ICHE 2014, Hamburg - Lehfeldt & Kopmann (eds) - © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8

Construction Effects of the Karun 4 Dam, Iran, on the Groundwater in the Adjacent Karstic Aquifer

S.M. Hosseiny Sohi & M. Koch
Department of Geohydraulics and Engineering Hydrology, University of Kassel, Germany

J. Ashjari
Geosciences Department, Tehran University, Iran

ABSTRACT: The Karun 4 concrete dam is with a maximum dam height above foundation of 230m the highest dam of Iran. It has been in operation since July 2011. It was constructed over a karst limestone and water leakage has been, and continues to be, one of the most important problems of this dam. The geological formations around the dam site consist of carbonate layers of the Asmari formation and marlstone and marly limestone of the impervious Pabdeh formation, upstream of the dam site. The object of this study is to determine the dam construction effects on the groundwater levels in the adjacent aquifer. Thus, before the dam construction, the natural groundwater levels at both banks were recorded to be 5-8m higher than the river stage. This indicates that the natural groundwater gradient at that time was from the banks towards the river, i.e. the latter was an effluent stream before the construction of dam. At that time no important springs were identified at the dam site., other than a minor spring with a discharge <5 lit/sec that emanated at the contact interface between the permeable Asmari- and the impermeable Pabdeh formation (perching aquifer conditions) on the left bank, upstream of the dam. A Lugeon test that was carried out at that time indicated that the permeability of the adjacent limestone is high, as it varies from 25 to 55 Lu in the layers above the river level, but it decreases gradually to 3 Lu in the formations below. After dam impounding, some changes in the borehole's water levels were observed. Thus it has been found, in particular, that the leakage from the reservoir has induced groundwater level rises between 12 to 17 meters.

Keywords: Karun 4 dam, Iran, Water seepage, Karst, Hydrogeology

1 INTRODUCTION

When it comes to the construction of dams and reservoirs in karsts, which are known for their high perviousness due to dissolution faults and conduits, the prevailing risk is water loss, while the risk of stability is considered to be considerably lower (Milanović, 2004). The term Karst is generally defined as a terrain underlain by rocks that are highly soluble (such as limestone) with well-developed secondary porosity, and a terrain that exhibits a distinctive hydrology and landforms such as sink holes, sinking streams, springs and caves (Ford & Williams, 2007). Water loss through basements and abutments of the dams constructed in karst areas leads to considerable costs and non-productivity of the dams. Although the construction of a grout curtain is the most common method to reduce or prevent the water loss, it can solve the problem only partly and in some cases this operation is even fruitless.

For example, the Lar Dam in Iran has used less than half of its conceived capacity, because of continuous leakage - about 10 m^3/s - through the dam foundations and abutments, since its construction in 1980 (Uromeihy, 2000). Although efforts, such as water injection into the fault, lining of parts of the bottom of the reservoir by thick blankets of clay, or the construction of cut off walls, have been made in recent times to prevent or, at least, to reduce the water leakage, successes to that regard have been very limited.

The main paths of water loss underneath dams and reservoirs in karst are the dissolution conduits and the main cause of this problem then is the poor identification of such conduits as being responsible for the leakage. The generation and development of karst conduits within a rock mass is not completely random, but is somehow guided by various chemical pre-requisites which drive the dissolution processes (Wright, 1991). In fact, the primary flow paths in karst rocks are discontinuities such as joints, faults and bedding planes (Kiraly, 1975), although intrinsic porosity plays also a non-negligible role ((Bakalowicz, 2005).

The Karun 4 concrete dam, which is the focus of the present study, is with a maximum dam height above foundation of 230m the highest dam of Iran. This dam sits on a carbonate (limestone) rock formation, so the problems mentioned above to exist in such a geological environment are to be expected. After the completion of the dam, the Karun 4 reservoir reached the full water impound phase in 2010.

The object of this study is to investigate the likely effects of the reservoir's water impound on the groundwater underneath the dam site. More specifically, this paper is concentrating on results of the analyses of various hydrogeological and hydrochemical investigations and, in particular, of Lugeon tests.

2 STUDY AREA

2.1 *Site specification and geology*

Karun is the largest river and the only navigable waterway in Iran. It originates in the Zagros mountains, west of Isfahan, flows out of the central Zagros range, traverses the Khuzestan plain, and joins the Shatt al-Arab, with the latter then discharging into the Persian Gulf. There are a number of dams on the Karun river, such as the Gotvand-, Masjed Soleyman-, Karun-1 (Shahid Abbaspour)-, Karun-3 and Karun-4 dam, all mainly built to generate hydroelectric power and to provide flood control.

The Karun 4 Dam itself is located on the Karun River in the state of Chaharmahal and Bakhtiari, at a distance of 180 km from the State Capital of Shahrekord, in southwest Iran (Fig.1).

