Using Monte Carlo simulation to estimate natural groundwater recharge in Qatar

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Abstract Rainfall is the only source of groundwater recharge in arid countries, where no surface water exists. Quantification of the total volume of rainfall recharge is essential for water resources management, development and protection, but it is challenging. Numerous recharge estimation methods can be found in the literature, but the selection of the most appropriate one depends on the hydrogeological setting of the area of study and on the available data. Qatar is an arid country as rainfall is very little and surface water is non-existent. Aquifer is the only conventional source of water, which has been over-exploited in the last few decades. One of the main country's grand challenges is to implement an aquifer storage and recovery scheme, which requires understanding of the flow regime and quantification of the natural rainfall recharge. This study uses a water balance model coupled with Monte Carlo Simulation to quantify rainfall recharge. Using a historical groundwater piezometric map, the flow to the sea was calculated by applying Monte Carlo Simulation to the Darcy's Law. The natural recharge was calculated considering all water budget components. Results reveal the groundwater rainfall recharge amounts to 58.7 million m³, which is close to literature values obtained by other means.

Keywords Groundwater recharge · Stochastic water budget · Monte Carlo simulation · Qatar · Arid regions

Introduction

Groundwater recharge is the total volume of water that inflow into the saturated zone of the ground. This water may originate from different sources such as surface water bodies, rainfall, and lateral flow. In arid countries, recharge might occur only during wet seasons through rainfall. It is important to quantify recharge as it helps manage water resources in any catchment, and identify the safe yield of an aquifer. Recharge quantification is also influential for groundwater quality and aquifer vulnerability (Robins 1998). Many pollutants, especially those of anthropogenic origin resulted from human activities on-land, infiltrate the ground with the mobility of water and find their way into the sub-surface zone (Baalousha 2008). Several methods can be found in the literature discussing groundwater recharge estimation in arid and semi-arid areas. The selection of a method depends on the area of study as particular methods suit certain conditions, and each method has its limitation and strength. Xu and Kinzelbach et al. (2002) made an extensive survey of recharge estimation methods, with advantages and limitation of each. Xu and Beekman (2003) listed 16 methods of recharge estimation in arid and semi-arid regions, with a discussion of advantages and limitation of each, whereas Healy (2010) classified recharge methods into seven. In general, methods of recharge estimation can be divided into four categories covering surface water, unsaturated zone, saturated zone and a mix of saturated–unsaturated.

Isotopes analysis and water chemistry is one of the widely-used methods for identification of recharge areas and understanding of groundwater flow systems. Numerous studies have used isotopes such as tritium and Oxygen, in addition to noble gases and chlorofluorocarbons (CFC's) for water aging and identification of recharge origin

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(Yurtsever and Payne 1978; Nkotagu 1996; Alyamani 2001; Seiler and Gat 2007; Morgenstern et al. 2012; Prada et al. 2016). Isotopes methods are useful for identification of recharge source and for understanding water mixing processes in a catchment, but they provide little insight into the total volume of recharge into an aquifer.

Other recharge studies use hydrogeological settings, with the help of geographical information system (GIS) to delineate recharge areas and to identify potential artificial recharge zones (Chowdhury et al. 2010; Machiwal and Jha 2015; Baalousha 2015a; Yeh et al. 2016; Senanayake et al. 2016). Although these methods are good for delineation of recharge/discharge zones within a catchment, their main limitation is the uncertainty in quantification of the total recharge volume.

In addition to the methods mentioned above, recharge can directly be obtained using lysimeters (Brutsaert, 1982), which can provide precise measurements (Healy 2010). Several studies were based on lysimeters measurements for recharge estimation and understanding of flow drainage in the unsaturated zone (Chapman and Malone 2002; Freyberg et al. 2015; Duncan et al. 2016). The drawbacks of lysimeters are that they are expensive to install and need careful calibration. In addition, drainage measurements using lysimeters can be affected by near surface flow (Kinzelbach et al. 2002). Regional estimation of recharge using lysimeter can be difficult as the obtained values can vary from one point to another (Kinzelbach et al. 2002). While Duncan et al. (2016) found that lysimeters may over-estimate recharge values in the case of irrigated dry land, Chapman and Malone (2002) found them underestimate recharge.

