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Evaluation of Renewable Water Resources and Estimating of Aquifer Parameters in Wadi Hubuna, Southwestern Part of Saudi Arabia

Omar H. Abdelaal^{1,*}, Tharwat H. Abdehafeez², Ayman I. Taha³

¹ Egyptian Mineral Resources Authority, Ministry of Petroleum, Egypt

² Geology Department, Faculty of Science, Al-Azhar University, Egypt

³ National Research Institute of Astronomy and Geophysics, Helwan, Egypt

* Correspondence: Geoomarhamdy@gmail.com

Abstract

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Water is one of the most vital natural resources in the Kingdom of Saudi Arabia and crucial for the survival of all living organisms; it is essential for agriculture, industry, and domestic uses such as drinking and cooking. This study aims to conduct a hydrogeological study to determine the hydraulic parameters of the aquifer, besides evaluating the renewable water resources for Wadi Hubuna in the southern Arabian Shield. Twenty dams were constructed to recharge renewable water resources in the wadi deposits aquifer, with a total capacity of 10.139 MCM. The depths of the examined wells in this study ranged from 9.6 m (well HAB10) to 79 m (well HAB21). The static water level also varies from 2.5 m at well HAB14 to 79.19 m at well HAB17. Alluvium thickness varies from 9.6 m at well HAB10 to 51.7 m at well HAB17. The saturated thickness ranges from 4.4 m in HAB2 to 27.6 m in HAB11. The results of a step and continuous pumping test conducted on ten wells revealed that the well loss varies from 0.03 m at well HAB03 to 5.52 m at well HAB02, the aquifer loss varies from 0.22 m at well HAB03 to 2.84 m at well HAB11, the transmissivity varies from $1.86 \times 10^{-4} \text{ m}^2/\text{s}$ at well HAB01 to $1.25 \times 10^{-2} \text{ m}^2/\text{s}$ at HAB03 well, and finally, the hydraulic conductivity varies from 3.54×10^{-5} at well HAB01 to 1.72×10^{-3} at well HAB03. The western, southern, and northern parts of the wadi are rated low and extremely low in renewable groundwater potentiality because of the limited width of the wadies, the thin surface sediment layer, and the little recharge from rainfall. In order to monitor the water levels in Wadi Hubuna and Wadi Sar, it is required to drill a series of piezometers along their lengths.

Keywords: Wadi Hubuna; Hydrogeology; Pumping test; Aquifer test; Water resources

1. Introduction

The study area comprises the western portion of the Najran region and a tiny portion of the Asir region in the southeast, and flows on the eastern side towards the Rub Al Khali desert. The altitudes of the area range from about 1200m a.s.l in the main channel of the wadi to more than 3000m in the Asir province. The catchment area is about 6837 km². The upper hard-rock area, which includes about 85% of the watershed of wadi Hubuna, is rugged mountainous terrain composed chiefly of igneous and metamorphic rocks and minor amounts of alluvial sediments. The lower alluvial area has little relief and

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is composed primarily of alluvium. Wadi Hubuna has an average rainfall of about 90 mm per year. The occurrence of groundwater was investigated using gravity and electrical resistance methods in the Sar Valley in the Hijaz Mountains (Ayman et al., 2021). The following results have been obtained; (1) the terrestrial water storage variations (ΔTWS) are estimated at -2.06 ± 0.34 mm/year; (2) the Global Land Data Assimilation System–derived soil moisture storage variations (ΔSMS) are estimated at -0.067 ± 0.005 mm/ year; (3) the groundwater storage variations (ΔGWS) show a negative trend estimated at -2.00 ± 0.34 mm/year during the period April 2002 to July 2017; and (4) the average annual precipitation (AAP) rate is estimated at 115 mm during the period 2002–2018 (Ayman et al., 2021). The hydrogeologic studies in Al-Abwa drainage basin, arid-terrain of Arabian Shield, Saudi Arabian Red Sea coastal belt was carried to evaluate the groundwater prospects in these areas (Zaigham, et al. 2020). 22 samples of groundwater were collected from different locations in the Najran region in southern Saudi Arabia to assess the quality of groundwater in this region (Alfaifi et al. 2020). The flood-prone areas in Wadi Baysh basin were evaluated based upon the integration of geographic information systems (GIS) and physiographic features of the hydrographic basins (Masoud et al. 2019). Groundwater is one of the most important natural resources stored in geological formations. Several techniques and studies, such as hydrochemical analysis and groundwater quality are used to evaluate the groundwater in different places. (Sarween and Shwan 2023), identify groundwater potential by using geographic information systems and remote sensing data (Mohamed et al., 2022), and assess unconfined aquifer hydraulic characteristics using the self-potential method (Zubair et al., 2022).

Wadi Hubuna was selected for the exploration and evaluation of the groundwater resources of the region. Both the quality and the effects of groundwater development have been taken into consideration. The aquifers of the study area differ from the upper part to the lower part of the wadi. In each case, major unconfined aquifers hold the principal groundwater resources of the area. The groundwater resource is the only source of irrigation water to ensure normal crop production in Wadi Hubuna. Considerable volumes of groundwater are currently withdrawn from underground storage. All these background problems have encouraged the researcher to carry out a detailed hydro geophysical study to extract as much information as possible on groundwater availability. The purpose of the study is to evaluate the present state of groundwater potential of these finite resources, to devise a possible solution as to how they can best be utilized for domestic use and irrigation.

2. Location of the Study area

The study area is located in southwest Saudi Arabia, between latitudes $17^{\circ} 31' 42''$ to $18^{\circ} 14' 44''$ N and longitudes $43^{\circ} 23' 58''$ to $44^{\circ} 39' 57''$ E (Fig.1). The study area is approximately 6837 km². It flows east from the Asir Mountains to the Ramlat Yam dunes in the Rub Al Khali. The catchment's terrain is steep in the western upper reaches, with small wadi channels giving way to broad, thick alluvial deposits in the east and north. The Wadi channel slope ranges from 0.1% in the eastern catchment to 3% in the eastern catchment boundary, with an average of 0.6%. The main length of the wadi is 135 km, while the perimeter is 522 km. Rainfall in Saudi Arabia significantly influences renewable water resources and varies yearly depending on geological, morphological, and climatological conditions. As a result, Saudi Arabia has an annual renewable water resource of 2.4 BCM (billion cubic meters) (GTZ/DCo, 2010). The Isohyetal rainfall map (Fig. 2) was created using rainfall data from seven sites in the study area and surrounding regions. The rainfall data of these seven sites reflect that; the rainfall ranges from 30.5mm at Bir Askar to 163.6 mm at Dhahran Al Janub, with a main average of 30.5 mm (Table 1). The analysis of the isohyetal rainfall map (Fig. 2) shows a large amount of rainfall occurred in the western parts and decreased gradually toward the eastern part of the study area.

