Tanzania Journal of Science 48(4): 962-972, 2022
ISSN 0856-1761, e-ISSN 2507-7961

Spatial Analysis of Groundwater Potential: A firsthand Approach towards Groundwater Development in Moroto District, Uganda

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Received 17 Oct 2022, Revised 30 Dec 2022, Accepted 31 Dec 2022, Published Dec 2022
DOI: https://dx.doi.org/10.4314/tjs.v48i4.21

Abstract

Groundwater is a vital resource that helps mankind and development. However, in Moroto District challenges of groundwater development has increased arising from changes in rainfall patterns coupled with high abstraction from population increase. In this study, the spatial variability of groundwater potential was assessed to develop a tool that will aid decision on groundwater potential sites selection for groundwater development/exploration. The study utilized an integrated technique and tools such as Remote Sensing (RS), Geographic Information System (GIS) and Multi Criteria Decision Analysis (MCDA) in analysis and delineation of potential areas for successful groundwater development. The generated map through weighted overlay of thematic layers (slope, soil, lithology, rainfall, land use and land cover) produced five categories of potential zones indicating 90% (i.e., 35% very high, 40% high and 15% moderate) of the study area to be suitable for groundwater development and only 10% (i.e., 2% poor and 8% very poor) exists as poor groundwater potential zones. Maps produced from this study can hence be used to identify appropriate sites for groundwater development, and therefore minimizing unsuccessful boreholes development.

Keywords*:* GIS; Groundwater Development; Groundwater Potential; MCDA; Spatial Analysis.

Introduction

Globally, groundwater is a vital resource that is affected by a number of factors resulting into groundwater variability. Among many factors affecting groundwater variability, climate change and human actions are listed to have significant influence (Li et al. 2014). For instance, climate change has led to increase in global atmospheric temperatures and resulted into transformation of precipitation patterns, which may have a direct effect on groundwater levels. Also human actions have caused changes to groundwater by modifying land use and land cover which result into decrease in groundwater recharge. Increased transformation of land cover can seriously affect infiltration and other hydrological processes which may lead to variations in the groundwater system (Mishra and Kumar 2016). Moreover, the study by Kumar et al. (2016) has shown that groundwater systems have undergone variations owing to human actions, including groundwater abstraction and reservoir construction. In Sub-Sahara Africa, high population growth have escalated demand for water which has resulted into over exploitation of groundwater (NASAC 2014). The dynamic nature of socio-economic activities such as agriculture, settlements and increased trends in irrigation technology have been well-known worldwide as common parameters triggering groundwater variability. Potential over-exploitation of groundwater for agricultural purpose was identified as one of the key water related climate change vulnerabilities in Uganda (Ministry of Water and Environment 2017).

In spite of Uganda's massive water resources, their spatial variability often makes many parts of the country water stressed over long periods of the year (Ministry of Water and Environment 2017, Nsubuga et al. 2014). The water resource management sub-sector development study of 2004 demonstrated that, districts in the northern-east where Moroto District is located and south-western parts of the country have the least per capita water accessibility. The study additionally uncovered that by 2015 over 75% of the country is water stressed. It is also estimated that groundwater withdraw will increase up to 15% by 2030 making groundwater development an important activity in Uganda (Katusiime and Schütt 2020). Moreover, occurrence of groundwater in Moroto District, is extremely uncertain (Fels Consultants Ltd 2012) with no proper ways of identify potential zones for groundwater occurrence which may result into unsuccessful developments. Thus, it is essential to provide a clear insight of spatial existence of groundwater potential in the study area for sustainable management of groundwater resource. The spatial distribution of groundwater potential zones is significant in an identification of appropriate sites for groundwater prospecting and therefore minimizing unsuccessful boreholes development.

Key factors that influence groundwater potential

Different hydrogeological factors, such as geomorphology, geology, land use/land cover, slope, soil cover, drainage density and surface temperature, have been reported to control groundwater potential of any areas. However, the extent to which they affect may differ spatially and temporally (Gates et al. 2014, Senthilkumar et al. 2015, Yeh et al. 2016). Thus, it is important to consider these factors with inputs from different scientific experts and field observations. Senthilkumar et al. (2015) indicated that, lithology is one of the key factors governing groundwater movements in that the geological structures such as fractures and lineaments work as barriers as well as transporters for groundwater movements. However, slope has become one of the key factors to be considered as it has a strong influence on groundwater infiltration. The rate of infiltration as well as surface run off are basically influenced by slope (Singh et al. 2013). Therefore, a sharp slope generates little recharge due to the fact that water resulting from rain moves quicker and has little time intended for infiltration, while a gentle slope provides sufficient time for infiltration of water to the subsurface.

