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Evaluation of Water Resources Exploitation in a Karst Region Using Intrinsic Vulnerability Assessment

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Abstract

Groundwater vulnerability assessment is of crucial importance for land use/cover management. Some methods have been proposed specifically for the karst hydrogeological settings. Among them, COP and PaPRIKa, as two commonly applied recent methods, were adopted for the resource vulnerability assessment of a humid temperate karst region, north of Iran. Comparison of water bacterial content and distribution of vulnerability classes within the catchments for nine springs suggests that PaPRIKa got some higher level of validity, showing more consistency to the catchment properties. Vulnerability class of "very low" was absent in the PaPRIKa map, while the "low", "moderate", "high", and "very high" classes comprised 31.7, 48.7, 12.4, and 7.2 percent of the total region, respectively. Distribution of vulnerability classes within the spring catchments was also surveyed. Importantly, the catchment area of the largest spring, namely Sefidab, which has been supplying drinking water for almost one hundred thousand people in Amlash and Roudsar cities, was predominantly located in the "very high" vulnerability class, enclosing 368 sinkholes. Presence of *Escherichia Coli* in water emerging from all springs stressed the importance of enforcing strict regulations on the land use planning and conducting required treatments for drinking water supply. Moreover, since infiltration from precipitation and direct-runoff is substantial in the "high", and "very high" vulnerability zones, rainwater and floodwater harvesting may face serious technical challenges there. Hence, intrinsic vulnerability assessment in a karst region can be deserved as a basic criterion for the design of water harvesting systems.

Keywords: Vulnerability Mapping, Karst, Design of Water Harvesting Systems, Dorfak.

1. Introduction

Karst aquifers are regarded as highly anisotropic heterogeneous groundwater systems. Due to development of interconnected wide solutional pathways of fast groundwater flow, the self-cleaning capacity of the aquifers are generally low, and the groundwater resources (i.e. aquifer media) and sources (i.e. springs and abstraction wells) are very vulnerable to contamination. Thus, evaluation of groundwater vulnerability should be a vital part of land cover/use management and planning in karst regions.

Groundwater vulnerability assessments can be focused on either the resources or sources. Based on the origin-pathway-target conceptual model utilized by the

European Karst Action 620 (Zwahlen, 2004), the resource assessment takes only the vertical pathway from the earth surface to the targeted saturated zone (i.e. the resource) into account. While the source assessment considers the saturated horizontal pathways to the final targeted discharge points (i.e. the sources), as well. Considering the assessment strategies relevant to the contaminant characteristics, two classes of assessments can be differentiated, intrinsic and specific groundwater vulnerabilities. Intrinsic (or natural) groundwater vulnerability assessment is independent of the nature of contaminants and contamination scenario, taking geological, hydrological, hydrogeological, and climatological characteristics into account; while specific vulnerability assessment considers the characteristics of contaminant(s) together with the intrinsic groundwater vulnerability assessment (Zwahlen, 2004).

Groundwater vulnerability assessments with the aid of mapping methods provide plain tools for decision-makers to set the required land management regulations. Groundwater vulnerability mapping is aged back to the 1970s, starting with the Albinet and Margat (1970) work on the French territory. The methods have been progressively developed and applied since then, especially with the enhancements of the Geographical Information System (GIS) tools and techniques. However, incapability of leading methods to reproduce acceptable results in karst regions was noticed in the very early applications (e.g. Sendlein, 1992); because the methods have been originally adopted for classical alluvial aquifers, disregarding hydrogeological incongruities encountered in karst regions, with different recharge and flow mechanisms caused by the embedded preferential pathways.

Karst hydrogeological experts around the European countries have gathered in the frame of European COST Action 620 from 1997 to 2003, to establish a framework for karst groundwater vulnerability assessments (Zwahlen, 2004). Vulnerability mapping of karst catchments has been attracting lots of attention since then, and several methods have been devised, including DIVERSITY (Ray and O'dell, 1993), EPIK (Dörfliger and Zwahlen, 1995), REKS (Malik and Svasta, 1999), PI (Goldscheider et al., 2000), RISKE (Pételet-Giraud et al., 2000), VULK (Jeannin et al., 2001), KARSTIC (Davis et al., 2002), RISKE2 (Plagnes et al., 2005), VURAAS (Laimer, 2005), COP (Vías et al., 2006), Slovene Approach (Ravbar and Goldscheider, 2007), COP+K (Andreo et al., 2009), PaPRIKa (Kavouri et al., 2011), PRESK (Koutsi and Stournaras, 2011), DRISTPI (Jiménez-Madrid et al., 2013) and APLIE (Guo et al., 2016). Many of these methods have been developed within or inspired by, the COST Action 620. Moreover, Marín and Andreo (2015), Wachniew et al. (2016), and Iván et al. (2017) reviewed some of the methods, highlighting their differences and similarities.

Comparative application of groundwater vulnerability assessments in karst regions revealed that the results by the different methods can markedly differ (e.g. Marín et al., 2012; Moreno- Moreno-Gómez et al., 2018), because of method and user subjectivities, as well as site-dependency of results (Goldscheider, 2002; Marín et al., 2012). Hence, it has been suggested to perform different methods, and subsequently to choose between them by validating the outcomes i.e. maps (Ravbar and Goldscheider, 2009)

In this research, intrinsic groundwater resource vulnerability in a karst region located in the north of Iran was assessed, employing the COP and PaPRIKa methods in a comparative way. The methods have been receiving widespread acceptance among the karst community, though they have not been examined in the Middle East, so far. *Escherichia Coli* bacteria content in the water emerging from nine springs, during high- and low-flow conditions was utilized to validate and compare the results of vulnerability mappings.

2. Materials and Methods

2.1. Intrinsic vulnerability assessment of karst groundwater resources

- *COP method*

The COP method was aimed at the assessment of intrinsic resource vulnerability of carbonate aquifers (Vías et al., 2006). The method is comprised of three main factors, Concentration of flow (C), Overlaying layers (O), and Precipitation (P). Comprehensive instructions for the method application were effectively supplied by Vías et al. (2006), providing a thorough flow diagram. Therefore, a brief explanation of the method was just given here.

The O factor considers the protection of karst aquifer saturated zone, i.e. the karst groundwater resource, afforded by the overlying soil and unsaturated zone (Vías et al., 2006). The factor is comprised of two sub-factors for the soil (O_S) and lithology (O_L). The O_S takes the texture, grain size distribution and thickness of the overlying soil into account, and ranges from 0 to 5. The O_L is determined by the type of rock, degree of fracturing, rock layer thickness, and the aquifer confining conditions, ranging from 1 to 10. The final O score is quantified by adding O_S and O_L, and is discretized to five protection values ranging from "very low" to "very high".

The C and P factors are modifiers to the O factor, representing the potential for contaminants to bypass the protection provided by the former (Daly et al., 2002). The C factor has two scenarios, according to the existence or absence of concentrated recharge over the catchment. The first scenario is applicable to the swallow-hole recharge areas, requiring data on the swallow-hole locations, slope, and vegetation cover; while the second is relevant to the rest, i.e. the area with distributed recharge. The second scenario needs information on the surface karst features, surficial layer permeability, slope and vegetation cover. Final C score is ranging from 0 to 1, and is discretized to five reductions of protection classes ranging from "very high" to "very low".

