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Water quality of the Gedaref basin, Sudan

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Abstract The Gedaref basin in eastern Sudan is believed to be a great tectonic depression filled mainly with continental deposits and Tertiary basalt lava flows. The main aquifers are the Gedaref sandstone aquifer system and the basalts. 70 wells drilled in the Gedaref basin were sampled and analysed for the major cations, major anions, total dissolved solids, alkalinity and hardness. The data were treated with simple statistics, represented with Piper trilinear plots and were the subject of cluster analysis. The interpretations of the applied methods confirm each other and the groundwater was classified into two groups. The water in the sandstone aquifer was dominated by $NaHCO_3$ while the water in the basalts was partially dominated by alkaline earth.

La qualité des eaux du basin de Gedaref, Soudan

Résumé Le bassin de Gedaref situé au Soudan oriental est une grande cuvette tectonique remplie de dépôts continentaux et de coulées de basalte d'âge tertiaire. Les principaux aquifères sont le grès de Gedaref et les basaltes. 70 forages réalisés dans le bassin de Gedaref ont été echantillonnés et les cations majeurs, les anions majeurs, la salinité totale, l'alcalinité et la dureté ont été analysés. Les résultats obtenus ont fait l'objet d'un traitement statistique simple, ont été représentés sur des diagrammes de Piper et ont été soumis à une analyse de partitionnement. Les différentes méthodes appliquées se confortent l'une l'autre et permettent de distinguer deux groupes d'eaux souterraines: le type $NaHCO_3$ domine dans la nappe des grès cependant que le type alcalin domine partiellement les basaltes.

INTRODUCTION

The town of Gedaref is the agricultural centre of grain production in Sudan. More than half of the millet and sorghum of the country is produced in this area. It provides the mainstay of the economy in Eastern Sudan. Almost all agricultural activities depend on seasonal rains but water supply systems for major town and villages away from rivers and water courses increasingly depend on groundwater. Modern hydrogeological research started in the area in 1968 (Suleiman, 1968). A number of successful wells were drilled some 7 km to the south of Gedaref and water was pumped to the town. Since then groundwater abstraction has increased and more drilling has taken place. Most of the drilled wells gave fresh water suitable for various uses though some

wells gave saline water not suitable for drinking and other household purposes. Kheir (1980) investigated the groundwater potential in terms of groundwater occurrences and quality characteristics. Adam (1987) made considerable efforts towards a water resources evaluation in the Gedaref basin. A few unpublished reports are available within the archives of the Rural Water Administration and the Sudan Geological Survey Department with some hydrogeological information about the area. The objectives of this study were to describe the composition of the groundwater in the Gedaref area, to describe the spatial variation in groundwater quality, and to account, as far as possible, for the