In the understanding of Yeh et al.(2016), alterations in land use and vegetation cover which reflect human activities have side effects upon groundwater flow. Within Moroto District, human activities for example agriculture, infrastructure development, deforestation along with settlements, possess distinct effects connected with transforming the land use cover. Meanwhile, soil type (sand, silt, clay and gravel) are known to influence the retention rate of water and control the percolation and permeability of water into the subsurface (Mockus et al. 2007, Boschetti et al. 2014).

Rainfall is the only source to groundwater, and therefore it is important on groundwater sustainability. According to Thomas et al. (2016), in semi-arid regions, infiltration of water into the subsurface normally happens during extreme occasions of rainfall and controlled by extreme potential evapotranspiration (Jasechko and Taylor 2015). Additionally, a study in the moist tropics of Uganda demonstrated that inability to think about anticipated changes in precipitation forces can impact on extent of the climate alteration indications for groundwater (Owor et al. 2009).

Materials and Methods

Materials

Description of the study area

Moroto District is situated in the north eastern part of Uganda on latitude 1°53´ N, 33°56´ E and longitude 3°05' N, 34°56' E at an altitude between 1356 m to 1524 m above sea level. It is composed of four sub counties; Nadunget, Katikekile, Rupa and Tapac; making a total land area of approximately 3,532.92 km^2 (Figure 1). There are two distinct seasons: wet and dry. January and February are the hottest months with temperatures higher above 30 °C, while October to December are the coolest with temperatures ranging between 15 °C and 17 °C. The area experiences low humidity during drought at an average of 46% in the afternoon hours and sharp values in the morning hours at relative humidity of 63% (Moroto District Local Government 2013). The climate is largely tropical with two rainy seasons per year, March to May and September to December. Furthermore, Moroto District is predominantly agropastoral community and highly dependent on groundwater resources for domestic uses, watering of livestock and agriculture (Ferreri et al. 2011). The water supply coverage varies across the district between 31.2% in Nadunget to 100% in Moroto Municipality (Ministry of Water and Environment 2017).

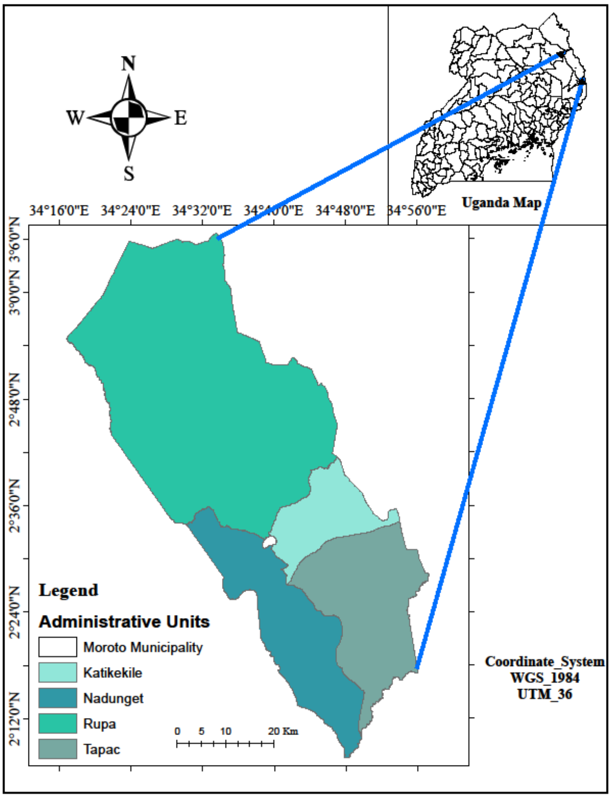

Figure 1: Description of the study area.

