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Selecting wells for an optimal design of groundwater monitoring network based on monitoring priority map: A Kish Island case study

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a novel approach, i.e. a combination of gamma test and monitoring priority map, for optimal design of groundwater monitoring network (GMN) by considering the cumulative effects of industries, human activities, and natural factors on the groundwater quality. The proposed method was successfully applied to design an optimal network for groundwater salinity monitoring on Kish Island, Persian Gulf. The priority map of groundwater salinity monitoring was obtained based on the GALDIT index and two new factors including the average fluctuation of groundwater electrical conductivity (F) and distance from industries discharging saline effluents (P). The optimal number of monitoring wells was determined using a data analysis based on gamma test method. Then, a practical algorithm was presented to determine the optimal location of monitoring wells. Based on the results, the optimal number of monitoring wells is 110 and their location have an equitable distribution on the whole island.

1. Introduction

Industry, human activities, and natural factors have destructive impacts on the groundwater quality, requiring the continuous monitoring of groundwater quality especially for coastal arid and semi-arid regions, as well as small islands where groundwater and desalinated water are the main sources of water supply due to the lack of freshwater. Here, optimal design of GMN is a crucial step in sustainable groundwater management and at the same time a significant challenge for specialists. A GMN will be optimal if it provides relatively accurate information about the actual groundwater condition with the minimum number of monitoring wells.

GMN can be optimized by methods such as entropy theory, genetic algorithms, machine learning, as well as MSANOS software- most of them require a large number of monitoring data and they are very time-consuming [1,2]. In other words, in these

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methods, the more data there is, the more accurate the optimization result will be. Literature indicates that these methods are highly efficient unless there is a limitation of the monitoring data number. However, the problem with these methods is that sometimes the optimization results of these methods indicate that the number and location of selected monitoring wells are inappropriate [3,4]. In this situation, despite spending a lot of time and money, the collected data give a rudimentary understanding of groundwater quality. Furthermore, these methods are incapable of determining the optimal number of monitoring stations, and consequently, this number is often selected empirically or based on available data and related budget constraint.

Another method for optimal design of the monitoring network, requiring less monitoring data, is to apply a monitoring priority map, indicating the most important areas to monitor. In this method, geographic information system is used to generate various spatial data layers of factors which have significant effects on groundwater quality. Then, a spatial multicriteria decision is developed to obtain the weights of the factors, overlay the data layers, and generate a groundwater monitoring priority map [5]. This method will be very efficient as long as geological and hydrodynamic information is available. Esquivel et al. (2015) designed the groundwater level monitoring network for Toluca Valley aquifer (Mexico). They considered six factors, including decline and rise in groundwater levels, the rate of decrease in groundwater levels, vertical hydraulic gradient, cracks, and well density, to prepare a monitoring priority map [6]. Singh and Katpatal (2017) designed an optimal groundwater level monitoring network for Wainganga basin (India). They considered nine factors, including command and non-command areas, geology, geomorphologic unit, land use/land cover, lineament density, groundwater level fluctuation, recharge, slope, and soil media, to generate monitoring priority map [7]. They determined the optimal number of monitoring wells by trial and error and their location using multi-criteria analysis. In their study, there is no correlation between the monitoring priority score and the density of the proposed monitoring wells in each area. Preziosi et al. (2013)

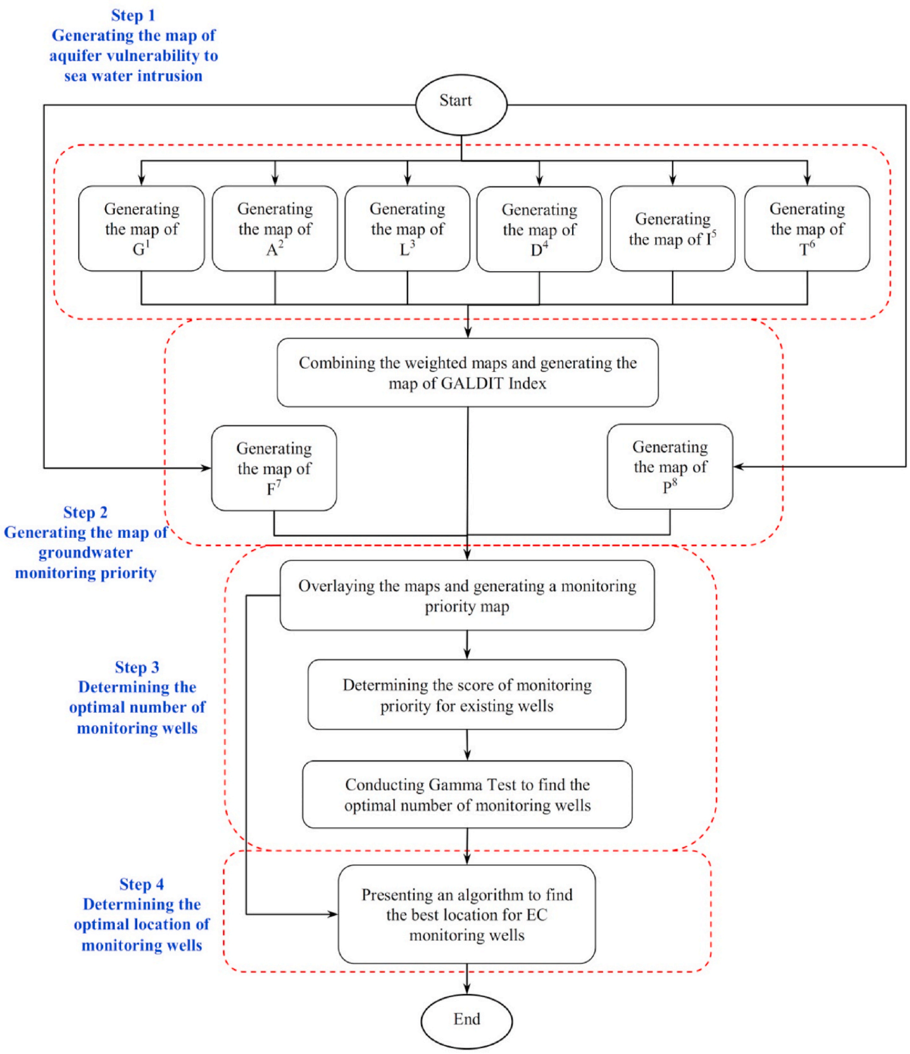


Fig. 1. Methodology flowchart to determine the optimal groundwater salinity monitoring network ([1]G: aquifer type; [2]A: aquifer hydraulic conductivity; [3]L: height of groundwater level relative to the sea level; [4]D: distance from the shore; [5]I: impact of existing status of seawater intrusion; [6]T: aquifer thickness; [7]F: the average fluctuation in groundwater electrical conductivity; [8]P: distance from industries discharging saline effluents).

