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REVIEW ARTICLE

Review: groundwater recharge estimation in northern China karst regions

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Abstract

Reliable estimates of groundwater recharge are crucial for the groundwater resources evaluating and sustainable utilization plans formulating. To protect the precious karst groundwater resources, this paper critically reviewed the previous studies on karst groundwater recharge in northern China karst regions from the perspective of diffuse recharge and focused recharge, and took Niangziguan Spring catchment as a case study. It is concluded that for the 119 karst groundwater systems, 52% occur diffuse recharge through precipitation infiltration, 48% occur both diffuse recharge through precipitation infiltration and focused recharge through surface water leakage. The mean annual precipitation, diffuse recharge and infiltration coefficient (IC, as percentage of precipitation) are 560 mm, 136 mm and 23.1%, respectively. A high correlation was observed between annual precipitation and annual diffuse recharge with a nonlinear relationship. The IC can vary substantially even with the same annual precipitation between 9.3 and 38.0%, with an evidently increasing trend eastward. This reflects a significant difference in the degree of karstification for the northern karst regions. The most commonly applied for recharge assessment in northern China karst regions is equal volume spring flow method, the chloride mass balance method is highly recommended for groundwater recharge estimation of the regions based on the case study. This work provides reference for recharge estimation, assessment and management of karst groundwater resources in northern China.

Keywords Groundwater recharge · Karst aquifer · Infiltration coefficient · Northern China · Niangziguan Spring

Introduction

Karst groundwater is of fundamental significance for community growth and development in many parts of the world. According to Ford and Williams (2007), roughly 20–25% of the world's population relies on karst groundwater as the primary source for drinking and irrigation. However, due to climate change as well as population expansion, the total karst groundwater depletion has increased worldwide. The contradictory between supply and demand of water resource becomes more and more pronounced. Groundwater recharge is a critical component in assessment of groundwater systems for sustainable utilization. Hence, understanding groundwater recharge is essential for the water managers to maintain viability of water resources and groundwater modeling as well as contaminant transport. Efforts have been made to investigate groundwater recharge in the Middle East (Marechal et al. 2006; Mohammadi et al. 2014; Jassas and Merkel 2014), Africa (Chung et al. 2016; Xu and Beekman 2018) and Northern China (Huang and Pang 2013), but all of these were mainly for water supply purposes. Some researchers studied the impact of climate change on groundwater recharge. For example, the global-scale groundwater recharge simulation based on the global hydrological model WGHM (Döll and Flörke 2005), the potential groundwater recharge variation under climate change in East Anglia (Holman et al. 2009) and Northern China (Jia et al. 2017), etc. Therefore, reliable estimation of groundwater recharge rate is crucial for the assessment of groundwater resource

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potential. However, the groundwater recharge can be affected by various factors such as rainfall intensity and frequency, geological settings, vegetation and land use types, etc. And it is known to be highly variable in both temporal and spatial scales (Healy 2010). In addition, karst groundwater has its distinctive characteristics: strong heterogeneity and anisotropy (Bakalowicz 2005). Hence, further research is needed to address the complexity and variability of karst groundwater recharge estimation.

In northern China, the carbonate rocks have an area of 68.5×10^4 km^2, the exposed areas, the covered areas and deep burial areas account for 11, 13 and 76%, respectively (Liang et al. 2018). When combined, these regions yield a total karst groundwater of 108.8×10^8 m^3/year. The groundwater from carbonate aquifer is the most important water supply sources due to the grave shortage of surface water. Currently, more than 30 large cities, 100 county-level cities, and numerous towns in karst mountainous areas depend on karst groundwater as the primary source for drinking. Especially in Shanxi Province, the outcrop area of Cambrian and Ordovician carbonate rocks account for 17.5% of the land surface and 60–80% of the water supply in the region comes from karst groundwater (Sun et al. 2016; Zhang et al. 2019). In northern China, a total of 119 karst groundwater systems (Fig. 1) have been delineated by their recharge, runoff, storage and discharge flows (Liang et al. 2013).

Springs are the most common mode of natural discharge for karst groundwater systems. According to the springs recorded in this region, 41 karst springs with a flow rate greater than 1 m^3/s and 170 with a flow rate higher than 0.1 m^3/s. However, the available water supply is not sufficient to meet the ever-increasing demand for water resources in northern China. Over the last 40 years, over-exploitation of karst groundwater has caused a series of environmental and geological issues, including the drying up of karst springs, a continuous decline of karst groundwater level, degradation of karst groundwater quality and so on. All these indicate that the northern karst springs have their own immediate issues. Therefore, it is of great significance to review the research findings on groundwater recharge estimation in northern China karst regions.

To protect the precious karst groundwater resources, this paper critically reviewed the previous studies on karst groundwater recharge in northern China karst regions from the perspective of diffuse recharge and focused recharge, and took Niangziguan Spring catchment as a case study. The objective of this research is twofold: (1) to present a synthesis of the infiltration coefficient (IC) in the carbonate aquifer from west to east in northern China; (2) to explore the relationships between the values of annual precipitation and IC. This review provides reference for recharge estimation, assessment and management of karst groundwater resources in northern China.

