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Estimation of Flood Peaks Using Remote Sensing Techniques; Case Study: Wadi Itwad, Southwestern Saudi Arabia

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ABSTRACT. The application of recently developed information techniques has received great attention in the last decade analyzing various hydrological processes. The main objective of this research is to couple the remote sensing techniques with hydrologic model approach in order to estimate peak discharge on small size catchments within Wadi Itwad located in the southwestern part of the Kingdom of Saudi Arabia.

Information on the lithology, drainage pattern, frequency and spatial distribution of the fractures for the small basins are collected, processed and presented as plates and figures. They are obtained through the study of False Color Composite (FCC) and ratio images of the Landsat Thematic mapper (TM).

The peak discharges for the small catchments are estimated through the application of hydrological model (TR-55) and the results are compared with the outputs obtained from the application of rational formula which is the method commonly applied in Hydrology. On the other hand, the peak discharges for the medium size catchments are determined by Creager Formula and Point Frequency Distribution Functions.

The results show that processed Landsat Thematic mapper data in colored form is highly appropriate for digitizing the information required as input parameters for hydrological model application. The model parameters represent non-parametric information in terms of curve numbers which are the digitized form of lithology, land use and soil formation.

Introduction

Description of Study Area

The study area, Wadi Itwad, is located in the southwestern part of the Kingdom of Saudi Arabia (Fig. 1). Full false color composite scene of Landsat TM (Plate 1) indicates the location of Wadi Itwad which is within the northwestern part of the Wadi Baysh quadrangle (Fairer, 1985). Wadi Itwad is one of the major wadis in the southwestern area. It has a drainage area of about 1350 km^2 draining towards the Red Sea. The Wadi is located within 17°45N and 18°15N Latitude and 42°15E-42°45E Longitude and surrounded by Wadi Hali in the Northwest and Wadi Baysh in the Southeast direction.

This study covers only the 14 km segment of the wadi channel and the surrounding small catchments which drain between km 19 to km 33 measured from town Ad-Darb.

Topographic and Geologic Description

The nature of the area is rugged and composed of mountain chain belts following the structural grain of the rocks. The wadi is torrent and has very steep slopes in the upstream portion where it originates near the escarpment. There are four major tributaries, the main wadi channel, Wadi Ad-dilah, Wadi Maraba and Wadi Talami which combine together in Wadi Itwad draining towards the Red Sea to the West of the study area.

The Wadi Baysh quadrangle was mapped by Fairer (1985). A geological map was extracted covering the study area (Fig. 2), showing that the basic lithologies consist of mainly schistosed, metamorphosed to the greenschist facies rocks (layered rocks). These types of rocks are generally considered impermeable and non-porous. The formations are much weathered at the surface, cracked and fissured below. These conditions affect the degree of water retention of a catchment area depending on the characteristics of the fissures. Minor and superficial cracks rarely penetrate more than a few meters and thus do not allow efficient infiltration. Deeper fissures may penetrate far into the underlying soil layers, however, they tend to become filled with silt carried by water percolating down, gradually reducing their efficiency. These Proterozoic layered rocks are exposed nicely throughout the study area and are assigned to four major lithostratigraphic groups: the Sabya formation in the south, the Baish in the southeast, the Bahah in the north, the Jeddah as basalt and andesite, and Ablah on the west side outside of the Wadi Itwad.

The Sabya formation consists of continent-derived clastic rocks, the most common rock is quartz-sericite schist. The Baish group consists of basaltic volcanic rocks. The Bahah group consists predominantly of immature andesitic volcaniclastic rocks which are tightly folded and have strong cleavage or schistosity. The Ablah group consists mainly of sedimentary and some volcanic rocks; the sedimentary rocks are more mature, and the volcanic rocks are more felsic than rocks in other units. The exposures of the Ablah group are folded, have strong cleavage or schistosity and forms

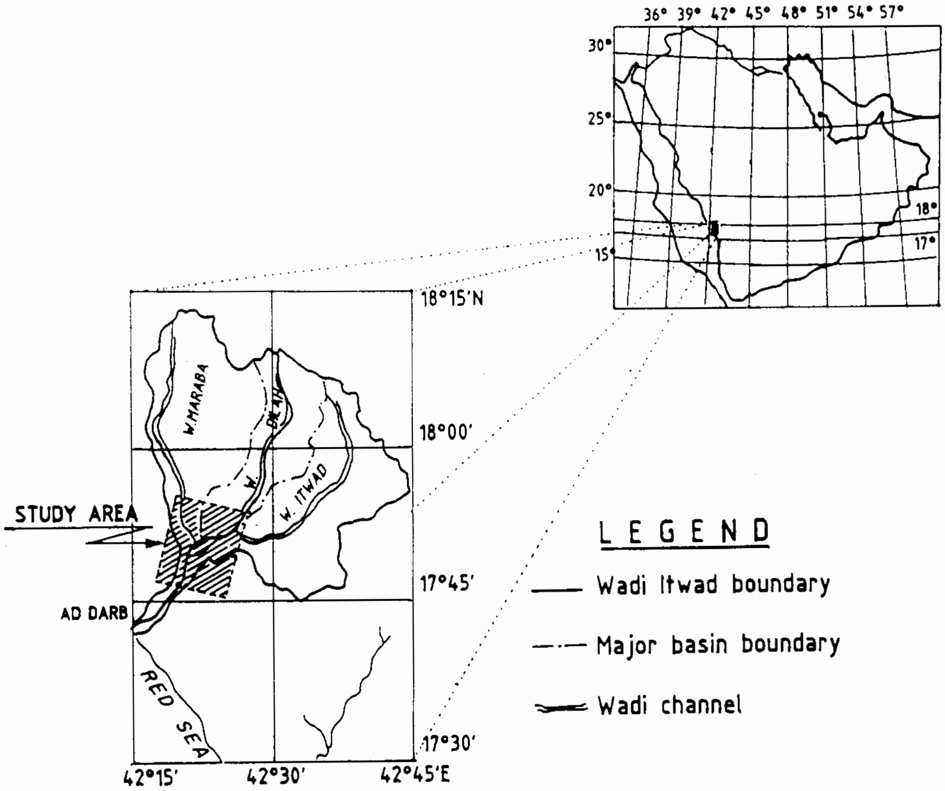


FIG. 1. General layout map of Wadi Itwad and its location.

a narrow belt which are part of a large belt that extends for hundreds of kilometers to the north and northwest of the Wadi Baysh quadrangle.

