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Comprehensive evaluation on the ecological function of groundwater in the Shiyang River watershed

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Abstract: With an arid climate and shortage of water resources, the groundwater dependent ecosystems in the oasis–desert ecotone of the Shiyang River Watershed has been extremely damaged, and the water crisis in the oasis has become a major concern in the social and the scientific community. In this study, the degeneration characteristics of the groundwater ecological function was identified and comprehensive evaluated, based on groundwater depth data, vegetation quadrat and normalized difference vegetation index (NDVI) from Landsat program. The results showed that (1) the suitable groundwater depth for sustainable ecology in the Shiyang River Watershed is about 2-4 m; (2) the terms of degenerative, qualitative and disastrous stages of the groundwater ecological function are defined with the groundwater depths of about 5 m, 7 m and 10 m; (3) generally, the groundwater ecological function in the oasis-desert ecotone of the lower reaches of Shiyang River Watershed is weak with an area of 1 397.9 km^2 identified as the severe deterioration region, which accounted 74.7% of the total area. In the meantime, the percentages of the good, mild and moderate deterioration areas of groundwater ecological function are 3.5%, 5.5% and 16.3%, respectively, which were mainly distributed in the Qingtu lake area and the southeastern area of the Shoucheng town; (4) the degradation and shrinkage of natural oasis could be attributed to the dramatic groundwater decline, which is generally caused by irrational use of water and soil resources. This study could provide theoretical basis and scientific support for the decision-making in environmental management and ecological restoration of the Shiyang River Watershed.

Keywords: Oasis-desert ecotone; Groundwater depth; Normalized difference vegetation index (NDVI); Desert vegetation; Degenerative change-qualitative change-disaster stages

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Introduction

Rational groundwater development and ecological protection in arid and semi-arid zones is a global issue and has received considerable research attention worldwide. The fifth phase of the International Hydrological Program (IHP-V) addressed the degradation risk of groundwater resources and ecohydrology in arid and semi-arid zones. The seventh phase of IHP (IHP-VII) focused on the identification, investigation and assessment of groundwater ecosystems. The eighth phase of IHP (IHP-VIII) proposed to use existing scientific knowledge to develop new methods, emphasize coordinated development of society, economy, water resources and ecology. The ecological function of groundwater in arid zones has received increasing research attention.

Inland river basins are mainly located in arid and semi-arid climate zones, accounting for 11.4% of the global land area (Li et al. 2018). Rapid socioeconomic development and the shortage of natural water resources have resulted in the over-exploitation of groundwater resources, which has caused many inland river basins to suffer from serious ecological and environmental crises, including land degeneration and sanding, reduction of surface ecological diversity, and the loss of terminal lakes (Zhu et al. 2016). Researchers worldwide have cond-

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ucted many studies on groundwater ecosystems in inland river basins of arid and semi-arid zones (Xu et al. 2004; Naumburg et al. 2005; MacKay et al. 2006; Amus et al. 2006; Cui et al. 2010; Glazer et al. 2012; Huang et al. 2014; Dong et al. 2015; Yang et al. 2018; Huang et al. 2019). For example, Amus et al. (2006) defined groundwater-dependent ecosystems, and they pointed out that vegetation ecology in arid and semi-arid zones depends entirely or mostly on groundwater resources. Glazer et al. (2012) stated that groundwater table changes are a key environmental factor influencing vegetation status. Naumburg et al. (2005) comprehensively investigated the species and environmental responses of shallow-water vegetation ecosystems in the Great Basin of the United States to groundwater table fluctuations, concluded that the fluctuations affect not only vegetation growth but also community structure and ecosystems, while good vegetation ecology can effectively prevent soil erosion and desertification.

