

INFLUENCES OF ANTICLINAL STRUCTURE ON REGIONAL FLOW, ZAGROS, IRAN

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Carbonate karstic formations outcrop in about 23% of the Zagros Region. Seventy-two karstic anticlines were selected to study regional flow. Based on geometry of the anticline and outflow position, a conceptual model is presented for delineation of flow direction, at least within Zagros. The anticlines were divided into two main groups based on presence or absence of hydraulic connectivity between the limbs. The geological and tectonic settings are the main controlling factors within these two groups. Sixty-four out of the seventy-two anticlines showed no hydraulic connectivity between their limbs. Each group was further classified into four subgroups based on the location of the discharge zones, namely one or both plunge apex noses, limb, traversing river, or a combination of plunge apexes, limbs and river. The discharge zones may be located in the adjacent or in the successive anticlines. The discharge zones are mainly controlled by local base level. In most of the cases having no hydraulic connection between the limbs, the direction of flow is initially along the bedding plane dip and finally parallel to the strike at the foot of the anticline. In most of the cases having connections between two limbs, the regional directions of flow, in the connected part, are opposite from the direction of bedding plane dip and eventually parallel to strike. The results show that the primary controlling factors of regional flow are the anticlinal structure of aquifers and geometry of the bedrock.

INTRODUCTION

From a theoretical point of view ground-water flow depends only on aquifer hydraulic parameters and boundary conditions (*i.e.*, geological and geomorphological factors exert their influence on the ground-water movement solely through the hydraulic-parameter fields and the boundary conditions). For instance, geology and geomorphology influence the hydraulic conductivity and porosity through the distribution of voids (Kiraly, 2002). An increase of the density and opening and connectivity of the voids therefore increases the hydraulic conductivity and the porosity. If fracture or microfracture families show a well defined preferred orientation the hydraulic conductivity may become anisotropic, thus conducting ground water better in one direction than in another.

Geological factors, in karst studies, include lithology, stratigraphy, fracture patterns and geological structure which are expected to define hydraulic-permeability fields. Relief and local base level are the main geomorphological factors defining boundary conditions and controlling the recharge and discharge location of the aquifer. Therefore, these factors control regional ground-water flow in karstic aquifers (White, 1969; Palmer, 2000) and there is abundant scientific literature on their control over the regional flow. The interested reader will find more in White (1969); Kastning (1977); Legrand (1983); Palmer (1991; 2000); Klimchouk and Ford (2000).

The aim of this paper is to study the link between aquifer characteristics (aquifer geometry and discharge location) and hydraulic response of karst systems (*i.e.*, delineation and major

flow direction). The establishment of such a relationship would help to estimate karst ground-water catchment areas and flow direction, which is often difficult (time consuming and expensive) to obtain, based on more easily obtained information (*i.e.*, aquifer geometry and discharge location). The result of this linkage is expected to show the main factors controlling the regional flow direction, such as the effect of an anticlinal structure. The present approach may be the first step of any study of regional hydrogeology, allowing for creation of a first conceptual model of flow in the region. Low cost investigation is very effective for establishing the first hypothesis, which can then be tested by any further investigation (tracing experiments, hydrographs analyses, chemograph analysis, isotopes, *etc.*). Examples from the Zagros Region of Iran will be used in order to support the proposed approach. Carbonate formations outcrop in about 23% of the Zagros Region (Raeisi and Kowsar, 1997). Information has been collected for 72 cylindrical anticlines in order to determine their flow characteristics and their geological/geomorphological settings.

APPROACH

Geometrically, the Zagros anticlines are cylindrical forms, which plunge down beneath younger sediments at both ends. The young sediments, which overly karstic aquifers, may be permeable or impermeable. Sediments form a thick cover over the synclines between anticlines. Only the top of the anticlines are bare and present exposed carbonate formations. At their bottom the karst aquifers are bounded by impermeable formations

(mostly marls and sandstone). Considering the aquifer geometry, there are two cases. If the elevation of the impermeable formation under the crest of an anticline is appropriately higher than the foot of the anticline most of the recharged water of each limb can flow towards the foot of the same limb (Figure 1). In this manner, the hydraulic connectivity of the limbs is disconnected and each limb becomes an independent subaquifer. The main source of recharge is direct precipitation on the karstic aquifer body. The recharge is mainly autogenic. A combination of joints and bedding planes plays a role in transferring the ground water through the vadose zone to the phreatic zone. The impermeable formation below the karstic aquifer and/or interbedded shales in karstic formations can block ground-water flow in a vertical direction. The steep slopes of the anticline limbs direct the flow toward the foot of the anticline via available pathways.

If the elevation of the impermeable formation under the crest of the anticline is lower than the karst-water level, resulting in the absence of any barriers, the karst water of one of the anticline limbs (donor limb) can flow towards the adjacent limb (receiver limb). Usually the contact elevations of karst formations with the adjacent non-karstic formation or alluvium are

higher around the donor limb than around the receiver limb. In other words, hydrological base level is located at the foot of the receiver limb and the easiest way for ground water to flow from donor limb to receiver limb, because the hydraulic gradient is steeper toward this limb. The hydraulic connection between the two limbs is often restricted to small areas of the donor limb. So, the infiltrated water flows first parallel to strike in a donor limb, towards a connection area, and then flows to the receiver limb at the connection area.

A main conduit system may develop at the foot of the anticline, parallel to strike where the branches of diffuse flow or small-conduit flow join each other. The direction of flow in main conduit systems at the feet of anticlines depends mainly on the location of discharge zones. Thus, anticlines of both groups can be further classified into four subgroups in which karst water discharges (I) Down-Plunge Nose: Only from one plunge apex or both plunge apices; (II) Limbs: Only from limbs; (III) Rivers: To a river traversing the karstic aquifer; and (IV) Combination: A combination of more than one of these subgroups (Fig. 1).

Therefore, the appropriate conceptual model defining regional flow in anticlinal aquifers is based on the presence or

