

A dye-tracing test as an aid to studying karst development at an artesian limestone sub-aquifer: Zagros Zone, Iran

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Abstract A dye-tracing test is employed to study the karst development and flow regime at an artesian limestone sub-aquifer, the Khersan3 Dam site, Zagros Zone, Iran. Tracer breakthrough curves showed an early dominant peak followed by a pronounced tailing effect. The peak concentration was a response to induced pressure during dye injection. The results suggest that the dye was pushed into the small pores and fissures around the injection point during dye injection. Hence, the dye moved out as a result of matrix and fissure diffusive processes and created a long pronounced tailing. The maximum flow velocity in the upper artesian sub-aquifer ranged from 0.97 to 2.9 m/h. However, the mean tracer velocity ranged from 0.19 to 0.51 m/h based on the mean residence tracer time; consequently, the flow regime in the artesian sub-aquifer was determined to be mainly diffusive. The results reveal (1) a low hydraulic gradient from upstream of the dam axis to downstream; consequently, there is no considerable flow; (2) poor karst development and diffuse flow at the tracing test area; (3) a discharge zone at a location downstream of the dam axis which is the main terminal of general flow direction at the dam site.

Keywords Artesian sub-aquifer · Dye tracing · Iran · Karst development · Zagros zone

Introduction

The Khersan3 site is under study as the location for the construction of a dam on the Khersan River, Zagros Zone, southern Iran (Fig. 1). The 148-m high double arch of the dam will regulate the floods of the Khersan River and generate power. Twenty-one piezometers have been drilled at the dam site to monitor pore pressure (Fig. 2). The predominantly Asmari Limestone outcrops at the dam site function as an aquifer system. This aquifer system at the Khersan3 dam site consists of one unconfined and three artesian sub-aquifers (upper, middle and lower), the latter separated by three marly impermeable layers (UCL, MCL and UCL, respectively, in Fig. 3). The depth of the artesian sub-aquifers below the designed dam axis is about 200 m, but it gradually decreases in the downstream direction, approaching the surface about 500 m from the dam axis (Fig. 3). Analyses of the geological setting, water head in the piezometers, hydrochemical and isotope evidence prove the existence of a discharge zone downstream of the dam axis where the artesian sub-aquifers are located near the surface (Mohammadi et al. 2006). As a result, the discharge is widespread along the river bottom rather than being concentrated; there is no spring at the dam site and downstream.

In a previous study (Bakalowicz 2005), artificial functioning of the karst system by means of dye tracing was applied with the aim of determining karst development at the upper artesian sub-aquifer. Water tracing is a well-developed, powerful tool of the karst hydrologist that enables catchment boundaries to be estimated, areas of recharge to be determined and sources of pollution to be identified (Ford and Williams 1989). In addition, one of the most unequivocal ways to

