Journal homepage: http://gwse.iheg.org.cn

Groundwater and environmental challenges in Asia

Yan-pei Cheng[1,2*], Fa-wang Zhang[3], Hua Dong[1,2], Xue-ru Wen[1,2]

[1] *Institute of Hydrogeology and Environmental Geology*, *Chinese Academy of Geological Sciences*, *Shijiazhuang* 050061, *China*.
[2] *Key Laboratory of Groundwater Sciences and Engineering*, *Ministry of natural Resources*, *Zhengding* 050803, *Hebei*, *China*.
[3] *Center for Hydrogeology and Environmental Geology Survey*, *China Geological Survey*, *Baoding* 071051, *Hebei*, *China*.

Abstract: Asia stands out as the most populous and geographically diverse region globally. The pressing issues of water resource development and the resulting ecological impacts are exacerbated by the region's rapid population growth and economic expansion. Groundwater, a vital source of water in Asia, faces significant disparities in distribution and suffers from unsustainable exploitation practices. This study applies groundwater system theory and categorizes Asia into 11 primary groundwater systems and 36 secondary ones, based on intercontinental geological structures, climate, terrain, and hydrogeological characteristics. As of the end of 2010, Asia's assessed groundwater resources totalled 4.677×10^9 m^3/a, with exploitable resources amounting to 3.274×10^9 m^3/a. By considering the geological environmental impacts of groundwater development and the distinctive characteristics of terrain and landforms, six categories of effect zones with varying distribution patterns are identified. The current research on Asia's groundwater resources, environmental dynamics, and human impacts aims to provide a theoretical foundation for sustainable groundwater management and environmental conservation in the region.

Keywords: Asia; Groundwater resources; Groundwater quality; Ecological environment; Environmental impacts

Received: 07 Sep 2023/ Accepted: 23 Apr 2024/ Published: 10 Jun 2024

Introduction

Asia is the largest continent, characterized by highly complex natural geography and geological conditions, covering approximately 29.4% of the Earth's land area and home to 61% of the world's population. Most of its 48 countries and regions are classified as developing nations. With the development of the global economy and society, coupled with climate and environmental changes worldwide, water resource issues have become increasingly prominent. The Qinghai-Tibet Plateau in Central Asia, also known as the "Roof of the World" and the "Third Pole" serves as Asia's water tower. In this high-altitude cold zone, with elevations above 4,500 meters, permanent ice and snow cover persist, and perennial island-like permafrost layers exist. Glaciers and snow contribute to groundwater through seasonal freezing and thawing cycles, where groundwater transforms from solid to liquid with rising seasonal temperatures, forming subterranean runoff that eventually converges into surface rivers. In many parts of Central and Western Asia, as well as the northwest region of China and the Mongolian Plateau, inland arid desert areas prevail. These regions, segmented by a series of mountain ranges into alternating basins, experienced significant variation in terrain precipitation. The vast deserts and barren lands between mountains receive minimal rainfall, with some areas even experiencing an average annual precipitation of less than 100 mm. These areas primarily rely on mountain precipitation converted into surface runoff or lateral infiltration to replenish groundwater in basin areas, where groundwater movement is sluggish and evaporation and discharge dominate.

Approximately one-third of Asia's territory falls within the semiarid to semi-humid climate zone, with precipitation ranging from 250 mm to 500 mm. Between various mountain ranges lie a series of large plains and basins, forming relatively independent hydrogeological units. Some of the larger

---

[*]Corresponding author: Yan-pei Cheng, *E-mail address*: yanpeicheng@tom.com

DOI: 10.26599/JGSE.2024.9280017

Cheng YP, Zhang FW, Dong H, et al. 2024. Groundwater and environmental challenges in Asia. Journal of Groundwater Science and Engineering, 12(2): 223-236.

plains and basins include the Northeast Plain, North China Plain, West Siberian Plain, and various-sized intermountain basins. These plains and basins, characterized by thick layers of loose Quaternary sediments, receive ample recharge from adjacent mountains, harbouring abundant groundwater resources that serve as crucial sources of water for local residents. Extensive groundwater extraction for agricultural irrigation and active water exchange processes, particularly in shallow aquifers, contribute to groundwater renewal, ultimately discharging downstream into plains and basins (Li et al. 2021; Zhao et al. 2021). In South Asia and the Indochinese Peninsula, subtropical climates prevail with abundant rainfall, exceeding an average of 1,000 mm annually. Well-developed surface water systems and ample groundwater recharge contribute to active water exchange processes, particularly favorable in loose aquifers of plains, river valleys, and deltaic regions. The Indo-Gangetic and Brahmaputra river plains in South Asia, characterized by thick Quaternary sediment deposits and favorable conditions for rainfall and surface water recharge, boast rich groundwater resources, serving as vital water sources for these plains (Zhang, 2012). Valleys in the Indochinese Peninsula, due to continuous surface water erosion, exhibit thinner layers of loose sediments, resulting in poor groundwater storage conditions and limited exploitation capacity, primarily suitable for general domestic water supply. Across Asia, numerous islands in the Pacific Ocean are located along tectonic plate boundaries, with active volcanic activity. The Pacific monsoon climate exhibits significant climatic disparities from temperate to tropical zones, with rainfall ranging from 1,000 mm to 2,500 mm. Most islands feature a radial drainage pattern due to high central terrain surrounded by lower perimeters, resulting in shallow aquifers with limited storage capacity in weathered volcanic rock fractures. Despite adequate groundwater recharge, rapid groundwater flow and discharge are common. Downstream and coastal areas of major Asian rivers often feature fertile and flat delta plains, with extensive loose sediment deposits harbouring abundant high-quality groundwater resources (Zhang, 2019). These regions are home to numerous important cities with intense socioeconomic activities, resulting in high demand for groundwater. However, excessive groundwater extraction near estuaries can lead to saltwater intrusion into freshwater aquifers and even land subsidence. These phenomena have been observed in coastal areas of eastern China, Taiwan, the Philippines, and other regions.

1 Asia's groundwater system and water resources

1.1 Groundwater system in Asia

The groundwater system in Asia is divided based on the hydrogeological structure, composition of aquifer systems, and the influence of climate and topography. It is recognized that the intercontinental groundwater system constitutes a large-scale macroscopic system, built upon geological plate foundations. It considers the spatial structure of Asia's hydrogeological composition, climatic topography, surface water systems, and hydrogeological aquifer groups to address the system's characteristics such as collectivity, correlation, purposefulness, and integrity, while also taking into account the boundary nature and spatial integration features of groundwater systems (Chen et al. 1984). The division of groundwater systems adheres to the principles of collectivity, correlation, and macroscopic purposefulness of system elements. It follows the principles of regional natural geographic zoning, considering the natural attributes of the spatial distribution of main aquifer systems in climatic topography and hydrogeological structural domains, rendering the groundwater systems relatively independent, with integrity principles governing the water cycle, hydrodynamics, and hydrochemistry systems. Taking into account the social attributes is conducive to the principles of resource assessment and management of intercontinental-scale groundwater systems (Engelen, 1984). Utilizing systems theory to categorize Asia, the continent is divided into 11 primary groundwater systems and 36 secondary groundwater systems (Fig. 1).

