Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

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Citation:
Li MY, Li CZ, Dong F, *et al*. 2024. Groundwater level thresholds for maintaining groundwater-dependent ecosystems in northwest China: Current developments and future challenges. Journal of Groundwater Science and Engineering, 12(4): 453-462.

View online: https://doi.org/10.26599/JGSE.2024.9280032

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Review article

Groundwater level thresholds for maintaining groundwater-dependent ecosystems in northwest China: Current developments and future challenges

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Abstract: Groundwater-Dependent Ecosystems (GDEs) in the arid region of northwest China are crucial for maintaining ecological balance and biodiversity. However, the ongoing decline in groundwater levels caused by excessive groundwater exploitation poses a potential threat to GDEs. This paper reviews the current developments and future challenges associated with defining groundwater level thresholds for maintaining GDEs in arid regions. It focuses on methods for identifying and investigating these thresholds, with particular attention to recent advances in northwest China. Additionally, this paper highlights the limitations and future challenges in determining these thresholds, including the complexities of ecological processes, groundwater systems, data availability, and methodological constraints. To address these issues, a multidisciplinary approach that incorporates new technologies, such as multi-source data fusion, machine learning models, and big data and cloud computing, will be essential. By overcoming these challenges and utilizing effective methods, appropriate groundwater level thresholds can be established to ensure the long-term sustainability of GDEs.

Keywords: Arid region; Vegetation; Groundwater level threshold; Depth to water table; Groundwater-dependent ecosystems (GDEs)

Received: 20 Mar 2024/ Accepted: 21 Oct 2024/ Published: 06 Dec 2024

Introduction

Groundwater-Dependent Ecosystems (GDEs), which are species and ecosystems sustained by direct or indirect access to groundwater, are of great importance for maintaining ecological balance and protecting biodiversity in arid areas. Groundwater, the most critical factor for GDEs, is fundamental to their stability and serves as a controlling factor in preventing ecological degradation. Changes in groundwater levels directly affect the health of these ecosystems, as the depth to water table determines the growth, coverage, age structure, population and biodiversity of vegetation (Zhai et al. 2021).

The arid region in northwest China is characterized by low precipitation, high potential evapotranspiration, and limited soil moisture. Groundwater is a reliable water source for sustaining desert vegetation, which is mainly composed of phreatophytes and xerophytes, with only a small proportion of mesophytes and helophytes. Typical Groundwater-Dependent Terrestrial Ecosystems (GDTEs) in this region include those ecosystems dependent on surface expression of groundwater, such as terminal lake wetland and spring wetland, as well as those dependent on subsurface groundwater, such as desert riparian forest and desert oases. These ecosystems are vital for preventing

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DOI: 10.26599/JGSE.2024.9280032

Li MY, Li CZ, Dong F, et al. 2024. Groundwater level thresholds for maintaining groundwater-dependent ecosystems in northwest China: Current developments and future challenges. Journal of Groundwater Science and Engineering, 12(4): 453-462.

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desertification and protecting biodiversity.

Groundwater supports these ecosystems by providing water with physical and chemical characteristics, which have important implications for vegetation structure, ecosystem function, as well as community succession. However, increased groundwater exploitation for irrigation has led to a continuous decline in groundwater levels threatening the health of GDTEs, especially during dry summer months and drought years. Shallow rooted vegetation in wetlands is particularly vulnerable to declining water levels. A decline in water levels can result in the loss of species that are intolerant to drying, gradually replaced by more drought-tolerant terrestrial species, as observed in some inland lake wetland ecosystems. Meanwhile, deep-rooted phreatophytes, though adapted to accessing deep groundwater, can experience severe stress and even mortality when rapid water level declines disconnect their roots from the aquifer. Progressive reductions in groundwater availability may deteriorate the health of these ecosystems, potentially causing irreversible damage. To prevent these adverse impacts, establishing groundwater level thresholds is essential to ensure the long-term stability and resilience of GDEs.

