Leakage in Bayer Dam in Jordan: Its Causes and Consequences

Hani Al-Omosh [1], Mohammad Al-Farajat [2] and Franz Zunic [3]

[1] Former Ph.D. Student, University of Jordan, Jordan
[2] Assistant Professor, Institute of Earth and Environmental Sciences, Al al-Bayt University, Jordan,
Correspondent Author, alfarajat@aabu.edu.jo
[3] Associate Professor, Institute of Hydraulic and Water Resources Engineering, Technical University of Munich, Germany

ABSTRACT

This research deals with engineering and environmental problems in karst in a geological context. In this study, geologic and geomagnetic investigations have been applied at the site of Bayer dam and revealed severe shallow karstic processes prevailing in the limestone bedrock – under a three meters thick alluvium cover – which forms the unsealed floor of the dam. The measurements done on groundwater of local ancient shallow dug wells in the surrounding of the dam showed the occurrence of fresh water which was attributed to the leakage that took place. The named wells have been known previously to be dry.

The quality of the collected water in the shallow aquifer is prone to drinking purposes. Saturation indices of minerals point to that the leaked water is under-saturated with respect to calcite, gypsum, aragonite, magnesite, dolomite and anhydrite. This emphasizes that more leakage of water through the narrow passages of joints and fissures in the rocks will accelerate karstic processes in the area. This enhances the secondary permeability of the shallow aquifer and calls for groundwater artificial recharge in the area, but on the other hand and with the presence of the prevailing cavities it threatens the dam, unless scientific solutions are found.

KEYWORDS: Karstification, Geomagnetic method, Groundwater recharge.

INTRODUCTION

Many efforts have been done in Jordan to overcome water scarcity, which is attributed to low rainfall amounts, high rates of evaporation, rising demands and overexploitation, besides that pollution of some surface and groundwater resources takes place (Salameh, 1996).

The government of Jordan with the aid of local and international programmes works on overcoming this situation, by working on short and long term plans like water harvesting, Dead-Red Sea project to desalinate seawater making use of difference in topographic elevations between Aqaba and the Dead Sea, installing a pipeline between Disi basin and Amman to make available around 100 MCM per year of drinking water, rehabilitation of drinking water nets in some cities like Amman and Irbid to reduce loss by leakage, in addition to other programmes (MWI, 2008).

Hashmite Fund (HF) is a national program put by the government to find producing projects related to water in the Jordanian desert (Badia) and villages. The outcome of the projects named contributed to find income sources for poor people and new job opportunities. Water harvesting and recycling treated domestic waste-water are targets HF makes use from (HF, 2008).

In 2006, HF decided to build a dam in the Bayer area (Fig.1), which is located about 200 km south eastern the capital Amman. The area is an unpopulated region and out of services and infrastructure. It forms a part of the

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Jordanian Badia, where some Bedouin tribes own lands and practice activities of animal husbandry like sheep and goats. This made the area in need for projects of stocks plantation to sustain the named activities.

Climatically, Bayer is a hot dry arid region, with an annual rainfall which amounts to less than 50 mm (Fig. 2). Floods occur only in winter in rainy wet years, and flow through the wadis. The dam has been chosen to be built on the Wadi of Bayer (Fig. 3).

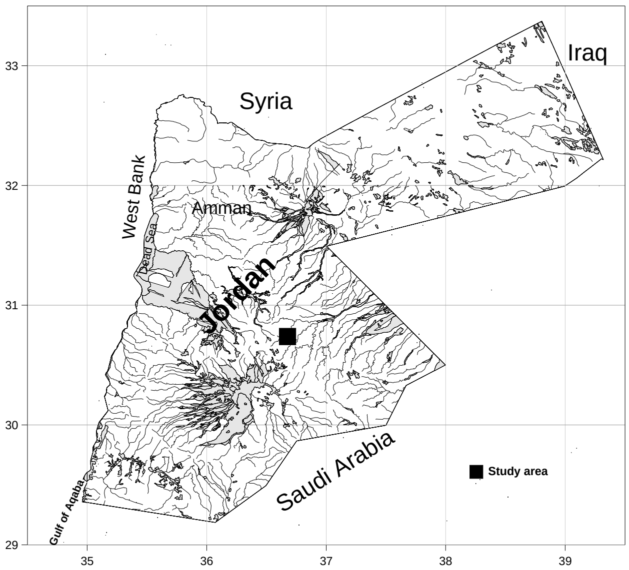

Figure (1): Location of the study area.

