Determining springs protection areas by combining an analytical model and vulnerability index

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ABSTRACT

Karstic springs are considered as an important source of drinking water in highland areas. Because of the high vulnerability of karst areas, any activities such as agricultural, livestock and even industrial ones in these areas can affect springs water quality. Therefore, it is essential to define qualitative limitations on human functions in these areas for the sake of springs protection from contamination. In this paper, a new method is introduced which combines the vulnerability index of a spring's outlet and the protection area of its basin. In the proposed method, the VESPA index is firstly applied to analyse the vulnerability of karst springs to contamination. Then, the protection areas of the springs are determined using the integration of the MDHT method and the result of VESPA. The method is examined to Parikedal and Sarab-e Taveh springs, located in the central Zagros, Iran. Based on the results, Parikedal vulnerability is classed as very high and two immediate protection zones are defined around Prikdal's outlet and its sub-basins, located on its inner protection zone. Sarab-e Taveh, in comparison with Parikedal, has less karstic development. Therefore, its vulnerability is classified as high. In addition, by considering the MDHT method, the main part of Sarab-e Taveh's water basin is located in outer protection zone and thus, some minor activities are allowed on it. The results of this study show that combining the analytical model and vulnerability could estimate springs' protection areas more accurately.

1. Introduction

Quality conservation of water resources is very important, particularly for groundwater that is the main supplier of water for drinking purposes (Foster et al., 2013). In arid areas that groundwater has usually low quality, the optimal use of high quality water is importance (Azarnivand and Chitsaz, 2015). Thus, the high-quality water of karstic springs is valuable for these regions, and their water resources are mainly used for domestic purposes (Kallioras and Marinos, 2015). Karstic springs are usually the outlets of karstic systems and provide water easier and more economical than pumping wells. Rainwater, snow melting, and runoff usually feed the karstic springs. They can undergo qualitative changes, during transferring from sinkholes to the outlets (Cleaves, 2003).

Karstic springs are highly vulnerable to pollution due to the thin layers of soil on their water basin. There is always the possibility of rapid and extensive transmission of contamination through the springs depending on the type of karst (Banzato, 2017) and thus, exploring susceptible areas in their basins is essential for protecting them. Vulnerability evaluation is a general assessment for identifying the probability of contamination occurrence (Focazio, 2002) and should not be considered as an indicator for determining the amounts of contamination (Focazio, 2002). The vulnerability of a karstic aquifer has been described by different indicators; such as EPIK (Doerfliger and Zwhalen, 1997), COP and COP + K method (Vías et al., 2006; Andreo et al., 2009), the Slovene approach (Ravbar and Goldscheider, 2007), PAPIKa (Kavouri et al., 2011), RISKE (Petelet-Giraud et al., 2000) and PI (Goldscheider, 2005). All of these indicators focus on aquifers or karst areas, while the VESPA method (Galleani et al., 2011) determines the vulnerability of an outlet point or a karstic spring. It considers the physical, chemical and hydrogeological characteristics of the spring in order to show its vulnerability to pollution. Banzato et al. (2017) have shown the reliability of VESPA for assessing the vulnerability of karst springs. According to VESPA, if the vulnerability of a spring is high or very high, a conservation area needs to be defined. In such protected areas, human activities have to be banned for preventing the entrance.
of pollution into the spring (Galleani et al., 2011). Some studies have been done to determine the quality protection area of springs. For instance, Pochon et al. (2008) have introduced three methods of calculating the springs protected areas. These methods were based on the amount of springs vulnerability, ‘Distance method’ for springs with low vulnerability and Isochrone method and DISCO for ones with high vulnerability. Based on springs’ hydrograph analysis, Civita (2008) has introduced four conservation scenarios called MDHT. More information about MDHT will be presented in coming sections.

A review of above methods shows that some of them determine the conservation areas with brief information. In this situation, the likelihood of contamination entrance to springs could increase. Besides, other methods such as the modelling need plenty of information and data about the geology and hydrogeological structure of the springs, which are costly. Therefore, this study tries to determine the protection zone of the springs by combining the springs vulnerability index and the MDHT scenarios.

In this paper, the VESPA index is firstly calculated for two springs located in the centre of Iran and then, the protection zones of them are defined based on the MDHT scenarios. In the next step, the VESPA index and the MDHT scenarios are combined to determine the protection area of the springs. Finally, three protected areas in their basin are introduced.

