Groundwater study using remote sensing and geographic information systems (GIS) in the central highlands of Eritrea

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The figures in this article were inadvertently printed in black and white instead of in colour. We apologize very much for this error and provide you here with the corrected printed version.

Abstract Remote sensing, evaluation of digital elevation models (DEM), geographic information systems (GIS) and fieldwork techniques were combined to study the groundwater conditions in Eritrea. Remote sensing data were interpreted to produce lithological and lineament maps. DEM was used for lineament and geomorphologic mapping. Field studies permitted the study of structures and correlated them with lineament interpretations. Hydrogeological setting of springs and wells were investigated in the field, from well logs and pumping test data. All thematic layers were integrated and analysed in a GIS. Results show that groundwater occurrence is controlled by lithology, structures and landforms. Highest yields occur in basaltic rocks and are due to primary and secondary porosities. High yielding wells and springs are often related to large lineaments, lineament intersections and corresponding structural features. In metamorphic and igneous intrusive rocks with rugged landforms, groundwater occurs mainly in drainage channels with valley fill deposits. Zones of very good groundwater potential are characteristic for basaltic layers overlying lateritized crystalline rocks, flat topography with dense lineaments and structurally controlled drainage channels with valley fill deposits. The overall results demonstrate that the use of remote sensing and GIS provide potentially powerful tools to study groundwater resources and design a suitable exploration plan.

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Résumé Télédétection, évaluation de modèles numériques de terrain (MNT), systèmes d'informations géographiques (SIG) et techniques de terrain ont été combinées pour étudier les eaux souterraines en Eritré. Les données de télédétection ont été interprétées pour la réalisation d'une carte lithologique et d'une carte des linéaments. Le MNT a été utilisé pour la cartographie des linéaments et de la géomorphologie. Les études de terrain ont permit d'étudier les structures et de les corréler avec l'interprétation des linéaments. Les sources et les puits ont été investigués sur le terrain, ainsi qu'à partir de log et d'essais de pompages. Toutes les couvertures thématiques ont été intégrées et analysées dans un SIG. Les résultats montrent que l'occurrence de l'eau souterraine est contrôlée par la lithologie, les structures et la forme des paysages. Les meilleurs débits se trouvent dans les roches basaltiques et sont dus aux porosités primaires et secondaires. Les puits et les sources possédant les meilleurs débits sont en relation avec les grands linéaments, les intersections de linéaments et leurs structures correspondantes. Dans les roches métamorphiques, intrusives et ignées, sous des paysages forts accidentés, l'eau souterraine apparaît essentiellement dans les chenaux de drainage des dépôts de fonds de vallée. Les zones présentant un excellent potentiel d'eau souterraine, sont caractéristiques des couches basaltiques recouvrant les roches cristallines latéritiques, les zones plates possédant un réseau dense de linéaments et structuralement contrôlées par les chenaux de drainage avec des dépôts de fond de vallée. Le résultat global démontre que l'utilisation de la télédétection et des SIGs procure des outils potentiellement puissants pour l'étude des ressources en eau souterraine et pour le montage de plans d'exploration convenables.

Resumen Se combinó el uso de sensores remotos, la evaluación de modelos de elevación digitales (MED), sistemas de información geográfico (SIG), y técnicas de trabajo de campo para estudiar las condiciones del agua subterránea

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en Eritrea. Se interpretaron los datos de sensores remotos para producir mapas de lineamientos y litológicos. Los MED se usaron para el mapeo geomorfológico y de lineamientos. Los estudios de campo permitieron estudiar las estructuras y correlacionarlas con interpretaciones de lineamientos. Se investigó el marco hidrogeológico de manantiales y pozos en el campo a partir de registros de pozos y datos de pruebas de bombeo. Todas las capas temáticas se integraron y analizaron en un SIG. Los resultados muestran que la presencia de agua subterránea es controlada por litología, estructuras, y paisajes. Los rendimientos más altos ocurren en rocas basálticas y se deben a porosidades primarias y secundarias. Los pozos con altos rendimientos frecuentemente están relacionados con lineamientos grandes, intersecciones de lineamientos y sus características estructurales correspondientes. En rocas ígneas intrusivas y metamórficas con paisajes accidentados, el agua subterránea ocurre principalmente en canales de drenaje con depósitos de relleno en valles. Zonas con muy buen potencial de agua subterránea son características de capas basálticas que sobreyacen rocas cristalinas lateritizadas, topografía plana con lineamientos densos, y canales de drenaje con control estructural con depósitos de relleno de valle. Los resultados globales demuestran que el uso de sensores remotos y SIG aportan herramientas potencialmente poderosas para estudiar los recursos de agua subterránea y diseñar un plan exploratorio apropiado.

Keywords Remote sensing · Geographic information systems · Digital elevation model · Eritrea

Introduction

Groundwater is an important source of water supply and plays a crucial role in domestic use in Eritrea. In most villages in Eritrea water supply comes mainly from dug wells, springs and to some extent from boreholes that are found along major streams and valleys. Studies of existing productive wells in relation to lithology and structures are absent. Selection of well sites for groundwater supply relies heavily on traditional field methods using known water yielding sites as guidelines. In general a systematic approach to groundwater exploration is lacking.

A large portion of the country is underlain by hard rock. The term “hard rock” commonly applies to hard and dense rocks with the main part of the groundwater flowing in secondary structures, mainly fractures. Groundwater in hard rock aquifers is essentially confined to fractured and/or weathered horizons. Therefore, extensive hydrogeological investigations are required to thoroughly understand groundwater conditions. Modern technologies such as remote sensing and geographic information systems (GIS) have proved to be useful for studying geological, structural and geomorphological conditions together with conventional surveys. Integration of the two technologies has proven to be an efficient tool in groundwater studies (e.g. Krishnamurthy et. al. 1996; Sander 1996; Saraf and Choudhury 1998). Lithology, lineament, landform, slope, vegetation, groundwater recharge and discharge are common features used for many groundwater resource assessments in hard rock areas. However, most of the studies lack detailed field data for example lithological well-log and pumping-test data to supplement their findings. Although the selected features such as lithology, lineament, landform and slope are few compared to studies done in other areas, this study incorporates field data and demonstrates their significance in understanding the groundwater systems. Remote sensing data provide accurate spatial information and are cost-effective compared with conventional methods of hydrogeological surveys. Digital enhancement of satellite data improves maximum extraction of information useful for groundwater studies. GIS techniques facilitate integration and analysis of large volumes of data, whereas field studies help to further validate results. Integrating all these approaches offers a better understanding of features controlling groundwater occurrence in hard rock aquifers.

Several groundwater related studies, mainly on a regional scale, have been conducted in Eritrea since its independence in 1991 (e.g. Euroconsult 1998; JICA 1997/98; Asgedom 1998; Drury et al. 2001). None of the studies conducted have applied an integrated approach. The main purpose of this study is thus to understand the groundwater conditions in the hard rock areas in the central highlands of Eritrea by utilizing more systematic methods. The specific objectives include:

- Preparation of thematic maps of the area such as lithology, lineaments, landforms and slopes from remotely sensed data and other data sources like digital elevation models (DEM).
- Assessment of groundwater controlling features by combining remote sensing, DEM and field studies.
- Identification and delineation of potential zones for obtaining groundwater through integration of various thematic maps in a geographic information system.

