ORIGINAL ARTICLE

Estimation of the groundwater balance of a mountainous basin based on long-term streamflow data: a case study of the Tao'er River Basin, China

Weifei Yang[1,2,3,4] · Changlai Xiao[1,2,3,4] · Zhihao Zhang[1,2,3,4] · Xiujuan Liang[1,2,3,4] · Zhang Fang[1,2,3,4]

Abstract

Groundwater resources of mountainous basins are particularly important for maintaining the ecological environment and downstream domestic water demands. Quantitative analysis of the groundwater balance in a mountainous area is very important for monitoring and management of groundwater resources. Conventional analysis methods usually require extensive field investigation for estimation of hydrogeological parameters, which can be challenging in a mountainous basin. This study applied a series of methods based on daily streamflow data to estimate the groundwater balance of the Tao'er River Basin in Northeast China and also analyzed the response characteristics of effective groundwater recharge to rainfall. The results showed that groundwater recharge in the Tao'er River Basin occurs mainly through rainfall percolation in summer, and that groundwater is rapidly discharged in the form of baseflow and evapotranspiration. Baseflow discharge accounted for ∼ 93% of recharge, whereas evapotranspiration accounted for the remaining ∼ 7%. The multi-year average effective groundwater recharge values of the Chaersen, Suolun, Dashizhai and Zhenxi sub-basins were 59.7 mm, 62.4 mm, 19.6 mm and 34.6 mm, respectively. Groundwater recharge showed a slow and weak response to rainfall before the rainiest month (January–July). In general, the recharge peak appeared ∼ 4 days after a rainfall event, and the recharge process continued for 13–16 days. However, the response was relatively rapid and obvious after the rainiest month (August to December). The recharge peak appeared ∼ 3 days after a rainfall event, and the recharge process continued for 7–9 days.

Keywords Mountainous basin · Groundwater balance · Streamflow · Baseflow separation · Groundwater recharge · Response function

✉ Changlai Xiao
   xcl2822@126.com

✉ Xiujuan Liang
   xjliang@jlu.edu.cn

✉ Zhang Fang
   azhang9456@126.com

1   Key Laboratory of Groundwater Resources and Environment (Ministry of Education), Jilin University, Changchun 130021, People's Republic of China

2   Jilin Provincial Key Laboratory of Water Resources and Environment, Jilin University, Changchun 130021, People's Republic of China

3   Drilling and Exploitation Technology for Oil Shale, National-Local Joint Engineering Laboratory of In-Situ Conversion, Jilin University, Changchun 130021, People's Republic of China

4   College of New Energy and Environment, Jilin University, No. 2519, Jiefang Road, Changchun 130021, People's Republic of China

Introduction

Groundwater resources in mountainous areas are important for maintaining the ecological environment and for meeting downstream domestic water demands, especially in some arid and semi-arid areas (Cambraia Neto and Rodrigues 2020; Moeck et al. 2020; Zheng et al. 2019). For example, the Greater Khingan Mountains area in Northeast China. Quantitative assessment of inter- and intra-annual variation in the groundwater balance is required to achieve reasonable monitoring and management of groundwater resources in mountainous areas (Cambraia Neto and Rodrigues 2020; Dralle et al. 2018). An understanding of the characteristics of groundwater circulation and response to precipitation in mountainous areas is also beneficial to effective groundwater management.

In general, the groundwater balance in a mountainous basin mainly includes percolation recharge (GWR) from

precipitation, baseflow drainage (Q_b), evapotranspiration (ET) and artificial extraction (A). Artificial extraction is usually negligible in mountainous basins that are less affected by human activities (Wittenberg et al. 2019). The temporal characteristics of recharge and discharge jointly determine the change in groundwater storage (S) in a basin, which can be expressed by a simple one-dimensional basin-scale groundwater balance equation (Aksoy and Wittenberg 2011):

$$S_{i-1} + \int_{t_{i-1}}^{t_i} GWRdt = S_i + \int_{t_{i-1}}^{t_i} \left(Q_b + ET + A\right)dt \qquad (1)$$

In Eq. (1), t_i and t_{i-1} are time steps. This equation is for the balance of saturated groundwater at the basin-scale, without considering surface water, soil water, and return flow. In addition, the boundaries of mountain basins are usually groundwater ridges, so lateral runoff is ignored. The present research is also based on the above assumptions. The groundwater recharge (GWR) mentioned later refers to the amount of precipitation percolated to the groundwater table. The groundwater evapotranspiration (ET) refers to the evapotranspiration loss of saturated groundwater under the influence of plant roots and capillary action, excluding the evapotranspiration of surface water and soil water.

Baseflow (Q_b) in a mountainous basin is usually determined through baseflow separation. Many different baseflow separation methods exist, including a nonlinear reservoir algorithm (Wittenberg 1999), a single parameter filtering method (Lyne and Hollick 1979), a two-parameter recursive filtering method (Eckhardt 2005) and a mass-balance method (Stewart et al. 2007; Yang et al. 2019a). Although the mass-balance method based on environmental tracers is generally considered to be the most reliable, a lot of time and money is required to obtain a long sequence of environmental tracer data (Yang et al. 2019b). Filtering methods are developed based on the principle of signal processing and have no clear physical basis. Therefore, they usually require correction by a mass-balance method or observation results (Saraiva Okello et al. 2018). The nonlinear reservoir algorithm is a reverse baseflow separation method proposed by Wittenberg (1999) based on the nonlinear reservoir model ($S = kQ^\beta$). This approach has been widely applied to basins in China (He et al. 2016), Germany (Wittenberg 2003), Australia (Zillgens et al. 2007), Turkey (Aksoy and Wittenberg 2011) and the United States (Srivastava et al. 2017) due to its clear theoretical basis and easy operation.

The estimation of groundwater evapotranspiration (ET) is usually based on the Penman formula and lysimeter, eddy correlation and pan evaporation data (Boronina et al. 2005). The Penman formula is used to estimate potential ET, which cannot be regarded as an accurate reflection of actual ET. Data collection though lysimeters, eddy correlation and

pan evaporation is only viable over small spatial scales, and therefore are often not representative of region-scale processes (Dias and Kan 1999). Alternatively, hydrologists have linked ET with fluctuations in streamflow for the calculation of basin-scale ET, and this approach has been applied to catchments in Australia (Wittenberg and Sivapalan 1999), Brazil (Dias and Kan 1999), the United States (Palmroth et al. 2010; Szilagyi et al. 2007), Germany (Wittenberg 2003), Cyprus (Boronina et al. 2005), Wales (Kirchner 2009) and Turkey (Aksoy and Wittenberg 2011). Palmroth et al. (2010) studied the feasibility of this method for estimating watershed carbon fluxes.

Various methods have been applied to quantify GWR, including the empirical coefficient method based on annual precipitation (Anderson et al. 1992) and methods based on environmental tracers, groundwater models and baseflow separation (Ajami et al. 2011). The empirical coefficient method has been found to be inaccurate since the method ignores the effects of storm characteristics, soil water storage and vegetation variation on recharge (Gee and Hillel 1988). The methods based on environmental tracers are not cost effective in large basins. Methods based on groundwater models usually require a large amount of input data. Although the baseflow separation method has long been used to estimate basin-scale GWR, it neglects ET and extraction (Szilagyi et al. 2003). Wittenberg and Sivapalan (1999) combined baseflow separation and inverse nonlinear reservoir routing to estimate GWR while considering ET. This method has been widely applied in catchments in Australia (Wittenberg and Sivapalan 1999), Turkey (Aksoy and Wittenberg 2011) and Germany (Wittenberg et al. 2019). Ajami et al. (2011) used a similar method developed by Kirchner (2009) to quantify the mountain block recharge of Sabino Creek in southern Arizona, United States. Wittenberg et al. (2019) used estimated GWR sequences and precipitation data to estimate the response functions of GWR to precipitation and obtained results which were consistent with lysimeter data and observations of groundwater level dynamics. In turn, these response functions can also be used to estimate GWR sequences based on precipitation data.

