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ORIGINAL RESEARCH

Assessment of groundwater potential using Geographic Information Systems and remote sensing techniques in Moses Kotane Local Municipality, Northwest Province, South Africa

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The sustainable supply of water in adequate quantities is fundamental for the economic growth of any country. In South Africa, the operation of all the major economic sectors requires significant quantities of water. However, South Africa continues to experience water shortages, exacerbated by low Mean Annual Precipitation (MAP) that is below the world's annual average. Groundwater offers an opportunity to mitigate the water challenges, yet its sustainability is hampered by inadequate groundwater resource planning and management. In this study, Geographic Information Systems (GIS) and remote sensing techniques are used to delineate groundwater potential zones in Moses Kotane Local Municipality, South Africa. Seven themes of remotely sensed parameters that influence the availability of groundwater were developed and assigned weights using the Analytical Hierarchy Process (AHP) before being overlaid in ArcGIS 10.3.1 software to create zones of groundwater potentiality. The final groundwater potential map was produced using the weighted overlay analysis. Five groundwater potential zones were produced, that is, very low, low, moderate, high, and very high. The areas covered by these zones are 1 291.6 km^2, 1 228 km^2, 1 081 km^2, 853.04 km^2, and 1 235.05 km^2, respectively. The groundwater potential map which was produced was verified using field determined borehole yields, and the prediction accuracy of the map was approximately 70%. The results can be used for further groundwater exploration in the study area and can form a basis for cost-effective groundwater resource planning and management. The study should be tried on a broader scale to assist water resource planners to develop sustainable groundwater strategies for semi-arid regions.

Keywords: groundwater, GIS, remote sensing, AHP

Bepaling van grondwaterpotensiaal deur gebruik te maak van Geografiese Inligtingstelsels en afstandwaarnemingstegnieke in Moses Kotane Plaaslike Munisipaliteit, Noordwesprovinsie, Suid-Afrika: Die volhoubare voorsiening van water in voldoende hoeveelhede is fundamenteel vir die ekonomiese groei van enige land. In Suid-Afrika vereis die bedryf van al die groot ekonomiese sektore beduidende hoeveelhede water. Suid-Afrika ervaar egter steeds watertekorte, wat vererger word deur 'n lae gemiddelde jaarlikse neerslag wat laer as die wêreld se jaarlikse gemiddelde is. Grondwater bied 'n geleentheid om wateruitdagings te verlig, maar die volhoubaarheid daarvan word belemmer deur ontoereikende grondwaterhulpbronbeplanning en -bestuur. In hierdie studie is Geografiese Inligtingstelsels en afstandswaarnemingstegnieke gebruik om grondwaterpotensiaalsones in die Moses Kotane Plaaslike Munisipaliteit in Suid-Afrika af te baken. Sewe temas van afstandswaargeneemde parameters wat die beskikbaarheid van grondwater beïnvloed, is ontwikkel en gewigte is daaraan toegewys deur gebruik te maak van die analitiese hiërargieproses (AHP) voordat oorlegging daarvan in ArcGIS 10.3.1-sagteware gedoen is om sones van grondwaterpotensiaal te skep. Die finale grondwaterpotensiaalkaart is geproduseer deur gebruik te maak van die geweegde oorleggingsontleding. Vyf grondwaterpotensiaalsones is geproduseer, naamlik baie laag, laag, matig, hoog en baie hoog. Die oppervlaktes wat deur hierdie sones gedek is, beslaan onderskeidelik 1 291,6 km^2, 1 228 km^2, 1 081 km^2, 853,04 km^2 en 1 235,05 km^2. Die grondwaterpotensiaalkaart wat geproduseer is, is geverifieer deur gebruik te maak van boorgatvloeitempo's wat in die veld bepaal is. Die voorspellingsakkuraatheid van die kaart was ongeveer 70%. Die resultate kan vir verdere grondwatereksplorasie in die studiegebied gebruik word en kan 'n basis vorm vir kostedoeltreffende grondwaterhulpbronbeplanning en -bestuur. Die studie moet op 'n breër skaal beproef word om waterhulpbronbeplanners te help om volhoubare grondwaterstrategieë vir semi-ariede streke te ontwikkel.

Sleutelwoorde: Grondwater, GIS, Afstandswaarneming, AHP

Introduction

Adequate water supply is a fundamental part of livelihood, poverty alleviation and socio-economic development of any society. Communities with abundant rainfall and adequate access to water sources have access to numerous opportunities to develop and improve their economic standing. However, arid and semi-arid nations experience perennial surface water shortages and rely on groundwater as their main source of water supply. Determining groundwater flow and levels with certainty is difficult and is compounded by the heterogeneity of aquifer formations (Ndambuki, 2011). Rich nations with good financial backing monitor groundwater flow and levels using a series of observation boreholes (Shamuyarira, 2017). South Africa, on the other hand, is a developing country with limited resources and therefore struggles to implement adequate monitoring wells across its borders. Furthermore, groundwater challenges in these regions are exacerbated by inadequate water resource planning and management caused by limited knowledge of aquifer parameters. Groundwater resource planning and sustainable use can, however, be achieved through cost-effective conceptual modelling on both national and local levels.

There is a limited understanding of groundwater in most developing countries, which leads to poor management and use of the resources. To improve the sustainable management of groundwater, it is imperative to understand the science behind the resource and all the parameters that contribute to its preservation (Smith, *et al*., 2016). Previous studies highlighted that poor groundwater resource planning and inadequate assessment of potentiality have led to problems of over-exploitation and aquifer depletion (Kumar, 2012; Waikar & Nilawar, 2014; Magesh, *et al.,* 2012). Understanding the factors that influence the occurrence and quantity of groundwater is a fundamental basis for effective resource planning. Through effective groundwater resource planning, groundwater can be equitably and sustainably harvested to meet the needs of the ever-increasing population and enhance economic growth.

The growth of computational intelligence and technological advancement has culminated in the use of computer models for groundwater management (Rwanga & Ndambuki, 2019). These modelling techniques are used in groundwater planning to predict the occurrence, quantities, quality and extent of groundwater. The choice of which modelling technique to use for groundwater modelling is usually dependent on the availability of data, costs, the geological setting of the area of interest, and a variety of other factors (Anastasiadis, *et al.,* 2013). Most groundwater modelling technologies in use today are numerical and deterministic in nature (Rwanga & Ndambuki, 2019; Konikow, 1996). Some of the most widely used numerical model codes are MIKE SHE, MODHMS, GSFLOW, MODFLOW, HydroGeoSphere and Parflow (Shamuyarira, 2017). While numerical modelling technologies are essential tools for groundwater management, there have been growing concerns relating to the limitations associated with using deterministic models without accounting for uncertainties linked to the models (Ndambuki, 2011; Zhou & Van Geer, 1992; Konikow, 1996). As a result of this limitation in numerical models, many researchers have begun to shift to stochastic and probabilistic groundwater modelling approaches to mitigate the short-comings associated with aquifer heterogeneity and uncertain groundwater parameters (Rwangwa & Ndambuki, 2019; Zhou & Van Geer, 1992; Ndambuki, 2011; Konokow, 1996).

GIS-RS groundwater delineation creates premises for the integration of multiple datasets, with various indications for groundwater availability as a high level conceptual inference, particularly in data-scarce semi-arid and arid regions (Magesh, *et al*., 2012). This multi-criteria modelling technique is important in improving safer decisions on groundwater management (Solomon, 2003). This study proposes the integration of GIS and RS techniques to demarcate high level groundwater potential zones. This method of groundwater delineation is cheap and particularly relevant to developing nations with limited financial resources. Moreover, the technology can model large areas over a short period with minimum fieldwork required as first order high level groundwater potential assessment.

In this study, GIS and RS tools were used to delineate high level groundwater potential zones in Moses Kotane Local Municipality that falls under the jurisdiction of the Bojanala District Municipality in the Northwest Province of South Africa. The study was geared towards forming a basis for groundwater resource planning for the area and in so doing assisting the affected stakeholders and policymakers with informed planning strategies to mitigate the water woes in the area, and in the country at large.

Description of the study area

The study was conducted in Moses Kotane Local Municipality that is situated in the Bojanala Platinum District in the Northwest Province of South Africa (Figure 1). The Bojanala District Municipality comprises the north-eastern section of the North-west Province. Moses Kotane Local Municipality is one of five local municipalities that form the Bojanala District Municipality. The study site is located to the west of Pilanesberg and lies between the latitudes 24.7° and 25.5° S and longitudes 26.4° and 27.5° E and has a surface area of 5 719 km^2. The Department of Statistics South Africa (Stats SA, 2011) published the census data and indicated that the population of Moses Kotane was 242 554 with an estimated population increase of 0.22% per annum. The 2011 Statistics South Africa census reports estimated that the number of households in the study area is 75 193. The MAP of the area varies between 600 and 800 mm per annum, with the higher rainfall experienced across the Pilanesberg Crater (Figure 2).

