Groundwater availability in the Khulais Plain, western Saudi Arabia

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Abstract The Khulais plain lies within a typical arid area in western Saudi Arabia. Groundwater occurs within two aquifers in the area: the alluvium of the wadi system, and the sandy layers of the Cretaceous-Tertiary sedimentary succession. Detailed field investigations and laboratory analysis helped in determining the aquifer properties for each of the water-bearing units. Groundwater movement has been thoroughly studied, and distribution maps prepared to explain the variations in transmissivity, permeability, porosity and specific yield. An attempt has been made to estimate volumes of groundwater flow towards the plain. This study presents a first attempt towards determining groundwater availability in the Cretaceous-Tertiary succession of this part of the world.

Disponibilité des eaux souterraines dans la plaine de Khulais à l'Arabie Saoudite occidentale

Résumé La plaine de Khulais est située dans une zone aride typique de l'Arabie Saoudite occidentale. On trouve des eaux souterraines dans les deux aquifères de la région: le système alluvial des oueds d'une part, les couches sableuse du Crétacé au Tertiaire de la succession sédimentaire d'autre part. Des examens détaillés sur le terrain et des analyses de laboratoire ont permis de déterminer les propriétés des différentes couches aquifères. La dynamique des eaux souterraines a été étudié et des cartes de répartition ont été établies dans le but d'expliquer les variations de transmissivité, de perméabilité, de porosité et d'apport spécifique. Le débit d'écoulement vers la plaine a également été estimé. Cette étude constitue une première tentative d'estimation des disponibilités en eaux souterraines des couches allant du Crétacé au Tertiaire dans cette partie du monde.

INTRODUCTION

The Khulais plain lies within the eastern region of Saudi Arabia between latitudes 22°00'-22°15' N, and longitudes 39°05'-39°30' E, some 110 km to the north-east of Jeddah. Three main wadis drain into the plain: Wadi Murawani, Wadi Abu Hulaifa and Wadi Ghiran. The stratigraphic sequence in the area starts with the Pre-cambrian and Cambrian crystalline basement complex overlain unconformably by a Cretaceous-Tertiary sedimentary succession. Both rock units are covered in places by Tertiary-Quaternary basalt flows. The Quaternary-recent deposits, including the materials deposited by the wadis, form the

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youngest unit of the sequence. Figs 1 and 2 summarize the stratigraphic sequence and the general geological setting of the study area.

The plain is structurally bounded on its eastern and western edges by elevated basement outcrops, thereby forming a sort of downthrown graben structure (Bazuhair *et al.*, 1992). The fault system in the area runs parallel to the Red Sea graben and is easily traced in the basement rocks. Swarms of dykes and sills also affect the basement rocks.