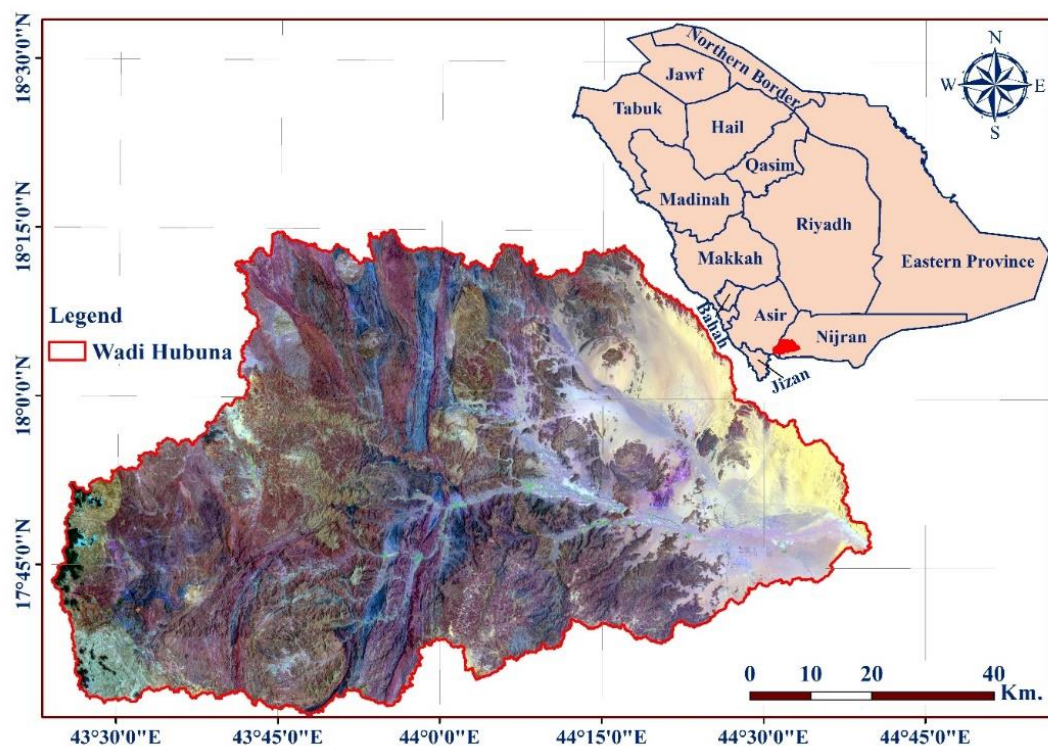


Fig.1. Location map of the study area

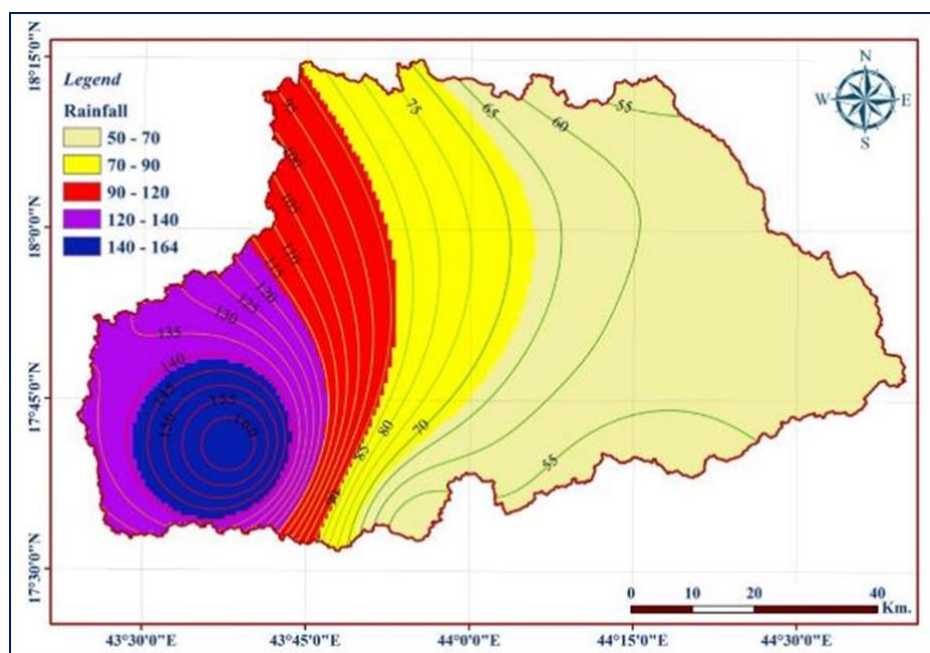


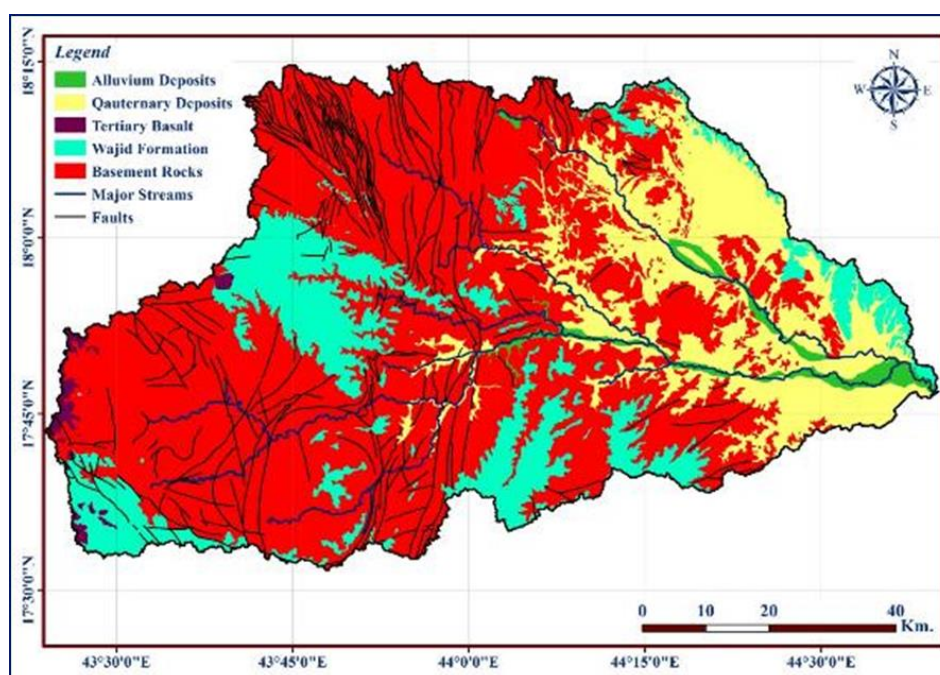
Fig.2 Isohyetal map of the Wadi Hubuna

Table 1. data derived from seven meteorological stations in the study area.

No.	Station Name	North	East	Elevation (m)	Average Rainfall (mm/year)
1	Najran	1940130.85	420283.05	1263	45.1
2	Bir Askar	1940730.77	386797.05	1810	30.5
3	Zawr Al Harith	1953968.51	337352.86	2251	50.3
4	Dhahran Al Janub	1955687.9	355051.22	2173	163.6
5	Al Harjah	1983573.62	327006.28	2287	38.2
6	Yadamah	2045692.12	415549.59	1242	40
7	Al Husainiah	1969916.71	441251.54	1189	55.1

3. Geologic Setting

Late Proterozoic metamorphic and plutonic rocks of the eastern margin of the Arabian Shield are unconformably overlain by flat-lying Cambrian-Ordovician sandstone, with some Tertiary basalt, Quaternary alluvium, and extensive Quaternary sand dunes (Fig.3). The Wajid Sandstone, the oldest sedimentary rock unit in the area, extensively outcrops in the western portion of the study area and is preserved only as dissected masses in the eastern portion. After the culmination of late Proterozoic igneous activity, the deposition of the Cambrian-Ordovician Wajid Sandstone occurred on a flat surface. The unconsolidated Quaternary alluvium deposits occur as small discontinuous patches along the major wadi channel in the upper catchment area. Basement outcrops are represented by various volcanic and metasedimentary rocks, mainly belonging to the Proterozoic Halaban Group, which include meta-andesite, meta-basalt, and meta-dacite in the western sections of the catchment. The upper portion of these basement rocks is typically weathered and has many deep fractures, up to 20 m depth (Fairer, 1985; Greenwood, 1985; Sable, 1985).

**Fig.3.** Geological map of Wadi Hubuna after (Greenwood, 1985)

4. Materials and Methods

The data obtained for this work was collected from seven meteorological stations, 31 wells and 26 dams (Table1) were used to evaluate renewable groundwater at Wadi Hubuna and determine the

hydraulic parameter of the shallow aquifer. wells and dam data were collected during the winter season (2020).

Table 2. Database of dams in the study area, derived after GTZ et al. (GTZ/DCo, 2010)

Surface Water Dam	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Dam Function	Capacity (MCM)
Kitam	17.5865	43.5426	2139	Flood Control	0.1
Hidadah	17.5961	43.7312	1790	Flood Control	0.5
Al Qabdah	17.6346	43.5257	2131	Aquifer Recharge	0.26
Al Rasheed	17.6565	43.4628	2278	Aquifer Recharge	0.5
Al Frowan	17.7223	43.4959	2191	Flood Control	0.15
Al Thabit Bil Ahmar	17.759	43.4703	2206	Aquifer Recharge	0.5
Afyad Al Talha	17.7842	43.51	2159	Domestic	0.748
Shraqib	17.7835	43.5088	2164	Aquifer Recharge	0.79
Al Mahjar	17.8513	43.7137	2080	Aquifer Recharge	0.3
Halal Sroum	17.8934	44.0946	1302	Aquifer Recharge	0.586
Badir Al Janoub	17.8946	43.6927	2127	Aquifer Recharge	0.6
Al Maleaha	17.9055	43.8409	1851	Aquifer Recharge	1
Alsharm	17.9561	43.7895	1938	Aquifer Recharge	0.18
Al Ishah	17.9772	43.7977	1970	Aquifer Recharge	0.5
Thar	17.9805	44.003	1372	Aquifer Recharge	0.36
Al Salamah	17.9847	43.8676	1699	Aquifer Recharge	0.2
Himairan	18.0005	43.8616	1702	Aquifer Recharge	0.492
Khudairan	18.0137	43.8581	1736	Aquifer Recharge	0.25
Yasan	18.0476	43.9615	1503	Aquifer Recharge	0.1
Qoton	18.1897	44.0158	867	Aquifer Recharge	0.581
Akthaba	18.1361	44.2567	1388	Flood Control	0.15
Makhdob	18.1846	44.1132	1463	Domestic	0.344
Al Yuttm	18.1906	43.8799	1851	Aquifer Recharge	0.3
Halal	17.6433	43.8614	1542	Aquifer Recharge	1.35
Al Khaniq	17.6736	43.6792	1734	Aquifer Recharge	0.82
Al Maleaha	17.9456	43.78	1952	Aquifer Recharge	0.47
12.13					

