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Method of leakage study at the karst dam site. A case study: Khersan 3 Dam, Iran

Zargham Mohammadi · Ezzatollah Raeisi · Michel Bakalowicz

Abstract The excellent topographic condition of the limestone canyons for dam construction may be rejected if they are karstified. Karst features cause the reservoir not to be impermeable enough to permit the water to fill it and leakage occurs and often increases with time. Moreover, karst features may involve the stability of the dam itself. A few operated dam sites at the Zagros Zone encountered a leakage problem. Furthermore, more than 30 dams are presently under study for construction in the Zagros Zone. Karst conditions and leakage potential were investigated at an under-study site (Khersan 3 Dam) for assessing the general methodology for the study of leakage potentials. Conventional methods for studying karst features, geological mapping, geomorphology and extensive borings were applied before the dam was constructed. These methods are not efficient enough to precisely reveal the karst structure, especially hidden and paleokarst, nor the hydrological behaviour of the karst structure in different settings of groundwater flow. Based on the present case study and previous applied approaches by other authors, this paper introduces a methodology by means of karst structure and functioning approaches at local and regional scales that cover the conventional methods and overcome their shortages. The proposed methodology should be applied before construction of a dam and should include three steps (a) recognition of geological and hydrogeological settings, (b) delineation and functioning of the karst system related to the future reservoir, and (c) assessment of the leakage potentials. Following this methodology, the most probable leakage zone(s) and path(s) at the dam site can be highlighted.

Keywords Dams · Leakage · Karst system · Functioning of karst aquifer · Zagros Zone · Iran

Introduction

Leakage from dam sites has been reported in numerous dams in karst areas over the world (see for example Milanovic 2004). Leakage is mainly enhanced by karst features directly or indirectly. Limestone solution forms conduits of unpredictable dimensions and geometry creating a high permeability often measured in centimeters or meters per second. In extreme cases flow through solution conduits has reached a volume equal to the average annual flow of the river, although leakage in the range of 5–10% of the average annual flow is more common. The importance of leakage is emphasized by the cost, which can approach 15–20% of the project cost for foundation treatment and other work related to limestone solution features (Merritt 1995). In most cases, the leakage has occurred during the first filling and reservoirs may fail to fill despite extensive investigation programs and sealing treatments. Comprehensive grouting carried out later may reduce this leakage to less than 5%, but only after considerable effort.

A considerable number of papers were published on dam leakage. Most of these papers deal with partial

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aspects of the problem. Many of them are simple suggestions of the authors for the application of a specific technique. However, many documents were presented about leakage and remediation in consulting reports without public access. An overview of these documents show that one or several of the following techniques have been used to obtain knowledge about karst development and leakage studies: (a) regional and dam site geological mapping (Anik 1973; Soderberg 1979; Fischer et al. 1988; Redwine 1993; Kath et al. 1995; Ertunc 1999; Pollak 2000; Altug and Saticioglu 2000; Satti 2000; Turkmen et al. 2002; Xu and Yan 2004); (b) boreholes and galleries (Soderberg 1979; Handfelt and Attwoll 1988; Bhattacharya 1989; Degirmenci 1993; Redwine 1993; Merritt 1995; Iqbal 1995; Satti 2000; Turkmen et al. 2002; Karimi 2003; Xu and Yan 2004; Guangcheng and Zhicheng 2004); and (c) geophysical methods (Fischer et al. 1988; Al-Saigh et al. 1994; Iqbal 1995; Milanovic 2004; Xu and Yan 2004; Guangcheng and Zhicheng 2004). In the best condition these approaches prove the existence of karst features only. Consequently, behaviour of the karst structures in groundwater flow may remain unknown. Consideration must also be given about reactivating paleokarst features due to new groundwater flow conditions or deplugging of filled material caused by increased hydraulic gradients created by water impound. Shortages of the above conventional approaches provoke the uncertainty in leakage delineation at the inherently non-homogeneous karst sites. The actual roles of karst features in contributing to groundwater flow can be highlighted by means of dye tracing, hydrogeology of springs and water table fluctuations in boreholes (Anik 1973; Handfelt and Attwoll 1988; Bhattacharya 1989; Redwine 1993; Degirmenci 1993; Asadi 1997; Talaei 1999; Kamali 1999; Altug and Saticioglu 2000; Asadpour 2000; Pollak 2000; Marinos and Kazilis 2000; Turkmen et al. 2002; Keshavarz 2003; Milanovic 2004; Xu and Yan 2004; Guangcheng and Zhicheng 2004; Ghobadi et al. 2005). Most of the cited studies on leakage prediction were done after dam construction during leakage remediation. Obviously, leakage estimation or remediation works do not follow a unique systematic procedure and methods were selected to face the problems. Milanovic (2001, 2004) believed that a detailed geological and hydrogeological map with application of remote sensing methods, combinations of different geophysical methods, neotectonic analysis, groundwater tracer tests, speleological investigations and long-term groundwater monitoring are basic requirements in a leakage study. One of the best-investigated cases is the Dinaric karst area in Herzegovina, which included seven dams, six

reservoirs, five tunnels 60 km in length, and 80 km of channel. Detailed hydrogeologic studies of springs and more than 150 tracing tests were applied for successful sealing treatment in this area (in Milanovic 2004, full reference list).

Lack of a detailed insight into karst conditions at dam sites, especially before dam construction, caused a huge leakage from dam sites in karst areas. This enforces the necessity of step-by-step methodology for leakage studies. According to the non-homogeneous character of karst and its role to leakage potential at the dam site, the following questions are raised: (a) does karst develop or not (at present and past time)? (b) Where are the most probable path(s) and location(s) of the karst features? (c) What is the behaviour of the karst features in the groundwater flow before and after the construction of a dam? And (d) does a potential for leakage exist?

The main objectives of this paper are answering the above questions by developing a detailed methodology for leakage study before dam construction in karst terrains with emphasis on Zagros Zone, Iran. Location(s) and path(s) of leakage can be shown during the process of leakage study. The Khersan 3 Dam is under study for construction in the Zagros Zone. Karst conditions and leakage potential at this site was investigated to access a general methodology.

