



Hydrogeologic assessment for groundwater prospects in Al-Abwa drainage basin, arid-terrain of Arabian Shield, Saudi Arabian Red Sea coastal belt

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Abstract

Arid regions are considered the most vulnerable areas regarding the water crisis. Al-Abwa drainage basin, situated at western arid part of the Saudi Arabian Shield region, presents a complex hydrogeological setup along the Red Sea coastline. Historically, the groundwater was used to extract from shallow thin alluvial aquifers underlain by the basement rock terrains. With time, rapid increase in population with changes in lifestyle and associated faster urban, industrial, and agriculture development activities caused stresses on the water demand for further socio-economic growth in the basin. As such, dependency on desalinated seawater supply from the Red Sea became unavoidable. A research study was carried out for appraisal of the groundwater potential associated with the thin alluvial aquifers, and new aquifers within the Cenozoic lava flows and Precambrian rock terrains in the basin. The study included the hydrogeological field investigations, the evaluation of exposed geological setup, the watershed characterization and the satellite remote sensing analyses and modeling. Results have provided clear understanding about the hydrogeological conditions in terms of tentative groundwater quality, expected quantity, utilization trends, hydro-characteristics of exposed rock units, precise delineation of Al-Abwa basin/sub-basins, structural impacts on flowing patterns of drainage networks, hydro-geomorphic parameters, recharging and discharging characteristics, impacts of auto-extracted lineaments and their density anomalies. Integration of various accomplished sub-studies revealed bright prospects of the fault/fracture zone(s) aquifers within Precambrian rock terrains in Al-Abwa drainage basin, which were recommended for further detailed geophysical and test drilling exploration.

Keywords Hydrogeo-evaluation · Watershed and remote sensing analyses · Lineament density · Fault/fracture zone aquifers · Al-Abwa basin (Saudi Arabia)

Introduction

Al-Abwa drainage basin is located about 195 km north of the second largest Jeddah city of Saudi Arabia between latitude 22°

58' 09" N to 23° 47' 10" N and longitude 38° 47' 00" E to 39° 52' 29" E covering an estimated area of about 5000 km² (Fig. 1). The basin has two small cities, the Mastorah at coast of Red Sea and the Al-Abwa in mountainous valley, developing with the faster pace since last few decades (Indexmundi 2012; TE, Saudi Arabia Population: Trading Economics (TE) 2013).

Conventional water sources were the randomly dug shallow wells within wadi alluvial terrains for the agricultural and domestic purposes, which are often threatened during the summer seasons. Now, other modern water supply source is from the desalinated water of the Red Sea mainly for domestic purposes. It was observed during the browsing on the Internet for the groundwater literature on the Al-Abwa drainage basin that the adequate systematic exploration activities remained limited as compared to the neighboring basins, like Rabigh drainage basin (Zaigham et al. 2017, 2015; El-Hames et al. 2011, 2013). Considering the fact that the urban and industrial

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development activities have rapidly grown and are further kept growing in the cities along the Red Sea coastal areas, they cause enormous pressure on the water demands. In such a situation, the water supplies from the indigenous new sources, like the groundwater from the Al-Abwa drainage basin, cannot be neglected as the seawater desalinated water supplies may have several natural and anthropogenic threats (Aburizaiza et al. 2013). Moreover, it was also identified as the Al-Abwa basin has its hydrogeological significance different from other neighboring basins, it needs specific exploration attention.

A research study was carried out for the appraisal of new groundwater potential associated with the thin alluvial aquifers, Cenozoic lava flows and the Precambrian rock terrains in the Al-Abwa drainage basin. The study included the hydrogeological field investigations, geological evaluation, watershed and the satellite remote sensing analyses, auto-extracted customized lineaments and their density anomalies, and the GIS-linked models generated by using the customized thematic layers.

The present paper describes the results of the integrated research study based on various accomplished sub-studies, which revealed bright prospects of the fault/fracture zone(s) aquifers mainly within the Precambrian rock terrains in the Al-Abwa drainage basin.

Methodology

The diversified sub-studies were treated differently by adopting the following specific steps for each one to achieve the final results of the present integrated research study.

Remote sensing analyses Acquired satellite ETM/ETM+ images of different periods were in their raw form in Geo-TIFF format with separate spectral bands. The images were orthorectified on datum of WGS-1984 and given the projection of Universal Transverse Mercator (UTM) coordinate system with zone-37, applicable to the study area. Furthermore, the images were processed for the customized histogram equalization, brightness inversion enhancement, and single thermal band classification for the RSA study. These thematic layers of the enhanced images were interpreted and modeled for hydrogeological assessment interacting with other thematic layers using standard steps of ArcGIS.

Auto-extraction of lineaments Processed images were also used for auto-extraction of the digital linear features by using PCI-Geomatica, ArcGIS, 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.

Extraction of drainage Semi-regional drainage was extracted manually from published geological maps pertaining to the Al-Abwa basin as the geo-maps show the wadi-width, whereas wadi-width on topo-maps (maps' source: Ministry of Petroleum and Natural Resources, Kingdom of Saudi Arabia), which were scanned, digitized, integrated, geo-referenced, and a larger map of whole of the Al-Abwa basin was prepared. The prepared map was used as a thematic layer for GIS-based analysis/modeling. Similarly, the acquired Shuttle Radar Mission Topographical Mission–Digital Elevation Model (SRTM-DEM) data from Consortium for Spatial



Fig. 1 Index maps show locations of Mastorah and Al-Abwa towns (a); and study area (b)

Information (CSI) were used to extract the boundary and drainage networks maps at 2 km² and 10 km² at minimum flow accumulation values by using the Watershed Management System (WMS) and ArcGIS software.