5. Results and Discussion

5.1. Hydrogeology

Wadi Hubuna is one of several wadis that drain from the Hijaz and Asir Mountains towards the east. The Wadi Hubuna catchment is bounded to the south by the Wadi Najran catchment and to the north by the Tathlith and Yadamah wadis catchments. Most of these wadis were developed during the Quaternary (Al-Sayari and Zötl, 1978). Quaternary sediments cover 1,394 km² of wadi streams and floodplains, representing 20 % of the Hubuna catchment's total area. These sediments commonly overlie basement rocks (Fairer, 1985; Greenwood, 1985; Sable, 1985) and are predominantly of alluvial origin with some eolian, colluvial, and terrace deposits. The well depths records reveal that the Quaternary deposits in the Wadi Hubuna mainstream attain their highest thickness near Hubuna Town and extend for about 13 km east of Al Hijf. The alluvium thickness attains about 50 meters within this transect, while it reaches up to 40 meters along Wadi Sikhi. The alluvial deposits along Wadi Thar, between Thar and Al Hijf, reveal reduced thicknesses compared to those of Wadis Hubuna and Sikhi, with various basement outcrops scattered throughout the floodplain. These deposits extend in a northeast direction downstream of Al Husayniyah, possibly for another 100 km (Figs. 4 and 5).

Age	Lithology		Hydro-Stratigraphy	Description
Quaternary	Wadi Deposits			Unsaturated Alluvium
				Saturated Alluvium
Paleozoic	Wajid			Wajid Fm.
Proterozoic	Weathered Basement			Aquitard
	Basement			Aquiclude

Fig.4. Lithostratigraphic and hydrostratigraphic cross section of the study area

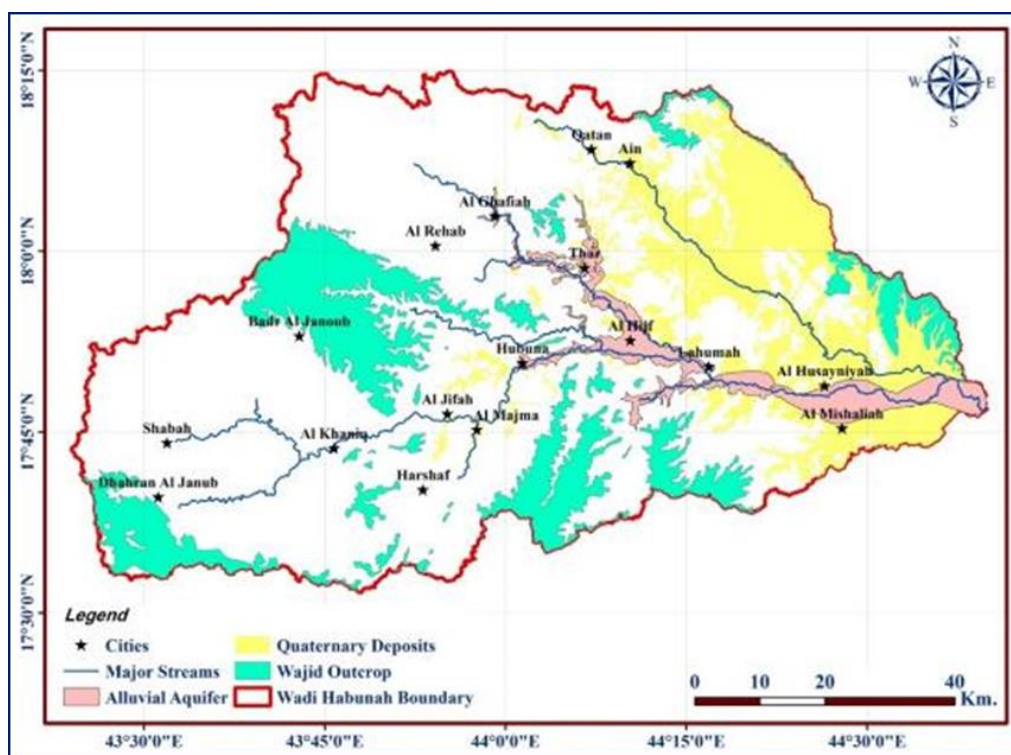


Fig.5. Hydrogeological map of the study area

5.1.1. Enhancement of renewable water resources

More than 90 % of the precipitation may be lost by evaporation without contributing to the water supply (GTZ/DCo, 2010). Various methods of rainfall harvesting attempt to capture a portion of this "lost rainfall." These methods vary from small-scale rainfall collectors (e.g., on roofs or backyards) to extensive drainage systems and landscaping of slopes and valleys. The southwest of Saudi Arabia receives the majority of the country's rainfall. This study aims to evaluate the efficiency of recharge dams, which hold surface runoff water and enrich groundwater recharge. Once water is held in shallow aquifers, it is no longer susceptible to evaporation, as in surface dams. Wadi Hubuna is home to 26 dams with a cumulative capacity of 12.13 MCM (Table 2). The geographic locations of these dams throughout the study area are depicted in Fig.6. They are constructed to serve as control dams, recharge dams, or drinking and irrigation water sources (GTZ/DCo, 2010).

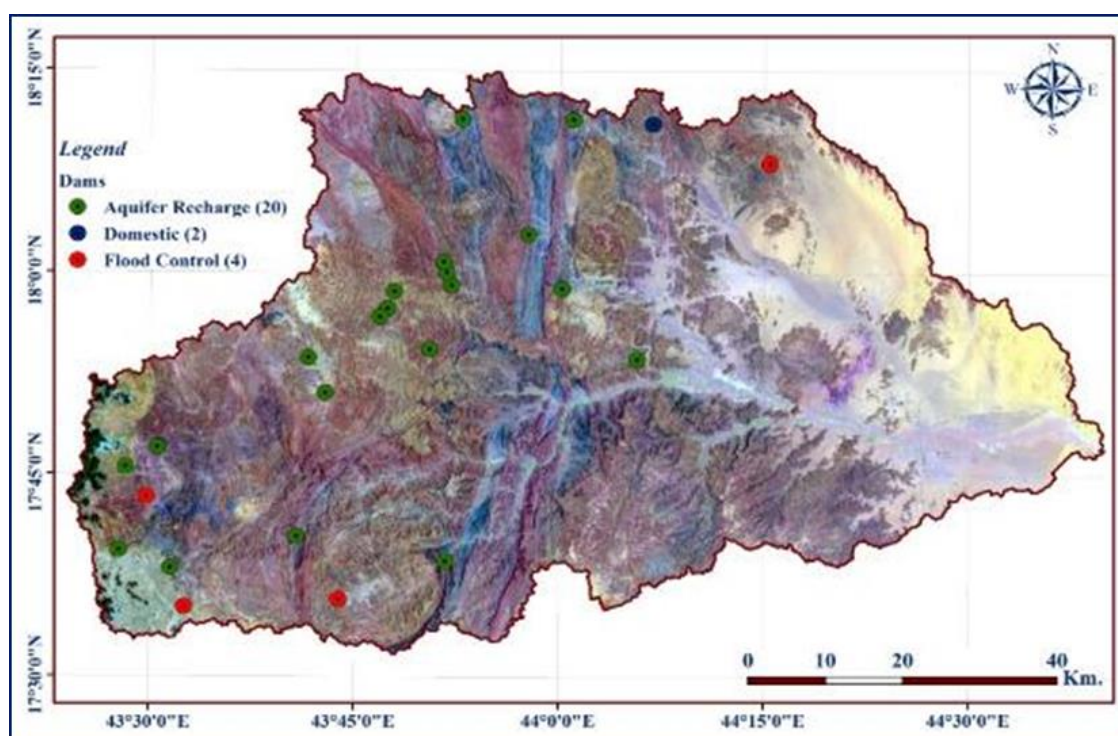


Fig.6. Distribution map of dams in the study area

5.1.2. Water resources in the alluvial deposits

Most of the wadi area is covered by alluvial deposits, which fill the channels cutting in the oldest rock by runoff during previous runoff wetter periods. Most alluvial material is also found on the coastal plains of the west, where the wadi systems debouch onto the more fertile land of the north and east. Wadis in the upper ranges of high mountains typically have a steep bed gradient. In contrast, the lower reaches are characterized by gentle bed gradients and shallow groundwater levels that tend to approach the ground surface. Wadis vary in width from less than 10 m up to 100 m along the reaches of some more deeply incised wadis but rarely exceed 100 meters. The relatively limited thickness and width of such unconsolidated deposits restrict their storage capacity, even though they may extend for tens of kilometers. The wadi system's permeability reveals considerable variations since it comprises materials ranging from coarse gravel to fine silt (MoWE, 2003).