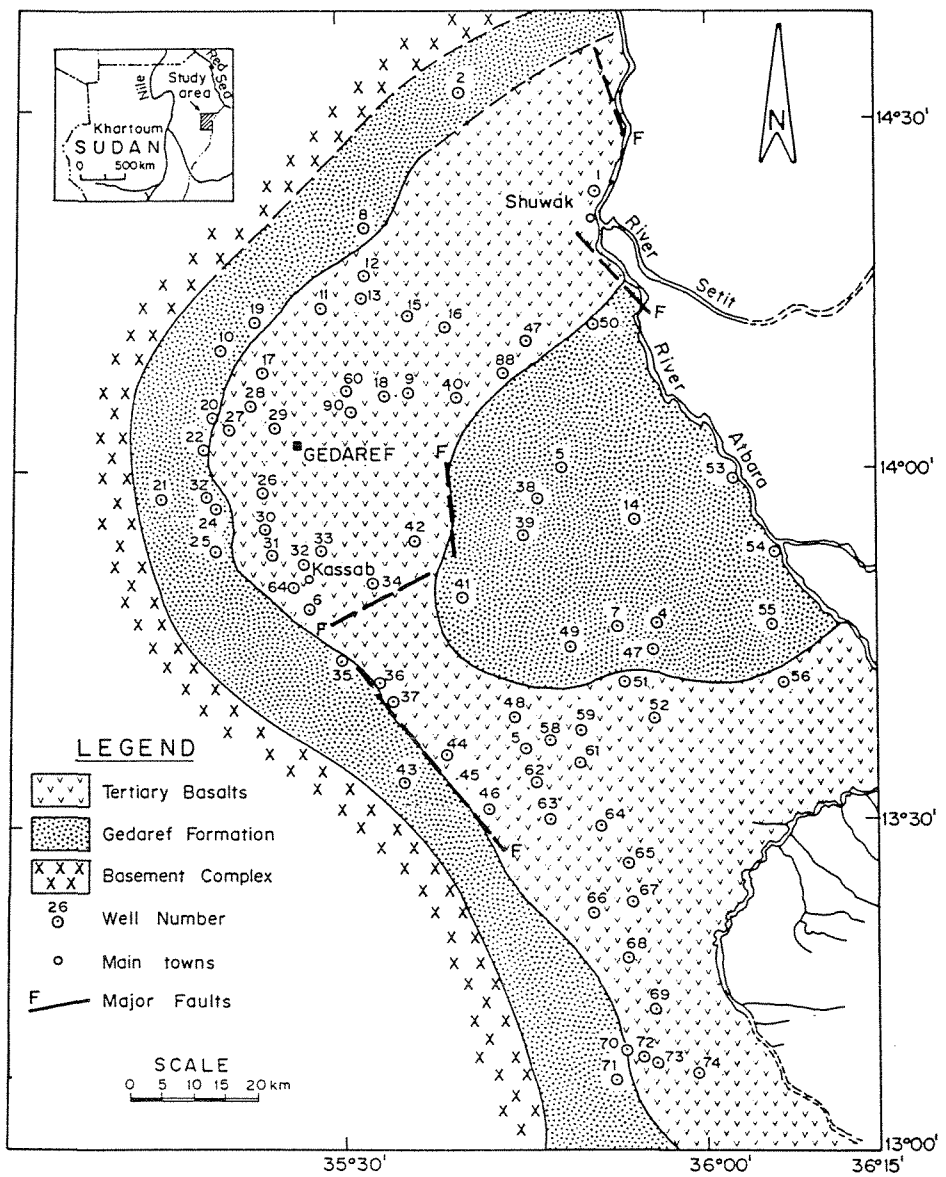


Fig. 1 Location and general geology map of the Gedaref basin, Sudan.

processes controlling the variation in water quality.

To achieve the above mentioned objectives water samples were obtained from 70 wells drilled in the Gedaref basin. Each well was pumped for at least 30 min and the samples collected in 1 litre plastic bottles. Electrical conductivity (EC), temperature and pH were measured in the field using portable Karl-Kolb equipment. The collected samples were then taken to the Geochemical Laboratory of the Geology Department, University of Khartoum, for analyses. The analytical techniques included the following: a flame photometer Corning-Eel Evans Electroselenium used for the determination of Na^+ and K^+; a nephlometer Corning-Eel Evans Electroselenium used for the determination of SO_4^{2-}; volumetric methods used for the determination of Ca^{2+}, Mg^{2+}, HCO_3^- Cl^-, total alkalinity and total hardness. A linear relation between EC and total dissolved solids (TDS) was used to determine the concentration of dissolved solids, *viz*:

$$TDS = C \times EC \tag{1}$$

where the constant C was estimated at 0.7.

The analyses conducted in the laboratory and the field measurements were considered as being sufficiently reliable.

The following chemical analyses evaluation techniques were adopted in this study:

(i) the accuracy of the chemical analyses was checked using a cations-anions balance;
(ii) the results of the major ions obtained as ppm were converted to equivalent per million (epm) and equivalent per million percent (epm %);
(iii) major ions relationships were examined with a correlation matrix, using the Statgraph computer program;
(iv) the Piper trilinear plotting system was used to help in the classification of groundwater types; and
(v) cluster analysis (Eriksson, 1985) was used to investigate the groundwater quality data.