2. Materials and methods

2.1. VESPA vulnerability index

As mentioned before, the vulnerability index of karst aquifers has been introduced by various researchers, however, few studies are conducted on the vulnerability of springs’ outlets. Galleani et al., 2011 has first applied the VESPA vulnerability index for estimating the protection zones of 12 karst springs located in the Piedmont region, Italy. VESPA is based on analysing springs hydrographs and considering their catchments situation. In this method, spring hydrographs’ response to infiltration processes is first examined. Analysing springs hydrographs and the observed relationship between the flow rate, temperature, and electrical conductivity (Ec) as a function of infiltration, determine the behaviour of springs to the transmission of contamination. These parameters are considered to be the main features affecting the vulnerability and their multiplication defines the vulnerability. The VESPA vulnerability index is presented by Eq. (1):

\[ V = c(\rho) \ast \beta \ast \gamma \]  

(1)

where \( c(\rho) \) represents the correlation between Ec and discharges from spring computed on the reference time interval \( t_0 = 1 \) year, \( \beta \) shows water temperature changes during discharge measurement, and \( \gamma \) introduces a discharge factor which is a function of the minimum, maximum, and average discharges during discharge measurement. It should be mentioned that a spring vulnerability level will be extracted from Table 1 after calculating \( V \).

Depending on the type and nature of data series, \( c(\rho) \) can be either parametric or non-parametric. It can be calculated using Eqs. (2) and (3):

\[ C(\rho) = \left[ U(-\rho) + \alpha U(\rho) \right] \]  

(2)

Table 1: Values of the VESPA index and the vulnerability level.

<table>
<thead>
<tr>
<th>Vulnerability</th>
<th>VESPA index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>( V \geq 10 )</td>
</tr>
<tr>
<td>High</td>
<td>( 10 &gt; V \geq 1 )</td>
</tr>
<tr>
<td>Medium</td>
<td>( 0.2 &gt; V \geq 0.1 )</td>
</tr>
<tr>
<td>Low</td>
<td>( 0.1 &gt; V \geq 0 )</td>
</tr>
</tbody>
</table>

2.2. Protection zone determination using MHDT

Protection zones for groundwater resources should be defined with considering the types of their water consumption and their catchments situation (Pochon et al., 2008). In other words, the protection zones of a spring with drinking consumption need be different from one with agricultural exploitation. Moreover, the protected areas require to be laid on its spring catchment (or its feeding area). It should be emphasised that several levels of protections and consequently several protection areas need to be determined for the spring to support the economy of the residents that live in the spring catchment.

Several methods have been proposed by researchers to define protected areas in karst springs, such as time of travel (TOT), geological structure and groundwater flow, the combination of karst vulnerability and modelling, and the time and speed of groundwater flow and the integration of hydrogeological criteria (Butscher and Huggenberger,
These methods are dependent on input data and the protection zone and privacy can be evaluated more precisely, if more input data are introduced to the models. The analysis of the spring hydrograph based on the transmission time of the contamination is one of these methods which has been introduced by Civita (2008) and named the MHDT method. In this method, spring characteristics such as discharge rates, reservoir capacity, and the speed and the duration of water renewability are calculated. Then, various scenarios of the spring pollution are defined based on flow speeds and the duration of the contamination transmission. Finally, the protection zones of the spring are determined. In this method, an indicator called 

$$DMH = \frac{Q_{max}}{2} \times t_i$$

where \(V\) is the coefficient of infiltration speed. This method advantage is its ability to identify the maximum speed of contaminant movement during the recharging of the aquifer, even in the absence of data and tests, such as pumping test, tracing test. \(t_i\) is approximately equivalent to the maximum withdrawal rate in half time of water discharging. Therefore, the MHDT index can be considered equal to \(t_i\), as presented in Eq. (8).

$$MDHT = \frac{Q_{max}}{2} \geq t_i$$

MHDT means the number of days since the recharge of the spring decreases from the maximum annual \(Q_{max}\) flow to \(Q_{max} / 2\). At this time, the infiltration through the unsaturated region becomes insignificant and thus, the contaminant gets a preferred route to the spring outlet which is direct and fastest way without any damping.

Based on this method, four scenarios are defined by considering the relationship between the flow velocity data and their related the MHDT values. Table 3 shows the basic scenarios of the contamination risk along with the relevant speed ranges.