Groundwater thresholds refer to specific hydrologic conditions, such as groundwater levels or water quality parameters, which are considered essential for maintaining the health of Groundwater-Dependent Ecosystems (GDEs). In arid regions, the influence of groundwater level is particularly important compared to water quality or chemical composition, as it is directly related to hydrological conditions. Generally, groundwater level thresholds represent numeric values (both maximum and minimum) that define the permissible range for water table depth, beyond which adverse impacts on GDEs are likely to occur. Consequently, in arid regions, the threshold of groundwater level is more concerned and studied than the threshold of water quality, especially in situations where water levels continually decline.

Numerous field-based studies on groundwater level thresholds have been conducted in arid northwest China (Gao et al. 2000; Fan et al. 2008; Guan et al. 2012; Wang et al. 2011; Feng et al. 2012; Zhai et al. 2021). These studies have identified two primary types of thresholds based on different ecologic targets. The first type aims to maintain ecological health, such as the suitable depth to water table (Wang et al. 2011). The second focuses on preventing soil salinization, with thresholds like the critical depth to water table (Fan et al. 2008; Guan et al. 2012). Feng et al. (2012) suggested "ecological warning groundwater level", where soil moisture falls below field capacity and approaches the plant's wilting point, threatening plant growth and potentially leading to ecosystem collapse, and the "critical groundwater level for salinity control", where evaporation during the driest season does not cause salt accumulation in the surface soil layer. These thresholds often emphasize individual biological responses to groundwater changes in specific species dependent on groundwater (Zhai et al. 2021). However, because groundwater processes and ecosystem responses operate across a wide range of spatial and temporal scales, establishing precise groundwater thresholds for GDEs at different spatial scales and defining and implementing management triggers remains challenging.

Considering that GDEs in arid northwest region are facing the risk of declining groundwater levels, this review focuses on groundwater level thresholds, including methods for identifying and investigating these thresholds in terrestrial environments. It summarizes recent advancements, and reviews the limitations of existing threshold studies in the region, and explores future challenges and prospects for accurately determining groundwater level thresholds in this area.

1 Methods for establishing the groundwater level thresholds

Groundwater level thresholds can be defined as the groundwater level that corresponds to a hydrologic state beyond the acceptable range of variation for ecologic targets within GDEs. This state results in the impairment of key functional traits, marking a transition towards an undesirable condition (Rohde et al. 2020). These thresholds, often referred to as groundwater depth thresholds, or depth to water table, represent specific groundwater depths that delineates the boundary between a healthy and unhealthy state for GDEs. Crossing these thresholds can lead to negative ecological impacts, such as reduced vegetation health, species decline, or even ecosystem collapse. Typically, these thresholds are defined as single values or a range, and they serve as "red flags" that alert decision-makers to potential ecological harm, triggering management actions (Rohde et al. 2020; Groffman et al. 2006; Moritz et al. 2013).

Various related concepts have been proposed to address different ecologic targets, including environmental groundwater depth (Huang et al. 2019), Depth To Groundwater (DTG) thresholds (Eamus et al. 2015; Irvine and Crabbe, 2024), ecological groundwater table (Zhang et al. 2003), and critical groundwater level (Liao et al. 2018). Recently, Rohde et al. (2024) proposed that DTG threshold refers to the specific depth at which groundwater availability becomes insufficient for the survival and health of GDEs. This threshold typically focuses on the maximum depth below the land surface that groundwater can reach and is generally more practical for regional-scale analysis. It is a critical parameter for ensuring the sustainability of GDEs and plays a key role in effective groundwater management and conservation planning, helping to maintain groundwater levels above these thresholds to protect ecosystem health.

