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# Satellite Remote Sensing Analyses for Hydrogeological Assessment of Rabigh Drainage Basin, Red Sea Coast, Saudi Arabia

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**Abstract:** In response to the rapid increase in the population with new adoptions in life-style and the associated faster urban, industrial and agriculture development activities caused stress on water demand for further socio-economic growth in and around the expending Rabigh coastal city of Saudi Arabia. As such, dependency on desalinated-water supply from Red Sea was become unavoidable. Wadi Rabigh drainage basin is significantly large in size covering about 5,300 km$^2$, which is seven-times bigger than Bahrain, a country of the Gulf. An integrated research study was carried out for the appraisal of the groundwater potential associated with the Precambrian crystalline rocks and the Cenozoic basaltic terrains exposed in the Rabigh basin. The study included the satellite remote sensing analyses, the extraction of satellite digital lineaments, the hydrogeological field traverses, the evaluation & characterization of geological setup and the development of the rational groundwater models. Results of the satellite remote sensing analyses and other supporting hydrogeological research have revealed the excellent recharge conditions for the aquifers in the upstream areas of the Rabigh basin and the enormous groundwater discharges along the coastline areas of Red Sea. On the basis of deduced hydrogeological model(s), it has been inferred that the Rabigh basin has the bright prospects of the fault/fracture zones' and/or basaltic aquifers. Further detailed integrated geophysical investigations have been recommended to decipher the precise subsurface location(s) of the aquifer(s) for the drilling investigation within the geological setup.

**Key words:** RSA Hydrogeo-models • Fault/fracture & basaltic aquifers • Groundwater-discharge into Red Sea • Rabigh basin • Saudi Arabia

## INTRODUCTION

Rabigh is located about 200 km north of Jeddah City on the coastline of Red Sea. The city has become one of the faster growing important coastal cities with the pace of rapid industrial development activities along the Red Sea coastal areas. Consequently, the water demands were exponentially increased too. Though, the major part of the domestic and industrial demands is presently being met through the water-supply from the Red Sea desalinated water. But the water-supplies from other indigenous sources, particularly the groundwater from the Rabigh drainage basin, which covers a large area of about 5310 km$^2$ between the latitude 22° 33' 18" to 23° 38' 46" N and longitude 38° 55' 30" to 40° 07' 6.4" E, cannot be neglected as the seawater desalinated water-supplies may have several natural and anthropogenic threats [1].

In the past, a few studies were conducted to assess the groundwater quality, which were based on the results of chemical analyses of 47-water samples collected from

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the existing shallow dug wells in different parts of the Rabigh basin [2, 3]. The review of these studies has shown complex variability trends of the chemical characters among the groundwater samples. A study was carried out on the basis of watershed analysis and concluded that the surface and the subsurface water-flows are being controlled by the prevailing typical features of the Cenozoic basaltic lava-flows and the structures of the Precambrian rocks [4].

The present paper describes the hydrogeological characteristics of the Rabigh drainage basin by adopting the concepts of the fault/fracture zone and basaltic lava-flow aquifers. The description of results is based on the satellite remote sensing analyses, the extraction of satellite digital lineaments, the hydrogeological field traverses, the valuation of the geological setup and the interdisciplinary GIS-linked hydrogeological modeling.

**Methodology:** The following steps were adopted to achieve the set objectives of the present research study:

The satellite ETM+ images (row: 044 and path: 170) of July-2000 period were acquired for the remote sensing analysis (RSA) study, which were in their raw form in Geo-TIFF format with separate spectral bands. The images were ortho-rectified on the datum of WGS-1984 and given projection of Universal Traversal Mercator (UTM) coordinate system with zone-37, applicable to the study area. Further, the images were further processed for the customized histogram equalization, brightness inversion enhancement and single thermal band classification. These thematic layers of enhanced images were interpreted and modeled for the hydrogeological assessment interacting with other thematic layers using standard steps of GIS.

The processed images were also used for auto-extraction of the digital linear features by using Arc GIS and Erdas Imagine. Subsequently, the extracted linear features were processed and formatted in the form of lineament length, numbers and cross points for determination of their densities; and the lineament density distribution anomaly map was generated, analyzed and interpreted.

Semi-regional drainage was extracted from published geological maps pertaining to Rabigh basin on scale of 1:250,000 (maps source: Ministry of Petroleum and Natural Resources, Kingdom of Saudi Arabia). The extracted drainage maps were scanned, geo-referenced, digitized, integrated and a larger map of whole of the Rabigh basin was prepared that was used as a thematic layer for GIS-based analysis/modeling.

Subsequent to the laboratory studies, the hydrogeological traverses were carried out to collect the field data and the hydrogeological observations from the study area. In addition, the technical field photography was done during the field investigations.

Based on the above thematic layers, different interactive overlays and models were generated, like the geological mapped faults, the extracted lineaments and the drainage networks generated from satellite DEM data and from the published geological maps. Moreover, the archive literature, related to groundwater studies for Rabigh basin, was acquired from different sources, which were reviewed and inferences drawn were incorporated in the text.

**General Geology:** Geologically, the exposures of the Cenozoic basalt terrain dominate in the form of basaltic lava-flows covering as well as enveloping the Precambrian rock suits of the Rabigh basin (Figure 1). The exposed basaltic lava terrain belongs to the Harrat Rahat, one of the main volcanic fields of Saudi Arabia. The eruptive centers, in the eastern part of the Rabigh basin, have occupied higher elevations, from where the strong southwestern lava flowing-trends were observed down to the Red Sea. As soon as the coastal plains start, the lava-flows lose their downward continuity due to either their erosion or burial under the thin cover of Quaternary deposits derived from land as well as from the sea.