The distances of protection area from the spring outlet are determined based on the type of the risk scenario and the way of exploration such as direct use (cave) or full aquifer (drainage gallery, wells, etc.). For this purpose, a distance from the spring outlet and its surrounding structure is firstly selected which it is called ‘D’ and then the spring protection area is defined by considering the distances ‘L’ and ‘d’ which are the lengths of this area from the end of ‘D’, towards the upstream and downstream of the spring, respectively. The values of ‘D’, ‘L’, and ‘d’ are presented in Table 4. Fig. 1 schematically illustrates the spring protection area.

### Table 4

<table>
<thead>
<tr>
<th>Exploration type</th>
<th>Scenario</th>
<th>D (m)</th>
<th>d (m)</th>
<th>L (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>A</td>
<td>40</td>
<td>10</td>
<td>All restrict</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>30</td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>20</td>
<td>5</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>10</td>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>Complete aquifer</td>
<td>A</td>
<td>30</td>
<td>5</td>
<td>All restrict</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>30</td>
<td>4</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>15</td>
<td>3</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>10</td>
<td>2</td>
<td>200</td>
</tr>
</tbody>
</table>

The classification of protected areas into three categories is based on the contamination risk scenario. The first zone is Immediate Protection Zone (Orange-IMPZ), where all human activities except for planting trees and seedling grass are prohibited. In scenarios A and B, all aquifers with high secondary porosity (karstic openings) or high permeability areas are considered to be in this zone. The discharge of liquefied sewage and animal grazing is prohibited in this zone and the quality of groundwater has to be measured and a fence around the protected area should be applied.

The second zone is Inner Protection Zone (Yellow-IPZ) where certain human activities and safeguards for specific water entry points (such as soakways, pits, caves, quarries, karst swallow-holes and sinks) need to be applied. Moreover, wastewater entrance and leakage of pollutants in this zone require be banned, especially in scenarios B and C, which they are clearly different from scenario A.

The third zone is Outer Protection Zone (blue-coloured - OPZ) where conservation strategies, along with auxiliary rules and legislation for changing the situation and limiting water utilisation should be applied. Moreover, automatic devices for measuring groundwater level and water quality monitoring need to be installed. Fig. 2 schematically shows the three protection zones for a spring.

### 2.3. Research method

A spring vulnerability is a function of its upstream characteristics and land use, which influences the potential of contamination entry. Therefore, the study of the spring's basin characteristics is very important to examine its vulnerability. Moreover, MHDT is a common method to determine a spring protection area, which divides the spring's basin into three areas and just considers spring maximum discharge for protection area definition. Then, the application of Vespa includes the qualitative evaluation for it. Accordingly, by integrating Vespa and MDHT, the protection area is categorised based on quantitative and qualitative terms. Fig. 3 shows the steps of combining the methods.

### 2.4. Case study

Several karst springs are in Zagros Mountains chain, central region of Iran, which are the main suppliers of drinking water. In this study, Sarab-e Taveh and Parikedal springs are selected to test the practicability of the introduced method for finding their protection zones. These springs are located within the Asmari geological formation. Asmari formation (Oligo-Miocene) is one of the most recent formations in the Zagros mountain range, southwest Iran. The formation is composed of carbonate, mixed carbonate, and mixed carbonate-siliciclastic facies (Van Buchem et al., 2009). Light yellow to brown limestone with hilly morphology of this formation are the most important reservoir in the Zagros sedimentary basin, internationally well known as the first oil reservoir in the Middle East. The formation has fossils of Oligocene to Miocene age.

The mean annual rainfall of their catchments is about 650 mm that
contributes to their high flow rate. Sarab-e Taveh and Parikedal supply the domestic demand of Yasouj city, an important city in centre of Iran and their water resources are also suitable for bottled water (EC < 400 μS/cm). Water quality of Parikedal is better than Sarab-e Taveh, because of locating at upstream of Sarab-e Taveh. Sarab-e Taveh and Parikedal basin area are 10.2 km² and 5.27 km², respectively. Fig. 4 shows their locations in Iran and in a karst area, named ‘Kenare Limestone Gorge’.

3. Results and discussion

3.1. Evaluation of VESPA

To evaluate the vulnerability of Parikedal and Sarab-e Taveh by VESPA, some parameters such as discharge, Ec, and the water temperature at the outlets of both springs were measured during Oct 2015 to Sep 2016. The results are presented in Table 5. Figs. 5 and 6 also present the monthly changes of springs Ec and discharges.

As shown in Fig. 5, the Ec of spring reaches to its maximum level from mid-spring to mid-summer, when its discharge decreases significantly. Sarab-e Taveh’s average annual discharge and Ec are 430 L/s and 332 ds/m respectively. At the same time, the discharge and Ec of Parikedal are less than Sarab-e Taveh. The fluctuations of discharge and Ec play an important role in their vulnerability.

