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Watershed Analysis of Rabigh Drainage Basin, Saudi Arabia

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Abstract: Rabigh, a coastal city along Red Sea, is situated within the downstream flood-plain area of an ephemeral 'Wadi' (river). The city is growing faster as an industrial city and consequently its needs have exponentially increased for the potable water. A research study mainly based on watershed and field investigation has been carried out for the assessment of water movement trend, natural behavior of water runoff and storage in the form of groundwater potential associated with the Precambrian crystalline rock and the Cenozoic basaltic lava-flow terrains in the Rabigh drainage basin. The main Rabigh drainage basin was extracted from the SRTM data by using relevant software. Considering the important outlets of large tributary networks, the basin was further demarked into three sub-drainage basins. The results of the watershed study indicate the complex hydro-morphological characteristics varying from sub-basin to sub-basin. On the basis of the end results, the prospective aquifers have been inferred associated with the fault/fracture zone(s) of the Precambrian rock terrain and/or basaltic lava-flows in the upstream Rabigh drainage basin and the strong runoff in the downstream coastline areas.

Key words: Watershed-analysis · Fault and basaltic-flow control · Rabigh basin · Saudi Arabia

INTRODUCTION

The coastal town, Rabigh, is situated about 200 km north of Jeddah City between the latitude 22° 33’ 18” to 23° 38’ 46” N and longitude 38° 55’ 30” to 40° 07’ 6.4”E, at the coastline area of Red Sea (Fig. 1). This small town has become one of the faster growing important coastal cities because of the rapid industrial development activities. Subsequently, the water demand has exponential increase too. Though, the major part of the domestic and industrial demands are presently being met through the water-supply from the Red Sea desalinated water, but the water-supplies from other indigenous sources, particularly the groundwater, cannot be neglected as the seawater desalinated water-supplies have several natural and anthropogenic threats [1].

A few studies were conducted to assess the groundwater quality, based on the results of chemical analyses of the 47 water samples collected from the existing shallow dug wells in different parts of Rabigh basin [2, 3]. The review of these studies has shown complex variability trends of the chemical characters among the groundwater samples.

The regional [4] and the detailed geological [5, 6, 7] exposures have been considered for the hydrological assessment of the rocks' characteristics. Geologically, the Cenozoic volcanic and Precambrian igneous, metamorphic, meta-sedimentary rocks are exposed mainly in and around the Rabigh basin (Fig. 1). At the foothills, a narrow strip of Quaternary Sabkha-plains extend all along the eastern coastline area of the Red Sea. The sedimentary sequences are practically absent except some younger Cenozoic scattered outcrops generally buried beneath the thin and highly weathered basaltic lava-flows within the coastal plains. In such geological setting where the aquifers are controlled by the complex geological structures, the groundwater exploration is a difficult task. Thus, the watershed analyses were carried out to resolve such complex hydrogeological problem(s).

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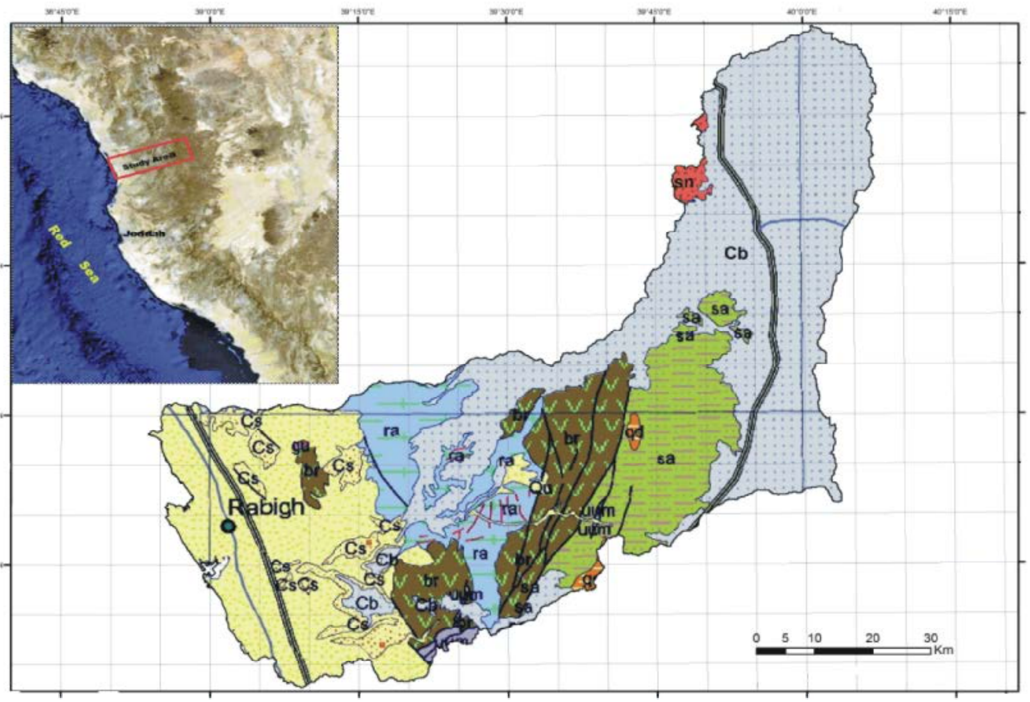

