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Hydrogeology of a part of the Bara basin in Kordofan province of the Sudan

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The main objective of hydrogeological investigation was to meet the expectations regarding the groundwater resources in the Bara Basin. First of all, to demonstrate groundwater quantity and quality, but also to state a possible yield of pilot wells and other pertinent data important for mathematical modelling and estimation of long-term water supply of El Obeid, Bara and villages between these towns.

Cilj hidrogeoloških istraživanja bio je da se potvrde očekivane zalihe podzemnih voda u Bara Bazenu. Prvenstveno se željelo dokazati količinu i kvalitetu podzemnih voda, kao i utvrditi izdašnost pokusnih bunara i prikupiti druge važne podatke za izradu matematičkog modela i ocjenu mogućnost dugoročne vodoopskrbe El Obeida, Bare i sela između ta dva grada.

INTRODUCTION

El Obeid is an important economic centre in Kordofan Province in the Sudan. It is also a well-known road junction in that part of the country. It is estimated that more than 300 000 inhabitants live in El Obeid now.

The city is provided with water by a system of few surface water impoundments in the south of town, which are filled during the rain-seasons. With the growth of the town the water requiremants had grown too, and the water supply system was enlarged by new accumulations at greater distances from the town. Such a system of water supply could not, however, fully satisfy the water demand. The enlargement of the town and the low rainfall in 1966, 1973 and 1984 have seriously jeopardized the population.

This was the reason why the »Geotehnika«, having wide experiences in well performance in the Sudan, began to work out the feasibility study of groundwater resources in 1985.

During the work at the study, data on 275 boreholes and 42 hand dug wells were analyzed, as well as the results of chemical analyses of water from 95 different locations from the broader area of El Obeid. Besides, satellite — and aero-records of the explored region were used, and all previous studies and projects were consulted.

Water supply of El Obeid by exploitation of groundwater was proved realizable. The most appropriate location for future well was proposed on the base of relevant data as well as according to the preliminary data of mathematical model.

Feasibility Study was the base of the further hydrogeological explorations in 1987 and 1988.

The explorations were concentrated to the area of El Obeid and Bara and the region between these two urbanized centres (fig. 1.). However, drilling operations and pertinent hydrogeological explorations were carried out in the area of the future Well Field, to the south-east of Bara.

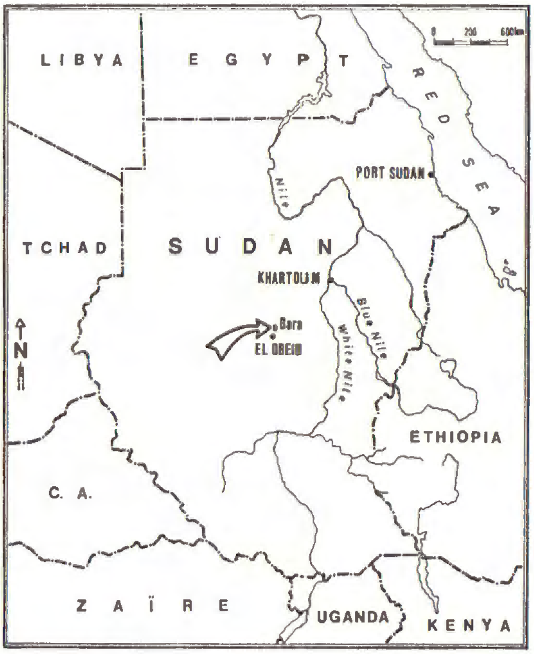

Fig. 1: SITUATION MAP
Sl. 1: SITUACIJSKA KARTA

Three of the nine planned observation boreholes were located in Guneina, Umm Khadmul and Mugheisiba, respectively. Further exploration drilling was based on the data from these initial boreholes and it was decided to locate pilot wells in Mugheisiba, Sider and Regeba. Each pilot well was supplied with at least two observation Wells. Hand-dug wells were used also for water level observations during pumping tests.

Lithological determination was based on samples of core and collected during drilling operations. On the basis of lithology and geophysical logging, it was decided to carry out screen installation for observation wells and pilot wells.

Observation wells yield was estimated by air-lift, while each pilot well was properly tested by a submersible pump. The continuous pumping and step test methods were applied.

Additional data on hydraulical relations between water bearing strata were given by the Borehole Fluid Resistivity (BFR) logging in each borehole, screened in a shallow and deep water bearing section.

The results of hydrogeological explorations are presented in the following part of this paper.

GEOGRAPHICAL AND CLIMATOLOGICAL CHARACTERISTICS

The area under exploration stretches between 13° 00′ to 13° 45′ N and 30° 00′ to 30° 30′ E in the central North Kordofan region in the Sudan. The area is part of the arid sub-Saharan region which has been struck by heavy droughts and famine in the last few years.

Poor living conditions in the villages and political unrest have caused an increased migration into large towns like El Obeid. Thus, the number of inhabitants shows a rapid increase, and so does the demand for drinking water. The population of El Obeid is now estimated at 320.000, while three years ago it amounted to 200.000 inhabitants. Such quick growth of the town has to be accompanied by development of infrastructure, primarily water supply.

Climatic conditions in North Kordofan have a crucial effect on the way of life and survival of the population. The inhabitants are mainly engaged in agriculture and stock-raising, the two branches of economy that are most gravely struck by droughts.

The rain season usually lasts from June to September. Rains are in the form of showers, of variable intensity and duration. The precipitation decreases towards the north, so that El Obeid gets an average of about 388 mm/year and Bara about 312 mm/year, according to the 30 year rainfall means. The water divide directs the flows towards the south and north from the El Obeid area. Precipitation south of the town flows through numerous wadis towards the impoundments of El Ain and Baggara, and further on to Khor Abu Habl. Surface waters collected in this way serve for the existing water supply system of El Obeid. Unfortunately, the expressly seasonal character of rainfall does not provide a reliable water supply source throughout the year. Considerable amounts of water lost from impoundments through evaporation and seepage.

All watercourses north of El Obeid, after flowing for a short stretch on the surface of the basement, are quickly lost in the dunes by infiltration into the water-bearing Umm Ruwaba formation. In this way the water-bearing strata in the Bara Basin are constantly recharged despite the seasonal character of rainfall.

In the dry season, rain is extremely rare and appears only dropwise. Daily temperatures are very high, varing between 30 and 40 °C, while 46 °C has also been recorded.

It is understandable that, in such a hostile region, with constant spreading of the desert, the water has vital importance.

GEOLOGY AND HYDROGEOLOGY OF THE BARA BASIN

Bara basin is a large tectonic depression filled with sediments of Umm Ruwaba series. The basin is surrounded by magmatic and metamorphic rocks of Basement Complex, as well as the older sediments of Nawa and Nubian formations (fig. 2.).

The west boundary of the basin is approximately defined by the north-south line running from 14° 15′ of north latitude accross Umm Zuriq to Umm Oozein. The south boundary goes from Umm Oozein to the east towards Umm Sot, from where it turns towards the southeast. The north boundary runs from. J. El Farddi in the west accross J. El Hamra and J. Bir Serar to J. Maghanus in the east, and then it turns towards southeast and gets approximately parallel with the south boundary. In the east, Bara basin is open towards the White Nile. The Bara basin area covers approximately 6000 sq. km.

