Geopersia 2023, 13(2): 415-425
DOI: 10.22059/GEOPE.2023.358106.648711

RESEARCH PAPER

Estimating recharge into the Semnan alluvial aquifer using saturated zone studies

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Received: 21 April 2023, Revised: 06 July 2023, Accepted: 20 July 2023

Abstract
The assessment of recharge is one of the most important issues in management and planning of the groundwater resources. In this study, the amount of recharge to the Semnan alluvial aquifer was investigated using methods of water table fluctuations (WTF), chloride mass balance (CMB), water budget and stable isotopes. The parameter is highly important for managing this vital aquifer as over-exploitations for drinking, agricultural and industrial uses occurred, resulting in water table decline with an average rate of about 80 cm annually. Based on the results, the values of recharge into the Semnan alluvial aquifer are estimated about 4.4, 2.5 and 2.1 MCM/year by WTF, CMB and water budget methods, respectively. The isotopic data (^{18}O and ^{2}H) do not show any significant effects of evaporation on recharge process, confirming the main role of highland recharge in this arid-land aquifer. Combining results of the recharge studies in saturated zone of Semnan aquifer, yields annual rainfall recharge of about 3 MCM, which is about 5% of the annual precipitations.

Keywords: Water Table Fluctuation Chloride Mass Balance Water Budget Isotope

Introduction

Todays, groundwater is more important than ever because of the increasing demands for growing population. It is undeniable and necessary to survey groundwater resources with more detailed studies to help their planning and maintenance as a complex issue with wide-ranging management topics. In this regard, estimation of recharge is one of the essential components that is needed to properly manage groundwater aquifers (Goes, 1999). The recharge phenomenon is defined as the volume of water that is added to the groundwater through a) direct recharge/dispersion b) indirect recharge/in-dispersion and c) local recharge as introduced by Lerner (1990) and De Vries & Simmers (2002). According to other studies (Xu & Beekman, 2003), four models have been explained for aquifer recharge including a) downward flow from an unsaturated zone, b) vertical and horizontal flow between aquifers, c) returned agricultural waters and d) artificial recharge.

There are number of methods for estimating groundwater recharge including physical-chemical and numerical methods (Sophocleous, 1991). The methods are also divided into surface water, unsaturated and saturated approaches based on the zones that required data for recharge calculations are attained (Healy, 2010). Water table fluctuation (WTF), chloride mass balance (CMB) and water budget methods in saturated zone are mostly used ones. They provide estimates of actual recharge that means the water that really arriving at the water table.

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Regarding the uncertainties inherited in groundwater recharge calculations, using multiple methods are highly advised (Healy, 2010). Depending on the outcome of the uncertainty that may influence the groundwater calculations, the use of various methods makes the results more reliable and accurate (Scanlon et al., 2002). Furthermore, the cost of studies including sampling, monitoring and analysis is always a limiting factor that can influence the recharge estimates. Climatic parameters such as temperature, precipitation, and evaporation are the most important factors that influence recharge rates (Green et al., 2011). In semi-arid and arid regions, determining the recharge is more difficult and complex because of the spatial and temporal changes in precipitation (Rivett et al., 1990; De Vries & Simmer, 2002). Many studies (e.g. Chenini & Mammou, 2010; Dash et al., 2019; Kennett-Smith et al., 1994; Machiwal et al., 2011; Priyan, 2021; Simmers, 2013; Tweed et al., 2011) have been conducted to estimate groundwater recharge by different methods in arid and semi-arid regions. As a general result, the rainfall values below 200 mm usually result in negligible recharge (Scanlon et al., 2002).

The Semnan alluvial aquifer at the north arid region of Iran is a crucial water resource upon which human activities heavily relied and then plays a vital role in the development of agriculture and industry. In order to properly manage this valuable water resource, estimating balance components of the aquifer is essential. So, this study was aimed to estimate actual groundwater recharge into the Semnan alluvial aquifer based on studies in saturated zone of aquifer using WTF, CMB, water budget and stable isotopes. The results were finally combined to provide coefficient of rainfall recharge in this important aquifer.

Area of Study

Semnan alluvial aquifer with an area of about 543 km^2 is located at latitude 53° 00′ N to 53° 40′ N and longitude 35° 22′ W to 35° 39′ W (Figure 1). The average height of the plain is about 1300 meters above sea level and the mean values of temperature and precipitation are 13 ^{o}C and 126 mm, respectively. The aquifer is unconfined which is mostly exploited for agricultural practices, industry and drinking. The general groundwater flow direction is from north to the south. The aquifer is mostly recharged from east to north and discharged in south. This is also discharged by many pumping wells.

