

Research Paper

Research on groundwater ecological environment mapping based on ecological service function: A case study of five Central Asian countries and neighboring regions of China

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Abstract: The groundwater system is a unique ecosystem that serves both resource and ecological functions. Hydrogeologists have conducted extensive theoretical research and practical work on groundwater ecological mapping. This paper, based on the study of groundwater resources and surface ecology in the five Central Asian countries and adjacent areas of China, introduces the concept of ecosystem service functions. It establishes a groundwater ecological zoning index system and conducts research of ecological mapping using the five Central Asian countries and adjacent areas of China as examples. Through this process, the ecosystem service functions of groundwater can be more comprehensively reflected, which can better guide regional geological environment protection and industrial planning. This approach helps coordinate the relationship between socio-economic development and water resource protection, maintain the health of the groundwater ecological environment, enhance the value of groundwater ecological services, and promote the sustainable development of regional economies and societies.

Keywords: Groundwater ecosystem; Groundwater ecological service; Ecological zoning of groundwater; Five Central Asian countries

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Introduction

Groundwater is the most active part of the geological environment and is closely related to human survival and development. Changes in groundwater have comprehensive and multi-level impacts on the environment, with both positive and negative effects. Rational utilization of groundwater resources, better protection of the ecological envi-

ronment, and mitigation of negative effects are essential for building a harmonious relationship between humans, natural resources, and the environment. During its cycle, groundwater directly or indirectly affects the surface ecological environment over time and space, and maintains or accelerates the transition of the surface ecological environment to a stable or unstable state (Zhang et al. 1992; Deng and He, 1993). Experts have noted the unique ecological functions of groundwater in arid areas, such as maintaining natural wetlands, natural vegetation oases, and farmland soil quality, referred to as "ecological functions" (Wang et al. 2011; Wang et al. 2018; Wang et al. 2021).

Ecosystem services refer to the conditions and processes through which natural ecosystems and their species sustain and fulfill human life (Daily, 1997). In recent years, the functions and values of ecosystem services have become a hot topic and frontier in ecological and ecological economic

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research (Yan et al. 2019; Humphreys, 2009; Cui et al. 2023; Qiao et al. 2005). Additionally, recent scientific investigations have shown that groundwater is not only a resource but also a unique ecosystem with both resource functions and ecological environment functions. As a water resource, it directly or indirectly supplies human society and surface ecosystems. The groundwater system is also a unique ecosystem which connects to and interacts with surface ecosystems, jointly providing services to human society. This study introduces the concept of ecosystem services to investigate the ecological functions of groundwater to reveal the relationships among groundwater and surface ecosystems, geological environments, and socio-economic factors, thereby deeply evaluate the resource and environmental value of groundwater.

Fundamental understandings of the groundwater system determine the form of groundwater mapping. Initially, scientists were more concerned with its resource attributes. Therefore, most of the maps compiled at that time displayed the quantity and quality of groundwater. For example, the "Groundwater Environment Map of China" compiled by Zhang and Sun (2006) evaluated groundwater quality and suitability from the perspective of water supply, reflecting groundwater quality, the environmental background of typical trace elements, and environmental geological problems induced by groundwater pollution and improper groundwater development and utilization, showcasing the status of the groundwater environment in China. With the deepening research on groundwater ecosystem, hydrogeologists have also aimed to reflect the ecological functions of groundwater and conducted a series of theoretical and practical studies in groundwater mapping (Dong et al. 2008; Dong et al. 2011; Cheng et al. 2010; Dong and Ge, 2015; Yi et al. 2015).

This paper introduces the concept of ecosystem service functions and constructs an index system for groundwater ecological zoning. It aims to comprehensively reflect the ecological service functions of groundwater, better guide regional geological environment protection and industrial planning, water resource utilization, and socio-economic development planning through a series of groundwater maps. This approach will facilitate the coordination between socio-economic development and water resource protection, maintain the health of the groundwater ecological environment, enhance the value of groundwater ecological

services, and promote the sustainable development of regional economies and societies.

