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Review

Influencing Factors and Evaluation of Groundwater Ecological Function in Arid/Semiarid Regions of China: A Review

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Abstract: In arid and semi-arid areas, due to drought climate and shortage of water resources, groundwater is crucial for natural ecological protection and economic development. It serves a dual role as a resource function and an ecological function. However, with the continuous improvement of the exploitation and utilization of groundwater by human activities during rapid economic development, the phenomenon of groundwater overexploitation is becoming more and more serious, which has destroyed the natural balance of groundwater recharge and discharge. As a result, natural vegetation has lost the maintenance of the ecological function of groundwater, and a series of ecological and environmental problems have occurred, such as natural vegetation degradation, land desertification, sandstorms, and so on. In recent years, scholars have carried out research on groundwater resource management and optimization of water resource allocation, trying to solve the problem of water balance in arid regions. However, there is still a lack of comprehensive understanding and systematization regarding influencing factors and degeneration mechanisms related to groundwater's ecological function. By summarizing and analyzing the previous research results, this paper summarizes the influencing factors, evaluation methods, existing problems and future directions of groundwater ecological function research in China to provide a reference for rational exploitation and utilization of groundwater and ecological protection. This paper is divided into four main contents. The first part introduces the definition of groundwater ecological function (GEF); the second part summarizes the research status of influencing factors of GEF, including the groundwater table depth, vegetation root system and lithologic structure of vadose zone, etc.; the third part analyzes the evaluation of groundwater ecological function; the fourth part discusses the existing problems in the study of groundwater ecological functions, and based on the above research the evaluation framework of GEF is proposed with the Shiyang River basin as a case study; and finally, it highlights the future research directions about GEF.

Keywords: groundwater; natural vegetation; northwest China; vadose zone; ecological water level

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1. Introduction

In arid and semi-arid areas of China, due to the arid climate and scarcity of rainfall, the ecological status of the local natural oases is closely linked to the groundwater table buried depth (GD). Consequently, the natural oases in the middle and lower reaches of each river basin exhibit a strong reliance on the GD. When GD exceeds the "limit ecological water level" depth for wetland or natural vegetation, there is an imbalance or failure in groundwater's ecological function (GEF). The prolonged absence of artificial water supply will lead to significant shrinkage or even complete drying up of natural wetland areas, as well as severe degradation or death of natural vegetation. In the past 50 years, with the development of society and economy, the utilization rate of water resources in the inland basins of northwest China has exceeded 65%, far surpassing the average water utilization rate of 30% in global arid areas. Shiyang River Basin is a typical area in Northwest China; due to the reuse of water resources and over-extraction of groundwater, its water resources utilization has reached 172%, which has exceeded the renewable water resources in the basin [1,2]. With the increasing exploitation of groundwater, the groundwater table in Northwest China has dropped sharply, and the problem of groundwater over-extraction is very serious; in some areas, the water resource depletion phenomenon has occurred. This unsustainable use and irrational exploitation have caused deterioration in groundwater's ecological function while triggering significant hydrological changes and environmental disruptions within arid regions, such as drastic reductions in water volume of downstream rivers or even cut-off flow, shrinkage or drying of terminal lakes, soil desertification and salinization, vegetation degradation, biodiversity reduction, frequent sandstorms, etc. It has seriously threatened the local natural ecological security [3].

In order to solve the problem of rational allocation of water resources between economic society and ecological protection and promote the harmonious and sustainable development of humans and water in arid and semi-arid areas, it is necessary to further understand the important role of groundwater in maintaining natural oasis ecology in arid areas. And a thorough study of the characteristics, influencing factors, and formation mechanisms of GEF's degeneration crisis is necessary to provide a scientific basis for rational groundwater exploitation and ecological protection in arid regions. In view of the above contents, scholars have conducted numerous studies. By summarizing and analyzing the previous research results, this paper has outlined the influencing factors, evaluation methods, existing problems and research trends of groundwater ecological function research in China. And it aims to provide a valuable reference for the rational exploitation and utilization of groundwater resources as well as ecological preservation efforts. This paper is divided into four main contents. The first part introduces the definition of GEF; the second part offers a comprehensive overview of the current research status regarding the influencing factors of GEF, including the GD, vegetation root system and lithologic structure of vadose zone, etc.; the third part puts forward the evaluation framework of GEF based on the above research; and finally, it highlights the existing challenges and future research directions about GEF.

