PHYSICOCHEMICAL TIME SERIES OF KARST SPRINGS AS A TOOL TO DIFFRENTIATE THE SOURCE OF SPRING WATER

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ABSTRACT: Podenow Anticline is located in the Zagros Mountain Range, southern Iran. This anticline is exposed in an outcrop of Tertiary karstic limestone-dolomite Asmari Formation which is sandwiched between two impermeable marly formations. Part of the Podenow aquifer is discharged by 23 springs on the southern flank. Nineteen of these springs are concentrated in an area less than 0.5 km^2. The major ions, electrical conductivity, temperature and pH of these springs were measured once every two to three weeks for a period of 17 months. Geological setting, geomorphology, topography, lithology of the karst aquifer and surrounding formations, ratio of SO_4 to total anions, time series of specific conductance, hydrograph of springs, elevation of water level in piezometers and aquifer water balance were used to determine the probable catchment area of the springs. These parameters indicate that the sources of four springs are most probably the southern flanks and the sources of the other springs are both the southern and northern flanks. The time series of specific conductance of the fourteen Atashkadeh springs overlap which implies that all of these springs share a common conduit and the same catchment area. But the catchment area of one of the Atashkadeh springs is different from the other springs, even though it is surrounded by those other springs. A later tracer study confirmed the above discussion.

Keywords: Groundwater, karst spring, hydrochemistry, catchment area.

INTRODUCTION

A karst aquifer is classified as diffuse, conduit, or mixed flow regimes (Garrel and Christ 1965; White and Schmidt 1966; Shuster and White 1971; Atkinson 1977). In a diffuse system, laminar flow occurs through interconnected fissures less than 1 cm in diameter. The flow is turbulent in a conduit system, sizes ranging from 1 cm to more than 1 m. Most karst aquifers contain both diffuse and conduit flow regimes. Water discharging from a diffuse-flow spring

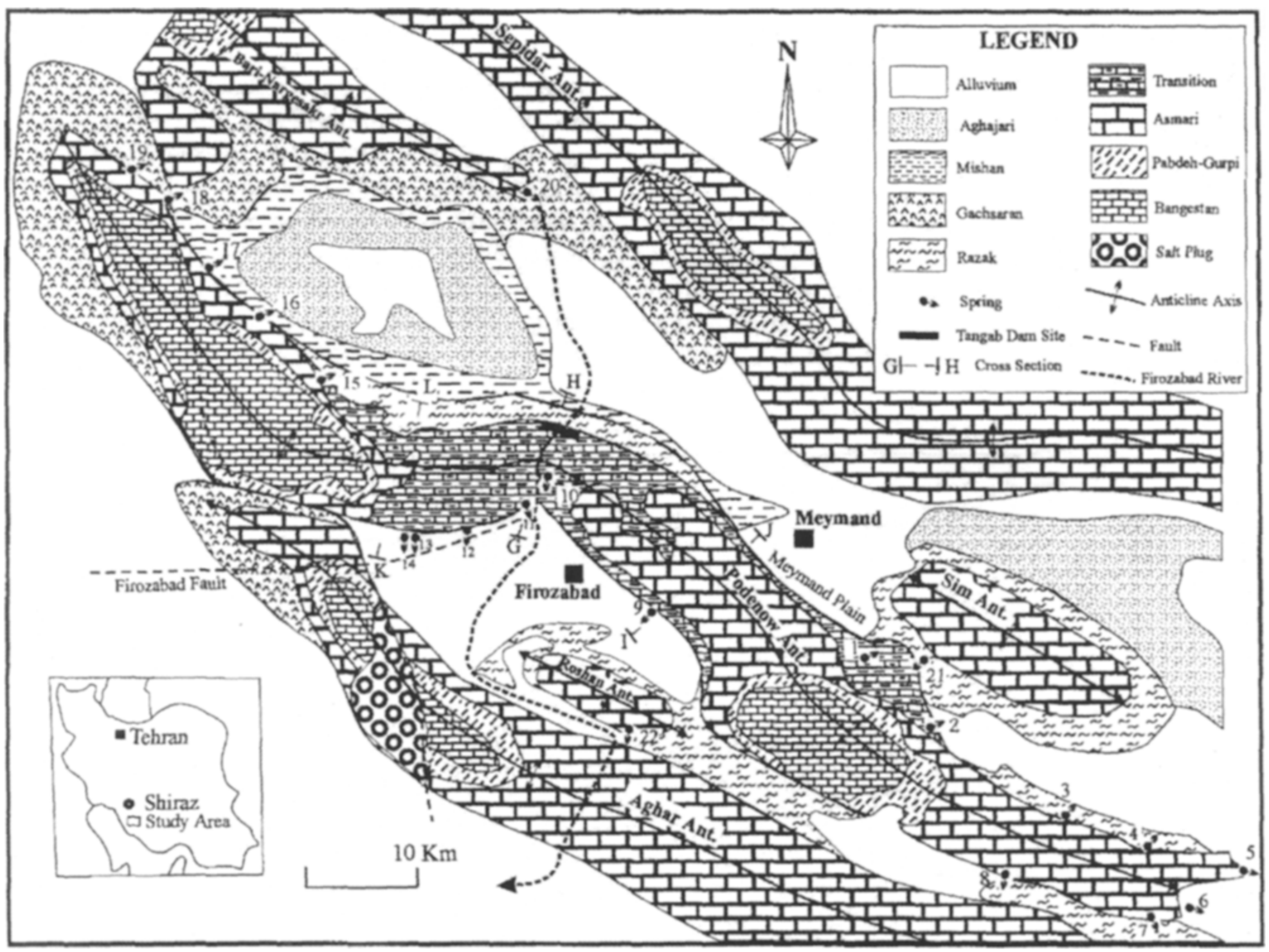

Figure 1. Geological map of the study area.

varies little with season. In contrast, water discharging from conduit springs has highly variable chemistry (White 1989). Jakucs (1959) showed that the chemical quality of a karst aquifer varies with time. Zölt (1960) and Smith and Mead (1962) used the time variations of chemical parameters to identify hydrogeological characteristics of karst aquifers. Raeisi and Karami (1996 and 1997) used the time series of physico-chemical parameters of several springs to determine the characteristics of karst aquifers in the south of Iran. Shuster and White (1971) concluded that the dominant type of flow (diffuse or conduit) can be determined by the chemograph. Bakalowicz (1984) has used principal components analysis to describe the quality of karst waters from springs and other sites. Lopez-Chicano et al. (2001) suggested that hydrodynamics and hydrogeochemical characteristics need to be taken into account to correctly explain the hydrochemical evolution of karst springs.