Since 2000, extensive studies have been conducted on the exploitation of groundwater resources and the ecological environment in the Shiyang River watershed (Liu et al. 2001; Ma et al. 2003; Yang et al. 2007; Zhang et al. 2009; Yang et al. 2011; Yang et al. 2017; Shi et al. 2017; Hao et al. 2017). These studies have included two main topics. The first focuses on groundwater dynamics and their ecological and environmental effects on vegetation at a regional scale (Ma et al. 2003; Zhang et al. 2009; Yang et al. 2011; Hao et al. 2017; Yang et al. 2017). For example, Ma and Wei (2003) addressed the issues of groundwater table decline, water quality deterioration, desertification, and salinization caused by the over development of groundwater resource in Minqin basin. Moreover, Zhang et al. (2009) investigated the characteristics and causes of groundwater dynamics in Minqin basin. The second topic covers the relationship between observed soil water contents and vegetation growth indicators at the field scale (Yang et al. 2000; Yang et al. 2007; Liu et al. 2013; Zhao et al. 2017; Xiang et al. 2017; Wang et al. 2018). For example, Yang et al. (2007) studied the effect of groundwater table changes on the species of niche at the edge of the Minqin oasis, and observed that they went through population degeneration as the regional groundwater table declined, while the *Nitraria tangutorum* population expanded as the groundwater table fluctuated in the depth range of 7.45-11.65 m. Liu et al. (2013) used species richness index, Shannon-Weiner index, evenness index, and Simpson dominance index combined with groundwater depth data from 11 observation wells and plant data from field survey to analyze the characteristics of groundwater table and species diversity in the riparian zone of the middle and lower reaches of the Shiyang River. They found that the species diversity was decreasing with increasing groundwater table depth, indicating that moisture was the main factor affecting the distribution and survival of vegetation. Wang et al. (2018) analyzed the changing patterns and interrelationships of vegetation ecological characteristics and soil environmental factors in four different desertification stages of the Minqin oasis - desert transition zone. In summary, extensive in-depth studies have been conducted on the groundwater dynamics and the responses of vegetation ecological indicators in the Shiyang River watershed, but few studies have combined these two aspects to evaluate the groundwater ecological function of the oasis–desert transition zone in the Shiyang River watershed.

The oasis–desert transition zone is an ecotone under the joint influence of two geographic processes, desertification and oasisification, and it plays an important role in oasis stabilization and desertification control (Jia et al. 2002). Compared with other ecosystems, the oasis–desert transition zone is characterized by simple community structure, relative abundance of plant functional types, high habitat heterogeneity on a micro-scale, and poor stability of ecological functions (Wang et al. 2018). Since the 1970s, the Shiyang River watershed has experienced a rapid increase in population and arable land area with water shortage, which results in long-term over-development of groundwater and a sharp decline in the groundwater table, leading to vegetation degeneration in the oasis–desert transition zone accompanied by increased sandstorm activities. Particularly, in the northern part of the Minqin oasis in the lower reach of the watershed, an ecological crisis of “sand advance and human retreat” has emerged. In this region, the ability of groundwater to sustain the surface vegetation has been compromised, causing a series of ecological and environmental problems, such as soil salinization, desertification, and wetland loss.

This study examined the relationship between groundwater table depth and normalized difference vegetation index (NDVI) in the oasis–desert transition zone of the Shiyang River watershed firstly. The observed relationship was then combined with the data of groundwater table depth and natural vegetation quadrat survey to examine the relationship between the spatial distribution of main desert vegetation types and the groundwater table depth. The research also aimed to explore the indicators of degeneration, qualitative change, and disastrous change of groundwater ecological function. Finally, based on the field survey data, the groundwater table depth, NDVI, vegetation type, species richness, and abundance indicators of dominant species were selected to comprehensively were selected evaluate the groundwater ecological function in the oasis–desert transition zone of the lower Minqin basin. This transition zone was selected because it is currently the focus of the Shiyang River watershed management. These findings may provide theoretical and scientific support for decision-making in environmental management and ecological restoration in the Shiyang River watershed.

1 Study area

The Shiyang River watershed is one of the typical watersheds in the arid inland region of northwest China, located at the eastern end of the Hexi Corridor, west of Wushao Mountain, north of the Qilian Mountains (101°41′– 104°16′E, 36°29′ – 39°27′N), with a total area of 4.16 × 10^4 km^2 (Fig. 1).

The topography is high in the south and low in the north, inclined from southwest to northeast. The upper, middle and lower reaches span three climatic zones. From the south to the north and from the upper reaches to the lower reaches, the climate zones are sequentially: (1) the alpine semi-arid and semi-humid zone of the southern Qilian Mountains, with an elevation of 2 000 - 5 000 m, annual precipitation of 300 - 600 mm, and annual evaporation of 700 - 1 200 mm; (2) the cool arid zone of the central corridor plains, with an elevation of 1 500 - 2 000 m, annual precipitation of 150 - 250 mm, and annual evaporation of 800 - 1 400 mm; and (3) the northern arid zone, with an elevation of 1 300 - 1 500 m, annual precipitation of less than 150 mm, and annual evaporation of 1 200 - 1 800 mm (Wang et al. 2012; Zhang, 2017). Excluding the southern Qilian Mountains, most areas in the watershed are characterized by arid climate, scarce precipitation, intense evaporation,

