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Delineation of groundwater potential zones using GIS based multi-criteria data analysis: A case study of Dodoma City, Tanzania

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Abstract

Groundwater is a precious resource that covers wide geographical extent. Proper evaluation is required in order to ensure prudent use of groundwater resources. Lack of proper knowledge accounting distribution of groundwater potential zones (GWPZS) has a negative implication on groundwater exploitation and management as the area will be explored with higher uncertainties. The objective of this study is to delineate the GWPZS in Dodoma City, Tanzania, using a Geographic Information System (GIS) based multi-criteria decision analysis (MCDA) technique. Various thematic layers which influence groundwater occurrence such as lithology, lineament density, drainage density, slope and land use/cover maps were used. The final groundwater potential map was prepared by assigning appropriate weightage and theme classes' ranks to different thematic layers using Saaty's analytic hierarchy approach. Following weightage and ranking, the rasterized and reclassified thematic layers were integrated using weight overlay tool of Arc Map 10 to generate the overall groundwater potential map. The integrated map shows different zones of groundwater prospects; very high (3% of the area), high (8% of the area), moderate (28% of the area), while poor and very poor are made up of (62% of the area). The very good potential areas are mainly concentrated along the Hombolo dam unit. This study clearly highlights the efficacy of GIS-based MCDA as useful modern approach for proper groundwater resources evaluation; providing quick prospective guides for groundwater exploration and exploitation. Further studies should focus in verifying and enhancement of the results by introducing more verified values for weights as well as exploring other factors that may contribute towards changing GWPZS.

Keywords Groundwater potential zones, Geographic information systems, Multi-criteria decision analysis

1. Introduction

Dodoma City depends mainly on groundwater as a vital natural resource and trustworthy water supply. Currently, groundwater accounts for more than 60 % of the total annual water supply for agriculture, domestic, and industrial purposes in the district which is the capital city of the Tanzania. The Government of Tanzania like many other developing countries is seeking various ways to increase the freshwater availability and ensure the continuous supply of water to individual households and the community (REPOA, 2007). Although the country receives higher rainfall in the wet season, most people often face water scarcity during the dry season especially in semi-arid regions like Dodoma. There are uncertainties and high degree of variation in aquifer types to explore the availability of groundwater resources in the watershed (Apolkarpi, 2007). Various factors are responsible for water scarcity in Dodoma area such as dependence on only one groundwater source, unfavorable topographical conditions, rapid population growth and urbanization, poor knowledge, and lack of better water management practices. In addition, only one-fourth of the Dodoma City contain of water bodies and alluvial plains which are favorable for groundwater recharge and storage. The groundwater in the alluvial plain is being exploited by constructing shallow and deep wells. The groundwater extraction is usually high during the dry season. Rapid population growth combined with increasing demand of water from multiple sectors such as municipal, agricultural, industries, and domestic uses is increasingly becoming a major issue of concern in the country, particularly in Dodoma City (WB, 2006). As a result, drilling and construction of new bore wells without proper knowledge have led to unsustainable water resource development. It is therefore imperative to investigate the suitable areas for groundwater extraction for the purpose of increasing the freshwater availability and curb the water scarcity in the watershed. Several conventional methods such as geological, hydrogeological, geophysical, and photo geological techniques have been employed to delineate groundwater potential zones (GWPZS). However, of recently, with the advent of powerful and high-speed computers, digital technique is used to integrate various conventional methods with satellite image/remote sensing (RS) data and geographical information system (GIS) technology. The GIS and RS tools are widely used for the assessment of various natural resources e.g. water, minerals and plants (Israil et al., 2004). These approaches are considered to be effective tools for delineating the GWPZS. Application of GIS and RS tools helps to increase the accuracy of results in delineation of GWPZS and also to reduce the bias on any single theme (Rao & Jugran, 2003). The widespread availability and use of satellite data with conventional maps and terrain correction processes have made it easier to create the baseline information for assessing GWPZS (Machiwal, Rangi, & Sharma, 2015; Nampak, Pradhan, & Manap, 2014). Remote sensing not only provides a wide-ranging scale of the space–time distribution of observations, but also saves time and money (Magesh, Chandrasekar, & John, 2012). In addition, it is commonly used to characterize the earth's surface (lineaments, drainage patterns, and lithology) as well as to observe the groundwater recharge zones (Kaliraj, Chandrasekar, & Magesh, 2014). Groundwater exploration combines several different thematic layer maps such as drainage density, slope, lineament density, land use and lithology—as different parameters to determine a groundwater potential area instead of just relying on the lineament factor (Olutoyin, Fashe, Tijani, Talabi, & Adedeji., 2014).

To date, no study has attempted to demarcate groundwater resources in Dodoma City. Thus, the present study attempts to assess the GWPZS using various variables in a multi-criteria decision analysis (MCDA). The choice of MCDA approach is based on the fact that it enables decomposition of a problem into hierarchy and assures that both qualitative and quantitative aspects of the problem are incorporated during the evaluation process. MCDA is a family of techniques that aid decision makers in formally structuring multi-faceted decisions and evaluating alternatives. We use Saaty's analytic hierarchy process (AHP). The Saaty's AHP is a widely used MCDA technique in the field of water resource engineering (Kaliraj et al., 2014).

Therefore, we employ AHP-coupled MCDA and GIS techniques to integrate hydro geological, geological as well as topographical data to evaluate groundwater resources. The major purpose is to delineate the groundwater potential zones of the study area and to develop a prospective guide map for groundwater exploration/ exploitation so as to ensure optimum and sustainable development and management of this vital resource.

