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Quality of Remote Sensing Data Affecting Thematic Mapping for GIS based Groundwater Assessment in Eritrea

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Keywords: remote sensing, SRTM, ASTER, data quality, groundwater, Eritrea

Summary: Geographic information systems and remote sensing data provide a powerful combination for the assessment of groundwater resources in arid to semiarid countries like Eritrea. In a study these techniques were combined with traditional investigations, pumping tests and structural measurements. This provided interesting insights in the groundwater situation in the central highlands of Eritrea and objectives for further investigations. Data quality affects the achieved results significantly. In this paper the effects of improved data quality is shown in a number of examples with regard to Global Positioning System (GPS) location, evaluation of digital elevation models derived from contours and through radar interferometry in the Shuttle Radar Topography Mission (SRTM) and comparison of multispectral data from ASTER, Landsat TM and SPOT.

Zusammenfassung: *Einfluss der Qualität von Fernerkundungsdaten auf die Thematische Kartierung zur Beurteilung von Grundwasser-Vorräten in Eritrea in einem GIS*. Geographische Informationssysteme und Fernerkundungsdaten liefern eine kraftvolle Kombination zur Beurteilung von Grundwasser-Ressourcen in ariden und semiariden Länder wie Eritrea. In einer Untersuchung wurden diese Techniken mit traditionellen Feldarbeiten, Pumpversuchen und Strukturmessungen kombiniert. Das lieferte interessante Einblicke in die Grundwassersituation im zentralen Hochland von Eritrea und Ziele für weitere Untersuchungen. Die Datenqualität beeinflusst die erzielten Ergebnisse deutlich. In diesem Beitrag wird der Einfluss verbesserter Datenqualität an den Beispielen Lokalisierung mit dem Global Positioning System (GPS), Auswertung von digitalen Höhenmodellen, die aus Höhenlinien bzw. durch Radar-Interferometrie in der Shuttle Radar Topography Mission (SRTM) gewonnnen wurden und Vergleich der multispektralen Daten von ASTER, LANDSAT TM und SPOT aufgezeigt.

Introduction

Water is scarce in Eritrea. In almost all villages water supply comes mainly from dug wells 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 and a systematic approach to groundwater exploration is lacking. Integration of remote sensing, GIS and traditional field studies has proven to be an efficient tool in groundwater studies (e. g. SANDER 1996). The overall aim of a Ph.D. thesis (SOLOMON 2003) was to contribute towards systematic groundwater studies combining remote sensing, field studies, digital elevation models (DEM) and geographic information systems (GIS) to assess groundwater resources in the central highlands of Eritrea. The specific objectives are:

- To prepare thematic maps such as lithology, lineaments, landform and slopes from remote sensing data and DEM.
- To assess groundwater controlling features by combining remote sensing, field studies and DEM.

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- To identify and delineate ground water potential zones through integration of various thematic maps with GIS techniques.
- To evaluate the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data for lithology and lineament mapping.
- To compare digital elevation models, derived from contours and from radar interferometry in the Shuttle Radar Topography Mission (SRTM) for geomorphological and lineament mapping applications.
- To make recommendations for the future work and provide guidelines for groundwater prospection.

The methodology employed is summarized in Fig. 1. It involves digital image processing and interpretation for the extraction of lithological and linear features, evaluation of digital elevation models as well as field studies for hydrogeological and structural investigations. DEMs were used to extract lineaments and to map drainage systems and landforms. All data were integrated in a GIS and analyzed to assess the groundwater controlling features. Finally groundwater potential maps were prepared based on the GIS analysis. This provided interesting insights in the groundwater situation in the central highlands and objectives for further investigations. However, data quality affects the achieved results significantly. The main objective of this paper is thus to show the effects of improved data quality with regard to location using the Global Positioning System (GPS), evaluation of digital elevation models and comparison of multispectral data from ASTER, Landsat TM and SPOT. 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.