Determining groundwater level thresholds is a complex process that requires careful consideration of various factors, such as vegetation type and its sensitivity to groundwater depletion, root depth, soil type and climate conditions. This process usually necessitates long-term ecological monitoring. Establishing groundwater level thresholds involves assessing the susceptibility of GDEs to changes in groundwater levels, understanding the adaptation mechanisms and ecological responses of these ecosystems, and predicting the impact of groundwater level changes on ecosystem functions and services.

Based on the studies by Rohde et al. (2020; 2024) and Kath et al. (2018), a general framework for identifying groundwater level thresholds for specific ecological targets is as follows:

(1) Identifying baseline conditions of groundwater level for GDEs

The baseline groundwater level refers to the historical average groundwater level over the long term, established in the absence of human disturbances and climatic influences. It represents the normal range of groundwater levels to which the ecosystem has adapted to and can function effectively (Rohde et al. 2020; 2024). This baseline serves as a reference point for assessing the impact of groundwater level changes on the ecosystem. The impact of human activities on the groundwater system and GDEs can be quantified by comparing the current groundwater level to the baseline. Thresholds are typically set relative to the baseline groundwater level, which helps in considering the different sensitivities of various GDEs. For example, some plant species may exhibit greater tolerance to fluctuations in groundwater levels than others. Analyzing long-term trends in groundwater levels during the baseline period allows for the assessment of any natural variability or cyclic patterns that need to be accounted for when establishing thresholds. This approach ensures that the thresholds are neither overly restrictive nor overly lenient based on short-term fluctuations. By incorporating the baseline groundwater level into the threshold determination process, we can develop more comprehensive and effective strategies to protect groundwater-dependent ecosystems and ensure their long-term health.

(2) Assessing ecologic responses to water level variations and quantifying the acceptable range of these variations for GDEs

To evaluate whether potential thresholds are sufficient to prevent adverse impacts on GDEs, it is crucial to assess their ecological responses to changes in groundwater levels. Quantifying the acceptable range of groundwater levels helps us understand the extent to which ecosystem can withstand before experiencing significant negative impacts. This acceptable range defines the levels that support the persistence and functioning of the ecosystem, reflecting its tolerance to natural fluctuations in groundwater availability, such as seasonal changes and droughts. The acceptable range can be determined based on the natural fluctuations identified from baseline data and ecological sensitivity assessments. Establishing this range provides a foundation for establishing groundwater thresholds. The threshold depends on a GDE's ability to adapt to groundwater changes, as well as the rate and magnitude of those changes. Typically, thresholds are set below the upper limit of the acceptable range to ensure that the ecosystem remains within its natural variability and avoids experiencing significant negative impacts.

(3) Developing groundwater level thresholds

Groundwater level thresholds associated with the declines of ecosystem health or ecosystem function can be identified by analyzing baseline data and the responses of GDEs to changes in groundwater levels. Both groundwater levels and ecological responses can vary both seasonally throughout the year and spatially, influenced by factors such as soil, vegetation, and topography. Additionally, climate change and human activities may induce long-term changes in groundwater levels and ecosystem conditions. Consequently, defining a static threshold may not accurately capture these dynamics. When establishing thresholds, it is essential to consider both spatial and temporal changes in groundwater levels and vegetations. Some ecosystems may exhibit multiple thresholds corresponding to different stages of degradation. Thresholds should account for the transition from a healthy to a damaged state, as well as potential delayed effects. The validity of identified thresholds can be evaluated through ongoing monitoring of changes in groundwater levels and assessing their impacts on GDEs. Potential impacts on GDEs can be identified and assessed by comparing current groundwater levels to baseline data. If significant changes in groundwater levels are observed, the thresholds should be adjusted to effectively maintain these ecosystems.

Various methods can be employed to quantify groundwater level thresholds for ecosystems (Rohde et al. 2020, 2024; Irvine and Crabbe, 2024; Wang et al 2021; Mu et al. 2020; Zhang et al. 2020; Kath et al. 2018). These methods can be primarily categorized into three types (Table 1).