The P factor is assessed by two sub-factors for the precipitation quantity (P_Q) and temporal distribution (P_I), which are determined for wet years when the annual precipitation exceeds the average by a factor of 1.15. Annual precipitation data and the number of rainy days are required to compute the sub-factors. The P_Q sub-factor was claimed to consider both the dilution and transfer processes for contaminants into account. The final P score ranges from 0.4 to 1, obtained by summing up the subfactors. The P score is also discretized to five reductions of protection classes ranging from "very low" to "very high".

The COP index value is determined by multiplying the factor scores, i.e.,

$$COP = C \times O \times P \tag{1}$$

The value can range from 0 to 15, and is discretized to five resource vulnerability classes from "very high" to "very low".

- *PaPRIKa method*

PaPRIKa is the French approach for assessment of karst aquifers resource and source intrinsic vulnerabilities, developed as an update to the EPIK (Dörfliger and Zwahlen, 1995), RISKE (Pételet- Giraud et al. 2000), and RISKE2 (Plagnes et al., 2005) methods. PaPRIKa stands for the Protection of the aquifer by means of four factors: Protectiveness, geological Reservoir, Infiltration, and Karstification degree. The factors are quantified as integer values that are individually multiplied by respective internal decimal weights of total unity. The weighted factors summed up to make the PaPRIKa index value, which is discretized to five vulnerability classes from "very low" to "very high". The classes are comparable to those of the COP's. Details of the PaPRIKa method were presented by Dörfliger and

Plagnes (2009) and Kavouri et al. (2011) providing relevant clarifying tables; hence a brief explanation was just provided here.
The P factor considers all surface and subsurface elements enabled to cause considerable delay to recharged water before reaching the saturated zone. In order to quantify the factor, the characteristics of sinking-stream catchment areas (Ca), soil (S), unsaturated zone (UZ), and epikarst (E) sub-factors have to be evaluated. The Ca sub-factor is only applicable to the sinking-stream catchment areas. Highly permeable sand and gravels are rated as one for the Ca, and marls and clays with very low permeability are rated as four. The rating of S sub-factors is dependent on the texture and thickness of soil cover, such that it can range from zero (e.g. for impervious formation outcrops) to four (e.g. for thin clayey soil or even thick sandy soil covers). The rating of UZ sub-factors is determined using the information on the thickness, lithology, and fracturing of the unsaturated zone, and it can range from zero (e.g. for a 15-meter thick clay with low to moderate fracturing) to four (e.g. for the zone of tectonic faults). The E sub-factor is assessed for an epikarst aquifer considering its hydrogeological functioning. The rating is ranged from one (e.g. for productive perched aquifers) to four (e.g. where the epikarst is absent). The final P index is a combination of all the described sub-factors, such that in each pixel of a P map, the highest value of all sub-factors (i.e. Ca, S, UZ, and E) is assigned, in order to evaluate the effectiveness of factor in the worst condition. The factor is discretized to five protection classes ranging from "very low" to "very high",

The R factor requires the lithology and degree of faulting/fracturing of aquifer saturated zone. This information can be obtained from geological maps/cross sections, observations, boreholes, and geophysical surveys. The rating of R factor is ranged from one (e.g. for low-developed karst aquifers with low fracturing) to four (e.g. for well-developed karst aquifers with drains and cavities, as well as fault zones, providing preferential flow pathways).
Two different I factor was proposed for PaPRIKa source or resource vulnerability assessments. The I factor for the resource vulnerability, $I_{resource}$, is of interest here and thus further described. $I_{resource}$, which is regarded as the main factor in the PaPRIKa, differentiates between concentrated and diffuse recharges. The factor evaluates the aquifer vulnerability as a result of bypassing the protective layers by both surface and subsurface flows. $I_{resource}$ factor requires data on slope percentage and karst features particular to concentrated recharge (i.e. sinkholes).

The Ka factor represents the karstification degree. The factor is estimable using the information on the catchment sizes, recharge types, karst networks, and flow velocities. Evaluation of the Ka factor, especially its spatial variation, is difficult, requiring an in-depth knowledge on aquifer functioning, through analysis of discharge and physicochemical time series, as well as tracer tests and field works. The classification of karst aquifers provided by Mangin (1975) was proposed to be utilized. If detailed data are not available, which is often the case, estimation of the Ka factor can be simplified (Kavouri et al., 2011). The rating of Ka factor is ranged from one (e.g. for catchments of smaller than 10 km^2, with low mean annual discharge and functionality and absence of fast groundwater flow indicators) to four (e.g. for water loss bearing catchments of any size; high hydrodynamic functionality and flow velocities).

PaPRIKa considers two groups of factors, for the aquifer structure and hydraulic functioning, such that P and R have belonged to the former, and the rest have relied on the latter. As it was mentioned, the PaPRIKa's factors are multiplied by some weights, then sum up to make the PaPRIKa's index.

$$PaPRIKa = pP + rR + iI + kKa \qquad (2)$$

Where p, r, i, and k are the relevant decimal weighting values attributed to the P, R, I, and Ka factors, respectively. The weighting values are empirically distributed based on the expert judgment, with a rule that the aquifer hydraulic functioning factors (i.e. I and Ka) gain more importance with a sum weight of 0.5 to 0.65. Different combination of weighting schemes has to be tested. The weighting tests gave more confidence in the determination of the priority zones where the catchment protection should be highest (Kavouri et al., 2011). PaPRIKa makes a simple conceptual model of karst aquifer that can be integrated into a distributed parameter flow model (e.g. Kavouri et al., 2017).

2.2. Case study: Dorfak Karst Region

Dorfak karst region covers ~512.8 km^2 mountainous area of the Astaneh-Kuchesfan coastal catchment, ~50 km away of the Caspian Sea (Fig. 1). Kardan Moghaddam et al. (2017) evaluated the vulnerability of the coastal alluvial aquifer to the seawater intrusion by a comparative study of GALDIT (Chachadi and Lobo-Ferreira, 2001) and DRASTIC (Aller, 1985) vulnerability assessment methods. The current study would just focus on the Dorfak karst region, hence a brief explanation of the geological and hydrogeological settings was given in the following.

- Geological and Hydrogeological settings

Dorfak karst region is located in the Western part of Alborz Mountains. Stratigraphy, lithology, and tectonic settings of the Alborz lithostratigraphic units were fairly well reviewed by Stöcklin and Setudehnia (1971), Stöcklin (1974), and Alavi (1996). Annells et al. (1975) and Ghalamghash et al. (2003) prepared the 1:250000 and 1:100000 scale geological map/sections encompassing the study area, respectively.

Field studies were carried out to improve the knowledge on local geological information, adopting a karst hydrogeological perspective. Characteristics of bedding, fracture, and fault planes, as well as karst features, were investigated all over the region. Fig. (1) presents the geological map of the study area, including lithological information of different lithostratigraphic units. K1-1, medium-bedded to massive limestone, is the most karstified formation. Due to the favorable tectonic setting and suitable climatic condition, karstification was also active in the K2-1, JK1, JKms, El, K1-v and Kc formations, while their members are not entirely made of limestone. The TRc-l formation, which is comprised of karstifiable dolomitic limestone in the upper part, is evidently covered by the TRJs-sh unit.

