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Topical Collection: Groundwater recharge and discharge in arid and semi-arid areas of China

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Abstract
The arid and semi-arid regions within China host 75% of the country's cultivated lands. These regions heavily rely on groundwater for drinking, irrigation, industry and energy production. Understanding recharge and discharge processes is critical to managing sustainable use and development of groundwater resources. Recently, groundwater recharge and discharge have been altered by climate change (air temperature, rainfall) and human activities (e.g. irrigation, pumping, reforestation), resulting in significant changes in the quantity, quality, and spatiotemporal distribution of groundwater resources. This essay describes some examples of the associated issues, challenges and opportunities in the arid and semi-arid areas of China.

Keywords Groundwater recharge · Discharge · Arid regions · China

Introduction

Arid and semi-arid areas cover more than 30% of the earth's land surface (Okin et al. 2006). Groundwater is a vital water resource in arid and semi-arid areas for humans and ecosystems due to scarce surface-water resources (Barthel et al. 2017). In spite of the emphasis on sustainability, groundwater resources, especially in arid and semi-arid areas, have been overexploited. In the future, water scarcity will be of higher significance since the population growth in arid and semi-arid areas surpasses that under more humid conditions (Scanlon et al. 2006). Groundwater recharge is small in arid and semi-arid regions and strongly influenced by climate change and human activities. The International Atomic Energy Agency (IAEA) estimates that the greater part of groundwater in arid and semi-arid regions is fossil water and its use is not sustainable (Scanlon et al. 2006). Accordingly, for the sustainable management of groundwater resources to satisfy human and ecosystem demands, groundwater recharge and discharge should be accurately estimated (Zhang et al. 2021).

Nearly 25% of China's land is arid or semi-arid (Chen 2004; Fig. 1), acting as the national energy and agricultural production bases—e.g., the Ordos Plateau in northwest China has abundant mineral resources (e.g., coal, natural gas, petroleum and halite), and this region has become one of the largest regions for energy and chemical production in the country (Yin et al. 2010). Although China's arable land only accounts for 8% of the global arable land, it feeds 19% of the world's population. The arid and semi-arid regions of China host 75% of the country's cultivated lands; however, the mentioned regions exhibit sparse precipitation, strong evaporation and scarce surface water, as well as a fragile ecological environment (Jian et al. 2015). Fortunately, groundwater resources are widely distributed in northwest China and are heavily relied upon for drinking, agriculture, industry. The northwest China aquifers hold 13.2% of China's groundwater resources (Wang et al. 2018). Over the past few years, the conditions of groundwater recharge and discharge have been significantly impacted by climate change and human activities (Cheng and Jin 2013); thus, the quantity, quality, and spatial and temporal distribution of groundwater resources have varied noticeably. As a result, a series of geological-ecological environmental problems has been induced (Xiao et al. 2020), thereby hindering sustainable social and economic development and ecological security.

However, the relatively deep unsaturated zone and complex climatic conditions make it challenging to estimate

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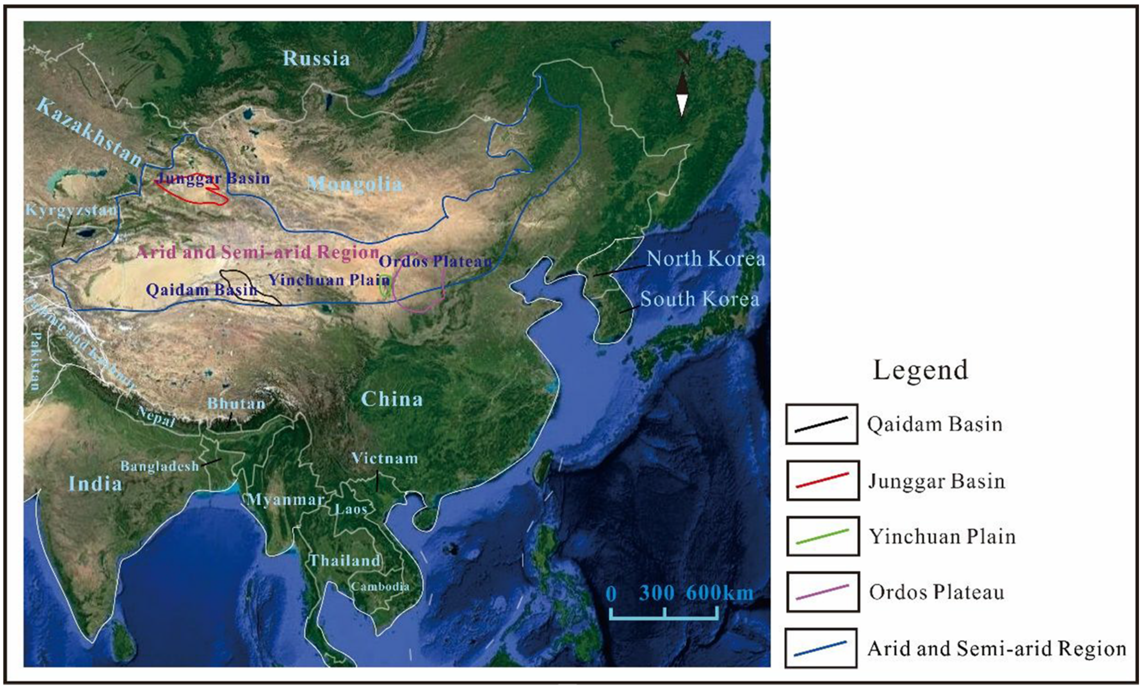