The study area shown in Fig. 1 is located in the southern central highlands of Eritrea. The local coordinates are between 1650,000–1680,000 N and 470,000–500,000 E in Universal Transverse Mercator (UTM) and lie in Zone 37 north. In a test site of 30 × 30 km major lithologies and structures were mapped. The method of study involves digital image processing for the extraction of lithologic data and linear features, and evaluation of DEM, as well as field studies. The field studies were comprised of hydrogeological and structural investigations. The DEM was used to extract lineaments and to map drainage systems and landforms. All data were integrated in a GIS and analyzed to assess features controlling groundwater occurrence. Finally maps of groundwater potential were prepared based on the GIS analysis. The image processing software ENVI (Environment for Visualizing Images) version 3.5 was used for the remote sensing study. GRASS (Geographical Resources Analysis Support System) versions 4.3 and 5.0 were utilized for the GIS analysis.

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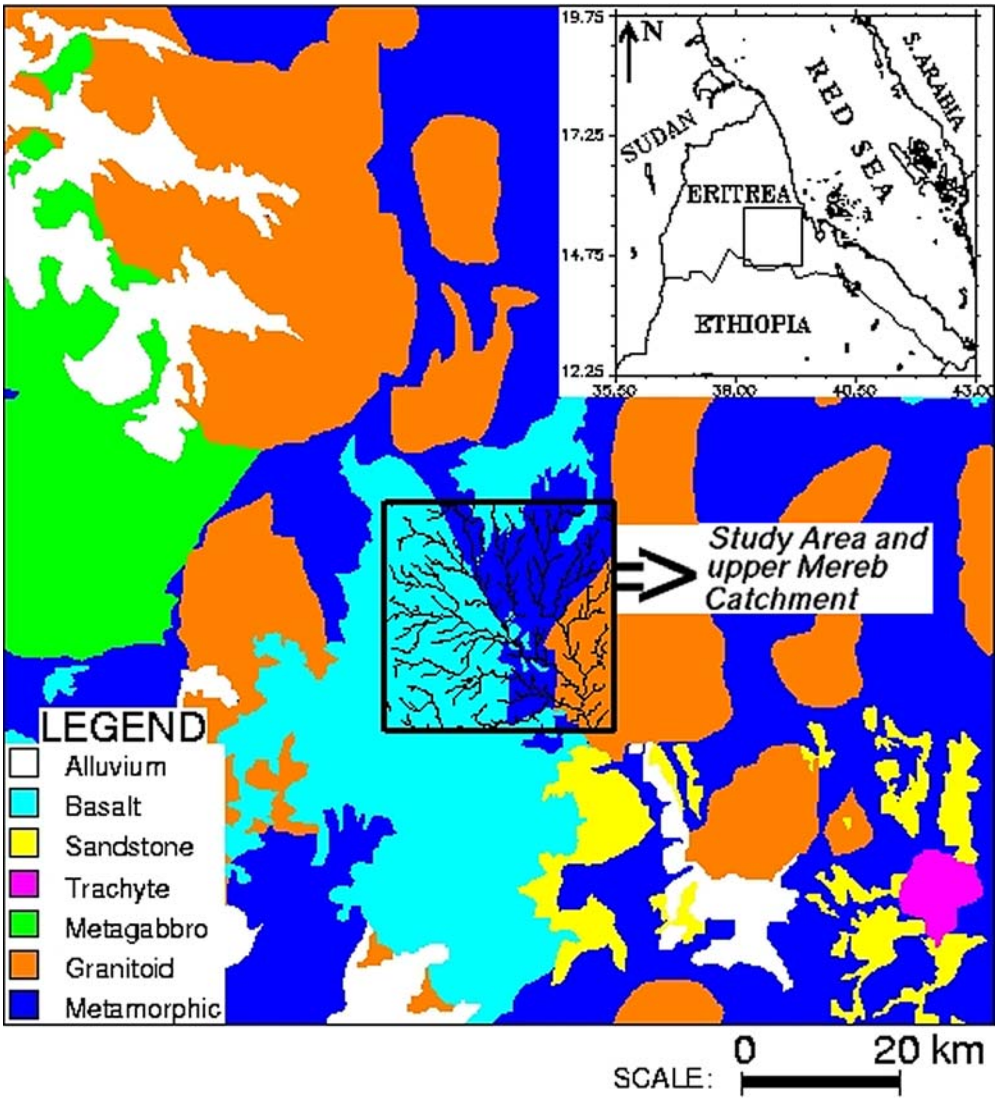

Fig. 1 Location, regional geology and the study area

Physiography and climate

Eritrea is located in the Horn of Africa (Fig. 1). It is bounded by Ethiopia to the south, Sudan to the west and north, the Red Sea to the east and Djibouti (not named on map) to the southeast. Three physiographic regions characterize Eritrea: the western lowlands with elevations 500–1,500 m, central highlands with elevations 1,500–2,500 m and the eastern coastal lowlands with elevations 0–1,500 m above sea level. The southern central highland is drained by the Mereb Catchment.

The climate is arid to semi-arid with two rainy seasons. The long rainy season in summer lasts from June to September, and the short spring rainy season occurs during March and April. Rainfall is intense during the period mid-July to mid-August. Average annual precipitation ranges from 300 to 600 mm in the central highlands. Potential evapotranspiration is approximately 1,700 mm/year. Daily temperatures usually vary from 10° to 30°C. Natural vegetation cover is sparse and consists dominantly of acacia trees and bushes occupying rocky steep slopes and lowlands. Dense vegetation cover is common along rivers and forms a limited woodland type of forest. Man-made plantations dominated by eucalyptus trees are common in the highlands. Vegetation cover from small-scale irrigation activity is dominant along river courses and on the basalt plateaus.

Regional geology

Eritrea is part of the Arabian-Nubian Shield, which extends from Saudi Arabia and Egypt in the north through Eritrea, Ethiopia and the Sudan to Somalia, Kenya and Uganda in the south. The Arabian-Nubian Shield consists dominantly of low-grade volcanic sedimentary-ophiolite assemblages, granitoids and gneisses (Vail 1987). The Precambrian terrain of Eritrea is in the least studied part of the Arabian-Nubian Shield and has been studied by several authors (e.g. Drury and Berhe 1993; Ghebreab 1996). In general it is comprised of metamorphic and granitic rocks (Fig. 1).

The metamorphic rocks consist of metavolcanic and metasedimentary units. The dominant metavolcanic rocks are schistose metavolcanics with chlorite epidote muscovite quartz schists and massive metavolcanics, which are strongly epidotized and include metabasalts and metafelsites (rhyolites, tuffs and pyroclastic volcanics); in places intermediate volcanics (andesites and dacites) alternate. Metasedimentary units are comprised of slates, in places black colored, and turbiditic sediments of greywacke with minor interbeds of metavolcanic rocks (Teklay 1997). A variety of felsic rocks with granitic-dioritic composition intruded the volcanic sedimentary sequence. The granitoid rocks show variations from foliated gneissose granite merging into surrounding schists, porphyritic granite and granodiorite to fine grained microgranite, syenite and diorite with subordinate gabbro in places. The form of the intrusions varies between huge irregular or elongated complexes with schistose rocks preserved as roof pendants, and rounded circular masses of quite restricted dimensions (Hamrla 1978).