GEOLOGY

The Gedaref basin is believed to be a tectonic depression (Ruxton, 1956; Kheir, 1980; Almond *et al.*, 1984; Adam, 1987) filled by continental deposits which make up the Gedaref Sandstone Formation. In the central part of the depression there are thick Tertiary basalt lava flows that originated from volcanos and poured out of eruptions aligned along a north-south trending fracture system (Adam, 1987). The bed-rock geology is illustrated in Fig. 1. The post-Basement sediments attained great thicknesses (≤ 2 km) in the tectonic depression (Ibrahim *et al.*, 1992). The Gedaref Sandstone Formation is divided into three sandstone units separated by claystone confining beds (Omer, 1978). A generalized geological column is shown in Fig. 2.

Age	Formation	Lithology	Description	Thickness (m)
Quaternary to Recent	Superficial deposits		unconsolidated clays, silts and sands	0 - 15 m
Tertiary	Basalts		mainly basalt volcanics	15 - 40 m
Jurassic to Cretaceous	Upper Gedaref Sandstone Formation		mainly sandstone	> 300 m
			claystone	
	Middle Gedaref Sandstone Formation		mainly sandstone	
			claystone	
	Lower Gedaref Sandstone Formation		mainly silicified sandstone	
Precambrian and Cambrian	Basement complex		igneous and metamorphic complexes	

Fig. 2 Generalized geological column, Gedaref area, Sudan.

