Integration of Geology, Remote Sensing and Geographic Information System in Assessing Groundwater Potential of Paiko Sheet 185 North-Central Nigeria

INTEGRATION OF GEOLOGY, REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM IN ASSESSING GROUNDWATER POTENTIAL OF PAIKO SHEET 185 NORTH-CENTRAL NIGERIA

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An integrated geologic, Remote Sensing (RS) and Geographic Information System (GIS) techniques have been adopted to assess the groundwater potential of Paiko Sheet 185 North-Central Nigeria in order to reduce failure of developing groundwater resources by delineating prospective aquifer zones from poor aquiferous zones. The study area, which is about 3025 km^2, is dominated by crystalline basement rocks comprising of migmatites, granites, amphibolites and schists. Sandstones and alluvial deposits are also present. Digitally enhanced colour composites and band 5 Landsat ETM+ were used to produce thematic maps of lineaments and land use/cover. Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was utilized to map geomorphology and topographic parameters such as slope and drainage systems. Five thematic maps were produced which included land use/ land cover, drainage density, slope, lithology and lineament density. These were integrated and analysed using ArcGIS 10.0 software. All the thematic layers were then assigned weights according to their relative importance in groundwater occurrence and the corresponding normalized weights were obtained based on the Saaty's analytical hierarchy process (AHP). GIS modeling technique employing the weighted overlay method was used to produce groundwater potential map. Four groundwater potential zones were identified namely: "very good", "good", "moderate" and "poor". The spatial distribution of groundwater zones show regional patterns related to lithology, lineaments, drainage systems and landforms. Very high and high potential zones correspond to areas composed of alluvial deposits, sedimentary rocks and high lineament densities. Moderate zones fall on areas within the channel plains, while the low potential zones fall around fresh rock exposures, ridges and peaks which contribute to high run-off. This study has shown that integrating remote sensing and GIS with a sound knowledge of geology is very effective in assessing groundwater potentials on regional scale.

Keywords: *Groundwater Potential, Remote Sensing, Geographic Information System, Analytical Hierarchy Process*

INTRODUCTION

Water forms an integral part of our lives. Groundwater is even a more important natural resource as it is the only source of fresh water available to man that is yet to be negatively impacted by the activities of man. The expenditure and labour incurred in developing surface water is much more compared to groundwater, hence more emphasis is placed on the utilization of groundwater which can be developed within a short time.

Worldwide, one-third of the global population heavily relies on groundwater for domestic, agricultural and industrial use (Kemper, 2004). For this reason, it has become necessary to ensure that there are significant quantities available.

Remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within short time has become an essential tool in the assessment of groundwater resources (Hoffmann and Sander, 2007). Satellite data has been used to provide important information on the parameters controlling the occurrence and movement of groundwater like geology, lithology/structural, geomorphology, soils, land use/cover and lineaments (Khairul *et. al.,* 2000). However, these parameters have infrequently been studied together because of paucity of relevant data, integrating tools and modelling techniques. Hence, a systematic study of these factors leads to better delineation of prospective zones in any area which is then followed up on the ground through detailed hydrogeological and geophysical investigations, thus reducing the odds of failed exploration and development of this natural resource.

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The study of lineaments has been applied successfully to structural geology studies and their applications to water resource investigations and groundwater studies (Lattman and Parizek, 1964; Mabee *et al*., 1994; Magowe and Carr, 1999; Fernandes and Rudolph, 2001; Hung *et al*., 2003). Lineaments are rectilinear or slightly curvilinear mappable surface linear features that differ distinctly from the patterns of adjacent features and presumably reflect a subsurface phenomenon (O'Leary *et al*., 1976). They are emphasised as structural features on the surface and as geomorphological features such as topography, drainage, and vegetation.

Studies of existing productive wells in relation to lithology and structures are almost completely absent. Selection of well sites for groundwater supply heavily relies on traditional techniques using responses from electrical resistivity surveys as guidelines (Ejepu and Olasehinde, 2014). In general, a systematic approach to groundwater exploration is lacking.
The aim of this study therefore, is to contribute towards systematic groundwater exploration studies utilizing integration of geologic mapping, Multi-Criteria Decision Analysis (MCDA), Remote Sensing (RS) and Geographic Information Systems (GIS) in the assessment of groundwater resources, demonstrated in the Paiko Sheet 185 of north-central Nigeria.

