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Landsat and SPOT Data Interpretations of Geo-Hydrological Aspects in Wadi Tabalah Area, Kingdom of Saudi Arabia

MOHAMMED YOUSEF H.T. QARI[1], ALI U. SORMAN[2]*, ABDULKADER M. AL-SARI[3] and MEHBOOB M. HASSANI[2]

[1]*Faculty of Earth Sciences, King Abdulaziz University, Jeddah,* [2]*Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University, Jeddah,* [3]*King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia.*

ABSTRACT. Remotely sensed digital satellite data play an important role nowadays in geo-hydrological studies, especially when integrated with GIS techniques. Landsat and SPOT imagery were utilized in a lithologically homogeneous terrain in the middle of the southern Arabian Shield to delineate land-classes, soil temperature, and soil moisture content quantitatively and qualitatively.

Four landuse categories (agricultural, urban, uncultivated, uncultivable) were identified from visible and infrared satellite data. Radiance temperature differences were computed for these categories from thermal infrared data and were found to be in good agreement with those predicted from the theoretical functions relating soil moisture to daytime temperature.

Results indicate that satellite imagery could be used successfully to predict soil moisture and to assess droughts in the Arabian Shield or any other arid land.

Introduction

Description of Study Area

Wadi Tabalah is located to the east of Asir Mountains in the southwestern part of the Kingdom of Saudi Arabia. The main wadi has a drainage area of 1900 km^2 with elevation ranging from 2440 to 1200 m. Geologically, the basin is entirely within the southern Arabian Shield and is underlain by Precambrian crystalline rocks. This study covers the upper catchment of Wadi Tabalah which is a fourth order stream with a drainage area of 170 km^2.

* Permanent Address : Middle East Technical University, Civil Engineering Department, Ankara, Turkey.

Upper Tabalah basin has four sub-catchments named Shaybanah, Al-Hamid, Ayn, Ghudar and Shaiba as presented in Table 1. The tributaries join and flow towards the north direction as shown in Fig. 1. Wadi Ayn has the largest percentage of agricultural development and urban settlements from the land use point of view and also the longest stream course of all orders. The total sum of lengths of the streams was measured around 300 km from the satellite imagery.

TABLE 1. Characteristics of Upper Tabalah Sub Basins.

ID #	Name	Area (km^2)	Stream length (km)	Bifurcation ratio R_B	Area ratio R_A	Length ratio R_L
1a	Shaybanah	46.5	64.0	3.162	4.29	2.65
1b	Al-Hamid	12.5	30.2			
2a	Ayn	53.0	87.1	5.385	6.71	2.93
2b	Ghudar	28.0	53.3			
3	Shaiba	21.6	43.4	N/A		
4	Tabalah	8.0	17.8			
Total		169.6	295.8			

Geology

As described by Prinz (1983), the study area is mostly composed of a predominant lithological unit which is tonalite as well as sub-ordinate diorite of Late Proterozoic age. The granitoid rocks form part of the western side of the large An-Nimas Batholith, a body that is 70 km wide and 150 km long in a N-S direction; the largest discrete dioritic batholith in the southern Arabian Shield.

Diorite is typically medium grained, darker colored and is formed of mafic minerals that constitute up to 60% of the rock. These minerals are mainly biotite and hornblende. Plagioclase which is mainly andesine in composition was observed to be present in these diorite, whereas tonalite ranges in texture from coarse to fine grained and has a lower color index, *i.e.* lighter grey. It consists mainly of plagioclase in the range of oligoclase-andesine, abundant quartz and biotite. Both tonalite and diorite have suffered metamorphism under the conditions of greenschist facies. Remarkable penetrative deformation is almost obvious in these rocks.

Numerous dykes of weakly metamorphosed basalt and andesite were observed in the study area, particularly in the southern half of the study area and they mostly follow a NW trend.

Methodology

Data Collection and Image Processing

The digital satellite data from Thematic Mapper (TM) sensor of Landsat-5 (spatial resolution = 30 m) and Multi-Linear Array (MLA) of SPOT's High Resolution Visible (HRV) sensor (spatial resolution = 20 m) were used. Three established enhancement techniques were followed, which include false color composite (FCC), principal com-