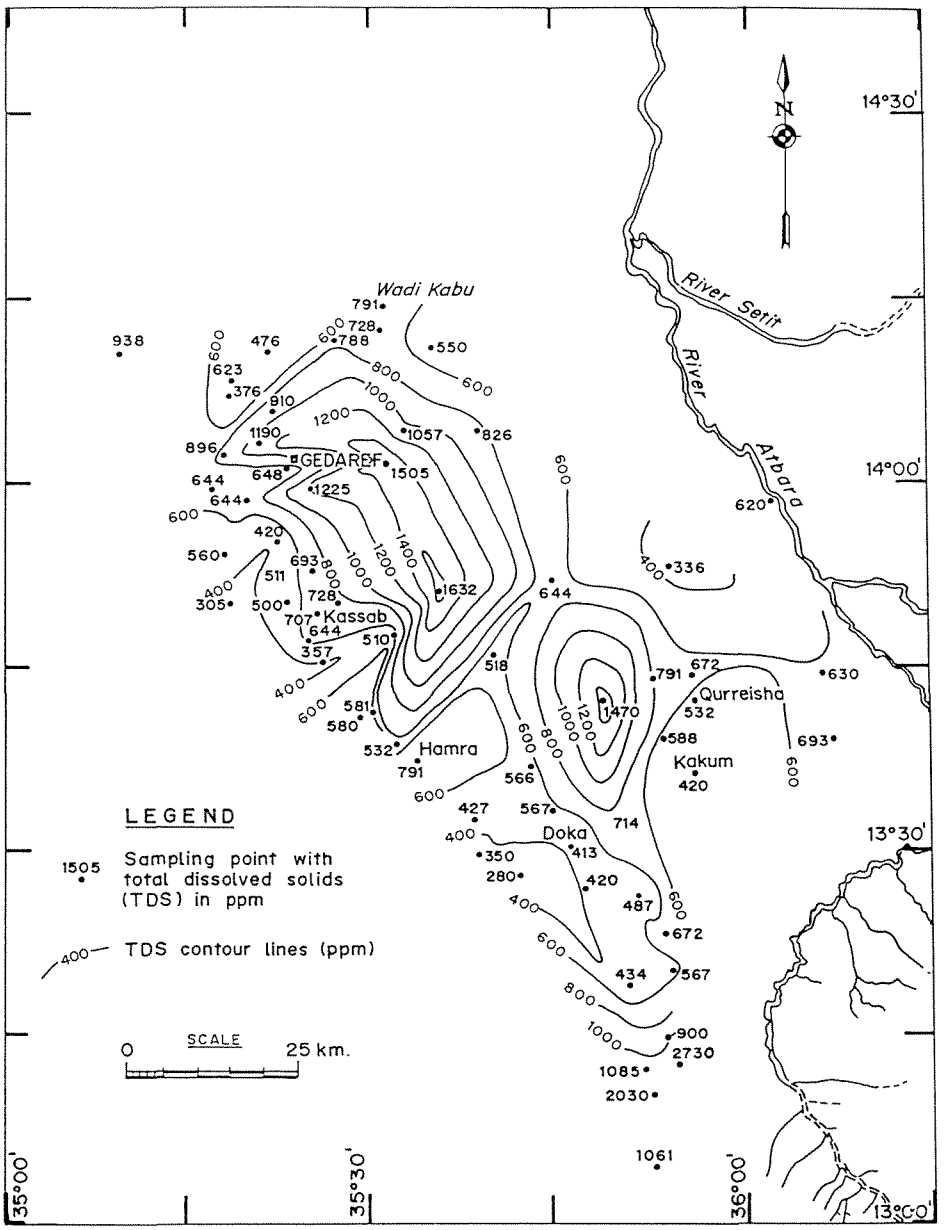


Fig. 3 Spatial distribution of total dissolved solids (TDS), Gedaref basin, Sudan.

GROUNDWATER CONDITIONS

The Gedaref basin encompasses two major aquifers. These are the Gedaref sandstone aquifer system and a basaltic aquifer. The two aquifers are hydraulically connected in most of the study area. Groundwater occurs at depths ranging from 15-200 m under unconfined, leaky, confined and artesian

conditions. Recharge is expected to take place from the rivers Setit and Atbara, ephemeral streams, through direct rainfall in outcrop areas, and runoff from the Basement Complex at the margins of the basin (Adam, 1987). The average transmissivity of the sandstone aquifer is about 280 m^2 day^{-1}, the average permeability is 0.75 m day^{-1}, the storativity varies between 6.3×10^{-2} and 2.0×10^{-7}. The basalt aquifer is characterized by a transmissivity of 100 m^2 day^{-1} and groundwater moves through fissures and joints with an average hydraulic gradient of 1:160 (Adam, 1987).

WATER QUALITY

Throughout the study area total dissolved solids (TDS) varied from 250 to 2730 ppm. Within the sandstone aquifer the TDS ranged from 280 to 1800 ppm. Salinities above 2000 ppm were encountered in the basalt aquifer and in some pockets within the sandstone aquifer. Figure 3 shows the spatial distribution of TDS in the Gedaref basin. There was a gradual increase in salinity down-gradient in the northwestern periphery of the study area from 550 to 1800 ppm. Two major zones or pockets of high salinities were encountered. Concentration by evaporation in the outcrop areas, the solution of evaporites within the aquifer body and the high percentage of mudstone in the sandstone aquifer may account for such concentrations.