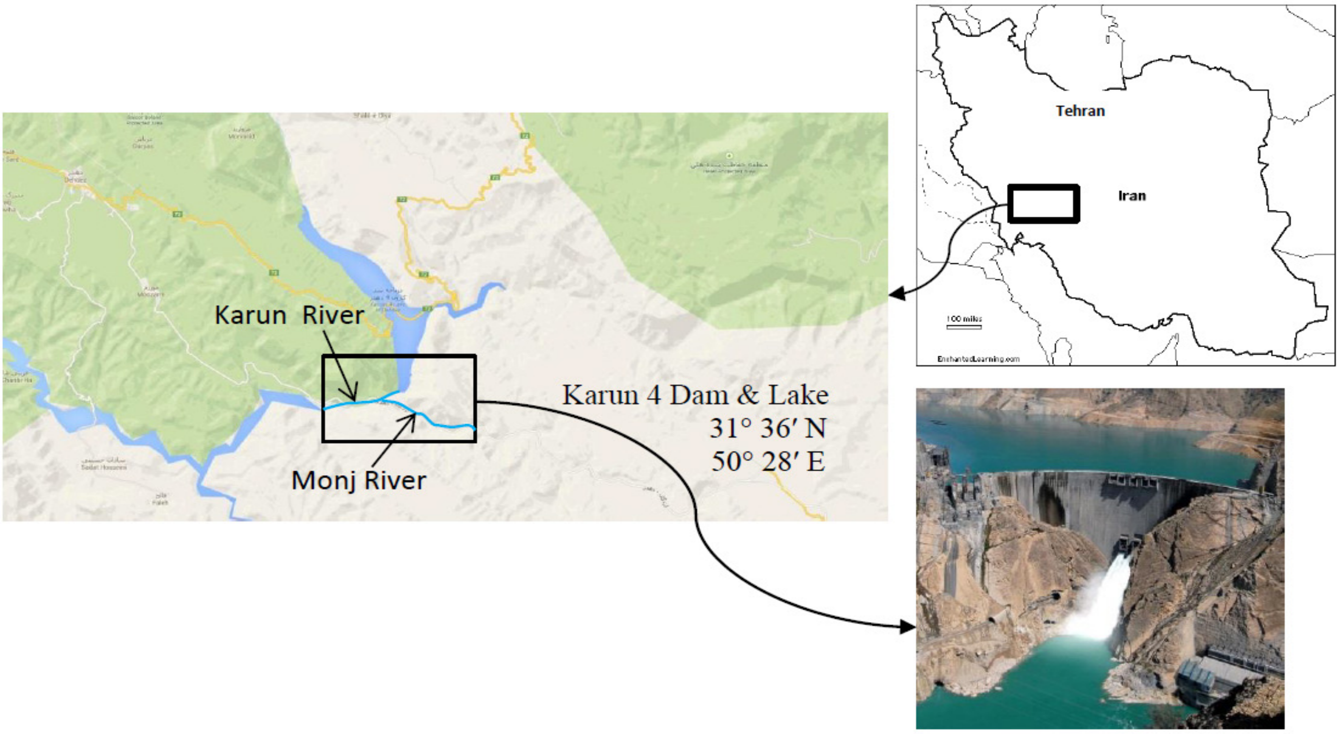


Figure 1. Location of the Karun 4 dam in Iran

The objectives of the Karun 4 Dam construction have been the following:
- regulation of the Karun river discharge of 3.7 billion m³/year
- control of destructive floods and overflows of Karun River
- generation of hydroelectric energy of about 2107 billion kWh per year.

The dam has been in operation since July 2011, after termination of the water impound phase, which started in 2010. Table 1 shows some technical specifications of the dam.

Table 1. Some Karun 4 dam technical specifications

Dam type	Concrete double arc
Height from foundation	230 m
Crest length /width	440 m / 7m
Foundation width	37 to 52 m
Total volume of concrete placement	1.65 million m^3
Total volume of the reservoir	2190 million m^3
Power Plant Type	Ground
Spillway	Chute, orifice types and free

The dam is located in the tectonically folded belt of the Zagros Mountains within a canyon that is located in the southwestern flank of the Kuh-Sefid anticline which has a NW-SE trend. Most of the reservoir is situated on Cretaceous to Miocene limestone and marly limestone (Haghnejad et al., 2014). The geological formations around the dam site consist of carbonate layers of the Asmari formation (As) which can be divided into lower (As1), middle (As2) and upper (As3) units and marlstone and marly limestone of impervious Pabdeh formation (Pd) on upstream of dam site (see Figs.2 and 3). The lower unit (As1) comprises limestone, porous limestone and some marly limestone with some marlstone, generally thick to very thickly bedded and highly karstic. The measured mean RQD (rock-quality designation) index (Deere, 1964) ranges between 55% and 83%. The middle unit (As2) is located downstream of the dam and comprises alternating limestone, dolomitic, marly limestone and marl. Karstification is limited and the RQD is between 53% and 84%. The upper part (As3) consists of alternating layers of limestone, marly limestone and marl with slight karstification and an RQD between 45% and 78%. These RQD-values indicate a fair to good quality rock in all three units (Koleini, 2012). As1 outcrops in the dam valley abutments are highlighted in the cliff around the site. The strike of the beddings is northwest to southeast, and southern limb slopes to the south with a dip of 70-80 degrees. The AS1 unit, with an apparent thickness of about 200 m in normal direction to the bedding, constitutes the foundation rock of the dam.

The geology of the dam site is affected by many faults, 122 major joints and 4 discontinuities sets. The strongly dipping reverse Monj fault, with a length of 14 km, is located at a distance of about 500 m downstream of the dam. The joint openings along the bedding at the ground surface range from 1 to 100 mm and decrease with increasing depth.