Karst specification at the study area

The Zagros Zone is one of five major structural zones in Iran (Stocklin 1968). The Zagros mountain range is divided into three structural zones: the Khozestan Plain, the Simply Folded Zone, and the Thrust Zone (Stocklin 1968). The geological series is about 12 km thick and mainly made of limestone, marl, gypsum, sandstone and conglomerate. Since the Miocene age, it has been folded into a series of huge anticlines and synclines. The Asmari Limestone, 500 m thick, outcrops at most dam sites in Zagros Zone. Generally, limestone canyons offer excellent topographic conditions for building dams. They fulfill the fundamental premises such as minimum width of canyon and strength to support the loads transmitted by the body of the dam and those from the reservoir when full (Eraso 1989). However, limestone may be karstified: the existence of irregular solution networks of pores, fissures, fractures and conduits of various sizes and forms makes the reservoir not impermeable enough to permit the water to fill it. Consequently, the dam does not reach its designed storage (Milanovic 2004). Numbers of dams in operation, in construction and

under study for construction in the Zagros Zone are 11, 21 and 39, respectively [The international committee of large dams (ICOLD) 2005]. Water leakage through karst features occurred at some of the operating dams (e.g., Karun1 and Marun Dams in Fig. 1 and Table 1). Furthermore, at several dam sites many karst features shown during construction were ignored before due to the lack of detail and systematic study for karst hydrogeology (e.g., Salman Farsi, Karun4 and Tangab Dams in Fig. 1 and Table 1).

Although Lar Dam is out of the Zagros Zone, its leakage problem is interesting and a unique case (Table 1). Lar Dam lies in a heavily faulted and fractured region close to the active Damavand Volcano, Alborz Montains north of Iran. Water leakage at Lar Dam is mostly due to the abundance of caves and conduits in the underlying limestone beds (Uromeihy 2000).

Khersan 3 Dam was selected as a representative case for studying karstification and leakage methodology. Khersan 3 Dam with a height of 145 m is to be constructed on the Khersan River, Zagros Zone, southern Iran.

Geological settings

The stratigraphy and structural framework of the Zagros Zone were studied in detail by James and Wynd (1965); Stocklin and Setudehnia (1977) and Alavi (2004). Three main formations are exposed in the Khersan 3 Dam project: Gachsaran (Miocene), Asmari (Oligocene–Miocene) and Pabdeh-Gurpi (Palaeocene–Oligocene)
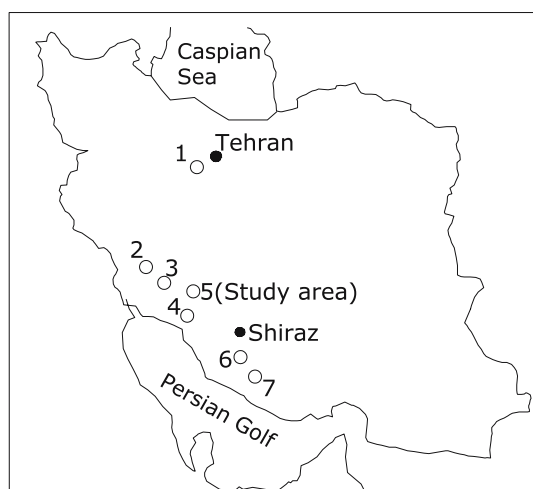

Fig. 1 Location map of the some karst dam sites in Iran (1: Lar, 2: Karun1, 3: Karun4: 4: Marun, 5: Khersan 3, 6: Tangab and 7: Salman Farsi. All dam sites are in the Zagros Zone except Lar Dam)

formations (Fig. 2). The Gachsaran formation, composed of salt, anhydrite, marl and gypsum, outcrops in some areas at the lowest elevation of anticlines. The Asmari formation, widely extended over the study area, is characterized by layered limestone with interbedded marl. The Asmari formation is divided into lower and upper units from different litho-statigraphical characteristics. The Lower Asmari, 250 m thick, is composed of sequences of thin limestone layers, marly limestone and dolomite. The Upper Asmari, 235 m thick, composed of thick-bedded limestone, shows many karst features on its outcrops. Underlying the Asmari formation, the Pabdeh-Gurpi formation is composed of clayey sediment, shale, marl and clayey limestone. As a result of its high clay content, the Pabdeh-Gurpi formation is characterized by a low permeability and by predominant surface flow.

The study area is surrounded by three anticlines, including Rig, Shorom and Laki (Fig. 2). The trend of these anticlines is NW–SE, parallel to the general structure of the Zagros Zone. The Pabdeh-Gurpi formation forms the core of these anticlines.

The Khersan 3 Dam site is in a narrow part of the Khersan River valley, which cuts through the plunge of the Laki Anticline (Fig. 2). The karstic Asmari formation crops out at the Khersan 3 Dam site and most parts of the dam reservoir. It makes up the only main aquifer system on both sides of the dam site. The Khersan 3 Dam reservoir is at the foot of the highly elevated Rig and Shorom Anticlines.

The structure of the karst system

The aquifer system at the dam site was first delineated by hydrodynamic data from piezometers and geological setting (Mahab Ghods consulting engineers 2000). Recently, one unconfined and three artesian sub-aquifers were recognized (Fig. 3), composing a complex aquifer system at the Khersan 3 Dam site that was supported by geological settings, water head, hydrochemistry and isotope data (Mohammadi et al. 2006a). The water level in the unconfined sub-aquifer ranges from 1,264 to 1,273.2 m above mean sea level (MSL). The piezometric level in the artesian sub-aquifers ranges from 1,297 to 1,359 m above MSL. Minimum and maximum flow rates in the artesian piezometers range from 0.4 l to 20 l s^{-1}. The artesian sub-aquifers are at depth 200 m below the dam axis, but their depth decreases downstream and the artesian sub-aquifers become close to the surface 500 m downstream from the dam axis (Fig. 3). This area was referred to the discharge (output) zone of the artesian sub-aquifers, despite the fact that no spring is known in this area.