Fig. 1: (A) Geological map of Rabigh drainage basin. Legend: Cb=Cenozoic basalt, Cs=Cenozoic sedimentary rock, sn=Shayma nasir group, sa=Samran group, br=Birak group, ra=Rabigh group, gu=Umm Gerad granite, qd=Qudayd suite, uum=Serpentinite and gabbro. Source of map: Johnson, 2006) and (B) Index map shows location of study area with respect to Jeddah city and Red Sea. Source of Image: Google Earth.

The present paper describes the results of the watershed analyses and their impact on the hydro-geo-morphological water-flow characteristics of the Cenozoic basaltic and Precambrian rocks' terrains within the Rabigh drainage basin.

MATERIALS AND METHODS

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

- Digital elevation models (DEM) of 90m resolution were acquired processed and the watershed modeling was performed by using Watershed Modeling System (WMS) and ArcGIS software.
- Initially, two types of stream (wadi) networks were extracted for minimum flow accumulation values of 2 and 10 km^2.
- Salient hydrological parameters like total areas, mean elevation, perimeter, sinuosity, shape-facts, lengths, slopes have been estimated for each sub-basin based on 10 km^2 accumulation grid factors for the analyses and hydrological interpretations.
- Field traverses were carried out to collect the field data and the hydrogeological observations from the study area.
- The archive literature, related to groundwater studies for the Rabigh basin, were acquired from different sources, which were reviewed and the inferences drawn have been incorporated in the text.

Watershed Analysis of Rabigh Basin: Hydrogeological assessment of the groundwater potential and the subsequent hotspot delineation of aquifers are the difficult tasks in the complex geological setup, like the Rabigh drainage basin. In relevance to this problem, the watershed analysis was considered to be one of the most important solutions, which has provided important determination of characteristic geomorphological parameters. Basically, all the land areas of the watershed drain water, through the tributaries of the catchment in the form of runoff to the outlets during the rainstorms, where the water-filled tributaries join another water body, such as the downstream part of the wadi/river, lake, reservoir, estuary, wetland, sea, or ocean. Practically, the draining trend of the precipitation plays vital role in the hydrology,