In karst aquifers, analysis of springs outflow was used to estimate groundwater recharge (Hughes et al. 2008; Geyer et al. 2008). Other studies on karsts are relied upon rainfall-runoff models to analyze recharge (Jukic and Denic-Juki 2009). The challenge facing the use of these methods in karst systems is that they require prior knowledge of conduit network (Hughes et al. 2008; Healy 2010). Tracers-based methods are more common for recharge estimation in karst aquifers as they produce more reliable results than rainfall-runoff methods (Greene 1997; Katz et al. 1997).

On a catchment scale level, water balance analysis is a simple method that has widely been used and applied to different study areas (Khazaei et al. 2003; Lee et al. 2006; Yeh et al. 2007; Baalousha 2007; Baalousha 2009a). In water balance models, recharge is calculated using all components of inflow and outflow into and out of a catchment. These components can be obtained using numerical models (Stoertz and Bradbury 1989; Dripps et al. 2006; Doble et al. 2008; Baalousha 2012a; b), but a good calibration is required to obtain reliable output (Kinzelbach et al. 2002). The advantage of water balance

models is that they provide insight to the hydrological system and the interaction between recharge and other water budget component (Healy 2010). In addition to the catchment scale, water balance models can also be performed on boreholes in an aquifer using fluctuation of groundwater level, and its relation to rainfall. Examples of rainfall-water level methods are Cumulative Rainfall Departure (CRD) (Xu and van Tonder 2001; Xu and Beekman 2003; Baalousha 2005), Saturated Volume Fluctuation (SVF) and EARTH model (Beekman et al. 1996). However, these methods require a long time series to have a reliable estimate of recharge (Kinzelbach et al. 2002). The problem with water balance methods is the accuracy, which depends on the quality and quantity of data (Xu and Beekman 2003). Another limitation of water balance models is the assumption of a uniform recharge in the study area.

Uncertainty analysis has been widely used to overcome accuracy problems of water balance models. Stochastic methods such as Monte Carlo Simulation and Latin Hypercube Sampling were used in many studies in hydrogeology and recharge estimation (Bekesi and McConchie 1999; Hunt et al. 2001; Baalousha 2006; Dages et al. 2009; Baalousha 2009b; Zhen-min 2011; Baalousha 2015b). Monte Carlo Simulation and all sampling methods use the probability distribution of uncertain parameters to generate random samples repeatedly. The model is then solved for each realization to create a large number of model output, and the mean and standard deviation are calculated based on the outcome of all runs. According to the law of large numbers, the mean value from a large number of realizations should be close to the expected value.

This study develops a stochastic water balance model using Monte Carlo Simulation to estimate natural groundwater recharge for Qatar. The model considers all components of inflow and outflow into the aquifer and applies MCS on uncertain parameters. Results obtained, using this method, are compared to the ones in the literature.

Methodology

Figure 1 shows the stepwise methodology of recharge analysis using water balance model coupled with Monte Carlo Simulation. As described in the study area, the country of Qatar is surrounded by the sea from all directions but the south. Hence, the sources of recharge are rainfall and lateral groundwater flow across the southern border. The lateral groundwater flow across the border with Saudi Arabia is estimated at 2.2 million m³ per year (Food and Agriculture Organisation of the United Nations (FAO) 2016). As the country is a peninsula surrounded by sea, outflow occurs in a form of groundwater abstraction and

Fig. 1 Stepwise methodology of the water balance model for Qatar

flow to sea. In steady-state conditions, inflow to the aquifer equals outflow; that is:

$$R + F_L + I_R = P + F_S, \quad (1)$$

where R is rainfall recharge, F_L is lateral flow, I_R is irrigation return flow, P is abstraction and F_S is flow to the sea. Equation (1) can be re-written as:

$$R = P + F_S - F_L - I_R \quad (2)$$

The two unknowns in Eq. (2) are the flow to the sea (F_S) and recharge (R). To obtain recharge, flow to the sea (F_S) will be calculated using Monte Carlo Simulation applied to Darcy's Law. The calculation of flow to sea is based on contour lines of piezometric survey and hydrogeological characteristics of the aquifer. Applying MCS to Darcy's Law parameters along the coastal contours enables the estimation of the total outflow to the sea.