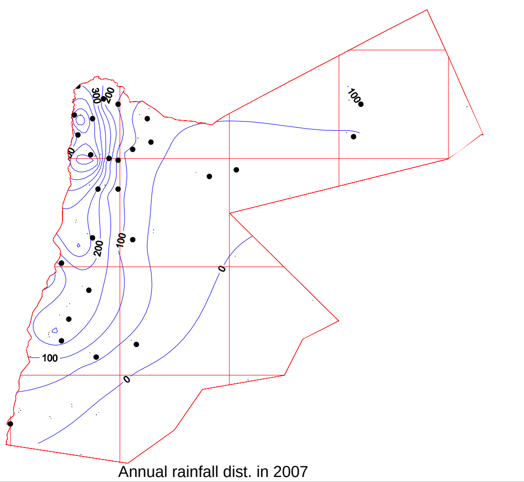

Figure (2): Annual rainfall distribution in Jordan in 2007.

Groundwater in the area is deep (more than 300 m) and is of brackish type. The absence of electricity in the area makes it difficult to extract that water. HF before some years drilled a deep well in the area and made available a generator working with oil to enable locals to obtain water for their animals.

Some shallow dug wells are present nearer to Bayer Wadi and are considered as ancient wells going back to some hundreds of years. Recent records and observations of the locals point to that the wells were almost dry.

The internal policy of HF tries to reduce expenses as much as possible to widespread projects where it is possible in the country to achieve its aims. Accordingly, Jordan Military Forces with there engineering abilities constructed the dam, building a 6 m high rockfill dam, intersecting Wadi Bayer (Fig 4).

In winter of 2007/2008 the dam has been ready to receive the first floods and was able to collect 0.5 MCM. Some days later, the whole retained water disappeared within only a few hours (as stated by some locals). After the mud got dry, the HF field staff found a newly formed sinkhole in the middle of the floor of the dam, which is unsealed, with dimensions of 4x4 meters, and a depth of 3 meters. This hole caused the water sudden loss (Fig.5: a, b).

Site investigations were rare and not enough, because the expected storage capacity of the dam was not that large (less than 1 MCM per year).

The dug wells have been found to collect fresh water only some days after the leakage from the dam.

This research aims at evaluating the shallow subsurface geology of the dam, because the direct geologic cause of the occurrence of the hole is still unknown, whether it is tectonic or related to soft rock dissolution processes (karst). On the other hand, the research aims at investigating the hydrogeological and hydrochemical situations of the dug wells in the surrounding and the role of the dam in recharging the upper aquifer.