2. Definition of Groundwater Ecological Function

The groundwater function refers to the impact or effect on human society and the environment caused by the changes in groundwater quality or quantity in time or space. This mainly encompasses the functions of groundwater as a resource supply for maintaining the stability of the ecological and geological environments [4]. The function of groundwater in maintaining an ecological environment, known as groundwater ecological function (GEF), refers to the positive role or effect that the groundwater system plays in maintaining the surface vegetation, lake, wetland or land quality. It is one of the important components of groundwater function. Groundwater can transport water to the surface of the vadose zone by supporting capillary action, thereby supporting natural vegetation and natural wetlands, etc. This process is intimately linked to the lithologic structure of the vadose zone and the depth of the root development within the vegetation community. Any changes to the groundwater system will have corresponding effects on the ecological environment. In arid and semi-arid areas, the ecological environment is closely related to groundwater, and further research on the GEF can provide a scientific foundation for the exploitation and utilization of groundwater resources and ecological protection in the basin [5].

3. Influencing Factors of Groundwater Ecological Function

It can be inferred from the definition of GEF that the factors influencing GEF mainly include GD, vegetation root system and lithologic structure of the vadose zone. The key index to measure the intensity of GEF is the threshold of limit ecological water level [6], which denotes the minimum GD at which groundwater must rise through capillary action to sustain surface moisture in the vadose zone, thereby ensuring ecological security of natural vegetation or natural wetland [7]. It is closely linked to the lithologic structure of the vadose zone and the depth of vegetation root development. Once the buried depth of the groundwater table is deeper than the threshold of limited ecological water level for a long time, the natural vegetation ecosystem will lose the water supplied by the capillary water from groundwater [8], which will inevitably lead to the degradation and even extinction of natural vegetation and thus land desertification [9,10].

3.1. The Influence of GD on GEF in Arid Region

The variation of water content in the root layer of natural vegetation is closely related to the dynamics of GD. Suitable GD varies across different ecological environments, consequently giving rise to diverse ecological functions associated with groundwater. Therefore, the ecological water level is composed of a series of GD that meet the requirements of the ecological environment [11,12]. Based on distinct growth characteristics exhibited by vegetation under varying GD conditions, the ecological water level can be further categorized into marsh water level, salinization water level, suitable ecological water level, ecological warning water level, desertification water level and so on (Figure 1) [13–15].

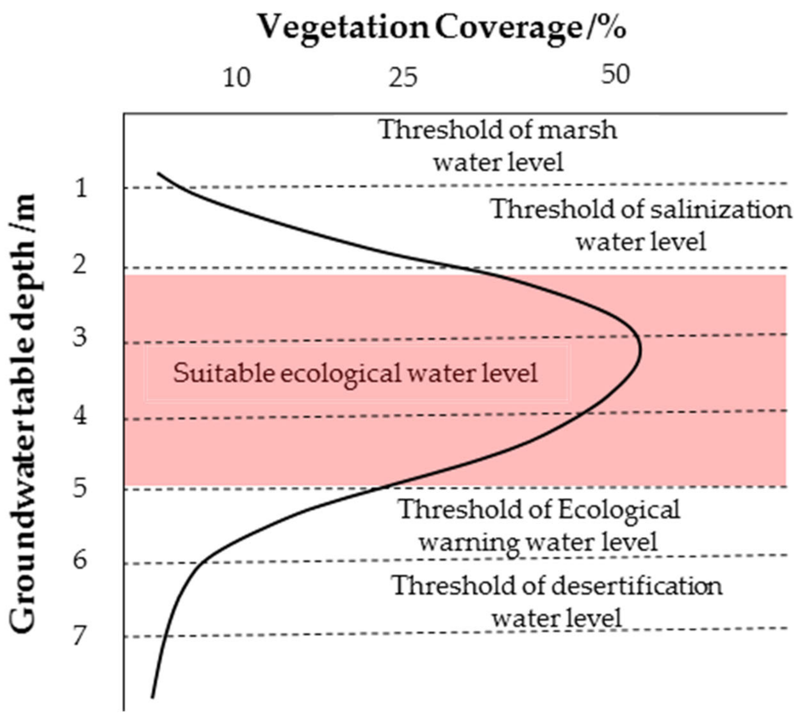


Figure 1. Coverage of natural vegetation under different ecological water levels in arid regions.