However, within the central portion of the basin, the Precambrian rock suits are exposed partially beneath the cover of the lava-flows. The Precambrian rock terrain is composed of the intrusive and layered metamorphosed red sandstone with pebble conglomerate & shale, various granites, monzogranite, quartz-greywacke with conglomerate & volcaniclastic rocks, amphibolites with metavolcaniclastic rocks & schiest, mafic volcanic rocks & marble, epiclastic rocks with conglomerate & volcanic rocks, granodiorite with tonalite. The regional trends of the structures, the contacts among different rock units, the formational lineations and other features of the Precambrian terrain strikes in NE-SW orientation, but most of local faults/fractures show more or less east-west striking trends. From the general observed trends of the exposed rocks, it was inferred that the basin was completely filled with the lava-flows. Later on, differential weathering of the basaltic lava-flows were removed and exposed the Precambrian basement rocks or the westward moving tongues of the lava-flows were followed the paleo-channels of the preexisted drainage system, the

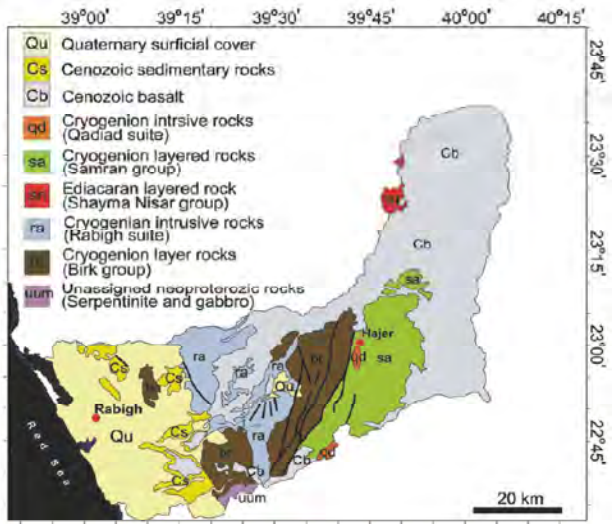


Fig. 1: Simplified geological map of Rabigh drainage basin. Map extracted and redrafted from [5].

semi-regional fault/fracture zones associated with the crystalline rock suits of Arabian Shield and the low lying tectonic depressions.

Hydrogeologically, two types of drainage networks were observed within the basin. The tributaries emerging from the northeastern volcanic ridge of the eruptive centers are strictly controlled by the incipient flow pattern of the basaltic lava. Thus, the courses of these tributaries ran within the basalts. On the other hand, another lava-flow tongue of Harrat Rahat partly has occupied the south and southeastern parts of the Rabigh basin. Several smaller northwestward bifurcations of this basaltic lava-flow tongue were found intruded into the fault/fracture zones prevailing within the Precambrian rock units. All these fault/fracture zones were also observed serving as the passage for the courses of the tributaries passing across the exposed Precambrian terrain forming a complex drainage network in the area associated with the main wadi Rabigh.

The drainage pattern in the downstream areas does not apparently show the distinct distributaries of the wadi Rabigh in coastal flood plain region. The development of tributaries is continuous even in the downstream portion of the basin from the relatively low elevated but steeper hilly mountainous front. This trend indicates steep gradient along the coastline areas, which in turn, shows the possibility of Holocene up-rising.

**Hydrogeological Field Investigation:** In general, the wadi flows towards Red Sea almost in east-west direction from the eastern mountainous terrain. Field traverse was carried out from the discharging location of Wadi Rabigh at the coast to the dam constructed on the upstream course of Wadi Rabigh. In the lower riparian area, it was observed that the Wadi has several distributaries spread over a vast area in the coastal belt in the form of three groups after passing the Rabigh city (Figure 2). One group of the distributaries swings to north from west-orientation and discharges into Khaur Al-Butan lagoon in northwest of the Rabigh city. The other group of distributaries swings southward and pours into the Rabigh creek. The central group of Rabigh distributaries flow perpendicular to the coastline, but before pouring into the Red Sea directly, it again spread in NW-SE orientation parallel to the coastline. Before the wadi Rabigh and its distributaries drain into the southern part of the Khur al-Butan or the creek, a number of brackish water pools/patches were observed (Figure 2B). These puddles were considered to be the result of the groundwater discharges brought by the groups of the distributaries parallel to the coastline of the Red Sea. In addition, significant soil moisture was observed within the channel of the Wadi, its distributaries and their flooding planes in and around the Rabigh city that supported greenery in the form of small bushes.

Numerous agriculture forms were observed within the downstream part of the Wadi cultivated from the dug-wells' water-supplies and/or the accumulated flood water by using old conventional techniques of constructing small series of earthen dikes/dams like structures.

Exposures of the highly shattered sedimentary rocks were observed at the entrance of the upstream mountainous area, from where the channel of the Wadi

Table 1: Physio-chemical components of water sample collected from Red Sea at Rabigh offshore locations and the surface water samples collected from channel of wadi Rabigh

| Sea Coastal Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|
| Location of Red Sea Samples | | | | | | | |
| Lat | Long | Locality | Depth/elevation | pH | Conductivity (is/cm) | Salinity (0/000) | TDS (mg/l) |
| 22.810 | 38.036 | offshore | -10 | 8.24 | 49.2 | 32.2 | 46248 |
| 22.798 | 38.950 | coastline | 0 | 7.68 | 50.1 | 32.8 | 46593 |
| Surface Water Quality | | | | | | | |
| 22.823 | 39.376 | Spillway: Rabigh Dam | 170+ | 7.79 | 0.63 | 2.0 | 590 |
| 22.808 | 39.025 | Spring water pool in mid of Wadi Rabigh | 2+ | 7.52 | 6.23 | 3.4 | 5857 |