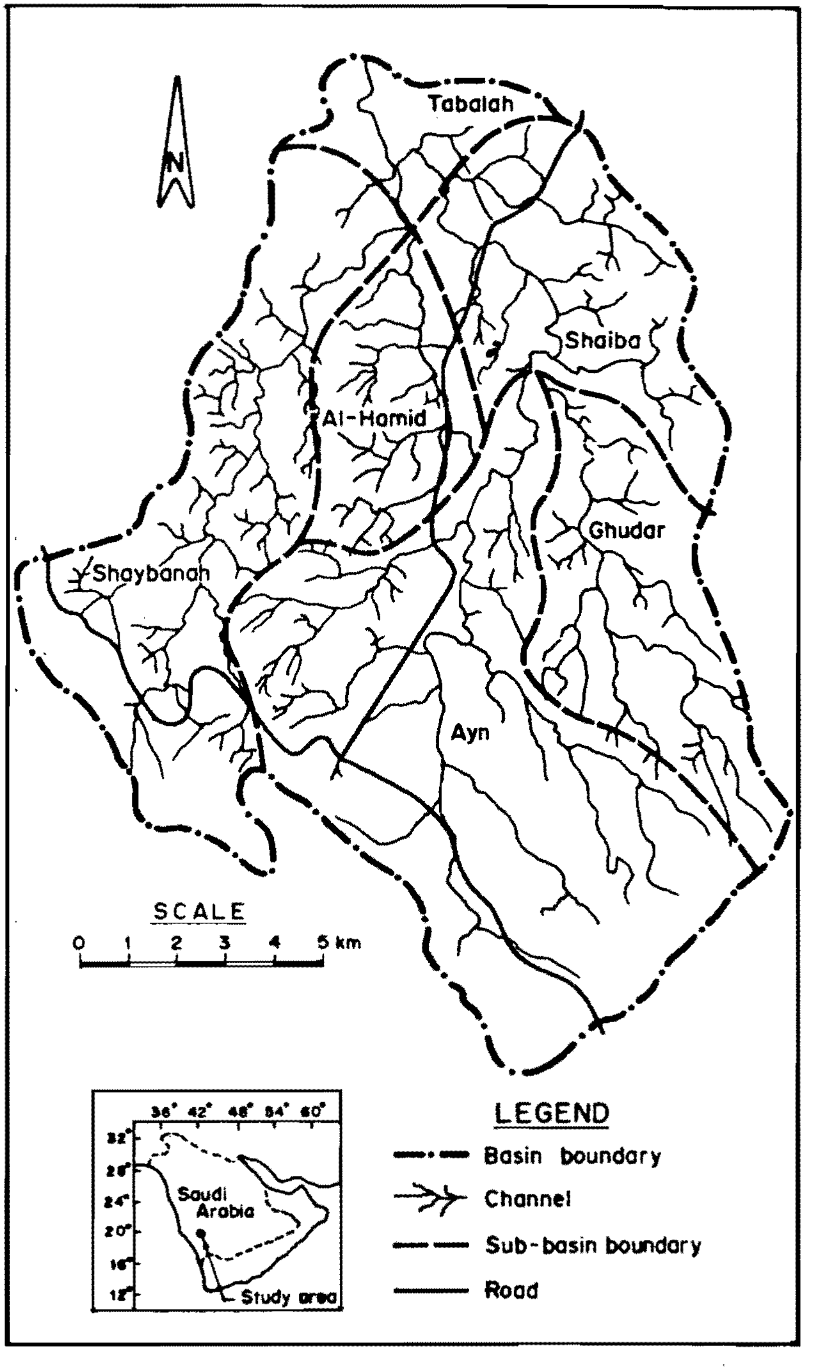

FIG. 1. Sub-catchments and stream-network density of Upper Tabalah.

ponents analysis (PCA) and ratio.

First step in image processing included the use of TM bands 1-5 (wavelengths 0.45-1.75 μm) to analyze the land use, type of land covers of soil and vegetation. The ratio technique using bands 2/3 of MLA and/or bands 3/4 of TM was selected to determine the drainage network and land topography. The mid-infrared (IR) band 7 of TM (2.08-2.35 μm) was used to analyze geological features and rock formations.

TM thermal IR band 6 (10.4-12.5 μm) was used for the spatial distribution of Digital Numbers (DN's) to verify wet and dry areas, whereas the ratio image was used to produce detailed morphological map of the stream configuration. The morphological map was georeferenced with the raster map (band 6) in a GIS environment, Fig. 2.

The FCC's obtained from other TM and MLA bands, and PCA techniques of TM and MLA images helped to delineate various land uses. For example, the first two groups constituted the vegetative and the urban settlement units. The uncultivated/uncultivable lands are forming the third group which is sub-categorized as foothills and mountainous uplands with medium slopes at the foothills of the escarpment as the first sub-group, and outcropping rocks with well defined peaks, crests and steep sided tectonic features as the second sub-group.

Processing of TM and MLA Data

Visual inspection of various land use types was done on color prints using TM or MLA images in different scales. Image interpretation of the area using FCC was carried out after bringing TM and MLA images to the same scale.

The georeferenced colored images with convenient scale and band combinations were produced from SPOT-MLA data. These selected images presented in Fig. 3 and 4 provide various landform and land uses. The boundaries of agricultural (red), urban settlement (blue) and uncultivated/uncultivable lands (dark and light green) as seen on SPOT images were delineated during the processing of the data.

SPOT-MLA images produced digitally by the ERDAS Imagine image processing system provided a better interpretation of land uses for the area because of their high spatial resolution. Enlargements of two areas outlined by boxes are also shown in Fig. 5. It is noteworthy to mention that mapping was done on a scale comparable to that shown in the enlarged boxes, Fig. 5.

Processing of TM Thermal-Infrared Band 6

The TM thermal infrared band 6 readings as DN's were obtained after correcting for the atmospheric effects utilizing the available histogram contrast in the ERDAS Imagine software. Image pixels were resampled at every five pixels in dense areas with cultival activity and ten pixels at every others. The values of DN range between 50-250 and are divided into six groups for analysis as presented in Table 2 using 30 as class interval. The corresponding radiant temperature differences are calculated for the limits of each subgroup using Landsat look-up tables and respective conversion equations as presented by Markham & Barker (1986). In addition, spectral radiances of TM band 6 at