Field traverses After the laboratory studies, the hydrogeological traverses were carried out to collect the field data and the technical field photographs to capture the hydrogeological observations from the study area. As the end products of the research study, different interactive overlay maps and models were generated to reveal the rational hydrogeological picture of the basin.

Hydrogeological field investigations in the Al-Abwa basin

In addition to study the geological map of the Al-Abwa basin, the hydrogeological field investigations were conducted to understand clearly the interrelationship among the exposed rocks, associated structures, and trends of the geomorphic features. The traverses were carried out right from the upstream mountainous terrains to downstream Red Sea coastline areas, which directly provided the opportunities to observe the detailed hydrogeological setup and the various ongoing-anthropogenic activities and also the visits of other interesting sites.

In general, the wadi Al-Abwa drainage network has flow trend from north and northeast to southwest to east-west and ultimately drains indirectly into the Red Sea through the sub-surface passage of the distributaries as observed in the associated shallow dug wells in coastline areas. In the upstream catchment areas, it was observed that the courses of the small and large tributaries and wadi Al-Abwa itself show straight alignment trend in between the mountainous ranges on either side. Developments of small agricultural farms and growth of the wild bushes, grasses, and trees were observed at places within the stream channels or their raised terraces (Fig. 2a). Moreover, the growth of small typical wild desertic trees, bushes, and grasses was also observed on the scree slopes and within fractures of the elevated exposed Precambrian terrains (Fig. 2b). Such growth trends indicated substantial water moisture/saturation that supports typical natural vegetal growth in harsh conditions.

From hydrogeological point of view, two important geological conditions were observed in the upstream areas; i.e., (i) the presence of widely distributed phyllites, which usually serve as the excellent aquifers because of their cleavage porosity and permeability under weathering and deformation conditions and (ii) the presence of abundant open fault/fracture zones \pm 1-km long, which hold weathered rock soils.

It was observed that just out of the mountainous terrain, the wadi Al-Abwa is divided into westward radiating network of

the distributaries in downstream areas because of the drastic change of the surface gradients. The tributaries constituted 20-km long alluvial fan that gently slopes to the Red Sea (Fig. 1a). Close to the exit point of the wadi Al-Abwa from the mountainous terrain, an excellent yielding of groundwater through tube well was observed in a big farm (Fig. 2d and e). However, more extensive development of the agriculture farms and the numerous shallow wells dug in alluvial deposits with very shallow water table were observed in and around the Mastorah vicinity close to the coastline (Fig. 2c, f, and g). It was deduced that considerable amount of the groundwater flows at very shallow depth and the excessive groundwater amount ultimately discharges into the Red Sea at the coastline areas, which provided better environments for the growth of the mangroves in front of the defused outlet(s) of the distributaries (Fig. 2h).

The representative groundwater samples were collected from different well sites in upstream to downstream areas. The quality of the groundwater was found tolerable, particularly for agriculture purposes with minor variations in chemical parameters (Table 1).

From the analytical results, it was identified that the groundwater quality is improving proportionally with respect to the increase in elevation of the groundwater samples in the mountainous terrain away from the coastal salt-affected areas. However, the groundwater of the basin, in downstream, can also safely be utilized for domestic purposes after specific low-cost water treatment technique(s). It was anticipated that the aquifer hosted in the fault/fracture zones in Precambrian rock terrains may serve the excellent quality groundwater particularly in upstream areas. In general, the field observations indicated encouraging hydrological conditions right from the mountainous region down to the coastline indicating the dominance of fluvial hydrodynamic domain against the marine hydrodynamics in the coastal areas.

Geological setup

Geologically, the exposed rocks are heterogeneous in nature, which mainly belong to the Precambrian period (Fig. 3). Cenozoic basalt flows also cover narrow zone along the eastern and southern boundary of the basin. However, most of the downstream part of the basin consists of coastal alluvial flood plain deposits. Precambrian terrains, composed of various igneous, metamorphic, and meta-sedimentary rocks, show the general northeast-southwesterly striking trends. All the rock units were found in the form of finite dimensions indicating complex multiple-server deformational history. Lithologically, the Precambrian rocks were categorized on their genetic characters into “suites” and/or “Group” (Johnson 2006).