There are clear differences between the above-mentioned methods for estimating the basin-scale groundwater balance based on streamflow data and conventional methods as they are holistic or "top-down" methods which mainly rely on a comprehensive understanding of characteristics of natural basins (Wittenberg and Sivapalan 1999). In addition, these approaches can avoid the errors associated with the use of empirical parameters and spatial generalization, and are cost effective and easy to operate.

In 2017, under the call of the Ministry of Water Resources of China, the provinces launched the third groundwater resource assessment. Due to the lack of detailed hydrogeological parameters, the amount of groundwater resources in

mountainous basins is usually approximated by baseflow, ignoring the amount of groundwater evapotranspiration. This will lead to some errors in the results and it is impossible to understand the characteristics of groundwater circulation in mountainous basins. A more reasonable assessment of groundwater resources and balance characteristics in mountainous areas based on limited data has become an important topic. The present study attempts to take the Tao'er river basin as an example to use the above methods to improve the rationality of the groundwater balance estimation in mountainous basins, and also provide references for other similar areas. The main contents of this research include: (1) estimating the groundwater balance of the Tao'er River Basin in Northeast China based on an extended streamflow dataset and analyzing the temporal and spatial variation in the groundwater balance; (2) analyzing the response of GWR to precipitation based on the estimated daily GWR series and precipitation data.

Study area and data

The Tao'er River Basin is located in Northeast China with a total drainage area of 41,200 km². The elevation of the basin ranges from 100 m above sea level (a.s.l.) to 1600 m a.s.l. (Fig. 1a). The basin falls within the temperate

continental monsoon climate zone and precipitation in the basin measured from 1953 to 2015 has an annual average of 463.6 mm, with ~50% concentrated in summer (July to August) and 85% concentrated in April to October (Kou 2016). The annual average water surface evaporation is 1687.9 mm while the annual average temperature ranges between −2.7 °C and 5 °C (Jia 2015). Figure 1b shows the perennial average meteorological characteristics of the basin. The headwaters of the Tao'er River begin in the Gaoyue Mountain, from which the river flows northwest to southeast with a total length of 563 km. The slopes of the river valleys decrease from upstream to downstream, ranging in incline from 1.66% to 0.02% (Yang et al. 2020).

The study area of the present study is a basin falling within the Greater Khingan Mountains area. This area has experienced long-term tectonic movement and volcanic activity; therefore, the geology of the area mainly comprises volcanic rocks, pyroclastic rocks and granites. Tectonic movement and long-term weathering have resulted in many joints and cracks in the mountainous bedrock. The thickness of the weathered fissure zone generally ranges from 10 to 30 m. Bedrock fissure phreatic water is widely distributed in these bedrock fractures, and the water yield of a single well in these areas is generally less than 100 m³ d⁻¹. Long-term river erosion and sediment deposition have resulted in a 25 m–45 m thick layer of
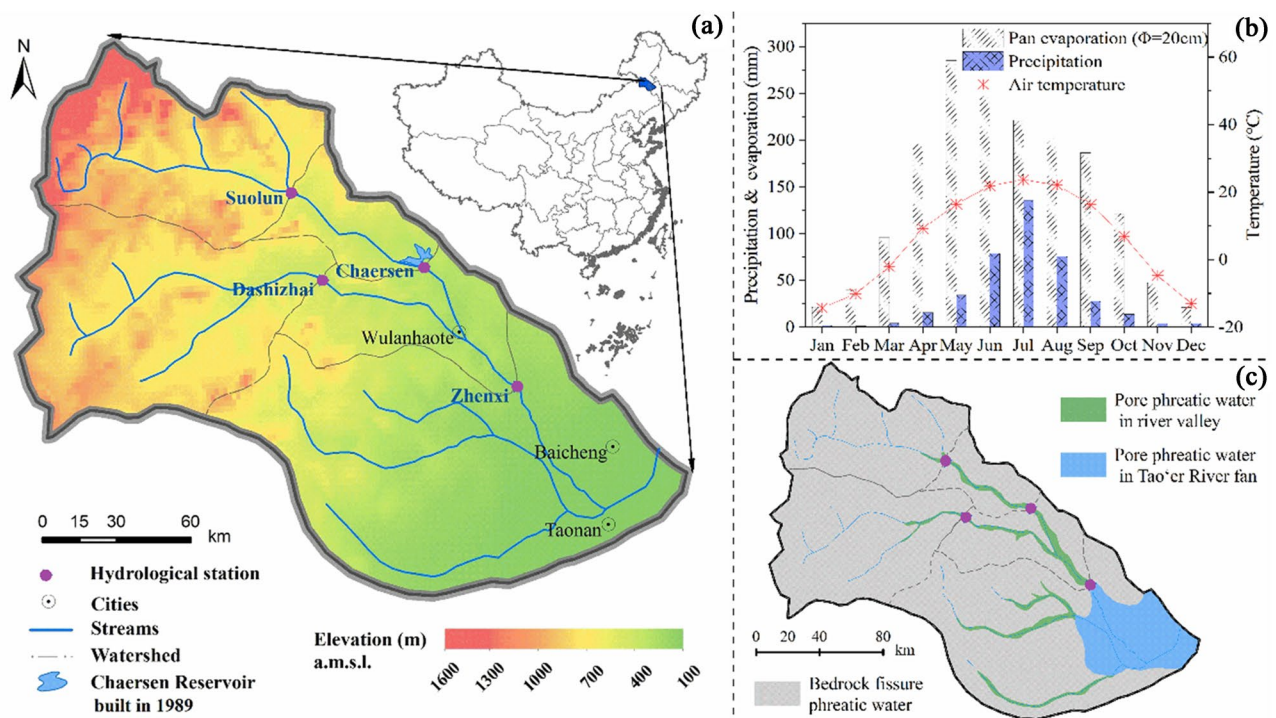

Fig. 1 The location, meteorology and spatial distribution of phreatic water in the Tao'er River Basin in Northeast China. **a** map of the Tao'er River Basin showing the Tao'er River and locations of hydro-logical stations and major cities; **b** seasonal distribution of meteorological variables in the basin; **c** spatial distribution of phreatic water in the basin

loose rocks in the valleys between mountains. This has provided a favorable environment for pore phreatic water, and the water yield of a single well in these areas can reach 1,000 m^3 d^{-1}. In addition, the long-term accumulation of sediment has led to the formation of an piedmont alluvial fan, and the water yield of a single well in this area can reach 5000 m^3 d^{-1} (Jia 2015; Kou 2016). Figure 1c shows the spatial distribution of the three types of groundwater in the basin. Discharge of baseflow during the dry season in the upper reaches of the mountainous area provides continuous groundwater recharge in the Tao'er River alluvial fan (Meng 2017). The majority of previous groundwater studies conducted in the Tao'er River Basin have focused on the alluvial fan and river valley areas (Jia 2015; Meng 2017; Xiao 2017), and conducted an analysis of the groundwater balance of a localized area. In contrast, the present study is a basin-scale study that mainly focused on the mountainous areas.