designed a groundwater quality monitoring network for a pilot area in central Italy. They considered different factors of hydrogeological setting, groundwater vulnerability, and natural and anthropogenic contamination levels to produce a monitoring priority map. In their study, the number of monitoring wells was not optimized and it was selected based on budget-related constraint [8]. Besides, the location of the wells was determined by an inaccurate method called point distance analysis. Reviewing the limited studies on the design of the GMN using the monitoring priority map specifies that the main focus of these studies has been on providing a more precise monitoring priority map. A simple and efficient method has yet to be established to determine the optimal number and location of monitoring wells taking into account the risk of groundwater contamination.

Recently, Azadi et al. (2020) have proposed gamma test method to determine the optimal number and location of monitoring stations. Gamma test is a nonlinear modeling tool which can be used to determine the minimum number of required data to create a smooth model [9]. In this method, the monitoring network is determined such that with the minimum amount of monitoring data, the spatial distribution of the desired parameter can be modeled with the maximum possible accuracy [10]. This method in which only the latitude and longitude of the monitoring stations are analyzed, is suitable for when the purpose is to prepare the zoning map of monitoring parameter in an area with the minimum amount of monitoring data. However, when the purpose is the groundwater quality monitoring based on the risk of groundwater contamination, the geological and hydrodynamic parameters of the area, as well as the damaging effects of human activities and industries should be considered in determining the location of monitoring wells. To solve this problem, this paper presents the idea of using a combination of gamma test and monitoring priority map for the optimal design of GMN.

There is evidence that applying GALDIT index is a popular method to provide an aquifer vulnerability map to seawater intrusion in coastal areas [11,12]. The GALDIT index, considering six parameters of aquifer type (G), aquifer hydraulic conductivity (A), the height of groundwater level relative to the sea level (L), distance from the shore (D), impact of existing status of seawater intrusion (I), and aquifer thickness (T), efficiently describes the seawater intrusion risk in coastal aquifers [13]. This indicator only takes into account the effect of seawater intrusion on the increase in groundwater salinity, while saline effluent injection into groundwater from different industries can exacerbate the groundwater salinity. For this reason, this paper uses FP-GALDIT index, a combination of the GALDT index and the factors of F and P, to generate the priority map of groundwater salinity monitoring for the first time.

This study provides a method to determine the number and location of optimal groundwater monitoring wells based on the monitoring priority map and gamma test. The proposed method was applied to design an optimal groundwater salinity monitoring network for Kish Island, Persian Gulf. In recent years, excessive extraction of groundwater, leading to extensive seawater intrusion into the aquifer, as well as injection of desalination plant concentrate of various industries into shallow wells have caused the increase in the groundwater salinity. Hence, designing an optimal groundwater salinity monitoring network is needed for better mapping of salinity distribution and managing of groundwater resources on Kish Island. For this purpose, the map of groundwater salinity monitoring priority or aquifer vulnerability is first required to determine for Kish Island. After providing the monitoring priority map for Kish Island, the optimal number of monitoring wells was determined using gamma test. Finally, a novel algorithm was applied to select monitoring wells using the monitoring priority map and gamma test result. The algorithm was defined such that the monitoring well density is proportional to the monitoring priority in different regions and the total number of monitoring wells is equal to the optimal number.

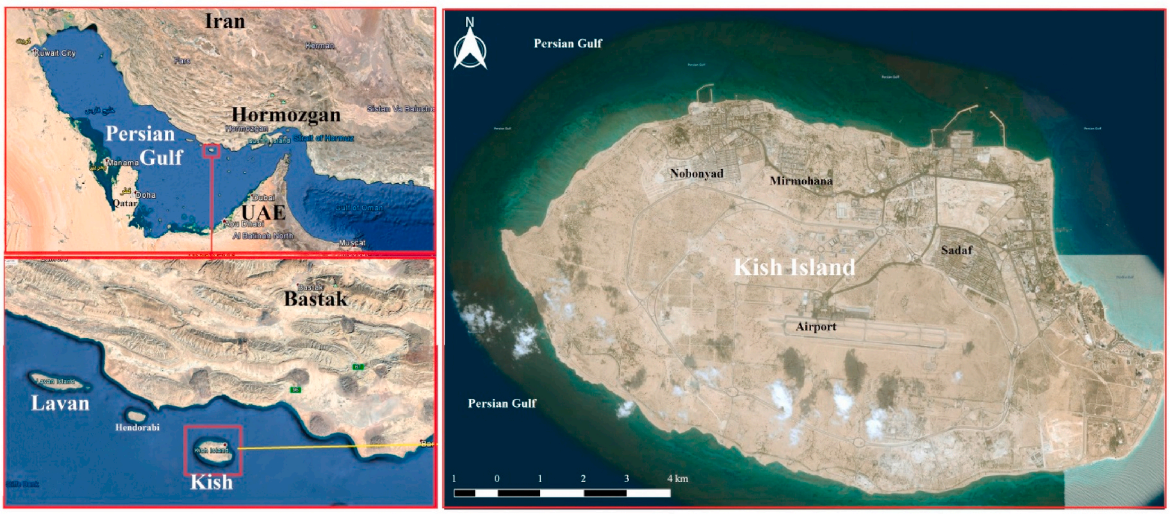


Fig. 2. The geographic location of the Kish Island in the Persian Gulf region.

2. Materials and methods

2.1. Overview

Fig. 1 illustrates the methodology flowchart used in this paper to determine the optimal number and location of groundwater salinity monitoring wells. As seen, the optimal network of groundwater monitoring is designed in a four-step process. At the first step, the map of aquifer vulnerability to seawater intrusion was developed using the GALDIT index. At the second step, the priority map of groundwater salinity monitoring was provided. For this purpose, the factors of mean groundwater EC fluctuation (F) and distance from industries discharging saline effluents (P) were first mapped. Then, the monitoring priority map was obtained by overlaying the map of GALDIT index, F, and P. At the third step, the optimal number of monitoring wells was specified. The data of latitude, longitude, and the monitoring priority score of all existing wells were extracted. Then, using these data and gamma test, the minimum number of required wells for salinity monitoring was determined. At the fourth step, the optimal location of the monitoring wells was specified based on the gamma test result and the monitoring priority map. This step was performed using a simple and efficient algorithm that will be described in section 2.6.