The karst features of the study area are sinkholes, caves, grikes, Karren-fields, and springs. The most important karst feature is the presence of 516 sinkholes, which are predominantly distributed alongside local tectonic patterns and geological contacts. Many of the sinkholes seemed to be connected to the subsurface conduit networks. Location and sizing of sinkholes were individually surveyed in the field studies. Accordingly, depths of the sinkholes are ranging from ~0.5 to ~150 meters, and their average diameters are ranging from ~0.5 to ~625 meters. The catchment areas of the springs were determined to combine information on groundwater balance, geology, topography, and water stable isotopes (Water Research Institute, 2016; see Fig. 1).

Table (1) presents the characteristics of nine springs emerging in the region, among them Sefidab (Sp1) is the largest. The table presents the discharges (maximum and minimum), major ions, and *E. Coli* content of water emerging from the springs. *E. coli* was observed in all springs, at-least during a high- or low-flow condition (Table 1 & Fig. 2). The presence of *E. coli* in spring water is commonly served as a strong indication of recent contamination by animal wastes.

The region, with a humid temperate climate, is predominantly covered by jungles, which are more abundant in the northern half. Natural pastures comprise almost one-fifth of the region between the jungles and bare limestone, frequently used for grazing livestock. The low altitude lands with gentle slopes are mainly covered with the quaternary alluviums, generally utilized for agricultural purposes. Dorfak peak with a 2720 m height is the highest point of the area.

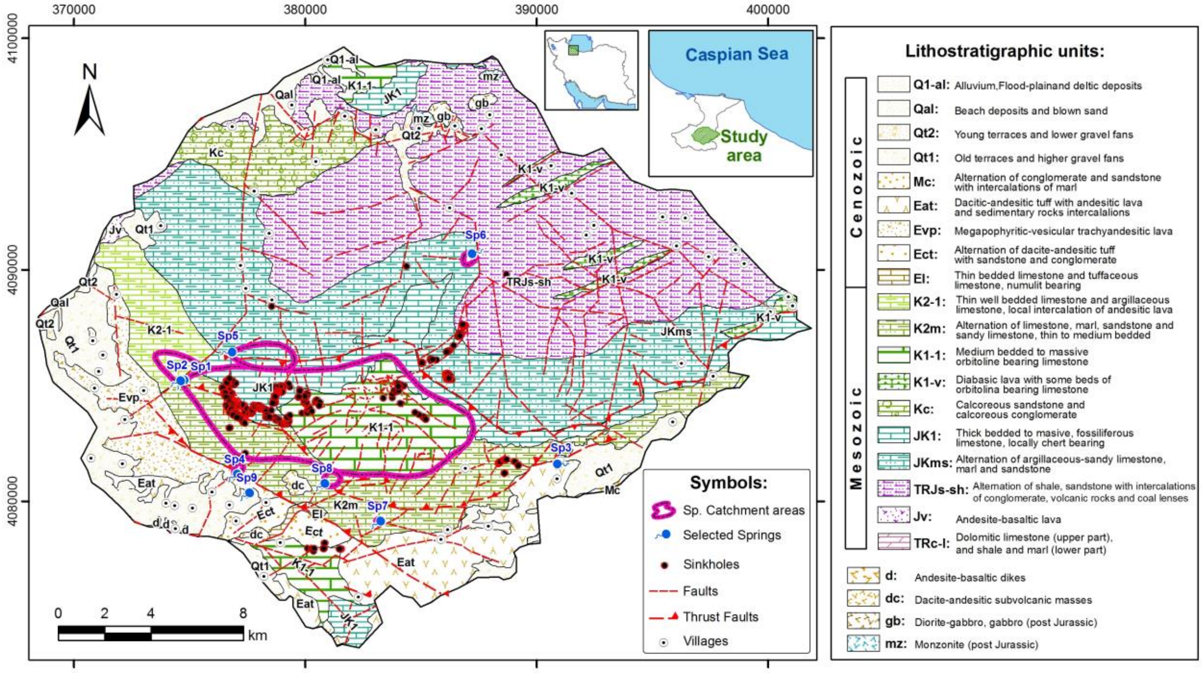

Fig. 1. Geological map of the study area; Location of sinkholes and approximate catchment boundaries of the springs were indicated

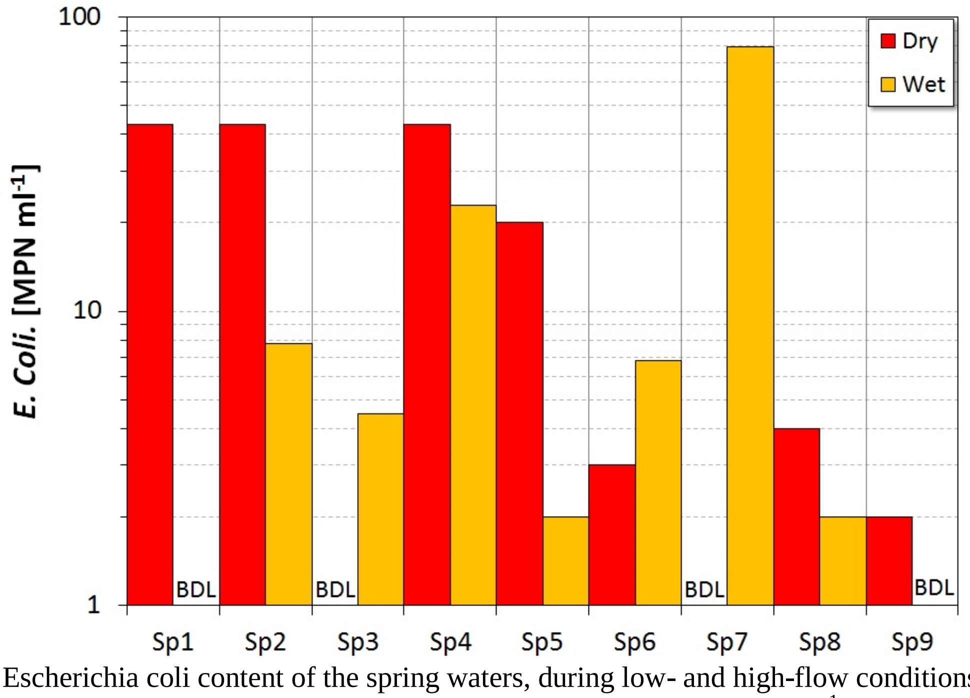

Fig. 2. Escherichia coli content of the spring waters, during low- and high-flow conditions. BDL stands for the below detection limit, which was 1.8 MPN dl^{-1}.

Table 1. Major ions and microbial content of some selected springs around the study area, during low- and high-flow conditions. The low- and high-flow conditions were corresponded to late August and mid-April, respectively. Detection limit for the *E. Coli* was 1.8 MPN dl^{-1}.