The present study used daily streamflow data of four hydrological stations (Suolun, Dashizhai, Chaersen and Zhenxi) located in the Tao'er River Basin collected by the Songliao Water Resources Commission, Ministry of Water Resources. These streamflow data are for 1964–1987 and 2011–2013. Table 1 and Fig. 1a summarize the basic characteristics and locations of the four stations. The construction of the Chaersen Reservoir in the Tao'er River Basin was completed in 1989 and has a design storage capacity of 11.48×10^8 m^3. The reservoir is mainly used for flood control and irrigation (Li 2018). Since the construction of the reservoir resulted in disturbance of the downstream runoff process, estimation methods based on streamflow sequence are no longer applicable in the basin. Therefore, an analysis of the response function of GWR to rainfall should be based on the period before the construction of the reservoir, after which the response function can be used to estimate GWR after the construction of the reservoir.

Methods

The methodology followed in the present research mainly included the following four steps: (1) the use of the nonlinear reservoir algorithm to determine the baseflow discharge sequence of the four sub-basins from 1964 to 1986; (2) estimation of the groundwater ET sequence of the four sub-basins from 1964 to 1986 based on the nonlinear reservoir model and the basin continuity equation; (3) estimation of the GWR sequence of the four sub-basins from 1964 to 1986 based on the baseflow and ET sequences; (4) an analysis of the response functions of GWR to rainfall in the four sub-basins, and a verification of the applicability of the response functions for estimating daily GWR from 2011 to 2013.

The methods used in steps 1–4 are mainly based on the nonlinear reservoir model [Eq. (2)], thereby demonstrating that the drainage volume of groundwater (baseflow) and the storage volume satisfy the power-law relationship. This relationship has been widely confirmed and applied (Thomas et al. 2015; Wang and Cai 2009; Wittenberg 1999; Wittenberg et al. 2019), and the analytical solutions of the relationship are shown in Eq. (3) and (4), which can be used to describe the baseflow recession process:

$$S = kQ_b^\beta \tag{2}$$

$$Q_{bt} = Q_{b0}e^{-\frac{t}{k}}(\beta = 1) \tag{3}$$

$$Q_{bt} = Q_{bo}\left(1 + \frac{(1-\beta)Q_{bo}^{1-\beta}}{k\beta}t\right)^{1/(\beta-1)} (\beta \neq 1) \tag{4}$$

In Eq. (2) to Eq. (4), S is groundwater storage (L^3), Q_{bt} is the baseflow at time step t (L^3 T^{-1}), Q_{b0} is the initial baseflow (L^3 T^{-1}) and k and β are the recession coefficients, the values of which can be obtained through recession analysis. Table 1 shows the recession coefficients of the four sub-basins, which are obtained through recession analysis according to the Brutsaert and Nieber (1977) method.

Baseflow separation

The reverse baseflow separation method, also known as the nonlinear reservoir algorithm, can be readily obtained by using Eq. (3) and Eq. (4) (Wittenberg 1999; Yang et al. 2020). The method starts from the last day of the study period and uses Eq. (5) and Eq. (6) to sequentially calculate baseflow. A more detailed description of the process can be found in (Wittenberg 1999):

$$Q_{b(t-\Delta t)} = Q_{bt}e^{\frac{\Delta t}{k}} (\beta = 1) \tag{5}$$

Table 1 The basic characteristics of the sub-basins of the Tao'er River Basin investigated in the present study

Hydrological station	Area km^2	Channel length km	k	β
Chaersen	7,872	285	52.5	0.75
Suolun	5,893	230	42.2	0.78
Dashizhai	7,656	215	30.2	0.83
Zhenxi	18,462	628	46.7	0.80

The periods of daily streamflow data for the four stations are all 1964–1986 & 2011–2013

$$Q_{b(t-\Delta t)} = \left(Q_{bt}^{\beta-1} + \frac{(\beta-1)\Delta t}{k\beta} \right)^{1/(\beta-1)} (\beta \neq 1) \tag{6}$$

Estimation of groundwater ET

When there is no rainfall, the continuity equation of a natural basin in which artificial extraction can be ignored can be expressed by Eq. (7). By substituting the nonlinear reservoir model [Eq. (2)] into the continuity equation, the basin-scale ET estimation formula [Eq. (8)] (Palmroth et al. 2010) can be obtained. It should be noted that ET estimated through this method includes groundwater ET and surface water evaporation. Exclusion of surface water evaporation is required when estimating the basin-scale groundwater ET:

$$-\frac{dS}{dt} = ET + Q \tag{7}$$

$$ET_t = -Q_t - k\beta Q_t^{\beta-1}\frac{dQ}{dt} \tag{8}$$

In Eq. (7) and Eq. (8), Q_t is the streamflow at timestep t and ET_t is the basin-scale evapotranspiration in timestep t. An approximation of the derivative of the streamflow can be calculated by the central difference method, $\frac{dQ}{dt} = \frac{Q_{(t+\Delta t)} - Q_{(t-\Delta t)}}{2\Delta t}$. The ET during the rainfall phase was ignored, and the phases with an absence of rainfall were selected based on $\frac{dQ}{dt} < 0$. At the same time, negative ET values in the calculation results were removed (Palmroth et al. 2010). This present study screened out the stages in which the daily baseflow ratio (Q_b/Q) was greater than 0.8 for the estimation of groundwater ET since the evaporation of surface water mainly occurs during the initial recession stage after a rainfall event.

Estimation of GWR

The GWR estimation equation can be obtained by substituting the estimated daily baseflow and ET sequence into Eq. (1):

$$GWR_t = S_t - S_{(t-\Delta t)} + \int_{t-\Delta t}^{t} Q_b dt + ET_t \tag{9}$$

In Eq. (9), S_t and $S_{(t-\Delta t)}$ represent actual storage as calculated by Eq. (2). The integral of baseflow (Q_b) is approximated using the trapezoidal formula, $\int_{t-\Delta t}^{t} Q_b dt \approx \Delta t(Q_{bt} + Q_{b(t-\Delta t)})/2$ (Wittenberg and Sivapalan 1999; Yang et al. 2020).

Response function of GWR to rainfall

The GWR response to rainfall can usually be represented as a similar time-invariant function, and the validity of this approach has been confirmed by lysimeter data (Wu et al. 1997) and measured groundwater level fluctuations (Jan et al. 2011). However, rainfall that occurs after a prolonged dry period usually results in a weak and delayed percolation response (Wittenberg et al. 2019), mainly because long-term drought results in a reduction in soil water content and a lowering of the groundwater table. Therefore, a longer duration is required for rainfall to infiltrate into the groundwater table after a prolonged drought.

The response function h, also called unit response, can be expressed by the travel time distribution of GWR in days resulting from a unit rainfall of 1 mm (Wittenberg et al. 2019). Similar to the unit hydrograph principle, GWR can be estimated by convolution of rainfall (P) and the response function (h):

$$GWR_i = \sum_{x=0}^{i} (P_{i-x} h_x) \Delta t \tag{10}$$

where, i is the calculation period, Δt is the time step, and x is the traveling time of precipitation percolation (the number of time steps) starting from 0. Conversely, h can also be estimated based on GWR and the rainfall series. In this case, Eq. (10) represents the overdetermined linear equation for h, and can be solved according to the Gaussian criterion of least squares (Wittenberg et al. 2019). By considering the effects of long-term drought, the present study determined the GWR response functions before and after rainiest month within the four sub-basins, which typically occur between July and August. The daily average rainfall of each of the four basins was calculated using the Thiessen polygon. The present study used the correlation coefficient (R^2) and Nash–Sutcliffe efficiency coefficient (NSE) to verify the consistency of GWR estimation results based on response function and streamflow data. For both the R^2 and NSE, a value closer to 1 indicated a higher correlation, whereas, a negative NSE indicated poor fitting performance of the model.

