

Hydro & Engineering Geological Implications of Extracting the Salty Deep Groundwater on the Mobilization of Fresh Water Resources in the Lower Zarqa River Area, Jordan

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ABSTRACT

Extractions of deep salty groundwater from the Triassic and Jurassic rocks in the lower reaches of Zarqa River have led to mobilizing overlying fresh ground- and surface water bodies to replace the extracted salty water leading herewith to the dissolution of evaporates from the rock matrix. This has, in turn, led to the formation of small (Decimeter) underground cavities which widened with time to form huge underground cavities many 10s of meters), which ceilings collapsed and created sink holes at ground surface.

This article discusses the geology, hydrogeology and hydrochemistry of the area of lower Zarqa River and quantifies the effects of the pumping of salty groundwater on the mobilization of fresh water, which is leading to the formation of underground cavities and sink holes at ground surface.

The study shows that understanding the groundwater recharge, flow and discharge regime and the effects of disturbing that regime must be clarified before deciding to implement projects which may lead to damage to the groundwater system and become fiasco projects. The study concluded that pumping water from the deep salty Triassic and Jurassic rocks is equivalent to extracting water from Zarqa River itself, because the extracted water is being substituted by the Zarqa River water.

Keywords: Deep mineralized water, extraction, hydro- and engineering geological implications, Zarqa River/Jordan

1. INTRODUCTION

This Zarqa River is the second largest River in Jordan in the area of its drainage basin and its mean annual discharge. The catchment area measures around 3200 km² and extends from the foothills of Jabel Druz in Syria to the Jordan River in Jordan (Fig.1). The Eastern branch of the ZR; Wadi Dhuleil used to discharge only flood flow water, whereas the western branch; Seel Amman-Zerqa, originating in the Amman area discharged flood and base flows.

As mentioned above the natural flow of the River consisted of flood and base flow water. After constructing the first sewerage system and waste water treatment plant in Ain Ghazal in 1961 for Amman City the ZR started receiving treated waste water. The

new treatment plant in Khirbet es Samra discharges to Dhuleil branch of ZR.

Along the whole length of the ZR the groundwater regime was naturally effluent where the ZR received discharges of groundwater. Groundwater extractions along the ZR upper reaches have, during the last 3 decades, led to declines in water levels and the surface water of ZR started recharging the aquifers underlying the area.

The lower Zarqa River (ZR), which extends from King Talal Dam (KTD) in the highlands to Deir Alla in the Jordan Valley, flows in a region covered by lower Cretaceous, Jurassic and Triassic rocks. The Triassic rock sequence consists, in its upper outcropping parts, of a series of evaporate composed mainly of gypsum and anhydrite, 40m in thickness. The Jurassic rocks consist of 440 m of limestone, marls, dolomite, sandstone and shale and the overlying Lower Cretaceous rocks consist mainly of sandstone, 200-250m in thickness [1]. The groundwater in the Jurassic rocks is effluent, generally thermal and salty with EC values of up to 15000µS/cm, whereas that in the Jurassic contains water with EC values of up to 3000 µS/cm and in the Lower Cretaceous it rarely exceeds 1200 µS/cm.

The ZR along its lower reaches discharges a mixture of base flow treated waste water and in the winter season flood flows. Its salinity is around 2000µS/cm, except during floods when it can go down to about 500µS/cm.

At the mouth of ZR into the Jordan Valley, in Abu Zigan area, the thermal, mineralized groundwater used to discharge from two springs at the entrance of ZR into the Jordan Valley. A series of wells was drilled here to extract salty water from the Triassic/Jurassic aquifer to be desalinated and used for drinking purposes. Pumping of groundwater has resulted in mobilizing the fresh groundwater in the overlying geologic units to percolate downwards substituting the extracted groundwater of the deep aquifer, which in turn led to the mobilization of ZR water to infiltrate into the Lower Cretaceous and Jurassic aquifers cropping out along the ZR course. It has also resulted in the drying up of springs and in the ZR water infiltrating into the aquifers along the lower reaches of ZR.

The fresh water percolating down from the ZR and from the alluvial aquifers along the ZR into the deeper Jurassic and Triassic

aquifers dissolved evaporate salts from these aquifers and created small cavities, which enlarged with time and their ceilings collapsed and formed sinkholes at the ground surface.

In this article The geology of the area, its hydrogeologic setting and the induced water mobilization, dissolution of salts and land collapses are discussed.

2. GEOLOGY OF THE AREA

2.1 Stratigraphy

The area is covered by sedimentary rocks of Triassic, Jurassic, Lower and Upper Cretaceous ages. These sediments are composed of sandstone, limestone, marls, dolomite, limestone, marly limestone and shales (Table 1).

Along the lower course of Zarqa River, downstream of King Talal dam Jurassic and Triassic rocks are outcropping [2,3]. In places along the ZR course, e. g. between Zarqa and Sukhna towns, alluvial and colluvial deposits are found. Figure 2 shows a simplified geological map of the study area.

Triassic rocks

Triassic rocks crop out at Zarqa River near the junction of wadi Huni consisting of a few meters of crystalline limestone alternating with thin bedded shales, with a 20 – 40m massive gypsum bed, followed by an argillaceous marly limestone bed, shales and iron oolites. Sandy limestone and ferruginous sandstones can be seen at the top of this succession at the contact with Jurassic sediments [1]. The exposed thickness of Triassic rocks along Zarqa River measures 150m. The bottom of the sequence is not exposed.

Jurassic rocks

Jurassic rocks are exposed in Zarqa River valley overlying Triassic rocks with a thickness of 440 m in Wadi Huna on the northern side of Zarqa River. [1]. The upper part of the Jurassic sequence consists of about 75m of limestone, marls, dolomite and shales. Below that, in the middle part of the Jurassic rocks, the portion of clastic sediments increases, where coarse sandstone and sandy limestone are found with a thickness of about 65m. The lower part of the Jurassic rocks consists of alternating calcareous, oolitic marls, gray shales, marly and crystalline dolomitic limestone of about 80m thickness.

Lower Cretaceous rocks

The Lower Cretaceous sediments are mainly composed of sandstones. At Zarqa River they overlie with a distinct erosional unconformity Jurassic sediment. They start with basal conglomerates or with sandstones intercalated with a conglomerate layer of up to 5m in thickness, this is then followed by varicolored alternating silty and marly, coarse to medium and fine grained sandstone with some shales and greenish marls, partly sandy or glauconitic and with some gypsum. Above follows a varicolored, medium to coarse grained sandstone alternating with shales, marls, dolomitic, marly limestone, and limy and glauconitic sandstone. The total thickness of the Lower Cretaceous ranges from 200 to 250m. Echinoidal fragments become more frequent and abundant in the upper most part of the sequence and give evidence of a marine depositional environment. [1,3].

Upper Cretaceous rocks

Upper Cretaceous marine sediments consisting of calcareous and siliceous sediments overlie the Kurnub Sandstone of Lower Cretaceous age. The Upper Cretaceous Formations play only a very limited role in the actual thesis of this article. They actually serve as rocks covering the surrounding mountains of Zarqa River where recharge takes place and from where infiltration water leaks down to recharge older rock units.

Recent rocks

Recent alluvial and colluvial sediments cover wadi courses in the upper reaches of ZR, but they are not found in appreciable thicknesses along the V-shaped lower ZR. Therefore they are of minor relevance to the present work.

2.2. Geologic Structures

The study area shows small anticlines, synclines, faults and flexures with also very limited impact on the workings in this study. Along the lower reaches of Zarqa River, downstream of King Talal dam a shallow (low amplitude) anticlinal uplift striking E-W is present (Figs. 2 and 3). The outcropping core of the uplifted strata consists of the upper parts of the Triassic rocks which are composed of evaporates, especially gypsum and anhydrite. It seems that the erosion of rocks overlying the Triassic rocks along Zarqa River course enhanced some type of anticlinal bending as a result of salt tectonics. This is especially true because the axis of the anticlinal bending strikes parallel to the river course, and hence to the maximal eroded rock thickness and pressure release. Changes from anhydrite CaSO_4 to gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ due to water molecules entering the crystal structure is accompanied by an expansion in volume of up to 60% [4] which may have played a major role in the formation of the anticlinal bending.

Structures

The most prominent regional structure affecting Jordan is the Jordan – Dead Sea – Wadi Araba Rift fault. The main structure of relevance to the present study is an anticlinal bending striking E-W; along the ZR area, perpendicular to the main Rift Valley Fault. Other minor structures consist of local folds, faults and flexures which could be explained as local reaction to the stress field affecting Jordan and acting in a N-NW to S-SE direction. Such minor structures have only limited effects on the groundwater flow regime.

Three aquifer systems underlie the study area namely, the deep Kurnub, Jurassic and Triassic Aquifer system, the intermediate A1 – A6 badly developed aquifer system and the shallow aquifer system consisting of B2/A7 or A7 alone or B2/A7 together with wadi fills and basalts. The main aquifer along the upper reaches of Zarqa River consists of the shallow system. Along the lower reaches of the River the main aquifer system is the deep one consisting of Lower Cretaceous, Jurassic and Triassic rocks.