In the arid area of northwest China, the suitable GD of natural vegetation communities ranges from 2 to 5 m [16]. When the GD is less than 2 m, surface salinization will occur, while when the GD is more than 5 m, the natural vegetation will be degraded to a different degree. However, the suitable GD can vary across different basins. For example, in Yanqi Basin, Wang Shuixian et al. [17] reported that the minimum GD for soil salinization control in an oasis irrigation area is about 2.5 m. In the Minqin Basin, the suitable GD of natural vegetation in the oasis is 2.5–3.9 m [18], and when the GD is less than 4 m, the normalized difference vegetation index (NDVI) of natural vegetation in Minqin Oasis is significantly negatively correlated with the GD. In Hunshendak Sandy Land, Inner Mongolia, Zhang Gaoqiang et al. [19] analyzed the relationship between the enhanced vegetation index (ENI) of vegetation and groundwater and found that the local natural vegetation coverage reached its peak at a GD of 1.5 m when the GD exceeds 8.0 m, the vegetation coverage does not change with the dynamic change of the GD, while when the GD is 1.5–8.0 m, the vegetation coverage decreases exponentially with the increase of the GD, but the response of vegetation growth state to the dynamic change of the GD has a certain lag effect [20]. In the Yerqiang River basin in the middle of the Tianshan Mountains, Xinjiang, based on the different guarantee rates (45–90%) of the ecological water demand of groundwater, the GD ranges from 2.89 to 4.65 m [21]. Zhang Guanghui et al. [22] studied the relationship between GD and vegetation growth in the Shiyang River Basin and showed that the GD had a significant impact on the growth of natural vegetation when it was less than 10.3 m. Depending on the different growth states of vegetation, the GD is divided into different sections (Table 1).

Table 1. Relationship between the status of GEF and GD in northwest China.

GD (m)	Status of GEF	Response Characteristics of Vegetation Key Indicators
1.0~3.2	Good	Both ecological NDVI index and vegetation coverage increased significantly and are positively correlated with GD.
3.2~5.3	Normal	Ecological NDVI index and vegetation coverage decreased significantly and are negatively correlated with GD. Most natural vegetation still shows a good growth state, but some moist vegetation, such as reed, is in poor ecological condition.
5.3~7.4	Gradual degeneration	The ecological NDVI index and vegetation coverage show a continuous decrease, and they are negatively correlated with GD. Some vegetation, such as licorice and reed, begin to wither and die.
7.4~10.3	Gradual degeneration	The ecological NDVI index and vegetation coverage show a slight decrease, and they are still negatively correlated with GD. The natural vegetation system shows a poor growth state on the whole.
>10.3	Catastrophic degeneration	Ecological NDVI index and vegetation coverage are not related to GD. Most of the desert vegetation is dead, the coverage is very low, and the surface has been desertification or desertification.

3.2. Effects of Vegetation Water Use Sources on GEF in Arid Regions

The research on water use sources of vegetation in arid regions has become a pivotal research topic both domestically and internationally. The characteristics of the root system, community, and water demand of different dominant vegetation all play a significant role in determining groundwater ecological level, which leads to differences in groundwater ecological functions.

In the natural environment, the water used by vegetation growth mainly includes atmospheric precipitation, surface water (rivers or lakes), soil water and groundwater (Figure 2) [23,24]. The depth and overlap of root distribution determine the dependence of vegetation on groundwater, especially for annual vegetation [25–28]. With the gradual increase in groundwater depth, the vegetation community in the ecosystem will transition from mesophytic series to xerophytic series, deep-rooted and xerophytic vegetation will become the dominant species in the ecosystem, and the community association will gradually become more monolithic [29]. The correlation between vegetation coverage, NDVI and GD is often used to reveal the succession process of vegetation community [30–32].

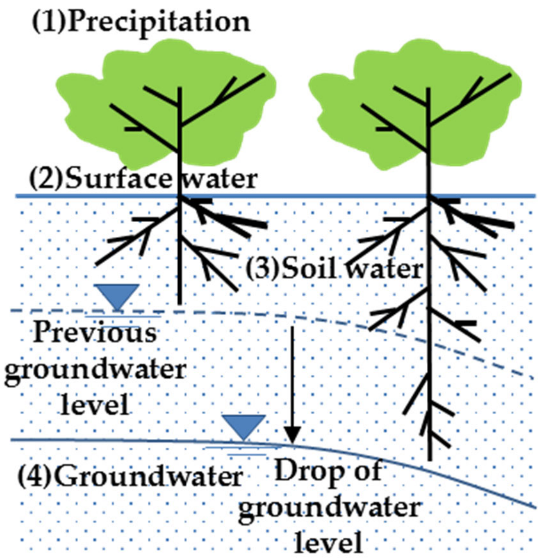


Figure 2. Water use sources and strategy of vegetation.