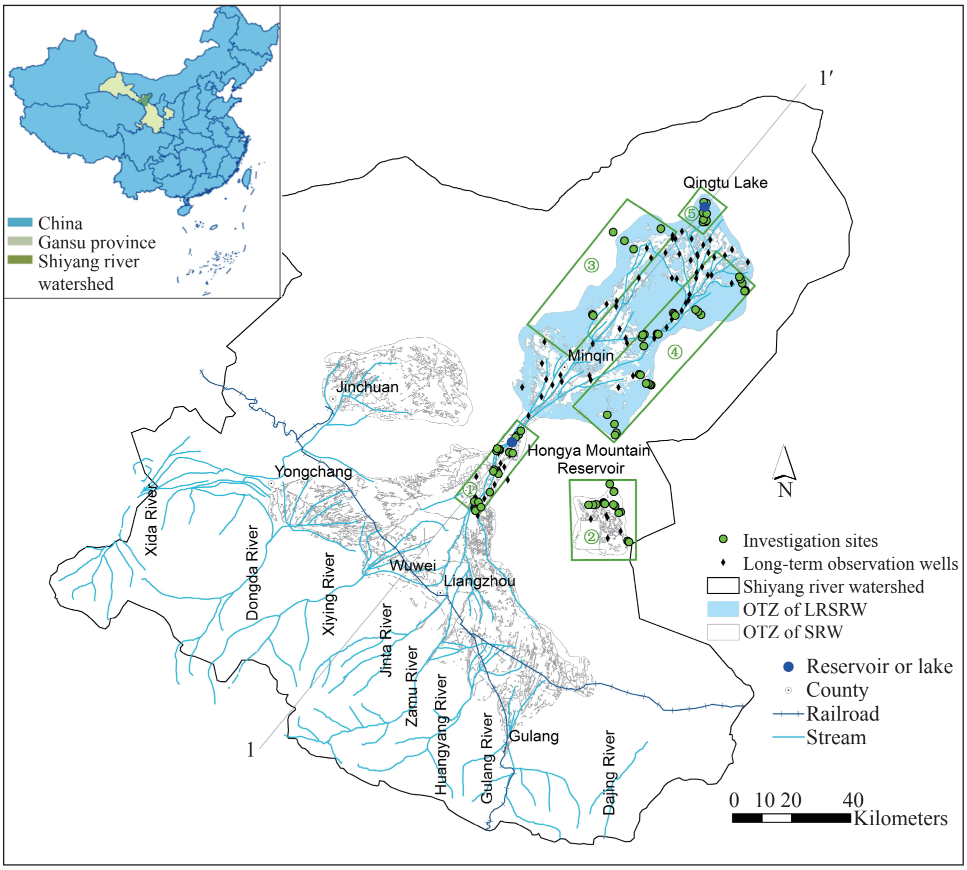

Fig. 1 Study area and the investigation sites

Note: SRB – Shiyang River Basin; LRSRB – the Lower reaches of the Shiyang River Basin; investigation sites – investigation sites of groundwater level depth and the ecological vegetation quadrat; ①②③④⑤represent the oasis–desert transition zones of the Hongyashan reservoir area, the South Lake area, the west of the Minqin irrigation area, the east of the Minqin irrigation area and the Qingtu Lake area, respectively.

and sufficient sunshine. From east to west, the Shiyang River watershed consists of eight major rivers (Dajing River, Gulang River, Huangyang River, Zamu River, Jinta River, Xiying River, Dongda River, and Xida River) and numerous small rivers. The river water is sourced from atmospheric precipitation in the mountains as well as alpine ice and snow melts, with a runoff generation area of 1.11×10^4 km^2 and a multi-year mean runoff of 15.60×10^8 m^3.

Groundwater in the watershed comes in three forms: In bedrock fissures, in clastic rocks with dual porosity, and in pores of rocks, the former two of which are mainly distributed in the mountainous areas around the basin. The mountainous areas in the south provide lateral recharge to the midstream basin, whereas the hilly areas in the middle and lower reaches have limited groundwater resources because of the scarce precipitation, and thus, they do not generally recharge the basin groundwater. Loose rocks are the most widely distributed and abundant water-bearing rocks with good-quality water in the region, and they are mainly distributed in the middle and lower reaches in the basin. In particular, the groundwater in the midstream Wuwei basin is mainly recharged by lateral runoff from bedrock mountains, rainfall, rivers, canals, and irrigation water infiltration, while the eastern Tengger Desert also provides some recharge to the basin. Groundwater eventually converges near the Caiqi section of Minqin, where it partly overflows to the surface in the form of springs, joining the major Shiyang rivers and flowing into Hongyashan Reservoir, and partly into the Minqin basin as lateral runoff (Fig. 2). The groundwater in the lower Minqin basin, which flows northwards, mainly receives recharge from lateral runoff (from the southern Wuwei Basin), rainfall infiltration, and irrigation return, with artificial extraction and natural evaporation being the most important forms of groundwater discharge (Fig. 2).