The ground surface is slightly wavy and generally inclined from south-southwest towards north—northeast. It is covered with sands and sand dunes of surface complex, while the basin underground structure depends upon the topography of Basement Complex and Umm Ruwaba series sedimentation conditions.

The depth to Basement Complex has been determined on around 70 boreholes at the places where the rocks of Basement Complex are nearer to the surface. Boreholes located towards the basin central parts have not reached the rocks of Basement Complex. The topography of Basement Complex in these parts of the basin has been defined exclusively on the basis of gravity investigation data (Ali and Whitely, 1981).

The Basement Complex rock surface forms an elongated depression streaching from the northwest towards the southeast. At the Bara basin periphery, the Basement Complex rocks occur on the ground surface. Going towards the basin central parts, Basement Complex surface is sinking. Sinking in the circumferential parts is relatively slow. The

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Fig. 2. Legend: 1 — surface deposits; 2 — alluvium, wadi fills, terraces, delta and swamp deposits; 3 — Umm Ruwaba formation; unconsolidated sand with some gravels, clays and shales; 4 — Nubian formation; continental clastic sediments (sandstones, siltstones, mudstones and conglomerates); 5 — basement complex; undiffirentiated schist group; 6 — undifferentiated basement complex; 7 — batholitic granites grey granites and pegmatites; 8 — sand dunes and sand shects; 9 — fault or shear zone; 10 — infered fault and fracture; 11 — Certain geological boundary; 12 — inferred geological boundary; 13 — unconformed geological boundary; 14 — Geological section; 15 — study area.

Sl. 2. Legenda: 1 — površinske naslage; 2 — aluvij, vadi nanos, terasne, deltne i močvarne taložine; 3 — Umm Ruwaba formacije; nekonsolidirani pijesci s nešto šljunaka, praha i gline; 4 — Nubijska formacija; kontinentalne klastične naslage (pješčenjaci, siltiti, glinci i konglomerati); 5 — nedefinirano temeljno gorje iz skupine škriljavaca; 6 — nedefinirano temeljno gorje; 7 — granitni batoliti, sivi graniti i peagmatiti; 8 — pješčane naslage i dine; 9 — rasjedna zona; 10 — pretpostavljeni rasjed; 11 — utvrđena normalna granica; 12 — pretpostavljena granica; 13 — erozijska ili tektonsko-erozijska granica; 14 — trasa geološkog profila; 15 — područje istraživanja.

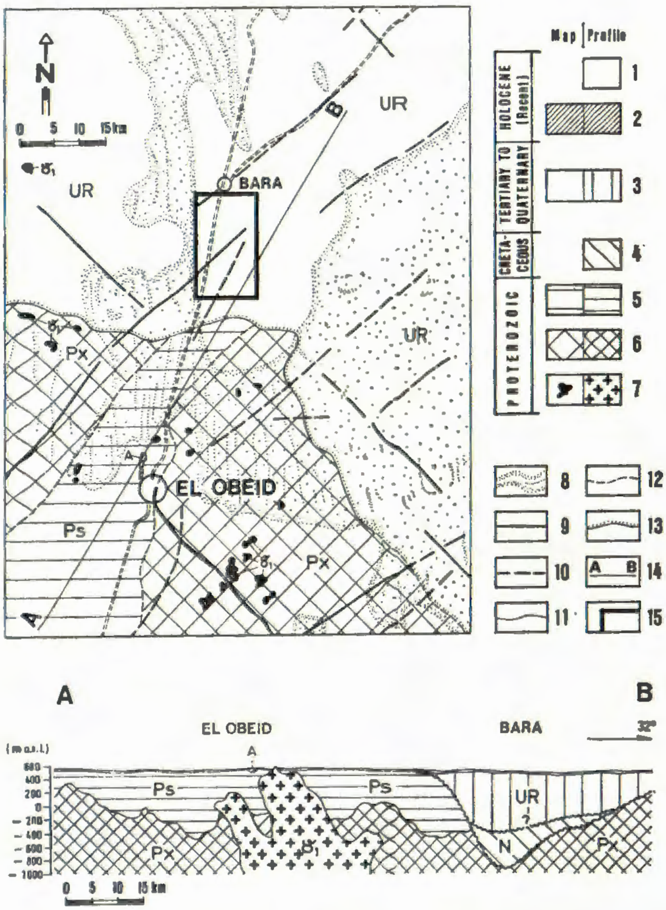

Fig. 2: GEOLOGICAL MAP OF A PART OF BARA BASIN AND GEOLOGICAL SECTION A-B

Sl. 2: GEOLOŠKA KARTA DIJELA BARA BAZENA I GEOLOŠKI PROFIL A-B

inclinations from 0 to —200 metres from the northeast, north, west and southwest towards the basin centre are around 0.5 per cent. The basin deepens more abruptly towards the basin centre on the south and southwest sides where the surface of Basement Complex from 0 to —200 metres has the inclination ranging between 1.5 and 3 per cent. After the depth of 200 metres, the Basement Complex depth increases more abruptly, so that the surface inclines 4 per cent in the northern part of the basin to arround 12 per cent in the south and southeast parts of the basin. The greatest depth occurs in the Bara area and, according to the geophysical data, it is around 1400 metres from the ground surface.

Some twenty kilometres to the southeast from Bara, a shelf has been recorded approximately 600 metres below the ground surface. Going further on towards the southeast, the depth of depression increases again to aproximately 1100 metres. In this part, the depression is elongated with a steeper inclination in the northwest part, i. e. in the zone of the previously mentioned shelf, with steep inclinations on the sides and relatively mild inclination towards the southeast.

Taking into consideration the tectonics and lithological structure of Basement Complex, processes of weathering have been undoubtedly going on with various intensities in particular parts of formation. On the other hand, this has caused the differential erosion, so that the topography of Basement Complex is probably more complicated. Nevertheless, we believe that this knowledge i. e. data on the Basement Complex topography are enough to serve as a basis for defining the volume of sediments and basic elements of the groundwater flow in the Bara basin.

GEOLOGICAL FORMATIONS AS WATER BEARING HORIZONS

The rock formations over the Kordofan Province belong to the basement complex of Precambrian age, the Nawa Series of late Paleozoic age, the Nubian Series of Mesozoic age, the Umm Ruwaba Series of Pliocene to Pleistocene age and surficial deposits of Quaternary age (Whiteman, 1971).

The Basement Complex consists mostly of compact primary impervious rocks. Groundwater occurs only in fractured and fissured parts of rocks or in the zones of intensive weathering. In such, spatially very limited, regions, groundwater is exploited through shallow, dug out wells and only in places through deeper, drilled wells. Well yields are low, and the quality of water unreliable.

The Nawa formation mainly consists of compact rocks, too. Where rocks are fractured, fissured, and weathered, they may contain groundwater. From the hydrogeological point of view they are an integral part of Basement Complex. Due to its small extent the Nawa formation is not very important for the region.

