



Review: Recent progress on groundwater recharge research in arid and semiarid areas of China

Mingyue Li^{2,1} · Yueqing Xie^{2,1} · Yanhui Dong^{3,4} · Liheng Wang^{3,4} · Zaiyong Zhang^{5,6}

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Abstract

Groundwater plays a critical water resources role in arid and semi-arid areas. Quantitative evaluation of groundwater recharge is crucial in hydrogeological investigations. Under the complex hydrogeological and climatic conditions in China's arid and semi-arid regions, groundwater recharge shows significant spatio-temporal heterogeneity. Although there has been much research, including hydrochemical analysis, isotope tracing, in-situ tests and numerical simulations, accurate quantitative groundwater recharge is still a great challenge. This paper reviews the progress in research on groundwater recharge in arid and semi-arid regions of China, focusing on the principles and current applications of the main techniques, as well as the achievements in nine typical arid and semi-arid regions (Tarim Basin, Junggar Basin, Shule River Basin, Heihe River Basin, Yinchuan Plain, Badain Jaran Desert, Loess Plateau, Ordos Plateau, North China Plain). The paper reveals that the chloride mass balance method is a popular method to estimate groundwater recharge rate, whereas stable isotopes and hydrochemistry analyses, as well as the joint use of both, have been widely used in the understanding of groundwater recharge processes and mechanisms in the arid and semi-arid regions of China. Numerical modeling and remote sensing technology will become important approaches to quantify large-scale groundwater recharge. It is also suggested that various estimation methods should be used in combination, in order to improve the reliability of recharge estimates. Furthermore, this review shows that the theoretical research so far still cannot meet the needs of regional development, and the paper highlights some scientific problems that need to be further explored.

Keywords Groundwater recharge · Arid regions · China · Review

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✉ Yueqing Xie
yxie@nju.edu.cn

- ¹ Key Laboratory of Surficial Geochemistry, Ministry of Education, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China
- ² Frontiers Science Center for Critical Earth Material Cycling, Nanjing University, Nanjing 210023, China
- ³ Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
- ⁴ College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
- ⁵ Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region, Ministry of Education, Chang'an University, Xi'an, China
- ⁶ School of Water and Environment, Chang'an University, Xi'an, China

Introduction

Groundwater, being the largest source of global freshwater, is an indispensable terrestrial water resource for human beings, and plays an important role in the sustainable development of ecosystems and society (Taylor et al. 2013; Gleeson et al. 2016; Aslam et al. 2018; Jiang et al. 2019). In China, groundwater accounts for ca. 17.5% of the country's current water consumption due to its stable volume and good quality (Feng et al. 2013; Hao et al. 2018; Wang et al. 2018c). In arid and semiarid areas such as northwest and north China, the scarcity of surface water resources has prompted people to utilize groundwater (Figs. 1 and 2; Ma 1997; Zhang et al. 2008; Jiao et al. 2015; Zeng et al. 2020). In some areas, groundwater is the only source of freshwater for water supply. However, due to a variety of factors such as rapid population growth, climate change, overexploitation of groundwater and water pollution, groundwater resources are facing not only depletion, but also a series of ecological,

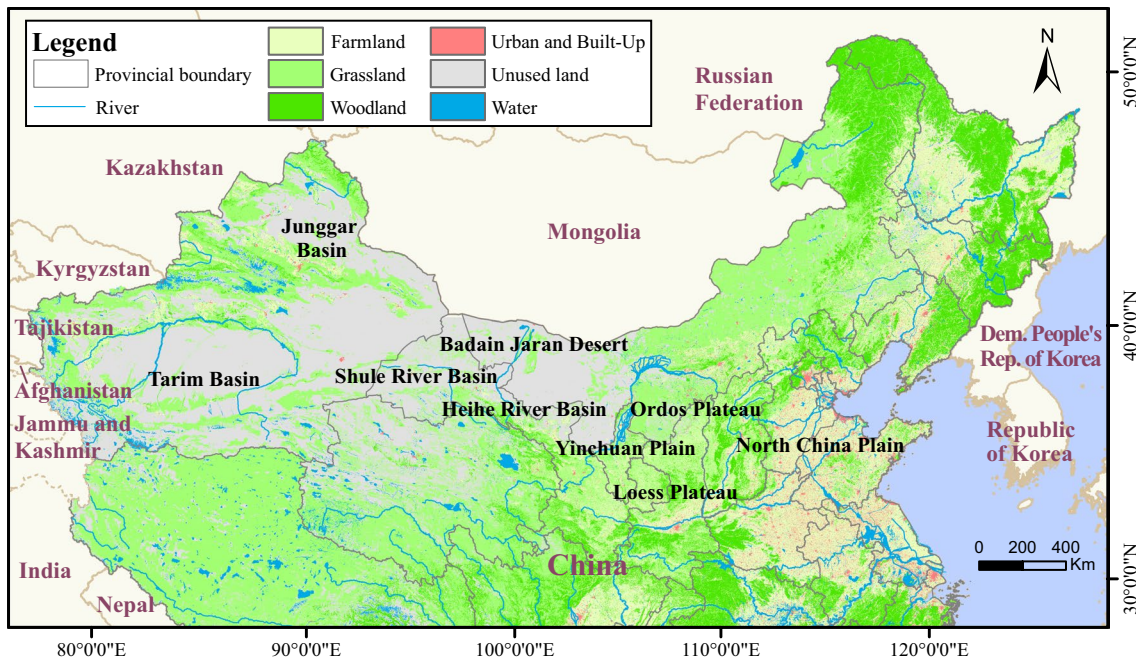
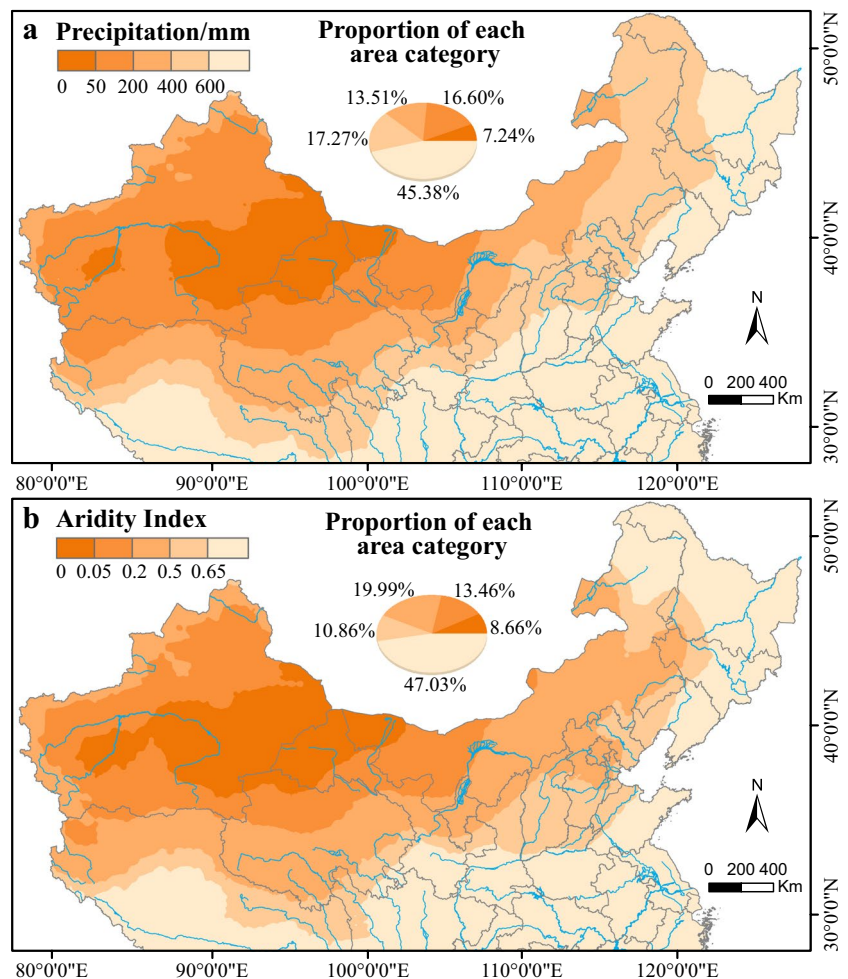


Fig. 1 Map of the drylands region in China, showing also the relevant basins, plateaus, plains and deserts involved in research projects mentioned in this review

Fig. 2 Distribution of climatological factors in the drylands of China in 2020: **a** the annual precipitation and **b** the aridity index. Based on annual precipitation (P , mm), aridity can be divided into hyper-arid (0–50 mm), arid (50–200 mm), semiarid (200–400 mm) and dry subhumid (400–600 mm) regions; Based on the aridity index (AI), defined as the ratio of annual precipitation to potential evapotranspiration, aridity can be divided into hyperarid (0–0.05), arid (0.05–0.2), semiarid (0.2–0.5) and dry subhumid (0.5–0.65) regions. Annual precipitation and potential evapotranspiration were obtained from the gridded time series (CRU TS) dataset from the Climatic Research Unit (University of East Anglia) and NCAS (2022)



environmental and geological problems such as land subsidence, ground collapse, saltwater intrusion and ecological degradation (Zhong et al. 2009; Qiu 2010; Xiao et al. 2019; Chen et al. 2020; Wu et al. 2020). In order to ensure the sustainability of groundwater resources, it is important to conduct research on groundwater recharge, especially in arid and semiarid areas, where groundwater recharge has always been highly valued by scientists and the government (Qi and Guodong 1998; Huang and Pang 2013).