As shown in Figs. 5 and 6, the reaction rate of discharge towards Ec in the Sarab-e Taveh is high. Since geological formations of springs’ basin are almost identical, the area of their basins makes a difference in their discharges. The basin area of Sarab-e Taveh is much bigger than Parikedal, hence, its discharge is significantly increased during the time. Moreover, the existence of a river which is fed from melting snow and rainfall and also surface water infiltration, play a remarkable role in increasing the discharge of Sarab-e Taveh. Regarding the position of Parikedal, where is the upstream of the basin, its average salinity is lower than Sarab-e Taveh. Moreover, the salinity fluctuations of Sarab-e Taveh are usually much larger than Parikedal and it is between 150 ds/m (during wetly periods) to 400 ds/m (for drought periods). These
significant variations in salinity are due to the high fluctuations of Sarab-e Taveh discharges, which is more than twice during wetly period in comparison with drought one. The similar condition can also be found for Parikedal.

The examination of the springs temperature changes in Table 5 shows that Parikedal reaction to temperature changes is much higher than Sarab-e Taveh. The reason is probably its small basin area and rapid effect of snow melting on its discharge temperature. This high reaction also shows that the transmission of contamination in Parikedal is faster than Sarab-e Taveh. It should be mentioned the variation of water temperature has a key role in the vulnerability of a spring. As shown in Table 5, the variation of Parikedal water temperature is more than Sarab-e Taveh. Regarding to the importance of springs for supplying the drinking water of Yasouj, considering special measures for protecting the springs is essential.

3.2. Analysis of the vulnerability and the protected zones

By considering the maximum recorded flow rate for one year, MDHT for both springs are > 50. Then, the scenario D can be considered for both springs with the smallest protection level. MDHT finds the protected zones of springs to decrease their environmental hazards. As mentioned before, MDHT determines the vulnerability scenarios of a spring regarding its flow speed and maximum discharge at half time of monitoring. It neglects many important factors such as quality, the trends of discharge changes, time, temperature, and so on, which affect the spring infiltration. For fixing these deficiencies, the VESPA vulnerability index is combined with MDHT to select an appropriate contamination risk scenario. The combination of these indicators means that the vulnerability of the spring has a direct relationship with the transition time, evaluating by MDHT. In other words, a more sensitive scenario of pollution and a wider range of quality protection should be devoted to vulnerable and sensitive springs.

The vulnerability indexes of the springs are first calculated using VESPA based on their physical and hydrological conditions. In the second step, the vulnerability indexes of springs are used to select their contamination risk scenario (MDHT). Four basic scenarios of springs’ contamination risk based on the VESPA index are presented in Table 7.

According to gained results, Scenario A and Scenario B are suitable for Parikedal and Sarab-e Taveh, respectively and the size of the protection zones of the springs are determined considering Table 7. Figs. 7 and 8 present the protection zones of Parikedal and Sarab-e Taveh, respectively.

Parikedal vulnerability analysis indicates that it is very vulnerable and thus the scenario A is selected for it.

The amount of protection area for the immediate protection zone, is determined using Eq. (9). Accordingly, by choosing scenario A for Parikedal (Table 4), the values of D (40 m), d (10 m) and A1 (IMPZ zone) are calculated as below:

\[
A_1 = (2D + D + (D-d-cot(\theta)) + dA_1 = (2 \times 40^2) + ((40-10-co(60^\circ))) + 10) = 35, 342.5 \text{ m}^2 \tag{9}
\]

There is a sinkhole in Parikedal spring’s basin and based on Eq. (10), the immediate protection zone (IMPZ zone) with 100 m radius is calculated 0.314 km². Then, the total area of the immediate protection zone (IMPZ) is calculated to be 0.35 km².

\[
A_2 = \pi \times r^2 = \pi \times (100)^2 = 0.314 \text{ km}^2 \tag{10}
\]

In order to determine the inner protection zone (IPZ) of Parikedal (A3 in Fig. 7), given the selection of the A scenario, which can be calculated by subtracting the immediate protection zone (A1 + A2) from the Parikedal basin area. It is calculated using Eq. (11) and is equal to 4.29 km².

\[
A_3 = A_{\text{basin}} - (A_1 + A_2) = 5.27 - 0.35 = 4.92 \text{ km}^2 \tag{11}
\]

In this equation, A3 is the area of the inner protection zone (IPZ) and A_{basin} is the total area of the spring’s basin. Fig. 7 presents the protection zones of Parikedal.