1.1 Study area

Dodoma City is bounded between the latitudes 5˚51′ 04″ S and 6˚28′ 00″ and longitudes 35˚29′ 08″ E and 36˚27′ 18″ E with 1104m elevation above the mean sea level (Figure 1). It covers an area of 2,669 square kilometers of which 625 square kilometers are urbanized. It is bordered to the north by Bahi district, to the east by Chamwino district, to the South by Bahi and Chamwino districts and to the west by Bahi district. Officially Dodoma City is the capital of Dodoma Region and capital of Tanzania, with a population of 410,956. The Dodoma City is administratively divided into 30 wards (Figure 1).

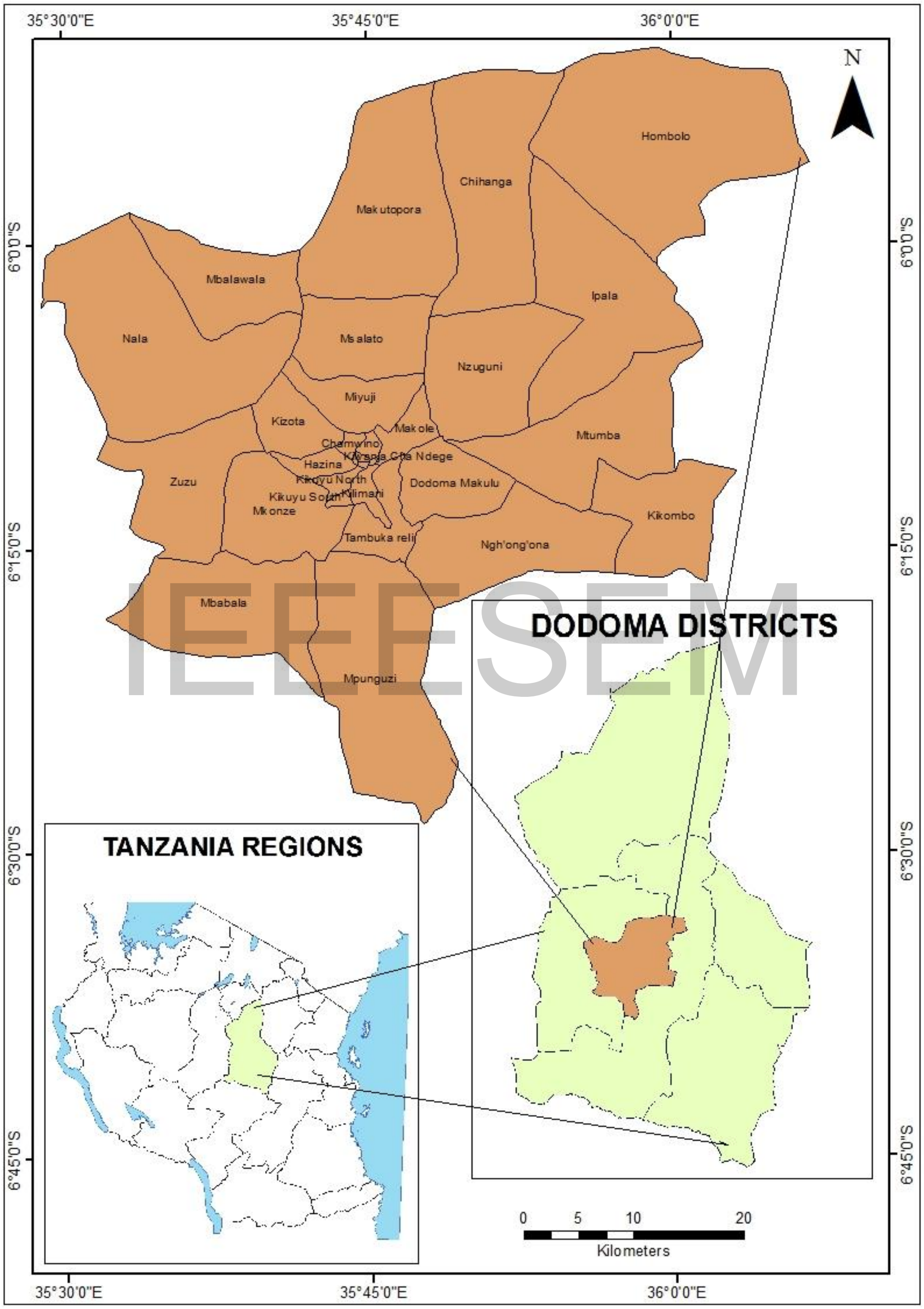

Figure 1: Location map of a study area

Dodoma features a semi-arid climate with relatively warm temperatures throughout the year. While average highs rise to 30 °C are somewhat consistent throughout the year, average lows dip to 13 °C in July. Dodoma averages 570 mm of precipitation per year, the bulk of which occurs during its wet season between November and April. The remainder of the year comprises the city’s dry season.

The economic base depends significantly on the services provided by both central and local governments. Other economic activities include public services, small-scale trading, agriculture and animal husbandry. Small-scale agriculture and animal husbandry are the major economic activities.

2. Materials and methods

2.1 Datasets

We use remotely sensed Global Digital Elevation Model (ASTERDEM), a product of the ministry of economy, trade and industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). The data was downloaded from NASA’s Land Processes Distributed Active Archive Center (LP DAAC) (URL: http://reverb.echo.nasa.gov/reverb/). GIS based geological, structural and land use/ cover data were also utilized. The geological and lineament maps were obtained from Geological Survey of Tanzania (GST) while the land use/cover map was acquired from the then Dodoma Capital Development Authority (CDA).

