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PROBLEMS IN ASSESSING GROUNDWATER RESOURCES IN BEDROCK AQUIFERS, ERITREA

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The problems associated with bedrock aquifers are discussed in reference to an unusual groundwater condition observed in the study area. To understand and explain the problem, a geologic and hydrogeologic investigation was carried out. First, the results of previous geologic and hydrogeologic investigations conducted by JICA and Euroconsult were obtained and analyzed. Secondly, a structural map and a drainage map of the area were prepared using information extracted from topographic maps, aerial photographs and SPOT images. In addition, fieldwork was conducted during which static water levels were measured in available wells. The field data were used to develop a water table contour map from which the general direction of groundwater flow was determined. Finally, the processed data and field observation were analyzed and interpreted to develop theories that explain the problem.

INTRODUCTION

In many regions of the world, groundwater is an essential commodity for life. Although groundwater makes up only 0.61% of the total volume of water available on Earth, it constitutes the main and most reliable source of water in arid regions. In United States, for example, 58% of all available water supplies are derived from groundwater sources (Fetter, 1994). This percentage is believed to be much higher for Eritrea, given the aridity of the country.

In Eritrea nearly all of the annual rainfall is received during the summer months, and stream systems in the country are seasonal in character. Most of the rain is delivered as high intensity, short duration storms which generate short-lived flash floods. In addition, there is a great variability in rainfall from year to year that can greatly reduce the volume and duration of flows in streams. For these reasons, surface water provides most of the water used during part of the year in Eritrea, but it is not considered a reliable source of water supply on a continuous basis.

A more reliable source of water supply that is put to different uses in Eritrea is groundwater. This is particularly true in the rural parts of country where communities use groundwater for domestic, livestock and agricultural purposes.

Both unconsolidated (alluvial) and bedrock aquifer systems are known to exist in Eritrea. Alluvial aquifers are found over extensive areas in the eastern lowlands and coastal areas, but are limited to valleys and flood plains of major stream systems in the rest of the country. Bedrock aquifers consisting of weathered and fractured basement rock have wide distribution throughout much of the central highlands and western lowland.

In such aquifers, the occurrence and movement of groundwater is largely controlled by geologic structures such as faults, joints, fractures, etc. As such, a good understanding of the type, orientation, density, and interrelationship of such structures is essential for assessing the storage and movement of groundwater and the potential yield of aquifers. Specifically, such an understanding is crucial to successful siting of high yield wells.

Unfortunately, detailed geologic structure maps at sufficiently large scale have not yet been developed for the country. In addition bedrock aquifers in Eritrea tend to be deep controlling structures often masked by thick layers of weathered material or alluvial deposits. Exploration and successful development of groundwater resources is made difficult by all these conditions. However, it is possible to partially overcome these problems through a combined use of topographic maps, aerial photographs, satellite images and carefully planned geophysical surveys. Proper analysis and interpretation of data collected from these sources can assist in siting wells with yields that are adequate for most purposes.

STATEMENT OF THE PROBLEM

This study began when the authors learned of the existence of uncommon groundwater conditions in the Dekemhare area based on their reading of reports of two separate investigations that were conducted in the area by the Japan International Cooperation Agency (JICA) and Euroconsult, an international consulting group contracted by the Government of Eritrea. As part of the sector study on National Water Resource and Irrigation potential, Euroconsult drilled an exploratory borehole at a site in the Adi-golgol plain. The borehole, which is located a few kilometers south of the town of Dekemhare, was dry and abandoned. The same, year JICA drilled test wells a few hundred meters on each side of the failed borehole and determined that both wells have reasonably good yields.

The main objective of this study is therefore to collect and analyze available geologic and hydrogeologic data for the area to supplement existing observation with limited field information in order to develop a realistic explanation for the discontinuity of groundwater occurrence as observed during borehole drilling in the area.

BACKGROUND

The present study was conducted in a 16 km section of the Adi-Golgol plain with extends southward from the town of Dekemhare in the Debub administrative region of Eritrea. The region is located in the southern end of the central highlands, which consists of extensive plateaus whose edges are marked by escarpments and deep valleys.

The area is drained by small ephemeral streams, which flow for short periods during the year. The flows of these streams, and storage of minor reservoirs along them, provide sources of water supply for part of the year. But the main source of drinking water in the area is groundwater, which also provides a reliable water supply for other uses when streams dry up during the dry season. The town of Dekemhare and the village of Adi-Golgol to the south obtain their drinking water from a few hand-dug wells and boreholes constructed in the area. One of these boreholes (BH14) is the main source of water supply for Dekemhare. Analysis of water samples collected from these sources by the Water Resources Department shows that groundwater in the area is generally of good quality.