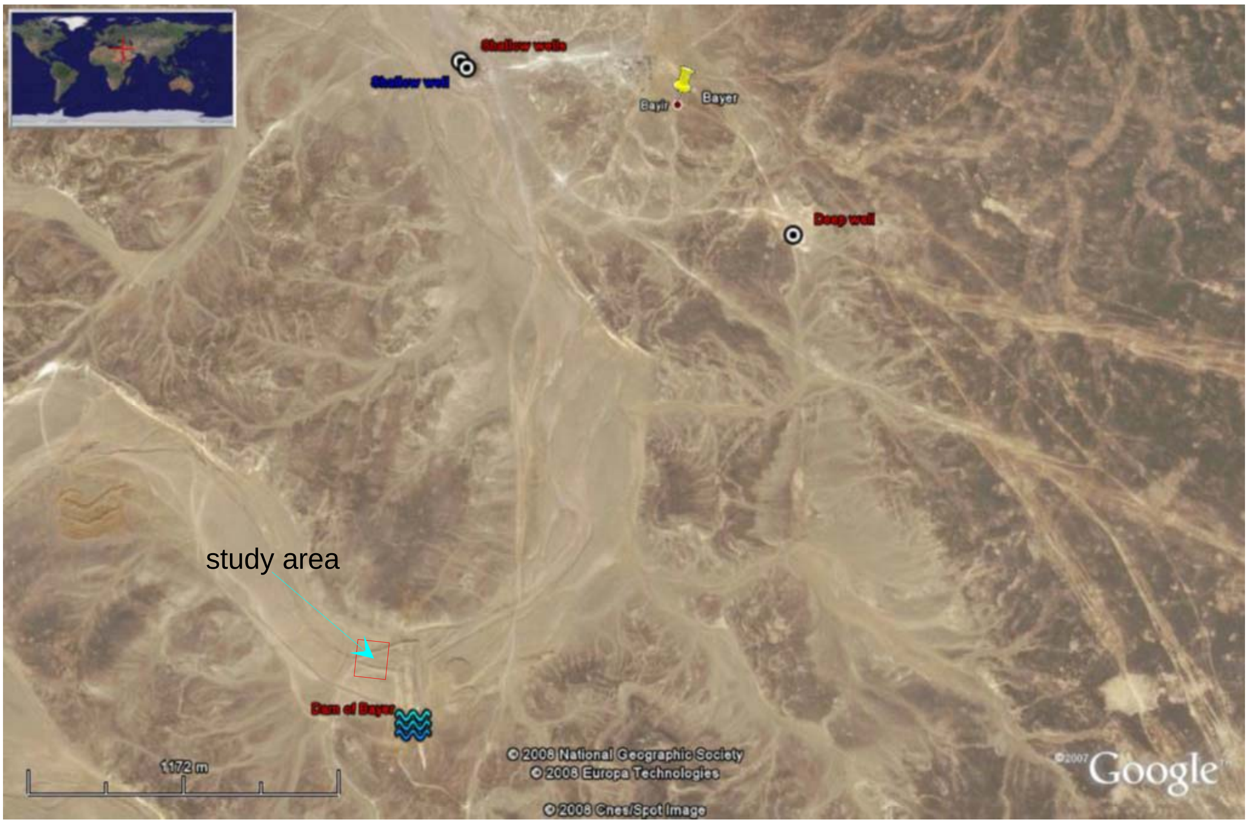

Figure (3): Location of the dam in Bayer Wadi, and the surrounding wells.

Figure (4): The rockfill and reservoir of Bayer dam.

Figure (5): (a) Location of the sink in the reservoir of the dam, and (b) The dimensions of the sink.

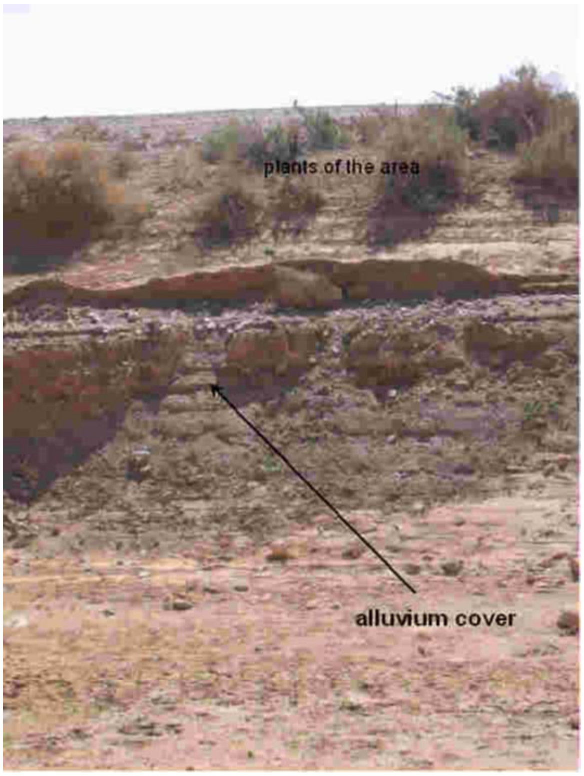

Figure (6): Alluvium covers in the study area.

Figure (7): Sinkhole in the study area.

Figure (8): Dissolution along joints.

Figure (9): (a) Dissolutional pipes in the rocks.

Figure (9): (b) Severe dissolution in the rocks.

METHODOLOGY

In this research, filed geological survey was applied in the area of the dam and the surrounding areas. The outcropped layers beneath the alluvium cover were measured. Joints, cracks and dissolution features were investigated and measured in continuity, in addition to widths and directions.

High resolution geomagnetic survey (1 meter X 1 meter) was applied in a grid around the sinkhole, with dimensions of 20 meters south-north and 8 meters east-west. Proton magnetometer was used for this purpose. All steps have been taken into consideration during the survey to enable improving the signal of any cavities or widened joints in the near subsurface. The operator was asked to get rid of all metals that can disturb the survey process, and a reference station was installed in the middle of the grid to ease recording daily variations, for the purposes of data reduction. Measurement points were regular, and a 50 meters long plastic tape was used for this concern. No sun storms were detected at that day in reference to the regularity of the readings and also the specialized internet sites.

Hydroscope was used to measure the depth to groundwater in the wells, and polyethylene bottles were used to collect water samples from them. GPS was used to register the locations of the wells. The samples have been exposed to chemical analysis using titration methods, spectrophotometer and ICP tools. The American Standard Method for Water Analysis and German DI- Norms were used in the analysis of different parameters.

Locals from Bedouin tribes assisted in building a good picture about prevailing water situations in the shallow dug wells which have been out of any registration of the Ministry of Water and Irrigation in Jordan. Also, time between filling of the dam and disappearing of water was observed by the locals and they assisted us relatively in understanding the velocity of groundwater in the shallow aquifer.