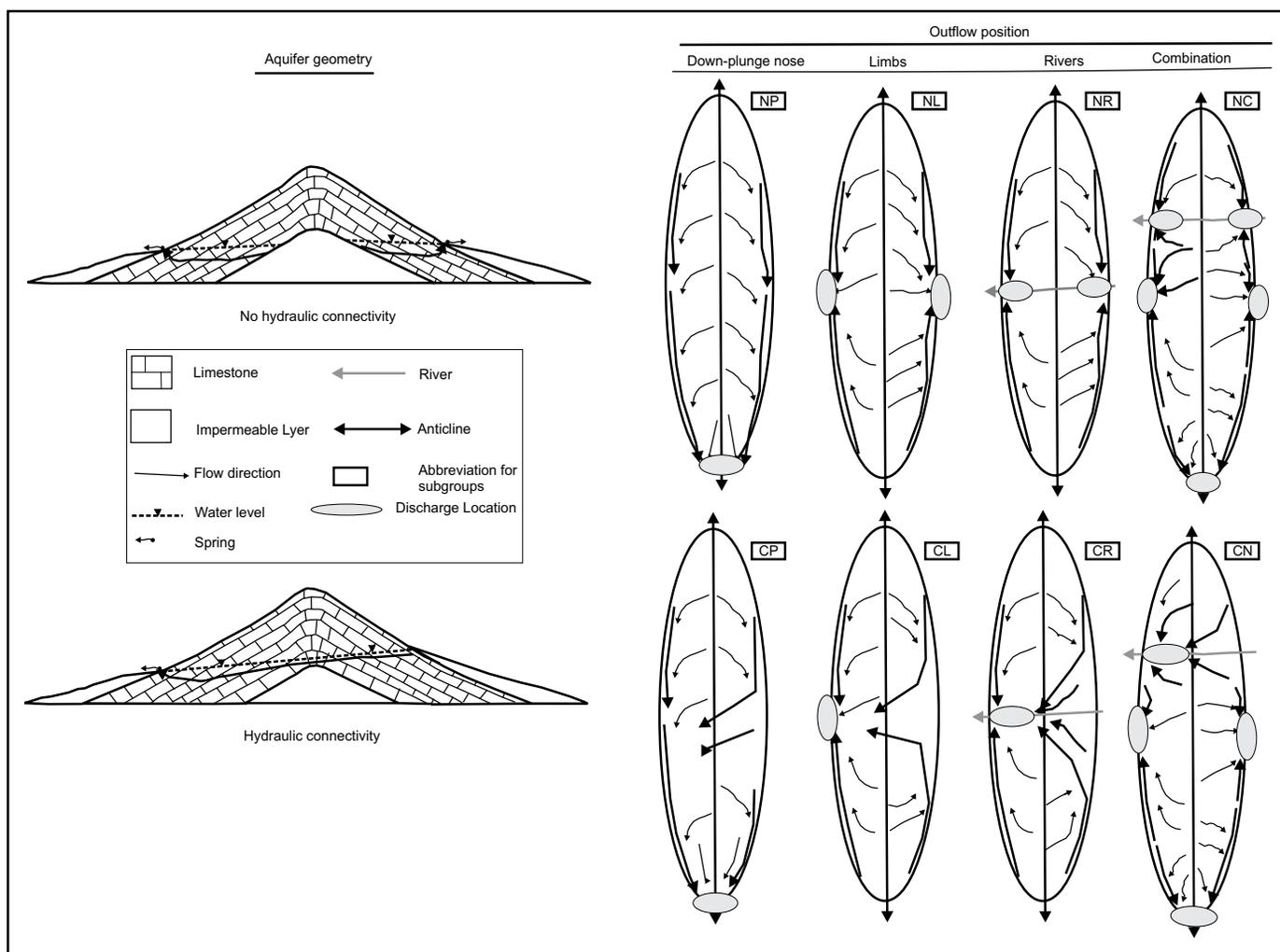


Figure 1: Proposed conceptual model based on geometry and output location.

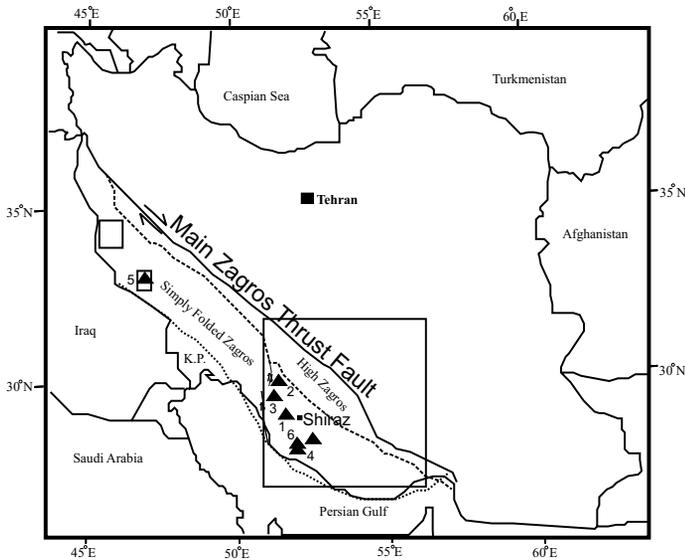


Figure 2. Location map of study areas (boxes and triangles) in relation to the position of selected anticlines discussed in this paper. 1-Derak, 2-Gar and Barm-Firooz, 3-Dashtak, 4-Rooshan, 5-Ravandi and 6-Podenow. Abbreviation K.P. is Khuzestan Plain

absence of hydraulic connectivity between limbs of anticlines and on the location of discharge zone, leading to eight alternative types of flow patterns.

GEOLOGIC SETTING

In Iran, Zagros extends from the west to south and southeast. The study areas are situated at three different points (Fig. 2). The Zagros consists of three zones, namely the Khuzestan Plain, the Simply Folded Zagros and the High Zagros (Darvi-

chzadeh, 1991). The Khuzestan Plain Zone consists of alluvial sediments, which cover all older formations. The Simply Folded Zagros consists of long, linear, asymmetrical folds. Anticlines are well exposed and separated by broad valleys (Miliareis, 2001). Fold axes have a northwest to southeast trend. The High Zagros is very close to the main Zagros thrust fault where it is crushed and intensively faulted.

The stratigraphy and structural characteristics of the Zagros sedimentary sequences have been described in detail by Stocklin and Setudehnia (1971) and Alavi (2004). The geological column of formations outcropping in the study areas is presented in Figure 3. In the following sections, the main outcropping formations of the study areas are discussed in decreasing order of age (Stocklin and Setudehnia, 1971; Darvichzadeh, 1991; Alavi, 2004). The Kazhdumi Formation, within the Bangestan Group, is composed of 230 m of marl at the top and dark argillaceous limestone and marl at the bottom. The Sarvak Formation consists of 250 m of argillaceous limestone at the bottom and 570 m of resistant, cliff-forming limestone at the top. The Gurpi is composed of 350 m of marl, marly limestone, and claystone. The Sachun with a thickness of 1400 m consists of argillite, shale, evaporates (mainly gypsum), and is intercalated with thin-bedded dolomite. The Jahrum Formation overlies it. Pabdeh consists of 800 m of calcareous shale, marl, and lime-mudstone with subordinate argillaceous limestone. Facies grade toward the southwest into the Jahrum carbonates. The Jahrum is composed of 485 m of cliff-forming dolomite interbedded with dolomitic limestone; it grades toward the deep-marine Pabdeh carbonates. The Jahrum Formation outcrops in most parts of the Zagros and is known as Shahbazan Formation in west of Zagros. The thickness of the Asmari Formation varies from a few meters up to 500 m, consisting of medium-bedded to thick-bedded, and well-jointed limestone. The Razak Formation has a highly variable thickness ranging between 150 to 1300 m. Its

Figure 3. Stratigraphic column through the Zagros in the study areas (Darvichzadeh, 1991; Alavi, 2004; McQuarrie 2004)

Age	Simplified Formations	Lithology	Thickness	
Miocene	Group			
	Upper Fars	Aghajari	Conglomerite, Sandstone	Up to 3000 m
	Lower Fars	Mishan	Marl, Shale	710 m
Eocene-Paleocene		Razak/Gachsaran	Marl/Anhydrite, Salt	150-1300 m/Up to 1940 m
		Asmari, Shahbazan/	Limestone	Up to 520 m
		Jahrum	Dolomite	480 m
		Sachun	Shale	1400 m
		Pabdeh-Gurpi,	Marl, Shale	1140 m
Cretaceous	Bangestan	Sarvak	Limestone	820 m
		Kazhdumi	Marl	230 m
		Daryian	Limestone	320 m
		Gadvan	Marl and Shale	120 m
Jurassic	Khami	Fahliyan	Limestone	360 m
		Hith	Gypsum and Anhydrite	100 m
		Surmeh	Dolomite and Limestone	700 m

lithology is mainly marl, interbedded with silty limestone. It interfingers with evaporites of the Gachsaran Formation. The Gachsaran Formation is composed of multiple sequences of variable thicknesses (up to 1900 m) and lithologies, including alternations of evaporites (gypsum, anhydrite, and subordinate halite), shale, marl, and locally conglomeratic calcarenite. The Mishan Formation is composed of marl, calcareous shale, siltstone, and sandstone. The Aghajari Formation is a thick, up to 3000 m succession, mainly composed of carbonate-clast and polymict conglomerate, calcarenite, cross-bedded sandstone, siltstone, marl, and lime-mudstone.