The catchment area of a karst spring cannot easily be determined by isopotential lines, because: a) the water table configuration depends on the piezometer location in the karst aquifer, and b) the construction of piezometers is very expensive in highland karst areas. The dye tracer test is the best method to determine the relation between injection and discharging points, however several dye tracer tests are needed to determine the catchment area. This is economically unfeasible. The objective of this study is to use the geological and lithological settings, water budget, hydrograph, time series of specific conductance of karst spring, topography and the available water level data or isopotential map to differentiate the source of karst springs and determine the probable catchment area.

Hydrogeological Setting

The study area is located in the central-south of Iran. The stratigraphy and structural characteristics of the Zagros sedimentary sequence have been described in detail by James and Wynd (1965) and Falcon (1974). A geological map of the study area is presented in Figure 1. The geological formations in decreasing order of age consist of the Bangestan group (Cenomanian-Turonian), Pabdeh-Gurpi (Paleocen-Oligocen), Asmari (Oligocen-Miocene), Transition Zone, Razak (Lower Miocene), Mishan (Middle Miocene) and Aghajari (Upper Miocene). The core of the Podenow Anticline is composed of the limestone Asmari Formation which is sandwiched between the two impermeable Pabdeh-Gurpi (marl, shale and marly limestone) and Razak (silty marl to silty limestone with interbedded layers of gypsum) Formations. The thickness of the Asmari Formation in the study area is about 400 m and its contact with the Razak Formation is transitional. The thickness of this Transition Zone varies from zero to 300 m, and it is composed of alternative layers of marl, marly limestone and limestone. Podenow Anticline, 120 km long and 7.5 km wide, is located in the Zagros Simply Folded Zone. This anticline

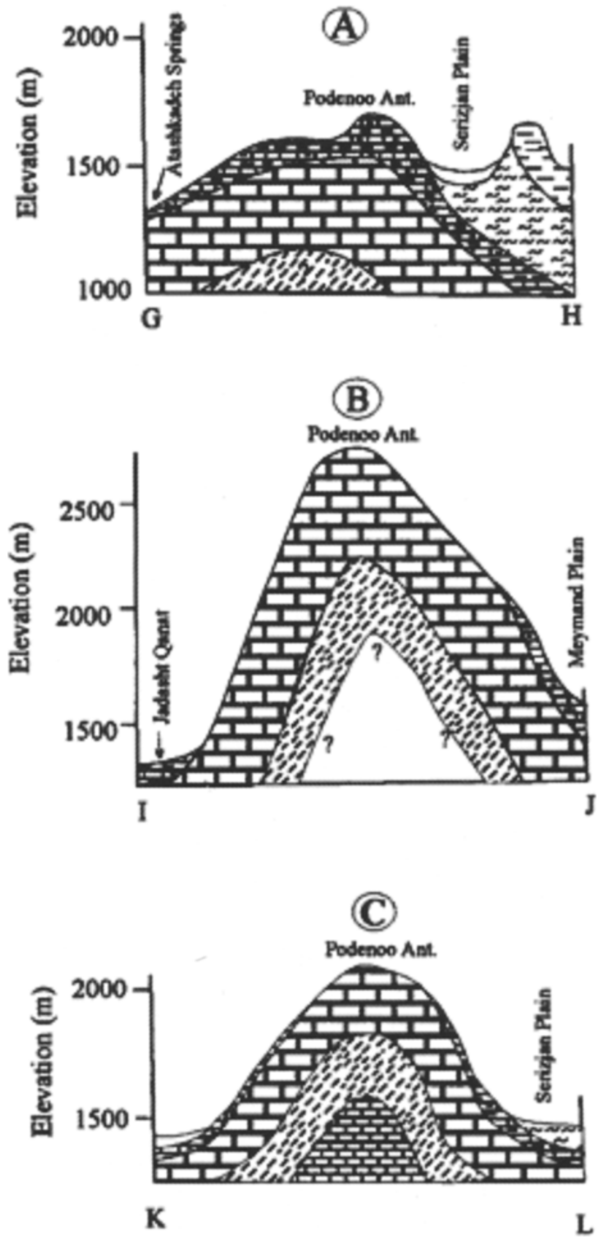

Figure 2. Geological cross section of the Podenow Anticline.

is divided into eastern, central, and western sections based on the orientations of the anticline. The eastern and western sections follow the general northwestern trend of the Zagros Mountain Range. The maximum elevations of the eastern and western sections are 2890 m and 2780 m respectively. There is no hydrogeological relationship between the southern and northern flanks in most parts of these two sections since the elevations of the Pabdeh-Gurpi Formations under the crest of the anticline are higher than the adjacent alluvium aquifers (Fig. 2). The central section is east-west oriented. The eastern and western sections slope down toward this saddle-shaped central section. Since the underlying Pabdeh-Gurpi Formations lies below the level