STUDY AREA DESCRIPTION

The area of study lies between latitudes 9°00′N and 9°30′N and longitudes 6°30′E and 7°00′E covering Paiko Sheet 185. It stands at an elevation of between 100 m and 600 m above sea level. River Gurara is the major river that drains the study area with its tributaries (Figure 1). These include rivers Gudna, Jedna Jednadalaso, Kudan and Jatau. The area falls within the guinea savannah vegetation. There are two seasons associated with the climate. These include the rainy and dry seasons. The total annual rainfall in this area is between 1270 mm and 1524 mm, spread over the month of April to October. The maximum daytime temperature is about 35^0C in the months of March and April, while a minimum temperature of about 24^0C is recorded in the months of December and January. The mean annual temperatures are between 32^0C to 33^0C (Njeze, 2011). It should however be noted that the above climatic conditions stated are subject to changes. The dry season is marked by influence of harmattan which is a result of North- East trade wind that blows across the Sahara and that is often laden with red dust and lasts from the month of December to the month of February.
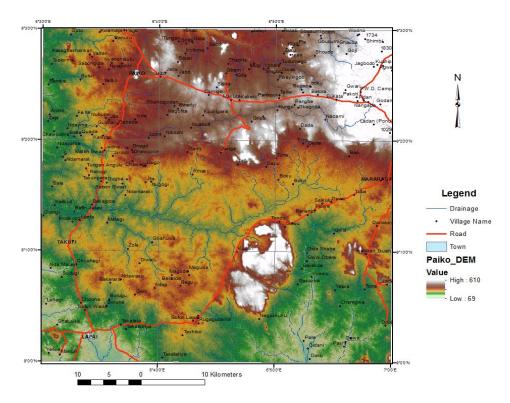

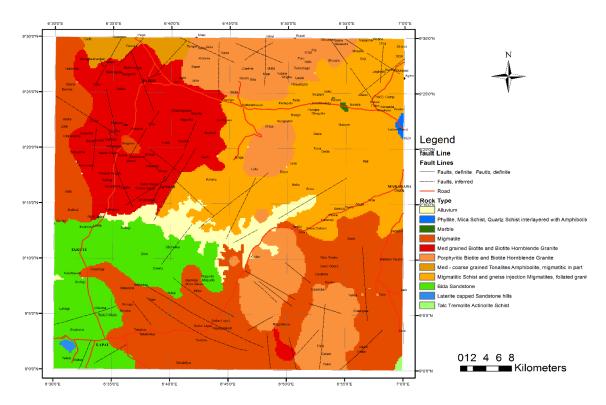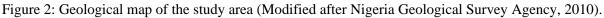Figure 1: Topographic map of the study area (Modified after OSGF, 2010)

The study area (Figure 2) is underlain by Precambrian rocks of the Nigerian Basement Complex, which cover about 85% of the land surface and sedimentary rocks which cover about 15% of the territory in the south-western part. The alluvial deposits of gravel, coarse and fine sand, silt and clay is found in the central portion. The Older Granites series outcrop as isolated hills, inselbergs and low whalebacks. They range in size from plutons to batholiths. The form of the bodies appears to be related to the environment in which the granite is emplaced. Circular to elliptical bodies occur in schist environment and more elongated bodies in migmatite-gneiss terrains. Contacts with pegmatites and gneiss, where exposed, are commonly sharp and contact metamorphosed (McCurry and Wright, 1977). The Older Granites lithologies consist mainly of coarse porphyritic granodiorite, tonalite, or granite. They show evidences of ancient tectonic activity in the form of major and minor faults, joints, fracture etc. The Older Granites are the most obvious manifestations of the Pan African Orogeny and represent significant additions of materials (up to 70% in some places) to the crust (Rahaman, 1988).

The Migmatite-Gneiss Complex rocks comprises mainly of migmatites and gneisses of various compositions such as biotite gneiss, hornblende gneiss, tonalities, amphibolites and granite gneiss. The rocks consist of mineral assemblages such as biotite, muscovite, quartz, almandine, garnet, oligoclase, microcline, actinolites and staurolites, which have been folded within the basement complex during the Pan African orogeny. Apart from being deformed, theses rocks have been faulted in different places and this gave rise to quartz vein intrusions in various parts of the rock.