After an individual storm, some direct infiltration from rainwater may occur and induce the recharging of deeper and larger aquifers when alluvium rests above it. According to site-specific studies, a wide range of generated surface runoff infiltrates wadi deposits and contributes to the average 75%

groundwater level in most wadi systems. This recharge level corresponds to only a small fraction (2-10%) of the entire precipitation that has fallen (Şorman and Abdulrazzak, 1987) .

The amount of water on the surface is liable for evaporation in the lower reaches, reducing its volume and deteriorating its quality. In the downstream path, evapotranspiration becomes increasingly active, which increases ground and groundwater salinities. On other occasions, low-quality groundwater with elevated nitrates and salinity levels was found to reach the sedimentary system to the east (Lloyd, 2001).

The measured water levels are listed in Table 3. Three MEWA observation wells were included in Dames (1988) study and have daily water level data from 1984 through 1987. These wells offer a direct comparison between 2016 and 2018. The depth distribution map of the study area (Fig. 7) displays that the total depth ranges between 9.6 at HAB10 and 150m at HAB21 with a mean value of 36.62 (Table 3). while the alluvium thickness (Fig. 8) varies from 9.6 m at well HAB10 to 51.7 m at well HAB17 with a mean value of 28.81 m (Table 3). Meanwhile, the saturated alluvium thickness (Fig. 9) varies from 0 m at wells HAB17, HAB21, HAB31 to 27.6 m at well HAB11 with a mean value of 12.25 (Table 3). The static water level (Fig. 10) varies from 2.5 m at well HAB14 to 79.19 m at well HAB17 with a mean value of 18.74 (Table 3).

Table 3. Hydrogeological characteristics for all wells that were investigated.

Well NO.	Total Depth (m)	Elevation (m)	Water Table BSL (m)	SWL (m)	Well Type	Alluvium thickness (m)	Saturated alluvium thickness (m)	Saturated thickness %
HAB01	31	1294	1268.26	25.74	Dug	31.0	5.3	17%
HAB02	38.4	1230	1200.38	29.62	Drilled	34.0	4.4	11%
HAB03	35	1264	1236.28	27.72	Dug	35.0	7.3	21%
HAB04	24.7	1322	1312.63	9.37	Dug	24.7	15.3	62%
HAB05	77.3	1324	1314.53	9.47	Drilled	23.5	14.0	18%
HAB06	30	1323	1313.86	9.14	Dug	30.0	20.9	70%
HAB07	19.3	1449	1444.38	4.62	Dug	19.3	14.7	76%
HAB08	21.35	1476	1472	4	Dug	21.4	17.4	81%
HAB09	29	1300	1280.37	19.63	Dug	29.0	9.4	32%
HAB10	9.6	1458	1454.65	3.35	Dug	9.6	6.3	65%
HAB11	34.5	1385	1378.05	6.95	Dug	34.5	27.6	80%
HAB12	30.0	1447	1433	14	Dug	30.0	16.0	53%
HAB13	40.0	1384	1366	18	Dug	40.0	22.0	55%
HAB14	18.0	1461	1458.5	2.5	Dug	18.0	15.5	86%
HAB15	20.0	1341	1329	12	Dug	20.0	8.0	40%
HAB16	18.0	1386	1378	8	Dug	18.0	10.0	56%
HAB17	85.0	1193	1113.81	79.19	Drilled	51.7	0.0	0%
HAB18	51.0	1156	1131	25	Dug	51.0	26.0	51%
HAB19	34.0	1174	1143.81	30.19	Drilled	36.0	5.8	17%
HAB20	21.0	1349	1342	7	Dug	21.0	14.0	67%
HAB21	150.0	1428	1368.81	59.19	Drilled	50.6	0.0	0%
HAB22	30.0	2117	2109	8	Dug	30.0	22.0	73%
HAB23	35.0	2082	2069	13	Dug	35.0	22.0	63%
HAB24	16.0	2135	2127	8	Dug	16.0	8.0	50%
HAB25	16.0	2193	2188	5	Dug	16.0	11.0	69%
HAB26	15.0	2087	2080	7	Dug	15.0	8.0	53%
HAB27	20.0	2175	2164	11	Dug	20.0	9.0	45%
HAB28	15.0	2141	2135	6	Dug	15.0	9.0	60%
HAB29	35.0	1281	1263	18	Dug	35.0	17.0	49%
HAB30	46.0	1221	1189	32	Dug	46.0	14.0	30%
HAB31	90.0	1174	1105.81	68.19	Drilled	36.7	0.0	0%
Min	9.60	1156.00	1105.81	2.50		9.60	0.00	
Max	150.00	2193.00	2188.00	79.19		51.70	27.60	
Mean	36.62	1508.06	1489.33	18.74		28.81	12.25	