Groundwater recharge refers to the process of water entering an aquifer through different interfaces (e.g., land surface, riverbeds and lateral boundaries). It is a very complex ecohydrological process, which is affected by various factors such as climate, lithology, water-table depth, soil and vegetation (Scanlon et al. 2006; Mensah et al. 2022). In this process, the salinity and energy of groundwater also change, which is reflected in the changes of physical and chemical indicators such as groundwater level, flow, hydrochemical composition and temperature (Si et al. 2009; Xi et al. 2010). In the last few decades, with the increasing concern around the world about groundwater recharge, there has been a significant increase in research related to groundwater recharge in arid and semiarid areas of China (Fig. 3). Since 2000, researchers have developed different methods to study groundwater recharge in the unsaturated zone or saturated zone, which can be roughly summarized into three categories: physical methods, tracer methods, and mathematical modeling methods (Scanlon et al. 2002; Koeniger et al. 2016; Singh et al. 2019). Each category has its own applicability at different spatiotemporal scales, so reliability is different. On a small spatial scale, point tests or field observations are usually carried out, including the use of the tracer method, flux method, water-table fluctuation method, numerical simulation method, etc. (Healy and

Cook 2002; Sun et al. 2016; Cartwright et al. 2017; Xu and Beekman 2019). On a large spatial scale, numerical models have certain advantages. Some studies use simplified physical models based on geographical information systems (GIS) or they combine models with remote sensing data to estimate regional groundwater recharge; however, this method is restricted by the accuracy of the various input parameters (Sanford 2002; Singh 2014).

This review captured literature from some of the main repositories, including Web of Science, Scopus, Science Direct, Google Scholar, and the China National Knowledge Infrastructure (CNKI). From January 2000 to October 2022, a total of 222 English and 134 Chinese studies were considered as meeting the review's criteria for topics related to groundwater recharge, while taking into account climatic and hydrogeological conditions in arid and semiarid regions of China. All of these studies have provided valuable information, among which the more typical 176 studies are discussed here in detail. In this review, based on a brief description of groundwater recharge types and mechanisms, commonly used methods are first analyzed for understanding and quantifying groundwater recharge, including their principles and current applications. Then the paper summarizes research achievements related to groundwater recharge in several typical areas of arid and semiarid China. Finally, some future development trends and research directions in this field are presented. Overall, this paper provides a valuable reference for properly understanding and accurately quantifying groundwater recharge in arid and semiarid areas of China. This review is of great strategic value when formulating scientific groundwater sustainable exploitation schemes and implementing water resource management plans.

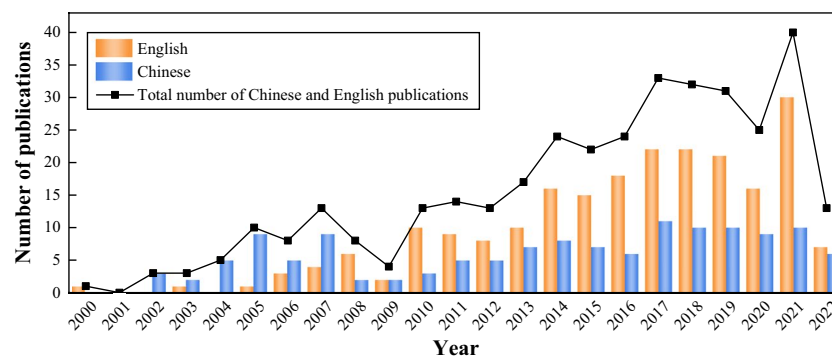


Fig. 3 Annual number of publications on groundwater recharge from 2000 to 2022. English literature was obtained from academic databases such as Web of Science, Scopus, Science Direct, and Google Scholar, while papers published in Chinese journals were retrieved from the China National Knowledge Infrastructure (CNKI). Boolean

search in scientific research engines and platforms were utilized, with an emphasis on keywords such as groundwater recharge. In keeping with the objectives of the review, only studies published from January 2000 to October 2022 were considered, with a focus on those connecting arid and semiarid areas in China

Conceptual understanding of recharge processes

Recharge types

Natural recharge and artificial recharge

Groundwater recharge is the primary manner in which water enters aquifers. It usually occurs in two forms—natural recharge and artificial recharge. Natural recharge means that groundwater is naturally replenished by rainfall, snowmelt, rivers, lakes, etc. Artificial recharge refers to a process that increases the amount of groundwater through various planned and human-controlled means. It has become a necessary choice for maintaining the water table and ecological security in some areas (Xu and Beekman 2019). The research achievements reviewed in this paper are mainly related to natural recharge.

Direct recharge, indirect recharge and localized recharge

Groundwater recharge processes can also be divided into direct recharge, indirect recharge and localized recharge depending on location (Fig. 4). Direct recharge is when precipitation infiltrates to groundwater through the unsaturated zone after replenishing the soil-moisture deficit and meeting evapotranspiration demand. Indirect recharge refers to a process by which water from surface-water bodies, such as rivers, canals and lakes, percolates to groundwater. Localized recharge is an intermediate form of groundwater recharge, whereby, water penetrates into an aquifer from low-lying surface areas with an absence of well-defined flow channels—examples being sink holes, earthworm holes, joints, depressions, etc. (de Vries and Simmers 2002). In reality,

these three recharge processes may occur simultaneously. In arid and semiarid regions, the probability of direct recharge will be significantly reduced due to the dry climate.

Diffuse recharge and focused recharge

Groundwater recharge can also be conceptualized into two categories with respect to topography—diffuse recharge and focused recharge. Diffuse recharge, similar to direct recharge, is derived from precipitation vertically penetrating an aquifer from the surface over a larger area. Focused recharge often occurs when rivers, lakes, seasonal ponds and depressions lose water to aquifers or when water flows through cracks. Such geographical features in semiarid and arid regions likely provide the main method of focused groundwater recharge in those regions worldwide (Scanlon et al. 2006).

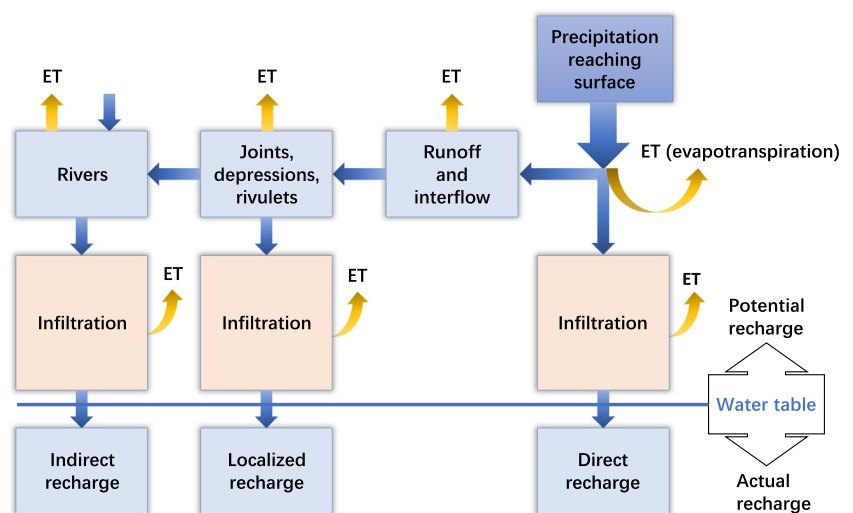
Actual recharge and potential recharge

At present, research projects on groundwater recharge are carried out with emphasis from different perspectives such as surface water, the unsaturated zone and the saturation zone. Thus, the water quantity determined may overrepresent different components (Fig. 4). Recharge determined based on the saturation zone is called actual recharge because it represents the actual amount of water entering the groundwater body. Recharge based on the unsaturated zone, however, is called potential recharge, considering that the water may not always reach the water table (de Vries and Simmers 2002).

Recharge mechanisms

Generally, there are two infiltration patterns of groundwater recharge through the unsaturated zones, namely

Fig. 4 Various processes of groundwater recharge in arid and semiarid areas (modified from de Vries and Simmers 2002). ET evapotranspiration



piston flow and preferential flow (de Vries and Simmers 2002). Under piston flow, the soil water moves in layers, indicating that the newer water replaces the older water and the newer water never overtakes the older water, so that the soil water is pushed downward. Under preferential flow, however, the newer water may bypass the older water already existing in the soil by shortcuts, so as to move quickly to deeper soil layers. The shortcuts here may include fractures, earthworm holes, decaying plant roots and other preferred paths (Cheng et al. 2021).

Differences in infiltration patterns can be reflected in the profile characteristics of soil water—for example, piston flow leads to a relatively uniform wetting front parallel to the soil surface, while preferential flow tends to form a “finger-like” wetting front. In addition, the distribution characteristics of isotope profiles are different, and isotopes can be used to inversely determine the type of water penetration in soil. Typically, both mechanisms of groundwater recharge in the unsaturated zones occur simultaneously. In areas with homogeneous soil, piston flow dominates, while in soils with developed cracks and biological cavities, preferential flow dominates.