Mesozoic sandstone and Cenozoic volcanic rocks lie unconformably over the volcanic sedimentary rock units and the granitoids (Fig. 1). The volcanic rocks are alkali-olivine basalt flows forming plateaus. The base of the basalt sequence is marked by a well-developed lateritic paleosol.

Methods and results

Remote sensing

Several digital image processing techniques, including standard color composites, intensity-hue-saturation (IHS) transformation and decorrelation stretch (DS) were applied to map rock types. The statistical technique adopted by Sheffield (1985) was employed to select the most effective three-band color composite image. The band combination 1, 4 and 5 is the best triplet and was used to create color composites with Landsat TM bands 5, 4 and 1 in red, green and blue, respectively. Good contrast in mineralogy between basalts and crystalline rocks is reflected by contrasting colors on the standard color composite and allowed one to differentiate most of the rock units. IHS transformation and DS were also applied to the selected band combination in order to enhance the difference between rock types. Better contrast was obtained due to color enhancement and this facilitated visual discrimination of various rock types. Seven lithologic units were mapped and could be distinguished by distinct colors in the processed images. These are: alluvium, basalt, laterite, kaolinized granite, foliated metavolcanics, nonfoliated metavolcanic and syn-tectonic granites. Figure 2 is a map of the interpreted distribution of rock types in the study area.

Lineaments are clearly discernible in all digitally processed color composites. Most of the linear features are enhanced due to color contrast. In addition directional filtering was applied to various single band images along N-S, NW-SE, NE-SW and E-W directions. The results show good enhancement of linear features along most of the directions except E-W. This is probably due to the lack of lineaments in this direction or use of a too small window size i.e. the filter dimension, which was 3×3 raster elements. Directional filtering along the N-S direction was most effective in detecting lineaments. It not only strongly highlighted lineaments along the filter direction but also emphasized NNE-SSW, NNW-SSE, NW-SE and NE-SW trending linear features, because these trends are oblique to the filter direction. Although major lineaments can be detected in the raw image data, most of the finer details are more clearly recognizable in the filtered image.

The DEM was very useful in delineating regional scale lineaments related to geomorphologic features, mainly drainage channels. Minor lineaments are more discernible in the remote sensing (Landsat TM and Spot) data than in the DEM. This is due to the higher resolution of TM (30 m) and Spot (20 m) in comparison to the DEM (50 m) data. Lineament maps produced from Landsat TM, SPOT and DEM digital data were used as input for the final lineament map. Figure 3a is the final lineament map created by combining the three interpretations and editing duplicates in each of the files. Length and trends of lineaments are displayed in the rose diagram presented in Fig. 3b. The azimuth sector size is 5 degrees and within each sector lineament lengths are cumulated. The number of lineaments is noted in the diagram (n). Lineament trends are strongest at N-S (NNW-SSE), NW-SE, NE-SW and ENE-WSW. All major linear features are detected in all imagery groups.

Structures

The major structures encountered in the study area are joints, dykes and faults. Comparison of rose diagrams of steeply dipping joints, dykes and lineaments reveal good agreement in orientations (Solomon and Quiel 2003). The major orientations are: NW-SE, N-S, NE-SW, ENE-WSW, NNE-SSW, WNW-ESE and NNE-SSW. A minimum of three joint sets is characteristic for most outcrops in the crystalline rocks. Most of the joint systems are closely spaced and crosscut each other suggesting that they are well connected in a three-dimensional network. The major structures observed in the basaltic rocks are dominantly primary jointing. These include sub-vertical columnar joints as well as sub-horizontal sheet joints. At places, the basaltic rocks contain vesicles.

The dyke swarms are sub-vertically dipping and exhibit variations in lengths, widths and spacing. The widths in all sets vary from a few tens of centimeters up to 15 m. The strike lengths can be traced from a few meters to hundreds of meters and the spacing from a few centimeters to a few tenths to hundreds of meters. The dykes are dominantly basaltic to doleritic in composition. All sets of dyke swarms cut the granites, lateritized basement and the overlying Tertiary basalts. Closely spaced dyke parallel fractures are well developed adjacent to most dyke swarms.

Two types of faults, namely strike-slip and normal, dominate the study area. The strike-slip faults are generally steeply dipping. The normal faults have a number of sets

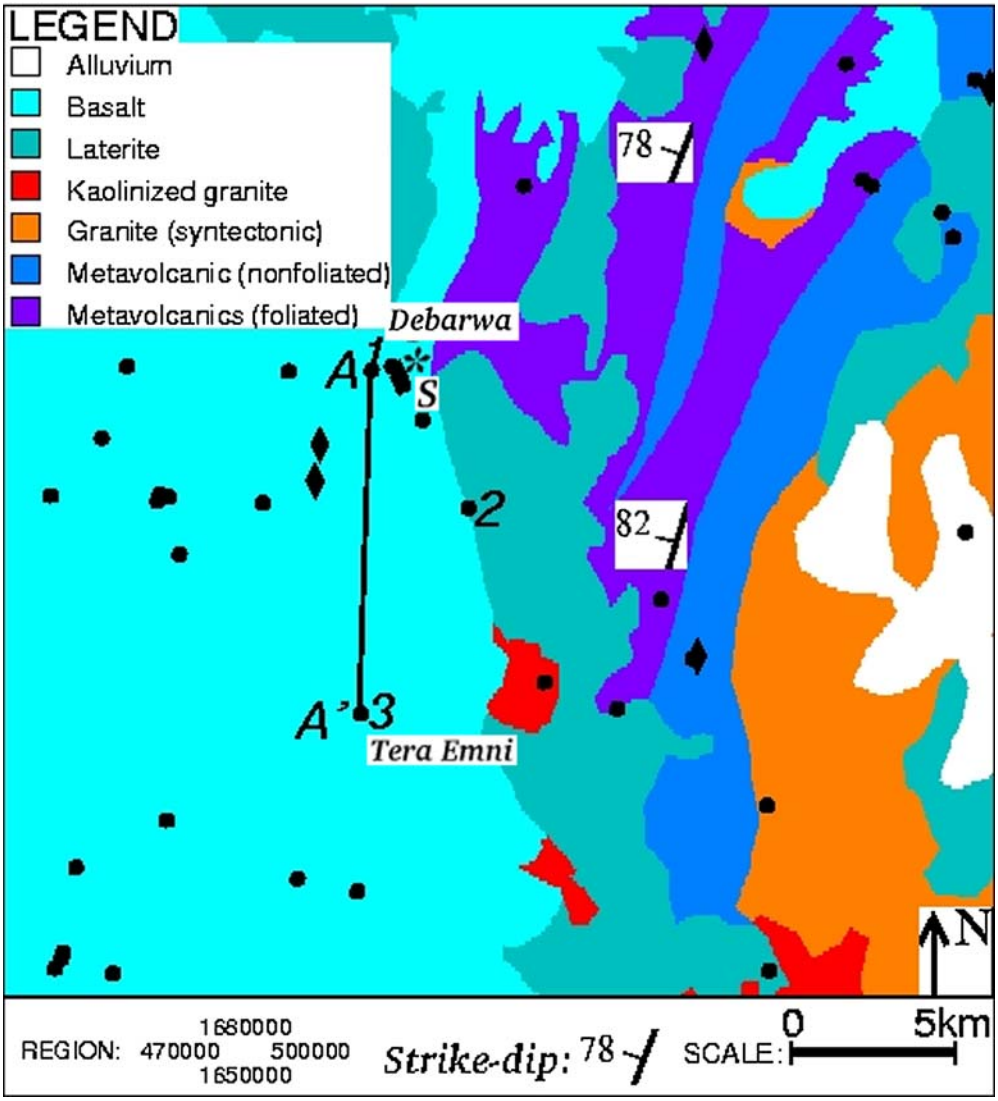

Fig. 2 Map of interpreted occurrence of rock types in the study area based on remote sensing and references cited in section on Regional Geology. Locations of wells (filled circles); springs (star S or filled diamond); groundwater discharge area in stream channel (filled diamond). Numbers are wells used to construct a conceptual cross-section along A-A′