The present study region mainly includes the oasis–desert transition zone in the middle and lower reaches of the basin, with a particular focus on the oasis–desert transition zone in the downstream Minqin basin. Minqin basin currently has a deep groundwater table, which is usually greater than 20-30 m in the irrigation zone and the west transition zone, but the groundwater table of the Qingtu Lake area on the east and south sides is relatively shallow, generally less than 10 m (Fig.3).

The natural vegetation of the oasis–desert transition zone of Shiyang River watershed is mainly temperate desert (arid desert) vegetation, which is dominated by arid and super-arid shrubs and semi-shrubs, with *Reaumuria soongorica* as the most widely distributed species. Other main shrub species include *Nitraria tangutorum*, *Tamarix chinensis*, *Haloxylon ammodendron*, *Caragana microphylla*, *Hedysarum scoparium*, *Kalidium foliatum*, and *Artemisia desertorum*. Trees mainly include *Populus diversifolia*, *Populus gansuensis*, *Elaeagnus angustifolia*, and *Salix matsudana*. Herbs are mainly *Phragmites australis*, *Achnatherum splendens*, *Sophora alopecuroides*, *Bassia dasyphylla*, and *Agriophyllum squarrosum* (Wang et al. 2018; Cao et al. 2020). Most of these plant species are groundwater dependent. Since the 1970s, the expansion of irrigated oases and the continuous decline of groundwater tables have led to serious degeneration of natural ecological vegetation in the oasis–desert transition zone and weakened groundwater ecological function. This has particularly occurred in the west of the Minqin oasis in the lower reach of the watershed, where the groundwater table is as deep as 20-30 m, and the ecological function of groundwater to maintain surface natural vegetation has almost disappeared.

2 Data and Methods

2.1 Data

The data used in the present study include ground-

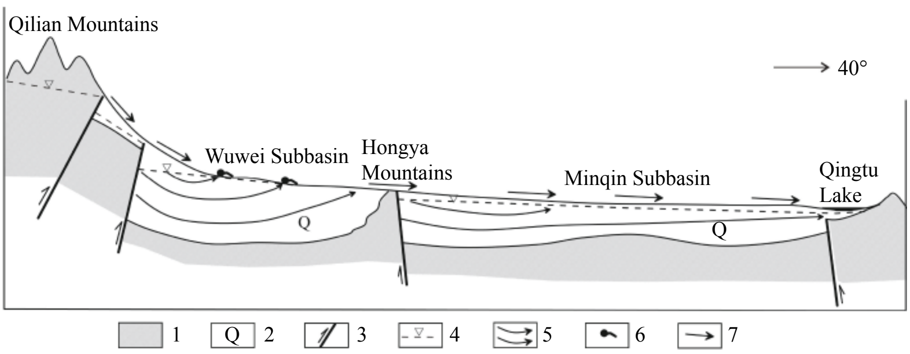

Fig. 2 Schematic diagram of groundwater flow system

1-Bedrock; 2-Quaternary; 3-Fault; 4-Goudwater table; 5- Groundwater movement; 6-Spring; 7-Surface runoff flow