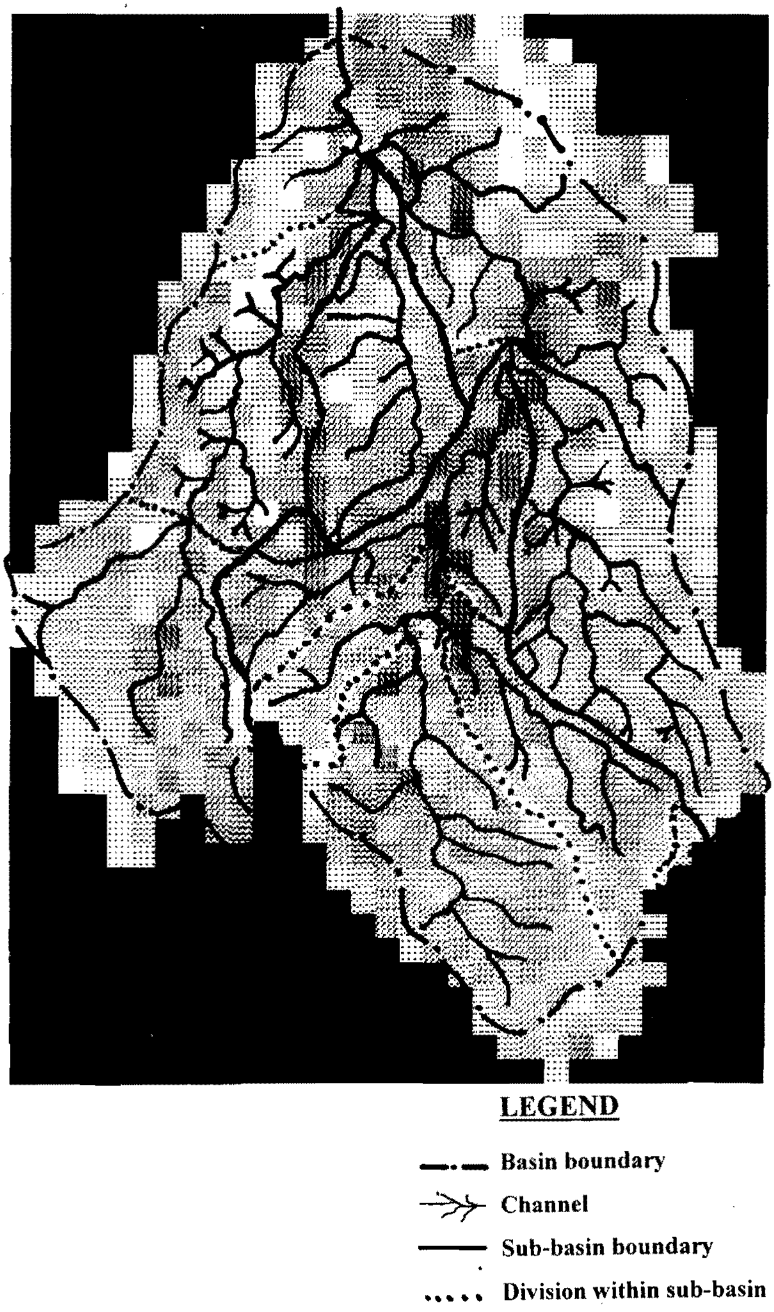

FIG. 2. TM band 6 DN's raster map superimposed with channel network for Upper Tabalah.

