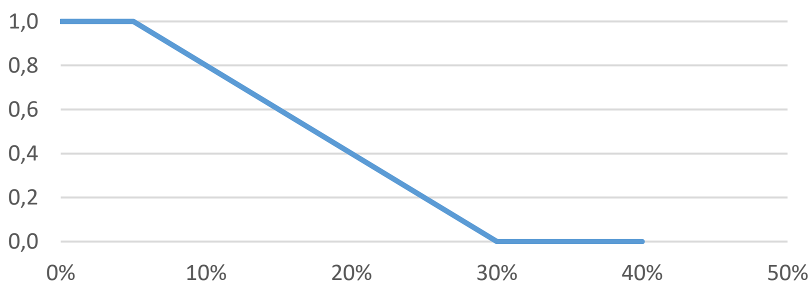

Figure 5: Slope classification based on MAR suitability (x-axis is slope in percent and y-axis represent standardized values)

Table 3: Slope classes and MAR suitability classes used to classify the spatial map of slope suitability for MAR application

REGIONAL SLOPE CLASSIFICATION	ORIGINAL SLOPE (%)	MAR CLASS	VALUE
Depression	**-**	**Very Suitable**	0.8-1.0
Flat	**0-5**		
Gently Undulating	5-10	**Suitable**	0.6-0.8
Undulating	10-15	**Moderately**	0.4-0.6
Rolling	15-25	**Low suitability**	**0.2 – 0.4**
Moderately steep			
Steep	>30	**Unsuitable**	**0.0 – 0.2**

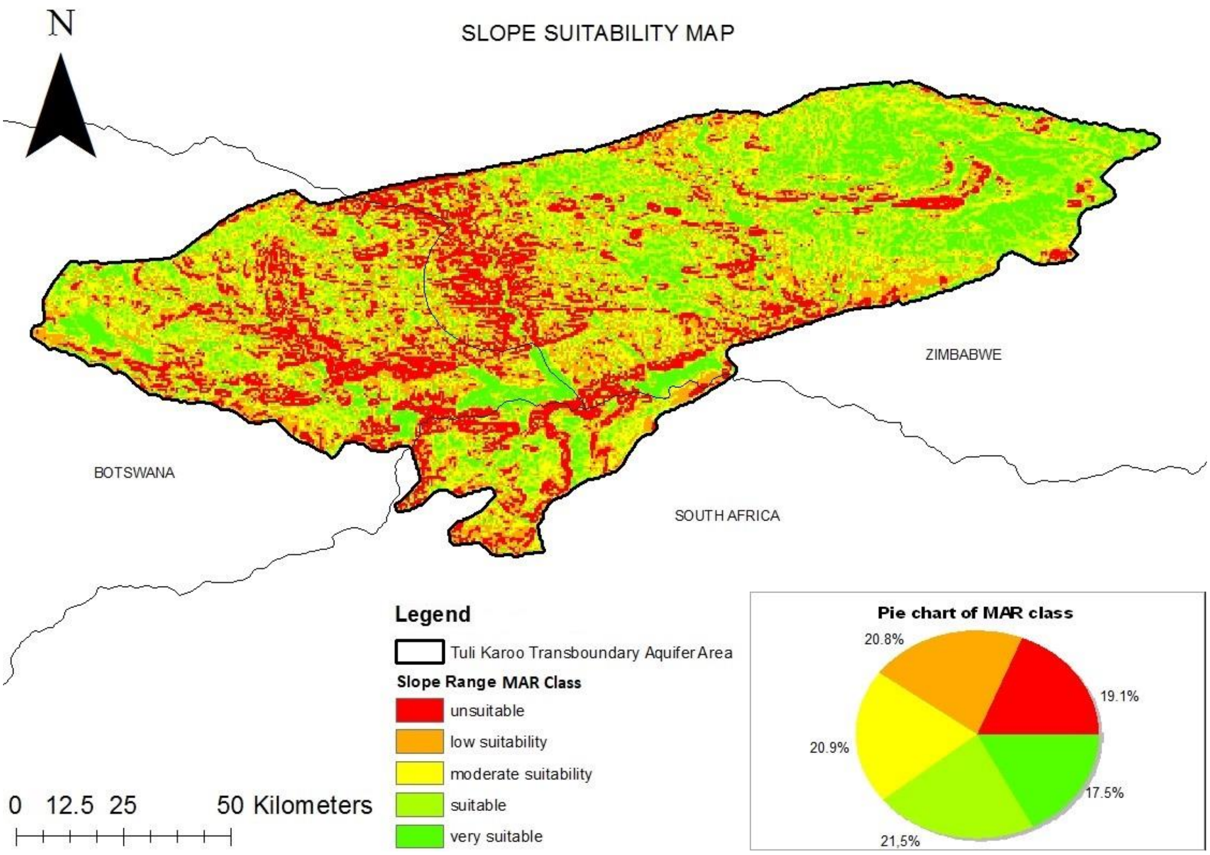

Figure 6: Slope suitability for MAR in Tuli Karoo Aquifer (slope map standardized based on Figure 5 but re-classified into MAR suitability classes based on Table 4)

CRITERIA 2: SOIL TEXTURE

Soil texture determines the infiltration capacity of the soil. The coarser the texture of the soils (e.g., sand), the larger the pore spaces that facilitate water drainage while the finer soils with smaller pores such as clay attenuate water drainage. In this report, soil texture is determined from soilgrids, global soil texture map known (International Soil Reference and Information Centre, 2020). Figure 7 shows the soil texture map for the Tuli Karoo Transboundary Aquifer. Soil texture can generally be classified according to its sand, clay and silt proportions with sand having the highest drainage and clay the lowest. Soil with a low clay fraction (<10%) and high sand percentage is considered ideal for infiltration. Based on the aforementioned proportions, a discrete function can be used for standardization by attributing the soil texture classes' values from 0 to 1 depending on texture class as presented in Figure 8. The standardized soil texture classes are classified into soil texture classes to MAR suitability based on Table 4. The resulting soil texture map suitability to MAR map is shown in Figure 9.

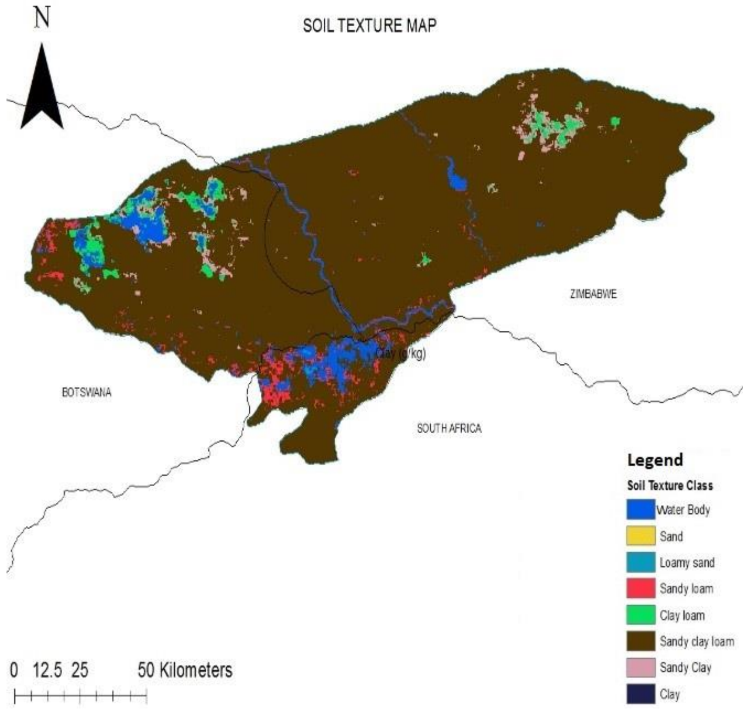

Figure 7: Soil texture class of Tuli Karoo aquifer at a depth of 250 mm (source: (International Soil Reference and Information Centre, 2020)

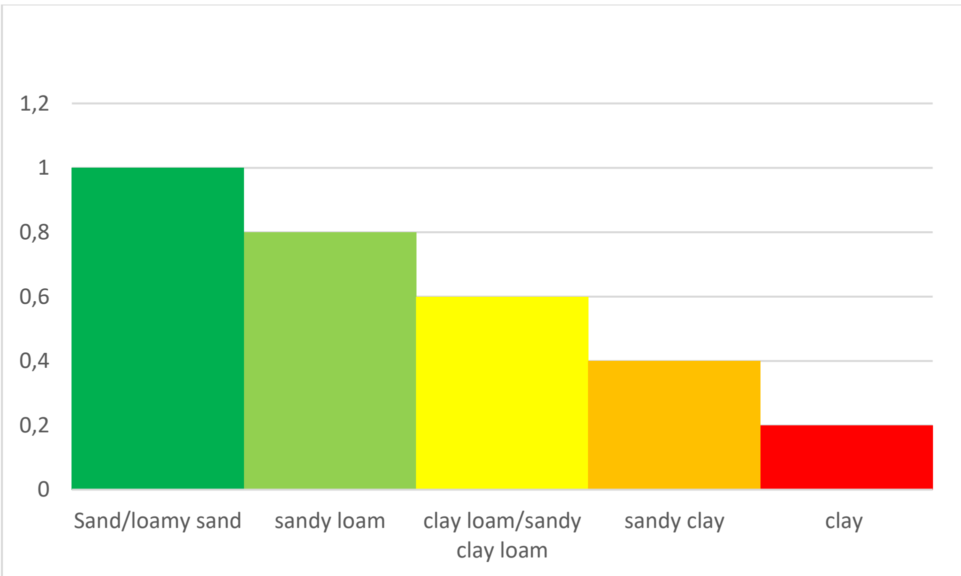

Figure 8: Soil texture class standardization (y-axis represent standardized value)

