Groundwater Modeling and Management under Uncertainty – Hadi & Copty (Eds)

Estimation of groundwater recharge using various methods in Neishaboor Plain, Iran

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ABSTRACT: Recharge rate is the most important component in water balance computation and ground-water modeling. Also, it is the critical factor in optimal planning and management of groundwater resources in arid and semi arid regions such as the eastern part of Iran. There are different techniques to quantify the recharge amount. Each of these methods has been developed in separate hydro-geological conditions and they will estimate completely different recharge value in an identical region. In this study, based on available hydro-geological information, three of these methods were selected to estimate the groundwater recharge. All of these methods are based on the water balance principle (rainfall-groundwater level relationship), including WTF (Water Table Fluctuation), DHB (Distributed Hydrological Budget) and HB (Hydrological Budget). These methods were useful, easy to be utilized, cost effective, simple, requiring few non-deterministic data such as groundwater level measurements, rainfall, aquifer properties, and groundwater extraction datasets. These methods were used to provide the percentage of irrigation return flow and the precipitation contribution to natural groundwater recharge. In order to apply the first two methods (WTF and DHB that are distributed techniques), the study area was classified to polygons based on the existing observation wells. Then, the natural recharge rate was estimated for each Thiessen polygon on a monthly scale. Utilizing these three methods, the groundwater level was simulated and also an optimization technique was applied to minimize the Root Mean Square Error (RMSE) between the simulated and observed groundwater level. The results showed that the simulated groundwater level matched well with the observed amount. An annual average recharge rate for Neyshabour plain, using WTF, DHB and HB was estimated at 228, 269 and 354 MCM, respectively. Finally, the estimated groundwater recharge of each method was compared and the results showed that thr WTF and DHB methods provided more reliable groundwater recharge.

Keywords: groundwater recharge, WTF, hydrological budget, rainfall, Neishaboor, Iran

1 INTRODUCTION

Estimating recharge is essential in any analysis of groundwater systems and the impacts of withdrawing native water from them (Sophocleous 2005). The study area of the current research suffers from inordinate groundwater drawdown due to irregular overuse and excessive groundwater withdrawal in agriculture sector. Although withdrawal from this area has been officially restricted since 1987 it has still encountered a severe water crisis and sustainability of groundwater resource has been called into question. Hence, to manage the groundwater resources the reliable estimation of the groundwater recharge is very crucial.

A couple of methods are presented in the literature which have their strengths and weaknesses. Scanlon et al. 2002 have subdivided techniques to estimate groundwater recharge on the basis of hydrological zones namely surface water, unsaturated zone, and saturated zone, and presented the advantages and disadvantages of each technique. Manghi et al. 2009 by using the HB method estimated an annual average rate of groundwater recharge for a Hemet subbasin in Western Riverside County, California at 12.5 MCM from 1997 to 2005. Healy & Cook (2002) reviewed the applicability of the WTF method and its theoretical basis for estimating groundwater recharge and demonstrated its limitations. Martin 2005 and Sandwidi 2007 used the WTF method to estimate the annual groundwater recharge to the Atankwidi and Kompienga dam basins in West Africa. The recharge ranged from 13–143 mm for the Atankwidi basin and 44–244 mm for the Kompienga dam basin. Moon et al. 2004 applied a modified WTF and statistical analysis of groundwater hydrographs to estimate groundwater recharge for a river basin of South Korea. The average recharge ratios of the monitoring stations, grouped according to their groundwater hydrographs, varied from 4.07 to 15.29%. Rasoulzadeh & Moosavi 2008 by using an inverse approach and considering the WTF model as a forward model estimated the groundwater recharge and WTF parameters for the vicinity of Tashk Lake (called Tavabe-e-Arsanjan) in Iran, Fars province. Ganji khorramdel et al. 2008 used Double Water Table Fluctuation to optimize an observation well network in order to estimate the groundwater budget of Astane-Koochesfahan aquifer in Iran, Gilan Province. The results showed that such an optimized network provides far fewer measurement points, i.e. 33 wells, without considerably changing the conclusions regarding groundwater budget.

In this research the Hydrological Budget method (HB) was applied by Geographical Information System (GIS) technique to estimate annual average groundwater recharge of the whole study area (Neishaboor Plain). The monthly groundwater recharge for each Thiessen polygon was estimated using Distributed Hydrological Budget (DHB). Moreover the WTF method and an inverse modeling approach was implemented to determine how much of precipitation and irrigation return flow contribute to natural groundwater recharge in monthly scale.