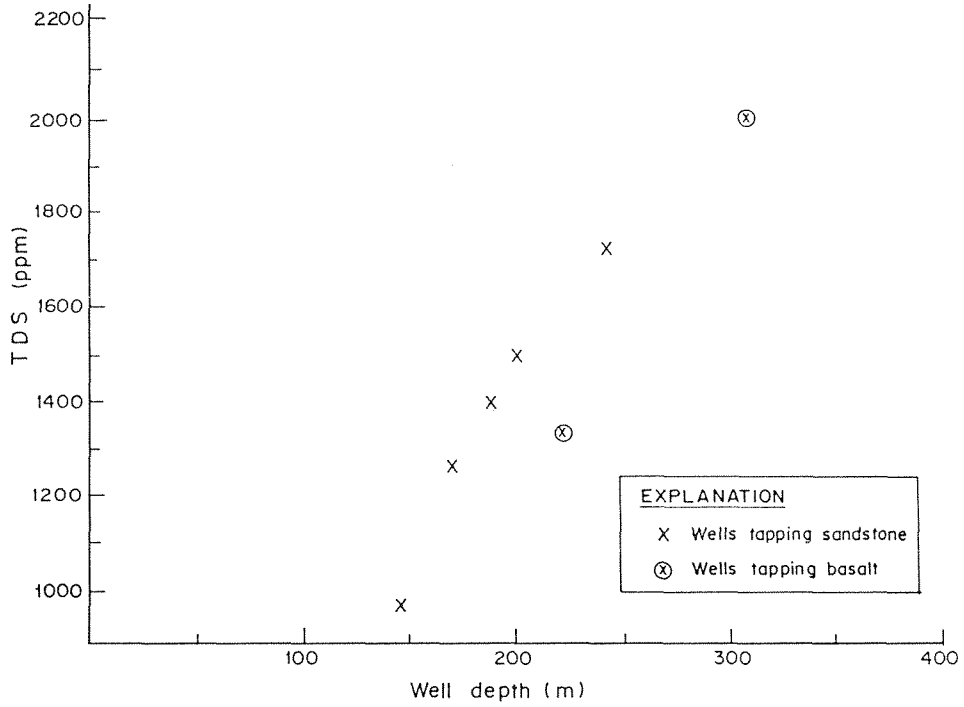


Fig. 4 Plot of TDS and depths in some wells located in the high salinity area, Gedaref basin, Sudan.

Salinity generally increased down-gradient and with depth. Figure 4 shows a plot of TDS with depth in some wells located in the high salinity area. Table 1 and Fig. 5 show the maximum, minimum, average and range of the major ions concentrations in each of the sandstone, basalt and sandstone-basalt water-bearing units within the Gedaref basin.

The cations relationship in the Gedaref groundwater was:

$Na > Ca > Mg > K$

The anions of the sandstone aquifer were characterized by:

$HCO_3 > Cl > SO_4 > CO_3$

while those of the basalt aquifer were:

$HCO_3 > CO_3 > SO_4 > Cl$

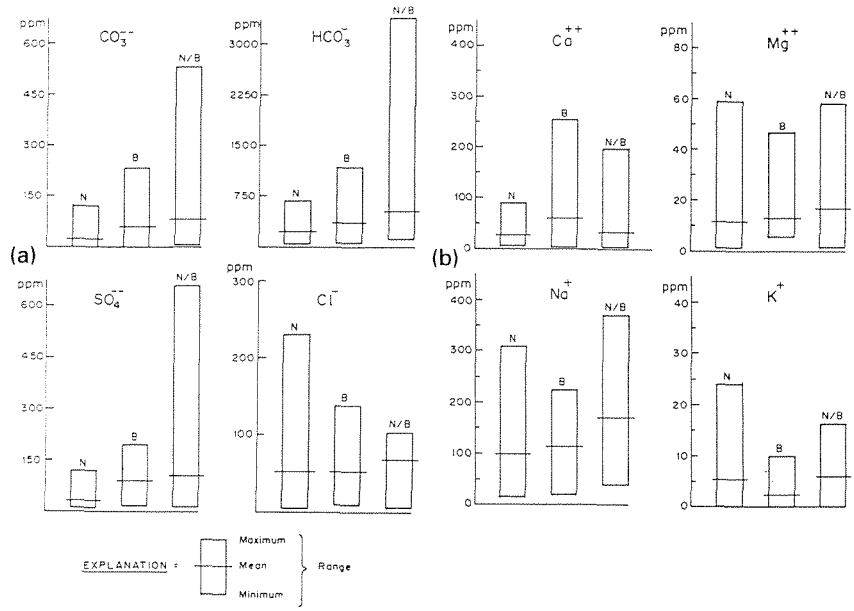


Fig. 5 Plots of (a) major cations; and (b) major anions, Gedaref basin, Sudan (N = sandstone aquifer, B = basalt aquifer).

Table 1 Summary statistics of major ions, Gedaref basin, Sudan (concentrations in ppm)

Major ion	Sandstone aquifer			Basalt			Sandstone/basalt		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Ca	5.4	86	26.1	2.4	252	61.3	3.2	196	32.6
Mg	1.2	59	11.5	5.5	46.5	13	1.4	57.9	16.4
Na	15	310	160	20	224	114	40	370	169
K	0.1	24	5.4	0.0	10	2.3	0.1	16.4	6.2
HCO_3	43	630	360	60	1000	420	120	3500	500
CO_3	-	120	23	-	230	62	3	500	70
SO_4	11	126	33	18	199	54	13	650	210
Cl	5	230	53	10	138	53	7	100	73

Min. = Minimum; Max. = Maximum; and Ave. = Average.