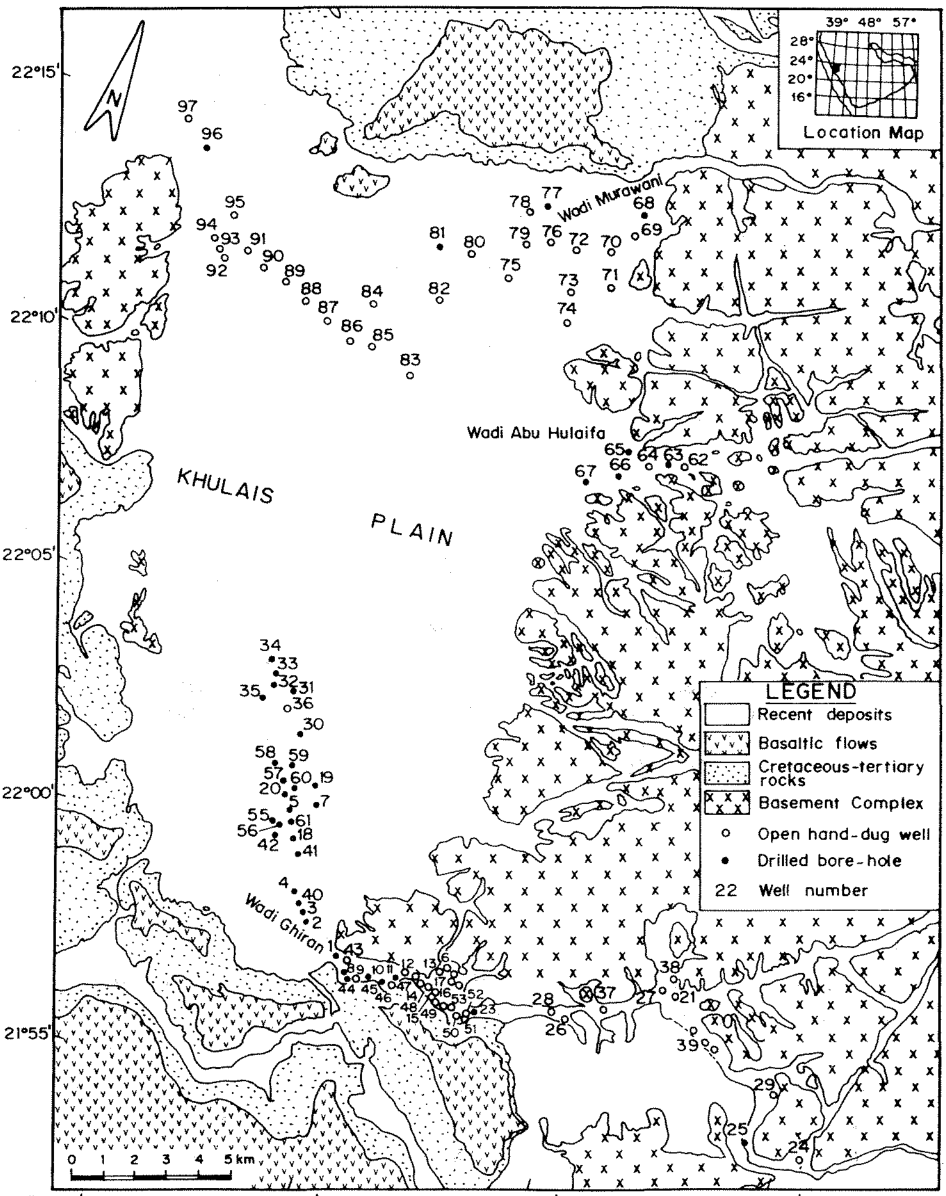

Fig. 1 Main rock units and well locations in the Khulais plain.

AGE	FORMATION	LITHOLOGY	THICKNESS (m)
Quaternary - Recent	Surficial deposits including alluvial deposits of the Wadi system	Heterogeneous assemblage of gravels, sand, silt and clay	≤ 30
Tertiary- Quaternary	Basalt flows	Basalts and andesite	≤ 60
Eocene - Oligocene	Shumaysl Formation	Sandstone, siltstone with oolitic ironstone bands	20-200
Maestrichtian	Usfan Formation	Sandstone, shales, marls and carbonate ledge	
Cretaceous	Haddat Al Sham Formation	Conglomerate, sandstone breccia with claystone and siltstone	250
Cambrian - Precambrian	Basement Complex	Igneous and metamorphic complexes	

***Fig. 2** Stratigraphic sequence in the Khulais area.*

The climate in the area is arid. Average annual rainfall is about 150 mm; it is irregular in distribution and torrential in nature and so any groundwater recharge is intermittent.

A number of hydrogeological research activities have taken place in the Khulais area (Al-Nujaidi, 1978; Italo-Consult, 1976; Jado & Zotle, 1984). Almost all concentrated their efforts on the Wadi Murawani. Other wadis, such as Wadi Abu Hulaifa, and Wadi Ghiran, and the plain itself, received less attention. The main purposes of the present study were to evaluate the groundwater availability and to determine the aquifer capability in the Khulais plain, including the downstream parts of Wadis Murawani, Abu Hulaifa and Ghiran. Those two main objectives were addressed through both field and laboratory methods. The field techniques included a detailed well inventory and a complete hydrogeological survey. Thirteen controlled pumping tests and five recovery tests were carried out during the study. Laboratory techniques were used mainly to determine the porosity, specific yield and permeability of aquifer materials.