METHOD OF STUDY

In the Zagros Region, 72 anticlines were selected for this study. The geologic maps of all anticlines were prepared based on geologic maps of 1/100,000 and 1/250,000 from the Oil Company of Iran. The anticlines consist mainly of several subaquifers. In order to get data on the flow system discharge, specific conductance, water temperature, pH, major ions of water, water level in karstic wells and piezometers, water-tracing results, and rainfall data were collected. The water budget of each sub-basin of each anticline was estimated if it had not already been calculated in previous studies. The inflow is mainly in the form of precipitation and in a few cases as seepage from rivers traversing the anticlines. The average precipitation over anticline sub-basin surfaces was estimated using the rainfall-elevation relation and the topographic map. The recharge coefficient was estimated according to previous studies on karstic regions of Iran (Pezeshkpour, 1991; Karimi, 2003; Karimi, *et al.*, 2005; Karst Research Centre of Iran, 1993).

The discharge rate was estimated based on annual discharge of springs, wells, and qanats (a qanat is a man-made underground gallery transferring ground water to the surface by gravity). In some cases subsurface flow to the adjacent alluvium aquifer had to be assumed to explain exceeding recharge volume compared to known springs, qanats and wells. If the difference between discharge and recharge was more than the maximum expected error (10%), the possibility of flow to or from the adjacent or successive anticlines was evaluated by the following decision criteria.

1. The geological settings confirm a possible flow route from the anticline under study to or from an adjacent or successive anticline;
2. The hydraulic head is sufficient to induce flow; and
3. The water surplus (or deficit) of the anticline corresponds to the water deficit (or excess) of one of the adjacent or successive anticlines.

The catchment area of each spring is determined by the following equation:

$$A = \frac{V}{10^3(PI)} \quad (1)$$

In which A is the catchment area of the spring (km^2), V is the total discharge of the spring during one hydrological year (m^3),

P is the annual precipitation (mm yr^{-1}), and I is the recharge coefficient (dimensionless) which varies from 0 to 1. In Equation (1), it is assumed that there is no allogenic stream input and the variation of storage over time is insignificant.

Then, the calculated surface area (A) was compared to the probable boundary of the spring catchment area, which was determined by the following assumptions and criteria (Karimi, 2003; Karimi *et al.*, 2005):

1. The catchment area is probably as close as possible to the spring;
2. The elevation of catchment area must be higher than that of the related spring and possible catchment can be determined using a topographic map of the region;
3. There must be no impermeable formations crossing the aquifer and possibly disconnecting one part from the spring;
4. The water budget must be balanced for the total area of the main aquifer (or anticline), in other words, the catchment area of all the subaquifers is determined;
5. Geomorphology, geology, and tectonic settings must justify the catchment area;
6. The physicochemical parameters should be in agreement with the lithology of the related karst aquifers and adjacent formations; and
7. Available dye-tracing data may be used to confirm or refute the proposal boundaries.

Each anticline under study was divided into ground-water catchment areas related to each discharge zone (spring, well, qanat, and flow to adjacent aquifers) based on geomorphology and geological settings.

RESULTS

In order to determine the validity of the proposed conceptual model (*i.e.*, the influence of the anticlinal structure on regional ground-water flow) 72 anticlines of the Zagros Region were examined. Table 1 presents a summary of the lithology, recharge area, recharge coefficient, presence or absence of faults, type of discharge zones, and appropriate model for each anticline. In the following text only one example for each subgroup defined in Figure 1 is presented.

NO HYDRAULIC CONNECTIVITY BETWEEN LIMBS

In aquifers of this group the elevation of the aquifer bottom (impermeable formation) under the crest of an anticline is higher than the feet of the anticline (*i.e.*, most of the recharged water on each limb can flow towards the foot of the same limb). Four subgroups have been distinguished considering the position of outlets (Fig. 1).

DISCHARGE FROM ONE OR BOTH PLUNGES OF THE FOLD

In three separate cases ground water is discharging from the plunging end of an anticline, and the Derak anticline is discussed as the type case of this subgroup. The doubly plunging Derak anticline is composed of the karstic Asmari-Jahrum Formations

which are overlain and underlain, respectively, by the impermeable Razak and Sachun Formations except for the southeastern plunge apex, which is in direct contact with the adjacent alluvium (Fig. 4A). The total area of outcropping carbonate formation is 73 km². The elevation of the impermeable Sachun Formation under the crest of the anticline is noticeably high, disconnecting the hydraulic connectivity of both limbs (Fig. 4B). Several faults cross the anticline, which are perpendicular to the fold axis.

The main source of recharge is diffuse infiltration. The karst water flows to the adjacent alluvium through the southeastern plunge apex, where water is exploited by several pumping wells in the southeastern part of the anticline with a total discharge of 757 L s⁻¹ (Karst Research Center of Iran, 1993). Parab Fars Consulting Engineering Company (1997) calculated the water budget of the Derak anticline in the 1992–1993 water year. The results confirm the unavailability of extra water for transference to the adjacent synclines or successive anticlines. The contact elevation of the Razak Formation with the Asmari-Jahrum Formations in the northwestern plunge apex is 500 m higher than the contact elevation of the Asmari-Jahrum Formations with the alluvium in the southeastern plunge apex. Therefore, a main conduit system has probably developed parallel to the strike, starting from the northwestern plunge apex and going toward the southeastern plunge apex. Karst water enters the adjacent alluvium of the southeastern plunge apex. Several faults cross the Derak anticline axis, but no springs are observed at the fault's trends, implying that the faults do not have any role in the regional ground-water flow. The schematic model of the regional flow in the Derak anticline based on the above discussions is presented in Figure 4A.

Consequently, karst water of the limb area may discharge from one of the plunge apices or from both plunge apices. In the single plunge apex case, karst water joins a main conduit system at the foot of the anticline, parallel to the strike, extending from the high elevation plunge apex and leading to the plunge apex related to the local base level. As the main conduit system gets close to the discharging plunge apex, it collects more water from the limb area. The karst water emerges as springs or flows to adjacent alluvium, or to a successive anticline in the plunge

apex fold area.

The one plunge apex case, as described above, can be extended to the case where springs are located at both plunge apices, or even if ground-water flows to alluvium or adjacent formation in both plunge apices. No spring or discharge zone is located along limbs because the contact elevation of impermeable formations or fine-grained alluvium with karstic formations along the limb of the anticline is higher than the elevation of both plunge apices. In the case where outflows are located at both plunge apices, the limb of the anticline is composed of two distinct subaquifers. Their catchment area is limited to the crest of the anticline, the adjacent impermeable formation or fine-grained alluvium, and by the water divide line between the two subaquifers. Three anticlines are typical of discharge from both plunge apices.

KARST WATER DISCHARGE FROM LIMBS

Twenty anticlines belong to this subgroup. Among them, Gar anticline will be discussed further. The northwestern successive anticline of Gar is the Barm-Firooz anticline. The exposed cores of the Gar and Barm-Firooz anticlines are dominantly made of the calcareous Sarvak Formation, underlain and overlain by impermeable shales of the Kazhdumi and Pabdeh-Gurpi Formations, respectively (Fig. 5A). The southern limb of both anticlines has been completely crushed. One hundred sixty dolines are present in the northern limb of the Gar anticline, and 99 dolines are found along the Barm-Firooz anticline (Fig. 5A). The northern and southern limbs of the anticline have been hydraulically disconnected by the action of a thrust fault, which shifts up the impermeable Kazhdumi Formation in the core of the anticlines (Fig. 5B, Fault F1). Karst water from the Sarvak aquifer of the Gar and Barm-Firooz anticlines discharges at 12 springs, 11 of which (including the Berghan Spring) emerges from the southern limb of the Gar anticline, and one large spring (Sheshpeer Spring) emerge from the northern limb of the Gar anticline. The mean annual discharges of Sheshpeer and Berghan Springs are 3,247 L s⁻¹ and 632 L s⁻¹, respectively, while the mean discharge of the other springs ranges from 1 to 68 L s⁻¹.