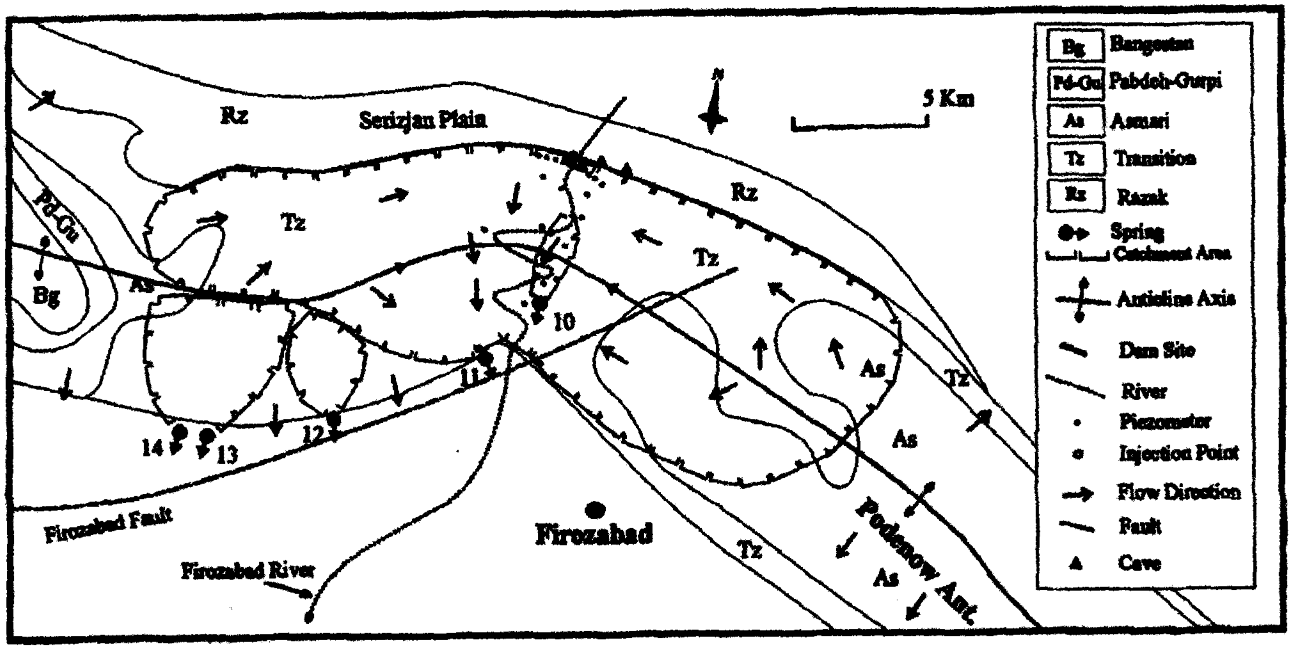

Figure 3. Probable catchment area of some of the karst springs in Podenow Anticline.

of the adjacent alluvium aquifers, water can flow from the northern to the southern flanks in the central section (Fig. 2A). Firozabad river flows through the U-shaped Tangab valley, in the central section of the anticline. Tangab Valley, with a maximum depth of 100 m, was probably developed through karstification by the Firozabad river in the past. The Tangab dam, under construction, is located in the beginning of the Tangab valley in the northern flank of Podenow Anticline (Fig. 1).

The most important karst features are dry valleys, caves, karrens, grikes, hidden shafts and springs. Shallow dry valleys perpendicular to the anticline axis are observed on the southern and northern flanks. Two caves have formed along joints on the northern flank, 500 m and 100 m from the inlet of Tangab Valley (Fig. 3). The elevations at the end of the caves are 35 m and 50 m lower than the inlet elevations. A 30 m deep shaft of 3 m diameter was discovered during tunnel excavation at the dam site. Karst water from the Podenow aquifer discharges from 36 springs, qanats, and pumping wells on the southern flank and 13 springs on the northern flank (Fig. 1). The biggest springs on the northern and southern flanks are the Atashgah and Ghomp Springs respectively. Table 1 shows the elevations, mean-annual discharges and specific conductance of these springs. The mean- annual discharges of the Ghomp and Atashgah springs are 1400 and 514 l/s respectively. For the other springs, the mean annual discharges range from 4.5 to 115 l/s. This study is focused on the location of the catchment area of Atashkadeh, Tangab, Dehbarm, Jastan and Morjshahrak springs (springs no. 11, 10, 12, 13 and 14 respectively on Fig. 3). Nineteen of these springs are collectively called the Atashkadeh springs (springs no. 11 on Fig. 3 and Fig. 4) which emerge from the alluvium adjacent to the southern flank of Podenow anticline in an area 700 m by 700 m (Fig. 4). The thickness of the adjacent alluvium in the Atashkadeh springs area is about 2 m, which covers the 15 m thick Transition Zone. These springs include Ghomp 1, 2, and 3, Bonab1, 2, 3, and 4, Saheli 1, 2, 3, and 4, Ghoratolein, Derakhat, Anjir, Bagh, Alaf, Kocheh, Khaneh and Jadeh. The combination average discharge of these springs is 1700 l/s. The Ghomp 1, 2 and 3 springs are the largest springs of the Atashkadeh springs. Ghomp 1 is an ascending spring with a diameter of 30 m. Ghomp 2 and 3 which are located 2 and 3 m away from the Ghomp 1 spring, join the latter spring. These three springs are measured at one station, therefore they are collectively considered as the Ghomp Springs. The elevations of Atashkadeh springs are presented in Figure 5. The Jadeh, Alaf, Kocheh, Bonab 1, 2, 3, 4, Ghomp 2 and 3 are located at higher elevations relative to the other Atashkadeh springs, and they ceased to flow during the dry season. The Tangab Spring is located in the Tangab Valley, on the north side of the Atashkadeh springs. The Dehbarm Spring is located 5.5 km west of the Atashkadeh springs. Jastan and Morjshahrak are qanat springs, 3.5 km west of the Dehbarm Spring. A qanat spring is an underground gallery inside the alluvium. The end of the gallery is connected to the karst aquifer. The gallery transfers water from the karst aquifer to the ground surface.

The average annual precipitation at the Tangab station was 889 mm and 365 mm in the water years 1995-1996 and 1996-1997 respectively. The elevation of the Tangab station is 1500 m and the Podenow mountain is as high as 2890 m, thus there is higher precipitation in Podenow mountain. All precipitation occurs in late fall, winter and early spring.