Ionic relationships

Generally, most of the ionic relationships could be considered weak. Nonetheless there were positive and negative ionic relationships exhibited in the Gedaref groundwater. The correlation matrix for the sandstone aquifer (Table 2) showed positive linear relationships for all the major ions, alkalinity and hardness. Relatively strong relationships were seem to exist between Na^+ and TDS, Ca^{2+} and CO_3^{2-}. Water samples from the basalt aquifer showed both positive and negative linear relationships (Table 3). Relatively strong positive relationships existed between HCO_3^- and TDC, CO_3^{2-} and TDS, Na^+ and TDS, Ca^{2+} and CO_3^{2-}, Ca and HCO_3^-, Mg^{2+} and CO_3^{2-}, Ca^{2+} and SO_4^{2-}. The extremely good correlation of Na^+ with TDS on one side and with HCO_3 on the other side threw some light on the relatively high $NaHCO_3$, a readily soluble salt in the soil zone which may be dissolved and transferred to the groundwater

Table 2 Correlation matrix (r) of the sandstone aquifer system (47 samples)

	TDS	ALK	HARD	Ca	Mg	Na	K	HCO_3	CO_3	Cl
ALK	0.555									
HARD	0.463	0.205								
Ca	0.690	0.663	0.298							
Mg	0.550	0.392	0.287	0.713						
Na	0.788	0.714	0.423	0.246	0.138					
K	0.115	0.049	0.276	0.120	0.231	0.048				
HCO_3	0.758	0.879	0.326	0.528	0.225	0.706	0.115			
CO_3	0.762	0.852	0.124	0.769	0.403	0.516	0.028	0.733		
Cl	0.414	0.026	0.524	0.195	0.407	0.365	0.350	0.066	0.028	
SO_4	0.388	0.147	0.420	0.277	0.467	0.259	0.393	0.158	0.118	0.639

Table 3 Correlation matrix (r) of the basalt and sandstone-basalt aquifer (23 samples)

	TDS	ALK	HARD	Ca	Mg	Na	K	HCO_3	CO_3	Cl
ALK	0.984									
HARD	0.658	0.558								
Ca	0.836	0.814	0.704							
Mg	0.731	0.742	0.547	0.932						
Na	0.943	0.934	0.530	0.648	0.541					
K	0.910	0.901	0.467	0.687	0.605	0.960				
HCO_3	0.964	0.966	0.556	0.812	0.733	0.939	0.937			
CO_3	0.949	0.961	0.558	0.854	0.785	0.850	0.816	0.941		
Cl	0.043	−0.081	0.455	0.024	−0.065	0.013	−0.034	−0.091	−0.120	
SO_4	0.927	0.913	0.513	0.716	0.615	0.969	0.994	0.947	0.832	−0.012

especially through a highly fractured and jointed zone. The relationship of calcium and magnesium concentrations to bicarbonate indicated that calcite and dolomite were the possible sources of these ions.

Hydrochemical facies

Piper trilinear plot was used to help in the classification of the waters of Gedaref basin (Piper, 1944; Hem, 1970). The diamond shapes (Fig. 6) distinguish two groups of water with a small zone shared between them. Group A represents the groundwater of the sandstone aquifer system and group B represents the basalt aquifer. In group A, all the samples were mostly Na – HCO_3 + CO_3 type with Ca and Mg increasing along the flow direction. The anions reflected a HCO_3 + CO_3 type with extension in the Cl and SO_4 directions. The waters of group A were strongly alkalinized probably by ion exchange because the water in the sandstone aquifer is mainly a Na – HCO_3 type water with a weak tendency towards a Na – HCO_3 – SO_4 type.

Group B waters were relatively dominated by alkaline earth (Ca + Mg) (Na + K), HCO_3 type with a tendency of SO_4 and Cl to increase at the expense of HCO_3. This is understandable since rain water percolates through weathered and highly fractured basalts. The zone of overlap represents water samples obtained from wells tapping both aquifers.