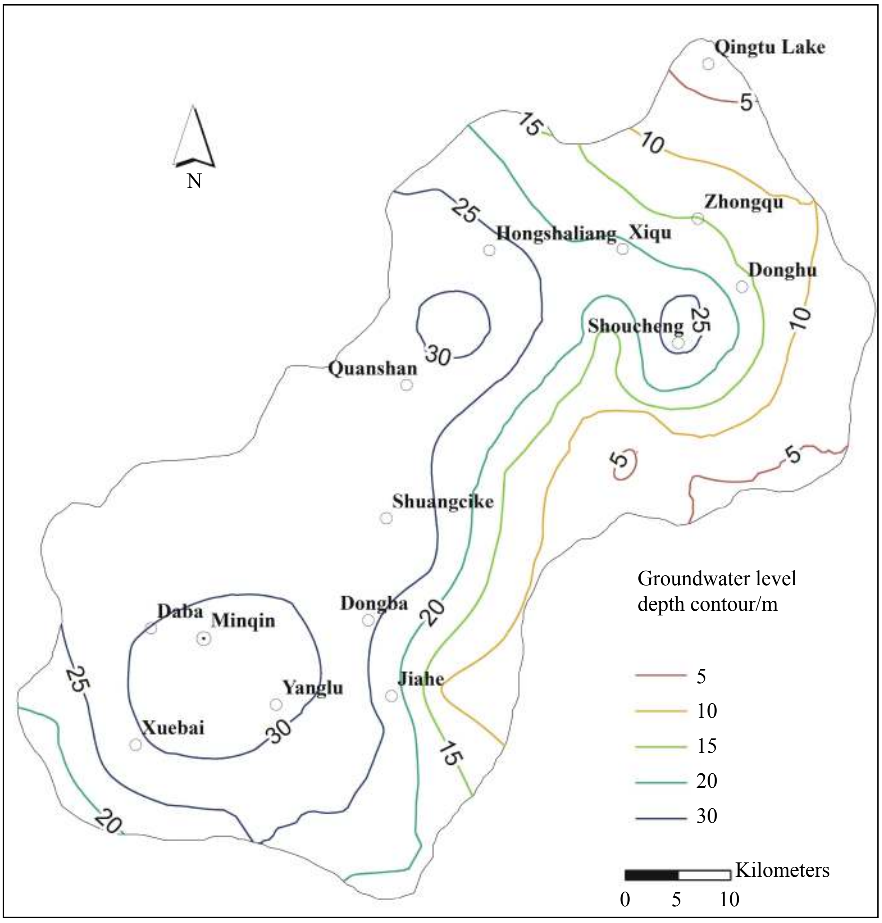

Fig. 3 Contour map of groundwater depth in the Minqin subbasin of the lower reaches of the Shiyang River Basin (August, 2018)

water table depth, species richness, vegetation type, vegetation coverage, normalized difference vegetation index (NDVI), dominant species abundance, and heights of dominant species. The groundwater table depth data were obtained from the groundwater table depth and natural vegetation quadrat joint survey in 2018 as well as long-term in situ measurements in observation wells in the Shiyang River watershed between 2000 and 2017, which covered 91 survey sites and 87 long-term observation wells. Species richness, vegetation type, dominant species abundance and height, and vegetation coverage data were obtained from the 2018 joint field survey, which covered 91 survey quadrats (Fig. 1). NDVI data were obtained by interpreting the 2000-2018 Landsat satellite remote sensing images.

2.2 Methods of natural vegetation quadrat survey

The method for groundwater table depth –natural vegetation quadrat survey was adapted from a previously published guideline (Fang et al. 2009) while considering the actual distribution of plant communities in the arid desert areas of Shiyang River watershed, as elaborated below.

2.2.1 Vegetation survey plots and quadrats

(1) Plot and quadrat locations

First, based on field exploration and literature research and considering the depth of groundwater tables and the distribution of surface vegetation types, vegetation survey plots and quadrats in the natural vegetation areas of the oasis–desert transition zone were selected as well as in nearby areas where observation wells were present. Plots and quadrats were arranged from upstream to downstream based on distances to the rivers.

(2) Quadrat location

When selecting quadrats, the following requirements were met: (1) species composition, community structure, and habitat within the community are relatively homogeneous; (2) community area is sufficient for each quadrat to be surrounded by a buffer zone of at least 10-20 m; and (3) except for communities dependent on specific habitats, quadrats were positioned on a flat surface (or terrace) or a gentle, relatively homogeneous slope while avoiding the top of the slope, valley or complex terrains.

(3) Quadrat layout

Three to five large quadrats were established at each plot. Tree quadrats were positioned first if there were trees, otherwise shrub quadrats were first. Each tree quadrat generally had a size of 30 m × 30 m, and the size was appropriately increased in areas with sparse surface vegetation. Shrub quadrats were generally arranged in a five-point pattern (or a three-point pattern), that is, five 10 m × 10 m shrub quadrats were set at the four corners and the center of a square area, and the quadrat size was adjusted according to the shrub density. Herb vegetation quadrats, each 2 m × 2 m, were set in the center of the shrub quadrats, and the size was adjusted according to the herb diversity and denseness. Each quadrat side was adjacent to a buffer zone with a width of at least 10 m.

(4) Setting up quadrats

Based on the preliminary field exploration and literature research and considering the distribution of vegetation types in different areas of the oasis–desert transition zone and its relationship with groundwater table depth, we set up plots and quadrats in five oasis–desert transition zones: (1) the Hongyashan reservoir area, (2) the South Lake area, (3) the west of the Minqin irrigation area, (4) the east of the Minqin irrigation area; and (5) the Qingtu Lake area. Moreover, 3-5 plots were set in area (1), 5-7 plots in area (2), only 2 plots in area (3) because the field exploration revealed that the groundwater table was generally deeper than 20 m and thus the surface vegetation showed no clear correlation with the groundwater, 4-5 plots in area (4), and 3-5 plots in area (5). Each plot was set to have 3-5 large quadrats, for a total of 91 quadrats (Fig. 1).

2.2.2 Survey content, materials, and time

The survey content included groundwater table depth, community type, vegetation type, abundance, species type, height, crown width, species richness, number, frequency, diameter at breast height, and basal stem diameter in each vegetation quadrat. Based on the ecological survey of vegetation quadrats, the density, importance value, richness, and dominance of plant communities were calculated . Groundwater table depth was also investigated near each quadrat. If no shallow well was available nearby, the exploration drill hole was widened and deepened on site into a simple well, and groundwater table depth was measured once the table had stabilized. The survey was conducted in August and September, 2018.