2.2 *Hydrogeology*

Before dam construction in year 2002, the natural groundwater level at both banks was recorded to be 5-8m higher than that of the river water level. This indicates that the natural gradient of groundwater at that time was from the banks toward river, i.e. the river was an effluent stream, which is the normal situation for most rivers in the world. In fact, the phreatic levels in the left and right banks of the river were measured as 848 and 845m NN, respectively.

In fact, at that time, before 2002, no important springs were identified at the dam site. The only minor spring, with a discharge of less than 5 lit/sec, emanated at the contact interface between the permeable Asmari Formation and the impermeable Pabdeh formation, upstream of the left abutment of the dam.

In the Asmari Formation dissolutional surface features such as vugs and small cavities along the discontinuities with infilling were observed. Some larger cavities (1 to 2m in diameter) were encountered during the excavation of the galleries. A porous limestone layer was identified, which had a vuggy feature and was recognized as a key bed underneath the dam site.

Lugeon tests were carried out at that time (2002), which resulted in a rather high permeability between 25 to 55 Lu in the limestone layers above the river level, but which decrease gradually to 3 Lu, as one goes towards the formations below the river water.

After dam impounding in 2010, some changes in the borehole water levels were observed and it was found that the leakage probability from the grout curtain had increased. This was corroborated by the studies of Shabab (2011) and Kamali and Ashjari (2012) who proved the existence of increased leakage, but these authors could neither specify nor identify the pathways of the leaking waters.

3 STUDY METHOD

Geology maps of the dam site were prepared, based on geology maps of 1/100000 Geology Surveys of Iran and 1/20000 of Mahab Ghodes Consulting Company. The geotechnical data of drilled boreholes, such as geological logs, RQD, Lugeon tests, and placement were collected. From the Water Resource Management Office of Iran data about the following hydraulic and hydrogeological features were gathered: the flow system and hydrogeological characteristics of the sites, water level measurements in boreholes in karstic rock mass or wells, locations of springs and their discharges.

With the geological logs and geotechnical data potential horizons of conduit developments were found. The Lugeon tests results identified high permeability zones in a borehole that could hint of leakage zones in the geological formations under the dam. Finally, temporal variations of ground water levels and several chemical parameters were correlated with the height/volume of the water impound in the reservoir.