Geological setting of the study area

Moses Kotane Local Municipality comprises a prominent sandy soil cover which is mainly underlain by layered rocks from the Transvaal System consisting of the Chuniespoort Group, comprised of dolomites, and the Pretoria Group that consists mainly of shale and quartzite with some basalts that form prominent ridges and outcrops through the study area (Pretorius, *et al*., 2015). The analysis of the geology shapefile determined that the study area is composed of a variety of stratigraphic formations. The predominant formations in the study area are as follows:

- The Bushveld complex consists of gabbro, norite and granite lithologies
- The Ventersdorp system
- The Pretoria groups
- The Rustenburg layered
- The Archaean complex, and
- Outcrops of the Swaziland system

A summary of the geological formations in the study area is shown in Figure 3. The Bushveld complex group constitutes 674.8 km^2 (11.79%) of the study area, the Pretoria group 1 107.6 km^2 (19.36%), Rustenburg layered 1 249.5 km^2 (21.84%), Chuniespoort 329.2 km^2 (5.75%), Transvaal group 78.4 km^2 (1.37%) and the Ventersdorp, Archaean and Swaziland groups constitute 2 282.4 km^2 (39.89%) of the study area.

Hydrogeology

Groundwater resources are available throughout the entire Moses Kotane Local Municipality, even though quantities available for abstraction are dependent on the hydraulic parameters of the underground geology (DWAF, 2006). The most prominent hydrogeological units in the study area are dolomitic lithologies and alluvial deposits, which assemble in the valley floodplains of large drainage systems, representing important groundwater resources (Pretorius, *et al*., 2015). Water strike depths throughout Moses Kotane vary from 28 metres below ground level (m.b.g.l.) to 120 m.b.g.l. while the water levels differ from 3.2 m.b.g.l. to 38 m.b.g.l (SRK Consulting, 2011). DWAF (2006) reports that a large portion of the Chuniespoort Group's Malmani Subgroup dolomite has expected yields greater than 3 l/s. A higher groundwater potential is expected in dolomitic regions owing to a well-developed fractures system with cavities, joints and contact zones associated with dolomitic aquifers. A review of hydrogeological literature in the study area indicates that high-level groundwater potential varies across the Moses Kotane depending on geological formations and varying groundwater recharge rates influenced by heterogeneous physical and manmade features.