The geological setting, the water budget calculation (Pezesh-

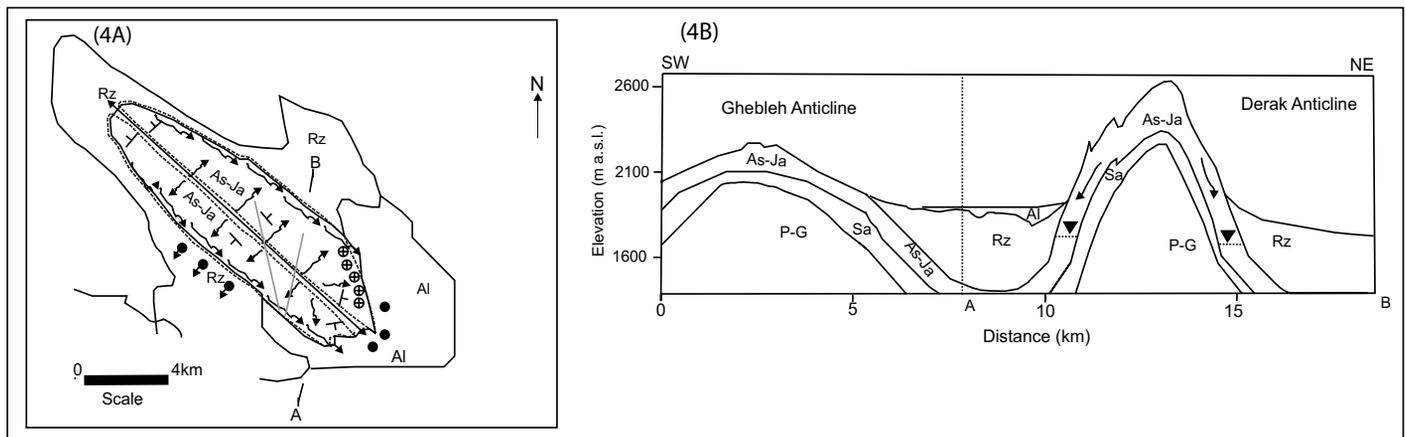


Figure 4. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Derak Anticline. Legend is referenced in Figure 5.

Table 1. Summary of geologic and geomorphologic characteristics of studied anticlines.

Anticline Name	Recharge	Annual	Recharge	Lithology	Position of Main Faults	Type of Discharge ^a	Type of Aquifer ^b
	Area (km ²)	Precipitation (mm yr ⁻¹)	Coefficient (%)				
Ab-Siah	210	370	70	Limestone. ^c	South limb.	S,A	CC
Ahmadi	360	490	30	Limestone and dolomite. ^c	South limb.	S,A,Q	NC
Alhare I/II	290	320	30	Limestone and dolomite. ^c	South limb.	S,A/S	NC/CL
Baghestan	80	650	60	Limestone and dolomite. ^c	Intensively.	S	NC
Bamu	220	520	21	Limestone and dolomite. ^c	Intensively.	A,Q	NC
Behkhun	40	250	35	Limestone and dolomite. ^c	South limb.	S	NC
Bareaftab	40	250	40	Limestone and dolomite. ^c	South limb.	S	NC
Bareh	50	600	75	Limestone.	No fault.	S,A	NC
Benekhoshk	110	485	57	Limestone. ^c	No fault.	S	NC
Chapeer	30	356	37	Limestone and dolomite.	South limb.	S	CL
Dalneshin	240	580	46	Limestone.	Transverses.	S,Q	NP
Daloo-sefidar	980	680	45	Limestone and dolomite. ^c	South limb.	S,Q,A	NC
Darishak	630	841	65	Limestone and dolomite. ^c	Intensively.	S,A	NC
Darughak	65	580	40	Limestone. ^c	North limb.	S,Q,A	NC
Dashtak-Fars	320	570	45	Limestone. ^c	No fault.	S,A	NC
Dashtak	240	813	37	Limestone and dolomite. ^c	South limb.	S,R	NC
Derak	37	660	50	Limestone and dolomite.	No fault.	Q,A	NP
Droudzan	131	560	70	Limestone.	South limb.	S,A	NC
Emam-Hassan	126	450	50	Limestone. ^c	South limb.	SU	NC
Gar/ Barm-Firooz	200	650	75	Limestone.	South limb.	S/S,SU	NL/NC
Ghalajeh	300	500	76	Limestone.	North limb.	S,SU	NL
Ghareh	610	500	50	Limestone and dolomite.	No fault.	S,Q,A	NC
Ghasreh-Ghomsheh	60	660	50	Limestone and dolomite. ^c	North limb.	S,Q	NC
Galisakan	200	700	40	Limestone and dolomite. ^c	Both plunges.	S,A	NC
Hajiabad	190	450	70	Limestone. ^c	South limb.	S	NL
Kaftarak	170	450	50	Limestone and dolomite. ^c	Both limbs.	S,Q,A	NL
Kalehbadi	160	460	35	Limestone. ^c	No fault.	A	CC
Kalkush	95	480	57	Limestone.	No fault.	SU	NC
Karba	240	320	35	Limestone and dolomite. ^c	South limb.	S	NC
Kartang	280	310	37	Limestone and dolomite. ^c	South limb.	S,A	NC
Khanehkat	310	420	35	Limestone and dolomite. ^c	Intensively.	S,Q,A	NC
Kharmnkuh	160	370	45	Limestone and dolomite.	No fault.	S,Q,A	NC
Khurmuj	140	410	37	Limestone and dolomite. ^c	Transverses.	S,Q	NC
Laeisavar/Plagan/ Zarabi	120	450	40	Limestone. ^c	North limb.	A/A/A	NC/NC/NC
Namak	280	260	28	Limestone and dolomite. ^c	Transverses.	S,A	NC
Nazarabad	20	610	40	Limestone and dolomite. ^c	South limb.	S,Q,A	NL
Omarmussakhani	240	370	35	Limestone. ^c	No fault.	A	NL
Patagh	230	510	63	Limestone. ^c	No fault.	S,SU	NC
Paree-Payeen	70	430	40	Limestone and dolomite.	Intensively.	S,Q	NL
Podenow				Limestone and dolomite. ^c		S,Q,A,R,SU	CC
Rahmat	220	510	50	Limestone.	South limb.	S,A	NC
Ravandi	50	210	50	Limestone and dolomite.	No fault.	S,R	CR
Rijab	450	550	40	Limestone. ^c	Intensively.	S,SU	NC
Rooshan	58	410	50	Limestone and dolomite.	No fault.	S,Q	CL
Sabzposhan	360	614	50	Limestone and dolomite.	North limb.	S,Q,A	NL
Salbiz	35	830	40	Limestone and dolomite.	South limb, south plunge.	S	NP
Sangesiah	130	450	37	Limestone. ^c	Both limbs.	S,A	NC
Saravn	140	470	62	Limestone.	South limb, north plunge.	S	NC
Sarbalesh	250	710	60	Limestone and dolomite. ^c	North limb, both plunges.	S	NP
Shahneshin	270	890	40	Limestone and dolomite. ^c	Intensively.	S,A	NC
Bostang	530	520	60	Limestone and dolomite. ^c	Intensively.	S,R	NC
Siah-Bushehr	150	410	37	Limestone and dolomite. ^c	Transverses.	S,Q,A	NC
Siah-Sydan	390	460	30	Limestone. ^c	South limb.	S,Q,A	NC
Sayeedmohammad	160	350	70	Limestone. ^c	North limb.	S,A	NC
Siah-Hosseini	190	480	60	Limestone. ^c	South limb, north plunge.	S,Q,A	NC
Sim	130	420	45	Limestone and dolomite.	No fault.	S,Q,A	NP
Sinehaftab/Gandash	40	450	50	Limestone and dolomite.	No fault.	A/A	NL/NL
Siroo/ Jayeen	120	210	35	Limestone and dolomite. ^c	South limb.	S,A/S,A	NL/NL
Tammar	20	950	75	Limestone.	Transverses.	S,A	NC
Vanaman	270	390	40	Limestone and dolomite. ^c	South limb.	S,A	NP
Layzangan	640	380	40	Limestone and dolomite. ^c	South limb.	S,A,SU	NL
Yar	220	540	60	Limestone and dolomite. ^c	Both limb.	S,A,SU,R	CC
Zarghan/Chahanari	200	410	36	Limestone and dolomite.	South limb.	A/A	NC/NC
Zena/Panjkarteh	200	550	47	Limestone. ^c	South limb.	S,A/A	NL/NC