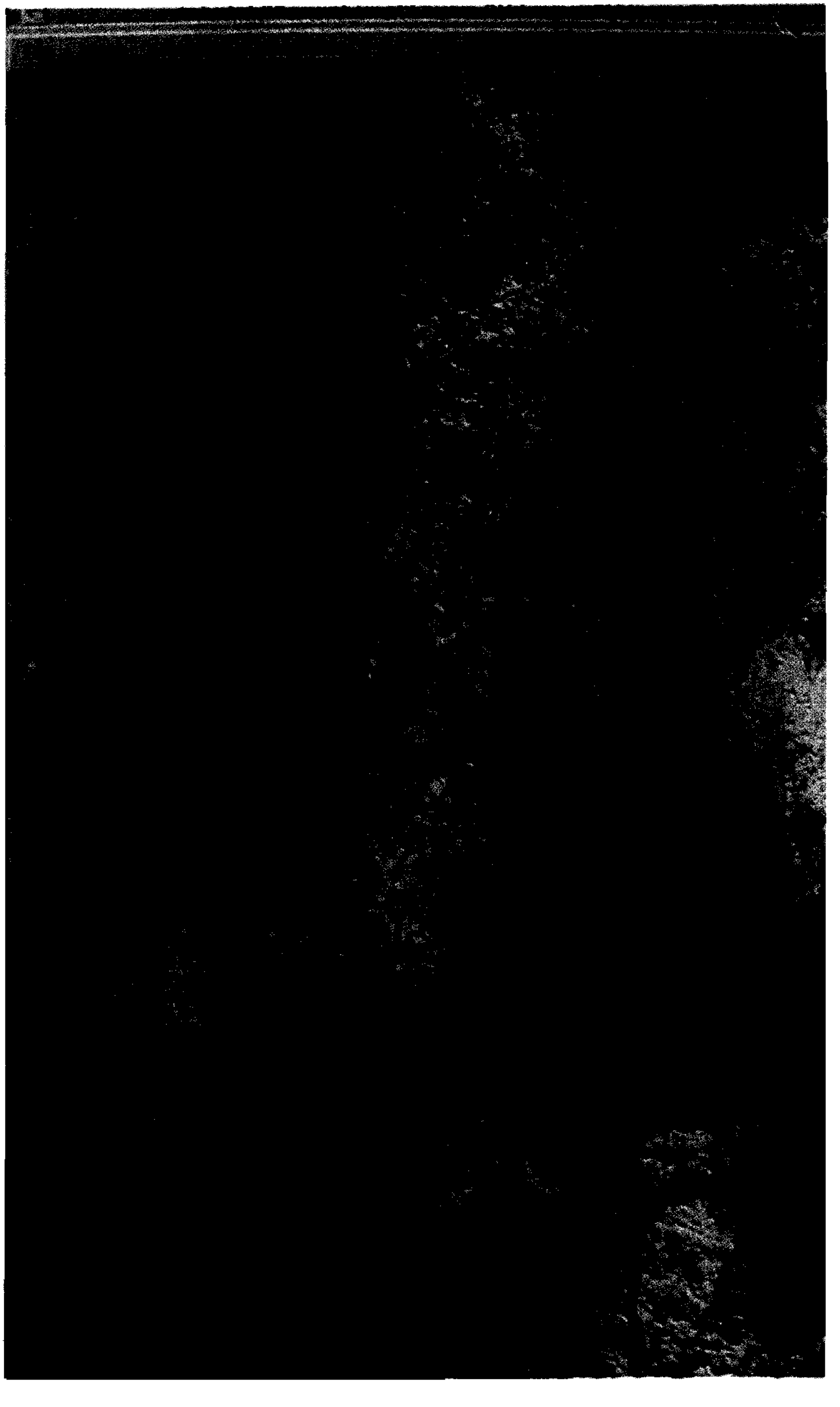

FIG. 3. SPOT-MLA FCC of bands 3, 2, 1 in red, green, and blue for the study area.

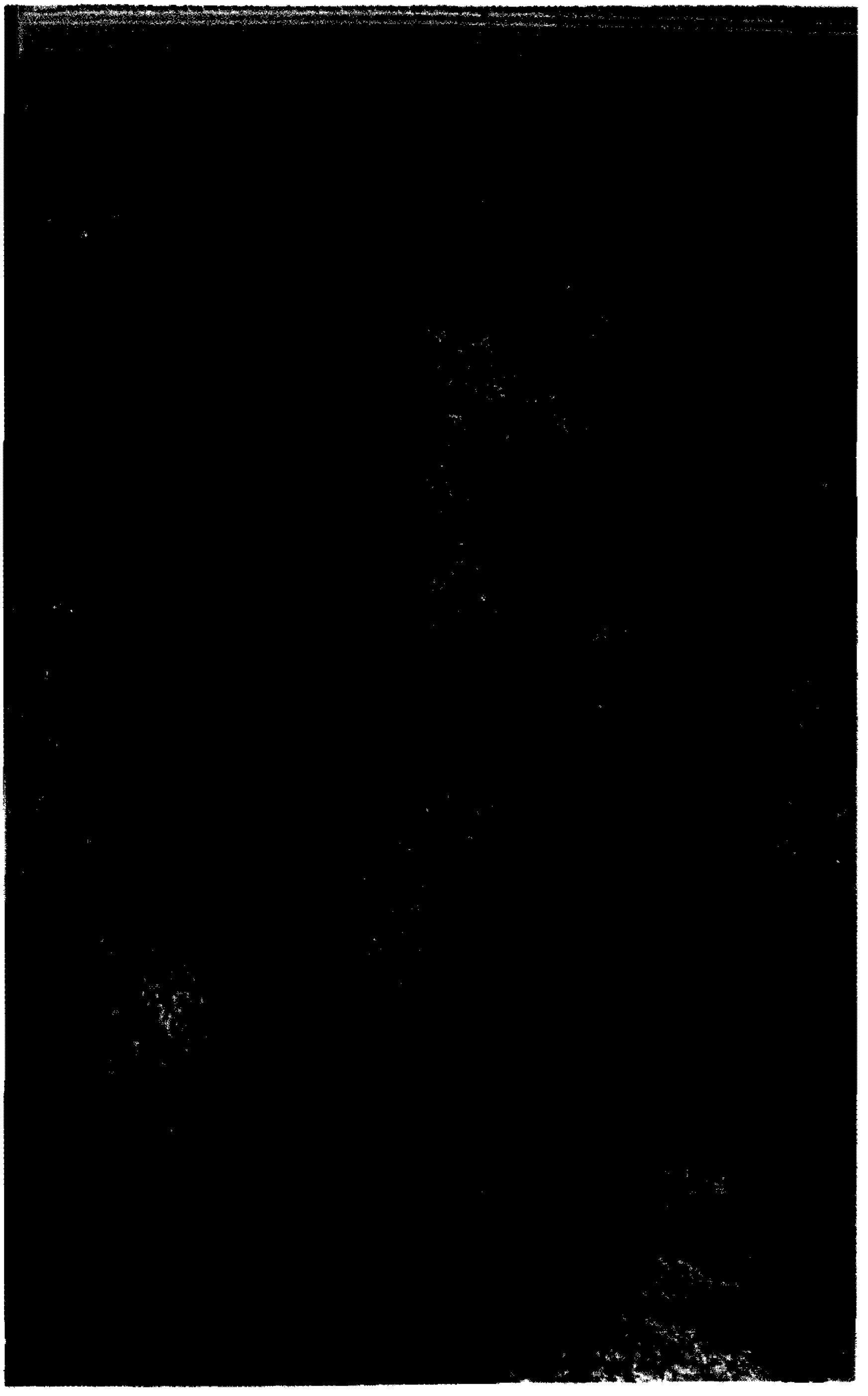

FIG. 4. SPOT-MLA PCA color composite for the study area (PC1 = red; PC2 = green; PC3 = blue).