The study area

Qatar is a small arid country located in the eastern side of the Arabian Peninsula and extending in the south-north direction in the Arabian Gulf (Fig. 2). It has limited water resources as the average annual rainfall is only 80 mm per year (Eccleston et al. 1981; Alsharhan et al. 2001). Rainfall is very erratic and occurs between November and March. The country is around 180 km long, and its maximum width is 85 km; thus the total area of Qatar is 11600 km² (Kimrey 1985). The terrain of Qatar is flat as the land surface elevation varies between 0 near the shoreline and a maximum of 107 meters above mean sea level at some locations in the southern part of the country.

Qatar topography is characterized by land depression originated as a result of land collapse because of limestone dissolution, forming karst features. These

Fig. 2 The study area (Baalousha 2016)

depressions are good for recharging the aquifer, as runoff accumulates in these depressions (Vecchioli 1976, Kimrey 1985).

Qatar hydrogeology comprises geological formations from Pliocene and Eocene age, with some Quaternary deposits near the coastline, in a form of salt-flats or Sabkha (Al-Yousef 2003). Three water-bearing layers exist in Qatar: (1) The Dam and Dammam Formation on the top, which covers most of the surface area of Qatar; (2) Rus Formation underneath; and (3) Umm er Radhuma Formation in the bottom. All these three formations are composed of limestone with different degrees of dolomite, clay and chalk. The top layer (Dam and Dammam Formation) has a maximum thickness of 50 meters and is generally dry except in low land and near the coastline, whereas the underneath Rus formation is the main aquifer, especially in the northern part of the country. The thickness of Rus Formation varies between 30 and 90 m (Kimrey 1985). This layer contains gypsum and anhydrite in the southern part of the country, making the groundwater quality poor. The bottom layer has a thickness of around 300 m (Kimrey 1985), and extends from the eastern side of Saudi Arabia eastward covering the entire region. The quality of groundwater in this layer varies from one location to another, but in Qatar, it is generally saline.

Water balance

Groundwater development started in the early 1950s using hand dug well, and the abstracted volume was small as the population of Qatar was 40,000 at that time (Al-Mohannadi et al. 2003). No records are available on the total volume of abstracted groundwater, but several reports indicated it was 50 million m³ in early seventies and increased to 60 million m³ per year in 1980 (Al-Mohannadi 2006; Schlumberger Water Services 2009). Irrigation return flow at that time is reported to be 20 % of abstraction (Al-Kaabi, 1987).

Figure 3 shows the peizometric contour map for Qatar and flow direction based on data from 1980 (Al Hajari 1990). This map shows the water level has a peak high of 6 meters above mean sea level in the northern part of the country and declines to 0 near the coast. The flow is obviously from the middle of the peaks towards the sea and shallow areas like Sabkhas.

Groundwater flow to the sea and to coastal salt-flat (i.e. Dukhan Sabkha) occurs along the coastline, as shown in Fig. 3, which is indicated by a blue line in Fig. 4. The dotted line in Figs. 3 and 4 shows the limit of aquifer boundaries at the west. The total flow across the coastal line is calculated using Monte Carlo Simulation, as it is explained in the next section.

Fig. 3 Piezometric map and flow directions of the shallow aquifer in 1980 (Al Hajari 1990)

Fig. 4 Aquifer outflow to the sea and to salt-flats

Monte Carlo simulation

Flow to the sea (discharge) across the blue line in Fig. 4 can be computed using Darcy's Law as follows:

$$F_S = LT \frac{dh}{dn} \quad (3)$$

where L is the length of the counter across which the flow occurs, T is the aquifer transmissivity, and dh/dn is the flow gradient perpendicular to the contour. Using GIS, the flow gradient was calculated based on the coastal contours. Values of transmissivity were obtained from pumping test data (Eccleston et al. 1981; Schlumberger Water Services 2009). Table 1 shows the descriptive statics of the randomized parameters used in Darcy's Law. The total length across which the flow occurs (Fig. 4) is 327295 meters, and the flow gradient was calculated using Spatial Analyst tool in ArcGIS by creating a raster slope map from contours.