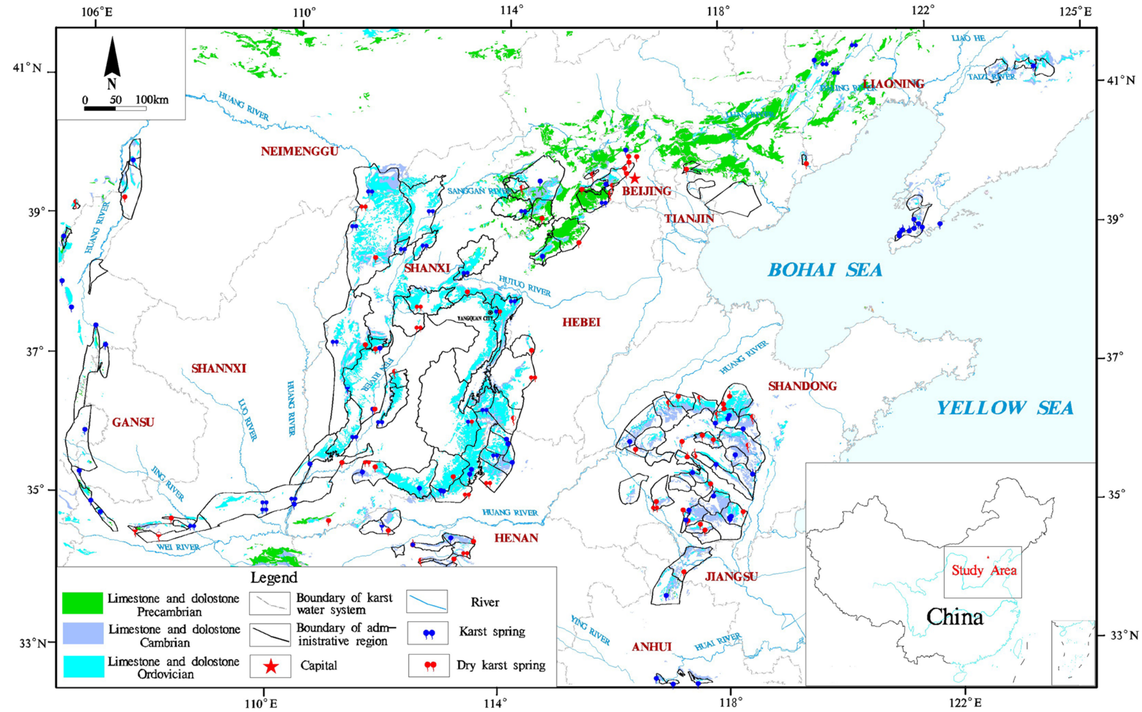

Fig. 1 The location of outcrop carbonate and karst groundwater systems in northern China (modified from Liang et al. 2018)

Overview of results

Groundwater recharge is defined as the downward flow of water reaching the water table, adding to groundwater reservoir (Healy 2010). This recharge has to be separated from what is the net recharge, which refers to what remains in the water table after discounting uptake by phreatophytes (De Vries and Simmers 2002). The latter does not occur normally in northern China karst regions, this is because the karst groundwater table is far below the root zone and has escaped from evapotranspiration.

Two main mechanisms of recharge have been conceptually defined by Healy (2010) as follows:

Diffuse recharge: precipitation infiltrating the soil surface and percolating through the unsaturated zone to the water table, it is distributed over large areas. The diffuse recharge is sometimes referred to as direct recharge (De Vries and Simmers 2002). In addition, diffuse recharge can be expressed in various forms, e.g., as a percentage of annual precipitation defined as infiltration coefficient (IC), or in mm/year.

Focused recharge: it is the movement of water from surface-water bodies, such as streams, canals, lakes or reservoirs, to an underlying aquifer. There are two main types of focused recharge, with localized recharge defined as concentrated recharge from small depressions, joints or cracks, and indirect recharge defined as recharge from rivers, canals, and reservoirs.

Groundwater recharge occurs in northern China karst regions also through diffuse recharge and focused recharge (Han 2015). As described above, diffuse recharge is recharge that is distributed in karst outcropped area and covered karst area (the carbonate rock is covered by sediments), it is the precipitation percolating through the vadose zone to the karst groundwater table. Focused recharge is the Surface water from rivers, lakes or reservoirs leakage into karst aquifer through the pores, fissures or fractures. Generally, diffuse recharge dominates in the east of the study area, but the importance of focused recharge in terms of total karst aquifer replenishment tends to increase from east to west. Out of the 119 karst groundwater systems, 62 are mainly fed by precipitation infiltration, 57 are recharged by precipitation infiltration and surface water leakage into karst aquifer (Liang and Wang 2010). It is clear that precipitation and surface water bodies are the main source of karst groundwater in this area.