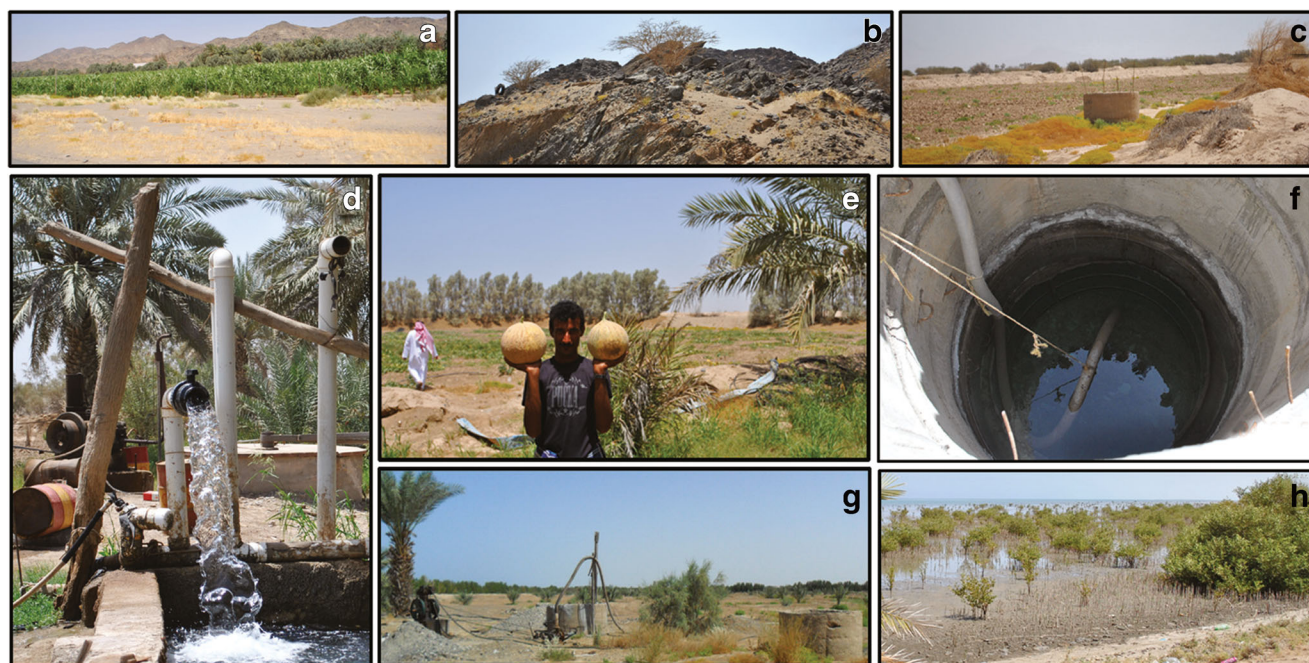


Fig. 2 a–h Collage of field-photos shows different scenes of hydrogeology versus agriculture activities in Al-Abwa basin

Ediacaran layered rocks, comprising Shayma Nasir Group (sn), are weakly metamorphosed polymict conglomerate; basaltic, andesitic, dacitic, and rhyolitic lava, tuff, and agglomerate; and red-brown arkosic, volcanoclastic, and calcareous sandstone (Ramsay 1986). Ediacaran intrusive rocks as Subh Suite (sf), consists of granite plutons of alkali granite, alkali-feldspar granite, alkali-feldspar syenite, and syenogranite; as Khuls Granite (kl) have elongated plutons of hornblende-biotite monzogranite, granodiorite, and subordinate syenogranite; and as Suwaylih Suite (ys) comprises elongate syenitic plutons of monzonite, quartz monzonite, and alkali-feldspar syenite (Camp 1986). The Cryogenion intrusive rocks as Rabigh Suite (ra) consists of tonalite, diorite, and gabbro (Ramsay 1986); and as Shufayyah complex (su) consists of the granodiorite, tonalite, diorite, and gabbro plutons. Whereas, Cryogenion layered rocks as Birak Group (br) have metamorphosed volcanic and sedimentary rocks, i.e., greenschist facies basaltic, andesitic, dacitic, and rhyolitic

flows, graywacke, marble, quartzite, and chert (Camp 1986); and as Furayh group (fu) have a widespread succession of deformed and weakly metamorphosed mafic to felsic volcanic and sedimentary rocks, like green and purple shale (phyllites), siltstone, volcanoclastic sandstone, graywacke (Delfour 1981); moreover, as Milhah Formation (mz) have massive basalt, subordinate rhyolite subvolcanic intrusions, sandstone, shale, conglomerate, mafic tuff, and minor limestone (Camp 1986). The unassigned granites (ugg) comprise undivided monzogranite, syenogranite, and alkali-feldspar granite. Among the younger rocks, only small Oligocene to Pleistocene Dafin formation, consisting of sandstone and pebble conglomerate, was reported overlain by basaltic lava flows at southwestern coastal boundary of the basin. Downstream coastal areas are composed of the “Recent” wadi alluvium deposits in the form of fan (Qal), quaternary shell-bearing beach sand covering raised reef-limestone (Qs), and raised alluvial terraces (Qu).

Table 1 Onsite determined chemical parameters of collected groundwater samples

Lat	Long	Location name	Elevation (m)	pH	Conductivity (mS/cm)	*Salinity (0/00)	TDS (mg/l)	Temperature (C)
23.0686389	38.8215556	Well near coastline	8	7.96	6.50	3.6	6110	29.4
23.1161944	38.8794167	Well in a farm in upper part of downstream area	22	6.91	8.50	4.8	7990	33.3
23.1163056	39.1102778	Water filling station in southern part of Wadi Qahah	87	7.47	6.03	3.3	5668	32.8
23.241	39.1829444	Well in upper part of Wadi Qahah	126	7.55	2.65	1.3	2491	33.7

*Salinity is a measure of dissolved salts quantity in seawater in parts per thousand (0/00) by weight