(1) Methods based on vegetation indicators

These methods involve analyzing vegetation characteristics, such as species diversity, coverage, and composition, to infer the suitable groundwater depth for plant growth and ecosystem health. Groundwater level thresholds can be identified by examining how these indicators change with variation in groundwater levels.

(2) Methods based on models

This category includes statistical models (such as hydrological models and eco-hydrological models), including linear regression and logistic regression, which determine groundwater level thresholds by analyzing the relationships between groundwater levels and vegetation. Hydrological models simulate groundwater dynamics to determine the thresholds, while eco-hydrological models consider the interactions between vegetation growth and soil moisture or groundwater to determine the thresholds based on ecosystem water demand.

(3) Methods based on remote sensing

These methods determine groundwater level thresholds by analyzing vegetation cover and growth status at various groundwater depths using

Table 1 Methods for quantifying groundwater level thresholds to protect GDEs

Methods		Explanations	Pros/Cons
Methods Based on Vegetation Indicators	Species Diversity Analysis	Determine groundwater thresholds by analyzing the changes in species diversity at different groundwater depths (e.g. Species richness, Shannon-Weiner index, and Simpson index)	Provide direct information about the response of vegetation to groundwater changes. Indicate the overall health and functioning of the ecosystem. Cannot provide insights into the ecological and hydrological processes affecting vegetation responses to groundwater changes. Limited by data availability due to difficulty in obtaining data.
	Vegetation Cover Analysis	Determine groundwater thresholds by analyzing the changes in vegetation cover at different groundwater depths	
	Vegetation Growth Indicator Analysis	Determine groundwater thresholds by analyzing the changes in plant growth indicators at different groundwater depths (e.g. height, biomass)	
Methods Based on Models	Empirical Models	Establish models based on historical data and expert experience to predict groundwater thresholds (Basic statistical analysis methods, e.g. linear correlations, stress gradients, ordination)	Does not require complex models and a large number of parameters. Can use existing/ historical observation data for analysis. Uncertainties due to large data gaps may exist.
	Statistical Models	Establish models based on statistical analysis methods to analyze the relationship between groundwater and vegetation, and determine groundwater thresholds (e.g. Functional linear model, Bayesian model, Gaussian regression model, forest gradient model)	Can intuitively reflect the relationship between groundwater thresholds and the ecological environment. Can deal with missing data. Most models require large sample sizes. Cannot explain the physical mechanism. Limited by the data distribution and model assumptions.
	Mechanistic Models	Establish models based on ecological hydrological processes to simulate the relationship between groundwater and vegetation and determine groundwater thresholds (e.g. MODFLOW)	Can provide quantitative relationships between groundwater level and vegetation. Can explain the eco-hydrological processes influencing vegetation responses to groundwater changes. Require calibration with field data. Uncertainty due to simplifications and assumptions.
Methods Based on Remote Sensing	Remote Sensing Image Analysis	Determine groundwater thresholds by analyzing vegetation cover and growth status at different groundwater depths using remote sensing images (e.g. NDVI method, NDVI-DTG method)	Allow for large-scale analysis of vegetation. Time-series analysis: Can be used to time-series analysis of changes in vegetation. Limitations in spatial and temporal resolution, which can affect the accuracy of results.
	Remote Sensing Inversion Models	Establish models based on remote sensing data and ground-based measured data to invert groundwater depth and determine groundwater thresholds	Can be affected by atmospheric conditions and topography, requiring careful processing and correction.

remote sensing images. Commonly, the Normalized Difference Vegetation Index (NDVI) reflects the growth status of surface vegetation. The correlation between NDVI changes and groundwater levels can be used to establish thresholds. Recently, Rohde et al. (2024) provided a widely applied method NDVI-DTG for determining DTG thresholds to maintain GDEs health. This method standardizes NDVI and Depth to Groundwater (DTG) data using Z-scores to facilitate comparisons across different regions and conditions, directly correlating NDVI data with groundwater level data. By employing a linear regression model, it identifies groundwater level thresholds corresponding to specific decreases in NDVI values. This approach provides a more accurate assessment of the impact of groundwater levels on vegetation health.