Table 4: Reclassified Soil classes based on MAR suitability

MAR CLASS	USDA CLASSES *Soil (100-200) cm*	TOP SOIL TEXTURE	DRAINAGE CLASS	CLASSIFICATION
Unsuitable	Clay	Fine texture(heavy clay)	Very Poor	**0 - 0.2**
Low Suitability	Sandy clay	Fine texture(light clay)	Poor	**0.2 - 0.4**
Moderately	Sandy clay loam Clay loam	Moderate fine texture	Imperfectly	**0.4 - 0.6**
Suitable	Sandy loam	Moderate Coarse texture	Moderately well	**0.6 – 0.8**
Very Suitable	Loamy sand Sand	Coarse	Somewhat excessive	**0.8 – 1.0**

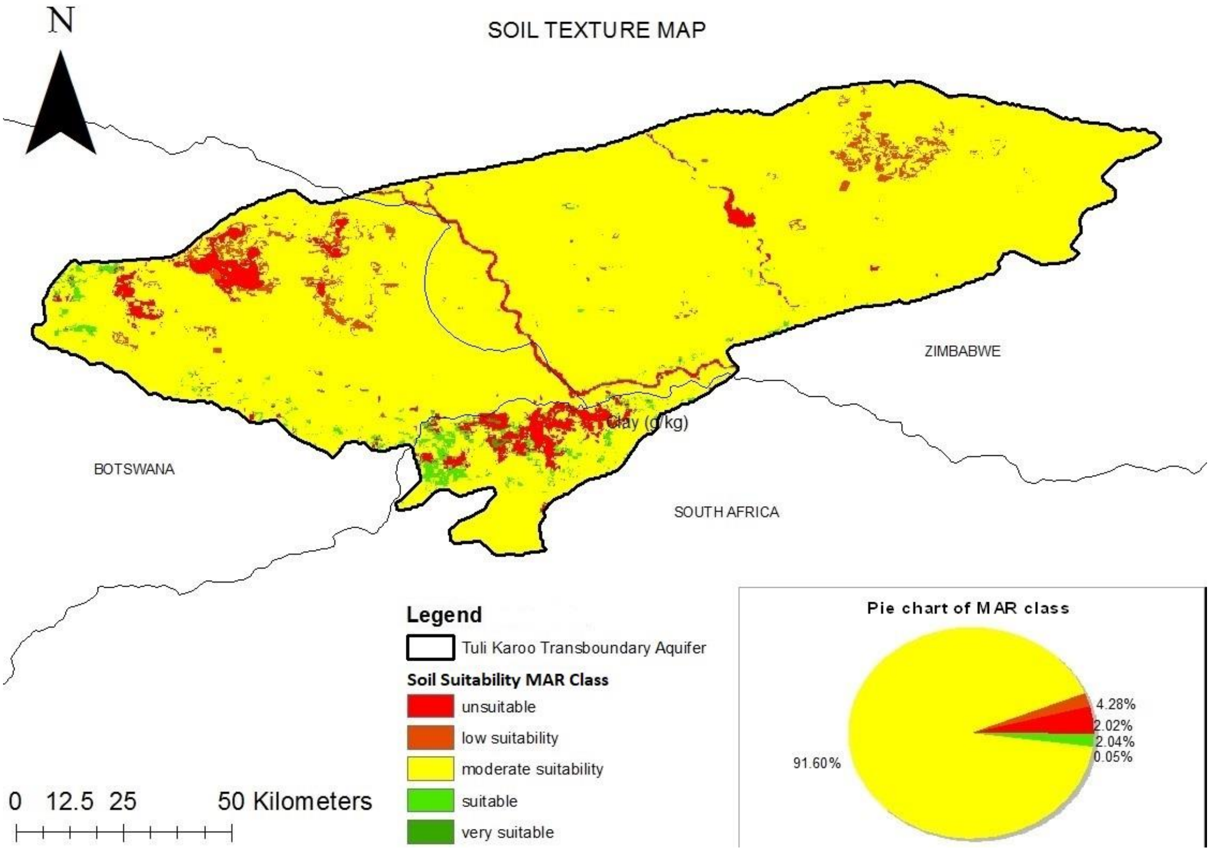

Figure 9: Soil suitability map for MAR of Tuli Karoo Aquifer

CRITERIA 3: LAND USE/LAND COVER

Land use/cover affect the infiltration capacity of the soil. Vegetation cover is known to affect soil infiltration or groundwater recharge in three distinct ways (Shaban et al, 2005). Firstly, the biological decomposition of the roots assist in loosening rock and soil, allowing easier water percolation into the subsurface. Secondly, vegetation acts as a buffers that prevents direct evaporation of water from the soil and thirdly, their roots can absorb water thus preventing water loss. The urban areas generally result in a decrease in infiltration rates and increased surface runoff owing to the impervious surfaces characteristic of such areas. Land use and land cover classification for MAR in this report is based on the context of land clearing and land preparation requirement for MAR using the spreading method. Hence, areas with high vegetation are less preferred.

The land use and land cover classification was carried out based on European Space Agency (ESA) Climate Change Initiative (CCI) – Land cover map (2015). Figure 10 presents the land use/land cover classes for the Tuli Karoo Aquifer. For the purposes of this study the land use/land cover classes were grouped into five suitability class categories (Figure 11). Areas with which are sparsely vegetated or bare are very suitable (value ‘1’), grassland and cropland (value ‘0.8’), low-forested areas of 15-40% (value ‘0.6’) , high forested areas of more than 40% forests (value ‘0.4’) and lastly, the artificial areas and water bodies are considered unsuitable thus have a value of ‘0.2’ as shown in Table 5. A detailed description of the land cover and land use classes are provided in Annex 2. Figure 12 presents land use/land cover suitability for MAR in Tuli Karoo Aquifer.

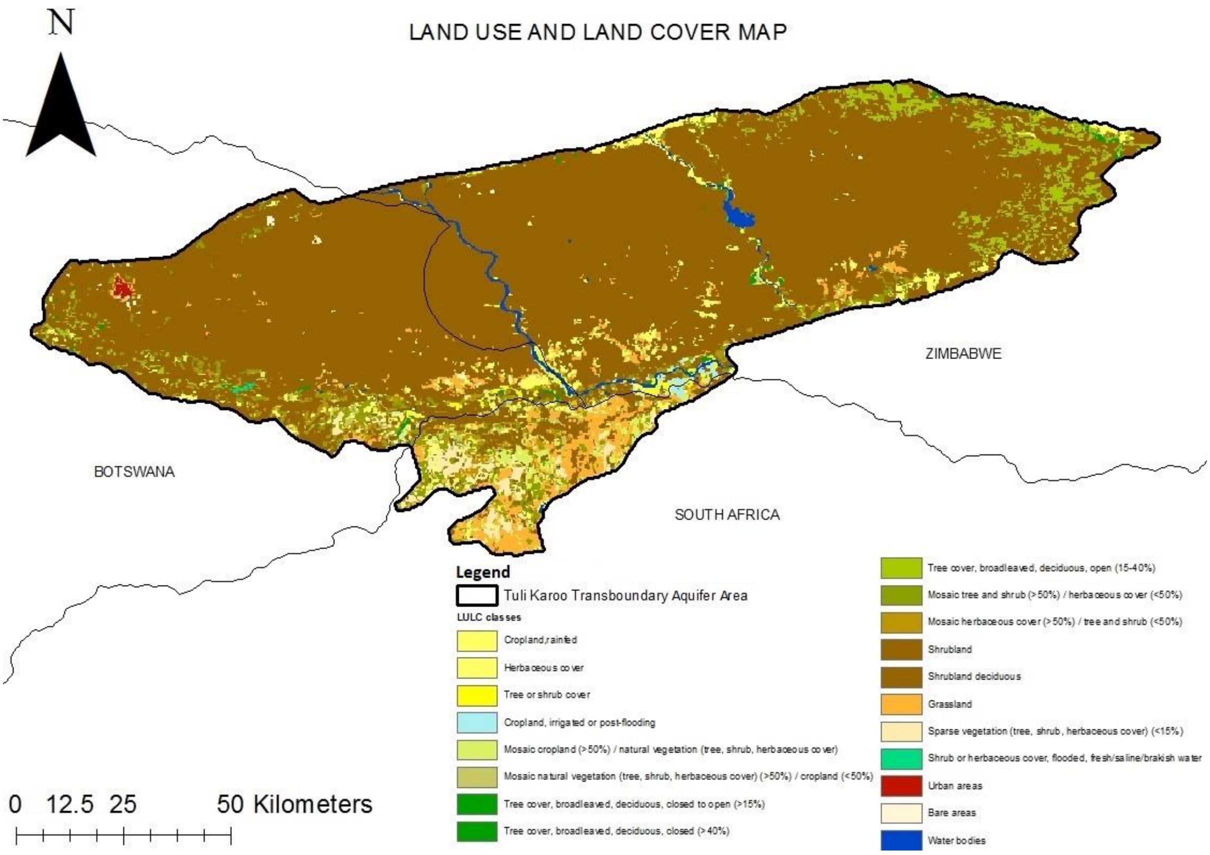

Figure 10: Land cover map of the Tuli Karoo Aquifer (Source: (European Space Agency (ESA) Climate Change Initiative (CCI), 2020))