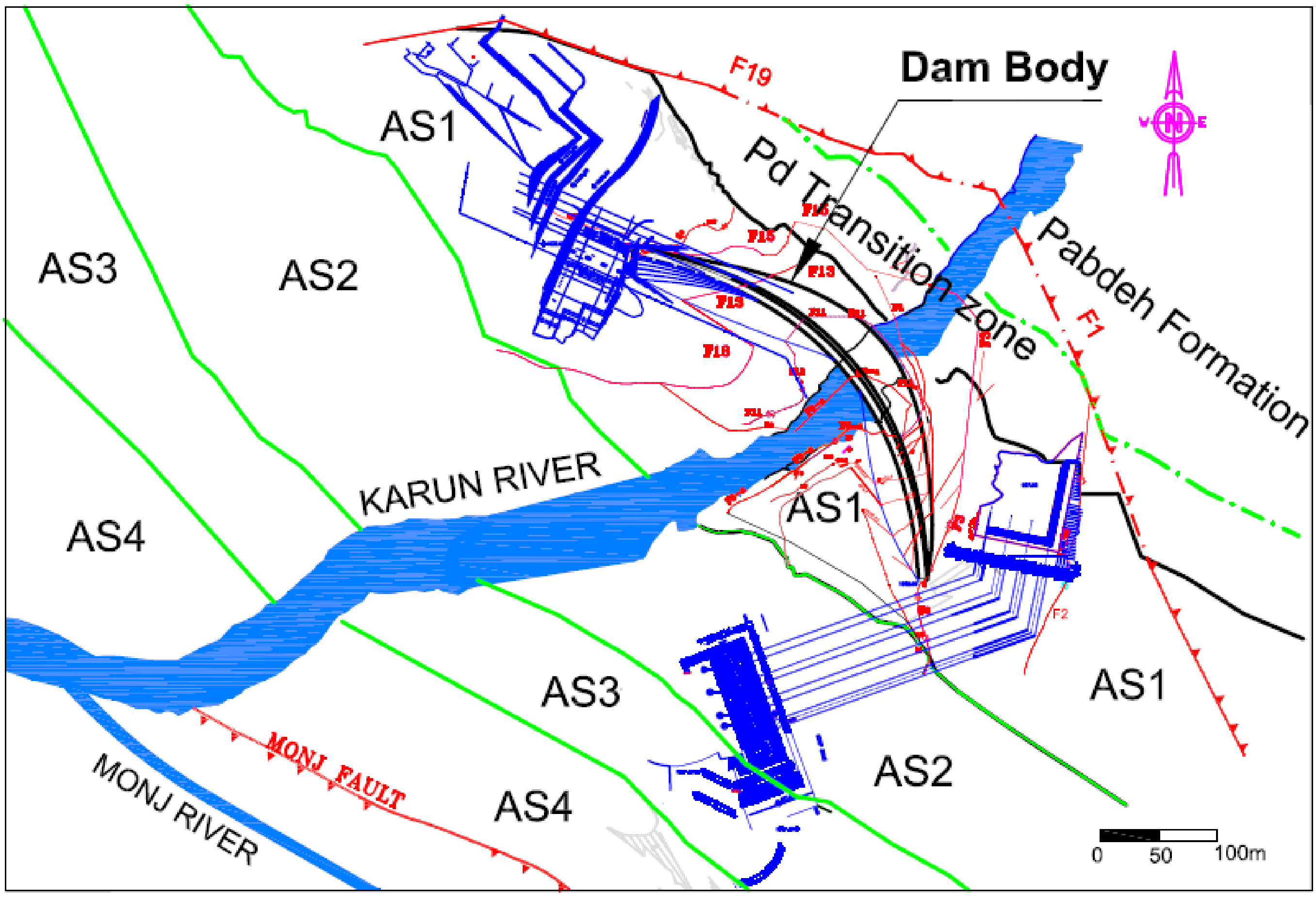


Figure 2. Karun 4 dam geological plan

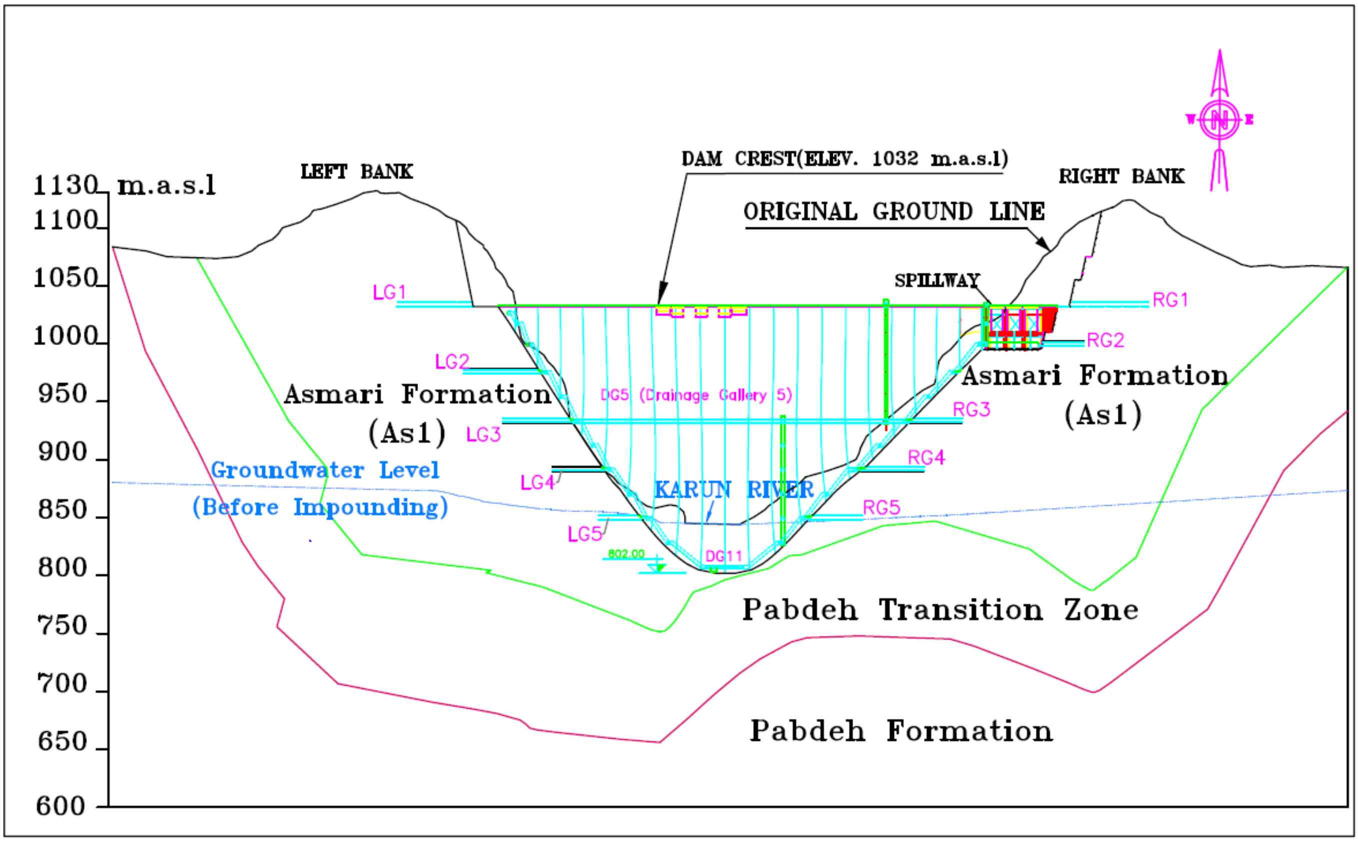


Figure 3. Karun 4 dam geological cross-section viewed from the reservoir downstream towards the dam

4 RESULTS

4.1 *Before water impound*

Lugeon tests and a hydrogeological assessment of the area were done before the dam water impounding in 2010, in order to evaluate the permeability properties of the karst formations at the dam site (Mahab Ghods 2002) and get some hints of possible leakage pathways. The results of these tests which were performed in boreholes drilled at a ground surface height, ranging between 867 and 885 m NN (see Fig. 2), indicate a high degree of heterogeneity in both vertical and horizontal directions in the left and right abutments and the foundation of dam.