Materials and methods

Three steps were involved in this research including 1) preparing data, 2) application of WTF, CMB, water budget and isotopes methods and 3) comparing results and estimating actual recharge into the Semnan aquifer (Figure 2).

The applied methods are briefly explained as the following:

Water-table fluctuations (WTF) method

WTF method is based on the increasing water table, which is caused by the amount of precipitation that arrives at an unconfined aquifer (Scanlon et al., 2002). The method calculates recharge by Eq.1 which is emanated from a simple water-budget equation where all the other components are assumed to be zero (Healy, 2010).

$$R = S_Y * \Delta H / \Delta t \qquad (1)$$

Sy denotes the aquifer specific yield, ΔH is the water-table rise, and Δt is the time range when the water table rises. The value of the rising annual water table (ΔH) is calculated from the distance between the rise's peak and its lowest position on the extrapolated antecedent recession curve at that point (Healy, 2010) (Figure 3).

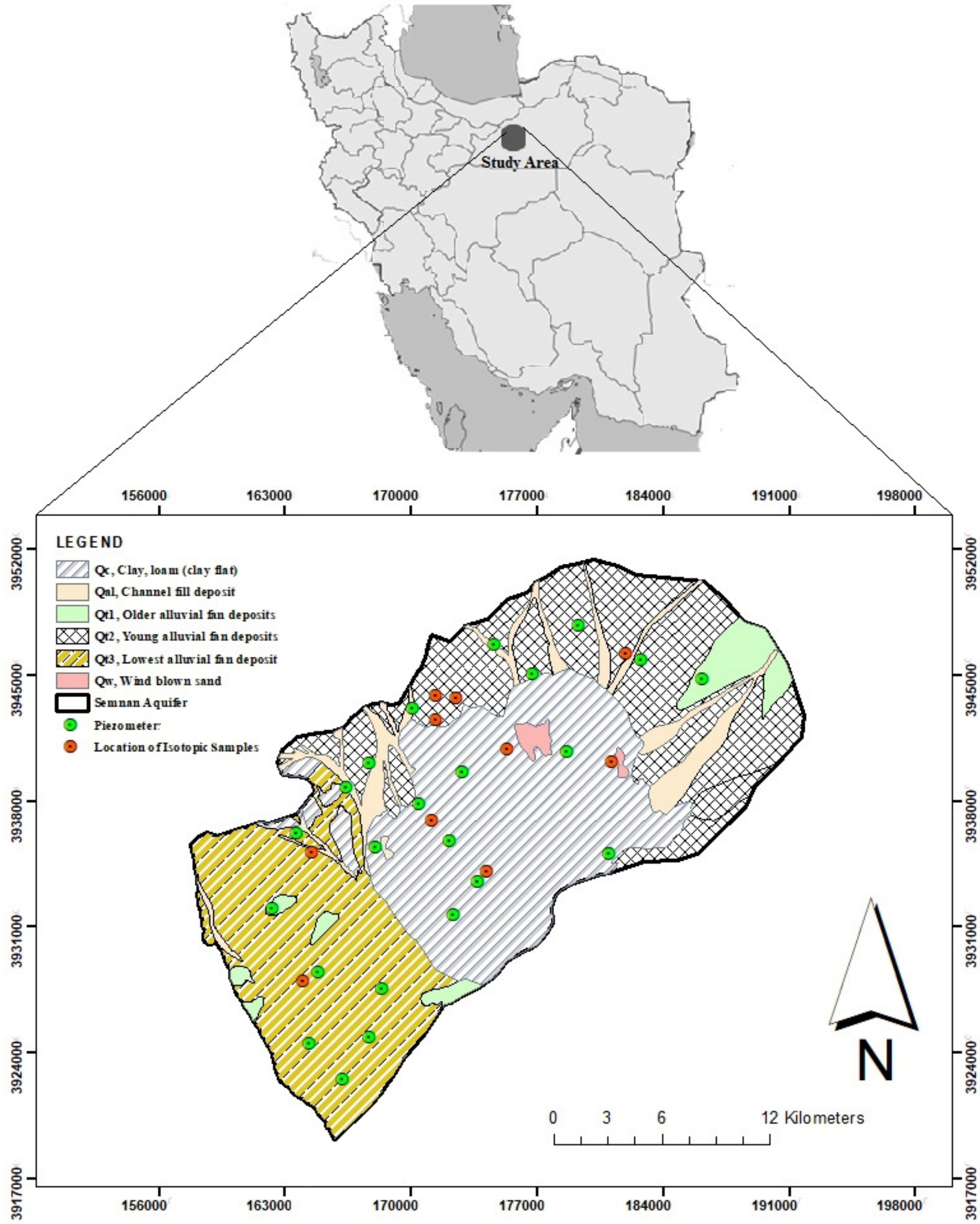

Figure 1. Geological map of the Semnan aquifer representing the piezometers for monitoring groundwater levels and location of samples for isotopic measurements

In order to calculate the water table fluctuations of Semnan aquifer, the water table data in 22 piezometers from 2009 to 2020 (a period of 11 year) was used. The location of piezometers is shown in Figure 1. Depth to water table in each piezometer is measured monthly by Semnan regional water authority.