The water consumption characteristic of vegetation is also an important factor in determining the suitable ecological water level, especially under the action of water stress; the absorption and utilization capacities of groundwater by roots are different [33–35], leading to different GEF. In arid regions, natural vegetation will choose the most suitable water source for absorption and utilization according to different external hydrological conditions and meet its own growth and development needs [36,37]. There are several methods for natural vegetation utilization of water sources, including the root excavation method [38], fluid flow technique method [39] and stable isotope method [40–42]. For example, Nie Yunpeng et al. [43] used liquid flow technology to qualitatively identify the source of water absorbed by vegetation through the difference of leaf stomatal conductance and vegetation water potential change. Wang Yanli et al. [44] emphasized that stable isotope method has the advantages of non-destructive and high accuracy. For most terrestrial vegetation, the isotopic composition of water does not change during the transport of water from roots to unsuberized vegetation stems. But, the deuterium–oxygen isotopes of water from different sources exhibit significant differences, supporting the use of stable isotope information to determine the water sources of vegetation.

The water sources utilized by different plants can vary depending on their species and growth stage. Yang Guang et al. [45] compared the water sources of two-year *Haloxylon ammodendron* and *Tamarix* in the lower reaches of Manas Basin. They found that the main water source of *Haloxylon ammodendron* is groundwater, followed by soil water at a depth of 80~150 cm, while the main water source of *Tamarix* is soil water at a depth of 60~150 cm, followed by groundwater. Wan Yanbo et al. [46] studied the water sources of young, mature and overripe *Populus euphratica* and found that at 2 m of GD, the surface water was the main source of young *Populus euphratica*, while groundwater and deep soil water were the main sources of mature and overripe *Populus euphratica*. And at 4.2 m of GD, the main water sources of *Populus euphratica* at different ages were deep soil water and groundwater. Gao Ya et al. [47] studied the water use sources of *Caragana* of different tree ages in the Gonghe Basin, Qinghai Province. Before rainfall, young *Caragana* mainly used shallow soil water, and mature *Caragana* mainly used middle and deep soil water. After rainfall, *Caragana* of all ages preferentially used shallow soil water supplied by precipitation. Wang Yuyang et al. [48] studied the typical desert vegetation oasis in the lower reaches of the Tarim River and found that the shallow soil water utilization was the main feature of *Alhagi* in the early growing season, while in the peak and the end of the growing season, the water used by *Alhagi* was mainly deep soil water and groundwater. Eggemeyer et al. [49] found that *Pondus pine* mainly used deep soil water below 0.9 m in winter and shallow soil water between 0.05 and 0.5 m in spring. Tian Lihui et al. [50] showed that in northwest China, due to the difference in soil texture and soil water content on the windward slope, dune top and leeward slope, the depth of soil water utilization by *Salix cheilophila* was greatly different.

The difference in water utilization by vegetation in the above areas is mainly controlled by the distribution of vegetation roots, soil water content and GD [51–53]. With the dynamic change of GD, vegetation will adjust the water use strategy. For the same vegetation species, when the GD is shallow, the roots are concentrated on the surface. However, with the increase in GD, the root distribution will show a deepening trend (Figure 2), and the root distribution will be more dispersed in the vertical direction so as to obtain survival water from a larger spatial range. Therefore, the water use strategy characteristic of vegetation with growth determines that the ecological function of groundwater is not static but changes with the growth of vegetation.

3.3. Influence of Vadose Zone on GEF in Arid Region

The vadose zone is the main water supply for the growth of natural vegetation, and it is also the link of water mutual transformation in the groundwater–soil–vegetation–atmosphere continuum, which is closely related to groundwater [54]. Vegetation roots can absorb soil water from the vadose zone. Therefore, the characteristics of water transport and lithologic structure of the vadose zone not only determine the distribution and redistribution process of soil water but also directly affect the growth of vegetation [55]. Furthermore, under extreme arid climate conditions, soil moisture stored in the vadose zone has the ecological function of maintaining vegetation survival [56]. Therefore, it is of great significance to further understand the influence mechanism of the vadose zone on GEF.