STRUCTURAL GEOLOGY

The structural elements in the study area include joints, fractures, lineations and folds (minor and major). They are deep seated in origin and ancient in age and resulted from various thermotectonic deformational episodes mostly of the Eburnean and Pan-African Orogeny (Oluyide, 1988). The dominant structural trend in the basement is essentially NE-SW trends in common with the tectonic grains of the schist belt. Subordinate directions, which are locally dominant, include E-W and variation from NW-SE. Several sets of fractures with NE-SW, NW-SE, NNE-SSW and NNW-SSE directions were also produced by transcurrent movement and shearing (Olasehinde *et al.*, 2013), (Ejepu and Olasehinde, 2014).

Figure 2: Geological map of the study area (Modified after Nigeria Geological Survey Agency, 2010).

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MATERIALS AND METHODS

The data used in this study were acquired using remote sensing tools. The main data sets were Landsat and Shuttle Radar Topographic Mission (SRTM) Digital Elevation Models (DEM) obtained from USGS and National Aeronautics and Space Administration (NASA) websites. Auxiliary data sets used as GIS layers include streams, roads and digitized geologic map. All data were integrated in a Geographic Information System (GIS) and analysed using multi-criteria decision analysis (MCDA) to assess factors the groundwater controlling features. Finally, a groundwater potential map was prepared based on the GIS analysis.

Five thematic maps were generated using Environment for Visualizing Image software (ENVI 4.7) and ArcGIS 10.0. These include: Drainage density, lineament density, land use/cover, slope/geomorphology and lithological maps. Drainage and catchments were extracted using Arc Hydro tools embedded as an extension in ArcGIS 10.0 and subsequently the drainage density was calculated.

The drainage system, which develops in an area, is strictly dependent on the slope, the nature and attitude of bedrock and on the regional and local fracture pattern. Drainage, which is easily visible on remote sensing imagery, therefore reflects to varying degrees the lithology and structure of a given area and can be of great value for groundwater resources evaluation. Drainage is studied according to its pattern type and its texture (or density of dissection) (Sener *et. al.,* 2005).

$$\text{Drainage Density } (m^{-1}) = \frac{\text{total length channels (m)}}{\text{basin area } (m^2)}$$

Drainage density is an indication of a rock's infiltration capacity and permeability, and hence, it's recharge potential. Drainage density is therefore a reflection of the rate of precipitation infiltrated into the subsurface compared to surface runoff. Where rocks are highly permeable, infiltration into subsurface is high, and less water is transported in rivers as surface runoff. But where rocks have low permeability there is little infiltration and large surface runoff (Bromley *et al.*, 1997). A measure for permeability is drainage density (i.e. total length of drainage channels per unit area), in the sense that permeable conditions are associated with low drainage density and vice versa (Meijerink 2007). Low drainage density is therefore related to higher recharge and higher groundwater potential.

It is well known that fracture traces and lineaments are important in rocks where secondary permeability and porosity dominate and where intergranular characteristics combine with secondary openings influencing weathering and groundwater movement. Fracture traces and lineaments are likely to be areas of secondary permeability and porosity development in rocks.

Digitization of lineaments was carried out through visual analysis on screen of Landsat ETM+ band 5, shaded relief images of SRTM DEM and of enhanced images. Special elaborations, such high pass, edge detection and directional filters were applied to scenes to extract more information.

An important factor that influences the occurrence of groundwater is the extant condition of land cover and land use of an area. The effect of land use/cover is expressed either by reduction of surface runoff or by water droplets being trapped by vegetation. These occurrences influence groundwater recharge.

Image classification involves the analysis of multispectral image data and the application of statistically based decision rules for determining the land cover identification of each pixel in an image. Land use/cover map of the area was interpreted from Landsat 432 (RGB) combination image by visual interpretation using unsupervised classification and supervised classification employing the maximum likelihood classification.

Implementation of Unsupervised classification was done so as to have a general idea of the area. Supervised classification was performed for final land use/cover mapping.