Chloride mass balance (CMB) Method

CMB method was used to calculate recharge value of the Semnan aquifer considering chloride concentrations in groundwater and precipitation. The following equation (Healy, 2010) estimates the aquifer recharge (R), according to CMB method:

$$R = P\, C_p / C_{gw} \tag{2}$$

in which R denotes the recharge value, P is the amount of precipitation, C_p is the chloride concentration (mg/l) in the precipitation, and C_{gw} is the chloride concentration in groundwater samples.

In order to use CMB method for calculating recharge, 36 groundwater and 3 rainfall samples were collected from Semnan aquifer in January 2021. The samples were analyzed for chloride concentrations by titration method with $AgNO_3$ as indicator in water and environment Lab of the Shahrood University of Technology.

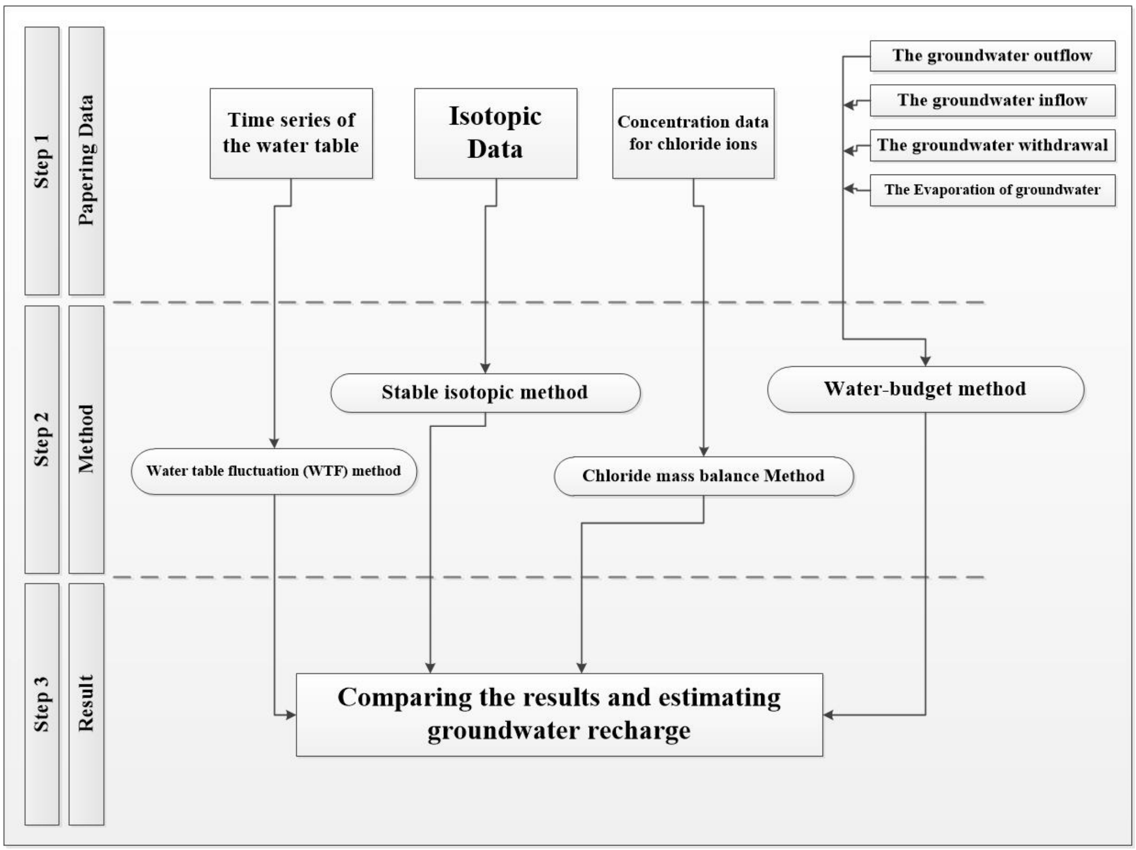

Figure 2. Flowchart of the research for estimating recharge values of the Semnan aquifer