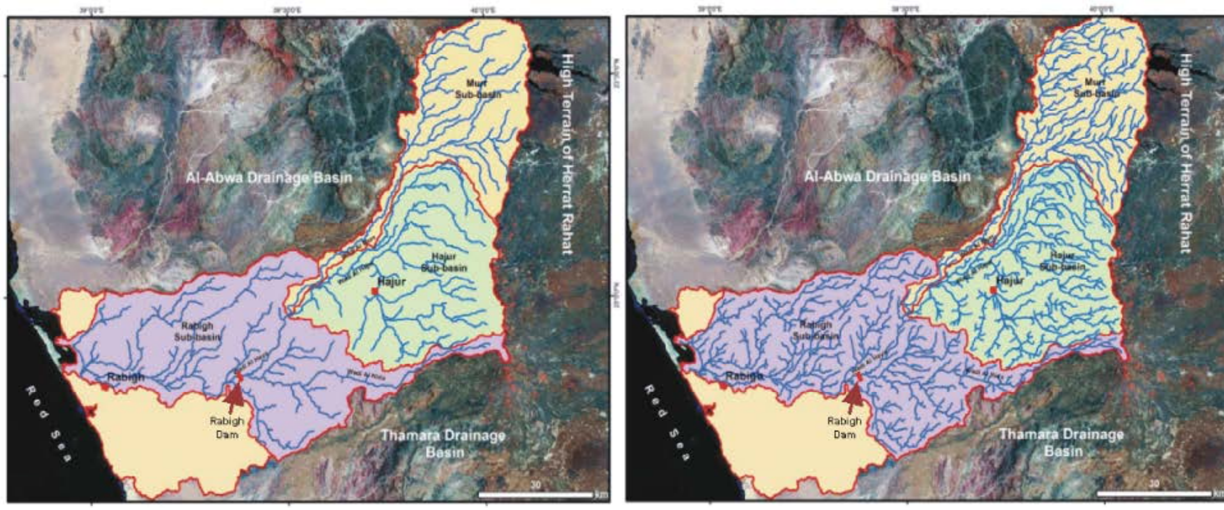

Fig. 2: Drainage basins of Wadi Rabigh, extracted at the minimum flow accumulation of 2 km^2 (left frame) and 10 km^2 (right frame), show flow trends and patterns with respect to their demarked sub-basins.

which is technically dependent on the geomorphological characteristics of the drainage basin, like, the total area, shape, length, slope, sinuosity index under the influence of the exposed geological setup of the basin. In case of the Rabigh drainage basin and/or sub-basins, the salient geomorphological parameters have been determined using watershed analytical approach with reference to the rainwater outlets of the wadis' networks.

The Rabigh basin was delineated and the drainage network has been extracted at selected grids of 2 km^2 and 10 km^2. Subsequently, the basin has further been subdivided into three sub-basins on the basis of the outlet significance of its main tributaries, i.e., the Rabigh, Marr and Hajer (Fig. 2). The extracted wadi networks, associated with the sub-basins, show different styles of flow-orientations of their axial-courses of the main wadi and its major and/or minor tributaries.

The northern tributaries of wadi Marr and wadi Hajer sub-basins show the typical arcuate to semi-arcuate flow trends in their upstream catchment areas. Correlating these trends with the exposed lithological units, it has been found that the north-convex flow-trends of the tributaries, from east to westward, correspond typically to the basaltic lava-flows of Harrat Rahat. Southward, width of the Marr sub-basin has uniquely reduced to a narrow strip striking in northeast-southwest direction. All the tributaries, originating from the elevated zone of the Rahat basaltic eruptive terrain, sharply merge together into the larger wadis flowing within the lava-flows at the northern point from where narrowing of the sub-basin starts.

Likewise, the northern tributaries of Hajer sub-basin have emerged from eastern elevated edge of the sub-basin flowing towards northwest and distinctly swung to attend northeast-southwest flow directions. It is interesting to observe that these tributaries have crossed the width of the sub-basin comprising mainly the Precambrian rock terrain and kept flowing along the northwestern edge of the sub-basin. It has been inferred that the basaltic lava-flows strongly control the flow-trends of the tributaries of Marr and northern Hajer sub-basins. On the other hand, the southern tributaries network of Hajer sub-basin, emerged from southeastern and southwestern boundaries, in different style of flow-pattern. The tributaries show a combination of rectangular and trellis flow-patterns indicating strong control of fault/fracture zones prevailing within the exposed Precambrian rock terrain in the sub-basin. However, this drainage network flows northwestward and merges into the main drainage system.