2.2 Methods

The approach utilized involves generation of thematic maps showing drainage pattern, lineament, slope, land use/cover and geology of the area. Thematic layers of land use/cover and lithologic units, slope, lineament and drainage density were generated and integrated in GIS environment to determine suitable zones for groundwater prospecting (Figure 2).

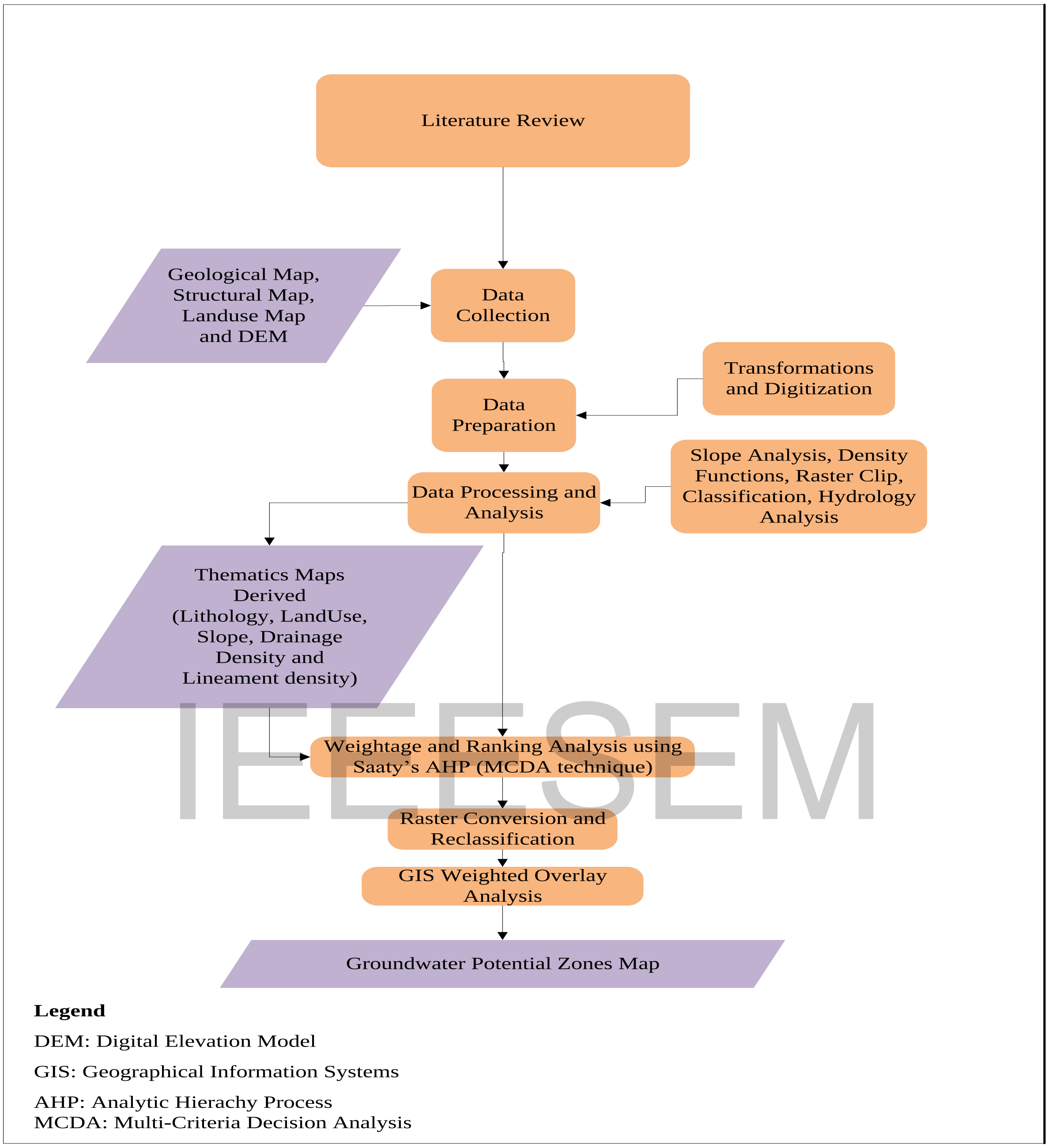

Figure 2: Research activity flow chart

2.2.1 Creation of thematic layers

The digitization process was employed to generate three thematic layers of lithology, lineaments and land use/cover from the analogue geological, lineament and land use/cover maps. The drainage and slope maps were generated from ASTERGDEM data.

2.2.2 Groundwater potential zones

To generate groundwater potential zones, the following steps were involved: 1) Conversion of the generated thematic layers (i.e. lineament density, drainage density, slope, LULC and lithology) into the raster format (reclassification) and 2) the overlay analysis. Groundwater potential zones were obtained by the weighted overlay analysis method using spatial analysis tools. During weighted overlay analysis, a rank was given for each individual parameter of each thematic layer map, and weights were assigned according to the output of the MCDM (AHP) technique to that particular feature on the hydro-geological environment of the study area.

The relationship between the five thematic layers and their respective classes was derived using the MCDM by computing the relative importance of theme and its classes. Two main steps in computing the AHP method are:

Step 1: Construction of model on the basis of a literature review, many models has been identified for mapping groundwater potential zones. For the construction of a model, the problem should be clearly defined and then decomposed into various thematic layers containing the different features/classes of the individual thematic map to form a network of the model.

Step 2: Generation of pair-wise comparison matrices. The relative importance values are determined using Saaty’s 1–9 scale, where a score of 1 represents equal influence between the two thematic maps, and a score of 9 indicates the extreme influence of one thematic map compared to other one. In the current study the nine points of the Saaty’s scale values to each thematic map and their respective classes were assigned according to their importance of influence in groundwater potential (Saaty, 1980). The Saaty’s nine points values were obtained from interview and group discussion with groundwater experts who are working for Government of Tanzania, Panel of Dodoma Urban Water Supply and Sewage Authority (DUWASA), Groundwater experts of GST and Department of Geology, The University of Dodoma.