1.2 Evaluation of groundwater resources in Asia

Groundwater resource evaluation involves comprehensive analysis, calculation, and demonstration of the quality and quantity of groundwater resources in terms of their utility value and economic benefits under certain natural and artificial conditions. The evaluation includes quantitatively assessing groundwater recharge resources, storage resources, and estimating exploitable resources (Cao et al. 2002). Estimating the exploitable groundwater resources is the core issue in groundwater resource evaluation. Currently, there are dozens of methods for evaluating groundwater resources (Guo et al. 2005), and the most widely used methods mainly

Fig. 1 Asian groundwater systems

Notes: Ⅰ$_1$—Groundwater system in Ob River Basin of west Siberia Plain； Ⅰ$_2$—Groundwater system in Yenisei River Basin of central Siberia Plateau； Ⅰ$_3$—Groundwater system in Lena river Basin of central Siberia Plateau； Ⅰ$_4$—Groundwater system in Kolyma River Basin of eastern Siberia； Ⅱ$_1$—Groundwater system in Heilongjiang River (Amur River)； Ⅱ$_2$—Groundwater system in Liaohe River Plain-Korea Peninsula； Ⅱ$_3$—Groundwater system in islands of northeastern Asia； Ⅲ$_1$—Groundwater system in Huang-Huai-Hai Plain-Shandong Peninsula； Ⅲ$_2$—Groundwater system in Shanxi-Hebei intermontane basin； Ⅲ$_3$—Groundwater system in Ordos-Loess Plateau； Ⅳ$_1$—Groundwater system in Mongolia Plateau； Ⅳ$_2$—Groundwater system in Hexi Corridor； Ⅳ$_3$—Groundwater system in Ili River Basin-Junggar Basin； Ⅳ$_4$—Groundwater system in Tarim Basin； Ⅳ$_5$—Groundwater system in Qaidam Basin； Ⅳ$_6$—Groundwater system in Kazakhstan hilly area-Tulan Plain； Ⅴ$_1$—Groundwater system in Asia Minor Peninsula(Anatolia Plateau)； Ⅴ$_2$—Groundwater system in Iran Plateau； Ⅵ$_1$—Groundwater system in Mesopotamian plain； Ⅵ$_2$—Groundwater system in Arabian Peninsula； Ⅶ$_1$—Groundwater system in Kashmir- Himalaya-Qiangtang Plateau； Ⅶ$_2$—Groundwater system in southern Tibet valley； Ⅷ$_1$—Groundwater system in India River Plain； Ⅷ$_2$—Groundwater system in Ganges River Plain； Ⅷ$_3$—Groundwater system in India Peninsula； Ⅸ$_1$—Groundwater system in upland and plain of Lancangjiang River- Salween River Basin； Ⅸ$_2$—Groundwater system in upland and plain of Lancangjiang River-Meikong River Basins； Ⅸ$_3$—Groundwater system in upland and plain of Red River Basin； Ⅹ$_1$—Groundwater system in Qinling-Dabieshan Mountains； Ⅹ$_2$—Groundwater system in terraced terrain of west Sichuan Plateau； Ⅹ$_3$—Groundwater system in Sichuan Basin； Ⅹ$_4$—Groundwater system in hilly area of middle and lower reaches of Yangtze River； Ⅹ$_5$—Groundwater system in karst upland of South China； Ⅹ$_6$—Groundwater system in coastal hilly area and islands of South China； Ⅺ$_1$—Groundwater system in Malay peninsula； Ⅺ$_2$—Groundwater system in islands of southeast Asia.

include the water balance method, pumping test method, analytical method, numerical method, and flow modulus method, among others.

The intricate natural geography and geological conditions in Asia have led to complex hydrogeological conditions characterised by relatively complex aquifer structures and boundary conditions. This complexity poses challenges for conventional methods like numerical approaches, pumping tests, and analytical techniques. Consequently, based on the available data, flow modulus method has been selected as the preferred approach for evaluating groundwater resources in Asia (Margat et al. 2013). By understanding hydrogeological conditions and utilizing hydrological flow data and the aquifer area in the control zones of groundwater flow, the groundwater flow modulus (recharge modulus), i.e. the recharge quantity or groundwater flow rate per unit time per unit area of aquifer, can be directly determined.

Based on the groundwater flow modulus, the natural recharge quantity or groundwater flow rate in the region can be indirectly inferred:

$$Q = M \cdot F \tag{1}$$

Where:

Q—Groundwater flow rate, m^3/s;

M—Groundwater flow modulus, $m^3/s\cdot km^2$;

F—Aquifer area, km^2.

From the above, it can be inferred that the groundwater flow modulus is an important indicator for evaluating groundwater resources in a region, and it is controlled by the recharge, flow, and discharge conditions of regional groundwater (Qian et al. 2001). Therefore, different approaches are adopted for evaluation based on different hydrogeological characteristics:

(1) Karst areas with developed underground rivers

In regions where underground rivers develop in karst areas, assessment of flow modulus can be achieved by managing underground river outlets or springs. This involves measuring their flow during low-flow periods and delineating the corresponding area of the underground drainage basin. The ratio of flow to the area of the underground drainage basin can be determined as the groundwater flow modulus.

(2) Non-karst areas with developed surface river systems

In regions characterized by fractured aquifer and porous aquifer in actively alternating zones, where recharge volumes contribute directly to groundwater flow and discharge into valleys and become part of river flow, existing hydrological data from river hydrographs at hydrological stations can be fully utilized to determine the groundwater flow modulus.

River water is primarily replenished by atmospheric precipitation and groundwater recharge. During dry periods, the majority of river flow comes from groundwater, whereas during flood periods, precipitation becomes the main contributor to river flow, leading to a decrease in groundwater recharge. In some instances, river water may even recharge groundwater in reverse. Therefore, when analysing river hydrographs, it is crucial to segregate the groundwater flow based on actual hydrogeological conditions. Currently, the division boundaries are often determined empirically.

For hydrological stations with single lithology and small drainage areas, a line is drawn on the flow process diagram from the start of the rising portion to the inflection point of recession, and the portion below this line is considered as base flow.

For hydrological stations with heterogeneous lithology and large drainage areas, the base flow is represented by the average flow during dry periods.

In the absence of hydrological stations, simple flow measurement methods can be deployed along upstream and downstream cross-sections of the river. The difference in flow between upstream and downstream sections can be used to determine the groundwater flow and the corresponding groundwater flow modulus in the control zone.

When one aquifer is discharged by a river along with another aquifer whose flow modulus is known, the flow modulus of the unknown aquifer can be calculated using the following formula:

$$M_2 = \frac{Q - M_1 F_1}{F_2} \tag{2}$$

Where:

M_2— Flow modulus of the unknown aquifer, $m^3/s\cdot km^2$;

F_2— Aquifer area of the unknown aquifer, km^2;

Q — Base flow rate of the combined aquifer, m^3/s;

$M_1 F_1$—Flow modulus and aquifer area of the known aquifer;

In groundwater systems with complex hydrogeological conditions and limited research, such as those found in mountainous regions with bedrock, karst water systems, fractured aquifer, or in large regions with complex hydrogeological conditions, this evaluation method proves to be straightforward and efficient.

