



# A GIS-expert-based approach for groundwater quality monitoring network design in an alluvial aquifer: a case study and a practical guide

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**Abstract** Groundwater quality monitoring is a critical part of water management in all groundwater basins. In order to be effective and to meet the required needs, groundwater quality monitoring networks (GQMN) must be designed to be able to operate long-term and economically without minimal disruption. The analytical hierarchical process (AHP), a multi-criteria decision-making program, was used to design a GQMN for an alluvial aquifer located in the Islam Abad plain west of Kermanshah province, Iran. This semi-arid area is

subject to groundwater depletion and water quality changes. The model used 8 primary criteria subdivided with 5 sub-criteria based on a combination of empirical data and expert opinion. The primary criteria included density of wells, well discharge, well depth, water quality (conductivity), flow direction, annual groundwater extraction, water level declines, and accessibility. The model showed that 59 of 254 production wells in the basin could provide optimal monitoring locations. When a second screening of the wells was used to determine constraints (physical conditions of the wells and pumps, owner permission of use, type of the pump, etc.), the number of wells was reduced to 13 wells. An initial round of water sampling and chemical analysis demonstrated that the design of the GQMN met the goals of the water management agency of the region.

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## Introduction

Groundwater is the primary supply source for many urban and industrial infrastructure development programs as well as for rural and agricultural land uses. This valuable resource is the only source of drinking water in many parts of the world (UNESCO 2009; Zektser and Everett 2004). These fresh-water resources are of critical importance in arid and semi-arid regions where climate change events, such as long-term droughts, are an integral part of water-use planning.

Groundwater management concerns not only include consumption and extraction of water but also the continuous monitoring of water quality, including natural or anthropogenic contamination, which require delineation to avoid loss of the water resources.

Groundwater monitoring programs should be able to provide useful information such as the water levels and quality, for decision-makers to allow more precise management of aquifer water resources and development of comprehensive water-management plans. Additional monitoring of water use coupled with aquifer monitoring can show the patterns of changing demands. Such information can be provided by designing and monitoring groundwater networks that have useful spatial coverage and temporal reliability (Baalousha 2010). In addition, a properly implemented groundwater monitoring network can provide a temporal image to allow quantitative assessment of contaminant issues or excessive use of groundwater in real time (Esquivel et al. 2015).

Water-quality monitoring includes a series of activities such as sample collection, and chemical and biological analyses governed by a quality control plan to assess the physical, biological, and chemical properties of water (Harmancioglu et al. 1998). Quantitative groundwater level monitoring is used mainly to analyze trends that aid in assessing changes in spatial and temporal water use. Many efforts have been made to design or redesign groundwater monitoring networks. The main objective of these studies has been to optimize the use of an existing monitoring network by redesigning or modifying it to supply the needs and desired objectives of groundwater management (Loaiciga et al. 1992). Two main methods for designing or redesigning groundwater monitoring networks are the use of statistical and/or hydrogeological modeling methods (Khan et al. 2008; Baalousha 2010).

Statistical methods used to evaluate monitoring systems include variance-based and probability-based simulations. In hydrogeological methods, a variety of different groundwater models can be used to optimize the monitoring network (Loaiciga et al. 1992; Datta et al. 2009; Masoumi and Kerachian 2010; Owlia et al. 2011; Singh and Katpatal 2017). Typically, the site-specific characteristics and/or the knowledge of the designer have dictated which method can be used to help design a monitoring system. However, no single model type can be proposed for universal use based on geological, hydrodynamic, economic, or even social

conditions (Badham 2015; Badham et al. 2019). In addition, the main problem in evaluating the network and redesigning it, is the lack of an approved guide or set of rules that should be used to evaluate the network components to produce a design approach that meets all needs and objectives (Harmancioglu et al. 1998).

A groundwater monitoring network design commonly uses a combination of observation and extraction wells (Tuinhof et al. 2003). The number and location of selected wells is one of the major issues impacting the design of the groundwater monitoring network. However, the time intervals of measurement are also a pillar of a useful monitoring system. This is more relevant to economic issues within a water management scheme than to network design. Choosing the correct number of wells in a groundwater monitoring network is an important issue that involves both the accuracy of the system to predict changes and the cost of operating it. These numbers should be based on the needs of water resources management planners and water-supply system operators that guide decision-makers on local and regional scales.

The use of multi-criteria analysis methods in concert with a variety of statistical and hydrogeological modeling methods has become more common in water resources management. The analytical hierarchical process (AHP) is one of the multi-criteria methods used in many branches of science (Vaidya and Kumar 2006; Tesfamariam and Sadiq 2006; Wind and Saaty 1980) including estimating and evaluating mineral reserves (Pazand et al. 2011), preparing sinkhole susceptibility maps (Taheri et al. 2015), solid waste landfill site selection (Ghobadi et al. 2017), and related groundwater studies (Rahmati et al. 2015). A number of research papers have been published on a variety of other methods used to design or redesign groundwater monitoring networks (Everett 1980; Rouhani and Hall 1988; Harmancioglu and Alpaslan 1992; Loaiciga et al. 1992; Wu and Zidek 1992; Meyer et al. 1994; Yang and Burn 1994; Geo et al. 1996; Mahar and Datta 1997; Angulo and Tang 1999; Harmancioglu et al. 1999; Mogheir and Singh 2002; Mogheir et al. 2003; Rivett et al. 2018). In addition, a number of geostatistics-based methods have been used in groundwater monitoring system design (Woldt and Bogardi 1992; Passarella et al. 2003; Dhar and Datta 2009; Dhar 2013; Bhat et al. 2015). However, the number of papers using the AHP method for monitoring network design is sparse. Esquivel et al. (2015) identified priority areas for qualitative monitoring

network design. They claim to be the first to use the AHP method for monitoring network design. Additionally, some researchers have also used this method to examine water quality networks in different parts of Asia (Kim and Kim 2009; Kim 2010). The most important advantage of this approach is the incorporation of expert opinion and experience in assigning ratings to the classes chosen for network design. In this method, if the weighting and criteria are correctly selected, the designed monitoring network will achieve the goals established by water managers and stakeholders.

Integrating AHP with GIS may increase the robustness of this approach. This is a systematic decision-making approach first introduced by Saaty (1980). It is a tool to break down a problem into a series of subsections that make it easier to subjectively understand the underlying issues within the context of the problem. In this way, subjective evaluations can be converted to values that are categorized on a numerical scale (Bhushan and Rai 2004).

In this investigation, the AHP method was selected to evaluate different factors that are relevant to selecting the best wells to use for monitoring of an alluvial aquifer located in the Islam Abad plain west of the Kermanshah province of Iran. Some of the limiting factors of using production wells include the power type used for the well pumps (e.g., electric or diesel pumping systems), the physical condition of the well, and owner consent for use. Use of existing production wells is necessary to evaluate density of extraction wells DEW (number per unit area), extraction well discharges EWD (number per unit area, l/s), depth of wells DWW (meter), groundwater quality (EC-based), and annual groundwater exploitation (million m<sup>3</sup> per year, mcm/year). Some key issues in use of the production wells for monitoring are the accuracy of the pumping rate and overall water use rate (does the well contain a flow meter) and the accessibility of the well for monitoring (close to a road). A combination of data collected from production wells and observation wells is used to determine flow direction in the aquifer and water level declines.

The advantage of using AHP in the selection of observation well locations is the ability to combine various data types to allow a greater degree of objectivity for selection of specific well locations. However, it has a disadvantage in that it does not specify a specific number of wells to be used. By combining AHP with GIS, a cohesion can be achieved wherein physical field conditions can be evaluated to optimize the observation

well locations with the number of wells required to evaluate a design that will achieve the desired quantitative and qualitative goals for water resources management of the aquifer. Similar to use of production wells in the monitoring process, the observation wells must also be accessible and functional for collection of usable information. Use of expert opinion input during this process allows a greater degree of efficiency to be achieved in comparison to using a strictly empirical approach to monitoring network design.

The purpose of designing this network is to allow routine water-quality monitoring of the aquifer system according to the instructions of the Iran Ministry of Energy, which is responsible for water management. Water changes may be caused by geological factors such as salt dome occurrences or dissolution of sulfate minerals, or anthropogenic factors that include over-pumping of the aquifer. The long-term collection of water-quality parameters is useful in building a database that can be used to assess major and minor changes within a GIS and statistical framework for water management purposes.