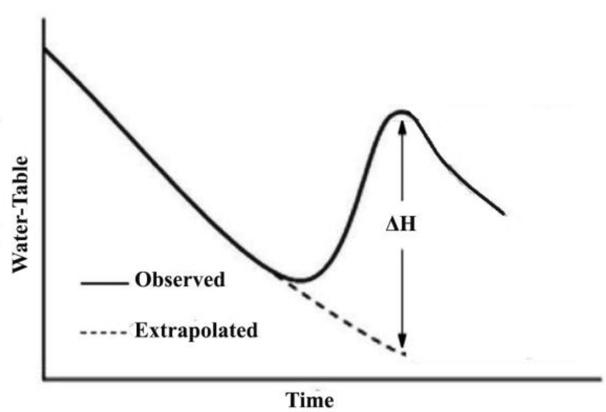

Figure 3. Calculating annual groundwater rise (ΔH) in a piezometer (Healy, 2010)

Water budget method

One of the methods used to calculate the recharge rate of the Semnan aquifer is the water budget, which considers the water movement into and out off of the groundwater reservoir (Healy, 2010). This residual approach is a common way to estimate recharge (R). In order to calculate the recharge as residual, all other components of the water budget are estimated (Scanlon et al., 2002), so the balance equation for Semnan aquifer was considered as following:

$$R = Q^{gw}{}_{off} - Q^{gw}{}_{on} + Q^{bf} + ET^{gw} \pm \Delta S \quad (3)$$

In which R is the groundwater recharge, $Q^{gw}{}_{off}$ the groundwater outflow, $Q^{gw}{}_{on}$ the groundwater inflow, Q^{bf} the groundwater withdrawal by pumping wells, ET^{gw} the evapotranspiration from groundwater and Δs the changes in groundwater aquifer storage. For all the terms, the volume of water per year was considered.

To calculate groundwater inflows and outflows, Darcy's equation was used according to the following equation:

$$Q = TiW \quad (4)$$

where T is considering transmissivity, i is the hydraulic gradients and W is the width of the inlet and outlet flow channels on iso-potential map of the aquifer.

Stable isotopes method

The isotopic method is one of the practical methods which is used to estimate the value of recharge. Groundwater recharge rates (mm) are calculated using oxygen-18 (^{18}O) and deuterium (^{2}H) in groundwater using empirical equations (Clark & Fritz, 2013). Displacement (shift) of groundwater isotopic contents from the local meteoric water line (LMWL) and the values of recharge are related as the following equations:

$${}^{18}_{1}O_{shift} = \frac{3}{\sqrt{Recharge\ (mm)}} \quad (5)$$

$${}^{2}_{1}H_{shift} = \frac{22}{\sqrt{Recharge\ (mm)}} \quad (6)$$

To estimate recharge using isotope methods, 8 samples were taken from Semnan aquifer (Figure 1) and one precipitation sample was collected and sent to the Atomic Energy Agency of Iran. Table 1 represents the values of stable isotopes in water samples.

The quality assurance/quality control (QA/QC) was carried out by qualified experts of the laboratory, including the analysis of reagent blanks, analytical duplicates, and certified reference materials.

Table 1. The values of stable isotopes in precipitation and groundwater samples from the Semnan aquifer (January 2021)

Sample Name	^{2}H (‰)	^{18}O (‰)
W3	-67.440	-11.25
W8	-55.460	-9.71
W23	-68.130	-11.93
W25	-58.590	-10.45
W28	-62.930	-11.96
W29	-60.790	-11.23
W30	-61.630	-10.73
W35	-61.680	-10.76
P3 (precipitation)	-51.740	-8.86

Results and discussion

Recharge estimates by WTF method

The representative (average) hydrograph of the Semnan aquifer is shown in Figure 4. In general, groundwater level of Semnan aquifer has been declined continuously between 2009 and 2020 with an average rate of about 80 cm per year. Groundwater level is fluctuating monthly in response to the changes in the recharge and discharge components of the aquifer. Groundwater level rises happen when the aquifer is recharged from a variety of sources like rainfall and irrigation return flows. It falls when the total discharges exceeding the recharges (Jafari et al., 2019).

In order to calculate the amount of recharge into the Semnan aquifer, water level rises in each piezometer during rainy seasons were measured separately and then combined to estimate the annual rise (ΔH). Based on the results, measured values of ΔH in piezometers of the Semnan aquifer vary in the range of 0 to 3.3 m per year and the average annual rise is about 0.3 m.

Based on the previous studies in Semnan aquifer (Mirbagheri, 2021) the specific yield (Sy) of the aquifer was determined in the range of 0.0008 to 0.06, averaging as 0.03 (3%).

The values of ΔH and average Sy were used by WFT method (Eq. 1) to estimate annual recharge of the aquifer and the results were presented in Table 2.