Table 1 Karst condition at some dam sites in Iran

Name	Dam type	Leakage value	Ignored studies issue to karst condition	Reference(s)
Lar	Earth-fill	~10 m^3 s^{-1}	Paleokarst evolution model of karst and hydrogeology of downstream springs were not studied. Very active tectonic movement, volcanic activity and favourable climate during the past created deep (>200 m) caves and conduits in Jurassic Lar Limestone that were hidden by lake deposits at time of dam construction.	Uromeihy (2000) and Milanovic (2004)
Karun1	Double-arch	~3 m^3 s^{-1} and continuously increased	The recharge area of springs downstream from the dam site was not determined. No consideration was given to cave studies, filled paleokarst and karst evolutionary processes in Asmari Limestone. The foregoing data indicates a connection of the reservoir with downstream springs. The leakage continuously increases due to washing the infilling material from caverns.	Milanovic (2004) and Ghobadi et al. (2005)
Marun	Rock-fill	~10 m^3 s^{-1} (decreased after remediation)	The hydrogeological role of the joints perpendicular to the geological structure and paleokarst were not considered. Old karst conduits along the Vuggy zone in Asmari Limestone were reactivated and leakage occurred.	Milanovic (2004)
Salman Farsi	Concrete-arch gravity	Under construction	According to drilling and surface geophysics no caverns were detected in Asmari Limestone on both sides. However, after excavation of the diversion tunnel and adits some big caves were detected. The karst channel and caverns (the largest dimension is $130 \times 20 \times 70$ m) developed along two sets of joints and steeply dipping bedding planes. A thermal groundwater (42°C) was distinguished.	Milanovic (2004) and Fazeli and Maleki (2005)
Karun4	Double arch	Under construction	No signs of karst caves and conduits were observed from surface geophysics and boreholes. But during dam construction and excavation of the grouting galleries in the left abutment some caves were detected in Asmari Limestone that developed along the large fault.	Maleki (2005)
Tangab	Rock-fill with clay core	Under construction	Paleokarst and effect of base of erosion were considered as negligible. No cavern and conduit were observed in boreholes and galleries. However, two caves have formed along joints and a 30 m deep shaft of 3 m diameter were discovered during tunnel excavation at the dam site.	Karimi et al. (2005) and Mohammadi and Raeisi (2005)

However, location of recharge areas of the artesian sub-aquifers was unknown. Consequently, all potentials for recharge areas of the artesian sub-aquifers at the reservoir area were analysed by means of functioning approach.

At the regional scale (reservoir area), the karst system was delineated from field survey, topography, geological settings, and location of the springs (Fig. 2). The groundwater of the Rig, Shorom and Laki anticlines are discharged by 14, 12, and 2 springs, respectively (Fig. 2). The Atashgah spring (R6 in Fig. 2), which has a mean discharge of about 900 l/s, is the largest spring issuing from Rig Anticline. The Gahkadeh spring (S3 in Fig. 2) with mean discharge of 600 l/s is the largest spring at the Shorom Anticline. The total discharge of two small stage springs (L1 and L2 in Fig. 2) at the Laki Anticline is 40 l/s. The absence of point (concentrated) recharge shows that the meteoric water recharges to the karst system over the whole catchment area as diffuse or autogenic recharge (White 1988). Recharge occurs as snow melting in some parts of high elevations. Water balance was attempted to

check the validity of the karst system in each spring by means of the most probable catchment area of the springs. The location, type, extension and relation between recharge and discharge of the karst system were defined in water balance computation. Consequently, areas with unknown discharge points that have potential as a recharge area of the artesian sub-aquifer were distinguished.