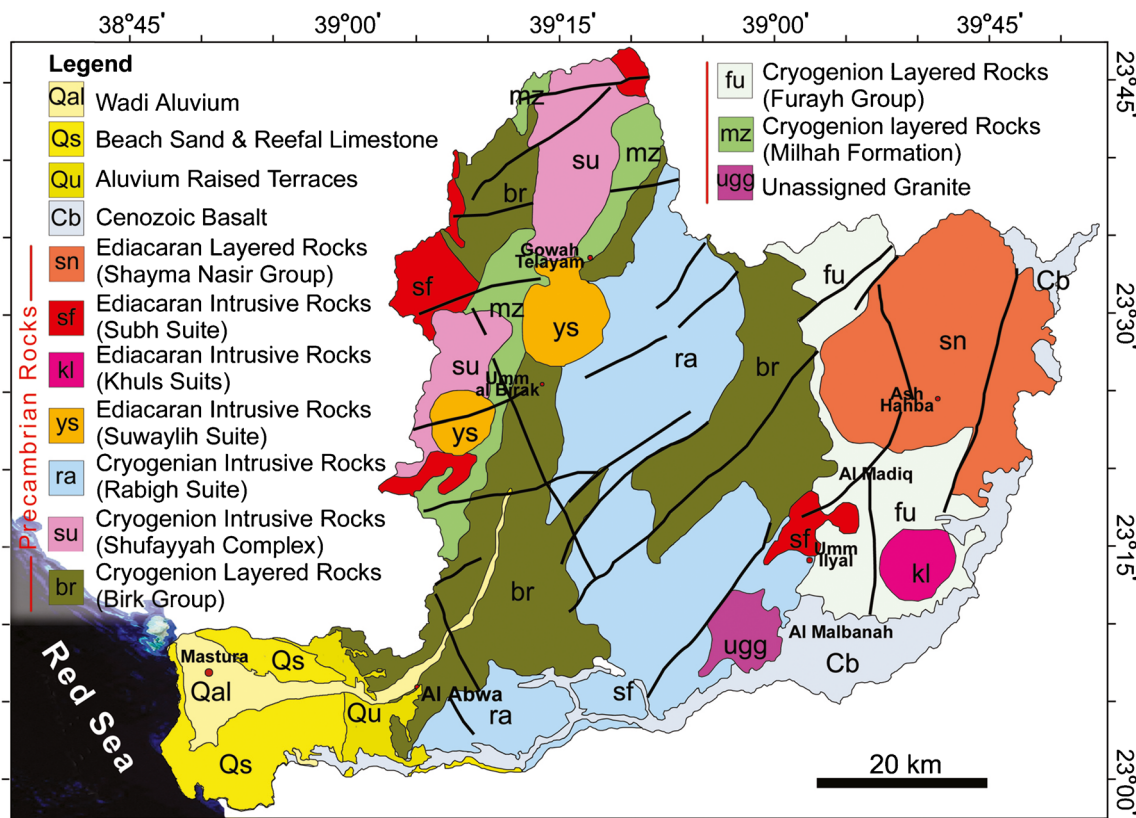


Fig. 3 Map shows simplified geology of Al-Abwa drainage basin

Al-Abwa watershed analyses

A clear understanding of the prevailing hydrological conditions is a difficult task in the groundwater exploration, particularly while the hotspot target(s) are associated with the complex geological setup, like the Al-Abwa drainage basin and its sub-basins. In relevance to this problem, the watershed delineation and determination of various geomorphological parameters were considered as the important solutions.

Al-Abwa drainage networks were extracted for the minimum flow accumulation values of 2 km² and 10 km², which were further subdivided into three sub-basins, by using software as discussed in section-2 “Methodology,” in relation to the outlets’ significance, i.e., Al-Qahah (WAQ), Al-Farra (WAF), and Al-Abwa (WAA) itself (Fig. 3a and b). Moreover, the salient geomorpho-hydrological parameters like total areas, mean elevations, perimeter, sinuosity, shape facts, lengths, and slopes were also determined, by the software, for each sub-basin considering the 10-km² flow accumulation value (Table 2).

Extracted drainage maps defined the straight flow orientation of main course of WAQ in NNE-SSW direction. The course of WAF displayed straight flow nature but has NNW-SSE direction in the upstream area, but gradually attained the general flow trend. In the downstream part, the flow direction

changed at about 90° into east to west direction. The outlets of the two major tributaries, WAQ and WAF, converged sharply at the northwest-southeast striking boundary of WAA sub-basin and developed a triple junction (TJ) of the main sub-drainage networks (Fig. 4).

Moreover, the drainage map, extracted on 2-km² accumulation factor, clearly displayed that the tributaries of any order take a turn at ± 90° and merge into larger tributary at almost ± 90° angles. Thus, these distinct drainage trends show rectangular and/or trellis patterns indicating strong structural control on the wadis flows. It was deduced that the main wadi and its major and minor tributaries flow within tectonically created fault/fracture zones hosted in Precambrian rock terrains of the basin.

The overall fan shape of the Al-Abwa watershed apparently presented a lower concentration time and higher runoff flow conditions of the rainwater. But, shapes of the sub-watersheds differ from each other. WAQ sub-basin presents fan shape, but the length is longer than the width of this sub-watershed. On the other hand, the WAF watershed has much longer length than the width. Shape is eastward-convex semi-rectangular indicating higher time of concentration that results in more water infiltration of the rainwater as compared to evaporation and runoff. Similarly, the geological surface-roughness, caused by the intense faulting/fracturing zones hosting wadis, was inferred to provide conducive hydrogeological conditions

Table 2 Some of the salient hydrological parameters of Al-Abwa Drainage basin

Basin name	Wadi Al-Abwa	Wadi Al-Qaha	Wadi Al-Faraa	Total
Basin area (km ²)	649.13	2054.72	2134.40	4838.25 or say = 5000
River bed mean elevation (m)	85.03	445.63	634.23	
Perimeter (km)	197.84	331.45	396.83	
Basin length (km)	456.71	713.20	877.14	
Sinuosity	1.43	1.12	1.49	
Basin shape fact	3.21	2.47	3.60	
Basin slope	0.03	0.18	0.18	

for more infiltration of rainwater than the runoff and evaporation.