that are variable in size and direction and amount of displacement. Prominent strain markers include Precambrian aplitic dykes/sills and Tertiary basaltic flows which display normal displacements that vary from centimeters to hundreds of meters. Fault breccia/gouge with associated slickenlines are usually well developed. Figure 4 represents a summary of all fracture systems in the region in relation to the regional tectonic features.

Geomorphology

Topographic model parameters were calculated from the digital elevation model and used for geomorphologic analysis. The topographic model parameters slope, longitudinal curvature, cross-sectional curvature, plan convexity and minimum curvature were calculated using a moving window of 5 × 5 raster elements. They are used as input bands for landform feature classifications. Different combinations of 2 and 3 input bands are used to characterize different types of features. The classification results were visually evaluated and reclassified into seven landform features to generate the geomorphologic map shown in Fig. 5. These are: peaks, ridges, scarps, pediments, terraces, plains and channels.

The ridges consist of mountain chains composed of basalts and crystalline rocks that form individual peaks. The scarps generally represent steep slopes formed adjacent to deeply incised V-shaped gullies. Some of the scarps are associated with tectonic activity and represent fault surfaces. The pediments are moderately inclined erosion surfaces that slope away from mountain fronts (ridges) and are typically formed by flowing water. In the pediments bedrocks may be exposed or thinly covered with alluvium and soils. Terraces in the basaltic rocks mark successive lava flows, whereas in alluvium

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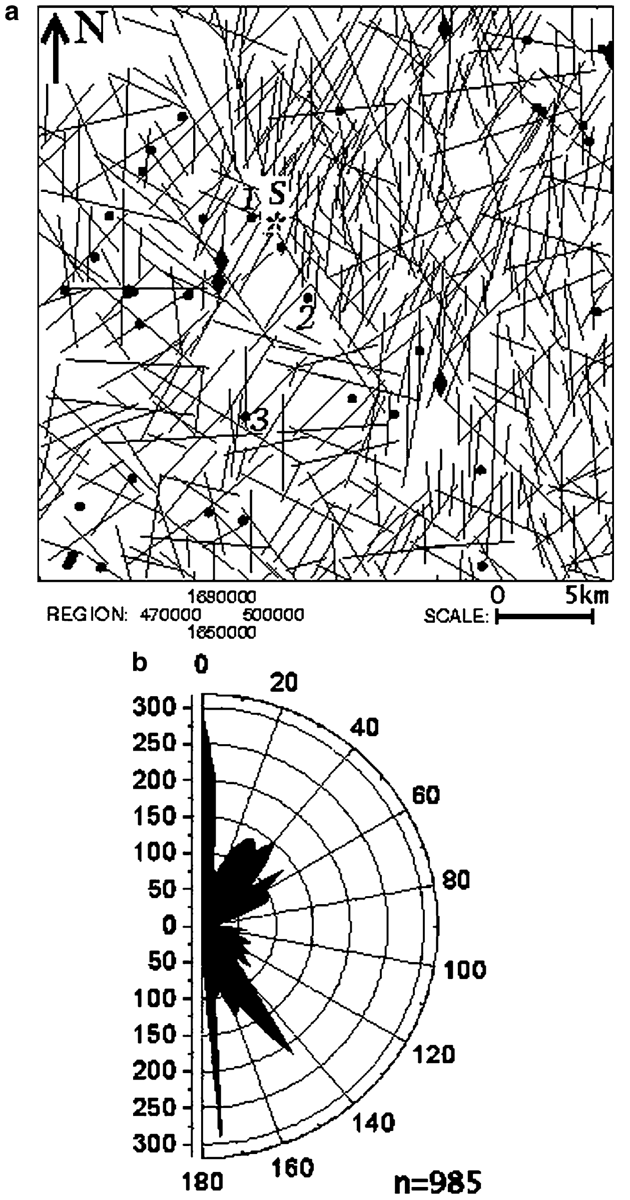

Fig. 3 (a) Lineament interpretation map of the study area. Location of wells (circles), springs (stars) and groundwater outcrops (diamond). S = location of spring and numbered boreholes used to construct cross-section along A-A′ in Fig. 2. (b) Rose diagram of all lineaments

they represent different flood plains. The plains are flat to gently sloping topographic features. In basaltic rocks they mark the top of individual lava flow surfaces. In crystalline rocks the plains represent peneplains or flood plains.

The peneplains are remnants of older erosional surfaces indicative of landscape features that are reduced through long and continued mass wasting, stream erosion and sheet wash (peneplanation). During periods of tectonic quiescence deep weathering of crystalline bedrock formations produced the laterites. Tectonic uplift resulted in terminations of the deep weathering and initiated a cycle of stripping. The periods of tectonic uplift, age of lateritization and cycles of stripping are not well known in Eritrea, however, remnants of the peneplanation surfaces are well preserved in the field. Some of the lateritic peneplains form isolated patches at the top of the ridges in the crystalline rocks. Valleys and gullies form the drainage channels and dissect most topographic features. Most of the drainage channels are straight and aligned in dendritic to rectangular patterns suggesting structural control. Valley fill deposits are clearly visible in Spot and TM data and constitute colluvial and/or alluvial materials.

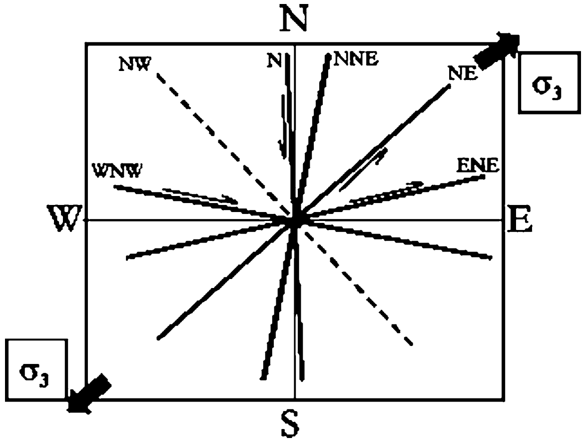

Fig. 4 Diagram showing the fracture systems in the study area in relation to the current tectonic features of the Red Sea rift. N, WNW, NE and ENE are shear fractures related to the Red Sea rift and associated transform faults. NNE and NW represent dilatational fractures with σ_3 showing direction of maximum extension along NE-SW and dashed line marks the Red Sea axial trend

Hydrogeology

GIS Analysis

Well yield data were collected from reports prepared by various companies and entered into a common database. Pumping test data were only available at three locations (see numbered wells in Fig. 2). All other yield estimates are based on observations made from wells equipped with motorized or hand pumps as well as bucket-drawn water. It is important to note that reported yield values are limited by the capacity of pumps and thus may underestimate the true capacity of wells. In addition to the type of pump the estimated yield depends further on the hydraulic characteristics of the aquifer such as the transmissivity and storativity and also well design parameters such as well penetration, and well bore storage which is related to the well diameter. Therefore many factors can affect the estimated yield values and their accuracy. To get a broader statistical base, well data outside of the study area were included in the analysis.