GROUNDWATER CONDITIONS

Groundwater in the Khulais area occurs within two main water-bearing units, within the alluvium of the wadis system under unconfined conditions and within the clastic sandy layers of Cretaceous-Tertiary sedimentary succession, mainly under confined and semiconfined conditions.

The depth to groundwater within the alluvium of the wadis ranges between 5 and 20 m. Groundwater flow in the system generally follows the surface drainage, which makes the regional picture (Fig. 3) take the form of a semi-radial flow from three directions towards a large depression in the west of the study area. In general, the hydraulic properties are more or less homo-

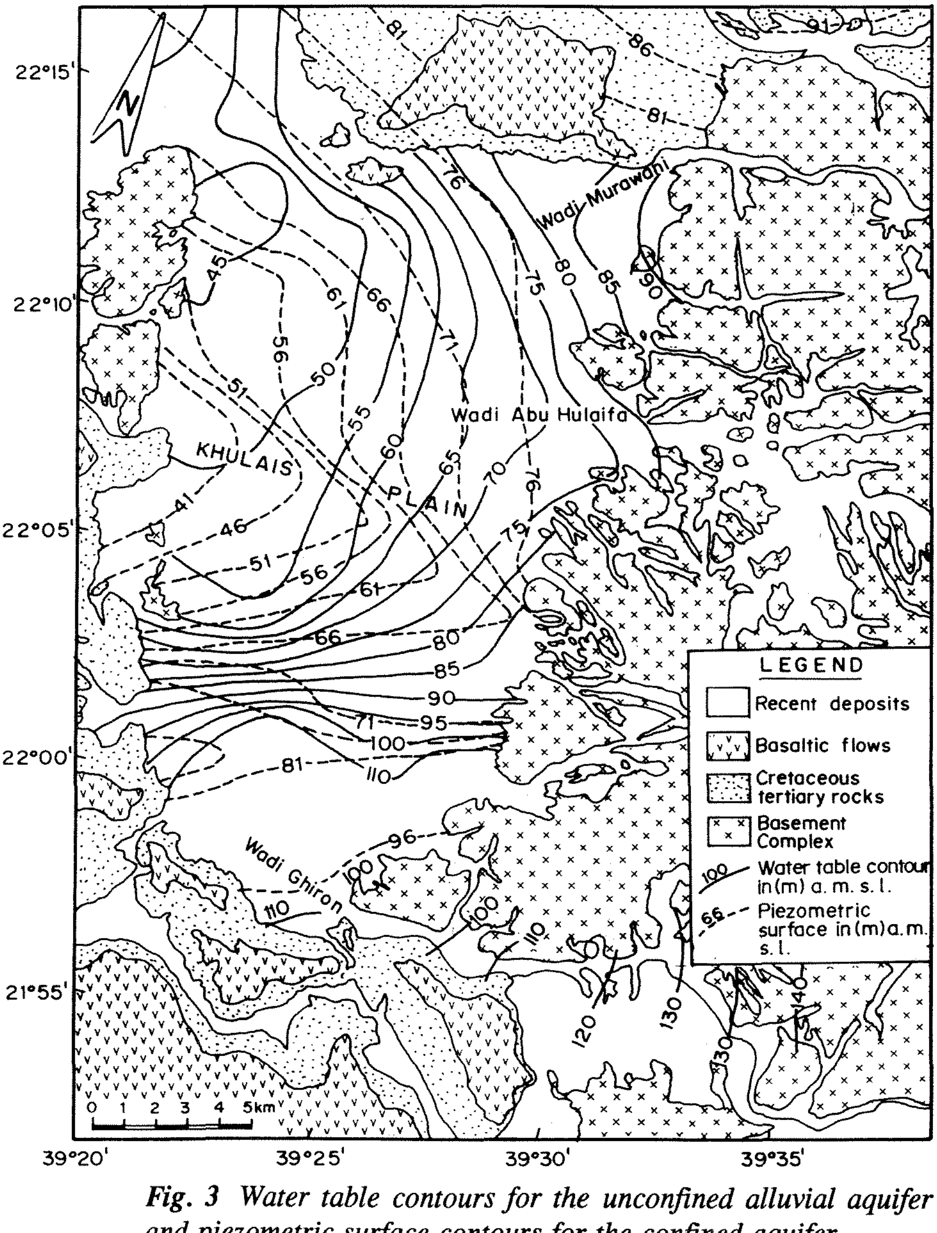

Fig. 3 Water table contours for the unconfined alluvial aquifer and piezometric surface contours for the confined aquifer.

geneous except where there are east-west extending contour lines close to each other in the lower part of the plain. The average hydraulic gradient in each of the three main wadis is in the order of 0.004.

Within the sedimentary succession, groundwater is first struck at depths of about 20-40 m and rises some 1-3 m. Figure 3 shows the horizontal groundwater flow within this water-bearing unit. The general pattern is similar to the shallow groundwater movement but with some local modifications.

Recharge seems to be limited to the north-east and south-west where the basalt flows exist and where sedimentary rocks outcrop. In those sectors the hydraulic gradient is about 0.002. The main feature of Fig. 3 is the appearance of a southeast-northwest contour right in the middle of the Khulais plain. This implies facies change or the existence of a low permeability feature along the aforementioned direction. Such a feature may be indicative of the last barriers of the wadis Murawani and Abu Hulaifa from the north and wadi Ghiran from the south, but it might also be due to a southeast-northwest trending fault. Perhaps this may be the better explanation, because the existence of such a fault disappears in the shallow water level map (Fig. 4).