1.3 Natural recharge of groundwater resources in Asia

Firstly, groundwater infiltration coefficients are categorized into zones based on variations in topography, average annual precipitation, hydrology, lithology of the vadose zone, and aquifer media (Fig. 2). The groundwater recharge intensity (mm/a) is uniformly converted into a standardized groundwater natural recharge modulus. Moreover, considering the relationship between surface water and groundwater, evaluations are made in surface water recharge areas in plains and basins, particularly in regions like the Siberian plains where significant seasonal thawing and freezing of

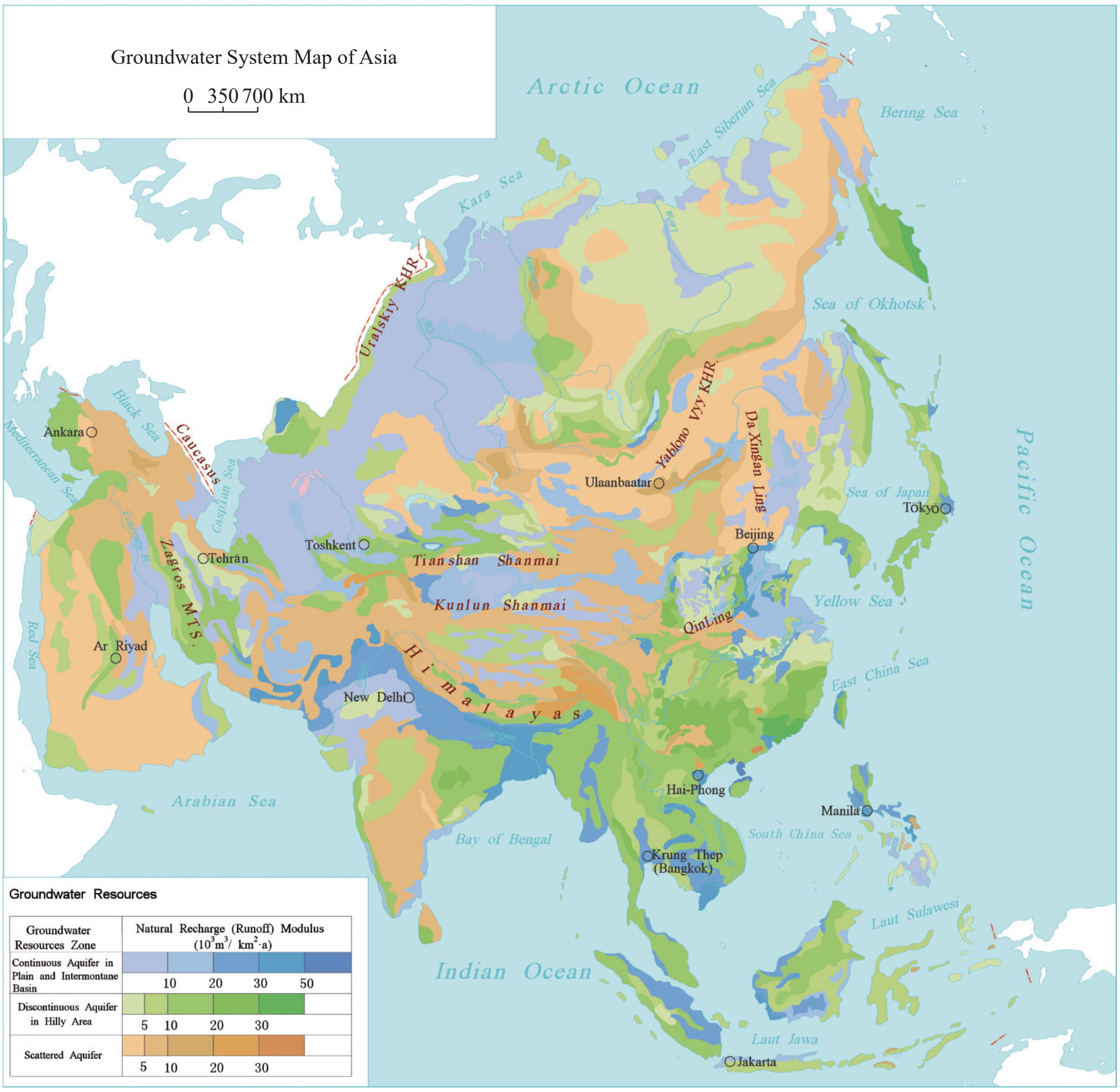

Fig. 2 Zoning map of natural recharge modulus in Asia

permafrost contribute to water recharge (Li, 2013). Based on the continuity of groundwater flow movement, aquifers are classified into three types: 1) Continuous aquifers of loose sediment in plains and intermountain basins; 2) Discontinuous aquifers in hills and mountainous areas with bedrock; 3) Sparse aquifers. The groundwater natural recharge modulus (10^4 $m^3/a{\cdot}km^2$) for these three types of aquifers are then categorized into five levels: <10, 10–20, 20–30, 30–50, and >50. From Fig. 1, it can be observed that the eastern and southeastern coastal regions of Asia mainly consist of discontinuous aquifers with groundwater natural recharge modulus of 20–30 (10^4 $m^3/a{\cdot}km^2$), while areas in the central and southwestern coastal regions have sparse aquifers with groundwater natural recharge modulus less than 20 (10^4 $m^3/a{\cdot}km^2$). The northern regions mainly comprise continuous aquifers in plains and intermountain basins with groundwater natural recharge modulus less than 30 (10^4 $m^3/a{\cdot}km^2$) (Cheng, 2015). This differential distribution is primarily due to the complex topographical conditions and uneven atmospheric precipitation in Asia. Using the flow modulus method, the natural groundwater resources of the three types of aquifers are determined (Table 1).

From Table 1, it is evident that the distribution of natural groundwater resources in Asia is extremely uneven. The groundwater natural recharge resources in sparse aquifers amount to only 386.14 × 10^9 m^3/a, accounting for merely 8% of the total natural groundwater resources in Asia. Meanwhile, the natural recharge resources in continuous aquifers in plains and intermountain basins, as well as in discontinuous aquifers in hills and mountains with bedrock, account for 52% and 40%, respectively, of the total natural groundwater resources in Asia. Among these, continuous aquifers in plains and intermountain basins have the highest natural

Table 1 Summary of natural groundwater resources in aquifers in Asia (10^9 m^3/a)

Aquifer type	Natural recharge resources	Percentage of total
Continuous aquifers in plains and intermountain basins	2,424.65	52%
Discontinuous aquifers in hills and mountains with bedrock	1,866.95	40%
Sparse aquifers	386.14	8%
Total	4,677.74	100%

recharge resources, constituting 52% of Asia's total natural recharge resources. This is due to the extensive distribution of continuous aquifers in plains and intermountain basins across Asia, with relatively high groundwater recharge modulus.