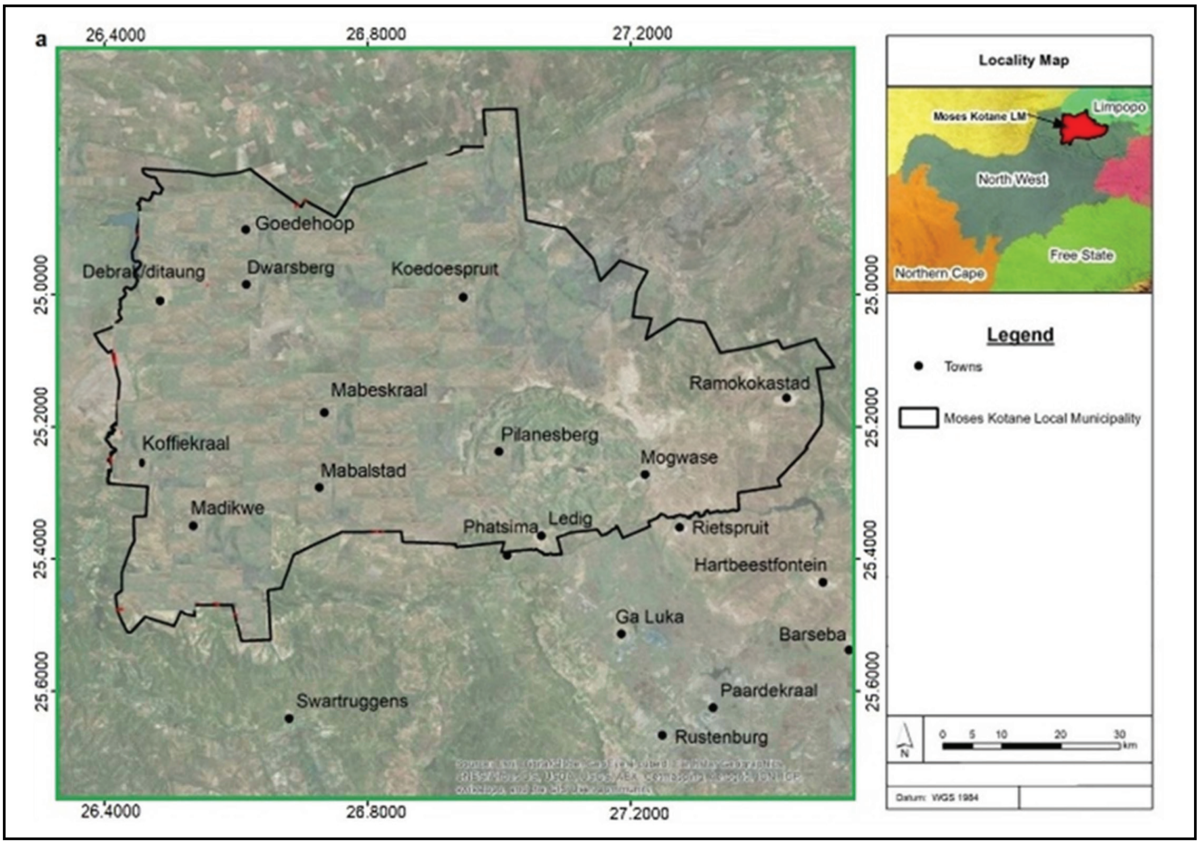

Figure 1: Location map of study area

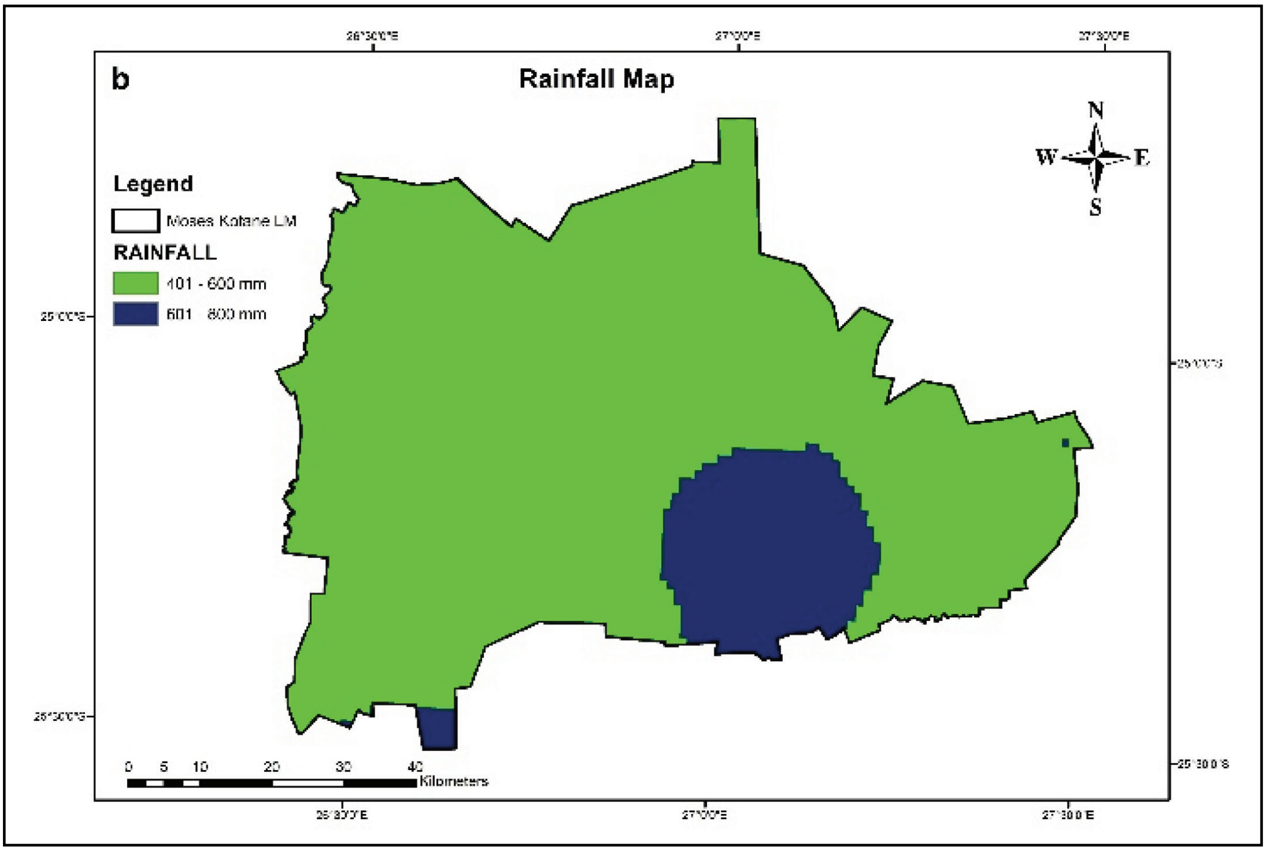

Figure 2: Rainfall map of the study area

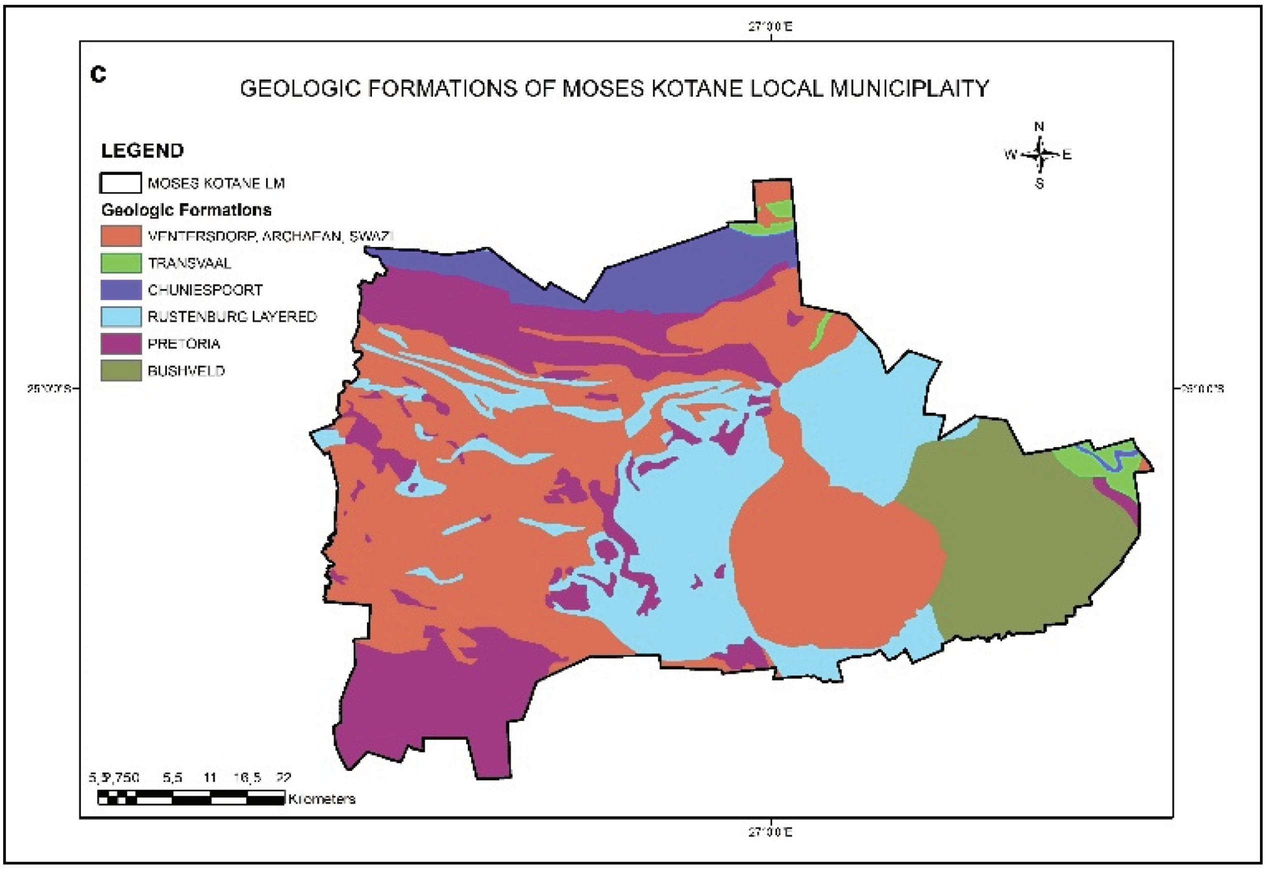

Figure 3: Geological formations of the study area

Methodology

Generation of thematic maps of the study area

Seven thematic maps of the study area were generated using ArcGIS 10.3.1 software. The themes were derived from remotely sensed geophysical data that influence high recharge rates. The identified parameters used in the generation of the thematic maps were geomorphology, geology, soil type, land use and land cover, rainfall, drainage density and slope of the study area. The generation of the thematic maps was done in two steps. The first step was to compute and assign weights to the themes and their features using the Analytical Hierarchy Process (AHP) (Saaty, 1980) while the second was to produce the thematic maps according to the computed and reclassified feature weights in the ArcGIS 10.3.1 platform.

Assigning of weights to themes using AHP

The AHP, developed by Saaty, (1980), was used as the decision-making method to assign weights to different themes and their corresponding features. The AHP is a mathematical multiple decision-making method that allows users to compare and apply relative weights to various criteria (Fashae, *et al*., 2013). The AHP was used to simplify comparisons and preferences between the various themes using the pairwise comparison technique. The thematic layers and their respective features were compared on a pairwise basis concerning their importance in influencing groundwater potentiality. The AHP was done in three steps as recommended by Saaty (1980). It entailed pairwise comparison of the themes' importance in influencing groundwater potentiality, matrix normalisation of thematic weights and ranking of the themes. Saaty's scale for assigning weights to themes was used to compare and assign weights to themes and their features (Table I). The scale was used in conjunction with expertise from previous research by Fashae, *et al*. (2013), Kumar (2012) and Machiwal, *et al.* (2010).

The scale was used as the basis for evaluating and assigning weights to the themes. The themes were arranged in a pairwise matrix and evaluated against one another in Microsoft Excel 365. The criteria comparison matrix which was produced was normalised by dividing each value in the column by the sum of the column values (Equation 1).

$$v_{jk} = \frac{x_{ab}}{\sum_{i=1}^{n} x_{ab}} \quad (1)$$

Where *v* is the normalised value in the Matrix, *j* and *k* are rows and column numbers for the normalised value, *x* is the value in the pairwise comparison table, *a* and *b* are row and column numbers for values in the pairwise comparison table, *i* is the theme and *n* represents the total number of themes that are being weighted in the pairwise comparison matrix.

The thematic weights were determined by calculating the mean of the normalised values across the rows of the matrix table (Equation 2).

$$w_a = \left(\sum_{i=1}^{n} x_a\right) \div n \quad (2)$$

Where *w* is the normalised weight of the theme and the other symbols are as outlined in equation 3.2 above.

A consistency check was done for the pairwise comparison and the weights assigning matrix. The consistency check was done using a ratio calculation to reduce the risks of intuitiveness and subjectivity in determining the comparison of themes during the weighting process. The consistency ratio was calculated using Equation 3 as recommended by Saaty (1980).

$$CR = \frac{CI}{RCI} \quad (3)$$

Where CR is the consistency ratio, CI is the consistency index and RCI is the random consistency index estimated by Saaty (1980). The RCI values are tabulated in Table II and CI is calculated using Equation 4 below.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (4)$$

In the above equation, λ_{max} is the maximum eigenvalue of the comparison matrix and is the order of the matrix.

The maximum eigenvalue (λ_{max}) was computed using both the pairwise comparison and the normalised matrix tables. The procedure entailed determining the weight sum vector (W_s) using Equation 5, computing the consistency vector (Equation

Table I: Saaty's scale of pairwise comparison (Saaty, 1980)

Less important				**Equally important**	**More important**			
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

Note: The numbers 2, 4, 6 and 8 are intermediate values representing compromise. They can be included in the pairwise comparison if the evaluator feels that the level of importance falls between the values in the above scale.

Table II: Random consistency index (RCI)

n	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0,58	0,90	1,12	1,24	1,32	1.41	1,45	1,51

6) and computing the average of the consistency vector (Equation 7).

$$w_s = c \times w \quad (5)$$

$$\{cons\} = w_s \times \frac{1}{w} \quad (6)$$

$$\lambda_{max} = Average\{cons\} \quad (7)$$

A consistency ratio of zero indicates the perfect consistency of the pairwise comparison. For pairwise comparison of at least 4 x 4 matrix, Saaty (1980) suggested that the consistency ratio should be less than 0.1 (10%). He argued that a consistency ratio of more than 0.1 shows inconsistency in the pairwise comparison.