A close comparative study of Figs 3 and 4 indicates that the shallow water levels are above the deep aquifer levels at the northern side of the southeast-northwest trending feature while at the southern side the opposite situation occurs. Consequently, there is vertical groundwater movement within the Khulais area, both affecting regional water exchanges within the area and causing natural mixing of groundwater quality.

AQUIFER PROPERTIES

Transmissivity and storage coefficient

Several methods were used to analyse pumping test and recovery data. The choice of a certain method for a certain test is based mainly on how far the field conditions and aquifer type are close to the requirements of such a method, though almost all field conditions are far from ideal. The methods used were Theis (1935), Jacob (1946), Boulton (1963), Papadopulos & Cooper (1967) and Sen (1986).

The results of the pumping and recovery tests carried out in the study area to determine the aquifer properties are summarized in Table 1. The transmissivity of the alluvial aquifer varies between 120 and 5800 m^2 day^{-1} and its storage coefficient ranges between 1×10^{-1} and 9×10^{-3}. The water-bearing horizon within the clastic rocks is characterized by a transmissivity of 90-250 m^2 day^{-1} and storage coefficient of 0.32-0.60. Both are thus aquifers of moderate potential.

A transmissivity (T) distribution map was constructed for the shallow alluvial aquifer (Fig. 5). It shows a general nonlinear parabolic trend which extends from the southeast towards the northwest where the maximum values appear. The 500 m^2 day^{-1} transmissivity contour line divides the area into two major sections. The area with T below 500 m^2 day^{-1} has a lower groundwater potential, which may be due to shallow Quaternary deposits or abundant fine material. The area with T above 500 m^2 day^{-1} has a high potential for well drilling, which increases diagonally towards the north-western corner.