The recharge modulus in Table 2 represents the recharge volume of natural groundwater resources per unit area in the groundwater system. The average recharge modulus across all of Asia is 10.55 (10^4 m^3/a·km^2).

1.4 Exploitable groundwater resources in Asia

Groundwater, as a vital component of the Earth's water resources, plays a crucial role in human societies. Stored underground like a vast reservoir, groundwater provides stable water supply and good water quality, making it an essential source for agricultural irrigation, industrial and mining enterprises, and urban water supply, thus becoming an indispensable water resource for human society. Due to its relatively low development and utilization costs, convenience of use, and resistance to pollution compared to surface water, groundwater is commonly used for public water supply. Many regions of the world rely on groundwater as a reliable source of freshwater. With the development of the world economy, the demand for groundwater in industries, agriculture, and other sectors is increasing. In recent years, there have been many problems in the development and utilization of groundwater in Asia, mainly including the continuous decline of regional groundwater levels, land subsidence, seawater intrusion, etc., which greatly hinder the economic development of cities in Asia that rely on groundwater as a water supply resource (Hao, 2011). Therefore, quantitatively estimating the exploitable groundwater resources in Asia will guide rational exploitation of groundwater resources in various countries in Asia, reducing geological disasters caused by irrational exploitation of groundwater (Liu, 1990). The estimation of exploitable groundwater quantity is the core issue in groundwater resource assessment. The magnitude of exploitable groundwater quantity mainly depends on the recharge amount and is also related to the economic and technical conditions of exploitation and the exploitation scheme (Wang, 2012). In this chapter, based on the hydrogeological conditions, groundwater exploitation conditions, and groundwater exploitation and utilization situations in different groundwater systems in Asia, the exploitable groundwater resources of the groundwater system are evaluated by multiplying the natural recharge resources of the groundwater system by the average exploitation experience coefficient of 0.7 (Table 3).

From Table 3, it can be observed that the exploitable groundwater resources in Asia amount to 3,274.40 × 10^9 m^3/a. Among them, the North Asian Plateau and Highland Cold Temperate Groundwater System account for 705.21 × 10^9 m^3/a, representing 21.5% of the total exploitable resources. This region covers a vast area, approximately 28.1% of the total area, with well-developed rivers. The unique continental climate results in much of the groundwater being in a state of continuous or intermittent freezing. Therefore, this groundwater system harbors a significant amount of groundwater resources, providing abundant exploitable resources for the region.

The Iranian Plateau - Anatolian Peninsula Subtropical Arid, Semi-Humid Groundwater System has exploitable resources of 110.26 × 10^9 m^3/a, representing 3.4% of the total exploitable resources. This region covers about 6.2% of the total area and features a subtropical arid to semi-humid climate. The Anatolian Peninsula experiences dry climates, forming salt flats and semi-desert landscapes. The Iranian Plateau, situated between the Pamir Plateau and the Armenian volcanic plateau, is a closed plateau. Although the western slope receives more precipitation, the groundwater recharge in this region is relatively low. Therefore, the exploitable resources of this groundwater system are comparatively limited.

2 Environmental impacts of groundwater extraction in Asia

Groundwater extraction varies significantly across Asia, presenting distinct challenges in different regions. In East Asia, South Asia, and Central

Table 2 Average recharge modulus of groundwater systems in Asia

Code	Groundwater system	Main areas covered	Average recharge modulus(10^4 m^3/a·km^2)
I	Sub-humid temperate groundwater system of North Asia Plateau and Highland	Ob River in Western Siberian Plain, Yenisei River in Central Siberian Plateau, Lena River and Kolyma River in Eastern Siberia	8.12
II	Sub-humid temperate groundwater system of mountainous and plain Northeast Asia	Amur River in Heilongjiang, Liaohe Plain-Korean Peninsula, and Northeast Asia Island Group	8.89
III	Semi-arid temperate groundwater system of North China Plain, Mountain, and Loess Plateau	Huaihe-Haihe Plain-Shandong Peninsula, Jin-Ji Mountain Basin, Ordos-Loess Plateau	12.83
IV	Arid temperate groundwater system of Inland Basins and Hilly Mountains	Mongolian Plateau, Hexi Corridor, Ili River-Junggar Basin, Tarim Basin, Qaidam Basin, and Kazakh Hills-Turpan Plain	11.67
V	Arid to sub-humid tropical groundwater system of Iran Plateau and Anatolian Peninsula	Anatolian Peninsula (Anatolian Plateau) and Iran Plateau	5.76
VI	Arid tropical groundwater system of Arabian Peninsula and Mesopotamian Plain	Mesopotamian Plain and Arabian Peninsula	5.35
VII	Subarctic groundwater system of Qinghai-Tibet Plateau	Kashmir-Himalayas-Qinghai-Tibet Plateau and Southern Tibet Valley	23.8
VIII	Tropical wet-humid to Sub-humid groundwater system of South Asia two River Plain and Deccan Plateau	Indus River Plain, Ganges River Plain, and Deccan Plateau in India	15.44
IX	Tropical wet groundwater system of Mountainous Hills of Mainland Southeast Asia	Nujiang-Salween River Mountain Valley Plain, Lancang River-Mekong River Mountain Plain, and Red River Mountain Plain	10.03
X	Subtropical wet groundwater system of Mountainous and Plain Southern China	Qinling-Dabie Mountain Region, Western Slopes of Sichuan Basin, Sichuan Basin, Hilly Plains in Middle and Lower Yangtze River, Karst Mountains in Southern China, and Coastal Hills and Islands in Southern China	11.68
XI	Equatorial humid tropical groundwater system of Southeast Asian Island Group	Malay Peninsula and Southeast Asian Island Group	15.34
	Overall Asia Region	-	10.55

Table 3 Groundwater resources in primary groundwater systems in Asia (10^9 m^3/a)

Code	Primary groundwater system	Natural recharge resources	Exploitable resources
I	North Asian Plateau and Highland Cold Temperate Groundwater System	1,007.45	705.21
II	Northeast Asia Mountainous and Plain Temperate Semi-Humid Groundwater System	323.42	226.39
III	North China Plain, Mountainous, and Loess Plateau Temperate Semi-Arid Groundwater System	165.86	116.1
IV	Inland Basin and Hill Mountain Temperate Arid Groundwater System	845.67	591.97
V	Iranian Plateau - Anatolian Peninsula Subtropical Arid, Semi-Humid Groundwater System	157.51	110.26
VI	Arabian Peninsula - Mesopotamian Plain Tropical Arid Groundwater System	213.6	149.52
VII	Qinghai-Tibet Plateau Cold Highland Groundwater System	490.96	343.67
VIII	South Asia Two Rivers Plain - Deccan Plateau Tropical Wet-Semi-Wet Groundwater System	587.8	411.46
IX	Indochina Peninsula Mountainous Hilly Tropical Wet Groundwater System	201.66	141.16
X	South China Mountainous Hilly and Plain Subtropical Wet Groundwater System	309.9	216.93
XI	Southeast Asia Island Group Equatorial Humid Groundwater System	357.45	250.21