Slope is an indication of the Topographic setting as it relates to the local and regional relief situation and it gives an idea about the general direction of groundwater flow and its influence on groundwater recharge and discharge. The slope amount map in degrees was prepared using contours produced from SRTM DEM data. Geomorphology maps depict landforms relating to groundwater occurrence as well as to groundwater prospects. The geomorphological map and statistical analysis of interpreted landforms was performed using the Topographic modelling module of ENVI 4.7.

The occurrence of groundwater and the extent and distribution of aquifers and aquitards in a region is determined by the lithology, stratigraphy and structure of the geological strata present (Hiscock, 2005).The area under investigation is considered a heterogeneous geological terrain. It is composed of igneous, metamorphic and sedimentary rock units. The sedimentary rocks have primary porosity and infiltration rate is high. Both the igneous and metamorphic rocks occurring in the area can be considered as "hard rocks" from a hydrogeological point of view. In this kind of rock, the amount of

groundwater available is entirely dependent on the storage and rate of infiltration in the fractures. This, in turn, depends on whether the fracture is open or tight. It can be said quite simply that a tight fracture contains no water while an open one may produce a considerable yield of groundwater. The lithological map was produced by digitizing existing geological map of the area under investigation.

Weight Determination and Reclassification of Thematic Maps
Analytical Hierarchy Process (AHP)

Assessment of regional groundwater potential is complex as many factors/criteria have to be considered. Making significant decisions of this nature tend to have a level of complexity, which requires the use of ordered or organized methods that can accommodate multiple criteria.

AHP simplifies the decision process by allowing the decision maker to look at one segment of the decision at time. This simplification helps to streamline the decision making process and gives it a more transparent structure. AHP therefore provides a way of organizing decisions, priorities, and judgments by allowing the decision maker to place them in a manner with the highest priority, or objective, at the top of the hierarchy (Saaty, 1980) (Table 1). This dissemination of issues that needs to be accounted for in the decision making process provides a means of meeting the overall objective while taking all criteria into consideration. In addition, AHP tests the consistency of judgments. This testing for consistency provides a means for understanding inconsistent decisions. Because the system is flexible, the decision maker can adjust his priorities so that they are consistent. Matrices with Consistency Ratio (CR) ratings greater than 0.1 should be re-evaluated (Saaty, 1992).

To determine the relative importance or weights of each thematic map (criteria) with another, paired comparison matrix was prepared by pair wise comparison on Saaty's importance scale using an AHP template (Goepel, 2013) (Figure 3). The result obtained was used in reclassification of various thematic maps. The reclassification or standardization of the maps was done using the Spatial Analyst tool of ArcMap 10.0. Higher classes were given to factors that have greater bearing on groundwater occurrence and accumulation.

Table 1: The Fundamental Importance Rating Scale (Saaty, 1980, 1986, 1992, 1997)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgments slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another and dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate value between the two adjacent judgments	When compromise is needed

Assignment of Weights to Different Criteria

Pairwise comparison was done on the various factors that were considered for the study. The weights assigned to different criteria for the determination of groundwater potential was based on their contributions and influences on groundwater accumulation. Hence, the various thematic maps produced were reclassified accordingly.

- Reclassification of land use/cover thematic map was done based on the disposition of the land surface to retention and infiltration of water to the subsurface.
- Drainage density map was reclassified based on their permeabilities and recharge potential.
- Slope map was reclassified based on the fact that lower slope angle influences groundwater accumulation and infiltration.

- Reclassified map of lineament was produced based on the fact that lineaments have the capability of creating secondary porosities especially in crystalline rocks and also being conduits for groundwater recharge.
- Reclassification of the lithologic thematic map was based on the effective porosities and permeabilities of the different lithologies and the susceptibility of the various rocks to weathering.
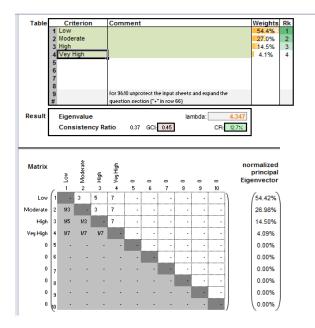

Figure 3: A typical Analytic Hierarchy Process (AHP) output.