1 Overview of groundwater resources in the five central Asian countries and adjacent areas of China

Central Asia and China's Xinjiang region are mostly composed of enclosed plateaus and basins, where climate and topography control the continental water vapor flux, making it difficult for sea winds to penetrate. As a result, the annual precipitation is generally less than 400 mm. Additionally, topographic precipitation significantly impacts the regional water cycle. The characteristics of atmospheric precipitation are unevenly distributed spatially and temporally, with the Qinghai-Tibet Plateau, Pamir Plateau, Tianshan Mountains, and Altai Mountains being mountainous precipitation areas, receiving 200–800 mm/a, with high mountains receiving over 1,000 mm/a, and gradually decreasing inland to less than 100 mm/a in the driest desert areas.

Atmospheric precipitation includes both mountain and basin precipitation. The unique natural geographical conditions, with three major mountain ranges and several basins, play a crucial role in the formation of water resources, concentrating precipitation mainly in mountainous areas. The precipitation resources formed in mountainous areas are more than five times those in plain areas. In both mountainous and plain areas, most precipitation that reaches the surface is consumed by evaporation and plant transpiration, with a small portion infiltrating underground to become groundwater resources. In mountainous areas, some precipitation directly forms surface runoff and converts into surface water resources. A small portion of storm floods in the piedmont zone infiltrates underground and convert into groundwater. Due to the strong topographic cutting effects in mountainous areas, most groundwater resources, except for a small portion that directly recharges plain groundwater through lateral flow in the piedmont zone, discharge to the surface in valleys, forming surface runoff and becoming an important part of surface water resources. When this surface runoff from mountainous areas enters the plains, some is diverted into reservoirs or irrigation channels for field irrigation. Apart from a small portion infiltrating underground to become groundwater resources, most surface water returns to the atmosphere through evaporation and plant transpiration. Precipitation infiltration, storm flood infiltration,

lateral flow and river infiltration from mountainous areas, reservoir water infiltration, channel water infiltration, and field irrigation infiltration (excluding minor urban and industrial wastewater infiltration) collectively form the groundwater resources in plain areas. In suitable locations, plain groundwater resources discharge back into the atmosphere through springs, phreatic evaporation, and plant transpiration.

Based on the hydrogeological conditions of Central Asia and the characteristics of groundwater recharge, flow, and discharge, this study analyzes climatic factors affecting groundwater recharge, and the interconversion relationships among atmospheric precipitation, surface water, and groundwater. In mountainous and hilly areas, the water balance method and groundwater runoff (hydrological partitioning) modelling method are used, while in plain basins (excluding repeated recharge), different hydrogeological parameters are used according to the primary groundwater system. The groundwater system used in this assessment mainly refers to the "Groundwater and Environment of Asia" compiled by Zhang et al. (2019). The five Central Asian countries and adjacent areas of China are divided into eight primary groundwater systems, with groundwater resources as shown in Table 1.

2 Distribution characteristics of terrestrial ecosystems in the five central asian countries and adjacent areas of China

The pattern and spatial structure of ecosystems reflect the spatial distribution patterns of various ecosystems and the spatial structural relationships among them. These are important factors determin-

ing the overall status and spatial differences of ecosystem service functions, and are also crucial references for humans to protect and utilize ecosystem service function based on different regional characteristics.

The distribution of various ecosystem types is often closely related to their natural environment, such as climate factors, topographic factors, soil composition, etc. Topographic factors mainly include altitude, slope, and direction, all of which influence the spatial pattern of ecosystems. Among climate factors, temperature and precipitation are important factors affecting the distribution of surface vegetation, commonly referred to as hydrothermal conditions. Environmental factors vary greatly across different latitudinal zones, leading to significant differences in ecosystem composition. System theory is used to establish an organic relationship between groundwater and the ecological environment. The map reflects the main types, temporal and spatial characteristics, and distribution patterns of groundwater ecological environments. It reveals the matter migration and energy conversion relationships among the atmosphere, lithosphere, hydrosphere, and biosphere, especially the control effects of climate and geomorphology on the groundwater ecological environment, as well as the transformative effects of humans and other organisms.