No.	Name	Code	Z [masl]	Q_{max} [l s^{-1}]	Q_{min} [l s^{-1}]	Sampling Date	Major ions [meq l^{-1}] NO_3^-	HCO_3^-	F^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	Charge Balance Error [%]	EC [µS cm^{-1}]	pH [-]	*E. Coli* [MPN dl^{-1}]
1	Sefidab	Sp1	384	1855.0	65.0	2014/08/20	0.104	2.428	0.001	0.038	0.095	0.062	0.063	2.351	0.246	0.93	220	7.9	43.0
						2015/04/11	0.130	2.208	0.002	0.094	0.084	0.050	0.003	2.416	0.257	3.99	236	7.6	<1.8
2	Pol-e Ahaki	Sp2	335	74.0	0.2	2014/08/20	0.069	4.209	0.005	0.046	0.137	0.117	0.029	3.586	0.436	3.47	441	7.5	43.0
						2015/04/11	0.080	4.072	0.004	0.301	0.364	0.076	0.010	4.823	0.296	3.82	474	7.5	7.8
3	Espahbadan	Sp3	1798	0.7	0.1	2014/08/25	0.172	2.299	0.009	0.060	0.118	0.937	0.037	1.376	0.422	2.03	230	6.9	<1.8
						2015/04/13	0.154	2.065	0.009	0.076	0.128	0.672	0.015	1.588	0.258	2.04	244	7.8	4.5
4	Rajeun	Sp4	657	4.0	0.5	2014/08/20	0.015	4.533	0.007	0.080	0.218	0.386	0.036	3.773	0.754	1.02	448	6.5	43.0
						2015/04/12	0.060	3.962	0.007	0.158	0.175	0.283	0.019	3.549	0.918	4.46	426	7.5	23.0
5	Korde-mir	Sp5	558	50.0	6.0	2014/08/21	0.048	2.687	0.006	0.020	0.151	0.170	0.013	2.490	0.170	1.22	244	7.0	20.0
						2015/04/15	0.037	2.428	0.003	0.130	0.087	0.108	0.082	2.080	0.440	0.46	236	7.7	2.0
6	Sardab-khani	Sp6	362	6.0	1.0	2014/08/22	0.084	3.335	0.005	0.038	0.147	0.188	0.047	3.435	0.264	4.24	368	7.1	3.0
						2015/04/17	0.062	3.360	0.009	0.069	0.128	0.127	0.014	2.980	0.494	0.16	340	7.4	6.8
7	Kalami	Sp7	1113	0.5	0.1	2014/08/24	0.014	4.857	0.008	0.081	0.136	0.195	0.023	4.626	0.732	4.49	475	6.2	<1.8
						2015/04/14	0.015	4.532	0.007	0.100	0.227	0.118	0.015	4.683	0.446	3.76	511	7.0	79.0
8	Mir-hoseyni	Sp8	951	7.0	2.0	2014/08/26	0.049	3.963	0.004	0.199	0.415	0.182	0.020	4.425	0.429	4.44	427	6.4	4.0
						2015/04/12	0.082	4.344	0.003	0.062	0.183	0.089	0.016	4.495	0.272	2.07	463	7.7	2.0
9	Estakhrgah	Sp9	634	0.3	0.1	2014/08/26	0.219	4.300	0.010	0.125	0.148	0.529	0.031	3.056	1.375	1.94	440	6.9	2.0
						2015/04/12	0.355	4.046	0.012	0.253	0.228	0.363	0.028	4.054	0.917	4.55	501	7.4	<1.8

3. Results and discussion

- COP

The COP index was determined over the catchment, based on the guidelines issued by the Vías et al. (2006). Calculation procedure and results are presented in the following.

The O factor was quantified based on the data and knowledge about the geology, soil cover, and land use. Field observations were utilized to check for data consistency. It should be pointed out that there is no direct information on the deep geological layers since there is no well drilled in the catchment. However, the formation of outcrops and regional geological maps (Ghalamghash et al., 2003) could help to estimate the local thickness, lithology, fracturing, and karst development conditions of the lithostratigraphic units. The O_S was ranging from zero (for bare rocky outcrops) to four (for thick silty soil covers), while the O_L was ranging from one (for the thin karstified unsaturated zone) to five (for an unsaturated zone with thick low conductive rocks). No confining conditions were considered over the catchment, though it could be the case for the TRc-l karstic formation, beneath the TRJs-sh low-conductive formation. Since there is no information on the aquifer condition within the TRc-l formation, the decision was made ensuring safety reasons. The overall O score was ranged from one to nine, comprising all protection classes from "very low" to "very high", such that the "high" protection class was the most abundant (Fig. 3).

The C score was calculated based on both scenarios. The sinkhole recharge area was considered for the first scenario, and the rest for the second. The slope was extracted from the digital elevation model (DEM), and the vegetation cover was estimated using land-use map and validated by remote sensing and field studies. There were 516 sinkholes within the swallow-hole recharge area. The condition of surface layers and karstic features were determined based on the field observations. The final C score was ranging from zero to one and 0.23 to one, for the areas of first and the second scenarios, respectively. In other words, the reduction of protection by the C factor was ranged from "very high" to "very low" and "high" to "very low", for the areas of first and the second scenarios, respectively (Fig. 3). It should be pointed out that the COP does not account for the characteristics of swallow-holes, treating all of them identically, in the first scenario of the C factor.

The P factor was assessed using a 20-year precipitation data at six gauging stations within and proximate to the catchment boundaries. Surprisingly, only three wet hydrological years could be found and be used. The wet hydrological years have considered as the years when the annual precipitation exceeding the average by a factor of 1.15, at least in three stations. Multilinear-regression (MLR) model was used to estimate the spatial distribution of P_Q over the catchment. The model has been previously utilized for mountainous regions (e.g. Marquínez et al., 2003; Naoum and Tsanis, 2004; Um, 2010; Kavousi and Raeisi, 2016). Average cumulative precipitation of wet years and geographical position (altitude Z, latitude X, and longitude Y) of the stations were served as response and predictor variables, respectively. Adjusted R^2, which is an indicator of the explanatory power of models, was near 1, showing the goodness of estimation. The P_Q value has all three classes of 0.2, 0.3, and 0.4, comprising the effects of both dilution and fast transfer processes, for the potential contaminants. The Pasikhan station in the northern part of the region was considered as the representative station for the number of rainy days during wet years. The average value of the parameter was 102.7 days, at the station. The computed P_I has two classes of 0.4, and 0.6. The overall P score has ranged between 0.6 and one, such that the "very high" class of protection reduction was not noticed over the

catchment, though the other classes were almost equally distributed (Fig. 3).
The overall COP index over the catchment was ranged from the zero to 8.1, comprising all vulnerability classes from the "very low" to "very high". The "high" and "low" vulnerability classes are the least and the most abundant, respectively; while 15.4% of the area is comprised of the very high vulnerability class (Fig. 3).