Overview of diffuse recharge

According to Han et al. (1993, 2015) and Hou and Zhang (2008), the mean annual precipitation on karst areas in northern China is 560 ± 154 mm/year (Table 1). For example, the Qianligou karst groundwater system, in the northwest sector, receives the lowest average annual precipitation, 153 mm/year. By contrast, the Taizihe karst groundwater system, in the northeast sector, receives an annual precipitation of 792 mm/year. The great variability of the annual precipitation is seen in Fig. 2, with an unclear increasing trend eastward except the Ordos basin located in the west part of the region.

Table 1 Statistic of annual precipitation (*P*), annual diffuse recharge (*R*) and infiltration coefficient (IC) measured for the 46 karst groundwater systems studied

Item	*P* (mm/year)	*R* (mm/year)	IC (%)
Mean	560	136	23.1
SD	154	61	6.8
Median	594	142	23.9
Max	792	265	38.0
Min	153	14	9.3

SD standard deviation, *Max* maximum, *Min* minimum

This significant spatial variability in precipitation is reflected by the variability of recharge rates. Groundwater recharge assessment in carbonate aquifers is more difficult than that in detrital aquifers. The high variability of porosity and permeability of carbonate rocks influences (1) the recharge process (diffuse and/or focused); (2) the flow across the unsaturated zone (matrix, factures and the karstic conduit network); and (3) the discharge (perennial, periodic or episodic springs) (Bakalowicz 2005; Ford and Williams 2007; Martos-Rosillo et al. 2015). In northern China, carbonate aquifers usually have deep water tables. This means that methods applied in unsaturated zone in non-carbonate rock areas, such as zero flux plane and soil water balance, or those based on Darcy's Law, may not be readily valid for estimating recharge. Because of karst groundwater discharged as individual or clusters of springs, the equal volume spring flow method (EVSF) is the most widely used technique for recharge estimation (Hou and Zhang 2008; Li and Kang 1998). The annual diffuse recharge in karst groundwater systems may range from 14 to 265 mm/year (Table 1), and the average annual diffuse recharge is 136 mm/year, with a standard deviation of 61 mm/year. The average annual IC is 23.1% of precipitation, with a standard deviation close to 7%. Figure 3 shows that the IC is between 9 and 18% in the west section, such as the Zhuozishan region in Inner Mongolia, whereas in the eastern part it reaches up to 26%, such as the Luzhongnan region in Shandong. It should be noted that Fig. 3 shows an evident increasing trend eastward.

Statistical analyses (Han et al. 1993; Li and Liu 1996; Hou and Zhang 2008) of the annual diffuse recharge and annual precipitation shown in Fig. 4 indicate that it is not