## Study area

### Geography and elevation

The study area is located in the Islamabad sub-catchment, an 875-km<sup>2</sup> area in the Kermanshah province of western Iran. Islamabad is the second largest city in Kermanshah province with a population of about 90,000 (Fig. 1). According to climatic classifications, the study area has Mediterranean climate with cold winters and hot summers. The average annual rainfall ranges from 273 to 621 mm for a period of 40 years (average 479 mm per year). From a hydrological point of view, the Ravand River is the main surface-water body in the region and is dry during most of the year. The highest elevation in the region is northeast of Mount Shirnari at 2342 m above sea level (asl) and the lowest point at the outlet of the Ravand River in the southeast of the region with an elevation of 1291 m asl (Fig. 1c). The average altitude of the study area is 1505 m asl, and the average slope is 13%.

The city of Islamabad is located in the northern part of Islamabad plain (Fig. 1c). Drinking water for the city is supplied by the Sharaf Abad spring using 10 deep karst wells, which have had reduced water discharge in

recent years. The alluvial aquifer covers an area of 328 km<sup>2</sup>, and it varies in thickness from 10 to 180 m with an average thickness of about 100 m.

In recent decades, groundwater over-exploitation has had adverse effects on the alluvial and karst aquifers. Drying of karst springs and decline in groundwater levels are its most noticeable impacts. Figure 1e shows the conceptual model of the aquifer system. Increased demand for water has impacted both deep wells tapping the karst aquifer and shallower alluvial wells. The combined water use from the two aquifers can be termed “mixed water.” The decline of the water levels dramatically shows a negative water budget over −2.16 million cubic meters per year (mcm/y) based on the latest balance of water resources study in Islam Abad sub-catchment (see Taheri et al. 2016). These induced impacts are a critical issue in the near future and suggest that groundwater quality degradation will result. Therefore, it is imperative that a proper groundwater quality network monitoring is designed and implemented to aid in the development of a regional groundwater management strategy.

## Geology and aquifers

The geological sequences of the region are composed mainly of the Asmari-Shahbazan and Tele-Zang limestone formations, Kashkan and Amiran formations. The limestone formations form the aquifers, and lower permeability sediments within other formations constitute confining units. In most parts of the plain, the rock below the alluvium is limestone, and many of the wells that penetrate the karstic rocks extract water from both the alluvial and karstic aquifers. The groundwater-monitoring network of Islamabad plain contains 20 piezometers and 4 karst wells. Karst springs have karst rather than alluvial aquifer characteristics, and also are used for qualitative monitoring.

## Materials and methods

### AHP method description

The AHP method was developed by Saaty (1980) and is one of the most commonly used methods for environmental decision-making (Sadiq et al. 2010) and groundwater evaluations (Taheri et al. 2020). AHP works with the premise that, in decision-making, complex issues

can be transformed into a simple, comprehensible hierarchical structure. When a hierarchical structure is developed, a pairwise comparison is made between the two selection criteria. In this case, 8 factors were considered to be important in the development of the monitoring plan (Table 1). Paired comparison levels range from 1 to 9 in which 1 indicates the same importance of the two criteria being compared, while 9 indicates one criterion is absolutely more important than the other. The Saaty ranking scale consists of 17 values ranging from 1/9 to 9 (1/9, 1/8, 1/7, 1/6, 1/5, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9). This method is summarized in the following steps:

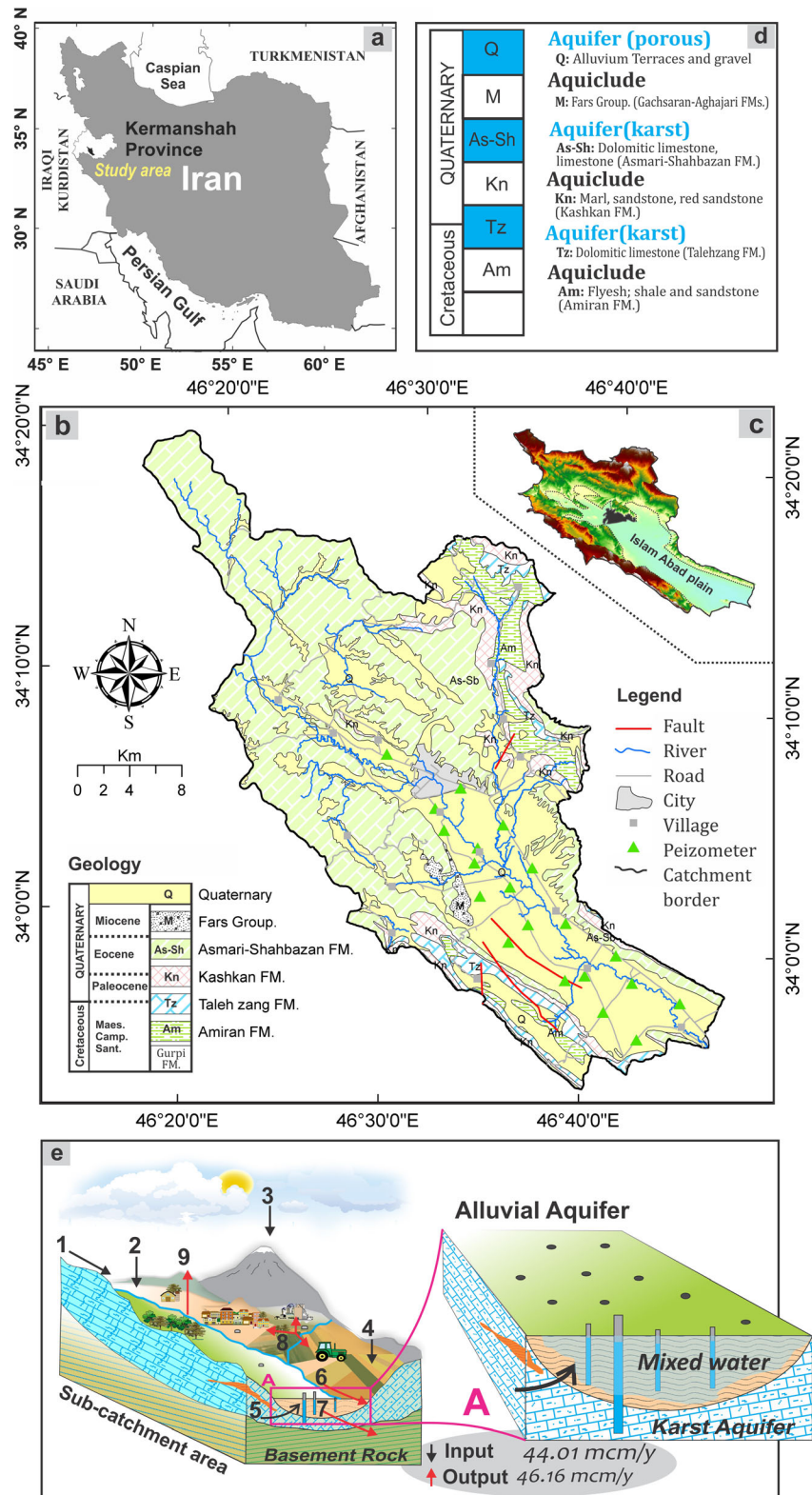
- 1 Structure of the problem in the form of a hierarchy consisting of the purpose, the criteria, the sub-criteria layers and its alternatives,
- 2 Paired comparison between elements in each hierarchical layer, and
- 3 Combining and prioritizing the overall priority of alternatives

### Criteria selection and thematic maps

The first task in performance of an AHP model is the determination of factors and constraints based on the purposes of the monitoring network. Eight different classes of relevant data were selected for analysis and creation of thematic maps for input into the AHP program (Table 2). These factors include the density of water wells (DEW), the discharge rate of the extraction wells (EWD), the depth of the wells (WWD), the groundwater quality (GQ), the groundwater flow direction (GFD), the annual groundwater extraction (AGE), water level declines in the aquifer (WLD), and accessibility of roads (AR) (Table 2). The technical data source for 7 of the 8 factors was the Kermanshah Regional Water Authority, and the data on the last factor originates from the Ministry of Roads and Urban Development of Iran. Selection of these criteria was based on expert opinion.