Table 1 summarizes hydrogeological and lithological data in the GIS. The log mean well yield within the different rock types is highest in basalts with 105 L/min followed by foliated metamorphic rocks with 81.5, alluvium 75, granitoids 70 and lowest in nonfoliated metamorphic rocks with 32 L/min. The high yield in the basalts is due to primary

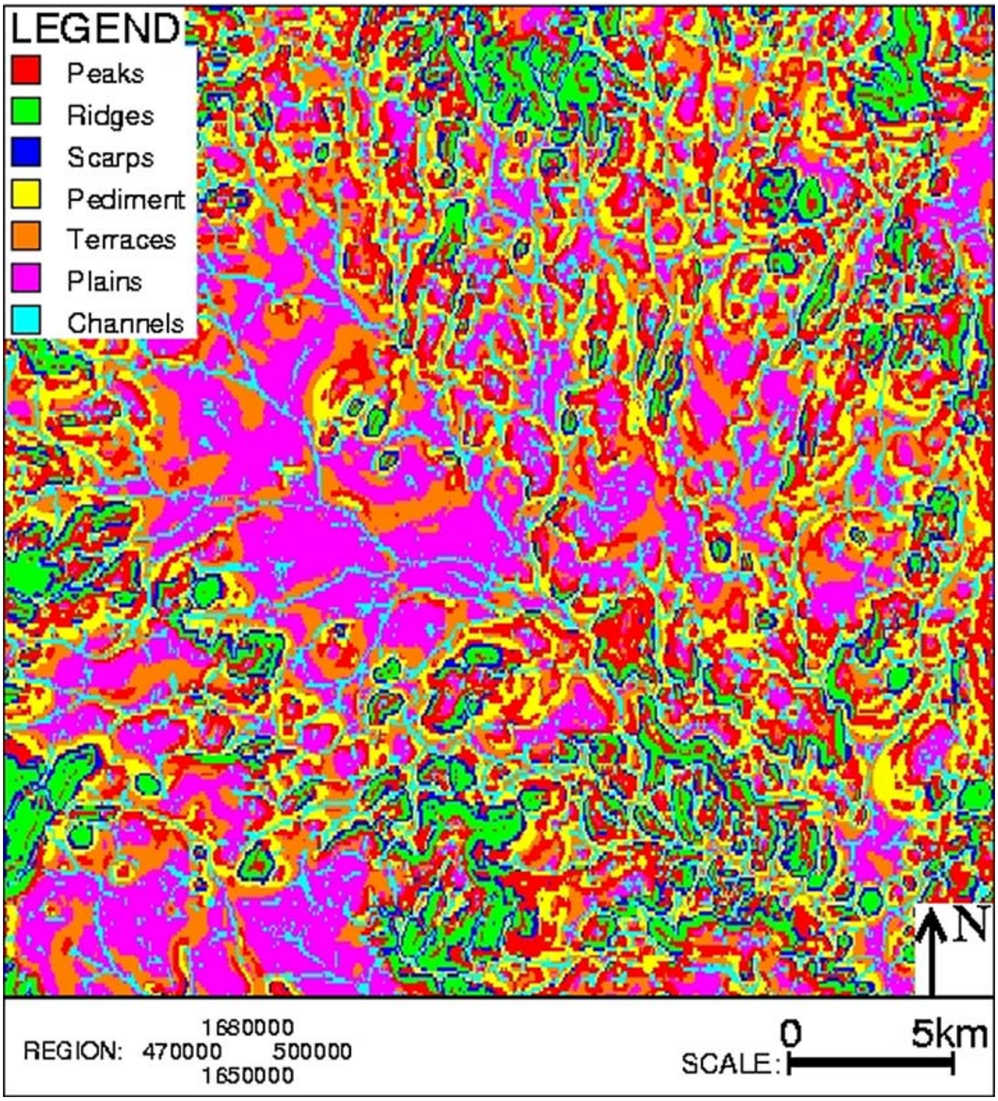

Fig. 5 Geomorphologic map of the study area

porosity in the form of columnar and sheet jointing as well as vesicles. Comparison of the metamorphic rocks shows that the foliated varieties are more permeable than the non-foliated ones due to foliation planes, which enhance permeability. In spite of high porosity and permeability in the alluvium the calculated average yield is low. This is due to the fact that some wells, which tap alluvium, also tap crystalline rock aquifers with low yields, thus decreasing the mean values. The variations of yield values within one rock type, for instance in basalts from 6 L/min to as high as 1,200 L/min, and among different rock types is due to heterogeneity of the hard rock aquifers. The heterogeneities are possibly attributed to both lateral and vertical variations in permeability of the weathered hard rock material owing to relict mineralogical (residual quartz veins) or structural features (residual fractures).

Due to heterogeneities and the difficulty in delineating them due to the scale effects in hard rock areas, correlation of yield and landform is problematical especially at the regional scale. However, in areas with limited

Table 1 Well yields by rock type (L/min) based on hydrogeological and lithological data in the GIS

Lithology	Basalt	Metamorphic (foliated)	Metamorphic (nonfoliated)	Granite	Alluvium
No. Wells	50	30	20	30	16
Min	6.00	12.00	2.00	12.00	17
Max	1,200.00	422.00	240.00	600.00	480
Log of mean yield	105.00	81.50	32.00	70.00	75.0
Standard deviation	3.25	2.73	2.92	2.61	3.2

Table 2 Output of geomorphology vs. yield from GIS analysis

Landforms	Log measured average yields (L/min)	Groundwater potential
Channels	130	Very good
Plains	115	Good to very good
Terraces	111	Good to very good
Pediment	97	Moderate to good
Scarps	13	Very poor
Ridges	30	Very poor
Peaks	–	Nil

previous investigations and few boreholes, groundwater studies could rely on other data sources such as DEM. DEM data proved to be useful for geomorphologic mapping and correlation of landforms with well yields. The measured average yield in each landform is given in Table 2. The channels show very good groundwater potential with high measured average yield and valley fill deposits of unconsolidated materials providing groundwater storage. Where the drainage channels in the basement are structurally controlled they can together with the valley fill deposits form an integrated aquifer system. The plains and terraces have good to very good groundwater potential with good measured average well yields. In the basaltic rocks, the plains represent different lava flow layers with gentle to flat slopes with individual flow layers forming terraces. In the crystalline rock areas the plains represent either peneplains or alluvial plains. The hydrogeology of the peneplains is discussed in detail in relation to field investigations in a following section. Pediments in basalt show measured average well yield values about 100 L/min (Table 2) and can be classified as having moderate to good groundwater potential. Scarps and ridges have very low measured average well yields and thus have poor to very poor groundwater potential. Peaks have no groundwater potential.