2 MATERIALS AND METHODS

2.1 *Description of the study area*

The Neishaboor plain is located between 35°40′ N to 36°39′ N latitude and 58°17′ E to 59°30′ E longitude with semi-arid to arid climate, in the northeast of Iran as shown in Figure 1. The total geographical area is 7,350 km^2, consisting of 3,160 km^2 mountainous terrain and about 4,190 km^2 of plain. The maximum elevation is located in the Binalood Mountains (3,300 m above sea level), and the minimum elevation is at the outlet of the plain (Hosein Abad Jangal) at 1,050 m above mean sea level. The average annual precipitation is 234 mm, but this varies considerably from one year to another. The mean annual temperatures at the Bar-Aria station (in the mountainous area) and Mohammad Abad-Fedisheh station (in the plain area) are 13 and 13.8°C, respectively. The annual potential evapotranspiration is about 2,335 mm (Velayati and Tavassloi 1991). According to official reports, about 93.5% of the withdrawals in the Neishaboor watershed are consumed by agriculture, mostly in irrigation.

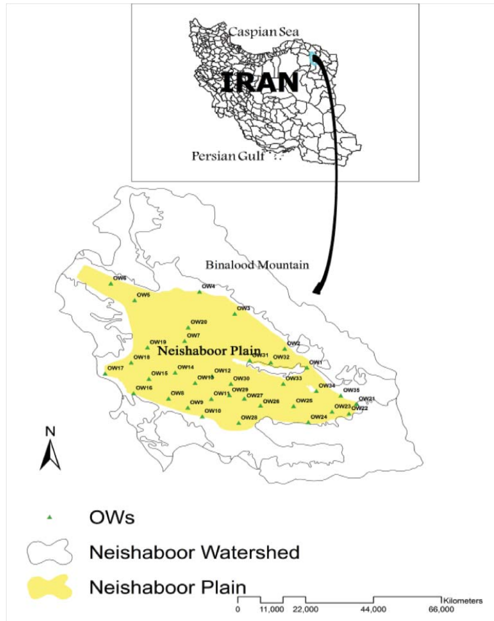

Figure 1. Location of study area in Iran, Khorasan-Razavi province.

Moreover, the share of surface-water resources in total consumption is about 4.2%. It means that groundwater is a primary source of water for different purposes and surface water plays a minor role in providing water supply services in the Neishaboor watershed. Therefore, crop evapotranspiration (ETc)—evapotranspiration from disease-free, well fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full reduction under the given climatic conditions—is responsible for about 90% of water-resources consumption (Hoseini et al. 2005).

2.2 *Theory of Hydrological Budget (HB) method*

The hydrologic budget for a geographic basin can be written as:

$$(W|Q_{in})(ET\backslash RO\backslash IP\backslash Q_{bf}\backslash Q_{out})\ Q_w = \Delta S \quad (1)$$

where W is the applied water on the ground surface; Q_{in} and Q_{out} are subsurface water fluxes into and out of a geographic basin along a boundary; ET represents evapotranspiration losses in surface and subsurface waters, including the unsaturated and saturated zones; RO is surface water runoff; IP is intercepted precipitation by vegetation; Q_{bf} is groundwater discharge to streams (baseflow);

Q_w is groundwater withdrawal through pumping wells; and ΔS is the change in saturated groundwater storage. The units for all components in the hydrologic budget equation are in volume per time period.

As groundwater recharge includes any percolated water that reaches the saturated portion of the water table aquifer per time period, and can be written as:

$$R_t = W - (ET + RO + IP + Q_{bf} + Q_{in} - Q_{out}) \tag{2}$$

where R_t is groundwater recharge.

Assuming water table aquifer conditions, the change in groundwater storage per time period can be written (Bredehoeft et al. 1982) as:

$$\Delta S - \Delta H \times A_{gb} \times S_y \tag{3}$$

where ΔH is the average change of the measured groundwater levels per time period; A_{gb} is the area of the geographic basin; and S_y is the average specific yield of the water table aquifer.