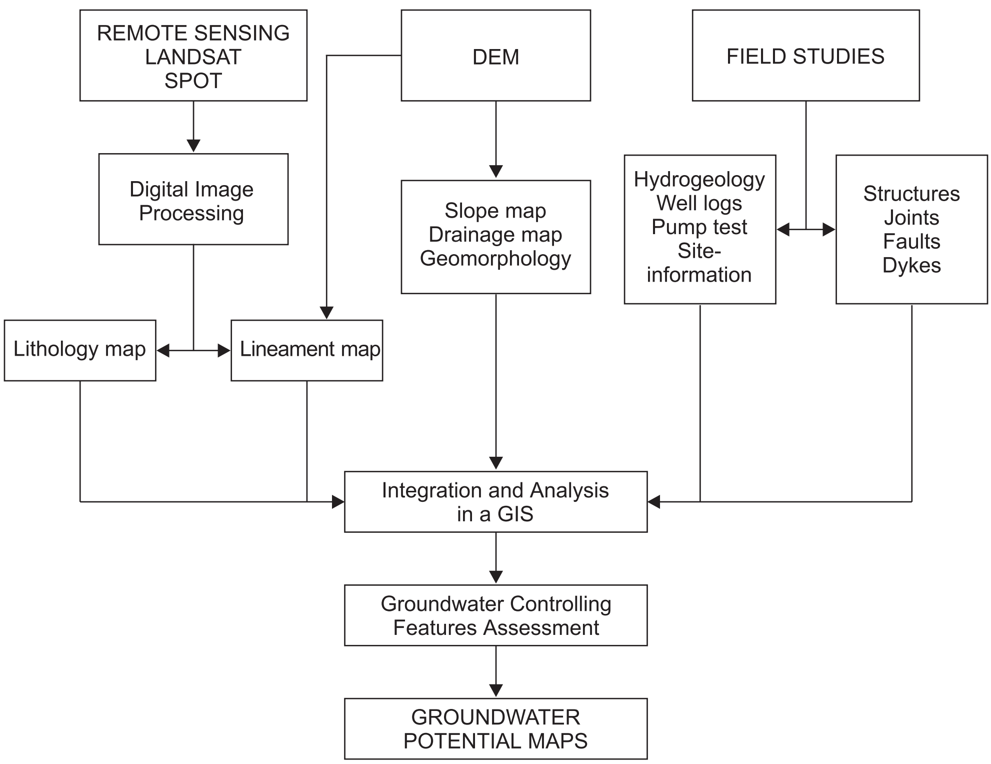


Fig. 1: Flow chart showing data and methods employed in the study.

Study area

Eritrea is located in the horn of Africa and is geographically bounded by Ethiopia to the south, Sudan to the west and north, the Red Sea to the east and Djibouti to the southeast (Fig. 2). The country is divided into three physiographic regions, namely: the western lowland (500–1500 m), central highland (1500–2500 m) and eastern coastal lowland (0–1500 m). The climate is arid to semi-arid with two rainy seasons in the study area. The long rainy season is during the summer from June to September, and the short spring rain during March to April. Rainfall is intense during the period from mid-July to mid-August. The average annual precipitation ranges from 300 to 600 mm. Potential evapotranspiration is approximately 1700 mm/year. Daily temperatures usually vary from 10° to 30 °C.

The country is part of the Arabian-Nubian Shield, which is characterized by a low-grade volcanosedimentary-ophiolite assemblage, granitoids and gneisses (e. g. Vail 1987). The regional geology of the central highlands where this study is focused is given in Fig. 2. The study area is 30 km by 30 km in size and is dominated by crystalline (granitoid and metamorphic) rocks, which form the highland plateau and a steep escarpment parallels the Red Sea rift towards the northeast. Elevations vary from 1300 m down the escarpment to 2600 m on the plateau.

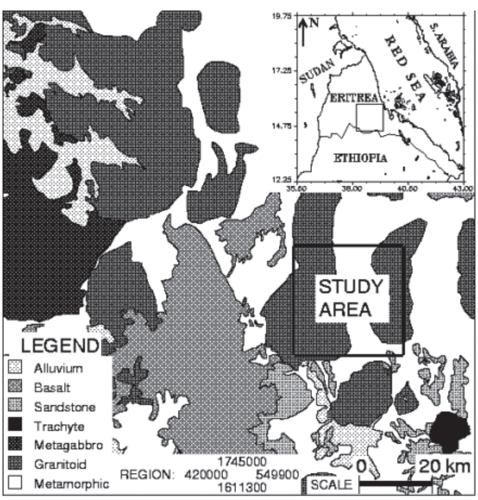


Fig. 2: Location and regional geology.

Data and Methods

GPS location of boreholes

The hydrogeological data consist mainly of a water point database with dug-well and borehole information. The data were entered into a GIS and site maps of water point yields were created and converted into raster format. The relationship between water point yield and distance from lineaments was examined. Buffer zones with 20 m distance interval were created and borehole yields correlated with proximity to lineaments. The correlation studies have been carried out using first the original location values for the boreholes and then GPS (Global Positioning System) positioned or surveyed boreholes.