^a Abbreviations on column: S=Spring, A=Alluvium, Q=Qanat, SU=Successive anticline, R=River.^b Abbreviations on column refer to Figure 1.^c The impermeable layers outcrop inside the anticline.

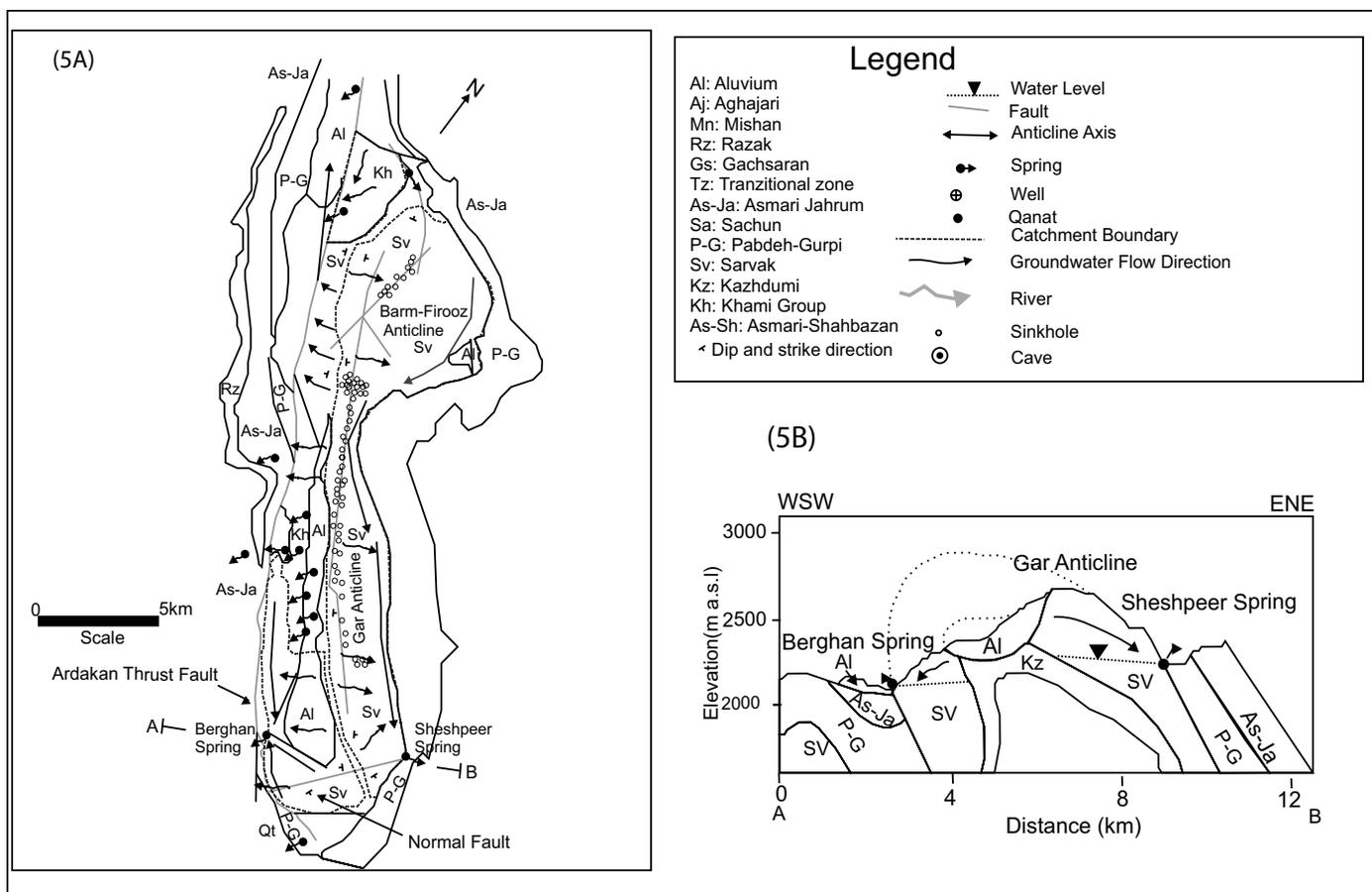


Figure 5. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Gar and Barm-Firooz Anticline.

kpour, 1991), and dye-tracer experiments (Raeisi *et al.*, 1999) have shown that the catchment area of the Sheshpeer Spring is the northern limb of the Gar and Barm-Firooz anticlines (Fig. 5A). Therefore, karst water of the northern limb area is expected to flow along the foot of the anticlines and finally emerge from the Sheshpeer Spring. Although the local base level is located further down the southeastern plunge, the Sheshpeer Spring emerges from the limb due to the presence of a normal fault.

Karst water of the southern limb discharges from several springs located along the foot of the limb area. It seems that the southern limb is composed of several independent subaquifers. The southern limb has been brecciated by one thrust fault and several normal faults. The autogenic water stored in a network of interconnected small fissures and pores seem to prevent the development of major karst conduit systems along the foot of the anticline. The southern springs show mainly diffuse recharge (Pezeshkpour, 1991; Raeisi and Karami, 1997). For example, autogenic recharge, the absence of any shafts or dolines, extensive non-cemented breccia in the catchment area, small values and slight differences in hydrograph recession coefficients, high percentage of base flow, and no significant variation in the time series of electrical conductivity, temperature, and major ions indicate diffuse recharge, flow, and discharge in the Berghan Spring.

Consequently, in this subgroup, karst water of the limb area joins the main conduit system parallel to the strike at the foot

of the anticline, but the regional ground-water flow direction is changed and the karst water emerges as springs, or flow to the adjacent alluvium aquifer, or adjacent syncline or anticline in the limb region. Each limb may be only one subaquifer with one interconnected main conduit system at the foot of the anticline with numerous overflow discharge zones, or it may consist of several subaquifers with independent conduit systems and catchment areas.

KARST WATER DISCHARGES TO THE RIVER TRAVERSING

No typical example of this subgroup has been found in any of the 72 cases studies.