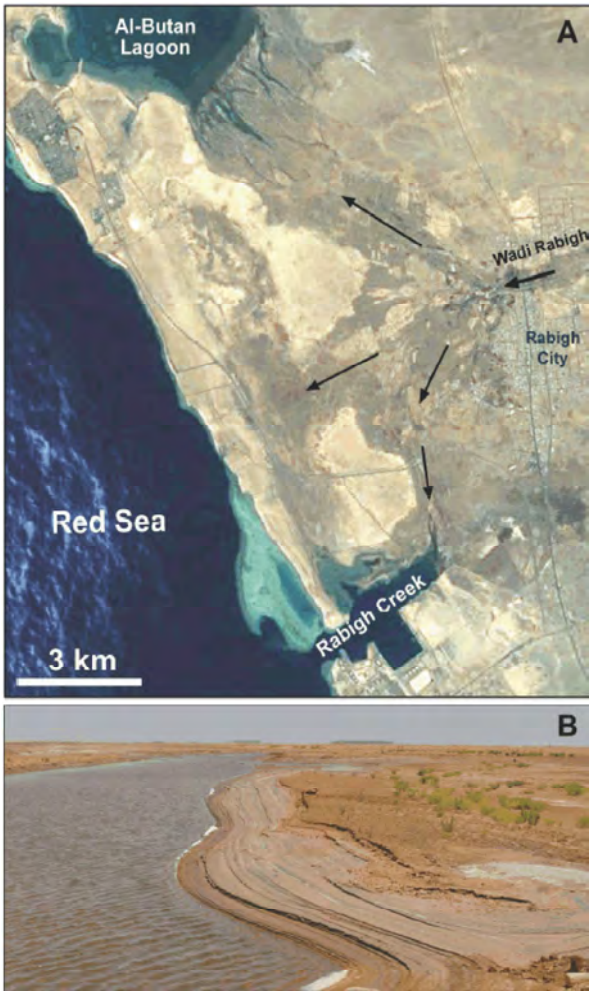


Fig. 2: Scenes show downstream hydrogeological conditions of wadi Rabigh. A) Image shows flow-pattern of wadi Rabigh and its distributaries; B) Field photo shows discharged water view of natural pool(s) at the back of coastline. Source of A: Google Earth (2015)

Fig. 3: Panoramic view of Wadi Rabigh shows its course passing across Cenozoic volcanic terrain. A series of raised terraces shows significant growth of desert-bushes and plants at the meanders indicating presence of considerable groundwater at shallow depth.

significantly deepened. Though this part of the Wadi does not have the perennial flow but distinct soil moisture was observed in the form of narrow strip of wild grasses and bushes within the wadi course. In the mid of Wadi Rabigh, large water ponds were seen within the course of river, in which the water was being accumulated due to the oozing of springs from the upstream area. Water samples were collected for tentative quality determination (Table 1).

Wadi Rabigh has made its course through the basaltic lava-flow terrain particularly in the upstream part. The close look of the lava terrain shows potential capability to retain the rainwater, which seems to be an excellent source of natural water harvesting in the region on either side of the Wadi (Figure 3). On the other hand, the exposures of the Precambrian rock units were observed in the central part of the Rabigh basin. The presence of highly fractured, jointed and weathered conditions indicates consequent higher secondary porosity and permeability of crystalline hard rocks.

A dam was constructed at about 30-35 km east of Rabigh city at the southern intersection of Wadi Nida and Wadi Marr, the major tributaries of Wadi Rabigh in

the upstream area. The discharge of the stored water had created an apparent perennial flow towards the downstream areas. Water samples were collected from the flowing channel downside of the dam for tentative assessment of the water quality (Table 1). On the reservoir side, it was observed that the water was stored in a narrow gorge-like condition rather than broad and open reservoir lake. The fractures and bedding planes/joints and other planes of weaknesses within the rock units were directly in contact with water of the reservoir causing erosional activity in terms of the widening of the fractures and development of large cavities.

The preliminary remote sensing analysis identified the anomalous thermal conditions indicating the possible groundwater discharges in offshore areas of Rabigh. A boat-traverse was also carried out to collect the water samples from the identified anomalous spots in the Red Sea offshore areas. In comparison to average high salinity of 40 ‰ [1, 5, 6], the salinity and other measurements have indicated considerable dilution of seawater within the identified anomalous offshore areas due to regular discharges through the distributaries of wadi Rabigh (Table 1).

## RESULTS

The processed images relevant to the Rabigh drainage basin, were enhanced for several functions, like, histogram equalization with 3, 5, 7 bands, principle component analysis, convolution kernel, resolution merge, haze reduction, brightness inversion with 4, 3, 2 and 3, 5, 7 bands, mineral composite, natural color function with 3, 5, 7 bands, decoloration stretch, texture function with 3, 5, 7 bands, thermal band classification, iron oxide indices, hydrothermal indices and others. Out of these enhancement options, only three functions, the histogram equalization, brightness inversion and thermal band classification, were selected for the present paper.

**Histogram Equalization Function (HEF):** The HEF enhanced image distinctly revealed the hydrogeological characteristics of Rabigh drainage basin from upstream catchment areas to downstream discharging coastal areas (Figure 4). The elevated terrain of the volcanic eruptive centers and the lava-flows were sharply delineated in northern, northeastern, eastern and southeastern areas of the Rabigh basin. Similarly, the Precambrian rocks, partly exposed in the mid of the basin in Hajer and its northeast & southwest areas, were distinguished from the intervening as well as the overlying basaltic lava-flows. The colour separation also differentiated among different types of the Precambrian rock units. Likewise, the HEF separately marked the younger and the older lava-flows of Harat Rahat too. The younger lava-flows show dark blue colour, the older flows show green colour and the eruptive centers were reflected by the fluorescent bluish green colour. The minor and major tributaries, originating from the zone of eruptive centers, were observed to have their flow-courses within the older lava-flows on the basis of blue colour tones.