Digital elevation models

Digital elevation models are useful to derive topographic parameters such as slope and surface curvatures and map drainage systems as well as landforms. Moreover DEMs can be used to extract lineaments useful for groundwater studies. Two types of digital elevation model data were available for this study. The first is a DEM with 50 m spacing derived from contours with 40 m equidistance in topographic maps at a scale of 1:100,000. Data to derive the second digital elevation model were acquired during the Shuttle Radar Topography Mission (SRTM) launched on February 11th, 2000. SRTM collected radar data in the X and C band, which are now processed using radar interferometry to generate a nearly global DEM with 1 arc second spacing, that is about 30 m, and an accuracy better than 20 m. Analysis of SRTM data by Koch et al. (2002) indicates that the height accuracy depends on land cover, in particular forests, settlements and water bodies and is about ± 3–4 m in open areas. They also suggested the existence of other systematic errors (see

Koch et al. 2002 for details). DEMs derived from contours and from SRTM were compared in relation to location and information content regarding drainage networks, linear features and morphological parameters.

Multi-spectral remote sensing

Landsat TM-4 (acquired September, 1987), SPOT (acquired April 6, 1996) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, acquired December 15, 2001) data were used to assess the effects of data quality for lithological and lineament mapping. The spectral bands and the pixel size of each sensor are given in Tab. 1. Geometric transformation with 30 m pixel size was carried out for all ASTER and Landsat TM bands using ground control points, the Universal Transverse Mercator (UTM) coordinate system and nearest neighbor resampling. The thermal infrared (TIR) bands were converted from unsigned integer to byte data type in order to avoid statistical bias during the principal component transformation. Furthermore the digital number values from the visible near-infrared (VNIR) and short wave infrared (SWIR) bands of ASTER data were divided by a factor of two to facilitate comparisons of image spectra of geological materials in all wavelength regions.

Tab. 1: Multispectral data used in the study.

Sensor	Band	Wavelength (μm)	Pixel size (m)
LANDSAT TM	1	0.45–0.52	
	2	0.52–0.60	
	3	0.63–0.69	30
	4	0.76–0.90	
	5	1.55–1.75	
	7	2.08–2.35	
SPOT	1	0.50–0.59	
	2	0.61–0.68	20
	3	0.79–0.89	
ASTER*	1	0.52–0.60	
	2	0.63–0.69	15
	3	0.78–0.86	
* Bands 1–3: VNIR (visible and near infrared)			
	4	1.60–1.70	
	5	2.145–2.185	
	6	2.185–2.225	
	7	2.235–2.285	30
	8	2.295–2.365	
	9	2.360–2.430	
* Bands 4–9: SWIR (short wave infrared)			
	10	8.125–8.475	
	11	8.475–8.825	
	12	8.925–9.275	90
	13	10.25–10.95	
	14	10.95–11.65	
* Bands 10–14: TIR (thermal infrared)			

The effect of pixel size and season on lineament mapping was evaluated by comparing color infrared composites from each sensor in Tab. 1 subjected to intensity-hue-saturation (IHS) transformation. Principal component transformation was performed on both the six reflective bands of Landsat TM and 14 bands of ASTER data (Tab. 1) to assess the effect of number of bands, their wavelength and bandwidth for lithological mapping. To better evaluate the spectral information contained in ASTER's three wavelength regions, single pixel image spectra of selected rock types were extracted and examined in relation to the color variations in PC color composite images.

Results

GPS location of boreholes

The yield-proximity relationship for boreholes without GPS positioning or surveying is ambiguous (Fig. 3). If well loca-

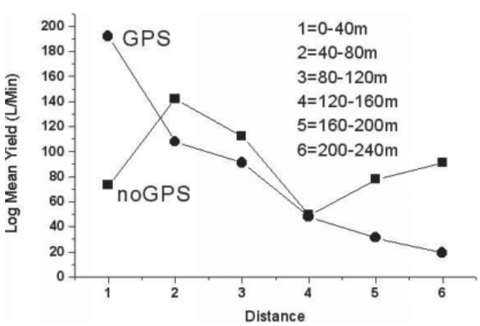


Fig. 3: Correlation between borehole log mean yield (Litres per minute) and distance from lineaments, before and after repositioning with GPS.

tions for the same boreholes are determined more precisely using GPS receivers or traditional surveying methods the correlation improves significantly and shows a clear inverse relationships between yield of GPS positioned boreholes and distance from satellite image lineaments (Fig. 3). Although based on a small borehole population, this study clearly demonstrates the need for accurate coordinates when comparing various spatial data in a GIS.