The AHP captures the idea of uncertainty in judgments through the principal eigen value and the consistency index (Saaty, 1977). Saaty gives a measure of consistency called the Consistency Index (CI) as a deviation or degree of consistency using the following Eq. (1):

$$\mathrm{CI} = \frac{(\lambda - \mathrm{N})}{(\mathrm{N} - 1)} \;\; . \; . \; . \; . \;\; (1)$$

Where λ is the largest eigen value of the pair-wise comparison matrix, and n is the number of classes or features. To control the consistency analysis and scale judgment, the Consistency

Ratio (CR) which is a measure of consistency pairwise comparison matrix is calculated by Eq. (2):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \;.\;.\;.\;.\;.\; (2)$$

Where RI is the Ratio Index. The value of RI for different n values is given, which in this research is equal to 1.12 (n = 5). If the value of the CR is less than or equal to 0.1, the inconsistency is acceptable, or if the consistency ratio CR is equal to 0.00, it means the judgment of the pair-wise comparison matrix is perfectly consistent. If the CR is greater than 0.1, we need to go back to the step pair-wise comparison matrix to rank the judgment value carefully with regard to the dominant factor that influences groundwater occurrences in the overall thematic layer map.

The relative weights obtained from AHP were assigned to each thematic map to generate a cumulative weight of the respective thematic maps and the weight value of each map with the highest or lowest weight was assigned in accordance with the real situation on the field. The summary of the assigned and normalized weights of the features/classes of the different thematic layers and the consistency ratio of its thematic map were also computed and assigned for respective thematic map. Then, the five different thematic maps were integrated as a summation of overall groundwater influencing factors to generate the groundwater potential map (GPM) for the study area.

3. Results and discussion

3.1 Drainage and drainage density maps

The drainage network was extracted from a digital elevation Model. The drainage network is more concentrated in the central and north-eastern parts of the study area (Figure 3a). The entire area is covered by undulating hilly tract intersected by gorges and passes. Besides the observed seasonal nalas, there were more than four perennial nalas in the region.

D**rainage density is a measure of how far the stream channels are separated from one another. Drainage density (Figure** 3b**) is calculated from drainage network layer using line density analysis tool in Arc GIS software. The drainage density of the study area was classified into five classes, namely; 'very high' (1.1-1.31km/km2) and 'high' (0**.98-1.1 km/km2) drainage densities were observed over the central parts and along the