The groundwater flow regime in the study area is generally directed towards the River. Along the lower reaches of Zarqa River the Lower Cretaceous, Jurassic and Triassic Formations are hydraulically inter-connected and the groundwater flow regime is also directed towards the River as an effluent stream (Figure 4, [7]). Direct recharge into the deep aquifer is very limited whereas indirect recharge takes place as downward leakages from the

overlying Upper Cretaceous aquifers cropping out to the south, north and east of the study area.

The lower Zarqa River was fed, in its natural state, by discharges of groundwater from the Lower Cretaceous and to a lesser extent from the Jurassic and Triassic rocks, which build the area.

3. HYDROCHEMISTRY

In the following the groundwater composition and the sources of dissolved solids for the different aquifers are discussed. The chemical and physical information has been obtained from own analyses and from analyses of the laboratories of the Ministry of Water and Irrigation [8].

The water samples collected in the course of this study from springs and wells were analyzed applying the Deutsche Einheitsverfahren zur Wasseruntersuchung (DIN) [9] and the Standard Methods for the Examination of Water and Waste Water (AWWA) [10]. HCO_3^- , Cl^- , Ca^{2+} and Mg^{2+} were analyzed by titration, Na^+ and K^+ by flame photometry, NO_3^- , PO_4^{3-} and SO_4^{2-} by spectro-photometry. The water analyses in this paper include the common ions Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^- and NO_3^- .

3.1 Groundwater in the upper part of the Upper Cretaceous (B2/A7)

The outcrops of the Upper Cretaceous receive direct recharge from precipitation and indirect from flood flows. The salinity of the groundwater here ranges from 540 to 800 $\mu\text{S}/\text{cm}$ reflecting the low concentrations of the salinity parameters in the water (Table 2a). The variations in water salinity are confined as can be seen from their values range in Table 2a.

In Piper diagram [11] the water plots within the earth alkaline type with prevailing bicarbonate (Fig. 5). In the Durov diagram [12] the water plots close to the line of dissolution of rock-matrix minerals or mixing with other types of waters (Fig. 6). Compared with the groundwater along the recharge areas of the sandstone aquifer (See Kurnub water below) the water in the B2/A7 contains slightly higher concentrations of Ca^{2+} , Mg^{2+} , Na^+ , Cl^- and SO_4^{2-} which is normal for a calcareous aquifer compared to a well flushed sandstone aquifer. The water is a typical carbonate water with $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ and $\text{HCO}_3^- + \text{Cl}^- > \text{SO}_4^{2-}$.

The ionic ratios of Na/Cl range from unity to about 0.5 indicating that Cl^- must have another source than halite. Also the higher than unity $(\text{Ca} + \text{Mg}) / (\text{HCO}_3^- + \text{SO}_4^{2-})$ ratios indicate that Ca and Mg must have other anions than SO_4^{2-} and HCO_3^- involved in the water. NO_3^- concentrations and the position of springs in highly and densely populated areas indicated that the water is somehow polluted, where additional Ca and Mg salts are added to the water (Table 2b).

The water in the B2/A7 aquifer is under saturated with respect to aragonite and calcite, strongly under saturated with dolomite, anhydrite, gypsum, and strongly under saturated with Halite (Table 2c).

3.2 Groundwater in the lower Upper Cretaceous (A1-A6)

The Upper Cretaceous aquifer consists of argillaceous limestone. This poorly developed aquifer receives very limited amounts of direct recharge by precipitation or flood flows. Its groundwater

results from downward percolation of overlying aquifers' groundwater, mainly in the B2/A7 aquifer. Due to the presence of evaporate residues in Formations A 1-3 and A 5,6 the salinity of the groundwater changes as a function of water residence time in the aquifer, recharge/discharge mechanisms and location relative to the evaporate residues concentrations in the rock formation. Therefore, the composition of the groundwater varies between that of the overlying B2/A7 aquifer, the source water and water affected by evaporates.

Table 3a lists some of the analyses of the groundwater in the A1-A6 with their salinities which range from about 845 to about 1210 $\mu\text{S}/\text{cm}$. In Piper diagram (Fig. 5) the water of this group plots within the earth alkaline type with no dominant cat ions but very close to sulphate and chloride waters. In the Durov diagram (Fig. 6) the water plots in the dissolution/mixing regime, but the geology, recharge and discharge mechanism of the groundwater suggests dissolution of the rock matrix rather than mixing with other groundwater types. With $\text{Ca}^{2+} \sim \text{Mg}^{2+} \sim \text{Na}^+ > \text{K}^+$ and $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$.

The Na/Cl and $\text{Ca} + \text{Mg}/(\text{HCO}_3^- + \text{SO}_4^{2-})$ meq ratios are around unity indicating at dissolution of aquifer matrix, without ion exchange reactions (Table 3b).

The water in these rocks is either slightly under saturated with respect to calcite, dolomite and aragonite and anhydrite, intermediately unsaturated in respect to gypsum and strongly unsaturated with respect to halite (Table 3c).

3.3 Groundwater in the Lower Cretaceous rocks (Kurnub); direct recharge

The Lower Cretaceous Sandstone Aquifer (Kurnub) receives direct recharge from precipitation falling over its outcrops along Wadi Zarqa and in Baqa'a areas. Indirect recharge takes place through downward infiltration from the overlying A1-A6 units.

The salinity of the groundwater along the outcrops of Kurnub Aquifer ranges from around 500 to 850 $\mu\text{S}/\text{cm}$ (Table 4a).

The groundwater along these outcrops plots in the Piper diagram within the earth alkaline type with prevailing bicarbonate (Fig. 5). In the Durov diagram the water plots close to the line of dissolution of rock matrix minerals or mixing with other types of waters (Figure 6) with $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+$ and $\text{Cl}^- = \text{HCO}_3^- > \text{SO}_4^{2-}$ (Figure 8c).

The Na/Cl and $(\text{Ca} + \text{Mg}) / (\text{HCO}_3^- + \text{SO}_4^{2-})$ ratios are around unity indicating dissolution of rock matrix without ion exchange. Mixing processes with other groundwater is improbable due to the geologic set-up of the area where the Kurnub sandstone crops out without overlying Upper Cretaceous rocks to be found in the immediate vicinity (Table 4b).

The water in this aquifer is slightly under saturated with respect to calcite, aragonite and dolomite and intermediately under saturated with respect to gypsum and anhydrite and strongly under saturated with respect to halite (Table 4c).

3.4 Groundwater in the Lower Cretaceous rocks (Kurnub) originating from the Upper Cretaceous rocks

Water in this aquifer originates from the upper Lower Cretaceous limestone containing evaporate residues. It is percolating into the underlying Lower Cretaceous (Kurnub Group) sandstones. The

Lower Cretaceous rocks crop out only along some deep incised wadis or in small areas, where the Upper Cretaceous has been totally eroded along the course of Zarqa River rather than mixing with other groundwater.

Groundwater in this Group shows moderate salinities ranging from 1120 to about 2300 $\mu\text{S}/\text{cm}$ (Table 5a). Generally, the water plots in the Piper diagram within the earth alkaline type with some groundwater sources having high contents of alkalis and prevailing bicarbonate and chloride (Fig. 5). In the Durov diagram the water composition plots with very good fit on the dissolution/mixing line (Fig. 6), with $\text{Mg}^{2+} > \text{Ca}^{2+} > \text{Cl}^- > \text{HCO}_3^- \geq \text{SO}_4^{2-}$.

When comparing the chemistry of the groundwater in the lower parts of the Upper Cretaceous with the major source of water in the Lower Cretaceous it can be recognized that the groundwaters in the Lower Cretaceous are less diversified and represent a very close, to each other, cluster of compositions. This can be explained by mixing of different amounts of downward leakages from the Upper Cretaceous groundwater, which results from leaching of randomly distributed evaporate residues, into the lower parts of the Upper Cretaceous Formations.

The Na/Cl ratios are about 1 and the $(\text{Ca}+\text{Mg})/(\text{HCO}_3+\text{SO}_4)$ ratios are in some samples more than 1 indicating leaching of some CaCl_2 brines, which might have resulted from dolomitization processes in the aquifer matrix (Table 5b).

The water in this group is slightly under saturated with respect to calcite, aragonite and dolomite and intermediately under saturated with respect to gypsum and anhydrite and strongly under saturated with respect to halite (Table 5c).

3.5 Groundwater in the Jurassic and Triassic rocks (Zarqa Group)

Naturally the groundwater in these Formations originates mainly from the Lower Cretaceous groundwater percolating down into Jurassic and Triassic rocks. The latter do not receive any appreciable direct recharge because they crop out only along the steep slopes of Zarqa River and the Jordan Valley. The groundwater of these formations shows relatively high salinity ranging from 2000 to about 9000 $\mu\text{S}/\text{cm}$ depending on the evaporates or evaporate residues, which vary strongly from one place to another within the Jurassic and Triassic Formations in Jordan [13].