All the thematic maps were reclassified and the features within the themes were assigned classes from 1 to 4 depending on their influence on groundwater potentiality. Features were ranked between 1 and 4 with 1 being the least influence and 4 being the most influence in groundwater potential. Features with intermediate influence in groundwater were assigned weights of 2 and 3.

Generation of maps

Seven thematic maps were generated in ArcGIS 10.3.1 using remotely sensed spatially and attribute data of geographic parameters that influence groundwater occurrence. The input data used was a Digital Elevation Model (DEM) derived from the United States Geological Survey (USGS) Shuttle Radar Topographic Mission at 1 arc-second (30-meter spatial resolution), shapefiles and raster data. The DEM was rectified to remove sinks and depressions in the spatial analyst toolbox of ArcGIS 10.3.1 before being processed to create drainage density and slope maps. The hydrology toolbox was used for parametric processing and creation of the drainage density map of the study area using the flow direction, flow accumulation and drainage network tools in ArcGIS. For ArcGIS to process and accurately compute the slope of the study area, the DEM was reprojected from the geographic coordinate system from which it was downloaded, to a Universal Transverse Mercator (UTM) projection. Geomorphology, geology, soil type and rainfall thematic maps were generated from shapefiles. The shapefiles were imported into ArcGIS 10.3.1 before being visualised and parametrically classified to create feature classes within each layer. The land cover thematic map was created using the 2018 South African National Land Cover raster thematic data encompassing the 2018 South African Land Cover. The data is available on national coverage of a 20-metre resolution raster format and has an overall mapping accuracy of 90.1% calculated over 6 570 reference points (DEA, 2019). The extracted land cover raster was categorised into 73 original land cover classes with colour codes representing various classes on the land cover map.

Mapping groundwater potential zones in the study area

All the thematic maps were converted into reclassified raster themes with equal grid size (30 x 30 metres). The calculated weights were assigned to the themes and their reclassified features using the weighted overlay feature of the spatial analyst tool in ArcGIS 10.3.1. The weighted themes and their features were integrated and overlaid in the ArcGIS 10.3.1 software to delineate the groundwater potential areas. The Groundwater Potential Index was calculated using Equation 8:

$$GWPI=\{(Gw * Gr)+(GLw * GLr)\ (Rw * Rr)+ (Sw * Sr)+ (Ew * Er)+ (Lw * Lr)+ (Dw * Dr)\} \quad (8)$$

Where GWPI refers to the Groundwater Potential Index while G, GL, R, S, E, L, and D refer to geomorphology, geology, rainfall, soil type, slope, land use/land cover, and drainage density, respectively. The subscripts *w* and *r* refer to the standardised weight of a theme and the assigned class of each feature of a theme, respectively.

Validation of groundwater potential map

The groundwater potential map was validated using borehole yield data. The borehole yields were categorised into five classes, which are < 1 ℓ/s, 1–2 ℓ/s, 2–3ℓ/s, 3–5ℓ/s and > 5 ℓ/s, and these categories were named very low yielding, low yielding, moderate yielding, high yielding and very high yielding, respectively. The boreholes yield data, and the coordinates were imported into ArcGIS 10.3.1 and overlaid onto the produced groundwater potential map. An analysis was done to evaluate the coherence between the delineated groundwater potential zones and the actual field-determined yields from the boreholes. To assess the accuracy of the delineated groundwater potential zones, each category of the borehole yields was checked if it was consistent with the produced map. A percentage coherence (Equation 9) was computed to determine how many of the boreholes are consistent with the delineated groundwater potential zones.

$$Accuracy\ prediction = \frac{Number\ of\ boreholes\ in\ the\ agreement\ of\ coherence}{Total\ number\ of\ analysed\ boreholes} \quad (9)$$

Discussion of results

Generation of thematic maps

AHP and thematic weights

The AHP was used to compute numerical weights for the themes before they were overlaid using the weighted overlay tool in ArcGIS 10.3.1. The pairwise comparison determined that geomorphology and geology were the most influential themes in groundwater recharge in the study area. The standardised matrix computations resulted in a weight of 25% (0.25) for both geomorphology and geology. The least influential theme was found to be land cover with a standardised matrix weight of 5% (0.05). Rainfall and soil type retained equal weights (8.2%), followed by slope and drainage density with weights of 14.4%. Ideally, rainfall would have the highest weight as it is the primary theme that influences groundwater recharge. However, the spatial variation of rainfall within the study area was minimal. The rainfall data indicated that there is a minimal variation of the MAP across the study area. Therefore, rainfall would not be a major determining factor in having varying groundwater potential areas within the study area. The results of the pairwise comparison and the normalised (standardised) matrix are presented in Tables III and IV, respectively. The pairwise comparison matrix was normalised by dividing each value in the column by the sum of the values in that column. The overall weights of the themes were determined by computing the mean of each row.

Consistency check

A consistency check was done to verify the absence of subjectivity in the pairwise comparison matrix. Saaty (1980) recommended that a 4 x 4 matrix should have a consistency ratio (CR) of less than 0.1 (10%). A CR of zero (0) would imply perfect consistency, and a CR of more than 0.1 is unacceptable and implies that there was inconsistency in comparing the themes under consideration. For this study, the computed CR was 0.006 which is approximately 0.01 (1%). The CR was therefore acceptable and falls within the recommended CR that verifies the absence of bias and inconsistency in assigning weights to the themes. The summary of the computations of the consistency index (CI), the consistency vector, the maximum eigenvalue, and the CR are shown in Table V.

Table III: Pairwise comparison of themes

Item Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Item Description	Geomorphology	Geology	Drainage Density	Slope	Rainfall	Soil Types	Land Cover
Geomorphology	1,00	1,00	2,00	2,00	3,00	3,00	4,00
Geology	1,00	1,00	2,00	2,00	3,00	3,00	4,00
Drainage Density	0,50	0,50	1,00	1,00	2,00	2,00	3,00
Slope	0,50	0,50	1,00	1,00	2,00	2,00	3,00
Rainfall	0,33	0,33	0,50	0,50	1,00	1,00	2,00
Soil Types	0,33	0,33	0,50	0,50	1,00	1,00	2,00
Land Cover	0,25	0,25	0,33	0,33	0,50	0,50	1,00
Sum	3,92	3,92	7,33	7,33	12,50	12,50	19,00

Table IV: Standardised matrix table and thematic weights

	Geomor-phology	**Geology**	**Drainage Density**	**Slope**	**Rainfall**	**Soil Types**	**Land Cover**	**Weight**
Geomorphology	0,26	0,26	0,27	0,27	0,24	0,24	0,21	25,0%
Geology	0,26	0,26	0,27	0,27	0,24	0,24	0,21	25,0%
Drainage Density	0,13	0,13	0,14	0,14	0,16	0,16	0,16	14,4%
Slope	0,13	0,13	0,14	0,14	0,16	0,16	0,16	14,4%
Rainfall	0,09	0,09	0,07	0,07	0,08	0,08	0,11	8,2%
Soil Types	0,09	0,09	0,07	0,07	0,08	0,08	0,11	8,2%
Land Cover	0,06	0,06	0,05	0,05	0,04	0,04	0,05	5,0%

Table V: CI and CR computation results

	Geo-mor-phology	**Geology**	**Drainage Density**	**Slope**	**Rainfall**	**Soil Types**	**Land Cover**	**SUM**	**SUM/ Weight**
Geomorphology	0,25	0,25	0,29	0,29	0,25	0,25	0,20	1,76	7,07
Geology	0,25	0,25	0,29	0,29	0,25	0,25	0,20	1,76	7,07
Drainage Density	0,12	0,12	0,14	0,14	0,16	0,16	0,15	1,01	7,06
Slope	0,12	0,12	0,14	0,14	0,16	0,16	0,15	1,01	7,06
Rainfall	0,08	0,08	0,07	0,07	0,08	0,08	0,10	0,57	7,02
Soil Types	0,08	0,08	0,07	0,07	0,08	0,08	0,10	0,57	7,02
Land Cover	0,06	0,06	0,05	0,05	0,04	0,04	0,05	0,35	7,02
								count	7,00
								Lambda-max	7,047
								CI	0,008
								CR	**0,01**
								constant	1,32

Thematic maps of the study area

Geomorphology

The geomorphology of Moses Kotane Local Municipality is categorised into five feature classes. These feature classes are plains, hills, slightly undulating plains, hills and lowlands, and lowlands and parallel hills. The produced geomorphology map is depicted in Figure 4**.**

The plains constitute approximately 3 508 km^2 (60.8%) of the study area. High rates of groundwater recharge are most likely to occur in flat areas with a gentle slope and low runoff. Therefore, plains retain high importance in influencing groundwater potentiality. Hills constitute 210.6 km^2 (3.65%) of the Moses Kotane Local Municipality. The hilliest areas are situated in the south-eastern part of the study area close to the Pilanesberg crater. Hills are usually made up of consolidated material that obstructs water infiltration. However, this may not always be the case in areas where the underground material is fractured rocks or unconsolidated material with high porosity and permeability. The hilly areas in Moses Kotane Local Municipality are mostly situated in the Pilanesberg region that is underlain by Pilanesberg National Park Alkaline Ring Complex.