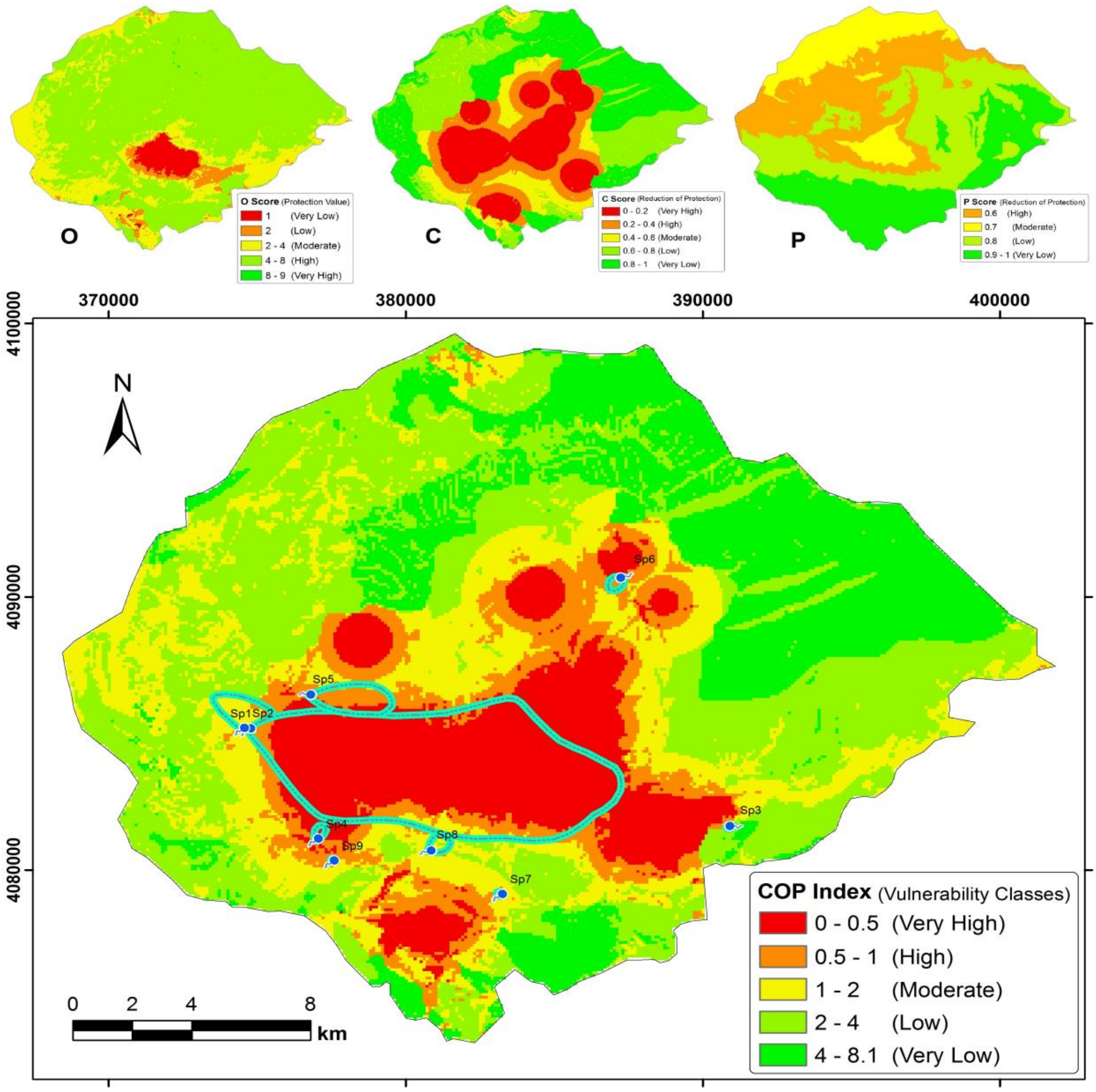

Fig. 3. COP groundwater vulnerability map of the Dorfak karst region. Individual factor maps are also included. Location of springs and their approximate catchment boundaries were indicated.

- *PaPRIKa*

The PaPRIKa index was assessed over the Dorfak catchment, following the instruction given by the Dörfliger and Plagnes (2009) and Kavouri et al. (2011). Calculation procedure and results are provided in the following.

The P factor was evaluated by three sub-factors on soil (S), unsaturated zone (UZ), and epikarst (E) characteristics, utilizing data on soil cover, geology, and epikarst over the catchment. The Ca sub-factor was not applicable, since there was no sinking-stream noticed. Information gathered from the field observations were employed in cross-checking. The S sub-factor was determined based on the data on soil cover characteristics, ranged from zero (for bare impervious formation outcrops) to four (for bare karstic limestone outcrops and loamy thin soil covers). The UZ sub-factor was determined based on the data on the unsaturated zone lithology, thickness, and fracturing degree. For this reason, spatial data on geological layers, outcrops, springs, main valleys, tectonic faults, and fractures were utilized. The UZ sub-factor was ranging from zero (for thick layers of shale and impermeable rock outcrops with low to moderate or even significant fracturing) to four (for tectonic fault zones). The E sub-factor was estimated using field observations, as well as hydrogeological measurements and principals. Dorfak region is located in the north of Alborz Mountain range of Iran, in a humid temperate climate zone, where the epikarst zone was developed throughout the catchment. The sub-factor has two indices of two and three over the region. The overall P score was determined to combine all its sub-factors, such that the highest vulnerability index by any sub-factors were assigned to the P factor. The P index was ranged from two to four, i.e. from moderate to very high vulnerability classes; such that the moderate vulnerability class was the most abundant (Fig. 4).

The R factor was determined from the available geological data and outcrop observations. The R index was ranged from one to four, i.e. from low to very high vulnerability classes; such that the moderate vulnerability class was by far the most abundant (Fig. 4).

The $I_{resource}$ factor was determined using DEM and field observations. The $I_{resource}$ index ranged from zero to four, i.e. from low to very high vulnerability classes; such that the moderate vulnerability class was most abundant (Fig. 4).

A detailed database on hydrodynamic functioning of aquifers within the study area is not available; therefore, a simplified method was applied to estimate the Ka factor, using the relevant table provided by Kavouri et al. (2011). Accordingly, the sinkhole areas with obvious water loss were considered as index four (i.e. the class "very high" of vulnerability). Water loss is evident in almost half of the Sefidab Spring catchment; therefore, the catchment was spatially divided into two parts with different Ka indices. The portion of the catchment with distinctive water loss was indexed as four (i.e. the class "very high" of vulnerability), and the portion of catchment without water loss were indexed as three (i.e. the class "high" of vulnerability) because the catchment area was larger than 10 km^2 (almost 21.6 km^2) and the aquifer shows high level of hydrodynamic functionality. The rest of study area, which comprises small catchments of minor springs (with few liters per second discharges) and low variability of physicochemical parameters, were considered as index one (i.e. the class "low" of vulnerability). Fig. 4 shows the spatial distribution of Ka factor over the catchment.

Different weighting combinations of PaPRIKa factors were tested, considering the general rule of weighting for aquifer structure and hydraulic functioning. It was noticed that the area with index four (i.e. "very high" vulnerability class) was almost identical in all the combinations. The combination of 0.2P+0.2R+0.4I+0.2Ka was the finally accepted, which was also usually retained in PaPRIKa's test and application sites (e.g. Dörfliger and Plagnes, 2009; Kavouri et al., 2011; Marín et al., 2012; Huneau et al., 2013). The overall PaPRIKa index over the catchment was ranged from 0.8 to 4, comprising vulnerability classes from the "low" to "very high". The "very high" and "moderate" vulnerability classes are the least and the most abundant, respectively, while the very low class was absent and the very high class comprised 7.2 percent of the area (Fig. 4).