3.6. Gypsum mines springs

Springs in the gypsum mines have salinities of about 3000 to 4500 $\mu\text{S}/\text{cm}$. Such water originates from the overlying rocks and have a short history of recharge, flow and discharge, hence their relative to other Triassic rocks their low salinity (Table 6a). In Piper diagram the water plots in the normal earth alkaline water with prevailing sulphate (Fig. 5) and in Durov diagram on the reverse ion exchange curve (Fig. 5) with $\text{Mg}^{2+} \geq \text{Ca}^{2+} > \text{Na}$ and $\text{SO}_4^{2-} > \text{Cl}^- > \text{HCO}_3^-$. The Na/Cl ratios of 0.46 to 0.75 and the $(\text{Ca}+\text{Mg})/(\text{HCO}_3+\text{SO}_4)$ ratios of 1.13 to 1.41 indicate that other Ca and Mg salts than sulphates and carbonates contribute to the composition of the water (Table 6b).

The Water is under saturated with respect to calcite, aragonite, gypsum anhydrite and intermediately under saturated with respect to dolomite and strongly under saturated with halite (Table 6c). Table 6a: Analytical results of the major constituents of the

springs in the gypsum mines EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l

The NO_3^- content is very low in areas not affected by human activity, but it increases dramatically in some deep wells such as JICA 1 and the deep source spring of Sweima. This indicates that Jurassic and Triassic evaporates may be the source of nitrate. Such high NO_3^- concentrations were also observed in the groundwater of the evaporate-containing Lisan deposits in the Jordan Valley area [14].

3.7 Triassic and Jurassic groundwater in the exploration boreholes of King Talal Dam

The groundwater in these rocks was analyzed during the investigations for the construction of King Talal Dam in the 70s of the last century. Samples were collected from bore holes and analyzed by Energo-Project facilities [15].

The results are listed in Table 7a. The water in these wells show generally high salinities and it seems that the higher salinities indicate at the contact of the water with the upper parts of the Triassic rocks containing the evaporates. It indicates also that the groundwater in the Jurassic and Triassic rocks used to be artesian at that time as the groundwater piezometric levels in the investigation study shows [15].

The salinity of the water ranged from 3200 to 10188 $\mu\text{S}/\text{cm}$. The water is mainly composed of NaCl with high calcium concentrations relative to Mg concentrations with the exception of sample Rd-1 which originates from the upper part of the Jurassic rocks, not affected by the lower Jurassic rocks but far more by the overlying far lower salinity Kurnub rocks.

In piper diagram the water plots in the earth alkaline type with increased portions of alkalis and prevailing sulphate (Fig. 5) and in Durov diagram on the reverse ion exchange curve (Fig. 6). $\text{Mg}^{2+} \geq \text{Ca}^{2+} > \text{Na}^+$ and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$. The Na/Cl and the $(\text{Ca}+\text{Mg})/(\text{HCO}_3+\text{SO}_4)$ equivalent ratios in Table 7b are around unity indicating the dissolution of halides and gypsum from the rock matrix which can be explained by the presence of evaporate formations in the Triassic rocks from where the groundwater moves up through the overlying Jurassic rocks to discharge at the surface. Effects of ion exchange are not to be expected. The water in this group is intermediately under saturated with respect to calcite and dolomite aragonite and anhydrite and strongly unsaturated with respect to halite (Table 7c).

3.8 Abu Zigan wells

Abu Zigan wells were drilled in the vicinity of the old Deir Alla thermal mineralized spring formerly used as spa [16]. They produce water originating from the Jurassic and mainly Triassic rocks which is then desalinated for use as drinking water. The salinity of the different springs range from 3980 to 13550 $\mu\text{S}/\text{cm}$. The pH values range from 6.28 to 6.94 indicating together with the

In Piper diagrams this water plots in the similar of alkaline to earth alkaline water with prevailing chloride (Fig. 5). In Durov diagrams (Fig. 6) they plot around the dissolution of gypsum, halides and carbonates seems to be the dominant process with water containing high concentration on Na^+ corresponding to Cl^- , Ca^{2+} and Mg^{2+} corresponding to SO_4^{2-} and HCO_3^- .

The Na/Cl ratios range from 0.8 to 1.28 and indicate dissolution of halite salt. The $(\text{Ca}+\text{Mg})/(\text{SO}_4+\text{HCO}_3)$ ratios range from 0.77 to 1.10 also together with high concentrations of all the

parameters indicate at dissolution of gypsum and carbonates, where the HCO_3^- concentration range from 9.00 to 24.6 meq/l, but is generally higher than 16 meq/l (Tables 8b).

The water of Abu Zigan wells is under saturated with respect to Anhydrite, Gypsum, Aragonite and calcite and very strongly under saturated in respect to dolomite and halite (Table 8c).

3.9 River deep well (Thermal mineral) a few km's from Abu Zigan

This well was drilled in the 90s of last century into the Triassic rocks producing artesian thermal water with a head of tens of meters above ground level. The salinity of the well has always been high of around 14000 $\mu\text{S}/\text{cm}$ (Table 9a). The water plots in Piper diagram in the alkaline water type with prevailing chlorides (Fig. 5). In Durov diagram it plots on the dissolution mixing line (Fig. 6). It is mainly composed of sodium chloride. The Na/Cl ratio is around 1.2 showing the excess Na content and the $(\text{Ca} + \text{Mg})/(\text{HCO}_3 + \text{SO}_4)$ of less than 1 indicate the presence of sodium carbonate in the well water (Table 9b).

4. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The groundwater chemistry along outcrops of rock formations, irrespective of the aquifer type such as sandstone, limestone, dolomite, etc. is of low salinity which generally does not exceed 1000 $\mu\text{S}/\text{cm}$ with pH values ranging from 7.0 to 8.3 and the water is generally of earth alkaline type with prevailing bicarbonates.

The down leaking groundwater from the recharge water along the outcrops of the Upper Cretaceous aquifer B2/A7 into the lower aquifers of the Upper Cretaceous A1-6 show higher salinities than the water in the in the B2/A7. They range between 845 and 1210 $\mu\text{S}/\text{cm}$. The pH values lie in the range of 6.5–8.3. The water is of earth alkaline type with increasing portions of alkalis and prevailing sulfate. The diversity of the water composition in this group reflects the different rates of dissolution of evaporates especially gypsum and/or anhydrite in accordance with the presence and distribution of evaporate residues in the A1-6 Formations.

The leakages from the A1-6 into the Lower Cretaceous sandstone (Kurnub) produces water with EC values of 1120 to about 2300 $\mu\text{S}/\text{cm}$ of earth alkaline type with increasing portions of alkalis and prevailing sulfates. Worth mentioning here is the high permeability of the Kurnub aquifer; $5 \times 10^{-5} \text{m/s}$ and hence its capability to enhance mixing processes of waters leaking from the overlying calcareous, low permeability, poorly developed aquifers waters. The mixing process compensates somehow the diversity of water chemistries of the overlying A1-6 Formations (Fig. 7).

The Jurassic and Triassic Aquifer contains water with higher salinities of more than 3000 $\mu\text{S}/\text{cm}$ which reflects dissolution of minerals from the rock matrix including gypsum and halite beds and their residues as disseminated in the rock matrix.

Triassic and Jurassic aquifers underlying the Lower Cretaceous rocks receive generally only leakages from the overlying rocks. Figure 8 shows the confined Triassic and Jurassic rocks in the study area which contain thick evaporate deposits, especially gypsum and anhydrite and which are reflected in the composition of their groundwater with salinities ranging from 2200 to 8700 $\mu\text{S}/\text{cm}$.

The water in the Triassic and Jurassic rocks is of earth alkaline to alkaline type with prevailing sulphate and chloride.

Historical consideration: After the last regression of the Tethys during the Miocene [3] the thickness of the sediments covering the Triassic Gypsum Formation must had been the total thickness of the overlying Jurassic, Cretaceous and Tertiary rocks of a range of 1390 to 1640 m (Calculated from Bandel and Salameh [1]. The lithologic pressure of this rock sequence, considering an average rock density of 2.5 g/cm^3 , is calculated to range from 347.5 to 410 kg/cm^2 or about 3500 to 4100 Newton. The temperature, at such a depth of around 1500m, of the evaporate formation, considering a geothermal gradient of 30 to 38.8 $^\circ\text{C}/1000\text{m}$ (along the mountains and in the Jordan Valley area [17], and adding to it a ground surface temperature of 20 $^\circ\text{C}$) result in a gypsum layer temperature of 63 to 78 $^\circ\text{C}$. Under such pressures and temperatures gypsum is not stable and it loses water to form anhydrite [4]. Erosion of the over burden and down cutting of the Zarqa River must have gradually relieved the Triassic Formations of the over burden pressure and the formation temperature must have accordingly dropped. The water of Zarqa River became in direct contact with the anhydrite, especially along weakness zones of cracks, joints and fissures and changed it into gypsum. That change from anhydrite into gypsum is accompanied with an increase in volume of up to 60%, hence leading to up-arching of the gypsum Formation along the Zarqa River course. Overlying rocks formed then an anticlinal bending and exposed the gypsum at the surface along the lower reaches of Zarqa River.