Digital elevation models

Fig. 4 shows DEM and elevation profiles along section A-A'. The profile from the contour derived DEM (Fig. 4a) generally smoothens the topography. The overall picture looks good but lacks details of drainage systems. In the SRTM DEM the elevation varies over short distances (Fig. 4b). Morphological details like small valleys, ridges but also small plateaus are clearly visible in the SRTM data, but are often less clear or even missing in the contour derived data. The difference of SRTM and contour DEMs is shown in Fig. 4c. Note that the peaks and depressions in the difference profile (Fig. 4c) coincide with the profile from the SRTM (Fig. 4b). This indicates that variations in elevation differences are mainly due to greater detail in the SRTM data. Adjacent large white and dark areas with sharp boundaries, e. g. in the eastern part of Fig. 4c indicate shifts in X and/or Y direction between the two DEMs.

The frequency distribution of the difference between the two digital elevation models shows near normal distribution from about −200 to +200 m. The mean elevation difference is about 40 to 50 m. In flat areas the elevation differences are small indicating that there is no systematic bias due to e. g. differences in datum. The positive differences are noted on higher grounds such as ridges and peaks. In contrast the negative differences are often related to narrow valleys and along sloping surfaces, which are underrepresented in the contour DEM.

The general pattern of the drainage network derived from the two digital elevation

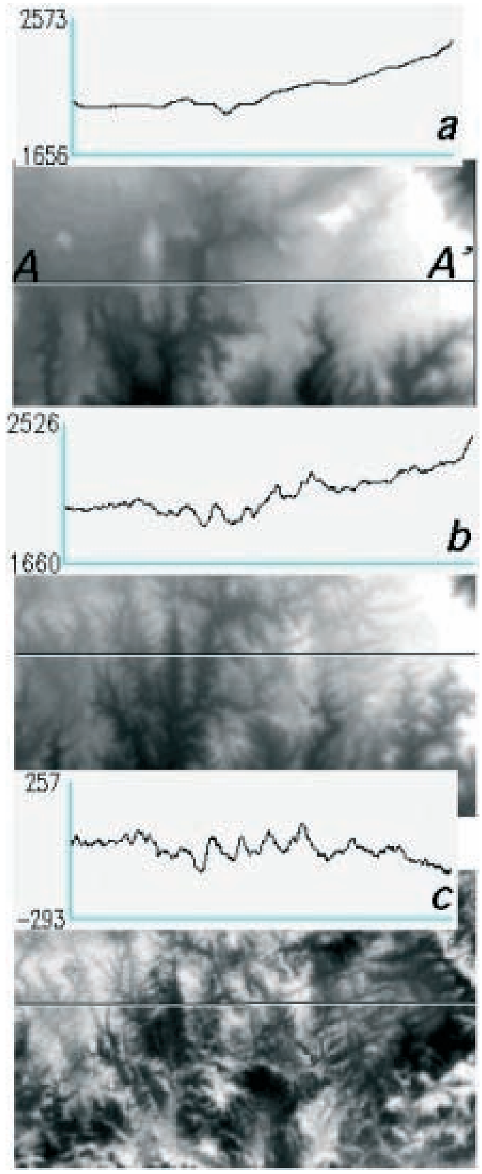


Fig. 4: DEM (12 km × 17 km) and elevation profiles along A-A' (a) from contours (b) SRTM and (c) difference of SRTM and contour DEM.

models is similar (Fig. 5). Major high order tributaries are apparent in both DEM's, while low order drainage channels are better delineated in the SRTM data. Moreover several drainage channels that are extracted from the SRTM DEM are not detected from the contour DEM due to lack of detail in