The selection of appropriate methods should consider the characteristics of the study area, the availability of data type, and accuracy requirements. It is often beneficial to combine multiple methods to comprehensively and accurately determine groundwater thresholds.

2 Current developments in groundwater level thresholds in northwest China

Chinese scientists have conducted extensive studies on the groundwater ecological threshold of GDEs in the arid northwest region. The main progress includes: (1) Various methods have been developed or applied to determine groundwater level thresholds, including ecological survey, statistical analysis, remote sensing statistical analysis, and modeling (Zhai et al. 2021); (2) Some studies assessed the susceptibility of GDEs to changing groundwater conditions, such as desert riparian forests, providing an important scientific basis for threshold determination; (3) Through long-term monitoring and model simulation in case studies, the groundwater level thresholds for different GDEs had been quantified, providing references for GDEs protection in other regions; (4) Models have been used to predict the responses of GDEs to changes in groundwater levels.

Most of these works have been concentrated in the lower reaches of the Tarim River and the Heihe River in inland arid areas. The primary focus was on specific vegetation species, with particular emphasis on identifying suitable depth to the water table for vegetation growth and establishing water level thresholds to prevent vegetation degradation. To apply these findings to GDEs, the thresholds for these individual species have been summarized in terms of community structure (Table 2).

As for the desert riparian forest ecosystem, the optimal depth to the water table for vegetaion growth falls within the range of 2 m to 4 m. When the depth to the water table exceeds 4 m to 6 m, vegetation growth begins to be inhibited, and significant degradation occurs when the depth exceeds 8 m. In the middle and lower reaches of Tarim River, Hao et al. (2010) employed the Detrended Canonical Correspondence Analysis (DCCA) to analyze two years of monitoring data encompassing groundwater levels, vegetation plots, and soil profiles. They determined that the suitable depth to the water table for vegetation growth was between 2 m and 4 m, with a threshold identified at approximately 6 m. Further studies on the response of vegetation to hydrological processes suggested that herb degradation occured when the depth to the groundwater table was between 4 m and 6 m, while tree degradation only happened when the depth exceeds 6 m. Mixed tree/shrub/herb communities were found in areas with a groundwater depth of 2 m to 4 m near the riverbank, while tree/shrub communities are located in areas with depths ranging from 4 m to 8 m. Areas with depths exceeding 8 m were characterized by degraded simple structures of *Populus euphratica/Tamarix chinensis* (Li et al. 2013; Chen et al. 2006). In the lower reaches of the Heihe River, similar findings were observed, where a depth of 2 m to 4 m to water table was deemed suitable for vegetation growth, and degradation occurred when the depth fell below 4 m (Ding et al. 2017; Feng et al. 2012). Comparable ranges of depth to the water table were found in the Manaz River Valley of the Junggar Basin, where the optimal water depth was 1 m to 4 m and the threshold for shrub plants was 5.5 m. For herbaceous plants, the most suitable water depth interval was between 0.5 m and 1.5 m, with a limit water level of 2.5 m (Cheng et al. 2018). In the Shiyanghe River, where the vegetation is mainly composed of shrubs such as *Nitraria spp, Tamarix chinensis, Reaumuria soongorica, Lycium ruthenicum*. The suitable depth to the groundwater table for vegetation growth was found to be between 8.6 m and 13.5 m, with vegetation degradation occurring when the depth exceeded 14 m (Liu et al. 2012).