There are significant differences in the area of various ecosystem types, with desert, grassland, and farmland ecosystems being the main ecosystems. The ecosystem types are ranked by area from largest to smallest as follows: desert ecosystems, farmland ecosystems, grassland ecosystems, forest ecosystems, aquatic ecosystems, and settlement ecosystems. Desert ecosystems have the largest area, while aquatic and settlement ecosystems have relatively smaller areas, with settlement ecosystems having the smallest area (Table 2, Fig. 1).

Table 1 Groundwater resources in the five central Asian countries and adjacent areas of China (10⁸ m³/a)

Code	Primary groundwater systems	Quantity of groundwater resources	
		Recharge resources	Extractable resources
A	Groundwater system in Ertix River Basin	203.23	60.97
B	Groundwater system in rivers in Kazakh Uplands	742.45	237.59
C	Groundwater system in Yili River - Balkhash Lake	450.92	144.29
D	Groundwater system in lower reaches of Ural River -Turanskaya lowland	518.98	166.07
E	Groundwater system in Syr Darya River - Amu Darya River - Aral sea	519.07	181.67
F	Groundwater system in Pamirs Plateau – Vakhsh River	160.76	48.23
G	Groundwater system in Junggar Basin	282.05	84.62
H	Groundwater system in Tarim Basin	469.19	187.45
	Total	3,346.67	1,110.89

Table 2 The area of different types of ecosystems in Central Asia (10⁴ km²)

Country/region	Grassland ecosystem	Settlement ecosystem	Farmland ecosystem	Forest ecosystem	Aquatic ecosystem	Desert ecosystem
Kazakhstan	65.94	0.18	82.70	12.96	12.97	154.26
Kyrgyzstan	0.01	-	2.00	6.59	0.82	12.08
Tajikistan	1.96	-	1.08	-	0.11	11.57
Uzbekistan	3.70	0.18	9.21	0.33	3.65	31.91
Turkmenistan	1.60	0.01	4.46	-	1.12	41.77
total	73.21	0.37	99.45	19.88	18.67	251.59

Note: “-” means no date.

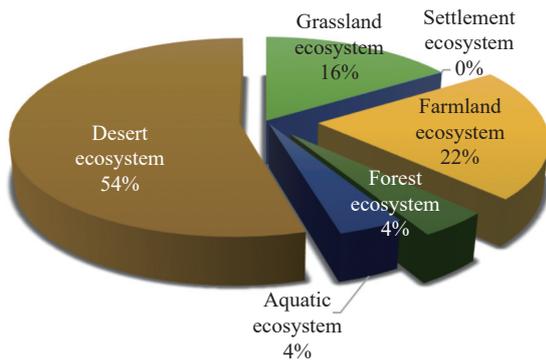


Fig. 1 The proportion of various ecosystem types

3 Research on groundwater ecological mapping in the five central Asian countries and adjacent areas of China

3.1 Index system construction of the groundwater ecological zoning

Groundwater ecological zoning is based on the

consideration of groundwater ecological service functions. It accounts for the distribution pattern of groundwater resources on a macro scale, comprehensively analyzing the key indicators such as topography and geomorphology, water resources density, and aridity (evaporation/rainfall). It also considers the spatial differences in water ecosystem service functions at regional scale, comprehensively analyzing indicators such as vegetation attributes, soil properties, land use types, water quality, pollutant types, aquatic organisms, socio-economic characteristics, population density, groundwater footprint and other indicators. The specific index system for groundwater ecological function zoning index system is shown in the following table (Table 3).