In the left abutment, the permeability variations define three major zones:

1) The carbonate rocks containing marl. These rocks have fractures and are very porous, due to faults and joints which cause a strong vertical variation of the permeability. A high value of the latter of more than 100 Lu, has been reported in a very deep seated layer, at depths between 193 and 200 m. But the thickest highly permeable zone lies in the depth range of 60 to 120 m.
2) Places with high variations of the permeability in a shallow depth range, but a consistently thick layer of very high permeability between 135 to 160 m depth.
3) Boreholes bottoming near to the contact zones of the named Asmari and Pabdeh formations show the lowest permeability in the left abutment of the dam body, with values lower than 3 Lu in the Pabdeh part of boreholes.

In the right abutment of the dam body, the permeability variation is more consistent with the lithology of the layers than in the left one. Thus, the permeability is very low, less than 8 Lu, in a depth of 100 m and below, whereas high permeability zones are located in depths less than 60 m.

The permeability of rocks beneath the foundation itself is very low, with the highest Lugeon values of only 8 to 32 determined in the depth range of 10.5 to 44 m , and of even less than 8 in other horizons.

The water levels of the Karun and Monj rivers are 806 and 805 above NN, respectively. The groundwater levels of karst aquifer varied from 852 to 855.5 at the dam site in 2002 (Fig 3), which means that they were higher than the Karun river stage and lower than that of the Monj river. Hydrogeologically, this confirms that at that time the Karun river acted as a gaining- and the Monj River as a loosing stream.

4.2 *During and after water impound*

The reservoir water impounding started on March 25, 2010. Up to date it has not yet reached the target level, due to a series of problems related to the dam structure and the named water seepage.

The following analysis is limited to data of year 2010, because of the inaccessibility of more recent data. During the six months after the beginning of the impounding phase (April – October, 2010) the reservoir water levels as well as groundwater levels in several boreholes of the grout and the drainage galleries were recorded on a weekly interval.

Fig. 4 shows these reservoir water levels together with groundwater levels in two selected boreholes of the left and right abutments. From April- October, 2010, the reservoir level increased steadfastly from 806 to 920m NN. In fact, a final recording at the end of that year provided a value of 946 m NN for the water level in the reservoir (Kamali and Ashjari, 2012).

One may notice that during the April- October, 2010 time period the groundwater levels in the boreholes of the left and right abutments show some different behavior. Thus, whereas in the right abutment a hydraulic head increase of up to 20 m is observed in the first three months, leveling off thereafter, the situation is opposite in the left abutment, as the groundwater level starts to rise only in the second half of the 6 months observation period.

In general, the groundwater level variations in the right dam abutment turned out to be more complicated and depend on the distance of the borehole from the junction of the dam with the drainage galleries. Thus, at a distance of less than 50 m, the head changes are less than 9 m, going up to 20-24 m in the distance range 50-144 m, and, eventually, reaching 15-17 m in the 44-250 m range. Therefore, the head variations in the right abutment are more responsive to the reservoir water impounding than those in the left one.

As for the boreholes in the abutment close to the dam (not shown here), only low groundwater head increases of about 5 m were measured during the named time period. On the other hand, at distances of 114 to 138 m upstream of the junction of the dam with one of the galleries in the left abutment, the increases are with 20 to 30 m the highest, but they become lower again further away.