At the entrance of Zarqa River into the Jordan Valley, a thermal mineralized spring discharged, until before around 15 years, 3-5 l/s of brackish water of about 8000mg/l, which was used for therapeutic purposes. Due to acute water needs and encouraged by the presence of this water, the Ministry of Water and Irrigation drilled a series of wells to exploit the source of this water at Abu Zigan, desalinate the pumped water and use it for drinking. The modest original natural spring flow of 3-5l/s was increased by artificially pumping the groundwater to about 500l/s. This policy turned to be a mining process of the aquifer. But water from Zarqa River seems to have started infiltrating along the intermediate river course into the river bed and its underlying aquifers to substitute the extracted water.

Discharge measurements of Zarqa River before the drilling of Abu Zigan wells in 1994 [18] show that upstream of Abu Zigan wells, in Tell Thahab area, the discharge during 22 to 24 September 1994 was 600 l/s, whereas downstream, in Abu Zigan area, it was 1450 and 1326, respectively, although along this reach of the River no surface water inflows are found in this time of the year. The outflow from the Triassic and Jurassic aquifers is the difference between these measurements of 726 – 850 l/s. The discrepancy can be related to illegal water pumping from the River along the measured portion. Another measurement after rainfall, resulted in an upstream discharge of 960 l/s whereas the downstream one reached 1670 l/s an increase of 710 l/s [18].

In average JICA [18] calculated a gain of 100 l/km of water for Zarqa River from the Jurassic and Triassic sequences. This shows that the Zarqa River along this portion, between Tell Thahab and Abu Zigan was effluent before starting pumping water from Abu Zigan, whereas, at the present time the River is influent into the groundwater. The whole system of surface and groundwater in the area and the water exchange has been artificially disturbed [19]: Surface water has been partially diverted for irrigation in closed pipe system to produce pressurized irrigation water in the Jordan Valley, some water is left to flow along the natural River course for local irrigation and to join KAC in the Jordan Valley and the

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deep groundwater which used leak upwards to join the Zarqa River has been extracted from Abu Zigan wells causing drops in the groundwater levels. And as a result of that the surface water of Zarqa River started to infiltrate into the aquifers to replace the exploited salty groundwater from the Jurassic and Triassic aquifers (Figs. 9 and 10).

The zigzag nature of the Zarqa River downstream of King Talal dam causes decreases in the water velocity of the River and allows for larger amounts of the River water to infiltrate and reach the lowered groundwater table due to pumping. This is in so far true because the zigzag course of the Zarqa River is a result of high rock jointing causing higher infiltration potential for the River water. In addition,

In Tell Thahab area a deep well was drilled into the Triassic aquifer. It produced flowing artesian thermal water with a salinity of around 14000 $\mu\text{S}/\text{cm}$. The piezometric head of a few tens of meters above ground surface after drilling has in the mean time gradually dropped and the water head is now at ground surface.

Zarqa River water has a salinity of around 2000 $\mu\text{S}/\text{cm}$ throughout the year, whereas the extracted groundwater has a salinity of 5000 to 10000 $\mu\text{S}/\text{cm}$ with an average weighted salinity of 6500 $\mu\text{S}/\text{cm}$. This means that each litre of extracted water in Abu Zigan area dissolves around 4500 $\mu\text{S}/\text{cm}$ of salts as a result of Zarqa River water infiltration (2000 $\mu\text{S}/\text{cm}$) into the Triassic rocks (6500 $\mu\text{S}/\text{cm}$) and extraction via the wells. 4500 $\mu\text{S}/\text{cm}$ are equivalent to about 3g of salts per litre of extracted water.

This means that the yearly extracted water amount of 16 MCM of the brackish Triassic water removes an amount of aquifers salts of 48×10^3 tons per year ($3\text{g}/\text{l}$ salt removal = $3\text{kg}/\text{m}^3$, multiplied by 16 MCM/yr = 48×10^6 kg). Considering evaporates density of $2\text{g}/\text{cm}^3$ results in creating a total cavity volume of 24×10^3 m^3/yr . When such cavities enlarge year after year they become interconnected and big cavities form and their ceilings start to collapse and to form sink holes at ground surface (Fig. 11 and 12). Sink holes in Abu Zigan area were not observed until before 6 years ago, but since then sink hole collapses started to form. First signs of collapses and sink hole formation were observed in 2010 and major collapses of 6 m in diameter and 5-6 m in depth started appearing in 2012. And although they were refilled by earth materials in 2013, they have been collapsing and sinking again since then.

The consequence of extracting the deep salty and brackish groundwater in Abu Zigan area is enhancement of infiltration of overlying fresh groundwater in the Lower Cretaceous rocks and the surface water of Zarqa River into the Jurassic and Triassic rocks where this infiltrating water dissolves evaporates; mainly gypsum and halite, creating cavities in these rocks which when progressing lead to collapses and formation of sink holes (Figs. 11 and 12).

Since the extracted groundwater is, at the end, being substituted by shallow aquifers water and surface water of Zarqa River, the whole process of extracting water from the Jurassic and Triassic Formations is in its end effects quasi extraction of water from Zarqa River itself.

The extraction of the deep brackish and saline water and desalinating it turned to be a vanity process with very huge environmental and economic consequences because, in addition to the above mentioned environmental negative impacts, the Water Authority is paying the cost of well construction, the pumping and the desalination among others, but at the same time allowing the

fresh water of Zarqa River to infiltrate down into the evaporate rock sequences, dissolve them and become saline. It would have been a more appropriate strategy from an environmental, geological and economic points of view to treat and use Zarqa River water with its impaired water quality instead of causing its water to infiltrate down to substitute the extracted salty water, and to become itself salty causing geological and engineering geological detriments in the form of sink holes and land collapses.

The case of Abu Zigan water scheme should serve as an example of the damage which can be caused by decisions taken without adequate rigorous environmental impact assessment of projects.

The study recommends to stop Abu Zigan saline water extraction and to use Zarqa River water instead, directly or indirectly from the shallow aquifer along its course and that is because of the negative environmental, hydrogeologic, engineering geologic and economic implication of Abu Zigan groundwater extraction and desalination project. Continuing with groundwater pumping, desalination and use through Abu Zigan scheme will cause further geotechnical, hydrological, hydro- and geochemical hazards. In addition the project is an unnecessary economic loss project to the government of Jordan.