METHOD OF STUDY

The discharge, major ions, pH, specific conductance and temperature of all nineteen Atashkadeh springs and the neighboring Tangab, Dehbarm Jastan and Morjshahrak springs emerging from the southern flank of Podonow anticline, were measured once every two to three weeks from April 1996 to September 1997. The discharge, specific conductance and temperature of the Ghomp springs were measured daily during the wet season and every two or three weeks during the dry season.

Table 1. Elevations, mean annual discharges, and specific conductance of main karst springs.

Spring	No on Figs.1 and 3	Elevation (m)	SC (µS/cm)	Mean annual discharge (l/s)
Atashgah	1	1410	568	514
Mazakan	2	1390	937	7
West Zighon	3	1212	541	86
East Zighon	3	1165	514	90
Abshaikh	3	1162	496	48
Mary	4	930	897	12
Majhol	5	925	871	18
Garmab	6	912	599	10
Baghdomani	6	945	1080	6
Modghon	7	1012	470	9
Majmoe Modghon	7	1044	1099	17
Raikan	8	1200	668	39
Jadasht Kanat	9	1355	293	62
Jadasht spring	9	1420	305	14
Tangab	10	1360	577	44
Ghomp 1	11	1350	546	
Ghomp 2	11	1350.7	482	1401
Ghomp 3	11	1350.5	521	
Derakht	11	1348.3	526	9
Bagh	11	1348.8	533	11
Angir	11	1348	534	
Jadeh	11	1356.9	473	
Khaneh	11	1356.3	472	
Kocheh	11	1352.6	499	
Alaf	11	1352.9	482	313
Bonab 1	11	1351.3	503	
Bonab 2	11	1350.9	519	
Bonab 3	11	1351	513	
Bonab 4	11	1350.8	563	
Ghoratolein	11	1350.2	360	70
Saheli 1	11	1348.4	524	5
Saheli 2	11	1348.5	517	5
Saheli 3	11	1346.3	541	5
Saheli 4	11	1345.1	567	4
Dehbarm	12	1364	482	44
Morjshahrak	13	1353	389	116
Jastan	14	1347	395	104
Kalmardy	15	1600	723	6
East Ganjon	16	1700	470	11
West Ganjon	16	1600	475	7
Chenar Sokhteh	17	1364	588	79
Bonab	18	1450	579	12
Khabreh	19	1310	571	7

RESULTS AND DISCUSSION

The catchment area of the Atashkadeh, Tangab, Jastan and Morjshahrak springs were determined by geological and water balance methods and the time series of physico-chemical parameters of the springs (Karimi 1997). The catchment area of each spring was calculated by the following equation:

$$A = V/PI \qquad (1)$$

In which A is the catchment area of the spring, V is the total annual volume of water discharging from the spring, P is the total annual precipitation, and I is the recharge coefficient. The recharge coefficient is estimated to be 0.3 for the Transition Zone and 0.5 for the Asmari Formation (Water Resources Investigation and Planing Bureau 1993). The catchment areas of some of the karst springs emerging from Podenow anticline are presented in Figure 3. Part of the karst water on the southern flank of Podenow anticline is discharged to the adjacent alluvium. This is confirmed by the water budget of the adjacent alluvium (Ab-Niro Consulting Engineers 1992). The probable location and boundary of the catchment areas were estimated by the following criteria:

1. The catchment area is probably as close as possible to the spring.
2. The elevation of the catchment area must be higher than that of the related spring.
3. There must be no impermeable formations under the karst outcrop disconnecting the hydrogeological relationship between the karst aquifer and the spring.
4. The water budget should be balanced for the total area of the main aquifer, or in other words the catchment area of all subaquifers is determined.
5. Geomorphology, geology and tectonic settings should justify the catchment area.
6. The general direction of flow can be determined using water table elevations or isopotential maps, if piezometers are constructed in the study area.
7. The chemical parameters of the spring display the characteristics of the lithology of the related karst aquifer and adjacent formations.
8. The hydrograph and time series of physico-chemical parameters of the springs may have similar trends or overlap with common catchment areas.

The Catchment area of the Atashkadeh, Tangab, Dehbarm, and Jastan and Morjshahrak is estimated on the base of the criteria given in the 8 items above (Fig. 3). The results suggest that the catchment area of 18 of the Atashkadeh springs, Tangab and Dehbarm springs are probably parts of both the southern and northern flanks of the Podenow anticline, while the catchment area of the Ghoratolein (one of the Atashkadeh springs), Jastan and Morjshahrak springs are only the southern flank.

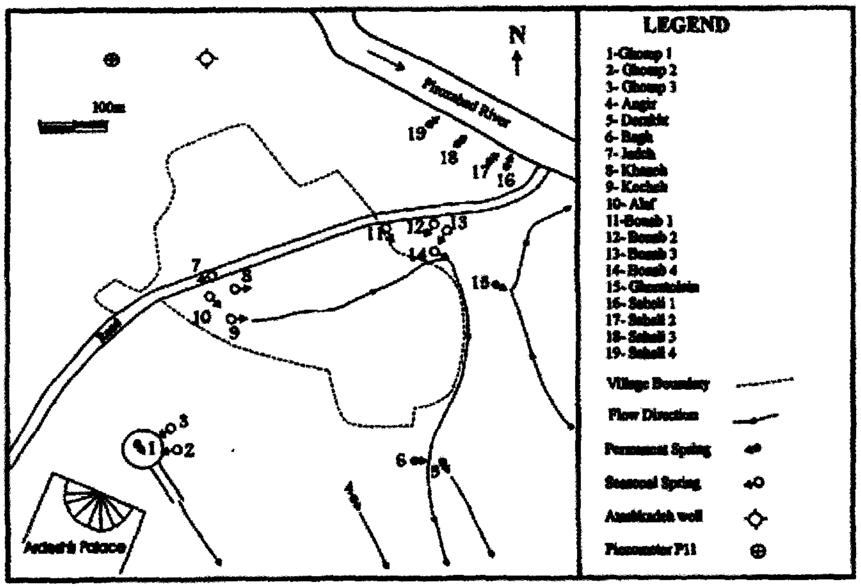

Figure 4. Location of the nineteenth Atashkadeh springs.