Substituting Equations 2 and 3 into Equation 1 and simplifying results in:

$$R_t = Q_w + (\Delta H \times A_{gb} \times S_y) \tag{4}$$

If the geographic basin area is divided into a grid, then the groundwater recharge per time period, R_t, equals the summation of groundwater recharge of the grid, and can be presented as:

$$R_t = \sum_{i=1}^{n} r_i = Q_w + \sum_{i=1}^{n} \left(\Delta h_i \times a_i \times S_{yi} \right) \tag{5}$$

where r_i, Δh_i, a_i, n and S_{yi} represent the associated quantity for each grid cell and n is the number of grid cells. The effect of groundwater withdrawal is assumed to be equally distributed on the grid. Any time period may be used, but for semi-arid regions where groundwater levels are very deep, it is best to assume a longer time period (for example 1 year time period) because of the lag time necessary for groundwater recharge to reach the saturated water table system (Manghi et al. 2009).

2.3 *Theory of Distributed Hydrological Budget (DHB) method*

The groundwater recharge can be estimated by classifying the study area into Thiessen polygons based upon observation wells and writing the water budget equation (Eq. 1) for each Thiessen polygon. The groundwater recharge for each Thiessen polygon in monthly scale is estimated from the Equation 6, i.e.,

$$R_t = Q_w + (\Delta H \times A_{gh} \times Sy) - (Q_{in} - Q_{out}) - ET - Q_{bf} \tag{6}$$

Since the groundwater depth in the study area is more than 5 meters and there is no river to drain the groundwater, the terms ET and Q_{bf} were negligible in the study area.

2.4 *Theory of Water Table Fluctuation (WTF) method*

The water table fluctuation method by analyzing water level fluctuations provides an estimate of groundwater recharge. For applying this method only groundwater level and specific yield data are needed. The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as (Healy & Cook 2002):

$$R = S_y dh/dt = S_y \Delta h/\Delta t \tag{7}$$

Where R is recharge; S_y is specific yield; h is water-table height, and t is time.

To derive Equation 7 one needs to assume that water arriving at the water table goes immediately into storage and that all other components of Equation 1 are zero during the period of recharge. A time lag occurs between the arrival of water during a recharge event and the redistribution of that water to the other components of Equation 1. If the method is applied during that time lag, all of the water going into recharge can be accounted for. This assumption is most valid over short periods of time, and it is this time frame for which application of the method is most appropriate (Healy & Cook 2002; Scanlon et al. 2002).

2.4.1 *Inverse modeling approach*

The Equation 7 could be rewritten as below:

$$dh/dt = R/S_y \tag{8}$$

The above equation considers the groundwater recharge as a whole. Recharge might be resulted from precipitation (P), irrigation return flow ($Q_{Irrigation}$) and net subsurface water flux (Q_{InOut}) into the aquifer or Thiessen polygon. The Equation 8 is rearranged as the following equation by considering these parameters within it:

$$\frac{dh}{dt} = \frac{\beta P}{S_y} + \frac{\lambda Q_{irrigation}}{S_y} - \frac{Q_{pumpage}}{S_y} + \frac{Q_{InOut}}{S_y} \tag{9}$$

where λ = percentage of irrigation return flow which contributes to recharge; β = percentage of precipitation which contributes to recharge; and

$Q_{Pumpage}$ = groundwater withdrawal through pumping wells (Rasoulzadeh & Moosavi 2008).

Inverse modeling approach considers WTF model as forward model and fits Equation 9 on observed data, then unknown parameters of WTF model are estimated with the help of one of optimization procedure in order to minimize objective function (difference between observed and simulated water level fluctuations with WTF model) (Eq. 10).

$$\mathrm{RMSE} = \frac{\sqrt{\sum (F(x_1,x_2,\ldots,x_n) - f(x_1,x_2,\ldots,x_n))^2}}{n} \tag{10}$$

where F = observed values; f = simulated values; and n = the number of observed values.

The optimization procedure was used with the help of Spss 18.0 to minimize Root Mean Square Error (RMSE) and to get the best fit between the two curves. Spss uses Levenberg–Marquardt and Sequential Quadratic Programming to minimize objective function.

2.5 *Conceptual model of study area*

To build conceptual model and preparing required data, at first point shape file of Observation Wells (OWs) added to ARCMAP (ARCGIS products) and Thiessen polygon were made based on them. Figure 2 illustrates the conceptual model of study area and Thiessen polygons.