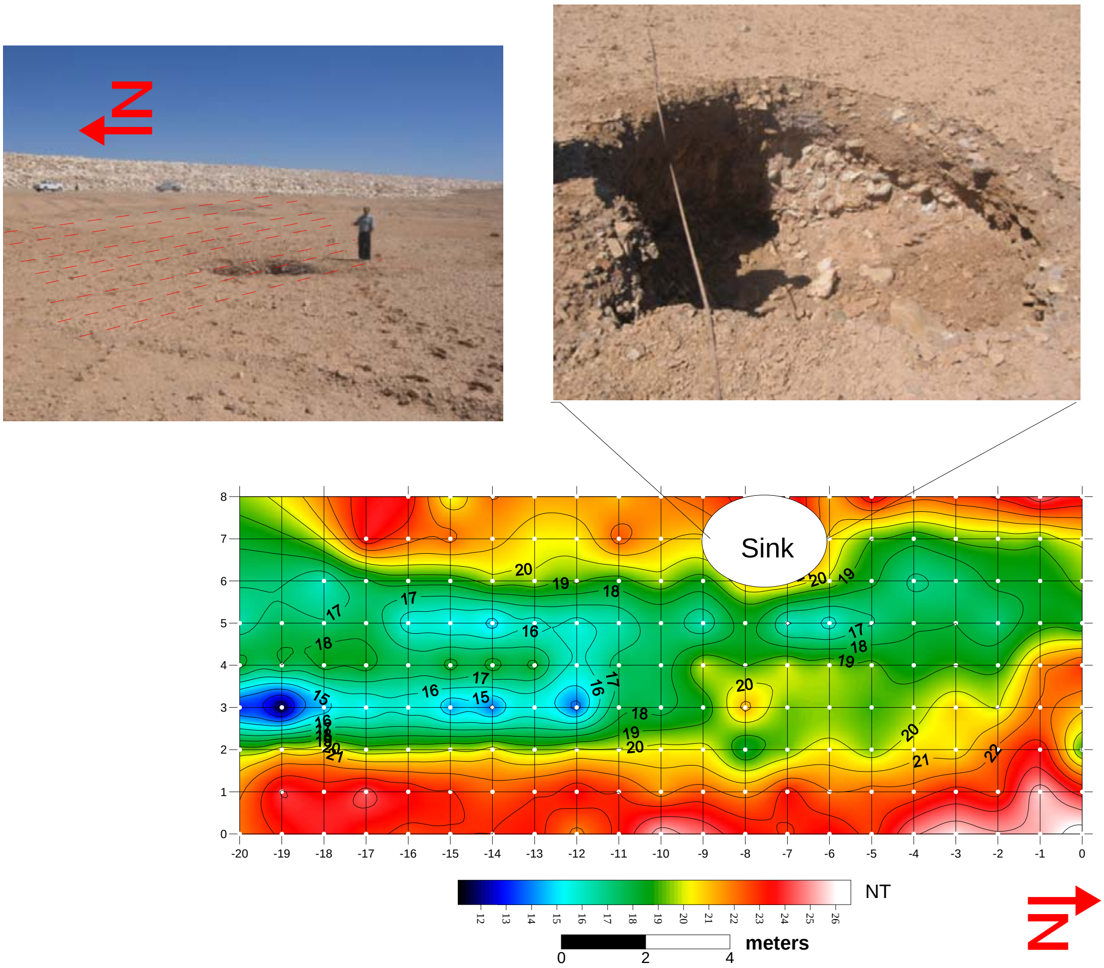

Figure (10): Location and extension of the geomagnetic profiles and the resulting map.

FIELD SURVEY (GEOLOGY)

In the course of this study, a geological field survey in the areas where the bedrock outcrops around the dam was done. Still the study area is out of the GIS national detailed geological mapping carried out by the Jordan Natural Resources Authority.

The study area which is a flat one mostly consists of hard carbonate rocks from Upper Cretaceous to Lower Tertiary, with no major and active faults. A three meters thick layer of alluviums (coming with floods) covers the rock formations all over the area (Fig. 6).

Only in lower floodplains, the upper geological formations can be outcropped. Several features of karst have been registered, including sinkholes of recent and old ages, with diameters between 2-8 meters and depths of a few meters (less than 4 meters) (Fig. 7). Land collapse was registered also in the body of the dam. Collapse sinkholes form when an underlying cave passage collapses forming a depression on the upper surface. These sinkholes are actually quite rare, as caves are generally stable.

Dissolution of rocks was found along joints and bedding plains, which in turn led to widening of these joints and plains to some centimeters (Fig. 8). The rocks are highly jointed and take two major directions; 10 and 130 degrees.

The rocks show dolines, connected dissolution channels and pipes. The named features are branched and extended (Fig. 9: a and b).

GEOMAGNETIC STUDY

Geophysical methods are known in the field of exploration of subsurface problems. Among them are seismic, resistivity, gravity and magnetic methods. Each method depends on the contrast of the received physical signals between the host and the guest rocks (Reynolds, 2000).