Data sources and acquisition

In this study, remote sensing data such ASTER global (DEM), soil, lithology, land use and land cover are considered in the analysis of groundwater potential area zones (Table 1). Moreover, the secondary data like rainfall data were obtained from Uganda Meteorological Service data center for the period of 25 years. Studies such Fenta et al. (2015) adopted the above kinds of data for their analysis and yielded significant results. The digital elevation model (ASTER-DEM) and land use cover were better surfaces for classification of information on factors affecting groundwater recharge (Fenta et al. 2015).

Table 1: Remote sensed data and their specifications

Data	Specifications	Source
ASTER	DEM (land surface slope) 30 m resolution	NASA
FAO-HWSD	Soil, 30 arc seconds	FAO
Landsat 8 image	Land use, land cover 1:100.000	USGS Landsat Global Archive
ASTER	Lithology 1:250.000	NASA

Methods

Multi criteria decision analysis for developing groundwater potential map

According to Saaty (2008), an analytical hierarchy process permits determination of weights according to the contribution of the factor under consideration over the others. The factors considered in this study were lithology, soil, slope, rainfall, land use and land cover. Figure 2 shows the flow chart illustrating the process in development of groundwater potential map based on Yeh et al. (2016) and Saaty (2008).

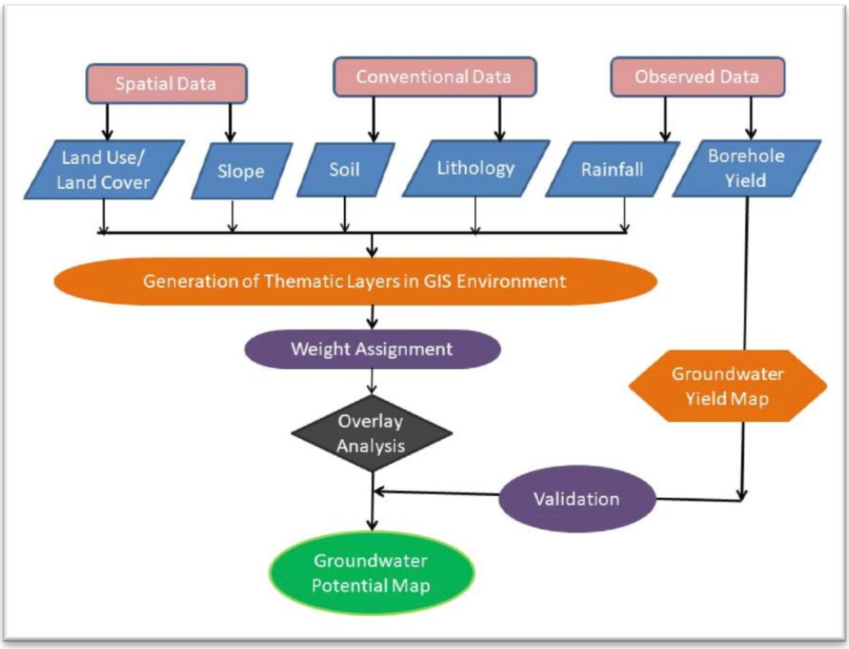

Figure 2: Flow chart for generating groundwater potential map.

Generation of groundwater potential map

Five different thematic layers were integrated with weighted overlay in GIS to generate groundwater potential zonation map. Each thematic map was assigned a weight to the factors based on their influence on groundwater potential (Raviraj et al. 2017). Higher weights were assigned to factors that influence variability for both storage and movement of groundwater. The sum of all weights adds up to 100%. The weights for respective thematic maps were calculated based on weight normalization using the principal component analysis followed by pairwise comparison matrix using Saaty's analytical hierarchy process (Saaty 2008). Different features of each theme were assigned rank on a scale of 0 to 9 according to their relative influence on the groundwater potential. Based on this scale, a qualitative evaluation of different features of a given theme was performed with very poor (weight 0–1.5); poor (weight 1.5–3.0); moderate (weight 3.0–4.5); good (weight 4.5–6.0); very good (weight 0–7.5); and excellent (weight 7.5–9). The weight and rank of each thematic layer are given in Table 2. To differentiate groundwater potential zone, scored maps of all the five thematic layers after assigning weights were integrated (overlaid) step by step using spatial analyst tool of ArcGIS. The total weights of different polygons (zones) in the integrated layer were derived from Equation 1 to obtain groundwater potential (Yeh et al. 2016):

$$\mathrm{GP} = \sum_{i=1}^{n} \mathrm{W_i C_i} \quad (1)$$

where: W_i is weight of factor; C_i is scale considered; n is total number of factors under consideration (i.e., for factors i = 1, 2, 3, …n); GP is a total groundwater potential weighed score. The resultant map was classified into very high, high, moderate, poor and very poor zones. The results were validated using observed groundwater levels field data. Hydraulic heads map was generated by the inverse distance weighting method. Flow chart for the methodology adopted in this work is shown in Figure 2.