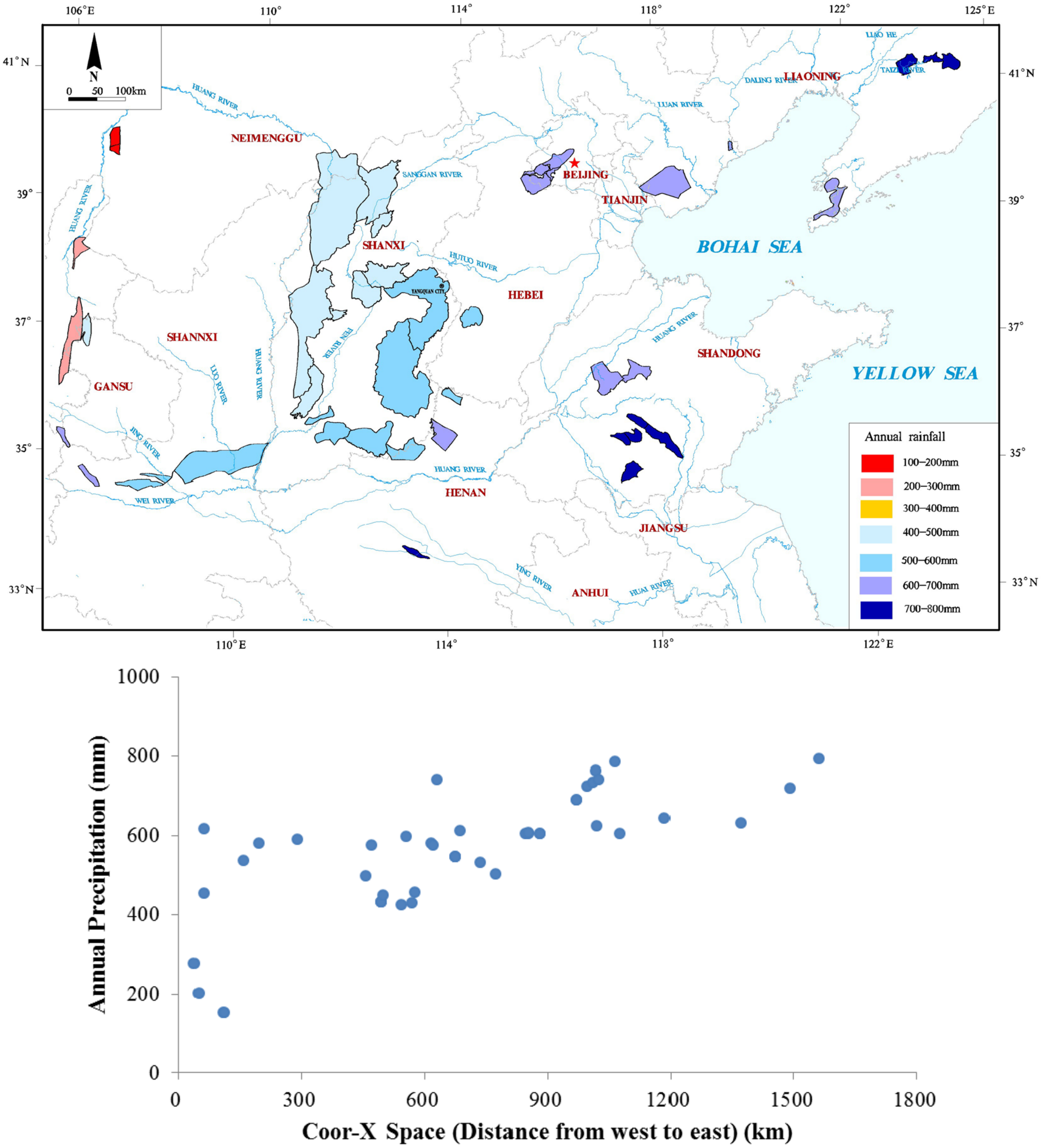

Fig. 2 Distribution of annual precipitation in northern China (updated after Han et al. 1993, 2015; Hou and Zhang 2008)

a linear relationship between the two. On an average basis, the IC is 0.09–0.13, 0.18–0.22 and 0.23–0.38 for the annual precipitation ranges of 0–400, 400–700 and 700–900 mm, respectively. The area of precipitation less than 400 mm is mainly distributed over the west of northern China karst region, and the degree of its karstification is weak. And the area of precipitation greater than 700 mm is mainly distributed over the east of northern China karst region with intensive karstification. Thus, the diffuse recharge in eastern part is higher than that in the western part. In northern China, the climatic characteristics of this region cause the IC to be low in comparison with the degree of surface karstification. Furthermore, IC is an important hydrological parameter for the quantification of groundwater. Nevertheless, the IC variations are due to the changes in climate, lithology, soil type, vegetation and land use, slope, karstification, and so on. Thus, the estimation of diffuse recharge to carbonate aquifers in semi-arid regions remains challenging.

Overview of focused recharge

In northern China, 48% of karst groundwater systems may occur in the form of focused recharge. Although it doesn't make up the majority of total recharge in this area, the