2.2. Study area

Kish Island with more than 91 km^2 area is an important tourist destination in the Persian Gulf region. This island is located about 18 km off the southern coast of Iran from 53°53’ to 54°04’ E and 26°29’ to 26°35’ N (Fig. 2).

Persian Gulf waters with total dissolved solids (TDS) of about 40 g/L surround the groundwater resource of Kish Island [14]. Geological formations and the topography of the bedrock surface cause underground waters to flow from the center to the shoreline of the island, and the hydraulic connection of the aquifer and sea to change along the coastline (Fig. 3). The geology of Kish Island consists of two main layers. The upper layer with 1×10^{-4} mean hydraulic conductivity contains condensed sand along with traces of crushed coral and the bottom layer with 1×10^{-6} m/s mean hydraulic conductivity contains clay with lenses of silt (Ataie-Ashtiani, 2010). Fig. 4b indicates the groundwater level in November 2009, the two aforementioned geological layers, and the depth of one well in a cross section of Kish Island. The thickness of the upper permeable layer decreases from the center of the island to the shores. Most of the seasonal precipitation penetrates into the upper permeable layer and stops at the boundary of the marl layer. According to previous studies, the groundwater lens on the island, due to its proximity to the coastline, is always affected by seawater intrusion. The average depth of wells on Kish Island is 12.5 m, and the average distance between the ground level and the water level of the wells was about 11 m.

On Kish Island, more than 244 wells are in operation in various sectors, such as irrigation and drinking, so that total annual groundwater consumption was estimated at roughly 3.7 MCM/yr in 2018. As the Kish Island is enclosed with Persian Gulf waters and the well density is high in the coastal strip, increase in groundwater salinity due to the seawater intrusion is a significant environmental issue. Also, more than 10 desalination plants discharge about 5500 m^3/yr saline effluent with the Electrical Conductivity (EC) between 6200 and 97,000 µS/cm into the aquifer of Kish Island. Although the Kish Island’s groundwater is of great importance, an optimal plan

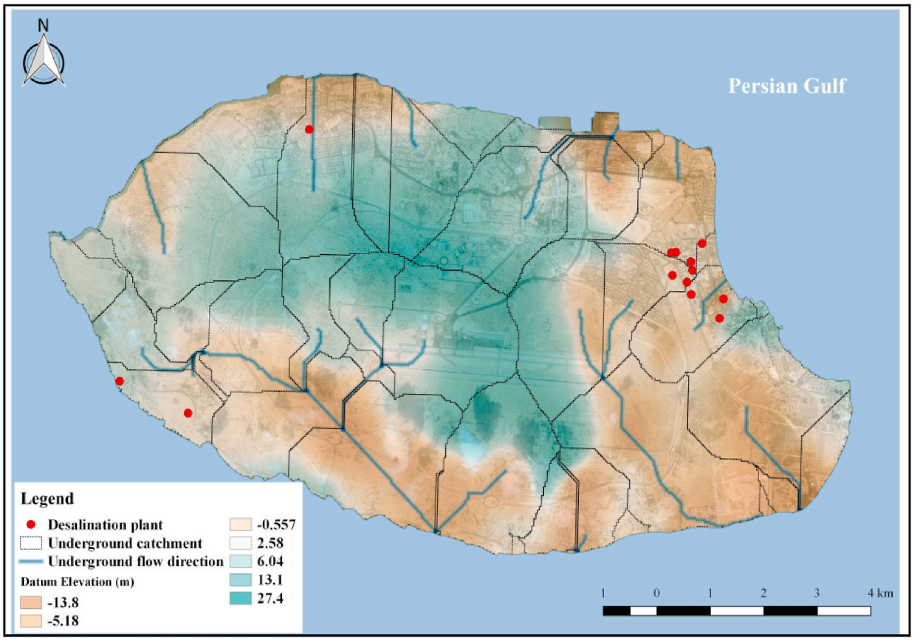


Fig. 3. Bedrock elevation and underground watersheds and waterways of Kish Island.

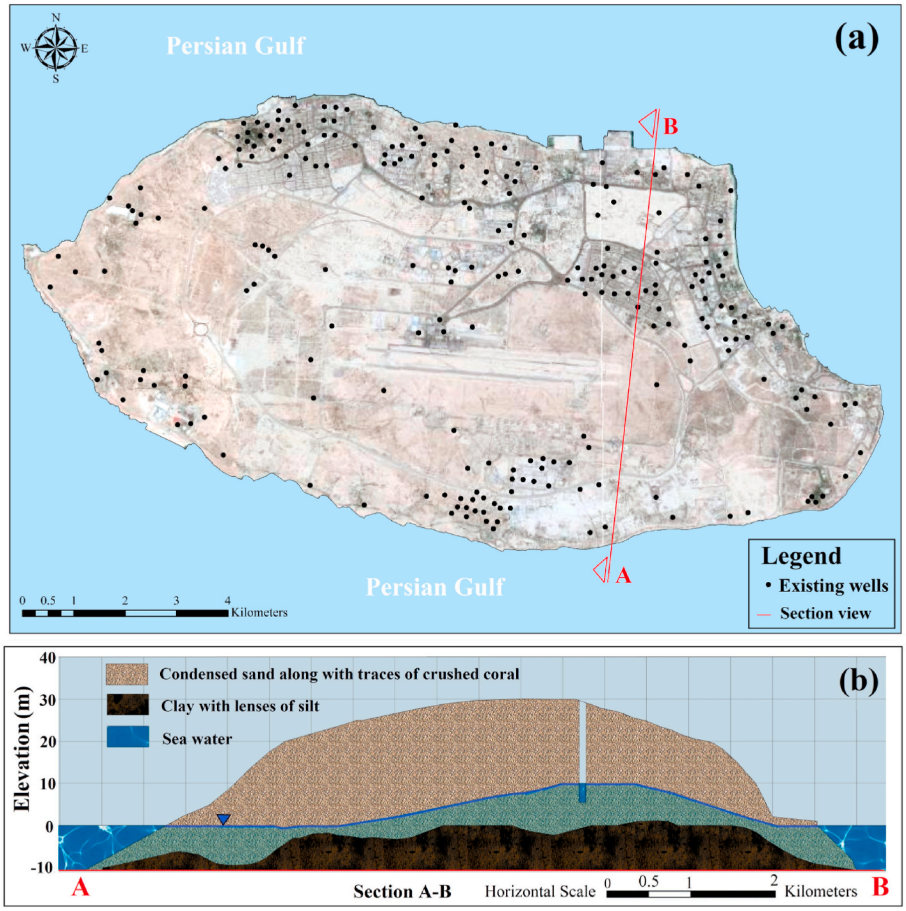


Fig. 4. a) The location of all existing wells and cross section A-B on Kish Island, b) geological properties of cross section A-B.

for groundwater salinity monitoring has yet to be established. Only in three sampling periods during 2009–2010, the water level and EC of some wells have been measured. Hence, an optimal network for groundwater monitoring seems more and more necessary to design for Kish Island.