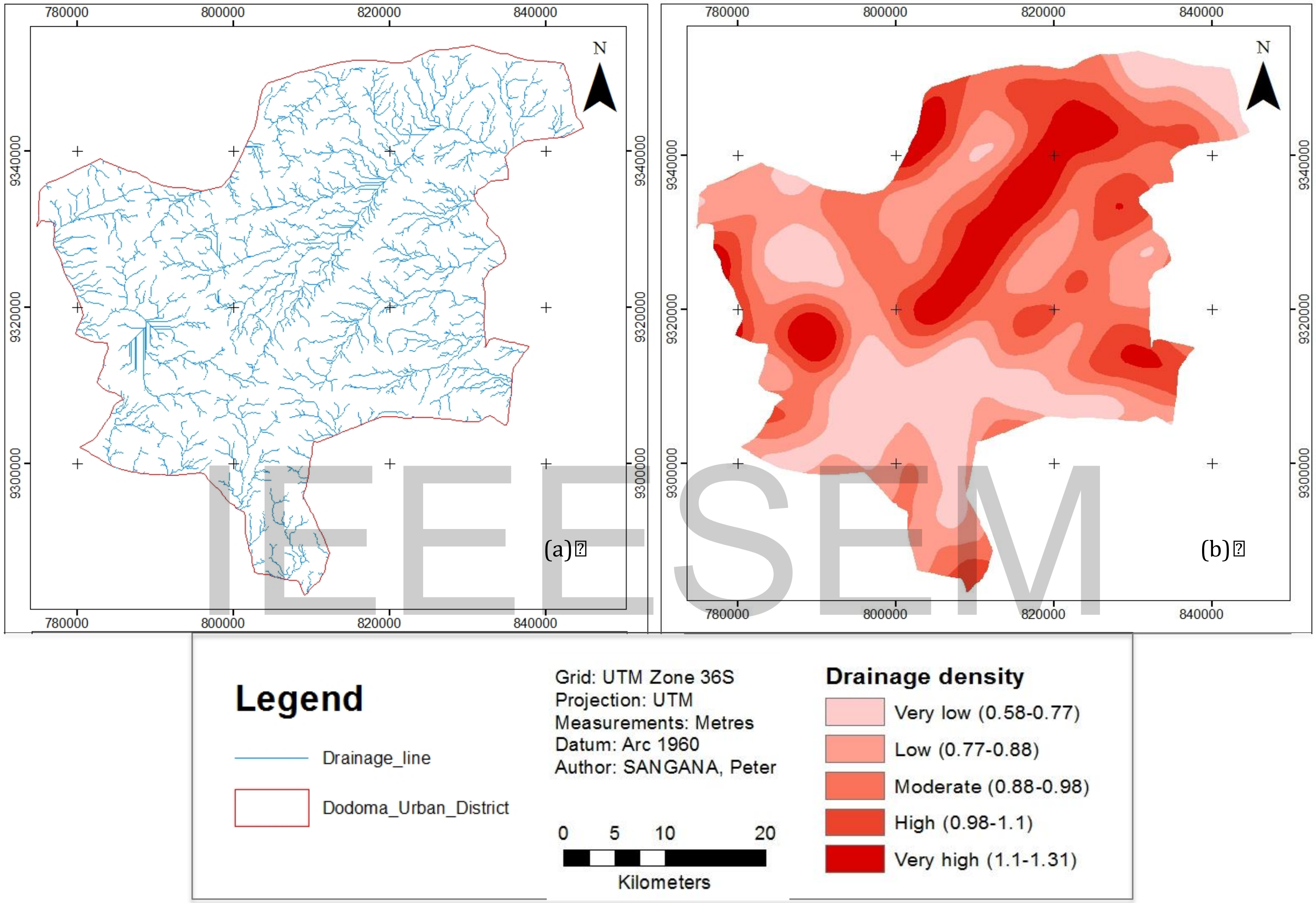

Figure 3: (a) Drainage network map**, (b)** Drainage density map

north-eastern direction, ‘moderate’ (0.88-0.98 km/km2) drainage density were observed over some central and north- eastern parts, the large area over the south and south-western parts is characterized by ‘low’ (0.77-0.88km/km2) and ‘very low’ (0.56-0.77) drainage densities (Figure 3b).

The area of very high drainage density represents more closeness of drainage channels and vice versa; hence, the higher the drainage density, the higher the runoff while the lesser the drainage density, the lower the run-off and the higher the probability of recharge or the higher is the potential for groundwater accumulation. Other studies show that permeability and drainage are closely related, such that permeable conditions are characterized by low drainage density, and vice versa (Machiwal et al, 2014). The estimated drainage density revealed moderately and low dense drainage network with values of 0.5 to greater than 1 km/km^2. Using Saaty’s AHP the drainage density classes were ranked and reclassified depending on their influence on groundwater availability. The high drainage density areas are ranked relatively lower with value of 3 compared with low drainage density areas that are ranked higher with value of 50 (Table 1).

3.2 Slope amount map

As an aspect of geomorphologic features, the slope is one of the key factors controlling the infiltration and recharge of groundwater system: thus the nature of the slope alongside other geomorphic features can provide an insight of the potential groundwater prospecting areas. In low slope areas the surface runoff is low allowing more time for infiltration of rainwater, while high slope areas enhances high runoff with short residence time for infiltration and recharge (Magesh et al., 2012).

The slope amount map as presented in Figure 4a was prepared from ASTERDEM data using the spatial analysis tool. Slope grid is identified as “the maximum rate of change in value from each cell to its neighbors”. Based on the slope, the study area can be divided into five classes. The areas having 0-2.2 slope are classified as the ‘very good’ category because of the nearly flat terrain and relatively high infiltration rate. The areas with 2-6 slopes are classified as ‘good’ categories. Such areas are characterized by slightly undulating topography allowing some rainwater runoff. The areas having a slope of 12-20 cause relatively high runoff and low infiltration, and hence are categorized as ‘poor’ while the areas having a slope > 20 are categorized as ‘very poor’ due to higher relatively higher slope and runoff.

Consequently, based on the influence of slope in rainwater infiltration and groundwater recharge, areas with less than 6% slope (i.e. nearly flat surfaces to very gentle slopes) which constitutes about 96 % of the study area considerably highly ranked in terms of groundwater potential with a rank factor of 49 compared with areas with slope greater than 18 % which were very lowly ranked with a rank factor of 3 (Table 1).

3.3 Lineament and lineament density maps

Lineaments are manifestation of linear features that can be identified directly on the rock units or from remote sensing data while lineaments and their intersections play a significant role in the occurrence and movement of groundwater resources (Rao & Jugran, 2003). The presence of lineaments may act as a conduit for groundwater movement which results in increased secondary porosity and, therefore, can serve as groundwater potential zone (Muralidhar, Raju, & Prasad, 2000). Figure 4b represents lineament map.

Lineament density map (Figure 4c) was generated and expressed in terms of length of the lineament per unit area (km/km2). In the study area, the lineament density was categorized into five classes as very high, high, moderate, low and very low density respectively as shown in Figure 4c. The lineament density polygons were dissolved into five classes based on the class ranks assigned as shown in Table 1 using pair-wise comparison methods and a reclassified GIS layer was prepared. The zone of low lineament density will have a poor groundwater potential as the lineament density gradually increases, the groundwater potential would also increase. Thus areas with higher lineament density are regarded as key potential sites for groundwater prospecting. Consequently, higher rank of 49 was assigned to area with high density of lineaments while a low rank of 3 was assigned to areas with low lineament density (Table 1).

3.4 Land use/cover map

Land use/land cover plays an important role in the occurrence and development of groundwater. Consequently, the identified land use/land cover classes include Agriculture land, Built-up areas, Water bodies, Nature preserve, Green belt and Open scrub/grass land (Figure 5a). Approximately 38 % of the total area is covered by built-up area, and 27 % of the area is covered by open scrub/grass land. Nature preserve represent 18% and 12 % of the area is covered by the green belt. Water bodies represent 3% and the remaining small part (2 %) represents agriculture land.