Xu Yuanzhi et al. [57] proposed that the characteristics and ecological effects of water transport in the vadose zone are related to the initial water content and lithologic structure of the vadose zone and are affected by rainfall, ground temperature and vegetation growth. Precipitation intensity, rainfall, duration of precipitation, and ground slope all affect the infiltration rate of precipitation and thus affect the characteristics of water transport in the vadose [58–60]. In arid regions, the significant change of soil temperature in the vertical soil profile can also affect the water distribution and transport in the vadose zone [61]. Studies have shown that the above variations are the result of changes in soil water potential [62]. Additionally, vegetation growth also has a certain impact on the change of water in the vadose zone. For example, groundwater evaporation in vegetated areas is higher than that in bare land, which is related to the vegetation type, vegetation growth stage and vegetation transpiration rate [63]. The lithologic structure of the vadose zone affects the infiltration process of soil water. Finer lithologic particles within the vadose zone result in lower infiltration rates. When the lithologic structure of the vadose zone presents different structural characteristics, such as interlayers of coarse and fine particles, the influence on water migration in the vadose zone is obviously different. Furthermore, the stratified structure in the lithologic structure of the vadose zone may hinder (or accelerate) vertical water migration [64], thereby affecting the ecological function of groundwater to maintain natural vegetation [65,66].

Simultaneously, the support capillary rise height of the vadose zone varies depending on its different lithologic structure, thereby affecting the groundwater ecological level and leading to different ecological responses of the natural vegetation (Figure 3) [67]. Through the layered soil column test, Zhang Ping et al. [68] found that when the thickness of the lower soil layer is less than the maximum height of the capillary water rise height within that layer, the capillary water can migrate through the lower soil layer to the upper soil layer. In such cases, the height of the capillary water rise is determined by the properties of the upper soil layer. Shi Wenjuan et al. [69] conducted a systematic study on the maximum rise height of capillary water in layered soil under different conditions. Their findings revealed that the maximum rise height of capillary water in layered soil depends on factors such as the texture, thickness, stratification and their relationship with each other. Conversely, in the process of water release, the unsynchronized release of water by pore channels in the soil delays gravitational drainage, leading to different water retention performance and water retention capacity of the vadose zone (Figure 3) [70,71]. Zhang Renquan et al. [72] discussed the water release mechanism of homogeneous soil and heterogeneous soil, pointing out that delayed water release is a common occurrence in both types, and the delayed water release effect of layered soil is more significant. The complex lithologic interlayer structure, more layers of fine-grained soil and large drop rate of water level will lead to a significant water release delay effect. Moreover, the varying thicknesses of each layer across layered soil impact water release differently, leading to diverse delayed water release processes in various vadose lithologic structures.

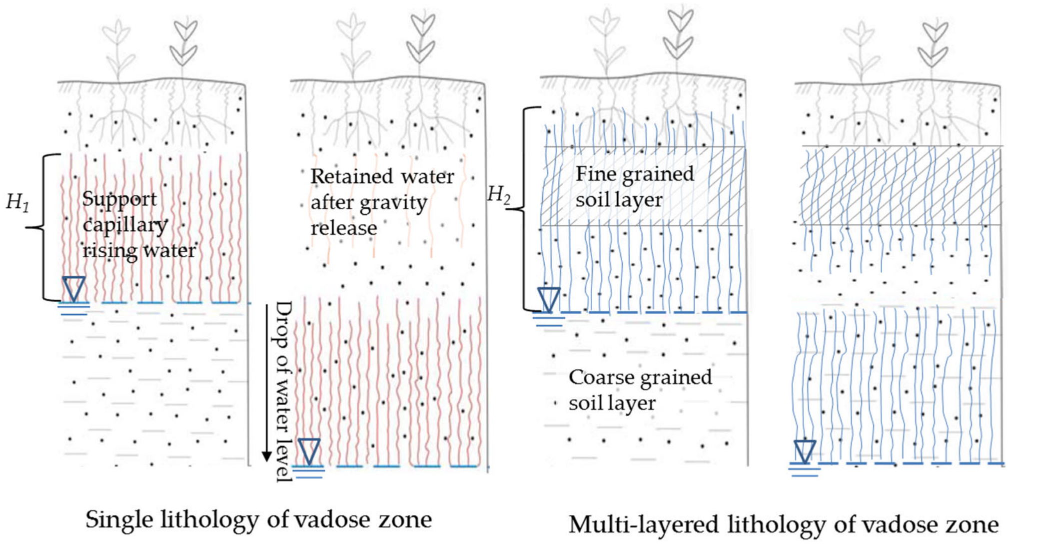
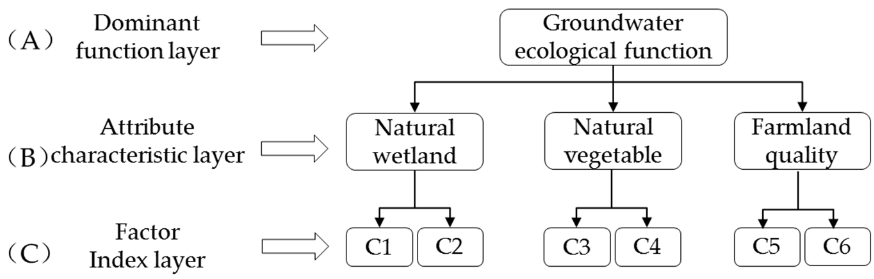