Following the construction of Thiessen polygons based on observation wells, the monthly records of groundwater levels at each polygon were arranged at 35 Excel spreadsheets for the period from October 2000 to September 2010. Then, monthly records of rainfall, net subsurface water flux and Abstraction Wells (AWs) data were listed against the corresponding groundwater level data for each sub-zone, and plotted against time.

Monthly net subsurface water fluxes were estimated using Darcy Flow function of ARCGIS. Monthly groundwater level, monthly saturation

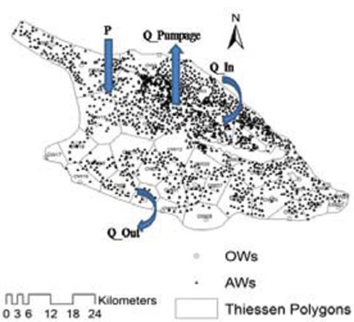

Figure 2. Conceptual model of the study area.

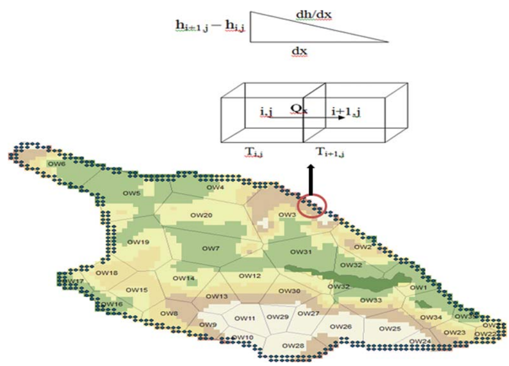

Figure 3. This picture illustrates that how the lateral groundwater inflow or outflow were calculated in boundaries.

thickness (i.e., subtraction of bed rock and groundwater level rasters), the porosity and transmissivity rasters are required for calculating groundwater flow across grid cells using the Darcy Flow function. These rasters were produced with Topo to Raster embedded in ARCGIS 9.3 3D Analyst function by pixcel size of 1000 by 1000 m. Monthly Darcy Flow outputs were summed for each sub-zone.

Since, the Darcy Flow function could not calculate the in/outflow for the boundary cells, the monthly lateral groundwater inflow and outflows were calculated by using Equation 11 as (Fig. 3):

$$Q_x(i+\tfrac{1}{2},j) = -30 * \frac{2(T_{i,j})(T_{i+1,j})}{T_{i,j}+T_{i+1,j}} \frac{h_{i+1,j}-h_{i,j}}{\Delta x} \Delta y \tag{11}$$

where Q_x = lateral groundwater inflow or outflow; T = transmissivity; h = groundwater level; i and j = represents each cell position at x and y directions, respectively; Δx = distance between two adjacent cell; and Δy = width of each cell. These lateral inflow or outflows were summed up by the net subsurface water fluxes which estimated for the boundary polygons.

For spatial distribution of rainfall in the study area the Inverse Distance Weighting method (IDW) was applied, then the monthly records of rainfall at each polygon were averaged to be used with DHB and WTF models. Groundwater withdrawals through pumping wells are used for irrigation purposes. So the monthly records of abstraction wells were summed for each polygon.

3 RESULTS AND DISCUSSION

For calculating groundwater recharge using the HB method (Eq. 5), the rasters of groundwater level of October and September of each year was subtracted to calculate Δh_i in each pixel (grid cell). The raster of specific yield was also used to compute the change in saturated groundwater storage. Then annual average groundwater recharge rate based on Equation (5) for Neishaboor Plain was estimated from 2000 to 2010 (Table 1).

The average contribution of groundwater recharge for a ten-year period was about 61% of the total groundwater withdrawal (Table 1). The average groundwater extraction from the Neishaboor Plain from 2000 to 2010 was 649 MCM. Therefore, 39% of exploitation was supplied from saturated groundwater storage and 61% was the result of groundwater recharge including net groundwater inflow, infiltration and irrigation return flow. If we subtract the net groundwater inflow (which equals 41 MCM based on Table 4) from annual average groundwater recharge rate, recharge from rainfall deep percolation and irrigation return flow would be estimated as 354 MCM. HB is a lumped method and wouldn't report any further information about distribution of groundwater recharge rate in the study area.