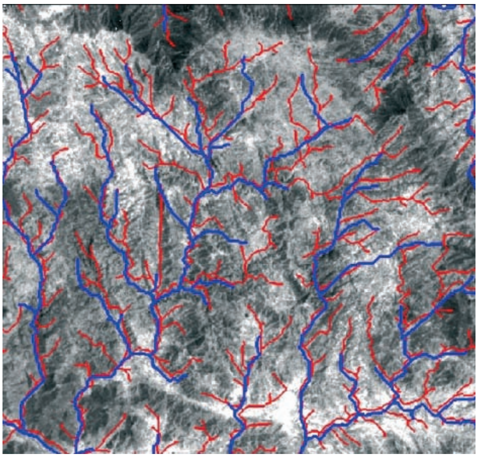
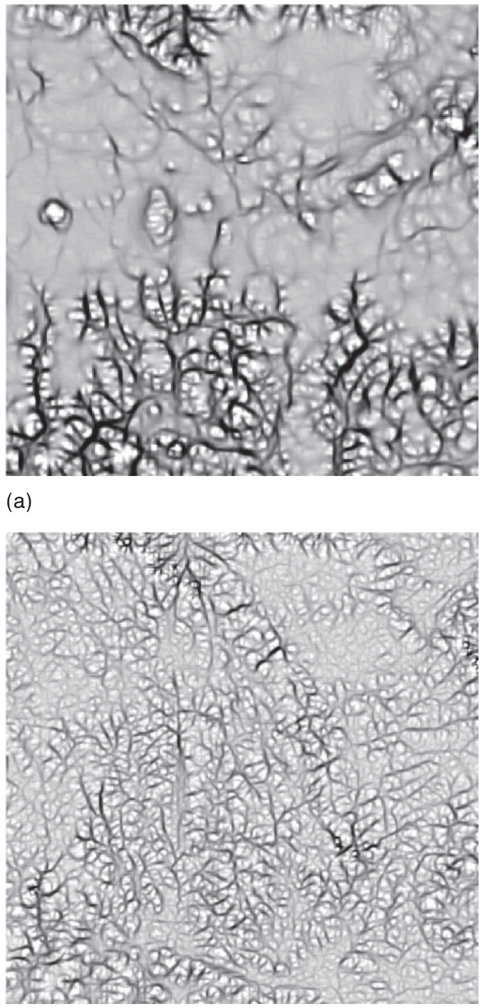


Fig. 5: Drainage networks derived from the contour DEM (blue) and the SRTM DEM (red) overlain on SPOT band 3 image. Area 17 km × 17 km.

the data set. In general topographic parameters like drainage systems are influenced by contour line spacing and resolution of the DEM and in flat areas not all characteristic features may be identified. The existence of systematic shift of location between the two data sets is clearly visible in the overlays of the drainage systems. Overlays of the drainage networks over a SPOT band 3 image shows additional shifts. Since the SPOT data were taken slightly oblique displacements due to height differences occur and this is sufficient to cause the additional systematic error. Because a DEM was not available during geometric transformation it was not possible to make height corrections. Highly accurate topographic information such as the SRTM data and/or use of GPS can reduce the geometric errors and thus improve data quality.

In minimum curvature images derived from both digital elevation models (Fig. 6) linear features are mostly expressed by alignment of drainage channels. The most conspicuous trends are N-S, NW-SE and NE-SW to ENE-WSW. The NE-SW/ENE-WSW is not obvious from the contour DEM. Other trends though discernible in the contour DEM generally are less numerous when compared with the SRTM data. Overlay of contours with line spacing of 40 m show wide spacing in the blurred areas (center of Fig. 6a) and dense spacing for instance at the bottom of the same figure. Comparison between the two digital elevation models demonstrates that the SRTM digital elevation model is better for detection of drainage systems and linear features than the contour DEM. This superiority is mainly due to greater detail in the SRTM



(a)

(b)

Fig. 6: Minimum curvature images derived from digital elevation models of the same area as Fig. 5 (a) contours (b) SRTM. White: positive (convex) curvature (e. g. ridges), grey: plane black: negative (concave) curvature (e. g. small valleys).

data as a result of a dense grid of measured elevation points. It also shows how the achieved results (drainage extraction and lineament interpretations) were affected by poor data quality due to interpolation from contour lines.

Multi-spectral remote sensing

In the Landsat TM color infrared image (bands 4, 3, 2) dyke swarms are hardly recognizable because of relative large pixels of 30 m (Fig. 7a). The dyke swarms are more obvious in the SPOT bands 3, 2 and 1 with 20 m pixels (Fig. 7b). Dyke swarms with dominantly NNE-SSW orientations are clearly visible in the color infrared composite with bands 3, 2 and 1 of ASTER with 15 m pixels (Fig. 7c). Vegetation cover in red varies significantly due to seasonal differences. Landsat data were collected at the end of the rainy season and large areas are covered by vegetation. The ASTER data were collected in the dry season and have less vegetation cover, which further improves visibility of linear features. This investigation shows the potential of ASTER data for lineament mapping as a result of the improved spatial resolution. Moreover the nadir and backward looking near-infrared bands provide stereo-coverage and can facilitate detailed lineament mapping. Lineaments such as dykes have great hydrogeological significance in hard rock areas with arid to semi-arid climate like Eritrea. This study already showed good correlation between well yields and proximity to lineaments mapped from Landsat TM and SPOT data. Thus improved data quality is crucial and has great hydrogeological significance.