Different landuse/cover classes were ranked and reclassified based on the land-use type, area coverage, properties to infiltrate water and their characteristics to hold water on the ground surface. The water bodies were given the highest rank over other landuse features since its

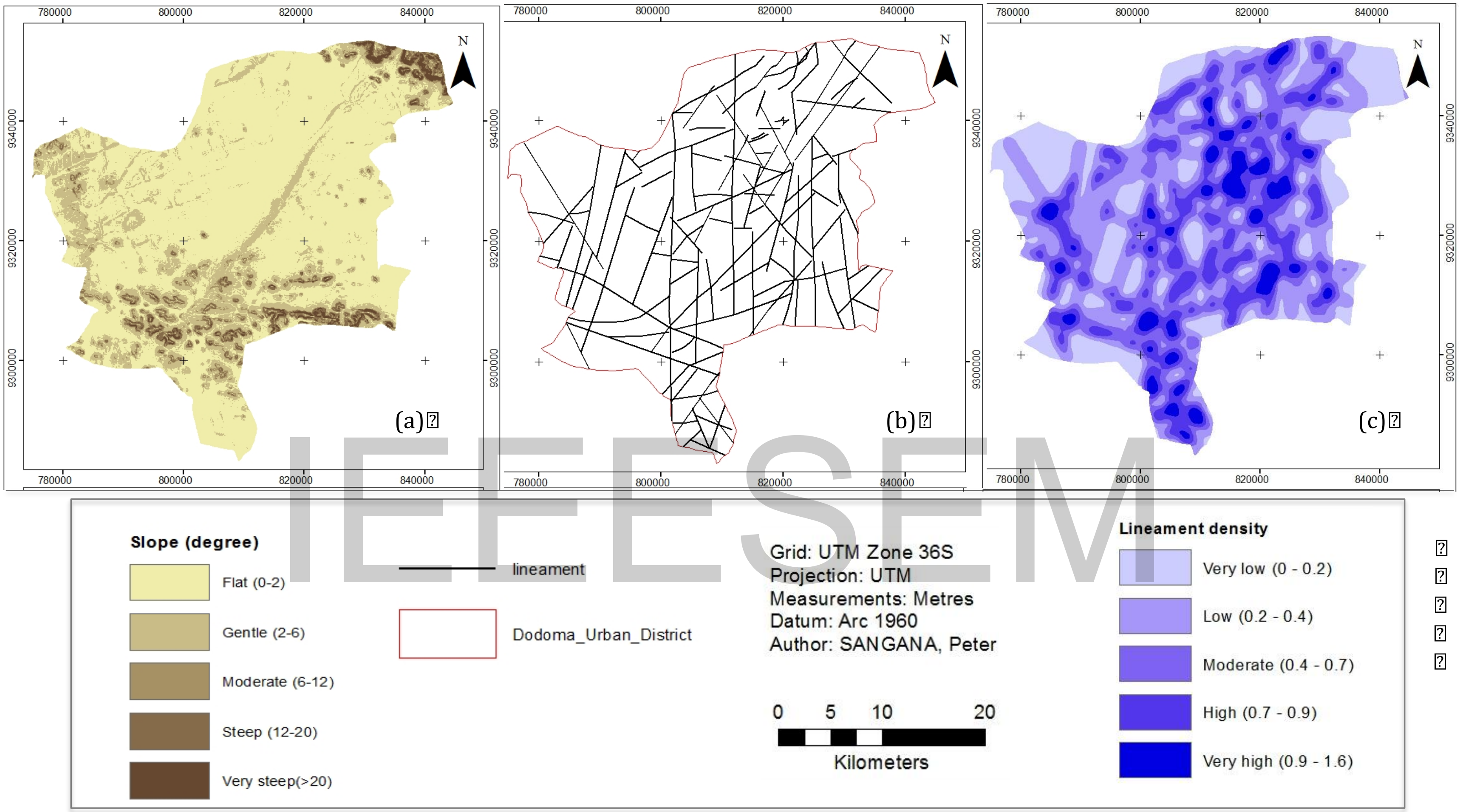

Figure 4: (a) Slope amount map**, (b)** Lineament map, and **(c)**Lineament density map

incessant recharge to ground, ensued by agriculture land only, which takes maximum amounts of water from the rain and irrigation, giving rise to water accumulation below the ground surface. The lowest rank was assigned at built-up areas as most of them lacked a vegetation cover. The various ranks of landuse/cover classes are presented in table 1.

3.5 Lithological map

Lithology is a very important aspect in predicting GWPZS. The GIS layer on lithology was studied with special reference to groundwater holding and conducting capacity of the individual lithology unit. The lithology of the study area is dominated by the Alluvium and mbuga soil, Hombolo Dam and Precambrian basement rock units consisting of igneous and metamorphic rock units, i.e. hornblende gneisses, granites, Amphibolite, Granodiorite, Tonalite and quartzites (Figure 5b).

The tonalite and granodiorite were widespread over the study area covering about 54 % and 13 %, respectively. Granites, amphibolites and quartzites were limited to the northern parts of the study area covering about 4 %, 0.07 % and 0.02%, respectively. Hornblende gneisses were limited to the southern parts of the study area covering about 7%. Alluvium and mbuga soil were limited to southern and some other parts of the study area covering about 21%. Hombolo dam unit is situated in the northern part covering 1% of the study area.

Usually, massive unfractured lithologic units has little influence on groundwater availability except in cases where there is secondary porosity through the development of weathered overburden and fractured bedrock units, which form GWPZS. Hence, on the basis of porosity, permeability and the presence and nature of the weathered regolith units and fracture systems, appropriate ranks were assigned to the lithological units in the study area. Hombolo dam was given the highest rank of 33 over other lithological units since its incessant recharge to ground. The lowest rank of 2 was given to quartizite. The various ranks of lithological units are presented in Table 1.