Sinuosity, the ratio between distances covered by the meander and the straight-line distance covered by the meander was calculated as 1.49, 1.12, and 1.43 for the WAF, WAQ, and WAA sub-basins, respectively. Theoretically, sinuosity values range from 1 (case of the straight line) to infinity (case of a closed loop, where the shortest path length is zero) or for an infinitely long actual path (Wikipedia 2018; Leopold et al. 1964). However, it was generally found that the sinuosity index and the wavelength and amplitude of meanders increase in downstream as the basin slope decreases. But the WAQ sub-basin, having 0.18-average slope of the mountainous terrain, had a low sinuosity index of 1.12 and distinct straight courses of wadi WAQ drainage network though its average river bed elevation is moderate (+ 446 m). Whereas, the average elevation of WAF sub-basin, comprising mountainous terrain, is higher (634 m) with an average slope of 0.18, but the sinuosity index 1.49 is much higher than the lower WAQ. On the other hand, the WAA sub-basin has very gentle slope of 0.03 as compared to Qahah and Faraa sub-basins, but the sinuosity index value (1.43) is greater than Qahah and lesser than Faraa. It was inferred that the meandering-cum-turning trends of the WAF drainage network is controlled by the fault/fracture zone(s) rather than the average higher slope or elevation.

Based on analyses of the determined hydrological parameters, it was identified that the WAQ, WAF, and WAA have collectively having higher concentration time depending on the length-width ratio, the complex lithology, and fault/fracture zones of Precambrian rock terrains and resulting trends of the structural-controlled tributaries of the sub-basins. Consequently, the higher resident time causes more infiltration of the rainwater as compared to evaporation and runoff. In the Al-Abwa watershed, the permeable substratum further indicated the subsurface groundwater flow even during the dry periods as also observed during the field investigation in the wells. It was also deduced that the convergence of Qahah and Faraa wadis, at the triple junction with wadi Al-Abwa, plays an important role with respect to the availability of the potential aquifer(s) as the better agriculture and mangroves growth were seen particularly in downstream coastal areas.

Remote sensing analyses

Three processed image mosaics were enhanced by applying the histogram equalization function, brightness inversion function, and thermal band classification to evaluate the hydrological conditions, which collectively revealed the baseline

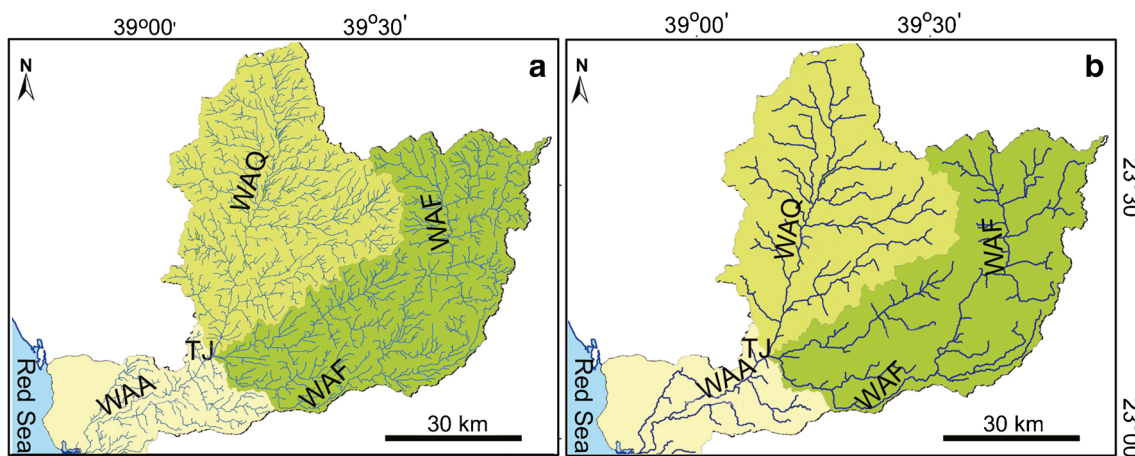


Fig. 4 Customized extracted drainage maps of wadi Al-Abwa basin and sub-basins at minimum accumulations values of 2 km² (a) and 10-km² (b)

characteristics of the prospective aquifers within complex geologic setup (Fig. 5).

Histogram equalization function

The HEF image displayed the pronounced contrast among various hydro-geomorphological features that provided a better understanding for the interpretation of the geological structures, the distribution pattern of the lithological rock units, and the drainage setups (Fig. 5a).

Geologically, the Al-Abwa basin has the heterogeneous distribution of Precambrian rocks, which were well-defined on the HEF image by their color contrast. Similarly, distinct continuity of linear features was also clearly observed. The WAQ, which flows in north-south direction, was distinguished by the boundary of two colors, violet on left and greenish-yellow on right. Both the colors represented different Precambrian rock suits, which indicated that there is a regional fault at the contact of these rock units that was camouflaged by the alluvium-filled course of WAQ. Likewise, the concealed regional fault zone, controlling flow of the main WAF, was identified based on the litho-color-contrast near Al-Faqirah village. The details of meta-sediments were also distinctly visible with their color contrast in WAF upstream part. In general, most of the smaller tributaries have their courses within relatively smaller faulted/fractured zones, which were reflected by white and light violate tones. Similarly, southeastern margin of the basin showed the outcrops of basalt flows, which were displayed by grayish-green tones. The tributaries of WAF, flowing within this basalt flows, were identified by white to light violate tones too.