The general climatic and geologic conditions of the study area are outlined in the following paragraphs.

Climate

The Debub region is generally characterized by a warm to cool semiarid climate. A review of available meteorological data shows that annual average temperature for the area varies between 15 ^{0}C and 21 ^{0}C. The monthly total rainfall is 99 mm and annual rainfall averages about 524 mm. Most of the total annual rainfall is received during the months of July through August. Available climatic records also indicate that the evaporation that occurs in the area reaches its maximum rate of 7.5 mm/day in April and a minimum rate of 4.6 mm/day during the month of August. More comprehensive climatological data for the region is presented in Table 1.

Table 1. Climate of the Study Area

Month	**Temperature** (^{0}c)	**R.H** (%)	**Wind speed** (m/see)	**Pan.Evapo** (mm/day).	**Sunshine** (hrs/day)	**Rainfall** (mm)
January	16.3	75	1.5	5.4	10.8	2.3
February	17.3	68	1.6	6.7	10.4	3.7
March	20.7	59	1.7	7.0	10.7	11.7
April	19.2	70	1.8	7.5	11.1	23.9
May	19.3	65	2.0	6.0	12.3	44.8
June	19.1	64	1.9	5.4	11.2	43.7
July	15.5	98	1.8	5.6	8.7	195.1
August	15.4	95	1.8	4.6	7.2	156.0
September	17.1	78	1.7	5.1	9.7	27.8
October	16.9	86	2.1	6.3	11.4	3.3
November	16.3	89	1.4	5.5	10.6	8.4
December	15.6	83	1.3	5.5	10.7	3.4

Source: Euroconsult (1998)

Drainage

The region in which the study area is located includes parts of two regional catchments. The north and northwest part of the region is drained by a number of streams, which flow eastward into the Red sea. A much larger portion drains into the westward flowing Mereb river system. Locally, the study area and its surroundings are drained by three small streams, namely the Mai-edaga, Ruba Koraro and Mai Elab. These streams, like the major rivers in the region, are seasonal and flow only during and shortly after the rainy season.

Local drainage in the study area is southward as controlled by the gentle slope of the Adi-Golgol plain.

Rainstorms that occur during the summer months generate flash floods in these streams, most of which normally leave the area or are lost to evaporation. However, a few micro-dams have recently been built on these streams retaining some of the stream flows. Water stored in these micro-dams is presently used for irrigation and watering livestock.

Vegetation

Vegetation in the study area and its surrounding is generally sparse and consists of eucalyptus (mostly planted by communities), acacia, and shrubs. The poor vegetation cover is largely a reflection of the aridity of the area (i.e. low rainfall and high evaporation losses). However, deforestation resulting from cutting of trees for firewood and over grazing may have reduced the area's vegetation cover over time.

Relatively dense vegetation is observed along stream courses, possibly because of the existence of thicker soils and better soil moisture conditions. The nearly flat topography of the Adi-Golgol plain and the reasonably thick soil cover observed over large parts of the area are conditions that promote better soil moisture retention capacity. Therefore it is likely that the ongoing national reforestation effort will succeed here in reviving the vegetation cover in the area.

Geology

The study area is underlain by Precambrian basement rocks, which are granite phase. Two types of granite have been identified in the area: the normal granite group and the marginal granite group. The normal granite is exposed over a large area in the eastern and western parts of the area. In general, this group has undergone a considerable degree of weathering. Outcrops of the marginal granites are found in the northern and southern sections of the study area. These granites are hard and dense and, therefore, show a lower degree of weathering than the former. Lithologic logs of boreholes drilled in the area show that weathering in this granite group may extend as deep as 40 m below ground surface. In places rocks of basaltic composition intrude into the granites and outcrops of these formations are observed south of the study area. Throughout most of the flat and wide plain that incorporates the study area, the granite bedrock is mantled by alluvial sediments composed of fine to medium sand. These sediments, which are believed to have been derived from weathering of the underlying granite, extend east-west from Tucul and Gura and as far south as Adi Edaga. The thickness of these alluvial sediments as revealed in borehole logs can be as much as 10-20 m.

This part of the highland has been mildly deformed as a result of tectonic processes that affected the region. The deformation is regional in character and is associated with the Red Sea detachment. The resulting linear structures are oriented differently in which the major structures have a NNE trend, which coincide with that of the Red Sea. Other minor lineaments are oriented at an angle to the major structures. The general geology of the study area is shown in Figure 1, which was adopted from the JICA report (1998).