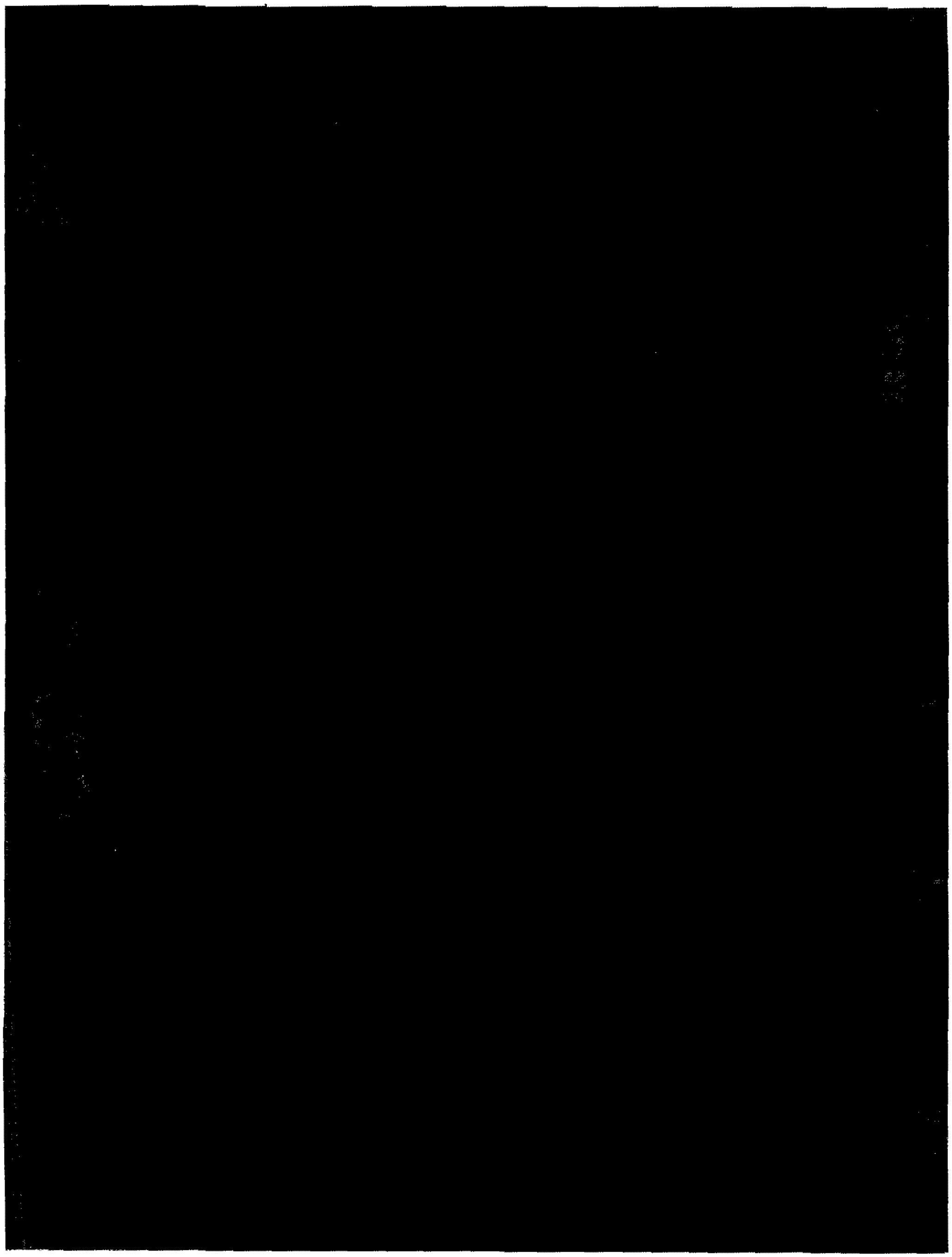

FIG. 5. SPOT-MLA FCC of bands 3, 2, 1 in red, green, and blue with zoomed portions (see text for details).

satellite temperature were calculated. The Landsat-5 data used through these analyses were capable of measuring radiant temperature differences from the background to the nearest 0.5°C.

TABLE 2. Classification of DN's using TM band 6.

Group no. (GN)	Digital no. (DN)	Frequency (%)	Spectral Radiance $L_\lambda^{(1)}$	Eff. Temp. $T°(K)^{(2)}$	Radiance Temp. Diff. $RT(°C)$
I	<110	4.2	>0.740	285	0
II	111-140	8.3	0.750-0.912	286.0-299.0	0.5-14.0
III	141-170	23.2	0.920-1.081	299.6-311.5	14.6-26.5
IV	171-200	45.9	1.087-1.250	311.9-322.9	26.9-37.9
V	201-230	14.8	1.25-1.419	323.2-333.4	38.2-48.4
VI	>230	3.6	1.425<	333.7<	48.8<

Spectral radiance

$$(1)\ L_\lambda - LMIN_\lambda + \left(\frac{LMAX_\lambda - LMIN_\lambda}{QCAL_{\max}} \right) * QCAL \quad (\text{mW.cm}^{-2}\ \text{ster}^{-1}\ \mu\text{m}^{-1})$$

TM band 6 at satellite temperature

$$(2)\ T°(K) = K_2 / ln\ (K_1 / L_\lambda + 1)$$

where the values for *LMIN*, *LMAX* and $QCAL_{max}$ are presented in Table 2; K_1 and K_2 are described in Table 5 of the paper published by Markham and Barker (1986).