3.2 Groundwater ecological environment mapping in the five central Asian countries and adjacent areas of China

In accordance with the principles of sustainable development and mutual coordination, the status of

Table 3 Index system for groundwater ecological function zoning

Zoning indicators	Ecological functional elements
Geomorphological attribute	Effects of cicada wings reflecting topography or landscape pattern on watershed water ecological functions at the macro-scale
Groundwater resources	Representing spatial variation law of groundwater resource
Rainfall, evaporation	Dryness (evaporation/rainfall)
Vegetation attributes	Vegetation types, vegetation status, species composition, vegetation coverage, plant functional groups, plant photosynthetic capacity, etc
Soil property	Soil type, available data
Land use	The change of land use types can affect the hydrological cycle by changing surface interception and evapotranspiration; Water quality of different land use types is also greatly affected.
Population density	Reflect the pressure of population on watershed ecosystem
Socioeconomic characteristics	Reflect regional GDP of socio-economic development of the basin and is the available data
Groundwater quality	Water quality monitoring data reflecting the basic health status of groundwater ecosystems, such as BOD, COD, TP, TN etc.
Pollutant type	Surface source, point source (chemical fertilizers, pesticides, industrial waste discharge area)
Groundwater footprint	Comprehensive reflection of the present situation of human utilization of groundwater resources, and reflection of the degree of human interference with groundwater resources and environment

human social activities, main ecological function zones, and major economic and social development operations in each region are integrated. Based on the renewable capacity of groundwater resources and the carrying capacity of the natural environment, groundwater resources will be scientifically and rationally developed and utilized, with allowances made to protect the water environment on which current and future generations depend for survival. This ensures human health and promotes the harmonious development of humans and nature. Comprehensive consideration is given to the complementary roles of groundwater ecological functions between regions, with integrated analysis, overall planning, and emphasis on key points. Both current usage functions and forward-looking aspects are considered, as well as the unification of groundwater quality and quantity. The groundwater ecological environment in the five Central Asian countries and adjacent areas of China is divided into three types and eight sub-regions (Table 4, Fig. 2).

3.2.1 Groundwater regulation and storage-supporting the ecological environment

(1) This region is mainly distributed in lowland plains along lakes. Human activities are relatively minimal. The area consists of river and lake alluvial layers, with a focus on protecting lakeside wetlands and lowlands. Groundwater extraction is restricted, and the water quality is generally average, supporting the socio-economic and ecological environment of the coastal areas.

(2) This region is mainly distributed in basin alluvial layers. Human activities are more prevalent. The groundwater recharge conditions are favorable, with strong storage and regulation functions. Important protection is given to water sources, and groundwater is moderately extracted to support socio-economic and ecological environments. These areas have extensive human socio-economic activities, involving more complex ecological environments with diverse influencing factors. Groundwater is relatively abundant, with good water quality, supporting strong ecological functions.

(3) This region is mainly distributed in piedmont alluvial and proluvial layers of basins, where intense human activities occur. This area is an active interchange zone between surface water and groundwater. Both protection and extraction of groundwater are emphasized to support socio-economic development and maintain the grassland oasis-agricultural and pastoral ecological environment. Groundwater regulation and storage are significantly influenced by surface water, capable of maintaining ecological environmental functions in arid grassland oasis-agricultural and pastoral areas. However, groundwater quality is relatively poor, with generally higher salinity at the front edge of alluvial fans.

3.2.2 Groundwater conservation-maintaining the ecological environment

(1) This region is mainly distributed in mountain bedrock fracture aquifers, where human activities