The Nubian formation contains considerable amounts of ground water in conglomerates and sandstones, while the shales are impervious interbeds, unless a secondary porosity developed. Exploitable quantities vary from place to place depending on the thickness of formation and the proportion of permeable members.

The Umm Ruwaba formation consists of porous, unconsolidated or poorly consolidated clastic sediments of variable permeability. Sands and gravely sands of various grain sizes represent aquifers separated by poorly permeable and relatively impermeable beds of silty material and clays. Owing to its thickness and extent, the Umm Ruwaba formation represents the most important reservoir of groundwater in the studied area (Mayer and Dulić, 1986.).

Pleistocene and recent unconsolidated surface sediments locally contain groundwater as well. The prospects of water accumulation and its yield depend on the permeability and thickness of the sediments, which vary considerably from site to site. If the surface deposits lie on impervious rocks of the Basement Complex, or on poorly permeable to impervious parts of younger formations, they are usually saturated with water during the rainy seasons. Later on, water is lost by evapotranspiration or is percolated into the deeper water bearing horizons. Thus, the surface deposits are mainly waterless at the time of the dry season. Consequently, groundwater extraction is restricted by space, as well as by rainfall and its seasonal distribution.

In any case, within the Umm Ruwaba series there is a considerable volume of primarily porous sediments which are either partly or completely saturated with groundwater. Consequently, the Umm Ruwaba series represents a potentially most important groundwater storage in the area dealt with in this Study, and, therefore, it will be described in the section on the Bara basin groundwaters.

LITHOSTRATIGRAPHIC CHARACTERISTICS OF THE WATER BEARING COMPLEX

In the area where investigations through the Pilot Study of El Obeid Water Supply Project were performed to a depth of 300 metres, three quite distinct lithological units, were established (see profiles A—B, C—D, figs. 3., 4. and 5.). The first lithological medium consists mainly of sands of quaternary age. They are about 45 metres thick. They are the thickest at the northern end of the investigated area (borehole OW-9), reaching 40 metres, and the thinnest (36 metres) in the south-east (borehole OW-2).

They are followed by older sediments (tertiary-quarternary), formed of sand and clay in various proportions. The examined core samples indicate that pure sand or pure clay are rare, and that poorly graded clayey sands, yellow and grey, or sandy clay with pebbles and calcite nodules prevail. Strata (or lenses) of pure clay, about 6 metres thick, were established only in boreholes OW-1 and OW-8. The bottom plane of this sandy-clayey lithological unit lies at about 150 metres below the ground surface. It is the deepest at the site of borehole OW-9, at the northern end of the area, being positioned at 173 m relative depth, and the shallowest at borehole OW-5, in the northeastern part of the area, where it was drilled at the depth of 136 metres. These data, allow a comparison of the thiknesses of this lithological units. They range from 90 to 132 metres, while the extreme values were determined at the

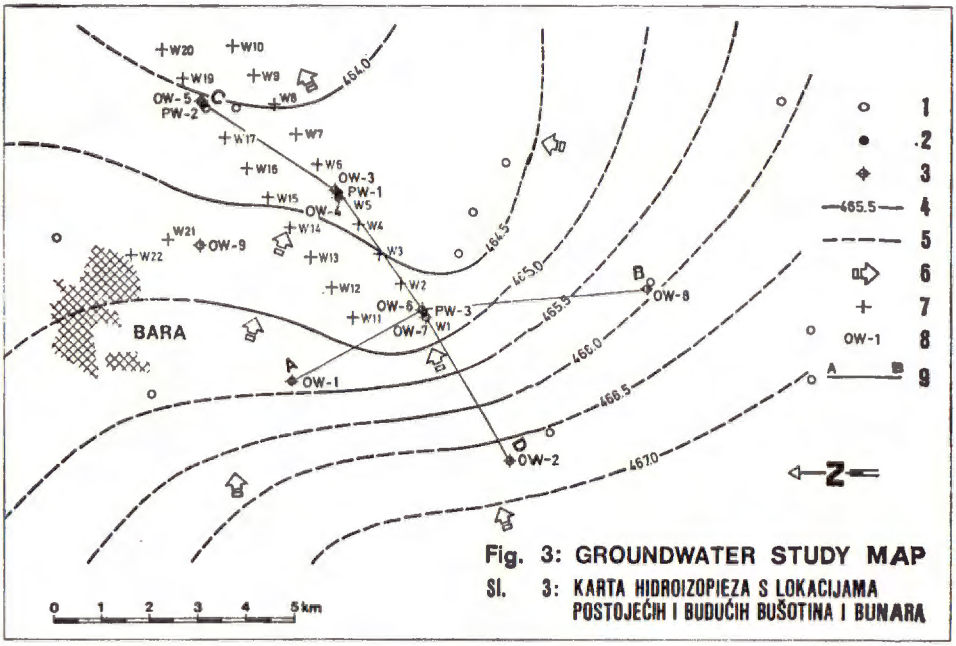

Fig. 3: GROUNDWATER STUDY MAP

Sl. 3: KARTA HIDROIZOPIEZA S LOKACIJAMA POSTOJEĆIH I BUDUĆIH BUŠOTINA I BUNARA

Fig. 3. Legend: 1 — borehole; 2 — pilot well; 3 — observation well; 4 — main aquifer water level contours; 5 — supposed water level contour; 6 — ground water flow direction; 7 — mathematical modelling — proposed wel sites; 8 — well number; 9 — profile A—B.

Sl. 3. Legenda: 1 — bušotina; 2 — pokusni bunar; 3 — opažačka bušotina; 4 — hidroizopieza glavnog vodonosnika; 5 — pretpostavljena hidropieza glavnog vodonosnika; 6 — smjer toka podzemne vode; 7 — lokacije bunara određene matematičkim modeliranjem; 8 — broj bušotine; 9 — profil A—B

mentioned sites of boreholes OW-9 (thickness 132 metres) and OW-5 (thickness 90 metres). The average thickness is about 110 metres.

The third lithological unit is characterized by distinct heterogeneity, maniftested by a clear »indentation« of the gamma-ray logging curve, going from its upper limit towards the end of the boreholes. There is frequent interchange of strata and interbeds of poorly bound sandstones, sands, silty sands, clayey sands and sandy clays, which often contain gravel pebbles. The thickness of particular strata varies from some tens of centimetres up to about 10 metres. Occurrences of interbedding and lateral changes in grain-size distribution and/or type of sediment are frequent. In this respect, boreholes OW-2 (profile A—B) (fig. 4.) and OW-8 (profile C—D) (fig. 5.) are particularly marked, so they can be considered untypical. Namely, all clayey intervals established in borehole OW-7 either interbed or laterally and gradually transit into a sandy sediment, following the direction towards borehole OW-2.

A similar situation occurs at the site of borehole OW-8. Here, the first two and the last stratum of clay can be well correlated with identical strata in borehole OW-7, while the remaining four interbeds, laterally towards borehole OW-8, get increasingly sandy.

Because of the described lateral changes, the number of relatively pure clay strata varies considerably, depending on the site, ranging from one in borehole OW-2 to twelve in borehole OW-6. It mainly varies between five and eight. Between these »pure« clays, predominantly sandy materials are found, taking up over 50 % of the total thickness of this lithological unit.