The digitized data (radiant temperature differences) were analyzed in a GIS environment to determine the spatial distribution of digital numbers indicating various forms of land uses, and to assess the distribution of radiant temperatures corresponding to various soil moisture condition of the soil surfaces. The digitized data in gray colors were found to match with the channel configuration when it was overlain to the dry and wet portion of the channel due to agricultural activities located around the main wadi channel, Fig. 2.

Results and Discussion

Ground-Based Study

In this study, the ground truth data (ground surface temperature and moisture content) which was previously collected (KACST, 1990) were used to validate inferences made from satellite data. A relationship between the ground surface temperature and soil moisture content was established using the same data along the alluvial wadi bed composed of fine to medium sandy soil. The setup relation was based on the continuous records of soil temperature data at 0.25m depth below the ground surface measured by temperature probe (TV10) and their respective soil resistivity values which were obtained by calibrated sensors (SM 900) in the laboratory and then installed in the field were connected to data logger units. The change in soil tension (ψ) of every 0.1 bars were stored on data storage modules with respect to time and the data storage packs were transferred to the office for processing and then the data were converted to the volumetric moisture content (θ) using the mathematical relationship derived between them.

The analysis of the processed data in different periods of time through reader implied that moisture content observed to be highly correlated with the temperature of the upper soil layer of a sandy soil in wadi beds. The soil moisture condition of the upper soil layers could, therefore, be predicted using the soil temperature records. The analysis of satellite based study using TM and MLA images in conjunction with the Landsat thermal IR band 6 as discussed in general provides the information as a response of the land surfaces.

As a result of these studies, soil temperature records in °C of various months of the year 1986 were correlated graphically and presented in Fig. 6 with respect to the soil resistivity. Resistivity values in ohms were converted to the volumetric soil moisture content in percentages using the polynomial equation. Accordingly, soil temperature measurements could easily be used in order to assess the soil moisture content which represents the ground truth data for analysis.

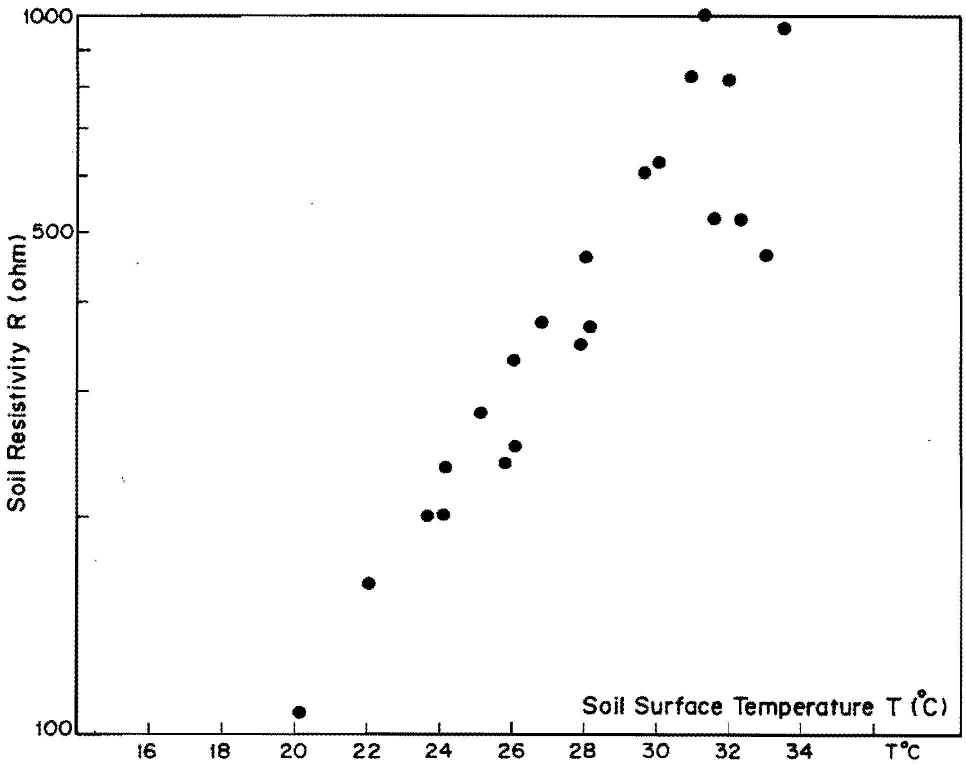

FIG. 6 Soil resistivity vs. soil surface temperature in various months.

Satellite-Based Study

The reflection in color of TM and MLA images and their tonal changes were analyzed in order to classify the different land uses. The classified land covers were named as cultivated areas with agricultural crops (AG), urban settlements (UR) and uncultivated and uncultivable lands (UC) within the basin boundary.

Network of wadi channels and geological information were configured using ratio, FCC and PCA techniques. Thermal infrared band (TM6) provided the distribution of radiant temperature indicating various forms of land uses. The DN's were interpreted and converted to radiant temperatures in order to isolate various moisture conditions of the soil surfaces.

The selected land use and thermal IR images were overlain. The results were analyzed and tabulated to assess the areal extent of the six radiance temperature groups. These groups (I-VI) were interpreted as relative moisture conditions of soil surfaces (hot-dry; cool-moist) and were assessed within each land use category (AG, UR, UC) over each sub-basin (1a, 1b, 2a, 2b, 3 and 4). The numbers presented in Table 3 are the counts for pixels with their respective areas (km^2). The latter was used to find out the percentage of distributions of different land uses within each sub-basin for each and all radiance groups (rows) as well as the numbers in each sub-group within each sub-basin keeping the same land use category (columns).