Figure 3. Capillary water rise height and retained water after the gravity release of different lithologic structures in the vadose zone. Note: H_1 is the height of support capillary water rise in a single lithology vadose zone, and H_2 is the height of support capillary water rise in a multi-layered lithology vadose zone. Due to the influence of the fine-grained layer in the multilayer structure, $H_2 > H_1$. The arrow indicates a groundwater table drop event. Both vadose zone structures will retain water in the former capillary zone after the groundwater table drops, but the vadose zone with a multilayer structure retains more water.

Currently, there is a certain understanding of the ecological effects of the vadose zone in arid regions, and various research methods have been widely applied in the study of water transport and ecological effects of the vadose zone in arid regions, such as capillary potential theory, wetting front infiltration theory and preferential flow theory [73], the model test method [74], zero flux surface method [75], tracer experiment method [76], lysimeter experiment method [77] and water balance method [78]. Different methods have their own advantages and applicable conditions. For example, the preferential flow theory has solved the heterogeneity of water transport in vadose zones, while the lysimeter experiment method is well-suited for field-scale application [79]. The combination of various methods [80], such as in-situ monitoring using the zero flux surface method and the numerical simulation techniques, can better describe the water transport process in the vadose zone. Nevertheless, the research on the transformation mechanism of water flux between vegetation-vadose zone-groundwater remains limited. In particular, the study of the influence of multi-layered vadose zone on the GEF is still an important research topic in the future.

4. The Evaluation of Groundwater Ecological Function

The method of groundwater function evaluation has been successfully studied and applied in different areas of China. The main idea of this method is to comprehensively consider the regional groundwater resource function, ecological environment function and geological environment function. It involves identifying appropriate indices for evaluating groundwater function based on driving, state, and response factors within the groundwater system. The analytic hierarchy process, comprehensive index method, and GIS platform are then utilized to evaluate the groundwater function. Subsequently, functional zones at different levels are delineated based on the evaluation results. However, scholars differ in the selection of indicators and the division of functional areas. For example, Huang Pengfei et al. [81] conducted a study on groundwater function evaluation in Minqin Oasis, pointing out that some indicators are only applicable to individual zones and suggesting that grade standards should be established for these indicators and "multi-indicator" evaluation should be carried out for individual zones by direct assignment method. Yan Chengyun et al. [82] constructed the groundwater function evaluation system of the middle and lower reaches of the Shule River Basin, divided and evaluated individual functions and comprehensive functions at five levels, and pointed out the application prospect of groundwater. During the functional characteristics and evaluation of groundwater in the North China Plain, Zhang Guanghui et al. [83] emphasized that the selected groundwater functional evaluation indexes should not only objectively express the natural properties of groundwater but also take into account the relevant social properties. If there are too many indicators, it will bring unnecessary basic data processing work. On the contrary, it will obviously affect the accuracy and reliability of the evaluation results. Sun Caizhi et al. [84] evaluated the groundwater function in the Lower Liaohe Plain, establishing a new groundwater function evaluation index system from the perspective of the supply and demand of groundwater function. By combining this with the existing evaluation index system, the research results have important reference significance for the normal maintenance of groundwater function and the scientific management of groundwater resources in the study area. Aiming at the need for rational groundwater development and ecological protection in arid and semi-arid areas, Wang Jinzhe et al. [85] developed a groundwater function evaluation and regionalization method suitable for these areas. This method fully considers the threshold correlation and spatial distribution characteristics between different types of ecological environment degeneration and groundwater table buried depth (Figure 4). However, it does not account for the characteristics of vegetation roots and the heterogeneity of lithologic structure in the vadose zone.



Note: Factor index layer represents the correlation between each factor and groundwater, C1 means correlation between wetland area and groundwater table buried depth (GD), C2 means correlation between lake area and groundwater recharge, C3 means correlation between natural vegetation growth and GD, C4 means correlation between coverage rate of natural oasis and GD, C5 means correlation between land desertification and GD, and C6 means correlation between soil salinization and GD.

Figure 4. Groundwater function evaluation and zoning system in arid region.