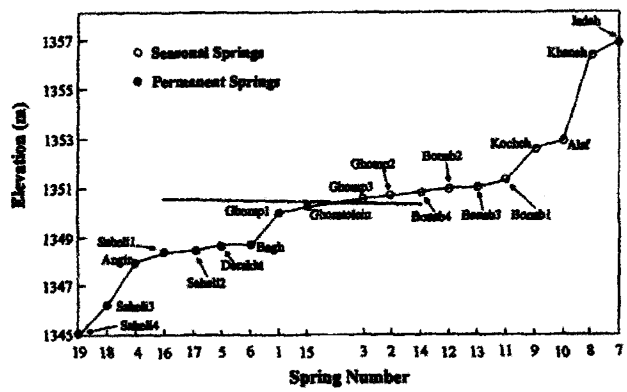

Figure 5. Elevations of Atashkadeh springs.

Using equation 1, the total annual recharge on the southern flank is 58.3 million cubic meters. The total volume of karst water emerging from the karst springs on the southern flank or flowing from Podenow anticline to the adjacent alluvium is about 94.2 million cubic meters. The water budget calculation in the Firozabad alluvium aquifer indicates that 67 million cubic meters of water must be provided by the adjacent Podenow karst aquifer (Ab-Niro Consulting Engineers 1992). Therefore, the total amount of water discharging from the southern flank is more than the amount of recharge on this flank. To balance the water on the southern flank requires the transfer of parts of the northern flank karst water to the southern flank.

The northern boundary of the Atashkadeh catchment area is bounded by the impermeable Razak Formation. The contact elevation of Razak and Asmari Formations on the northern flank is at least 150 m above the Atashkadeh springs.

The elevation of the impermeable Pabdeh-Gurpi Formation is lower than the Atashkadeh and Tangab springs in the central section of Podenow anticline (Fig. 2A), therefore the karst water can flow from the northern flank to the southern flank through the central section.

The elevations at the end of the caves on the northern flank are 35 m and 50 m lower than the inlet elevations. This implies that the direction of flow may be from the northern flank to the southern flank. Firozabad River was in direct contact with the northern flank in the past and these caves were probably formed through karstification by Firozabad River. The Firozabad fault extends from the northern flank up to the vicinity of the Atashkadeh springs (Fig. 1 and 3). The main conduit may have been developed in the vicinity of this fault.

The water table elevations in all the piezometers on the Tangab dam site are lower than the elevation of the Atashgah spring. This is a clear indication that this area is not the catchment area of the Atashgah spring. The water table elevations of all of these piezometers are higher than the elevations of Atashkadeh and Tangab springs which indicate the water in the northern flank has the potential of flowing to the southern flank.

The Razak Formation with interbedded gypsum layers, is located on the northern boundary of the Atashkadeh catchment area (Fig. 1). The general direction of flow is from the northern flank to the southern flank, therefore part of the water in the Razak Formation mixes with the karst water and consequently decreases the quality of the water in the northern flank of the Podenow anticline. The specific conductance (SC) of all the springs in the northern flank is higher than 400 microsiemens and the ratio of SO_4 to total anions range from 15 to 30. In addition, the thickness of the Tranzition Zone is much higher in the northern flank than the southern flank, therefore the quality of recharge water decreases by passing through marly layers of the Transition Zone. It may be concluded that the water which originates from the northern flank has a lower concentration of dissolved solids than that of the southern flank. The average SC of Tangab and all the Atashkadeh springs, except that of Ghoratolein spring, are higher than 400 μsiemens/cm. The average SC of the Ghoratolein, Jastan and Morjshahrak are less than 400 μsiemens/cm and the ratio of SO_4 to total anions is less than 15. Therefore if the water of some of the springs on the southern flank must be provided by the northern flank, most probably the springs with higher SC such as Tangab and Atashkadeh springs (except Ghoratolein).

The discharges of Bonab 1, 2, 3, 4, Bagh, Kocheh, Khaneh and Jadeh were collectively measured at one station. Figure 6 presents the hydrograph of these springs, in addition to the Ghomp and Goratolein springs, using discharge measurements of once every two to three weeks. Differentiation between the catchment areas of the karst springs would be more reliable if daily discharges were available. The hydrographs of these springs have similar trends (Fig. 6), therefore it may be concluded that these springs have a common main conduit and the same catchment area. The main conduit branches into several smaller tributaries near the springs. The hydrograph trends were not similar in the other springs of the study area. In spite of the similarity of hydrograph trend of some of the Atashkadeh springs, it is not possible to generalize this criterion for distinction of karst spring sources for the following reasons:

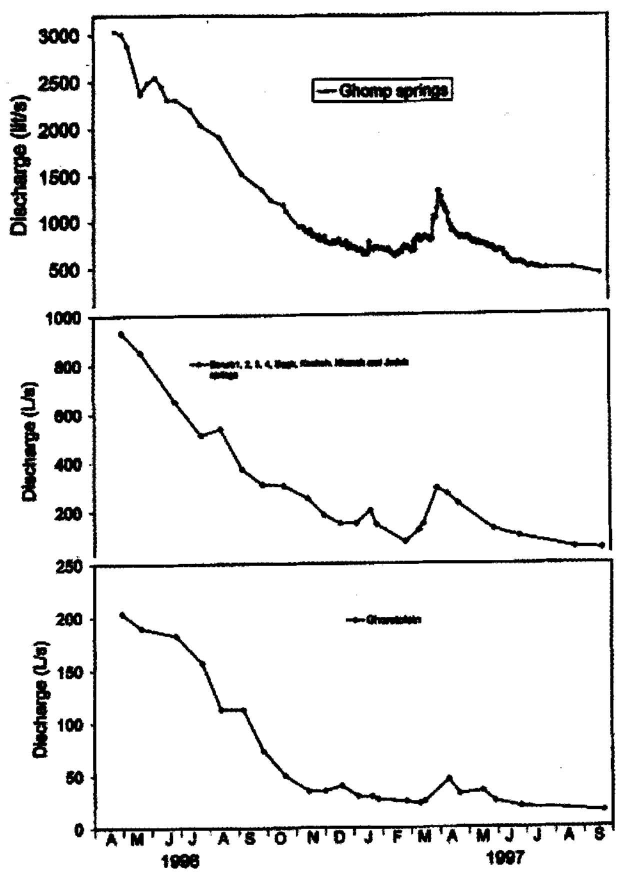

Figure 6. Hydrograph of the Ghomp, Goratolein, and Bonab 1, 2, 3, 4, Bagh, Kocheh, Khaneh and Jadeh (collectively measured at one station).

a) The hydrograph of a karst spring, especially a conduit one, is a response to rainfall. Therefore, springs with independent catchment areas may have similar responses to rainfall and consequently similar hydrograph trends.

b) Springs with common catchment areas with one major conduit branching near the discharge points, may show different hydrograph trends. Those springs emerging from higher elevations have a steeper recession and may dry up in summer. The water table elevation and rate of water table drop are the same in the main conduit for all the springs, but the ratio of water table drop to head above the spring discharge point are lower in high elevation springs than low elevation ones. Therefore, the rate of discharge variations and consequently the hydrograph shapes are not similar in high-elevation and low-elevation springs.

c) Recharge from the alluvium surface due to precipitation or irrigation reaching the karst spring has more effect on the hydrographs in small springs compared to the larger ones, because the share of alluvium recharge water is higher in the total discharge of small springs.

The time series of specific conductance in the fourteen Atashkadeh springs are presented in Figure 7. The time series of the major ions of these springs are rather similar to the SC time series, but only the SC time series are presented, because: a) They are representative of total dissolved solids; b) The SC time series of the springs overlap in most parts of the curve and they have less differences than major ion time series. The SC time series of the Jadeh, Alaf, Kocheh, Bonab 1, 2, 3, 4, Ghomp 2 and 3 are not complete, because they dry out during the low discharge period.

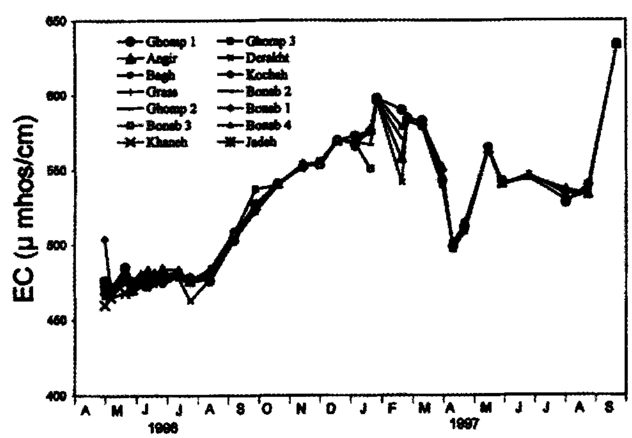

Figure 7. Time series of specific conductance in the fourteen Atashkadeh springs.

The SC time series of the fourteen Atashkadeh springs overlap one another, with the exception of one measurement during a rainy day, in which SC dropped in some of the small springs namely Derakht, Angir, Bonab 2 and Bagh. This is probably due to the different proportion of run-off and alluvium recharge in the total discharge of these springs. It may be concluded that all of these springs share a common conduit and the same catchment area. The catchment area of these springs consists of the northern and southern flanks, as discussed above. The SC time series of the Ghomp springs is selected as representative of the Atashkadeh springs for further discussion. The SC time series of Saheli 1, 2, 3, and 4 lie between the SC time series of Ghomp and Tangab springs (Fig. 8). Saheli 1, 2, 3 and 4 are small springs with average discharges of less than 5 l/s. Therefore their SC time series may easily effected by any temporary water source such as recharge from irrigation or precipitation. It is difficult to determine the source of these small springs with the available information. Even though they are located within the area of Atashkadeh springs, they cannot be fed by the tributaries of the main conduit of the 14 Atashkadeh springs, because their SC time series are higher than those of the 14 Atashkadeh springs. The sources of these springs are probably from the northern and southern flanks and on the border of Tangab and Atashkadeh catchment areas. The SC time series of Ghomp, Ghoratolein, Dehbarm, Jastan and Morjshahrak springs are presented in Figure 9. The catchment area of Ghoratolein is probably located on the southern flank in the vicinity of the Atashkadeh springs' area because: a) the SC time series of Ghoratolein spring is not similar to those of Ghomp springs. b) the catchment area of Ghoratolein spring is 8.2 km^2 and the area on the southern flank in the vicinity of the Atashkadeh springs is large enough to provide the total volume of the Ghoratolein spring water, and c) the low values of SC and the similarity of the SC time series of the Jastan and Morjshahrak springs justify the proposed catchment area. Ghomp and the Dehbarm neighboring springs have similar trends, which is expected from their partly overlapping catchment areas. The lower SC of Dehbarm spring compared to Ghomp springs is a result of the extra water joining the tributary between Atashkadeh springs and Dehbarm springs. This extra water probably originates from the southern flank, which as mentioned earlier, has a high quality. The SC time series in Jastan and Morjshahrak springs are not similar to those of Ghomp springs. This is probably due to their different catchment areas. The SC time series of Jastan and Morjsharak springs do not show any dominant response to rainfall, which implies that the flow regimes are mainly diffuse. The catchment area of the Jastan and Morjsharak springs is located in the southern flank with a thin transition zone, which may be the main reason for their lower SC values in the study area. The area on the southern flank in the vicinity of the Jastan and Morjshahrak springs is enough to provide the total discharging volume of these springs. These springs are located near one another, therefore they may have a common catchment area. The catchment area of Tangab spring is about 3.4 km^2. The SC time series of Tangab spring and Firozabad River are presented in Figure 10. The amount of seepage from the Firozabad River into the karst aquifer is about 100 l/s between the beginning of Tangab valley in front of the Tangab Spring. It may be concluded that part of the Tangab spring water is provided by Firozabad River, therefore the calculated catchment area should be reduced. The main reason for the high SC of the Tangab spring may be due