Functioning of the karst system

Following the structure approach, monitoring points were selected to characterize the Asmari Limestone aquifer by its functioning at the regional (reservoir area) as well as local scale (dam site area). The functioning of the karst system was approached by means of artificial and natural tracings. Artificial tracing was applied by using dye tracers, while natural tracing was studied by the hydrochemical and isotope content variations in space and time, and hydrodynamics, i.e., the spring discharge and piezometric level time series. Dye tracing suggests a range from 0.19 to 0.51 m/h for
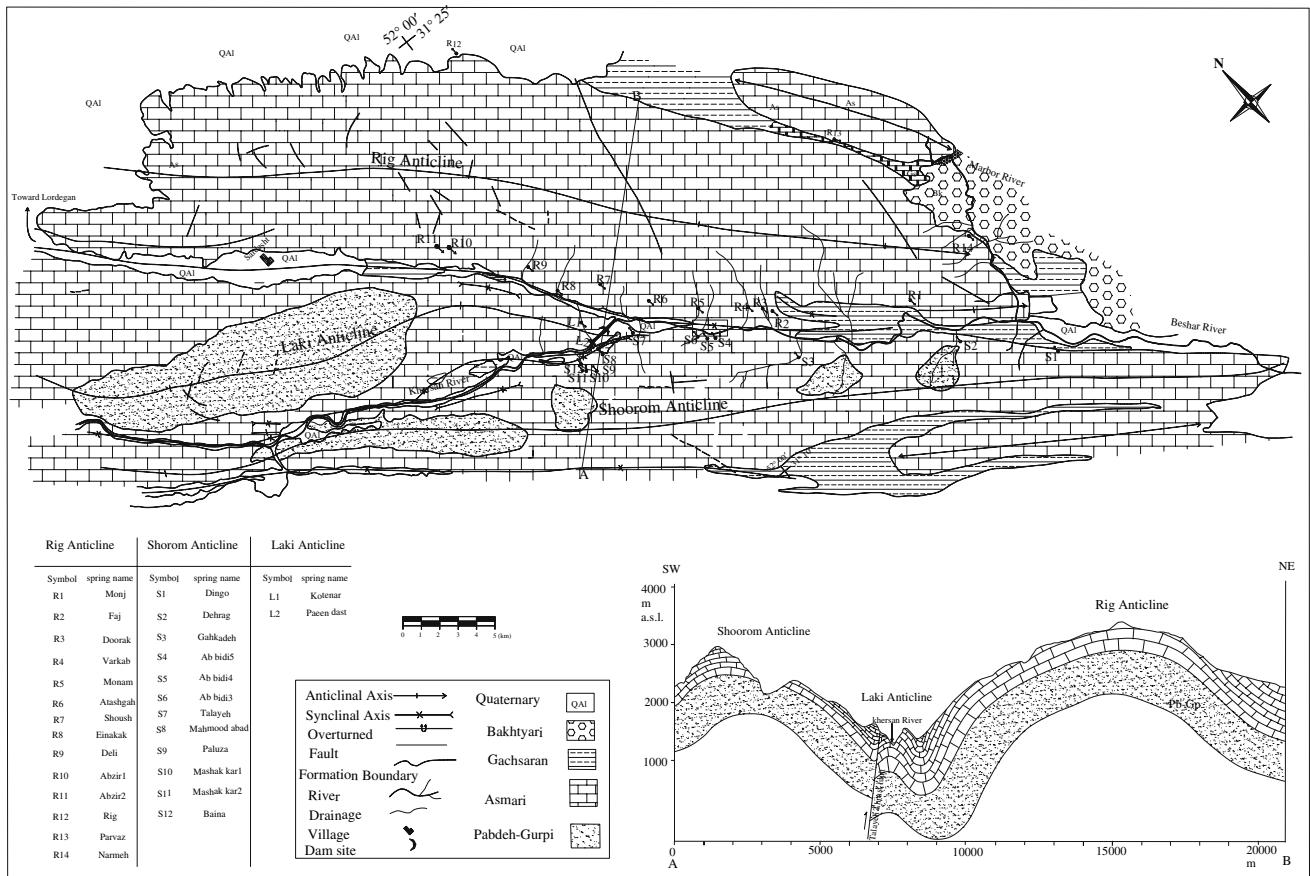
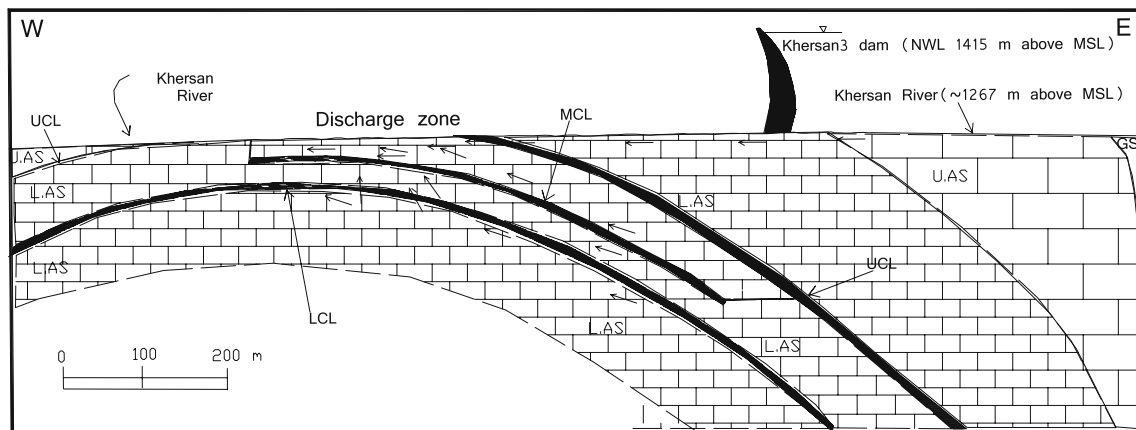**Fig. 2** Regional geological map of the Khersan 3 Dam project (modified from Keshavarz 2003)

Fig. 3 Cross-section of the aquifer system along the Khersan River (*U.AS* and *L.AS*: upper and lower Asmari, respectively; *GS* Gachsaran formation; *UCL MCL* and *LCL*: upper, middle and lower confining layer, respectively; *arrows* direction of flow in the aquifer system). The river flows westwards

mean tracer velocity that belongs to the diffuse flow system (Mohammadi et al. 2006b). Keeping in mind, these values are valid only close to piezometers used in dye tracing. The main objectives of functioning by natural tracers were to determine the extension of

karst development in the aquifer, its depth and role on regional groundwater flows and location of recharge areas of the artesian sub-aquifers at the reservoir area. This approach demonstrated that karst features are well developed and play a regional and local role in

groundwater flow. Springs and piezometers were differentiated according to the hydrochemical and isotope data. The Atashgah Spring (R6 in Fig. 2) with average discharge of 997 l/s emerges at an elevation of 1,710 m a.s.l. The minimum and maximum discharge in the Atashgah spring is 733 and 1,533 l/s, respectively. The catchment area of Atashgah spring is about 68 km^2. This means that recharge is spread out over the whole recharge area as autogenic recharge. However, fast flow should be developed for transforming the recharge water from the whole recharge area to the spring. The main storage of water in this spring is small openings and major conduits that have a transport role. Analysis of recession curve by means of exponential model (Mangin 1994) reveals that 13 and 87% of discharge water from this spring belongs to quick and base flow, respectively.

Electrical conductivity (EC) shows that the water mineralization consequently can be selected as representative of ions content in water. EC in the study area ranges from 240 to 597 μS/cm. It is possible to roughly classify the springs into two groups; that EC is less and more than 350 μS/cm, respectively. Most springs from Rig Anticline emerge at high elevation (more than 1,500 m above MSL) and Gashsaran formation is absent at recharge areas; consequently, EC is lower than those in low elevation (lower than 1,300 m above MSL) at Shorom and Laki Anticlines. EC in most springs and piezometers decrease (about 50 μS/cm) with respect to starting the rainfall season as well as fluctuation during the rainy season (Fig. 4). Such behaviour is common in the karst system (White 1988). However, the average EC in the artesian and unconfined sub-aquifers was 385 and 454 μS/cm, respectively.

High mineralization in the unconfined sub-aquifer can be caused by outcrops of Gachsaran formation.

The stable isotope composition of groundwater allowed the determination of the mean elevation recharge areas of the springs and dam site sub-aquifers (Fig. 5). The springs from Rig Anticline and the unconfined sub-aquifer belong to the highest and lowest recharge area at the study area. According to Fig. 5, mean elevation of the recharge areas of the artesian sub-aquifers is lower than springs from Rig Anticline that is supported by geological setting and hydrochemical data. From tritium contents, the water circulation path and depth were estimated. Tritium content in most springs (4.5 Tritium Unit, TU) and the unconfined sub-aquifer (3.8 TU) is close to those found in precipitation (5.7 TU), which means a significant contribution of recent precipitation. However, the lowest tritium values (1.7 TU) in the artesian sub-aquifers show deeper circulation and higher contribution of old groundwater than others.