Overview and application of methods used for estimating and understanding recharge processes

Many methods are available for groundwater recharge estimation and recharge process analysis (Scanlon et al. 2002). Due to the complexity of groundwater recharge, various methods have different applicability in different countries and regions (Fig. 5). For arid and semiarid areas of China, this paper summarizes the different methods into several categories based on previous practical applications, including methods based on physical parameters, chemical and isotopic methods, numerical modeling and empirical methods, stable isotopes of hydrogen and oxygen, and hydrogeochemistry.

Methods based on physical parameters

There are several techniques for estimating groundwater recharge based on physical parameters. For studies in arid and semiarid areas of China, these techniques mainly include the hydrologic budget method, zero-flux plane (ZFP) method, water-table fluctuation (WTF) method, and Darcy’s Law method.

The hydrologic budget method, as an indirect or residual approach, quantifies groundwater recharge after estimating all other components in the hydrological system (precipitation, runoff, evapotranspiration, etc.). It has been used to estimate groundwater recharge rates in the Ordos Plateau (Yin et al. 2011c) and quantify river seepage rates in the lower reaches of Heihe River Basin (Xi et al. 2018). In general, groundwater recharge estimation methods based on the hydrologic budget are less reliable when applied in arid and semiarid regions. This is mainly because the groundwater recharge is very small due to low precipitation (P) but high potential evapotranspiration (PET). The errors involved with calculating PET may be far greater than those for groundwater recharge (de Vries and Simmers 2002).

A ZFP is located below the root zone with zero vertical hydraulic gradient. Soil-water storage change below the ZFP can be assumed to be groundwater recharge. The ZFP method is usually used to estimate groundwater recharge rates in relation to precipitation. Yang et al. (2021) conducted experiments in Yinchuan Plain and calculated groundwater recharge based on the ZFP method. Zhang (1988) employed the ZFP method to determine annual groundwater recharge in northern China. As the ZFP can exist for about 80% of the time over a year, Zhang (1988) suggested wide application of the ZFP method to estimate groundwater recharge. However, this method has strict requirements for data and equipment as well as certain limitations in spatial scale. It is only suitable for study areas with a small spatial scale.

The WTF method is a highly attractive approach used to obtain groundwater recharge rates or recharge coefficients (Luo et al. 2020; Zhao et al. 2021). It assumes that the rise

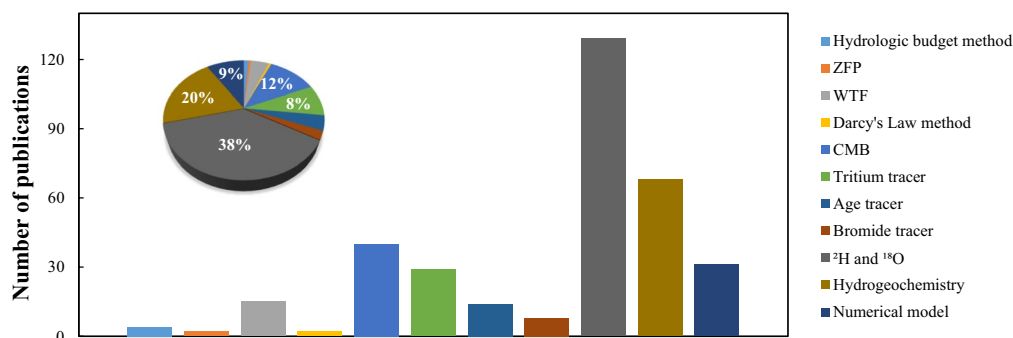


Fig. 5 Publications on groundwater recharge using different methods in arid and semiarid areas of China

of groundwater level is exclusively attributed to precipitation infiltration regardless of whether the recharge is diffuse or focused. Over the past years, it has been employed to estimate groundwater recharge rates at different temporal scales (Yin et al. 2011c; Zhang et al. 2019) and also to determine major factors controlling the change in groundwater level (Jia et al. 2021). Given its simplicity, this method has also been effectively applied in solving practical problems such as agricultural production and ecological security in arid and semiarid areas of China, e.g., drip irrigation efficiency (Li et al. 2016), river lateral seepage (Xi et al. 2018). Despite being widely used, this method has great uncertainty in estimating the parameter of specific yield (Gong et al. 2021a). Zhang et al. (2020) showed that the WTF method based on a lab-derived specific yield value significantly overestimated groundwater recharge.

The Darcy's Law method has also been successfully applied to groundwater recharge estimation in arid and semiarid areas provided that hydraulic gradient and hydraulic conductivity can be determined. Yin et al. (2011c) employed this method to estimate the average groundwater recharge rate in the Ordos Plateau. This method is generally easy to apply, as the parameters needed for the calculation can be obtained through field observation and/or laboratory experiments. It is also suitable for study on both the saturated zone and unsaturated zone. However, given the potentially large uncertainty in the hydraulic conductivity, estimation errors can also be large.

There are other methods such as base flow measurements and lysimeter observations. However, their applications are rarely found in arid and semiarid areas of China, although some scholars have made some attempt by conducting field experiments in recent years (Gong et al. 2021a; Zhang et al. 2020, 2021).

Chemical and isotopic methods

Chloride mass balance

Chloride has stable physical and chemical properties. Chloride mass balance (CMB) assumes that the chloride comes from atmospheric precipitation and it migrates downward in the unsaturated zone during infiltration and accumulates near the land surface due to evaporation (Fig. 6). Therefore, the CMB method is usually used to evaluate precipitation recharge, once chloride concentrations in precipitation and groundwater are determined (Scanlon et al. 2002; Xu and Beekman 2019). In the arid and semiarid areas of China, the CMB method is widely used to estimate groundwater recharge rates in the Badain Jaran Desert (Gates et al. 2008b), the Ordos Plateau (Yin et al. 2010), the Zhangye Basin (Nie et al. 2011), the piedmont area of the North China Plain (Min et al. 2015) as well as semiarid regions of northwest China (Deng et al. 2015). The CMB method has

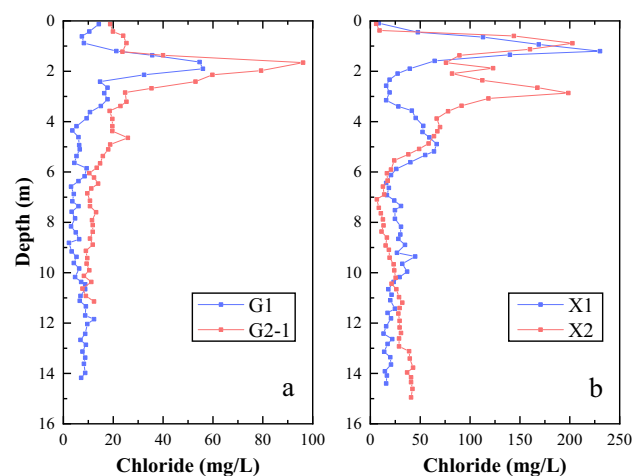


Fig. 6 Chloride concentration profiles in **a** Guyuan and **b** Xifeng in China's Loess Plateau (modified from Huang and Pang 2011)

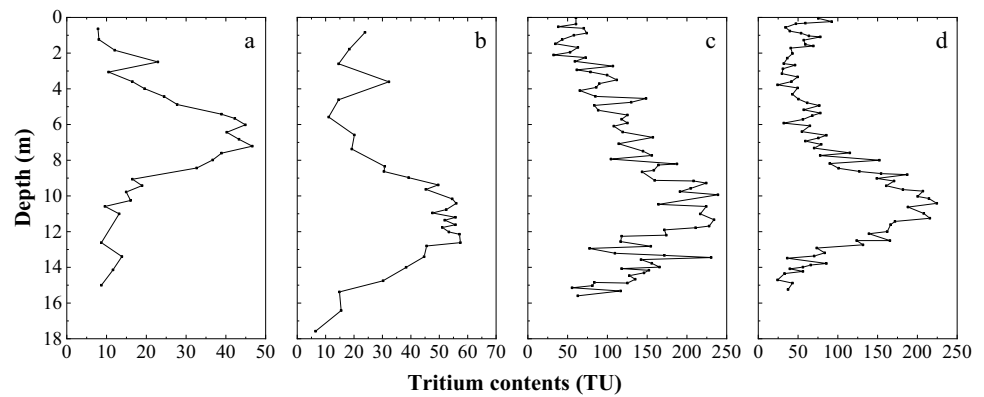
also proved to be effective in evaluating the impact of land use change on groundwater. It has been employed in various studies to study different influential factors on groundwater recharge, such as the effect of regional afforestation and/or various land uses (Huang and Pang 2011; Huang et al. 2018, Huang et al. 2020b), the impact of the transformation from shallow-rooted farmland to deep-rooted apple orchards (Zhang et al. 2018), and the effect of rural ponds (Cheng et al. 2021).

Generally, the CMB method can be used to study long-term historical recharge processes. Zhang et al. (2003) successfully applied the CMB method to estimate the variation of diffuse groundwater recharge in typical areas of piedmont plain of Taihang Mountains in the past 300 years. Deng et al. (2017) used the CMB method to reconstruct the groundwater recharge history of 71 years in the northwest Loess Plateau. Of course, it also has some limitations, such as obtaining reliable chloride end members and the interference of background chloride and chloride from fertilizers.