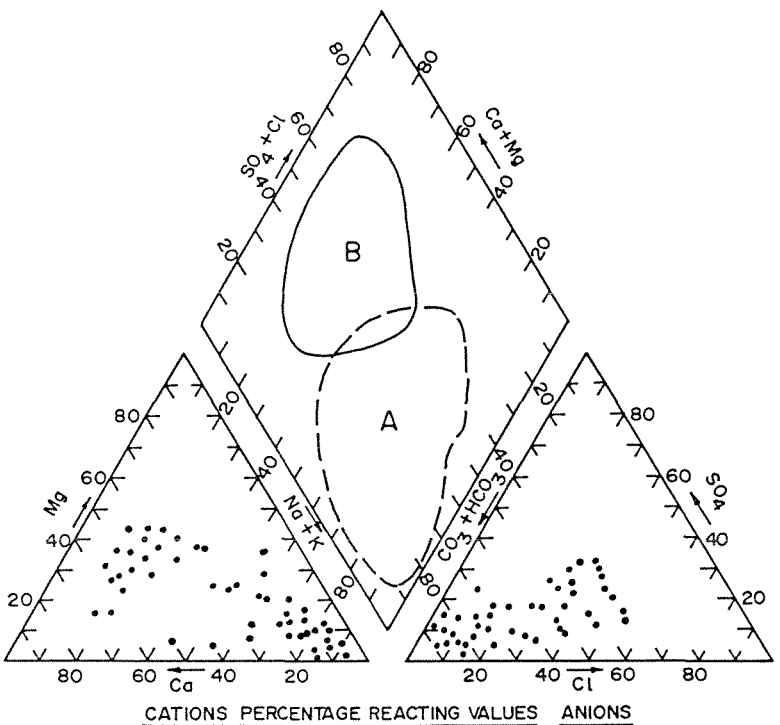


Fig. 6 Piper diamond shape, Gedaref basin, Sudan.

Cluster analysis

The Piper trilinear plot presented in Fig. 6 considered only the major ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, HCO_3^-, CO_3^{2-}, Cl^- and SO_4^{2-}). Cluster analysis can consider as many variables as are available. It is a method of grouping samples into clusters based on similarities and differences between individuals (Davis, 1973). Before dealing with cluster analysis the data were first standardized using:

$$K_{ij} = \frac{X_{ij} - \bar{X}_{ij}}{S_i} \tag{2}$$

where K_{ij} is the standardized ith variable for the jth sample, X_{ij} is the data value, $\bar{X}_{ij}$ is the mean value of the ith variable and S_i is the standard deviation. This procedure applies equal weights to each variable. The variables considered in the study were the TDS, total alkalinity, total hardness, Ca^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, Cl^- and SO_4^{2-}.

The measure of similarity used was the Euclidean distance between samples in N-dimensional space where N is the number of different variables considered. The distance between two samples (j, k) is given by:

$$d_{ik} = \left[\sum_{i=1}^{N} (K_{ij} - K_{ik})^2 \right]^{1/2} \tag{3}$$

The computation was carried out with the help of an SPSS package. The cluster tree or dendogram obtained for the Gedaref basin is shown in Fig. 7.

There appeared to be two main clusters in the Gedaref basin. Cluster I included all the wells tapping the sandstone aquifer system with only two wells tapping both the sandstone and the basalt. All the wells of the basalt and sandstone-basalt aquifer appeared in Cluster II. Wells tapping the sandstone aquifer with TDS exceeding 1000 ppm appeared in Cluster II as well. These wells correspond to the overlap zone in the Piper trilinear plot (Fig. 6).

CONCLUSION

The groundwater of the Gedaref basin occurs mainly in the Gedaref Sandstone Formation and the Tertiary basalts. Water obtained from each of these aquifers had its own hydrochemical properties. The sandstone aquifer was characterized by a TDS of 280-1800 ppm, water mainly of the $NaHCO_3$ type with calcium and magnesium increasing down-gradient with the flow. Almost all the sandstone aquifer waters were clustered in one separate group. The basalt aquifer was characterized by a TDS of 250-2730 ppm, the alkaline earth relatively exceeded the alkalines, water was predominantly of the bicarbonate type. Waters from the basalt aquifer appeared in a separate cluster.