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APPENDIX

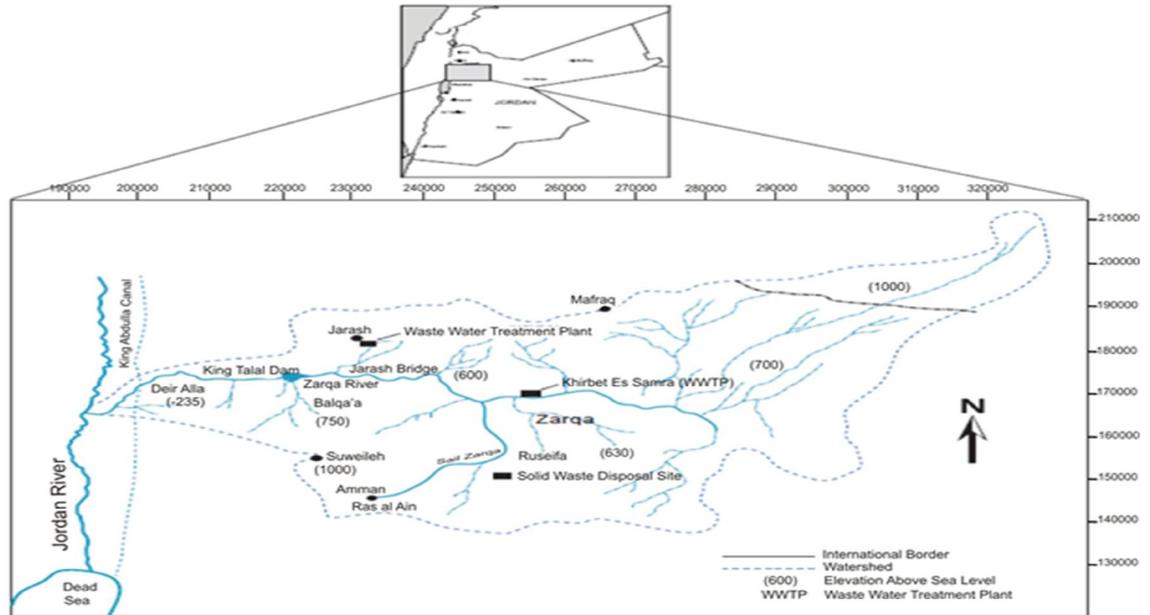


Fig. 1: Location map of the study area

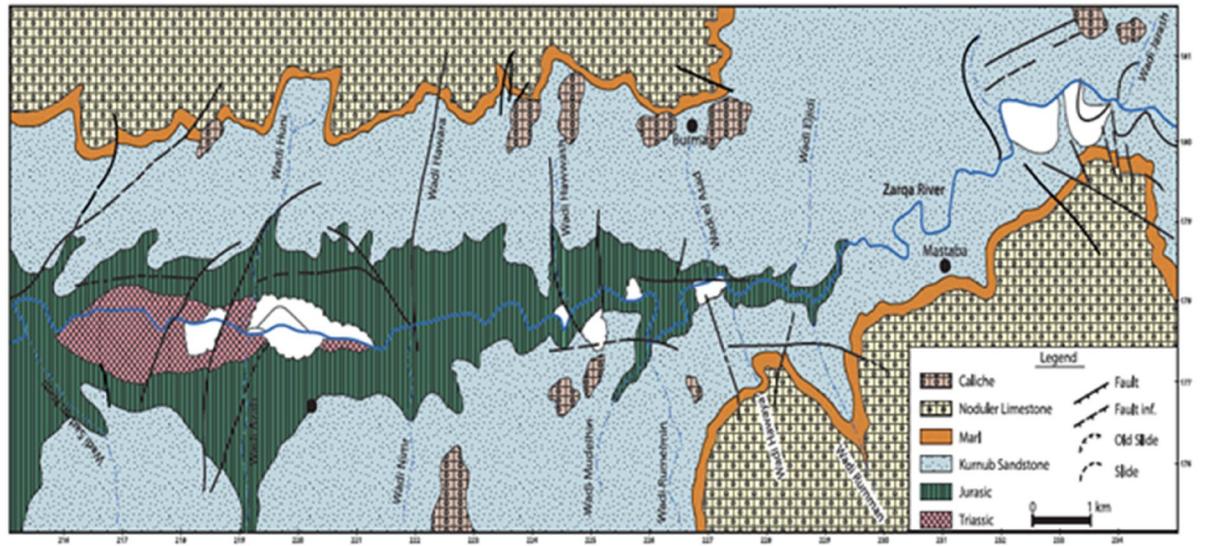


Fig. 2: Geologic map of the lower Zarqa River (modified from NRA map; Salt Sheet)

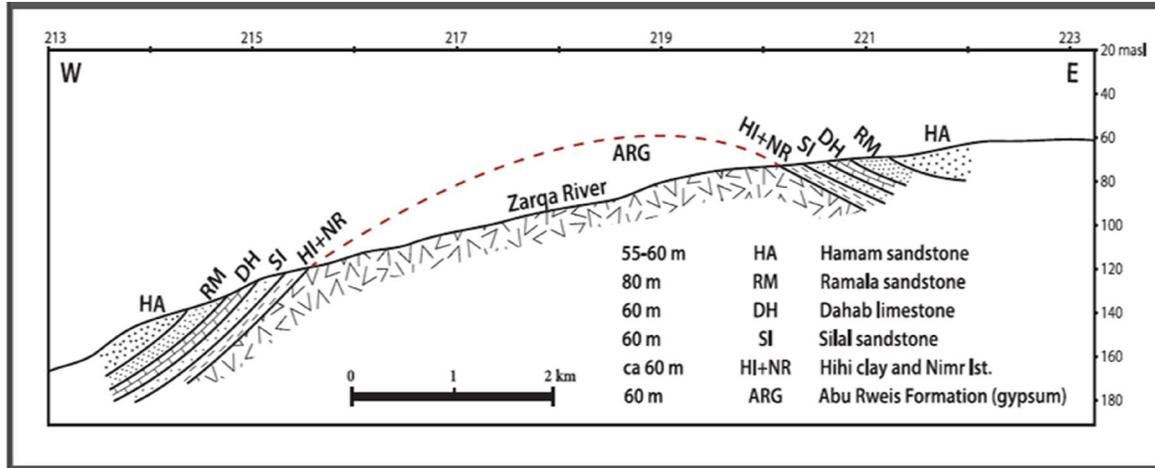


Fig. 3: Anticlinal bending as a result of salt (Gypsum) tectonics in the lower reaches of Zarqa River (Corresponding to Fig. 2. For more details on the geologic sub units refer to Bandel and Salameh [1] or to NRA open files Salt sheet[6])

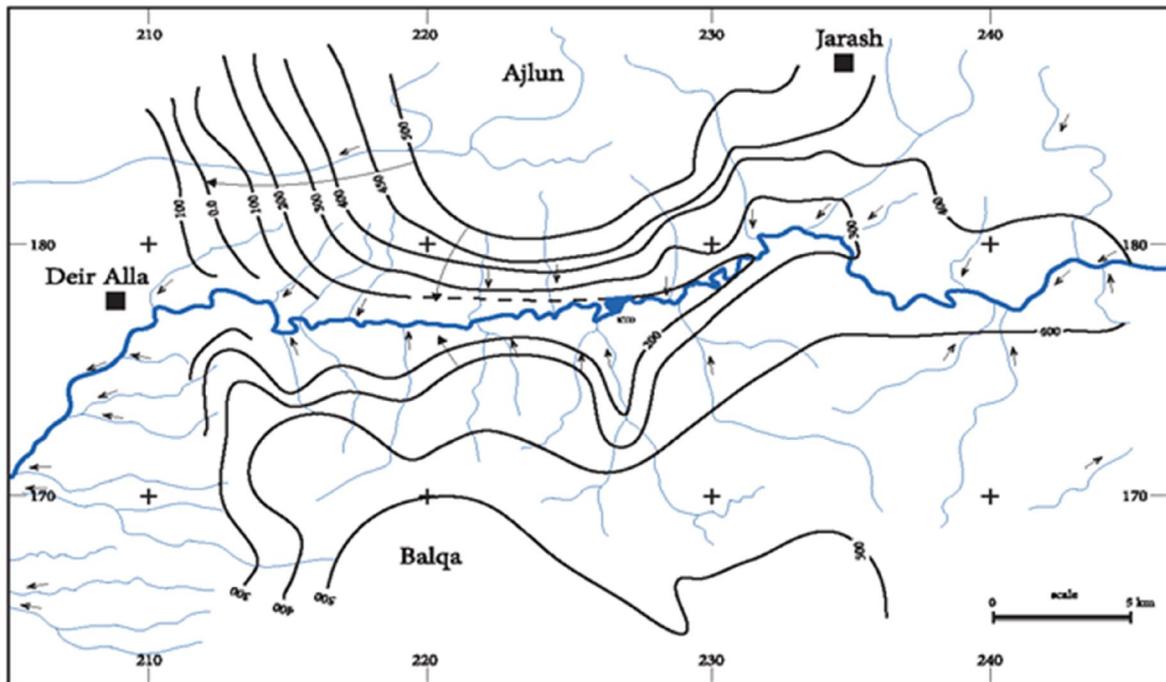


Fig. 4: The Groundwater flow pattern in the Deep Aquifer Complex (Kurnub, Jurassic and Triassic) along the Zarqa River (Groundwater Resources Northern Jordan BGR [4])