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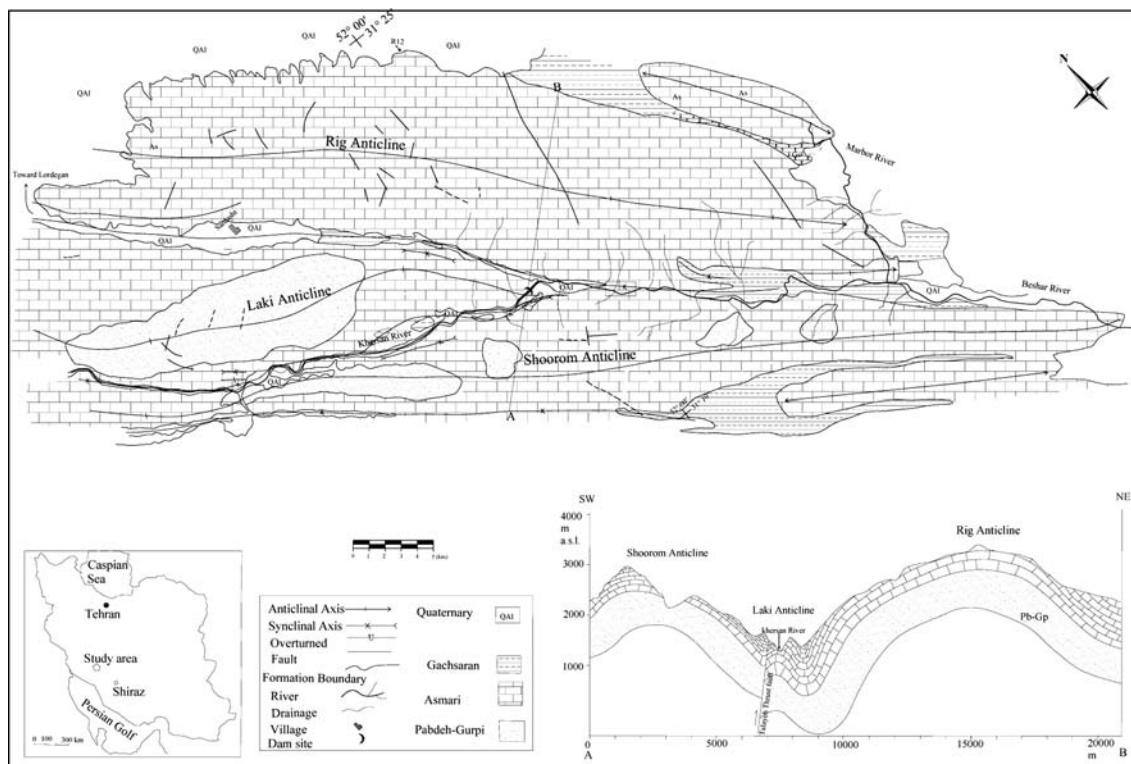


Fig. 1 Location map and regional geological map of the study area

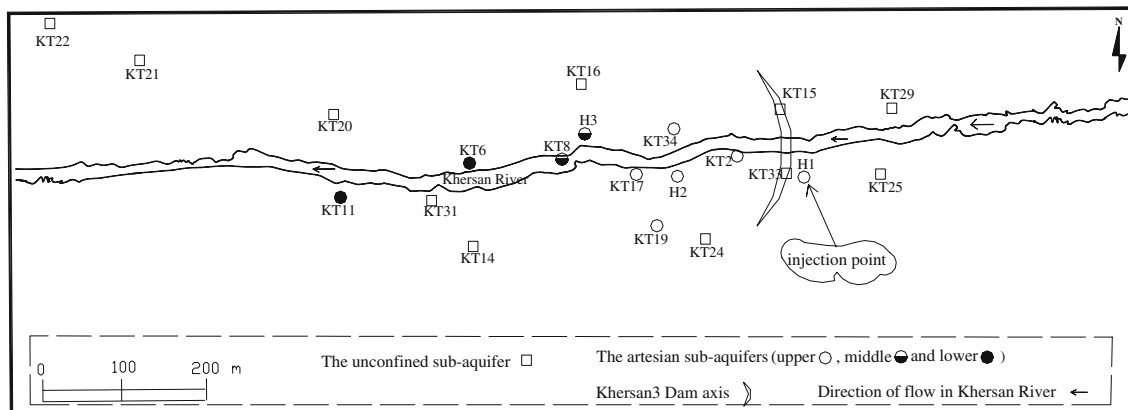


Fig. 2 Location of piezometers at the Khersan3 Dam site

ascertain the hydraulic properties of an aquifer, the velocities and pathways through a hydrological system is artificial tracing. Many groundwater-tracing studies have also employed the Uranin dye since it is inexpensive, easily detectable, non-toxic and stable over time (see Smart and Laidlaw 1977; Smart 1988; Meus and Kass 1992; Schindel et al. 1995; Raeisi et al. 1999, 2001; Maloszewski et al. 1998; Hauns et al. 2001). However, this dye will break down if exposed to direct sunlight.

In the study reported here, a dye-tracing test was carried out in an artesian limestone sub-aquifer with-

out any spring. The main objectives of the investigation were to study the karst development and the flow direction and to interpret the breakthrough curves at the upper artesian sub-aquifer. Karst development was characterized by means of residence time and groundwater velocity.

Geological setting

The study area is located at the Laki Anticline, Zagros Zone, southern Iran. The Zagros Zone is one of five

major structural zones in Iran (Stocklin 1968). It is about 12 km thick and mainly comprises limestone, marl, gypsum, sandstone and conglomerate. Since the Miocene, it has been folded into a series of huge anticlines and synclines.