Despite the absence of solution cavities and major conduits in boreholes and galleries at the dam site, karst is evidenced not only from surface karst features, but also from large springs (Fig. 2) and variations of the natural tracers at springs and boreholes. In particular, the annual mean groundwater temperature in the deep artesian sub-aquifers (14.5°C) lower than in the shallow unconfined sub-aquifer (16.8°C) shows that some karst conduits should allow rapid groundwater flow from the recharge areas at high elevations, influenced by snow melting. Such condition is an indication of fast groundwater flow in the deep artesian sub-aquifers without being affected by the geothermal gradient (Mohammadi et al. 2006a).

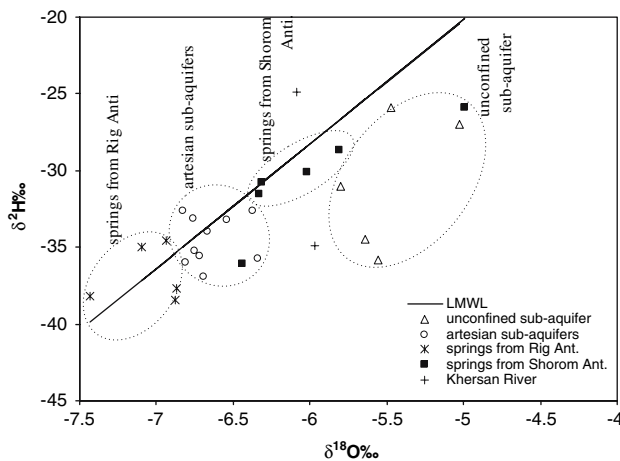**Fig. 4** Time variation of EC in selected spring and piezometers
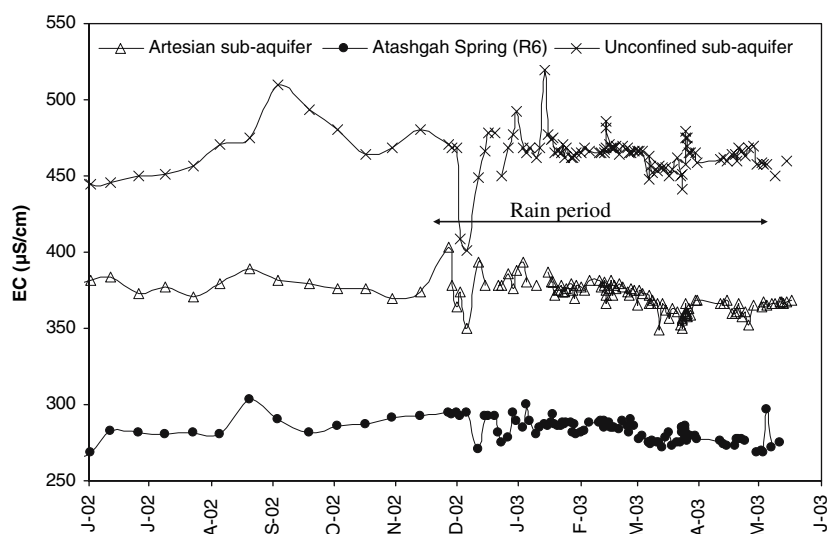
Fig. 5 Diagram of $\delta^{18}O$ versus δ^2H in all samples of the study area (October 2002)

These results show that the analysis of the aquifer functioning at least during a hydrological year may provide indirect information on the aquifer structure, i.e., on the development of karst and its role in determining groundwater pathways, and allow integration of local data from boreholes in the regional hydrogeological scheme.

Assessment of leakage

The hydrogelogical setting of the aquifer system at Khersan 3 Dam site, i.e., location of the discharge zone and hydrogeological data analysis proves that there is a leakage potential through the unconfined and artesian sub-aquifers. The leakage potential can be discussed following the delineation of sub-aquifers due to general flow direction (recharge-discharge zones) and karstification conditions in each sub-aquifer.

The normal water level (NWL) in the reservoir will be in direct contact with the unconfined sub-aquifer at left and right banks. It is expected that an adequate control of leakage through the unconfined sub-aquifer can be obtained by developing a grout curtain into the upper Asmari Limestone at depth and extending it laterally to the abutments. The karst condition at the unconfined sub-aquifer is concluded based on structure and functioning data of borings close to dam site. However, areas beyond the grout curtain boundaries and above the present water level in the unconfined sub-aquifer give potential to leakage as a critical area due to probable development of a karst conduit. The maximum water level in the unconfined sub-aquifer (1,273 m above MSL) is about 142 m lower than NWL (1,415 m above MSL); therefore, despite the mainly

diffuse flow under the present water level at the unconfined sub-aquifer, the karst conduits may be developed in the critical area (beyond the grout curtain boundaries and above the present water table to NWL).

An integrated interpretation of structure and functioning data reveals that the recharge areas of the artesian sub-aquifers are located at the Rig Anticline (Fig. 2) close to the planned reservoir. As the recharge area of the artesian sub-aquifers is located at a higher elevation than NWL, no leakage is directly expected from the artesian sub-aquifers. However, leakage through the artesian sub-aquifers may occur because the water head in the unconfined sub-aquifer will increase up to 1,415 m above MSL which may invert the head gradient between the sub-aquifers and favour leakage from the upper unconfined sub-aquifer toward the lower artesian sub-aquifers through the confining layers. Confining layers, 5 m thin, are not too strong as shown by disappearing of their confining role in the discharge zone.

Proposed methodology

Behaviour of the unknown karst features, i.e., paleokarst, hidden and filled karst, may cause some problems after construction of a dam such as (a) a considerable leakage after the first impounding, (b) a rapid increasing of leakage above a specific level in the reservoir, and (c) a series of collapses as sinkholes in the reservoir. These problems demand the necessity for developing the new grout curtain in depth and/or abutments. Accordingly, detailed investigations for karst features and their behaviour in the groundwater flow should be taken into consideration before designing, building and operating a dam. Water may leak directly or indirectly through the karst features. Consequently, the inception point for developing a method for leakage study is a question "Does karst develop or not?" For determining the answer to this main question, it seems that knowledge about karst development condition plays the leading role. The mechanisms responsible for developing karst were studied by Mangin (1978, 1994), Bakalowicz (1986), White (1988) and Ford and Williams (1989). In context of natural conditions for limestone formations, two mechanisms act together for developing a karst structure in a carbonate aquifer, as follows (Bakalowicz 1986):

- An "engine" for driving groundwater,
- A solution power.