Remote Sensing Studies

Fracture Analysis

Landsat satellite data (images) are especially suited for lineament analysis in relatively high relief and rugged areas (Qari, 1990; 1991). Lineaments can be defined as "mappable, simple or composite linear features of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship which differ distinctly from the patterns of adjacent features and presumably reflect a subsurface phenomenon" (O'Leary *et al.* 1976).

The lineaments in the study area were identified by visual inspection and recorded on a transparent overlay as ruled lines using the ratio Landsat imagery of Thematic Mapper Sensor (TM) band 3/4 as shown in Plate 2. A remotely sensed geological fracture map (Fig. 3a) and drainage density map with basin boundaries (Fig. 3b) were constructed based on the knowledge of the terrain and the Landsat TM data.

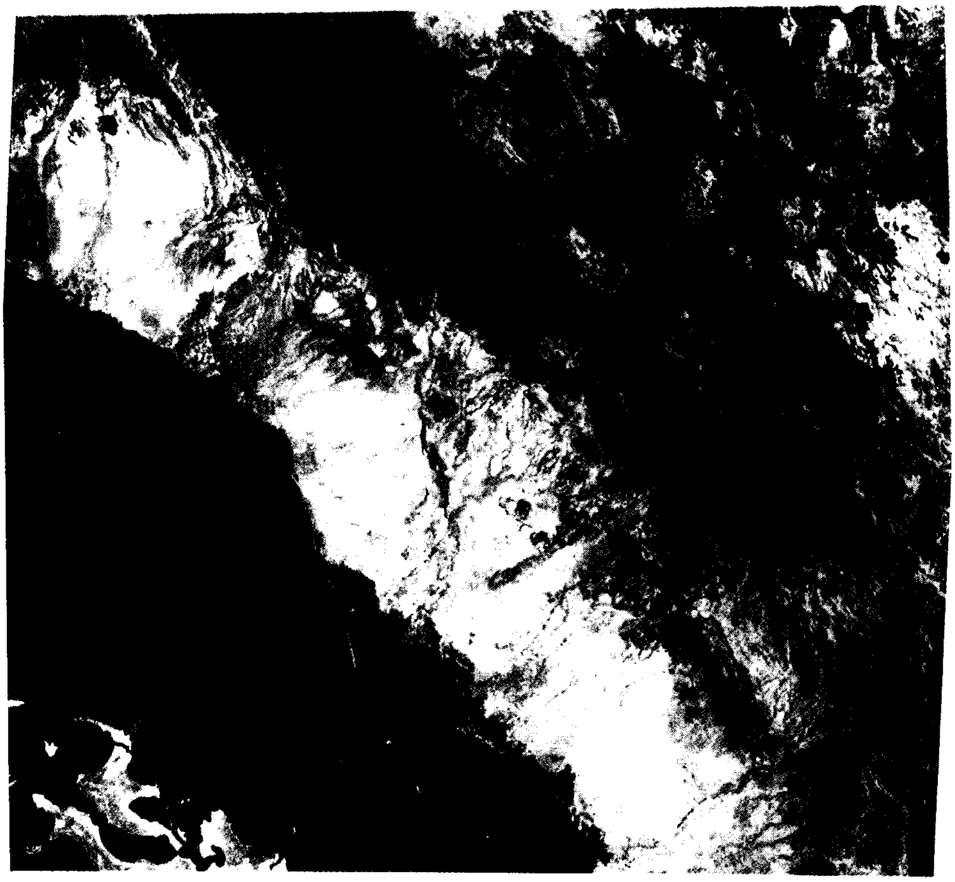


PLATE 1. Full scene of Landsat TM, Path 167, Row 048, for the southwest part of Saudi Arabia, show the main wadis in the south, Wadi Itwad appear in the northwest of the image.

Computer processing of these data provides an objective method of interpretation. The significance of the interpreted lineaments was analyzed correlating the frequency and the total length of fractures and presented as histograms in Fig. (4a). There are three dominant preferred orientation of lineaments in the ENE-WSW, NNW-SSE and WNW-ESE directions. There is also good relationship between the total length of these fractures and their distribution throughout the study area, *i.e.* the higher the number of the fractures are in specific direction, the higher total length is and vice-versa (Fig. 4b). These measured fractures are nearly sub-vertical, so they were only treated in terms of azimuth of the strike direction.

Considering another perspective angle of opinion, four groups are selected in the NE and NW direction as follows: 1) lineaments which are not along the wadi course, 2) lineaments along the main wadi channel, 3) lineaments along the wadi tributaries and, 4) lineaments outside of the wadi boundary.