As to the grain-size distribution, the sandy materials are relatively uniform. They contain about 20 % to 30 % of fine gravel particles, 65 % to 75 % of sand and about 5 % of silt and clay particles. An exception is the material obtained from borehole OW-9, whose content of silty-clayey particles is over 12 %. The basic granulometric parametres are shown in the Table.

Table 1. Granulometric data of sandy layers

Tablica 1. Granulometrijske karakteristike pješčanih slojeva

Borehole Bušotina	Depth Dubina m	Median Md Median mm	First quartile Q_1 Prva kvartila mm	Third quadrile Q_3 Treća kvartila mm	Sort. Coef. S_0 Koef. sortiranosti	Coef. of asymm. S_k Koef. asimetrije
OW-2	264	1,1	0,38	2,8	2,71	2,2
	267	1,2	0,38	2,8	2,71	1,68
OW-3	157	0,75	0,35	2,3	5,56	3,48
	183	0,70	0,34	1,6	2,17	2,57
	230	0,55	0,30	0,75	1,58	1,50
	260	0,75	0,36	1,80	2,23	2,57
OW-5	209	1,40	0,46	3,00	2,55	1,29
	243	0,60	0,28	1,20	2,07	2,55
	275	1,70	0,80	3,20	2,00	0,83
	278	0,44	0,28	0,70	1,58	2,21
OW-7	201	0,80	0,40	1,8	2,12	2,18
	213	0,75	0,36	1,6	2,11	2,21
OW-9	260	0,70	0,19	2,6	3,69	4,92

From the data presented in the table 1 it can be seen that the grain-size distribution coefficients range between 1.58 and 3.69 and are predominantly greater than 2, which means that these are very poorly graded materials. As the coefficient of asymmetry is in all cases, except one, greater than one, grain-size distribution curves are asymmetrical towards the side of grains finer than the median value, i. e. grains finer than the median predominanting in samples. On the basis of the data from literature (Terzaghi and Peck, 1948), it can be estimated, to a great degree of certainty, that the porosity of the material having characteristics given in the above table, ranges between 30 and 40 %.