Results

Basin-scale groundwater balance

Figure 2 shows the estimated daily groundwater balance of the four sub-basins from 1964 to 1986. All results were represented as water depth (mm) per unit area for consistency. Since the four sub-basins have similar climatic characteristics, the long-term fluctuations in the groundwater balance were similar among the four sub-basins. However,

Fig. 2 The daily groundwater balance of the four sub-basins of the Tao'er River Basin, Northeast China, from 1964 to 1986. **a** Chaersen, **b** Suolun, **c** Dashizhai, **d** Zhenxi. Q and Q_b represent streamflow and baseflow, respectively, GWR is effective groundwater recharge and ET is evapotranspiration. Another enlarged and clear version of this figure is shown in Figure S1
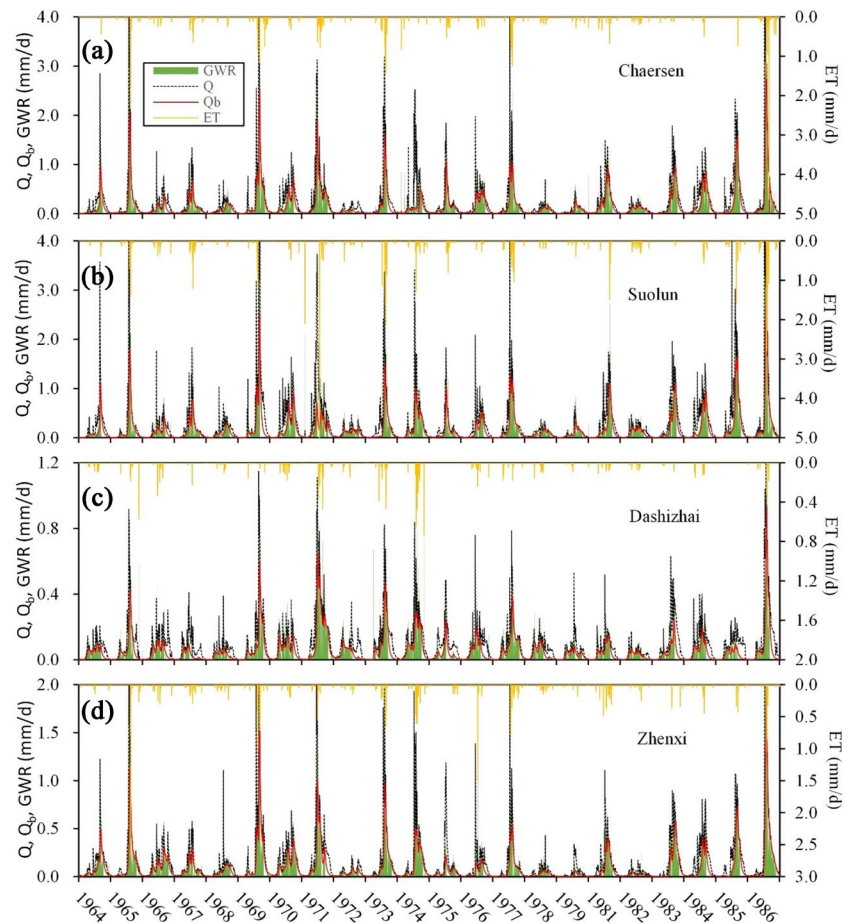
within individual subbasins, the sizes of components of the groundwater balance varied across the different years. During wet years when rainfall was abundant, streamflow was relatively large, resulting in relatively large estimates of baseflow, ET and GWR. In contrast, estimations of components of the groundwater balance were generally low during dry years.

Table 2 shows the annual estimates of the groundwater balance. Although rainfall showed little variation across the four sub-basins, the runoff depth and components of the groundwater balance of the Dashizhai sub-basin were only one-third of those of the Suolun and Chaersen sub-basins. Since the Zhenxi sub-basin encompasses the other three sub-basins, the groundwater balance of this sub-basin reflects the average characteristics of the other three sub-basins. The

Table 2 A statistical summary of the estimations of components of the annual groundwater balance for the Tao'er River Basin, Northeast China from 1964 to 1986

Hydrological station	Mean ± Stand derivation & ratio to annual precipitation								
	P	Q	Q/P	BF	BF/P	ET	ET/P	GWR	GWR/P
	Mm	mm		mm		Mm		mm	
Chaersen	451.9 ± 83.1	92.8 ± 45.3	20.5%	55.6 ± 29.8	12.3%	3.4 ± 2.8	0.7%	59.7 ± 33.5	13.2%
Suolun	455.6 ± 96.6	104.1 ± 50.4	22.8%	58.1 ± 26.4	12.8%	4.2 ± 3.4	0.9%	62.4 ± 28.8	13.7%
Dashizhai	438.4 ± 83.7	33.8 ± 14.8	7.7%	18.6 ± 10.7	4.2%	1.0 ± 0.8	0.2%	19.6 ± 11.3	4.5%
Zhenxi	440.9 ± 80.7	54.9 ± 30.2	12.4%	32.3 ± 20.2	7.3%	2.2 ± 1.4	0.5%	34.6 ± 21.3	7.9%

This study focuses on the balance of saturated groundwater, so the hydrological components such as overland flow, return flow, and soil water are not shown in this table. *P* precipitation, *Q* runoff, *BF* baseflow, *ET* saturated groundwater evapotranspiration, *GWR* precipitation percolation recharge

coefficient of variation (CV = standard deviation/mean) of multi-year rainfall, streamflow, baseflow, ET and GWR ranged from 0.18 to 0.19, from 0.44 to 0.55, between 0.45 and 0.63, between 0.61 and 0.84 and between 0.46 and 0.61, respectively. Streamflow and components of the groundwater balance presented greater interannual differences compared to that of rainfall, and ET showed the greatest interannual variation.

The multi-year daily averages of the components of the groundwater balance of the four sub-basins were calculated to more clearly show the daily variations in the groundwater balance (Fig. 3). The four sub-basins showed similar variation in the daily groundwater balance. Both baseflow and GWR showed three peaks, with the smallest peak appearing in March to April, the maximum peak appearing in July to August and the median peak appearing around the beginning of September. Although the peaks of GWR and streamflow basically coincided, the baseflow peak occurred later.
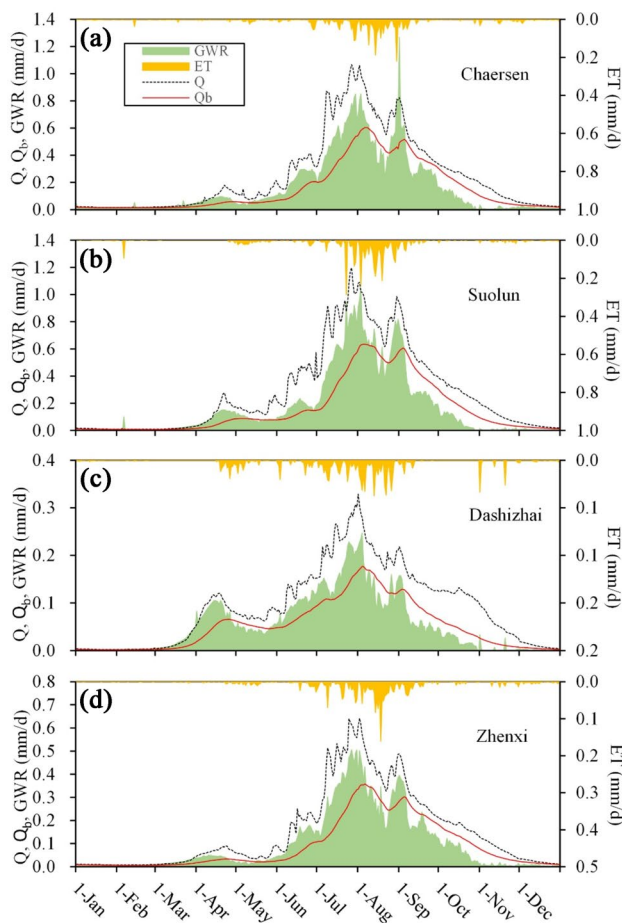