The stratigraphy and structural framework of the Zagros Zone have been studied in detail by James and Wynd (1965), Stocklin and Setudehnia (1977) and Alavi (2004). The geological map and the cross-section along the dam axis are presented in Fig. 1. The valley of the dam is surrounded predominantly by a Asmari Limestone (Oligo–Miocene) Formation. The Asmari Formation can be classified into two units – the upper Asmari and lower Asmari. The lithology of the upper Asmari consists of thick limestone layers, while the lower Asmari includes sequences of limestone, thin marl and marly limestone. The thickness of the upper and lower Asmari is about 200 and 250 m, respectively. The Asmari layers dip steeply (more than 65°) upstream of the dam axis. The Gachsaran Formation (Miocene age) overlies the Asmari Formation and is composed of salt, anhydrate, marl and gypsum.

Surface karst features, such as small caves, have been mainly observed in the upper Asmari at the dam site. However, a few karst features have developed at bedding planes of thin layers at the lower Asmari. No solution cavities or major karst conduits have been observed in boreholes and galleries at the dam site. The results of 2930 joints in the core of the boreholes show that these are mainly filled by calcite and clay, rendering apertures of less than 1 cm (Mahab Ghodss Consulting Engineers 2000). A few minor faults have been observed at the dam site: 27 and 11 faults on the right and left bank, respectively. Vertical displacement along these faults is small, ranging from a few centimeters to 5 m. However, a major thrust fault with

about a 200 m vertical displacement intersect the Asmari Formation on the left bank, about 500 m away from the dam site (Fig. 1).

Hydrogeological setting

Asmari Limestone is the major constituent of the main aquifer system at the Khersan3 Dam site (Mahab Ghods Consulting Engineers 2000; Karimi 2003; Mohammadi et al. 2006). Twenty-one piezometers were drilled at the dam site to assess the pore pressure (Fig. 2). The aquifer system at the dam site consists of unconfined and artesian parts. In general, unconfined and artesian sub-aquifers are formed in the upper and lower Asmari Limestone, respectively. The artesian part can be differentiated as upper, middle and lower artesian sub-aquifers. These conclusions were supported by geological setting, water head and time series analyses of hydrochemical and isotope data. The water level in the unconfined sub-aquifer ranges from 1264 to 1273.2 m a.s.l. The piezometric level in the upper, middle and lower artesian sub-aquifers ranges from 1321 to 1359, from 1297 to 1343 and from 1270 to 1280 m a.s.l., respectively. The average electrical conductivity (EC) and temperature in the unconfined sub-aquifer is 454 $\mu\text{s}/\text{cm}$ and 16.8°C. Average EC and temperature in the artesian sub-aquifers are approximately the same (about 380 $\mu\text{s}/\text{cm}$ and 14.5°C, respectively). However, time variations in the EC and temperature show different behaviours. The sub-aquifers are separated by an upper, middle and lower confining layer (UCL, MCL and LCL in Fig. 3), respectively. These layers, which are approximately 5 m thick, are marly interbeds in lower Asmari. The depth of the UCL is about 200 m at the dam axis,