The density of wells criterion was selected based on the number of wells per unit area, which assesses water use and conflicts in water use. A general wells list was obtained from the Kermanshah Regional Water Company database, and after making necessary corrections in the GIS environment, a density of wells thematic map

**Fig. 1** The geographical location (a), geological map and uni, geological map and units of the study area (b), elevation model of the study area (c), hydro-stratigraphy of geological formations (d), the conceptual model of the aquifer functioning and water budget components: 1: recharge from adjacent basin (0.68 mcm/y); 2: precipitation (p) (215.5 mm/y); 3: precipitation (m) (222.75 mm/y); 4: return water from irrigation (22.48 mcm/y); 5: recharge from karst; 6: surface flow (runoff) (19.6 mm/y); 7: discharge into adjacent basin (p) (0.68 mcm/y); 8: agricultural, industrial and other uses (60.28 mm/y); and 9: evapotranspiration (p) (46.6 mm/y) (e)



**Table 1** Saaty (1980) scale for pairwise comparisons

Preference judgments	Ranking
Both criteria are equally important or preferred	1
One criterion is moderately more important than the others (weak preference)	3
One criterion is strongly more important than the others	5
One criterion is very strongly more important than the others	7
One criterion is extremely more important than the others	9
Intermediate values	2–4–6–8

was prepared. This layer was classified into five sub-groups from highest to lowest density. Because the high-density wells had greater utilization and the possibility of quantitative and qualitative changes was high, the highest and lowest density values were given the highest and lowest weighting.

Extraction well discharge (EWD) was determined based on the National Database and Census, and the rate of discharge was reported in liters per second. This criterion was sub-divided into 5 drainage area zones in a GIS environment using the inverse distance weighted (IDW) method. Because of the importance of high-discharge wells (a function of other factors such as aquifer characteristics), they were assigned the highest value of the sub-divisions. The lowest score was given to low discharge because these wells could be affected by climatic and operational conditions. In addition, these wells could have construction and/or pump issues that impact their use.

The depth of water wells (DWW) is a function of localized aquifer hydrogeologic conditions including geology, hydraulic conductivity, and other factors that control discharge. The DWW is important in the design of a water-quality monitoring network, because shallow wells can be affected by drainage changes, and a lower potentiometric surface position can impact yield and the pump discharge rate. However, a definite depth cannot be determined based on an expert because of limited information in the database on well construction details. Because of the severe decline of the potentiometric surface in most of the plains of Iran, deeper wells are more important in this study and yield more value. Other wells are still useful as long as they are viable and yield significant quantities of water. This factor is also divided into 5 categories based on the following well depth ranges: 0–40, 40–60, 60–85, 85–110, and 110–185 m.

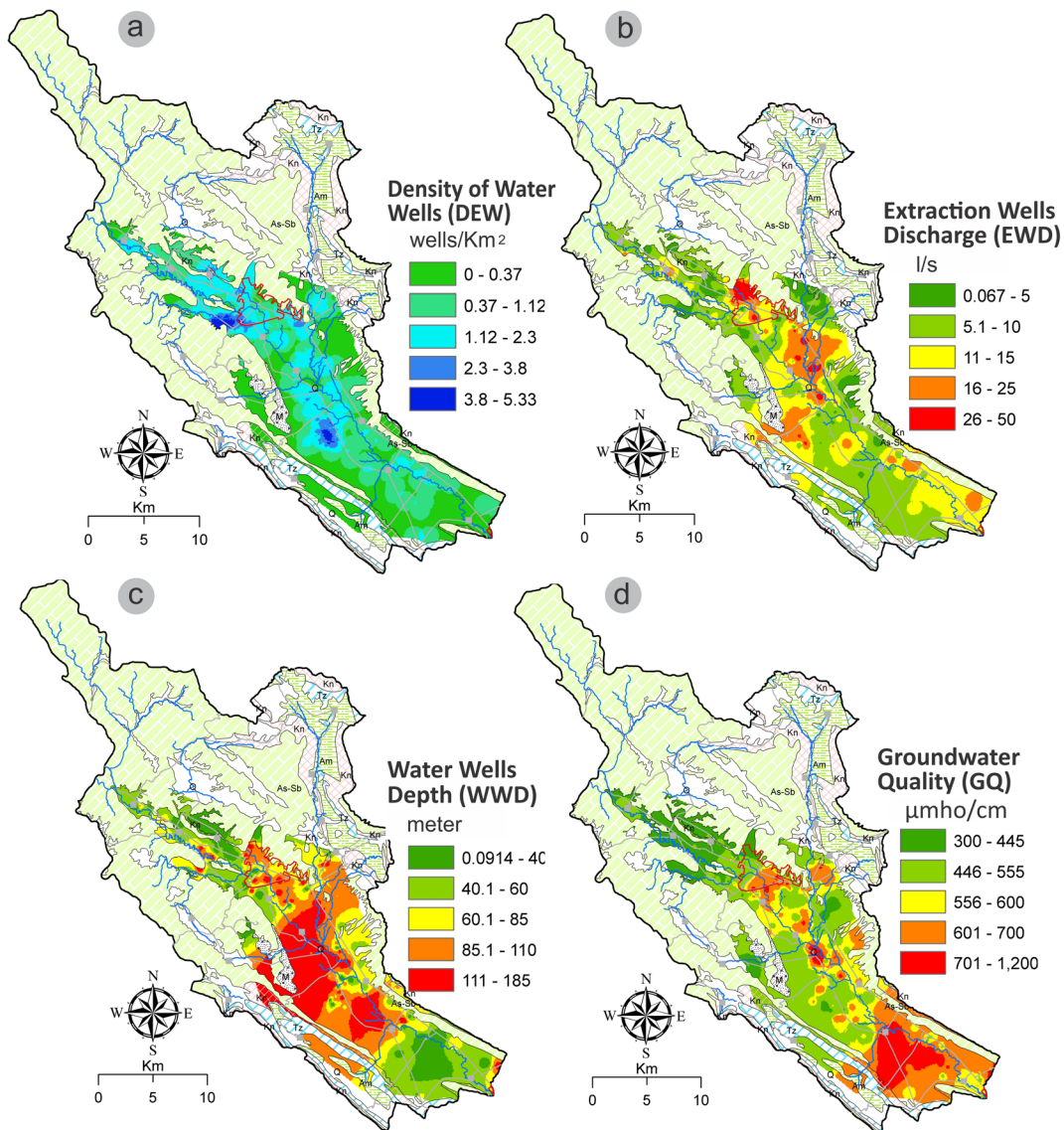
Groundwater quality (GQ) is an important factor in designing quantitative and qualitative monitoring networks that impact all water management decisions. Proximity to contaminating geological or other anthropogenic factors that influence water quality can alter the quantity of groundwater available for use. Water quality (e.g., salinity) is monitored using electrical conductivity (EC) as a proxy to represent water-soluble salts. A higher EC is associated with the greater need to select an observation well at or near a site. Accordingly, the highest EC layer received the highest score and the lowest EC layer received the lowest score. This layer was also sub-divided into 5 zones in GIS using the IDW method. The zones include 300–445, 445–555, 555–600, 600–700, and 700–1200  $\mu\text{mhos/cm}$ . For comparison, distilled water has a conductivity of 1  $\mu\text{S/cm}$ , groundwater can range from 50 to 50,000  $\mu\text{S/cm}$ , and seawater is commonly 50,000  $\mu\text{S/cm}$  or greater.

Flow direction (FD) (elevation change) is an important factor in pollutant transport and groundwater quality and determined by relative elevation in many cases. Determination of the groundwater flow path of high salinity water was used to determine potential contamination of down-gradient wells. Use of observation wells in different parts of the groundwater basin fronts is particularly important to assess potential impact areas. Although flow direction on a map is a graphic image based on elevation change of the potentiometric surface and does not represent all of the aquifer features, it is a good way to help distribute the observation wells in a meaningful manner. This layer was also sub-divided into 5 zones in GIS using the IDW method. These zones are elevation ranges of 1289–1301, 1302–1311, 1312–1318, 1319–1326, and 1327–1333 m asl. The groundwater-flow direction map is based on an elevation map and observation well data. There will likely be more error in the lowest basin elevations because well pumping can overcome the regional potentiometric surface changes to produce more localized groundwater flow directions. The zones at higher potential levels (large elevation changes) were assigned higher scores.