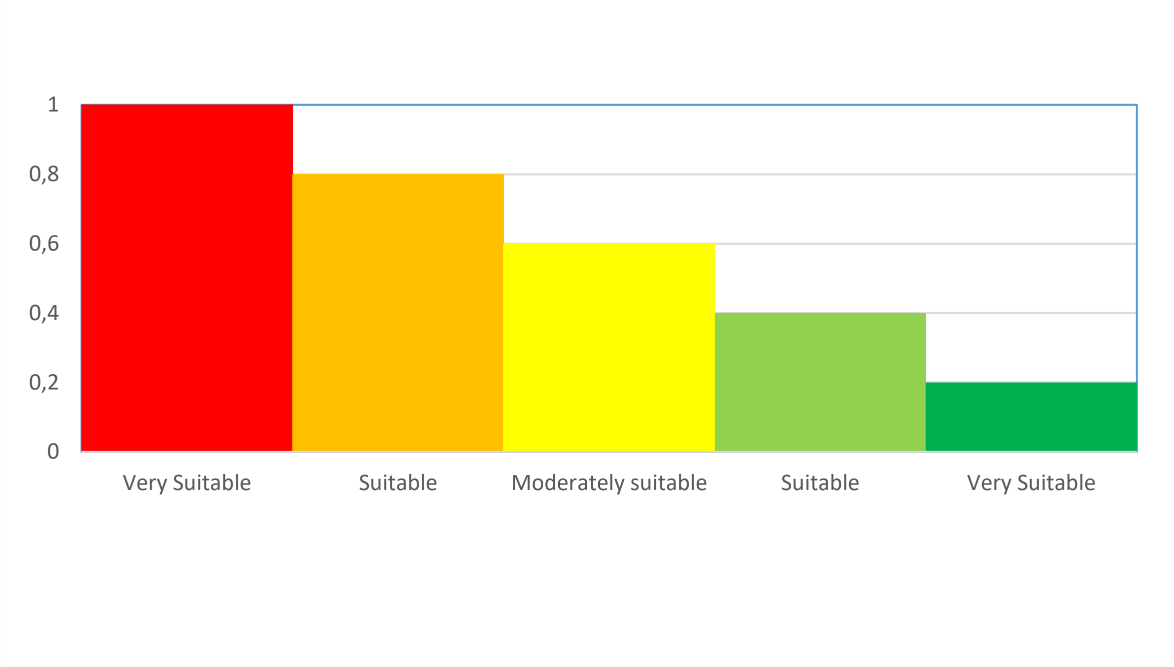

Figure 11: Stepwise classification of Land use/land cover MAR suitability classes (Y-axis represent standardized value)

Table 5: Reclassified Land use and land cover change classes

European Space Agency (ESA) Climate Change Initiative (CCI) – Land cover classes	Value	MAR class
Water bodies	0.2	Unsuitable
Urban areas	0.2	
Tree cover, broadleaved, deciduous, closed (>40%)	0.4	Low Suitability
Tree or shrub cover	0.4	
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	0.4	
Herbaceous cover	0.6	Moderate suitability
Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	0.6	
Tree cover, broadleaved, deciduous, closed to open (>15%)	0.6	
Tree cover, broadleaved, deciduous, open (15-40%)	0.6	
Shrub land	0.6	
Shrub land deciduous	0.6	
Cropland, rain fed	0.8	Suitable
Cropland, irrigated or post-flooding	0.8	
Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	0.8	
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	0.8	
Grassland	0.8	
Shrub or herbaceous cover, flooded, fresh/saline/brackish water	0.8	
Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	1	Very Suitable
Bare areas	1	

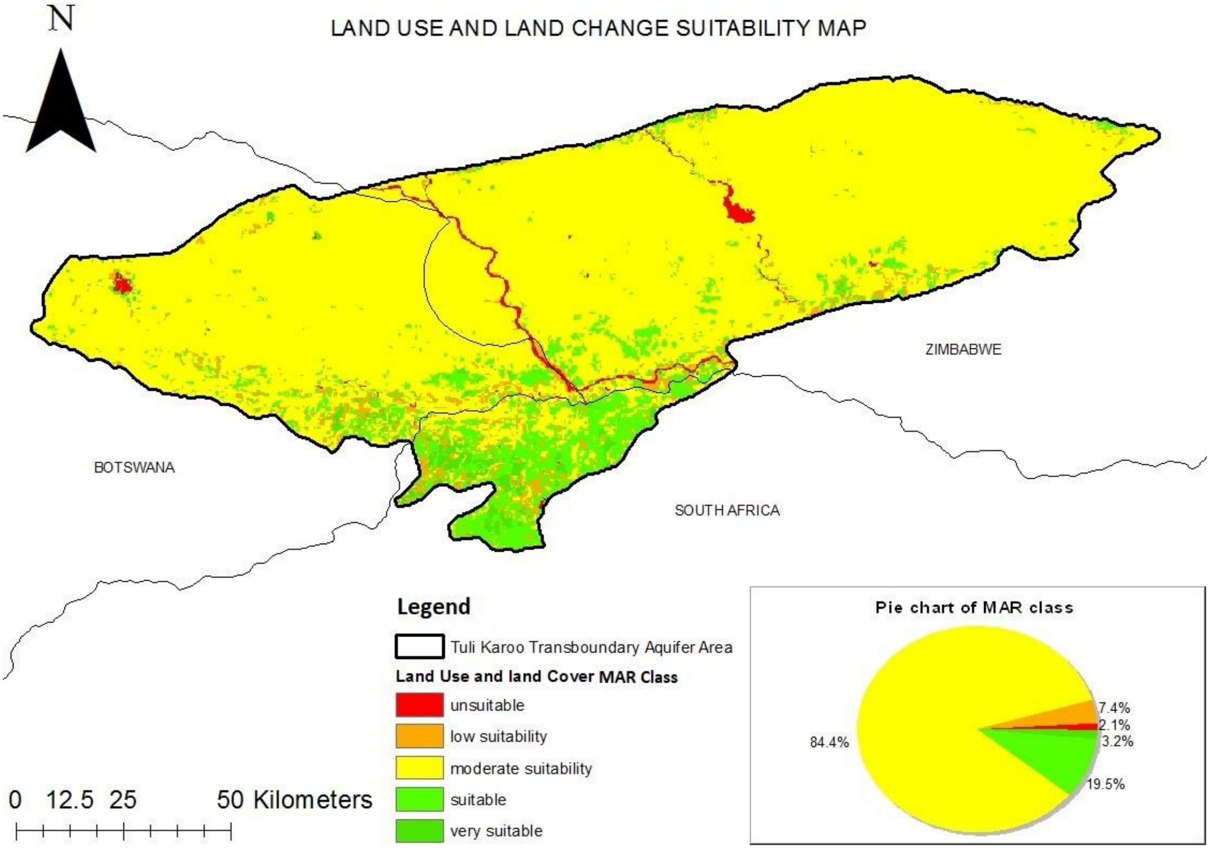

Figure 12: Land cover suitability map for MAR of the Tuli Karoo Aquifer

CRITERIA 4: LITHOLOGY

The type of rock that is exposed to the surface is a major factor in groundwater recharge (Shaban et al, 2005). This is mainly achieved through its control of the percolation of water flow into and in the subsurface. Some investigations have ignored lithology in favor of lineaments and drainage as the main functions of primary and secondary porosity (Yeh et al, 2009). However, lithology was included in this in order to reduce uncertainty of the final suitability map. The lithology map of the Tuli Karoo Aquifer is shown in Figure 13. Figure 14 shows the standardized value of the geologic classes.

The highest values were assigned to fluvial sediments where direct recharge of the aquifer can occur thus received the highest value range of '0.8 - 1'. Sedimentary rocks such as the sandstones and arkose also received high value of '0.6 - 0.8' due to their high filtration rates (Food and Agriculture Organization (FAO) and International Soil Reference and Information Center (ISRIC)., 2020). Gneiss formation was assigned a value of "0.2 - 0.4". Furthermore, low infiltration sedimentary rocks such as mudstones and siltstones were deemed unsuitable and assigned a value of '0.0 - 0.2'. The basalt which occupies most of the aquifer is of moderate suitability and was assigned a value of '0.4 - 0.6'. This is because even though it is the second main aquifer, its porosity is secondary and dependent on lineaments (Water Surveys Bostwana (pty) ltd, 2007). The lowest suitability was assigned to very fine grained sedimentary rocks and gneiss, which have a very low primary porosity. However it should be noted that in places where there is fracturing and contact between formations the recharge is increased substantially thus the value cannot be '0'. Table 6 presents MAR suitability lithological classes for the Tuli Karoo Aquifer. Figure 15 shows lithological suitability of MAR for the Tuli Karoo Aquifer.