RESULTS AND DISCUSSIONS

Lithology:

The geology of the area has been categorised into six lithologic units. These include alluvium, sandstone, schist/amphibolites, marble, migmatites and granites. This is in an attempt to encompass all available lithogies in the area. Alluvium occupies 115 km^2 (3.5%), schist/amphibolite 790 km^2 (25%), granites 1010 km^2 (32%), Marble 5 km^2 (0.5%), migmatite 810 km^2 (27%), sandstone 370 km^2 (12%). Alluvium is found in the central portion of the map while the sandstones are located at the northwester portion of the study area.

On the basis of the influence of lithologic units on the availability of groundwater, higher weights were assigned to those lithologic units that favour groundwater storage and accumulation. The figure below shows different lithologic units and weights assigned to them.

Lineament density:

Areas having high lineament densities are the highest zone of increased porosity and permeability which in turn have greater chance of accumulating groundwater. Spatially, very good and good groundwater potential categories are found where higher lineament densities were delineated. The north-western portion of the map has the highest lineament density (Figure 4). This is due to the intersection of several lineaments oriented in different directions. Major lineament directions obtained after rose diagram was plotted (Figure 5) trend NE-SW and NW-SE.

Drainage density:

Drainage density plays a major role in groundwater infiltration and accumulation. It is an inverse function of permeability. Areas having higher drainage densities are associated with less infiltration of water to the ground, which consequently

leads to higher surface runoff. Conversely, areas having lower drainage densities are associated with more infiltration of water to the ground, which consequently leads to lower run off. In evaluating the drainage system of the area, which is predominantly dendritic, revealed that the drainage system of the area is structurally controlled as drainage paths followed lineaments directions. This strongly suggests the presence of structures that may act as conduits for groundwater accumulation. Spatial distribution of drainage densities is shown in Figure 6. It is evident that higher drainage densities are found concentrated in the northern, middle and southern portion of the map.
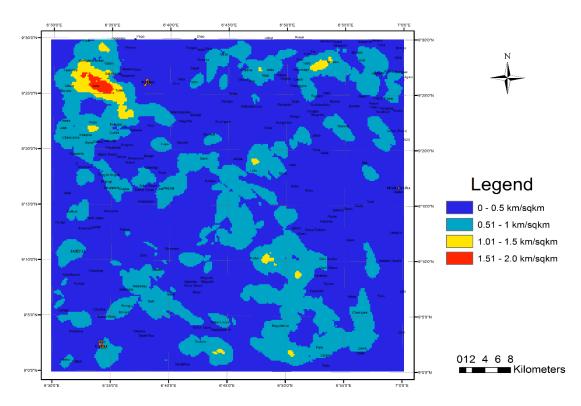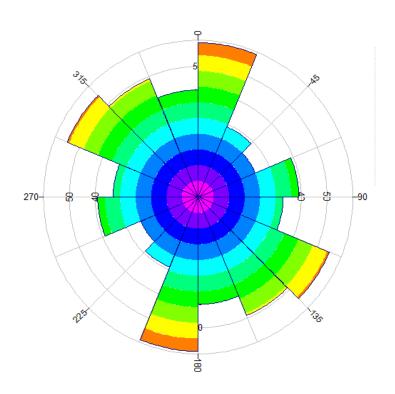

Figure 4: Lineament Density map of the study area.

Figure 5: Rosette diagram showing principal joint directions of some selected outcrops in the study area

Land use/cover:

Land use/ cover contribute in some way to availability of groundwater resources. The classes of land use/ cover delineated from remotely sensed image include vegetation, bare rock surfaces, soil surfaces, built up areas, crop land and water bodies. Of these classes, bare rock surfaces and vegetation and soil cover contribute the least and most respectively to groundwater availability (Figure 7). Factors like transpiration and evaporation rates lean their influence on groundwater availability
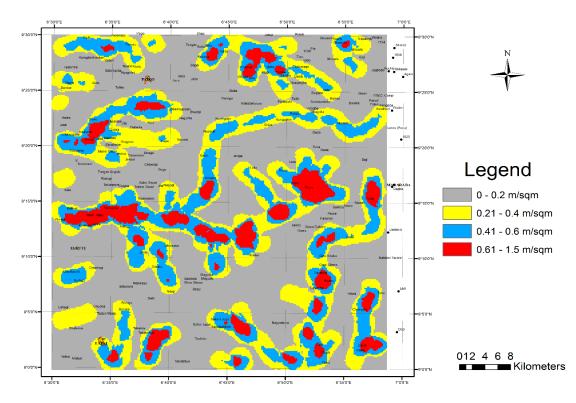
Figure 6: Drainage density map of the study area