2.3 Comprehensive evaluation method of groundwater ecological function

The comprehensive multi-indicator evaluation method of groundwater ecological function in the present study drew on the idea of fuzzy comprehensive evaluation (Liu et al. 2014). For two finite sets, $U=\{U_1,U_2,\cdots\cdots,U_m\}$ and $V=\{V_1,V_2,\cdots\cdots,V_m\}$, where U represents a set of indicators based on which comprehensive evaluation is performed and V is a set of judgments made on groundwater ecological function, fuzzy comprehensive evaluation is a fuzzy transformation process as follows:

$$B=A\circ R. \tag{1}$$

Where: A is a fuzzy subset of U, and the evaluation result B is a fuzzy subset of V. $A=\{a_1,a_2,\cdots\cdots,a_m\}$, $0\le b_j\le 1$, where a_i is the degree of membership of U to A. a_i represents the relative importance (weight) of the indicator U_i among all evaluation indicators, and also represents the ability of U_i to determine the grade, satisfying $\sum_{i=1}^{m}a_i=1$. b_j is the degree of membership of grade V_j to B, representing a comprehensive evaluation result.

The fuzzy transformation matrix is:

$$R=\begin{bmatrix} r_{11}, & r_{12}, & \cdots & r_{1n}\\ r_{21}, & r_{22}, & \cdots & r_{2n}\\ \cdots & \cdots & & \cdots\\ r_{m1}, & r_{m2}, & \cdots & r_{mn}\end{bmatrix}, \tag{2}$$

Where: r_{ij} is the degree of membership of grade V_j for U_i; the ith row $R_i=(r_{i1},r_{i2},\cdots\cdots,r_{in})$ in matrix R represents the evaluation results of U_i.

In this study, the indicators to be used for comprehensive evaluations were determined based on the groundwater table depth and natural vegetation quadrat joint survey. Five factors were selected: Groundwater table depth, NDVI, vegetation type, species richness, and dominant species abundance. The evaluation procedure involved the following steps: (1) selection of a range of potential indicators, (2) determination of each indicator' s critical values and calculating memberships, (3) determination of indicator weights, and (4) calculation of the comprehensive evaluation score of each grid cell and generation of an associated map of the study region.

3 Results and discussion

3.1 Relationship between groundwater table depth and NDVI

The relationship between groundwater table depth and NDVI was analyzed using the long-term observed data of groundwater table depth for 2000 - 2017 and the corresponding Landsat satellite remote sensing data at 30 m spatial resolution after conversion of the raw data to annual means. The observed groundwater table depth data were interpolated to grid cells at 30 m × 30 m resolution. Grid cells were sorted in order of increasing groundwater table depth at 0.1 m intervals, and the NDVI values of the grid cells with the same groundwater table depth were averaged to give a mean value corresponding to that depth. The relationship of groundwater table depth versus depth-specific mean NDVI is shown in Fig. 4.

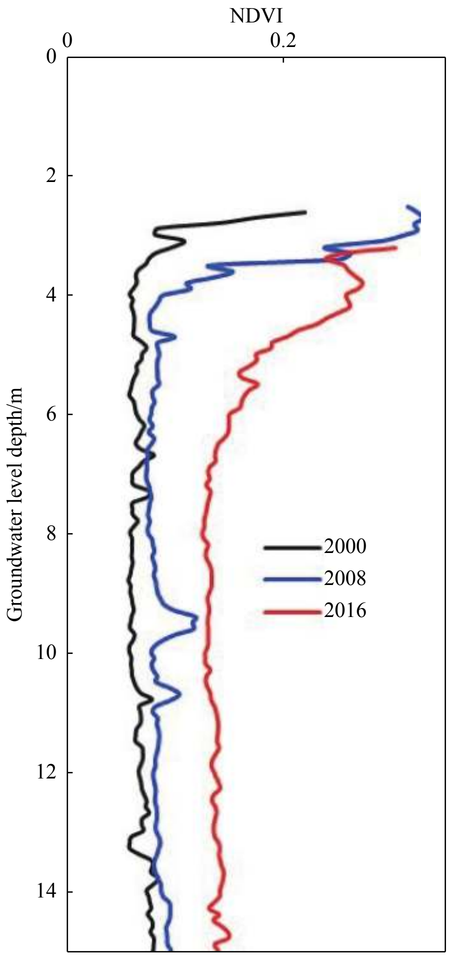

Fig. 4 Relationship between NDVI and groundwater level depth in the Oasis-desert ecotone (Cao et al. 2020)