Fig. 3 The multi-year (1964–1986) daily average groundwater balance of four sub-basins of the Tao'er River Basin, Northeast China. **a** Chaersen, **b** Suolun, **c** Dashizhai, **d** Zhenxi. Q and Q_b represent streamflow and baseflow, respectively, GWR is effective groundwater recharge and ET is evapotranspiration

Groundwater ET mainly occurs from July to September, with the peak occurring during the initial recession stage after the GWR and baseflow peaks had occurred. Some abnormal groundwater ET values occurred between November and February, which may be attributed to human activities such as groundwater extraction.

Functions describing the response of GWR to rainfall

The GWR rainfall response functions for the four sub-basins were estimated according to the method described in "Response function of GWR to rainfall ", with Fig. 4 showing the results. The response of GWR to rainfall was relatively slow and weak before the rainiest month (January–July). The recharge peak usually occurred approximately 4 days after the rainfall event, following which recharge gradually decreased. The entire recharge process had a duration of 13–16 days. The sum of the unit response values of the Chaersen, Suolun, Dashizhai and Zhenxi sub-basins were 0.108, 0.092, 0.033 and 0.071, respectively. These values reflect the proportion of total rainfall that infiltrates the soil to recharge groundwater. For example, 10.8% of rainfall acts to recharge groundwater in the Chaersen sub-basin. However, there was a clear and rapid response of GWR to rainfall subsequent the rainiest month (August–December). The recharge peak appeared approximately 3 days after rainfall, following which recharge decreased rapidly. Compared with January to July, the percolation process in August to December lasts shorter, about 7 to 9 days. The sum of the unit response values of the four sub-basins increased to Chaersen: 0.175, Suolun: 0.175, Dashizhai: 0.047 and Zhenxi: 0.109, respectively.

The multi-year (1964–1986) daily average GWR was estimated based on these response functions and daily rainfall data using Eq. (10), with the results shown in Fig. 4. These estimation results showed a good fit to those based on streamflow. The correlation coefficients of the Chaersen, Suolun, Dashizhai and Zhenxi sub-basins were 0.94, 0.96, 0.89 and 0.95, respectively, whereas the NSE values were 0.87, 0.93, 0.75 and 0.88, respectively. However, the method based on the response function was not able to represent the smaller peaks from March to April.

The present study then used these response functions to estimate the daily GWR of the four sub-basins from 2011 to 2013, with the results shown in Fig. 5. Since the Suolun and Dashizhai sub-basins are not affected by the Chaersen Reservoir, the GWR of these basins could be estimated using streamflow, with the results shown in Fig. 5b and c. The correlation coefficients of the estimated results based on the response function and streamflow at the Suolun and Dashizhai sub-basins were 0.76 and 0.74, respectively, whereas the NSE values were 0.62 and 0.55, respectively. In general, the response functions were able to estimate a

Fig. 4 The unit response functions and the multi-year (1964–1986) daily average effective groundwater recharge (GWR) of the four sub-basins of the Tao'er River Basin, Northeast China. **a** Chaersen, **b** Suolun, **c** Dashizhai, **d**Zhenxi. P is rainfall
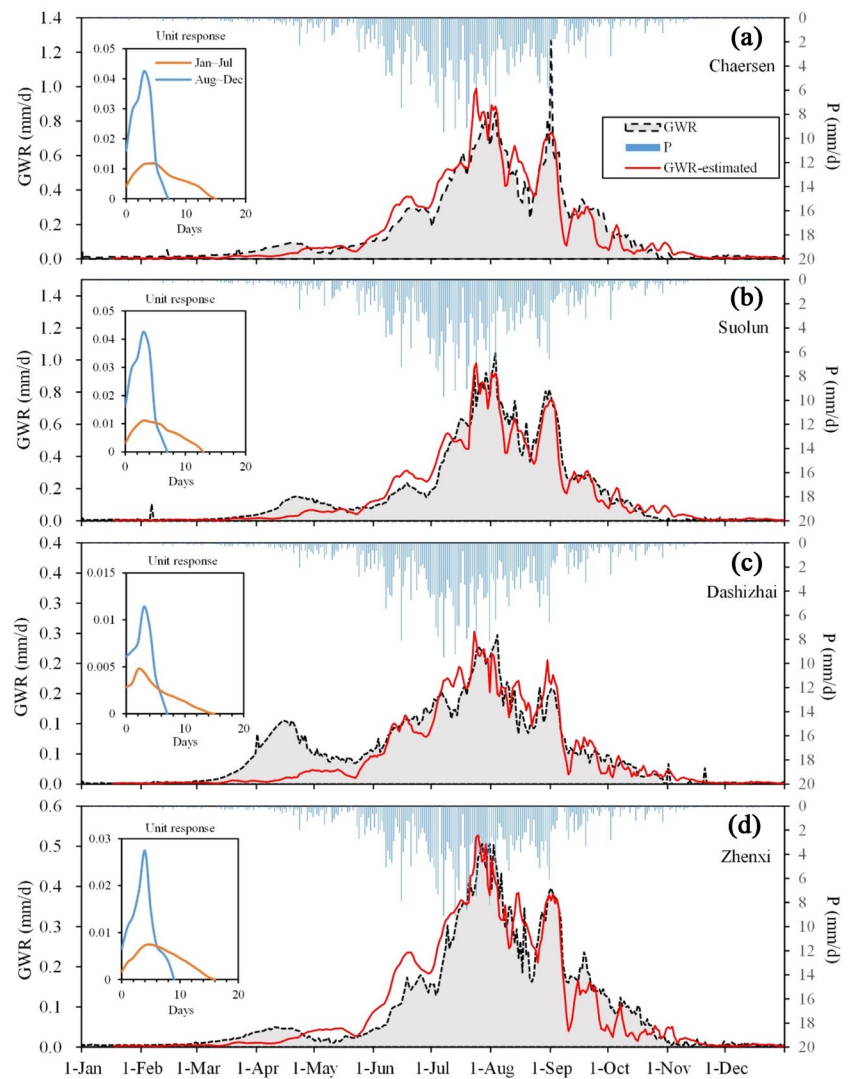
relatively reliable daily GWR, and therefore, could be used to estimate the basin-scale GWR under a situation of scarce or unreliable streamflow data.