Asia, groundwater issues are particularly prominent. Since the 1980s, rapid economic development in East Asia has led to a sharp increase in water demand. In Central Asia, rivers such as the Amu Darya and Syr Darya rely heavily on meltwater from Central Asian mountains, with lakes like the Aral Sea and Lake Balkhash also contributing to water sources (Jiao, 1992). In West Asia, which is characterized by arid conditions, water resources are scarce. With a total area of over 7 million square kilometers, over three-quarters of the region lacks surface runoff and annual precipitation is less than 200 mm in most areas, with very few areas receiving over 600 mm of annual precipitation. Water resources in West Asia are primarily used for agricultural irrigation. Due to the development of the petroleum economy, rapid urbanization and industrial expansion have led to increased water demand, resulting in water shortages in many cities. Groundwater in this region primarily occurs in deep rock aquifers, often with high salinity, posing challenges for extraction. Southeast Asia, on the other hand, is abundant in water resources. Major rivers such as the Irrawaddy, Salween, Mekong, Red River, Chao Phraya, Nujiang, Lancangjiang and Yuanjiang Rivers contribute to the region's water wealth. The natural recharge of groundwater resources in the region is estimated at 1,927.21 billion m^3/a, with plains and basins contributing 42%, hills and mountainous areas 24%, plateaus and mountains 20%, and the rest in cold and thaw areas. The plains and basins are the largest storage areas in the basin, mainly distributed in coastal areas and delta basins. Groundwater in hills and mountainous areas is widely distributed inland, with high storage volumes due to extensive rainfall and recharge areas. Groundwater development and utilization in Southeast Asia have a long history but are not significant in terms of extraction. Groundwater plays an important role in supplying water to pastoral areas, mountainous regions for drinking water, mining areas, industrial and mining bases, islands, and border denfense points, mainly extracting groundwater for irrigation and domestic water use (Wang, 2013). In major cities like Hanoi and Phnom Penh, groundwater serves as a significant source of urban water supply. In North Asia, the Asian part of Russia has much richer surface water resources compared to China, with an average annual precipitation of 590 mm providing a renewable water resource of 43,130 billion m^3/a, 1.5 times that of China, and a per capita possession of 29,115 billion m^3, 12 times that of China. Lake Baikal accounts for 20% of the world's freshwater (Chen, 1996), so Russia's surface water resources are very rich and can meet industrial, agricultural, and domestic water needs. According to data from the Food and Agriculture Organization (FAO), groundwater resources in Russia are still relatively underutilized, with groundwater extraction accounting for less than 5% of the annual recharge of 9,000 billion m^3. Therefore development of groundwater resources in Russia is relatively low despite significant potential.

In most cities across Asia, groundwater is the primary source of water supply. Over the past two decades, groundwater extraction in Asia has seen significant growth, with India and China leading in terms of increased extraction volume. The primary purposes for groundwater extraction vary, with more than 50% of the total groundwater extraction in China, India, and Pakistan being used for irrigation. In India, out of 5,723 assessment units, 839 units are experiencing groundwater overexploitation, accounting for 14.7% of the total, leading to declining groundwater levels in many areas, especially coastal regions. For instance, in the Mesana region, groundwater extraction amounts to 950 million cubic meters, while recharge is only 417 million m^3, resulting in a substantial decline in groundwater levels. In Tamil Nadu, intensive agricultural irrigation has led to a 25 m to 30 m decline in groundwater levels over the past decade. In regions like Rajasthan, Punjab, and Haryana, covering approximately 43,800 km^2, groundwater levels have been decreasing at an average rate of 0.3 m per year (Zhong et al. 2011). In India's islands and western regions, groundwater levels have dropped to depths beyond the reach of manual pumps. In Gujarat, for example, wells that were only 10 m to 15 m deep 30 years ago now require depths of 400 m to 450 m. Coastal areas are also experiencing seawater intrusion due to groundwater overexploitation, leading to deterioration of the groundwater environment. In parts of Gujarat and Tamil Nadu, overexploitation of coastal aquifers has resulted in seawater intrusion into freshwater aquifers, rendering approximately 120 villages and 130,000 wells saline. In the Madras coastal area, the saltwater interface has intruded inland by 8 km to 10 km. In the Kutch coastal area, seawater intrusion has affected 245 villages and 23,280 hectares of land (Fang, 1996). Along the Saurashtra coast of Gujarat, rapid seawater intrusion into coastal aquifers, caused by excessive groundwater extraction, has led to the collapse of the "well economy" as the intrusion has extended from 1 km to 7 km inland. In some parts of Pakistan, groundwater levels are declining, making it challenging for 60% of the population to access clean water sources. Water scarcity also affects various sectors such as electricity, industry, and agriculture. Meanwhile, remote sensing mapping of groundwater in India indicates alarming rates of depletion in the northern part of the Indian subcontinent.

The North China Plain in China is an area where negative geological effects are particularly concentrated. Compared to the Indo-Gangetic Plain, the similarity lies in the high population density, but the difference is that the North China Plain receives less than half the annual rainfall of the Indo-Gangetic Plain, resulting in less groundwater recharge. Consequently, groundwater overexploitation is more severe in this region, leading to a greater diversity of geological harzards. Seawater intrusion is a widespread issue in many coastal cities such as Dalian, Shanghai, Laizhou, and Huludao. Dalian is one of the cities severely affected by seawater intrusion, which has already impacted the national welfare. Seawater intrusion in the coastal areas of Shanghai has been a long-standing issue. As early as the spring of 1979, the Yangtze River estuary experienced the most severe seawater backflow in nearly a decade, affecting an area extending more than 170 km upstream to the mouth of the Wangyu River and Hupu River in Changshu City, Jiangsu Province. In recent years, seawater backflow, influenced by both natual processes and human activities, has also affected shallow groundwater. Laizhou City in Shandong Province, located in the northwest of the Jiaodong Peninsula and bordering the Bohai Sea, has experienced prolonged low rainfall. With increased economic development and water usage for industry and agriculture, excessive groundwater extraction has caused a significant decline in groundwater levels, leading to the formation of groundwater cones and seawater intrusion, adversely affecting the ecological environment. In coastal cities such as Qinhuangdao in Hebei Province, Dalian, and Huludao in Liaoning Province, seawater intrusion has occurred in most areas, severely impacting economic development, people's livelihoods, and public health. Karst collapses caused by groundwater overexploitation account for 29.3% of the total collapse nationwide, with urban areas and railway lines being the most affected. Among them, cities such as Guiyang, Kunming, Wuhan, Hangzhou, Nanjing, and Guangzhou, as well as smaller cities like Guilin, have been significantly affected.