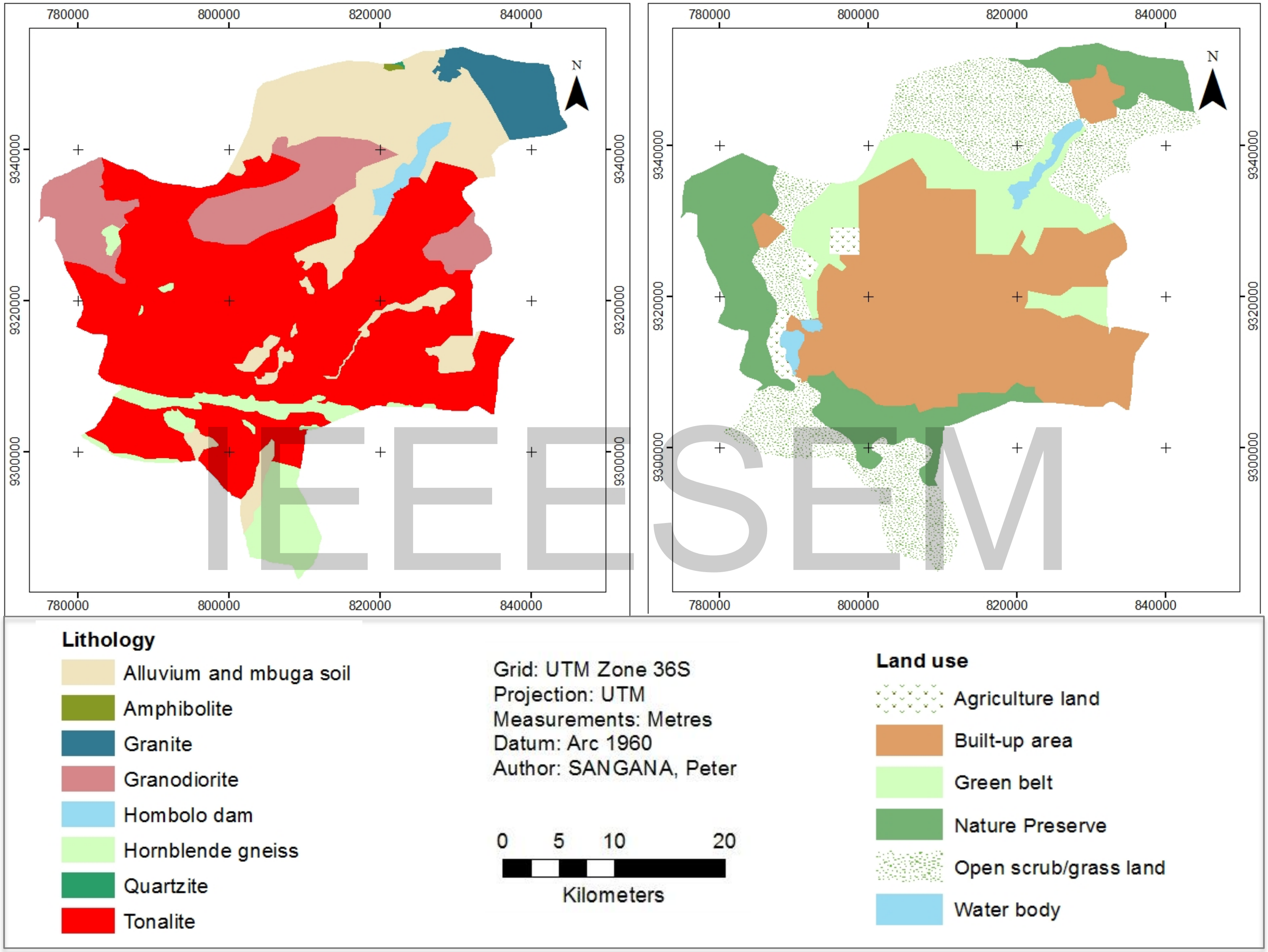

Figure 5: (a) Land use/cover map, (b) Lithological map

3.6 Groundwater potential zones map

All the thematic maps derived were integrated and final groundwater potential map was generated (Figure 6). The GWPZS were grouped into five different potential zones viz; very good, good, moderate, poor and very poor. Theme weight and class rank generated using AHP techniques, assigned to the different parameters considered for groundwater prospects evaluation in this study are given in Table 1.

Table 1: Weights and ranks of different thematic maps used for groundwater prospect calculated using Saaty' AHP

Thematic map	Class	Rank	Weight/Influence (%)
Lithology	Hombolo dam	33	42
	Alluvium and mbuga soil	23	
	Hornblende gneiss	16	
	Amphibolite	11	
	Tonalite	8	
	Granodiorite	5	
	Granite	3	
	Quartzite	2	
Lineament density	Very high	49	26
	High	27	
	Moderate	14	
	Low	7	
	Very low	3	
Drainage density	Very low	50	16
	Low	26	
	Moderate	13	
	High	7	
	Very high	3	
Slope	Flat	49	10
	Gentle	27	
	Moderate	14	
	Steep	7	
	Very steep	3	
Land use/cover	Water bodies	40	6
	Agriculture land	25	
	Open scrub/grass land	18	
	Nature preserve	10	
	Green belt	6	
	Built-up areas	3	

Analysis of the potential zones shows that the very good GWPZS constitute just less than 3 % of the study area. Few patches of this zone were observed at areas associated with Hombolo dam unit along the north-eastern parts of the study area. Good GWPZS are seen at the south, north, and west and towards the north-eastern parts and constitute 8 % of the study area. This zone is associated with low drainage density and alluvium and mbuga soil with high lineament density in the southern and northern parts of the map. Moderate GWPZ occupy about 28 % of the total study area, scattered all over the map. The poor and very poor potential zone constitute the largest area of about 62% of the study area and are mostly seen along denudational hills with steep slope, built-up areas and high drainage density.