Table 2: Assignments of weights on factors that influence groundwater potential

Parameters	Scale	Groundwater potential	Percentage of influence (%)
Lithology			
Metamorphic rock	7	Poor	25
Sedimentary rock	1	Good	
Soil			
Sand	1	Very good	25
Sandy clay	3	Moderate	
Sandy loam	1	Very good	
Clay loam	7	Poor	
Clay light	3	Moderate	
Land surface slope			
Below 7%	1	Nearly flat	15
7–15%	2	Moderate	
15–27%	7	Steep	
> 27%	9	Very Steep	
Land use and land cover			
Natural forest	1	Very good	25
Bush land	1	Good	
Grass land	2	Moderate	
Wood land	3	Poor	
Agriculture	7	Very poor	
Settlements	9	Very poor	
Rainfall			
435 mm	7	Very poor	10
568 mm	3	Moderate	
628 mm	2	Good	
681 mm	1	Very good	
730 mm	1	Very good	

Results and Discussion

Factors that influence groundwater potential

Land surface slope

Figure 3 shows the landscape derived from the digital elevation model indicating variations of degrees of slopes across the study area. The slope is estimated in degrees as proposed by Monkhouse and Wilkinson (1964), and the arrangement is dependent on topography of the landscape. As observed on Figure 3, areas under the slope below 7° were categorized as high potential areas since it is nearly flat and allows more infiltration of water into the subsurface. Moreover, the areas under slopes between 7°–15° fall in moderate groundwater potential since they possess a mild rise in landscape and moderate runoff. In addition, the areas under slopes of 15°–27° have similar high runoff and low infiltration subsequently and fall in the low groundwater potential zone. Lastly, the areas with slopes of more than 27° are very steep with exceptionally high runoff and low infiltration, therefore deemed as very low groundwater potential zones. The inclination of landscape governs the surface runoff thereby leading to low or high infiltration of water into the ground.

Land use and land cover

Land use and land cover (LULC) play vital roles in groundwater potential. They control hydrogeological processes such infiltration, surface runoff and evapotranspiration (Yeh et al. 2016). Landsat images were processed using ENVI 5.2 Software to study information on the types of land uses and their spatial patterns. Figure 4 illustrates that, the land uses in the study area are classified into six groups such as agriculture (14%) that influence groundwater potential by modification of the soil which may have effects on groundwater recharge. Other groups are grassland contributing 3%, woodland 49% and natural forests 20% which reduce the surface flow and increase the infiltration of water into the sub surface hence, recharging the groundwater. Additionally, 8% of the land is bare land, while 6% is used for settlements that have effects on groundwater by creating impervious surfaces through infrastructure development, hence reducing infiltration of water into the ground.

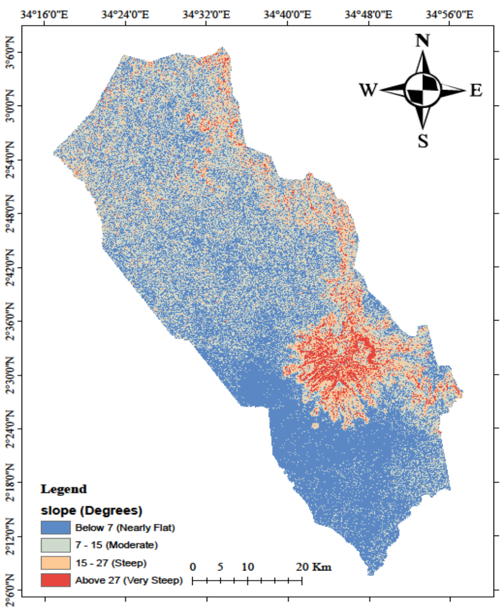

Figure 3: Slope map of the study area.