2.3. Determining the map of aquifer vulnerability to seawater intrusion

One of the useful indicators to evaluate and quantify the vulnerability of the coastal aquifers to seawater intrusion is the GALDIT index [15]. GALDIT index, which was first developed by Chachadi and Lobo-Ferrerou (2001), considers the effect of six hydrogeological factors on seawater intrusion risk.

The first factor is G which has a significant effect on the boundary interface of saline water and freshwater. In unconfined aquifers, if the groundwater level is reduced by 1 m, the boundary interface of saline water and freshwater will raise by about 40 m [16]. Since the cone of depression in a confined aquifer is larger than that of in an unconfined aquifer for the same pumping rate, the vulnerability of confined aquifer to seawater intrusion is higher than that of unconfined aquifer [17]. Bounded aquifer is another type of aquifer whose recharge and/or impervious boundary is parallel to the coast [18,19]. The lowest risk of seawater intrusion is considered for this type of aquifer [18]. The second factor is A which affects the shape of depression cone during pumping. The more the hydraulic conductivity, the wider the depression cone and consequently the more the vulnerability to seawater intrusion [20]. Tidal pumping, a natural phenomenon occurring in coastal areas, can exacerbate the seawater intrusion in regions with high hydraulic conductivity [21]. The third effective factor is L, which provides a hydraulic pressure against the seawater intrusion [22]. The salinity intrusion risk is higher in areas where the groundwater level is lower than the sea level [17]. Ghyben-Herzberg showed that the height of the fresh groundwater column at each point is about 40 m per each meter of fresh groundwater above sea level [23]. D is the fourth factor in GALDIT index. Obviously, as the distance from the coastline decreases, the aquifer vulnerability to seawater intrusion increases. The fifth factor is I, which provides a proper understanding of the current condition of the seawater intrusion. Chemical components of groundwater, such as TDS, EC, and major cations and anions, are usually used as a sign of the seawater intrusion [17]. The sixth effective factor is T. The higher the saturation aquifer thickness, the higher the salinity intrusion risk [24]. The aquifer thickness depends on the physical and geological conditions of the bedrock.

Calculating the GALDIT index is started by identifying the effect of each factor on seawater intrusion for the study area. Then, the values of each factor are scored between 1 (lowest impact) to 10 (maximum impact) based on the effect of different ranges of each factor on the seawater intrusion. Afterward, the map of each factor is created. Next, a weight is assigned to each map based on the relative importance of each factor in seawater intrusion. Finally, the vulnerability is mapped by overlaying the weighted map of the factors.

2.4. Determining the map of groundwater monitoring priority

As mentioned before, the GALDIT index only indicates aquifer vulnerability to seawater intrusion, while the destructive effect of human activities and industries on groundwater salinity must be considered for the monitoring priority map. Hence, two factors of F and P are considered as indicators for the effect of human activities and industries on groundwater salinity. F factor represents the quantitative and qualitative changes of groundwater. This parameter induces the effect of anthropogenic activities and natural aquifer recharge due to rainfall. Not only groundwater EC but also its fluctuation is important to determine groundwater monitoring priority. Without parameter F, we cannot achieve a correct map of groundwater monitoring priority. If in a place groundwater EC is low but EC fluctuation is high, this place has to be prioritized for monitoring because it has the potential to be saline in the future. Besides, as the value of the P factor decreases, the priority of groundwater monitoring increases. Then, the map of each factor is created. The values in each map are scored between 1 (lowest impact) to 10 (highest impact) based on the effect of different ranges of each factor on the increase in groundwater salinity. Next, the map of each factor is created. Finally, the monitoring priority map is created by overlaying the map of F, P, and GALDIT index with equal weights.

2.5. Determining the minimum number of required monitoring wells using gamma test

Gamma test is an analytical tool and allows users to specify the minimum number of required datasets of independent variables to model a dependent variable directly from the datasets and before modeling [25–27]. The primary assumption of gamma test is that the variation of the dependent variable for two considered datasets must be relative to the variation of independent variables unless there are two reasons: 1) inadequacy of datasets; 2) Noise in the measurements [25]. The results of the gamma test are obtained based on the calculation of a statistical parameter, named gamma. The gamma statistic is calculated in a four-step process. At the first step, datasets are defined as $\{(x_i, y_i), 1 \le i \le M\}$ where M is the number of datasets, x_i is the vector of independent variables, and y_i is the scalar of the dependent variable. At the second step, the *k*th nearest neighbors ($x_{N[i,k]}$ (must be determined for each vector x_i. The value of k varies from 1 to p; a number between 10 and 20 is usually a suitable choice for p. At the third step, the delta function for the vector of independent variables and the gamma function for the dependent variable scalar are computed according to Eqs. (1) and (2), respectively [25,26,28]:

$$\delta_M(k) = \frac{1}{M}\sum_{i=1}^{M} \left|x_{N[i,k]} - x_i\right|^2 \ (1 \le k \le p) \tag{1}$$

$$\gamma_M(k) = \frac{1}{2M}\sum_{i=1}^{M} \left|y_{N[i,k]} - y_i\right|^2 (1 \le k \le p) \tag{2}$$

where | … | represents the Euclidean distance; and $y_{N[i,k]}$ is equal to the values of y corresponding to each of $x_{N[i,k]}$. At the fourth step, a linear regression model with the equation of $\gamma = A\delta + GT$ is fitted on the points p (δ_M(k),γ_M(k)). The parameters *A* and *GT* are the slope and the intercept of the regression line, respectively. *GT* represents the gamma statistic.