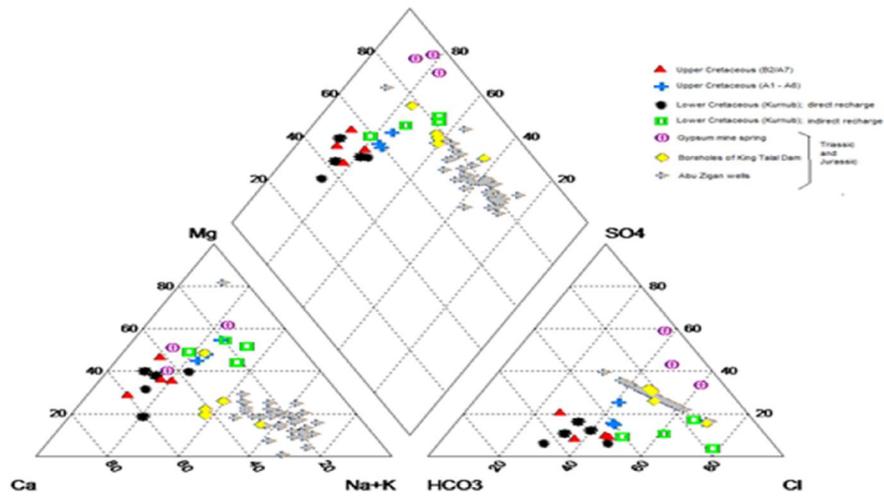


Fig. 5: Piper diagram for the different aquifers' waters in the study area

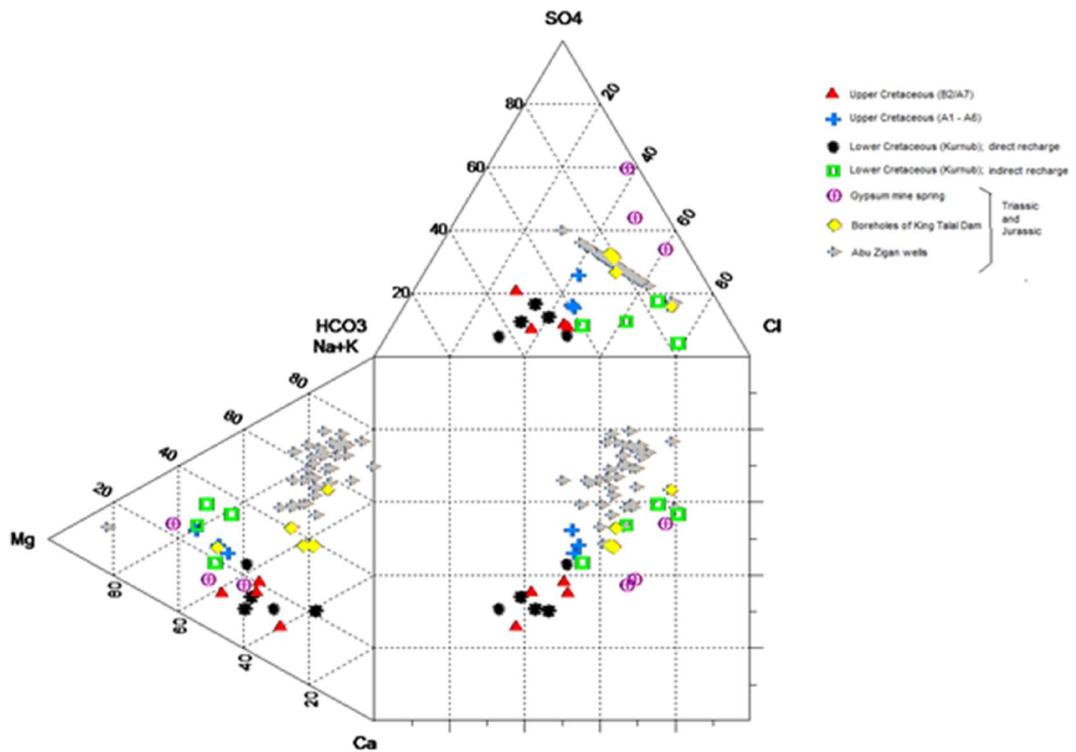


Fig. 6: Durov diagram of the different aquifers water in the study area

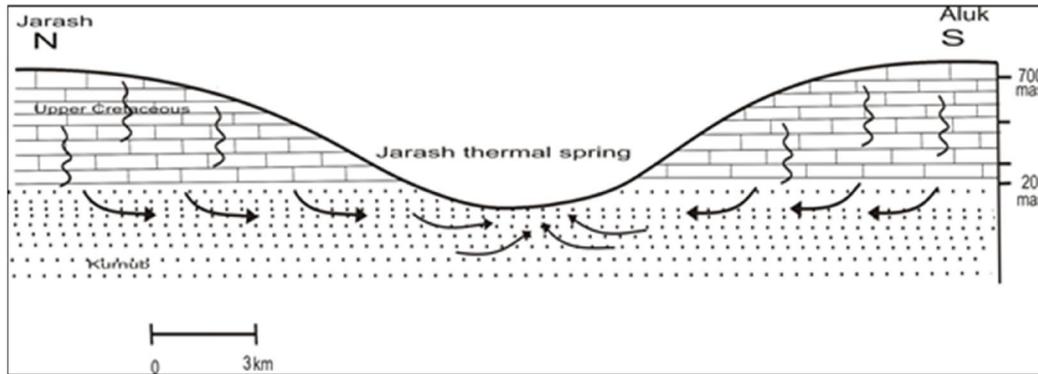


Figure 7: Water leakages from the Upper Cretaceous A1-6 Formations into the Lower Cretaceous Kurnub Formation dissolving evaporate residues from the A1-3 Formations and feeding Zarqa River in its upstream area

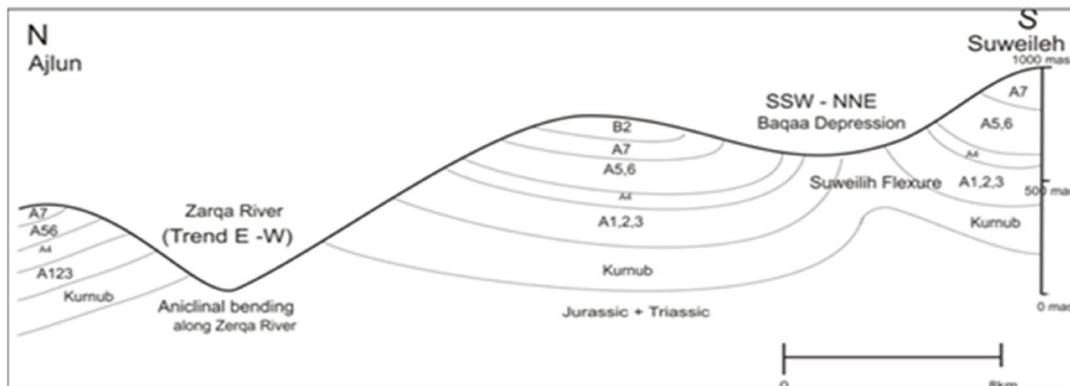


Figure 8: General simplified geological cross section from Ajlun to Suweilih area showing the general structure of the highlands and the recharge area along the out crops of rock formations where the water salinity is low and the confined Triassic and Jurassic rocks which contain the thick evaporate deposits, especially gypsum and anhydrite (Balqa and Ajlun Mountains)

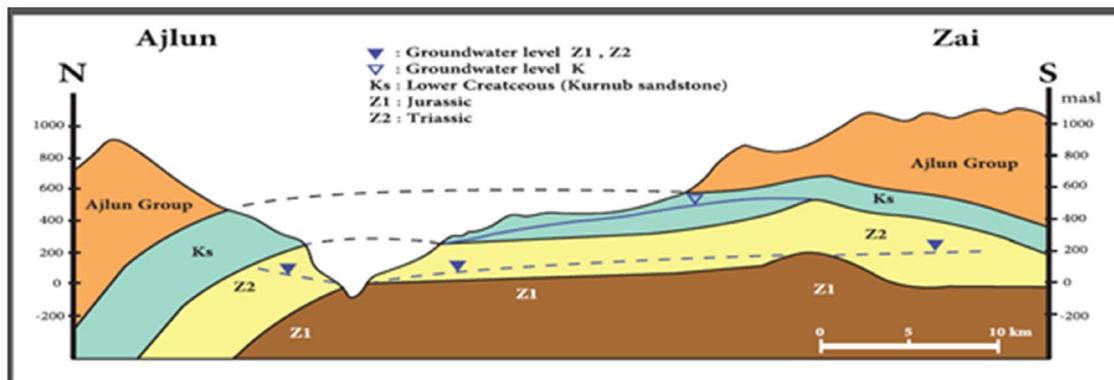


Figure 9: Geologic cross section along Zarqa River from Ajlun to Zai area showing the tilting of beds as a result of evaporates uplift and the naturally effluent deep aquifer complex, which after drilling Abu Zigan wells stated to be recharged from the overlying aquifers and from Zarqa River water

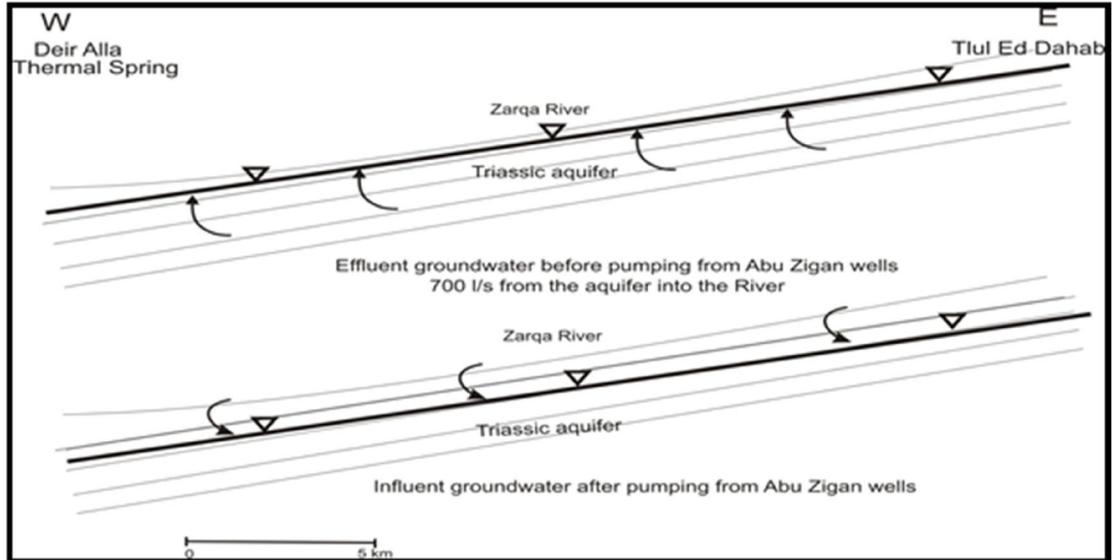


Figure 10: Changes from influent to effluent Zarqa River due to groundwater extraction in Abu Zigan area



Fig. 11: Sink holes developed in the same place of at the end of 2014, although it was filled in 2012



Fig. 12: A sink hole as developed in 2012. It was filled with earth in the same year

Table 2a: Analytical results of the major constituents of the B2/A7 sampled water sources (EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l)

Sample	EC	pH	Temp.	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-
Yajuz	542	7.5	18.5	3.4	1.6	1.42	0.038	1.5	0.455	3.8	0.46
Ras el Ain	750	7.82	26.5	4.1	2	2.11	0.12	2.5	0.73	4.33	0.71
Ruseifa	650	7.6	22.6	3.28	2.23	1	0.09	2.06	0.54	3.39	0.32
Suweileh	800	7.75	18.7	5.46	1.6	1.15	0.1	1.57	1.6	5.22	0.4