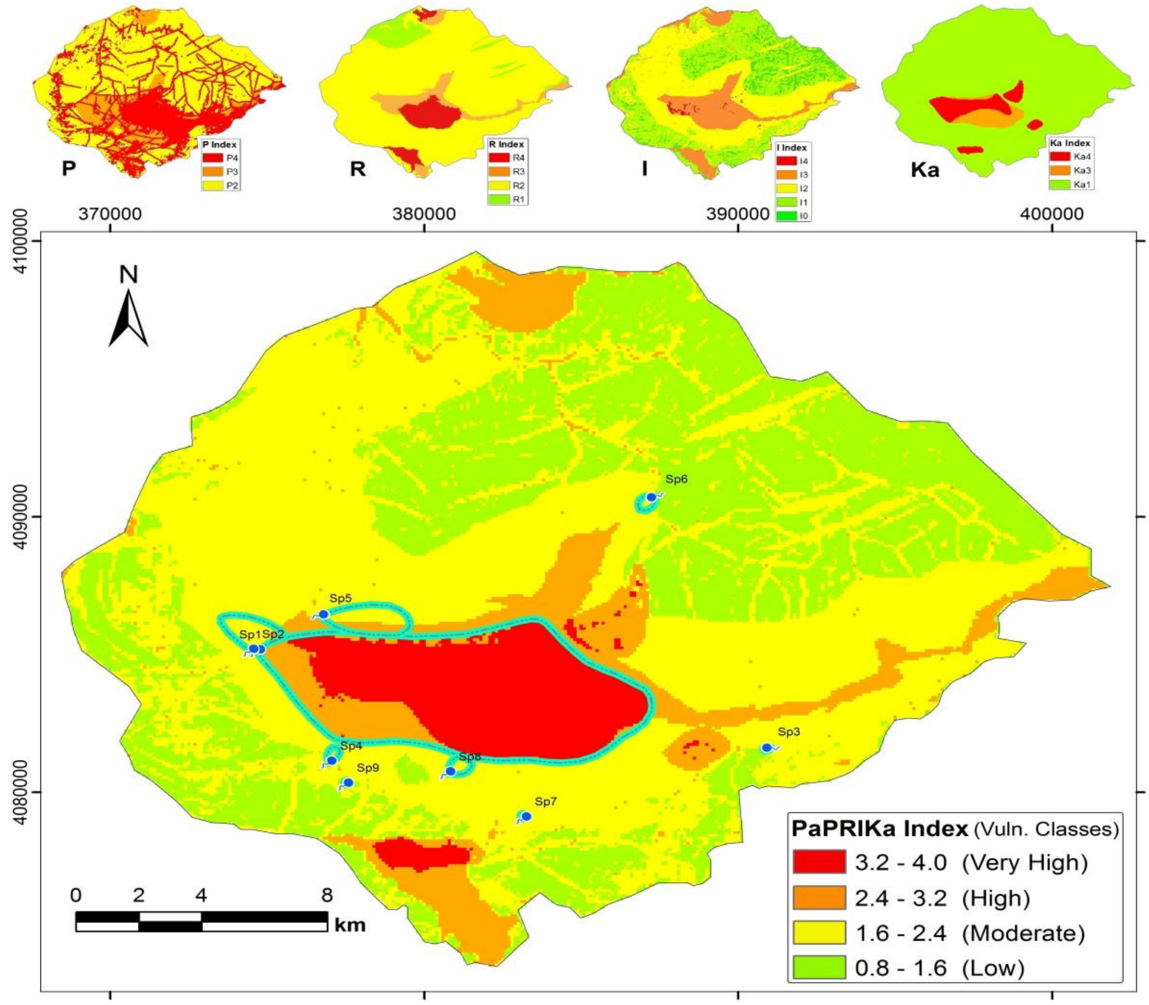

Fig. 4. PaPRIKa groundwater vulnerability map of the Dorfak karst region. Individual factor maps are also included. Location of springs and their approximate catchment boundaries were indicated.

- *Comparison and validation*

Fig. (5) shows the distribution of COP and PaPRIKa vulnerability classes over the whole study area, providing an easy tool to compare the distribution of different vulnerability classes. The discrepancy between COP and PaPRIKa resource vulnerability maps was evident even with visual comparison (compare Fig. 3 and 4). Absence of "very low" vulnerability class in the PaPRIKa map was the most noticeable difference. Nearly half of the PaPRIKa map was covered by the "moderate" vulnerability class, while the "low" vulnerability class was the most abundant in the COP, accounting for almost one-third of the study area.

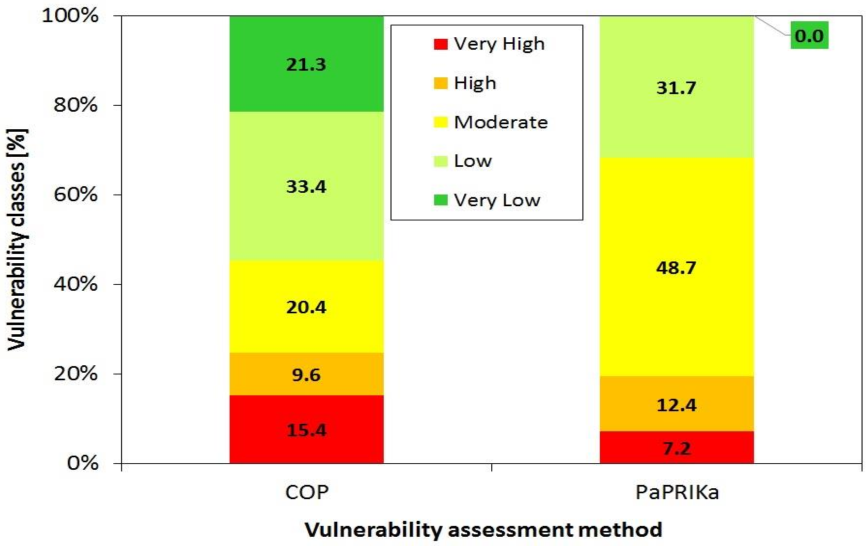

Fig. 5. Distribution of vulnerability classes over the Dorfak karst region.

The global vulnerability parameter, which is defined as the weighted average of vulnerability classes (Vías et al., 2010), was not here utilized for comparison of COP and PaPRIKa results, because the classes of vulnerability are the discretized version of the indices. Weighted averaging the original index values would be more reasonable for comparison purposes; though the resultant mean index values are not directly comparable, needs to be discretized to the mean classes, before the comparison.

The mean (i.e. weighted average) of vulnerability indices for COP and PaPRIKa were 2.42 and 1.92, respectively; such that the mean vulnerability indices corresponded to the "low" and "moderate" vulnerability classes, respectively. Therefore, while the "very high" vulnerability class was more abundant in the COP map than that of the PaPRIKa's, the former offered a more vulnerable region, on average.