In some cities in Thailand, irrational groundwater extraction has caused land subsidence. In Bangkok, land subsidence has reached 30 cm to 80 cm over the past 30 to 40 years, with half of the city currently lying below an average sea level of 0.5 m. Irrational groundwater extraction has also led to seawater intrusion into coastal freshwater aquifers, resulting in groundwater salinity levels ranging from 3 g/L to 4 g/L, reaching as high as 10 g/L in some areas, rending the groundwater unsuitable for drinking. In inland areas of Vietnam, such as Hanoi, groundwater is mainly extracted for irrigation and domestic use. Approximately half of the area of the Kinh Oa Peninsula is affected by seawater intrusion, with the salinity of shallow groundwater several times to ten times higher than that of deep groundwater. Severe groundwater overexploitation is observed in coastal areas of the Korean Peninsula. In some cities in South Korea, industrial groundwater extraction has led to groundwater levels dropping by 10 m to 50 m. Rapid industrial development on Jeju Island in South Korea has resulted in seawater intrusion due to extensive groundwater extraction. In densely populated cities like Tokyo, Nagoya, and Osaka in Japan, groundwater overexploitation is severe. Tokyo, in particular, experiences the most severe groundwater overexploitation in Japan, causing extensive land subsidence.

2.1 Analysis of geological environmental negative effects caused by excessive groundwater exploitation

Based on the regional data currently available, a macroscopic analysis categorizes the adverse geological environmental effects caused by irrational groundwater development into seven types: Continuous decline in regional groundwater levels, land subsidence, karst collapse, ground fissures, seawater intrusion, groundwater level decline due to oil extraction water injection, and subsidence in mining areas (Bedient, 1994). The environmental and ecological problems caused by excessive groundwater exploitation do not exist in isolation but manifest in various forms simultaneously in a given area. Using the adverse geological environmental effects caused by groundwater exploitation as a basis for partitioning, different terrain and aquifer types are important criteria for judging partitioning, with the severity of hazards being used for double analysis and judgment. Based on terrain features and typical effects, along with the different categories and distribution patterns of adverse geological environmental effects caused by groundwater development, classification is conducted according to the severity of geological environmental negative effects arising from different degrees of groundwater exploitation (EPA, 2002).

2.2 Zoning of geological environmental negative effects caused by excessive groundwater exploitation

Based on the environmental effects of groundwater development and utilization in Asia, six types of effect zones are identified: 1) Large-scale gradual hazard effect zones of strong groundwater exploitation in plain basins, 2) Zones of general groundwater exploitation in plain basins without obvious adverse effects, 3) Zones of easily occurring sudden hazard effects due to localized karst groundwater exploitation, 4) Zones of easily occurring sudden hazard effects due to dewatering and exploitation in mining areas, 5) Zones of dispersed groundwater exploitation in hilly and mountainous areas without obvious adverse effects, and 6) Normative effect zones of sporadic groundwater exploitation in other areas (Zhang, 2015). The distribution of these zones is illustrated in Fig. 3.

2.2.1 Large-scale gradual hazard effect zones of strong groundwater exploitation in Plain Basins

These zones are primarily located in East Asia, South Asia, and West Asia. In East Asia, they include the Northeast Plain and North China Plain of China, the northern basin of the Tarim River Basin, the northern basin of the Heihe River Basin in the Hexi Corridor, the northern basin of the Shiyang River Basin, and the middle and lower Yangtze River Plain. They also encompass coastal areas of the Korean Peninsula and eastern coastal areas of Japan. In South Asia, they include the Indus River Plain and the Ganges River Plain. In West Asia, they include the Mesopotamian Plain. Most areas in these zones have flat terrain, with some located in undulating hills and plateaus. The groundwater is characterized by loose sedimentary micro-pore water, and the aquifer structure is homogeneous and isotropic. The adverse geological environmental effects in this zone are diverse.