Table 2. The values of annual groundwater recharge into the Semnan aquifer calculated by WTF method

Water-year	Precipitation (mm)	Groundwater Recharge (MCM/year)
2009-2010	120.4	5.98
2010-2011	110.9	4.19
2011-2012	183.2	6.75
2012-2013	106.2	5.15
2013-2014	102	4.47
2014-2015	125.2	3.55
2015-2016	106./7	3.33
2016-2017	110.4	2.31
2017-2018	75.3	2.47
2018-2019	183.1	5.70
2019-2020	155.4	4.97
Mean	**126**	**4.43**

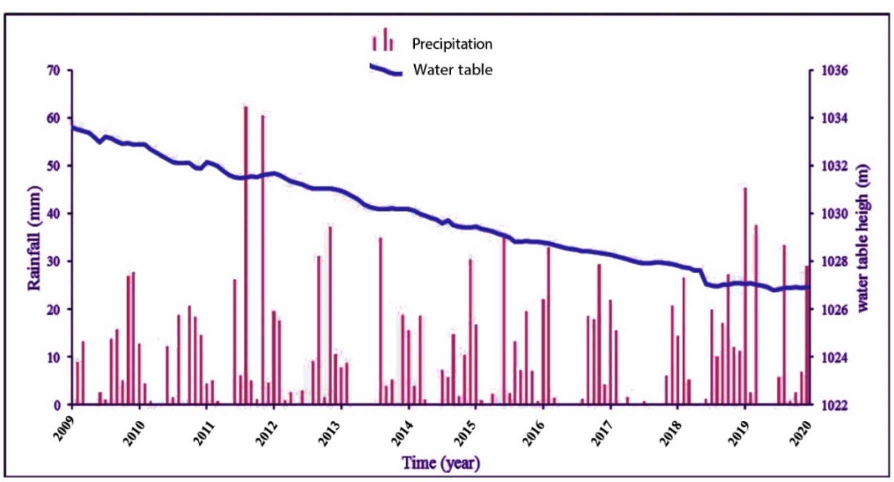

Figure 4. The hygrograph of the Semnan aquifer representing temporal variations of the average groundwater level.

The results show that the annual rate of groundwater recharge into the Semnan aquifer range between 2.31 and 6.75 million cubic meters (MCM) during 2009-2020 (starting September 20) and the average rate of aquifer recharge is about 4.43 MCM/year. Temporal variation of aquifer recharge and precipitations is presented in Figure 5, showing the highest and lowest recharge rates in water-years 2011-2012 and 2016-2017, respectively.

Recharge estimates by CMB method

Based on the chemical analysis of 36 water samples collected from Semnan aquifer, chloride concentrations in groundwaters range between 39 and 1892 mg/l (Figure 6) and the mean value is about 390 mg/l. The chloride concentrations are highly correlated with sodium contents of groundwater samples, suggesting other sources for chloride like halite dissolution in addition to concentrating by evaporation. In this regard, the samples with lower values of chloride concentrations (W3, W6, W9, W10, W22 and W32 in Figure 6) that represent fewer impacts from excessive external sources were considered in recharge estimation by CMB method.

Chloride concentrations in precipitation samples collected from different locations in Semnan plain range between 1.5 and 2.3 mg/l and the average value is about 1.7 mg/l.

Regarding the average chloride concentrations in groundwater and precipitation samples and the mean value of annual rainfall in Semnan plain, the average amount groundwater recharge to the aquifer was estimated about 2.5 MCM/year by CMB approach (Eq. 2).

With respect to the balance equation of Semnan aquifer (Eq. 3), the outflow ($Q^{gw}{}_{off}$) and inflow ($Q^{gw}{}_{on}$) components needs to be calculated using iso-potential (contour) map and Darcy's equation (Eq. 4). The iso-potential map of the Semnan aquifer in which the inflow and outflow boundaries are depicted is shown in Figure 7.

The values of transmissivity in the inlet and outlet zones of the aquifer are in the range of 300 to 400 m^2/day (Mirbagheri, 2021). Hydraulic gradients were calculated in each flow channel on the iso-potential map of the aquifer that range from 0.005 to 0.01. Darcy's equation was used to calculate inflows and outflows into/out the aquifer, resulting in total groundwater inflows and outflows of about 47.85 and 13.47 MCM/year, respectively.