Table 2b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components B2/A7 sample

Sample	Na/Cl	Mg/Ca	Ca/HCO_3	HCO_3/Cl	$(\text{Ca}+\text{Mg})/\text{HCO}_3$	$(\text{Ca}+\text{Mg})/(\text{HCO}_3+\text{SO}_4)$	$(\text{Na}+\text{K})/\text{Cl}$	Ca/SO_4
Yajuz	0.95	0.47	0.90	2.53	1.32	1.32	0.97	7.47
Ras el Ain	0.84	0.48	0.95	1.73	1.41	1.41	0.89	5.62
Ruseifa	0.49	0.68	0.97	1.65	1.63	1.63	0.53	6.07
Suweileh	0.73	0.29	1.05	3.33	1.35	1.35	0.80	3.41

Table 2c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the analyzed B2/A7 samples

Sample	SI (Anhydrite)	SI (Aragonite)	SI (Calcite)	SI (Dolomite)	SI (Gypsum)	SI (Halite)
Yajuz	-4.85	-2.36	-2.21	-4.37	-4.63	-9.80
Ras el Ain	-5.08	-2.83	-2.68	-5.21	-4.85	-10.19
Ruseifa	-4.41	-2.34	-2.18	-4.65	-4.17	-10.24
Suweileh	-5.15	-2.92	-2.77	-5.62	-4.90	-10.17

Table 3a: Analytical results of the major constituents of the A1-6 sampled water sources (EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l)

Sampling site	EC	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Abu Hamed sp.	1200	8.35	3.2	5.1	4.2	0.34	4	1.9	6.2
Mobas	885	7.5	3.36	2.86	2.74	.08	3.1	1.35	4.70
Abu Nusseir	845	7.35	3.16	3.26	3.07	0.09	2.83	2.33	3.96

Table 3b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components A1-6 samples

Na/Cl	Mg/Ca	Ca/HCO ₃	HCO ₃ /Cl	(Ca+Mg)/HCO ₃	(Ca+Mg)/(HCO ₃ +SO ₄)	(Na+K)/Cl	Ca/SO ₄
1.05	1.59	0.52	1.55	1.34	1.02	1.14	1.68
0.88	0.09	7.15	1.52	7.76	6.03	0.91	24.89
1.08	1.03	0.80	1.40	1.62	1.02	1.12	1.36

Table 3c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the analyzed A1-6 samples

Sampling site	SI (Anhydrite)	SI (Aragonite)	SI (Calcite)	SI (Dolomite)	SI (Gypsum)	SI (Halite)
Abu Hamed sp.	-4.5897	-1.9006	-1.7532	-3.0211	-4.3524	-9.2843
Mobas	-4.4872	-3.0749	-2.9274	-5.5587	-4.2499	-9.567
Abu Nusseir	-3.8078	-1.8746	-1.7271	-4.2411	-3.5706	-9.596

Table 4a: Analytical results of the major constituents of the sampled water sources from the Kurnub Direct recharge (EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l)

Sampling site	EC	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Jazzaza sp.	680	7.30	3.97	1.92	1.37	0.08	1.50	0.64	4.40
Subeihi sp. 6	850	6.50	3.90	2.50	2.56	0.28	2.90	0.48	4.90
Burma sp. 30	508	8.0	3.72	0.68	1.43	0.04	1.63	0.66	3.41
Burma sp. 20	756	7.42	4.59	2.24	1.10	0.05	1.68	1.06	4.20
Shami well	590	7.40	3.55	1.25	1.00	0.22	1.11	0.29	4.16

Table 4b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components Kurnub direct recharge samples

Sampling site	Na/Cl	Mg/Ca	Ca/HCO ₃	HCO ₃ /Cl	(Ca+Mg)/HCO ₃	(Ca+Mg)/(HCO ₃ +SO ₄)	(Na+K)/Cl	Ca/SO ₄
Jazzaza sp.	0.91	0.48	0.90	2.93	1.34	1.17	0.97	6.30
Subeihi sp.	0.88	0.64	0.80	1.69	1.31	1.19	0.98	8.13
Burma sp. 30	0.88	0.18	1.09	2.09	1.28	1.08	0.90	5.61
Burma sp. 20	0.59	0.48	1.09	2.26	1.62	1.29	0.60	4.33
Shami Ibrahim	0.90	0.35	0.85	3.75	1.15	1.08	1.11	12.24

Table 4c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the analyzed Kurnub direct recharge water sources (EC in $\mu\text{S}/\text{cm}$)

Sampling site	EC	SI (Anh.)	SI (Ara.)	SI (Calcite)	SI (Dol.)	SI (Gyps.)	SI (Halite)
Jazzaza sp.	680	-2.34	-0.39	-0.24	-0.73	-2.1	-7.35
Subeihi sp. 6	850	-2.48	-0.36	-0.21	-0.54	-2.25	-6.8
Burma sp. 30	508	-2.31	-0.51	-0.37	-1.4	-2.07	-7.29
Burma sp. 20	756	-2.08	-0.36	-0.21	-0.68	-1.85	-7.36
Shami Ibrahim	590	-2.69	-0.44	-0.29	-0.97	-2.45	-7.61

Table 5a: Analytical results of the major constituents of the Kurnub samples water (indirect recharge) (EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l)

Sampling site	EC	pH	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	Cl^{-}	SO_4^{-2}	HCO_3^{-}
Burma Sara sp.	1435	7.70	3.97	4.9	7.24	0.05	9.05	0.55	3.6
Burma sp. 19	1287	8.22	3.16	5.31	4.59	0.39	5.49	1.25	4.4
Sihan sp.	1120	6.75	4.59	4.18	2.99	0.04	3.85	0.95	5.4
Um Tell sp.	2290	8.10	4.18	8.67	10.57	0.09	12.2	4.19	5.3

Table 5b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components of the Kurnub(indirect recharge) water samples

Sampling site	Na/Cl	Mg/Ca	Ca/ HCO_3	HCO_3/Cl	(Ca+Mg)/ HCO_3	(Ca+Mg)/ (HCO_3+SO_4)	(Na+K)/Cl	Ca/ SO_4
Burma Sara sp.	0.80	1.23	1.10	0.40	2.46	2.14	0.81	7.22
Burma sp. 19	0.84	1.68	0.72	0.80	1.93	1.50	0.91	2.53
Sihan sp.	0.78	0.91	0.85	1.40	1.62	1.38	0.79	4.83
Um Tell sp.	0.87	2.07	0.79	0.43	2.42	1.35	0.87	1.00

Table 5c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the analyzed Kurnub (indirect recharge) water

Sampling site	EC	SI (Anh.)	SI (Ara.)	SI (Cal.)	SI (Dol.)	SI (Gyps.)	SI (Halite)
Burma Sara sp.	1435	-2.54	-0.55	-0.4	-0.64	-2.3	-5.88
Burma sp. 19	1287	-2.26	-0.55	-0.4	-0.51	-2.02	-6.29
Sihan sp.	1120	-2.21	-0.3	-0.15	-0.27	-1.97	-6.63
Um Tell sp.	2290	-1.75	-0.44	-0.29	-0.19	-1.51	-5.61

Table 6a: Durov diagram of the different aquifers water in the study area

Sample	EC	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁺	CO ₃ ²⁺	HCO ₃ ⁻	NO ₃ ⁻
Wadi Alhuna	3550	7.70	15.56	13.32	6.31	0.39	13.60	16.90	0.00	4.88	0.02
Mine Quarry 2	3040	7.60	22.60	12.78	10.10	0.30	13.50	28.90	0.00	2.49	0.52
Mine Quarry 2	3040	7.90	6.14	15.01	10.60	0.11	16.10	12.02	0.00	3.01	0.80

Table 6b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components of the gypsum mines water samples

Sample	Na/Cl	Mg/Ca	Ca/HCO ₃	HCO ₃ /Cl	(Ca+Mg)/HCO ₃	(Ca+Mg)/(HCO ₃ +SO ₄)	(Na+K)/Cl	Ca/SO ₄
Wadi Alhuna	0.46	0.86	3.19	0.36	5.92	1.33	0.49	0.92
Mine Quarry 1	0.75	0.57	9.08	0.18	14.21	1.13	0.77	0.78
Mine Quarry 2	0.66	2.45	2.04	0.19	7.03	1.41	0.67	0.51

Table 6c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the water samples of the gypsum mines

Sample	SI- Anh.	SI -Arag.	SI -Cal.	SI -Dolo	SI -Gyps.	SI Halite
Wadi Alhuna	-2.70	-2.26	-2.11	-4.19	-2.46	-8.40
Mine Quarry 1	-3.60	-2.42	-2.27	-3.879	-3.36	-8.29
Mine Quarry 2	-3.067	-2.01	-1.86	-3.51	-2.83	-8.60

Table 7a: Analytical results of the major constituents of the Triassic and Jurassic groundwater in the exploration boreholes of King Talal Dam (EC in µS/cm; concentrations in meq/l)

Sample	EC	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Bu-4-1 (L. most Ju)	10188	6.72	33.6	10.08	70.5	3.75	72.22	21	24.7
Rd-3 (L. Ju)	6200	6.9	24.56	11.12	30.5	3.1	27.95	19.32	22.34
Rd-1 (Upper Ju)	3200	7	11.18	11.48	10	0.7	12.56	10.75	9.89
Rd-4 (L. Ju)	6500	6.69	32.25	8.6	30	4.9	27.93	26.01	23.17
Rd-4 (L. Ju)	6810	6.5	30.9	9.99	29	4.15	27.74	24.72	21.8
Rd-3 (L. Ju)	6690	6.5	32.25	8.9	30	4.9	27.93	26.01	23.17

Table 7b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components of King Talal Dam exploration wells water samples.