In other countries, the research on GEF mainly focuses on the identification and regionalization of groundwater-dependent ecosystems. The main research methods used include field ecological survey [86], remote sensing [87] and geographic information technology [88]. Through the scientific zoning of groundwater ecological functions on the basin scale, the interaction between groundwater and the ecosystem, as well as the rational allocation of regional water resources, are deeply understood. For example, Australia carried out a study on the regionalization of watershed-scale groundwater-dependent ecosystems in 2016, which provided a scientific basis for natural resource management [89]. Jeanette

Howard et al. [90] clarified the interconnections between groundwater and surface ecosystems by identifying and mapping the distribution of groundwater-dependent ecosystems in California. Cruz et al. [91] identified and regionalized the ecological functions of groundwater in the Azores Volcanic Islands and divided the dependence of the ecosystem on groundwater into five levels. Liu et al. [92] carried out the regionalization of groundwater-dependent ecosystems in Central Asia by remote sensing and verified the accuracy of the regionalization results by superposition analysis, correlation analysis and water balance method. The verification results were consistent. Based on field ecological surveys, remote sensing and geographic information technology methods, some scholars have developed a time-comprehensive method for regionalization of groundwater-dependent ecosystems, which has been applied and verified in Chile. The results showed that this method could regionalize and analyze the spatio-temporal changes of groundwater-dependent ecosystems on an annual scale [93].

5. Discussion and Case Study

In the arid inland region of Northwest China, the population and its living and production water consumption have far exceeded the local catchment-scale water resources carrying capacity. Addressing the conflict between economic and social water consumption and natural ecological water demand is one of the most critical challenges. Ensuring orderly and reasonable restoration, as well as effective protection of groundwater ecological functions in natural oases, while achieving "harmonious" development between humans and nature, remains a significant challenge. In order to solve the above problems, many scholars at home and abroad have carried out scientific research on efficient agricultural water-saving and water source replacement, optimal allocation of water resources in river basins, artificial planting of xeromorphic vegetation to control desertification and artificial external ecological water transfer, evaluation and regionalization of groundwater ecological functions in arid regions [94–96] and so on. In the northwest inland river basin, the key to the rational allocation of water resources is to determine the proportion of socio-economic water and ecological water under the premise of meeting the minimum ecological water consumption [97–100]. A research finding from the Chinese Academy of Engineering [101] pointed out that groundwater and surface water come from the same source in the northwest inland river basin. Therefore, in the allocation of water resources, it is not only necessary to perform overall planning for the whole basin but also to fully consider the mutual transformation of groundwater and surface water so as to maintain the sustainable use of water resources while ensuring ecological and social economic water use.

The groundwater ecological function evaluation and regionalization technology is the basis of the above research work. The rational allocation of water resources can only be achieved through detailed regionalization and evaluation of the groundwater ecological function. Although scholars have conducted many studies on GEF and proposed theories and research methods for groundwater function evaluation and regionalization, or groundwater-dependent ecosystem evaluation and regionalization, which have been widely applied and verified in different regions, the quantitative evaluation of the GEF in arid and semi-arid areas needs to be further studied.

Taking the Shiyang River basin as a case study, this paper put forward a theoretical formula to express the quantitative expression of groundwater ecological function based on the above literature review and comprehensive consideration of the influencing factors of groundwater ecological function [102–104].

$$A_{gw} = \frac{W_s\left(h_{\mathrm{gw}}, H_{\mathrm{mx}}, D_{zb}\right)}{W_p\left(E_{\mathrm{zs}}, \theta_{\mathrm{sm}}\right)} \times 100\% \quad (1)$$

The meanings of each parameter in the formula are as follows.

A_{gw} is the ecological function intensity of groundwater, which represents the percentage value of groundwater water supply capacity and vegetation water demand. Under the premise of a certain amount of vegetation water demand, the stronger the water supply capacity of groundwater, the stronger its ecological function.

W_s is the amount of water supplied by groundwater to natural vegetation, which is the function of the buried depth of the groundwater table (h_{gw}), supporting capillary water rise height (H_{mx}) and root development depth (D_{zb}) of natural vegetation community in the area.

(1) Under the same buried depth of groundwater table: The deeper the root development, or the higher the support capillary water rise height, the stronger the groundwater supply capacity, showing the stronger groundwater ecological function;
(2) Due to the hydrotaxis of vegetation root development in arid regions, the slower the groundwater table decline, or the more significant the annual fluctuation of the groundwater table, the more conducive to the vertical development of vegetation root system, thus absorbing more water from groundwater, showing a stronger groundwater ecological function. Furthermore, when the buried depth of the groundwater table exceeds the limited ecological water level threshold, the delayed water release effect of the vadose zone will store part of the water and continue to supply water to vegetation, extending the role of groundwater ecological function. The more complex the lithologic structure of the vadose zone, the more obvious this effect is.