Environmental tritium

Tritium is considered to be an effective tracer for identifying the recent recharge, movement and residence time of groundwater in hydrogeological studies (Fig. 7). There are two methods based on tritium, namely, the tritium peak method and the tritium storage method. Li et al. (2019) compared the recharge rates estimated with the two methods by analyzing six tritium profiles (>15 m below surface) in the Loess Plateau. They found that the results of the tritium storage method with respect to recharge were twice that of the tritium peak method, and concluded that the tritium peak method was more reliable. The tritium peak method has been successfully applied in China's arid and semiarid areas (Ji

Fig. 7 Tritium profiles in **a** Changwu, **b** Qingjian, **c** Pingding and **d** Wudan in China's Loess Plateau (modified from Li and Si 2018). TU tritium unit



et al. 2021; Li et al. 2018; Cao et al. 2016b; Tao et al. 2021; Wang et al. 2008). However, it should be noted that recharge estimated with the tritium peak method could be underestimated (Lin and Wei 2006). It is worth mentioning that tritium reconstruction is usually needed for this method as only a few places in the world have long-term precipitation tritium records. Li and Si (2018) evaluated the results and reliability of four tritium reconstruction methods for estimating groundwater recharge with the tritium peak method. Their results suggest that the tritium reconstructed in their research generally overestimated the groundwater recharge; therefore, care should be taken during tritium reconstruction.

Age tracers

Radioisotopes such as ^{14}C , ^{36}Cl and ^{81}Kr are often used as effective tracers to determine groundwater age and groundwater recharge. According to the basic principles of radioactive decay, the age of groundwater can be estimated after determining both current and initial radioisotope activities in groundwater. By estimating the age of groundwater, scholars can have a clear understanding of the sources, mechanisms, and processes of regional groundwater recharge (Ma et al. 2013; Wu et al. 2019). He et al. (2012) derived the corrected age of groundwater and estimated groundwater recharge in the Jiuquan Basin based on ^{14}C . This method was also used to estimate groundwater age and recharge rates in the Shule River Basin (He et al. 2015). Wei et al. (2014) successfully determined the age of deep groundwater in the Jilantai Basin using ^{14}C dating. Wang P et al. (2020) also determined the age of groundwater in the Santanghu Basin of the Junggar Basin. ^{14}C has displayed its value in multiple studies related to groundwater age, allowing scholars to better understand groundwater recharge and flow systems. In practical applications, some scholars often combine the radioisotope ^{14}C with other techniques. Huang et al. (2017a) studied the characteristics of shallow groundwater recharge in an integrated loess tableland in the Loess Plateau based on ^{14}C and other environmental tracers. The results showed that piston flow is

the main recharge mechanism of shallow groundwater. Similarly, these multiple tracers, including ^{14}C , were applied to the Ordos Basin by Huang et al. (2017b), and the corrected ^{14}C age for shallow groundwater in the area was identified between 4,327 and 29,708 years. Further, Ma et al. (2019) studied the average groundwater residence time and aquifer recharge of fault-influenced hydraulic drop alluvium aquifers in the Manas River Basin based on ^{14}C and other tracers.

Bromide tracer

Bromide has often been used as a tracer to quantify potential groundwater recharge because it is environmentally friendly and easy to test (Tan et al. 2014; Lin et al. 2016). When used, a certain amount of bromide solution is manually injected into a certain depth of soil, and then soil samples are regularly collected to construct bromide profiles. Groundwater recharge is calculated based on the traveling speed of the tracer concentration peak of the profile (Fig. 8; Cong et al. 2018). Wang et al. (2008) applied the bromide tracer

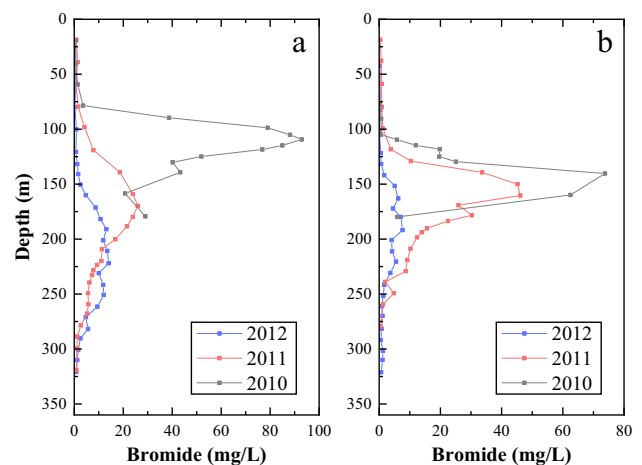


Fig. 8 Bromide concentration profiles in two typical areas of the North China Plain (modified from Shuai et al. 2014)

method in Hebei Plain to explore the impact of different soil types, land use patterns, irrigation and crop planting on groundwater recharge. Similarly, Tan et al. (2013) and Shuai et al. (2014) both used bromide as a tracer to study groundwater recharge characteristics under different landforms of the North China Plain, to compare recharge rates in irrigated areas to those in nonirrigated areas. Wu et al. (2016) conducted bromide tracing experiments while combining other methods to estimate the groundwater recharge in the North China Plain during 2003–2007. However, it is worth noting that in areas with shallow groundwater level, the application of bromide tracing method is limited and cannot accurately reflect the actual local recharge situation (Wang et al. 2008).

Numerical modelling and empirical methods

Many scholars have established and applied various numerical models to simulate regional groundwater recharge in arid and semiarid regions of China (Liu et al. 2012; Cao et al. 2016a; Shao et al. 2019; Zhang et al. 2021). One of the most widely used is the HYDRUS model. It has been employed to examine the impact of irrigation and groundwater depth on recharge (Lu et al. 2011; Jie et al. 2022), to quantify the effect of increasing thickness of the unsaturated zone on recharge processes, amount and time (Huo et al. 2014), to understand soil moisture movement processes and quantify rainfall-induced recharge rates (Ge et al. 2018; Yang et al. 2019), and to investigate the effect of film-mulched drip irrigation on recharge (Chen et al. 2021). Other models that have been used are the Soil-Water-Atmosphere-Plant (SWAP) model (Ma Y et al. 2015), a lumped parameter model of EARTH (Wang B et al. 2015), the SWAT model (Wang et al. 2020), the Community Land Model (CLM) (Shao et al. 2019), etc. The numerical modeling method can also be used to predict the change of groundwater recharge with land cover change and climate change (Yin et al. 2015; Chi et al. 2022). One example is that the CLM model has allowed Shao et al. (2019) to understand how groundwater recharge evolved spatially from 1901 to 2015, mainly by analyzing vegetation types and rooting depths under

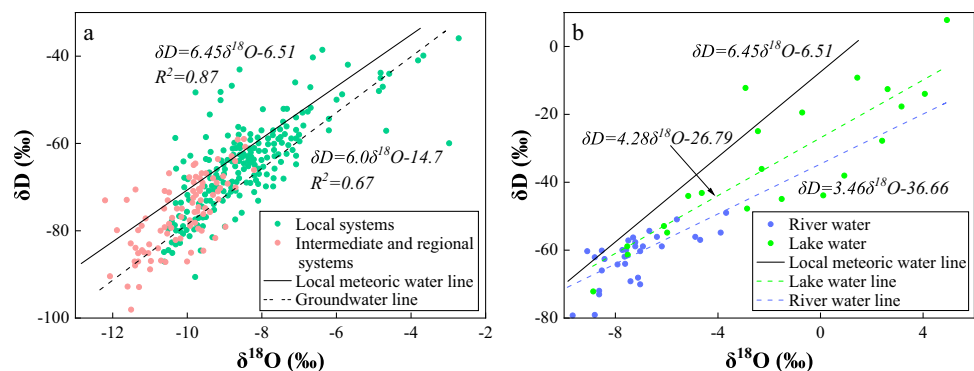
different land covers. As another representative example, Wang et al. (2020) predicted the change of groundwater recharge in the Heihe River Basin under the climate change scenario in the next 45 years (2019–2063) using the SWAT model. In general, this method is theoretically applicable to the simulation of various conditions, and it is not limited by space and time scales. However, the modeling method has a high demand for field observations, such as lysimeter data, tracer data, water quality and temperature data.

Stable isotopes of hydrogen and oxygen

Stable isotopes of hydrogen and oxygen are frequently used to in groundwater studies (Fig. 9; Zhang et al. 2014; Qin et al. 2017; Guo et al. 2019b; Li et al. 2020; Cao et al. 2022). Although it is hard to provide groundwater recharge rates based on stable isotopes, they have been widely used in arid and semiarid areas of China to understand groundwater recharge sources, recharge mechanisms, seepage processes and evapotranspiration losses by comparing the isotopic composition of groundwater and precipitation (He et al. 2012; Zhan et al. 2017; Zhu et al. 2018; Huang et al. 2020a; Zhang et al. 2020). So far, stable isotopes have been employed to identify sources of groundwater recharge in the Zhangye Basin (Chen et al. 2014), the Huhhot Basin (Liu et al. 2016), the Loess Plateau (Tan et al. 2017b), the northern Ordos Basin (Wang et al. 2017), the northern Tarim Basin (Wang et al. 2020), and the Taihang Mountains (Li et al. 2007).