Lineament interpretations of the study area were correlated with existing boreholes in a GIS. Results show a good correlation between well yield and proximity to satellite imaged lineaments (Solomon and Quiel 2003), supporting the fact that groundwater flow is predominantly in the fracture systems. It demonstrates also the significance of the mapped lineaments as well as the quality of the image data and the role of remote sensing techniques. Furthermore, groundwater "outcrops" in the form of springs and riverbed groundwater discharge areas as well as wells often lie on major lineaments of different orientations (Fig. 3a). For instance, the spring at Debarwa (star S in Fig. 3a) is flowing along a NW-SE oriented lineament intersected by a NNE-SSW trending dyke. A high yielding borehole (480 L/min, borehole 1 in Table 3) is within 100 m of the same dyke. The high yield could be due to increased permeability owing to parallel joints in or adjacent to the dyke. All these observations emphasize the hydrogeological significance of lineaments. It is important to note, however, that proximity to lineaments does not necessarily imply that the borehole yield is high. Low yielding boreholes sited on satellite-imaged lineaments could occasionally be connected to poorly transmissive dykes or clay gouge in fracture zones (Sander 1996). Moreover fractures and their delineation are subjected to scale assessment problems and thus high yielding wells could be located far from major lineaments owing to local fractures that are associated with lineaments but may not be distinguished at the mapping scale.

Field investigations

Figure 6 shows a cross-section along A-A′ constructed from the logs of three boreholes as a conceptual model. The stratigraphy established from the lithological logs shows different basaltic flow layers. Boundaries between successive layers are marked by highly weathered and lateritized

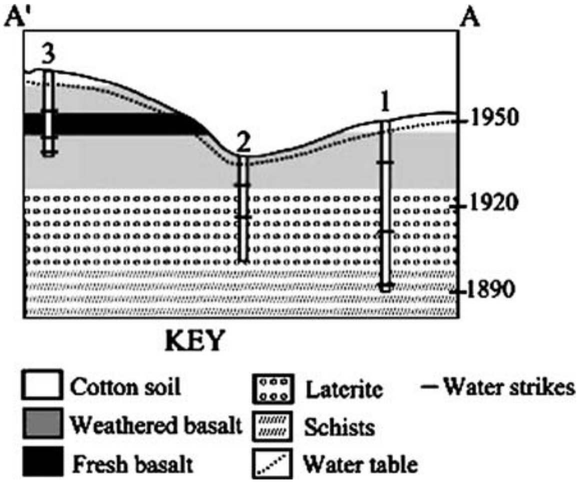

Fig. 6 A conceptual lithological cross-section along A-A′ in the basaltic rock aquifers; for location see Fig. 2

Table 3 Borehole information used to construct the cross-section in Fig. 6

Boreholes	Total depth (m)	Depth to SWL[a] (m)	Pumping rate (L/min)	Water strike depths[b] (m)	Remark
1 Debarwa	60	5.3	480	1st 16 m 2nd 38 m 3rd 55 m	W[c]. basalt Laterite Schists
2 Adi Watot	37	4	120	1st 12 m 2nd 21 m	W. Basalt Laterite
3 Tera Emni	29	5.8	480	1st 15 m 2nd 24 m 3rd 28 m	W. Basalt W. Basalt W. Basalt

[a] SWL – Static Water Level

[b] Water strike depth is equivalent to the depth of permeable water-bearing zones

[c] W – Weathered

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basalts and/or basement rocks. The top layer consists of cotton soil derived from in situ weathering of the parent material with a depth of 3–10 m, with an average of 5 m. The thickness of the weathered basalt varies from sequence to sequence and from site to site and ranges from 7 to 30 m with an average of 20 m. The thickness of the fresh basalt layers varies from 5 to 25 m with an average of 15 m. The thickness of the lateritized basement varies from 25 to 40 m.

Table 3 shows borehole information used to construct the cross-section in the basaltic rocks (Fig. 6). In basaltic aquifers, the water strike depths mostly correspond to weathered zones at varying depths. In certain cases the water strikes occur at greater depth in other lithologic horizons such as the lateritized and fresh crystalline basement rocks (borehole 1) and also at the boundary between weathered and fresh basalts of vesicular nature (borehole 3). Increased yield was observed in borehole 1 at the third water strike depth near to the contact of deeply weathered schists (laterite) and fresh schists with a yield of 480 L/min. At the base of the weathered zone, rounded sand to gravel sized particles of lateritic origin were observed during drilling. In weathered crystalline mantles, aquifers tend to occur at the base of the mantle where less aggressive weathering is associated with saturated conditions and where coarse, partly weathered sand-sized clasts predominate (e.g. McFarlane 1992; Taylor and Howard 2000). The high yield is attributed to the increased permeability.

The static water level in the basaltic aquifers occurs at shallower depth (about 5 m) than the depth at which water was first encountered during drilling. Enhanced weathering in the unsaturated zones as well as saturated zones produces a clay-rich material of lower permeability and is responsible for apparent semi-confined to confined conditions in weathered aquifers both of basalt and other crystalline-rock origin. The permeability contrast among the various layers (Fig. 6) determines whether the aquifer systems will react as a confined or unconfined condition. However, pumping test results suggest that the weathered basalt aquifer is more transmissive than the weathered crystalline rock aquifers implying unconfined conditions. Furthermore the water strikes at different depths (Table 3) hints that groundwater occurrence is partly controlled by local fractures or fracture zones. Therefore a common water table is considered realistic assuming that all the aquifer systems are hydraulically connected through relict or fresh fracture zones.

Pumping tests are commonly used to better understand the aquifer system, to quantify hydraulic characteristics and to assess yield. However, to determine the hydraulic characteristics as well as the relationship between yield (pumping rate) and drawdown, data over longer time periods are required. Drawdown behavior in pumped hard rock aquifers is usually affected by its heterogeneity and the scale of heterogeneity may be large relative to the scale of the test. This makes it very difficult to get reliable values for hydraulic parameters, but despite their short duration the pumping tests provide some knowledge about the hard rock aquifers. A log-log plot of drawdown vs. time for two pumping tests is given in Fig. 7. In the basaltic aquifers the drawdown plot for borehole 1 at Debarwa (Fig. 7) shows a straight line suggesting linear flow. Although water strikes are recorded at three lithological units (Table 3), the pumping test indicates flow from fractures or fracture zones associated with dykes. The overlying weathered horizon provides storage for the fractured bedrock aquifer, and thus the two units form an integrated aquifer system. For borehole 3 (Tera Emini) the curve can be fitted to a Theis type curve suggesting a radial flow pattern, indicating homogeneous conditions in the basalt aquifer generally hydraulically similar to those of a porous medium and good storage characteristics in the deeply weathered zone. In spite of similar pumping rates in the two wells, at 0.5 min after pumping started (Fig. 7), the drawdown in borehole 3 was about 2.2 m but 3.2 m in borehole 1. This difference indicates that the transmissivity is higher in borehole 3 than in borehole 1 since boreholes tapping less transmissive bedrock experience greater drawdown in the fractured bedrock aquifer and induce increased drawdown in the weathered mantle (Taylor and Howard 2000). In the basaltic aquifers the occurrence of groundwater is thus controlled both by lithologic and structural factors.