Permeability

Permeability (K) measurements were carried out with a constant head permeameter (KARL KOLB apparatus 503-650). The results are shown in Table 2. The alluvial aquifer is characterized by K values between 7 and 1000 m day^{-1}. Exceptionally high values may be due to the disturbed nature of the samples. The water-bearing layer within the sedimentary succession has K vales of 8-

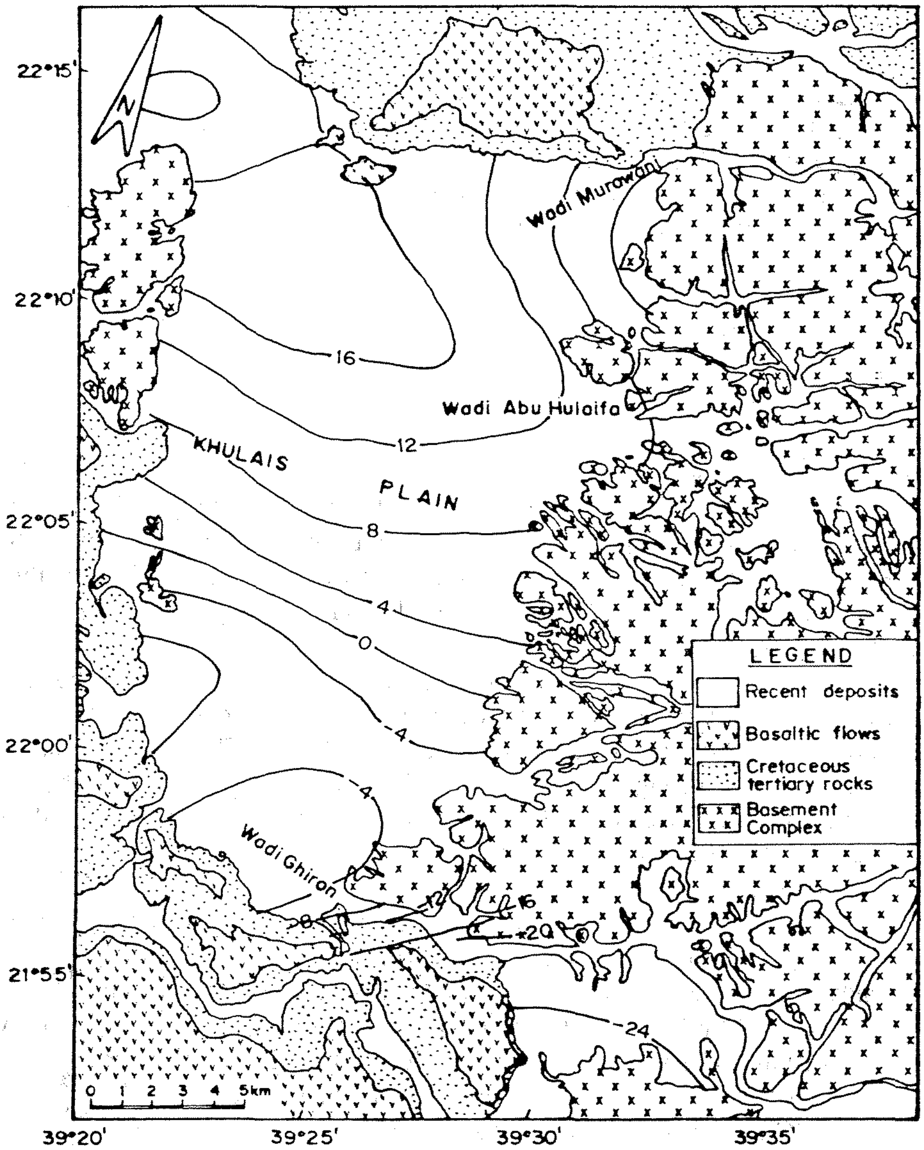

Fig. 4 Comparison of the water table and the piezometric surface (values in m).

***Table 1** Transmissivity (T) and storage coefficient (S) values in the Khulais area*

Well no.	T (m^2 day^{-1})	S
14	120	1.4×10^{-1}
15	185	-
17	190	9.0×10^{-3}
21	266	1.6×10^{-1}
43	245	8.5×10^{-3}
49	438	1.3×10^{-1}
69	132	1.3×10^{-3}
77	325	4.0×10^{-3}
79	730	1.0×10^{-3}
80	2606	1.2×10^{-3}
82	2074	5.8×10^{-3}
83	1307	1.9×10^{-3}
88	5813	2.3×10^{-3}

22 m day^{-1}. Figure 5 shows a K distribution map for the alluvial aquifer. Generally, the permeability increases northward from 80 m day^{-1} to 800 m day^{-1}. A general increase is also noticed downstream in Wadi Murawani while no significant change in K values is noticed in the wadis Ghiran and Abu Hulaifa.