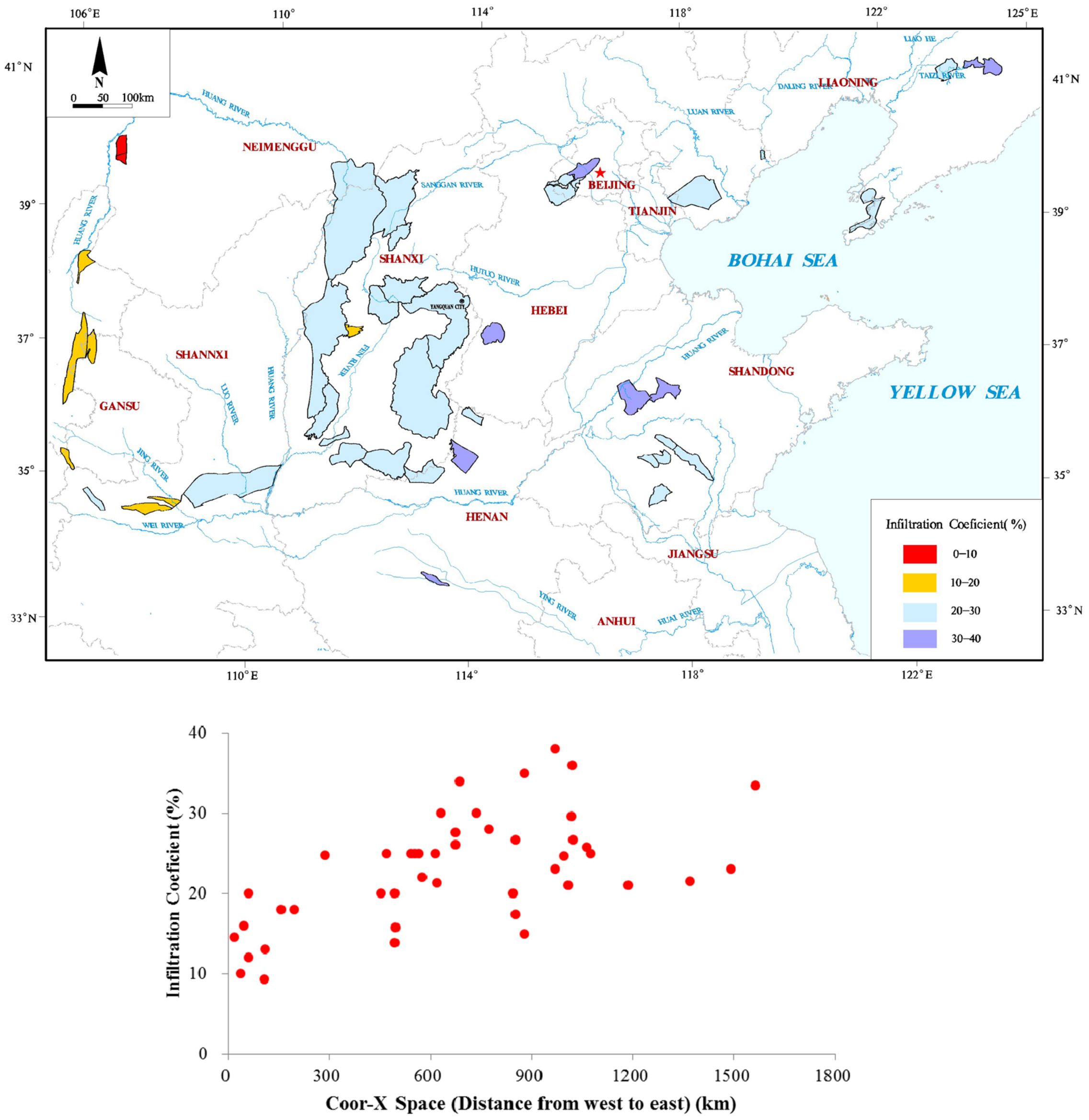

Fig. 3 Distribution of infiltration coefficient (IC) in northern China (updated after Li and Kang 1998; Hou and Zhang 2008)

surface–subsurface water interaction plays an important role in controlling groundwater dynamics and storage. Therefore, focused recharge evaluation is important to planning, development, management and protection of karst groundwater. Under natural conditions, there are basically three pathways of the surface water leakage into karst groundwater (White 1988). The first and the second are referred to as the transformation of surface water into ground either via swallow holes, or via sinkhole as internal flow, and the third is the leakage through carbonate bedrock beneath the river bed, which is the major pathway in northern China karst area. However, such leakage process is difficult to be quantitatively studied, this is attributed to the extreme complexity of the dissolution cavities and the regional scale of the leakage (Wang et al. 2001).

In general, the most direct method to estimate losses of stream flow into karst groundwater system is to measure the runoff discharge at the start and at the end of the section of a leaking river, the leaked amount was then obtained by subtracting the discharge at the start with that at the end (Wang et al. 2001). Using this method, the relationship between runoff and leaked amount on a typical leaking section of Niangziguan Spring catchment is established. The leakage coefficient (LC) is defined as the leakage amount as a proportion of runoff discharge per unit length. There is a typical negative power function relationship between LC and runoff

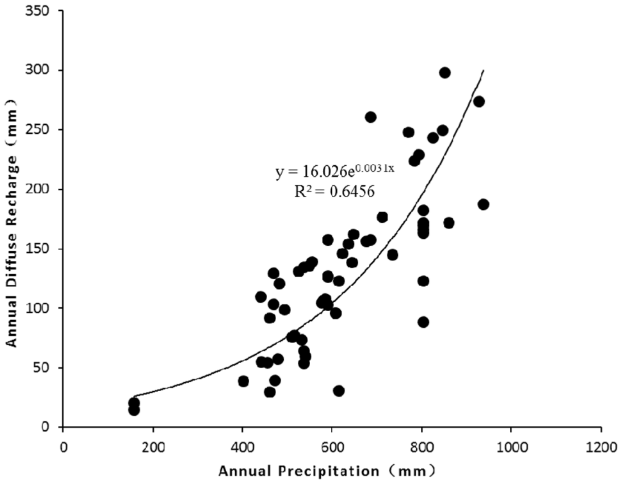

Fig. 4 Result of diffuse recharge studies in northern China karst area (Han et al. 1993; Li and Liu 1996; Hou and Zhang 2008)