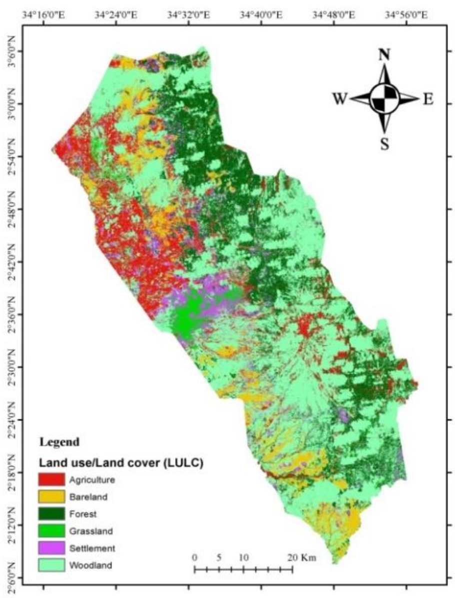

Figure 4: LULC clasification map of the study area.

Soil type

Figure 5 shows the classification of soil as sand, sandy loam, sand clay loam, clay loam and clay light. Soil type in an area has effects on groundwater potential as it controls the percolation and permeability of water into the subsurface (Mockus et al. 2007). The type of soils, were categorized according to their effects on groundwater based on Hydrological Soil Classification Group (Mockus et al. 2007). Sandy loam and sand fall under group A which has high infiltration rate of water into the subsurface with low runoff, thus high groundwater recharge. Clay Light and sandy clay loam are in group B in which infiltration is unobstructed and has modest runoff, hence slight recharge for groundwater. Finally clay loam falls under group C in which water transmission into the soil is limited due to high runoff of water at the surface hence classified as low groundwater potential. Figure 5 represents various types of soils that exist and control the infiltration of water into the subsurface, hence groundwater recharge in Moroto District.

Lithology

Lithology is one of the key factors governing groundwater movements in that the geological structures such as fractures and lineaments work as barriers as well as transporters for groundwater movements (Senthilkumar et al. 2015). Figure 6 clearly shows that, the study area is predominantly occupied by three types of rocks which are metamorphic rocks that comprise of aquifuges, sedimentary rocks and volcanic rocks. The three categories of rocks were classified according to their effects on groundwater flow and the distributions were as follows: Sedimentary rocks 20.47%, volcanic rocks 21.65% and metamorphic rocks 57.88%. Since metamorphic rock is a poor groundwater conductor, it can be classified as low groundwater potential as opposed to sedimentary rock which is a better conductor for groundwater flow.

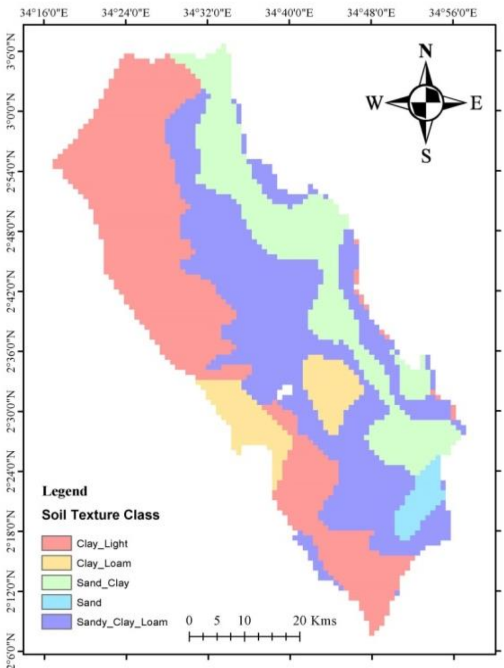

Figure 5: Spatial variations of soil texture of the study area.