A general view of Fig. 5 gives the impression of a "permeability high" in the north-western corner. From there it decreases in a systematic manner in all directions. This area corresponds with a narrow plain on the geological map (Fig. 1). It is assumed that, prior to the Khulais plain deposition, a subsurface dam effect occurred because of the narrow passage between basement rocks on

***Table 2** Permeability (K), porosity (n) and specific yield (Sy) of samples from the Khulais area*

Well no.	K (m day^{-1})	n (%)	Sy (%)
6	82	31.0	26.0
7	62	31.5	24.2
8	61	26.3	20.3
9	22	28.3	20.2
10	11	29.0	21.0
11	12	27.8	18.0
14	41	29.0	24.0
15	47	31.0	25.0
17	13	35.0	25.8
20	38	29.0	25.0
21	65	36.0	29.8
36	8	25.0	18.3
42	7	29.0	24.0
43	60	32.0	24.0
45	22	30.0	25.0
46	22	27.3	23.0
49	20	29.8	25.8
62	8	23.5	15.5
64	51	25.0	17.0
69	14	--	--
77	58	--	--
79	445	--	--
80	965	--	--
82	1035	--	--
83	360	--	--
84	750	--	--

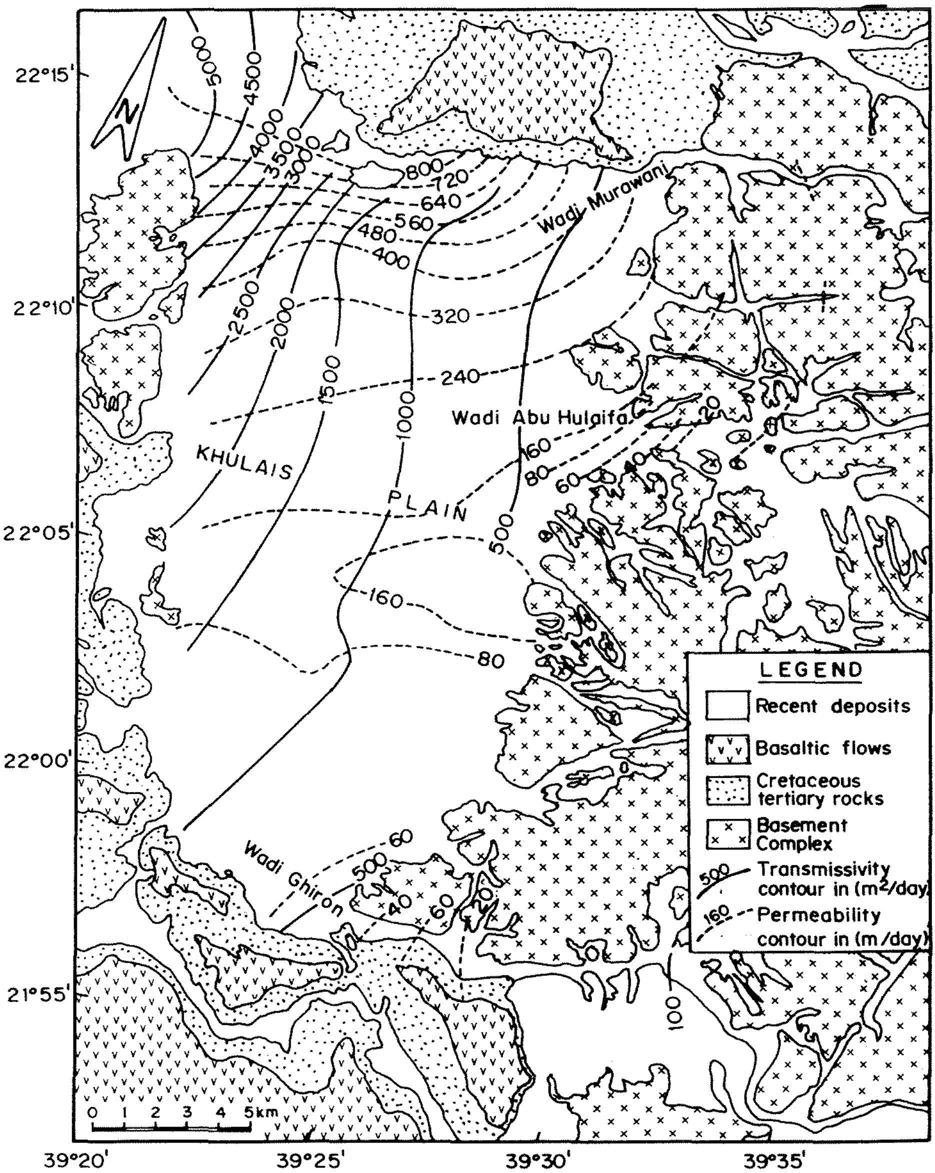

Fig. 5 Transmissivity (m^2 day^{-1}) and permeability (m day^{-1}) distribution in the Khulais area.

the left and Cretaceous-Tertiary rocks on the right. Surface water from everywhere within this catchment washed towards this passage. Comparison of transmissivity and permeability (Fig. 5) indicate that the Quaternary deposit thickness is smaller at the passage than in the Khulais plain itself. This point proves the above-mentioned effect. As a result of such configuration, various depositional periods gave rise to the deposition of fine material within the plain. The local high permeability in the south is due to tributary wadis.

Porosity and specific yield

Porosity and specific yield measurements were carried out on disturbed samples and are therefore likely to give high values. Nonetheless they give the relative distribution and variation of both properties within the study area. It is clear from the porosity map of the alluvial aquifer (Fig. 6) that the central Khulais