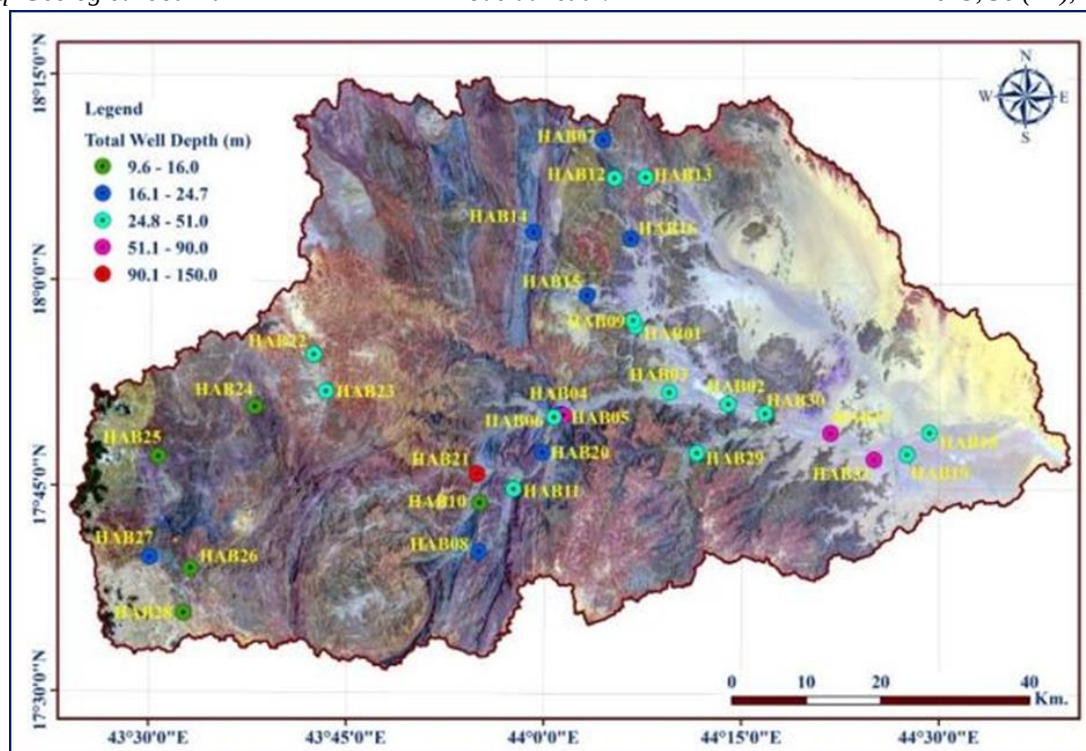


Fig.7. Total well depth distribution map in the study area

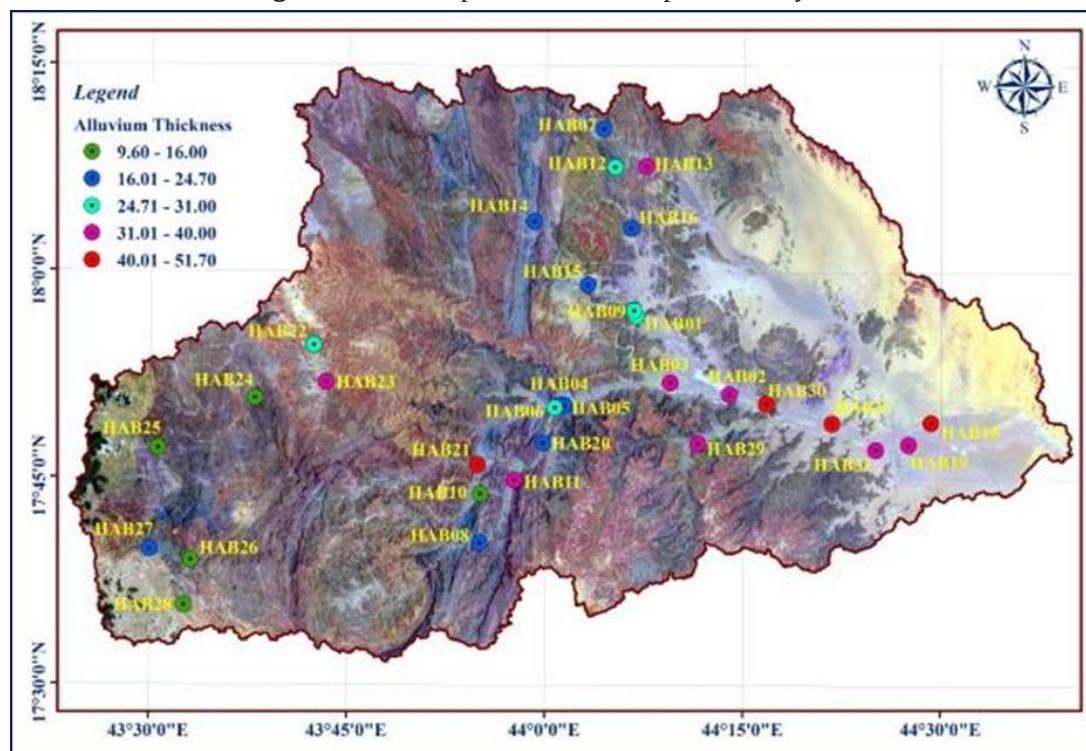


Fig.8. Alluvium thickness distribution map in the study area

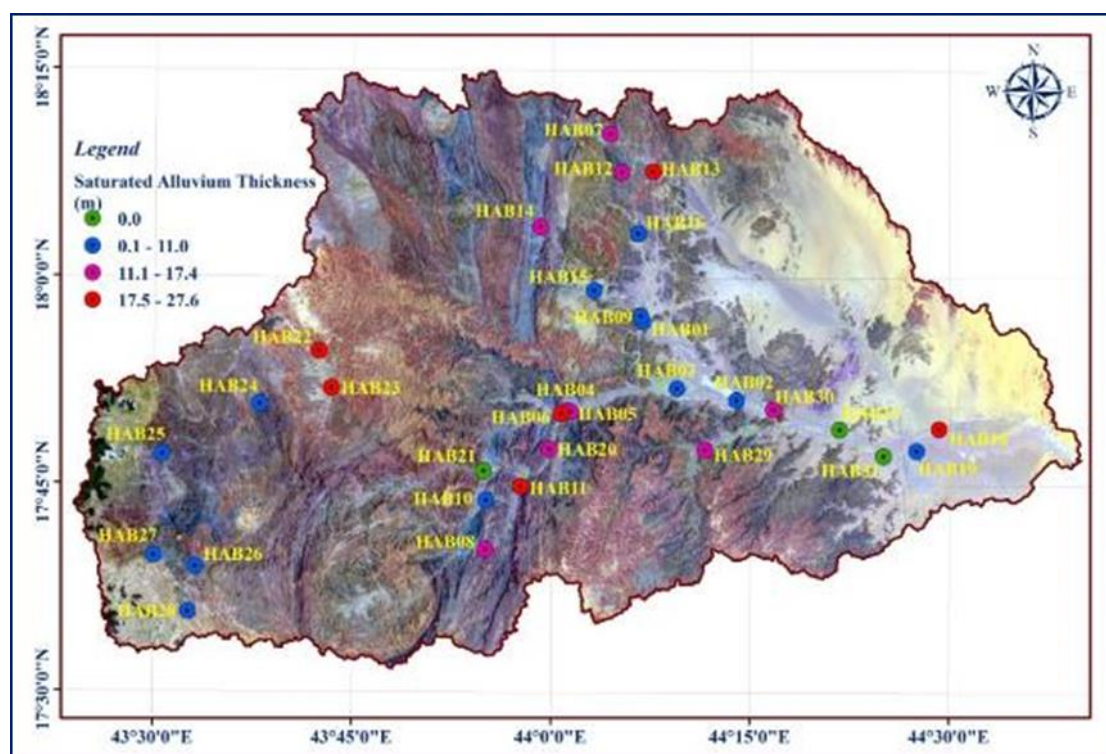


Fig.9. Saturated alluvium thickness distribution map in the study area.

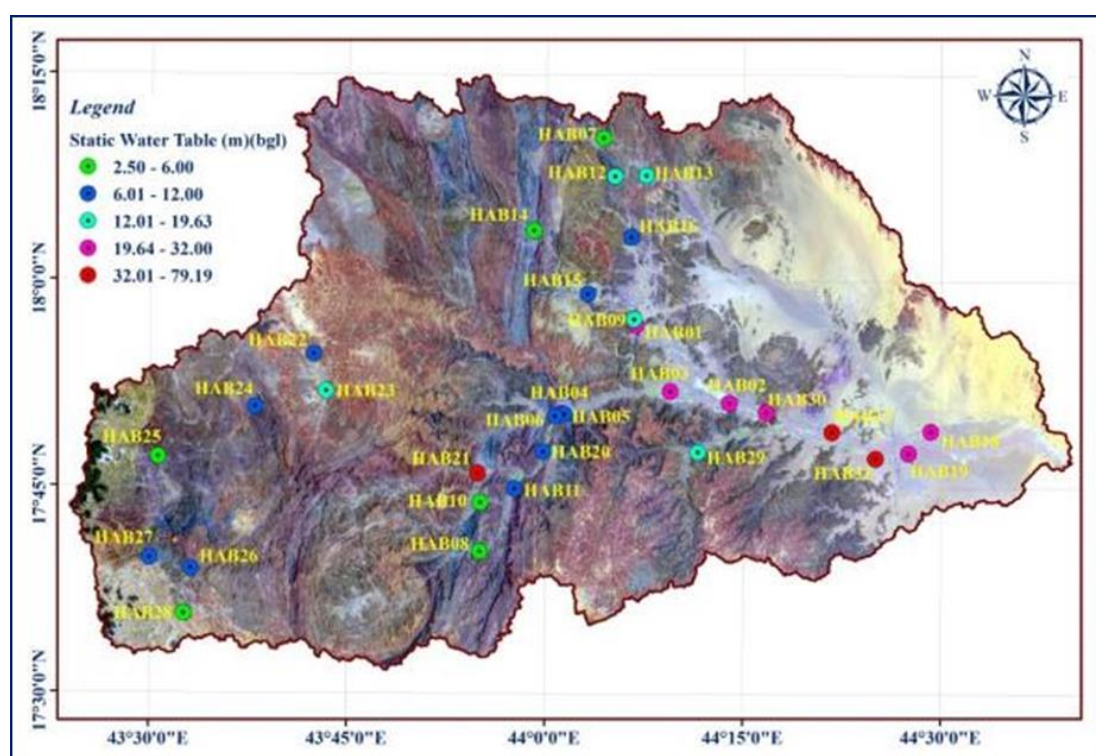


Fig.10. Static water level distribution map of wadi Hubuna.