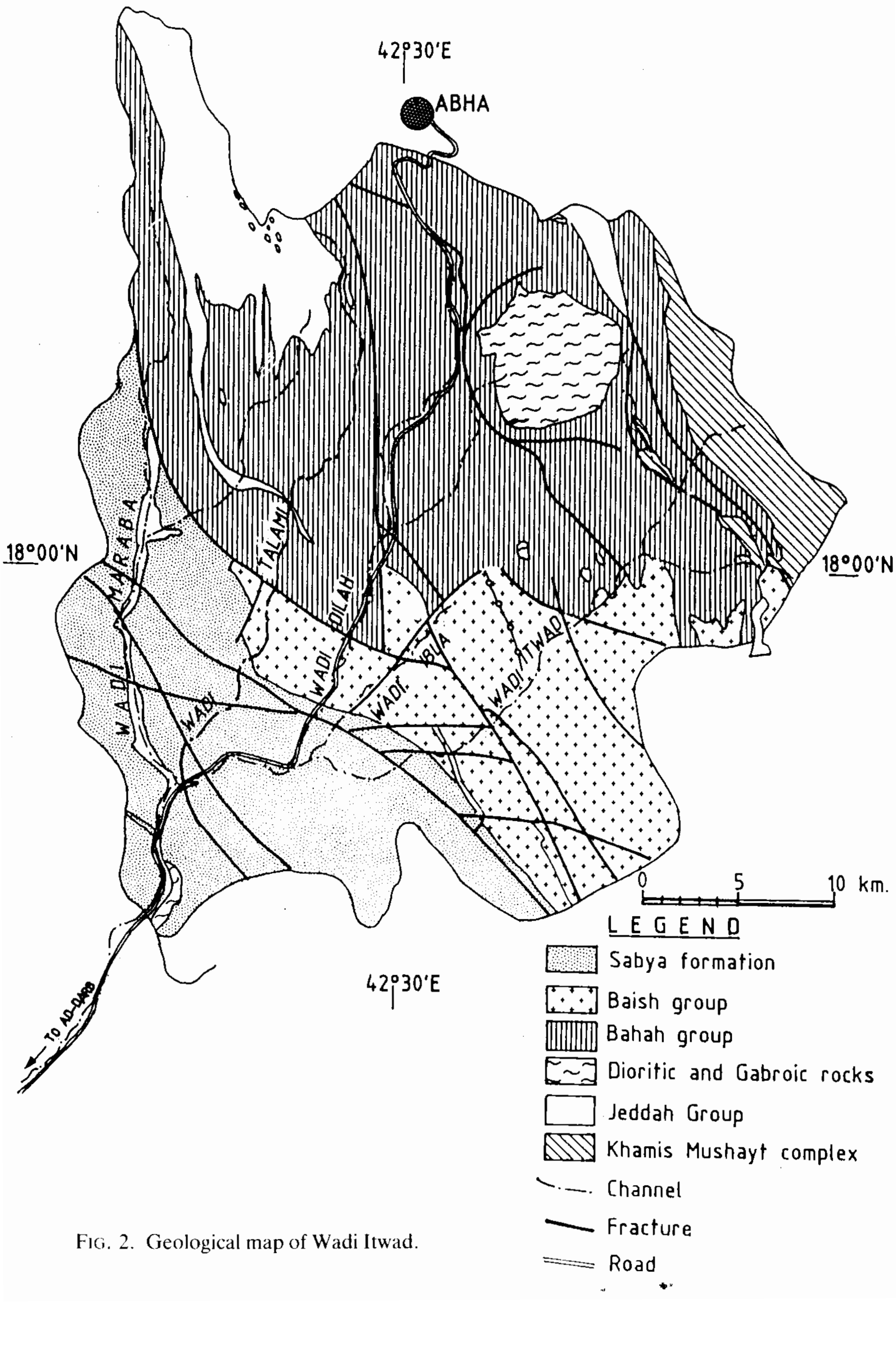


FIG. 2. Geological map of Wadi Itwad.

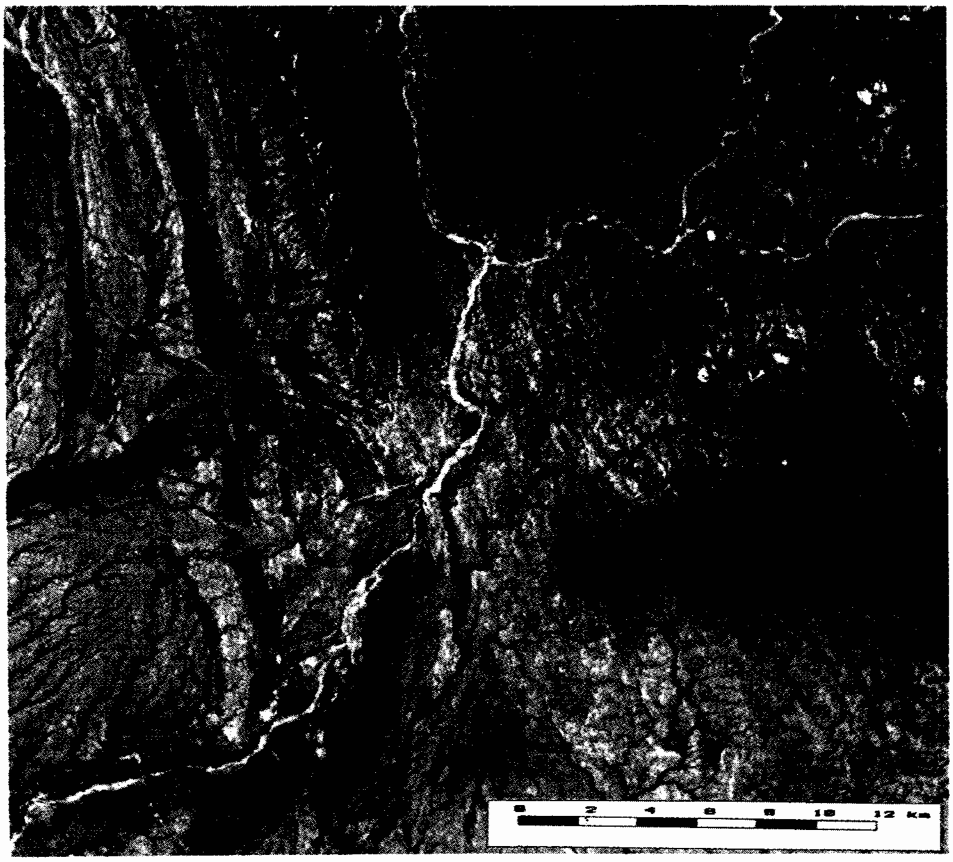


PLATE 2. Ratio image of Landsat TM 3/4 show the linear features and main drainage system in the area.