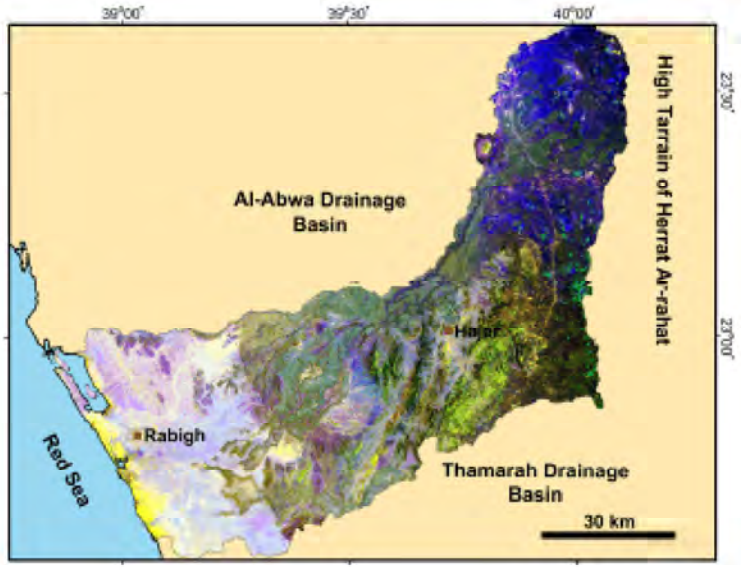


Fig. 4: Satellite image of the Rabigh drainage basin enhanced by using Histogram Equalization Function (HEF).

On the contrary, it was observed on the HEF enhanced image that the younger lava-flows pinch out against the heads of the tributaries in the upper most upstream areas and the tributaries flow further downward within the older basaltic lava-flows. On the basis of this hydrogeological setup of older and younger lava-flows, it was inferred that the tributaries were initially originated from the highest points of the eruptive centers of the older lava-flows, which were later on buried during the younger phase(s) of the eruptions. As such the younger eruptive lava-flows followed the already established channels of the older tributaries within the scoria cone region of the Harrat Rahat, which serves as water storage for recharging the tributaries of older basaltic lava-flow habitat(s).

The basement rocks and the associated structural trends, enveloped by the basaltic lava-flows, were clearly separated by their distinct colour contrast; like the Precambrian strong NE-SW striking faulted zone and the large circular intrusive body in the southeast of Hajer locality. The partially covered circular intrusive body shows interesting structural control on the drainage networks. In northwestern part, the lava-flows exit cutting across the circular body, which host the tributaries flowing in the northeast-southwest direction indicating strong control of the basaltic flow-trends. On the contrary, the tributary wadis within the half circular body in the southeastern part show E-W flow direction, which ultimately merge at angle ranging between 45º-90º into the wadis flowing in the half northwestern part of the circular body. It was observed that the regional NE-SW trending faulted crush zones and the circular body, which control the tectonic setup of the Precambrian rock units, has apparently no control on the flow of main wadi Rabigh and its tributaries. Rather, they cut across by the fault-controlled tributaries orientated in SSE-NNW direction as revealed by tonal differences between the rock units and the tributaries. Moreover, it was also observed that the lava-flows at the southeastern boundary of the Rabigh basin shows plunging of the lava-offshoots within most of these SSE-NNW fault/fracture zones and are hydrogeologically important because these faults/fractures became the courses of the tributaries flowing towards the circular Precambrian intrusive body across the NE-SW oriented thrust zone. It was also deciphered on the basis of HEF image analysis that the lava-flows initially covered the geology in the downstream area of the Rabigh drainage basin along the coastal region of Red Sea, which were partly eroded living behind the scattered isolated remnants of the basaltic flow. Moreover, violet color matching with the exposed Precambrian rock units indicated the basement rocks also at shallow depths, which strongly control the tributaries along the coastal region.

In general, the HEF has also revealed the attitude of the drainage network with respect to the agriculture activities, natural growth patterns of the wild plantation, presence of weeping water springs and/or shallow groundwater or rich moisture contents. Where there are groundwater springs making elongated water pools along the margins of the wadi courses, the HEF separated these wadis or portions of these wadis with deep bluish colour. On the other hand, the dry channels of the wadis are reflected with mixed pattern of yellow and red colors. The agriculture activity areas were reflected with the deep bright green colour tones within the courses of the wadis.

**Brightness Inversion Function (BIF):** BIF enhanced image has quality to differentiate the details of the objects, which are mostly camouflaged due to very dark tones and/or high reflective white colour tones. It was observed that the younger and older lava-flows were not very distinct on HEF image near the eruptive center of the volcanic activities (Figure 4), but the BIF image differentiated their details very sharply (Figure 5). Moreover, the emergence of the tributaries from the younger volcanic-flows, the scoria region, was seen sharp and distinct on BIF image. The tributaries flowing through the older lava-flows were also more prominent. Cultural features, like roads particularly the Makkah-Madinah highway, were also revealed clearly in the eastern part of the basin. Though, the HEF image differentiated the Precambrian rock units of different lithological characters, but not so clearly as compared to the BIF image that revealed pronouncedly the potential fault/fracture zones associated with these rock units. The agriculture activities, restricted within the wadi channels, were also delineated easily with their turquoise colour tones.