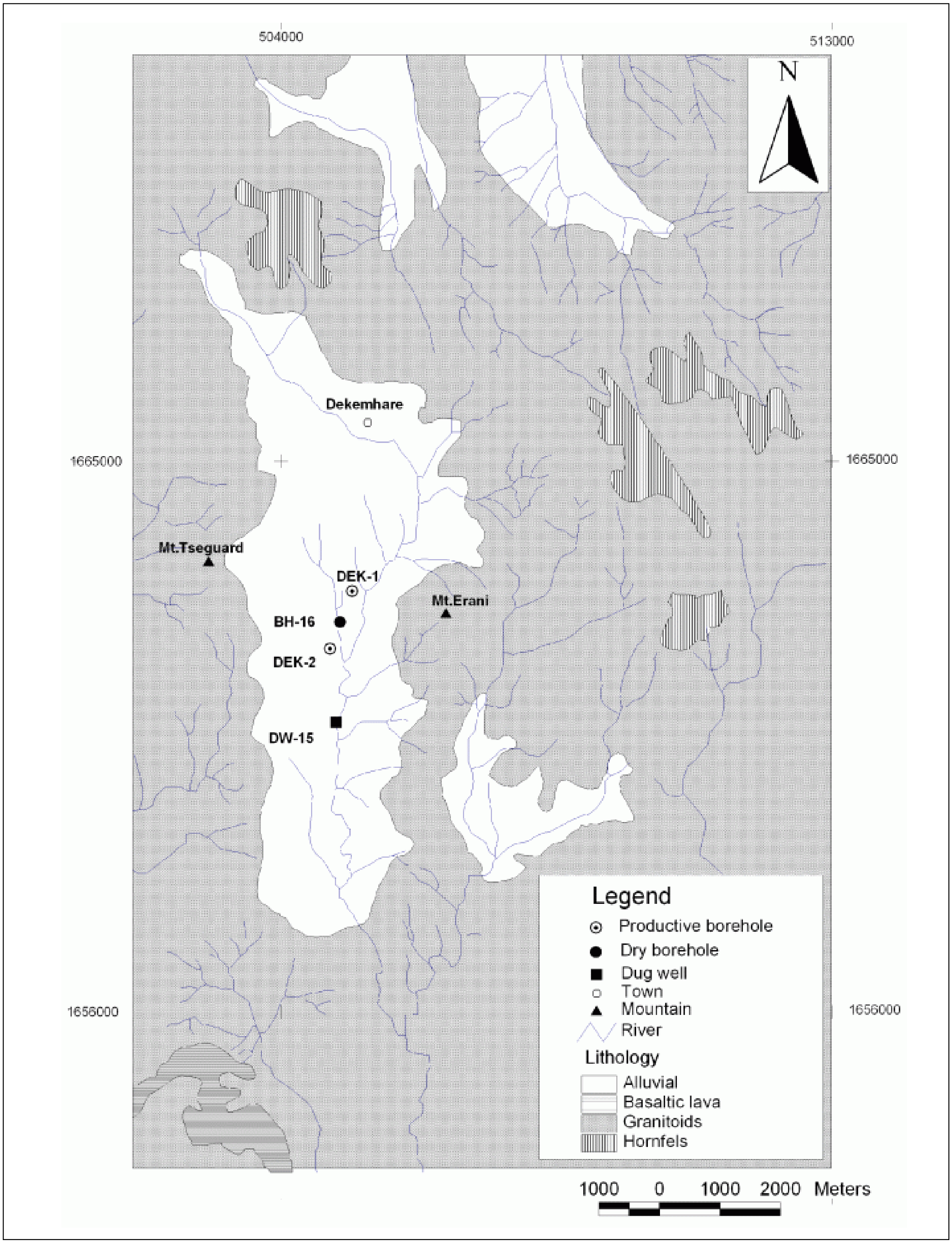

Figure 1. Geology of study area.

PREVIOUS HYDROGEOLOGIC WORK

Two important hydrogeological surveys were conducted recently in this area. These studies were conducted by the Japan International Cooperation Agency (JICA) and Euroconsult (an international consulting company) which implemented the sector study on National Water Resources and Irrigation potential.

JICA carried out their exploratory work during August 1997 to November 1998. The objective of their study was to evaluate the potential of the water resource, focusing on groundwater, to formulate a development plan for a water supply project for the town of Dekemhare. In this study first hand geologic information was obtained, a hydrogeologic map of the area was produced, and two successful test wells (DEK-1 and DEK-2) were drilled.