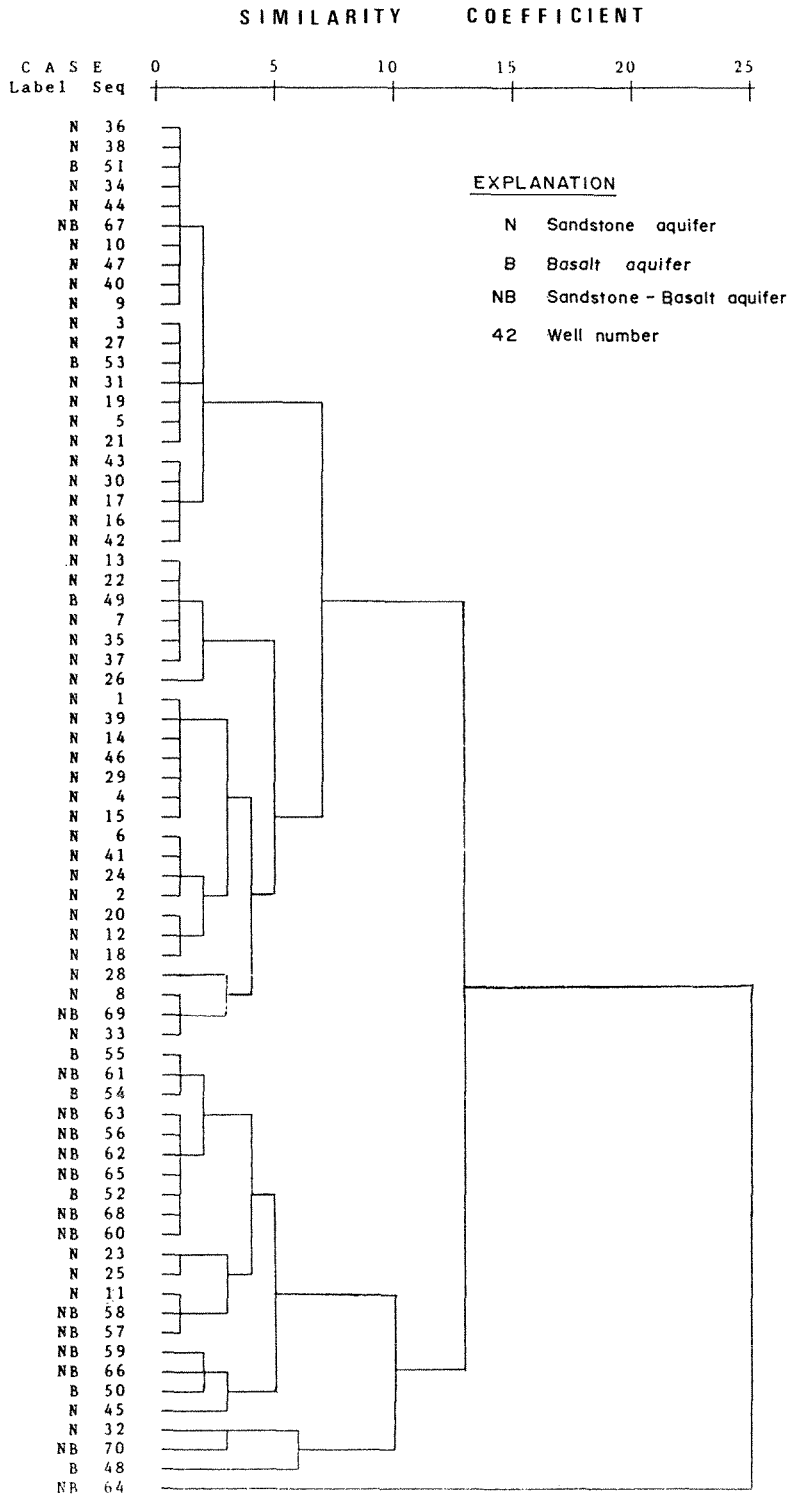


Fig. 7 Dendogram of cluster analysis, Gedaref basin, Sudan (N = sandstone aquifer, B = basalt aquifer).

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