As long as the gamma statistic is small in relation to the variance of the dependent variable, the dependent variable will be predictable by a smooth model of independent variables [29].

The value of gamma statistic and consequently the modeling accuracy are sensitive to the number of datasets. The increase in the number of datasets up to the minimum required number for modeling decreases the value of gamma statistic or increases the modeling accuracy, but afterward, the increase in the number of datasets have no noticeable effect on the value of gamma statistic and modeling accuracy [25,26]. Therefore, to determine the minimum number of required datasets, the graph of the gamma statistic is plotted against the number of datasets. The number of datasets after which the graph is stabilized to an asymptote is the minimum required data to model the considered dependent variable.

In this study, the gamma test was conducted using WinGamma software to determine the optimal number of groundwater monitoring wells for Kish Island. The latitude and longitude of 244 existing wells as independent variables and the monitoring priority score of wells as the dependent variable were considered.

2.6. Determining the optimal location of monitoring wells

Anessential step in the optimal design of GMN is to specify the optimal location of monitoring wells. It should be mentioned that designers prefer to select monitoring wells among existing wells. After generating a monitoring priority map, existing wells can be assigned a number as a monitoring priority score. Provided monitoring wells are selected based on the monitoring priority score, all wells will be located in highly vulnerable areas; while no well is located in the vast areas whose monitoring priority score is less than the other areas. Therefore, in addition to monitoring priority score, the equitable distribution of the monitoring wells is essential [8, 30]. To consider the simultaneous effect of these two parameters and select wells from existing wells, the flowchart shown in Fig. 5 can be applied. At first, the study area is divided into n sub-areas on the basis of the monitoring priority score. Then, the distribution factor (X) is defined as follows (Eq. (3)) for each sub-area:

$$X = \frac{W}{A \times P} \tag{3}$$

where W is the number of required monitoring wells in each sub-area; A is the area of each sub-area; P is the mean monitoring priority score calculated for each sub-area. Then, as observed in Eqs. (4) and (5), the number of required monitoring wells in each sub-area is calculated such that firstly the distribution factor is equal in all sub-areas, and secondly, the total number of wells is equal to the minimum number of required monitoring wells computed by gamma test.

$$\frac{W_1}{A_1 \times P_1} = \frac{W_2}{A_2 \times P_2} = \ldots = \frac{W_n}{A_n \times P_n} \tag{4}$$

$$W_1 + W_2 + \ldots + W_n = \mathit{Minimum\ number\ of\ required\ monitoring\ wells} \tag{5}$$

Several states may be obtained in this process:

1. If the number of required wells is equal to the number of existing wells in a sub-area, the existing wells will be selected as monitoring wells.
2. If the number of required wells in a sub-area is equal to 1 and more than one well exist, a well with the highest monitoring priority score will be chosen as monitoring well.

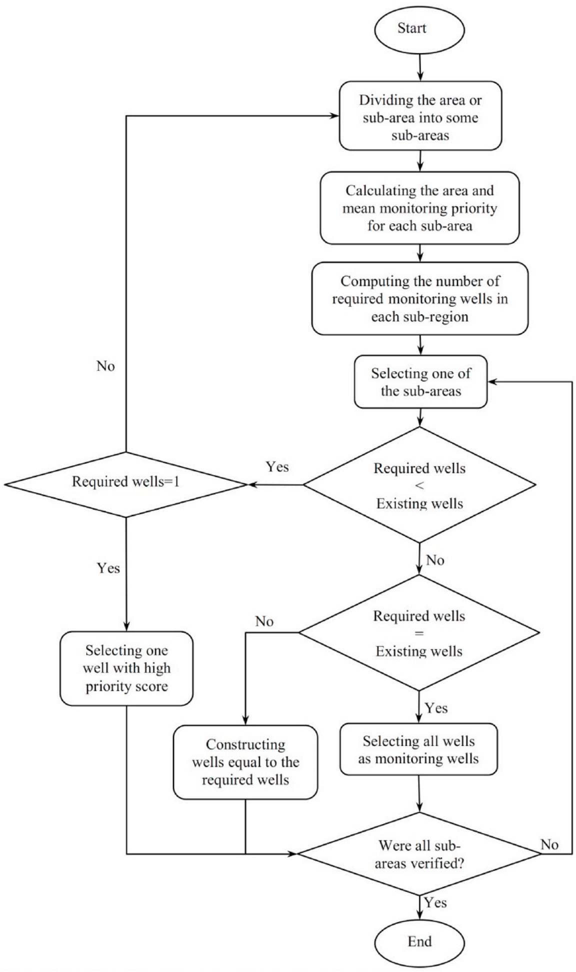


Fig. 5. Flowchart to determine the optimal location of monitoring wells.

Table 1
Scores and ranges of GALDIT factors.

Factor	Unit	Score									
		1	2	3	4	5	6	7	8	9	10
Aquifer type	–	–	Bounded Aquifer	–	–	Unconfined	–	–	Leaky Unconfined	–	–
Aquifer hydraulic conductivity	m/day	<2	2–5	5–10	10–15	15–20	20–30	30–40	40–60	60–80	>80
The height of groundwater level relative to the sea level	m	>10	8–10	6–8	4–6	2–4	1–2	0–1	-1–0	-1–-2	<-2
Distance from the shore	m	>2000	1500–2000	1000–1500	800–1000	600–800	400–600	300–400	200–300	100–200	<100
The existing status of seawater intrusion	μS/m	–	<5000		5000–9000	–	9000–15000	–	15,000–25000	–	>25,000
Aquifer thickness	m	<5	5–7.5	7.5–10	10–12.5	12.5–15	15–20	20–25	25–30	30–35	>35

3. If the number of required wells is greater than the number of existing wells in a sub-area, in addition to selecting the existing wells as monitoring wells, the required wells will be constructed in the sites whose monitoring priority score is higher than the others.
4. If the number of required wells in a sub-area is more than 1 and less than the number of existing wells, this sub-area will be divided into several sub-areas and again the number of required wells will be calculated for each sub-area.