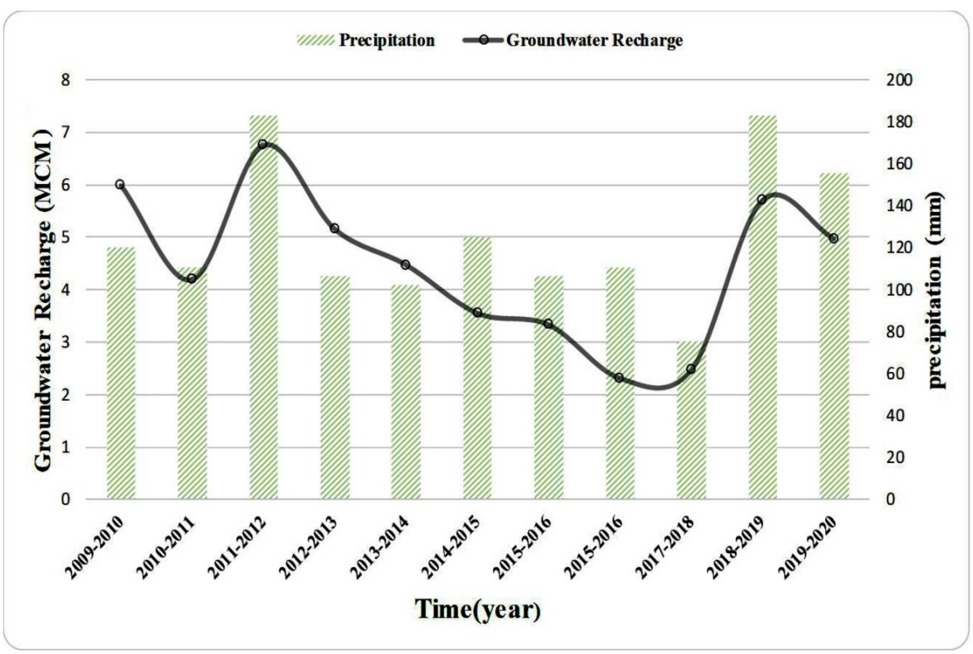

Figure 5. Temporal variations of annual precipitation and groundwater recharge (calculated by WTF method) in Semnan aquifer during 2009-2020

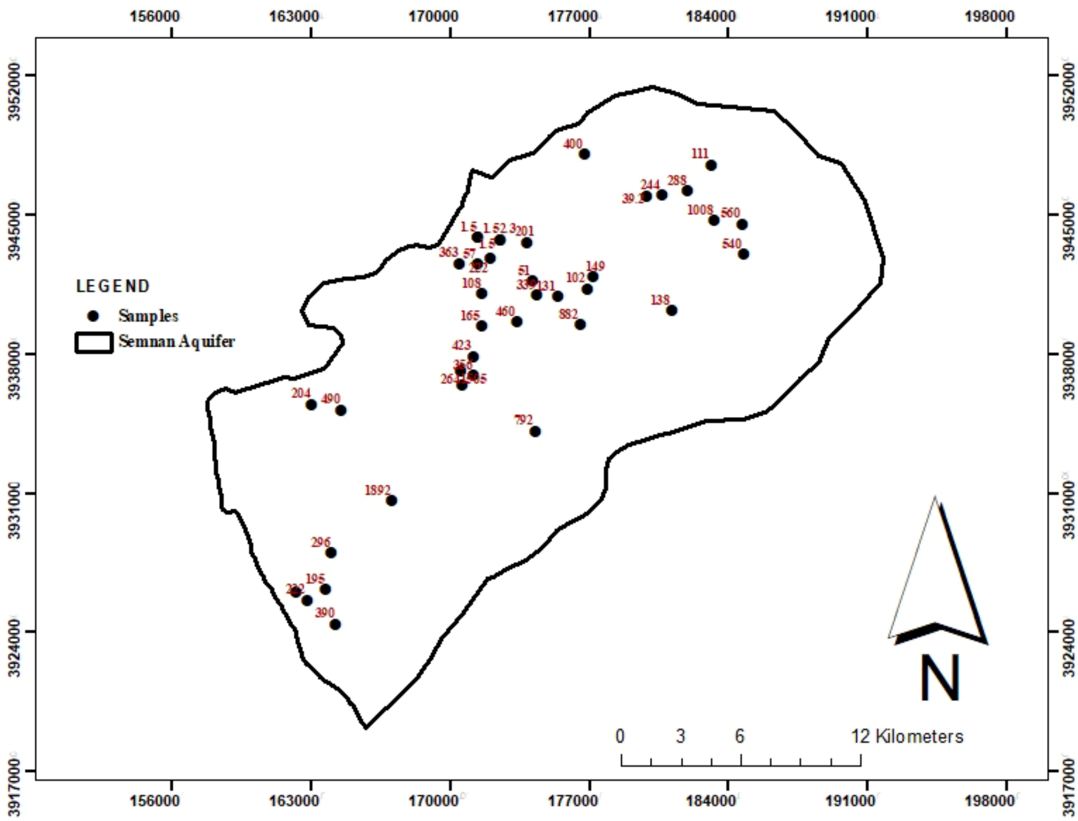

Figure 6. Chloride concentrations (ppm) in Semnan aquifer (January 2021)