Table (2) presents the min, max, and mean index values of COP and PaPRIKa encountered within the catchment area of nine selected springs. The color of each table cell represents the vulnerability class corresponded to the relevant index value. The vulnerability classes of all provided descriptive statistical measures were the same in both methods, only for Sp3 and Sp7; moreover, the mean vulnerability classes were the same for Sp1, Sp2, and Sp8.

Table 2. Comparison of the PaPRIKa and COP index values, encountered in the spring catchments. Cell colors represent the vulnerability classes by the relevant method.

Spring code	PaPRIKa index values within the catchment			COP index values within the catchment		
	Min	Max	Mean	Max	Min	Mean
Sp1	2.00	4.00	3.26	2.04	0.00	0.21
Sp2	1.80	3.00	1.96	2.03	0.51	1.19
Sp3	1.40	1.40	1.40	3.80	3.80	3.80
Sp4	1.80	2.20	2.09	0.51	0.20	0.30
Sp5	1.80	3.20	2.25	1.22	0.23	0.60
Sp6	1.40	2.20	1.83	0.82	0.41	0.74
Sp7	2.00	2.00	2.00	1.28	1.15	1.22
Sp8	2.00	2.20	2.12	2.14	0.92	1.61
Sp9	1.40	1.40	1.40	0.77	0.77	0.77

Vuln. Classes
Very low
Low
Moderate
High
Very high

In order to check the validity of COP and PaPRIKa results, their mean index values were correlated with measured *E. Coli* content of the spring water (Table 3). Accordingly, the achieved Pearson correlation coefficients for the low flow condition were higher for the PaPRIKa, highlighting the more reasonability of the method. Moreover, the correlation for the high-flow was very weak for both COP and PaPRIKa methods (e.g., the correlation coefficient was below 0.3); which may be resulted from the fact that different mechanisms are responsible for the variation of *E. Coli* during high-flows.

Table 3. Pearson correlation coefficient between *E. coli* contents of spring waters and the mean index values by the PaPRIKa and COP methods, encountered in the spring catchment.

	Mean index values	
E. coli	**PaPRIKa**	**COP**
Low flow	0.62	-0.49
High flow	-0.04	-0.04

4. Conclusion

Several methods have been adopted for vulnerability assessment of karst aquifers. Due to the site-dependency of results and subjectivity inherited by the developers pursued by the employers of the methods, comparative application of vulnerability assessments is very meaningful. Intrinsic resource vulnerability of the Dorfak karst region wa assessed with the COP and PaPRIKa methods. The vulnerability maps presented here were prepared for the resource (i.e. groundwater), using the available database on the catchment, as well as field observations and measurements. The PaPRIKa results presented a closer matching with the current knowledge on the catchment characteristics; therefore, the PaPRIKa map was proposed to be adopted for the land use management policies. According to the PaPRIKa results, almost one-third of the region was just classed as "low" in terms of vulnerability, whereas one-half and one-fifth of the region are classed as the "moderate" and "high + very high". It should be pointed out the catchment area of Sefidab Spring, which has been supplying drinking water for almost one hundred thousand people in Amlash and Roudsar cities, was mainly located in the "very high" vulnerability class, enclosing 368 sinkholes. Presence of *Escherichia Coli* in water emerging from all springs emphasized the importance of enforcing strict regulations on land use planning and performing required treatments for drinking water supply. Furthermore, since infiltration from precipitation and direct-runoff is generally significant in the "high", and "very high" vulnerability zones, implementation and maintenance of rainwater and floodwater harvesting systems may face serious technical challenges in these zones. Hence, intrinsic vulnerability assessment in a karst region can be indirectly applied as a basic criterion for the design of water harvesting systems.

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5. References

Alavi, M. (1996). Tectonostratigraphic synthesis and structural style of the Alborz mountain system in northern Iran. *Journal of Geodynamics*, 21(1):1-33.

Albinet, M., & Margat, J. (1970). Cartographie de la vulnerabilite a la pollution des nappes d’eau souterraine. *Bull. BRGM 2ème série*, 3(4):13-22.

Aller, L. (1985). *DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings*. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

Andreo, B., Ravbar, N., & Vías, J. M. (2009). Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: application to pilot sites. *Hydrogeology Journal*, 17(3):749-758.

Annells, R. N., Arthurton, R. S., Bazley, R. A., & Davies, R. G. (1975). Explanatory text of the Qazvin and Rasht quadrangles map 1:250000. *Geological Society of Iran, E3 and E4*, 94 p.

Chachadi, A. G., & Lobo-Ferreira, J. P. (2001). Seawater intrusion vulnerability mapping of aquifers using GALDIT method. *Coastin—A Coastal Policy Res News*, 4:7-9.

Daly, D., Dassargues, A., Drew, D., Dunne, S., Goldscheider, N., Neale, S., Popescu, I., & Zwahlen, F. (2002). Main concepts of the" European approach" to karst-groundwater-vulnerability assessment and mapping. *Hydrogeology Journal*, 10(2):340-345.

Davis, A. D., Long, A. J., & Wireman, M. (2002). KARSTIC: A sensitivity method for carbonate aquifers in karst terrain. *Environmental Geology*, 42:65–72.

Dörfliger, N., & Plagnes, V. (2009). Cartographie de la vulnérabilité des aquifères karstiques guide méthodologique de la méthode PaPRIKa [Mapping the vulnerability of karst aquifers. Guidelines of the method PAPRIKa]. *Rapport BRGM RP-57527-FR, BRGM, Orleans, France*, 100 pp.

Dörfliger, N., & Zwahlen, F. (1995). EPIK: a new method for outlining of protected areas in a karst environment. *In*: Günay, G., & Johnson, I. (eds.) *Proceedings 5th International symposium and field seminar on karst waters and environmental impacts*, Antalya, Sep 1995, Balkema, Rotterdam, p 117–123.

Ghalamghash, J., Rashid, H., & Mehrparto, M. (2003). *Geological Map of Jirandeh (1:100000).* Geological Survey of Iran, Tehran, Iran.

Goldscheider, N. (2002). *Hydrogeology and vulnerability of karst systems – examples from the Northern Alps and Swabian Alb.* Dissertation Universität Karlsruhe, Fakultät für Bio- und Geowissenschaften, Germany.

Goldscheider, N., Klute, M., Sturm, S., & Hötzl, H. (2000). The PI method: a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. *Z Angew Geol.*, 463: 157–166.

Huneau, F., Jaunat, J., Kavouri, K., Plagnes, V., Rey, F., & Dörfliger, N. (2013). Intrinsic vulnerability mapping for small mountainous karst aquifers, implementation of the new PaPRIKa method to Western Pyrenees (France). *Engineering Geology,* 161:81–93.

Guo, Y., Zhai, Y., Wu, Q., Teng, Y., Jiang, G., Wang, J., Guo, F., Tang, Q., & Liu, S. (2016). Proposed APLIE method for groundwater vulnerability assessment in the karst-phreatic aquifer, Shandong Province, China: a case study. *Environmental Earth Sciences*, 75(2):1-14.