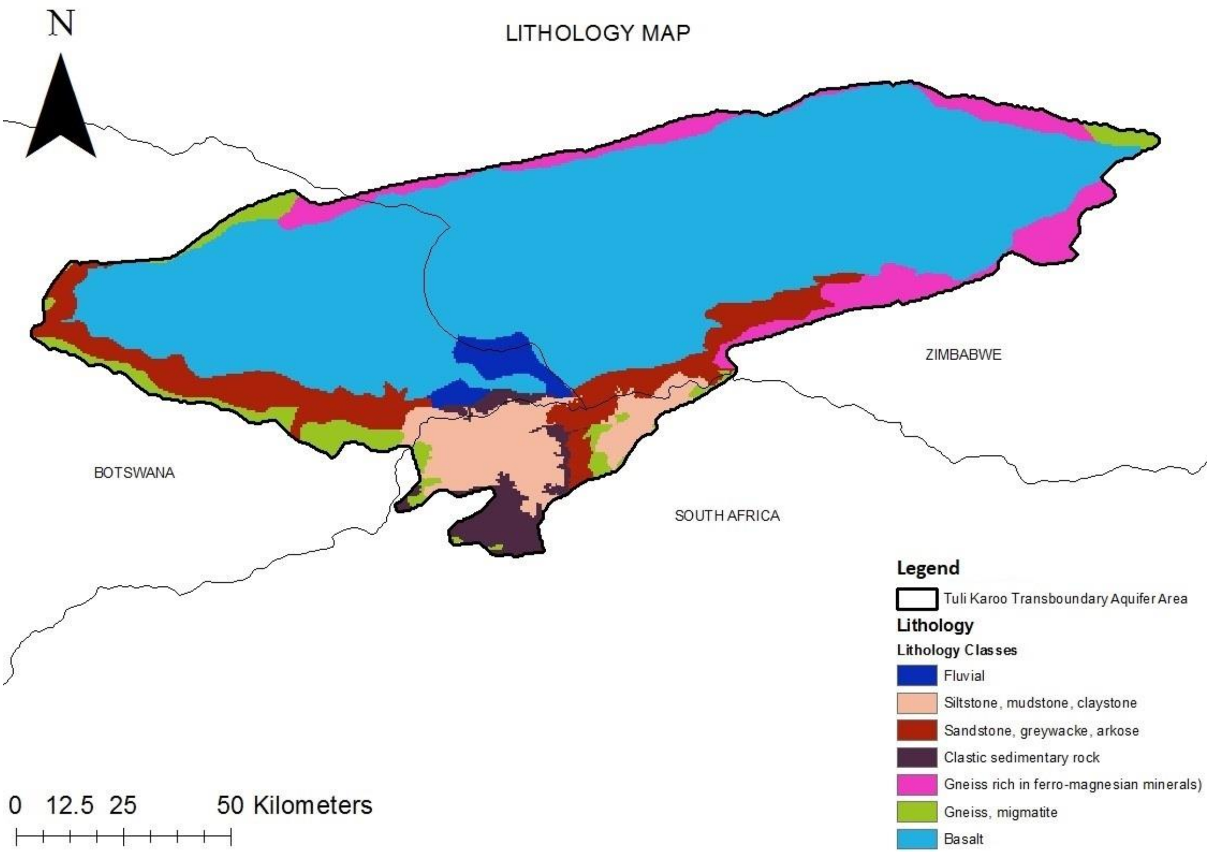

Figure 13: Lithology of the Tuli Karoo Aquifer (International Soil Reference and Information Centre, 2020)

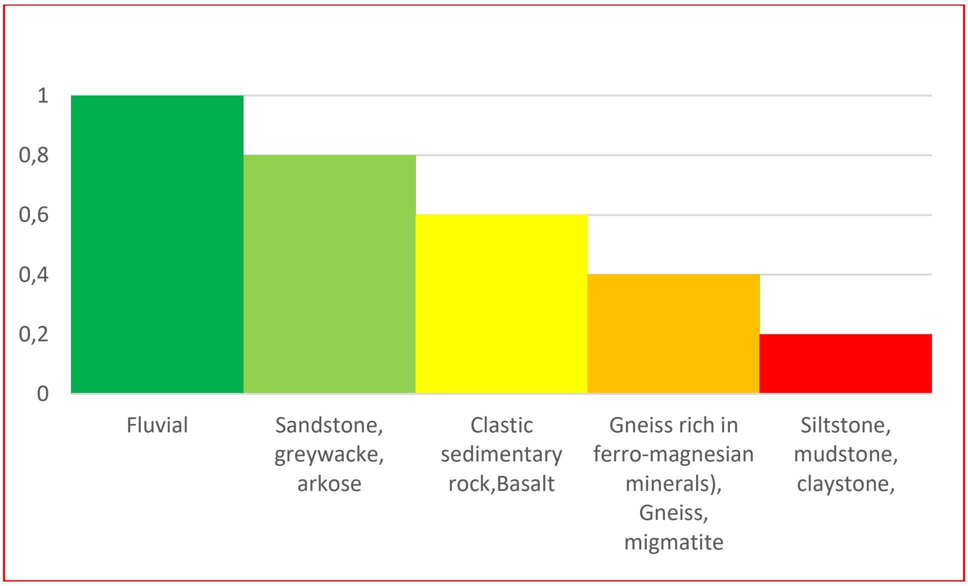

Figure 14: standardize values of geologic classes (Y-axis represent standardized value)

Table 6: Lithological classification based on MAR suitability

MAR CLASS	LITHOLOGY CLASSES	CLASSIFICATION
Unsuitable	Siltstone, mudstone, claystone,	0.0 – 0.2
Low Suitability	Gneiss rich in ferromagnesian minerals), Gneiss, migmatite	0.2 – 0.4
Moderately	Clastic sedimentary rock, Basalt	0.4 – 0.6
Suitable	Sandstone, greywacke, arkose	0.6 – 0.8
Very Suitable	Fluvial	0.8 – 1.0

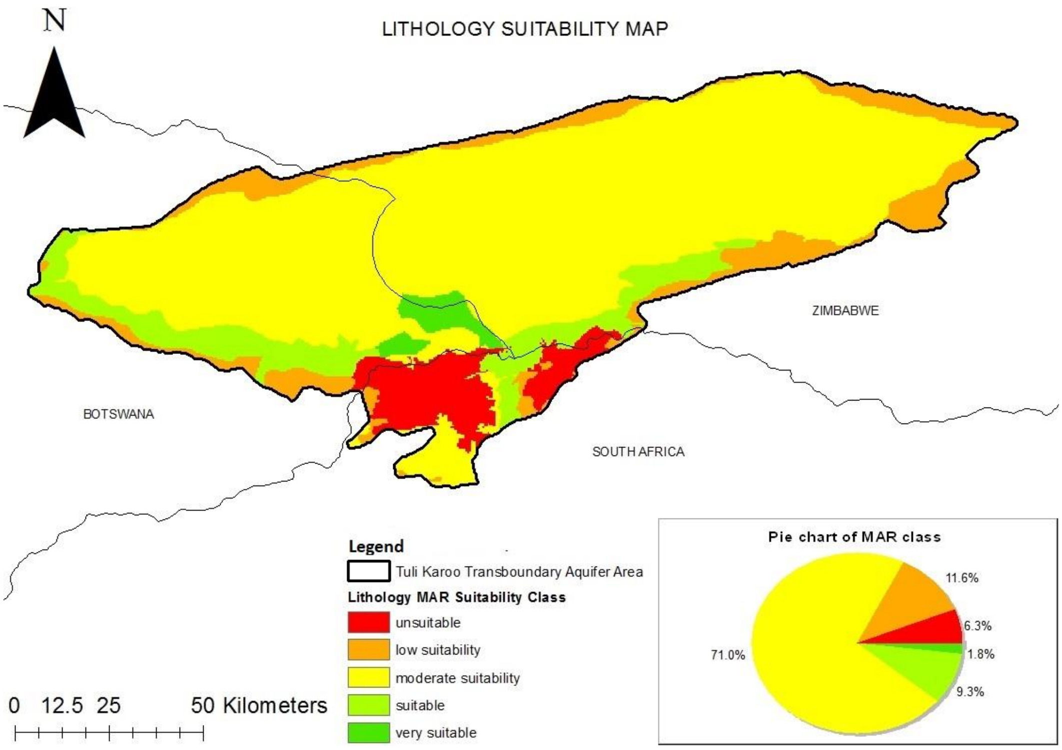

Figure 15: Lithological suitability map of the Tuli Karoo Aquifer

CRITERIA 5: DRAINAGE DENSITY

Drainage density is considered to be the most important morphometric properties of a drainage system (Valverde et al, 2016). Drainage density is considered to be a natural indicator of a terrain. Therefore, a higher drainage network density reflects a higher runoff hence a less infiltration. Thus, areas with low drainage densities are considered optimal for MAR. The drainage density can be calculated by dividing the length of all the channels in the basin by the area of the basin (kilometer per square kilometer) (Chenini & mammou, 2009). Figure 16 shows drainage density for the Tuli Karoo Aquifer. The drainage density was standardized using the stepwise function adopted from Valverde (2016) as shown in Figure 17. The classification system will range from "excellent" (0.046-0.17 km/km^2) to poor (0.55-0.68km/km^2) with class limits increments of 0.75. Drainage density of less than 2 km/km^2 is considered ideal for MAR (Shankar & Mohan, 2005). A value of '1' is assigned to a 0 km/km2 drainage network density and a value of '0.0' to the maximum drainage network density. The standardized map was re-classified in to drainage density suitability for MAR classes using Table 8. Figure 18 shows suitability of drainage density for MAR for the Tuli Karoo Aquifer.