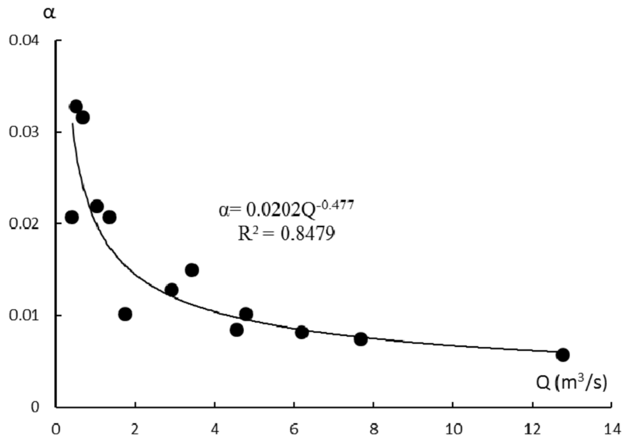

Fig. 5 Relationship between runoff discharge (*Q*) and leakage coefficient (*α*) in Niangziguan Spring catchment (Liang et al. 2011; Wang et al. 2015)

discharge (Liang et al. 2011; Wang et al. 2015), as shown in Fig. 5. The smaller the runoff discharge, the larger the LC value.

Undoubtedly, it remains the most accurate method to calculate leaked amount by subtracting the discharge at the upstream with that at downstream of the section of a leaking river. However, this method is time and effort-consuming and the effects of flood water on runoff should be excluded in the rainy season or when the leaking section is a complex water system. Hydro-geochemistry has proved to be an effective tool for studying surface water-groundwater interaction (Negrel and Lachassagne 2000; Wang et al. 2006). Different hydro-chemical parameters such as major and minor ions, silica, stable isotope ratios were used in previous studies (Abu-Jaber 2001; Gao et al. 2010; Li et al. 2021). However, these methods are unsuitable for regions of several thousand square kilometers, where groundwater flows in anisotropic and heterogeneous aquifers, especially in karst area.

In addition, the loss of surface water stored in reservoir built in carbonate areas is also to produce focused recharge in northern China karst regions. Table 2 shows the major reservoirs located in carbonate areas in northern China (Hou and Zhang 2008). The leakage into Jinci Spring karst groundwater system has been calculated by water balance method, the leaked amount of Fenhe 2nd reservoir is about 2.5 m^3/s, while the natural discharge of Jinci Spring is about 1.3 m^3/s (Guo et al. 2018). However, due to unknown karstic heterogeneity and lack of monitoring data, little research has been completed on losses of reservoir into karst aquifer in northern China.

Case study in Niangziguan Spring catchment

The Nianzigguan Spring, one of the major karst springs in northern China, is located in the Mian River Valley, Eastern Shanxi Province, with latitude ranging from 36º 55′ to 37º 50′ and longitude ranging from 112º 20′ to 113º 55′ (Zhang et al. 2016). The clusters of Niangziguan Spring are distributed along 7 km of the Mian riverbank with altitude range of 360–392 m. The springs discharge at an annual average rate of 9.67 m^3/s based on the records from 1956 to 2014, and it is the major source of water supply for Yangquan City with a population over 1.3 million. Therefore, the karst groundwater is very important for the water supply of Yangquan City.

A number of investigation projects on the hydrological or water chemistry processes of Niangziguan Spring have been carried out since the 1970s (Hao et al. 2012; Gao et al. 2011). The first systematic studies of Niangziguan Spring date back to the early 1970s, which were conducted mainly for the water supply. The catchment area was measured 2600 km^2 in 1975. But as time goes on, the area of the karst groundwater system was continuously increasing. According to the latest investigation result carried out in 2018, the area is expanded to 7436 km^2 (Table 3). There are two reasons that must be taken into account. The first is that the boundary of the system has been redefined in the latest study. The second is the original hydrogeological conditions that have been modified because of human activities, such as the underground watershed shift at the boundary between the Niangziguan Spring catchment and Xin'an Spring catchment. Thus, with large amounts of data and increasing accuracy in hydrogeological surveys, the groundwater system of the Niangziguan Spring catchment is well-characterized.

An overview of commonly used recharge estimation methods and the estimates in Niangziguan Spring catchment are given in Table 3. The methods include water balance method (WBM) and isotope tracing. The most employed

Table 2 The reservoir distributed in carbonate areas in northern China

Reservoir	Subordinate to the river	Volume of reservoir/10^4 m^3	Stratum	References
Wanjiazhai reservoir	Yellow River	97,000	Cambrian and Ordovician	Hou et al. (2008)
Tianqiao reservoir	Yellow River	6600	Ordovician	
Sizhuanhe reservoir	Sizhuang River			
Panhe reservoir	Pan River			
Longzui reservoir	Wen River			
Taoqupo reservoir	Qishui River	5720	Ordovician	
Guxian reservoir	Baishui River	686	Ordovician	
Qingxing reservoir	Baishui River		Ordovician	
Shengli reservoir	Dayu River	520		
Yangmaowan reservoir	Qishui River	12,000	Ordovician	
Qianling reservoir	Moxi River	200	Ordovician	
Xiaohe reservoir	Gan River	100	Ordovician	
Dianwa reservoir	Ru River	40	Ordovician	
Fenhe 2nd reservoir	Fen River	13,300	Ordovician	Guo et al. (2018)