Table 4 Groundwater ecological environment zoning

Type	Serial number	Main features of ecological environment zoning
Groundwater regulation and storage-supporting the ecological environment	1	Less human activities, river-lake alluvial and lacustrine deposits; Wetland-low land under special protection; Restricted exploitation of groundwater; Supporting coastal socio-economic eco-environmental areas.
	2	More human activities; Basin alluvium is dominant; Better groundwater recharge conditions; Strong reservation function; Key protection of water source; Moderate exploitation of groundwater, Supporting socio-economic and eco-environmental areas.
	3	Increased human activities, alluvial flood deposits in front of mountain; Active intersection zone of surface water and groundwater; Equal emphasis on groundwater protection and exploitation, to support social and economic development, and maintain prairie-oasis agro-pastoral ecological environment.
Groundwater conservation-maintaining the ecological environment	4	Human activities are scarce; Mountain bedrock fissure aquifer is dominant; Plateau mountain forest ecology, water resource recharge ecological protection zone.
	5	Human activities are scattered; Low hills fissure aquifer and river alluvial aquifer are in alteration; Forest grass-farming-grazing ecology is dominant; Slight desertification; Soil conservation and ecological environment protection areas.
	6	Less human activities; Fissure pore aquifer is dominant; Sparse grassland and shrub; Gobi desert transitional zone etc.; Moderate desertification, vegetation afforestation and eco-environmental transformation zones.
Groundwater scarcity-fragile ecological environment	7	Desert and desertification are unsuitable for human existence; Dry climate, Scarce rainwater; Strong sand flow; Lack of ground water; Plants are scarce; Natural reserves.
	8	Gobi desert is unsuitable for human existence; Dry climate; Ground water evaporated quickly; Shallow surface layer; Vegetation is scarce; Natural reserves.

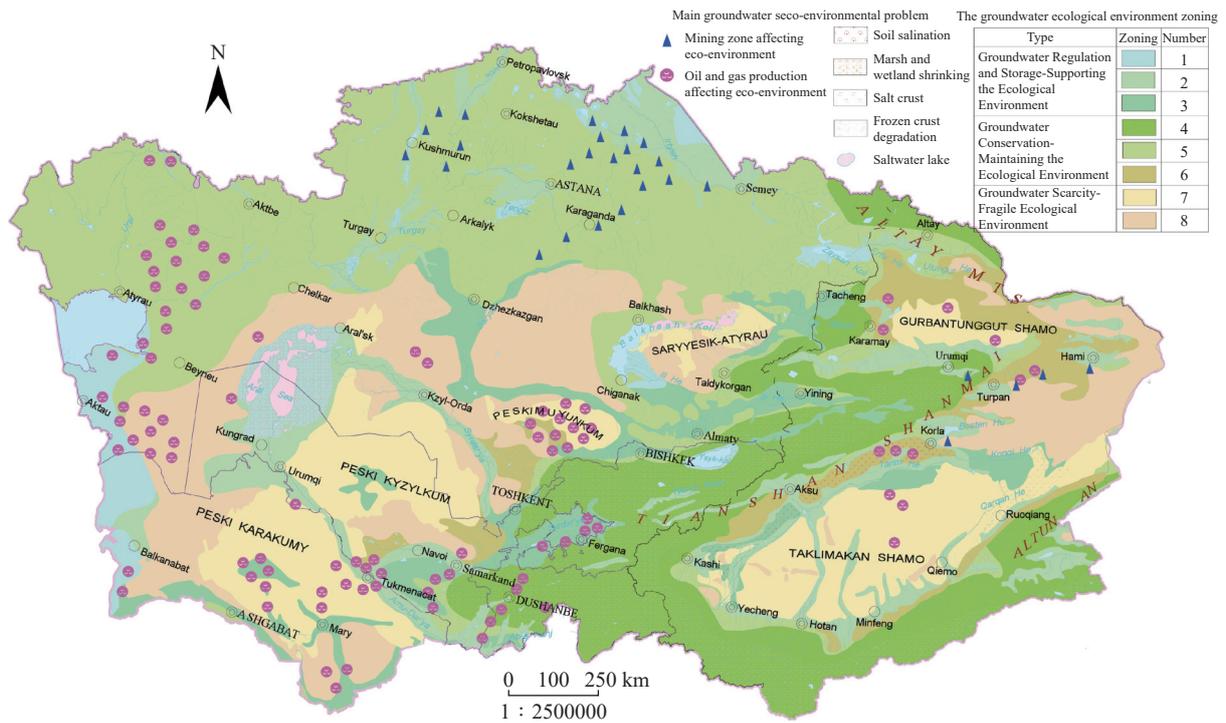


Fig. 2 Map of groundwater ecological environment in the five central Asian countries and adjacent areas of China