Fig. 1 The distribution of arid and semi-arid areas in China. Articles of the topical collection in this issue of *Hydrogeology Journal* mainly focused on the regions of the Ordos Plateau (purple line), Junggar Basin (red line), Yinchuan Plain (green line) and Qaidam Basin (black line)

groundwater recharge/discharge in arid and semi-arid regions of China. This essay presents a general overview of the problems and challenges concerning groundwater recharge and discharge in arid and semi-arid areas in China.

The problems of groundwater recharge and discharge in arid and semi-arid areas in China

Groundwater recharge

Groundwater resources in arid and semi-arid areas have varied significantly over time. For instance, in Shiyang River Basin, the groundwater recharge reached an estimated 1.58 billion m^3 in the 1950s, decreased to 0.98 billion m^3 in 1970, and decreased to 0.75 billion m^3 in 1990 (Ma et al. 2005). These changes have primarily two causes—first, the temperature in most areas has risen, extreme weather events have occurred more frequently, and rainfall patterns have changed; second, human activities have significantly altered the spatial patterns and intensity of groundwater recharge. In addition, the diurnal temperature ranges in arid and semi-arid area are large, and the effect of temperature and vapor flux on estimating groundwater recharge should be considered (Zhang et al. 2021).

River leakage

Recharge from disconnected-river seepage is one of the major sources of groundwater recharge in arid areas, and river leakage accounts for more than 60% of the total groundwater recharge in the Yellow River basin (Wang et al. 2013). However, human activities have intensified in arid and semi-arid areas since the late 1970s when China started its economic reforms (Wang et al. 2018). To reduce surface-water loss to groundwater, in order to more efficiently exploit the surface waters, a considerable number of rivers have been channelized to prevent leakage; as a result, groundwater recharge from rivers has rapidly decreased. Moreover, increasing pumping rates, which can locally favour disconnection of groundwater and surface water, as well as more frequent and intense drought events, further reduce groundwater recharge from river leakage. Estimating the amount of groundwater recharge taking place through riverbed interfaces and thick vadose zones (thickness ranging from a few meters to hundreds of meters) remains challenging. The main problem is reflected by the lack of comparative analysis between various methods typically applied in the China context, as well as lack of research on uncertainty analysis and the long-term viability of these methods (Wang et al. 2018).

Effect of climate change

In China, the average annual mean surface-air temperature rose by 1.12 °C from 1901 to 2015 (Ren et al. 2017); however, it grew more rapidly in arid and semi-arid areas. For instance, the mean surface-air temperature rose by about 1.49 °C in Guanzhong basin from 1950 to 2010 (Wang et al. 2018). It has been suggested that with the rise in evapotranspiration resulting from increasing temperature driven by climate change, groundwater recharge will reduce (Ojha et al. 2015). On the other hand, permafrost thawing in high-elevation headwater catchments, as a result of global warming, promotes groundwater recharge. The number of extreme precipitation events has also increased in the arid and semi-arid region of China (Huang et al. 2014). Increase in extreme rainfall events potentially leads to groundwater recharge increase (Zhang et al. 2021). The potential opposing effects on recharge, in a context of climate change, is not well understood.