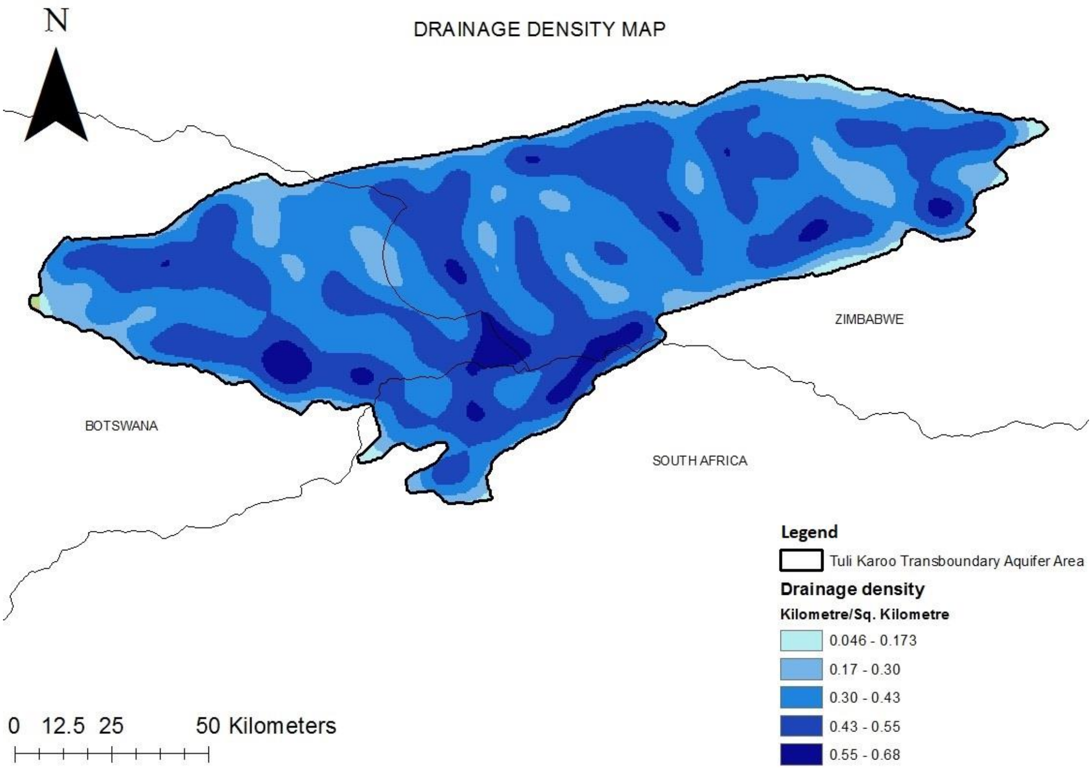

Figure 16: Drainage density map of Tuli Karoo Aquifer

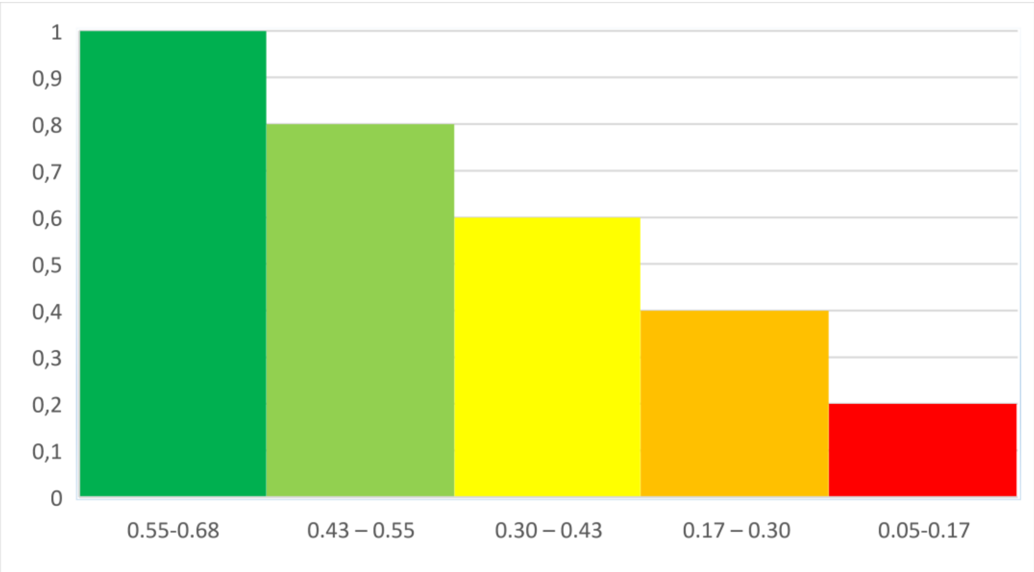

Figure 17: Step wise standardization of drainage density (X-axis represent drainage density classes and Y-axis represent standardized value)

Table 7: Reclassified Drainage density classes

MAR suitability Classes	Drainage density classes (km/km^2)	MAR Suitability standardized values
Unsuitable	0.05-0.17	0.2
Low Suitability	0.17 – 0.30	0.4
Moderately	0.30 – 0.43	0.6
Suitable	0.43 – 0.55	0.8
Very Suitable	0.55-0.68	1.0

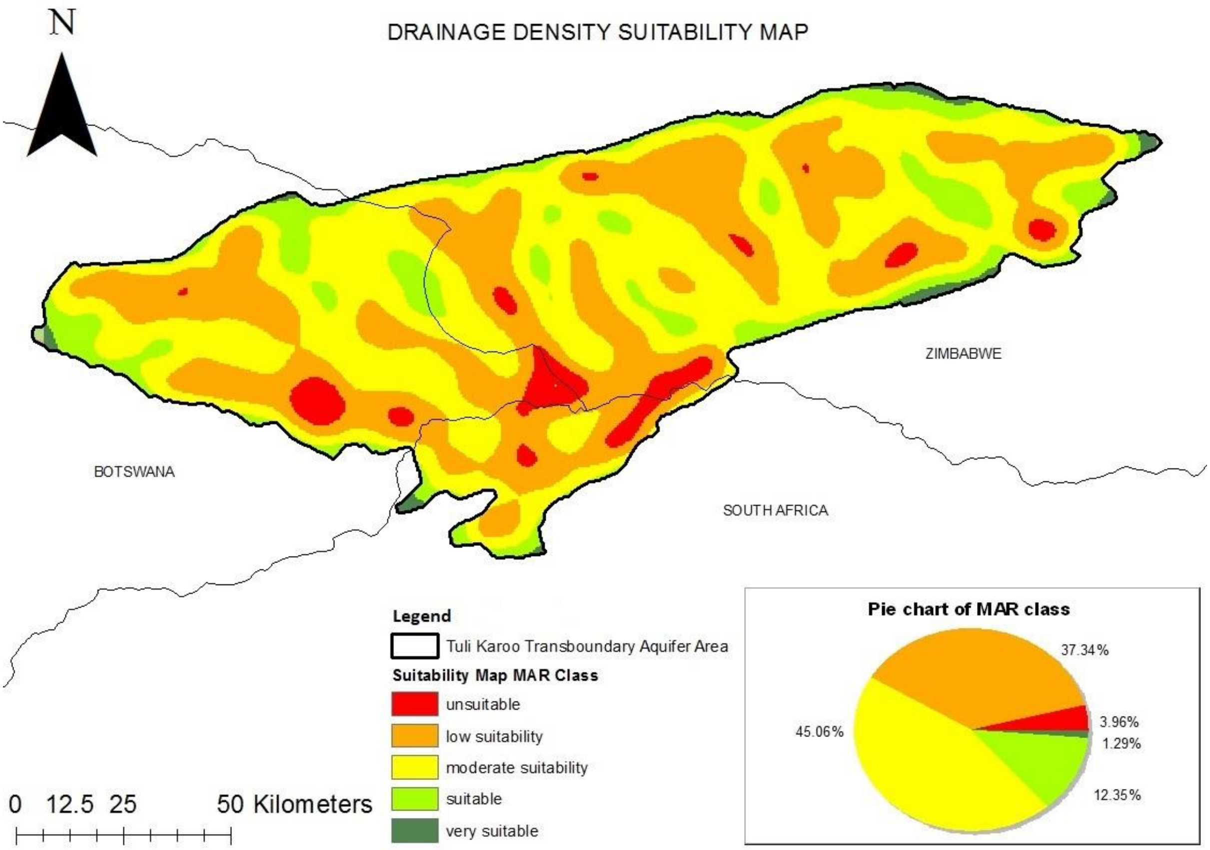

Figure 18: Drainage density classes based on MAR suitability for Tuli Karoo Aquifer

CRITERIA 6: LINEAMENT DENSITY

Lineaments are linear features on the Earth's surface that reflect a general surface expression of underground fractures as identified from satellite images and aerial photography (Abdullah et al, 2015). These features facilitate surface runoff infiltration into the subsurface and thus important to the storage and movement of groundwater into an aquifer (Rejith et al, 2019). In the Tuli Karoo Aquire Area, most of the lithology consists of basalt rock that has little primary porosity, but likely the presence of secondary porosity. Lineaments act as the main conduits for groundwater and storage. The lineament density is defined as the total length of all the recorded lineaments divided by the area under consideration (Edet et al, 1998). The lineaments map was prepared by digitizing lineament maps from the SADC groundwater management institute's groundwater information portal (GROUNDWATER MANAGEMENT INSTITUTE, 2020). The lineament density map for the Tuli Karoo Transboundary Aquifer is shown in Figure 19. The lineament density of the Tuli Karoo Aquifer area is standardized using the five classes shown in Figure 20. Higher values of lineament density favor groundwater potential thus assigned the highest suitability class and suitability decreases with a decrease in density. Table 8 was used to re-classify the standardized lineament density map based on its suitability for MAR. Figure 21 shows the lineament density map classes based on MAR suitability for the Tuli Karoo Transboundary Aquifer.

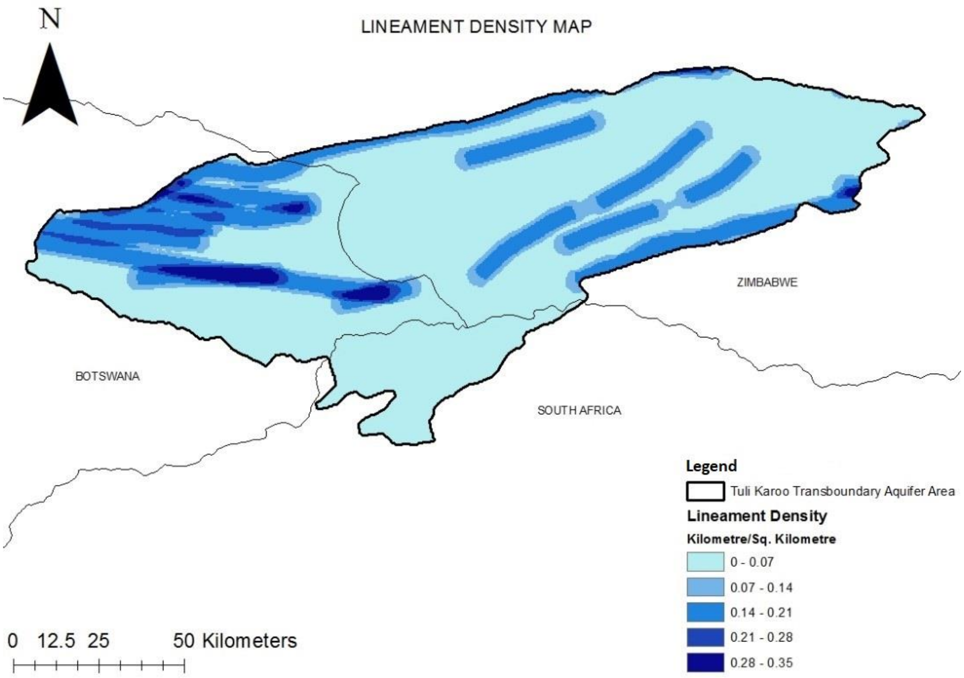

Figure 19 : Lineament density of the Tuli Karoo aquifer (SADC-GMI, 2020)