The datasets for the water table from 2016 and 2018 are displayed in Fig.11. The hydraulic gradient ranges from roughly 0.004 m/m in the west to 0.003 m/m in the east. The analyzed data are obtained from drilled wells beside the three MEWA observation wells, where the alluvium thickness in each site is considered to encompass the total well depth. The saturated alluvium thickness ranges from 5 meters

to 26 meters. Taken as a fraction of total alluvium thickness, the saturated thickness of the alluvium ranges from 17% to 86%, with a median value of 33%. Where the alluvium is saturated, it would be hydraulically connected with the weathered basement, which is assumed to be fully saturated (100%). However, as noted above, the basement is considered a poorly productive aquifer compared with the alluvium. The water table for 1985 and 2018/2019 in the three MEWA observation wells is displayed in the cross-sections of Wadi Hubuna and Wadi Thar (Figs.11 and 12). These measurements reveal that the water table has declined by four meters along Wadi Hubuna, as measured at the two MEWA wells, H-11-P and H-3-P. However, water level data collected from the H-8-P well in Wadi Thar between 1985 and 2018 did not exhibit significant changes in the water table. (CDM et al, 2021)

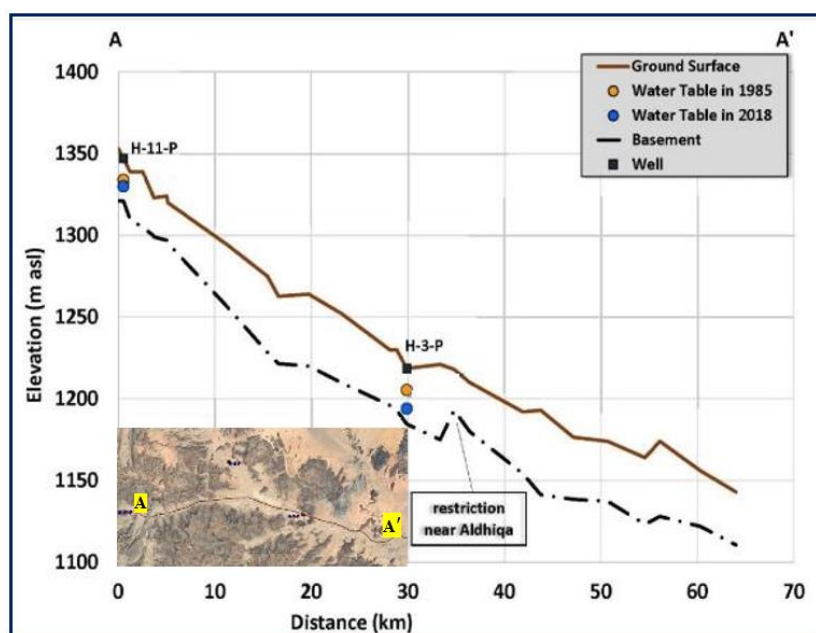


Fig.11. Groundwater elevation comparisons within wadi Hubuna (1985, 2018)

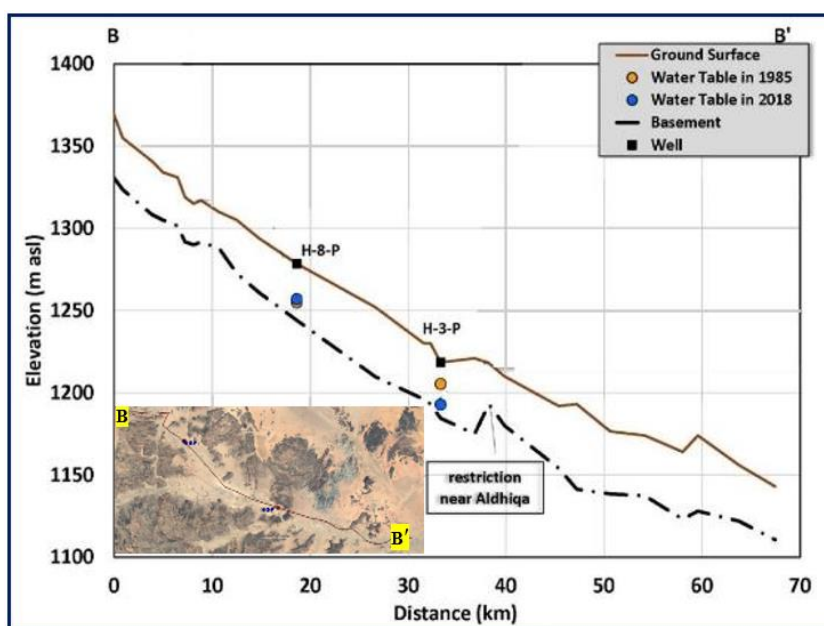


Fig.12. Water table comparisons within wadi Thar and Hubuna (1985, 2018).

5.1.3. Hydraulic parameters

Transmissivity (T), Hydraulic conductivity (K), and storativity (S) are hydraulic properties of the aquifers that determine how fast water moves through a porous and permeable medium and how groundwater levels are affected (Bouwer, 1978).

Because large-diameter test wells are the only accessible ones, our discussion will be focused on these kinds. The tests require single-pump wells in which the response to pumping could be measured. (Papadopoulos and Cooper, 1967). Before describing the Papadopoulos-Cooper method, the modified volumetric method (Ferris et al., 1962) approach, and the step drawdown method.

- Step drawdown test

A step drawdown test is a pumping test in which the monitoring drawdown in a well while the discharge rate from the well is increased in steps. Through a series of pumping intervals (steps) with increasingly greater constant rates, the discharge rate in the pumping well is increased from an initially low constant rate. Each stage is typically the same length, lasting between 30 minutes and 2 hours (Kruseman and De Ridder, 1990). The step-drawdown test data were employed to give an idea about the design and efficiency of the water wells and to estimate the recommended safe yield of the well and the pump setting depth by calculating the aquifer loss coefficient (B) and the well loss constant (C).

Jacob, (1947), Rorabaugh, (1953), Walton, (1962) introduced the step drawdown test and have proposed expanded methods of analysis and interpretation. Jacob's approach was used to analyze and interpret step drawdown test results. Jacob, (1947) stated that the drawdown in a pumped well has two flow components: the first is the resistance of the water-bearing formation (formation loss), which is proportional to discharge. Whereas the second accounts for the well loss, which is the loss of head that accompanies the flow through the screen or perforations and upward inside the casing to the pump intake that is proportional approximately to the square of discharge. Each pumped well underwent three and four-step drawdown tests at varied pumping rates (Table 6).

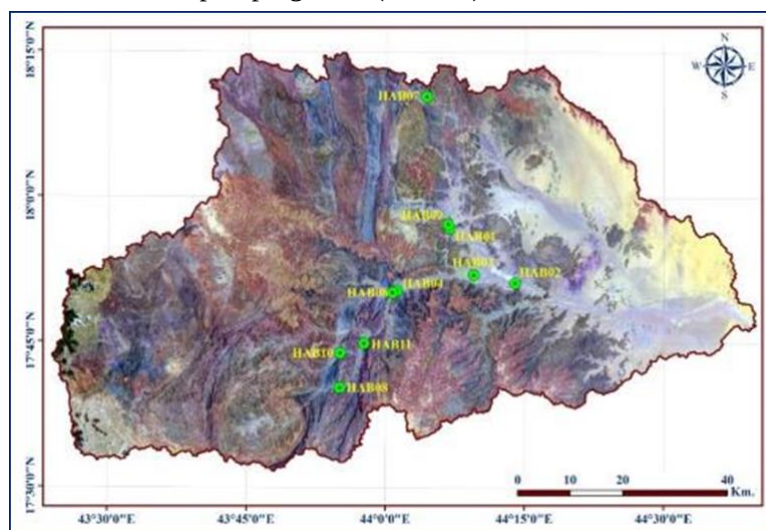


Fig.13. Locations of the wells on which pumping tests were conducted.

Table 6 shows the data used to compute aquifer loss and well loss by plotting S/Q versus Q (Fig.14) and fitting a straight line through the points. The well loss coefficient C is given by the slope of the line, whereas the line's intersection gives the formation loss coefficient B with the S/Q axis ($Q = 0$) (Todd, 1980). The entire decline is approximately described by the following equation (Jacob, 1947):

$$S = BQ + CQ^2 \quad (1)$$

where S is the total drawdown in m, Q is the rate of discharge in m³/d, C is the well loss in d²/m⁵, and B is the formation loss constant in d/m² (due to aquifer properties).

The calculated well loss coefficient and aquifer loss coefficient are presented in Table 7; thus, we can determine the well efficiency. The efficiency of pumping the well expresses the ratio of aquifer loss (theoretical drawdown) to total (measured) drawdown in the well (Kruseman and De Ridder, 1990). A well efficiency of 70% or more is usually considered acceptable, with 65% being accepted as the minimum efficiency (Kresic, 1997). The well efficiency is defined by the following equation:

$$\text{Well Efficiency (E)} = \frac{\text{aquifer loss}}{\text{aquifer loss} + \text{well loss}} * 100 \quad (2)$$

The term “aquifer loss” represents the head losses caused by laminar flow in the aquifer and is proportional to the discharge (i.e., BQ: aquifer loss). The term “well loss” is a non-linear term, and represents turbulent flow in the vicinity of the well and in the well. The well loss can be a substantial fraction of total drawdown when pumping rates are large. To quantify these components, the well must be pumped at multiple variable flow rates (commonly called "steps"). As shown in Table 7, the Well efficiency (%) range between 26.23 % (HAB01), and 90.97 % (HAB03), while the well loss ranges from 0.22 m (HAB04) to 2.84 in (HAB11).