The drainage network of Rabigh sub-basin has its own unique flow-pattern. The main course of the wadi Rabigh passes close to the southern boundary of the sub-basin unlike to main courses of wadi Marr and wadi Hajer, which pass close to the northwestern boundaries of these sub-basins. Moreover, the drainage networks of Marr and Hajer merge together at the intersection of all the three sub-basins and continue flowing southwestward until merged into the wadi Rabigh in downstream area. Several wadis also drain directly, emerging from northern as well as southern boundaries, into wadi Rabigh. These tributaries of wadi Rabigh, flowing across the exposed Precambrian rock terrain partially overlain by the weathered basaltic lava-flows, show the typical rectangular drainage pattern. On the basis of the present analyses, it has been inferred that the major flow-trends of the sub-basin main wadis and their tributaries are controlled by the external and/or internal structures of the basaltic lava-flows and the fault/fracture zones associated with the Precambrian exposed and/or buried rock units in the Rabigh drainage basin.

RESULTS

In view to study the various aspects of runoff after the precipitation, the salient hydrological parameters of the Rabigh drainage basin, like the sub-basins' areas of coverage, mean elevations, perimeter, sinuosity, shape-facts, lengths, slopes, have been estimated for each sub-basin based on the 10 km^2 accumulation grid factor (Table 1). In addition, the general climatic input, specifically the precipitation, has also been assessed and incorporated in the study, because it provides the energy of flow for the system and directly influences the flow of its tributaries.

The Rabigh drainage basin covers a total area of about 5310 km^2. The topography varies from coastline to mountainous areas with respect to average elevation of its sub-basins. In such a situation, the precipitation intensity can vary in case of the study area. The precipitation data show strong orographic effects from the coastal areas of Red Sea to the eastward lying mountainous elevated terrain. 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 hilly areas respectively [8, 9]. On the basis of these observations, it is inferred that the eastern sub-basins, the Marr, Hajer and upstream part of Rabigh sub-basin, receive relatively higher rainfall as compared to the downstream part of the third sub-basin, Rabigh, situated within the low-lying Red Sea coastal flood-plans. Thus, the possible average rainwater captured by the Hajer, Marr and Rabigh sub-basins is estimated as 0.29 km^3, 0.22 km^3 and 0.12 km^3 respectively with the total of 0.61 km^3 by using the calculated areas of the sub-basins (Table 1). If an average precipitation of 100 mm/year is taken into account for the average recharge estimation of the cumulative 5310 km^2 area of whole Rabigh basin, it has been calculated that the Rabigh drainage basin captures about 0.53 km^3 rain water annually. However, the total rainwater received by the Rabigh basin may be between 0.5 and 0.6 km^3 for the recharge of the aquifers and the runoff into the Red Sea directly or indirectly.

The shape of the watershed is also one of the important factors in assessing the rate of runoff in a drainage basin. As a thumb of rule, it has been found that an elongated watershed boosts the storm movement more strongly than a delta-shaped watershed does as that is the ratio of length:width. In case of Rabigh basin, as a whole it is neither delta-shape nor simply elongated, but it has crescentrically elongated shape, which seems to be due to the complex shapes of its sub-basins. The shapes of the sub-basins show drastic variations among themselves indicating independent specific recharge and the runoff characteristics.

The sub-basin Marr, which is dominantly covered by the basaltic lava-flows, has a unique shape and may be further subdivided accordingly into two parts. The northeastern part, the catchment area, has fan-like shape covering about half-length of the sub-basin, which indicates the lower concentration time of rainwater and consequent higher runoff corresponding to relatively higher shape-fact value. On the other hand, the remaining half-length represents a very narrow rectangular shape striking in NE-SW direction. This part of the basin shows typical meandering within its narrow course hosted in basaltic lava-flow (Fig. 3). Such attitude corresponds to the relative lower basin-slope. The sinuosity, which indicates the lower outlet flow as the consideration time is expected to be higher. It has been inferred that though the lowest sub-basin slope (Table 1) corresponds to the typical meandering of wadi Marr, but the average elevation of 995m indicates elevated low-sloped or the

Table 1: Hydro-geomorphological parameters of sub-drainage basins of wadi Rabigh watershed

	Basin Name	Wadi Rabigh	Wadi Marr	Wadi Hajer
1	Basin Area (km^2)	2330.58	1291.12	1687.75
2	Basin Length (km)	111.6	94.6	59.0
3	Perimeter (km)	507.8	372.3	263.4
4	Mean Elevation (m)	273.32	995.42	924.11
5	Basin Slope	0.08	0.04	0.12
6	Shape Fact	5.34	6.92	2.06
7	Sinuosity	1.16	1.16	1.39

Fig. 3: The narrow part of the Marr sub-basin shows typical meandering trend of wadi Marr hosted within basaltic lava-flow.

flatten terrain of thick basaltic lava-flows. Hydrogeologically, the relative decrease in runoff provides excellent percolation of rainwater into the thick basalts and further into the Precambrian terrain buried below the basalt-flows.