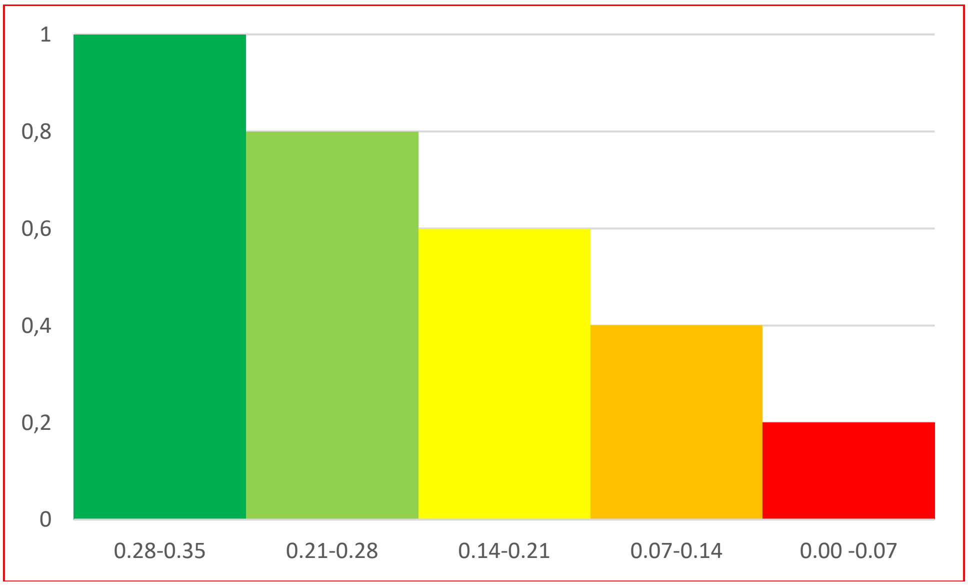

Figure 20: Step wise standardization of lineament density for the Tuli Karoo Transboundary Aquifer (X-axis represents lineament density classes and Y-axis represents standardized value)

Table 8: Reclassified lineament density classes

MAR CLASS	LINEAMENT DENSITY CLASSES (km/km^2)	CLASSIFICATION
Unsuitable	0.00 -0.07	0.0 – 0.2
Low Suitability	0.07-0.14	0.2 – 0.4
Moderately	0.14-0.21	0.4 – 0.6
Suitable	0.21-0.28	0.6 – 0.8
Very Suitable	0.28-0.35	0.8 – 1.0

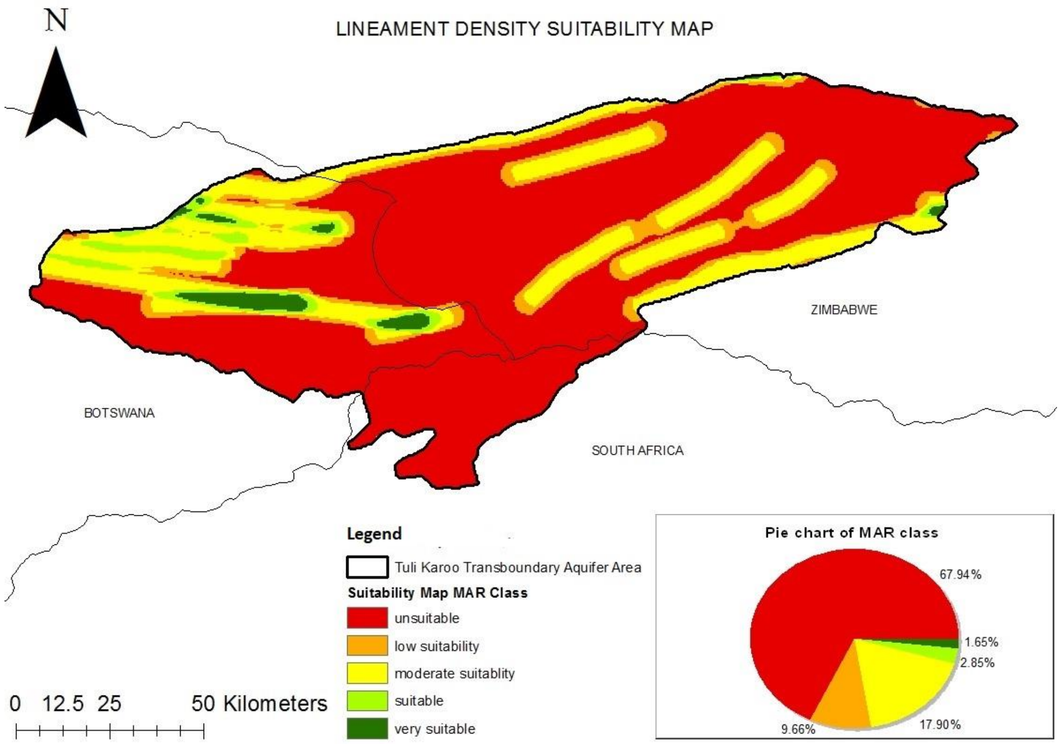

Figure 21: Lineament density classes based on MAR suitability for Tuli Karoo Aquifer

3.5 ASSIGN WEIGHTS FOR EACH CRITIERA

The ranking method was used to assign importance weight for each criteria following Ebrahim et al.'s (2017) approach. The ranking method, on the other hand, involves ranking of criteria according to their rank order from the most important to the least. The weights are calculated using the following equation:

Weight = $((N-r+1)/\Sigma (N-r+1))$

Where:

N is the total number of criteria
r is rank order

Table 9: Criteria weight based on the ranking method

N = 6	Rank, r	N-r+1	Weight	Priority %
soil	2	5	0.24	24
lithology	1	6	0.29	29
LULC	3	4	0.19	19
Slope	4	3	0.14	14
drainage density	6	1	0.05	5
lineament density	5	2	0.10	10
	Total	21	1	100

Applying the weighting criteria above, lithology emerged as the most important criterion (Table 9). Soil and LULC were also important. Drainage and lineament density were relatively less important.

3.6 COMBINATION OF CRITERIA TO SUITABLITY MAP

The weighted overlay analysis of the six criteria maps were carried out using weighted linear combination method based on weights calculated using the ranking method. Each criteria is weighted according to their importance and combined using WLC Equation 1. Raster layers are overlaid, multiplying each raster cell's suitability value by its layer weight and totaling the values to derive a suitability value. Assigning a weight to each raster in the overlay analysis allow for control on the influence of different criteria in the suitability mapping.

4. RESULTS

4.1 MAR SUITABLITY FOR TULI KAROO AQUIFER

MAR assessment results for the Tuli Karoo Aquifer were combined with the constraint map to produce the final suitability map (Figure 22). Following Ebrahim et al.'s (2017) approach, the final suitability map was classified into seven classes as shown in Table 10. Very high and high suitability areas cover 0.3% and 6.5 % of the Tuli Karoo TBA, respectively. These areas are located along the major lineaments. Suitable areas cover 57.3% of the aquifer with most of this areas located in areas underlain by basalt. The concentration of very suitable areas along lineament routes shows the heavy influence of lineaments even though it is ranked second from the last. The basalt being the second main aquifer after the sandstone, is also mainly covered by sandy clay loams that has the moderate suitability.

A comparison of suitability for MAR in the three countries was carried out in order to discern differences and similarities across the three countries. Suitable to very high suitability areas cover most of the center of the TBA with low suitability areas being towards the south of the aquifer in South Africa. Unsuitable areas were mainly located in the southern part of the Aquifer. Most of the Botswana portion of the aquifer area lies in suitable classes.

Botswana's high suitability may be attributed to its portion having a high lineament density compared to other two countries with at least 75.3% of the area being suitable or better. South Africa's unsuitable and low suitability prevalence can be attributed to its portion of the aquifer being at the confluence of the main river stem, the Limpopo River and its tributaries. Only 39.9% of this area is suitable or better. The area has a high drainage density which increase runoff thus reducing recharge and the presence of water bodies is entirely not suitable for MAR. This is further evidenced by the unsuitable areas being concentrated along the Limpopo River, a very high drainage density area.

Zimbabwe has the largest area of suitable and moderate suitability sites, comparatively, mainly because it occupies the largest majority of the aquifer. It has the second highest percentage of suitable or better areas at 56%. The prevalence of suitable to very suitable areas is a result of the proliferation of the second main aquifer in the area being the Basalt. Furthermore, areas further away from the Limpopo river stem are flatter which increases recharge in addition to the presence of faults and Dolerite dykes in the area.