Annual groundwater exploitation was selected as a single layer based on the latest annual census of total water wells in the region in million cubic meters per year. Using these data, 5 sub-criteria were determined for annual utilization rate. These five groups have yield ranges of 1.2–0.5, 0.5–0.3, 0.3–0.2, 0.2–0.12, and 0–0.12 million  $\text{m}^3$  per year. The highest extraction rate was given the greatest weight.

**Table 2** Classes of data, sources, and applications for the monitoring evaluation

Factor	Abbreviations	Data sources	Description	GIS technique
Density of water wells	DEW	KRWA Data bank of total number of water wells in the Islam Abad Sub-catchment (ISC)	The layer was obtained from calculate water wells number per area (km <sup>2</sup> )	Using the point density option in the spatial analyst tool in ArcGIS
Extraction wells discharge	EWD	KRWA Data bank of licensed water wells discharge by l/s in the ISC	The layer was obtained from pumping test of water wells discharge by l/s.	Using the IDW method in ArcGIS
Water wells depth	WWD	KRWA Data bank of licensed water wells drilling logs in the ISC	The factor is essential for water level fluctuations and its effects on groundwater monitoring act.	Using the IDW method in ArcGIS
Groundwater quality	GQ (EC)	KRWA Based on groundwater EC electrical conductivity	In the lack of data bank of groundwater pollutant the EC is optimal factor for water quality evaluation	Using the IDW method in ArcGIS
Groundwater flow direction (elevation map)	GFD	KRWA Based on changes of piezometric level records of ISC (1997–2016)	The factor can effect on pollutant movement in the aquifer	Contour and IDW approaches in ArcGIS
Annual groundwater extraction	AGE	KRWA was obtained from a database consisting of pumping records from licensed water wells located in the ISC	The factor can effect on pollutant concentration in the aquifer	Using the IDW method in ArcGIS
Water level decline	WLD	KRWA Based on piezometric records of 20 piezometers of ISC (1997–2016)	Water level decline shows the range of changes in groundwater	Using the IDW method in ArcGIS
Accessibility of roads	WITH	MRUDI Ministry of Roads and Urban Development of Iran	Economic effect on operation of groundwater monitoring network costs	Using the buffer option in the spatial analyst tool in ArcGIS



**Fig. 2** Hierarchical structure of groundwater quality network design of Islamabad plain based on quantitative and qualitative changes; therefore, the highest and lowest values were given to highest density and lowest density, respectively

In order to map groundwater level declines in the observation wells (piezometers), a two-year baseline was used. In the first phase, water level data were selected from 1997 and compared with 2014 water level data. Using the IDW method in GIS, the groundwater loss layer or water level decline (WLD) in the study area was obtained. This layer was sub-divided into 5 groups, which are  $-35$  to  $-20$ ,  $-20$  to  $-15$ ,  $15$  to  $10$ ,  $10$  to  $5$ , and  $0$  to  $-5$  m. The highest water level decline field was given the highest weight.

Although access to primary and secondary roads or pathways technically does not have a significant impact

on how wells are selected, it can play a limiting role in the cost of operating a groundwater-monitoring network. The map was prepared by determining distances from primary and secondary roads or pathways. Five sub-divisions were created with distances of 500, 1000, 2000, 5000, and 15,000 m.

Weighting process and evaluation using the AHP model

After selecting the criteria and constraints and preparing the relevant thematic maps, the second step is determining the weight and importance of each criterion in the



design of the qualitative network of the study area. The weighting of criteria is not arbitrary and is based on expert opinion and local conditions. To achieve proper weighting, expert opinions of groundwater professionals at the Kermanshah Regional Water Company and regional universities were used. There were several methods used for evaluating criteria weights. In this study, AHP was used to compare different criteria.

The weighted overlay analysis of layers is one of the most common methods of surveying in GIS (Esri 2011). Using this method, different raster layers based on the given scales and weights are combined using each thematic map representing the eight factors in this study. To apply the thematic overlap technique, each raster layer is reclassified based on the final weight of pairwise comparisons in AHP. The priority zone for observation of the wells is obtained using Eq. 1 and the overlapping 8 different layers.

To design the final groundwater quality-monitoring network after converting the overall problem structure into a hierarchy and defining its different criteria and alternatives, pairwise comparisons between the elements in each hierarchical layer are made and the overall ranking of alternatives ranked (Fig. 2). In each square matrix, the elements of the original diameter of the matrix are equal to 1 (Table 2). Since only one side of the matrix is filled with comparative numbers, the other side needs to be completed as well. After completing the matrix, the sum of the elements of each column is obtained. To normalize the matrix, it is necessary to divide each matrix element by the sum of its columns. The next step is to determine the weight of each option using the arithmetic mean of each row.

Each of the data classes was further broken down into five sub-criteria. For pairwise comparison of the eight main criteria in a square matrix, the main criteria were followed by the sub-criteria which were compared in pairs (Table 3). The final weighting of the eight criteria including the sub-criteria is given in Table 4.

In the next step, the weight of each option is multiplied by its upper criterion to obtain the local weights of that option against each criterion. Then, the local weights are multiplied by the weight of the upper criteria to obtain the final weights of the options.  $\lambda_{max}$  can be obtained using the weights obtained from the hierarchical analysis process as well as the initial normalized matrix. In a consistent matrix,  $\lambda_{max} = n$  and, therefore, the rest of the eigenvalues are zero. Thus, the difference of the maximum eigenvalue ( $\lambda_{max}$ ) and then the matrix  $n$  is considered the consistency index and the matrix consistency index is expressed as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

If the matrix is fully consistent, the value of the CI will be zero, and the greater the deviation from the full consistency in the agreed matrix, the greater the value. The consistency ratio (CR) was defined as follows (Saaty 1980):

$$CR = CI/RI \tag{2}$$

where RI is a random index and is obtained from the Saaty (1980) suggested table (Table 5). If this value is less than 0.1, the judgment is acceptable.

**Table 3** Paired comparison of main criteria used in the current study

	DEW	EWD	WWD	GQ	GFD	GLD	AGE	WITH	weight
DEW	1	0.33	0.33	1	3	0.33	0.2	7	0.08
EWD	3	1	2	5	3	3	1	9	0.23
WWD	3	0.2	1	3	3	2	0.33	5	0.144
GQ	1	0.2	0.33	1	2	0.33	0.2	3	0.058
GFD	0.33	0.33	0.33	0.5	1	0.2	0.33	5	0.066
GLD	3	0.33	0.5	3	5	1	0.33	7	0.136
AGE	3	1	3	5	3	3	1	7	0.264
WITH	0.142	0.111	0.2	0.33	0.2	0.142	0.142	1	0.021