Sample	Na/Cl	Mg/Ca	Ca/ HCO ₃	HCO ₃ /Cl	(Ca+Mg)/ HCO ₃	(Ca+Mg)/ (HCO ₃ +SO ₄)	Na+K)/Cl	Ca/SO ₄
Bu-4-1 (L. most Ju)	0.98	0.30	1.36	0.34	1.77	0.96	1.03	1.60
Rd-3 (L. Ju)	1.09	0.45	1.10	0.80	1.60	0.86	1.20	1.27
Rd-1 (U. Ju)	0.80	1.03	1.13	0.79	2.29	1.10	0.85	1.04
Rd-4 (L. Ju)	1.07	0.27	1.39	0.83	1.76	0.83	1.25	1.24
Rd-4 (L. Ju)	1.05	0.32	1.42	0.79	1.88	0.90	1.20	1.25
Rd-3 (L. Ju)	1.07	0.28	1.39	0.83	1.78	0.84	1.25	1.24

Table 7c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the water samples of King Talal Dam exploration wells water samples

Sample	SI-Anhy	SI-Arag	SI-Cal	SI-Dol	SI-Gyp	SI-Hal
Bu-4-1 (L. most Ju)	-2.73	-2.00	-1.85	-3.95	-2.49	-6.84
Rd-3 (L. Ju)	-3.38	-2.53	-2.39	-4.48	-3.15	-8.43
Rd-1 (Upper Ju)	-2.62	-2.25	-2.10	-4.47	-2.38	-7.62
Rd-4 (L. Ju)	-2.85	-1.97	-1.83	-3.71	-2.61	-7.61
Rd-4 (L. Ju)	-2.66	-2.29	-2.14	-4.49	-2.42	-7.64
Rd-3 (L. Ju)	-2.62	-2.06	-1.91	-4.11	-2.38	-7.62

Hydro & Engineering Geological Implications of Extracting the Salty Deep Groundwater on the Mobilization of Fresh Water Resources in the Lower Zarqa River Area, Jordan

Table 8a: Analytical results of the major constituents of the Triassic and Jurassic groundwater in Abu Zigan wells (Sub numbers of wells refer to analyses number, EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l H₂S smell of the water at reducing conditions (Tables 8a)

Sample	EC ($\mu\text{S}/\text{cm}$)	pH	Temp	Ca ²⁺	Mg	Na ⁺	Cl ⁻	SO ₄	HCO ₃ ⁻
Well 1	3980	6.35	26.30	12.00	8.00	22.79	21.77	12.03	8.99
Well 2	6590	6.59	28.20	28.00	18.00	30.27	35.93	29.35	17.51
Well 3	7820	6.93	28.30	27.00	10.00	51.25	48.86	27.07	18.11
Well 4	13390	6.61	28.60	37.00	19.00	92.37	91.971	34.96	23.40
Well 5	6410	6.50	32.90	29.00	11.00	39.56	33.10	29.25	17.052
Well 6	7920	6.32	28.90	32.00	13.00	47.68	43.83	28.25	19.50
Well 7	16350	6.57	27.80	48.00	5.00	119.77	114.25	47.58	26.67
Well 8	4880	6.23	28.00	29.00	8.00	18.76	20.12	25.61	17.91
Well 9	7710	6.44	28.10	27.00	9.00	50.70	46.71	27.81	17.91
Well10	9040	6.44	28.30	26.00	13.00	64.14	56.05	27.63	19.10
Well 11	10060	6.67	27.40	31.00	10.00	69.34	63.95	28.73	19.900
Well 12	4310	6.43	27.20	14.14	8.08	24.77	22.30	13.23	11.27
Well 13	8320	6.33	27.20	36.00	5.00	53.60	50.30	5.71	18.11
Well 14	16120	6.24	26.80	39.00	40.00	106.31	140.94	26.54	17.56
Well 15	12560	6.26	27.00	34.00	21.00	82.29	81.96	31.94	23.38
Well 16	13750	6.44	26.80	35.00	16.00	100.71	100.66	26.19	24.85

Table 8b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components of Triassic and Jurassic in Abu Zigan wells

Sample	Na/Cl	Mg/Ca	Ca/HCO ₃	HCO ₃ /Cl	(Ca+Mg)/HCO ₃	(Ca+Mg)/(HCO ₃ +SO ₄)	Ca/SO ₄
Well 1	1.05	0.67	1.33	0.41	2.22	0.95	0.10
Well 2	1.07	0.53	1.55	0.60	2.36	0.95	1.05
Well 3	1.05	0.37	1.49	0.37	2.04	0.82	0.10
Well 4	1.004	0.51	1.58	0.25	2.39	0.96	1.06
Well 5	1.195	0.379	1.701	0.52	2.346	0.864	0.99
Well 6	1.09	0.41	1.64	0.45	2.31	0.94	1.13
Well 7	1.05	0.10	1.80	0.23	1.99	0.71	1.01
Well 8	0.93	0.28	1.62	0.89	2.07	0.85	1.13
Well 9	1.09	0.33	1.51	0.38	2.01	0.79	0.97
Well10	1.14	0.50	1.36	0.34	2.04	0.84	0.94
Well 11	1.08	0.32	1.56	0.31	2.06	0.84	1.08
Well 12	1.11	0.57	1.25	0.51	1.97	0.91	1.07
Well 13	1.07	0.14	1.99	0.36	2.26	1.72	6.30
Well 14	0.75	1.03	2.22	0.12	4.50	1.79	1.47
Well 15	1.00	0.62	1.45	0.29	2.35	0.99	1.06
Well 16	1.00	0.46	1.41	0.25	2.05	1.00	1.34

Table 8c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the water samples of in Abu Zigan

Sample	SI Anhy	SI Arag	SI Cal	SI Dol	SI Gyp	SI Hal
Well 1	-3.29	-3.10	-2.96	-5.73	-3.07	-7.85
Well 2	-2.63	-2.23	-2.09	-3.98	-2.43	-7.53
Well 3	-2.66	-1.89	-1.74	-3.54	-2.46	-7.17
Well 4	-2.50	-1.99	-1.85	-3.61	-2.29	-6.65
Well 5	-2.58	-2.24	-2.10	-4.20	-2.39	-7.46
Well 6	-2.69	-2.38	-2.24	-4.39	-2.48	-7.01
Well 7	-2.59	-2.39	-2.25	-4.49	-2.39	-7.25
Well 8	-2.25	-1.89	-1.74	-4.09	-2.04	-6.45
Well 9	-2.63	-2.54	-2.40	-4.98	-2.42	-7.98
Well10	-2.65	-2.38	-2.24	-4.57	-2.44	-7.19
Well 11	-2.60	-2.07	-1.93	-3.97	-2.39	-6.92
Well 12	-3.18	-2.84	-2.70	-5.27	-2.97	-7.80
Well 13	-3.20	-2.36	-2.22	-4.92	-2.99	-7.13
Well 14	-2.67	-2.51	-2.37	-4.36	-2.45	-6.41
Well 15	-2.57	-2.40	-2.25	-4.35	-2.36	-6.75
Well 16	-2.64	-2.18	-2.04	-4.05	-2.43	-6.57

Table 9a: Analytical results of the major constituents of the Triassic and Jurassic groundwater in river deep well (EC in $\mu\text{S}/\text{cm}$; concentrations in meq/l)

Sample	EC	Temp	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Thermal well	14270	35.2	6.19	15.3	10.25	141.7	2.9	112.3	21.6	34.8

Table 9b: Equivalent ionic ratios of parameters relevant to the present study as indicators of dissolution of rock components of Triassic and Jurassic in river deep well

Sample	Na/Cl	Mg/Ca	Ca/HCO ₃	HCO ₃ /Cl	(Ca+Mg)/HCO ₃	(Ca+Mg)/(HCO ₃ +SO ₄)	(Na+K)/Cl	Ca/SO ₄
Thermal well	1.26	0.67	0.44	0.31	0.73	0.45	1.29	0.71

Table 9c: Saturation indices (SI) for anhydrite, aragonite, calcite, dolomite, gypsum and halite for the water samples of in in river deep well

Sample	SI Anhy	SI Arag	SI Cal	SI Dol	SI Gyp	SI Hal
Thermal well	-3.0132	-2.5191	-2.3824	-4.4928	-2.8429	-6.3916