Slope and geomorphology:
Due to the effect of tectonic activities and different land use condition over time, the study area has moderately simple to complex landform features, which is manifested by hills, plains and undulating surfaces. In relation to groundwater flat areas where the slope amount is low are capable of holding rainfall, which in turn correspond to recharge zones whereas in elevated areas where the slope amount is high, there will be high runoff and low infiltration. The steeper the slope, the greater will be the runoff and thus, lesser is the groundwater recharge Therefore, areas with low slope angles favour groundwater availability (Figure 8). Geomorphologic units which have been identified and delineated from the study area include peaks, ridges, flood plains and river channels. The presence of ridges, peaks and other elevated areas, favour loss of water and hence, not favourable for groundwater accumulation. From the groundwater potential map (Figure 9), peaks and ridges were clearly delineated as having poor groundwater potential.
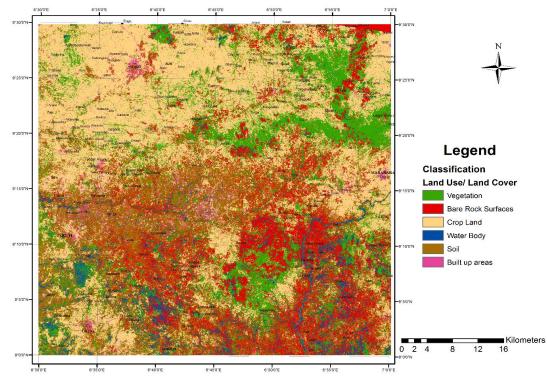
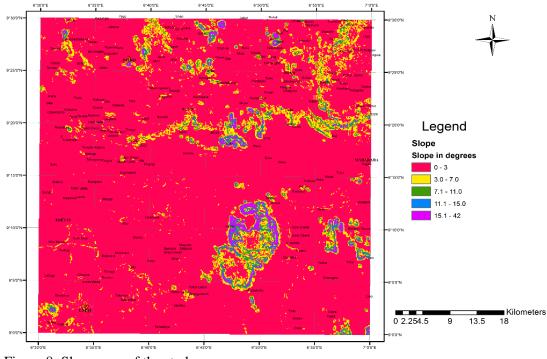Figure 7: Land use/ Land cover map of the study area

Figure 8: Slope map of the study area.

CONCLUSION

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This study, using Multi Criteria Decision Analysis, Remote Sensing and Geographic Information System has been able to demonstrate the effectiveness of integration of multiple data sets, with various indications of groundwater availability, which can decrease uncertainties and lead to safer and more reliable decisions in choosing sites for the development of groundwater resources.

The caveat is that this approach is suitable only for regional groundwater exploration studies.

A full suite of the methodology used in this study should incorporate other datasets like rainfall, borehole/well yield data and so on. Because this is more or less a preliminary report, these datasets will be included in subsequent publications so as to validate the results of the study. Efforts have been made to get verbal reports from researchers in the study area on the potentiality of the some of the areas covered in the study and there was a strong agreement between the delineated areas and the verbal report.

It should be noted however, that ground geophysical studies for individual site selection cannot be replaced in our search for groundwater resources.
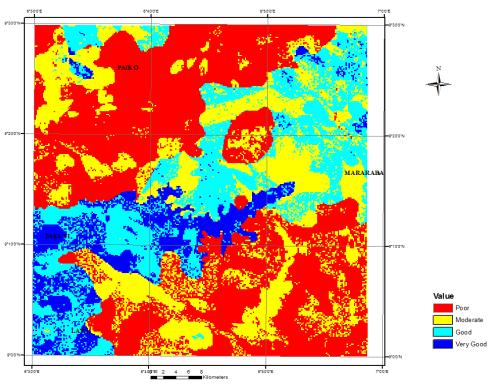

Figure 9: Groundwater potential map of the study area.

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