Iván, V., & Mádl-Szőnyi, J. (2017). State of the art of karst vulnerability assessment: overview, evaluation, and outlook. *Environmental Earth Sciences*, *76*(3), 112.

Jeannin, P. Y., Cornaton, F., Zwahlen, F., & Perrochet, P. (2001). VULK: a tool for intrinsic vulnerability assessment and validation. *Sciences et techniques de l'environnement*, *Mémoire hors-série*, 185-190.

Jiménez-Madrid, A., Carrasco, F., Martínez, C., & Gogu, R. C. (2013). DRISTPI, a new groundwater vulnerability mapping method for use in karstic and non-karstic aquifers. *Quarterly Journal of Engineering Geology and Hydrogeology*, 46(2):245-255.

Kardan Moghaddam, H., Jafari, F., & Javadi, S. (2017). Evaluation vulnerability of coastal aquifer via GALDIT model and comparison with DRASTIC index using quality parameters. *Hydrological Sciences Journal*, 62(1):137-146.

Kavouri, K. P., Plagnes, V., Tremoulet, J., Dörfliger, N., Rejiba, F., & Marchet, P. (2011). PaPRIKa: a method for estimating karst resource and source vulnerability—application to the Ouysse karst system (southwest France). *Hydrogeology Journal,* 19(2):339-353.

Kavouri, K. P., Karatzas, G. P., & Plagnes, V. (2017). A coupled groundwater-flow-modeling and vulnerability-mapping methodology for karstic terrain management. *Hydrogeology Journal*, DOI: 10.1007/s10040-017-1548-6.

Kavousi, A., & Raeisi, E. (2016). A new method to estimate annual and event-based recharge coefficient in karst aquifers; case study: Sheshpeer karst aquifer, south-central Iran. *Journal of Cave and Karst Studies*, DOI: 10.4311/2015ES0139.

Koutsi, R., & Stournaras, G. (2011). Groundwater vulnerability assessment in the Loussi polje area, N Peloponessus: the PRESK method. *In*: Lambrakis, N., Stournaras, G., & Katsanou, K., (eds.) *Advances in the Research of Aquatic Environment*. Springer, Berlin, Heidelberg. p 335-342.

Laimer, H. J. (2005). Die Erfassung der Karstgrundwasser-Vulnerabilität mit der Methode "VURAAS", *Grundwasser*, 10(3):167-176.

Malik, P., & Svasta, J. (1999). REKS—An alternative method of karst groundwater vulnerability estimation, Hydrogeology, and land use management. *Proceedings of the XXIX Congress of the International Association of Hydrogeologists*, Bratislava, 79–85.

Mangin, A. (1975). *Contribution à l'étude hydrodynamique des aquifères karstiques*. Thesis, Université de Dijon, 422 pp.

Marín, A. I., & Andreo, B. (2015). Vulnerability to Contamination of Karst Aquifers. *In*: Stevanovic, Z. (eds.) *Karst Aquifers—Characterization and Engineering*. Springer. p 251-266.

Marín, A. I., Dörfliger, N., & Andreo, B. (2012). Comparative application of two methods (COP and PaPRIKa) for groundwater vulnerability mapping in Mediterranean karst aquifers (France and Spain). *Environmental Earth Sciences*, 65(8):2407-2421.

Marquínez, J., Lastra, J., García, P. (2003). Estimation models for precipitation in mountainous regions: the use of GIS and multivariate analysis. *Journal of Hydrology*, 270(1):1–11. DOI: 10.1016/S0022-1694(02)00110-5.

Moreno-Gómez, M., Pacheco, J., Liedl, R., & Stefan, C. (2018). Evaluating the applicability of European karst vulnerability assessment methods to the Yucatan karst, Mexico. *Environmental Earth Sciences*, *77*(19), 682.

Naoum, S., & Tsanis, I. K. (2004). Orographic precipitation modeling with multiple linear regression. *Journal of Hydrologic Engineering*, 9:79–102. DOI: 10.1061/(ASCE)1084-0699(2004)9:2(79).

Pételet-Giraud E, Dörfliger N, Crochet P (2000) RISKE: Méthode d'évaluation multicritère de la vulnérabilité des aquifères karstiques. Application aux systèmes des Fontanilles et Cent-Fonts (Hérault, Sud de la France). Hydrogéologie. 4:71-88.

Plagnes, V., Théry, S., Fontaine, L., Bakalowicz, M., & Dörfliger, N. (2005). Karst vulnerability mapping: improvement of the RISKE method. *KARST 2005, Water Resources and Environmental Problems in Karst*, Belgrade-Kotor, Serbia.

Ravbar, N., & Goldscheider, N. (2007). The proposed methodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Slovenia. *Acta carsologica*, 36(6):397-411.

Ravbar, N., & Goldscheider, N. (2009). Comparative application of four methods of groundwater vulnerability mapping in a Slovene karst catchment. *Hydrogeology Journal*, 17(3):725-733

Ray, J. A., & O'dell, P. W. (1993). DIVERSITY: a new method for evaluating the sensitivity of groundwater to contamination. *Environmental Geology*, 22(4):345-352.

Sendlein, L. V. A. (1992). Analysis of DRASTIC and wellhead protection methods applied to karst terrain, In Quinlan, J. (ed.) *Proceedings of the Third Conference on Hydrology, Ecology, Monitoring, and Management of Groundwater in Karst Terrains*. National Groundwater Association. p 669-685.

Stöcklin, J. (1974). Northern Iran: Alborz Mountains. *Geological Society London, Special Publications*, 4(1):213-234.

Stöcklin, J., & Setudehnia, A. (1971). Stratigraphic lexicon of Iran: Part 1, Central, North, and East Iran. *Geology Survey of Iran*, *report 18*, 370 p.

Um, M. J., Yun, H., Cho, W., & Heo, J.H. (2010). Analysis of orographic precipitation on Jeju-island using regional frequency analysis and regression. *Water resources management*, 24(7): 1461-1487. DOI: 10.1007/s11269-009-9509-z.

Vías, J. M., Andreo, B., Perles, M.J., Carrasco, F., Vadillo, I., & Jiménez, P. (2006). The proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. *Hydrogeology Journal*, 14(6):912-925.

Vías, J., Andreo, B., Ravbar, N., & Hötzl, H. (2010). Mapping the vulnerability of groundwater to the contamination of four carbonate aquifers in Europe. *Journal of* *environmental management*, 91(7), 1500-1510.

Wachniew, P., Zurek, A. J., Stumpp, C., Gemitzi, A., Gargini, A., Filippini, M., Rozanski, K., Meeks, J., Kværner, J., & Witczak, S. (2016). Towards Operational Methods for the Assessment of Intrinsic Groundwater Vulnerability: A review. *Critical Reviews in Environmental Science and Technology*. 46(9):827-884. DOI: 10.1080/10643389.2016.1160816.

Water Research Institute. (2016). Investigation of Dorfak karst region, Bijar Watershed, North of Iran: *Final report, Guilan Regional Water Authority Company, Rasht, Iran.*

Zwahlen, F. (2004). Cost Action 620. Vulnerability and Risk Mapping for the Protection of Carbonate (Karstic) Aquifers: *Final report. Office for Official Publications of the European Communities.*