As stated in the methodology, a high resolution geomagnetic survey was applied in a grid around the produced sinkhole site. The measurements have been corrected after the readings of the base station. The results have not been reduced to the pole because the area of survey is less than 500x500 m, a matter which cancels effects of the distance to the pole.

The obtained results have the following statistics: number of values 176, minimum 11.1, maximum 26.6, mean 20.14 and standard deviation 2.934. Figure 10 illustrates the field survey in directions, locations and results. Units of survey are in NT (nano Tesla).

HYDROGEOLOGY AND WATER QUALITY

Some shallow dug wells (20-30 m deep) are available in the wadis overlooking the dam. But they seem to be dry since along time before the dam leakage (Fig. 11). The only available deep well is that which was drilled by HF. Two shallow wells and the deep well have been sampled. The water samples have been exposed to chemical analysis. The results are listed in Table 1.

Figure (11): An ancient well in the study area.

Using HYDROWIN, the analysis of the groundwater samples has been conducted on their statistics, and on the WHO regulations of drinking water quality. Potential for irrigation purposes has also been tested in terms of conductivity and Sodium Adsorption Ration. See Tables 2, 3, 4 and 5 consequently.

DISCUSSION

Bayer dam was constructed in the years 2006 and 2007 by the Jordanian Hashmite Fund in the eastern part of Jordan. As groundwater in the area is deep and brackish, the dam was built to collect around 1 million cubic meters of freshwater annually, to provide water for the dwellers in the nearby Bedouin communities and to cover the demands of animal husbandry. The 6 m high rockfill dam was constructed in Wadi Bayer to retain floods taking place in winter, although the climate there is described as hot and dry, with an annual rainfall of less than 50 mm. In the winter of 2007/2008 the dam collected around 0.5 million cubic meters, which suddenly disappeared within a few hours, some days later. The reason was a newly formed 3 meters deep sinkhole with dimensions of 4x4 meters that existed in the middle of the reservoir. Nowadays, dams have become multipurpose. A lot of relocation of resources needs to be undertaken before building a dam. Highways, railway tracks as well as homes need to be cleared to build dams. Detailed site investigation for dam constructions is a very important step that must be applied before any construction takes place. Dissolution in rock formations (karst) beneath the floor of body of the dam can contribute to a severe damage to the project, and cause unwanted consequences of both human and money loss.

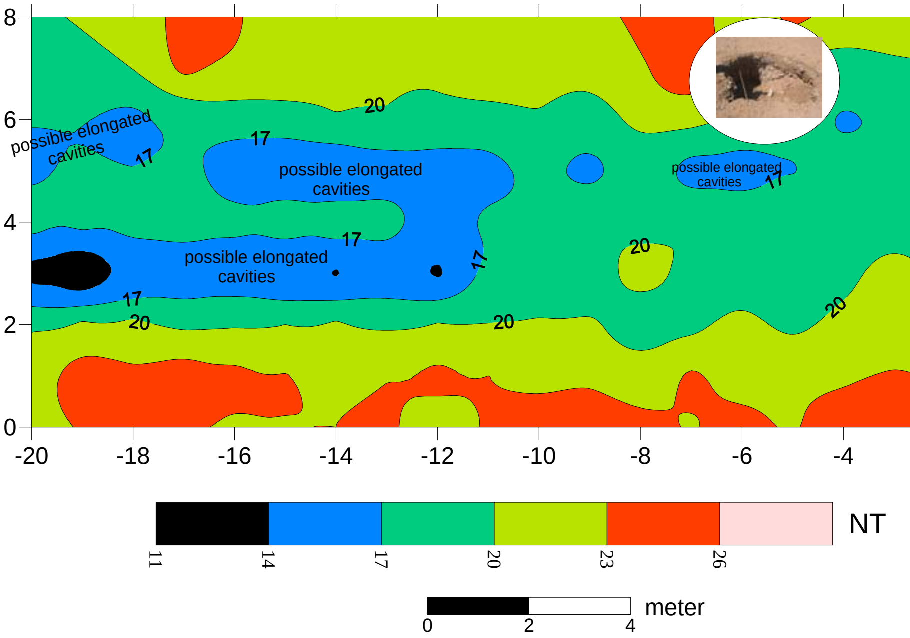

Figure (12): **Resulting map from the geomagnetic survey, showing the extension of the caves and dissolution features.**