Slightly undulating plains and hills and lowlands constitute 687.9 km^2 (11.9%) and 592.6 km^2 (10.27%) of the study area, respectively. The land is overlain by geomorphology features that can either promote easy groundwater recharge or restrict it. Undulating plains have both low-lying areas which promote ease of infiltration and recharge, and high relief terrains that are unfavourable for recharge.

The lowlands constitute 772.1 km^2 (13.38%) of the study area. Lowlands have the highest importance in groundwater potentiality. Generally, a larger portion of the study area is underlain by geomorphological features that promote higher levels of groundwater recharge.

Soil types of the study area

The soil types that overlay the study area are shallow soils, rock outcrops, black clay, loamy and freely drained soils (Figure 5). Shallow soils and rock outcrops are predominant in the eastern part of the study area and along the Goedehoop region to the north of Moses Kotane. The most predominant soil types are the freely drained and black clay soils that are scattered over the study area. Red and yellow loamy soils are the least occurring soil types in the area. Freely drained soils are composed of unconsolidated material and have good permeability which enhances high rates of infiltration and groundwater recharge. High groundwater potential is less likely to occur on regions of consolidated rock outcrops unless the rock material has cracks which can increase groundwater recharge and form karst aquifers. Loamy soils have a mixture of sand and clay material and have moderate permeability and porosity while clayey soil has very low permeability and poor drainage. Even though clayey soils have a good porosity due to greater surface area than loamy soils, they are generally poor groundwater holding units because of their low effective porosity. Thus, higher groundwater potential is expected on sandy and loamy soils than it would be in clayey regions. The soil types within the study area show that low groundwater potential is expected on the eastern part of the study area whereas medium to high groundwater potential is expected in the west and northern regions of the study area.

Land use and land cover of the study area

The entire study area is overlain by vegetation and built-up areas (Figure 6). The built-up areas are mostly constituted of rural residential units since the Moses Kotane Local Municipality is predominantly rural. The main water bodies are the Madikwe, Molatedi and Pella dams and a few tributaries of the Marico River System. Moses Kotane villages practise subsistence farming, hence, the study area is overlain by cultivated lands across its boundary. Bare lands are situated in the central part of the study area and to the west and northwest of the local municipality. Built-up areas promote higher rates of surface runoff and thus reduce infiltration and groundwater recharge. In addition, human activities like deforestation and infrastructure development are predominant in built-up areas. Human activities increase the rate of surface runoff and reduce infiltration, thereby reducing groundwater recharge and thus reducing groundwater potentiality. Vegetation constitutes the largest land cover class in Moses Kotane Local Municipality with an area of 5 041.5 km^2 (87.37%). Bare land covers the smallest area in the study area (117,2 km^2), followed by water bodies and bare land. Cultivated land, with the highest assigned class weight, constitutes 239,5 km^2 (4,15%) of the Moses Kotane Local Municipality.

Geology

The rock formations and underground lithology are essential parameters that influence groundwater availability. The study area is underlain by volcanic rocks, sedimentary, quartzite and granite rocks. Usually, volcanic rocks do not decompose, and as a result, do not form fractures, and are therefore generally poor groundwater holding units. Low groundwater potentiality is expected in areas that are predominantly underlain by consolidated volcanic rocks, unless in special circumstances where the rocks have fractures (Nel, 2017). This is because volcanic rocks are generally poor in permeability and porosity. Dolomitic rocks underlay the region further north in the study area. High groundwater potential is expected in these regions. Nel (2017) notes that dolomitic rocks have significant groundwater potential because of their porosity and specific yield. Furthermore, boreholes drilled in carefully delineated dolomite areas can yield very high volumes of water (DWAF, 2006).

Granite, gabbro and norite rocks underlay the eastern part of Moses Kotane Local Municipality. The rocks are metamorphic and have very low porosity and permeability unless they develop fractures (Nel, 2017). In terms of geology, the eastern region of the study area is expected to have low groundwater potential. On the other hand, Quartzite and arenite rocks are good groundwater influencing units (Nel, 2017). This is because the lithologic units are fractured and have high porosity and permeability. Thus, the central and western regions of Moses

Kotane underlain by the arenite and quartzite geology units are expected to be good groundwater potential areas.

Rainfall

The MAP is constant across the study area with higher precipitation in the Pilanesberg crater. Rainfall is an important parameter as it is the primary source of groundwater recharge. Fashae *et al.* (2013) note that the rate of groundwater recharge is directly related to the amount of water that percolates into the saturated zone of the subsurface geological medium. Although precipitation intensity is a major factor in determining groundwater recharge (Thomas, *et al.,* 2016), the amount of rainfall that an area receives is also an important factor in determining the amount of groundwater recharge. Therefore, areas with high MAP are more likely to have higher groundwater potential compared to those with low MAP, even though this is dependent on other groundwater influencing parameters. Thus, in terms of rainfall, the Pilanesberg region with a MAP of 601–800 mm is expected to have higher groundwater potential than the other parts of the study area. However, many other parameters discussed earlier also contribute to recharging and groundwater potentiality.

The rainfall thematic map retained a normalised weight of 8.2%. Rainfall is naturally the most important factor that influences groundwater potentiality because water on the subsurface is primarily dependent on precipitation and recharge. Notwithstanding its importance, rainfall scored less weight on geology, geomorphology, slope, and drainage density because of the lack of significant variation in MAP across the study area. A large portion of the study area has a MAP of between 401–600 mm (5 054.6 km^2), while 725.9 km^2 (12.58%) have a MAP of between 601 and 800 mm.

Drainage density

Four drainage density classes were produced (very high, high, medium, low and very low) (Figure 7). The drainage density thematic map retained a 14.4% normalised weight during pairwise comparison. Very high drainage density areas are susceptible to high runoff and lower infiltration of rainfall while low drainage density areas promote higher infiltration, thus high groundwater recharge.

The western regions of the study area formed a dendritic drainage pattern illustrating that the region is underlain by homogeneous material. On the other hand, the eastern region formed a radial drainage pattern, with streams developing around the Pilanesberg mountain. The central region of the study area and the Pilanesberg crater are the drainage networks' headwaters, while the outskirts to the west, east and northeast are low lying areas that receive the discharge from the centre of Moses Kotane. Evaluation of the derived drainage networks indicates that less drained regions are more likely to be prospects of high groundwater potentiality.

The analysis determined that 1 510 km^2 (26.17%) of the Moses Kotane Local Municipality has a high drainage density. Low and very low drainage densities constitute 1 643 km^2 (28.47%) and 942 km^2 (16.33%) of the study area, while 1 675 (29.03%) is medium density area.

Slope

The slope of Moses Kotane ranges from 0 degrees to 49.1 degrees. The steep slopes are situated in the Pilanesberg crater with very low slopes on the far west of the study area. Stripes of steep slopes are also situated to the north along the Goedehoop region. The derived slope is consistent with the produced drainage networks. The conceptual drainage networks indicate that water flows from steep terrains towards lower-lying regions. Flat and gentle slopes promote higher recharge while steep areas have lower rates of recharge. Groundwater recharge is inversely proportional to slope, thus high groundwater potential areas are more likely to be situated in flat terrains. Areas with steep slopes experience high surface runoff and less water infiltration during precipitation, thus the rate of groundwater recharge is lower in steep terrains than it is in flat ones. The thematic pairwise comparison produced a 14.4% weight for the slope theme. Slope plays an important role in influencing or restricting groundwater recharge. The steepness or gentleness of the terrain is a determining factor in how much water can infiltrate the subsurface zone during precipitation. The slope map was categorised into 4 slope degree classes (Figure 8), and each class was assigned a weight. A significant amount of area (3 921.7 km^2) within the Moses Kotane Local Municipality is generally flat with slopes that are less than 4 degrees. Steep slopes (greater than 8 degrees) constitute approximately 9% (520 km^2) of the study area, with a large portion of the area around the Pilanesberg mountains.