KARST WATER DISCHARGES FROM A COMBINATION OF PLUNGE APEX(S), LIMB(S), AND/OR RIVER

Karst water discharges from a combination of plunge apex(s), limb(s) and/or river in the fourth subgroup. In other words, it is a combination of at least two of the above-mentioned subgroups. Karst water may discharge from a) limbs and one or two plunge apexes, b) limbs and river, c) one or both plunge apexes and river, and d) one or both plunge apexes, limbs and river. The Dashtak anticline will be discussed as a typical case among the 38 anticlines belonging to this subgroup. The Dashtak anticline consists of the Asmari-Jahrum (221 km²) and Sarvak (17.1 km²) Formations. The Sarvak Formation is sandwiched

between the Kazhdumi and Pabdeh-Gurpi Formations, breaking the hydraulic connection of the Sarvak and Asmari-Jahrum Formations (Fig. 6A). The Asmari-Jahrum Formations are in direct contact with the Gachsaran Formation and alluvium. The Gachsaran Formation is covered, in some parts, by thin alluvium. The Shapour River traverses the Dashtak anticline near the north-eastern plunge apex, developing a deep valley, namely the Chugan Valley, resulting in the flow of this river over the impervious Pabdeh-Gurpi Formations. Therefore, hydraulic connectivity of the Asmari-Jahrum Formations in the northern and southern limbs is disrupted by the high elevation of the Pabdeh-Gurpi Formations beneath the crest of the anticline, except in the northwestern plunge apex area (Figs. 6B and 6C). The Pabdeh-Gurpi Formations outcrop in some parts of the southern limb at high elevations. The Shapour River acts as a local base level. The karst water of the northern limb in the east of the Chugan Valley flows partly to the adjacent coarse-grained alluvium aquifer, appearing as the upper and lower Renjan Springs (discharge 590 L s^{-1}), and partly as direct discharge from the Asmari-Jahrum Formations into the Shapour River at the beginning of the Chugan Valley. The small Pire-Sabz (40 L s^{-1}) and Shir Springs (8 L s^{-1}) discharge a small area of the northern limb at the west side of the Chugan Valley. The Sasan and Sarab-Shir Springs, with an average annual discharge of 2.6 and $1.8 \text{ m}^3 \text{ s}^{-1}$, respectively, appear on the southern limb at the west side of the Chugan Valley. Sasan Spring emerges near the end of the Chugan Valley, a few meters above the Shapour River water level. The karst area of the west side of the Chugan Valley is 24 km^2 in surface area, which is not large enough to supply the high discharges of the Sasan and Sarab-Shir Springs. Water budget and dye-tracing studies revealed that the recharge areas of these springs are located in adjacent anticlines and reach the Dashtak anticline via its northwestern plunge apex (Karst Research Center of Iran, 2002; Milanović and Aghili, 1993).

The extensive outcrop of Pabdeh-Gurpi Formations in the southern limb at the eastern side of the Chugan Valley creates several isolated areas of Asmari-Jahrum Formations. The outcrop of the Pabdeh-Gurpi is most probably due to the action of local faults. Karst water of these areas discharges into the Sarab-Dokhtaran Spring, adjacent alluvium aquifers, the Ghaleh-Naranji Spring, and the Parishan Lake (Fig. 6A). The Sarvak Formation is limited to small parts of the southern limb and its karst water emerges from the Pole-Abgineh Spring. The general direction of flow is mainly towards the Shapour River in the Dashtak anticline, except in some parts of the southern limb at the eastern side of the Chugan Valley in which the Pabdeh-Gurpi Formations have created isolated aquifers.

Therefore characteristics of this subgroup are complex, depending on the type and numbers of elements involved in the combination and on those subgroup properties that play a dominant role in controlling the regional ground-water flow. As a result, each limb may be composed of one subaquifer with several discharge zones, or several subaquifers with a distinct catchment area. These subaquifers may have one or more discharge zones.

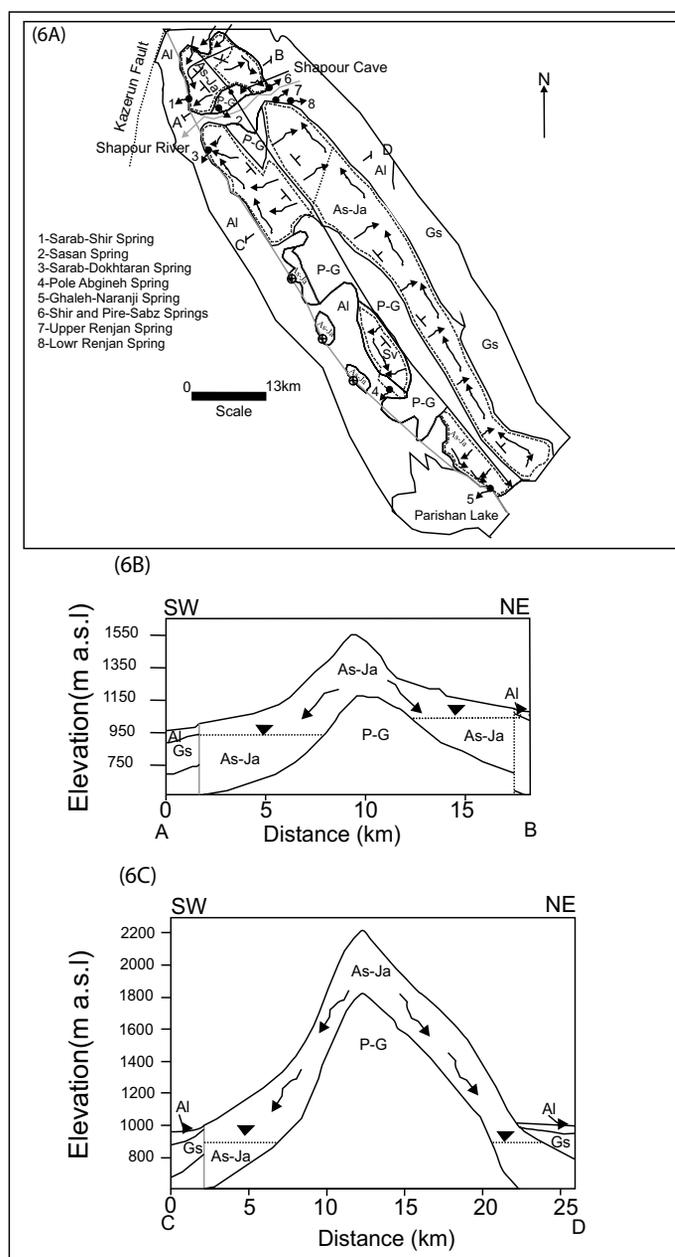


Figure 6. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B and C) of Dashtak Anticline. Legend is referenced in Figure 5.

NORTHERN AND SOUTHERN LIMBS ARE CONNECTED

In this situation karst water of one of the anticline limbs (the donor limb) flows towards the adjacent limb (receiver limb) either through a restricted number of link areas or all along the anticline. After the transfer of karst water to the receiver limb, the flow patterns are similar to anticlines which have no connectivity between limbs. For this reason, the group is further classified into four similar subgroups as the cases with separate limb hydraulic (Fig. 1).

KARST WATER DISCHARGE FROM ONE OR BOTH PLUNGE APEXES

No case representative of this subgroup was found in any of the 72 anticlines under study.