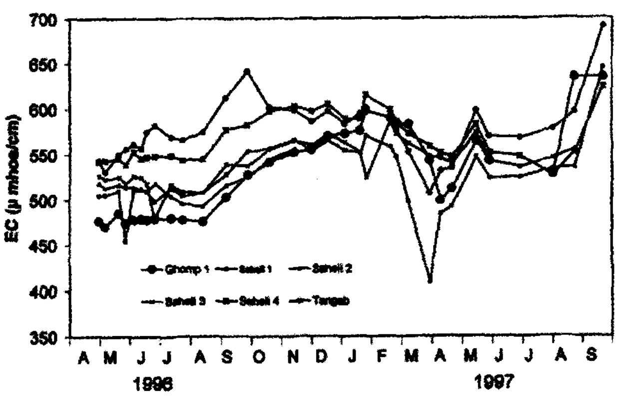

Figure 8. Specific conductivity (SC) time series of Ghomp, Saheli 1, 2, 3, and 4 Tangab springs.

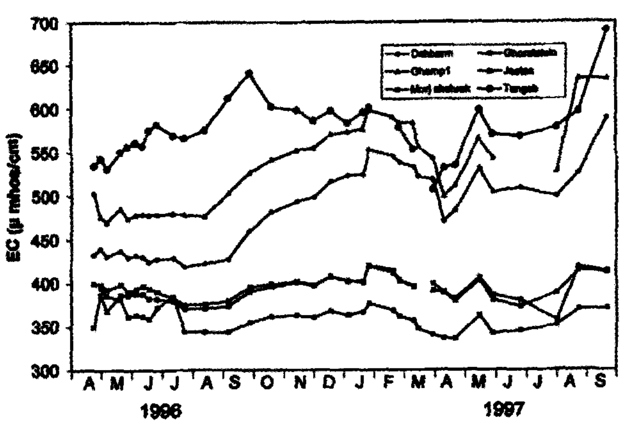

Figure 9. Specific conductivity (SC) time series of Ghomp, Ghoratolein, Dehbarm, Jastan, and Morjshahrak springs.

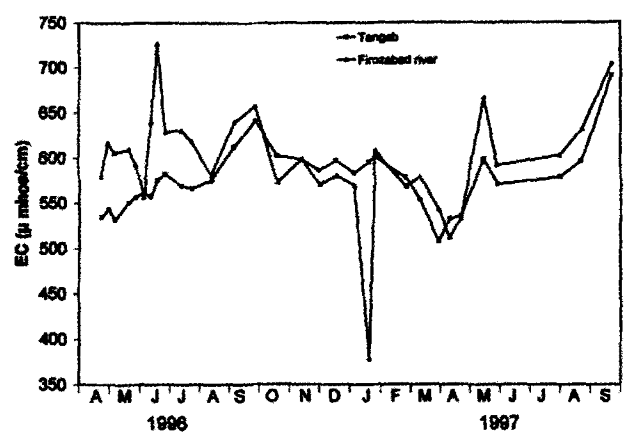

Figure 10. Specific conductivity (SC) time series of Tangab Spring and Firozabad River.

to the sink contribution of Firozabad River in the water of this spring. It is very difficult to determine the location of the Tangab spring catchment area with the available information. The catchment area is probably part of the southern and northern flanks of Podenow anticline near the Firozabad River.

The schematic model of the flow direction in the study area based on the above discussion is presented in Figure 11. The catchment area of Atashkadeh springs is bounded by the Razak Formation or impermeable sections of the Transition Zone on the foot of the northern and southern flanks. The western and eastern boundaries are limited to the water divide of the catchment area of the adjacent springs. The Tangab dam site is probably located within the catchment area of Tangab and all the Atashkadeh Springs, except for Ghoratolein. The catchment area of Tangab spring is located inside the catchment area of Atashkadeh springs. Two hypothesis can be proposed to justify the relationship between Tangab and Atashkadeh springs: Tangab is an independent spring. The conduit of this spring is located at an upper level, draining the seepage water from the Firozabad River and a restricted low elevation karst area near the Firozabad River. The conduit of Atashkadeh springs is located in a lower level, collecting the recharge water from high altitude areas. The crossing of two karst conduits over each other without any hydrogeological relationship has been reported by Ford and Williams (1989).