Table 10: MAR suitability classes and their percentage area

Suitability classes	Percentage area of the Tuli Karoo Aquifer Area
Unsuitable	0.01
Very low Suitability	0.6
Low Suitability	3.5
Moderate suitability	31.8
Suitable	57.3
High suitability	6.5
Very high suitability	0.3

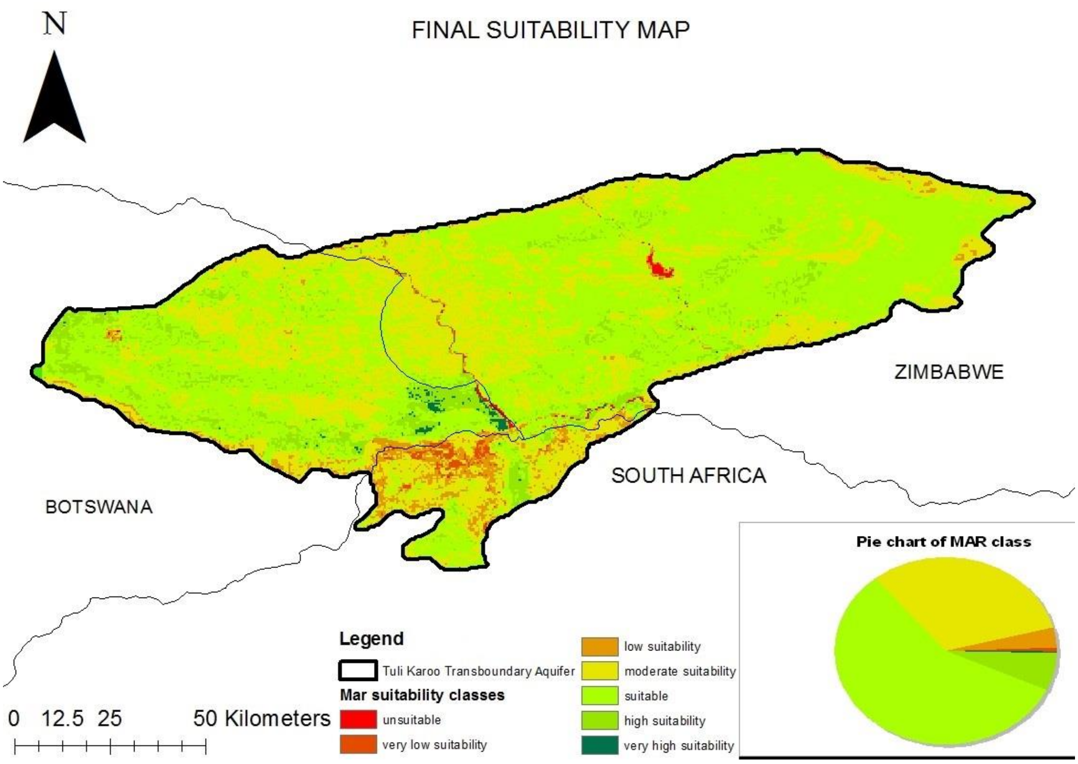

Figure 22: MAR suitability map for the Tuli Karoo Aquifer

4.2 SENSITIVITY ANALYSIS

A sensitivity analysis was carried out to determine the influence of different criteria weights on the spatial pattern of the suitability classification. Following Fathi's (2017) approach, sensitivity analysis was carried out for each criterion by first increasing the weight of one criterion by 10 % weight and reducing the weight by 2 % for the remaining criteria. The step was then repeated by reducing the same criterion by 10 % and evenly distributing weight to the remainder criteria (Table 11). This means for example increasing one criterion by 10%, and reducing the other criteria weights by 2% to enable the same total 100% for all criteria. Each increase and decrease for a criterion was named a scenario and given a number; a total of 12 scenarios were created to analyze the sensitivity of the suitability map.

The change in MAR suitability class with change in criteria weights is presented in Table 12. Results show that soil and land use/land cover are the most sensitive criteria that result the most change in their suitability classes. Lineament density showed the least amount of change of all the classes and thus is the least sensitive of all the layers. This shows that soils has the most influence on the final suitability map while lineament density has the least influence. Comparatively, land use and land cover covers a large portion of the Tuli Karoo as moderately suitable, while in lineament density better suitability values are mostly restricted to high lineament density areas.

Table 11: Sensitivity analysis of criteria weights for the Tuli Karoo Aquifer MAR suitability mapping

		Soil		**Lithology**		**LULC**		**Slope**		**Drainage density**		**Lineament density**	
Scenario		**1**		**2**		**3**		**4**		**5**		**6**	
Layers	**%**	+10	-10	+10	-10	+10	-10	+10	-10	+10	-10	+10	-10
Soil	23	33	13	21	25	21	25	21	25	21	24	21	25
Lithology	29	27	31	39	19	27	31	27	31	27	30	27	31
Lulc	19	17	21	17	21	29	9	17	21	17	20	17	21
Slope	14	12	16	12	16	12	16	24	4	12	15	12	16
Drainage	5	3	7	3	7	3	7	3	7	15	0	3	7
Lineament	10	8	12	8	12	8	12	8	12	8	11	20	0
	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 12: Results of sensitivity analysis (change in percentage area due to change in the weights)

Suitability classes	**(%) area of the Tuli Karoo Aquifer**	**Soil**		**Lithology**		**LULC**		**Slope**		**Drainage density**		**Lineament density**	
		+	**-**	**+**	**-**	**+**	**-**	**+**	**-**	**+**	**-**	**+**	**-**
Unsuitable	0.00	0.03	0.51	0.03	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.03	0.00
Very low Suitability	0.58	0.69	4.52	0.75	0.00	0.41	0.00	0.70	0.00	0.20	0.00	0.80	0.00
Low Suitability	3.49	2.83	32.55	4.64	0.01	2.76	0.00	4.41	0.01	2.49	0.00	6.05	0.01
Moderate suitability	31.52	27.81	54.49	27.27	0.04	26.47	0.04	33.40	0.05	25.20	0.04	49.36	0.08
suitable	56.83	62.51	7.46	59.45	0.09	63.20	0.10	42.93	0.07	62.68	0.10	39.40	0.06
High suitability	6.45	5.94	0.46	7.13	0.01	6.85	0.01	17.70	0.03	8.86	0.01	4.20	0.01
Very high suitability	1.12	0.19	0.01	0.73	0.00	0.31	0.00	0.85	0.00	0.56	0.00	0.16	0.00

5. DISCUSSION

The Tuli Karoo Transboundary Aquifer, like many other transboundary aquifers in rural areas of sub-Saharan Africa, is critical to rural communities cannot be overstated since groundwater resources hold potential for cross border impacts such as water quality and supply degradation that affect rural livelihoods and might ultimately lead to regional political differences. It does, however, offer an opportunity to enhance cross border collaboration regarding research and data. Furthermore, it has a strategic location since the three countries use the same aquifer for different economic activities. So it is in the best interest of all countries to cooperatively manage the aquifer in a way all can sustainably benefit from it without detriment to another. The aquifer is already identified as being in need of international resource management in the SADC region (Davies, et al., 2013). This means it is likely to cause friction between neighboring states and would benefit from shared management through regional or international co-operation.

The research gives a clear picture of suitable areas in terms of infiltration/groundwater storage. Its findings can assist interested stakeholders. For example, when the distance to water public networks is far, MAR can help provide solutions for farmers looking for alternate water sources and storage. The economic aspects of implementing MAR systems to improve potable water and agriculture are, however, highly system specific (Dillion et al, 2009). Currently, a feasibility study carried out in the Botswana side is the closest thing to such an assessment (Lindhe A. et al, 2014). There is a need to identify sites with the suitability map that can undergo further analysis and validate the results of this report.

This report did not apply all restrictions on areas that render a site to be unsuitable, instead focusing on three constraints. The constraints selected were the most appropriate for the Tuli Karoo based on the literature review and available data. Potential constraints in the area such as the Tuli safari Area and Northern Tuli Game reserves located within areas deemed to be suitable may prove otherwise if restrictions are put in place. Factors such as water availability, water quality, unsaturated zone, transport, site access and groundwater levels were not accounted for. These factors should be considered when doing a project scope, pilot test and evaluation of basin management in broader scope (Russo et al, 2014). The degree of detail and quality of the results is ultimately determined by the available data sets. Therefore, updating the results as data become available is necessarily. Submission of the map and its accompanying data to global groundwater management sites like IGRAC can help give access to a wider audience.

The GIS-MCDA based analysis shows suitability being better on the most prominent feature being the Basalt. The basalt covers 90% of the aquifer area and is the second main aquifer after the sandstone. The edges of the aquifer are generally low in suitability due to either presence of soils with higher clay content, water bodies or urban areas. Even though the suitability map shows a large proportion of the area is at least suitable for MAR, the degree of detail and accuracy is limited by available data sets. Land use and land cover possesses the highest sensitivity, which may be due to most of the aquifer being covered by a single class of moderate suitability.

Thickness and depth of the different strata within the aquifer is not uniform due to its half pipe shape (Water Surveys Botswana (pty) ltd, 2007). The Basalt is relatively thinner towards its edges with sandstone outcrops in some areas compared to the centers of the aquifer that can reach thicknesses of up to 746 metgers (Water Surveys Botswana (pty) ltd, 2007). In addition, due to its permeability and porosity being discontinuous, not all of the basalt will be suitable for MAR. Zones of weakness such as faults, lineaments and weathering zones are the best places on the basalt for MAR practices. The sandstone, on the other hand, is laterally extensive and maintains a somewhat regular thickness of about 228 m and 8 meters along the edges of the aquifer (Water Surveys Bostwana (pty) ltd, 2007).

However, the sandstone is mostly beneath the basalts which can act as an Aquitard or water movement conduit. Therefore, MAR efforts could be better concentrated along the edges of the aquifer where the basalt layer is thinner and sandstone outcrops.

Wellfields in the area can be potentially used for MAR especially if they are within areas deemed suitable. Bobonong wellfield is one of such possible wellfields, which forms part of the south eastern Tuli Karoo aquifer (Water Surveys Botswana (pty) ltd, 2007). Data from the daily pumping regime show the boreholes being pumped for long periods and numerous archive records show a similar pattern of over pumping (Water Surveys Botswana (pty) ltd, 2007). MAR can be explored as way to increase water supply in the area as it is being currently explored in other wellfields in the country, specifically the Palaroad wellfields. The results from the suitability map shows that these wellfields are in areas identified as suitable or better show the area's promise. However, as previously mentioned other factors to deduce the true suitability of the area such as drilling will have to be conducted first.