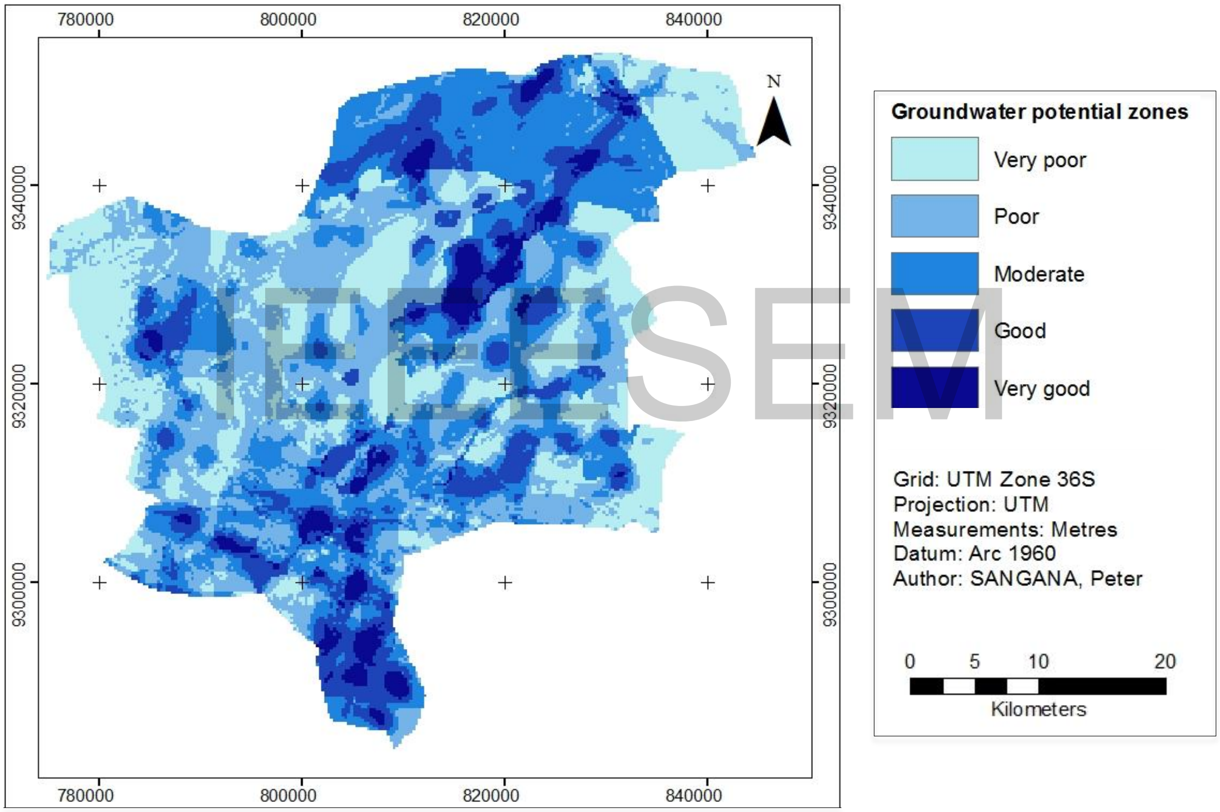

Figure 6: Groundwater potential zones map

4. Conclusion

The five key factors influencing groundwater recharge, namely; lineament density, drainage density, slope, land use/cover and lithology were generated using a GIS-based MCDA technique for delineation of GWPZS. Further work to combine the five thematic layers generated from different sources, multi-criteria evaluation was performed using Saaty's 9 point continuous scale for assigning of thematic layers weights and ranks for individual thematic layers classes. The nine points of the Saaty's scale values for each layer and layer classes were assigned on the basis of importance in groundwater availability. The weight and class ranks of each thematic layer were established using the pair-wise comparison method. The five thematic layers were rasterised and then reclassified based on the established rank values using raster conversion and reclassify tools. Then the percentage weights/influence of each of the five thematic layers on groundwater availability was established.

WLC method for MCDM analysis was used to combine the five thematic layers and identify the GWPZS of the study area. The WLC decision rule requires that the reclassified thematic layers and their respective weights/influence be used as input values to determine the GWPZS. The multi-criteria evaluation using WLC decision rule was performed using the weighted overlay tool. Each location in Dodoma City was presented as either 'very poor', 'poor', 'moderate', 'good' or 'very good' GWPZS. Moreover, most of the moderate, good and very good GWPZ were located around Hombolo Dam unit.

The resulting groundwater potential zones map was classified into 5 classes, namely; very good, good, moderate, poor and very poor. The analysis reveals that out of 2577 km^2 total investigated area, around 49.6 km2 is identified as a very good potential zone for groundwater occurrences and mostly cover areas around Hombolo Dam located along the north-eastern part of the District, which constitute only 3 % of the study area. About 209 km^2 of the District was identified as a high potential zone which covers 8 % of the area, while around 711.9 km^2 of the area was identified as a moderate potential zone constituting 28% of the area. The remaining larger areas of 1592.6 km2 cover 62 % is identified as poor and very poor groundwater potential zones and are mostly confined in built-up areas and hilly terrain. The poor zone was indicating the least favorable area for groundwater prospect; whereas very good zone indicates the most favorable area for groundwater prospect.

This study provides the baseline information to local District authorities and planners about the potential sites for groundwater prospecting and exploration. The results can also be used to layout strategies for protecting the groundwater wells from contamination resulting from domestic and industrial activities. It can be considered as a time and cost-effective tool for delineations and identification of high groundwater potential target area.

5. Acknowledgement

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6. Authors contribution

PS, DD and JC contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. DD and JC supervised the research. All authors discussed the results and contributed to the final manuscript.

7. Conflicts of Interest

The authors declare no conflict of interest.

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