Comparison, between the tributaries flowing within the basaltic terrain and the tributaries flowing within the Precambrian terrain, shows the clear colour difference. The wadi flowing within the basaltic terrain shows green patches associated with the dark gray colour continuously bordered by the prominent pinkish-white colour in the northeastern part of the basin. Green colour represents to natural growth of wild vegetation and the presence of longitudinal water bodies. On the other hand, the tributaries flowing within the Precambrian rock terrain around the Hajer locality in the central part of the basin show mainly gray colour of fault/fracture controlled

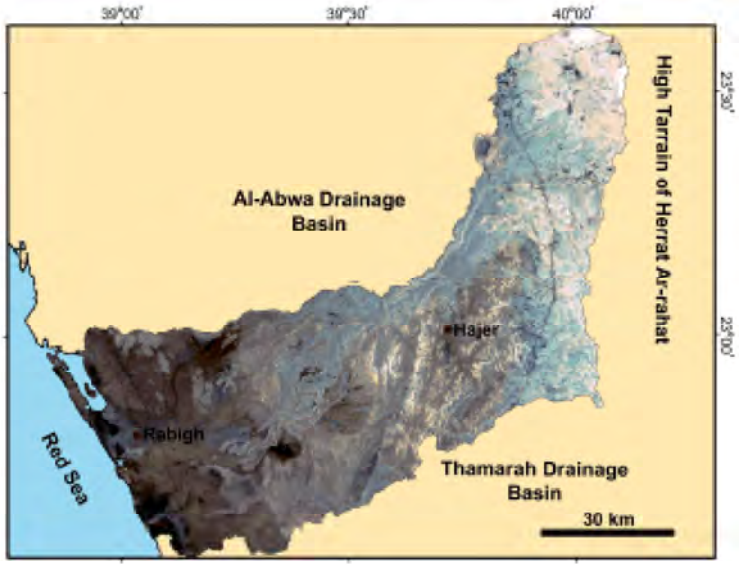


Fig. 5: Satellite image of Rabigh Drainage Basin enhanced by using Brightness Inversion Function (BIF).

tributaries' courses. At places where more clayey environment persists in the wadi courses the colour changes to black particularly in the coastal belt areas.

In the downstream areas, the dominance of clay was reflected by the dark tones of black/brownish black colours. Moreover, the BIF image also reflected presence of the groundwater bearing tributaries and the associated agriculture developments representing with the fluorescent greenish tones just before exit of wadi Rabigh from the mountainous terrain. Similarly, these conditions were also observed associated with the distributaries just after the exit of wadi Rabigh from the mountainous terrain to the coastal area. The BIF colour contrast shows that the distributaries, flowing parallel to each other, merge into a wider channel westward till it reach to Rabigh city. Further westward of the city, the wadi course again divides into three directions as identified by light grayish tone, which indicated the subsurface discharge of the groundwater into the offshore area near the coastline of Red Sea.

**Thermal Band Classification (TBC):** The TBC enhanced image represents the customized classification of the thermal digital values in terms of lowest/coolest (green), low/cooler (yellow), moderate (violate), high (red) and highest (blue) depending on the thin skinned digital thermal characteristics of the rock types. The distribution and the trends of thermal anomalies have helped to decipher the hydrogeological characteristics of the rocks and soils in the Rabigh drainage basin (Figure 6).

It was observed that the south-easternmost coolest (green) thermal digital values seem to be associated with the axial eruptive zone of the Harrat Rahat, which is partly reflected as a thin strip of green anomaly. However, the cooler (yellow) thermal digital values were found associated with the basaltic lava-flows of the Harrat Rahat exposed southeastward of the basin. Moreover, the trend of these anomalous values continued westward and shown thin fringe-extensions from the eastern main zone towards west heading to the exposed Precambrian rock complex in Hajer area. Another zone of cooler and dominantly coolest values was observed at the eastern margin of the exposed Precambrian rocks and also within the central part of the exposed Precambrian rocks. The interesting observation was that these thermal zones show their strong relationship with the NEE-SEE oriented Precambrian rocks bounded by older fabrics of intense deformational features and almost perpendicular to the present day wadis network system emerging from southeastern higher mountains of the Rabigh drainage basin. From this trend of thermal anomalies in relation to the wadi flow trends, it was clear that these thermal anomalies have no direct relationship with the shallow flow courses of the wadis.

The interactive correlation study of these thermal anomalies with the geological map of this area indicated that these anomalies were found directly associated with the Precambrian Shayban formation and its minor members, which are composed of Quartzofeldspathic and lithic volcanic clastics (Tuff, Agglomerate) and epiclastics, (arenite conglomerate) with subordinate mafic

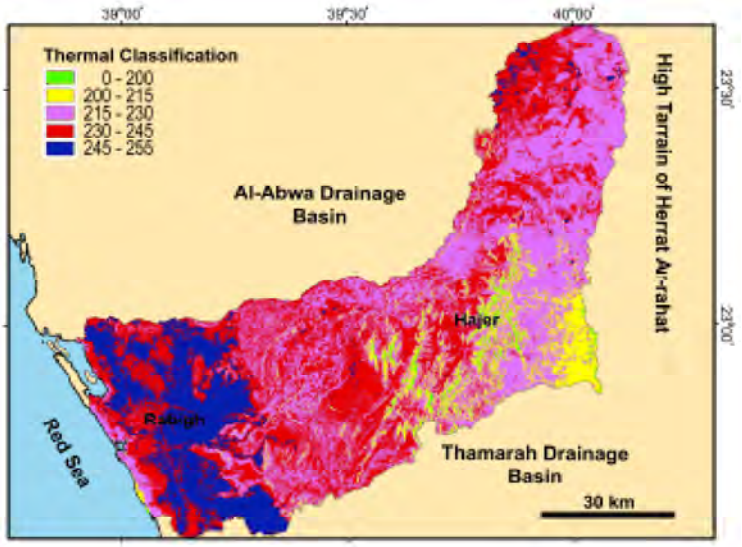


Fig. 6: Map shows the customize-enhanced satellite image of the Rabigh drainage basin.

volcanic marble and pyroclastics. Moreover, this area also contains different types of Precambrian schist. From that study, it was revealed that those Precambrian rocks have enormous dual porosity, which provides sufficient storage for the groundwater in this area. This inference also supported by the presence of dense development of wide desert plantations and the agriculture activities in the western part of main thermal anomalous zone depending on the present near surface availability of groundwater.