Through the quantitative analysis of the lineaments after tabulation and graphical representation, the following items are observed: i) the highest number and length of fragments (fractures) crossing the wadi channel are aligned in the N0-10°W and also N50-70°E, ii) most of the major wadi channel aligned are in N10-50°E, iii) the major tributaries are located between N50-90°W and N50-90°E direction with a high amount of total length, iv) the inspection of the geological map of the area, shows that the main fractures are along N10-20°W over the Sabya formation which matches with the highest percentage of the fractured lines located within the study area.

Contour Map Analysis

The fracture map is digitized and the map area is divided into a grid of square cells, each cell is 1 by 1 inch. Three variables are calculated utilizing a computer program (Mostafa and Qari, in prep.). These variables are (i) number of fractures within each cell, (ii) total length of these fractures within the cell and (iii) the number of intersections of the fractures with the cell border.

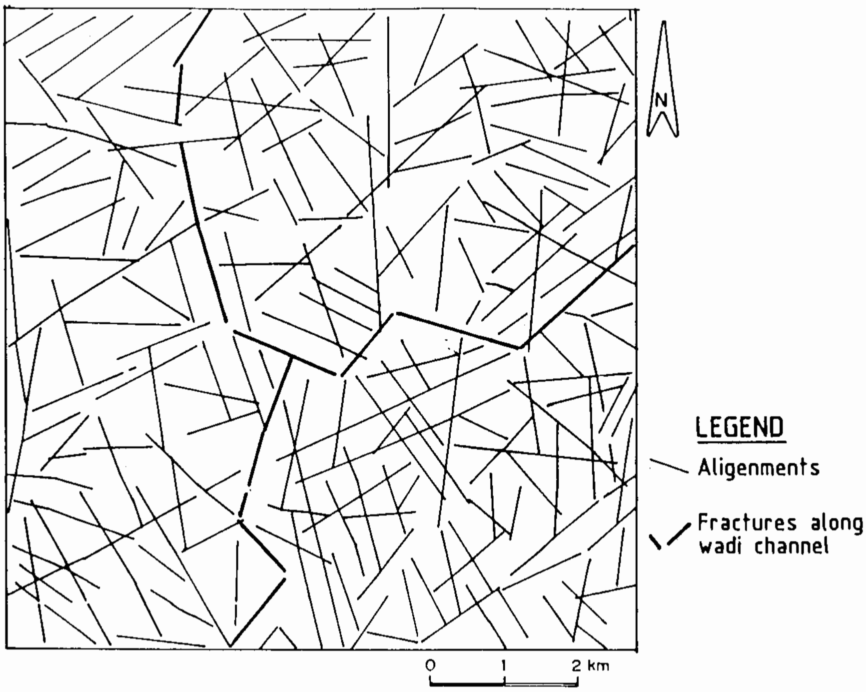


FIG. 3a. Geological fracture map.

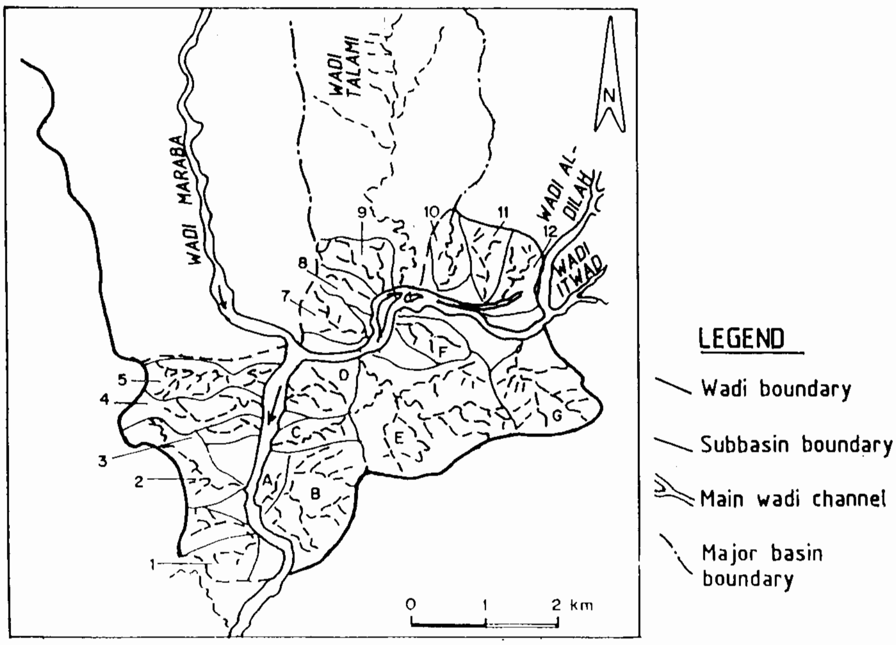
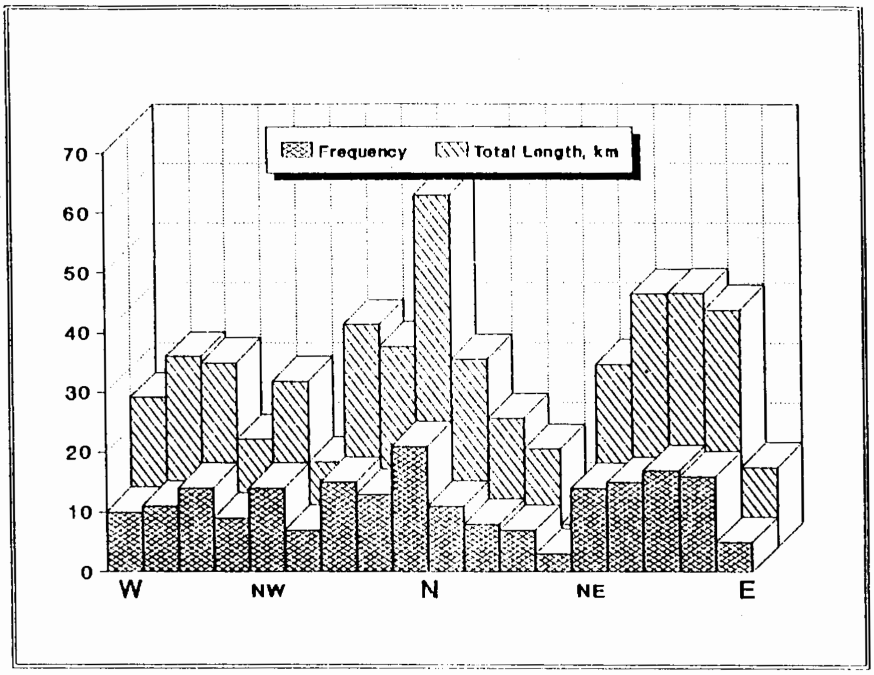