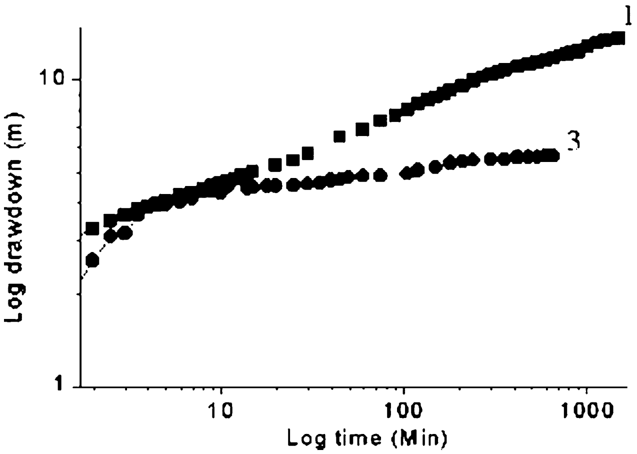

Fig. 7 Pumping test results in basaltic aquifers wells 1 and 3, see Fig. 3a for locations

GIS Modeling

In models derived through integration of various thematic maps using a GIS approach, several parameters are commonly involved to assess groundwater potential in hard rock areas. Precipitation and runoff are vital to estimate different recharge conditions and assess the groundwater yield. Unfortunately the few available precipitation and stream flow data do not allow one to model the spatial variation of rainfall within the small project area. Data indicate that local and regional showers are typical. Recharge is considered indirectly in the model since areas with high well yields are often also areas with comparatively high recharge. Complex local aquifer systems are quite common with e.g., alluvial fill hydraulically connected to fracture systems in granites. It was not attempted to model this situation in detail, but to consider this in providing suitable categories for e.g., lithology and geomorphology. Thus the existence of different rates and flow patterns (in different interacting aquifers) was not considered in the current study due to the heterogeneity in hard rock areas as well as their scale effects, which were discussed earlier.

The modeling involves delineation of zones of varying groundwater potential based on integration of four thematic maps in a raster based GIS. The four parameters considered are:

(i) Lithology
(ii) Lineaments
(iii) Geomorphology
(iv) Slope.

Every class in the thematic layers was placed into one of the following categories viz. (i) Very Good (ii) Good (iii) Moderate (iv) Low and (v) Poor, depending on their level of groundwater potential. Considering their behavior with respect to groundwater control, the different classes were given suitable values, according to their importance relative to other classes in the same thematic layer. The values assigned to different classes in all thematic layers are given in Table 4.

The values assigned to the lithology layer take into account the hydrogeological significance of the rock types. The characteristics considered for lithology are: rock type, type and thickness of weathering, fracture density, occurrence of dykes etc. For instance, a maximum value of 80 was given for alluvium and basalt due to their favorable properties for storing and transmitting groundwater owing to their primary porosities and permeabilities. The granitoid and schistose metamorphic rocks were assumed to have better aquifer properties than the remaining rock types due to primary structures owing to joints and secondary structures owing to foliations, respectively. Furthermore, overall lineament density was also considered in assigning values for the lithology. For example, visual inspection of the lineament map showed high lineament density in the granitoid rocks compared to other rock types.

In general, lineaments act as conduits for groundwater flow, and hence are hydrogeologically significant. The values given for lineaments were based primarily on the relation of well yields to proximity of lineaments. Accordingly five classes were defined based on distance from lineaments (Table 4) with decreasing values as the distance from lineaments increase. It is assumed that the intensity of fracturing decreases with increasing distance away from the lineaments. This implies that the best chances for groundwater targeting are close to lineaments.

The landforms of the study area were classified into seven classes and values were assigned according to the landform type. For instance, channels and plains were considered the best targets for locating groundwater and thus were assigned values of 80 and 70, respectively. In contrast, scarps, ridges and peaks are given the value of 10 as poor candidates for obtaining groundwater. The digital elevation model was also used to produce a slope map. Five slope classes were defined (Table 4), with a decreasing value as the slope increases. This implies that the flatter the topography the better are the chances for obtaining groundwater.

After assigning values for each class in each layer, these four layers were added and the sums were grouped into groundwater potential zones (Table 5). The highest value that the sum can attain is 320 (80 + 80 + 80 + 80) and the lowest value is 40 (10 + 10 + 10 + 10), see Table 4. The minimum of 40 was set as the class interval and all areas with a sum not larger than 50 % of the maximum, that is a value of 160, were considered to be zones of poor groundwater potential. Based on this model a map of the distribution of zones of varying groundwater potential was prepared (Fig. 8a). The validity of the model was tested against the borehole yield data, which reflect the actual groundwater potential. Although very low yielding wells exist in all the zones due to heterogeneity, the highest yields occur in the *very good* and *good* zones for groundwater prospecting (Fig. 8b). The *very good* zones delineated through this model have average yields of 201 L/min. *Good* zones for groundwater prospecting have average well yields of 102 L/min. The *moderate*, *low* and *poor* zones have average yields of 85, 56 and 25 L/min, respectively. All

Table 4 Values assigned for different groundwater control parameters (modified after Krishnamurthy et al. 1996)

Parameter		Value	Parameter		Value
Lithology			*Geomorphology*		
Alluvium	(VG)	80	Channels	(VG)	80
Basalt	(VG)	80	Planes	(G)	70
Foliated metamorphic	(G)	70	Terraces	(G)	60
Granite (syntectonic)	(M)	60	Pediment	(M)	50
Nonfoliated metamorphic	(M)	50	Scarps	(P)	10
Laterite	(L)	40	Ridges	(P)	10
Kaolinized Granite	(P)	10	Peaks	(P)	10
Distance from lineaments			*Slope*		
0–50 m	(VG)	80	0–3°	(VG)	80
50–100 m	(G)	70	4–7°	(G)	70
100–150 m	(M)	60	8–11°	(M)	60
150–200 m	(L)	40	12–15°	(L)	40
>200 m	(P)	10	>15°	(P)	10

VG = Very Good G = Good M = Moderate L = Low P = Poor

Table 5 Groundwater potential zones

Zone	Class Interval	Groundwater potential
1	281–320	Very good
2	241–280	Good
3	201–240	Moderate
4	161–200	Low
5	≤ 160	Poor