The Hajer sub-basin has fan-like shape and is bigger in area, but smaller in length than the Marr basin. The Precambrian rocks are dominantly exposed within this sub-basin unlike the Marr sub-basin. The Precambrian rock terrain has its own impact on the flow-pattern of the drainage sub-systems too, in addition to the exposures of the Cenozoic basaltic-flows at peripheral areas of the sub-basin. Also it has been observed that the tributaries' flow-trends are different as compared to the Marr sub-basin. The correlation between the flow-trends and the exposed geological terrains show that the variation of flow-trends is simply controlled not only due to its shape, but also by the Precambrian rock terrain and the partially exposed Cenozoic basaltic lava-flows at northeastern and northwestern areas of the sub-basin. In the northeastern and northwestern parts, the tributaries follow the same flow-trends as that of Marr's tributaries indicating apparently the dynamic control of the basaltic lava-flows. Moreover, it is also observed that the Cenozoic basaltic lava-flows themselves are being controlled by the pre-existed fault/fracture zones of the Precambrian terrain. Subsequently, the inferences drawn were confirmed in the field particularly in the northeastern part of the Hajer sub-basin. On the other hand, the southeastern sub-system of tributaries has reverse flow-trend from south to north and passing across the width of the sub-basin and ultimately merges at right angle into the northwestern drainage sub-system parallel to that of Marr sub-basin. Considering the relative lower values of length and shape-fact and the higher value of basin-slope (Table 1), it has been inferred that the Hajer sub-watershed represents lower consideration time after the rainfall and consequently generates higher flow in general and particularly in case of southeastern sub-drainage system. It is also inferred that the relative higher sinuosity value is subjected due to the rectangular drainage pattern associated with the Precambrian terrain.

The Rabigh sub-basin represents neither fan nor elongated or rectangular shape, but a unique fish-like shape with tail at the mountainous area and head towards the coastline of Red Sea. Area-wise, length-wise and perimeter-wise, this sub-basin is the largest than Marr and Hajer sub-basins (Table 1), which shows significantly larger exposure to rainfall as well as the coastal dew due to the possible higher humidity factor. The sinuosity is smaller than that of Hajer, but same as that of Marr sub-basin, which reflects that wadi Rabigh flows within the relatively narrow structurally controlled zone. Topographically, the major area of the Rabigh sub-basin consists of low-lying coastal plains, which receive low rainfall and the narrow mountainous part may be subjected to better rainfall due to the orographic effects. The length of the sub-basin is much larger than the width indicating a lower outlet-flow as the concentration time is higher after the rainfall. The basin-slope and the shape-fact are moderate.

From the hydrogeological point of view, the most important feature of the Rabigh main drainage basin is the drastic shift in the main axial flows of upstream and downstream areas as well as reversal of flow directions of their sub-drainage networks, which indicate major regional changes in the geomorphology under the ongoing tectonic processes associated with the Red Sea rifting. It has been observed that the tributaries of Marr and Hajer sub-basins originate from their eastern and southern boundaries and flow towards northern boundary areas and attend their main axial flow-trends striking northeast to southwest direction close to the northwestern boundary of the main Rabigh drainage basin. Both the sub-drainage systems merge together just before they encounter the eastern boundary of Rabigh sub-basin and flow further southward merging into the wadi Rabigh as it is the most potential tributary close to the southwestern boundary of the main drainage basin. On the other hand, the wadi Rabigh has its main course in east-west direction passing close to southern boundary of the main drainage basin. All the tributaries originating from the northern boundary areas of the Rabigh sub-basin have ultimate southward flow-trends passing across the width of the sub-basin. It has also been observed that the tributaries of the Rabigh sub-basin show sharp turning-pattern of their courses, unlike the turning-pattern of Marr and northern tributaries of Hajer sub-basins, which indicates structural controlling impact of the Precambrian and/or Tertiary rock units buried beneath the thin cover of Quaternary and/or the Recent windblown sand deposits.