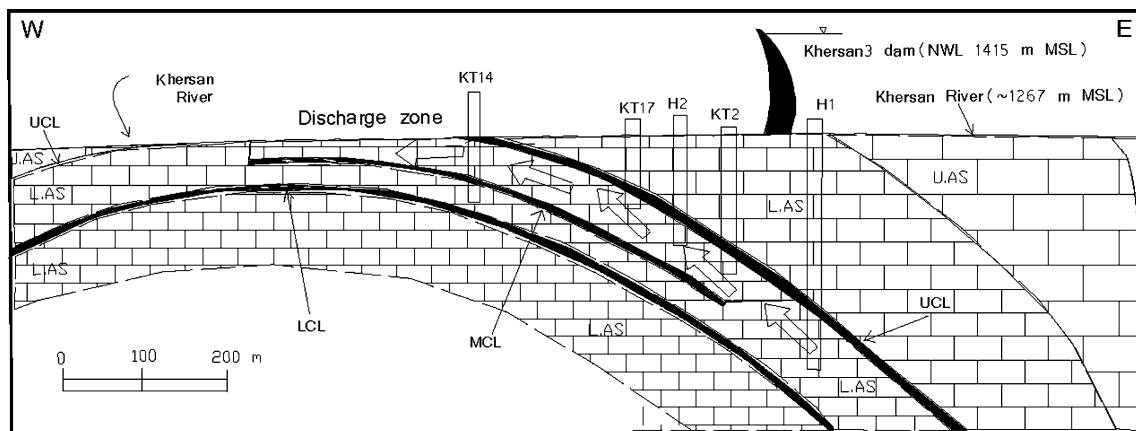


Fig. 3 Cross-section along the Khersan River. U.A.S and L.A.S Upper and lower Asmari, respectively, UCL, MCL and LCL upper, middle and lower confining layer, respectively. Arrows show the schematic direction of flow

decreasing gradually in the downstream direction and outcropping to the surface about 500 m from the dam axis. MCL and LCL follow an anticline form, similar to that of the UCL. The confining layers lose their impermeable character near the surface (about 60 m depth) due to weathering and solution along the joints, which are common occurrences at the top of anticlines. Therefore, three impermeable layers – the upper, middle and lower – create three superimposed artesian sub-aquifers close to the dam axis. These sub-aquifers can lose their artesian character as the confining layers are partly open as they approach the surface downstream of the dam axis. Accordingly, this area acts as a discharge zone of the artesian sub-aquifers, which is supported empirically by data on the geological setting, water level and hydrochemical and isotope analyses (Mohammadi et al. 2006). Keeping in mind that the average discharge of the Khersan River is more than 25 m³/s, no measurement of river discharge has been carried out upstream and downstream of the discharge zone. It would appear that the discharge of the artesian sub-aquifer to the river is very small in comparison to the discharge of the Khersan River itself. The general flow direction in the artesian sub-aquifers at the dam site is toward the discharge zone. However, piezometric data are not sufficient for drawing a conclusion on the flow direction in the artesian sub-aquifers due to the limited amount of available data and the poor sealing condition. The schematic flow direction is from the right bank to the discharge zone; this is supported by maximum pressure and discharge in the KT34 piezometer on the right bank (Fig. 2).

Consideration to injection

A study of the geological setting revealed that the discharge zone of the artesian sub-aquifers is located downstream from the dam axis. The tracer injection point was selected to yield access to the upper artesian sub-aquifer and to be near the designed location of the Khersan3 Dam axis. The H1 piezometer, at a depth of 275 m and 1280 m a.s.l., is located on the left bank (Fig. 2) as well as upstream of both all other piezometers and the planned dam axis (Fig. 2); it intersects the UCL at a depth of 205 m and, consequently, fully penetrates (70 m) into the upper artesian sub-aquifer. The hydraulic connection between the unconfined and artesian sub-aquifers is exactly sealed at the H1 piezometer. The measured permeability in the H1 piezometer opens into the upper artesian sub-aquifer (from a depth of 205–275 m) ranges from 2 to 14 lattice-units ($3.4\text{--}23.8 \times 10^{-5}$ cm/s).

Most of the artesian piezometers were closed prior to the dye tracing test. However, some of them were opened for short time for the filling of tanks used in drilling or construction. The natural condition at the H1 piezometer was measured at 7 atm (pressure) and 4.5 l/s (discharge) before dye injection. As it is possible to disturb the natural condition of groundwater in the upper artesian sub-aquifer as a result of the high pressure and high injection rate during dye injection, we have concluded that the following conditions must be maintained to avoid an unrealistic direction and velocity: (1) all artesian piezometers were closed 2 days prior to the dye injection and (2) the pressure and rate of dye injection were controlled to about 7.4 atm and 2–3 l/s, which is as close as possible to the natural condition. The dye was injected for a period of 4 h and then freshwater was immediately injected at the same rate and pressure for an additional period of 17 h.

