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Groundwater vulnerability mapping of Qatar aquifers

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A B S T R A C T

Qatar is one of the most arid countries in the world with limited water resources. With little rainfall and no surface water, groundwater is the only natural source of fresh water in the country. Whilst the country relies mainly on desalination of seawater to secure water supply, groundwater has extensively been used for irrigation over the last three decades, which caused adverse environmental impact.

Vulnerability assessment is a widely used tool for groundwater protection and land-use management. Aquifers in Qatar are carbonate with lots of fractures, depressions and cavities. Karst aquifers are generally more vulnerable to contamination than other aquifers as any anthropogenic-sourced contaminant, especially above a highly fractured zone, can infiltrate quickly into the aquifer and spread over a wide area.

The vulnerability assessment method presented in this study is based on two approaches: DRASTIC and EPIK, within the framework of Geographical Information System (GIS). Results of this study show that DRASTIC vulnerability method suits Qatar hydrogeological settings more than EPIK.

The produced vulnerability map using DRASTIC shows coastal and karst areas have the highest vulnerability class. The southern part of the country is located in the low vulnerability class due to occurrence of shale formation within aquifer media, which averts downward movement of contaminants.

1. Introduction

The concept of aquifer intrinsic vulnerability is based on the idea that some areas above an aquifer provide more resistant to contamination than others (Vrba and Zaporozec, 1994). Mapping groundwater vulnerability using hydrogeological settings gives a clear understanding of natural variation from one point to another within an aquifer.

Vulnerability assessment of aquifers has widely been used to predict the likelihood of aquifer contamination, design of monitoring networks and to help land-use management (Secunda et al., 1998; Ceplecha et al., 2004; Baalousha, 2006, 2010; Cucchi et al., 2008). Index methods are very popular in vulnerability assessment where dimensionless classification of aquifer area is done based on geological and hydrogeological settings of an aquifer (Gogu and Dassargues, 2000). DRASTIC approach is one of the most widely used index method. Geostatistical analysis is another method of vulnerability assessment and modelling approach (i.e. Soutter and Musy, 1998; Assaf and Saadeh, 2009).

The acronym DRASTIC comes from seven hydrogeological parameters, and DRASTIC method has been used for a long time to assess aquifer vulnerability. It uses seven rated maps of depth to water table, recharge, aquifer media, soil media, topography, vadose zone and hydraulic conductivity to calculate a weighted index map of vulnerability (Aller et al., 1987). Each map of the previously-mentioned parameters is rated using a standardized rating system and the index map is the sum of rated maps multiplied by a special weight depending on the importance of each parameter. The higher the calculated index is the higher the vulnerability. This method has been used to assess contamination risk, especially from agriculture in many areas around the world (i.e. Babiker et al., 2005; Assaf and Saadeh, 2009; Baalousha, 2011; Neh et al., 2015). Some studies modified the original DRASTIC that was proposed by Aller et al. (1987) to suits local settings of an aquifer (i.e. Huan et al., 2012; Neshat et al., 2014). DRASTIC approach assumes that contaminants are introduced into the aquifer from land surface and moves by the mobility of water.

DRASTIC approach is normally used to assess granular aquifers. Fractured aquifers with karst features need special consideration as they can be highly vulnerable to contamination compared to granular aquifers. Contamination can percolate into the aquifer

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very fast via sinkholes and fractures, which needs to be considered when assessing vulnerability. DRASTIC method has no consideration for fractures and sinkholes. The shortcoming of DRASTIC is its inaccurate results compared to other methods being used for karst aquifers (Polemio et al., 2009). It was also found that DRASTIC underestimated vulnerability in fractured aquifers (Abdullahi, 2009).

Several methods have been developed to assess vulnerability of karst aquifers. The most famous method is EPIK (Doerfliger et al., 1999). This method conceptualizes karst aquifer system and uses four parameters to classify the aquifer system in terms of vulnerability. These parameters are: epikarst (the uppermost layer of karst formation), protective cover, infiltration conditions ad karst network. Each of these parameters is classified into different classes based on its nature. The resulting map shows the vulnerability index in a similar way as with DRASTIC. Goldscheider (2005) proposed alternative method to EPIK, based on two parameters: protective cover (P) and infiltration conditions (I). According to the Goldscheider (2005), the protective cover included all layers from topography to water table whereas infiltration conditions account for the likelihood of passing the protective cover. PI method classifies P and I parameters into 5 classes from very low to extreme and the final vulnerability map is the product of both P and I.

Human activities on the land surface have the greatest impact on groundwater quality (Baalousha, 2008). Most pollutants leach into the ground and percolate the aquifer if hydrogeological conditions allows; that is, the aquifer at the leaching area is vulnerable. Nitrate is one of the main pollutants that originate from agricultural activities or sewage infiltration.