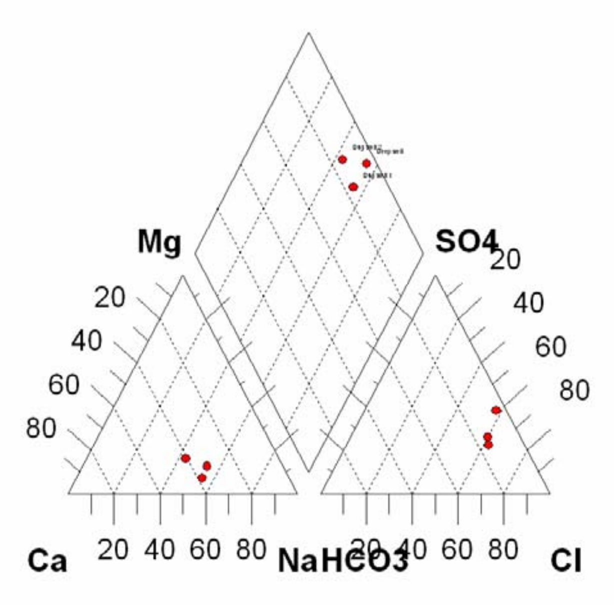

Figure (13): Piper diagram and water classes.

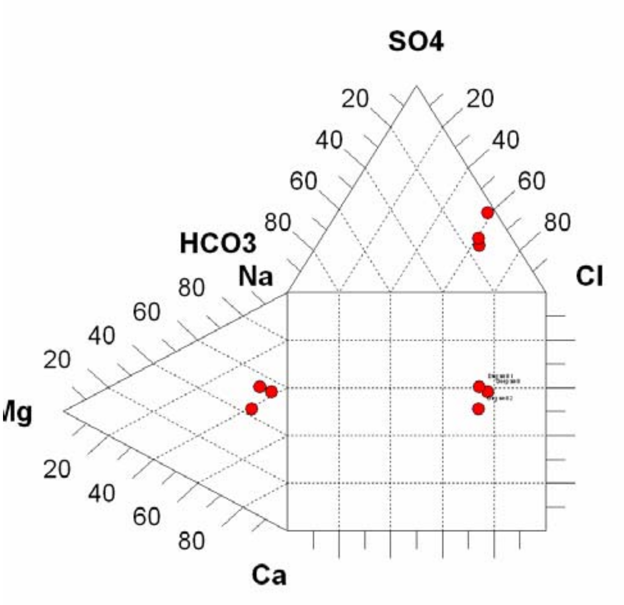

Figure (14): Durve Diagram and processes prevailing in water.

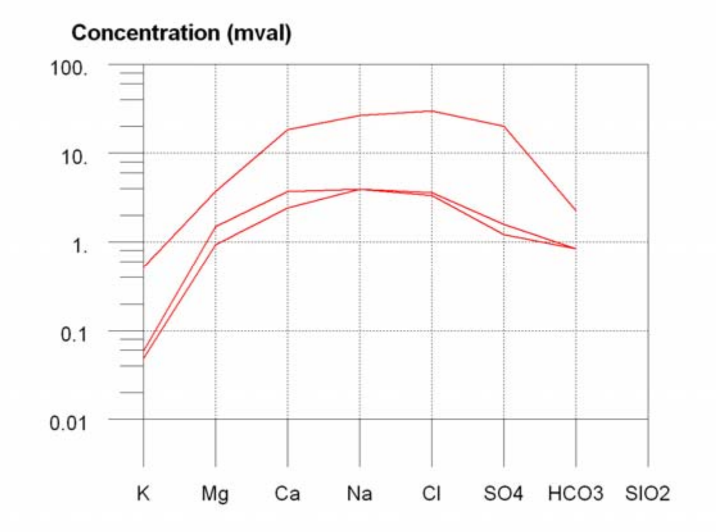

Figure (15): Schoeller diagram showing distribution of major constituents in the water samples.

Karst topography is a landscape shaped by the dissolution of a layer or layers of soluble bedrock, usually carbonate rock such as limestone or dolomite. Due to subterranean drainage, there may be very limited surface water, even to the absence of all rivers and lakes. Many karst regions display distinctive surface features, with sinkholes or dolines being the most common. Some karst regions include thousands of caves, even though evidence of caves that are big enough for human exploration is not required. Karst regions contain aquifers that are capable of providing large supplies of water. More than 25 percent of the world's population either live on or obtain their water from karst aquifers. Natural features of the landscape such as caves and springs are typical of karst regions. Karst landscapes are often spectacularly scenic areas (White et al., 1989). Common geological characteristics of karst regions that influence human use of its land and water resources include ground subsidence, sinkhole collapse, groundwater contamination and unpredictable water supply. Much of the present knowledge on the hydrogeology of karstic regions is found in textbooks by Ford and Williams (1989) and White (1988). Engineering aspects in karst regions are discussed in textbooks by James (1992), Breznik (1998) and Milanovic (2000).

The revealed geological features through the geological survey in the study area like dolines, cavities, sinkholes, widened joints and cracks, pipes and channels inside rocks point to that the area is karstified. However, distinctive karst surface features may be completely absent where the soluble rock is mantled, such as by glacial debris, or confined by superimposed non-soluble rock strata like in our case in the site of Bayer dam, which is covered by alluviums.