DISCUSSION

In general, it has been observed during the assessment of the hydrogeological field investigations that in most of the drainage basins of this region, the groundwater exploration and the water-wells digging and/or drilling in the past were based on the conventional methods that seek out groundwater in horizontally extended layers. Likewise, a groundwater quality zonation was performed by interpolation on the basis of results of the chemical analyses of 47 water samples collected from the existing shallow dug-wells and springs of the Rabigh basin [2, 3]. As such, most probably the quality zonation needs to be reconsidered as the aquifer target(s) are controlled by the fault/fracture zones of Precambrian rocks and the Cenozoic basaltic lava-flows [1]. However, from these studies it was concluded that very limited area of the aquifer can be used for domestic purposes as most of the aquifer water is brackish that might be used for agriculture purposes and the downstream area of the aquifer is very saline due to sea water intrusion effect. Moreover, the studies have also not discussed the recharge and discharge assessments of the aquifers. On the other hand, the present study has analyzed the Rabigh watershed characteristics in terms of the recharge and the discharge trends indicating the better surface and subsurface prospects.

In general, it is observed that the size of catchment can be expected to influence runoff on not only the average runoff characteristics, but on their relative variability [10, 11]. Thus, it is inferred that more water may infiltrate, evaporate or get utilized by the vegetation within the Rabigh basin by virtue of its overall length and width.

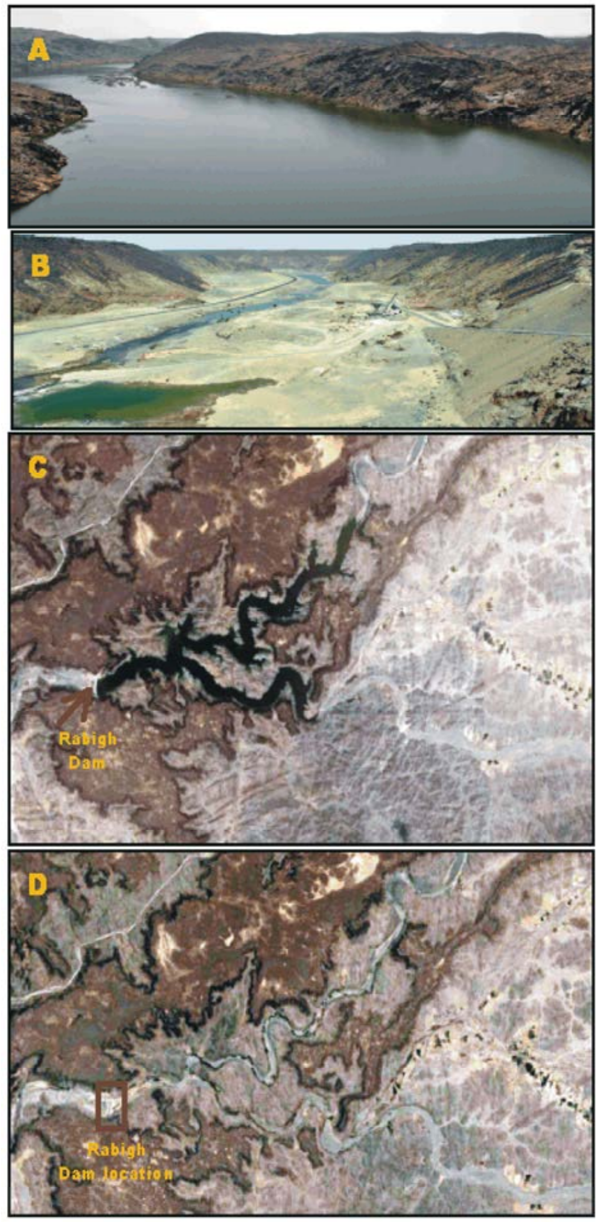

Fig. 4: Satellite images and field photos show the encouraging water potential in Rabigh basin. A: shows accumulation of large volume of water in the channel of the wadi as reservoir behind the Rabigh dam; B: shows the discharged water the spillway from the dam; C: shows extent of accumulated water in the channels of wadis, which used to serve as reservoir of the dam with reference to image of May 2014; D: shows the presence of groundwater springs within the channels of wadis flowing through basaltic lava before the completion of the dam with reference to image of July 2005. Source of images: Google earth.