The JICA primarily carried out a regional geological study to delineate structure of the area and to select geophysical prospecting sites. They conducted surface investigations in which three kinds of geophysical surveys were used: very low frequency electromagnetic wave sounding (VLF-EM), horizontal electric sounding (HS) and vertical electric sounding (VES). The overall analysis of the geophysical data led them to the identification and drilling of the bore holes DEK-1 and DEK-2. Well yields, transmissivity and water quality were determined after performing lithologic logging, pumping tests and chemical analyses (JICA, 1998).

A reconnaissance geological and hydrogeological study of the same area was carried out earlier by Euroconsult. Assessment of the groundwater resource, in terms of their distribution, quality, quantity and their potential was the main objective of the study. Also geological characterization was one of the specific aspects in the study.

Euroconsult conducted successive investigations at the study area. After applying the full range of geophysical techniques including TDEM and VES sounding (Euroconsult, 1998), they drilled a single borehole (BH-16) as an exploratory well. Although they report that they encountered high conductivity, the borehole was found to be dry. In their report, there are some missing data, and their description of the location of the borehole is ambiguous. Besides, they did not give a description of what was performed at the site, and an adequate explanation for the failure of the drilling effort.

PRESENT STUDY

Data Collection

The topographic, geologic, hydrologic and hydrogeologic data of the study area, which are relevant to the objectives of the present study, were obtained from different sources. The basic sources of information include topographic maps, aerial photographs, SPOT images and existing reports of geologic and hydrogeologic investigations and studies that were conducted in the study area by other investigators. These resource materials were obtained mostly from the Department of Mines (Ministry of Mines and Energy) and the Water Resources Department (Ministry of Land, Water and Environment)

In addition, the authors spent time discussing various aspects of the project with geologists and hydrogeologists at that same institution. Most of these professionals had either worked in the area or were familiar with its geology and hydrogeology. Therefore they were in the position to provide additional useful information, and to discuss problems and ideas that are of relevance to the present study. Finally, the authors conducted a reconnaissance field visit to the area to verify aspects of information obtained from the above sources. The field visit also allowed static water level to be measured in all accessible boreholes in the study area.

The desk study, library research, and the field visit conducted by the authors allowed the following products to be developed for the study:

Drainage map: in the present study the drainage network was reproduced from maps in order to examine and analyze the characteristics of the network with the aim of making inferences on the infiltration conditions in the study area. To accomplish this task, all the streams in the study area were first traced on an overlay that was placed on the topographic map (scale 1:100,000) of the area. The resulting drainage network was refined and augmented by extracting additional information from aerial photographs (scale 1: 50,000) and SPOT images (scale 1:100,000) of the area. In addition to their larger scales (thus greater detail), these additional sources provided the advantages of tone and color which were very helpful in delineating even the smallest tributaries. For example, the red color of riparian vegetation on SPOT images helped trace the stream courses more accurately in areas where the topographic map was not clear. The drainage map is presented in Figure 2.

Figure 2. Drainage map of study area.

Structural map: Although the major lineaments in the study area have been delineated in one of the maps produced by JICA (1998), an effort was made in this study to produce a more complete structural map. An interpretation of geologic structures of the study area was carried separately on spot images (Figure 3a) and on aerial photographs (Figure 3b). Again the different resolutions and tonal contrast of these remotely sensed data allowed theidentification and delineation of many small structures, most of which are not represented in JICA map. The final structure map that was developed through the procedure outlined above is shown in Figures 3a and 3b.