W_p is the maximum value of water required by a natural vegetation community for normal growth, which is the function of vegetation transpiration intensity (E_{zs}) and soil moisture content (θ_{sm}) in the root layer, and is related to vegetation type, depth of root layer development and meteorological (light, temperature, etc.) conditions.

According to the proposed formula, the quantitative changes in groundwater ecological function intensity from 2018 to 2021 were calculated for the Shiyang River Basin (Figure 5). The results indicated that groundwater ecological function plays a significant role from April to September each year, while it reaches its minimal state from October to March of the following year, corresponding to the end of the vegetation growth period. It is evident from the figure that there is a strong correlation between the strength of GEF and the GD, and it exhibits an inter-annual periodic change. However, the existing research often provides a static assessment of the current status of groundwater ecological function, which does not reflect its dynamic change characteristics, and cannot formulate and revise groundwater management strategies in real-time. Therefore, the combination of groundwater ecological function zoning and dynamic real-time evaluation is one of the important contents to be further studied so as to guide the fine optimal allocation of basin water resources.

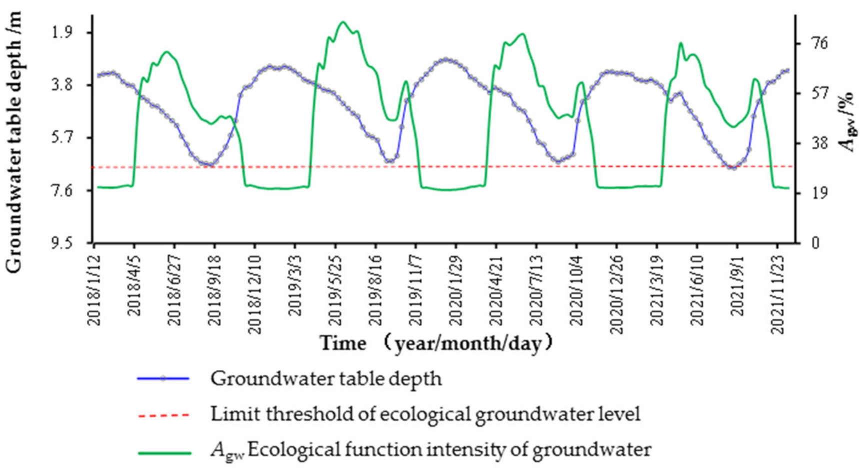


Figure 5. Change characteristics of groundwater ecological function in natural oasis area in the lower reaches of the Shiyang River basin.

6. Conclusions and Future Directions

This paper presents the definition of groundwater ecological function (GEF), provides an overview of the research status of influencing factors of GEF, analyzes the evaluation of groundwater ecological function, discusses the existing challenges in the study of GEF, and proposes an evaluation framework of GEF with Shiyang River basin as a case study. However, the current research on groundwater ecological function primarily focuses on assessing the present situation and lacks real-time dynamic monitoring, prediction and early warning capabilities for future trends. Therefore, the research on groundwater ecological function should be strengthened in the following aspects in the future:

(1) Quantitative evaluation of groundwater ecological function.

All the factors that affect the ecological function of groundwater should be considered comprehensively, including the changes in groundwater depth, the characteristics of vegetation root development, the lithologic structure of the vadose zone and meteorological conditions. However, there is limited understanding regarding how vadose zone lithologic structure affects groundwater ecological function, particularly concerning delayed release water's ecological effects under drought stress, which requires further exploration;

(2) Cyclical variation of groundwater ecological function.

Revealing the annual and interannual cyclical variation of groundwater ecological function can enhance the understanding of the degeneration mechanism of groundwater ecological function and provide accurate guidance for sustainable groundwater exploitation and oasis ecological protection;

(3) Strengthen the dynamic monitoring of groundwater ecological function.

With the advent of cutting-edge technologies such as cloud services, the Internet of Things, big data and artificial intelligence, there is a growing need to establish a sophisticated technology platform (or system) for real-time dynamic monitoring, early warning and management that integrates air, sky, earth and water [105]. On the basis of a deep understanding of evolving patterns of groundwater ecological functions, real-time dynamic monitoring of groundwater ecological functions can be carried out to guide the allocation of basin water resources by zoning and grading. This approach allows for continuous optimization and adjustment, ultimately preventing and mitigating groundwater overexploitation and natural ecological degradation.

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