Percentages of the entire study area corresponding to the three categories of land use (AG, UR and UC) were also studied as shown in Table 4. The agricultural lands include alluvial wadi channels with slopes of less than 0-2%, the urban areas cover the roads and other infrastructures and finally the UC sub-category has two classes, the first class includes the inner sub-basin boundaries with foothills and rugged upland areas with mild slope (0-30%) and the second class is made of uncultivable lands which are covered by rock outcrops with steep slopes (30-75%). Their respective areas for three categories are configured to be 13.8% and 10.5% for AG and UR, respectively, and the two classes within the third category were determined as 57.5% and 17.3%, Table 4.

The agricultural areas (AG) cultivated by local farmers were mostly located around the alluvial channels and irrigated by water pumping from shallow aquifers through hand-dug wells. They were displayed as red and blue colors on the SPOT FCC and PCA images, respectively (Fig. 3 and 4). The most active irrigated cultivated areas following the course of the main wadi were noticed in Wadi Ayn (2a) with a crop area 10.3 km^2 (6%). However, other sub-catchments showed almost the same but smaller size of cultivated activities which were around 3 km^2 (1.8%) (Table 3). Two sub-catchments (1a and 2a) showed the terrace irrigated lands located on the upper reaches of Wadi Tabalah.

The urban lands (UR) indicated either the locations of small villages or the dwelling units for the farmers shown as pink colors surrounding the agricultural areas in PCA image (Fig. 4). It was observed that local farmers mostly settled along the main wadi channels in order to produce their products from the cultivated lands. Wadis with numbers 2a, 2b and 3 (as presented in Table 1), represent typical examples in the basin with 16.83 km^2 (9.9%) area (Table 4).

The third land use category (UC) being the largest (74.8%) (Table 4) has two classes with their distinct lithologic characteristics and the range of digital numbers which are

TABLE 3. Classification of pixel numbers in each sub-group within sub-catchments.

Sub-catchment	Area (km²)	Land use	(GN) I			II			III			IV			V			VI			Total Pixel no.			Total Area (km²)		
			(DN) < 110			110-140			140-170			170-200			200-230			> 230								
			(RT) 0°C			0.5-14°C			14.6-26.5°C			26.9-37.9°C			38.2-48.4°C			> 48.8°C			AG	UR	UC BB	AG	UR	UC BB
1a Shaybanah	46.5	1	–			7			3			5			–			–			15			3.15		
		2		–			–			–			–			–			–			–			–	
		3			5			14			35			80			42			10			186			39.0
		4																					20			4.2
1b Al-Hamid	12.5	1	2			2			6			3			1			–			14			2.9		
		2		–			–			2			4			1			–			7			1.5	
		3			2			3			9			7			8			–			29			6.1
		4																					10			2.1
2a Ayn	53.3	1	8			11			16			13			1			–			49			10.3		
		2		3			3			14			16			–			–			36			7.6	
		3			3			8			52			82			9			–			154			32.3
		4																					15			3.2
2b Ghudar	28.0	1	3			2			6			3			–			–			14			2.9		
		2		2			3			3			12			1			–			21			4.4	
		3			–			2			11			52			19			3			87			18.3
		4																					10			2.1
3 Shaiba	21.6	1	4			4			1			5			–			–			14			2.9		
		2		1			2			4			4			1			2			14			2.9	
		3			–			–			10			36			18			4			68			14.3
		4																					7			1.5
4 Tabalah	8.0	1	–			4			2			–			–			–			6			1.3		
		2		–			–			–			–			2			–			2			0.4	
		3			1			1			7			13			3			5			30			6.3
		4																					–			–
All	170		17	6	11	30	8	28	34	23	124	29	36	270	2	5	99	–	2	22	112	80	554	23.5	16.8	116.3
								–			7			35			15			5			62			13.1
Sub-total (no. of pixels)			34			66			188			370			121			29			808			23.5	16.8	129.4
Area (in %)		%	4.2			8.2			23.3			45.8			14.9			3.6			100			170		

GN = Group no. DN = Digital no. RT = Radiance temperature
1 - Agriculture (AG) 2 - Urban (UR) 3 - Uncultivable (UC) 4- Inner basin boundary (BB)
(1 pixel image = 0.21 km²)

TABLE 4. Results of satellite based sutdy (Landsat and SPOT images are used with ground survey maps).

Group no.	Land use category	Digital no.	Lithologic and soil classification	Slope (%)	Area (%)	Sub-total (%)
1	Agricultural land and alluvial wadi channel	50-200	Alluvial terraces with loamy sandy soil	0-2%	8.8%	13.8%
					5.0%	
2	Urban area and roads	140-200	Roofs, asphalt	Flat	9.9%	10.5%
					0.6%	
3a	Uncultivated area with inner sub-basin boundaries	<140	Foothills and rugged upland areas with mild slopes	0.30%	3.6%	57.5%
		140-170			16.2%	
		170-200	loamy and loamy skeleton		37.7%	
3b	Uncultivable area with outside basin boundary	200-230	Mountaineous outcrops with steep slopes	30-75%	14.0%	17.3%
		>230	Granitoid fractured rocks		3.3%	

mostly distributed under five groups according to their radiant temperature differences (wet to dry soil moisture conditions).