FIG. 3b. Drainage density map.



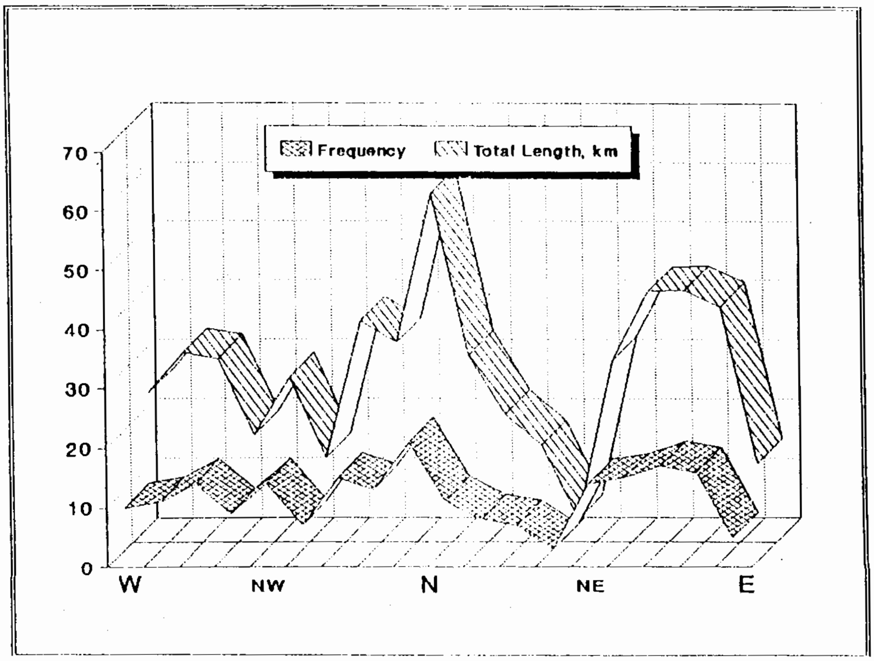


FIG. 4a-b. Histogram and linegraph for frequency and total length distribution of fractures.