Table 2: Results of chemical analyses of water samples collected from the Rabigh dam and water-pool within the downstream channel of wadi Rabigh

Lat	Long	Label	Type	pH	Conductivity (mS/cm)	Salinity (0/00)	TDS (mg/l)
22.823	39.376	Rabigh Dam Spillway/Head	Dam	7.79	0.63	0	590
22.808	39.025	Wadi Rabigh Downstream	Pool	7.52	6.23	3.4	5857

The monthly flow characteristics were analyzed between natural rivers and regulated river, which indicated that watershed size significantly influences the extent of the hydrological changes induced by dams and these changes are variable by seasons [12]. Similarly, it has been observed in the case of Rabigh dam that the hydrological changes have been induced. Field hydrogeological traverses show that the dam reservoir was significantly filled with surface of the rains as well as groundwater discharges in form of springs from mainly the basaltic lava-flows in the upstream areas (Fig. 4A). On the downstream side of the Rabigh dam, significant accumulated water was being discharged through the controlled spillway from the dam (Fig. 4B).

A correlation study of the high resolution images of 2014 (Figure 4C) and 2005 (Figure 4D) shows the drastic hydrological changes within the Rabigh drainage basin. The latest image shows enormous water accumulation, which has changed the attitude and dimensions of the contributories. The channel in front of the dam has width of more than 0.4 km for a distance of about +2.0 km. Onward towards upstream side, the water filled channel of the northeastern Wadi Al-Haya extends for about 7. 7 km and the water-filled channel of southeastern wadi Al-Nida extends for about 6.5 km with an average width of 0.28 km ranging between 0.18 and 0.48 km. The periphery of water-filled channels has been estimated as about 48.0 km. On the other hand, before the completion of the dam structure, there was water in the form of small groundwater springs within channels of the wadis exposing at edges of the basaltic lava-flows at places (Fig. 4D).

As far as the quality of accumulated dam's water is concerned, the water samples were collected from the water released through spillway and the water-pool within the downstream part of the wadi Rabigh. The results of the analyses shows that the quality of the water accumulated in reservoir of the dam is excellent as compared to water from the downstream pool (Table 2).

CONCLUSIONS

In Rabigh basin, the Cenozoic basaltic lava-flows are dominantly exposed covering most of the Precambrian igneous, metamorphic and meta-sedimentary rocks, which has caused the complex hydrogeological setup. It has been estimated that the Rabigh basin captures annual precipitation ranging between 0.5 and 0.6 km^3 for the recharge of the aquifers hosted in the terrains of the lava-flows and the faulted/fractured Precambrian rocks and also for the runoff into the Red Sea directly or indirectly. Watershed analysis has provided important hydrogeological determinations on the basis of identified various geomorphological characteristic parameters under the influence of the exposed geological setup and the prevailing precipitation conditions. Considering i) the extracted drainage patterns at 2 and 10 km^2 grid; ii) the trends of the determined areas, shapes, lengths, slopes, sinuosity index of the sub-basins; and iii) the water samples' results of the chemical analyses, it has been assessed that the captured precipitation percolates more as compared to the runoff directly into Red Sea and/or evaporation. In addition, the field observations and the high resolution satellite images of 28th July 2005 and 5th May 2014 also show the presence of numerous springs and huge accumulation of water in the channels of wadis (as the reservoir) behind the built Rabigh dam respectively. Thus, it is concluded that the Rabigh drainage basin has relatively excellent groundwater potential and needs the strategic exploitation, development and management of the water resource.

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