Sampling and analysis

Twenty-five points were selected as sampling points. These points belong to drilled piezometers at the aquifer system including (1) KT34, KT2, H2, KT17 and KT19 at the upper artesian sub-aquifer; (2) KT8 and H3 at the middle artesian sub-aquifer, (3) KT6 and KT11 at the lower artesian sub-aquifer; (4) KT29, KT15, KT16, KT20, KT21, KT22, KT25, KT33, KT14, KT24 and KT31 at the unconfined sub-aquifer; (5) five sections along the Khersan River.

Water samples were collected from unconfined piezometers by means of individual mechanical samplers. The samples from artesian piezometers were collected under natural pressure after discharging the water volume in the piezometer casing. For establishing the natural condition, all artesian piezometers were closed between sampling intervals. All samples were stored in 75-cc dark glass bottles and transported in a lightproof container to prevent any reduction of the fluorescence due to photochemical decay.

The initial sampling frequency was 48 times per day, which was subsequently reduced to 12, six and two times per day and then to daily and weekly sampling, depending on the level of dye concentration appearing in the samples. The samples were collected for 8 months, which came to a total of 3000 water samples. The Shimadzu spectrofluorometer model RF-5000 with a detection limit of 0.001 ppb was used to measure the sodium fluorescein concentration. Several calibration curves were prepared for different dilution ranges.

Results

The analysis of the water samples revealed that dye was present in the three artesian piezometers (KT2, H2 and KT17 in Fig. 2) located on the left bank and one unconfined piezometer (KT14 in Fig. 2). Karst condition can be characterized by means of tracer breakthrough curve analysis. These analyses can be applied within both a quantitative (residence time and tracer velocities) and a qualitative (organization of karst network) framework.

Qualitative analysis

The tracer breakthrough curve of the KT2 piezometer shows a predominant peak concentration of about 157 ppb after 37.5 h of injection followed by an approximately constant concentration of about 65 ppb for a period of 60 days (from 60 to 120 days after dye injection in Fig. 4). The breakthrough curve of the KT2 piezometer was not complete at the end of observation period, and high concentrations of dye (about 30 ppb) were still being detected for a period of 80 days (from 140 days after injection until the end of sampling in Fig. 4). Thus, it would appear that a significant portion of dye remained in the aquifer, indicating that this piezometer was poorly connected with active the flow paths within the aquifer. The hydraulic gradient between the injection point and the KT2 piezometer increased about 5% during the dye injection process, consequently, peak concentration in the breakthrough curve of the KT2 piezometer occurred as a response to injection pressure. It seems that the tailing shape (long constant concentration) represents the natural flow condition. A long and flat curve without any bearing on the peak in Fig. 4 may have occurred by diffuse flow.

Tailing effects are mostly attributed to diffusion phenomena (i.e. matrix or fissure diffusion), and tailing itself may occur by (1) tracer movement under low flow stage or low hydraulic gradient (Milanovic 1981; Stevanovic and Dragvsic 1992), (2) mixing of tracer with an underground lake (Zhengxing 1988), (3) diffusive tracer exchange to huge volume of dead-end pores (Seiler and Behrens 1992), (4) tracer transport at the layered heterogeneity in subsurface geologic materials (Iqbal 2000) and (5) the existence of two main transport/hydraulic behaviour components, including a rapid turbulent component and a slower component due to friction forces in a single conduit (Massei et al. 2006). A low hydraulic gradient and the absence of large solution conduits may have caused the tailing part in the KT2 piezometer. Moreover, the absence of a complete sealing condition at the boundary of the unconfined and artesian sub-aquifers at the KT2 piezometer (UCL in Fig. 3) would provoke the tailing effect because a continuously artificial discharge takes place through the unconfined sub-aquifer.

The breakthrough curve of the H2 piezometer has a typical positive skewed shape with a peak concentration of 146 ppb (Fig. 5). The peak concentration is mostly enhanced by the elevated hydraulic gradient (about 2.5%) between the injection point and the H2 piezometer during the dye injection. The rising limb of the tracer breakthrough curve in the H2 piezometer is the same as that in the KT2 piezometer, but the recession limb is clearly different (Figs. 4, 5). The different karst structure may cause different karst functioning in flow routes between the injection point and these piezometers. In this situation, different sealing conditions provoke a tailing effect with different concentrations. The H2 piezometer is exactly sealed at UCL (Fig. 3) and there is no continually