The percentage of uncultivated area (UC) in each sub-basin change according to group and DN's as presented in Table 5. In sub-group (III), the digital numbers (DN's) ranging between 140-170 correspond to cool soil surfaces with the radiant temperature of 14.6 to 26.50°C. The uncultivated areas constitute up to 16.2% of the total area with the distribution of percentages for each small basin. Sub-group (IV) with DN's 170-200 corresponds to partly dry-moist soil condition with higher radiance temperature differences (26.9-37.9°C). Sub-group (V) with DN's 200-230 corresponds to conditions of dry soil moisture with much higher temperature differences (38.2-48.4°C). The uncultivable lands were formed by outcropping rocks in each-sub-basin with the highest percentage of 5.2% in Wadi Shaybanah. The last sub-group (VI) with DN's 230 or above and very dry rock surfaces appears mostly in Wadi Shaybanah at a total aerial extent of 3.3% (Table 5).

Conclusion and Recommendations

Remotely sensed satellite images were used to distinguish principal land use categories: Agricultural, urban and uncultivated/uncultivable lands. Thermal IR image of Landsat-TM band 6 was superimposed on the land use image through the use of GIS. Radiance temperature differences were presented in five groups corresponding to different soil moisture contents assessed within each land use category.

The irrigated agricultural land and urban land use categories have generally lower thermal IR response (DN's) than the uncultivable areas which are mostly in dry condition. The results are in good agreement with the theoretical functions expressed by Price

TABLE 5. Distribution of uncultivated / uncultivable land use (3a and b) according to Group and Digital Numbers (in percentages).

Wadi name	Wadi ID no.	Group number			
		III	IV	V	VI
		Digital number			
		(140-170)	(170-200)	(200-230)	(>230)
Shaybanah	1a	4.3	10.0	5.2	1.2
Al-Hamid	1b	1.1	0.9	1.0	–
Ayn	2a	6.4	10.0	1.0	–
Ghudar	2b	1.4	6.4	2.3	0.4
Shaiba	3	1.2	4.4	2.4	0.5
Tabalah	4	0.9	1.6	0.4	0.6
Sub-total	(%)	15.3	33.3	12.3	2.7
Inner Basin Boundary	(%)	0.9	4.3	1.7	0.6
Total	(%)	16.2	37.6	14.0	3.3

(1980) and conclusions made by Idso *et al.* (1975); *i.e.*, that the daytime temperature is inversely related to the soil moisture.

The thermal IR response (DN) was found to be inversely related to the soil moisture condition in Wadi Tabalah in Saudi Arabia. The soil moisture conditions corresponding to TM band 6 groups were observed to be wet, moist, partly moist, dry and very dry.

Results indicate that the agricultural areas can be wet around field capacity with DN's of thermal IR less than 110 and be dry with DN's equal or greater than 200 when they are not irrigated or receive no rainfall in dry periods. The urban areas mostly show a range of DN's 140-200 with partly moist to dry soil condition. The uncultivated lands with DN's 140-200 are mostly foothills and rugged uplands with mild slopes. The land covers became very dry due to rocky outcrops with steep slopes and sharp crests when the digital numbers increase much higher than 200.

Further research is needed to assess the applicability of this technique regionally. The results of such research could potentially be used for assessing the drought areas, mapping of soil moisture and identifying the wet-lands which can be incorporated for land use planning and expanding agricultural areas for maximum production of crop yields.

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تفسير بيانات لاندسات وسبوت في دراسات شواهد جيولوجيا المياه الأرضية في منطقة وادي تباله ، المملكة العربية السعودية

محمد يوسف هداية الله قاري[١] ، وعلي أونال شورمان[٢] ، وعبد القادر محمد السري[٣] و محجوب محمد حساني[٢]

(١) كلية علوم الأرض ، جامعة الملك عبد العزيز ، جــدة ، (٢) كلية الأرصاد والبيئة وزراعة المناطق الجافة ، جامعة الملك عبد العزيز ، جــدة ، (٣) مدينة الملك عبد العزيز للعلوم والتقنية الريـــاض ، المملكة العربية السعودية

المستخلص . تلعب بيانات الأقمار الصناعية الرقمية للاستشعار عن بعد دوراً مهمًا في هذه الأيام في دراسات المياه الأرضية ، خاصة إذا تم دمجها مع تقنيات نظم المعلومات الجغرافية . تم استخدام بيانات لاندسات و سبوت في منطقة ذات تجانس صخري في منتصف جنوبي الدرع العربي لكي تحدد طوائف استخدامات الأراضي ودرجة حرارة التربة ومحتوى رطوبة التربة كميًا ونوعيًا .

تم التعرف على أربعة أنماط لاستخدامات الأراضي (زراعية ، وحضرية ، وغير مزروعة ، ولايمكن زراعتها) من بيانات الطيف المرئي وتحت الحمراء للأقمار الصناعية ، وتم حساب فروقات درجة الإشعاع لتلك الأنماط من بيانات تحت الحمراء الحرارية ، ووجدت مطابقة مع ماتم استنتاجه من المعادلات النظرية التي أوجدت علاقة بين رطوبة التربة ودرجة الحرارة أثناء النهار .

بينت النتائج أن صور الأقمار الصناعية يمكن استخدامها بنجاح للتنبؤ برطوبة التربة وتقييم الجفاف في الدرع العربي أو أي أراضٍ أخرى جافة .