Fig. 6 General assessment of hidden and exposed karst features (*PKD* potential for karst development)
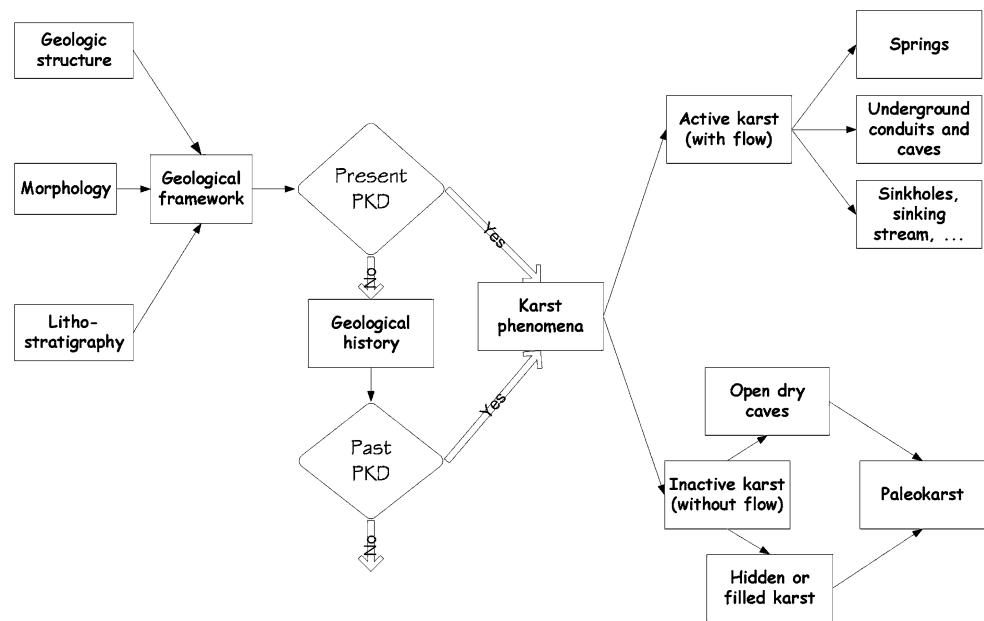
These two mechanisms constitute the potential for karst development (PKD). In classical karst, groundwater flows are driven by the gravity and the solution potential results on the flux of groundwater in which acidity is given by dissolved soil CO_2. In some other special situations other causes for acidity may occur, such as deep CO_2, H_2S, mixing of salt water with fresh water. Furthermore, groundwater flow can be partly controlled by density gradient, because of the difference either in salinity, or in temperature or gas lift (Bakalowicz 1986). The PKD applies to different geologic and geomorphologic settings, which differ in formation thickness and lithology, sequence of formations, faults, joints, bedding plans, unconformity, etc. Different karst features are formed in response to these settings. Therefore, solution process can be initiated by a sufficient difference in elevation to initiate a groundwater flow and by favourable climate conditions, producing soil CO_2 and infiltration water.

Some karst features such as springs, sinkholes, caves, etc. are exposed and may be active, but some others are hidden. In addition, the contribution of karst features to groundwater flow is not identical and some of them may be inoperative in present flow conditions, being abandoned because of changes in karst base level. The process for developing the karst features (hidden or exposed) is briefly presented in Fig. 6. Among leakage studies, detailed knowledge about two points is essential: (a) existence of karst features (hidden and exposed); and (b) behaviour of karst features in the groundwater flow (before and after dam construction) at local and regional scales.

Conventional methods for finding the karst features include geomorphology, field survey, geophysics and boring (boreholes, galleries and tunnels). Despite the valuable information about the existence of karst features, especially exposed and partly hidden, these methods do not give any information about the hydrological behaviour of karst features, and their role in the regional groundwater flow. The authors introduce an improved structure and functioning approach (Bakalowicz 2005) covering the conventional methods and overcoming their shortages. The concept of a karst system is taken into account in these approaches. A karst system is defined by its physical boundary conditions (extension, location and types of recharge and discharge e.g., point or diffuse) and its internal conditions (development of conduits and karst network). Field survey, topography, geological settings, location of springs and water balance are applied to define and delineate the structure of the karst system. In this approach the relation between recharge and discharge of the karst system is evidenced from the location, type and extension. The functioning of the karst system is approached by means of natural tracers (e.g., hydrochemical and isotope) and hydrodynamics (i.e., analysis of spring hydrograph and water level time series in boreholes), so that the internal conditions of the karst system, i.e., the stage of karst development, are defined. The analyses of the karst system functioning

Fig. 7 Proposed
methodology for leakage
study in three steps
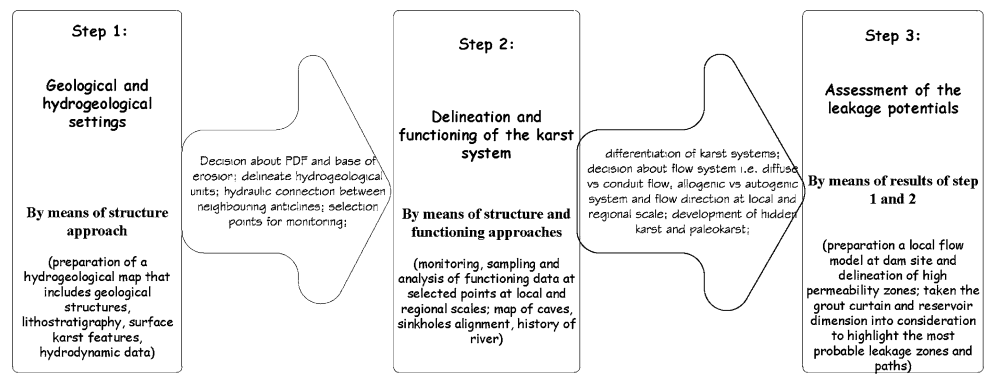
and karst efficiency are interesting approaches not only for studying the role of karst features in groundwater flow, but also for recognizing the existence of hidden features.