2.2.2 Zones of general groundwater exploitation in Plain Basins without obvious adverse effects

These zones are characterized by terrain with high

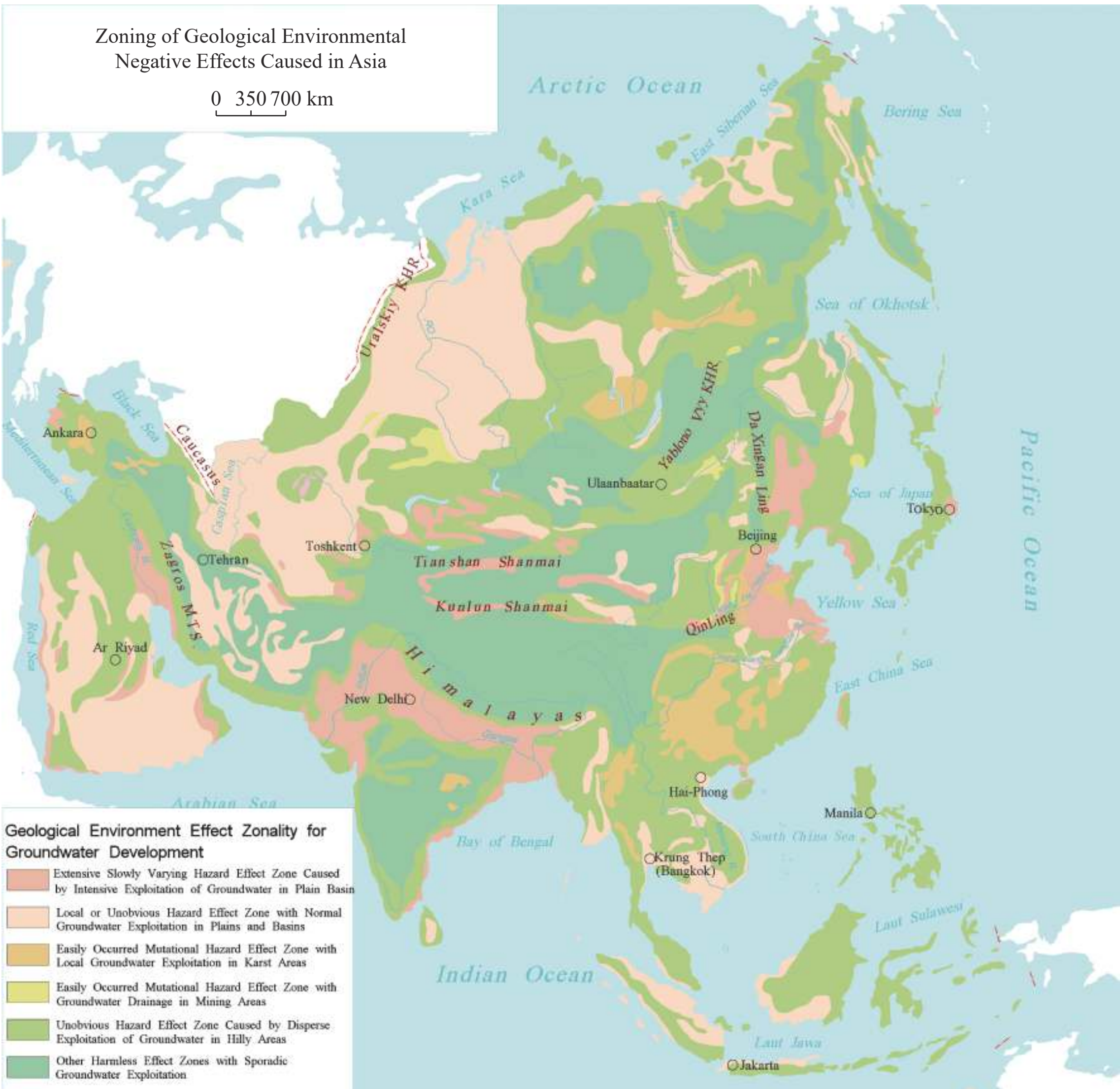

Fig. 3 Zoning of geological environmental negative effects caused in Asia

and low undulations, relatively thin aquifers, complex aquifer structures, poor aquifer productivity, and low groundwater exploitation rates, leading to minimal adverse effects. They are mainly distributed in North Asia, Central Asia, West Asia, and Southeast Asia, including the Kolyma Lowland and the West Siberian Plain in North Asia, the Aral Sea Lowland and the Tural Plain in Central Asia, the Arabian Plateau in West Asia, and the mainland of the Indochina Peninsula in Southeast Asia. The distribution of this zone is more scattered and sporadic in North Asia, East Asia, and Southeast Asia. The adverse geological environmental effects caused by excessive groundwater development in plain basins include continuous decline in groundwater levels due to oil field groundwater exploitation, continuous decline in groundwater levels due to regional groundwater over-exploitation, mining-induced subsidence, and ground fissures, ranked by their distribution areas.

2.2.3 Zones of easily occurring sudden hazard effects due to localized karst groundwater exploitation

These zones are characterized by distinct geographical features, occurring in areas with intense and moderately developed soluble carbonate distribution. They are distributed in North Asia, East Asia, and South Asia. In North Asia, large numbers of soluble rocks are found in the eastern and central parts of the Central Siberian Plateau, with scattered distributions in the Chersky Range. In East Asia, continuous distribution of soluble rocks is observed in the karst areas of the Yungui Plateau, the hills, basins, and plains in southern China. This region exhibits developed karst formations and concentrated collapses, making it the area with the most karst collapses and karst disasters in China. The North China Mountains, Plateau, and Huanghuaihai Plain have exposed and hidden karst formations with occurrences of sinkholes and collapses. The Liaodong Peninsula exhibits moderately developed karst formations with numerous occurrences of karst collapses. In Northeastern South Asia, exposed and hidden karst formations are distributed.

2.2.4 Zones of easily occurring sudden hazard effects due to dewatering and exploitation in Mining Areas

These zones are primarily distributed in Central Asia, North Asia, and East Asia between 30° and 60° north latitude. They include mining areas in northern Kazakhstan in Central Asia, mining areas north of the Sayan Mountains and on the eastern edge of the Ural Mountains in North Asia, as well as mining areas on the northern and southern edges of the Stanovoy Range and the Choba Mountains in Central Asia. In East Asia, mining areas include the Sikhot-Alin Mountains and the western edge of the Changbai Mountains in Northeast China, as well as mining areas in the North China Mountains and the Liaodong Peninsula (Zhou, 2015).

2.2.5 Zones of dispersed groundwater exploitation in Hilly and Mountainous areas without obvious adverse effects

Apart from the zones distributed in hilly and mountainous mining areas with easily occurring sudden hazard effects due to dewatering and exploitation, most hilly and mountainous areas in Asia belong to zones of dispersed groundwater exploitation without obvious adverse effects. These areas have low human activity, excellent ecological environments, minimal groundwater development, and essentially no occurrences of groundwater over-exploitation, resulting in dispersed groundwater exploitation without obvious adverse effects.

2.2.6 Other normative effect zones of sporadic groundwater exploitation

These zones are mainly distributed in plateau regions. Due to the low temperatures and unsuitability for human habitation, groundwater exploitation levels are very low in plateau regions. Examples include the Iranian Plateau in West Asia, the Qinghai-Tibet Plateau, the Mongolian Plateau, the Yungui Plateau, the Loess Plateau, the Inner Mongolian Plateau, and the Mongolian Plateau in North Asia, as well as the Central Siberian Plateau and East Siberian Highlands and Kamchatka Peninsula in North Asia, and the Deccan Plateau in South Asia.

3 Conclusions

Groundwater, as a valuable resource and a key environmental factor, is essential for sustaining life and ecosystems. However, excessive exploitation of groundwater resources can lead to a range of negative geological, ecological, and environmental effects, including sustained declines in groundwater levels, deterioration of water quality, and associated adverse impacts. Moreover, it jeopardizes spatial security for human existence. Therefore, it is imperative to protect the finite groundwater resources. Currently, in the Asian region, there are some deficiencies and issues in groundwater resource protection efforts. Suggestions and recommendations for improving groundwater resource protection systems in Asia can mainly be proposed from the perspectives of policies, laws, regulations, and institutional arrangements.

(1) Enhancing legal frameworks and institutional constraints

Improving the legal system governing groundwater resources management is essential. This includes consolidating scattered provisions related to groundwater protection, amending and refining existing laws and regulations, and providing detailed specifications. It's crucial to establish water resource assessment systems, water resource management responsibilities, and laws for groundwater management. Implementing groundwater total control systems and delineating restricted and prohibited extraction areas are also necessary. Enhancing the water resource demonstration system, formulating regulations on water resource demonstration, regulating the planning of water resource demonstration, expanding the scope of water resource demonstration for construction projects, improving the system for the water resource demonstration of construction projects, ensuring that the planning of national economic and social development and urban overall planning is in line with local water resource conditions, and playing a guiding role of water resource elements in transforming the economic development mode and adjusting the economic structure. Clearly defining the responsibilities, objects, obligations, management systems, and legal measures for groundwater management, implementing the groundwater total control system. For areas with severe over-extraction, concentrated water supply network coverage, geological disaster-prone areas, and important ecological protection areas, basic principles and requirements for controlling groundwater extraction should be proposed, restricted and prohibited extraction areas should be delineated, the objects and requirements for restricted and prohibited extraction should be specified, and the control indicators for groundwater extraction and monitoring and control aspects should be specified, promoting the management of groundwater over-extraction. Intensifying the legal construction of water resources protection, improving the management system of water function areas, based on the practice of water function area management and water function area planning, comprehensively regulating the layout, monitoring supervision, assessment and evaluation of water function areas, and simultaneously establishing and improving the system of protecting drinking water sources, establishing and improving the planning, monitoring and supervision, and safety assessment system of drinking water sources, and effectively guaranteeing the safety of drinking water. When amending and improving the legal system for groundwater protection, it is necessary to link the provisions of groundwater resources protection with the protection of surface water and soil safety, and coordinate them reasonably. Particularly, detailed and strict regulations are needed for groundwater over-extraction under specific conditions.