The desert terrestrial GDE ecosystem (desert oasis), primarily consists of drought-resistant and salt-tolerant shrubs and herbs. Zhai et al. (2021) summarized the research findings on the suitable depth to the water table for oasis vegetation growth

Table 2 The suitable ranges of depth to groundwater and thresholds for maintaining healthy GDEs, NW China

Area	GDEs	Species and communities	Suitable (m)	Thresholds (m)	Sources
Middle and lower Tarim Rive Basin	Desert riparian forests	Mixed forest-shrub-herb: *Populus euphratica, Tamarix spp., Phragmites australis*	2–4	8	Li et al. 2013
			2–4	6	Hao et al. 2010
		Forest-shrub: *Populus euphratica, Tamarix spp., Haloxylon ammodendron*	4–8	8	Li et al. 2013
			4–6	6	Hao et al. 2010
		Herb: *Phragmites australis*	0.5–1	2	Li et al. 2013
Manaz River Valley (Junggar Basin)	Desert riparian vegetation	Shrub: *Ulmus glaucescens Franch; Tamarix spp*	1–4	5.5	Cheng et al. 2018
		Herb: *Phragmites australis*	0.5–1.5	2.5	Cheng et al. 2018
Lower Heihe River Basin	Desert riparian forests	Forest-shrub: *Populus euphratica, Tamarix spp.*	2–4	4	Ding et al. 2017 Feng et al. 2012
	Desert Terrestrial GDEs (Ejina oases)	Shrub: *Tamarix spp., Nitraria spp., Haloxylon ammodendron, Artemisia arenaria*	2–5	5	Jin et al. 2010; Yu and Wang, 2012
	Desert wetland (Juyan lake wetland)	Salt marsh grassland: *Phragmites australis, Agropyron cristatum, Tamarix ramosissima*	1.5–2	2	Feng et al. 2012
Middle and lower Shiyanghe Rive Basin	Desert riparian vegetation	Shrubs: *Nitraria spp., Tamarix spp., Reaumuria soongorica, Lycium ruthenicum*	8.6–13.5	14	Liu et al. 2012
	Desert Terrestrial GDEs (Minqin oases)	Shrubs: *Nitraria spp., Tamarix spp., Haloxylon ammodendron, Kalidium foliatum, Reaumuria soongorica, Artemisia arenaria*	2.5–3.9	4	Cao et al. 2020
	Desert wetland (Qingtuhu lake wetland)	Herb-shrub ((Halophytic Marsh Grassland): *Phragmites australis*, *Kalidium foliatum*	0.5–2.0	2	Hu et al. 2021; Zhang, 2021
				3	Liu et al. 2022
Shulehe River Basin	Desert Terrestrial GDEs (Oases)	Shrub-herb: *Alhagi sparsifolia, Nitraria spp, Sophora alopecuroides, Phragmites australis*	2–4	6	Ma et al. 2005; Ye et al. 2013
	Desert wetland (Xihu lake, Dunhuang)	Herb (Halophytic Marsh Grassland: About 0-5 km from lake): *Agropyron cristatum, Phragmites australis*	1.07–2.03		Chen et al. 2021
		Shrub-herb (desert woodland: About 10–50 km from lake): *Lycium ruthenicum, Phragmites australis, Populus euphratica, Tamarix ramosissima*	2.78–5.42		Chen et al. 2021
Qaidam Basin	Desert wetland (Spring and lake wetland)	Salt marsh grassland: *Phragmites australis, Agropyron cristatum, Kalidium foliatum, Nitraria spp.*	0.3–0.9	1.1	Dang et al. 2019
	Desert riparian vegetation	Herb-shrub: *Apocynum venetum, Nitraria spp., Tamarix ramosissim, Tamarix spp., Artemisia arenaria, Phragmites australis, Kalidium foliatum, Achnatherurn*	1.4–3.5	5	Dang et al. 2019
Northern Ordos basin	Desert wetland (Riparian and lake wetland)	Shrub: *Salix mongolica, Artemisia sphaero—cephala Krasch, Pulus simonii Carr.*	1.5–3	5	Yang et al. 2006