The downstream part of the drainage basin also displayed violate dominance but in light tones over the dry silty coastal plain between the Al-Abwa and Mastorah localities except the WAA course, which was reflected in whitish tones. Furthermore, the aeolian sand-covered alluvial deposits along the coastline areas have displayed by the yellow tones. The color change of coastline alluvium was inferred related to the water moisture/saturation as a result of the subsurface discharges of the groundwater flowed from the upstream areas.

In the downstream areas, the HEF has also delineated significant agriculture activities in the form of dark green patches within the WAA course right from the triple junction (TJ) of WAA, WAQ, and WAF down to coastline areas. These observations were also reconfirmed during the field investigations.

Brightness inversion function

Generally, it was observed that details of the darker features sometimes are not clear or obscured. Likewise, sometimes lighter features are also not visible due to higher reflectance. In view to obtain sharp and clear details of darker, lighter, or obscured features, the BIF image plays key role to identify objects with a better resolution (Fig. 5b). Whereas, the BIF image has not much helped in differentiating among Precambrian rock types. However, the Cenozoic lava flows and the Precambrian intrusive bodies were distinguished most probably as they host significantly varying percentages of the water/moisture content at the reflecting surfaces.

The distinct differentiation of the drainage system was one of the most significant features of BIF. It was inferred that BIF has filtered out the wadi channels due to the presence of varying percentages of the moisture content within the crystalline rocks exposed in the basin. Dry mixture of sand, silt, and clay was also identified from the darker tones associated with river channels. Similarly, the northwestern Precambrian intrusive rocks and the southeastern alluvial deposits have also been distinguished from their typical dark tone in between Al-Abwa town and Mastorah coastal areas. Moreover, vegetal growth, natural, and/or manmade was distinctly observed by the turquoise color patches in the basin because of the evapo-transpiration giving a cooler effect to the atmosphere.

Another important interpretation was made based on the whitish tonal differences of the wadi alluvial deposits. It was identified that the dry alluvium gives darker tone as compared to the moist alluvium. In the basin, the upstream part of the tributaries has a lighter tone indicating the presence of better water content at near surface, but at the downward slope, the tones become darker indicating the subsurface flow of groundwater below the dry alluvium layer. This phenomenon

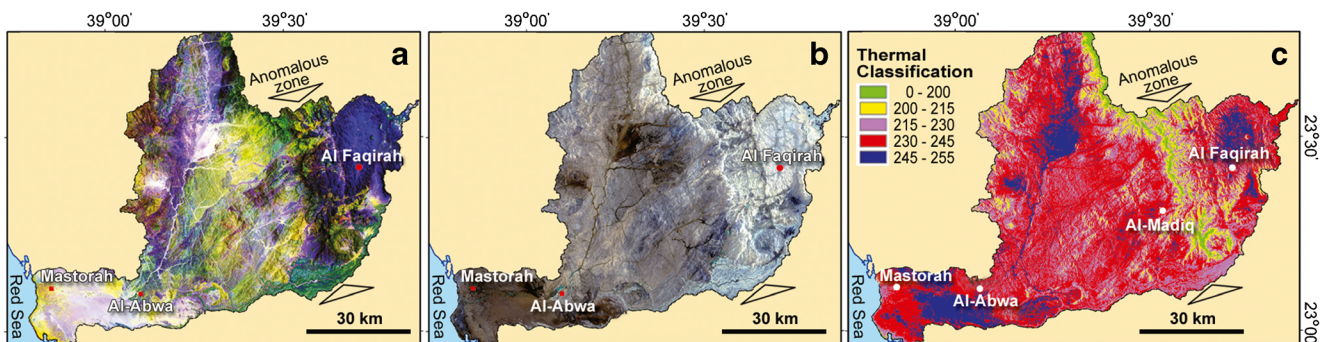


Fig. 5 Maps show enhanced outputs of histogram equalization function (a), brightness inversion function (b), and thermal band classification (c) for Al-Abwa drainage basin

was observed associated with the tributaries of WAQ and downstream part of WAA. However, the surface alluvial deposits within the WAF and its tributaries show lighter tone indicating better moist conditions. Similar to the HEF image, the alluvial deposits exposed along the coastline areas have displayed by the BIF as defused bluish white color tones. The color change along coastline reconfirmed the inferences drawn earlier related to the water moisture/saturation as a result of the subsurface discharges of the groundwater flowed from the upstream areas.

Thermal band classification

The thermal band-7 was classified into 5 categories of digital thermal values, which displayed their association with different geological terrains of the study area (Fig. 5c). In general, the different terrains, comprising the igneous and metamorphic rock suits, basaltic lava flows, moist/dry soils and vegetation, and courses of the river/streams, were differentiated by their respective low, moderate, and/or high digital thermal values. Maximum thermal value (245–255: dark blue), was mainly associated with (i) dry clay-dominated parts of the WAQ course passing across the upstream Precambrian intrusive rock terrains, (ii) the central part of the WAF Precambrian meta-sedimentary synclinal structure in the northeastern part, and (iii) the downstream dry alluvial-dominated coastal flood plain part of the basin. Next category of higher thermal values (230–245: red tone) associated with the Al-Abwa basin as an average background. In the WAQ sub-basin, the thermal red terrain (associated with Precambrian rocks) is crossed by the main faulted/fractured course of WAQ (reflected as thermal blue tone) that indicated deposition of relatively thick dry alluvial material in the faulted wadi's course, whereas the thermal conditions are reversed. After triple junction (TJ), the WAA-braided course is reflected as "red" narrow feature across the thermal blue anomalous area indicating shallow substantial water saturation.