6. CONCLUSIONS AND NEXT STEPS

The Tuli Karoo transboundary aquifer shows great potential for MAR The use of GIS -MCDA has proven to be a valuable tool in the selection of potential MAR sites in The Tuli Karoo Aquifer. It represents a useful way to assist in planning for groundwater management using publicly available data. Approximately 57% of the area belongs to the suitable class and while 7% is of the high and very high suitability class. With at least 64% of the area a suitable or better class for MAR, it shows the area has great potential for recharge sites. The research provides evidence that the type of criteria heavily influences the outcome of the site suitability map through the sensitivity assessment of the criteria weights. Criteria such as soil and land use/land cover showed high sensitivity.

Potential limitations of the report The suitability map produced is based on physical environment criteria of the area thus may not provide the most ideal sites for MAR. Criteria such as distance to water sources, water quality, depth to groundwater, demand and intended use of the stored water has not been considered. This omissions such as the depth to groundwater is due to a general lack of groundwater data for the area. Thus to improve the accuracy of the map, its results can be updated as data becomes available. Furthermore, this was mostly a desktop study owing to the study area being across three countries and travel restrictions due to Covid- 19 pandemic. There is still need for the suitability map to be validated against field data. Information on suitability maps in the southern Africa region was also noticeably low especially on feasibility studies and ongoing MAR schemes.

Identification of water sources and their availability The Tuli Karoo Aquifer has multiple natural sources of water for recharge. These include the main Limpopo River and its tributaries including Shashe, Mzingwane, Motloutse and Bubi Rivers. The area experiences good rainfall during the months of November to March which may be the best periods for recharging the aquifers. It should be noted that the rivers experience a seasonal flow thus may recharge the aquifer only during wet seasons. There are multiple dams in the area along the rivers such as the Dikgatlhong dam in Botswana and Zhove Dam in Zimbabwe whose storage may be affected by MAR especially upstream of the dams. Furthermore, other potential sources of water include wastewater from towns in and near the area including Beitbridge, Musina and Bobonong. However, this water will need to be treated before being introduced into the aquifer which might prove expensive.

Water quality concerns The area is home to economic activities that may pose danger to the water in aquifer. This include mining activities around the vicinity of the area such as the Beit bridge colliery company in Zimbabwe, Tati Nickel mine in Botswana and Venetia Diamond mine in South Africa. Such activities can lead to Acid mine drainage where iron sulphide oxidized due to being exposed to air and water by mining leads to acidic waters containing heavy metals which pollute surface waters (Akcil &

Koldas, 2006). The location of the mines is fortunately near the edges of the aquifer especially its southern portion, where the area's MAR suitability is already low. Agricultural areas such as the Tuli block farms in Botswana are located in suitable areas but might be a source of agricultural pollutants. Lastly, the basin has previously been under threat of the invasion of aquatic weeds specifically water hyacinth (Kurugundla et al, 2016). This might affect the infiltration ponds especially if eutrophication from aforementioned agricultural activities are not managed properly.

Risk management analysis MAR is associated with many risks such as those related to the technical and non-technical aspect of recharge (Rodriguez-Escales et al, 2018). Those risks are thought to be related to water availability, recharge performance, water quality, legislation and social issues. The methodology to assess the risks involves a two part entry level assessment. The first part will focus on the viability of the study such the intended water use, source water availability, right of access, hydrogeological assessment, space for water capture and treatment and capacity to design and construct MAR sites (Page et al, 2010). The second part will assess the degree of difficulty of recharging from the source of water, its quality to groundwater environment values, recovered water end use and clogging. In addition, it will use the groundwater quality in regards to recovered water end use, drinking water quality, salinity and recovery efficiency. Furthermore, protection of water quality in unconfined aquifers if present can be assessed, the type of aquifer, similar successful projects, management capability and planning (Page et al, 2010).

Economic feasibility analysis Despite the many benefits and advantages shown by MAR, the uptake and growth of this solution remains lower than expected as a result of lack quality economic feasibility analysis (Maréchal, et al., 2019). A cost-benefit analysis on the performance of MAR schemes is key in ensuring its sustainability. The cost is influenced by a myriad of factors including hydrogeological, socio-economic, legal and institutional factors. Through literature review, it is evident the cost is rarely included in such analysis which may be as a result of a lack of feedback on costs and financial data on MAR projects. The aim of the feasibility analysis would be to show the need for increased water supply safety, and assessment to determine if MAR can provide the desired increased water supply safety and assess its economic viability for provision of the desired water supply safety.

Field work In order to advance the project and realize some of the aforementioned steps, field work in the area is vital. In addition, as mentioned previously, it will also help validate the suitability map through the verification against field data. Fieldwork activities may include hydro-chemical, soil infiltration test and groundwater level assessments. It will also include the engagement of relevant stakeholders and capacity building increasing the knowledge base on MAR.

MAR potential assessment using hydrogeological modelling Focused hydrogeological modelling is needed in order to fully characterize the aquifer's suitability for MAR. Additional data obtained from field work such as pumping test, drilling and hydrochemistry assessment can be used to create such a model. Depending on data availability further investigation with the hydrogeological model scenario analysis can be done. According to Ebrahim et al (2017), further investigation will help assess the aquifer's response to induced recharge, change in groundwater level and change in flow patterns. In addition, it will help determine the volume of water that can be potentially stored as well as the duration it remains in the aquifer. The results from such a model including the groundwater balance, storage, and extraction and infiltration capacity can be included in a water balance model.

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Annex 1: MAR/Artificial recharge project stages, key activities and authorization requirements adapted from: (Murray & Ravenscroft, 2009).

Project Stage	Key Activities	Authorization requirements
Pre-feasibility Stage	Identify the potential AR project and describe the information currently available	None
	Based on existing information, comment on the feasibility of the project.	
	Describe the work required for the Feasibility Stage and estimate the cost of undertaking the feasibility study.	
	Establish existing water use Licence conditions and authorization requirements from DWA.	
Feasibility Stage	If needed, obtain a water use Licence and environmental authorization for the recharge tests.	None, or a short-term water use Licence for AR testing and possibly environmental authorization for AR testing
	Conduct the feasibility study. This should include AR testing (e.g. injection tests, infiltration tests, pumping tests, water quality assessments, etc.)	
	Develop a preliminary infrastructure design	
	Identify the project implementation phases if a phased approach is necessary (eg starting small and expanding after successive recharge cycles).	
	Estimate the costs of the project	
	Identify funding sources	
	Compile a detailed project implementation plan	
Implementation Stage	Obtain the necessary water use license and environmental authorization for the AR scheme	Water use License and possible environmental authorization
	Drilling and testing new injection and abstraction boreholes or infiltration basins	
	Set up the groundwater and recharge water monitoring system	
	Develop the detailed infrastructure design, carry out the tendering processes, and construct the project.	
	Compile monitoring, operation & maintenance procedures	

Operation and Maintenance Stage	Carry out performance monitoring during production.	Compliance monitoring and reporting.
	Modify operation & maintenance procedures based on scheme performance.	
	Develop final monitoring and reporting system.	

Annex 2: Land use Land cover classification on MAR suitability modified from Bontemps (2011)

MAR classes	LULC Classes	GLOBCOVER 2009 LULC classes
unsuitable (0.0)	Unfavourable	No Data
		Water bodies
		Permanent snow and ice
		Artificial surfaces and associated areas (Urban areas >50%)
Low suitability (0.25)	Forest (>40%)	Closed (>40%) broadleaved forest or shrub land permanently flooded - Saline or brackish water
		Closed (>40%) broadleaved deciduous forest (>5m)
		Closed (>40%) needle leaved evergreen forest (>5m)
		Mosaic forest or shrub land (50-70%) / grassland (20-50%)
moderately suitable (0.5)	Forest (15-40%)	Closed to open (>15%) mixed broadleaved and needle leaved forest (>5m)
		Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water
		Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
		Closed to open (>15%) (broadleaved or needle leaved, evergreen or deciduous) shrub land (<5m)
		Closed to open (>15%) herbaceous vegetation (grassland, savannahs or lichens/mosses)
		Mosaic vegetation (grassland/shrub land/forest) (50-70%) / cropland (20-50%)
		Open (15-40%) broadleaved deciduous forest/woodland (>5m)
		Open (15-40%) needle leaved deciduous or evergreen forest (>5m)
Suitable (0.75)	Grassland and cropland	Mosaic grassland (50-70%) / forest or shrub land (20-50%)
		Rain fed croplands
		Post-flooding or irrigated croplands (or aquatic)
		Mosaic cropland (50-70%) / vegetation (grassland/shrub land/forest) (20-50%)
		Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water
Very suitable(1.0)	Sparse vegetation and bare areas	Sparse (<15%) vegetation
		Bare areas

**areas highlighted in yellow are the classes that appear in the study area*

Annex 3: Lithology reclassification

Abbreviation	Description	New value
MB3	Gneiss rich in ferromagnesian minerals)	0.4
MA2	Gneiss, migmatite	0.4
IB2	Basalt	0.6
SC2	Sandstone, greywacke, arkose	0.8
UF	Fluvial	1
SC3	Siltstone, mudstone, claystone	0.2
SC	Clastic sedimentary rock	0.6
NoData		

Annex 4: Soil reclassification

Soil Texture	Description	New Value
Clay	Sand: 0–45%, Silt: 0–40%, Clay: 40–100%	0.0 – 0.2
Sandy clay	Sand: 45–65%, Silt: 0–45%, Clay: 35–55%	0.2 - 0.4
Sandy clay loam	Sand: 45–80%, Silt: 0–28%, Clay: 20–35%	0.4 – 0.6
Clay loam	20–45%, Silt: 15–53%, Clay: 27–40%	
Sandy loam	43–85%, Silt: 0–50%, Clay: 0–20%	0.6 – 0.8
Loamy sand	70–90%, Silt: 0–30%, Clay: 0–15%	0.8 – 1.0
Sand	85–100%, Silt: 0–15%, Clay: 0–10%	