According to the above theoretical arguments, the framework of a practical methodology for leakage study is proposed in three steps (Fig. 7): (a) recognition of geological and hydrogeological settings, (b) delineation and functioning of the karst system, and (c) assessment of leakage potentials. This methodology is developed by means of two approaches (structure and functioning) at two scales, local and regional.

Generally, step 1 dealing with the approach of the karst structure is applied independently prior to others. Recognition of geological and hydrogeological setting and preparation of a hydrogeological map by means of structure approach is the main objective in step 1. A hydrogeological map includes geological structure, i.e., folding, anticline plunge, faults; soluble and non-soluble formations; surface karst features i.e., caves, sinkholes, blind streams and springs; and hydraulic characteristics. Some data on water electrical conductivity, temperature and discharge of springs will be helpful at this step to give an order of magnitude of their regional significance. According to this map, potential for karst development, hydraulic connection between neighbouring hydrogeological units and physical boundary of the study area will be revealed. Following step 1, a decision about the outline of step 2 is made. Hence, points for monitoring (functioning) and geologically ambiguous are selected for detailed studies in step 2.

Step 2 will take longer than step 1, because several methods will be used to analyse and delineate the karst system. This is the core of the study, based on structure and functioning approaches at the regional and local scales (Figs. 8, 9). Generally, regional scale is considered first, but most studies can be applied in parallel at the two scales. The structure approach at regional scale consist of studying (a) the faults and joints, i.e.,

statistical analysis and hydraulic behaviour; (b) the folding structure, anticline plunge and hydraulic connection of neighbouring anticlines; (c) the geological cross sections; (d) sinkholes, mapping them in dimension, orientation and frequency; (e) making an inventory of caves, mapping them, analysing their genesis for proposing a model of development; and (f) rivers for defining their history, behaviour and role in karst development as the base level. The functioning approach at the regional scale includes (a) the analysis of time series of discharge, electrical conductivity, temperature, pH, water chemistry and stable isotope, daily in wet season and weekly in dry season, at sampling points, e.g., springs, river, sinking stream and sinkholes; and (b) gauging and sampling rainfall at different elevations to estimate the mean elevation of recharge area of springs from the regional isotope gradient. Therefore, sampling points may be classified and located with respect to the regional flow pattern in the karst aquifer, and water balance and general flow direction are determined. Integrated interpretation of available data gives valuable information about karst development, flow system, diffuse or conduit, hidden karst, and paleokarst. Finally, an evolution model of karst development may be proposed, including a map of assumed high permeability zone(s).

Most items in the structural and functioning approach have been applied at local as well as regional scale even when there is no spring at the dam site. For that reason, attention was focused on boreholes and wells at the dam site (Fig. 9). Detailed geological studies, e.g., analysis of discontinuities, i.e., joints, faults, cavities and bedding plans, are explored by logging at boreholes. Geophysics allows a local description of geology at the dam site (Fig. 9). Hydraulic connections downstream and upstream from the dam site, local karst development and flow system can be precisely recognized by means of hydrodynamics, and natural and artificial tracing. Following the delineation and functioning of the karst system, two different models may be proposed:

Fig. 8 Delineation and functioning of karst system at regional scale in step 2
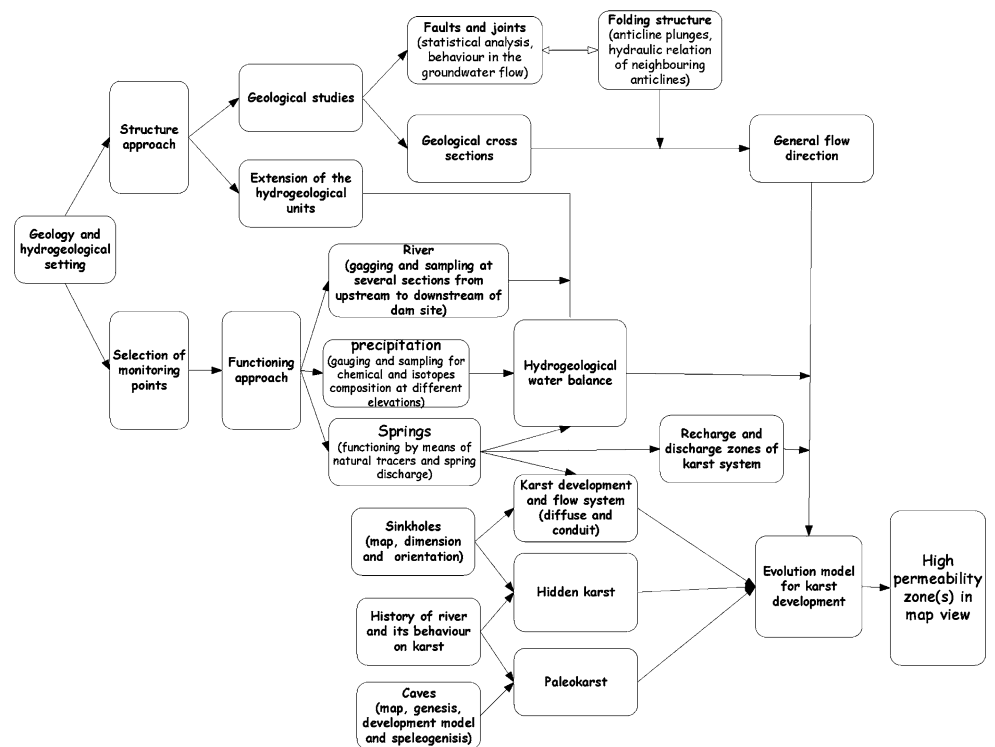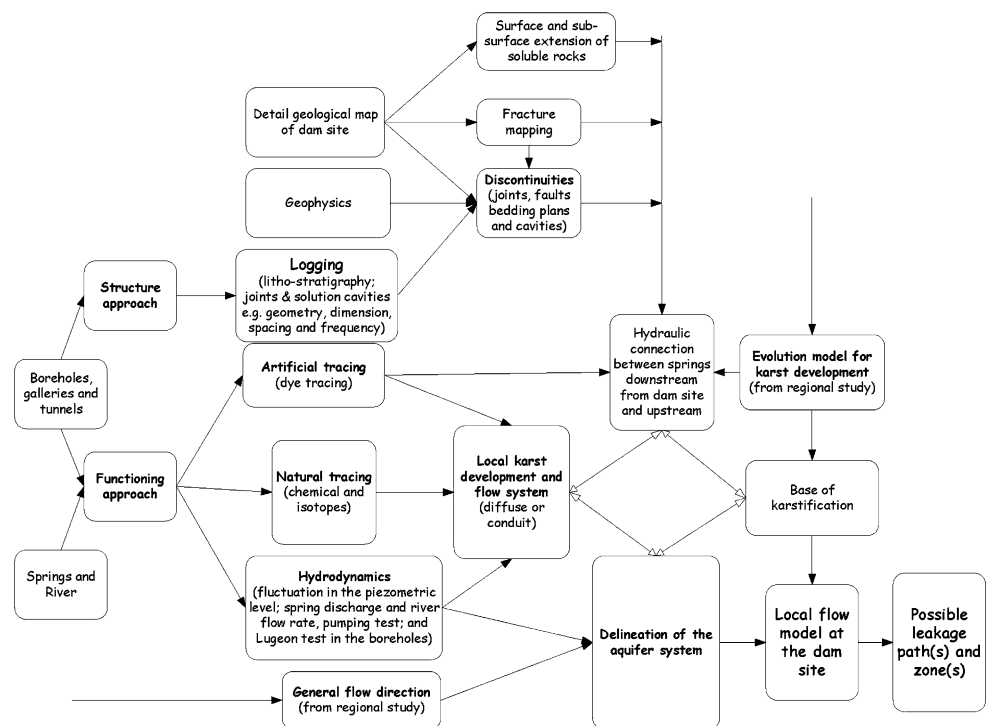