in arid northwest China. The suitable depth to the water table for different vegetation types are as follows: 1.0 m to 4.7 m for trees (Populus euphratica), 1.0 m to 6.0 m for shrubs, and 0.5 m to 4.0 m for herbs, respectively. Additionally, the critical depth to the water table for preventing soil salinization was identified to be greater than 2.0 m to 3.0 m. In the Ejina Oasis, located in the lower reaches of the Heihe River, studies suggested that depths within the range of 2 m to 5 m were suitable for vegetation growth. However, when the depth exceeded 5 m, the root systems of existing species struggled to access sufficient water. Consequently, ecological warning groundwater depth thresholds were set between 4 m and 6 m (Jin et al. 2010; Yu and Wang, 2012). Furthermore, based on long-term observations of the relationship between psammophyte communities and groundwater levels, Feng et al. (2012) suggested that the groundwater threshold for indicator plant species, such as *Elaeagnus angustifolia, Tamarix chinensis, and Nitraria tangutorum*, is approximately 4 m.

In desert wetland ecosystems, changes in groundwater depth have a direct impact on wetland area and vegetation growth. The optimal conditions for vegetation growth and the maximum wetland area occur within a groundwater depth range of 1 m to 2 m. When the depth to the water table is less than 0.5 m or exceeds 2 m to 3 m, both the wetland area and vegetation growth are adversely affected (Chen et al. 2021; Dang et al. 2019; Li et al. 2013; Zhang et al. 2021; Yang et al. 2022).

It is important to recognize that the groundwater level threshold for different plant communities is influenced by a variety of factors, including climate, hydrology, geology, soil, and vegetation types. To ensure the health of these ecological ecosystems, groundwater level threshold should be treated as elastic indicator or ranges rather than fixed values. Zhang et al. (2020) conducted a metadata analysis of ecolocigcal groundwater depth across various vegetation types (such as trees, shrubs, and herbs) in the arid northwest region. They suggested that the average depth for suitable ecological groundwater levels was approximately 2.9 m, while the extreme ecological groundwater level was around 5.5 m. The control ranges for these depths were 2.3 m to 3.9 m for suitable conditions and 4.0 m to 7.2 m for extreme conditions. Recent surveys indicate that the depth to the water table is a primary controlling factor for the stability of natural ecosystems in the arid northwest region, with suitable groundwater depths ranging from 2 m to 5 m. A significant decline in groundwater levels can lead to the degradation and collapse of natural ecosystems, with critical thresholds identified at groundwater depths of 5 m and 10 m, respectively (Liu et al. 2021).

3 Future challenges

Current researches on groundwater level thresholds in the arid region of northwest China predominantly focused on individual vegetation species. There is a lack of studies that assess multiple biological responses across various groundwater-dependent species. The function of GDEs depends not only on the survival of individual species, but, more importantly, on the structure and function of the entire community. Given that GDEs are composed of multiple species, each with distinct water demands, tolerance to water stress, and adaptation strategies, the threshold established for a single species may not accurately reflect the health and status of the entire community. Therefore, when determining groundwater level thresholds, it is necessary to consider the collective structure and function of the entire community, combined with the tolerance and adaptation mechanisms of different species. This holistic approach will contribute to more effective protection and management of GDEs.

Determining groundwater level thresholds is inherently challenging due to the complexity of ecosystems and groundwater systems, coupled with difficulties in data acquisition.

Defining a single threshold for all vegetation types within a GDE is particularly problematic. GDEs are diverse and complex, with different species and habitats exhibiting varying sensitivities to groundwater regimes. In addition, the effects of groundwater pumping on GDEs may not be immediately; instead, they can lag for months or even years. As a result, thresholds must consider not only the transition from a healthy to a damaged state but also the potential lag time. Even if groundwater levels return to pre-impact conditions, ecosystems may not fully recover due to the delayed effects of stressors.