3. Results and discussion

3.1. Determining the vulnerability map to seawater intrusion for Kish Island

A four-step process was conducted to calculate the GALDIT index which is an indicator of coastal aquifer vulnerability to seawater intrusion. At the first step, six effective factors on the seawater intrusion risk were investigated for Kish Island. The first effective factor in the GALDIT index is G. Based on the morphology of impermeable underground layer and permeability of the coastal strip, the Kish Island's aquifer is divided into three types: bounded aquifer, unconfined, and Leaky unconfined. The second factor is A. Based on the collected data from boreholes, the aquifer permeability is less than 4 m/d in most areas of Kish Island. The third factor is L. For this factor, the average difference between groundwater and the sea level through three monitoring periods was specified for different points on Kish Island. The fourth factor is D. Obviously, the middle area and the coastal strip of the island have the least and most probability of seawater intrusion, respectively. The fifth factor is I. For this factor, the average water EC of wells in the coastal strips (at a distance of less than 600 m from the shoreline) was applied. The sixth factor is T which was determined based on the morphology of the impermeable underground layer and average groundwater level in different parts of the island.

After identifying the GALDIT factors for Kish Island, at the second step, the values of each factor were scored between 1 (lowest impact) to 10 (the highest impact) based on the effect of different ranges of each factor on the seawater intrusion (Table 1). Then, the map of each factor was created based on the assigned scores (Fig. 6).

At the third step, according to the Kish Island's conditions and considering the literature, a weight was assigned to each factor (Table 2). These weights indicate the relative importance of the factors. As shown in Table 2, the L and D factors have the highest and G and I factors have the lowest weight. Finally, the summation of weighted maps of the aforementioned effective factors was obtained as GALDIT index map for Kish Island (Fig. 7). As seen in Fig. 7, the coastal strip and the center of the island generally have the highest and the lowest seawater intrusion risk, respectively. Furthermore, the seawater intrusion risk is high in the eastern and southeastern parts

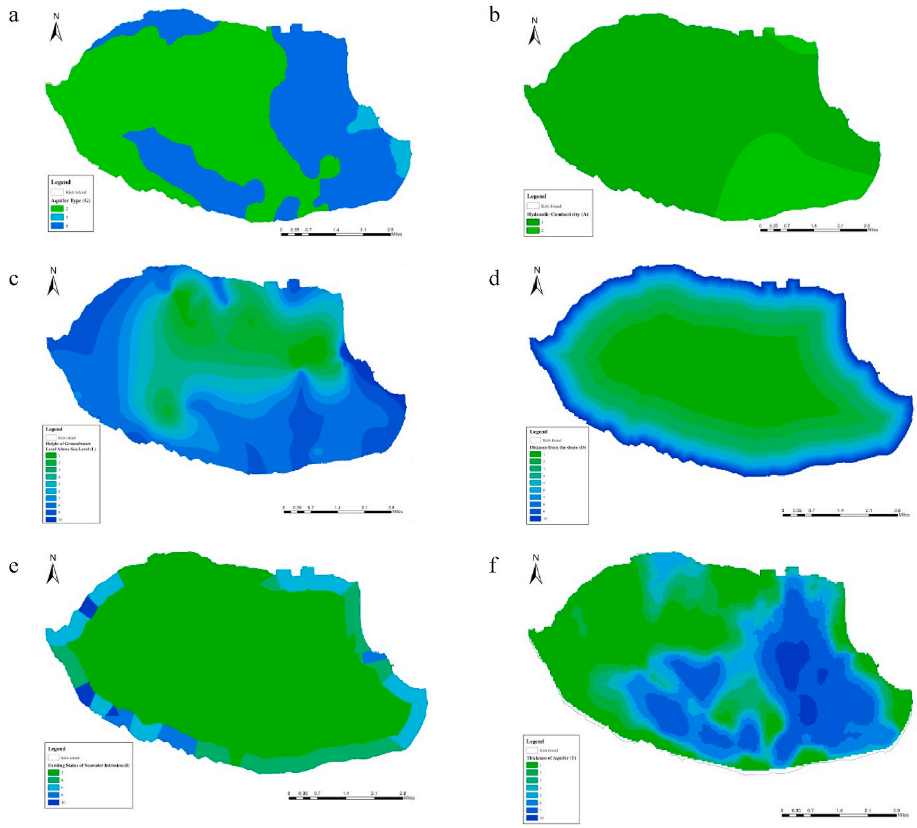


Fig. 6. Map of GALDIT factors: a) aquifer type, b) the aquifer hydraulic conductivity, c) the height of groundwater level relative to the sea level, d) the distance from the shore, e) the existing status of seawater intrusion, f) aquifer thickness.

Table 2
Weights assigned to the effective factors on the seawater intrusion risk [24].

Factor	Unit	Weight
Aquifer type	–	1
Aquifer hydraulic conductivity	m/d	3
The height of groundwater level above sea level	m	4
Distance from the shore	m	4
The existing status of seawater intrusion	μS/m	1
Aquifer thickness	m	2

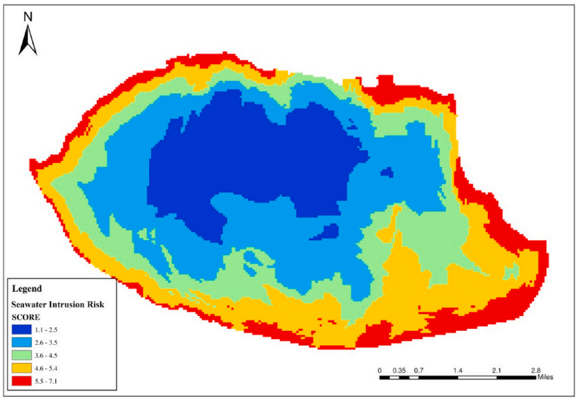


Fig. 7. Map of seawater intrusion risk based on GALDIT index for Kish Island.

of the island.

3.2. The priority map of groundwater salinity monitoring for Kish Island

A three-step process was conducted to determine the monitoring priority map for Kish Island. At the first step, the effect of F and P factors was identified for Kish Island. Based on the findings, due to the lack of a centralized and comprehensive water supply system on Kish Island, 13 industries including hotels, entertainment, and construction apply groundwater as the main source of water supply and feed-water to their desalination plants. These industries discharge saline effluent directly into the groundwater through shallow wells. According to the field observations and McLin's (1986) study, the adverse impact of these wells is maximum up to a radius of 200 m [31]. For radial distances more than 200 m, the adverse impact decreases. The second effective factor in determining the priority of groundwater salinity monitoring is F. To identify this factor, the EC fluctuations through three monitoring periods were specified for different points on Kish Island. At the second step, the values of F and P factors were scored between 1 (lowest impact) to 10 (the highest impact) based on the effect of different ranges of each factor on the seawater intrusion (Table 3). Then, based on the assigned scores, the map of each factor was created (Fig. 8).