Table 6. Pumping test data for wadi Hubuna wells.

Well NO.	Total Depth (m)	SWL (m)	Well Type	Aquifer	R (m)	Aquifer Type	Average Discharge (g/m)	Max. D.D (m)	Depth to Pump (m)
HAB01	31	25.74	Dug	Alluvial Sediments/ Fractured Basement	5	Unconfined to semi- Confined	64	3.93	30.5
HAB02	39.4	29.62	Drilled		0.36		142	7.97	38.4
HAB03	35	72.72	Dug		5		223	1.15	34
HAB04	26.5	9.37	Dug		5		223	5.73	24.7
HAB06	30	9.14	Dug		5		239	2.6	27.85
HAB07	19.3	4.62	Dug		5		309	3.98	18.85
HAB08	21.35	4	Dug		5		159	9.02	18.85
HAB09	29	19.63	Dug		5		133	5.55	27.5
HAB10	9.6	3.35	Dug		5		106	3.86	9
HAB11	34.5	6.95	Dug		5		277	7.2	32.5

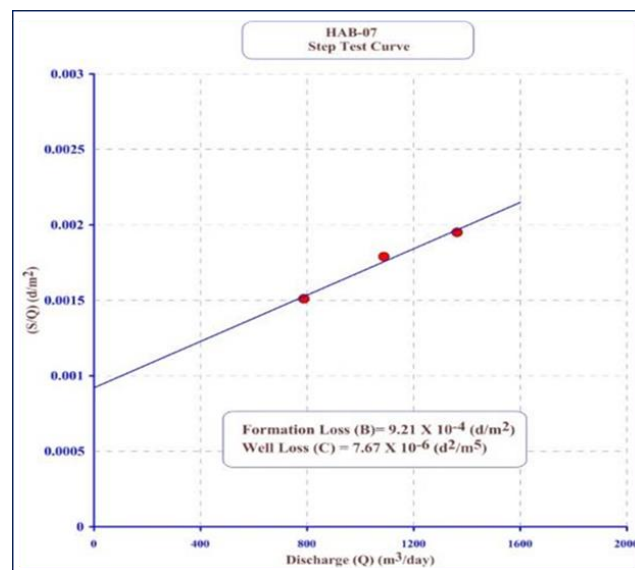


Fig.14. Step test curve for well No. HAB07.

- Constant discharge test

The constant rate pumping test is the most frequent type of pumping test, in which the control well is pumped at a constant rate, and the drawdown in water level is observed in the control well and one or more adjacent observation wells. By plotting the observed drawdown (s) vs. time (t) on semi-logarithmic paper (t on the log scale), we obtain a straight line of slopes for the constant test (Fig.17) (Jacob, 1947)

$$T_{(p)} = 0.183 * \frac{Q}{s} \quad (3)$$

where T_p (m^2/d) is the transmissivity value of the constant test, s is the slope of the line, meters per log cycle, while Q is the discharge (m^3/d). The constant rate pumping test aims to determine an aquifer's transmissivity and hydraulic conductivity.

Table 7. Hydraulic parameter for wells from step test.

Well NO.	Step NO.	Q m^3/hr	Drawdown (m)	Specific Drawdown	Aquifer Loss (m)	Well Loss (m)	Efficiency %
HAB01	1	14.99	1.31	0.0036413	0.62	0.70	46.87
	2	29.45	4.02	0.0056876	1.22	2.71	31.20
	3	37.33	5.84	0.0065184	1.55	4.36	26.23
HAB02	1	13	1.9	0.0060897	0.99	0.91	52.00
	2	22.72	4.54	0.0083260	1.73	2.79	38.24
	3	31.94	7.94	0.0103580	2.43	5.52	30.60
HAB03	1	14.44	0.24	0.0006925	0.22	0.03	90.97
	2	29.28	0.57	0.0008111	0.44	0.11	80.49
	3	46.00	0.95	0.0008605	0.70	0.27	71.80
HAB04	1	15.26	0.93	0.0025393	0.71	0.2	78.1
	2	37.08	2.76	0.0031014	1.73	1.17	59.5
	3	50.45	4.63	0.0038239	2.35	2.17	52
HAB06	1	32.83	1.19	0.0015103	0.73	0.48	60.47
	2	45.38	1.95	0.0017904	1.00	0.91	52.30
	3	56.82	2.66	0.0019506	1.26	1.43	46.70
HAB07	1	16.6	0.5	0.0012550	0.43	0.06	87.4
	2	54.76	1.91	0.0014533	1.41	0.64	68.92
	3	72.36	3.1	0.0017851	1.87	1.11	62.86
HAB08	1	14.93	0.52	0.0014512	0.45	0.19	69.98
	2	32.55	2.42	0.0030978	0.98	0.9	51.94
	3	48.99	3.1	0.0026366	1.47	2.04	41.87
HAB09	1	22.95	2.4	0.0043573	1.11	1.18	48.47
	2	29.9	3.21	0.0044732	1.44	2	42.08
	3	41.64	6.01	0.0060138	2.02	3.87	34.19
HAB10	1	12.5	0.79	0.0026333	0.4	0.39	51.19
	2	22.7	2.04	0.0037445	0.73	1.29	36.35
	3	34.5	4.08	0.0049275	1.12	2.97	27.29
HAB11	1	21	1.22	0.0024206	0.91	0.32	73.72
	2	41.7	3.1	0.0030975	1.8	1.27	58.64
	3	62.5	5.52	0.0036800	2.84	2.7	48.71

- Transmissibility

This parameter indicates how quickly water can pass through a geological formation and defines the capacity of an aquifer to carry water. It is the rate of water transmission over a unit width of an aquifer at a hydraulic gradient unit. Jacob calculated the vector's coefficient using the following equation:

$$T = 2.3 * \frac{Q}{4\pi\Delta S} \quad (4)$$

where T is the coefficient of transmissibility (m²/day), Q is the Pumping rate (m³/day), and ΔS is the value of the change in drawdown in a single logarithmic cycle.

To calculate the ΔS, the test data are plotted on a semi-logarithmic sheet with the vertical axis representing the drawdown value (S). The horizontal axis represents the logarithmic time of the drawdown value per minute (Fig.17). The resultant line passes between most of the points and can be used to calculate the change in the value of the decline in the second session of the logarithmic time. The transmissibility coefficient ranges from 0.0125 m²/s (HAB03) to 0.000186 (HAB01) (Fig.15).

Table 8. Hydraulic parameters for wells from the constant discharge test.

Well NO.	Discharge (m ³ /h)	Drawdown (m)	Pumping Duration (min.)	Specific Capacity	transmissibility (m ² /s)	Hydraulic Conductivity (m/s)
HAB01	14.59	3.91	324	3.73	0.000186	0.0000354
HAB02	32.3	7.96	480	4.06	0.00228	0.000233
HAB03	50.69	1.15	360	44.08	0.0125	0.00172
HAB04	50.67	5.73	360	8.84	0.00461	0.000269
HAB06	54.36	2.57	360	21.15	0.00974	0.000446
HAB07	70.18	3.98	360	17.63	0.00954	0.00065
HAB08	36.09	9.02	361	4.00	0.00118	0.000068
HAB09	30.2	5.55	361	5.44	0.0019	0.000203
HAB10	24	3.86	361	6.22	0.00276	0.000442
HAB11	62.8	7.2	361	8.72	0.00441	0.00016

- Hydraulic conductivity

The Hydraulic Conductivity (K) is the volume of water that will move through a porous medium in one unit of time under a unit hydraulic gradient through a unit area measured at right angles to the flow direction (Wenzel and Fishel, 1942). Many factors, such as porosity, particle size, shape, distribution, density, and viscosity of the groundwater, control the hydraulic conductivity. Using the constant pumping test and recovery test results for the evaluated wells, the hydraulic conductivity values can be derived using the following equation:

$$K = \frac{T}{D} \quad (5)$$

where D is the saturated thickness and T is the transmissibility in m²/day. The Hydraulic conductivity (k) value ranges from 0.00172 m/s (HAB03) to 0.0000354 (HAB01) (Fig.16).