Consistency ratio: 0.07

**Table 4** Paired comparison of sub-criteria

	a	b	c	d	e	Weight	CR: 0.01
<b>DWE</b>							
(a) 0–0.37	1	0.5	0.33	0.2	0.143	0.050	
(b) 0.37–1.12	2	1	1	0.33	0.2	0.097	
(c) 1.12–2.3	3	1	1	0.5	0.2	0.115	
(d) 2.3–3.8	5	3	2	1	0.33	0.230	
(e) 3.8–5.37	7	5	5	3	1	0.506	
<b>EWD</b>	a	b	c	d	e	Weight	CR: 0.02
(a) 0–5	1	0.33	0.2	0.143	0.111	0.036	
(b) 5–10	3	1	0.5	0.33	0.2	0.090	
(c) 10–15	5	2	1	0.5	0.33	0.158	
(d) 15–25	7	3	2	1	0.33	0.242	
(e) 25–50	9	5	3	3	1	0.471	
<b>WWD</b>	a	b	c	d	e	Weight	CR: 0.01
(a) 0–40	1	0.5	0.33	0.2	0.143	0.051	
(b) 40–60	2	1	0.5	0.33	0.2	0.087	
(c) 60–85	3	2	1	0.5	0.33	0.15	
(d) 85–110	5	3	2	1	0.33	0.239	
(e) 110–185	7	5	3	3	1	0.471	
<b>GQ</b>	a	b	c	d	e	Weight	CR: 0.01
(a) 300–445	1	0.5	0.33	0.2	0.142	0.052	
(b) 445–555	2	1	0.5	0.33	0.2	0.088	
(c) 555–600	3	2	1	1	0.33	0.171	
(d) 600–700	5	3	1	1	0.33	0.211	
(e) 700–1200	7	5	3	3	1	0.476	
<b>GFD</b>	a	b	c	d	e	Weight	CR: 0.01
(a) 1289–1300	1	0.5	0.33	0.25	0.2	0.061	
(b) 1300–1310	2	1	0.5	0.33	0.2	0.092	
(c) 1310–1318	3	2	1	0.5	0.33	0.158	
(d) 1318–1325	4	3	2	1	2	0.257	
(e) 1325–1333	5	5	3	0.5	1	0.429	
<b>WLD</b>	a	b	c	d	e	Weight	CR: 0.02
(a) – 17.8 to – 13	1	1	3	5	7	0.404	
(b) – 13 to – 8.2	1	1	2	3	3	0.287	
(c) - 82 to - 4.4	0.33	0.5	1	1	3	0.141	
(d) – 4.4 to – 1.4	0.2	0.33	1	1	1	0.094	
(e) - 1.4 to 4.2	0.143	0.33	0.33	1	1	0.072	
<b>AGE</b>	a	b	c	d	e	Weight	CR: 0.02
(a) 0–0.11	1	0.5	0.33	0.2	0.143	0.05	
(b) 0.11–0.18	2	1	0.5	0.33	0.2	0.084	
(c) 0.18–0.29	3	2	1	0.33	0.2	0.123	
(d) 0.29–0.49	5	3	3	1	0.33	0.245	
(e) 0.49–1.14	7	5	5	3	1	0.496	
<b>AR</b>	a	b	c	d	e	Weight	CR: 0.02
(a) 0–500	1	2	3	5	7	0.43	
(b) 500–1000	0.5	1	2	3	5	0.253	
(c) 1000–2000	0.33	0.5	1	3	5	0.182	
(d) 2000–5000	0.2	0.33	0.33	1	3	0.089	
(e) 5000–15,000	0.143	0.2	0.2	0.33	1	0.044	

In the study, suitability of sites for establishing monitoring a network was calculated by weighted linear combination (WLC) of controlling factors and ranks of each factor (Voogd 1983). Based on Eq. 3, the suitability of the regions for determining the quality network is obtained:

$$\text{Priority zone} = \sum_{j=1}^N W_j w_{ij} \tag{3}$$

where P is the suitability for determining the qualitative network,  $W_j$  is the weight of  $w_{ij}$  using the main criterion  $j$  and the weight of the class  $i$  is the factor of  $j$  and  $N$  is the number of criteria. The final weights of the criteria and sub-criteria are given in Table 6. The final map was obtained from the overlap of the eight weighted maps using the weighted sum command (Fig. 2d).

### Sensitivity analysis

A sensitivity analysis was used to analyze the impact of each parameter on the final suitable zones for selection of groundwater quality network wells. Sensitivity analysis can be performed in a variety of ways (Hamby 1995) and provides valuable information on the influence of rates and weights of each parameter on the final result (Gogu and Dassargues 2000). Sensitivity analysis is important from the perspective that the adequacy of the layers used to determine the appropriate zone of the qualitative network can be examined (Pathak et al. 2009; Napolitano and Fabbri 1996).

Sensitivity analysis is used to assess the importance of the eight factors used in determining the appropriate areas for a qualitative groundwater network and whether all these of factors are important in determining the appropriate zones for network design. Many scientific papers have described the two methods of map removal sensitivity analysis (Lodwick et al. 1990). The map removal method delivers one or more input layers to the sensitivity of the final map of the appropriate zones. Depending on the number of input layers, appropriate zoning maps will be obtained. This method can be evaluated using Eq. 4:

$$S = \left( \frac{\left| \frac{V - V'}{N - n} \right|}{V} \right) * 100 \tag{4}$$

where S is the sensitivity, and V and v are unperturbed (suitable zone without removing any parameters) and perturbed (suitable zone after removing one or more parameters). N and n are the number of input layers for v and v'.

The sensitivity analysis using the relative deviation ratio (RDR) was applied to evaluate the impact of specific parameters (subject map) on the final zoning map suitable for defining a groundwater quality network. This method can also be used to evaluate sensitivity using Eqs. 5 and 6 (Hamby 1995). An RDR greater than 1 indicates greater model sensitivity and less than 1 indicates less model sensitivity to the elimination of the subject layer in the final evaluation.

$$\text{RDR} = \frac{\text{Standard deviation} * 100}{\text{Mean}} \tag{5}$$

$$\text{RDR} = \frac{\text{Output distributions relative deviation}}{\text{Input distributions relative deviation}} \tag{6}$$

## Results and discussion

### Thematic maps

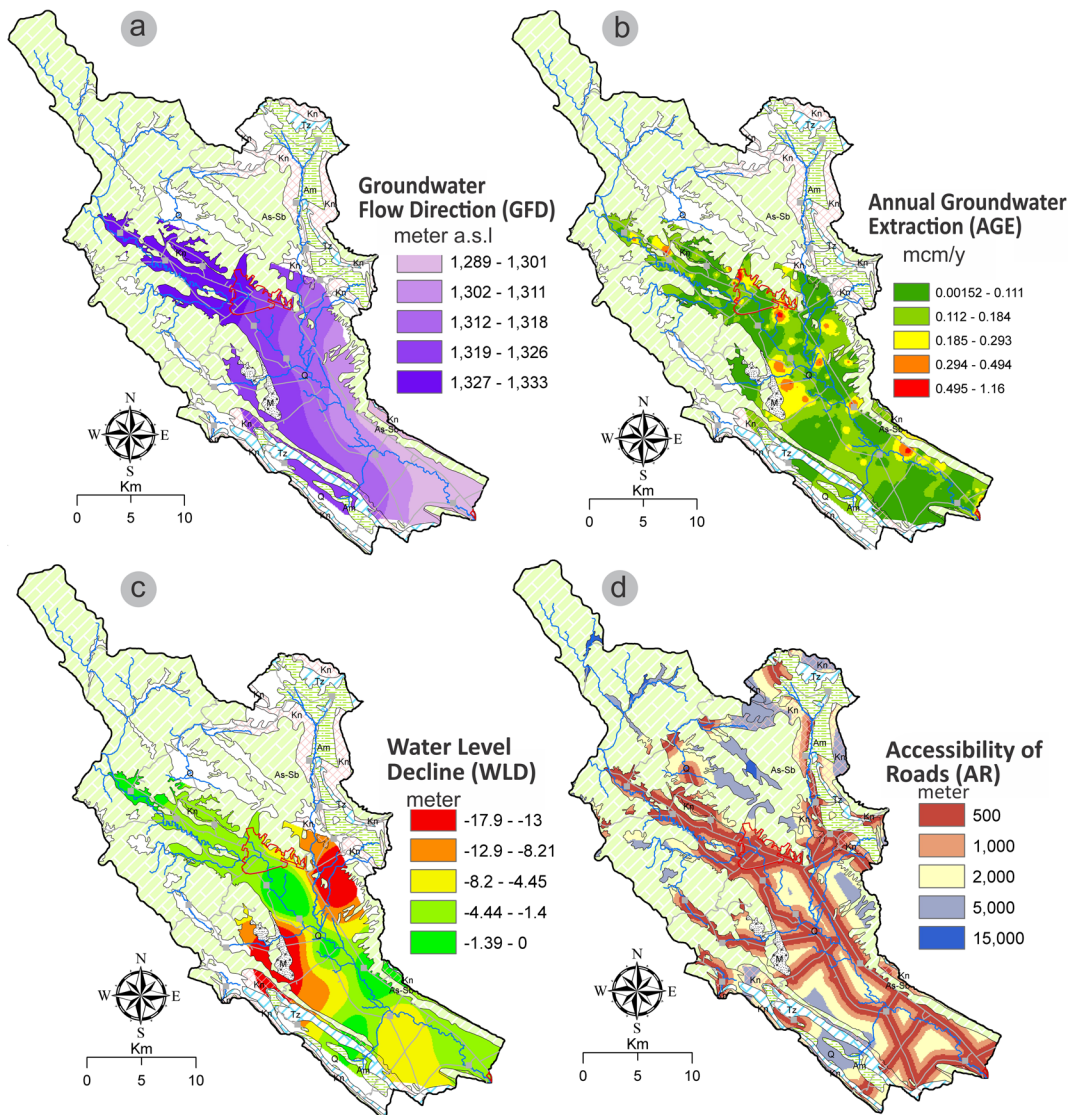
Eight thematic maps were created in GIS for each of the major evaluation criteria based on consultation with a group of experts from the Kermanshah Regional Water Company and regional universities. The first four maps show the density of wells (Fig. 3a), the well discharge (Fig. 3b), well depth (Fig. 3c), and groundwater quality using conductivity (Fig. 3d). The second four maps include groundwater flow direction (Fig. 4a), annual groundwater extraction Fig. 4b), water level decline (Fig. 4c), and accessibility of roads (Fig. 4d). All of the thematic maps show the detailed contours of the sub-criteria within the study area.