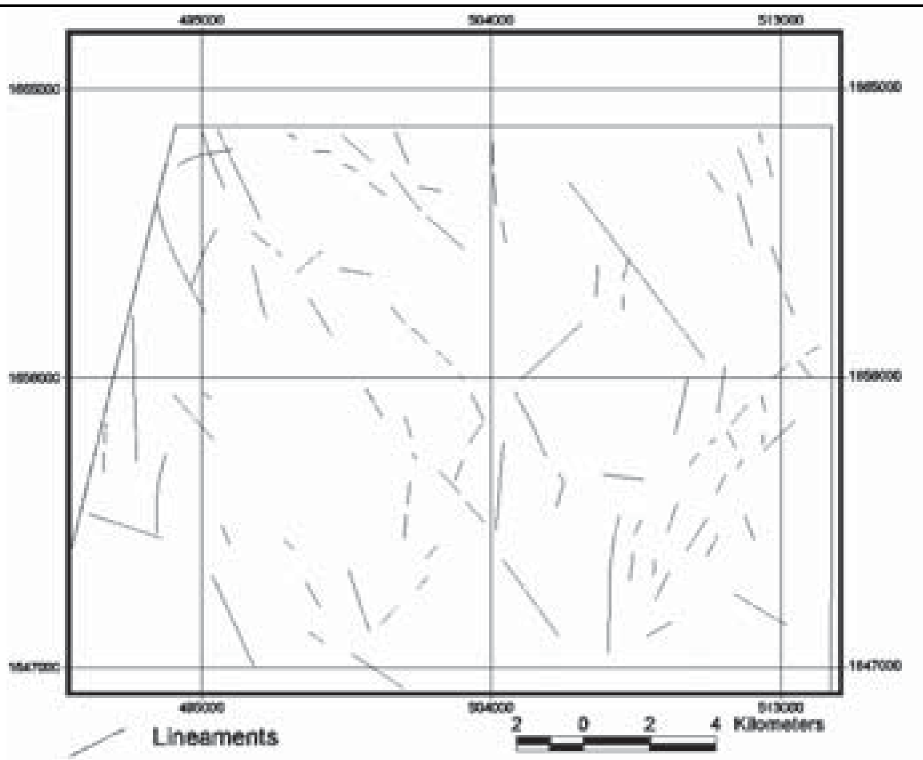

Figure 3a. Structural map of the study region.

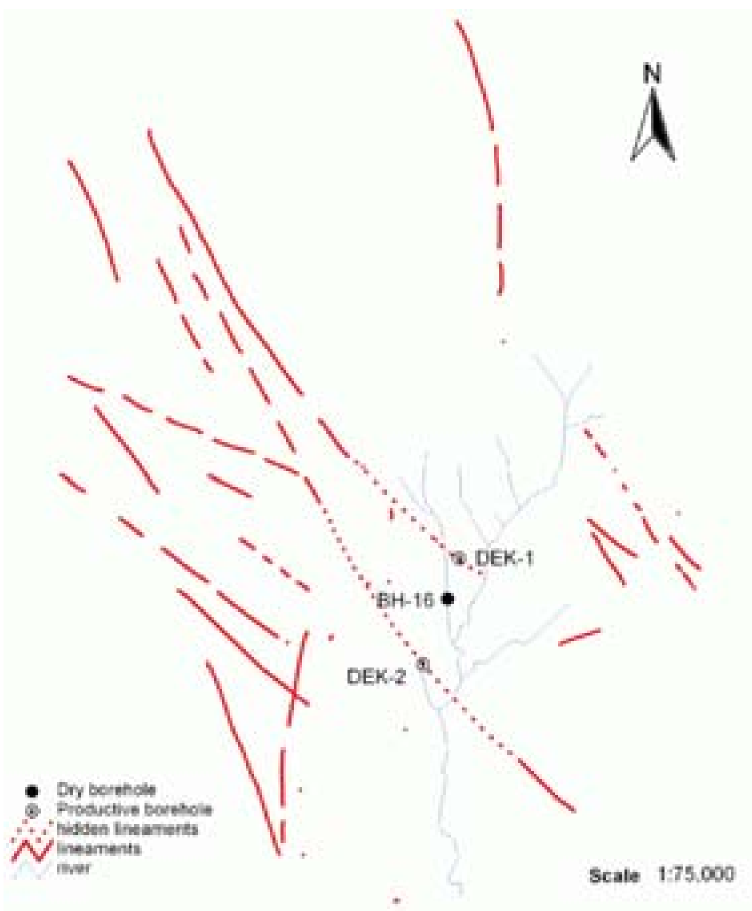

Figure 3b. Structure map of the study area.

Water table contour map: several hand dug wells and boreholes constructed at different times were located during the field visit. Unfortunately most of these water points were either not accessible or were too dry to allow measurements of static water level (SWL). Therefore, the SWL data consisted of two measurements made by authors and those provided by JICA (1998) for the boreholes they drilled. These data, which are presented in Table 2, were plotted on a map of the study area. Combining them with the topographic map and a general groundwater understanding of the area, a water-table contour map was prepared. Figure 4 shows the location of measured boreholes and the contour map of the water table.

Hydrologic data: although no drilling and pump testing was conducted in the present study, an attempt was made to compile all available hydrogeologic data that exist for the area. As was pointed out earlier, the only hydrogeologic information available for the study area comes from the studies conducted by JICA and Euroconsult. Data that are relevant to the present study were extracted from the report of these investigations and are presented here.