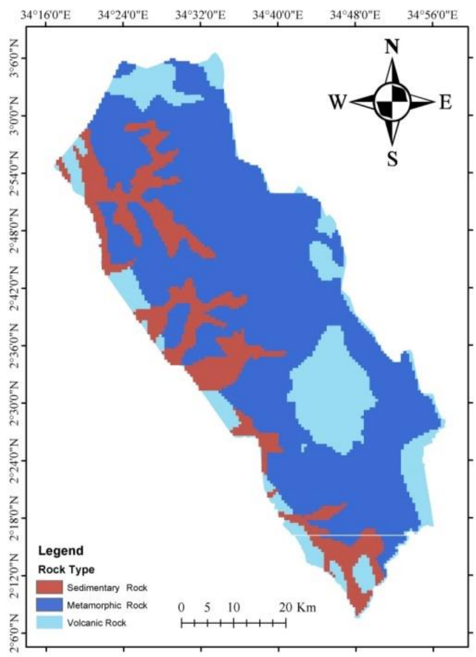

Figure 6: Lithology map of the study area.

Rainfall

Rainfall is a standout amongst the most critical sources of groundwater recharge through infiltration into the subsurface. As observed in Figure 7, the average annual rainfall is clustered into five classes. To be specific, 435–499 mm very low, 499–568 mm low, 568–628 mm moderate, 628–681 mm high and 681–730 mm very high. However, rainfall distribution alongside the surface slope influence the infiltration rate of surface runoff hence increase in the likelihood of groundwater potential zones. It is apparent that, variations in groundwater potential are due to changes in hydrogeological patterns.

Prediction of groundwater potential

Figure 8 illustrates the groundwater potential map which was generated by integration of thematic layers using the weighted overlay in Geographic Information System. It was observed that, 75% of the study area (35% and 40%) fall in the zone of high and very high groundwater potential and 15% in the modest groundwater potential, while 10% (8% and 2%) fall in low and really low groundwater potential zones, respectively. Naturally, 90% (35%, 40% and 15%) of the area under study has the potential for groundwater development, while 10% of the area exists as poor zones for groundwater development. Table 3 shows the percentage coverage for potential zones and borehole distribution.

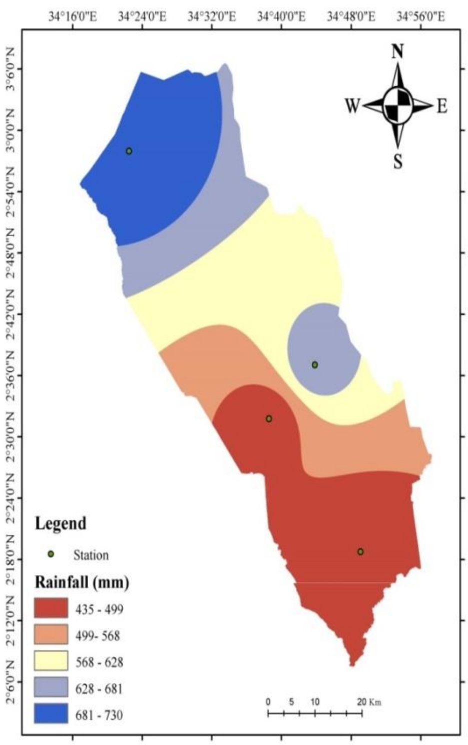

Figure 7: Rainfall distribution map of the study area.

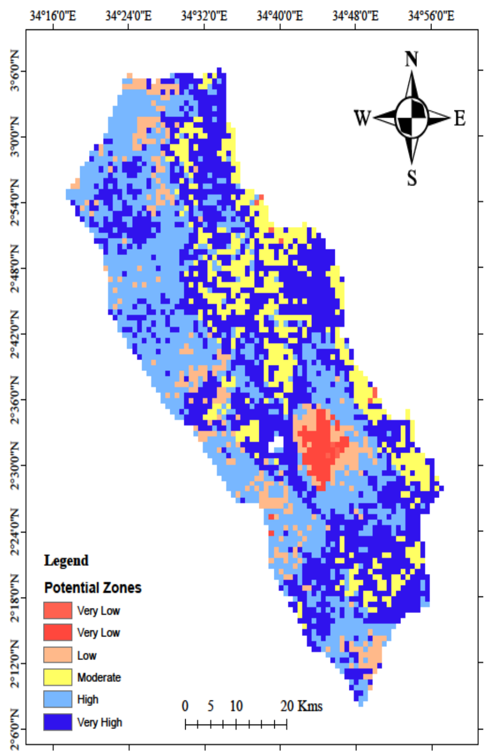

Figure 8: Map representing groundwater potential zones.