Moderate thermal category (215–230: light violet), indicated its association with the lithological units of the Precambrian rocks having relatively smaller faults, joints, and fractures and bounded by the regional faults/fractures/lineaments representing the thermal values ranging 230–245 (red tone). It was interpreted that the moderate thermal anomalous conditions reveal a near surface presence of moisture associated with the exposed structures causing secondary porosity and permeability in Precambrian rock terrains, wadi-course(s) hosting groundwater springs within basaltic lava flows and coastline groundwater-discharging areas of the Al-Abwa drainage basin.

The strong appearance of low thermal values (200–215: yellow tone) indicated the presence of moisture or water saturation associated mainly with the eastern part of the Al-Abwa basin in prominent NNW-SSE trending narrow parallel zones.

The normal trends of low thermal values were also observed at the northwestern border and central areas of the basin in northwest-southeast and northeast-southwest directions respectively associated with the fault/fracture narrow features across the WAQ. The tributaries of WAF flowing within the basaltic lava flows show the presence of the low thermal tones indicating the presence of weeping discharges within the channel at places. The deductions were already cross-confirmed during the field investigations.

A small portion of the Regional Escarpment Ridge, running in NNW-SSE direction, constitutes the northeastern part of the Al-Abwa basin, which was distinctly identified by the lowest thermal values (green tone: 0–200) and the lower thermal values (yellow) marked as anomalous zone. All the eastern tributaries of WAQ and western tributaries of WAF are originating from the western escarpment higher slopes of the elevated ridge, which was inferred to be the major recharging source. At the southern limit, the Precambrian circular granitic intrusive body also showed presence of the circular coolest thermal environment that indicates the excellent storage condition for the groundwater potential.

One of the most interesting thermal variation trends was observed along the coastline areas, which displayed decrease from the very high to lowest thermal values towards the Red Sea. The lower thermal values were deduced as a result of the groundwater discharges along the coastline areas as the same was also observed in the case of HEF- and BIC-enhanced images and field investigation.

Analysis of extracted lineaments

The linear deformed micro, macro, and/or other tectonic fabrics/lineament, associated with different rock units, were extracted by using the processed images and specific software. The extracted lineaments showed several striking directions within the basin (Fig. 6a). Occurrence of the lineaments was found significantly high all over the area, particularly, where the Precambrian rocks are exposed, except the areas covered by the alluvium. In downstream coastal plains, though, no significant rock exposures were observed, but the east-west trending lineaments were observed, which were practically inferred to be associated with the traces of the smaller distributaries of the WAA- and localized-raised alluvial terraces.

Furthermore, the extracted lineaments were processed and formatted in the form of the lineament length, numbers, and cross-points with their occurring frequencies and subsequently the customized lineament density anomaly map was generated for the Al-Abwa basin (Fig. 6b). The central and northeastern parts of the basin indicated the highest lineament density. The central high-density area corresponded to the Precambrian rock terrains and the eastern high-density area, which is relatively smaller, corresponded to the synclinal part

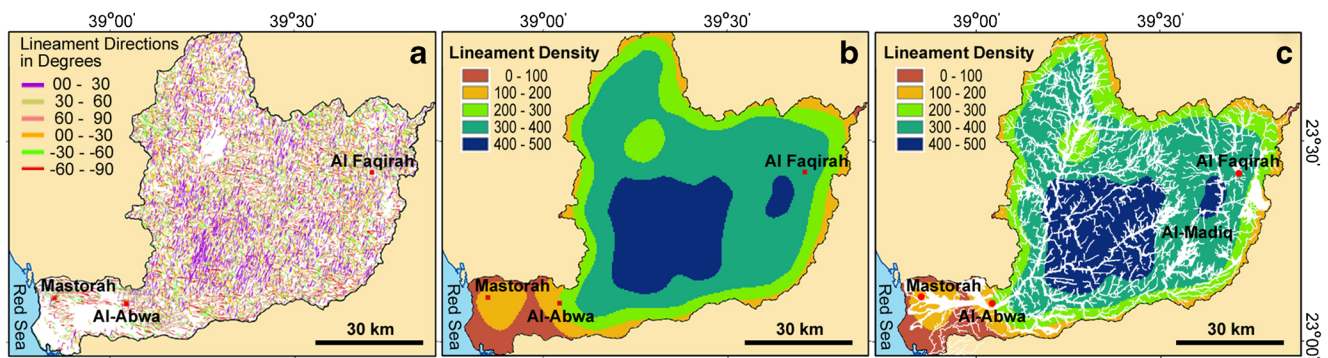


Fig. 6 Maps show the extracted lineaments in Al-Abwa drainage basin (a), the lineament density anomalies (b), and the lineament density model in relation to wadi Al-Abwa drainage network (c)

of the Precambrian meta-sediments. The high-density behavior was considered important as it revealed the development of the excellent secondary porosity and permeability within the Precambrian rocks. Thus, the area indicated bright prospects for the fault/fractures zone aquifer(s) within the Al-Abwa basin. In the north of the high-density area, a low-density circular area was observed, which corresponded to one of the Precambrian intrusives covered by thin layer of silt and clay camouflaging the lineaments trends. It was inferred based the integrated hydrogeological studies that beneath the thin alluvial layer highly fractured/faulted intrusive body exists.