The NDVI values generally peaked when groundwater table depth was 2-4 m, with a mean depth of 2.96 m. NDVI decreased significantly when groundwater table depth exceeded 5 m. In contrast, when the depth was greater than 7-10 m, NDVI tended to be stable and was generally less than 0.1 (except after the afforestation project in 2012), indicating that groundwater table depth is a key limiting factor for vegetation growth in arid desert areas. When groundwater table depth was less than 5 m, a negative correlation between the two indicators was observed in most years, indicating that NDVI tended to decrease with increasing groundwater table depth in shallow groundwater areas. Groundwater table depth was greater than 10 m in some parts of the oasis–desert transition zone (e.g. the west side of Minqin), and there was no direct relationship between surface vegetation ecology and groundwater in these areas. However, the increase in vegetation coverage and NDVI since the implementation of afforestation policy in the Shiyang River watershed may have caused a statistically significant yet physically meaningless correlation between groundwater table depth and NDVI despite the continued annual increase in groundwater table depth. To avoid this interference, the present study further analyzed the correlation between groundwater table depth and NDVI in the Qingtu Lake area, a typical shallow groundwater area of the oasis–desert transition zone (Fig. 5). The two indicators were significantly negatively correlated when groundwater table depth was less than 5 m, with a correlation coefficient (r) reaching 0.85.

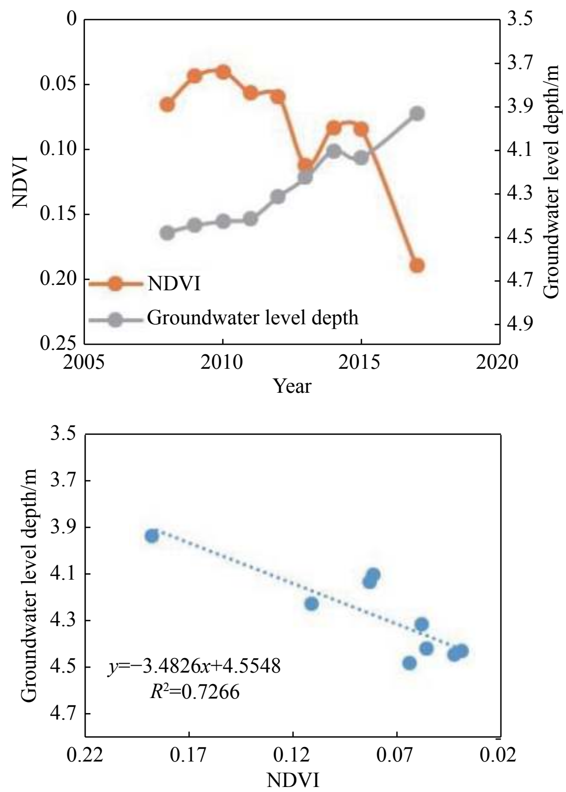

Fig. 5 Relationship between NDVI and groundwater level depth in the shallow groundwater area (less than 5 meters) of the Oasis-desert ecotone

3.2 Spatial distribution of the relationship between groundwater table depth and desert vegetation

Analysis of the joint survey data revealed the relationship between groundwater table depth and the main ecological indicators of desert vegetation (Table 1), as well as the relationship between groundwater table depth and species richness (Fig. 6).

The main desert vegetation species were *Elaeagnus angustifolia*, *Tamarix chinensis*, *Haloxylon ammodendron*, *Caragana microphylla*, *Hedysarum scoparium*, *Artemisia desertorum*, *Nitraria tangutorum*, *Agriophyllum squarrosum*, *Peganum harmala*, *Halogeton arachnoideus*, *Kalidium foliatum*, *Achnatherum splendens*, *Phragmites australis*, *Sophora alopecuroides*, and *Chenopodium album*.

The lake area was mainly dominated by *Kalidium foliatum* and *Phragmites australis* (groundwater table depth of 0-2 m in general). *Tamarix chinensis* and long-stem *Phragmites australis* were generally distributed in the near-riparian zone, where groundwater table depth was generally 1-3 m. Far from the riparian zone, in areas with groundwater table depth of 3-5 m, *Elaeagnus angustifolia*, *Caragana microphylla*, *Hedysarum scoparium*, *Artemisia desertorum*, and *Halogeton arachnoideus* were dominant. *Reaumuria soongorica*, *Peganum harmala*, and *Achnatherum splendens* were generally distributed closer to the oasis, where groundwater table depth was generally 3-7 m. *Nitraria tangutorum*, *Haloxylon ammodendron*, and *Agriophyllum squarrosum* were located within the oasis–desert transition zone but near the desert, in areas with groundwater table depth of around 3-7 m. When groundwater table depth exceeded 7 m, the association between surface vegetation distribution and groundwater table depth weakened, with only artificially planted *Haloxylon ammodendron* and *Nitraria tangutorum* remaining as the surface vegetation species. When groundwater table depth exceeded 10 m, the surface was mostly desertified, and the remaining vegetation species were herbs maintained by individual rainfall events or *Nitraria tangutorum* with little dependence on groundwater table depth. Vegetation coverage gradually decreased in the riparian zone > transition zone > desert area direction. In the oasis–desert transition zone, where groundwater was insufficiently deep to be used by the surface vegetation, vegetation species richness first increased and then decreased as groundwater table became deeper, peaking at approximately 3 m with 10 species and then slowly declining as depth increased thereafter (Fig. 6).