**Table 5** Random ratio values of RI

n	3	4	5	6	7	8	9	10
RI	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854

**Table 6** Final weight (overall priority) of the 8 criteria

Criteria	Sub-criteria	Criteria weight	Sub-criteria weight	Final weight
MUST	(a) 0–0.37	0.08	0.05	0.004
	(b) 0.37–1.12		0.097	0.00776
	(c) 1.12–2.3		0.115	0.0092
	(d) 2.3–3.8		0.23	0.0184
	(e) 3.8–5.37		0.506	0.04048
EWD	(a) 0–5	0.23	0.036	0.00828
	(b) 5–10		0.09	0.0207
	(c) 10–15		0.158	0.03634
	(d) 15–25		0.242	0.05566
	(e) 25–50		0.471	0.10833
WWD	(a) 0–40	0.144	0.051	0.007344
	(b) 40–60		0.087	0.012528
	(c) 60–85		0.15	0.0216
	(d) 85–110		0.239	0.034416
	(e) 110–185		0.471	0.067824
GQ	(a) 300–445	0.058	0.052	0.003016
	(b) 445–555		0.088	0.005104
	(c) 555–600		0.171	0.009918
	(d) 600–700		0.211	0.012238
	(e) 700–1200		0.476	0.027608
GFD	(a) 1289–1300	0.066	0.061	0.004026
	(b) 1300–1310		0.092	0.006072
	(c) 1310–1318		0.158	0.010428
	(d) 1318–1325		0.257	0.016962
	(e) 1325–1333		0.429	0.028314
WLD	(a) – 17.8 to – 13	0.136	0.404	0.054944
	(b) – 13 to – 8.2		0.287	0.039032
	(c) - 8.2 to - 4.4		0.141	0.019176
	(d) – 4.4 to – 1.4		0.094	0.012784
	(e) - 1.4 to 4.2		0.072	0.009792
AGE	(a) 0–0.11	0.264	0.05	0.0132
	(b) 0.11–0.18		0.084	0.022176
	(c) 0.18–0.29		0.123	0.034272
	(d) 0.29–0.49		0.245	0.06468
	(e) 0.49–1.14		0.496	0.130944
WITH	(a) 0–500	0.021	0.43	0.0093
	(b) 500–1000		0.253	0.005313
	(c) 1000–2000		0.182	0.003822
	(d) 2000–5000		0.089	0.001869
	(e) 5000–15,000		0.044	0.000924

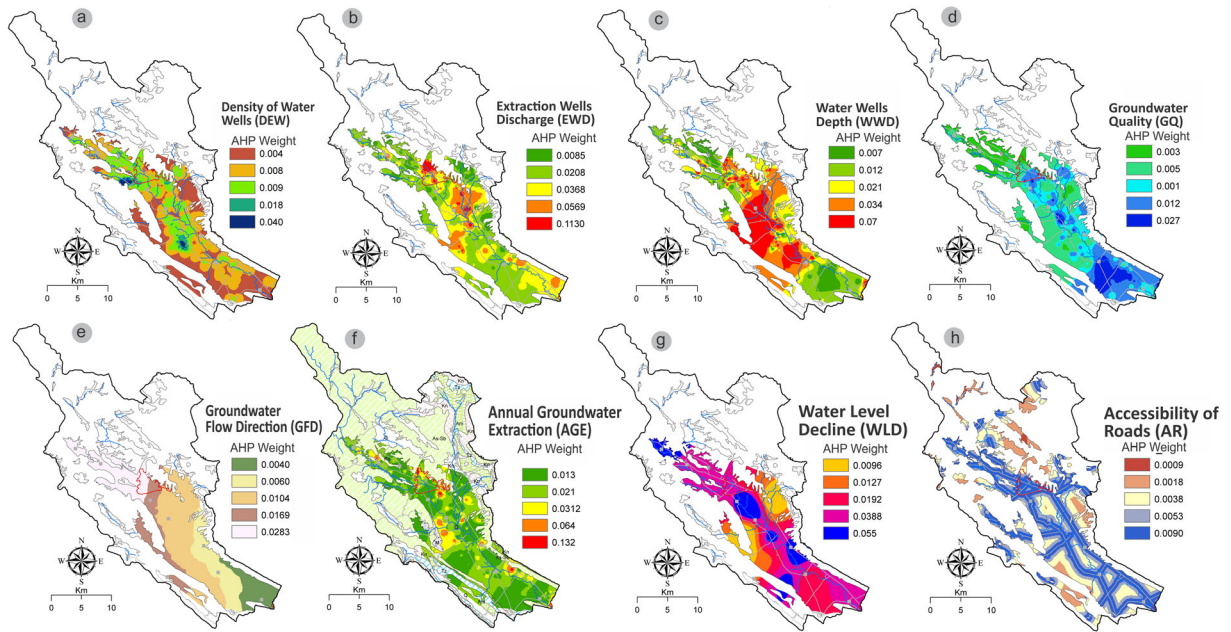


**Fig. 3** Thematic maps showing well density in the study area (a), well discharge (b), depth of wells (c), and groundwater quality using EC changes in the study area (d)

Compilation of the final map

To obtain the overall priority of each criterion, the coefficients obtained from each criterion and sub-criterion are multiplied as described in Table 6. After applying these weights, the eight layers were reclassified in the GIS environment and the final weight of each layer was prepared as shown in Fig. 5. Subsequently, in the GIS environment, a final map of the appropriate zones was obtained using the defined overlay analysis illustrated in Fig. 2 to produce the final map (Fig. 6).

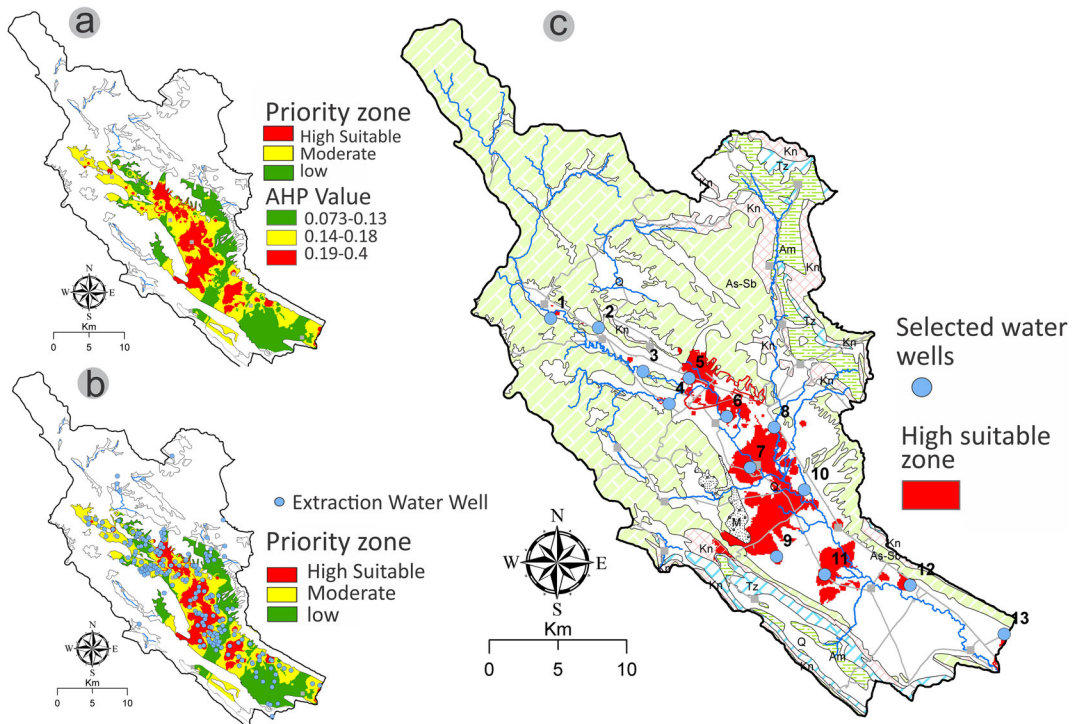
The final map scale ranged from 0.073 to 0.4 (AHP calculated values), based on the natural break method. It was divided into three categories of importance namely a highly suitable zone, a moderately suitable zone, and a low suitable zone (Figs. 6a–b). This method has been used to classify different zones in landslide surveys and potential sinkhole development areas (Taheri et al. 2015). In this study, 15% of the plain is in the highly suitable zone, 43% is in the moderately suitable zone, and 42% is in the low suitable zone. In the next step, only the zone that was most suitable for the criteria of action was considered (Fig. 6c).