The distribution of the moderate thermal digital values (violet) seems to be associated mainly with the basaltic lava-flows. On the other hand, the wadis originated and subsequently flowing within the bodies of the basaltic flows of the basin in general reflected distinct cooler thermal values (yellow) indicating near-surface substantial groundwater flow and/or presence of the numerous small pools of spring water within the channel of the wadis, particularly in the upstream areas. It was also observed that the anomalous high thermal digital values were mainly associated with the thin alluvial covers of the coarser sediment deposits of the wadis' courses, surfaces of the Precambrian rocks terrain and/or basaltic lava-flows, whereas, the clay deposits were represented by the highest thermal digital values.

The sequence reversal of the digital thermal anomalous values, from eastern mountainous ranges to western coastline areas of the basin, was inferred to be very important from the hydrogeological point of view. The upstream catchment and the upper part of downstream areas show the lowest to the highest thermal values indicating bright recharge conditions for the aquifers associated with the basaltic lava-flows, fault/fracture zones of the Precambrian rock units and/or thin alluvial deposits within the wadi courses. On the other hand, the downstream areas of the Rabigh drainage basin shows a prominent decreasing trend from the highest thermal values prevailing in the coastal flood-plain areas to the lowest thermal value prevailing along the coastline of the Red Sea. Such setup of the observed anomalous thermal values indicates significant groundwater discharge into the offshore area. On the basis of these observations, it was inferred that the Rabigh drainage basin holds bright groundwater prospect as the over-saturated part of the potential fault/fracture zone(s) aquifer(s) discharging into the Red Sea.

**Extraction of Lineaments:** On the basis of the RSA analytical results of enhanced images, it was inferred that the geo-structural setup of the basin is extremely complex. In view to understand the attitudes as well as the density of the linear deformational structures like faults, fractures, fissures, joints and other lineation associated with the terrains of the Cenozoic basaltic lava-flows and Precambrian rock units, it became important to extract the linear features in more details within the Rabigh basin. Thus, the processed images were also used for the auto-extraction of the digital linear features. Subsequently, the extracted linear-features were processed, formatted, interpreted and modeled.

The lineaments extracted for the Rabigh basin indicated different trending patterns, which correspond to the exposed geological rock units of different types of terrains and their controlling structure behaviors

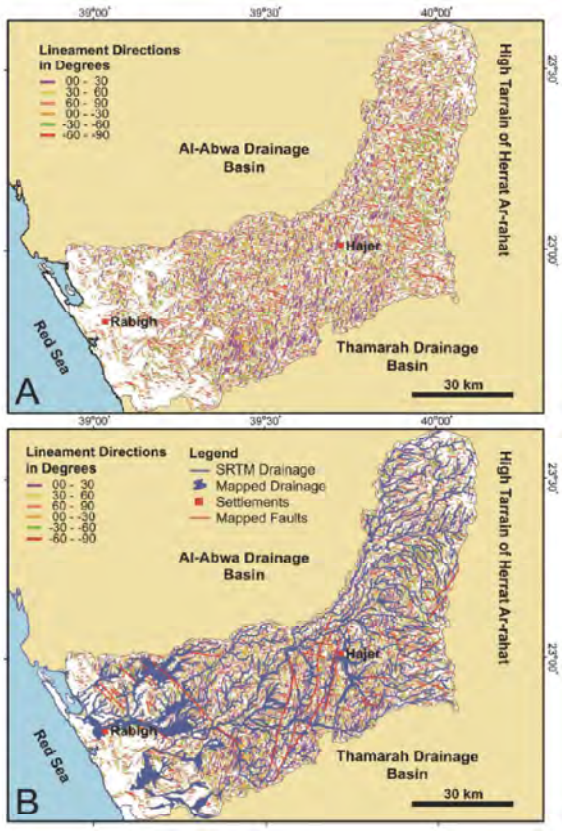


Fig. 7: Maps show extracted lineaments from TM image (A) and the model using thematic layers of drainage network, extracted lineaments and mapped faults (B).

(Figure 7A). As such, the varying attitude and density were observed associated with the lava-flows, the Precambrian rock terrain and the downstream coastal areas of the basin. In general, the lineaments were identified in the northeasterly, northwesterly, east-west and north-south trending directions. In the northeastern area, the complex set of lineaments shown crisscross pattern, where only the lava-flows were exposed. Whereas, in the southern part of that area, from where two major basaltic lava-flow tongues envelop the Precambrian rocks on northern and eastern sides, strong trend of rotational lineaments were observed. This lineament-trend corresponds to the exposed lava-flow trends at the dividing junction in terms of the circular wrapping of the northwest-trending subsurface continuation of the Precambrian rocks.