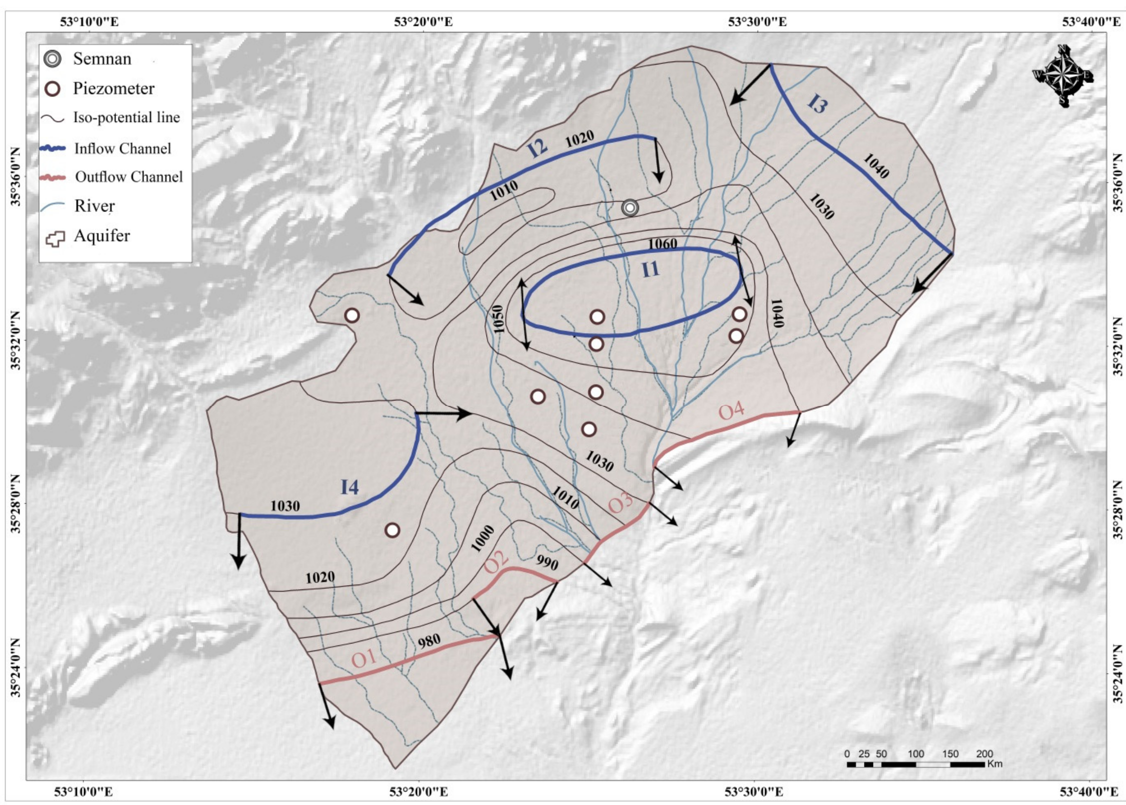

Figure 7. The iso-potential map of the Semnan aquifer in which inflow and outflow channels with direction of the groundwater flow are displayed

Recharge estimates by water budget method

Total discharge of the Semnan aquifer by the pumping wells is about 55 MCM/year. There are no aquifer drainages into the surface waters, as well as the direct evapotranspiration from groundwaters as the depth to water table is more than 5 m everywhere (Todd & Mays, 2005).

Groundwater level of the Semnan aquifer is declining annually with an average rate of 80 cm/year. Therefore, the change in aquifer storage during water-year 2019-2020 (starting September 20) is calculated about -13 MCM/year as the following:

$$\Delta S = A*\Delta h*Sy = 543*(-0.8)*0.03 = -13 \text{ MCM/year}$$

where A stands for aquifer surface area, Δh is declining rate and Sy symbolizes the specific yield of the aquifer.

All the budget components of the Semnan aquifer are presented in Table 3 and the values of total recharge into the aquifer was calculated as the residual of water balance equation. Based on the calculations the value of the total recharge into the Semnan aquifer is about 7.6 MCM/year. It must be mentioned that this value characterizes total recharge into the groundwater aquifer which comprises rainfall recharge and return flows from irrigation and other uses. Considering an average return flow coefficient of about 10% for this arid region (Jafari et al., 2012), return flows are estimated about 5.5 MCM/year and then rainfall recharge into the Semnan aquifer is calculated about 2.1 MCM/year.

Recharge estimates by isotopic method

The values of stable isotopes in groundwater samples from Semnan aquifer vary in the range of -6.73‰ to -11.96‰ for ^{18}O and -51.74‰ to -68.13‰ for ^{2}H. The average contents in precipitation samples are about -8.86‰ and -51.74‰, respectively.