Soils and irrigation

Before the 1990s, most farmlands used a broad range of irrigation techniques from surface water, with an average annual water volume of 4,500–7,500 m^3/ha in Guanzhong Basin alone. Since the 1990s, new techniques such as spraying, narrow-borders and drip irrigation, have been progressively popularized (Wang et al. 2018), enhancing irrigation efficiency. Concurrently, these new techniques have decreased groundwater recharge compared with the broad irrigation methods (Wang et al. 2021a)—for instance, drip irrigation techniques are capable of saving approximately 50% of irrigation water. It is noteworthy that the irrigation water largely originates from surface water; thus, the decrease in irrigation return flow is one of the major reasons for the decrease in groundwater levels in the late 1990s (Wang et al. 2018). Therefore, finding a balance between water-saving irrigation and maintaining groundwater recharge from irrigation remains a big challenge.

Groundwater discharge

Reforestation

Ecosystems in the arid and semi-arid areas of China are fragile. One of the critical environmental problems is desertification. About 10,000 ha/year of land have become desert since the 1960s. To control and prevent desertification effectively, the Chinese government has implemented a series of policies, for example, "Returning farmland to forest and grassland". China and India account for nearly one-third of the observed total new net increase in green leaf area globally. Such an extraordinary achievement however has raised serious concerns with respect to availability of already limited groundwater resources (Zastrow 2019). Due to low rainfall and scarce surface-water bodies, roots of trees or shrubs uptake deep soil moisture and even groundwater resource in areas of shallow water table. As revealed by existing studies, water tables have been declining, and groundwater-dependent lakes have shrunk due to vegetation cover increase in the Ordos Plateau (Zhang et al. 2018).

Pumping

With the rapid development of China's economy, groundwater resources have been increasingly extracted since the 1970s. The northern Tianshan Mountains area, part of the Junggar Basin, has been the most flourishing economic area, and the economic activity has consumed about 69% of the water resources of the entire basin (Deng et al. 2010). Overexploitation of groundwater has changed the natural distribution of groundwater resources in time and space and destroyed the water-dependent ecosystems. In the alluvial-proluvial fan aquifers, irrational groundwater exploitation has caused continuous water-table decline (which leads to reducing spring flows and shrinking of the northward groundwater seepage belts). For example, in the Manas River Valley of Junggar Basin, groundwater levels are declining annually by 0.4–1.1 m, spring flow is reduced annually by about 494×10^4 m^3, and the groundwater seepage zone has migrated northward by about 9 km since the 1960s (Shang et al. 2016).

Soil salinization

The overall surface of saline soil in China makes up nearly 3.6×10^7 ha, accounting for 4.88% of the country's total land surface. In most arid and semi-arid areas of China, river channels have been used for irrigation. When considerable quantities of surface water are introduced for irrigation, groundwater levels rise, thereby causing soil salinization due to groundwater salt concentration as a result of intense evaporation (i.e. evapoconcentration). For instance, a large volume of water was diverted from the Manas River, northwest China, for irrigation, and the groundwater levels in the irrigated region have subsequently risen up too close to the land surface. As a result of evapoconcentration, salt was left in the topsoil. As another example, in Manas and Shawan counties, respectively 47.2 and 66.8% of the farming area, have been salinized. The mechanisms and evolution of soil salinization remain unclear.

Future work/challenges

Evaluation of the impact of environmental changes on groundwater resources

In recent years, human activities have greatly changed the land surface hydrological conditions in arid and semi-arid regions of China—for example, through channeling of river beds, returning farmlands to forests, and the change in irrigation methods. In addition, extreme weather events occur more frequently due to climate change; therefore, quantitative evaluation of the impacts of human activities and climate change on groundwater resources are an important research focus in the future.

Intensify study on the mechanisms of groundwater recharge and discharge

Water-table depth is generally deep in the arid and semi-arid regions of China. The thickness of the vadose zone has a large effect on groundwater recharge and discharge; however, groundwater resource management usually neglects the impact of the vadose zone on groundwater recharge and discharge due to the complexity of unsaturated-zone flow processes. Application of coupled models of precipitation (evapotranspiration), surface water, vadose zone water, vegetation root absorption and groundwater is essential to better quantify groundwater recharge and discharge.

Construction of field in-situ monitoring observatories

Since the 1980s, several field in-situ monitoring bases have been built in the arid and semi-arid regions of China. However, most of them have been closed for economic reasons. At present, neither monitoring infrastructures nor the observed data can meet the requirements for investigating groundwater recharge and discharge. Developing and strengthening research observations is important in order to better understand the mechanism of groundwater recharge and discharge.

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Note This topical collection considers articles that bring together studies illustrating investigation methodologies (Zhang et al. 2021), modelling (Zhao et al. 2021; Wang et al. 2021a), and management (Li et al. 2021; Cui et al. 2021; Wang et al. 2021b) of groundwater recharge and discharge in the arid and semi-arid regions of China

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