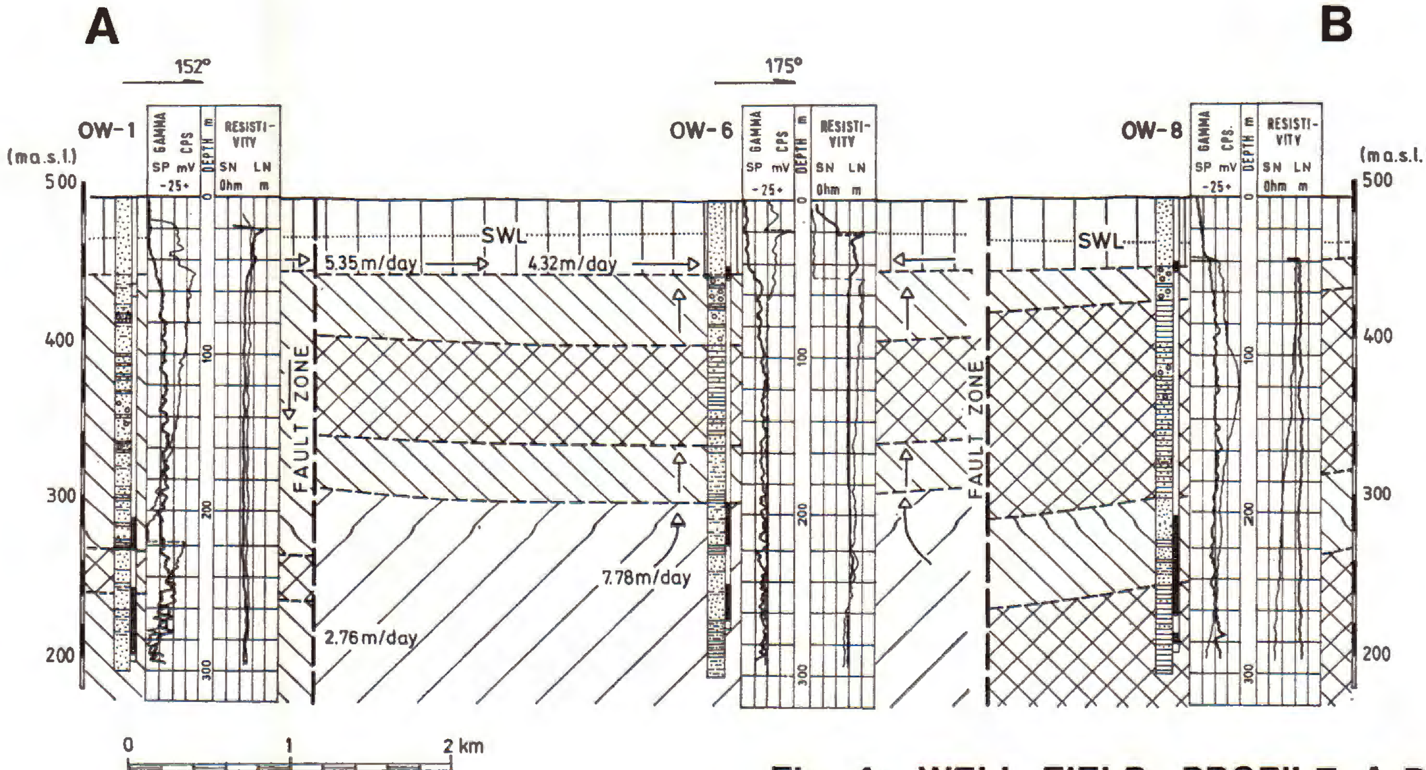

Fig. 4: WELL FIELD, PROFILE A·B

Sl. 4: PROFIL A·B BUNARSKOG POLJA

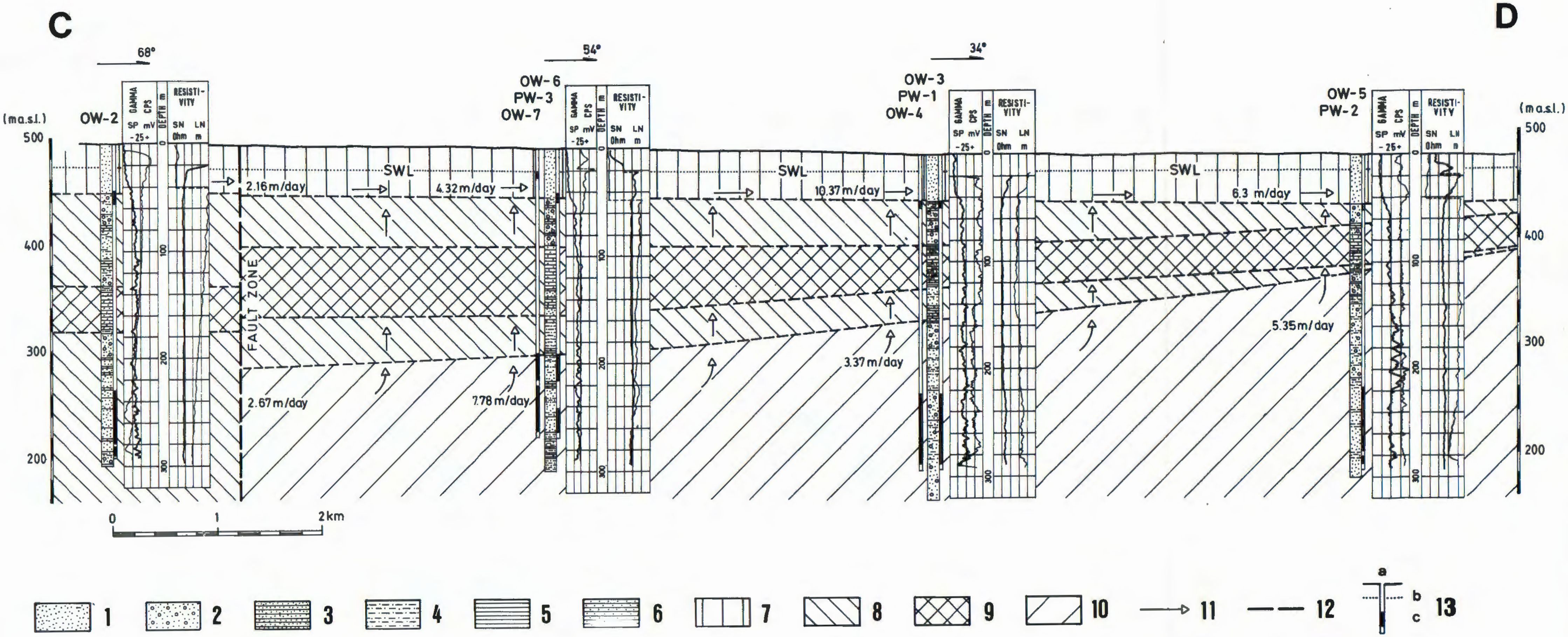

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Fig. 4. and 5. — Legend: 1 — sand; 2 — gravely sand; 3 — silty sandy clay; 4 — clayey sand; 5 — clay; 6 — sandy clay; 7 — upper aquifer; 8 — semipermeable layers; 9 — aquiclude; 10 — main aquifer; 11 — direction of water flow; 12 — inferred fault; 13 — a) borehole, b) Static water level, c) screen section.

Sl. 4. i 5. — Legenda: 1 — pijesak; 2 — šljunkoviti pijesak; 3 — prašinasto-pjeskovita glina; 4 — zaglinjeni pijesak; 5 — glina; 6 — pjeskovita glina; 7 — gornji vodonosnik; 8 — polupropusne naslage; 9 — nepropusne naslage; 10 — glavni vodonosnik; 11 — smjer toka podzemne vode; 12 — pretpostavljeni rasjed; — 13 a) bušotina, b) statički NPV, c) bunarski filter.

Fig. 5: WELL FIELD, PROFILE C·D

Sl. 5: PROFIL C·D BUNARSKOG POLJA

HYDROGEOLOGICAL FUNCTION OF PARTICULAR LITHOLOGICAL MEMBERS

Lithological members described in the previous chapter have different hydrological minings, although all of them are, to a certain extent, saturated with groundwater.

The top lithological unit, composed of quarternary sands is a water-table aquifer. It is saturated with water at a depth below 15 to 20 metres below the ground surface. It is recharged by precipitation, so that the ground water level varies depending on the season. Water is exploited by means of hand-dug wells.

The second lithological unit is also saturated with water. As fine-grained clayey-silty sediments prevail in this unit, the water is bound, mostly by physical forces, in the interparticle space. Therefore it can be said that most of these sediments are poorly permeable. The thickness of this lithological unit being over 100 metres, it serves as an insulator between the upper aquifer and the third lithological unit.

The third lithological unit was drilled through for approximately 100 metres. As previously described, it consists of alternatively more and less permeable materials. Due to a relatively lesser thickness of less permeable interbeds and lateral transitions of poorly permeable strata into more permeable strata and vice versa, the whole complex of sediments within the third lithological medium can be taken as a uniform aquifer. According to the satellite photos, this aquifer probably crops out on the surface to the south-west and south of the investigated area, where it is recharged by precipitation water and surface waters from the wadis in the south.

To the north-east the aquifer dips and acquires sub-artesian and artesian characteristics. In the area foreseen for the future well field there is no hydraulic connection between the main water bearing horizon and the first aquifer with the water-table. The fact that the groundwater level did not drop during the ten-days pumping in Mugheisiba strengths of this hypothesis. Although wells and boreholes were drilled to approximately 300 metres below the ground surface, they did not reach a well-defined bottom of the aquifer, so that, a lithologically and hydrogeologically similar situation continues at a certain depth. However, it can be expected that the proportion of poorly permeable materials in the down-ward direction and that the degree of consolidation of sands and sandstones grows, so that the hydrological characteristics gradually deteriorate. The data from wells and boreholes within the wider area confirm that there is a »third« aquifer at a certain depth, where the water is under a considerably lesser pressure, so that its hydraulic connection with the main aquifer can be neglected.

HYDROGEOLOGICAL PARAMETERS OF THE AQUIFER

Hydrogeological parameters are defined by graphoanalytic methods of interpretation of the test pumping and measuring of the ground water recovery after development of observation boreholes. As a starting point were used hypotheses that the water bearing horizon is apparently boundlessly spacious, homogeneous and isotropic, while being penetrated by test wells along its whole thickness. The first hypothesis is true, because the aquifer is certainly more spacious than the area effected by test pumping.

However, as already described, the aquifer is neither homogeneous nor isotropic. But, as permeable parts certainly have horizontal as well as vertical hydraulic connections, »macrohomogeneity« and »macroisotropy« exist, while the calculated values of hydrogeological parametres represent an average value for the aquifer as a whole. It is also maintained that the aquifer was not drilled through down to the bottom stratum, but, since during pumping the flow mainly takes place through horizontal permeable strata affected by the well screen the inflow of water from permeable parts under the well bottom can be disregarded, so it can be considered that the condition of total aquifer penetration is also fulfilled.

Table 2. Hydrogeological parameters of the aquifer
Tablica 2. Hidrogeološki parametri vodonosnika

Well No Bušotina	Continous pump Test — kontinuirano pokusno crpljenje					Airlifting Čišćenje zrakom
	Pumping — Crpljenje				Recovery Vraćanje nivoa	Recovery Vraćanje nivoa
	Theis		Jacob			
	$T (m^2/d)$	S	$T (m^2/d)$	S	$T (m^2/d)$	$T (m^2/d)$
OW-1	—	—	—	—	—	133
OW-2	—	—	—	—	—	10
OW-3*	517	$5,6\times10^{-4}$	650	$4,3\times10^{-4}$	620	265
OW-3**	614	$5,1\times10^{-4}$	718	$4,2\times10^{-4}$	806	—
OW-4[1]	583	$1,6\times10^{-4}$	594	$1,7\times10^{-4}$	533	533
OW-4**	409	$3,6\times10^{-4}$	507	$2,7\times10^{-4}$	617	—
PW-1*	—	—	520	—	472	—
PW-1**	—	—	476	—	549	—
OW-5	373	$5,8\times10^{-4}$	278	$5,9\times10^{-4}$	297	16
PW-2	—	—	469	—	427	—
OW-6	272	$1,4\times10^{-4}$	288	$1,8\times10^{-4}$	260	166
OW-7	238	$1,6\times10^{-4}$	269	$6,0\times10^{-4}$	202	—
OW-8	—	—	—	—	—	—
OW-9						329

Note: * = 3 days test — trodnevno crpljenje
Opaska: ** = 10 days test — desetdnevno crpljenje

The pumping test curves show that the data obtained correspond to the theoretical curve for a confined aquifer and the non-steady state of flow. Therefore, the Theis curve method and the Jacob straight line method were used in the interpretation of test pumping (Theis, 1935; Cooper and Jacob, 1946).