are rare. These areas are characterized by highland mountain forest ecosystems with vegetation cover that serves as a water source recharge and ecological conservation zone. Major mountain ranges include the Pamir Plateau, Kunlun Mountains, Tianshan Mountains, and Altai Mountains. Highland areas above 4,000 meters in elevation are widely distributed with continuous and discontinuous island-like permafrost layers. Groundwater is influenced by temperature changes, remaining frozen or undergoing seasonal freeze-thaw cycles. The terrain and precipitation in these mountains are influenced by monsoon climates. The vegetation in these mountains functions like human skin, conserving moisture and regulating temperature, preventing the loss of water and other substances, and protecting the shallow geological environment. These mountains are the source of Asia's surface water systems. During dry periods, the surface runoff in the mountains is equivalent to the discharge of groundwater, with surface water entering basins and recharging groundwater.

(2) This region is mainly distributed in low mountain and hill fracture aquifers, where human activities are scattered. These areas alternate with river alluvial aquifers and are primarily forest-grassland and agricultural-pastoral ecosystems, serving as water and soil conservation and ecological protection zones. Groundwater in low mountains and hills supports forest-grassland and agricultural-pastoral ecosystems, with the conserva-

tion of shallow water and soil being crucial. Particularly in intermountain valley loose accumulation aquifers, water is abundant in groundwater convergence zones, acting as an ecological barrier for plains.

(3) This region is mainly distributed in fracture-pore aquifers located in the transition zone between basins and mountains, where human activities are minimal. These areas are characterized by sparse grasslands, shrubs, and the transition zones of deserts and Gobi, with moderate desertification. They serve as ecological environment improvement zones for vegetation greening.

3.2.3 Groundwater scarcity-fragile ecological environment

(1) This region is mainly distributed in deserts and desertified lands, where groundwater is scarce, making human habitation unsuitable. The climate is arid with infrequent rainfall, strong wind and sand mobility, and very sparse vegetation. These areas are designated as nature reserves. When vegetation is destroyed by wind and sand activity, the dunes form a landscape similar to deserts, leading to ecological degradation.

(2) This region is unsuitable for human habitation due to groundwater scarcity, leading to a fragile ecological environment. These areas are characterized by exposed surfaces, barren land, deserts, rocky deserts, Gobi, and vast expanses of wasteland. The climate is dry, groundwater evaporates

intensely, surfaces are exposed, and drought-resistant vegetation is extremely sparse. These areas are also designated as nature reserves.

4 Conclusion and prospect

The ecosystem service function and its values have become a current hotspot and frontier in ecological and ecological economic research. Groundwater ecosystem services encompass both the resource and ecological attributes of groundwater, broadening the scope of groundwater ecological research, and more accurately reflecting the support and services groundwater provides to human society and natural ecosystems.

This study introduces ecosystem service indicators and considers the coordinated development of Central Asia and adjacent areas of China. The classifications are based on the natural environmental attributes of groundwater's alternating effects, water-rock interactions, ecological types, and the degree of human activity impact. The mapping scheme for the groundwater ecological environment in the five Central Asian countries and adjacent areas of China is created using multiple methods such as the top-down approach of geographic elements, correlation analysis, cluster analysis, principal component analysis, and spatial overlay method etc. The regional groundwater ecological environment types are divided into three types and eight sub-regions: groundwater regulation-supporting ecological environment, groundwater conservation-maintaining ecological environment, and groundwater-deficient-vulnerable ecological environment.

The effectiveness of this research scheme needs further testing and revision during implementation. Additionally, more in-depth research is required on the evaluation indicators of groundwater ecological service value. Using ecological service value evaluation as a theoretical basis, a more comprehensive zoning indicator system should be established to optimize the groundwater ecological function zoning. This will help reveal the health status and evolution trends of groundwater ecosystems, scientifically and rationally develop and utilize groundwater resources, protect the water environment on which current and future generations depend, ensure human health, and promote the coordinated development of humans and nature.

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