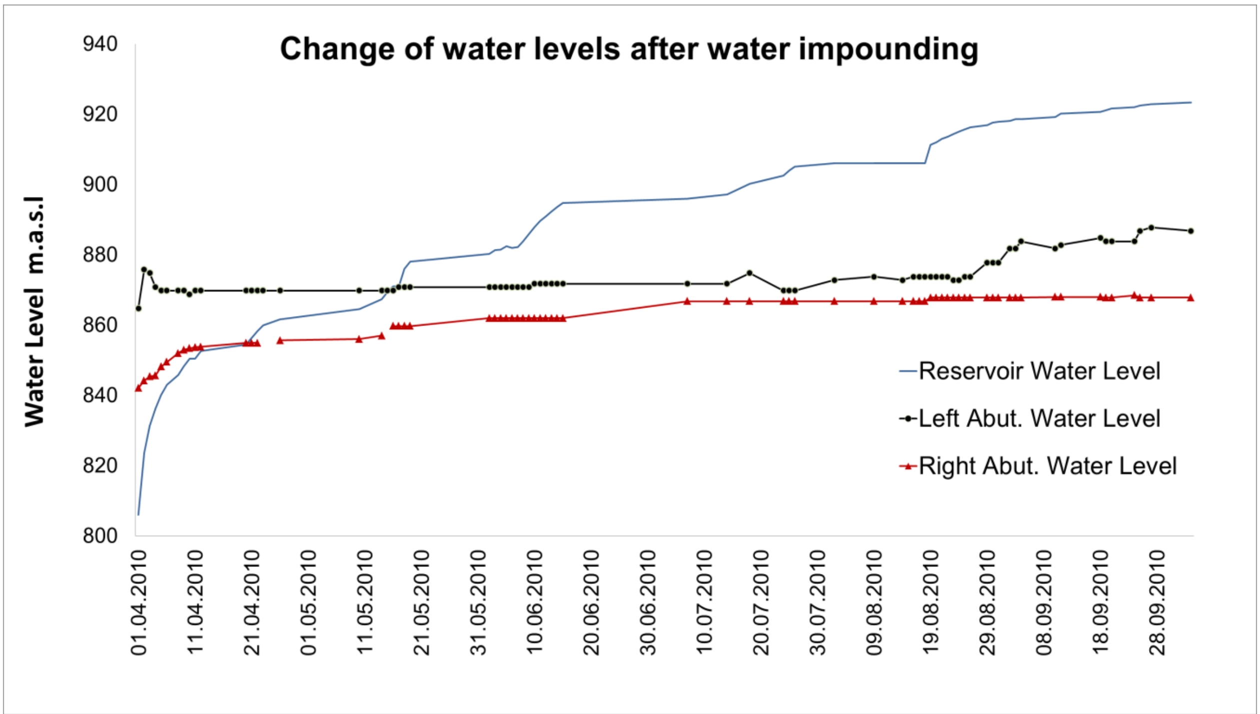


Figure 4. Change of water levels after water impounding of Karun 4 dam (2010)

4.3 *Hydrochemistry of the groundwater*

Since 2010, after commencement of the water impounding, electrical conductivity (EC) and major ions including CO_3, Cl, Na, Ca, K, Mg and SO_4 have been measured on a monthly basis in the boreholes as well as in downstream sections of the Karun and Monj rivers. The temporal variations of these parameters over a time period of nearly four years are shown in the various panels of Fig.5. Regarding the EC, one can notice from the corresponding plot that the EC of the Karun river has been varying in a rather narrow range of 400 to 560 µS/cm since the time of water impounding and it has been consistently lower than that of the Monji river, up to the end of 2011. After that time the EC- values and trends in both rivers are similar, owing to the fact that the impounded reservoir started to extend to the Monj river catchment.

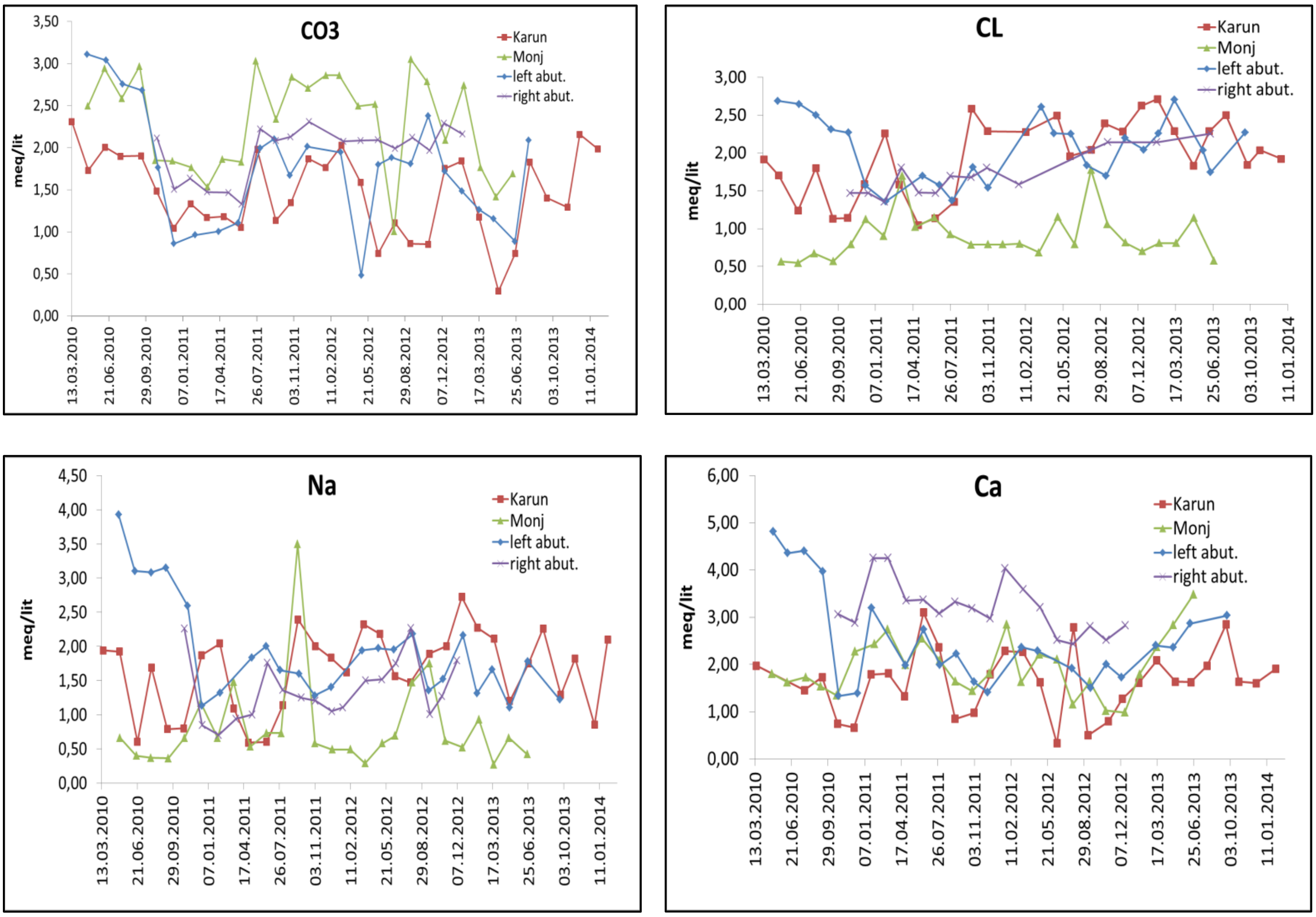
The ECs of the left abutment are high in the beginning of the water impounding phase and decrease slowly with the progressive water level increase in the reservoir. They become then closer to the EC-values of the Karun river.