Table 2. Water Table Elevation of Measured Boreholes

No.	Borehole I.D.	Ground Surface Elevation (m)	Static Water Level BGS (m)	Water Table Elevation (m AMSL)
1	DEK-1	1941	13	1954
2	DEK-2	1952	12	1964
3	DEK-3	2029	9	2020
4	DEK-4	1939	6	1945

BGS: Below ground surface

AMLS: Above mean sea level

Data Analysis

Drainage map: the pattern and density of a drainage network often provided useful information on the geologic and hydrogeologic characteristics of the soil and bedrock on which the drainage system has developed. The map in Figure 2 shows that the drainage system of the study area is moderately dense and has a dendritic pattern. Since the area has sandy soils and gentle slops, most of the rain that falls would be expected infiltrate into the ground producing a less dense drainage network. Therefore the dense drainage network indicates that, because of the intensity of rainstorm in the area, water does not have time to infiltrate. It may also indicate that the permeability of surface soils may have been reduced by the presence of a silty or clayey fraction.

As was stated in the section on geology, there are many fractures in the study area. Therefore, a structurally controlled drainage pattern (e.g. a rectangular pattern) would be expected for the area. However, the thick soils or weathered materials that cover most of the study area have minimized the effect of the underlying structures on the drainage system, giving rise to dendritic drainage pattern as shown in Figure 2.

Structural map: the structural map (Figures 3 a and b) that was delineated from aerial photographs and SPOT images shows dense linear features (or lineaments) some of which are clearly seen and others are tonal. The lineaments are thought to be fractures from their distribution. As the map indicates, there are two sets of fractures oriented at an angle to the first set.

Some of the fractures in both sets may be interconnected providing a continuous conduit for the flow of groundwater. But others are certainly not interconnected and although they may contain water, they do not play a role in the movement and circulation of groundwater in the area. The importance of these fractures in the storage and movement of groundwater also varies depending on their extent (i.e. width and length). Groundwater and its occurrence in the granitic aquifer of the area is largely controlled by the major fractures in the area and less by the minor ones, which have limited length and width.

Infiltrating water may transport near surface sediments and deposit them in the fracture openings within alluvial or bedrock aquifers. The hydrogeologic importance of fractures is therefore also dependent on whether they are still clear or whether they have subsequently been filled with sediments. In the latter case, the original porosity and permeability of the aquifer is reduced with time, limiting the capacity of the fracture to contain and transmit groundwater.

Water table contour map: the water-table elevations of the four wells in Table 1, were determined by subtracting the field measured water depth from the elevation of the ground surface at the well sites. Generally, the shape of the water table is similar to that of ground surface. In the study area, this was confirmed by the fact that both the ground surface and water table (as determined from the four water table elevations) slope southward.

The four water table elevation values determined in the study were not sufficient to draw a water table contour map. But use was made of the above relationship and approximate water table contours