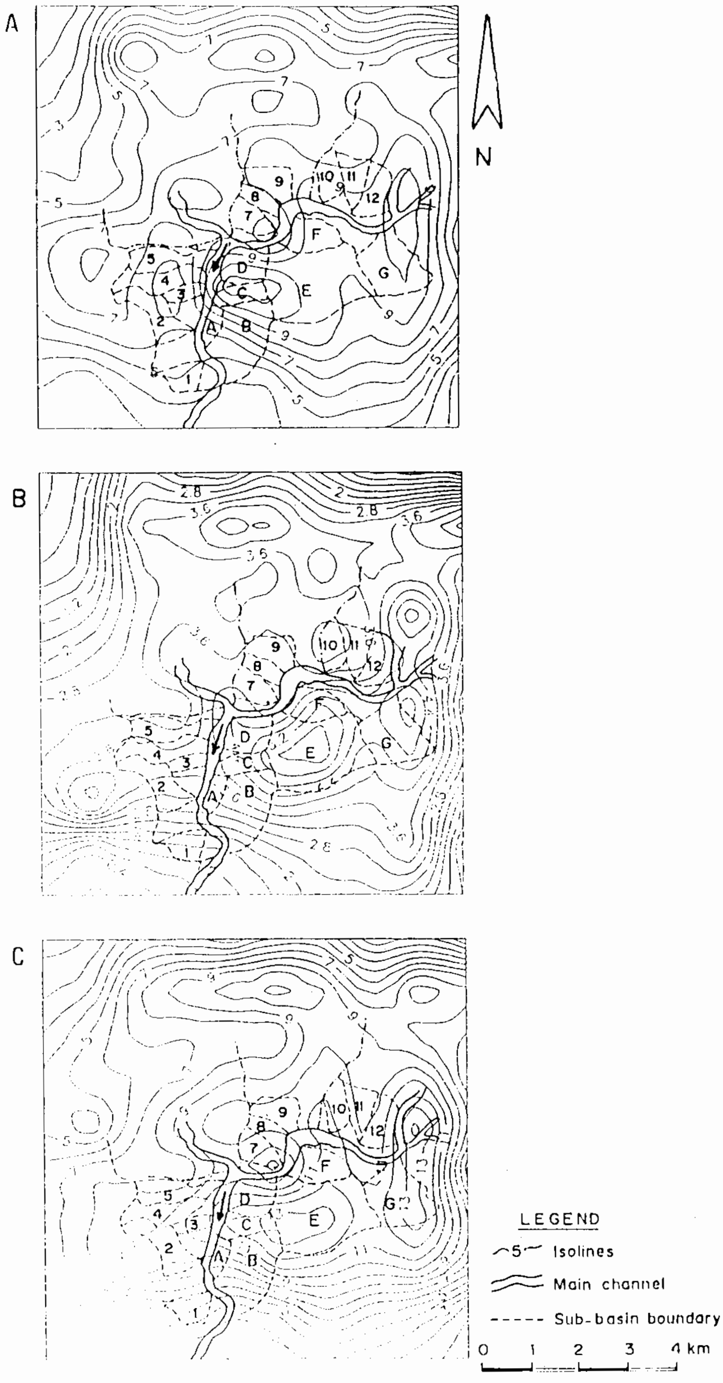


FIG. 5a-c. Contour maps of fracture intensity (a), length (b), and intersections (c) of the study site.

Hence, x, y, and z values were obtained where x and y are the center coordinates of the cell and z is one of the above mentioned three variables. Contour maps showing isolines of each variables are presented in Fig. (5a-c) with the overlaid boundaries of the selected basins. The three contour maps give the same conclusive results indicating that the maximum point of concentration is in the lower right quadrant of the mapped area. This may suggest that the southeastern part of the study area has been subjected to intensive geological deformation which has affected the Wadi Itwad region, or it is lithologically composed of Sabya Formation which was widely converted to micaceous schist, known to be highly affected by weathering.

The findings of contour map analysis are as follows: The area as a whole was subjected to intensive geological deformation which was originally composed of Sabya formation and then converted to schist. More specifically, the left side of the wadi channel has more number of streams per unit area varying between 9.5-11 and more fragment intersections (11-13) than the right side as well as the subcatchment draining to the wadi channel from north for which the contour maps provided the values 7.5-8.0 for fracture intensity and 8-11 for number of intersections. Concerning the average length of fragments, the values range from 3.5-5.5 km on the eastern side and 3.2-4.0 km on the west and north of the mapping areas (Table 1).

Hydrologic Model Studies

Historical Floods

On February 13, 1982, wadi Itwad was exposed to a catastrophic flood which caused extensive damages to human and structures. A high rainfall depth of 81 mm was recorded between 1-2 pm with a total precipitation depth of 182.2 mm in two days. Eight of the 33 reinforced concrete bridges located on small tributaries collapsed, 12 culverts were damaged, 1500 m of retaining wall, 6 km of riprap and 6 km of asphalt were destroyed. The layout plan of the catchment where most of the damages occurred are located within the 14 km length as shown with a shaded area in Fig. 1.

After a year, on February 3, 1983 there was a very heavy rainfall on the escarpment near Abha City (to the NE of the study area) with a total precipitation depth of 240 mm, in three days, a maximum intensity of 50 mm/hr which is considered to be the second highest in the record of the study area. Several damages occurred again and four reinforced concrete bridges were destroyed, roads overtopped and embankment was partly washed away. But the flood level did not reach the height of the earlier flood of 1982. It has been estimated, from the earlier studies (RRI, 1984; Abdulrazaak *et al.*, 1993), that the 1982 flood had a return period of 100 years by the flood frequency studies.

The question which needs to be answered in this paper is how to estimate the flood magnitudes contributed by the small tributaries using hydrologic modelling and other traditional methods (empirical or statistical), so that the results would be comparable with the early studies and the observed records, such as the one carried out

TABLE 1. Topographic and geomorphologic characteristics of small basins.

Location	Areas	Topographic parameters				Geomorphologic parameters		
		Size		Slope	Length	Fract. intensity	Fract. length	Node intersec.
		(km^2)	(acre)	(%)	(km)	(no/km^2)	(km)	(no)
East	1	1.525	377	9.1	1.76	5.0	2.0	6.0
	2	2.367	585	15.0	3.08	7.5	3.6	10.0
	3	0.567	140	10.0	1.44	8.0	3.8	10.5
	4	1.628	402	8.0	2.90	8.0	3.6	9.5
	5	0.926	229	11.0	2.12	7.5	3.2	8.0
North	7	1.41	348			8.0	3.8	11.0
	8	0.846	209	26.0	2.18	8.0	3.8	10.0
	9	1.23	304			8.5	3.7	10.3
	10	1.40	346			9.0	4.2	9.5
	11	1.09	269	25.0	2.20	9.0	3.7	9.8
	12	1.58	390			9.0	4.0	11.0
West	A	0.88	217	N.A.		7.0	3.2	8.0
	B	4.57	1129			7.0	3.6	9.0
	C	1.05	260			11.0	4.4	12.5
	D	1.94	479			10.0	4.4	11.0
	E	8.08	1997			9.5	5.6	12.5
	F	1.58	390			9.5	4.4	11.5
	G	3.87	956			10.0	4.4	13.0

for the King Abdulaziz City of Science and Technology in Riyadh (Abdulrazaak *et al.*, 1993).

Methods of Flood Estimation

Estimation of flood peak discharges for small to medium size catchments is one of the oldest problems in applied hydrology. There are many uncertainties and confusion regarding the principles and methods involved and the requirements of each of the methods. Three of the commonly used methods will be mentioned here.