Groundwater potential zones

The weighted overlay of the seven thematic maps produced the overall groundwater potential map with weights ranging from 2 to 4. Quantile classification of the map produced five classes of groundwater potential zones. The classified weights were 0–1, 1–2, 2–3, 3–5 and > 3.5 and represented very low, low, moderate, high and very high groundwater potential zones, respectively (Figure 9). Very high groundwater potential zones are situated on the far north side of the Moses Kotane Local Municipality. The area covers the Goedehoop and Nonceba dolomitic area. The very high groundwater potential zones constitute 1 235.05 km^2 (21.7%) of the study area. High groundwater potential areas are scattered over the study area, more prominently in plains and low-lying areas with low drainage densities and permeable soils. The high groundwater potential areas constitute 853.04 km^2 (15%). Moderate groundwater potential areas are concentrated in the centre of Moses Kotane, with few moderate zones at the outskirts of the municipal boundary and in the northern and north-western regions of the municipality. The moderate groundwater potential zones make up 19% (1 081 km^2) of the study area. Low and very low groundwater potential areas are scattered over the study area but mostly concentrated on the high lying areas across the Pilanesberg crater. The low groundwater potential areas constitute 1 228 km^2 (21.6%), while very low groundwater potential zones are 1 291.6 km^2 (22.7%).