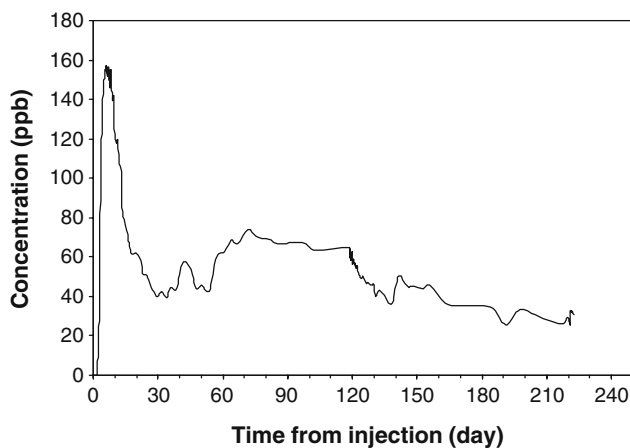


Fig. 4 Tracer breakthrough curve in the KT2 piezometer

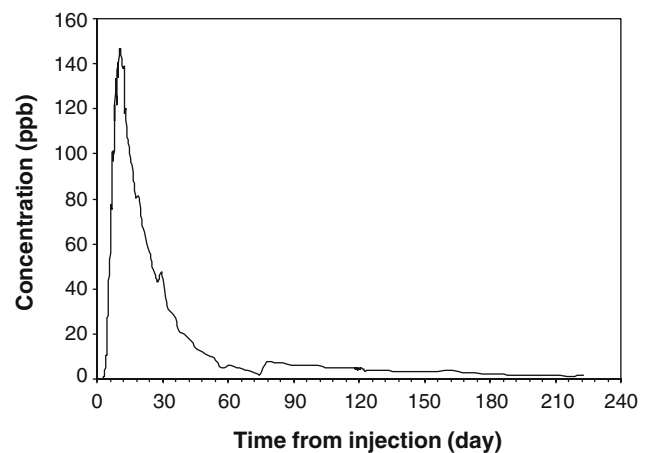


Fig. 5 Tracer breakthrough curve in the H2 piezometer

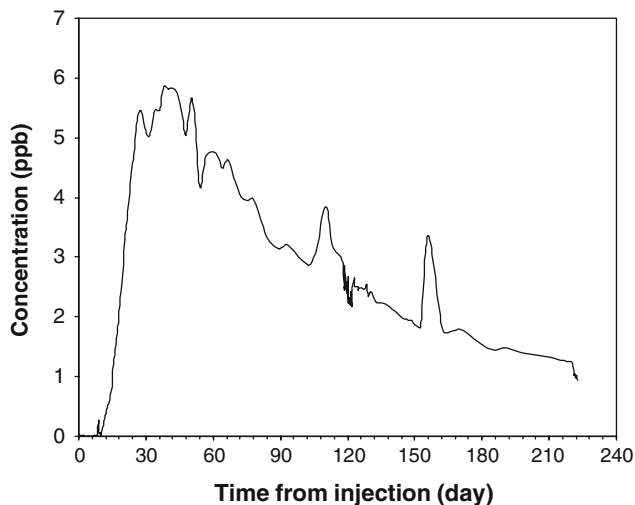


Fig. 6 Tracer breakthrough curve in the KT17 piezometer

artificial discharge from the artesian to the unconfined sub-aquifer.

The peak concentration in the KT17 piezometer was observed to be about 5.8 ppb (Fig. 6). The distance of the KT17 piezometer from the injection point (253 m) was just enough to ensure a dilution in the diffusive condition of tracer transport (Seiler and Behrens 1992). A concentration of the dye was detected in a seepage face close to the outlet of the KT17 piezometer by activated charcoal samples, thereby proving an incomplete sealing condition in this piezometer. The shape of the breakthrough curve can be affected by incomplete sealing condition.