The isotopic contents of the water samples were compared with local meteoric water line (LMWL) and Global meteoric water line (GMWL) on Figure 8. It must be mentioned that as the LMWL has not been determined for the Semnan area yet, the LMWL from nearby Shahrood area (Kazemi et al., 2015) was used. The isotopic contents of the precipitation sample from Semnan area is lying on the LMWL, validating the line to be used for Semnan plain. Comparing the values of isotopes in groundwater samples from Semnan aquifer (Figure 8) confirms all the samples are lying near the LMWL representing more depletion with respect to the local precipitation sample. It reveals the minor effects of evaporation on recharge water of the aquifer. As the isotopic data do not show any measurable shift (displacement) from LMWL, the method cannot be applied to calculate groundwater recharge quantitatively. However, the absence of evaporation on the recharged waters and more depletion related to the local rains falling on the plain surface, confirm that the aquifer is being recharged mainly from highlands (mountain areas).

Table 3. Budget components of the Semnan aquifer in water-year 2019-2020 (starting September 20) and calculating the total groundwater recharge based on water balance equation approach

Name of budget component	Volume (MCM/year)
Groundwater outflow	13.47
Groundwater inflow	47.85
Withdrawal by pumping wells	55
Change in aquifer storage	-13
Total groundwater recharge	**7.6**

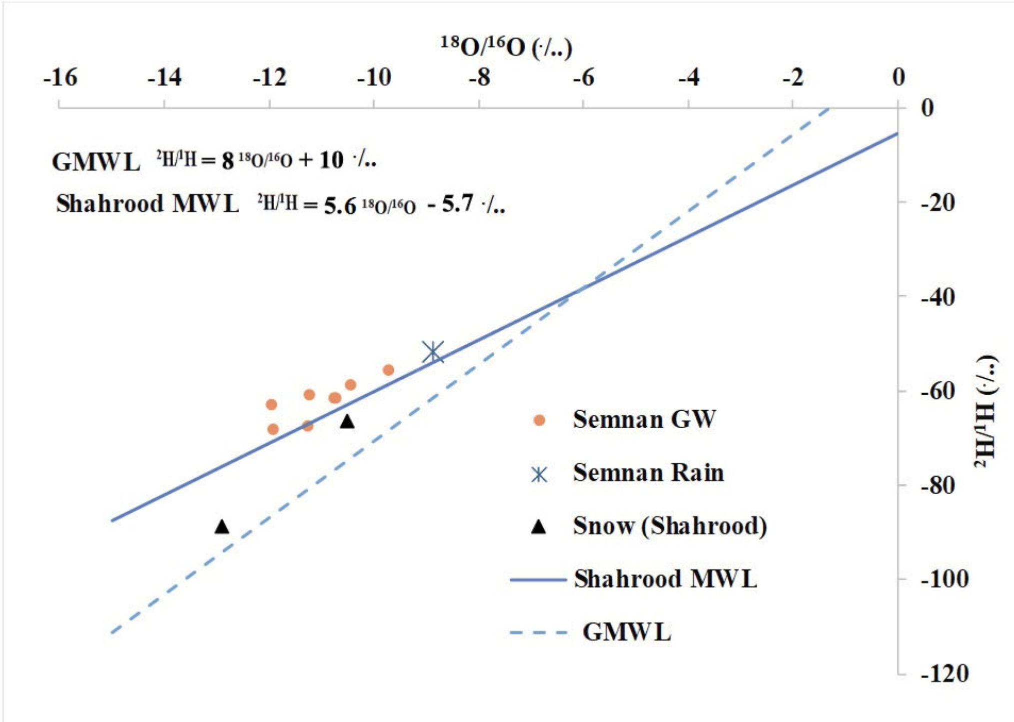

Figure 8. Comparing isotopic contents of the groundwater samples from Semnan aquifer with meteoric water lines. Snow data was taken from Kazemi et al. (2015)

Conclusion

Recharge values into the Semnan aquifer were determined by a multi-method approach considering studies in saturated zone of the groundwater reservoir. Annual recharge values were estimated about 4.4, 2.5 and 2.1 MCM using WTF, CMB and water-budget methods, respectively. Regarding the uncertainties inherited with the applied methods, rainfall recharge value of about 2 to 4 MCM/year (averagely as 3 MCM/year) is recommended for the Semnan alluvial aquifer which is about 5% of the total precipitations on the plain. The value is introduced as the rainfall recharge coefficients (percent) of the Semnan aquifer that can be used in budget calculations to properly manage this vital declining aquifer of the region. Isotopic contents of the groundwaters display more depletion related to the local precipitations, confirming the main role of highland recharge in this arid-land aquifer.

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