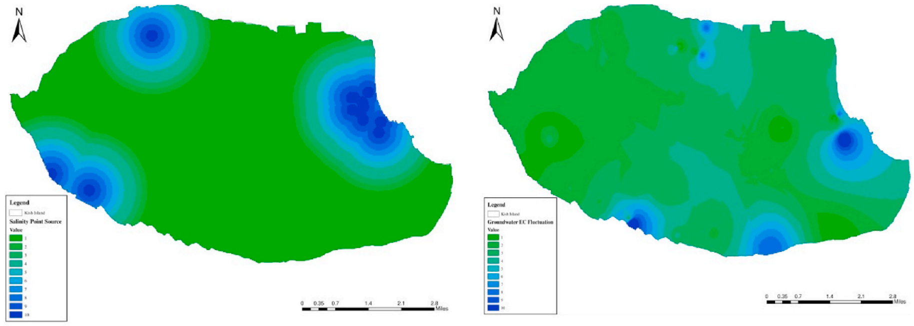
At the third step, the maps of GALDIT index, F, and P were combined to determine the priority map of groundwater salinity monitoring. Fig. 9 shows the priority map of groundwater salinity monitoring for Kish Island. As observed, the monitoring priority in the eastern, northwestern, and southwestern part of the island is much greater than the other parts.

3.3. Determining the number of required wells using gamma test

After generating the priority map of groundwater salinity monitoring for Kish Island, all 244 existing wells were assigned a score for groundwater monitoring priority. The latitude and longitude of all 244 existing wells as independent variables and their monitoring priority scores as dependent variable were considered. Then, the gamma test was applied to determine the minimum number of required wells for groundwater salinity monitoring on Kish Island. As shown in Fig. 10, the gamma statistic graph is approximately

Table 3
Scores and ranges of F and P factors.

Factor	Score									
	1	2	3	4	5	6	7	8	9	10
Distance from industries discharging saline effluent (km)	>1.8	1.6–1.8	1.4–1.6	1.2–1.4	1–1.2	0.8–1	0.6–0.8	0.4–0.6	0.2–0.4	<0.2
The average fluctuation in groundwater EC (%)	<5	5–10	10–15	15–20	20–25	25–30	30–35	35–40	40–45	>45



(a) (b)

Fig. 8. The map of: a) distance from industries discharging saline effluents, b) the average fluctuation in groundwater EC.

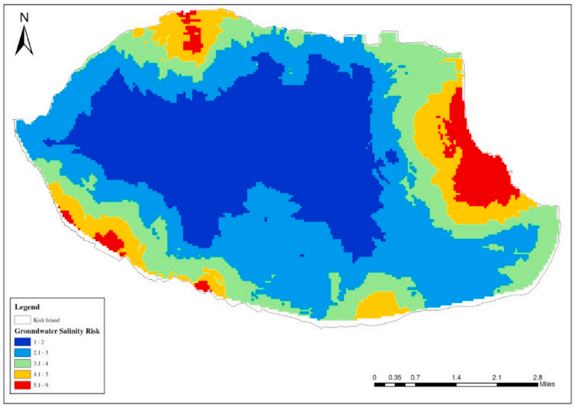


Fig. 9. Priority map of groundwater salinity monitoring for Kish Island.

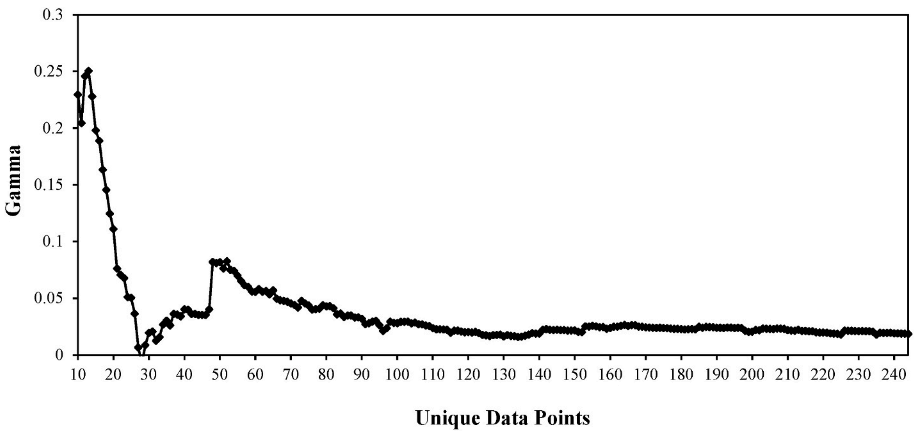


Fig. 10. The variation of gamma statistic by increasing the number of datasets.

smoothed for datasets more than 110. Therefore, at least 110 wells must be monitored on Kish Island to achieve sufficient data to model the groundwater salinity of the whole island.

3.4. Optimal location of monitoring wells

3.4.1. Selecting the location of monitoring wells using priority score

After determining the minimum number of salinity monitoring wells (110 wells), the optimal location of monitoring wells is needed to determine among existing wells. So long as the monitoring wells are selected based on the highest priority scores, the location of monitoring wells will be according to the green circles in Fig. 11. As observed, the spatial distribution of monitoring wells is uneven and no monitoring well is located in the wide areas of the island with low priority score. Moreover, in some northern areas of the island, the density of the proposed wells is high and their distances are too low while monitoring can be performed with a less number of wells in those areas. As a result, the priority score alone is an inappropriate criterion to find the optimal location of monitoring wells.

3.4.2. Selecting the location of monitoring wells using distribution factor

The proposed method in this study was applied to determine the optimal location of 110 monitoring wells among existing wells using the parameters of monitoring priority score and uniform distribution of monitoring wells simultaneously. For this purpose, Kish Island was first divided into five sub-areas based on the monitoring priority score. Then, the number of wells in each sub-area was calculated such that the distribution factor is equal for all sub-areas and the total number of monitoring wells is equal to 110. Since the computed number of monitoring wells in each sub-area was larger than one and less than the number of existing wells, the process of dividing each sub-area was continued until the exact location of the monitoring wells was determined. Fig. 12 shows the optimal location of the monitoring wells with green triangles. As seen, proposed monitoring wells have a proper distribution on the whole island. This proves the importance of such a planning protocol for effective environmental monitoring.