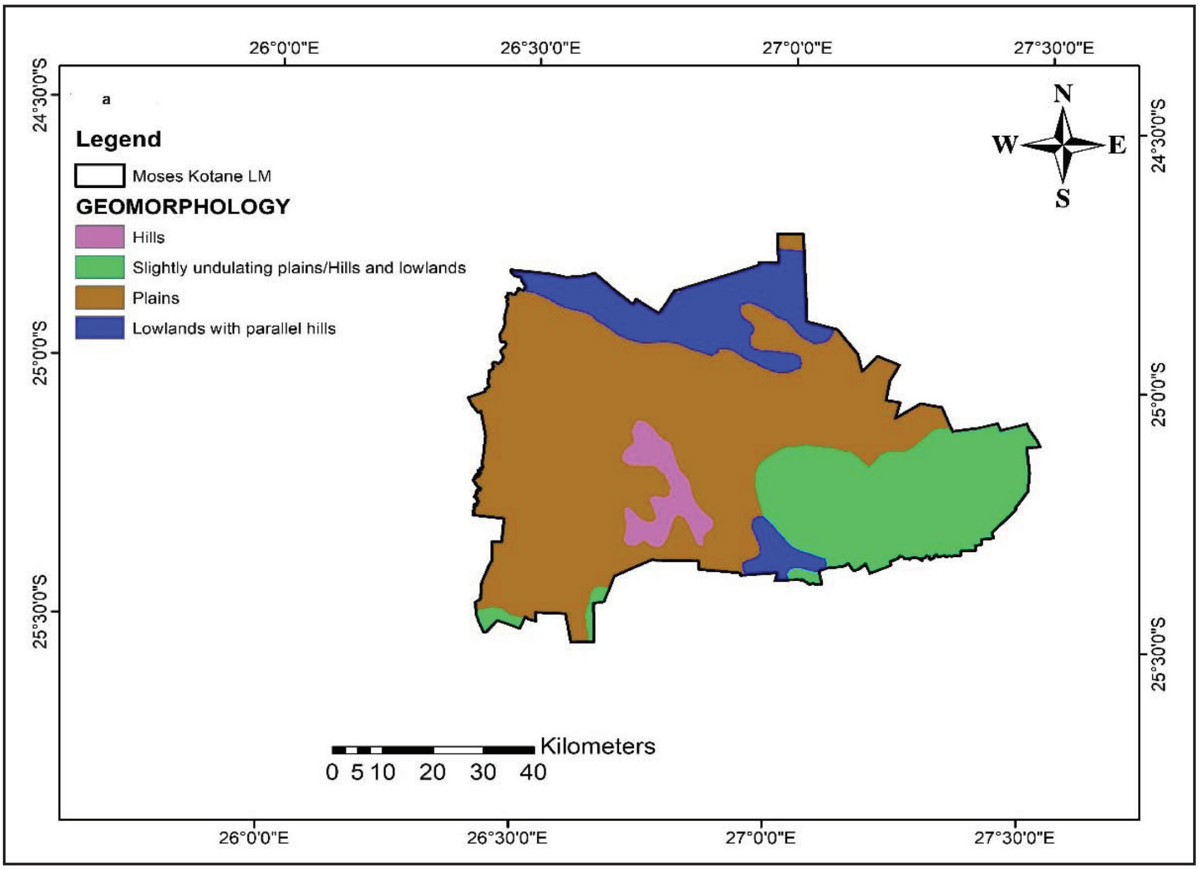

Figure 4: Produced geomorphology map

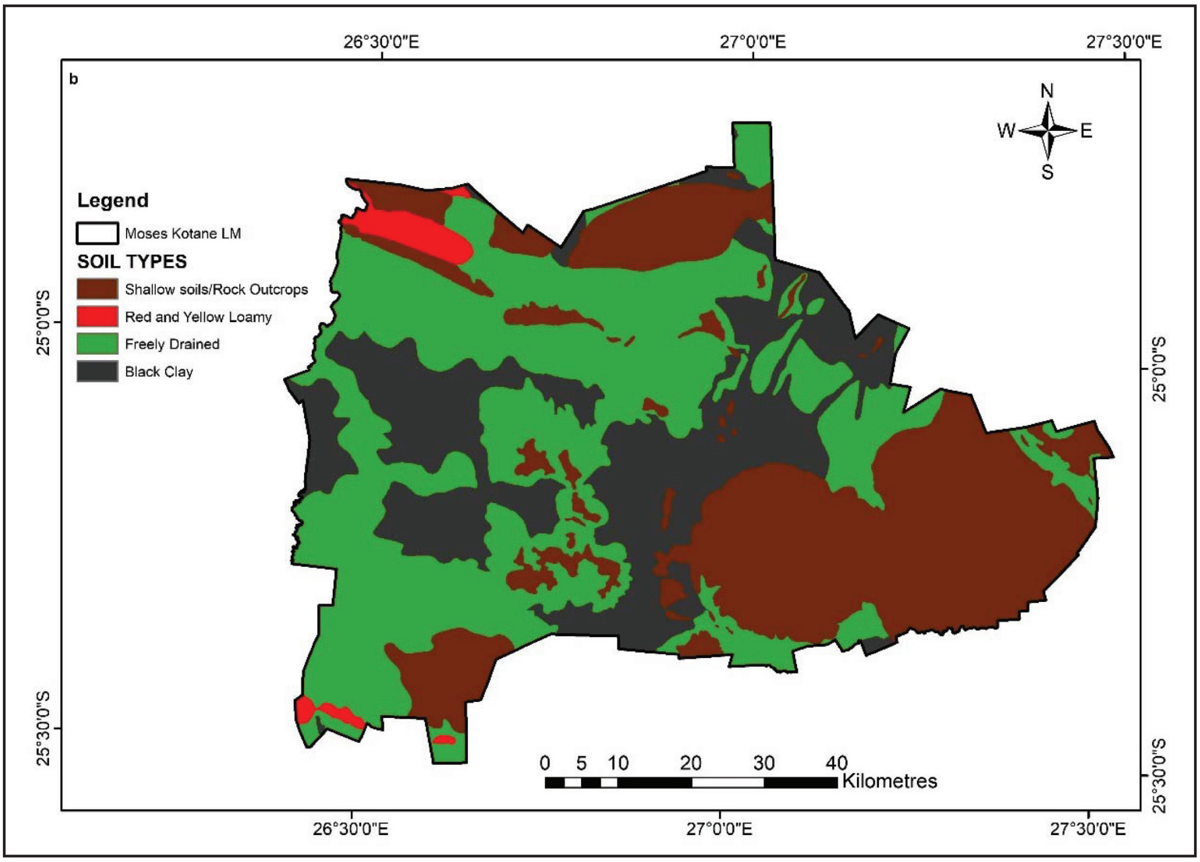

Figure 5: Produced soil map

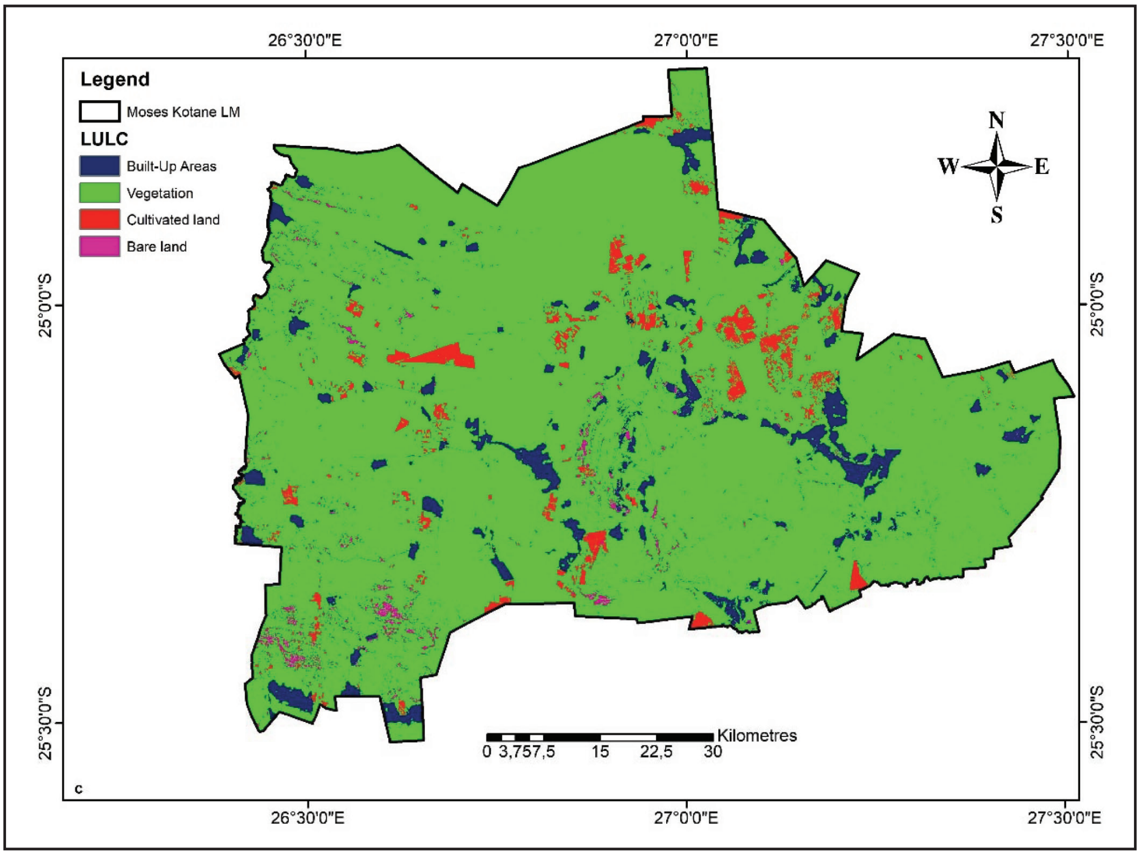

Figure 6: Produced LULC map

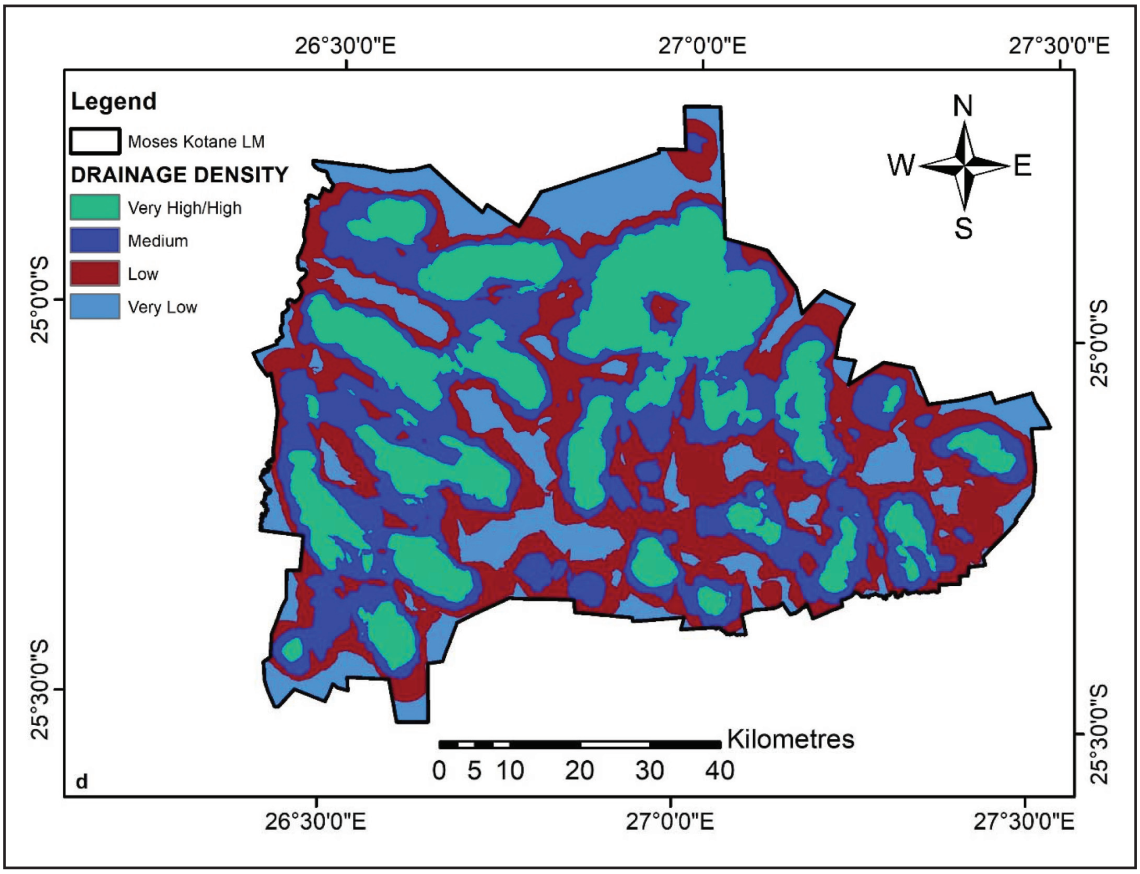

Figure 7: Produced drainage density map

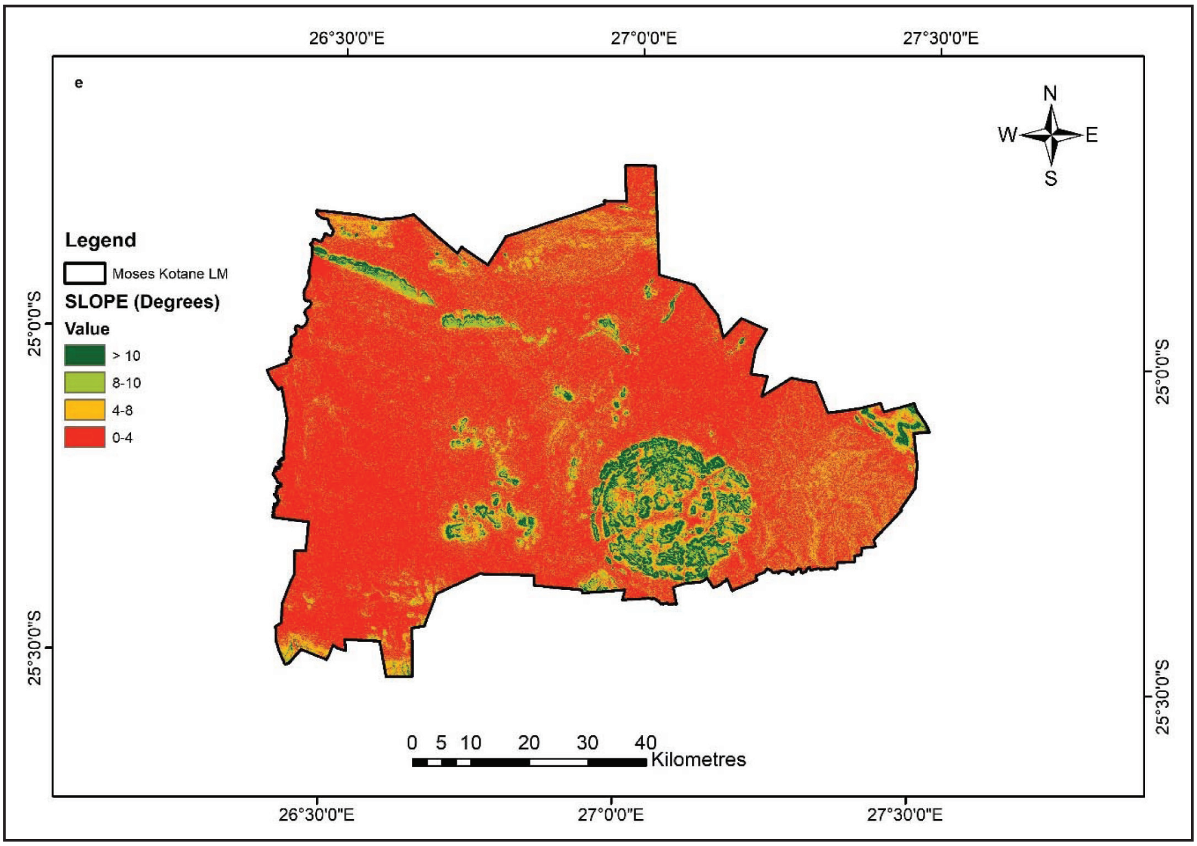

Figure 8: Produced slope map

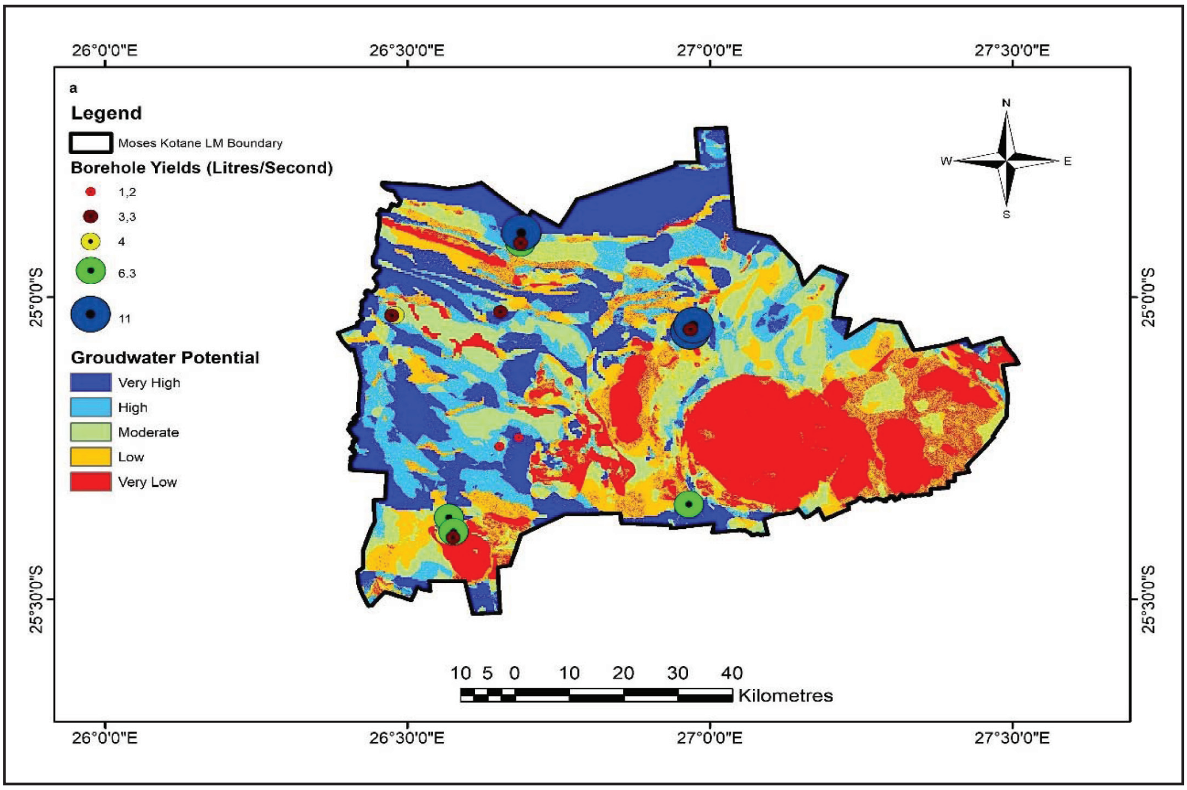

Figure 9: Produced map showing potential zones and actual borehole locations

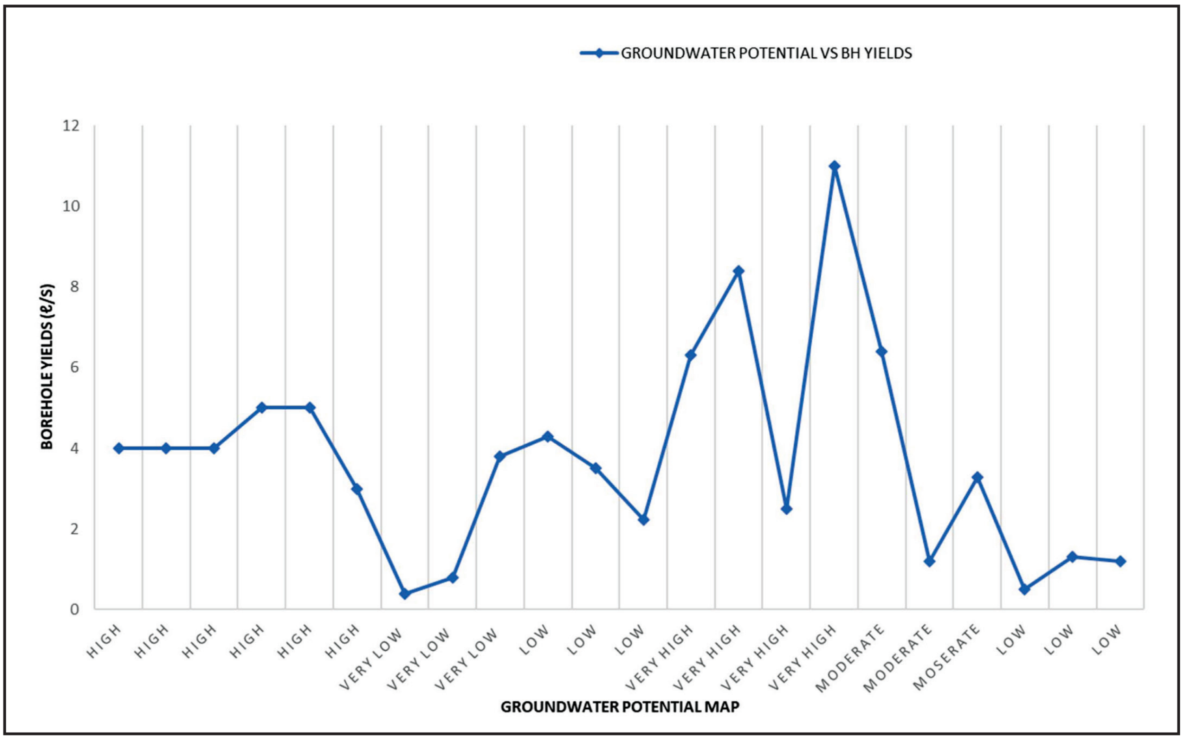

Figure 10: Correlation between produced map and actual borehole yield tests

Validation of groundwater potential map

The borehole evaluation determined that 17 out of the 22 field-collected borehole yields were consistent with the delineated groundwater potential zones. Overall, only five boreholes' yields were inconsistent with the delineated groundwater potential zones. The computed accuracy prediction was 77.2%. However, of the five inconsistent boreholes, only two borehole yields were identified as extreme outliers that did not correlate with the produced groundwater potential map. The extreme outlier boreholes may be attributed to inaccurate borehole siting or differences in pumping rates. However, the percentage correlation between the field-collected borehole yields and the delineated potential zones confirmed that the delineated groundwater potential map is accurate. The linear correlation between the produced groundwater map and the field determined borehole yields is shown in Figure 10. From the figure, it is evident that boreholes in the high groundwater potential have yields ranging from 4 ℓ/s to 5 ℓ/s. Boreholes with yields above 5 ℓ/s are scattered on very high groundwater potential zones, except for one outlier that has a yield of 2.1 ℓ/s. The borehole yield data thus validates the groundwater potential map.

Conclusions

In this study, the use of GIS and remote sensing techniques to demarcate groundwater potential zones is proposed. The proposed methodology was demonstrated by assessing the groundwater potential of Moses Kotane Local Municipality situated in the Northwest Province of South Africa. The groundwater potential assessment was done by determining geological, hydrogeological, meteorological, and physical parameters believed to influence groundwater availability. A groundwater potential map indicating various groundwater potential zones was developed. These zones can be used as first-order conceptual borehole drilling sites for further groundwater development. It is recommended that policymakers and water resource management authorities use this cost-effective conceptual modelling technique to improve sustainable groundwater use.

Dates

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