The surface geology in the area is composed of carbonate rocks in different forms like limestone, dolomite, silicified limestone, marl and chalk, all belonging to the Upper Cretaceous and Lower Tertiary. Mostly the layers are flat suffering no tectonics, a matter which is normal in the eastern part of Jordan (Abed, 2000). The alluviums in the area cover the kart phenomena, and the possibility to observe karstic features exists only in outcrops of the bedrock in low floodplains. Relatively, it seems that the phenomena took place in accelerating rates in previous periods when the area had higher rainfall amounts. On the other hand, it seems also that the filling of the dam with water increased the load on the weak roofs of some caves and led to the existence of the sinkhole in the dam reservoir.

Table (1): Results of the chemical analysis on the water samples.

Sample	EC	TDS	pH	Ca	Mg	Cl	Na	SO_4	K	HCO_3	CO_3	PO_4	NO_3
Deep well	3400	2900	7.8	370.7	45	1064.2	610	967.31	20.2	136.7	0	0	14.66
Dug well 1	650	400	6.9	48.2	11.3	118.48	90	58.47	1.9	51	0	0	8.24
Dug well 2	680	430	7.14	74.2	18.1	127.9	90	75.72	2.3	51.3	0	0	9.64

Table (2): Statistics on the different chemical items.

	Coeff.Var.%	Max.	Min.	Average	St. Dev.	Dev.
K	1.9	20.2	8.133	10.452	128.508	91.0
Mg	11.3	45.0	24.8	17.821	71.859	75.0
Ca	48.2	370.7	164.367	179.162	109.002	87.0
Na	90.0	610.0	263.333	300.222	114.008	85.0
Cl	118.48	1064.2	436.86	543.313	124.368	89.0
SO_4	58.47	967.31	367.167	519.811	141.574	94.0
HCO_3	51.0	136.7	79.667	49.393	61.999	63.0
pH	6.9	7.8	7.233	0.493	6.82	12.0

Table (3): Drinking water quality regulations of dug well 1.

Element		Recommended	Maximum
pH	6.9	7- 8	< 9.2
Na	90	< 20	< 150
Cl	118.48	< 20	< 200
SO_4	58.47	10- 50	< 200

Irrigation water:
Conductivity = 650 µS (group C2: Medium salinity water).
Sodium Adsorption Ratio (SAR) : 3.03

Table (4): Drinking water quality regulations of dug well 2.

Element		Recommended	Maximum
pH	7	7- 8	< 9.2
Na	90	< 20	< 150
Cl	127.9	< 20	< 200
SO_4	75.72	10- 50	< 200

Irrigation water:
Conductivity = 680 µS (group C2: Medium salinity water).
Sodium Adsorption Ratio (SAR) : 2.43.

Table (5): Drinking water quality regulations of the deep well.

Element		Recommended	Maximum
TDS	2900	100- 500	< 1500
Na	610	< 20	< 150
K	20.2	0- 10	
Mg	45	5- 30	< 50
Ca	370.7	40- 100	
Cl	1064.2	< 20	< 200
SO_4	967.31	10- 50	< 200

Irrigation water:

Conductivity = 3400 μS (group C4: Very high salinity water).

Sodium Adsorption Ratio (SAR) : 7.96.

Table (6): Saturation indexes of the different minerals in regard to the groundwater.

Mineral	**Deep well**	**Dug well 1**	**Dug well 2**
Calcite	0.8	-0.86	-1.129
Aragonite	0.656	-1.004	-1.273
Dolomite	1.018	-1.985	-2.54
Magnesite	-0.349	-1.693	-1.978
Gypsum	-0.396	-1.698	-1.941
Anhydrite	-0.617	-1.918	-2.162

Al-Farajat (1997) studied the role of karstification in the Tertiary rocks in north Jordan in enhancing human impacts on the local groundwater resources. He used the horizontal geoelectirc method to reveal extensions of the tunnels and caves. In 2007, Al-Farajat used the high resolution geomagnetic method to reveal cavities in the solid wastes of gypsum behind the Fertilizers Factory in Aqaba. The method was successful in discovering subsurface caves and widened joints. The revealed cavities ranged in values between 5-20 NT. The drilling validated his results.

The map in Figure (12) has resulted from modeling of the geomagnetic study. It shows the potential locations of some near subsurface cavities and holes, in addition to extended dissolution pipes in the rocks beneath the lake of the dam. It is obvious from the map that the low values point to the presence of subsurface cavities and tunnels of dissolution. They take directions parallel to the major directions of the joints in the area (10 and 130 degrees). The revealed shapes of the cavities show that they are connected. They can reach more than 8 meters in length. Normally, they are located at depths of around 5 meters.