To show the necessity of using hydrogeological information along with gamma test in determining the optimal monitoring network, the result of this study is compared with the result of Ref [10], in which the gamma test alone was applied to determine the optimal monitoring network. Fig. 13 shows the optimal groundwater monitoring network proposed by the gamma test alone. As seen, the proposed network does not have a good distribution throughout the island. In the east, south and a part of the north of the island, a lack of monitoring wells is observed. Although gamma test can be a good method for the initial design of monitoring network in the absence of timely data and hydrogeological information, its combination with the monitoring priority map and using the distribution factor is an efficient method for designing the monitoring network.

The proposed algorithm in this study is feasible to determine the optimal GMN among existing wells by considering the cumulative effects of industries, human activities, and natural factors on the groundwater quality not only for coastal areas but also for areas where a groundwater monitoring priority map is available.

3.5. Applicability of the method in industry

Damaging environmental impacts and the deterioration of groundwater resource associated with different industries is a significant problem. On the one hand, industries use a significant amount of groundwater in different processes, such as cooling, cleaning, and facilitating waste discharge. On the other hand, extremely high water quality is required for some purposes. In addition, highly toxic wastewater with a high potential for contaminating groundwater resource is commonly produced. Therefore, due to the extent of industrial activities, considering preventative measure is vital to manage the adverse environmental impacts of industries. Based on the "polluter pays" principle, a company causing environmental damage must implement appropriate preventative or remedial measures and cover all the related costs. Since the remediation of groundwater contamination is a long and costly process, stakeholders prefers to take necessary measures to avoid the groundwater pollution. In this regard, groundwater monitoring is an effective management step that, if optimally designed, can identify potential adverse impacts of industrial activities at the lowest cost before leading to irreversible damage to the groundwater resource. The method proposed in this study helps stakeholders to design an optimal groundwater monitoring network in and around their operations based on the geological and hydrodynamic parameters of area, as well as damaging effects of desired industrial activities. The main aim of this method is to present an optimal monitoring network consisting an adequate number of wells that are installed at optimal locations to achieve holistic and representative information about the quality of up and down gradient groundwater of the facilities.

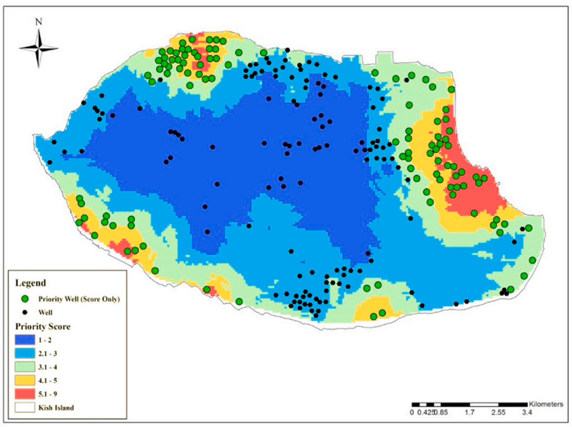


Fig. 11. The location of proposed wells based on the monitoring priority score.

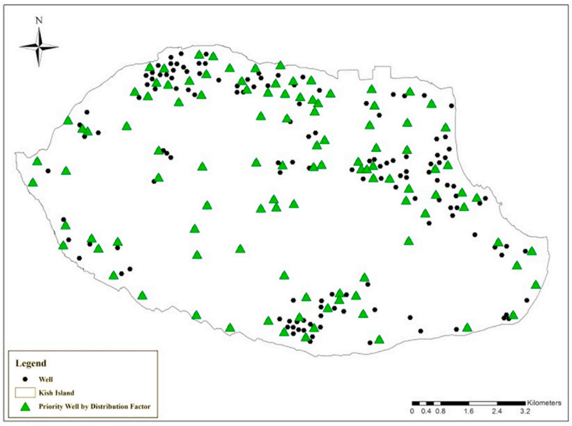


Fig. 12. Proposed monitoring wells based on the distribution factor.

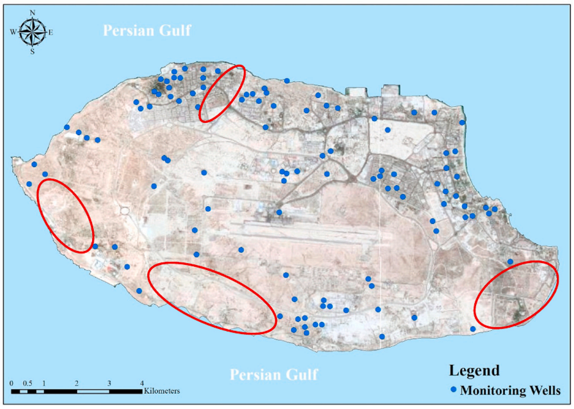


Fig. 13. Proposed monitoring wells based on the gamma test alone.

4. Conclusions

This paper, which presents a practical approach to design the GMN, solves two major researchers' issues during the design of GMN, including firstly the minimum number of required wells to monitor and secondly the optimal location of monitoring wells. The method proposed in this paper was successfully applied for the optimal design of groundwater salinity monitoring network on Kish Island, Persian Gulf. For this purpose, the monitoring priority map of the island was created based on the combination of three factors, including F, P, and GALDIT index. As a result, the monitoring priority in the eastern, northwestern, and southwestern part of the island was much greater than the other parts. Then, gamma test was applied to determine the minimum number of required wells for groundwater salinity monitoring on Kish Island. Based on the results, at least 110 wells must be monitored on Kish Island to achieve sufficient data to model the groundwater salinity of the whole island. Finally, a practical algorithm was applied to determine the optimal location of 110 monitoring wells among existing wells.

Using the proposed method which considers the detrimental effects of industries, human activities, and natural factors on the groundwater quality, optimal GMN could be designed for areas where initial data of aquifer hydrogeological characteristics and wells are available. Besides, one could significantly reduce the high cost of monitoring programs and optimize the cost efficiency of the programs.

CRediT authorship contribution statement

Hamid Amiri: Investigation, Formal analysis, Conceptualization, Methodology, Validation, Data Curation, Writing - Review & Editing, Sama Azadi: Investigation, Formal analysis, Conceptualization, Methodology, Validation, Data Curation, Writing - Review & Editing, Sirus Javadpour: Review & Editing, Supervision, Project administration, Ali Asghar Naghavi: Data collection, Data curation, Validation, Review & Editing, Grzegorz Boczkaj: Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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