(1) *Rational method and Creager Formula* for small to medium size catchments are the empirical approach used in early years when there was a limited hydrologic information. The estimate of discharges from small catchments is done using the ra-

tional formula in which the runoff coefficient C can be assumed to vary between 0.1 and 0.9 depending on the area cover and land use (urban or rural). On the other hand, the relationship between the peak discharge and medium size catchment area is described by an exponential function (Creager formula) in which the factor C characterizing form of an envelope curve is assumed to vary between 30-60 as the lower and upper limits of the expression. The observed flood events, indicate that February 83 flood provided a factor of C = 32 in Creager equation, while the flood of 1982 reached a factor of C = 60.

(2) *Flood frequency analysis* can be followed using some selected distribution functions (Extreme, General Extreme, Pearson etc.) at a point or on a regional scale for medium to large basins. Determination of flood peaks for the four medium size basins draining to the concerned wadi reach is also done using flood-index procedure by point frequency analysis through which peak discharges are estimated for 50 and 100 year return periods. Extreme (EV1) and General Extreme Value (GEV) functions were selected as the best and the probable weighing moments (PWM) procedure is followed to estimate the model parameters.

(3) *Hydrologic model* approach is coupled with remote sensing information for each of the small basins. The selected model TR-55 [Soil Conservation Service (1986), Sorman (1993)] requires the following information as input; area size (A), Soil Conservation Service (SCS) curve number (CN), time of concentration (t_c), rainfall distribution type (I, II or III), rainfall depth (P) in 24 hr time for the selected storm frequency (T) such as 50 yr or 100 yr. The outputs of the program are discharge hydrograph peak using unit hydrograph peak and the formula :

$$Q_p = q_u * A * R$$

where q_u is the peak discharge of Unit Hydrograph (UH), A is the basin area and R is the runoff depth.

Lithology, topography and land use are selected as critical input parameters of the model in order to get non-parametric information in the form of curve number for each sub-basin. This procedure has been followed by Mancini and Rosso (1989) for predicting the discharge hydrograph with a discussion of the assessment of such a criterion. An estimate for curve number is presented (Table 2, page 439) based on lithology (rock type) and land use as parameters (bare, vegetative forest, etc).

The high CN estimates are found on fractured rocks in the neighbors of streams with less degree of drainage density (low lineament intensity and fracture length), the values decrease inversely when the formation becomes more pervious, dense vegetation cover and an increase in fractured formation.

Data Collection and Processing

Since the main objective of this research is to couple the remote sensing techniques with hydrologic model approach in order to estimate the peak discharge on small catchments, the following informations were collected, processed and presented as full false color composite (Plate 1), ratio image (Plate 2) and contour maps (Fig. 5), in order to achieve the intial task :

i) Lithologic information of the small basins are identified using remote sensing and compared with the geological map obtained from published information, Fig. (2).

ii) Drainage patterns and fracture formations of the sub-basins are determined as presented in Fig. (3a-b) using ratio image of the Landsat-TM data (Plate 2).

iii) Frequency distribution of the fractures (direction and length) are studied and graphically presented in Fig. (4).

iv) Spatial distribution of fracture intensity, length and intersection on a grid 1″ * 1′ over the study area is presented as contour maps which are presented in Fig. (5a-c).

Before the application of the model, the boundaries of the sub-basins are overlaid on top of topographic maps, on the false colored imageries as well as on contour maps in order to derive the model parameters for the sub-basins which are designated by numbers (1-12) and letters (A-G). The size, slope and main channel length parameters are measured and tabulated in Table (1) using the topographic map. The mean values for the geomorphologic characteristics to represent the fracture intensity, length and number of intersections are determined from the Landsat-TM data (Plate 2). The results are also presented by numbers in Table (1). The numbers indicate that the basins (numbered from 1-5) draining from the east side considering the flow direction as downstream are small in size, have milder channel slopes and lesser degree of fractured formations. But the catchments located on the southeastern part (indicated by letters A-G) have larger area size with higher rate of intensity, longer fracture length as a result of which more number of fracture intersections are observed due to deformation of Sabya formation and by weathering affect which converted the lithologies of Sabya formation to micaceous schist or other similar units.

Model Application

The peak discharge estimation through the use of model (TR-55) as well as the application of Rational formula for small wadis are presented in Table (2a) so that the model outcomes with the results of the traditional approach can be compared when there is a limited hydrologic and geologic information available.

During the model application phase of the study, some input parameters are considered to be different for the east, north and west sub-basins. For example, time of concentration (t_c) of 0.1 hr, storm distribution type (II and III), the curve number (CN) around 70-75 and Unit Hydrograph (UH) peak discharges (q_u) produced from 1 mm depth of effective rain are 0.73 and 1.12 m^3/sec for 50 and 100 years return periods respectively are considered for the wadis draining from east and introduced as inputs to the model. For the western sub-basins, t_c is increased to 0.2 hr because of bigger area size, UH peak discharge as 0.79 and 0.85 m^3/sec for 50 and 100 years return periods and the CN has been lowered down to 50-60 for the similar storm types where number II is only considered for short duration and intensive storm with return periods 50 and 100 years. The wadis which are draining from north have shown the model input parameters in between the above mentioned values as indicated in Table (2a).

In the meantime, the Creager formula described in the first method using two C values (30 and 60) is applied together with the point frequency using two distribution functions in order to compare the estimated flood peaks for 50 and 100 years return periods for medium size basins. The comparable results are obtained as presented in Table (2b) using the methods 1 and 2.

TABLE 2a. The peak discharge estimation using two methods for small size basins.