The tracer breakthrough curve in the KT14 piezometer shows a low concentration with high variations and a peak concentration of about 1.3 ppb (Fig. 7). Contrary to the flowing artesian piezometers

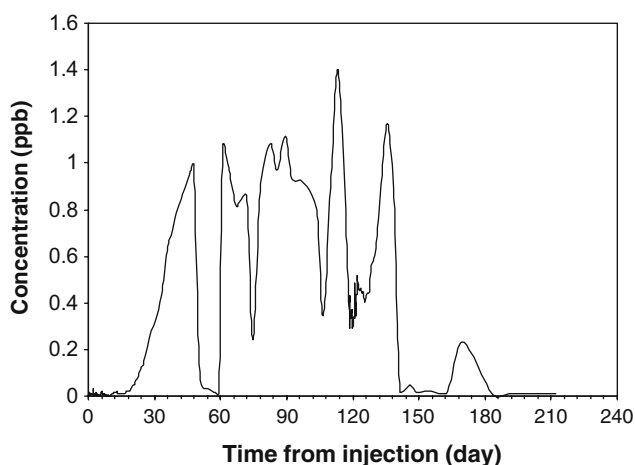


Fig. 7 Tracer breakthrough curve in the KT14 piezometer

(KT2, H2 and KT17) mentioned above, KT14 is an unconfined watertable piezometer located close to the discharge zone (Fig. 2). Fluctuations in the dye concentration may be caused by (1) a larger distance between the injection point and KT14; (2) sensitivity of a low concentration of dye to mixing with even very low volumes of fresh water; (3) sampling conditions as a result of the depth of sampling, the speed of sampler movement or sampling without discharge of casing water volume; (4) the rainy season, which started 90 days after dye injection.

Quantitative analysis

Computed velocities according to breakthrough curves are presented in Table 1. Maximum, mean and peak velocities are computed based on the first arrival of dye, the mean tracer residence time and the time to peak concentration, respectively. Mean tracer residence time (\bar{t}) is the length of time required for the centroid of the tracer mass to traverse the entire length between the injection and sampling points and may be estimated as following (Field 1999):

$$\bar{t} = \frac{\int_0^{\infty} tC(t)Q(t)dt}{\int_0^{\infty} C(t)Q(t)dt} \quad (1)$$

where t is time of sample collection, C is tracer concentration and Q is groundwater discharge. Mean tracer velocity (\bar{v}) is a measure of the velocity of the tracer centroid estimate by the following (Field 1999):

$$\bar{v} = \frac{\int_0^{\infty} \frac{x_s}{t} C(t)Q(t)dt}{\int_0^{\infty} C(t)Q(t)dt} \quad (2)$$

where x_s is tracer migration distance. The maximum velocity was found to range from 0.97 to 2.9 m/h, while mean velocity ranged from 0.19 to 0.51 m/h. Maximum velocity is a highly unrealistic parameter due to the uncertainties of the initial tracer arrival time (Field 1999) and non-homogeneity of karst aquifers, consequently it is not a representative character of the karst system. In the present study, induced pressure during the dye injection may have provoked an unrealistic maximum velocity. Mean tracer velocity, however, can represent the contribution of the whole system close to the tracing test area. The computed mean tracer velocities were determined to be less than the reported velocity range for the conduit flow, such as from 7.2 to 1,880 m/h by Milanovic (1981) and from 4.5 to 1450 m/h by Ford and Williams (1989). This suggests that the dye was pushed into the small fissures and captured by small dead-end pores, then diffusion processes mixed

Table 1 Computed velocities between injection point and sampling points

Name	Distance from injection point (m)	First arrival of dye (h)	Time to peak concentration (h)	Mean tracer residence time (h)	Maximum velocity (m/h)	Peak velocity (m/h)	Mean tracer velocity (m/h)
KT2	95	37.5	144.5	497.3	2.53	0.66	0.19
H2	190	65.5	241.2	373.55	2.9	0.79	0.51
KT17	253	260.5	668.4	799.21	0.97	0.38	0.32
KT14	536	391.2	1400	1203.1	1.37	0.38	0.45

the dye, with a low hydraulic gradient flow towards the discharge zone. All peak velocities were found to be less than 1 m/h (Table 1).