The Monte Carlo Simulation was implemented using parameters in Table 1. The probability distribution was assumed to be log-normal to exclude negative values (Helsel and Hirsch, 2002). Fifteen million realizations were created for T and dh/dn and the mean values of all realizations were used to calculate F_S using Eq. (3). The expected value of flow to the sea F_S is given by:

Table 1 Descriptive statistics of flow parameters

Parameter	Min	Max	Mean	Standard deviation
Transmissivity (T) [m ² /day]	2	714	139.75	154.11
Flow gradient	0.000205	0.013752	0.00333	0.004582

Table 2 Water balance components in 1980

Component	Value (million m ³)
Irrigation return flow (in)	12
Lateral groundwater inflow (in)	2.2
Recharge (in)	58.73
Groundwater abstraction (out)	−60
Flow to the sea (out)	−12.93
Total	0.0

$$E(F_S) = \mu_{MC} = \frac{1}{n} \sum_{i=1}^n L \left(T \frac{dh}{dn} \right)_i \quad (4)$$

where μ_{MC} is the mean value of Monte Carlo and n is the number of realizations. The variance of Monte Carlo estimation is:

$$\sigma_{MC}^2 = \frac{1}{n} \sum_{i=1}^n L \left(T \frac{dh}{dn} - \mu_{MC} \right)^2 \quad (5)$$

Using Eqs. (4) and (5), the total mean annual flow to the sea, and its variance were found to be 12.93 million m³ and 0.42 million m³ per year, respectively. Applying these values to Eq. (2), recharge (R) equals 58.73 million m³ per year.

Table 2 shows the components of water balance based on 1980. Negative values indicate the flow is out of the aquifer, whereas positive values mean inflow.

Table 3 Estimates of groundwater recharge from different sources

Method	Recharge volume (million m ³)	Reference
SWAT2005 model	66.6	Schlumberger Water Services (2009)
Water Balance for the year 1971–1983	21–166	Harhash and Yousif (1985)
Groundwater flow model	68	Baalousha (2016)
GIS analysis	25.4	Baalousha (2015a)
Percentage of rainfall	27	Eccleston et al. (1981)
Water balance for the years 1971–1974	20.9	Parker and Pike (1976)
Estimated from several sources	56	Food and Agriculture Organisation of the United Nations (FAO) (2016)
Stochastic water balance	58.73	This study

Results and discussion

Several studies have been done to estimate groundwater recharge in Qatar, as listed in Table 3. The wide range of recharge estimation reflects the high variability of rainfall from one year to another, in addition to differences in the outcome of each method. For example, Harhash and Yousif (1985) estimated recharge to be 21 million m³ in a dry year and 166 million m³ in a wet year. Schlumberger Water Services (2009) listed the estimate of groundwater recharge for the years from 1971 to 2005, collected from different sources. The recharge values for this period vary between 22 and 162 million m³ per annum.

Result of this study is consistent and within the range of all previous studies. It is close to the one included in Food and Agriculture Organisation of the United Nations (FAO) (2016). Given the high variability of rainfall, the results of this study represent the long-term average.

Conclusions

Rainfall recharge quantification is essential for water resources management, planning and development. Due to scarcity of water, and in the light of Qatar National Vision for 2030 (Qatar General Secretariat for Development Planning, 2009), aquifer storage and recovery scheme has been identified as a means to increase the national water security. The first step towards aquifer storage and recovery implementation is to understand the flow regime and to quantify the natural groundwater recharge from rainfall.

Recharge estimation is very challenging as no particular method can be considered to be accurate, and every approach has its limitations. The selection of a recharge method may vary from one case to another depending on available data and hydrogeological characterization. The main drawback of most of the recharge estimation methods is the uncertainty of involved parameters in estimation. This study used Monte Carlo Simulation to overcome the uncertainty problem. The main advantage of the method used in this study is its low data requirement, and its suitability to Qatar hydrogeological setting. Being surrounded by the sea means the groundwater flow to the sea is the only outflow components, in steady-state conditions.

Monte Carlo Simulation was used to create random samples of aquifer transmissivity and head gradient. Darcy's Law was used to calculate the total groundwater influx to the sea. The estimated recharge in this study amounts to 85.73 million m³ per year, which is comparable to values in the literature obtained by other means.

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