(2) Strengthening technical systems and comprehensive planning

Developing comprehensive plans and employing integrated management measures are essential for centralized and unified groundwater management. This involves formulating plans for groundwater development and utilization, controlling the growth of total water consumption, and optimizing the structure of groundwater use. Coordination among departments and centralized management are critical. Focus should be placed on monitoring groundwater, developing information systems, and constructing measuring facilities. This will establish a centralized management system for coordinating urban and rural groundwater resources, rationalizing the management of groundwater quantity and quality, and resolving conflicts between surface water and groundwater management. Strengthening the legal construction of water conservation, establishing a sound water conservation management system, improving various water conservation systems, strengthening water conservation management, integrating water conservation into the entire process of economic and social development and people's livelihood and production, improving water resource utilization efficiency, and promoting the construction of a water-saving society. Developing supporting regulations for water-saving management of construction projects, strictly implementing the water-saving measures for construction projects, ensuring that water-saving facilities are designed, constructed, and put into operation simultaneously with the main projects, giving full play to the benefits of water-saving facilities, and emphasizing water-saving management in key links, establishing water use quotas for high-water-consuming industries and service industries, and mandating the application of water-saving products and equipment. It is recommended to adjust the unreasonable industrial technical specifications in conjunction with other industries, and solve social, economic, and environmental problems related to groundwater issues through the adoption of multiple comprehensive measures. Sustainable development is a comprehensive and dynamic concept, involving economic, social, environmental, and ecological issues. Resource issues are interrelated and coordinated. Society is the goal of sustainable development, the economy is the driving force, the environment and ecology are the guarantees, and resources are the foundation of sustainable development. The formulation of principles for sustainable development strategies should reflect the principle of the comprehensive entity.

(3) Establishing groundwater management information systems to achieve information sharing

Establishing groundwater management information systems based on national water resource information systems, groundwater monitoring projects, and water consumption monitoring is essential. This system will facilitate dynamic monitoring of groundwater levels, quality, development, utilization, and over-extraction. It will also enable dynamic assessment of groundwater resources and balance, planned management of groundwater extraction and pressure, and rational allocation and integrated management of groundwater resources in conjunction with surface water resources. According to the dynamic monitoring of groundwater, predicting the future development trends of groundwater, discovering problems in groundwater development and utilization, and further formulating reasonable strategies for the rational exploitation of groundwater resources provide a basis for the protection of groundwater resources. For the development and utilization of groundwater using well drilling, water resource demonstration must be conducted, the approval system for well drilling must be standardized, and the increase in groundwater extraction must be strictly controlled.

(4) Promoting ioint use of groundwater and surface water

The joint use of groundwater and surface water is a fundamental policy for developing water resources in many countries. Comprehensive development of both resources and joint scheduling are necessary to achieve rational and full utilization of water resources.

(5) Rational exploitation of groundwater

To ensure sustainable development and utilization of water resources, rational allocation and management of groundwater are crucial. This involves adhering to principles of rational extraction, comprehensive utilization, scientific management, and strict protection. It's important to avoid environmental geological disasters caused by blind over-extraction and to achieve a basic balance between artificial extraction and natural replenishment.

(6) Scientifically delineating groundwater functional zones

Delineating groundwater functional zones is essential to maximize the benefits of limited groundwater resources. By adopting the principle of optimal water use and considering regional water supply conditions and water usage, it's possible to allocate allowable extraction quotas for each well. This ensures that the total extraction volume remains within permissible limits.

References

Bedient PB, Rifai HS, Newell CJ. 1994. Groundwater Contamination: Transport and Remediation. Prentice Hall, Inc. , Englewood Cliffs, NJ.

Chen MX, Xu ZR. 1984. Basic Concepts and Research Methods of Groundwater Systems. 8−29. (in Chinese)

Cao JF, Chi BM, Wang WK, et al. 2002. Special Hydrogeology. Science Press, 13−19. (in Chinese)

Cheng YP, Dong H. 2015. Groundwater system division and compilation of Groundwater Resources Map of Asia. Journal of Groundwater Science and Engineering, 3(2): 127−135. DOI: 10.26599/JGSE.2015.9280015.

Chen BR. 1996. Impact of Human Activities on Groundwater - Summary of the 26th International Association of Hydrogeologists Congress. Hydrogeology and Engineering Geology, 2: 1−4. (in Chinese)

Engelen GB. 1984. Hydrological Systems Analysis: A Regional Case Study. Arnhem east. Report OS 94-20. TNO-DGV Institute of Applied Geo-science, Deft: Netherlands.

EPA. 2002. How to evaluate alternative cleanup technologies for underground storage tank aites: A guide for corrective action plan reviewers. US Environmental Protection Agency Publication No. 510-R-04-002, Office of Solid Waste and Emergency Response, Washington, DC.

Fang S. 1996. Issues of Groundwater Development and Utilization in India. Groundwater, 18(1): 45−46. (in Chinese)

Guo MZ, Zhao H. 2005. Current Situation of Utilization and Management of Global Groundwater Resources. China Water Resources, 3: 59−62. (in Chinese)

Hao SY. 2011. Exploration of Legal Issues in Transboundary Groundwater Utilization and Protection. Hebei Law, 4: 76−83. (in Chinese)

Jiao SQ, Dong H, Dai XS. 1992. Map of China's Groundwater-Induced Hazards (1: 6,000,000). China Cartographic Publishing House. (in Chinese)

Qian JZ, Wu JF. 2001. Research Progress on Evaluation and Management Models of Groundwater Resources. Chinese Science Bulletin, 46(2): 99−104. (in Chinese) DOI：10.1360/csb2001-46-2-99.

Li HX, Han SB, Wu X, et al. 2021. Distribution, characteristics and influencing factors of fresh groundwater resources in the Loess Plateau, China. China Geology, 4(3): 509−526. DOI：10.31035/cg2021057.

Li GZ, Lu X, Yang ZS. 2013. Reflections on Strengthening Groundwater Protection. Water Resources Development Research, 11: 72−78. (in Chinese)

Liu XJ. 1990. Analysis of Policy Function.Theoretical Exploration, 5: 64−68. (in Chinese)

Margat J, Van der Gun J. 2013. Groundwater Around the World: A Geographic Synopsis. CRC Press, 1−6.

Wang C. 2013. Research on Groundwater Resource Management Issues and Countermeasures in the Haihe River Basin. Tianjin University Press, 29−33. (in Chinese)

Wang XG. 2012. Research on Groundwater Resource Protection. Yellow River Water Conservancy Press, 20−23. (in Chinese)

Zhang JK, Wen XR, Gao Y. 2015. Analysis of the negative effects of groundwater exploitation on geological environment in Asia. Journal of Groundwater Science and Engineering, 3(2): 202−212. DOI：10.26599/JGSE.2015.9280024.

Zhang FW, Cheng YP, Dong H, et al. 2019. Groundwater and Environment in Asia. China Science Press, 3−15. (in Chinese)

Zhang FW, Cheng YP, Dong H, et al. 2012. Atlas of Asian Groundwater (1: 8,000,000). China Cartographic Publishing House. (in Chinese)

Zhao W, Lin YZ, Zhou PP, et al. 2021. Characteristics of groundwater in Northeast Qinghai-Tibet Plateau and its response to climate change and human activities: A case study of Delingha, Qaidam Basin. China Geology, 4(3): 377−388. DOI：10.31035/cg2021053.

Zhou QH, Fang QM. 2015. Development, Utilization, and Protection of Groundwater Resources. Science and Technology Prospect, 5: 256−259. (in Chinese)

Zhong HP, Wang JS, Du ZY. 2011. Analysis of Water Resources and Development in India. South-to-North Water Transfers and Water Science and Technology, 9(1): 151−155. (in Chinese) DOI：10.3724/SP.J.1201.2011.01151.