Romanova et al. (2003) stated that water flowing through narrow fissures and fractures in soluble rock, e.g. limestone and gypsum, widens these by chemical dissolution. This process, called karstification, sculptures subterranean river systems which drain most of their catchment. Close to dam sites, unnaturally high hydraulic gradients are present to drive the water impounded in the reservoir downstream through fractures reaching below the dam. Under such conditions, the natural process of karstification is accelerated to such an extent that high leakage rates may arise, which endanger the operation of the hydraulic structure. They modelled simulations of karstification below dams by coupling equations of dissolution widening to hydrodynamic flow presented.

Johnson (1981, 1985 and 1987) studied karst in relation to hydrogeology and recharge in salt rocks and the development of Texas sink. The key of his studies was the models and calculations done on the thermodynamics of groundwater in terms of minerals saturation indexes. Saturation indexes of water samples have been calculated using HYDROWIN. Table 6 points to that the leaked water is under-saturated in regard to calcite, dolomite, gypsum, anhydrite and aragonite. This emphasizes that the leaked water will increase the karstification process in the area by dissolving the named minerals contained in the rocks of the study area.

On Piper diagram (Fig. 13), the samples cluster in the fields of earth alkaline water with increased portion of alkalies, with prevailing sulphate, and alkaline water with prevailing sulphate – chloride. It is obvious that high soluble minerals dissolved in water led to this classification on the diagram. Durve diagram (Fig. 14) point to that the water samples locate between ion exchange and simple dissolution or mixing processes. This is typical in karstic regions. Schoeller diagram (Fig. 15) shows that the difference in ion constituents between the deep and shallow wells is very high even in the logarithmic scale. This confirms the role of the dam in recharging the upper aquifer with relatively fresh water (Lloyd et al., 1985).

The deep groundwater well of the area shows a TDS value of about 2900 and a pH value of about 7.8. The shallow well nearer to the dam (1 km to the north of the dam site) shows a TDS value of around 400 mg/1 and a pH value of about 6.8, while the well located farther from the dam (3 km north of the dam site) shows a TDS value of about 430 mg/l and a pH value of about 7.14. It seems that the leakage improved the quality of the water by decreasing its salinity. But on the other hand, and with more water flow TDS increases and pH gets more alkaline.

This reflects the rock-water interaction processes, emphasizing the tendency of the leaked water to create more karstification in the rocks.

The leakage from the dam impacted the surrounding groundwater aquifer positively, when it elevated levels of water in the wells in the surrounding, and it also decreased the TDS of groundwater and made it prone for more uses.

The deep well shows high TDS (2900 mg/l), for this reason it does not fit for drinking purposes. The newly recharged wells show lower TDS values, and are found not to exceed the maximum regulations.

For irrigation purposes, the deep well shows very high salinity hazard. Other wells show lower hazards. All of the wells show low sodium hazard.

No signs on pollution have been recorded, where PO_4 has been found zero in all wells. The area is out of industrial activities and thus out of any industrial pollution of groundwater. Depending on the values of TDS the water in the deep well is classified as brackish, while the water in the dug wells is classified as fresh. Self purification processes in such an area are absent; this makes the study area vulnerable to any type of human activities.

CONCLUSIONS

In this study and through the results of the geological field survey besides the results of the geomagnetic investigations, karst has been registered in the area of Bayer characterizing some features like sinkholes, dolines, dissolution of rocks and widened joints and fissures. On the other hand, it has been proved that the dam has been constructed on karstified carbonate rocks, mainly limestone, which refer to the B2/A7 formations. The recent alluvium ranges between 2-3 meters in thickness and covers most of the features. The sink which swallowed the water from the dam was attributed to the presence of karst in the bed rock under the alluvium covers. The high rates of the water leakage through the sink indicate good permeability in the shallow aquifer, which is attributed to the karstification processes are as secondary permeability.

The water which was found aggressive in respect to the rocks leaks into the layers of the shallow aquifer and exposes the area for occurrence of more sinks in the future, and the wall of the dam itself is threatened by sudden collapse, where some sinks may form beneath it.

Models of rock-water interactions through Piper and Durve diagrams indicate that karstification processes are still taking place, or at least can take place in the presence of circulating water, despite the fact that most of the karstic features in the area are of old ages.

The quality of the collected water from the leakage has been found fit for drinking and irrigation purposes.

The study recommends the dam to be used for recharging purposes for the shallow groundwater aquifers in the downstream. Intensive geophysical investigations of high resolutions should be carried out to investigate the near surface geology of the wall of the dam, to check for the presence of cavities, to avoid the risk of sudden collapse and to delineate seepage paths in the karstic limestone which are located between the dam and the spillway.

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