In the area, where the Precambrian rocks were exposed, the varying trends of lineaments were also observed, but the lineaments oriented in northeasterly direction and represented by violet colour tones showing the strong trends as compare to the area dominated by the lava-flows in northeastern part of the basin. The western edge of the Precambrian circular intrusive was also sharply delineated by these trends. The northeasterly trends dominate the area over all in comparisons to the other trends. On the other hand, the second dominating zones of lineaments were those, which were oriented in NNW-SSE direction and represented by dark red colour. General assessment indicated that those lineaments were associated with the lava-flows and gave their cumulative trend following the lava-flow trends themselves. In the downstream areas of the Rabigh basin, the dominance of the trend represented by violet colour, was decreased and the trend represented by red colour, which shows relative domination over the other lineament-trends indicating the extension of the lava-flows within the sediments of the coastal plain.

**Model: Lineaments & Hydro-Features:** A model was prepared by overlying the various thematic layers, which shown inter-relationship among the faults, the drainage network and the extracted lineaments (Figure 7B). It was observed that the drainage followed more or less the general trends of the lineaments. It was also observed that at places where strong interactions of the lineaments occurred, the tributary wadis as well as the main trunk of the wadi Rabigh indicated the widening of their courses/channels within the restricted zones in the central part of the basin. However, this phenomenon was more prominent in the downstream area.

On the other hand, the general drainage-flow cut across the regional mapped faults particularly in the central part and the areas at the junction of coastal flood plains and the westward mountainous front of the basin in southwest of Hajer locality. This imbricated NE-SW striking fault zone, associated with the Precambrian basement rocks, was inferred to be older, which seems to have been refilled by the re-crystallization of the crushed material during the earlier phases of tectonic deformations. However, the segments of these faults, which reactivated partially during the younger tectonic phases, were observed partially occupying by the wadis/tributaries' courses. This observation also indicated that the younger deformation activities were more prone to provide better hydrogeological conditions to allow the flow of the wadis within them.

But the regional mapped fault, striking in NW-SE direction at the junction of the coastal flood plains and the westward mountainous front, passes across the whole of Rabigh drainage system parallel to mountainous front.

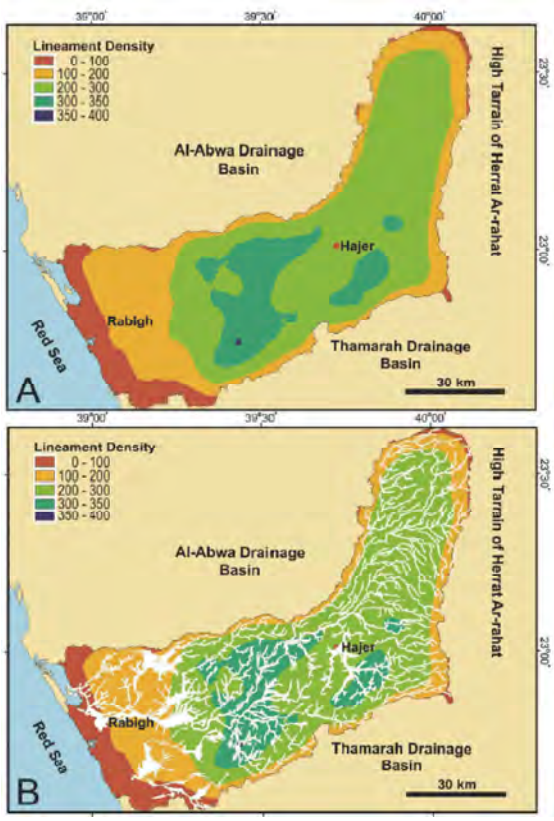


Fig. 8: Maps show lineament density anomalies (A); and the model by using thematic layers of the lineament density and the drainage network of Rabigh basin (B).

Similarly, a cluster of smaller parallel faults, in the northern areas of Rabigh city, indicated the same attitude as that of the eastward lying frontal regional fault. In the downstream area, it was inferred that these faults were associated with the Neogene activities of the ongoing tectonic processes related to the Red Sea rifting. As such, these inferences needed for special consideration to incorporate their impact while planning for the coastal management of groundwater and/or otherwise.

**Lineament Density Model:** In view to develop the lineament assessment model, the statistical calculations were performed related to lineament lengths, numbers and cross points. Based on the overall counted lineaments estimated by using geo-statistical tool in Arc GIS, the density anomaly map was prepared (Figure 8A). The highest lineament density, represented by the dark blue colour, was restricted only in a very limited area on negligible scale and as such was not considered to discuss here in detail. However, the map shows the irregularly-shaped higher lineament density anomalies in the central areas of the basin. The moderate lineament anomaly extends from mid to upstream areas covering major part of the Rabigh drainage basin. Presence of the low and the lowest lineament anomalous areas, enveloping the moderate lineament density anomalous areas on the northwestern, northern, eastern and southeastern sides, seem to be the edge effect-output of the software processing. But the westward zones of the low and the lowest lineament density reflected the natural correspondence with downstream hydrogeological environments of the basin.

In view to assess the overall interactive impact and the inter-relationships of lineament density anomalies, the hydro-model was developed overlying the drainage network of the Rabigh basin by using GIS tool (Figure 8B).

Geologically, the Precambrian rocks are exposed on eastern and western sides of the main NE-SW oriented thrust-fault zone in the south and southwest of Hajer locality. The exposed rock units of the buried Precambrian terrains were found associated with the high lineament density anomalies. But the Precambrian thrust-fault zone illustrated its association with the moderate lineament density zone instead of high or very high lineament density. It was inferred that the imbricate-thrust-fault zone seems to be recrystallized, diffused and became massive, but retained the fault/fracturing imprints. The average lineament density was dominantly associated with the basaltic flows. The lineament density decreased as the major part of rocky terrains was buried beneath the coastal alluvial plains.