The vulnerability of Sarab-e Taveh is high. Accordingly, by choosing scenario B for Sarab-e Taveh (Table 4), the values of D (30 m), d (5 m) and A1 (the area of the immediate protection zone) are calculated by Eq. (9) as below:

\[
A_1 = (2 \times 30^2) + ((30-5-cot(60^\circ))) + 5) = 2085.5 \text{ m}^2 \tag{12}
\]

The inner protection zone (IPZ) of Sarab-e Taveh is calculated by multiplying the value L to the average width of the Sarab-e Taveh basin (Eq. (12)). Based on Table 4, L is equal to 2000 m and the average width of the Sarab-e Taveh basin (B) is 600 m. Therefore, the inner protection zone of Sarab-e Taveh is 1.2 km².
The area of the Sarab-e Taveh outer protection zone (OPZ) is calculated by subtracting the areas of IPZ and IMPZ from the Sarab-e Taveh basin area (Eq. (13)), which is 8.9 km². In this equation, A3 is the outer protection zone. Fig. 8 presents the protection zones of Sarab-e Taveh. Table 8 shows the dimensions of the springs' protection zones.

\[ A_3 = A_{\text{basin}} - (A_1 + A_2) \]
\[ A_3 = 10.2 - (0.002 + 1.2) = 8.9 \text{ km}^2 \]  

4. Discussion

In this paper, a new method for defining the protective zones for karstic springs is introduced. It is based on combing springs' outlets vulnerability and various contamination risk scenarios for their basins, which leads to three levels of protective zones. An important advantage of the proposed method is the availability of its required information, which are already prepared for springs or can be provided by field measurements.

The given results from the Parikedal and Sarab-e Taveh springs show that the temperature variation is very important in the springs' protective zone determination, when Sarab-e Taveh vulnerability is lower than Parikedal and its discharge is more than Parikedal. Moreover, the amounts of springs vulnerability can play an effective role in determining the conservation areas, while by increasing springs vulnerability level, their immediate protection areas increase.

Vespa is only applied to determine the vulnerability of a spring outlet and cannot be used for specifying a protection area. Previous studies have shown the role of discharge characteristics, EC, and temperature in determining the vulnerability of a spring (Galleani et al., 2011; Banzato et al., 2017; Banzato et al., 2015; Amanzio et al., 2015).
Table 5
Monthly average of collected data from Parikedal and Sarab-e Taveh.

<table>
<thead>
<tr>
<th>Month-year</th>
<th>Discharge (l/s)</th>
<th>Temperature (°C)</th>
<th>Ec (ds/m)</th>
<th>Discharge (l/s)</th>
<th>Temperature (°C)</th>
<th>Ec (ds/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarab-e Taveh</td>
<td></td>
<td></td>
<td></td>
<td>Parikedal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct-2015</td>
<td>192.8</td>
<td>14.2</td>
<td>383</td>
<td>23.5</td>
<td>10</td>
<td>282</td>
</tr>
<tr>
<td>Nov-2015</td>
<td>158.4</td>
<td>12.2</td>
<td>406</td>
<td>16.8</td>
<td>6.2</td>
<td>224</td>
</tr>
<tr>
<td>Dec-2015</td>
<td>447</td>
<td>12.45</td>
<td>422</td>
<td>33</td>
<td>8.1</td>
<td>283</td>
</tr>
<tr>
<td>Jan-2016</td>
<td>467</td>
<td>12.3</td>
<td>398</td>
<td>52</td>
<td>7.7</td>
<td>212</td>
</tr>
<tr>
<td>Feb-2016</td>
<td>503</td>
<td>11.5</td>
<td>340</td>
<td>68</td>
<td>6.8</td>
<td>198</td>
</tr>
<tr>
<td>Mar-2016</td>
<td>619</td>
<td>10</td>
<td>261</td>
<td>135</td>
<td>6</td>
<td>144</td>
</tr>
<tr>
<td>Apr-2016</td>
<td>592</td>
<td>11.8</td>
<td>133</td>
<td>72</td>
<td>8.3</td>
<td>167</td>
</tr>
<tr>
<td>May-2016</td>
<td>579</td>
<td>12</td>
<td>138</td>
<td>58</td>
<td>10</td>
<td>122</td>
</tr>
<tr>
<td>June-2016</td>
<td>589</td>
<td>12.8</td>
<td>374</td>
<td>25</td>
<td>16</td>
<td>273</td>
</tr>
<tr>
<td>July-2016</td>
<td>474</td>
<td>12.8</td>
<td>372</td>
<td>20.5</td>
<td>14.6</td>
<td>264</td>
</tr>
<tr>
<td>Aug-2016</td>
<td>284</td>
<td>12.6</td>
<td>370</td>
<td>15.1</td>
<td>12.6</td>
<td>258</td>
</tr>
<tr>
<td>Sep-2016</td>
<td>256</td>
<td>13</td>
<td>395</td>
<td>18.4</td>
<td>11</td>
<td>243</td>
</tr>
<tr>
<td>Average</td>
<td>430.1</td>
<td>12.3</td>
<td>332.7</td>
<td>44.7</td>
<td>9.7</td>
<td>222.5</td>
</tr>
</tbody>
</table>