Tangab is an overflow spring of the Atashgah springs. A

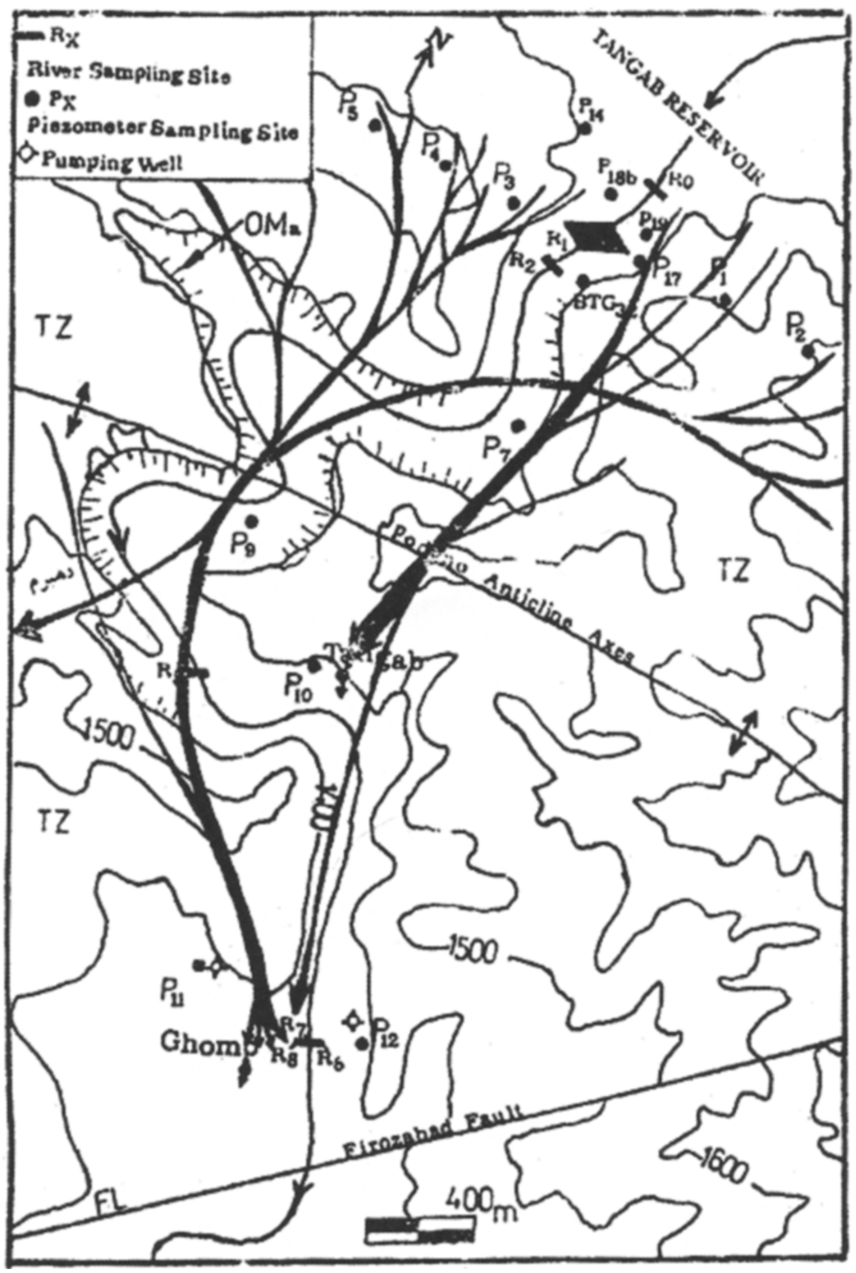

Figure 11. Schematic model of flow in the study area.

small conduit is separated from one of the Atashkadeh tributaries, forming the Tangab spring. This tributary is close to the Firozabad River and it has higher values of SC because its water originates from both the northern flank and the Firozabad River. The lower values of Atashkadeh spring SC can be explained by the share of lower SC of the tributaries collecting water of the southern flank.

Later dye tracer tests confirmed most of the proposed catchment area. The uranine dye tracer injected in the right abutment of Tangab dam was detected in fourteen of the Atashkadeh springs, which had previously exhibited overlapping SC time series, namely Ghomp 1, 2 and 3, Bonab 1, 2, 3 and 4, Anjir, Bagh, Alaf, Derakht, Kocheh, Khaneh and Jadeh springs (Asadi 1999). The dye breakthrough curves of all these springs overlap one another, having only one peak. This implies that only one major conduit system transfers water to these fourteen springs. The main conduit branches into fourteen springs only near the Atashkadeh area. The dye detected in Dehbarm spring had a lower concentration (by about 1/5) which implies that a tributary is separated from the main conduit. The dye is diluted by the extra water added to the tributary conduit at a distance of 5.5 km between Atashkadeh and Dehbarm springs. The dye was detected in very low concentrations in the Tangab and Saheli 1, 2, 3, 4 springs, no dye in any of the boreholes in the right and left abutments of Tangab dam. This implies that there is no direct conduit connection between the injection point and these springs and boreholes. The catchment areas of Tangab, Saheli 1, 2, 3, and 4 springs are located adjacent to the catchment area of the fourteen dye-detected Atashkadek springs. The dye was transferred to these springs by dispersion. It was not detected in any of the other springs emerging from Podenow anticline, including the Ghoratolein, Jastan and Morjshahrak springs.

Rhodamine dye tracer (Talaei 1999) was injected in a borehole 100 m from the Firozabad river on the left abutment of Tangab dam on the northern flank (Fig. 3). The dye was detected only in the Tangab and Saheli 1 springs. The lower dye concentration in Saheli spring implies that additional water joins the tributary of Saheli 1 spring between the Tangab and Saheli springs. Therefore, it can be concluded that the catchment area of Ghoratolein, Jastan and Morjshahrak is not the northern flank. The two dye tracer tests confirm the hydrogeological connection of the area near the Firozabad River on the northern flank and the springs emerging downstream on the southern flank. The catchment area of the springs are greater than the small area near the Firozabad River, therefore, other hydrogeological methods should be used to determine the extent of the catchment area.

CONCLUSION

The time series of specific conductance of the fourteen Atashkadeh springs overlap. This implies that all of these springs share a common conduit and the same catchment area. But the catchment area of one of the Atashkadeh springs is different from the other springs, even though it is surrounded by those other springs. A later dye tracer test confirmed the results of the SC time series. The catchment area of the karst spring cannot be practically determined using the conventional method of equipotential map. Dye tracer tests determine point to point relationships. Several dye tracer tests must be done to find the catchment area. The high expenses of dye tracer tests limit the application of this method. The combination of parameters such as geological and structural settings, topography, geomorphology, water budget, effect of karst aquifer lithology and surrounding formations on hydrochemistry of karst springs, classification of karst springs based on water chemistry factors, spring hydrographs and time series of physical-chemical parameters can be used to determine the probable boundary of the catchment area of karst springs. This method is acceptable, especially under financial limitations. Water level elevations in piezometers or equipotential maps can increase the accuracy of this method. A combination of dye tracer tests and the proposed method gives greater capability to determine the catchment area boundary.

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