The objective of this study is to prepare a vulnerability map that suits the hydrogeological settings of Qatar, and can be used for groundwater protection and planning. Two main threats to groundwater exist in Qatar: pollution from agricultural activities (Farms in Fig. 1) and saline water intrusion along the coast line. While salinity of groundwater results in deterioration of water quality and abandoning of farm lands, nitrate has more severe impact on health and nerve system, especially for babies (Chern et al., 1999).

This paper presents the development of groundwater vulnerability maps for Qatar based on two different approaches: DRASTIC and EPIK. Vulnerability maps from both methods are discussed and compared to check which approach conforms to Qatar hydrogeological settings. DRASTIC has been widely used and applied to different areas all around the world and to different types of aquifers whereas EPIK has been used and applied to only karst aquifers. Because the study area in Qatar contains both karst and non-karst, in addition to lack of data on karst network and extension, both models have been used.

1.1. The study area

Qatar is an arid country located in the eastern part of the Arabian Peninsula and extending in the north-south direction. Its length is approximately 180 km in the south-north direction, and its maximum width is 90 km; thus the total area of Qatar is 11,586 km^2. The country is surrounded by the Arabian Gulf from all direction but the south, where it borders Saudi Arabia (Fig. 1).

As a result of rapid economic expansion over the last decade, the population of Qatar has dramatically increased from 600,000 in 2000 to 2,172,000 in 2014 (World Bank, 2015). With little rain and no surface water, Qatar is relying on desalination of seawater to meet the increasing domestic demand for water, whereas groundwater has been used for irrigation. As a result of overpumping, aquifers have been overexploited over the last three decades, resulting in a great decline in groundwater levels and deterioration of water quality. The abstracted groundwater is mainly used to irrigate farms, which are concentrated in the northern and central parts of the country (Fig. 1).

The country is underlain by a series of gentle dipping and flat lying deposits over the rocks basement. Several anticlines rose above the main geological platforms in the Arabian Shelf, and extending in the north south direction. Two major anticlines exist; the Dukhan anticline in the west and Qatar anticline (Qatar Arch) in the middle of the country.

Fresh groundwater occurs in the form of lenses mainly in the northern part of the country, sitting atop brackish and saline groundwater. Seawater has progressively intruded inland over the last decades resulting in shrinkage of fresh groundwater lenses.

Rainfall is the main source of aquifer replenishment, with an annual average between 10 mm and 200 mm (Alsharhan et al., 2001) and a long term average of 76 mm per year. The highest rainfall occurs in the north and gradually decreases southward (Alsharhan et al., 2001).

Prior 1960, municipal water supply in Qatar used to come exclusively from groundwater (Vecchioli, 1976). At present, all municipal supply comes from desalination plants and groundwater is used mainly for agriculture, while small proportion goes to industrial and domestic use. The agricultural water demand in Qatar has increased from 44 million m^3 in 1974 (Kimrey, 1985) to 238 million m^3 per year in 2013. About 70% of abstraction takes place in the northern part of the country, where wells penetrate the Rus formation with a depth between 60 and 70 m. The total number of different purposes wells is more than 8500 (Schlumberger Water Services, 2009).

1.2. Vulnerability assessment approached

In the following sections, two approached of vulnerability are presented: DRASTIC and EPIK. DRASTIC is a general approach for intrinsic vulnerability whereas EPIK is used exclusively for karst aquifers.

1.3. DRASTIC approach

DRASTIC approach was first suggested in by Aller et al. (1987) as an index-based method to assess vulnerability of aquifers to contamination. It assigns relative rate for each class of the seven hydrological parameters. These parameters are depth to water table (D), net groundwater recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity (C). More details about rating can be found in Aller et al. (1987). The final vulnerability index map of DRASTIC is given by:

$$\text{DRASTIC index} = 5*\text{Dr} + 4*\text{Rr} + 3*\text{Ar} + 2*\text{Sr} + 1*\text{Tr} + 5*\text{Ir} + 3*\text{Cr} \quad (1)$$

Where r subscripts indicate rated maps. Different standard rates for each paramour are given by Aller et al. (1987). As appears in Equation (1), DRASTIC assigns a different weight to each parameter. The highest weight goes to depth to water table and vadose zone and the lowest assigned to topography. The resulting map is the sum given in Equation (1). In this study the ArcGIS software was used to create rated maps and Raster Calculator was used to obtain the sum of Equation (1).

1.4. EPIK approach

EPIK is an approach for vulnerability assessment in karst, and it