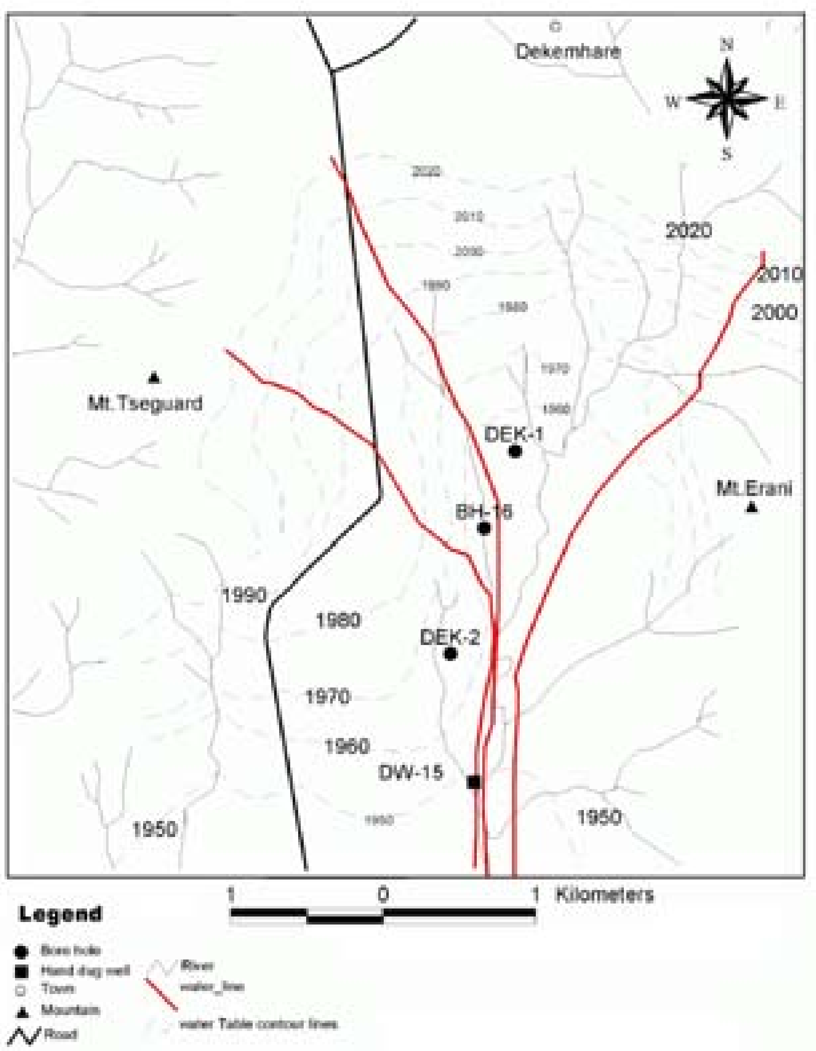

Figure 4. Water table contour map

were drawn by using the topographic contours of the area as a guide. This produces a water table contour map for part of the study area (see Figure 4). The approximate nature of the contour map is indicated in the figure by drawing the individual contours as dashed lines.

Groundwater flows in the direction of steepest hydraulic gradient or water table slope. Thus, once the contour lines were drawn, it was possible to include in the map representative but approximate groundwater flow paths (i.e. lines showing the direction of groundwater flow) by drawing lines that intersect the contour lines at right angles. These lines have been drawn in red in Figure 4.

Hydrologic data: the data obtained from previous hydrogeologic investigations of the study area is from lithologic logs of boreholes that were drilled by JICA (1998) and by Euroconsult (1998). These lithologic logs, shown in Figure 5, provide additional information on the granitic aquifer of the study area and overlying sediments. These logs supplement the information already given in previous sections of this paper. The logs are self-explanatory and require no further discussion. A review of the data in Table 3 shows that the two JICA wells (DEK-1 and DEK-2) have yields that are much higher than the 1-2 l/s yield that is common in most parts of the country. The transmissivities of the part of the aquifer into which they were drilled are also high. These high values indicate that