The model, generated by overlaying thematic layers of the drainage networks on the lineament density map, indicated that the main lineament high-density anomaly corresponded to areas lying between the tributaries of WAQ and WAF, showing strong rectangular trellis flow patterns, east of TJ (Fig. 6C). It was inferred that such intense faulted and fractured conditions can be an excellent source of the groundwater aquifers. Similarly, the smaller lineament high-density anomaly, representing a thrust-syncline with an average dimension of about 25×15 km, in the eastern part of the basin situated at the inter-junction area of WAF and its tributaries in the upstream part, was identified as the focal point of interest where several faults/fractures and/or lineaments are cutting across to each other at south of Al-Faqirah locality.

It was summarized based on results of the RSA, watershed, analyses and field investigation that both the wadis, WAQ and WAF, drain their subsurface flowing groundwater at the TJ into the WAA. Thus, the drainage network particularly supports the large agriculture activities between Al-Abwa and Mastorah.

Precipitation captured in Al-Abwa basin

In and around the study area, it was estimated that the main geomorphological units may have average precipitation in order of 50 and > 170 mm/year in the coastal low-lying and mountainous areas respectively under the influence of the orographic impact (PME 2005; Subyani et al. 2010). Thus,

in case of the Al-Abwa drainage basin, an average precipitation of 150 mm/year was considered for the average recharge estimation. Based on the delineated total area of about 5000 km² (Table 2) and the average precipitation at the rate of 150 mm/year, it was calculated that the Al-Abwa drainage basin used to capture about 0.75 km³ rainwater annually.

Discussion

An old unpublished report described that the most important water-bearing formation was the alluvial filled valley in upstream catchment areas of the wadi Faraa (Sogreah 1970). It also described that the water wells were not economical to operate due to the extremely low permeability of basement formations and abundant clay deposition in their weathered layers. On the contrary, the same report narrated about the good springs' water flows from the basement rocks at places. From such hydrogeological inferences discussed in the report, it was envisaged that the watershed analyses, satellite remote sensing, and/or other systematic hydrogeological assessment of area(s) were not considered at that time because of the time-gap between the old conventional exploration methods and the new exploratory conceptual developments as well as the updated modern exploration techniques and tools.

The modern technologies, like the satellite remote sensing analysis (RSA), the watershed analyses, the geographic information systems (GIS) and the available software, play the key role for the rapid and precised exploration of surface and subsurface water resources. Moreover, these modern techniques are capable to delineate all possible features connected to the hydrogeological conditions prevailing over large and inaccessible areas directly and/or indirectly. These techniques also minimize cost, labor and time too (Patra et al. 2016; Gebre et al. 2015; Sreedevi et al. 2013; Jha and Chowdary 2007).

In case of WAA, the complex geological setup displayed that most of the exposed Precambrian rocks are heterogeneous from upstream to downstream, in addition to the minor Cenozoic basaltic lava flows, the scattered patches of younger Cenozoic sedimentary rocks buried beneath the lava flows,

and/or coastal and wadi alluvial deposits. Considering such complex hydrogeological setup, the GIS-linked watershed and satellite remote sensing analyses, auto-extraction lineaments, and density modeling provided clear hydrogeological details of the basin, like the structural control vision of drainage, runoff, evaporation and percolation of the rainwater, the trends of aquifer-recharging in upstream catchment areas to groundwater-discharging in downstream Red Sea coastline areas, the vegetal growth natural and/or manmade, the behavior of digital thermal variations associated with various terrains, and the lineament and lineament density distribution within the basin.

In downstream coastal areas, the rifted marginal tectonic block(s) of the Precambrian basement was anticipated, based on the geological setup and enhanced satellite images, to encounter at shallow depths beneath the recent fluvial-marine sediment deposits. However, based on the geological-log of a drilled hole, 5 km south of Mastorah, Sogreah (1970) interpreted the presence of marly clay sequences of the Tertiary Period, which was considered to serve as the impervious bedrock controlling the shallow groundwater flow in downstream coastal areas. More drilling sites were not available. However, the inferred hydrogeological situation, derived from available drilling results, corresponded with the results of the present satellite remote sensing analyses and the field investigations, which demonstrate the shallow groundwater presence and its ultimate discharge along the shoreline of the Red Sea.

Conclusions

The integrated research study revealed several important hydrogeological conditions in the Al-Abwa drainage basin, like the presence of (i) the highly faulted/fractured Precambrian meta-sedimentary, metamorphic and plutonic rocks, and Cenozoic basaltic lava flows, which are considered to serve as potential aquifers because of their dual porosity and permeability factors; (ii) the densely distributed open fault/fracture zones, which hosted total drainage network holding weathered rock soils in upstream and downstream areas; (iii) the development of many agriculture farms from upstream to downstream coastline areas; (iv) the numerous dug wells with very shallow water table observed in Mastorah coastline areas; (v) the near surface discharging of the excessive groundwater flow into offshore Red Sea coastline as reflected from the distinct growth of the mangroves; (vi) the chemical results of groundwater samples, collected from dug well sites, show that the groundwater quality improves slightly in proportion to the increase in the elevation of the drainage network; (vii) it was calculated that the Al-Abwa drainage basin captures $\pm 0.75 \text{ km}^3$ of rainwater annually; and (viii) the overall integrated analyses and assessments displayed that the drainage

network flows strictly under control of the fault/fracture zone(s) through the anomalous geological units of high lineament density anticipating excellent groundwater potential in the Al-Abwa basin.

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