On the basis of the interactive analyses, it was deduced that the prevailing high to moderate lineament density conditions seem to be encouraging from the hydrogeological point of view. The structural characters of the basaltic lava-flows and the Precambrian rock terrain demonstrate to hold the bright prospects for the presence of groundwater aquifers controlled by the fault/fracture-zones.

## DISCUSSION

The RSA study, based on the enhanced HEF, BIF, TBC images and the lineament models, provided a clear understanding regarding (i) the characteristics of drainage flow trends; (ii) the presence of vegetation, cultivation and natural springs along the wadis' channels passing within the Cenozoic lava-flows and/or the Precambrian rock terrains; (iii) the complex distributions of rocks

related to Precambrian, Cenozoic and Quaternary ages; the geo-structural setup; (iv) the recharge and the discharge of the aquifer(s); and (v) the interactive impacts on each other from (i) to (iv).

Particularly, the TBC enhanced image demonstrated the excellent conditions for the rainwater recharge to aquifer(s) and the discharge of the groundwater as revealed by the distribution of the digital thermal anomalies associated with upstream catchment and the downstream coastline areas. Considering the total area of about 5310 $km^2$ of Rabigh basin and the average precipitation of 100 mm/year, it was calculated that the Rabigh basin receives the rainwater ranging between 0.5 and 0.6 $km^3$ for the recharge of the aquifers and the runoff into the Red Sea directly or indirectly [4]. A detailed study was recommended to carry out for the estimation of the amount of groundwater being discharged along the Rabigh coastline areas. However, Basaham [7] reported regarding the discharging of the water through the distributaries of wadi Rabigh in the form of the groundwater and/or flashfloods that the contents of Al, Fe, Mn, Cu, Ni, Cr, V and Ba were contributed in northern part of the lagoon mainly by the ephemeral fluvial wadi-flow as the terrigenous origin materials.

Moreover, the RSA hydrogeological models show that the quality and groundwater yield of the aquifers are being controlled by the structural trends and the type of rock materials of the Cenozoic basaltic lava-flows and the fault/fracture zones of the Precambrian rock terrain. In such hydrogeological conditions, the quality as well as the groundwater yield may vary at place to place in the shallow wells. But it may be better while aquifers may be located in fault/fracture zones, which is a difficult task and needs followup detailed integrated geophysical investigations. In such hydrogeological conditions, some errors might have been introduced during the determination of the areal extent of individual elements using GIS statistical extrapolation techniques applied for Rabigh basin by [2], which needs due consideration as recommended above.

The construction of dam across a wadi/river system significantly influences the flow-dynamics and consequently causes the hydrological changes in the drainage basin, which are variable by seasons too [8]. A correlation study of the high resolution images of July-2005 and Feb-2013 indicated the similar drastic hydrological changes within the Rabigh drainage basin with reverence to the Rabigh dam's construction [4]. The RSA study of ETM/ETM+ archive images and the high resolution images of 2005 also indicated the numerous springs all along the wadi channels in upstream catchment areas before the construction of the dam.

The field hydrogeological traverses made in 2011 and the high resolution satellite images of 2013 also revealed that the dam reservoir was significantly filled by groundwater discharges in form of springs mainly from the basaltic lava-flows as well as by the runoff of rainwater in the upstream areas. Such water accumulation now has changed the attitude and dimensions of the tributaries.

As the Rabigh dam was constructed at the intersection of all the major tributaries passing across the upstream parts of the Cenozoic basaltic lava-flows and the Precambrian rocks terrains, the presence of relatively excellent quality-water accumulated in wide spread-reservoir area indicates the relatively higher water potential associated with the Rabigh basin. Thus, it was recommended that the Rabigh drainage basin needs the strategic exploitation, development and management of its water resources prevailing on the surface and/or flowing in subsurface within the fault/fracture zones as the invisible river(s).

## CONCLUSIONS

HEF and BIF enhanced images delineated that in the Rabigh basin, i) the Cenozoic basaltic lava-flows dominantly exposed covering most of the Precambrian igneous and metamorphic rocks, which caused a complex hydrogeological setup; ii) the drainage networks found completely controlled by the lava-flow trends and/or the faults/fractures/fissures zones of the Precambrian rock terrain; and iii) the numerous springs existed in the channels of wadis flowing within lava-flow terrains in upstream areas.

The TBC image analysis revealed the presence of low (cool) to lowest (coolest) digital thermal values in the upstream catchment mountainous areas indicating high water saturation providing the excellent recharging conditions within the elevated Cenozoic volcanic terrain of the Harrat Rahat and the intensely deformed Precambrian terrain. The lineament density models identified enormous dual porosity and permeability within the Precambrian rock terrain, which also provide sufficient recharged storage and flowage conditions for the groundwater associated with basin. On the other hand, the downstream areas show a prominent decreasing trend from the highest thermal values prevailing in coastal flood-plain areas to the lowest thermal value prevailing along the coastline of the Red Sea, which indicate significant groundwater discharges along the coastline as well as into the offshore areas.

On the basis of all the observations, it was inferred that the Rabigh basin holds bright groundwater prospect as the over-saturated part of the potential fault/fracture zone(s) aquifer(s) discharging even into the Red Sea. The above aquifers' recharge and discharge inferences have supported by i) the construction of Rabigh dam and consequent accumulation of enormous water in the channels of major tributaries as reservoir areas and ii) the estimated annual captured precipitation of 0.5 - 0.6 $km^3$ for the recharge of the aquifers hosted in the terrains of the lava-flows & the faulted/fractured Precambrian rocks and also for the runoff into the Red Sea directly or indirectly.

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