The results of estimates are shown in the Table 2.

The mean coefficient of transmissivity amounts to 406 m^2/day. However, if values obtained from the data on the water level recovery after cleaning piezometers by airlifting are excluded as unreliable due to the monitoring technique, then the average value of permeability increases to 465 m^2/day. The mean value of the storage coefficient is 3.7×10^{-4}.

GROUNDWATER DYNAMICS

There are relatively few data on the movement of groundwater in the area under exploration, so they cannot serve as a basis for any far-reaching conclusions. Monitoring of the groundwater level changes in piezometers installed into the shallow and the deep aquifer, from January to May 1988, showed that water level oscillations in the shallow aquifer, depending on the site, vary from 1.19 m in borehole OW-3 to only 0.1 m in borehole OW-1. However, they mostly vary from 0.30 to 0.50 metres.

Results of the groundwater level monitoring in the second, deeper aquifer are even more uniform (fig. 3.). Groundwater level oscillations range between 0.30 m in borehole OW-5 to only 0.03 m in borehole OW-7. In most cases, the differences between the minimum and maximum registered water level on particular piezometers vary between 0.10 and 0.15 metres. An exception is borehole OW-8, where this difference is as much as 2.30 metres. But, as data on absolute groundwater levels from this borehole illogically deviate from all other monitorings by several metres, we think that they should be excluded from consideration for the time being.

If absolute water-table levels from the shallow aquifer are compared with piezometric levels from the deeper aquifer, it can be seen that water-table levels in the shallower aquifer are, in most boreholes, by 0.2 to 2.3 m higher than piezometric levels in the deeper aquifer.

Borehole OW-1 is an exception, where the groundwater piezometric level from the second aquifer is by 0.90 metres higher than the water-table level in the shallow aquifer.

These differences in levels, point to the conclusion that there is no hydraulic connection between the shallow and the deeper aquifers, or that it is very limited in natural conditions.

Conclusions on the direction and speed of the groundwater flow in the deeper aquifer can be based on the piezometric conture line map, which was drawn on the basis of ground water monitoring data in boreholes of 25 May 1988. It can be seen that the prevalent direction of groundwater flow is from the west towards the east, and/or from the south-west towards the north-east. In natural conditions, hydraulic gradients range from 0.0002 to 0.0004. Supposing that seepage coefficients are about 4 m/day and that the porosity is about 30 %, in natural conditions groundwater flows at a speed of no more than 0.0026 to 0.0053 m/day or 0.95 to 1.90 m/year.

In short, groundwater dynamics depends on regional tectonics, the slope of water-bearing layers and the way of recharge.

It is reasonable to suppose that both the shallow water table aquifer and the deeper subartesian aquifer are recharged by seasonal rain. As the ground slopes from El Obeid to Bara, the numerous water-courses direct all precipitation water, by surface and subsurface ways, towards the Bara Basin. It is certain that all the rain that falls north of the »water divide« effects, to a greater or smaller degree, the groundwater balance in the Bara Basin.

Rechanrging of the upper open water table aquifer is mainly restricted to the area covered by the water-bearing medium. However, the main aquifer is recharged from a much wider area in the part where it emerges to the surface, which can be seen from the geological map and geological profile. The determined directions of groundwater flow point to the conclusion that the main aquifer is largely recharged from the El Kheiran region to the north of the future well field.

The explorations performed justify the assumption that the recharge of the main aquifer can cover the pumped quantities of water. The way of recharge and the natural geological structure of this area and of the Bara Basin have created subertesian and artesian conditions in the main aquifer.

WATER QUALITY

Water samples (14 in all) were collected and referred to chemical analysis in the period of field explorations. One sample was taken from each of the seven observation boreholes (OW-1, OW-2, OW-3, OW-4, OW-5, OW-8 and OW-9), as well as from well PW-3, three samples were taken from well PW-1 and two samples from PW-2. Analyses were made in two institutions:Khartoum Province Water Corporation, Central Laboratory, Mogren Waterworks and in El Obeid Regional Laboratory. The components determined in these two institutions were not the same and different methods of analysis were used, so the results cannot be unambiguously compared. Yet, they provide a satisfactory insight in the groundwater quality over the investigated area. Components which were determined and the results obtained are shown in the Table 3.

If the results obtained are compared with the maximal concentrations of particular components allowed by the World Health Organisation (WHO) criteria, it can be seen that only in three cases the water does not satisfy the set standards. Thus, the water from borehole OW-5 has a higher calcium concentration (110 mg/l, while 100 mg/l is permitted), while waters from boreholes OW-2 and OW-8 show higher contents of iron. While there is no other logical explanation for the calcium in borehole OW-5, than a methodological error during determination, because two water samples from PW-2, which is positioned at practically the same site, had only 32 and 36 mg/l of calcium, respectively, the iron in observation boreholes is most likely a consequence of a relatively long contact between the water and pipes in the borehole, as well as insufficient pumping before sample taking.

Anyway, it can be said that the groundwater in the investigated area is generally of exceptionally good quality and that no additional processing will be required during exploitation, apart from preventive chlorination or some other way of desinfection.

MATHEMATICAL MODELLING

As the exporation results show that there is an aquifer of relatively good hydrogeological characteristics within the investigated area, and that groundwater is of exceptionally good quality, and the test pumping established a quantity between 20 and 25 l/s of water per well, development of a mathematical model was undertaken to simulate the situation of large-scale, long-term exploitation. For mathematical simulation, an analytic mathematical model was used as a means of calculating drawdowns at given points, with defined aquifer characteristics and pre-supposed conditions of exploitation. It was taken into account that this is a confined aquifer of unlimited stretching, with the coefficient of transmissivity of $T = 400$ m²/day and the storage coefficient of $S = 6 \times 10^{-4}$. As it can be seen, a somewhat higher value of the storage coefficient than that calculated from the test pumping results was taken (that value was about 3.7×10^{-4}). This was done because a part of the storage of the bordering strata will certainly get activated in the course of enclosed pumping, so that a value nearer to the realistic one was adopted.

SIMULATION OF GROUNDWATER PUMPING

The mathematical model was prepared for two dispositions of wells and for two quantities of pumping. In one case twenty wells were arranged in a line at intervals of 650 metres, while 2 wells are positioned to the southeast of Bara, about 5 km far from the row of wells.