Precipitation infiltration, soil water transport and groundwater recharge are complicated processes. Stable isotopes can also be used to study the recharge mechanism of groundwater and determine whether the recharge process is dominated by piston flow or preferential flow. Liu et al. (2011) applied ^{18}O and ^2H to the hilly area of the Loess Plateau. Ma et al. (2021) found in their study on the Loess Plateau that the groundwater recharge by precipitation was mostly a combination of piston flow and preferential flow, and the preferential flow was the main one. Ma et al. (2017) similarly used ^{18}O and ^2H in precipitation, soil, and groundwater samples to

Fig. 9 Relationship between hydrogen and oxygen isotopes for **a** groundwater, and **b** river water and lake water in the Ordos Plateau (modified from Yin et al. 2011b)



study groundwater flow pathways in three regions with different land use patterns in the central North China Plain. Hao et al. (2019) applied stable isotope analysis to determine the groundwater recharge mechanism of the Ebinur Lake Basin in northern Xinjiang, whereas Zheng et al. (2019) applied similar isotopes to study the mechanism of soil water transport and groundwater recharge under cultivated land and natural vegetation in normal and extreme precipitation years, respectively. Yuan et al. (2013) conducted various statistical analyses based on the distribution characteristics of ^2H and ^{18}O , and finally explained in detail the upward recharge induced by the depression cone of the North China Plain.

Hydrogeochemistry

Groundwater chemical composition changes constantly along flow paths due to water–rock interactions (Fig. 10). Using hydrochemical data, one can better understand recharge sources, flow processes and energy exchange of groundwater, thus revealing the regional circulation of groundwater (Edmunds et al. 2006; Wei et al. 2016; Luo et al. 2017; Wang et al. 2018a; Wu et al. 2019; Liu et al. 2020). Hydrochemical methods are usually combined with isotope techniques to investigate groundwater recharge processes and mechanisms. Wang et al. (2013) proved that the main recharge sources for the phreatic aquifer of the Ejina Basin were the Heihe River and groundwater in Badain Jaran Desert. Wei et al. (2014) reported that the shallow groundwater in the plain of the Jilantai Basin and desert was largely replenished by intermediate formations. Wang et al. (2015b) determined the recharge sources and evolution of groundwater in the upper and middle reaches of the Shule River Basin through hydrochemical and isotope characteristics. Subsequently, the recharge source and geochemical evolution processes of groundwater in the lower reaches of Shule River were also identified (Wang et al. 2016). Similarly, Zhao et al. (2016) investigated the distribution characteristics of

stable isotopes and ionic concentrations in the precipitation of the Shule River Basin, which provided a more scientific understanding of the regional water cycle and groundwater recharge associated with precipitation. In general, regional hydrogeochemical information largely reflects the evolution process of groundwater quality under the influence of natural climate conditions and human activities, which is of great significance for the study of groundwater recharge.

Summary of application limitations of various methods

Similar to many other countries and regions in the world, current methods for assessing groundwater recharge in arid and semiarid areas of China remain largely uncertain (Allison et al. 1994; Yin et al. 2011c; Chung et al. 2016). Each of the methods has its own limitations in terms of accuracy and applicability considering the distinct sources and processes of recharge (Xu and Beekman 2019). As such, researchers should consider the method that best suits their particular situation before attempting to assess groundwater recharge. It is also important to take into account the potential limitations of the chosen method in order to ensure reliable results. The formation of arid and semiarid areas with unique hydrogeological conditions in China is closely related to the Qinghai-Tibet Plateau topography, subsidence of the Hadley circulation, Asian monsoons, westerly belts, urbanization and land-use changes (Huang et al. 2019). The uncertainty of all the methods based on the physical parameters discussed previously largely comes from the estimation error of each water flux. The recharge flux generally decreases with increasing aridity (Yin et al. 2011c). For the hydrologic budget method, there are usually very large estimation errors for each water flux, and the error for PET may be much larger than that for groundwater recharge (Gee and Hillel 1988; de Vries and Simmers 2002). The ZFP method is inevitably only applicable when there is a vertical hydraulic gradient of zero, and due to its strict requirements on data acquisition and equipment, it can only determine the groundwater recharge at a small spatial scale, with obvious changes in soil-moisture content and a relatively deep water table (Scanlon et al. 2002). The WTF method is applicable when the water level variation in the observation well can represent the dynamics of the entire study area. And one limitation of its application is the determination of the specific yield of the aquifer, which is difficult to obtain accurately (Zhang et al. 2020). Similarly, the main limitation of the application of the Darcy's Law method is the great uncertainty generated by the required parameters, such as the hydraulic conductivity.

When groundwater recharge is only a few millimeters or less per year, chemical and isotopic methods, which are

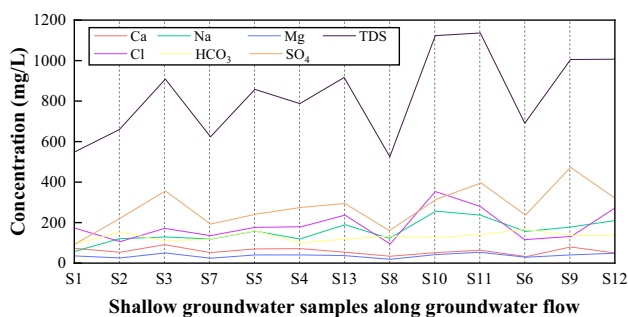


Fig. 10 Groundwater major ions and total dissolved solids (TDS) concentrations, showing changes along the groundwater flow direction for shallow groundwater samples in a natural grassland in the arid western Ordos Basin (modified from Huang et al. 2017a)

highly attractive in China, tend to be more successful than those based on physical parameters (Ma et al. 2010; Tao et al. 2021). In particular, the CMB method is a widely used method for quantifying groundwater recharge in arid and semiarid regions of China (Fig. 5). However, it is difficult to collect data on chloride sources in the long term (Wu et al. 2016). Moreover, the CMB method requires achieving a steady state of water and chloride flux, which may be difficult in areas that have undergone land use change (Huang et al. 2020b; Yin et al. 2011c). And the application of this method may be limited in northwest China due to the impact of Three-North Afforestation Program, the Conversion of Cropland to Forest Program and other ecological rehabilitation approaches (Huang et al. 2020b). In response to this problem, Chinese scholars have made continuous attempts and explorations. Huang et al. (2020b) proposed a method for assessing the steady state by comparing the history of land use change and chloride cumulative age at the sampling depth, as well as examining the breaks in the slope of the line for cumulative chloride and soil water, which provided valuable guidance for the application of the CMB method in arid and semiarid areas of China. Tracer techniques such as tritium and bromine are commonly employed to estimate groundwater recharge from precipitation and irrigation, but are limited in that they do not measure water flow directly, which has the potential to overestimate or underestimate recharge (Gee and Hillel 1988; Liu et al. 2012). The applicability of the tritium tracer is additionally restricted by the fact that the level of tritium in the environment at present may be quite low and difficult to measure in many areas (Tao et al. 2021).

For various numerical models, it is necessary for the study area to be able to provide the parameters and historical data required by the model. This is not easy, especially to obtain information about the aquifer over a large area as it takes a lot of time and work to complete the establishment and correction of the model (Cao et al. 2016a; Jie et al. 2022). Although the HYDRUS model has been widely used by Chinese scholars, it may fail when surface conditions are too complicated to acquire exact data such as evapotranspiration, soil evaporation and irrigation (Huang et al. 2018). In addition, the stable isotopes of hydrogen and oxygen are generally qualitative techniques in China, and their combined application with hydrogeochemical analysis plays an irreplaceable role in the study of the sources and processes of groundwater recharge in arid and semiarid areas of China (Chen et al. 2014; Wei et al. 2014; Yang et al. 2018a). Although some scholars around the world have estimated groundwater recharge rates by using the profiles of stable isotopes of hydrogen and oxygen in the unsaturated zone, few cases in China

are based on this method to quantitatively estimate the groundwater recharge rate (Boumaiza et al. 2021).

Achievements of groundwater recharge in typical regions

In the arid and semiarid areas of northern China, previous studies on groundwater recharge mainly focused on nine typical regions, including the Tarim Basin, the Junggar Basin, the Shule River Basin, the Heihe River Basin, the Yinchuan Plain and the Badain Jaran Desert in the western arid areas, the Loess Plateau and the Ordos Plateau in the middle semiarid and arid areas, and the North China Plain in the eastern semiarid areas (Fig. 1).

The Tarim Basin

As the largest inland river in China, Tarim River has an extremely arid continental river catchment basin, in which the ecological environment is vulnerable (Zhang et al. 2013). Recharge studies in the Tarim Basin are limited. Given the arid nature of the basin, the Tarim River is the largest source of freshwater for ecosystems and aquifers. Several studies have focused on recharge due to river leakage. Pang et al. (2009) examined recharge processes in the middle reaches of the basin through chemical and isotopic analysis of river water and groundwater. Their results showed dominant localized recharge through river leakage. Xu et al. (2007) investigated the dynamic changes in groundwater level and the relationship between groundwater level and natural vegetation in the lower reaches of the Tarim River under an ecological water transfer project. Huang and Pang (2010) evaluated groundwater changes caused by water diversion in the lower reaches of Tarim River based on environmental isotope and hydrochemical data. Some other studies examined irrigation-induced potential recharge. Li et al. (2016) estimated potential recharge at an irrigation test site in a national key oasis, and found that potential recharge accounted for 53.2% of the irrigation water, indicating that there was serious water loss. Wang W et al. (2020) investigated the sources of groundwater recharge as well as surface water in the northern Tarim Basin. Their analysis indicated that shallow groundwater was mainly replenished by river and irrigation water infiltration and also lateral groundwater flow.