Discussion

The Tao'er River Basin, Northeast China, is a mountainous basin located in a high latitude (45–47°N). Since the basin falls within the semi-arid monsoon climate zone, the basin shows distinct groundwater circulation characteristics that are different from those of humid and warm regions. Recharge of groundwater in the basin is mainly by rainfall percolation over the rainy season, following which groundwater is rapidly discharged in the form of baseflow and evapotranspiration. Baseflow in the basin accounts for ~93% of total recharge, whereas evapotranspiration accounts for only ~7% (Table 2). Rainfall in the basin is concentrated over the rainy season from May to September, during which

a large amount of groundwater recharge occurs, leading to a rapid rise in the groundwater level and a concurrent increase in baseflow. Significant evapotranspiration occurs during intermittent rainfall due to higher temperatures and shallower groundwater depth. Rainfall is scarce and there is a gradual drop in temperature during the dry season. Evapotranspiration during this period is almost zero and baseflow continues to decline. The temperature during winter generally falls below 0 °C, and snow accumulates on the ground surface. The snowmelt process initiates during spring of the following year, forming a small recharge peak from March to April. However, basins in humid and warm areas experience continued rainfall percolation during the wet season, and consequently, evapotranspiration accounts for a larger proportion of the groundwater balance (Fan et al. 2014). In addition, snowmelt has no effect on the groundwater balance.

Two mechanisms of GWR exist, namely diffuse recharge and focused (or localized) recharge (Ghasemizade
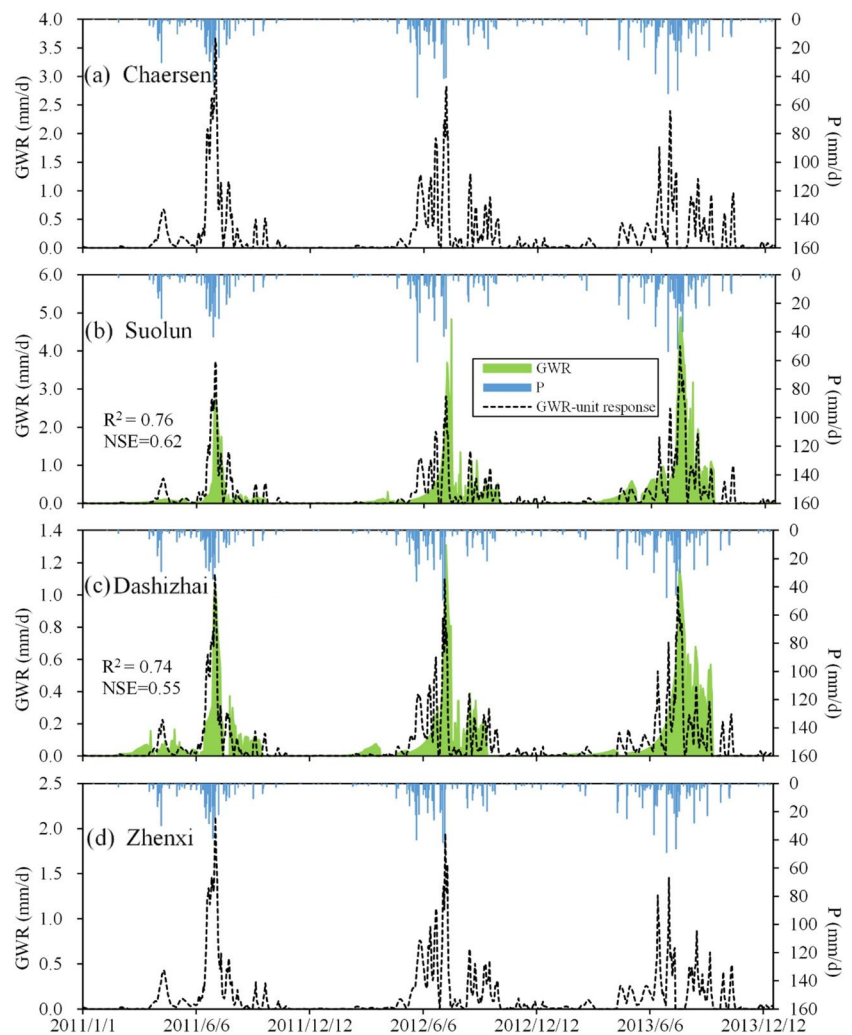
et al. 2015). Diffuse recharge is groundwater recharge through the process of rainfall penetrating the unsaturated zone and finally reaching the groundwater table due to matrix flow. In contrast, focused recharge involves more rapid groundwater recharge during which rainfall flows through vertical joints and cracks in the vadose zone. In general, diffuse recharge is dominant in humid environments, whereas focused recharge mainly occurs in semi-arid or arid environments (Herrera et al. 2018). The importance of focused recharge gradually increases as the degree of drought increases (Alley 2009). The Tao'er River Basin falls within a semi-arid climate zone and contains widely distributed weathered fissures. In addition, the basin experiences heavy monsoon rainfall in July to August. The basin therefore experiences the basic conditions required for the formation of focused groundwater recharge. The results shown in "Functions describing the response of GWR to rainfall" indicate that peak percolation recharge usually occurs 3 to 4 days after a rainfall event, following which percolation recharge decreases

rapidly, thereby indicating that groundwater in the basin is recharged mainly by focused recharge. Wittenberg et al. (2019) similarly reported the rapid response of groundwater to heavy rainfall in a basin in northern Germany.

The response of GWR to rainfall is influenced by many factors, including lithology and thickness of the unsaturated zone, the intensity and duration of rainfall, soil moisture content and vegetation characteristics (Moeck et al. 2020). The thickness of the vadose zone is positively correlated to the duration required for rainfall to penetrate to the groundwater table (Cao et al. 2016) and the soil sand content is positively correlated to the rainfall recharge rate (Cook and Kilty 1992). The greater the rainfall intensity, the longer the duration of recharge and the greater the recharge rate (Taylor et al. 2013). The smaller the soil water content, the larger the water retention in the soil and the smaller the recharge rate (Sørensen et al. 2006). A compilation and analysis by Moeck et al. (2020) of more than 5000 rainfall percolation rates worldwide showed that climatic parameters, particularly rainfall rate and seasonality of temperature and rainfall,

were the most important factors affecting the recharge rate, followed by soil and vegetation factors. In the present study, the shapes of the response functions before and after the rainiest month were different, mainly due to the differences in soil moisture content and groundwater depth. Wittenberg and Sivapalan (1999) similarly showed that the shapes of response functions of GWR to rainfall in the Harris River Basin in southwest Australia were different for different months. As shown in Fig. 6, the annual rainfall percolation recharge ratio (α) of the four sub-basins of the Tao'er River Basin fluctuated within a relatively large range from 1964 to 1986. While α tended to be positively correlated to annual rainfall, the correlation was weak. Even under conditions of the same annual rainfall over different periods of the same sub-basin, there are still large differences in the recharge ratio. This illustrates that the percolation recharge process is also a function of the intra-year rainfall or spatial distribution of rainfall in addition to annual rainfall. Therefore, the use of a constant or regular (variable with rainfall) percolation recharge ratio will not provide an accurate estimate of GWR. Therefore, future studies should focus on exploring the synergy between factors affecting groundwater recharge to estimate the response function of GWR to rainfall under different conditions.

The basin-scale groundwater balance estimation method used in the present study relied solely on streamflow data, and is therefore a simple, convenient and effective method.