In the second case, twenty wells were arranged in two rows of ten wells each. The distance between wells in one row is 1000 metres and that between rows is 1250 metres. Two wells are positioned south-west of Bara, exactly as in the first case. The effect of pumping on the environment was monitored at ten observation points. Both well dispositions were formed in such a manner as to include the existing wells PW-1, PW-2 and PW-3. Also, out of ten observation points four are the existing piezometers OW-1, OW-2, OW-8 and OW-9.

The total pumping rate of 1400 m³/day is taken as though the pumping operation will be continous. This was done so because it would be exceptionally complicated to prepare an analytical model which could calcuate the water level recovey during four hours and then, the next day, take up the achieved level at the starting point. As the model simulated a non steady-state of flow, the level recovery would decrease every day, and after a longer period it would become almost negligible. The simulation with a continuous, though smaller, quantity of pumping is therefore more rational, while its results are on the safe side.

For all these situations (two dispositions of wells) four variants of recharge were simulated. Namely, it can be seen from the piezometric contour line map that also in the natural state there is an inflow of groundwater into the future well field site, both from the west and the south-west. During the exploitation, this inflow will greatly increase, due to increased hydraulic gradients. As there are no data on groundwater level monitoring during a longer period and over a wider area between El Obied and Bara, the quantity of inflow, i.e. the recharge of the aqui-

T a b l e 3. Ground Water chemistry
T a b l i c a 3. Kemijski sastav podzemne vode

	OW-1	OW-2	OW-3	OW-4	OW-3	OW-8	OW-9	PW-1			PW-2		PW-3	Permissible by WHO Dozvoljeno prema SZO
								a1	a2	a3	a1	a2		
1. Turbidity (F.T.U.) Mutnoća	—	—	—	—	0	—	—	—	0	0	0	0	0	25
2. Temperature (°C) Temperatura	26	35	26	35	35	31	36	31	36	36	32	36	24	—
3. Odour Miris	—	—	0	0	0	—	0	0	0	0	0	0	0	Acceptable prihvatlj.
4. pH	6,6	8,5	6,8	7,8	6,8	—	7,5	—	7,1	6,9	7,1	7,1	6,9	8,5
5. Total hardness as $CaCO_3$ (mg/l) Ukupna tvrdoća	156	—	162	—	—	136	140	67	150	150	130	140	170	—
6. Temporary hardness as $CaCO_3$ (mg/l) Privremena tvrdoća	—	—	—	—	—	—	135	—	120	120	110	125	140	—
7. Permanent hardness (mg/l) Stalna tvrdoća	—	—	—	—	—	—	0	—	30	30	20	15	30	—
8. Alkalinity (mg/l) Alkalnost	178	110	165	201	174	—	—	—	—	—	—	—	—	—
9. Calcium as Ca (mg/l) Kalcij	42	36	28	—	110	92	30	—	34	34	32	36	44	100
10. Magnesium as Mg (mg/l) Magnezij	—	—	—	—	—	—	14,4	—	15,6	15,6	12	12	14,4	150

11. Silica as SiO_2 (mg/l) Silicij	—	—	—	—	—	—	22	—	11	11	34	39	5	—
12. Sulphate as SO_4 (mg/l) Sulfati	46	40	100	80	30	30	52,8	75	91,2	91,2	72	76,8	86,6	400
13. Chloride as Cl (mg/l) Kloridi	140	76	96	—	—	75	125	82	167	167	155	150	150	250
14. Iron as Fe (mg/l) Željezo	0	1,2	0	0,1	0,15	0,8	0	0	0	0	0	0	0	0,3
15. Nitrite as N (mg/l) Nitriti	—	—	—	—	—	—	0	—	0,022	0,010	0,022	0	0,055	—
16. Nitrate as N (mg/l) Nitrati	—	0,5	—	—	1,1	0	—	3,0	0	0	0	0	0	45
17. Amonical amonia as NH_3 (mg/l) Anorganski amonijak	—	—	—	—	—	—	—	—	trace tragovi	trace tragovi	0	0	0	—
18. Albusinoid amonia as NH_3 (mg/l) Organski amonijak	—	—	—	—	—	—	—	—	—	—	—	—	—	—
19. Total dissolved solids (mg/l) Ukupno otopljenih tvari	—	—	—	—	—	—	359	—	470	470	390	470	720	1000
20. Conductivity	950	650	850	650	650	800	—	850	—	—	—	—	—	—

fer at the future well site is impossible to quantify. The influence of the inflow was, therefore, simulated so that it was supposed that a certain quantity of water penetrates into the well field at its western and southern boundaries. The simulation was accomplished by introduction of imaginary infiltration wells. Four variants of recharge were simulated for each disposition of wells and each quantity of pumping, respectively. According to the first variant, there is no recharge whatsoever. This is the most unfavourable variant, but it certainly does not correspond to the natural state. According to the second variant, 75% of water which is pumped flows in from the west and 25% from the south, which means that the whole quantity of water is recovered within a longer period of time. In the third variant, an inflow of 50% from the west and 25% from the south were supposed, while in the fourth variant a total of 50% of pumped water is recovered, with an inflow of 25% from the west and 25% from the south. For all combinations of well dispositions, pumped quantities and variants of recharge, calculations were made of drawdowns in wells and observation points after pumpings lasting 1 day, 3 days, 10 days, 30 days (one month), 90 days (3 months), 180 days (6 months), 270 days (9 months), 365 days (1 year), 730 days (2 yeras), 1460 days (4 years), 1825 days (5 years), 3650 days (10 years), 7300 days (20 years), 10950 days (30 ears) and 18250 days (50 years).

Results have shown that drawdowns in well arrangements in two rows are 3 to 6% larger than when wells are arranged in a line. A smaller quantity pumped will cause decreases of almost 20% below those given by continuous pumping of 1728 m^3/day.

The good effect o recharge gets considerably increased with time. Thus, in the case of 100% recharge after the first year, the maximum decrease in wells will be by about 12% less than in the case without recharge. After 10 years the decrease will drop by about 34% and after 50 years by almost 45%.

Suppositing a 75% recharge after 1 year, the decrease is about 9%, after 10 years about 25% and after 50 years about 30% smaller than in the case without recharge.

If only 50% of the pumped quantity is recovered, decreases will fall by about 6% after one year, about 16% after 10 years and approximately 22% after 50 years.

It is obvious that well disposition has the least influence upon the decreases, so that technically and economically more advantageous layouts should be chosen. In the case of concentration over a smaller area, this is probably the layout with wells in two rows.

ASSESSMENT OF GROUNDWATER RESOURCES

The future well field covers an elongated area south of Bara of the total area of 9.0×10^7 m^2. Considering the depth of the main water bearing horizon of at least 100 m, the volume of the main aquifer amounts to about 9.0×10^9 m^3. This does not include the upper shallow water bearing medium, nor the volume of the main aquifer exceeding the depth of 100 m. The drilling site Mugheisiba confirmed the confined aquifer depth of 170 m. Thus, the total main aquifer bulk volume is considerably larger, since its overall area surpasses the well field limits, so that such an estimate is on the safe side.

If the specific yield of the aquifer of 0.05 (Hunting Technical Services, 1975) is accepted, the available water would be about 4.5×10^7 m^3 for 10 m of draw down. However, in view of the aquifer being confined or semiconfined, the available water will be somewhat greater, depending on the recharge mechanism by horizontal or vertical leakage.