Location	Area #	Drainage Area $A (km^2)$	Rainfall intensity I(mm/hr)		Rational formula[1] (Q_p m^3/sec)		TR-55[2] (Q_p m^3/sec)		Input model parameters for TR-55		
			Return period		Return period		Return period		Storm type ST	Curve no. CN	Concentration time t_c (hr)
			50 yr	100 yr	50 yr	100 yr	50 yr	100 yr			
East	1	1.525	157.8	182.4	33.4	70.0	32.28	72.77			
	2	2.367	143.4	166.2	47.2	98.0	42.36	83.96	III	70	
	3	0.567	171.6	200.0	13.5	28.0	13.88	30.89			0.1
	4	1.628	130.8	151.8	29.6	61.80	24.53	58.57	II	75	
	5	0.926	153.0	1743.6	19.70	40.4	18.57	41.40			
North	7	1.41	175.2	205.2	34.34	72.39	34.07	70.53			
	8	0.846	205.3	351.7	24.1	77.4	26.26	91.48	III	70	
	9	1.23	175.2	205.2	29.95	63.15	29.81	61.61			0.1
	10	1.40	175.2	205.2	34.09	71.88	33.79	70.13	II	70	
	11	1.09	173.5	202.0	26.4	55.2	25.84	53.15			
	12	1.58	175.2	205.2	34.48	81.12	39.04	79.05			
West	A	0.88	175.2	205.2	10.72	25.10	10.98	25.10			
	B	4.57	175.2	205.2	55.64	130.35	56.76	130.3			
	C	1.05	175.2	205.2	12.78	29.95	13.10	30.00	II	50	
	D	1.94	175.2	205.2	23.62	55.33	24.0	55.3			0.2
	E	8.08	175.2	205.2	98.38	230.46	100.37	230.5	II	60	
	F	1.58	175.2	205.2	19.24	45.07	19.68	45.0			
	G	3.87	175.2	205.2	47.12	110.38	48.0	110.3			

TABLE 2b. The peak discharge estimation using two methods for medium size basins.

Area #	Drainage area A (km^2)	Creager formula[3] ($Q_p = m^3/sec$)		Point frequency[4] ($Q_p = m^3/sec$) Return period			
				50 yrs		100 yrs	
		C = 30	C = 60	EV1	GEV	EV1	GEV
W. Maraba	540	1572.25	3144.5	1040.85	1709.41	1203.41	2254.72
W. Talami	32.5	289.52	579.04	314.38	516.32	363.48	681.0
W. Dilah	285	858.71	1717.43	792.77	1301.98	916.58	1717.33
W. Itwad	548	1548.19	3168.37	1047.4	1720.24	1211.0	2269.02

(1) Rational formula $Q_p = 0.278$ CIA where C = 0.3 ~ 0.5 for 50 years and C = 0.5-0.9 for 100 years.
(2) TR-55 model $Q_p = q_u \cdot A \cdot R = f$ (storm type, CN, t_c).
(3) Creager formula $Q_p = 1.302C(0.386A)\exp(0.936A^{-0.048})$ where C = 30-60 for 50 and 100 years.
(4) Point freq. analysis using extreme value type I(EV1) and general extreme value (GEV).

Conclusions

The results of this study demonstrate that processed Landsat Thematic mapper data is highly appropriate for digitizing the information to use as input parameters for hydrological model applications in order to estimate the flood peaks. Even the simple models such as the one used here requires some non-parametric information in the form of curve number which represents the lithology, soil and land use. The simulated hydrograph peak data from intensive storms can only be estimated using the appropriate model coupling with the remote sensing technology to determine the best representative values for spatially varied data. This is the case in the Kingdom of Saudi Arabia where data is scarce and highly variable in time and space.

Further studies of this kind are however required to assess an objective criteria to select the methodology and model application so that a better estimate for spatially variable data can be obtained from remote sensing data in order to couple them with the models after several model calibration studies. The real objective is "trying to simulate complex rainfall-runoff processes with a simple hydrologic modelling approach".

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تقدير ذروات الفيضان باستخدام تقنيات الاستشعار عن بعد
دراسة تطبيقية في وادي عتود في جنوب غرب المملكة العربية السعودية

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جدة ، المملكة العربية السعودية

المستخلص : أصبح الاهتمام بتطبيقات الطرق الحديثة للحصول على المعلومات كبيرا في الآونة الأخيرة . أهم أهداف هذا البحث هو ربط تقنيات الاستشعار عن بعد مع النمذجة الهيدرولوجية لكي يتم تقدير ذروة التدفق في أحواض صغيرة الحجم في وادي عتود الواقع في الجزء الجنوبي الغربي من المملكة العربية السعودية .

تم تجميع المعلومات عن أنواع الصخور وأنماط التصريف والتوزيع العددي والمكاني لشقوق الأحواض الصغيرة ومن ثم تمت معالجتها وأظهرت على شكل صور ورسومات وتمت هذه الدراسة باستخدام بيانات « لاندسات » من نوع الراسم النيماتي على هيئة صور ملونة زائفة وصور ملونة نسبية .

أمكن تقدير ذروة التدفق للأحواض الصغيرة بتطبيق النموذج الهيدرولوجي (TR-55) وتمت مقارنة النتائج مع ما تم الحصول عليه بتطبين المعادلة النسبية وهي الطريقة المستخدمة عادة في الهيدرولوجي ومن جهة أخرى تم أيضا تقدير ذروة التدفق لأحواض التصريف المتوسطة الحجم بواسطة معادلة كريجر ودوال التوزيع الترددي للنقط .

أظهرت النتائج أن بيانات « لاندسات » والتي عولجت بالألوان مناسبة جدا لتحويل المعلومات إلى أرقام يمكن الاستفادة منها في تطبيق النموذج الهيدرولوجي ، وتظهر المتغيرات في النموذج كمعلومات ثابتة على هيئة أرقام للمنحنيات والتي تعتبر شكلا رقميا للمعلومات الصخرية واستخدامات الأراضي .