Furthermore, GDEs are often interconnected with other hydrological features like springs, rivers, and wetlands, making it difficult to establish specific thresholds for individual components. Changes in groundwater levels can trigger cascading effects throughout the entire ecosystem, complicating the identification of isolated thresholds.

Additionally, groundwater levels and vegetation health can vary significantly throughout the year due to seasonal rainfall patterns and evapotranspiration, making it difficult to define static thresholds that accurately capture these fluctuations. Climate change and human activities further exacerbate this challenge by causing long-term alterations in groundwater levels and ecosystems, complicating the establishment of thresholds that account for such shifts.

Another significant challenge in determining groundwater level thresholds is data availability. In many cases, data on groundwater levels, hydrology, and ecology are incomplete or entirely lacking. Existing datasets may be limited or missing for certain areas or time periods, which hampers efforts to establish accurate baseline conditions and trends over time. This issue is particularly pronounced in riparian corridors and wetlands, where long-term monitoring of shallow groundwater is often insufficient. The lack of comprehensive data restricts the ability to assess thresholds effectively, hindering accurate modelling and predictions of ecosystem responses to groundwater changes. Furthermore, obtaining representative data that encompass the entire GDE is challenging.

The Methods for quantifying thresholds depend heavily on the available data and the specific targets. Existing hydrological models and ecological models serve different purposes and have limitations in their ability to simulate and predict changes in GDEs and groundwater levels. Their capacity to provide insights into complex spatiotemporal changes is often insufficient. To address these challenges, interdisciplinary research is essential for comprehensively understanding the ecological processes and responses of GDEs to fluctuations in groundwater levels. This necessitates integrating multiple disciplines, such as ecology, hydrology, remote sensing, geographic information systems, big data, and artificial intelligence.

By combining groundwater level data with multi-source remote sensing data, climate models, and hydrological models, a more comprehensive understanding of the relationship between groundwater level changes and vegetation health status can be achieved. This approach enhances the accuracy of determining groundwater thresholds. For instance, machine learning models can establish quantitative relationships between groundwater levels and various data sources, such as vegetation, soil, and climate variables, improving predictive capabilities. Utilizing big data analysis and cloud computing technologies to process and analyze massive datasets related to groundwater and ecological monitoring can lead to a deeper understanding of the correlations between groundwater changes and the health of GDEs. Additionally, dynamic models can be established to simulate groundwater level changes and GDE responses under varying conditions.

In summary, determining groundwater level thresholds is a complex and challenging process that requires careful consideration of ecological, hydrological, and social factors. By addressing these challenges and utilizing appropriate methods, it is possible to develop thresholds that effectively protect GDEs and ensure their long-term sustainability.

4 Conclusions

(1) Establishing and implementing groundwater level thresholds are essential for protecting the health of groundwater-dependent ecosystems and maintaining ecological balance. These thresholds serve as early warning indicators, alerting decision-makers to potential negative impacts on ecosystems and triggering necessary management actions.

(2) Establishing groundwater level thresholds requires careful consideration of various factors, including vegetation type, root depth, soil type, and climate conditions. Common methods for establishing these thresholds include vegetation-based indicators, statistical models, and remote sensing techniques.

(3) Research on groundwater level thresholds for GDEs in the arid northwest of China has advanced significantly. Efforts have focused on assessing the susceptibility of different GDEs to changing groundwater conditions and quantifying groundwater level thresholds through long-term monitoring and modeling. However, it still faces limitations, such as a predominant focus on individual species, the complexity of ecological processes, challenges related to data availability, and methodological constraints.

(4) Determining groundwater level thresholds is challenging due to the intricate nature of ecological processes, groundwater systems, and data availability. However, advancements in technology and interdisciplinary research offer promising solutions to these challenges, enhancing our ability to protect GDEs and ensure their long-term sustainablity.

Acknowledgements

This work was financially supported by the China Geological Survey Project (No. DD20230472).

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