Using the DHB method the groundwater recharge resulted from both rainfall deep percolation and irrigation return flow for each sub-zone was estimated. Utilizing the WTF method was

Table 1. Estimated groundwater recharge (MCM) for Neishaboor Plain form 2000/2001 to 2009/2010.

Time period (Year)	Qw (MCM)	ΔS (MCM)	Rt (MCM)	Rt (%)
2000–2001	690	–379	311	45
2001–2002	679	–308	371	55
2002–2003	671	–204	467	70
2003–2004	663	–274	390	59
2004–2005	654	–227	427	65
2005–2006	643	–251	392	61
2006–2007	633	–216	417	66
2007–2008	623	–226	396	64
2008–2009	616	–220	396	64
2009–2010	616	–233	384	62
Mean	649	–254	395	61

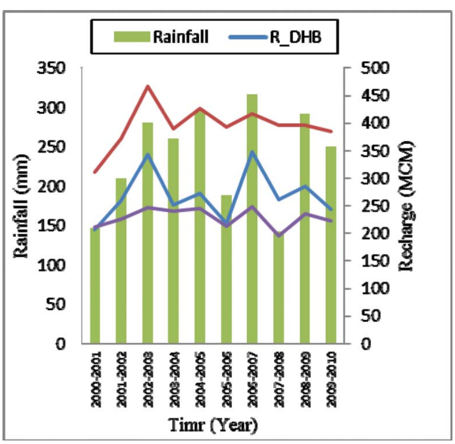

Figure 4. Comparison between groundwater recharge estimated through HB, DHB and WTF methods.

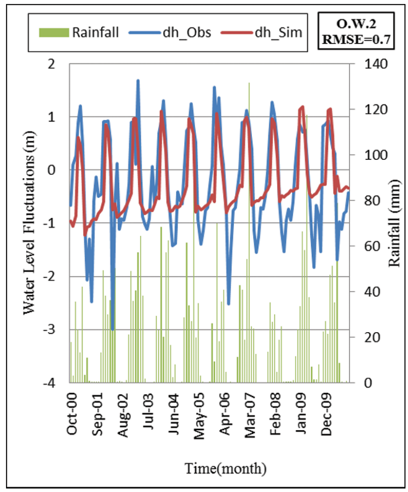

Figure 5. Comparison of observed and simulated water level fluctuation with WTF model for OW2.

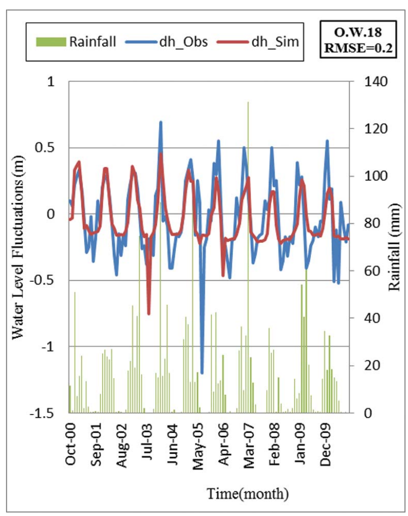

Figure 6. Comparison of observed and simulated water level fluctuation with WTF model for OW18.

Table 2. Annual groundwater recharge estimated with WTF model for Neishaboor plain from 2000 to 2010.

Time (Year)	Rainfall (mm)	Total recharge (MCM)	Recharge from infiltration (MCM)	Recharge from other sources (MCM)
2000–2001	146	211	44	167
2001–2002	209	226	62	164
2002–2003	280	247	85	162
2003–2004	260	240	79	160
2004–2005	296	245	87	158
2005–2006	188	213	57	155
2006–2007	317	248	95	153
2007–2008	142	194	44	150
2008–2009	292	235	86	149
2009–2010	250	223	74	149
Mean	238	228	71	157

Table 3. Groundwater inflow and outflow into/out of plain boundaries computed from Darcy flow equation.