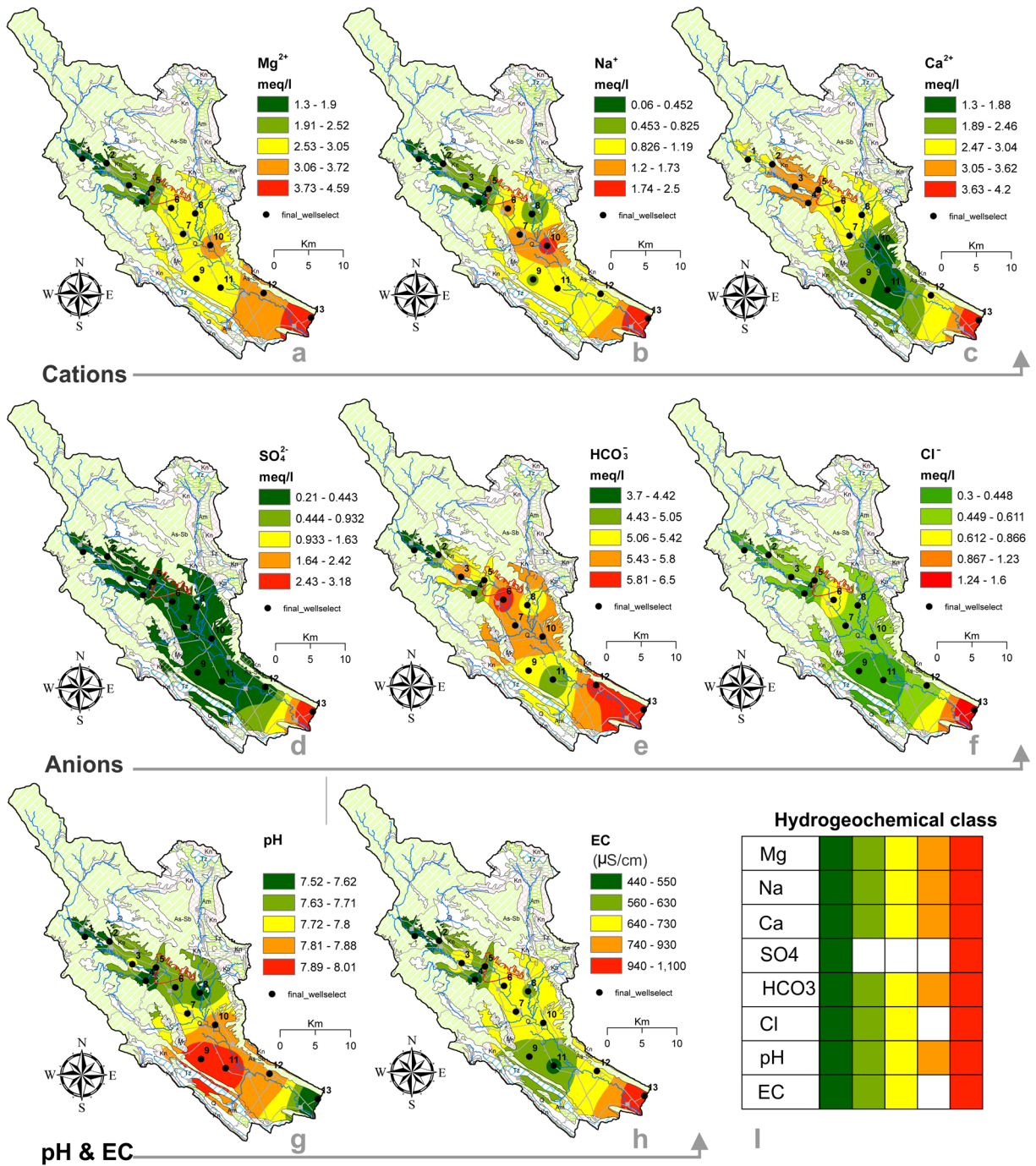
**Fig. 4** Groundwater flow direction (a), annual groundwater extraction (b), water level decline (c), and accessibility to roads (d)

Then, based on zone locations, a number of wells in the zones were extracted from the list of available wells (59 wells out of 254 wells). As previously mentioned, three zones were obtained using the AHP method;

however, only highly suitable zone wells were considered for the GWMN design. The 59 wells from 254 water wells are located in this zone. Finally, 13 wells from 59 wells obtained from AHP result zone were



**Fig. 5** Weighted map of the eight factors in this study



**Fig. 6** The final map of the appropriate zones (a, b) and high suitable zone and selected water wells for groundwater quality network

selected by applying the constraints (physical condition of the wells, owner satisfaction, and the type of electric or diesel pump engine) (Fig. 6c). These 13 water wells are at the best locations for water quality analyses monitoring in the study area.

### Sensitivity analysis results

Two different sensitivity analyses were used to assess the AHP-derived monitoring plan. The map removal method using Eq. 4, as proposed by Lodwick et al.

**Table 7** Results of sensitivity analysis by map removal and RDR methods

a: Removal map sensitivity analyses				
Factor	Min.	Max.	Mean	SD
DEW	0	24.5	9.21	2.24
EWD	0	49.5	9.4	7.5
WWD	0.01	41.7	10.35	9.61
GQ	0.02	15.7	8.62	3.37
GFD	0	22.1	7.15	3.56
AGE	0	59.17	4.13	4.46
WLD	0	37.45	13.24	8.52
WITH	0.23	13.2	9.32	2.34
Final map	0.39	0.069	0.069	0.035
b: RDR sensitivity analyses				
Factor	RD output	RD input	RDR	Ranking
DEW	24.32	50.72	0.48	8
EWD	79.79	50.72	1.57	3
WWD	92.85	50.72	1.83	2
GQ	39.1	50.72	0.77	6
GFD	49.79	50.72	0.98	5
AGE	107.99	50.72	2.13	1
WLD	64.35	50.72	1.27	4
WITH	25.11	50.72	0.49	7

(1990), was completed. Then, the RDR method using Eqs. 5 and 6 was used. In this method, one of the eight layers was compared with the overlay layers and the statistical data from the map obtained from 7 parameters. The results of the sensitivity analyses using the map and RDR deletion methods are shown in Table 7a–b.

The results of the map removal sensitivity analysis were computed by removing one or more data layers at a time as presented in Table 7a. Removal of the WLD parameter followed by the WWD parameter causes the highest variations, whereas the least variation is observed after removal of the AGE parameter. Even though the most effective layers were considered every time, the interpretation of the increasing average is not clear. This could be either due to weights assigned to the parameters, internal variability of the parameter, or an inaccurate depiction of the actual condition (Babiker et al. 2005).

In the RDR method, an RDR greater than 1 indicates greater model sensitivity and less than 1 indicates less model sensitivity to the elimination of the subject layer in the final evaluation. The result of the sensitivity

analysis by RDR indicates that the WLD is highly sensitive followed by WWD and EWD.