The Junggar Basin

The Junggar Basin is a sedimentary basin located in northwest China and the geographic centre of the Asian Continent.

The large geographical distance from the surrounding ocean and the rain-shadow effect caused by the surrounding orographic conditions contribute to the arid climate of the basin (Zhu et al. 2016). Zhu et al. (2017) present a comprehensive and detailed discussion of the groundwater recharge process and its influencing factors. They emphasized that the overall recharge processes of the Junggar Basin were quite heterogeneous. Most of the scholars mainly studied groundwater recharge in subbasins of the Junggar Basin, including the Santanghu Basin (Wang et al. 2020), the East Junggar Basin (Li et al. 2015) and the Manas River basin (Ma et al. 2018). For example, the Santanghu Basin is one of the subbasins of Junggar Basin. The research by Wang P et al. (2020), based on hydrochemistry and isotope methods carried out in Junggar Basin, was representative and demonstrated the age, recharge sources and flow paths of groundwater in this basin. The hydrogeochemical study conducted by Li et al. (2015) in the East Junggar Basin also provided inspiration for regional groundwater recharge. The Manas River basin, located in the southern Junggar Basin, is the most intensively studied area for groundwater recharge. Wang et al. (2019) investigated the hydrogeochemical characteristics of the Manas River Basin and determined the influencing mechanisms of groundwater composition and evolution during the flow process. Similarly, Ma et al. (2018) analyzed hydrogeochemical and various environmental isotope information in precipitation, rivers, reservoir water and groundwater in the Manas River Basin in detail, and based on this, identified groundwater recharge sources, mixing processes and metallogenic characteristics in the basin. Wang et al. (2021) also revealed the groundwater flow characteristics of the highly exploited aquifer system in the Manas River Basin based on isotopic and hydrogeochemical analyses.

Some studies also focused on the impact of agricultural activities on groundwater recharge. Liu et al. (2012) compared the groundwater recharge of flood-irrigated and water-saving irrigated lands in the Manas Basin of China, and further explored the relationship between irrigation methods and groundwater response. The study showed that compared with overflow irrigation, the groundwater recharge intensity of water-saving irrigation is relatively weaker, but the groundwater flow is relatively larger. Chen et al. (2021) estimated the groundwater recharge of the cotton field under film-mulched drip irrigation, and the result was 5.5–37.0 mm/year.

The Shule River basin

The Shule River is an important river in the Hexi Corridor, and the Shule River basin is located in the west of Gansu Province in northwest China, with a total area of about 41,300 km². Up to now, the research on groundwater recharge in the Shule River Basin has mainly relied on the analysis of

hydrogeochemical and isotopic data. He et al. (2015) systematically studied the groundwater recharge and evolution of the sedimentary basin by using hydrogeochemical analysis, the stable isotope method and the radiocarbon method. Their results showed that recharge to the unconfined aquifer mainly occurred in the fine-soil plain and the piedmont of the Qilian Mountains, and consisted of river infiltration, irrigation returns, and fracture leakage. In comparison, deep groundwater in the middle and lower reaches was replenished during the period of abundant precipitation from the late Pleistocene to the middle Holocene. Guo et al. (2015) analyzed the hydrochemical characteristics and recharge sources of piedmont springs in Qilian Mountains, Yangmen-Tashi groundwater and Guazhou groundwater. The results showed that piedmont springs mainly came from precipitation, upstream meltwater infiltration and rivers, while the Yumen-Tashi groundwater mainly came from piedmont lateral groundwater and river water in the middle stream. The Guazhou groundwater was mainly replenished by lateral groundwater flow from the Yumen-Tashi Basin. In the middle and upper reaches of the Shule River, Wang et al. (2015b) identified the groundwater recharge sources in the local area and its adjacent areas, including Changma, the Shule River Valley and the Beishan area. Their results showed that the infiltration of rainwater and meltwater in the Qilian Mountains was the main source of groundwater recharge in Changma, the lateral flow from Changma was the main source of groundwater recharge in Shule Valley, and the local precipitation was the main source of groundwater recharge in the Beishan area. In the lower reaches of the Shule River, the study of Wang et al. (2016) showed that the groundwater of the Tashi Basin was mainly derived from meltwater of Qilian Mountains, while the groundwater of the Guazhou Basin may be replenished by the Shuler River.

The Heihe River Basin

The Heihe River Basin is the second-largest inland river basin in the arid part of China and one of the important river basins in the Hexi Corridor. It covers an area of about 130,000 km² with a fragile ecological environment and a shortage of water resources. Over the past years, understanding of groundwater recharge and flow in the Heihe River Basin has gradually developed and improved, and the existing studies have provided a relatively clear and scientific explanation for the groundwater flow system in the Heihe River Basin (Zhang et al. 2005a, b, c; Qin et al. 2012). The study of Chen et al. (2006a) showed that the groundwater in the Heihe River Basin was mainly replenished by the drainage of mountain rivers close to the Qilian Mountains. Xi et al. (2018) found that as the distance from the river bank increased, the lateral seepage rate of the river decreased. Cao et al. (2016b) comprehensively analyzed groundwater

recharge sources and geochemical evolution in the Heihe River Basin, and found that infiltration through irrigation canals and irrigation return flow were the main factors that increased the recharge of young groundwater. Zhang et al. (2021) yielded more quantitative results. They showed that the runoff from Qilian Mountains replenished the groundwater by about $4.64 \times 10^8 \text{ m}^3/\text{year}$, accounting for about 28% of the inflow of the Heihe River. This is consistent with the results of Chen et al. (2006b), showing that the groundwater recharge and proportion were $4.4 \times 10^8 \text{ m}^3/\text{year}$ and 27%, respectively.

The Zhangye Basin and the Ejina Basin are two typical study areas of the Heihe River Basin. Zhangye Basin is the largest oasis, located in the middle reaches of the Heihe River. The study of Nie et al. (2011) showed that the soil water in the unsaturated zone in the non-irrigated area of the basin came from precipitation infiltration. They found that the precipitation infiltration rate was controlled by the lithology of the unsaturated zone, and precipitation infiltration recharge still exists in Zhangye Basin when the groundwater level depth is greater than 5 m. Chen et al. (2014) further clarified the recharge sources of groundwater in the Zhangye Basin based on the ^2H and ^{18}O characteristics, and then they abandoned the traditional understanding that the local groundwater is recharged by precipitation and the infiltration of Heihe River in the alluvial plain. Qin et al. (2011) explored in detail the effects of irrigation water on groundwater recharge and water quality based on chlorofluorocarbons (CFCs), tritium and stable isotopes. The Ejina Basin is located in the lower reaches of the Heihe River. Guo et al. (2019a) found that the shallow groundwater of the Ejina Basin was modern water, of which 13% came from local precipitation and 87% from river infiltration. Moreover, the semiconfined groundwater here was replenished by a mixture of shallow groundwater, lateral groundwater and confined groundwater, contributing 30, 52 and 18%, respectively.

With the concern of climate change, some researchers are committed to determining the impact of future climate change on groundwater. Wang et al. (2020) predicted the changing trend of groundwater recharge in the Heihe River Basin in the next 45 years (2019–2063), and they believed that groundwater recharge would reach the maximum value in 2037–2046.

The Yinchuan Plain

In the Yinchuan Plain, surface water from the Yellow River is widely used for irrigation, but the region's overall water needs still depend heavily on groundwater resources. Wang et al. (2013) systematically discussed the recharge and discharge characteristics of groundwater based on the analysis of groundwater hydrochemistry and isotope indices in

the Yinchuan Plain. And then, Wang et al. (2015a) further conducted groundwater hydrochemical investigation and found that there were several local groundwater flow systems in Yinchuan Plain from south to north, and the recharge sources included atmospheric precipitation, bedrock fissure water, and seepage from the irrigation canals and fields. Yang et al. (2018b) used the isotope mass balance method to determine the recharge proportion of precipitation and the Yellow River, which were 87.7 and 12.3%, respectively. Furthermore, the study of Gong et al. (2021) provided quantitative indicators for recharge and mixing characteristics of the shallow unconfined aquifer in Yinchuan Plain, enabling one to comprehensively understand the flow processes and recharge of the regional groundwater system. In addition, some studies have been carried out in some local areas of Yinchuan Plain. The study of Yang et al. (2021) revealed the water transport characteristics of the unsaturated zone and groundwater recharge mechanisms in the Yongning irrigation area of Yinchuan Plain, and they calculated that the local soil water recharge to groundwater was 434.4 mm, accounting for 68.6% of the infiltration volume. Li et al. (2021) established a two-dimensional (2D) conceptual model which clearly revealed the recharge sources in the middle of Yinchuan Plain, along with flow patterns and hydrogeochemical evolution characteristics of groundwater in this region.

The Badain Jaran Desert

The Badain Jaran Desert, due to its special geographical location and geomorphic landscape, has attracted the attention of many scholars. Especially in the southern Badain Jaran Desert, sources of groundwater recharge have been a hot topic, given the presence of numerous perennial lakes. Ma et al. (2003) reconstructed the history of groundwater recharge and climate change in the past 1,000 years in the unsaturated zone of the southeastern Badain Jaran Desert. Huang and Pang (2007) estimated the diffuse recharge rate to be as low as 1.0 mm/year, accounting for less than 2% of the annual precipitation. Gates et al. (2008b) found that the diffuse recharge was insufficient to support the existence of the perennial lakes. Their findings indicated that diffuse recharge plays a negligible role in the overall water balance of the desert's shallow Quaternary aquifer. Wang et al. (2021) quantitatively calculated the desert groundwater recharge based on the principle of water balance. They pointed out that although the local atmospheric precipitation recharged the shallow groundwater in the south of the desert, the recharge was low due to less precipitation and strong evapotranspiration. In comparison, Gates et al. (2008a) conducted research in the desert's southeastern margin and reported that the Yabulai Mountains was the dominant recharge source area in the southeastern desert. Wei et al.