Year	Groundwater inflow (MCM)	Groundwater outflow (MCM)
2000–2001	55	–13
2001–2002	56	–13
2002–2003	56	–13
2003–2004	57	–13
2004–2005	55	–14
2005–2006	56	–14
2006–2007	55	–14
2007–2008	54	–14
2008–2009	55	–14
2009–2010	55	–15
Mean	55	–14

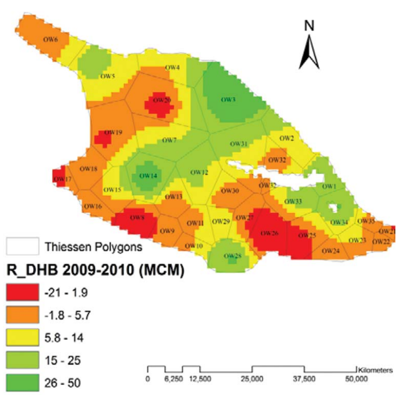

Figure 7. Zoning of Groundwater recharge estimated with DHB method for the year of 2009–2010.

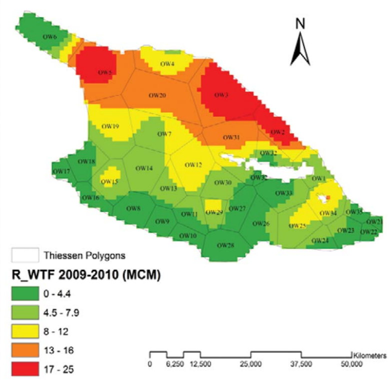

Figure 8. Zoning of Groundwater recharge estimated with WTF method for the year of 2009–2010.

distinctly designated how much of rainfall and irrigation return flow contributes to groundwater recharge within each polygon.

Figure 4 shows the comparison between groundwater recharge estimated through these three methods. As shown in Figure 4 annual groundwater recharge estimated using various methods matched well with the average annual precipitation. As the annual rainfall decreased, the recharge declined and vice versa. In the HB method the specific yield is the only estimated parameter. Although it plays a critical role in the water budget, this parameter has a limited domain of variation. So the result of the HB method could be considered as a lumped reliable value. Figure 4 shows good agreement between groundwater recharge estimated using the DHB and WTF model. The difference between the results and those of the HB method arises from (1) considering net groundwater inflow as an average groundwater recharge in this method and (2) assuming constant groundwater level to calculate groundwater flow from one cell to adjacent cell during a month time period which is not well matched with aquifer condition in reality. But for estimating groundwater recharge in a distributed manner the utilization of this assumption is unavoidable. The difference between groundwater recharge rate estimated through DHB and WTF is less than 20% in contrast to the HB method, thus, using this assumption can be justified with regards to the uncertainty of the parameters.

Figures 5 and 6 illustrates the results of applying the WTF model. As shown in Figures 5 and 6 there is a fairly good agreement between the observed and simulated groundwater level fluctuation with the WTF model for some piezometers. These results were achieved by minimizing Root Mean Square Error (RMSE) between observed and simulated groundwater level fluctuations. The values of groundwater recharge estimated through WTF model from 2000 to 2010 are presented in Table 2. Groundwater flows into/out of plain boundary which were obtained from Darcy Flow (Eq. 11) are presented in Table 3. It is noteworthy that the WTF method considers specific assumptions that do not hold precisely for the Neishaboor plain. It seems that considering the lag time and effective period of precipitation and irrigation will enhance the results.

Figures 7 and 8 exhibit zoning of groundwater recharge estimated through DHB and WTF methods during the year of 2009–2010, respectively

4 CONCLUSION

In this study, natural groundwater recharge for the Neishaboor plain and groundwater inflow and outflow into/out of the plain boundaries were estimated with the help of water budget approaches such as Hydrological Budget, Distributed Hydrological Budget, and Water Table Fluctuation methods as well as utilizing a Geographical Information System (GIS). These methods were useful, easy to be utilized, cost effective, simple, requiring a few non-deterministic data such as groundwater level measurements, rainfall, aquifer properties, and groundwater extraction datasets.

Accuracy and reliability of groundwater recharge estimated with these methods depends on those of the input datasets and their assumptions. We couldn't definitely say which of the applied methods are more reliable and well matched with the physical and geological properties of the plain, but if a model is more distributed, less dependent on non-deterministic parameters and easy access to more accurate information, its results are more reliable.

Applying these methods for groundwater modeling would result in more useful information. The DHB and WTF models provided spatial and temporal distribution of natural groundwater recharge for the study area. The WTF model clearly exhibited groundwater recharge components. Since the WTF method assumption did not hold completely, the results of CRD and RIB methods which consider lag time and effective recharge period will enhance the results.

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