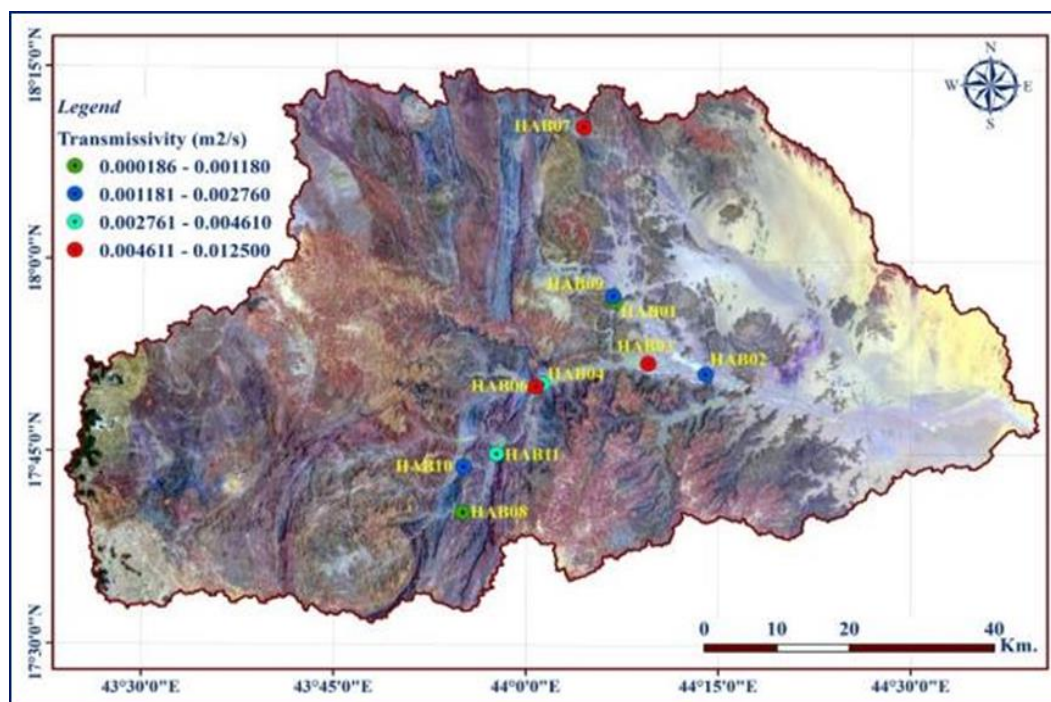


Fig.15. Transmissivity distribution Map for wells

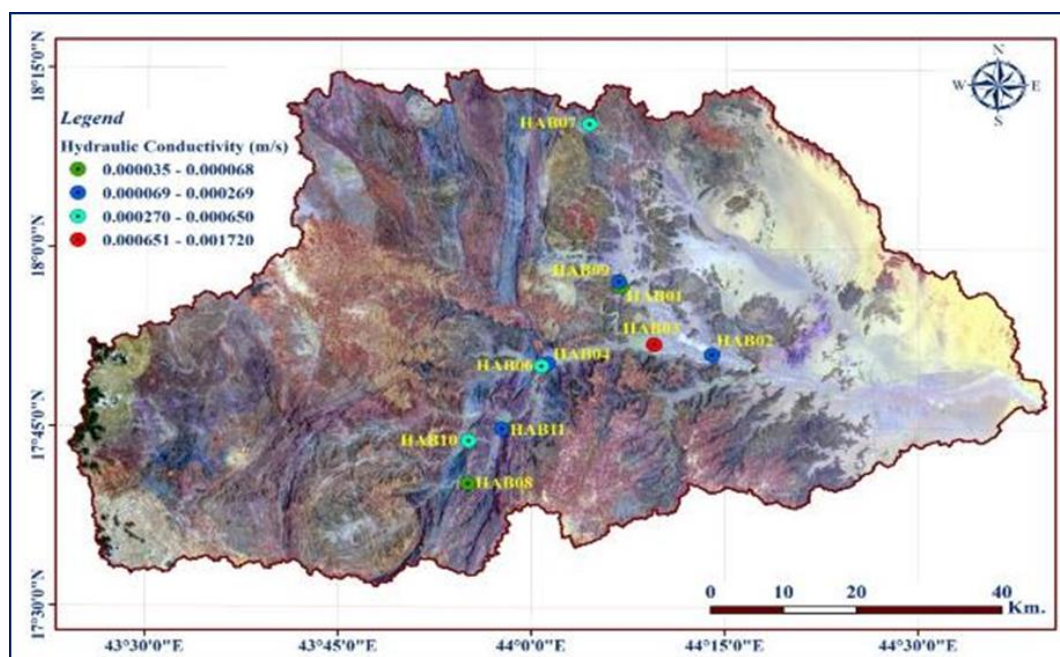


Fig.16. Hydraulic conductivity map for wells in the study area

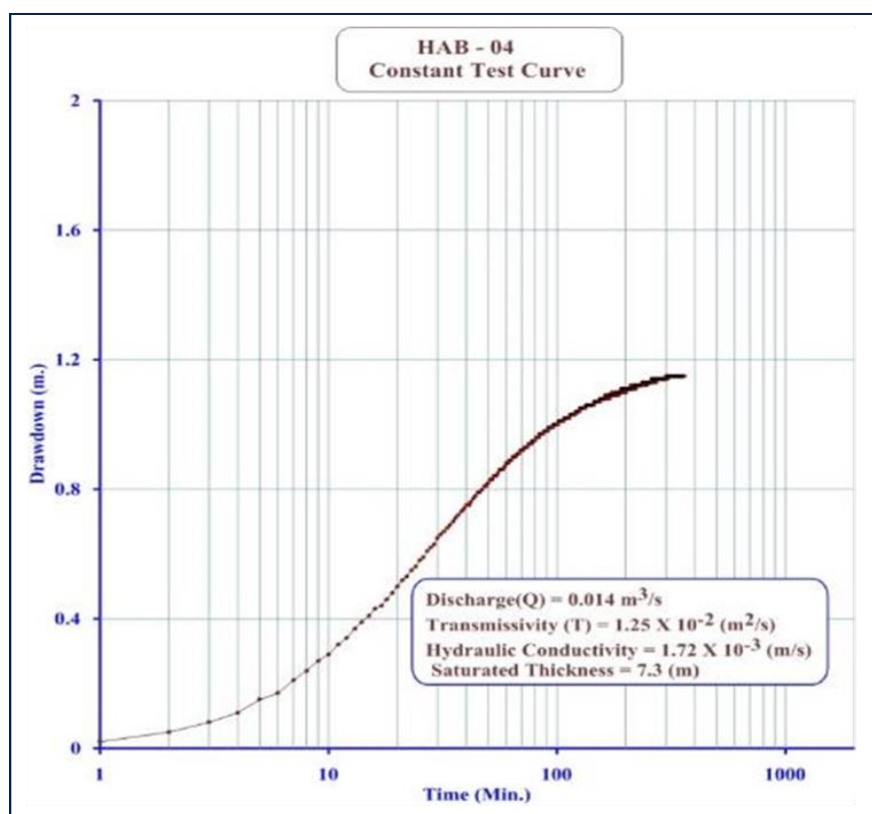


Fig.17. Constant test curve for well No. HAB04.

6. Conclusions

About 20% of the study area is covered with Quaternary deposits, which are made up of alluvial, eolian, colluvial, and terrace deposits and typically occur over the basement complex. The alluvial deposits of the Quaternary are thickest in the Wadi Hubuna mainstream, near Hubuna Town, and extend approximately 13 km east of Al Hijf.

The present study depends on 31 wells with depths varying from 9.6 m at well HAB10 to 79 m at well HAB21. The static water level also varies from 2.5 m at well HAB14 to 79.19 m at well HAB17, alluvium thickness varies from 9.6 m at well HAB10 to 51.7 m at well HAB17, and saturated thickness varies from 0 m at wells HAB17, HAB21, HAB31 to 27.6 m at well HAB11. The pumping test findings suggest that the well loss varies from 0.03 m at well HAB03 to 5.52 m at well HAB02, aquifer loss varies from 0.22 m at well HAB03 to 2.84 m at well HAB11, Transmissivity varies from 1.86×10^{-4} m²/s at well HAB01 to 1.25×10^{-2} m²/s at well HAB03, and finally, hydraulic conductivity varies from 3.54×10^{-5} at well HAB01 to 1.72×10^{-3} at well HAB03.

In order to develop the groundwater in Wadi Hubuna, Southwestern Part of Saudi Arabia, we recommended the following:

- Due to the narrow width of the wadies, the thin surface sediment layer, and the little recharge from rainfall, the western, southern, and northern parts of the wadi are considered low and very low in renewable groundwater potentiality.
- It is necessary to drill a network of piezometers along Wadi Hubuna and Wadi Sar in order to record changes in water level.
- The competent authorities should organize random drilling operations by the resident population to extract water. It was also noted that the wells currently operating in the study area are very close

to each other; this may lead to the deterioration of renewable groundwater resources when the matter is not controlled in an orderly manner.

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