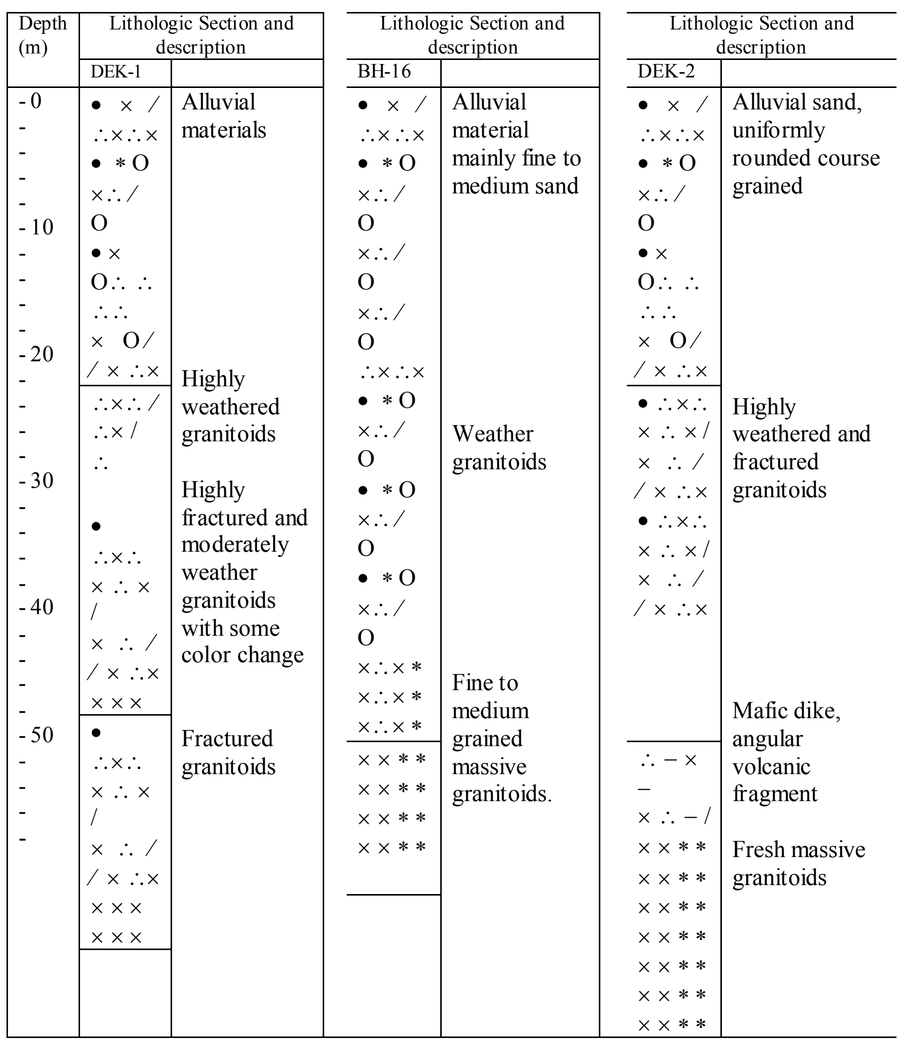

Figure 5. Borehole logs.

Table 3. Hydrogeologic Parameters Determined for Successful Boreholes (after JICA, 1998)

No.	Borehole	Total Borehole Depth (m)	Static Water Level BGS (m)	Yeld (l/sec)	Transmissivity (m^2/day)
1	DEK-1	53	13	4.0	100
2	DEK-2	60	12.2	7.0	206.5
3	BH-16	49	Dry	-----	------

the two boreholes have been drilled in major fractures, which form the main conduits for groundwater flow in the area. The hydrogeologic data of the boreholes therefore confirm the accuracy of the structural map presented in Figure 3 and the validity of the structural and hydrogeologic interpretations discussed in the next section of this paper.

Interpretation of results

The primary factor in this investigation, which was focused upon during the interpretation of results, was geologic structures. As previously pointed out, the main aquifer in the area is fissured granite. Thus, the investigation of groundwater is essentially about identification of fractures so as to locate zones of fracture alignment. The structural map (Figures 3a and b) shows the presence of two major fractures to northwest of the boreholes, which are roughly oriented NNW. The southeastern extension of these fractures could not be detected on aerial photos or on SPOT images because they are masked by alluvial deposits in that part of the study area. By interpolation and extrapolation, these major fractures appear to pass through the two boreholes drilled by JICA (DEK-1 AND DEK-2). These fractures possibly form a network with other sets of small fractures, resulting in a movement of substantial amount of water. These major fractures are therefore possible conduits of groundwater for DEK-1 and DEK-2. On the other hand, no major fracture passing through the borehole drilled by Euroconsult (BH-16), is observed on the structure map. The minor fractures in the vicinity of BH-16 and which are seen on the structure map to have a roughly N-S orientation, may not be interconnected. Thus, there appears no conduit exists by which groundwater flow can reach the site where BH-16 is located. This borehole was possibly drilled in massive or poorly fractured granite, which is the cause of the lack of water.

An argument could be made that within the alluvial deposit, a fractured zone, that extends through BH-16, may exist in between the two major fractures . If such a fracture is present, its continuation has not been observed in areas of granite outcrops. It has therefore to be relatively minor, i.e. small in extent and width. Obviously, the probability of fractures being filled with sediments is higher for this type of fracture than for the major fractures and, therefore, fracture openings might be filled with sediments. Also this fracture might be crossed by other fractures oriented at different angleswhich could divert the groundwater flow. Another possibility is that since a fracture is a linear feature, there is a likelihood of missing it during drilling. Fractures can be oriented vertically, horizontally and inclined, which can be identified from geophysical surveys. In this case, the geophysical survey that was conducted may be improper or the orientation was wrong, and thus the drilling was off the mark.

CONCLUSION

Geological structures often play a major role in hydrogeology. In bedrock aquifers, the existence and density of geological structures control the occurrence and flow of groundwater. Further, their extent and orientation determine the characteristics of the aquifer and circulation of groundwater contained therein. But, the complex nature of such structures is the main problem encountered during assessment of groundwater resources and siting of production wells. In this study, all the possible explanations that the authors have presented for the stated hydrogeologic problem is directly or indirectly related to geological structures. Thus, in siting wells in bedrock aquifers, all existing structures must be identified and delineated from all sources, including aerial photographs and satellite images. Analyzing and interpreting information obtained from these sources together with the results of properly conducted geophysical surveys, are vital in the investigation of such aquifers.

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