Table 3: Area per groundwater potential zone

Groundwater potential zone	Area covered (%)	Boreholes distribution (%)
Very high	35	29.63
High	40	44.44
Moderate	15	10.58
Low	8	12.7
Very Low	2	2.65
Total	**100**	**100**

Validations of groundwater potential map

To validate the generated groundwater potential map, field data of 189 sampled boreholes pumping yields were superimposed and consequently, there was excellent correlation with the generated potential map (Figure 9). The results of the validation showed that, there was a correlation between the groundwater potential zones generated and the field data boreholes pumping yields as shown in Figure 5. It was further observed that most of the area with low borehole yield lie into the poor groundwater potential zones. Boreholes location data (Figure 9) superimposed on groundwater potential map identify their distribution and it showed boreholes concentration on area with groundwater prosperity (Table 3). The area around the alluvial plain, gentle topography and good vegetation cover had good groundwater prospects, while areas with high slopes and low lineaments were poor to very poor in groundwater prospects.

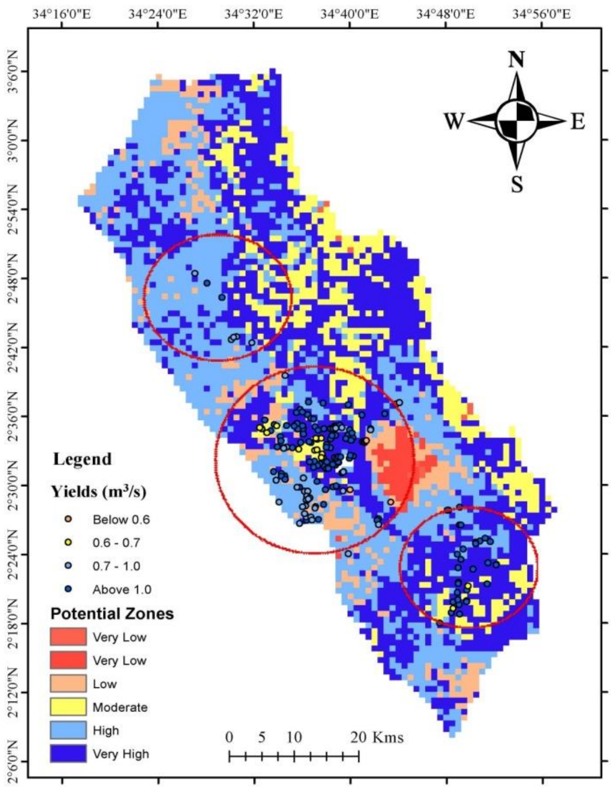

Figure 9: Map of groundwater potential zones and borehole yields.

Conclusion

An integrated use of remote sensing and GIS for determination of groundwater potential has demonstrated to be an efficient first-hand tool toward successful groundwater development. Five different thematic layers, namely, lithology, soil type, slope, land use/land cover and rainfall were prepared using satellite imageries, topographic maps, and secondary data set. Thematic layers were weighted using analytical hierarchy process and integrated with weighted overlay in GIS to generate groundwater potential map for Moroto District area of study. The results showed that the study area can be divided into five groundwater potential zones, such as very high (35% of the area), high (40% of the area), moderate (15% of the area), poor (8% of the area), and very poor (2% of the area). The findings of this study revealed the best areas of high groundwater potential are concentrated in the north-eastern and south-eastern sides of the study area due to their gentle slope nature with sand-clay soil type and dense forest land which favour infiltration. The gentle landscape has high infiltration of water into the ground, while natural forest minimizes the surface runoff and allows groundwater recharge. Though the soils type and rock compositions are the ones governing the flow and storage of groundwater, rainfall distribution chiefly accounts for the recharge in the area. Therefore, it can be concluded that 90% (i.e., 35% very high, 40% high and 15% moderate) of the study area is suitable for groundwater development, while the remaining 10% of the area is unsuitable. Moreover, the findings of the study provided a guideline and insights on suitable areas for groundwater exploitation and development in the study area. Furthermore, it should be realized that in the Moroto area where information/data on groundwater is scarce, the generated groundwater potential map will provide a good tool for quick identification of suitable sites for groundwater development that may lead to cost effectiveness and an increase in water supply.

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