Table 3 The area of Niangziguan Spring catchment and IC in different periods

Catchment	Time	Catchment area/km^2	IC (estimation method)			References
			Moderate karstification area	General karstification area	Covered karst area	
Niangziguan Spring catchment	1975	2600	0.32 (water balance method)			Shanxi electric power engineering institute (1975)
	1983	3601	0.35 (water balance method)			Qian (1983)
	1990				0.09 (isotope tracing)	Zhang et al. (1990)
	1993	4667	0.28 (water balance method)			Han et al. (1993)
	2018	7346	0.28 (water balance method)	0.12 (water balance method)		Shen et al. (2018)

method was WBM, and it is based on the water budget of recharge and discharge in the groundwater system. Therefore, due to the continuous expansion of the Niangziguan Spring catchment, especially the area of outcrop carbonate rock, the IC obtained from the groundwater balance method gradually decreases with time. Thus, the WBM may have a fairly high uncertainty when the hydrogeological condition of the water system is not clear.

Because of uncertainties associated with each approach for recharge estimation, the use of many different approaches is recommended to constrain the recharge estimates (Xu and Beekman 2003). The chloride mass balance (CMB) approach has been employed to estimate the IC in Niangziguan Spring catchment both in moderate karstification area (Duolegou station) and covered karst area (Donghui station). The IC is 21.19% of the precipitation in Duolegou station, and it is 11.06% in Donghui station (Shen et al. 2018). In the covered karst area, the result is close to the latest value using the isotope tracer method as shown in Table 3. But in the moderate karstification area, the result is lower. Experience has shown that the results of different methods are quite different and the IC in recharge assessment is improved when applying a combination of different methods. Thus, the results of this case study may serve to improve the assessment of groundwater recharge in Niangziguan Spring catchment (Table 4).

Challenges in estimating karst groundwater recharge in northern China

Choosing realistic estimation methods

Currently, groundwater recharge estimation methods can be roughly classified as physical methods, chemical (tracers) methods and groundwater modeling methods. The physical methods include water budget, zero-flux plane, seepage meters, water-table fluctuation, and stream hydrograph

Table 4 Groundwater recharge estimation using CMB method in Niangziguan Spring catchment

Station	Average annual precipitation (mm/year)	Chloride in precipitation (mg/L)	Chloride in groundwater (mg/L)	Point groundwater recharge (mm/year)	IC (%)	References
Duolegou station	546	1.89	8.92	116	21.19	Shen et al. (2018)
Donghui station	520	2.29	20.71	58	11.06	

separation and so on (Richards et al. 1956; Lee and Cherry 1979; Healy and Cook 2002; Meyboom 1961). The tracer techniques include heat tracer, isotopic tracers, chloride tracer, etc. (Wood and Sanford 1995; Saghravani et al. 2015). However, choosing an appropriate technique is often difficult among those methods, especially in karst area.

Due to the complex and original characteristics of karst medium, the zero-flux plane method, lysimeter, Darcy method, and other conventional methods cannot be used in the karst region. In addition, the space and time scales of the various methods also affect the choice of method used (Scanlon et al. 2002).

For the water budget method, it is based on the balance of water resources and it includes the surface water balance method and groundwater balance method. These are considered as conventional methods in groundwater recharge research and are widely used. Most precipitation infiltration studies on the northern karst region mainly employ these methods. However, it is difficult to determine some balance items when applying the mentioned methods. Such as in the surface water balance method, accurately estimating the evapotranspiration of groundwater remains difficult in hydrogeological research; and in the groundwater balance, estimating changes in groundwater storage and determining the amount of groundwater exploitation also pose great difficulty. Accurately estimating these balance items is a prerequisite for applying the water balance method.

Baseflow discharge method is used to estimate groundwater recharge in surface-water hydrology, which is based on the principle of stream flow and is mainly from groundwater recharge during the dry season. This method is simple and was often used in earlier studies. However, due to the aggravation of human activities and large-scale construction of reservoirs as well as artificial lakes in northern karst regions in recent years, baseflow discharge is not necessarily directly equated to recharge because the pumpage, evapotranspiration, and underflow to deep aquifer may also be significant.

Chemical methods used in research on infiltration recharge in northern karst regions currently include the tritium isotope and CMB methods. The tritium isotope method has been widely used in the last 50 years. The main reason is that large-scale nuclear testing in the 1960s resulted in water tritium levels reaching a peak value. However, as its half-life is relatively short ($T_{1/2} = 12.3$ years), results from studies employing this method has gradually decreased in recent years. The CMB method uses the conservation of chloride ions when precipitation is converted into groundwater. This method is widely applicable, simple to use, and has been employed in many precipitation infiltration recharge studies in the saturated and unsaturated zones in loose medium. However, one assumption is that groundwater flow has one-dimensional vertical movement and the groundwater recharge method is a piston-type recharge. In karst regions, piston-type recharge and short-circuit recharge coexist while short-circuit recharge is primary during the wet season. This poses challenges for using the CMB method in research on precipitation infiltration recharge in karst regions.