A color composite created from Landsat PC 3, 2 and 4 is given in Fig. 8a. In this image the post-tectonic granite unit appears less

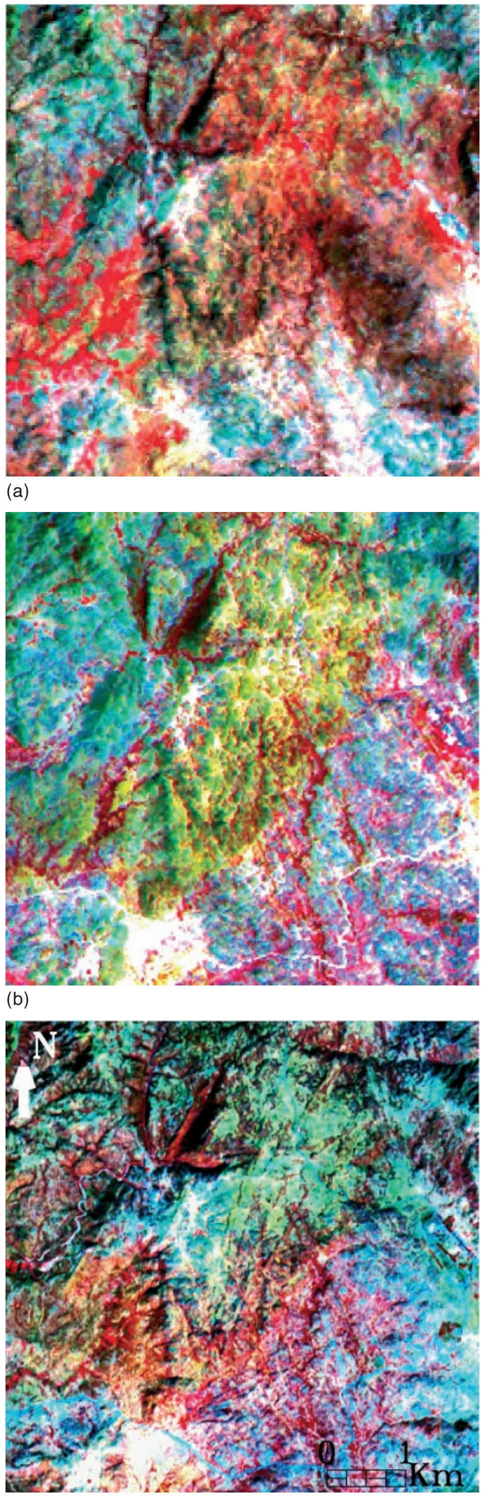
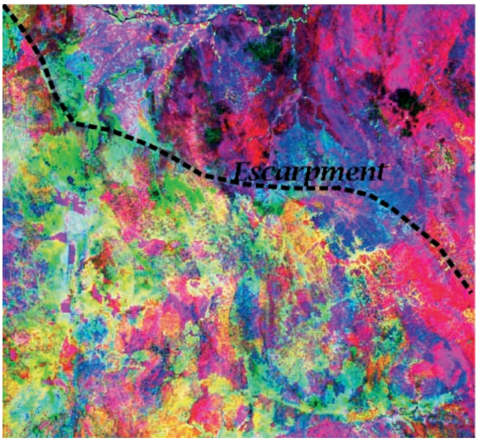
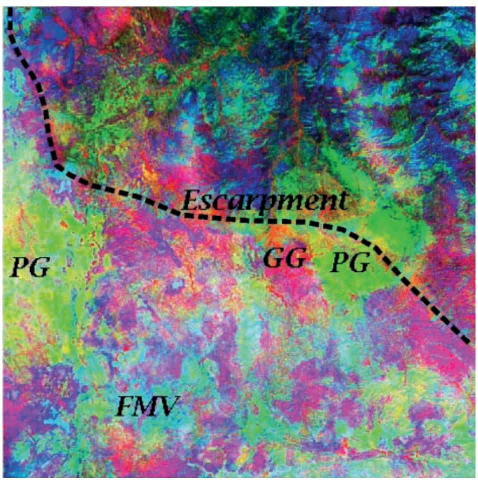


Fig. 7: IHS-transformed color composites in RGB order (a) TM bands 4, 3, 2; 30 m pixels (b) SPOT bands 3, 2, 1; 20 m pixels and (c) ASTER VNIR bands 3, 2, 1; 15 m pixels. Dyke swarms are mainly located near the image center in (c). Vegetation cover appears in red color. Area 6 km × 6 km northwest of the study area.