## Validation

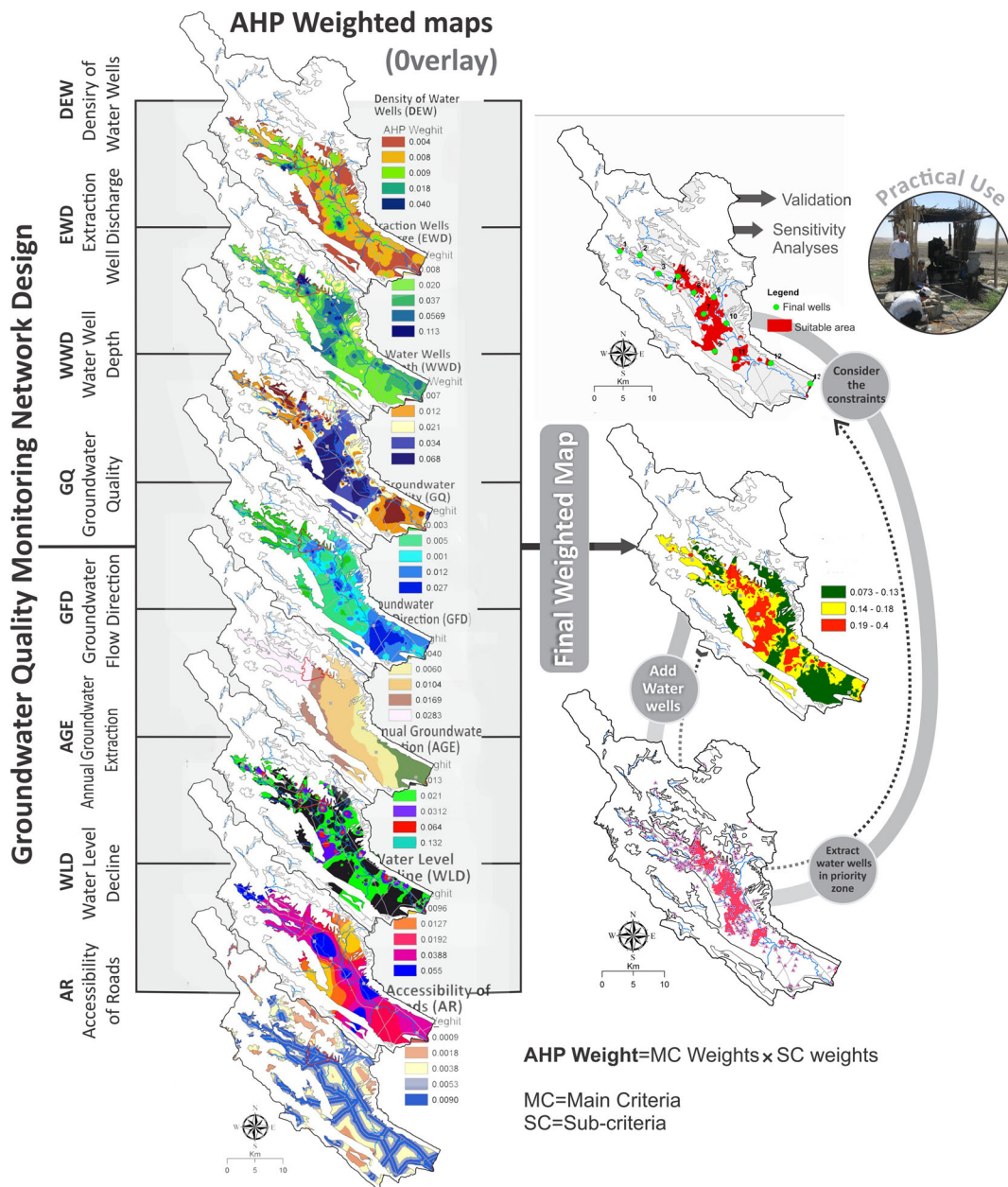
Chemical analyses were performed on water samples collected from the 13 wells designated for monitoring using the AHP analysis. In Fig. 7, the hydrogeochemical distributions of the major cations and anions are presented. As the maps show, the hydrogeochemical zones are clearly identified using the wells selected for the design of the monitoring system.

Distribution maps were created for water quality parameters (i.e., ions, conductivity, and pH) using 13 samples from selected wells (hereinafter referred to as monitoring wells) and were subjected to an interpolation technique in ArcGIS. These distributions are presented using 5 classes: very high, high, medium, low, and very low (Fig. 7 a to h). As illustrated in Fig. 7, there is at least one selected well for monitoring of all parameters measured in each class except for SO<sub>4</sub>, Cl, and EC (no monitoring well in three classes). The values of Cl and EC were not significant and can be ignored based on the absence of high class values for these parameters (orange in the Fig. 7 legend).

The absence of monitoring wells in the range of three classes of sulfate distribution (high, medium, and low), orange, yellow, and green colors respectively, may be due to the uniformity of sulfate distribution in groundwater in upper areas of the Islam Abad Sub-catchment. The SO<sub>4</sub> concentration increases in lower parts and at the groundwater outlet from the catchment. The very slight increase of SO<sub>4</sub> is caused by the groundwater flow direction to the catchment outlet in south part of the study area and local dissolution of gypsum within the Gachsaran Formation that is in contact with groundwater flow. Well number 13 is located at the outlet and is at a suitable location to monitor sulfate concentration changes. It allows the monitoring network design to function as desired.

If the logistics of the monitoring and operational finances are appropriate, sampling can be conducted using 12 to 13 wells from the 59 wells in the high suitability zone, based on the results of the study. At present, the designed network by AHP method and expert field correction can also meet the management and protection needs of groundwater resources for water managers and policy makers in the region.





**Fig. 7** Hydrogeochemical maps based on water collected and analyzed from selected wells (a to h), and the state of selected wells in different hydrogeochemical classes (i)

**Conclusions**

Groundwater quality monitoring network (GQMN) design is one of the main pillars of water resource management in all global regions. Proper GQMN design should be able to economically characterize the hydrogeological conditions and groundwater quality changes in the area of consideration. In this study, using

the AHP model within a GIS framework, the most suitable areas for installation of monitoring wells or utilization of existing production wells were defined to establish a groundwater monitoring network in the Islamabad plain of Iran. The AHP/GIS analysis was based on eight different but related criteria. The endpoints were selected based on expert opinion and applying logical constraints (e.g., distance to access points). In

addition, some statistical methods were also used in the design process. Given the importance of expert experience in benchmarking and in the application of the AHP method, this study attempted to identify endpoints that relied on field visits and limit controls as well as empirical data.

In Iran, the law of fair distribution of water was adopted over four decades ago; however, legal details for the recognition of sustainable protection of groundwater resources have not yet been published as a set of comprehensive guidelines. The Groundwater Monitoring Network Guidelines have been published in Bureau of Standards and Standards of the Ministry of Energy of Iran. One of the highlights in this set of guidelines is the definition of distance as a criterion for determining qualitative monitoring well location (considers every 5 km as a well for qualitative monitoring location). Due to the geological complexity and the dynamic nature of the aquifers, this method is not suitable or practical in many regions. In the plains of Iran, including Kermanshah Province, springs have been selected in the past as one of the main sources for groundwater quality monitoring. As a result, hydrogeochemical results from these sources indicate karstic aquifer conditions rather than groundwater quality in the alluvial aquifer, which is a heavily used aquifer system.

The advantage of the AHP/GIS approach is the incorporation of expert opinion and practical constraints, as well as local facts based on field visits; unlike some mathematical and statistical methods, it does not rely solely on data entry. The results of this study indicate that AHP is a useful method for selecting suitable zones for determining groundwater monitoring network well locations. The AHP method with eight factors in this study indicates the high capability of this method to determine the appropriate spatial zones for selection of observation wells from a large number of existing agricultural irrigation wells.

The only major downside of this method is the lack of determination of the final number and the most suitable wells from the number of wells selected for possible use. This flaw is remedied by the use of site-specific expertise and practice limitations within the appropriate zones (e.g., access to wells, permissions for use). The eight factors selected could change based on aquifer conditions. In other words, several factors could be determined based on geological structure, geomorphology, and so on;

however, these eight factors are considered the most appropriate and influential factors affecting the groundwater quality network design in areas such as Kermanshah province. Access to the data and their accuracy are among the main limiting factors in choosing some of the more desirable criteria such as hydraulic conductivity of each aquifer, hydraulic properties of basement rocks and others.

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