Fig. 5. Time series of measuring the electrical conductivity and discharge in Sarab-e Taveh.

Fig. 6. Time series of measuring the electrical conductivity and discharge in Parikedal.
Furthermore, in studies which intend to define the qualitative boundaries of springs by MDHT, the time series of discharge or maximum discharge is only used (Pochon et al., 2008; Civita, 1995; Civita, 2008). Scenarios presentation is an advantage of MDHT, which they divide the basins of springs into different areas with human activity limitation. In this study, the qualitative boundaries of springs are determined by combining two methods and make the use of their effective parameters for the first time.

5. Conclusion

Large karst springs have an important role in their region development. Therefore, the protection of their quality and the determination of their protection zone need be taken into consideration. In this study, the qualitative vulnerability of two springs in the centre of Iran, Parikedal and Sarab-e Taveh are determined using the VESPA index. The VESPA results have indicated the vulnerability of Parikedal, which has the smaller catchment is very high, while it is high for Sarab-e Taveh. Besides, combining VESPA and the MDHT method is used to figure out the conservation areas of two springs. Finally, three protection zones; immediate, internal and external have been determined based on the vulnerability of springs. According to the proposed method, Scenario A of the vulnerability contamination has been assigned to Parikedal. Its entire catchment locates in the internal protection zone. Moreover, its outlet and a sinkhole in its catchment lie in the immediate protection zone. Sarab-e Taveh has been categorised into Scenario B of the vulnerability contamination. Under this circumstance, the immediate protection zone is considered for its outlet (with 1.2 km² area) and the internal protection zone for about 8.9 km² of its catchment. The rest of its catchment lies in the outer protection zone. The

<table>
<thead>
<tr>
<th>Spring</th>
<th>ρ</th>
<th>C(ρ)</th>
<th>β</th>
<th>γ</th>
<th>VESPA index</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarab-e Taveh</td>
<td>0.84</td>
<td>0.42</td>
<td>17.6</td>
<td>1.07</td>
<td>8</td>
<td>High</td>
</tr>
<tr>
<td>Parikedal</td>
<td>0.67</td>
<td>0.34</td>
<td>100</td>
<td>2.67</td>
<td>90.07</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Table 6
Vulnerability analysis for the springs based on the VESPA index.

<table>
<thead>
<tr>
<th>Pollution of scenario</th>
<th>VESPA index</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>V ≥ 10</td>
</tr>
<tr>
<td>B</td>
<td>10 ≥ V ≥ 1</td>
</tr>
<tr>
<td>C</td>
<td>0.2 ≥ V ≥ 0.1</td>
</tr>
<tr>
<td>D</td>
<td>0.1 ≥ V ≥ 0</td>
</tr>
</tbody>
</table>

Table 7
Determining the contamination risk scenarios based on the VESPA index in a full aquifer.

Fig. 7. Protection zones of Parikedal.
The results of this study have shown that the combination of VESPA and MDHT can determine the protection zones of springs more accurately. To verify the proposed method, tracking tests are necessary in order to accurately determine the springs protection zone boundaries.

Acknowledgement

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References


Table 8
The dimensions of the protection zones of Parikedal and Sarab-e Taveh.

<table>
<thead>
<tr>
<th>Spring</th>
<th>TPZ (km²)</th>
<th>IPZ (km²)</th>
<th>OPZ (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parikedal</td>
<td>8.9</td>
<td>5.21</td>
<td></td>
</tr>
<tr>
<td>Sarab-e Taveh</td>
<td>5.21</td>
<td>1.2</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Fig. 8. Protection zones of Sarab-e Taveh.