(2019) found that the groundwater in the desert terrain may come from the southern mountains and flash floods in the desert area.

In general, due to the lack of comprehensive information on the hydrogeological conditions and accessibility issues that hinder field investigation and sampling, understanding of the groundwater system in the entire Badain Jaran Desert is still limited. More data should be collected to improve understanding of recharge processes and study on recharge still needs to be further improved.

The Loess Plateau

The Loess Plateau, located in the middle reaches of the Yellow River Basin, has serious soil erosion and a fragile ecological environment. Groundwater is the main available water resource, so it is very important to understand the groundwater processes for effective management of water resources. Tan et al. (2017b) showed that soil water was involved in groundwater recharge in the Loess Plateau, and proved that seasonal precipitation was the main source of soil water and groundwater recharge based on hydrogen and oxygen stable isotopes. In recent years, many scholars have conducted research projects on the Loess Plateau to explore its groundwater recharge mechanisms (Fig. 11a). It is generally believed that precipitation can recharge shallow groundwater through dual processes, including preferential flow and piston flow (Deng et al. 2017; Tan et al. 2017a; Xiang et al. 2019). Tan et al. (2016) conducted research in high mountains–hills in the western Loess Plateau and found that the groundwater recharge mechanism may include rapid preferential infiltration in addition to the common piston vertical infiltration. Huang et al. (2017a) comprehensively applied various tracers to study the recharge characteristics of shallow groundwater in an integrated tableland of the Loess Plateau, and found that piston flow was the main recharge mechanism of shallow groundwater. Similarly, Huang Y

et al. (2019) used a variety of tracers to conduct research in the Luochuan loess tableland to quantify the relative importance of piston flow and preferential flow in groundwater recharge. They found that the unsaturated zone was dominated by piston flow, and the saturated zone was composed of modern and pre-modern water, with piston flow and preferential flow. Luo et al. (2020) showed that the amount and seasonal distribution of precipitation directly affected the changes in shallow groundwater and base flow, and the shallow groundwater was replenished through vertical infiltration and lateral groundwater movement. Ma et al. (2021) carried out experiments in two small basins in the north of the Loess Plateau and found that groundwater recharge by precipitation was generally occurred in a combination of piston flow and preferential flow, with the latter being the main one.

In the process of exploring the groundwater recharge mechanism in the Loess Plateau, various techniques and methods have been gradually improved. Huang et al. (2016) assessed groundwater recharge rate and infiltration rate in Luochuan Loess Plain from three aspects: chloride peak, chloride mass balance, and nitrate level. This confirmed that solute profiles in the unsaturated zone can provide much information on groundwater recharge by tracers methods. Xiang et al. (2020) pointed out that the combined application of ^2H , ^{18}O and ^3H can identify the source and recharge mechanisms of the thick deep soils on the Loess Plateau. Furthermore, Huang et al. (2020a) indicated that homogeneous infiltration may be an inherent characteristic of loess, and comprehensive evaluation using a variety of environmental tracers can often be used as a general framework to study the recharge processes of thick unsaturated zones. In addition, some scholars have focused on the impact of land use change on groundwater recharge (Li et al. 2018; Zhang et al. 2018). Huang and Pang (2011) applied the CMB method to estimate the reduction of groundwater recharge after land use change. Huang et al. (2013) also comprehensively applied a

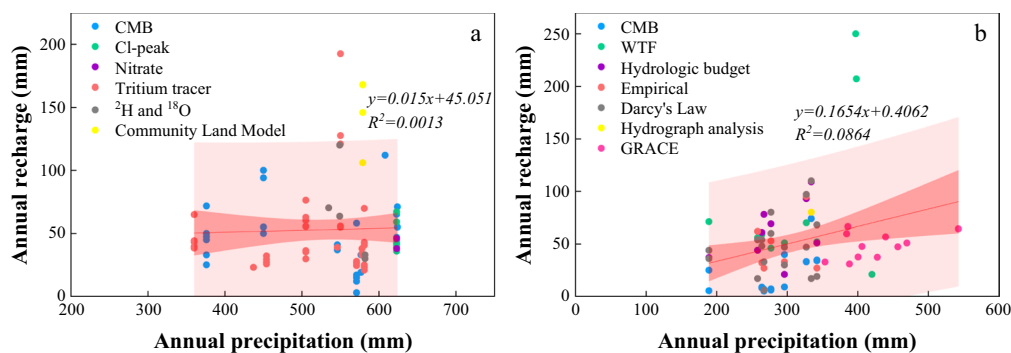


Fig. 11 Typical results of recharge studies in the **a** Loess Plateau (China) and **b** Ordos Plateau. The data for China's Loess Plateau was collected from Cheng et al. 2021, Deng et al. 2017, Huang and Pang 2011, Huang et al. 2013, 2016, 2017a, 2018, 2020a, Huang Y et al.

2019, Ji et al. 2021, Li et al. 2018, 2019, Ma et al. 2021, Shao et al. 2019, Tao et al. 2021, Zhang et al. 2018. The data of the Ordos Plateau was collected from Jia et al. 2021, Yin et al. 2010, Wu Q et al. 2019, Yin et al. 2011c

variety of tracers to explore the groundwater recharge mechanism in the loess agricultural area, and studied the impact of long-term land-use change on groundwater recharge and water quality based on the soil chloride profile. Huang et al. (2018) compared groundwater recharge under three land use patterns in the southern Loess Plateau, and found that due to slow water migration, the impact of land use change in the past decades has not affected groundwater, although it may be affected in the long term. Zhang et al. (2018) combined the CMB method with the principle of water balance to estimate the groundwater recharge of deep-rooted fields, and quantified the impact of the transformation from shallow-rooted farmland to deep-rooted apple orchards on groundwater recharge. Ji et al. (2021) conducted research in Shenmu County and showed that deep soil water recharge was greatly affected by land use, and deep-rooted plants prevented rainfall from replenishing deep soil water. Cheng et al. (2021) quantified the role of widespread village ponds on groundwater recharge in the Loess Plateau, and found that the transformation of farmland to apple orchards and the reduction of village ponds caused a decrease in diffuse recharge and centralized recharge, respectively.

The Ordos Plateau

The Ordos Plateau, one of China's great sedimentary basins, has been controversial in the past with respect to its groundwater recharge sources and flow system. Dou et al. (2010) carried out research in the northern Ordos Basin and found that precipitation was the main recharge source of groundwater in the study area, followed by rivers and field irrigation. Yin et al. (2010) used stable isotope and CMB methods to study the sources and recharge rates of groundwater in each basin of the Ordos Plateau, and the results showed that the groundwater in the study area was of atmospheric origin, and 2.93–22.11% of precipitation could recharge the groundwater. Yin et al. (2011b) analyzed the recharge mechanisms of shallow and deep groundwater using stable hydrogen and oxygen isotopes, and their results showed that 98.6% of groundwater recharge came from precipitation infiltration. Furthermore, Ma H et al. (2015) conducted research in the north of Ordos Basin and determined that the lowest single precipitation intensity of local precipitation recharge groundwater was 6.2 mm. Although many scholars believed that the groundwater in the Ordos Basin was mainly recharged by local precipitation in the past, some scholars still doubted it. Ge et al. (2016) conducted research in Hopq Desert in the north of the Ordos Basin and found that soil water and surface water were maintained by groundwater, and the groundwater was recharged by exogenous sources. Wang et al. (2017) used stable isotopes of hydrogen and oxygen to identify the groundwater source in the northern Ordos Basin. They believed that the groundwater was not

replenished by local precipitation, but speculated that it might come from the Qinghai-Tibet Plateau. For the quantification of groundwater recharge, scholars have tried various methods (Fig. 11b). Yin et al. (2011c) estimated the mean annual recharge rates of different groundwater systems in the Ordos Plateau by using various methods such as the WTF method (46–109 mm/year), the hydrologic budget method (21–109 mm/year) and the saturated zone Darcian method (17–54 mm/year). Then, Yin et al. (2011a) tried to carry out groundwater research for a specific lake basin, and analyzed the groundwater evolution characteristics of the Haber Lake Basin in the middle of the Ordos Plateau by using hydrochemical and isotope data. Further, Wu Q et al. (2019) successfully applied GRACE and GLDAS to the quantification of groundwater recharge in Ordos Basin. The results showed that the annual groundwater recharge varied greatly, ranging from 30.8 to 66.5 mm during 2002–2012, but there was no significant change in the long term.