Fig. 9 Delineation and functioning of karst system at local scale in step 2

- A conceptual model of the karst system functioning at present,
- A model of its evolution through geological times, based on geological data on paleokarst, changes in base levels related to sea level and/or tectonics.

According to these models the high permeability zone(s) and possible leakage path(s) and location(s) are highlighted at the dam site. The need for complementary investigations may be recommended at the end of step 2.

The potential for leakage under several conditions such as before and after dam construction and construction without or with a grout curtain with different dimensions is analysed in step 3.

Conclusions

Several experiences are known from dams built in karst regions of Iran related to leakage problems occurring during or after dam construction or operation. They appear as representative of most comparable study cases known over the world, generally showing that the hydraulic effects of karst features on groundwater flow are not studied before dam construction at regional and even local scales. These examples show the lack of understanding the karst and inadequate knowledge of karst hydrogeology.

The conventional methods for studying the development of karst and the leakage potential before constructing the dam are usually local borings and geophysics at the dam site and geological mapping. Experience is replete with cases of drill holes that just missed a major cave or similar feature. However, dye tracing, water table variation, spring hydrogeology and new boring were applied in most of dam sites for exploring karst development in and around the dam and reservoir. Often these approaches were applied after the leakage occurred and during remediation work without a systematic procedure.

Huge leakage values of karst dam sites and lack of a detailed insight into karst condition for leakage study, especially before construction of the dam, enhanced a step-by-step methodology for leakage study in karst areas. The proposed methodology is still a draft inspired by that set up for analysing the functioning of karst aquifers and assessing their groundwater resource and storage capacity (see Bakalowicz 2005 for a detailed reference list). It consists of three steps: (a) gathering of the geological and hydrogeological settings and completion of maps; (b) delineation and functioning of the karst system involved in the dam and reservoir project; and (c) assessment of the leakage potentials.

These steps (but not all items in the proposed flowcharts) have been applied to the Khersan 3 Dam project, in Zagros range, Iran, at local and regional scales, following the structure and functioning approaches. Karst development and leakage potential were shown based on the proposed methodology as follows:

- Step 1: (1) The aquifer system consists of one unconfined and three artesian sub-aquifers, (2) the

discharge zone of the aquifer system is downstream of the dam axis, and (3) surface karst features were identified and catchment areas of the springs were determined;

- Step 2: (1) Despite the absence of solution cavities and major conduits in boreholes and galleries at the dam site, some karst evidences were observed, i.e., surface karst features in the recharge area, springs and variations of discharge, water level and natural tracer contents in springs and boreholes; (2) the functioning of the karst system shows variations are driven by the recharge conditions, starting with the wet season as commonly observed in karst systems; (3) the aquifer heterogeneity, the evidence for local groundwater fast flow in the deep artesian sub-aquifers are obvious facts accounting for a certain degree of karst development in all parts of the aquifer system; (4) structure and functioning of the system reveal that the discharge area of the aquifer system is downstream from the dam axis; (5) the recharge zone of the artesian sub-aquifers is at the south flank of Rig Anticline and higher than NWL; and (6) consideration of all probable recharge zones of the artesian sub-aquifers at the reservoir area and neighbouring anticlines emphasize the necessity of a regional study of the karst system;

- Step 3: (1) The unconfined sub-aquifer will be subject to leakage beyond the designed grout curtain dimension at left and right banks due to probable developed karst features; and (2) although no direct leakage through the artesian sub-aquifers is concluded due to higher recharge elevation than NWL and higher piezometric level than the unconfined sub-aquifer, the reservoir head may invert the flow gradient from the unconfined sub-aquifer toward the artesian sub-aquifers and consequently leakage will occur.

The above three steps profited by structure and functioning approaches. These approaches cover the conventional methods and overcome their shortages. Field survey, topography, geological settings, location of springs and water balance are applied to delineating the karst system and approaching its structure at the regional scale. The functioning of the karst system is determined by means of artificial and natural tracers, e.g., hydrochemical and isotope contents, and hydrodynamics, i.e., spring discharge and piezometric level. The functioning of the karst system is determined by the stage and type of karst development. It accounts for the role of karst features in groundwater flow even if they are hidden or plugged. Location(s) and path(s) of leakage finally result on the detailed

study of the site, considering the results from the study of the regional structure and functioning of the karst system.

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