KARST WATER DISCHARGES ONLY FROM ONE LIMB OF THE ANTICLINE

The subgroup contains three anticlines. Rooshan anticline is the type case of this subgroup. It is a small anticline with an area of 58 km² (Fig. 7A). It consists of the Asmari-Jahrum Formations surrounded by impermeable transition and Razak Formations. The geological setting indicates the northern limb is higher than the southern limb (Fig. 7B). A spring and a qanat emerge from the southern limb. Geological setting and water budget show that the karst water of the northern limb of Rooshan anticline and a part of the water from the southern limb of the adjacent anticline (Podenow anticline) emerge from the spring and the qanat (Karimi et al. 2005). The karst water of the northern limb flows towards the foot of the southern limb.

GROUNDWATER DISCHARGES TO THE RIVER

Only one case study belongs to this subgroup. The Ravandi anticline consists of the Asmari-Shahbazan Formations underlain and overlain by the Gachsaran and Pabdeh-Gurpi Formations respectively (Fig. 8A). At the foot of Ravandi anticline, a thin alluvium overlies the Gachsaran Formation in small parts. The Symareh River, with an average discharge of 12.5 m³ s⁻¹, flows on the surface of the Gachsaran Formation and through a narrow and vertical cliff valley in the Asmari-Shahbazan Formations. The impervious Pabdeh-Gurpi Formations are located below the river, allowing hydraulic continuity between the northern and southern limbs (Fig. 8B). Karst water of the Ravandi anticline discharges only into the Symareh River along both sides of the valley via 39 springs on the eastern and two springs on the western side of the valley, respectively. The locations of all the springs are below and around the anticline crest line, implying that the water of the northern limb transfers to the southern limb. Water budgets, together with the absence of any

other discharge zones around the anticline, confirm that all the karst water of the Ravandi anticline emerges into the Symareh River (Asadpour, 2001). The Symareh River has incised the canyon, which controls karstification processes in the anticline (*i.e.*, the Symareh River is the local base level).

Groundwater discharges from a combination of limb, plunge apex and river: The subgroup consists of four anticlines. A typical example of this subgroup is the Podenow anticline, which displays a combination of limb, plunge apexes, and river discharge zones.

Karst water of the Podenow anticline discharges from 60 springs, wells, and qanats on the southern and northern limbs, plunge apexes and river. The Podenow anticline is a very long anticline and divided into eastern, central, and western parts. The central and part of the eastern and western sections are shown in Figure 9A. There is no hydraulic connectivity between the southern and northern limbs in most parts of the anticlines, except in the central part and in both plunge apexes (not visible on Figure 9A), because the elevation of the Pabdeh-Gurpi Formations under the crest of the anticline in these areas is higher than the adjacent alluvium aquifers. The northern and southern limbs of the eastern and western sections are independent aquifers, discharging at the foot of the anticline and plunge apexes as karst springs or flowing to the adjacent alluvium and flowing through the intervening syncline to parallel anticline (Karimi, 1998). Central sections slope down toward the saddle-shaped area, including the U-shaped Tangab Valley. The Firoozabad River flows through this valley. This central section is composed mainly of carbonate formations of the Asmari-Jahrum. The contact of Asmari-Jahrum Formations with the Razak Formation is transitional with alternating layers of marl, marly limestone, and limestone. Since the underlying Pabdeh-Gurpi Formations are below the level of the adjacent alluvium aquifers, water can flow from the northern to the southern limb in the saddle area of the central section (Fig. 9B). Uranine and Rhodamine B dyes (Acid Yellow 73 and Basic Violet 10, respectively) were injected into two drillholes on either side of the Tangab Valley on the northern limb, and they appeared in Tangab and in 18 small and

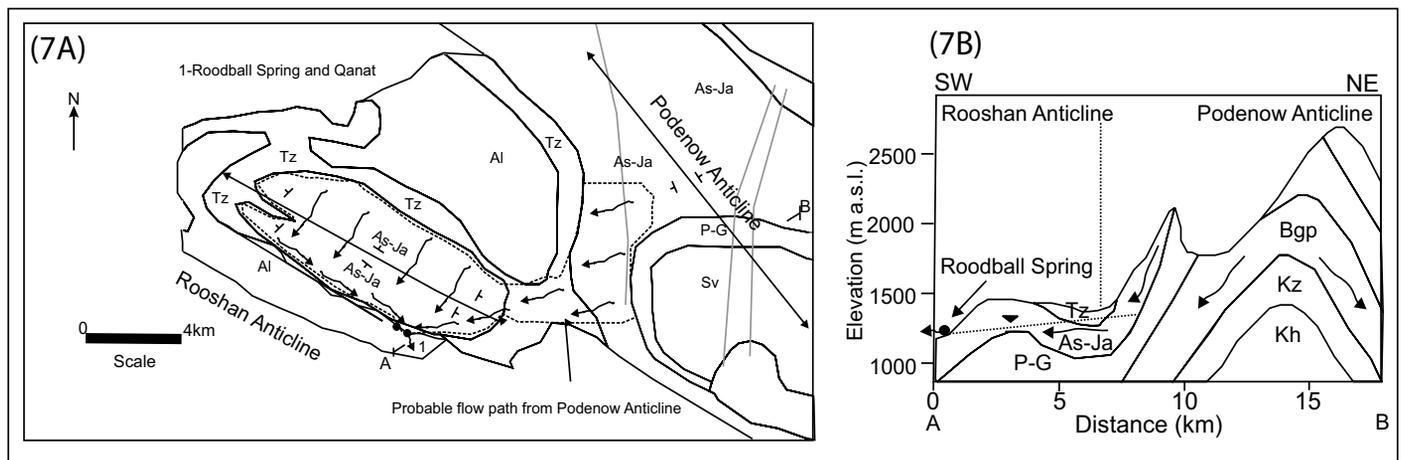


Figure 7. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Roshan Anticline. Legend is referenced in Figure 5.

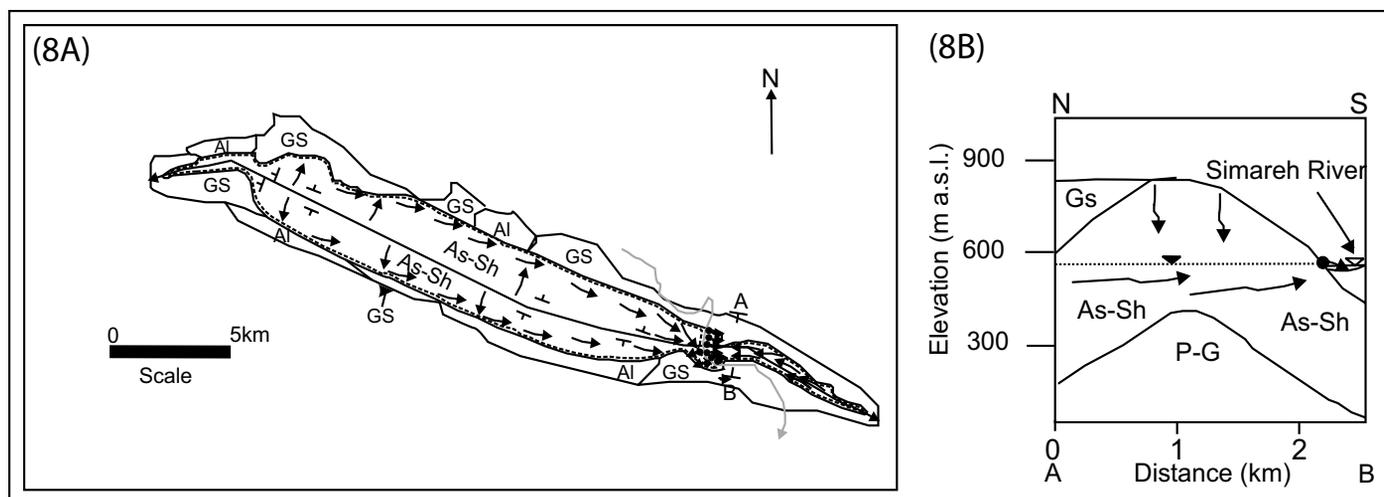


Figure 8. Hydrogeological maps and regional flow pattern (A) and geological cross sections (B) of Ravandi Anticline. Legend is referenced in Figure 5.

big springs (Asadi, 1998). The catchment areas of these springs were determined using water budget and geological setting (Karimi, 1998). Consequently, the Tangab Valley and the feet of the anticline at the southern limb act as base levels for the central section.