With the understanding of the groundwater system in the Ordos Basin and the development of related research technologies, scholars have gradually paid attention to exploring the factors affecting the change in groundwater recharge. Huang et al. (2017b) used the CMB method to study the groundwater recharge of the grassland in the western Ordos Basin, and determined that the diffuse recharge under the grassland was 0.11–0.32 mm/year. Huang et al. (2019) used a variety of geochemical tracers to study the reconstruction of groundwater recharge history, the determination of groundwater recharge mechanisms, and the impact of vegetation change on groundwater recharge. They pointed out that soil texture, vegetation and precipitation were the main factors controlling the recharge rate. Zhang et al. (2019) identified and quantified the seasonal variation of the precipitation recharge coefficient, which ranged from 0.14 to 0.18. Zhang et al. (2021) evaluated the effect of nonisothermal flow on groundwater recharge through field experiments and numerical simulations. Jia et al. (2021) estimated groundwater recharge based on the diurnal water-table fluctuations of three observation wells, and found that the main factors affecting the change of groundwater level were rainfall and groundwater evapotranspiration.

The North China Plain

The North China Plain, as the most populous plain in China, has been involved in the overpumping of groundwater, leading to many problems. It is urgent to carry out groundwater related research here for effective groundwater management (von Rohden et al. 2010; Su et al. 2014; Yin et al. 2020). Groundwater recharge has been extensively studied in the past. It is generally agreed that natural precipitation and artificial irrigation are the main recharge sources of the shallow groundwater (Fig. 12). As an example, Min et al.

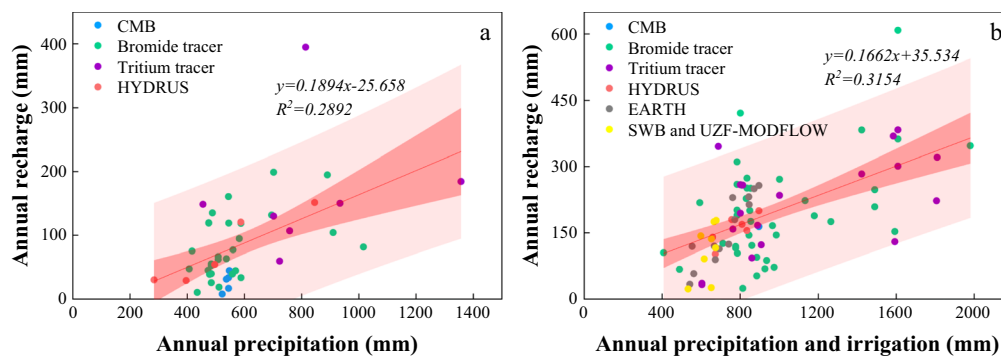


Fig. 12 Typical results of recharge studies in the North China Plain, for **a** annual precipitation alone, and **b** annual precipitation and irrigation. The data were collected from Cao et al. 2016a, Huo and Jin 2015,

Lu et al. 2011, Min et al. 2015, Shuai et al. 2014, Tan et al. 2013, Wang et al. 2008, Wang B et al. 2015

(2015) analyzed groundwater recharge processes in the deep drainage zone of typical farmland in the piedmont area of the North China Plain. Huo and Jin (2015) simulated the vertical infiltration recharge of the city of Hengshui in the central North China Plain under natural precipitation conditions in the past 60 years based on HYDRUS software. In local areas, there may be seepage recharge of surface water. For instance, Yan et al. (2013) found that the groundwater in this region came from precipitation and the leakage of the Yellow River by combining isotopic and chemical methods. In addition, Tan et al. (2014) used the improved INFIL3.0 model and bromide tracer to assess the temporal and spatial distribution of groundwater recharge in the North China Plain. Dun et al. (2014) studied the interaction between surface water and groundwater in the North China Plain and showed that the average proportion of surface-water replenishment to groundwater was 50–60%.

On the basis of a certain understanding of groundwater recharge processes, scholars have carried out a lot of research on the influencing factors of recharge. The study of Ma Y et al. (2015) showed that groundwater recharge was related to local precipitation and irrigation, while water-table depth and soil texture mainly affected the delay time of groundwater recharge relative to water input events. Tan et al. (2013) and Shuai et al. (2014) both used bromide as a tracer to study the groundwater recharge characteristics under different landforms of the North China Plain, revealing that the average recharge rate and recharge coefficient of irrigated areas were greater than those in nonirrigated areas. The study conducted by Wu et al. (2016) at representative stations in the North China Plain showed positive correlation between groundwater recharge and the sum of irrigation and precipitation at the spatial and temporal scales. Cao et al. (2016a) clarified how the thickening of the unsaturated zone affects both temporal distribution and magnitude of recharge in the North China Plain. The study of

Ma et al. (2017) showed that the unsaturated water flow was affected by a variety of factors such as soil-moisture content, soil texture, vegetation type and precipitation intensity. The study of Zheng et al. (2019) showed that precipitation infiltration under natural vegetation conditions was faster than that under farmland conditions. Moreover, in wet years, heavy precipitation events were the main recharge sources of groundwater, mainly due to the activation of preferential flow channels, while under normal wet conditions, soil moisture mainly moved downward in the way of transitional flow.

Future research opportunities

Improved quantification of groundwater recharge

This review identified that stable isotopes, hydrochemistry and their combined application were the most popular choices in previous studies. These methods have made important contributions to the identification of groundwater recharge sources, estimation of groundwater age and determination of groundwater mechanisms in arid and semiarid areas of China. Other methods, although not being used as frequently as stable isotopes and hydrogeochemistry, made significant contributions to estimating groundwater recharge rates. All the methods together have significantly improved understanding of groundwater recharge processes and potential recharge rates in different arid and semiarid areas of China. Due to the complexity of the hydrogeological conditions in arid and semiarid areas, as well as the different applicability and limitations of each groundwater recharge estimation method, each method may yield recharge at different spatial and temporal scales. To improve the reliability of recharge rates, multiple methods should be used in consideration of the specific scientific problems to be solved (Singh et al. 2019).

Understanding of groundwater systems and recharge processes

Although a lot of progress has been made, the theoretical research so far still cannot meet the needs of regional development, and the understanding of the sources and processes of groundwater recharge in many areas remains unclear and even controversial (Ge et al. 2016; Wang et al. 2017). Due to the complex environmental and geological conditions in the northwest arid area of China, the hydrogeological significance of hydrogen and oxygen stable isotopes in surface water, groundwater and precipitation has not been clearly understood (Jiang et al. 2019). Some hydrogeological parameters such as aquifer thickness are often obtained by estimation in the Tarim Basin, the Junggar Basin, the Shule River Basin, the Heihe River Basin and the Yinchuan Plain. In the Loess Plateau, the huge water storage system formed in the deep loess layer leads to complex underground hydrological processes (Xiang et al. 2020). Therefore, it is difficult for traditional soil-moisture and groundwater-level monitoring techniques to directly characterize the relationship between precipitation and groundwater; thus, limiting the study of regional groundwater systems and recharge processes.

Understanding of groundwater recharge processes at various scales

Obtaining reliable quantitative information is still one of the difficulties in the research of groundwater recharge in arid and semiarid areas. On the one hand, it is still necessary to improve the quantitative assessment scheme of groundwater recharge at a large regional scale. On the other hand, quantifying the relative contribution of preferential flow and piston flow is difficult due to the high spatial and temporal heterogeneity of the occurrence of preferential flow. For example, previous studies on groundwater recharge in the Loess Plateau mainly focused on the assessment of piston flow recharge on some small sites, applying the CMB method, the tritium tracer and the numerical model, etc., just as many scholars carried out relevant site experiments on the Loess tableland (Huang et al. 2018, 2020a; Xiang et al. 2020). Research on groundwater recharge assessment at the regional scale can be considered limited. Furthermore, there is a lack of analysis of groundwater recharge mechanisms and dominant mechanisms in the region, with very few studies assessing groundwater recharge from preferential flows, limiting the estimation of total groundwater recharge (Huang et al. 2019; Tan et al. 2017b).

Impacts of external drivers on groundwater recharge

With the emergence of groundwater-related environmental problems, the spatio-temporal uncertainty of groundwater recharge needs to be further explored. In particular, the

groundwater recharge assessment should fully consider the influence of climate, land use patterns, water-saving agricultural activities and other conditions (Lin et al. 2016; Liu et al. 2018; Scanlon et al. 2006; Wang et al. 2018b; Wang et al. 2020). In addition, land use change does not only change soil water balance, but also affects the occurrence of preferential flow by destroying preferential channels in soil, thus causing changes in groundwater recharge rates. Therefore, the relationship between groundwater recharge and land use change is often unclear, such as in the Loess Plateau (Huang and Pang 2011; Huang et al. 2018). It is necessary to further explore the mechanism of soil water movement, which is not only helpful to study the spatio-temporal uncertainty of groundwater recharge under land use change, but is also crucial for land use planning and regional development.

Use of innovative techniques to generate a multitude of observation data

Measured data such as climate, groundwater levels and various hydrogeological parameters in a study area are still the prerequisite for accurate assessment of groundwater recharge. Many remote sensing technologies and geophysical methods can provide data related to groundwater recharge, which will become an important research direction (Singh 2014). Remote sensing, for example, has great potential for solving the problem of large-scale calculation of precipitation and evapotranspiration, enabling one to better understand the water balance in large study areas (Liu et al. 2021; Singh 2014; Zuo et al. 2021). Despite some drawbacks, the study of water balance modeling based on remote sensing is considered to be very promising. When calculating with high frequency and long time series, the remote sensing method is expected to overcome the difficulty of spatio-temporal variation of large-scale groundwater recharge under climate change (Singh 2014).

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