In comparison with conventional methods, this method does not require extensive field investigation to quantity hydrogeological parameters. The method also rapidly provides long-term characteristics of the groundwater balance and facilitates an understanding of groundwater balance and groundwater circulation in mountainous basins characterized by a scarcity of survey data. The groundwater balance estimation method used in the present study can therefore contribute to the rational management and sustainable use of groundwater resources in mountainous basins. However, it should be noted that this method is based on a series of assumptions: (1) the watershed boundary is also a groundwater ridge, and lateral runoff can be ignored; (2) the relationship between groundwater storage and discharge meets a non-linear reservoir relationship (Eq. 2); (3) there is a direct connection between saturated groundwater and rivers. Not all basins can meet these assumptions. For example, the lateral runoff of watersheds in karst areas can often not be ignored, and some basins with multiple aquifers may not meet the non-linear reservoir hypothesis between groundwater storage and discharge (Ajami et al. 2011; Markovich et al. 2019; Wittenberg and Sivapalan 1999). Future applications in other regions should consider whether these assumptions can really be met. It should also be noted that the method used in this study only estimates the balance elements of shallow saturated groundwater that are directly connected to the rivers, and does not include soil water, return flow, and deep groundwater.

Fig. 6 The relationship between the annual rainfall recharge ratio (α) and rainfall (P) of the four sub-basins of the Tao'er River Basin, Northeast China. **a** Chaersen, **b** Suolun, **c** Dashizhai, **d** Zhenxi
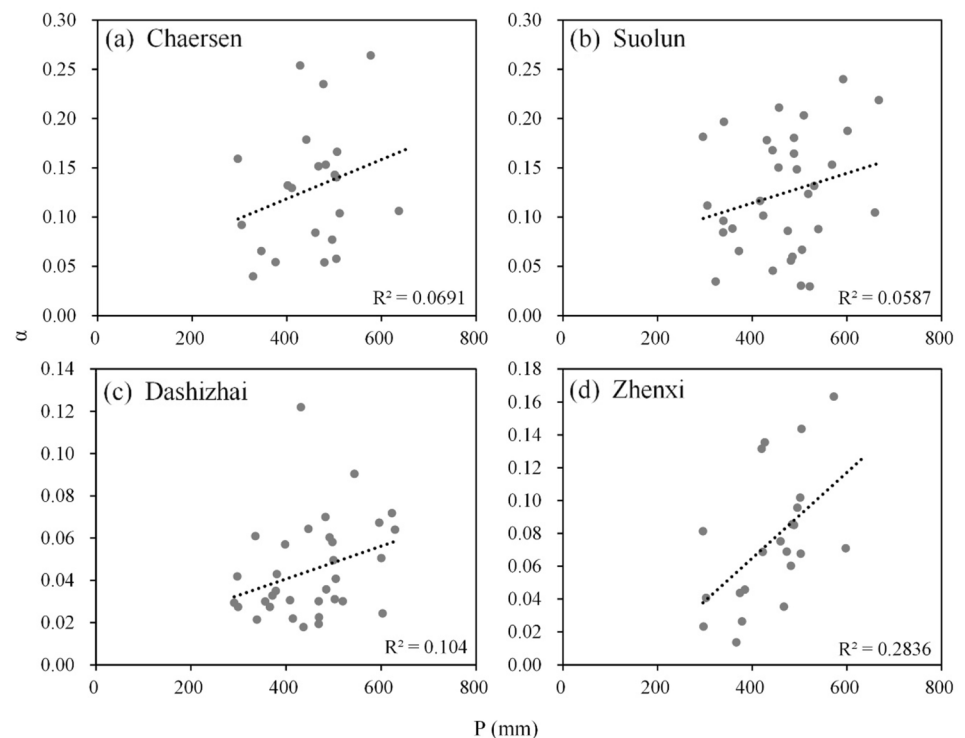
Conclusions

The present study utilized a series of "top-down" methods based on streamflow data to estimate the components of the daily groundwater balance (baseflow, evapotranspiration, recharge) in four sub-basins of the Tao'er River Basin, Northeast China, and analyzed the response functions of groundwater recharge to rainfall. The main conclusions of the present study are listed below.

1) Groundwater recharge in the Tao'er River Basin occurs mainly through focused percolation by heavy rainfall during the rainy season, and following recharge, groundwater is rapidly discharged in the form of baseflow and evapotranspiration. Baseflow in the basin accounts for ~93% of total recharge, whereas evapotranspiration accounts for the remaining ~7%. The multi-year average GWR of the Chaershen, Suolun, Dashizhai and Zhenxi sub-basins were 59.7 mm, 62.4 mm, 19.6 mm and 34.6 mm respectively (Table 2). All components of the groundwater balance showed obvious inter-annual fluctuations.

2) The responses of GWR to rainfall were different before and after the rainiest month, with a relatively slow and weak response pre-peak (January–July) and a relatively rapid and clear response post-peak (August–December). This observation could be mainly attributed to differences in soil moisture content and groundwater depth before and after the rainiest month. The GWR rainfall response functions can be used to estimate basin-scale GWR in a situation of scarce or unreliable streamflow data.

3) The basin-scale groundwater balance estimation method used in the present study relies solely on streamflow data, and is therefore simple, convenient and effective. The method facilitates an understanding of the groundwater balance and groundwater circulation in mountainous basins in which there is a scarcity of survey data, and can contribute to the rational management and sustainable use of groundwater resources in mountainous basins.

Data availability The data that support the findings of this study are available from Songliao Water Resources Commission, Ministry of Water Resources, China.

Code availability Not applicable.

Declarations

Conflict of interests The authors declare that they have no conflict of interest.

References

Ajami H, Troch PA, Maddock T, Meixner T, Eastoe C (2011) Quantifying mountain block recharge by means of catchment-scale storage-discharge relationships. Water Resour Res. https://doi.org/10.1029/2010wr009598

Aksoy H, Wittenberg H (2011) Nonlinear baseflow recession analysis in watersheds with intermittent streamflow. Hydrolog Sci J 56:226–237. https://doi.org/10.1080/02626667.2011.553614

Alley WM (2009) Ground Water. In: Likens GE (ed) Encyclopedia of Inland Waters. Academic Press, Oxford, pp 684–690

Anderson TW, Freethey GW, Tucci P (1992) Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent states, - edn. doi:https://doi.org/10.3133/pp1406B

Boronina A, Golubev S, Balderer W (2005) Estimation of actual evapotranspiration from an alluvial aquifer of the Kouris catchment (Cyprus) using continuous streamflow records. Hydrol Process 19:4055–4068. https://doi.org/10.1002/hyp.5871

Brutsaert W, Nieber JL (1977) Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res 13:637–643. https://doi.org/10.1029/WR013i003p00637

Cambraia Neto AJ, Rodrigues LN (2020) Evaluation of groundwater recharge estimation methods in a watershed in the Brazilian Savannah. Environ Earth Sci. https://doi.org/10.1007/s12665-020-8884-x

Cao G, Scanlon BR, Han D, Zheng C (2016) Impacts of thickening unsaturated zone on groundwater recharge in the North China Plain. J Hydrol 537:260–270. https://doi.org/10.1016/j.jhydrol.2016.03.049

Cook PG, Kilty S (1992) A helicopter-borne electromagnetic survey to delineate groundwater recharge rates. Water Resour Res 28:2953–2961. https://doi.org/10.1029/92WR01560

Dias NL, Kan A (1999) A hydrometeorological model for basin-wide seasonal evapotranspiration. Water Resour Res 35:3409–3418. https://doi.org/10.1029/1999WR900230

Dralle DN, Hahm WJ, Rempe DM, Karst NJ, Thompson SE, Dietrich WE (2018) Quantification of the seasonal hillslope water storage that does not drive streamflow. Hydrol Process 32:1978–1992. https://doi.org/10.1002/hyp.11627

Eckhardt K (2005) How to construct recursive digital filters for baseflow separation. Hydrol Process 19:507–515. https://doi.org/10.1002/hyp.5675