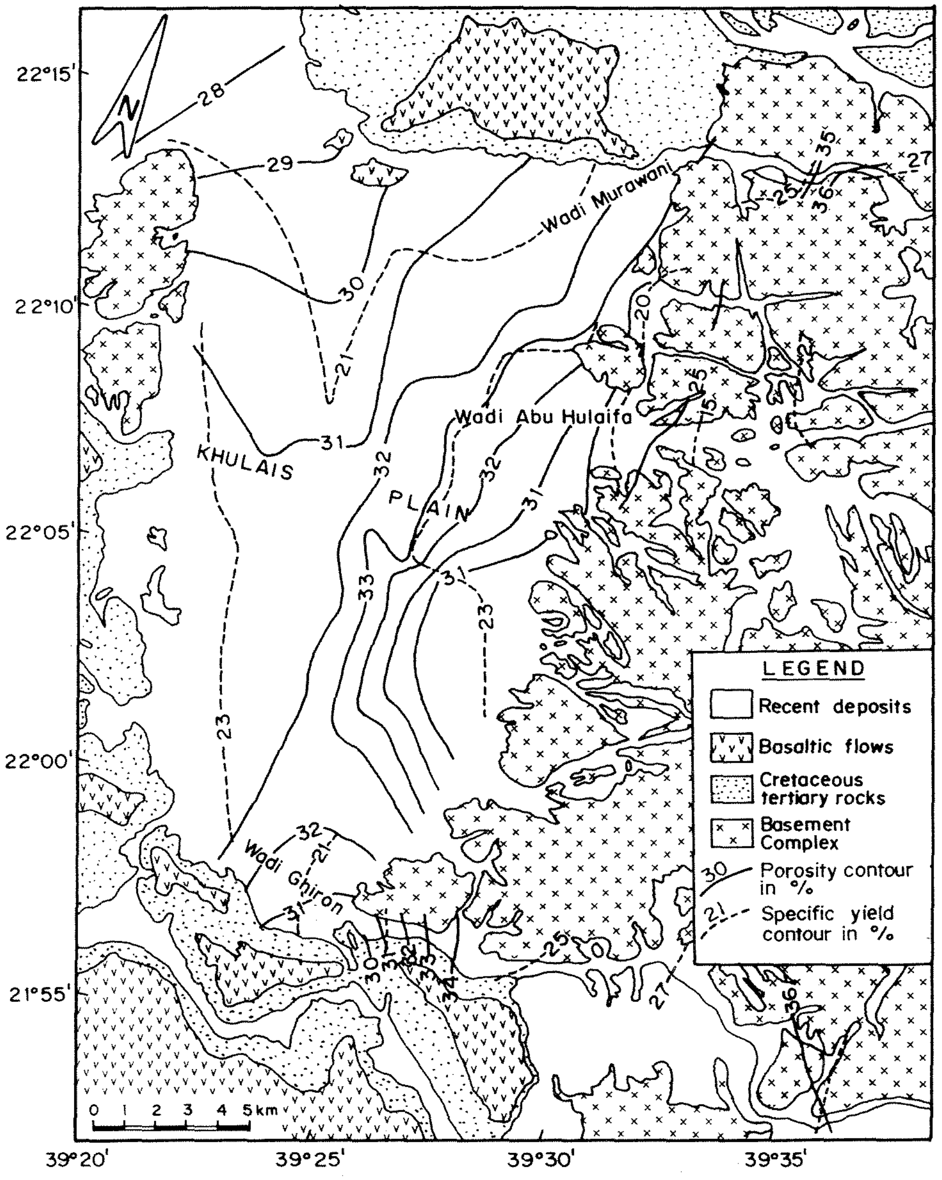

Fig. 6 Porosity (%) and specific yield (%) distribution in the Khulais area.

plain is composed of rather fine clayey and silty materials. Relatively low values in the northwestern corner suggest that such fine material is carried away due to high water velocities; consequently these are the locations where permeabilities are significantly higher than in the surrounding areas.

The specific yield (*Sy*) map (Fig. 6) shows that the distribution is relatively uniform. Comparison of the specific yield and porosity distributions shows that the difference attains its maximum in the central Khulais plain, which implies lower permeability and higher specific retention and thus difficulty for groundwater abstraction.

GROUNDWATER VOLUMES

The volume of groundwater flowing in the direction of the Khulais plain from the three main wadis can be estimated by Darcy's equation as follows:

$$Q = TIL \tag{1}$$

where Q is the quantity of flowing water in m^3 day^{-1}; T is the transmissivity of the aquifer in m^2 day^{-1}; I is the hydraulic gradient; and L is the length of the traversed section.

Q_M, Q_G and Q_A were designated for the quantities coming from the wadis Murawani, Ghiran and Abu Hulaifa respectively.

The estimated volumes are: $Q_M = 1100$ m^3 day^{-1}; $Q_G = 900$ m^3 day^{-1}; and $Q_A = 600$ m^3 day^{-1}; making a total of 2600 m^3 day^{-1} of groundwater flow towards the Khulais plain. Considerable quantities of water infiltrate during flood periods and from direct rainfall. Aforementioned vertical groundwater movement within the plain could cause additional volumes of water to be available for abstraction and for groundwater outflow through the passage in the northwestern corner. Estimation becomes complicated and numerical modelling would be needed for this purpose.

CONCLUSIONS

The Khulais plain has a good potential groundwater resource in both the alluvial aquifer of the wadis system and the clastic members of the Cretaceous-Tertiary sedimentary succession. Detailed hydrogeological investigations helped to understand groundwater occurrence, prevailing hydraulic gradients and directions of movement both in the horizontal and vertical senses. Transmissivity, permeability, porosity and specific yield distribution maps correlate with each other and give a detailed picture of these properties in the Khulais plain.

The results of this study provide information for the numerical modelling of the alluvial aquifer. The identification of individual clastic layers within the sedimentary succession is necessary for the overall planning and management of the groundwater resources. In this respect, exploratory drilling in the Khulais plain is recommended.

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