(a)



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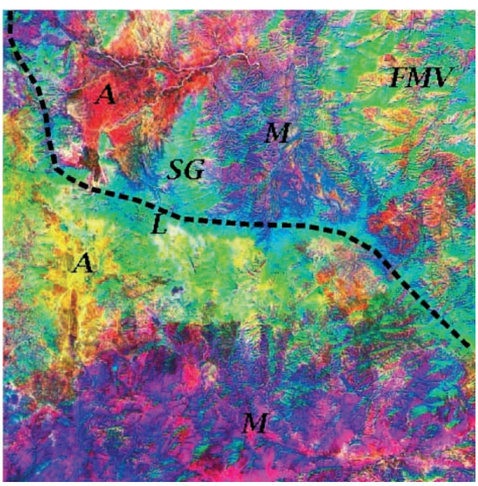


(c)

obvious when compared with the principal component color composite image (PC 4, 5 and 6) derived from ASTER data (Fig. 8b). Despite similarity in the composition of rocks to the south and north of the escarpment, variations in color are conspicuous in Fig. 8b. Rocks on the north side of the escarpment (down) show dominantly blue color whereas rocks on the south side of the escarpment (up) show dominantly magenta, cyan and green colors. These variations are due to variations in the degree of weathering and are in this form not obvious in the Landsat TM principal component color composites (Fig. 8a). A color composite of the first three ASTER principal component images is presented in Fig. 8c. The regional geology including local variations in geologic materials are apparent on this image. The metamorphic rocks to the south (bottom of Fig. 8c) appear in magenta and red colors. Yellow to light green to cyan colors immediately south of the escarpment represent the granitoid rocks. The metamorphic and granitoid rocks also persist down the escarpment to the north with different colors in the PC 1, 2, 3 image. The alluvial materials exhibit yellow color (south of the escarpment) and red color (north of the escarpment). Lateritized crystalline rocks (metamorphic and granitoids) appear in white with shades of yellow colors. The regional geology that is conspicuous from the ASTER data is not apparent in the Landsat TM data.

Fig. 9 shows for the northeastern part of Fig. 8a comparison of Landsat PC 3, 2 and 4 (Fig. 9a) and PC 7, 8 and 9 (Fig. 9b) derived from ASTER data. The various units in the metamorphic rocks are hardly differentiated in the PC image derived from the Landsat TM data, but are clearly apparent

Fig. 8: Principal component color composite images from (a) Landsat TM PC 3, 2, 4 (b) ASTER PC 4, 5, 6 (c) ASTER PC 1, 2, 3. All in RGB order. Escarpment marked by dashed line, A: alluvium, PG: post-tectonic granite, GG: granite gneiss, FMV: foliated metavolcanics, SG: syntectonic granite, M: metamorphic and L: laterite. Area 30 km by 30 km.

(a)

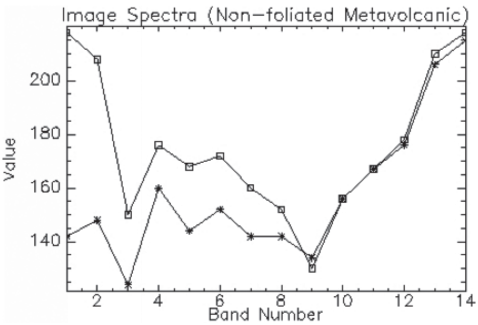
(b)

Fig. 9: Comparisons of principal component images northeast of the escarpment in metamorphic rocks (a) PC 3, 2, 4 derived from Landsat TM and (b) PC 7, 8, 9 derived from ASTER, both in RGB order. A: non-foliated metavolcanics, B: foliated metavolcanics and C: metasediments. Area 10 km × 10 km.

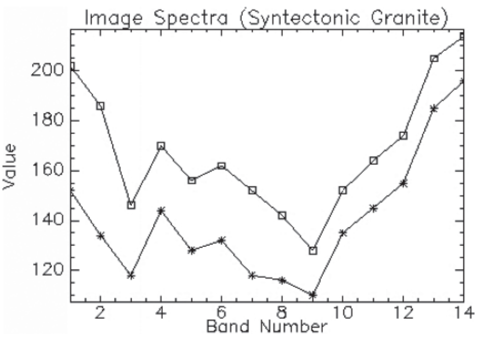
in the PC image derived from ASTER data. This shows the level of detail that can be extracted from ASTER data for lithological mapping purposes even from lower principal components.