Fan J, Oestergaard KT, Guyot A, Lockington DA (2014) Estimating groundwater recharge and evapotranspiration from water table fluctuations under three vegetation covers in a coastal sandy aquifer of subtropical Australia. J Hydrol 519:1120–1129. https://doi.org/10.1016/j.jhydrol.2014.08.039

Gee GW, Hillel D (1988) Groundwater recharge in arid regions: Review and critique of estimation methods. Hydrol Process 2:255–266. https://doi.org/10.1002/hyp.3360020306

Ghasemizade M, Moeck C, Schirmer M (2015) The effect of model complexity in simulating unsaturated zone flow processes on recharge estimation at varying time scales. J Hydrol 529:1173–1184. https://doi.org/10.1016/j.jhydrol.2015.09.027

He S, Li S, Xie R, Lu J (2016) Baseflow separation based on a meteorology-corrected nonlinear reservoir algorithm in a typical rainy

agricultural watershed. J Hydrol 535:418–428. https://doi.org/10.1016/j.jhydrol.2016.02.010

Herrera C et al (2018) Groundwater origin and recharge in the hyper-arid Cordillera de la Costa. Atacama Desert, Northern Chile Sci Total Environ 624:114–132. https://doi.org/10.1016/j.scitotenv.2017.12.134

Jan C-D, Chen T-H, Huang H-M (2011) Analysis of rainfall-induced quick groundwater-level response by using a Kernel function. Paddy Water Environ, 11:135–144. https://doi.org/10.1007/s10333-011-0299-6

Jia H (2015) Analysis and calculation of groundwater resources in the Southern Valley of Inner Mongolia Autonomous Region Wulanhaote. China university of geosciences

Kirchner JW (2009) Catchments as simple dynamical systems: catchment characterization, rainfall-runoff modeling, and doing hydrology backward. Water Resour Res. https://doi.org/10.1029/2008wr006912

Kou L (2016) The situation analysis of water resources in Tao'er river basin based on SWAT model. Dalian university of technology, Master

Li S (2018) Analysis of reservoir flood scheduling scheme of Chahar Tao'er river basin. Jilin university, Master

Lyne V, Hollick M (1979) Stochastic Time-Variable Rainfall-Runoff Modeling vol 79. Australian National Conference Publication, Australian., Canberra

Markovich KH, Manning AH, Condon LE, McIntosh Jennifer C (2019) Mountain-block recharge: a review of current understanding. Water Resour Res. https://doi.org/10.1029/2019wr025676

Meng F (2017) Research on transform relationship between surface water and groundwater in Tao'er River fan. Jilin University, Master

Moeck C, Grech-Cumbo N, Podgorski J, Bretzler A, Gurdak JJ, Berg M, Schirmer M (2020) A global-scale dataset of direct natural groundwater recharge rates: a review of variables, processes and relationships. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.137042

Palmroth S, Katul GG, Hui D, McCarthy HR, Jackson RB, Oren R (2010) Estimation of long-term basin scale evapotranspiration from streamflow time series. Water Resour Res. https://doi.org/10.1029/2009wr008838

Saraiva Okello AML, Uhlenbrook S, Jewitt GPW, Masih I, Riddell ES, Van der Zaag P (2018) Hydrograph separation using tracers and digital filters to quantify runoff components in a semi-arid mesoscale catchment. Hydrol Process 32:1334–1350. https://doi.org/10.1002/hyp.11491

Sørensen R, Zinko U, Seibert J (2006) On the calculation of the topographic wetness index: evaluation of different methods based on field observations Hydrol Earth. Syst Sci 10:101–112. https://doi.org/10.5194/hess-10-101-2006

Srivastava A, Wu JQ, Elliot WJ, Brooks ES, Flanagan DC (2017) Modeling streamflow in a snow-dominated forest watershed using the Water Erosion Prediction Project (WEPP) Model T Asabe 60:1171–1187 doi:https://doi.org/10.13031/trans.12035

Stewart M, Cimino J, Ross M (2007) Calibration of Base Flow Separation Methods with Streamflow Conductivity Groundwater 45:17–27. https://doi.org/10.1111/j.1745-6584.2006.00263.x

Szilagyi J, Harvey FE, Ayers JF (2003) Regional Estimation of Base Recharge to Ground Water Using Water Balance and a Base-Flow Index Groundwater 41:504–513. https://doi.org/10.1111/j.1745-6584.2003.tb02384.x

Szilagyi J, Gribovszki Z, Kalicz P (2007) Estimation of catchment-scale evapotranspiration from baseflow recession data: Numerical model and practical application results. J Hydrol 336:206–217. https://doi.org/10.1016/j.jhydrol.2007.01.004

Taylor RG, Todd MC, Kongola L, Maurice L, Nahozya E, Sanga H, MacDonald AM (2013) Evidence of the dependence of groundwater resources on extreme rainfall in East Africa Nature. Clim Change 3:374–378. https://doi.org/10.1038/nclimate1731

Thomas BF, Vogel RM, Famiglietti JS (2015) Objective hydrograph baseflow recession analysis. J Hydrol 525:102–112. https://doi.org/10.1016/j.jhydrol.2015.03.028

Wang D, Cai X (2009) Detecting human interferences to low flows through base flow recession analysis. Water Resour Res 45:W07426. https://doi.org/10.1029/2009wr007819

Wittenberg H (1999) Baseflow recession and recharge as nonlinear storage processes. Hydrol Process 13:715–726

Wittenberg H (2003) Effects of season and man-made changes on baseflow and flow recession: case studies. Hydrol Process 17:2113–2123. https://doi.org/10.1002/hyp.1324

Wittenberg H, Sivapalan M (1999) Watershed groundwater balance estimation using streamflow recession analysis and baseflow separation. J Hydrol 219:20–33. https://doi.org/10.1016/S0022-1694(99)00040-2

Wittenberg H, Aksoy H, Miegel K (2019) Fast response of groundwater to heavy rainfall. J Hydrol 571:837–842. https://doi.org/10.1016/j.jhydrol.2019.02.037

Wu J, Zhang R, Yang J (1997) Estimating infiltration recharge using a response function model. J Hydrol 198:124–139. https://doi.org/10.1016/S0022-1694(96)03309-4

Xiao X (2017) Research on the theory and technology of groundwater reservoir artificial regulation of Taoer River alluvial fan in Jilin province. Jilin University, Master

Yang W, Xiao C, Liang X (2019a) Technical note: Analytical sensitivity analysis and uncertainty estimation of baseflow index calculated by a two-component hydrograph separation method with conductivity as a tracer. Hydrol Earth Syst Sci 23:1103–1112. https://doi.org/10.5194/hess-23-1103-2019

Yang W, Xiao C, Liang X, Zhang Z (2019b) Two baseflow separation methods based on daily average gage height and discharge. Water Supply 19:1978–1985. https://doi.org/10.2166/ws.2019.074

Yang W, Xiao C, Liang X (2020) Extraction method of baseflow recession segments based on second-order derivative of streamflow and comparison with four conventional methods. Water. https://doi.org/10.3390/w12071953

Zheng W, Wang S, Sprenger M, Liu B, Cao J (2019) Response of soil water movement and groundwater recharge to extreme precipitation in a headwater catchment in the North China Plain. J Hydrol 576:466–477. https://doi.org/10.1016/j.jhydrol.2019.06.071

Zillgens B, Merz B, Kirnbauer R, Tilch N (2007) Analysis of the runoff response of an alpine catchment at different scales Hydrol Earth. Syst Sci 11:1441–1454. https://doi.org/10.5194/hess-11-1441-2007