Groundwater numerical simulation requires accurate generalization of the hydrogeological conditions of the study site and long-term monitoring data series. Currently, this method is mainly used in areas with higher study and more complete information. Examples include the Jinci Spring catchment and the Jinan Baotu Spring catchment. This method is often quite limited because of scarce hydrogeological data.

Recharge processes

In the karst area, karst fissure, sinkholes, and collapse columns all can become a direct recharge route for groundwater, resulting in the coexistence of both piston-like and short-circuit recharge methods. In addition, devices cannot be installed in bedrock for direct observation of recharge processes. This poses large challenges for studying the recharge processes and its mechanisms in carbonate rock regions. Li and Liu (1996) took the Jiaozuo karst recharge region as an example to establish a random model of diffuse recharge and examined the effects of effective precipitation, ineffective precipitation, and precipitation intensity on diffuse recharge. Huang et al. (2006) introduced the concept of precipitation coefficient to regulate corresponding diffuse recharge with different amounts of precipitation and the coefficient is used in numerical simulation of Yanhe Spring karat water system in Shanxi Province. However, it is not reasonable to use IC to estimate the amount of diffuse recharge in the northern karst region, because it is not a linear relationship between precipitation and recharge, as shown in Fig. 4. In addition, the recharge response with time, the highly variable area distribution of groundwater recharge, the scarcity of hydrogeological data, and the complexities of the hydrologic balance are the major challenges in a process of recharge estimation.

Recommendations

Based on the current status and characteristics of groundwater recharge research in the northern China karst region, this review recommends the continued focus on the following aspects.

Current results have shown the nonlinear relationship between precipitation and diffuse recharge. However, the linear relationship has been established for most of karst groundwater resources assessment. Moreover, the IC will vary with precipitation in the same region because of the effects of precipitation amount and intensity (Jemcov and Petric 2009). Thus, it is necessary to conduct research on the spatiotemporal variation patterns of the IC for accurately evaluating the renewable karst groundwater resources.

With regard to the aspects of the recharge processes and its mechanisms, classical regions should be selected to establish as field observation station network. Hydrodynamic observation series and sample collection combined with the water balance method, hydrologic process curve, hydrochemistry, and environmental isotope methods can be used to understand diffuse recharge and focused recharge in the karst region. These would further reveal recharge mechanisms under different geological and climatic conditions and quantitatively analyze the effects of climate change and human activities on karst groundwater recharge.

Hydrological functional studies on the unsaturated zone in the karst region should be implemented. These would include better monitoring of hydrological processes in the unsaturated zone of the thick exposed carbonate rock layer, examining the effects of unsaturated zone thickness on diffuse recharge, investigating the methods for effective precipitation and its influencing factors, and examining the hysteresis problem in diffuse recharge and multi-year regulatory patterns in major karst springs in northern China.

The hydrologic effects of afforestation in the northern China karst region should be examined. Scholars (Shen et al. 2017) have different opinions on the impact of large-scale afforestation on conserving water sources. The relationship between vegetation type, coverage, and amount of recharge should be further investigated in the northern karst region, particularly the exposed carbonate rock. This will improve our knowledge of the recharge processes in different underlying surfaces.

Conclusion

In northern China karst regions, groundwater stored in carbonate aquifers is a strategic resource of vital importance. At present, there is an increasing water demand for the agricultural, industry and drinking, especially in a scenario of drought periods. Nevertheless, the estimation of groundwater recharge in this area proves challenging. There are two main mechanisms of recharge in northern China karst regions, the precipitation direct recharge to karst groundwater as diffuse recharge, the leakage of surface water from river or surface reservoir into karst aquifer as focused recharge. In the 119 karst groundwater systems, 52% occur diffuse recharge through precipitation infiltration, and 48% occur both diffuse recharge through precipitation infiltration and focused recharge through surface water leakage. The diffuse recharge makes up the majority of total recharge in this area.

In northern China karst regions, the mean annual precipitation is 560 ± 154 mm/year with an unclear increasing trend eastward. The diffuse recharge ranges from 14 to 265 mm/year. The mean annual infiltration coefficient is 23.1% of the precipitation, with fluctuation ranging between 9 and 38%. A high correlation between annual diffuse recharge and annual precipitation was obtained from the 46 karst groundwater systems. Nevertheless, even with the same annual precipitation, the IC can still be very different. The bibliographic data show an evident increasing trend eastward due to the degree of surface karstification. Furthermore, result of the case study about groundwater diffuse recharge estimation in Niangziguan Spring catchment area shows that the CMB method is suitable for the estimation of IC in local epikarst zone and covered karst area. Thus, the chloride mass balance (CMB) method is highly recommended for groundwater recharge estimation of the northern karst regions. This review provides a key reference for recharge estimation, assessment and management of karst groundwater resources in northern China.

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Data availability All the data are available upon request.

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