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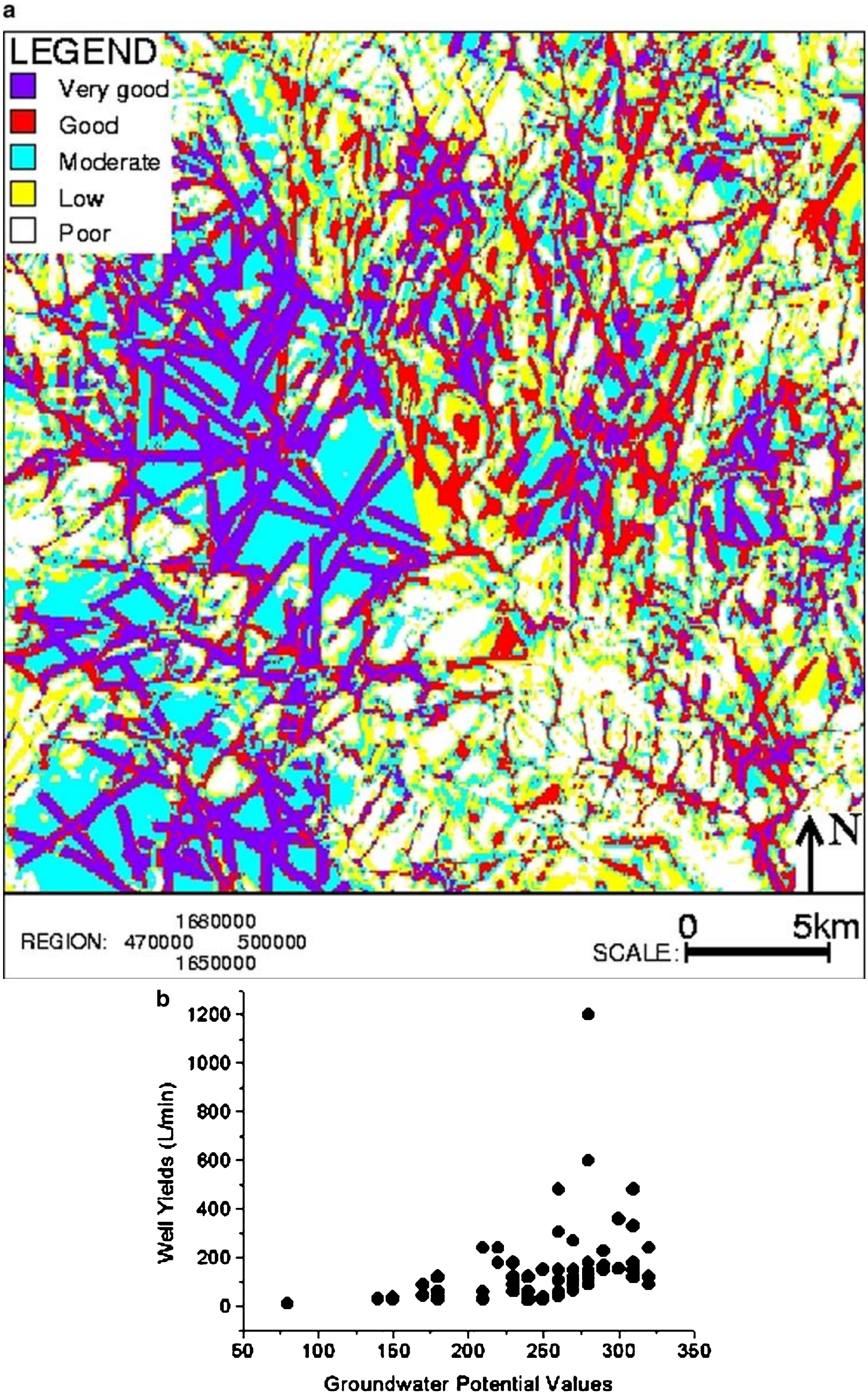

Fig. 8 (a) Groundwater potential zone map (b) Scatter plot of well yield vs. groundwater potential values as model validation results

well yields in each category represent average logarithmic values because the yield data show a lognormal distribution. It should be pointed out that though the GIS approach is very efficient in data integration and analyses, data from discrete points, such as boreholes, are often extrapolated over large areas. This is especially problematical in hard rock areas, as the hydrogeological characteristics can vary by several orders of magnitude over short distances. Nevertheless such models can serve as a good starting point to design a suitable groundwater exploration plan.

The spatial distribution of the various zones of groundwater potential obtained from the model generally shows regional patterns related to lithology, drainage, landform and lineaments. The *very good* and *good* zonal categories are along major lineaments and drainage channels with and without structural control, highlighting the importance of lineaments and geomorphological units for groundwater investigations. Areas with *moderate* groundwater potential are attributed to combinations of lithology, slope and landform. The *low* to *poor* categories of groundwater potential are distributed mainly along ridges and pediments and to some extent along lineaments in the *low* to *poor* slope classes. The basalts in the west (Fig. 8a) are classified as having *moderate* to *very good* groundwater potential. Densely fractured basaltic rocks show *good* to *very good* groundwater potential.

Discussion and conclusions

Due to insufficient data coverage, groundwater studies often require interpolation or extrapolation from a few observation points into large areas. This is especially critical for hard rock aquifers with complex and extensive hydrogeological heterogeneities at extremely varying scales. In areas with limited previous investigations and few hydrogeological data, remote sensing and GIS methods provide support in groundwater studies. Lithological and lineament maps, very useful for groundwater studies, were prepared based on optical satellite data. Digital elevation models were used for geomorphologic mapping and identification of the potential for using landforms to interpret zones suitable for groundwater development in addition to lineament delineation. Field studies were helpful to discern the nature of structures and correlate lineament interpretation with geological structures. Moreover they provided an understanding of the hydrogeological conditions of the hard rock aquifers.

The occurrence of groundwater is controlled by rock type, structures and landforms as revealed from GIS analyses and field investigations. In basaltic rocks intensely weathered lava flows largely control groundwater storage and availability. High yields are due to primary and secondary porosities. Flat topography with dense lineaments characterize zones of high groundwater potential. Basaltic layers overlying lateritized crystalline rocks form multiple aquifer systems. In metamorphic rocks foliations serve as planes of weakness and facilitate flow and storage of groundwater. In the nonfoliated metamorphic and granitic rocks in combination with rugged landforms, groundwater occurs mainly in drainage channels with valley fill deposits. Fractures aligned with drainage channels containing valley fill deposits form an integrated aquifer system and have high groundwater potential. A high correlation of well yield with the proximity to lineaments interpreted from satellite images confirms the fact that high yielding wells and springs are often related to large lineaments, lineament intersections and corresponding structural features with dense fracture spacing.

Remote sensing data cover large areas with direct observations, allow the interpretation of landforms, geology, land cover etc. and thus minimize the need for interpolation from point observations of these features. Digital elevation models allow the delineation of drainage systems, catchments, geomorphological features and slope conditions over large areas. All this information is available in a GIS. Observations from wells, springs and outcrops provide point information and can be used to investigate correlation of hydrogeologic properties with e.g. rock types and geomorphological features. This knowledge can then be used to establish a model of the hydrogeological conditions, to apply this model to estimate groundwater yield and to determine suitable strategies for groundwater exploration.

Due to the limited number of observation points in this study only a qualitative model was used with four to five levels for each factor. The resulting map of zones of groundwater potential summarizes the results of this model and accounted for heterogeneities in hard rock aquifers in different ways. Typical heterogeneities that were identified include, e.g. columnar joints in basalts, and the occurrence of fracture zones along lineaments. Channels are often structurally controlled and contain valley fill deposits in hydraulic contact with the underlying hard rock fracture system. Small-scale heterogeneities are observed in outcrops, but cannot be mapped at the scale of the map of zones of groundwater potential. The overall results demonstrate that remote sensing and GIS provide potentially powerful tools for studying groundwater resources and designing a suitable exploration plan.

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