It should be noted that the first few records of the EC in the right abutment are missing, so that the EC-variations at the beginning of the water impounding process are not known. Nevertheless, it appears that the EC- decreases in the right abutment are similar to those of the left one . However, because of the higher permeability in the right than in the left abutment, it is of no surprise that the EC in the former decreases also faster than that of the latter towards the value of the river water.

The hydrochemistry of the groundwater and two rivers around the Karun dam site consists of mainly bicarbonate or bicarbonate-sulfate ions, owing to the contact of these waters with the named Asmari and Gachsaran limestone formations. Now, if one assumes the possibility of leakage of reservoir water into the aquifer, the chemical properties of the water in the reservoir boreholes and the reservoir should become similar after some time. In fact, the concentration plots of the various ions in Fig. 5 show, overall, a decreasing trend of the borehole concentrations in the beginning of the water impounding phase, after which they follow fairly well the trends of the corresponding parameters measured in the Karun River. Therefore, these chemical variations of boreholes provide evidence for water seepage from the dam site. These trends are weak for the bicarbonate (CO_3) variations, due to the effect of carbonate formation and dissolution along the water pathways though the limestone layers.

5 CONCLUSIONS AND OUTLOOK

The following results obtained from the various hydrological and hydro-chemical analyses show that water seepage from the dam reservoir to the aquifer has occurred since the commencement of water impounding in the Karun 4 dam reservoir in early spring of 2010:



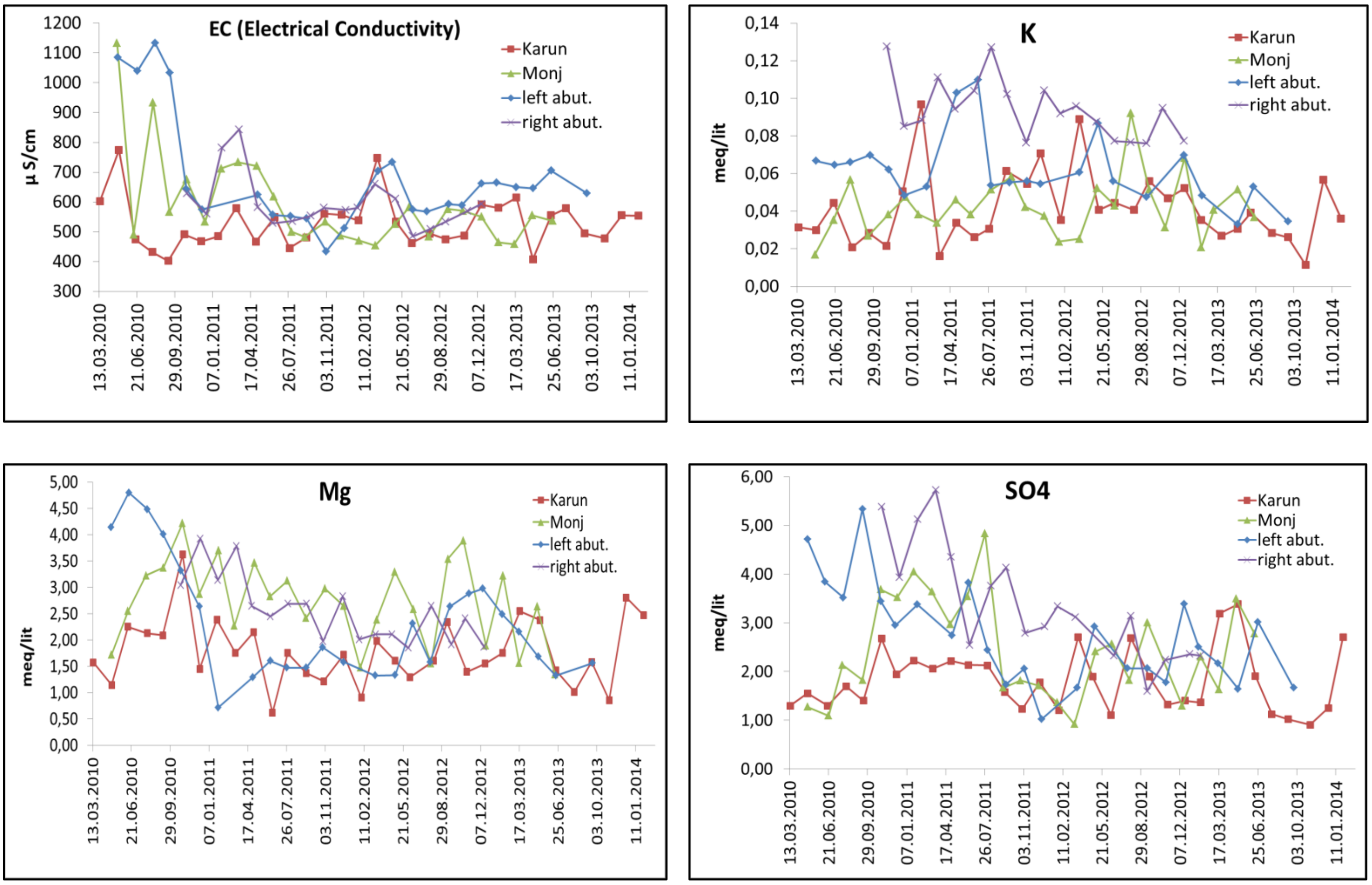


Figure 5. Variations of hydrochemical parameters between 2010 and 2014

1) Groundwater levels have increased significantly by up to 20 m in both abutments of the dam.
2) The left abutment shows a lower hydraulic head increase than the right one.
3) With ongoing water impounding, the concentrations of the major ions and as well the EC of the groundwater get closer and closer to those in the reservoir.

The major reason of such a response of the groundwater to the water impounding in the reservoir is the high karstification of the limestone at the dam site, as indicated by the following factors:

1) Lithologically, the dam site consists of pure limestone which is highly prone to dissolution.
2) Caves, which are a main surface indicator of karstification in a region, have also been reported at the Karun 4 dam site.
3) The faults and fractures created during the karstification process provide suitable water pathways from the dam site to the aquifer.
4) Lugeon test results show high permeability values in different horizons of the karst terrain around and underneath the dam site.

Today (2014) the dam is going to be repaired, due to improper grout curtain installation in the abutment and the foundation. In fact, based on the various indices of karstification in the region, the mentioned problems with the Karun 4 dam were already partly predicated in some of the early planning reports (Kamali and Ashjari, 2012), however, the recommendations of various geologists were not adhered to, with, in addition to an unsuitable monitoring of the grout curtain installation, has led to the series of problems encountered at the dam at present time.

The next step in this ongoing study is the development of a groundwater flow and transport model, capable of simulating water leakage and solute transport through the karstic formations at the dam site. Much research along these lines is still needed, as the numerical flow and transport models for non-Darcian porous media like in karst, which consists of a mixture of pores and conduits are still lacking reliability (Bakalowicz, 2005). Various model approaches have been proposed to tackle this problem, the most notable ones known under the notation of double continuum (porosity) models, which represent the fractured limestone as a mixture of a conduit matrix and a classical porous medium, with appropriate exchange terms (Teutsch and Sauter, 1998; Scanlon *et al.*, 2003).

The outcome of the research proposed further is of particular importance for the country of Iran, the more so, since the Karun 4 dam, as Iran's highest dam, has a strategic place in its water and power national network, so that any instability- or safety problems with this dam would result in irrecoverable losses to the country as a whole.

REFERENCES

Bakalowicz, M. (2005). Karst groundwater: a challenge for new resources, Hydrogeol J., 13,148–160

Deere, D U (1964). Technical description of rock cores, Rock Mechanics Engineering Geology, 1, 16-22.

Ford, D. and Williams, P. (2007). Karst Hydrogeology and Geomorphology. Wiley Ltd, England.

Haghnejad, A., Ahangari, K., Noorzad, A. (2014). Investigation on various relations between uniaxial compressive strength, elasticity and deformation modulus of Asmari formation in Iran. Arab. Journ. Science and Engineer., 39, 4, 2677-2682.

Kamali, M. and Ashjari, J. (2012). Determination of efficiency of grout curtain of Karun 4's Dam by dye tracing test. Report to IWPC (Iran Water & Power resources development Company), 124 p.

Kiraly, L. (1975). Rapport sur l'état actual des connaissances dans le domaine des caractères physiques des roches karstiques, in: Bueger and Dubertret (Eds.), International Union Geol. Sci., Series B. 3, pp.53-67.

Koleini, M. (2012). Engineering geological assessment and rock mass characterization of the Asmari formation (Zagros range) as large dam foundation rocks in southwestern Iran. Ph.D thesis, University of Pretoria, South Africa.

Mahab Ghods Consulting Engineering Co. (2002). Karun 4 dam project. Final engineering geological report (phase 2).

Milanović, PT. (2004). Water resources engineering in karst. CRC Press, Boca Raton.

Scanlon, B.R., Mace, R.E., Barrett, M.E., Smith, B. (2003). Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA. J. Hydrol., 276, 137–158.

Shabab Boroujeni, B. (2011). Determination of effective factors on permeability in karstic dams in west of Zagros. M.Sc. thesis, Tehran University, Iran.

Teutsch, G., Sauter, M. (1998). Distributed parameter modelling approaches in karst-hydrological investigations. Bull. d'Hydrogeologie, 16, 99–109.

Urumeihy, A. (2000). The Lar Dam; an example of infrastructural development in a geologically active karstic region. Journal of Asian Earth Sciences. 18, 25-31.

Wright, V.P. (1991). Palaeokarst types, recognition,controls and associations, in: Wright, V.P., Esteban, M., Smart, P.L. (Eds.), Palaeokarsts and Palaeokarstic Reservoirs, Reading: P.R.I.S. Occasional Publication Series 2, pp.56-88.