DISCUSSION

All 72 anticlines under study have been categorized into six subgroups expected by the model, which is therefore confirmed by field data.

Subgroups of the two main groups have similar geometric characteristics, except on bedrock geometry. Discharge from one plunge apex fold can be observed in anticlines having the following characteristics: (I) The local base level is in one of the plunge apex folds or in a successive anticline; (II) The aquifer, at the feet of anticline, is surrounded by impermeable formation(s) or fine-grained alluvium such that the regional groundwater flow is parallel to the strike and directed towards the local base level; (III) There are no deep subsurface flows of karst water to the karst formations of adjacent synclines or anticlines; (IV) The contact elevation of the impermeable formation(s) or fine-grained alluvium with the karstic formation in the limb area is higher than the water table in the karst aquifer, preventing the formation of overflow springs at the foot of the limbs; (V) There are no extensive faulted zones in the anticline to create independent aquifers.

For the limb subgroups, the lowest outcrop of carbonate formation has to be located along the limbs instead of plunge apex. Faults and/or impermeable layers inside the karst formation block the discharge to the plunge apexes. If the water level in the karst formation is higher than the contact elevation of the karstic formation with the adjacent impermeable layer, overflow springs are expected. If the karst formation is in direct contact with permeable alluvium, the karst water may seep into the alluvium in the large contact area.

The geometry in the subgroup with discharge only to the

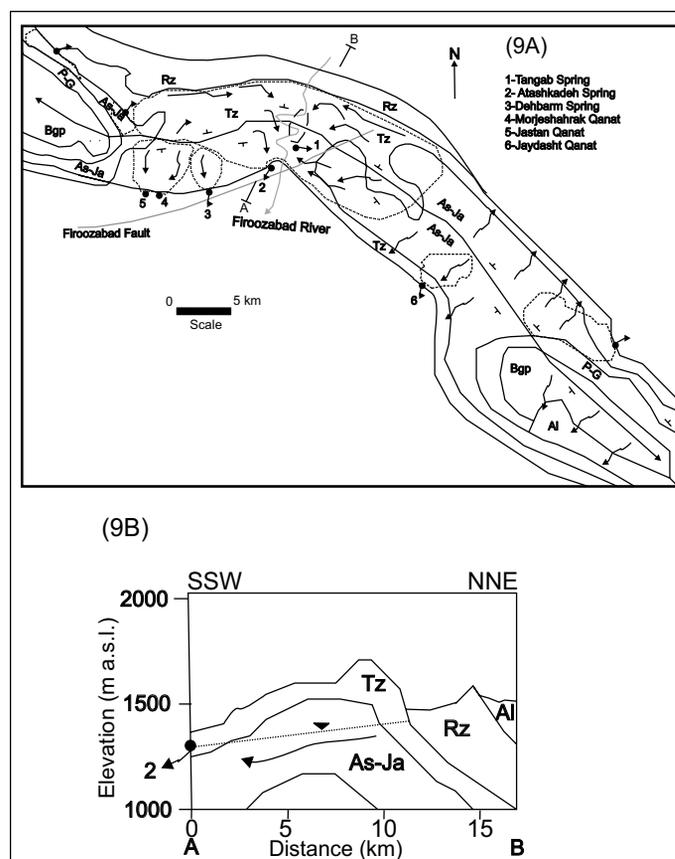


Figure 9. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Podenow Anticline. Legend is referenced in Figure 5.

river is similar to plunge apex subgroup, except that the river is the only local base level of the anticline. The combination subgroup has complex geometric properties and depends on the type of configuration between river, plunge apex, and limbs.

Consequently, various configurations of geological parameters result in different regional flow patterns. The main controlling factor is the lowest outcrop of the aquifer. This point is the best probable place for outflow position. Together with the

overall geometry of the aquifer (*i.e.*, geometry of impermeable bedrock) this parameter makes it possible to predict the flow direction, at least in a general sense. The presence of discontinuities such as fractures, faults, an incised river, or the outcrop of an impermeable layer inside the catchment area often induces deviation from this simple model. This explains why 42 cases of 72 examined belong to combination subgroups of the model.

In Zagros, perennial high discharge rivers, originating from the non-karstic rocks, traverse the karst formations and develop deep valleys. The gradients of rivers in valleys are low and these rivers act as regional base levels. It is likely that the karst water of each limb area drains into the river as springs or seeps into the riverbed. A typical example of this subgroup is not found in any of the 72 case studies. Most of the rivers flow on the plain parallel to the strike of the karstic anticline or turn on the plain between the plunge apexes of two adjacent anticlines instead of cutting through the karstic formation. Rivers traverse only five anticlines in the study areas, and it seems that the low frequency of cases where rivers incise anticlines and special geometry of subgroups is the main reason for this missing case in this subgroup.

In Zagros, the transfer of karst water from the donor limb to receiver limb is a rare case because it requires special tectonic settings. With respect to the receiver limb, the donor limb must be relatively elevated so that the hydraulic gradient is steep enough to change the direction of flow towards the receiver limb. Tectonic displacements uplift not only the donor limb, but the plunge apexes as well. Therefore, the local base level is located at the foot of receiver limb instead of the plunge apexes. Consequently, no case representative of subgroup with hydraulic connectivity between limbs and discharge from plunge apexes was found in any of the 72 anticlines under study.

CONCLUSIONS

Aquifer geometry and discharge location are linked to the catchment area and flow direction. It has been theoretically shown that there are eight configurations of aquifer geometry and discharge zones (Fig. 1). The validity of conceptual models was tested by using the Zagros Region anticlines. Based on the presence or absence of hydraulic continuity between the northern and southern limbs, the anticlines of Zagros are classified into two main groups. Out of 72 anticlines, 64 have no hydraulic connectivity between their northern and southern limbs. Because the impermeable formations below the crest of the anticlines are significantly higher than the feet of the anticlines, both limbs are hydraulically independent. The large number of cases with no hydraulic connectivity indicates that folding and sandwiching of karst formations between two thick impermeable formations is the prominent factor controlling the regional direction of flow, forcing the karst water of each limb area toward its foot. The numerous cases with no hydraulic connectivity are expected because folding is one of the main characteristics of the Zagros Region. Groups with or without hydraulic connectivity are each classified into four subgroups based on the location of discharge zones, mainly along one or both plunge

apexes, limb, river, and combination of plunge apexes, limb and river. The discharge zones can be in the form of springs, seepage into river, adjacent alluvium and/or successive karstic anticline, or adjacent syncline.

The main discharge zones are both located in limbs or as combination of limbs and other type of discharge zones. In most anticlines, karst water discharges from several discharge zones, rather than one.

The main controlling factor of the discharge zone location is the local base level, not the regional one. Numerous local base levels are created by differential erosion and tectonic settings in the study area. Faults and later differential erosion outcrop the underlying impermeable formation, generating several independent blocks of karst aquifers, each block having its own discharge zone. Karst waters are in direct contact with different lithologies such as alluviums and impermeable formations creating numerous discharge zones. Consequently the configuration of discharge zone, and folding and geometry clearly define the regional flow in aquifers.

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