Examples of image spectra collected from rocks up and down the escarpment are given in Fig. 10. The spectra collected from rocks on the down side of the escarpment are marked with squares and those on the up side of the escarpment marked with asterisk. In metamorphic and granitoid rocks spectral profiles collected down the escarpment generally show higher reflectance and emissivity in all wavelength regions than those collected on the upper side of the escarpment (e. g. Figs. 10a and 10b). These spectral variations are clearly visible on the PC 4, 5, 6 (Fig. 8b) and reflect the degree of weathering of the rocks involved (see e. g. Younis et al. 1997, Hunt 1977). This observation is further supported by the ease in discriminating lithological units in the metamorphic rocks down the escarpment because of less alteration and absence of thick soil cover. Thick soil development derived from chemical weathering and dense natural vegetation cover caused difficulty in lithological discrimination south of the escarpment. Fig. 10c shows image spectra taken from the post-tectonic granites (east and west in Fig. 8b). Agreements in the spectral profiles from the two suggest similarity in minerals that make up the rocks and this is conspicuous in the PC 4, 5, 6 color image where they appear in green. Spectral profiles from the alluvial materials are given in Fig. 10d. Difference in colors in the PC 1, 2, 3 image (Fig. 8c) is also shown in the image spectra. Variations in color in the PC 1, 2, 3 image in alluvial materials are attributed to differences in brightness from PC1. Variations in brightness are partly due to higher surface temperatures caused by lower elevation down the escarpment. Improved ASTER data products with reflectance and emittance values will facilitate image spectra interpretation.

However, general inferences can be made from the data. Difference in the VNIR bands reflect the degree of weathering of iron-bearing minerals, for instance, chlorite, actinolite and hornblende in the non-foliated metavolcanic rocks on both sides of the escarpment (Fig. 10a). The cause of the variations in the VNIR bands in the post-tectonic granites and alluvium is similar to non-foliated metavolcanic rocks. A continuous decline in the reflectance curves in the SWIR



(a)



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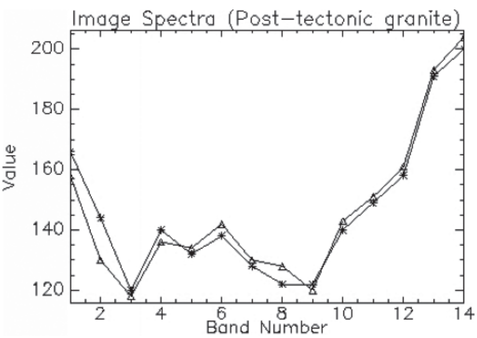

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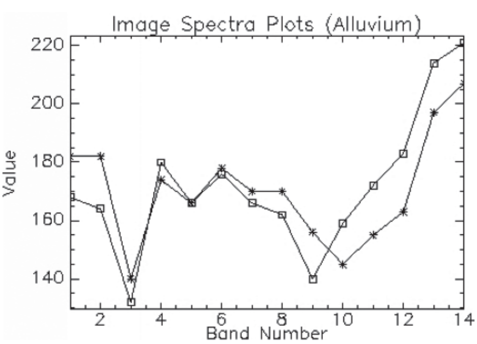

(d)

bands in all spectral profiles suggests presence of clay minerals derived from chemical weathering of crystalline rocks. No significant variations in the emissivity of the less weathered (down escarpment) and highly weathered (up escarpment) metamorphic rocks are observed in the TIR wavelength region (Fig. 10a). This is probably due to lower amounts of silica-bearing minerals in the metamorphic rocks when compared to the granitoid rocks, which show variations in the emissivity in the TIR bands.

Conclusions

Effects of remote sensing data quality on the production of thematic maps used to assess groundwater resources have been demonstrated in a number of examples. Accurate coordinates are essential when comparing various spatial data in a GIS. GPS technology can improve coordinate accuracy significantly and facilitate data integration in a geographic information system. Digital elevation models derived from modern remote sensing systems such as SRTM data are better for detection of drainage systems, linear features and have high geometric accuracy compared to those derived from contours. This superiority is mainly due to the dense grid of measured elevation values in the SRTM data and interpolated grid points derived from contours. The improved data quality in terms of spectral and spatial resolution from ASTER data compared to other satellite data such as Landsat TM and SPOT, is a significant advantage in preparing detailed lithological and lineament maps of excellent quality that have great hydrogeological importance. Modern systems such as ASTER and SRTM as well as GPS

Fig. 10: Image spectra collected from selected rocks (a) non-foliated metavolcanic rocks (b) syntectonic granites (c) post-tectonic granites and (d) alluvium. In figures (a), (b) and (d) spectra with squares are from down the escarpment and asterisks from up side of the escarpment. In figure (c) both spectra are from the up side of the escarpment with the asterisks from eastern and triangle from western post-tectonic granite rocks (see location in Fig. 8b and 8c).

technology provide high quality data crucial for assessment of groundwater resources using remote sensing and geographic information systems.

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