Discussion

The detection of dye downstream of the injection point on the left bank (KT2, H2 and KT17 piezometers in Fig. 2) reveals the presence of a flow component in the same direction as the Khersan River. This means that dye moved from the injection point in the upper artesian sub-aquifer towards the discharge zone downstream of the dam axis on the left bank only. The absence of any concentration of dye in the piezometers from the upper artesian sub-aquifer on the right bank emphasizes the absence of a flow component from the left to right bank. The detection of dye (maximum: 1.4 ppb) in the KT14 piezometer reveals a general flow direction to the discharge zone. The dye may have been moved around piezometers close to the discharge zone (e.g. KT6, KT11, KT31 and KT20 in Fig. 1), but if so, it was extensively diluted by mixing during diffusive movement and its concentration was under the detection limit of our instruments. Furthermore, no dye concentration was found in the Khersan River even close to the discharge zone. Although the general flow direction is supposed to be toward the discharge zone, dye was not detected close to this zone nor downstream due to its high dilution in the river.

The induced pressure that resulted from injection of the dye created a high hydraulic gradient between the injection point and the KT2, H2 and KT17 piezometers (about 5, 2.5 and 2%, respectively), suggesting that most of dye mass was pushed to small pores and fissures around the injection point. After unloading of the injection pressure, the dye moved under the very low hydraulic gradient of the natural condition. Accordingly, the shape of the breakthrough curves (Figs. 4, 6) consists of two parts: (1) an early peak response to induced pressure during the injection of the dye and (2) a pronounced tailing response to diffusive movement of the dye. Therefore, we conclude that the dye mainly moved by diffusion of the matrix and fissure.

However, the tailing effect in the KT2 and KT17 piezometers was provoked by the lack of a completely sealed condition at UCL (Fig. 3). These findings prove that (1) the hydraulic gradient from upstream of the dam axis to downstream is very low and, consequently, there is not any considerable flow, (2) karst is not developed near the tracing test piezometers and (3) the diffuse flow condition can justify the breakthrough curves. By subtracting the primary peak from all breakthrough curves, \bar{t} and \bar{v} can be considered to be much lower than the values presented in Table 1. However, from the karst development point of view, all mean tracer velocities are in the range of the diffuse flow regime and these give the same result.

Conclusions

A dam will be constructed at the Khersan3 site on Asmari Limestone, Zagros Zone, southern Iran. The Asmari Limestone that functions as an aquifer system at the dam site consists of one unconfined and three artesian (upper, middle and lower) sub-aquifers. The artesian sub-aquifers are located at a depth of about 200 m below the dam axis; however, this depth gradually decreases in the downstream direction, outcropping about 500 m from the dam axis. These sub-aquifers can lose their artesian character as the confining layers are partly open as they get closer to the surface downstream of the dam axis. The discharge zone is sited where the confining layers outcrop or get closer to the surface.

The dye tracing test is applied to study the karst development at the upper artesian sub-aquifer. Twenty kilograms of sodium fluorescein was injected into a piezometer from the upper artesian sub-aquifer. The injection piezometer was located on the left bank, and its pressure and discharge before injection was 7 atm and 4.5 l/s, respectively. The dye was detected on the left bank only in three artesian piezometers (KT2, H2 and KT17) and one unconfined piezometer (KT14). Groundwater flow velocities in the upper artesian sub-aquifer between the injection point and sampling points were computed on the basis of the breakthrough curves. Maximum and mean velocities, ranging from

0.97 to 2.9 and from 0.19 to 0.51 m/h, respectively, indicate a diffuse flow regime in the upper artesian sub-aquifer and, consequently, most probably a poorly developed karst network. The induced pressure required for the injection of the dye created a high hydraulic gradient between the injection point and the KT2, H2 and KT17 piezometers (about 5, 2.5 and 2%, respectively) and, as a result, a pulse of dye reached the piezometers as a peak concentration in the breakthrough curves. A very long tailing in the breakthrough curves revealed that the dye moved primarily by diffusion in the matrix and fissures. The following arguments confirm a poorly developed karst condition on the left bank: (1) absence of solution cavities and major conduits in boreholes and galleries; (2) low groundwater velocities; (3) a pronounced tailing which may be an indication of diffusivity. The appearance of dye in the unconfined piezometer (KT14) reveals that artesian water can be discharged into the unconfined sub-aquifer. The dye moved toward the discharge zone downstream of the dam axis, thereby indicating the general flow direction at the dam site.

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