The explorations carried out show that the main aquifers gets recharge from the south-west, where it comes out to the surface. The water level contour lines are a result of the rifting system and the manner of recharge. On the basis of satellite imageries it is possible to determine the area subject to infiltration. This is a wide arch-like zone covering 1.4×10^9 m^2 in which all perennial streams north of El Obeid disappear. The area is partially covered with dunes but the absence of wadis indicates that all the precipitation to the north of the water divide gets infiltrated in this area.

The upper Umm Ruwaba formation and the shallow water table aquifer cover a much smaller area and are recharged by the precipitation in the closer area around Bara. This explains the seasonal variations of water level in the shallow hand-dug wells.

However, this medium is important for continuous recharging and a balance of groundwater resources over the marginal part of the basin.

Considering all these elements as well as the thirty-year rainfall means between 312 mm (Bara) and 388 mm (El Obeid), the recharge rate is estimated at about 65 mm/year, making up the total recharge potential of 9.1×10^7 m^3 water/year. In the long-term water level observations in the Bara Basin (Ramsis, 1971), no significant changes in the water level had been recorded since 1936. This confirms the assumption that the quantity of water extracted from the aquifer is recharged by seasonal rains.

By mathematical modelling, the yield of a single well was estimated at 20 l/s. (1728 m^3/day). One simulation was performed supposing that all wells function continuously 24 hours a day, which means that 34,560 m^3/day for El Obeid and 3456 m^3/day for Bara would be exploited in the well field. As requirements for El Obeid were estimated at 28,000 m^3/day, it is clear that wells will not operate continuously for 24 hours a day, but that they will be out of operation throughout he four night hours. In this way, a daily recovery of the water level to the initial conditions will be possible.

As 25,000 m^3/day of water will satisfy the needs of El Obeid until 1995, installation of 18 water wells in the well field area is suggested for the first stage. According to the investigation, the quantity of available water considerably exceeds the actual long-term water demand of El Obeid and Bara.

The same design of exploitation wells is proposed for the future well field as it was for the pilot wells included in the exploration program. This enables a relatively simple installation and construction of water wells with high efficiency, while a casing diameter of 219 mm enables installation of a pump of 20 l/s capacity.

As the main aquifer is completely independent of the shallow and deep water bearing formations, the exploitation of the main aquifer will not greatly affect the existing hand-dug wells and boreholes in the area. Also, the extension of the aquifer under investigation enables a considerable expansion of the well field to as many as 50 wells in the future. This guarantees a longterm and large-scale exploitation of groundwater resources in the region.

CONCLUSION

El Obeid is an important economic centre in Kordofan Province in the Sudan with more then 300 000 inhabitants. The existing sistem of water supply could not satisfy the water demand. This was the reason why we began to work out the feasibility study of groundwater resources in 1985. The existing data on the geological structure and the constructed wells and satellite derived data served as the basis for this study. It was found out that the groundwater resources of Kordofan are still unexploited and offer great potentials for the long-term planning of water supply. Groundwater exploitation in the Bara Basin was specially pointed out as a potential source of water.

Hydrogeological explorations performed in 1987 and 1988 showed that there are three quite distinct lithological units to the depth of 300 m. The third lithological unit consists of more or less permeable materials, and the whole complex of sediments within this unit can be taken as a uniform aquifer. The coefficient of transmissivity of this aquifer amounts about 400 m^2/day, and storage coefficient is $3{,}7 \times 10^{-4}$. The explorations performed justify the assumption that the recharge of this aquifer can cover the pumped quantities of water. The groundwater in the investigated area is of exceptionally good quality and that no additional processing will be required during exploitation.

As 25,000 m^3/day of water will satisfy the needs of El Obeid until 1995, instalation of 18 water wells in the well field area is sugested for the first stage. According to the investigation, the quantity of available water considerably exceeds the proposed long-term water demand of El Obeid and Bara.

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Hidrogeologija dijela Bara bazena u provinciji Kordofan u Sudanu

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Hidrogeološka istraživanja dijela Bara bazena u provinciji Kordofan započela su 1985. godine s ciljem pronalaženja dovoljne količine kvalitetne podzemne vode za vodoopskrbu grada El Obeida (slike 1. i 2.). Najprije je načinjena studija mogućnosti na temelju postojećih elaborata, podataka o 275 bušotina i dubokih bunara, 42 kopana bunara i rezultata kemijskih analiza podzemne vode s 95 lokacija, te satelitskih i aero snimaka. Zaključeno je da se najpovoljnije područje za potencijalno crpilište nalazi oko 40 km sjeverno od El Obeida u blizini grada Bare. Predložen je program terenskih istražnih radova kojima bi se dokazala pretpostavljena povoljna hidrogeološka situacija i kvantificirali hidrogeološki parametri.

Terenska istraživanja provedena su 1987. i 1988. godine, a sastojala su se od izvedbe 10 strukturno-pijezometarskih bušotina dubine do 300 metara, tri pokusno-eksploatacijska bunara, karotažnih mjerenja i pokusnog crpljenja (slika 3.). Istraživanjima je utvrđeno da se u prvih 300 metara mogu razlikovati tri vodonosnika od kojih je za eksploataciju najpovoljniji onaj na prosječnoj dubini između 150 i 300 metara (slike 4. i 5.). U tom intervalu smjenjuju se tanji i deblji slojevi pijeska, šljunkovitog pijeska i slabovezanih pješčenjaka s proslojcima i slojevima glinovito-prašinastog materijala.

Cijeli ovaj paket naslaga predstavlja hidrauličku cjelinu. Saturiran je podzemnom vodom pod subarteškim tlakom, tako da statička razina podzemne vode u bušotinama dopire do desetak metara ispod površine terena. Srednja vrijednost koeficijenta transmisivnosti kreće se oko 465 m^2/dan, a koeficijentna uskladištenja oko $3{,}7 \times 10^{-4}$.

Kemijskim analizama uzoraka vode iz bušotina i bunara ustanovljeno je da mineralizacija ne prelazi 550 mg/l, što je za ovaj dio Sudana izuzetno povoljno.

Iako za sada ne postoji dovoljan broj podataka o razinama podzemne vode na širem prostoru, može se reći da podzemna voda teče od juga i jugozapada prema sjeveru i sjeveroistoku, što navodi na pretpostavku da se vodonosnik prihranjuje na jugu infiltracijom vode iz vadija tamo gdje oni dopiru do propusnih sedimenata.

Simulacijom pomoću matematičkog modela definiran je optimalni raspored bunara na budućem crpilištu. Predloženo je da se u prvoj fazi izvede 18 bunara prosječne dubine od 300 metara s međusobnih razmakom od 650 metara. Uz eksploataciju od 20 l/s po bunaru dobilo bi se dnevno 25.000 m^3 kvalitetne vode, što će zadovoljavati potrebe El Obeida do 1995. godine. Na temelju do sada prikupljenih podataka pretpostavljamo da se u kasnijoj fazi crpilište može značajno proširiti, no to će trebati dokazati novim istraživanjima.