3.3 Ecological groundwater table depth in the watershed

The findings presented in the previous sections indicate that: (1) NDVI generally peaked where groundwater table depth was 2-4 m (Fig. 3), and the multi-year mean of peak-NDVI groundwater table depth was 2.96 m; (2) vegetation coverage generally peaked where groundwater table depth was 2-4 m, with the coverage of *Tamarix chinensis and Phragmites australis* thickets in the near-riparian zone reaching 100% (Table 1); (3) and species richness generally peaked where groundwater table depth was approximately 3 m, and varied between 2 and 10 species depending on water quality, soil texture and salinity, and plant population interaction relations (Zhao et al. 2017; Cao et al. 2021). In

Table 1 Relationship between groundwater level depth and the index of the dessert vegetation quadrats

Groundwater level depth/m	Species richness/No.	Total coverage/%	Dominant species	Dominant species height /m
0-2	1-3	75-90	Tamarix spp.	3.8
			Phragmites australis	1.0
			Kalidiumfoliatum	0.6
2-4	2-7	45-100	Elaeagnus angustifolia	6.0
			Tamarix spp.	2.6
			caragana microphylla	2.2
3-6	3-10	30-70	Reaumuriasoongorica	0.6
			hedysarumscoparium	1.2
5-7	2-4	20-30	Nitraria spp.	0.5
			Reaumuriasoongorica	0.5
>7	1-2	<25	Haloxylonammodendron	1.2
			Nitraria spp.	0.4

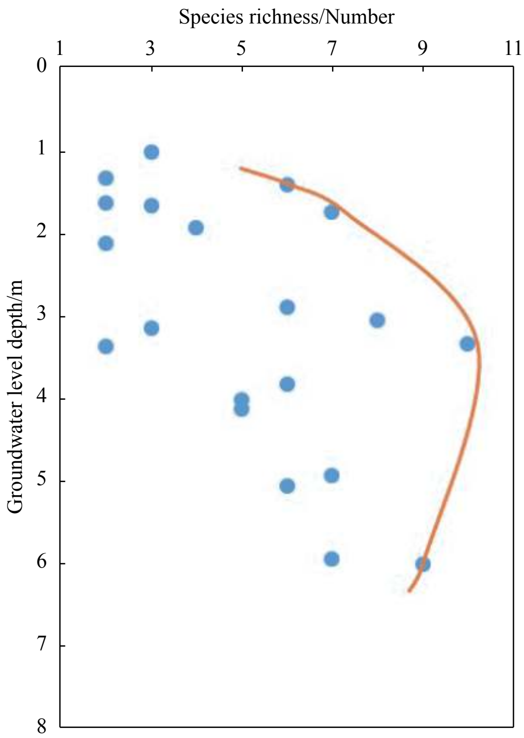

Fig. 6 Relationship between species richness and groundwater level depth in the Oasis-desert ecotone

contrast, when groundwater table was less than 2 m deep, although the vegetation coverage was high, there were relatively few species (usually 1-3 species and *Tamarix chinensis* and long-stem *Phragmites australis* in the near-riparian zone, and *Kalidium foliatum* and *Phragmites australis* in the near-lake area; Table 1). This optimal range of groundwater table depth (2-4 m) was consistent with that reported for desert vegetation in other similar watersheds in the arid zone of northwest China (Wang et al. 2002; Xu et al. 2004; Ma and Wang, 2005; Guo and Liu, 2005; Jin et al. 2010; Cao et al. 2020). Therefore, the ecological groundwater table depth in the Shiyang River watershed was determined to be 2-4 m in the present study. In areas with groundwater levels within this range, vegetation species were generally diverse, species richness was high. The dominant species had large height, large basal stem diameter, and large crown diameter, with a stable and high-level community structure.

3.4 Indicators of the degeneration, qualitative change, and disastrous change of groundwater ecological function

Based on the above findings and existing studies on the relationship between water uptake depth by root systems and groundwater table depth in similar watersheds of the northwest arid zone (Wang et al. 2002; Xu et al. 2004; Guo et al. 2005; Ma et al. 2005; Jin et al. 2010; Huang et al. 2019; Cao et al. 2020), groundwater table depth, NDVI, vegetation type, dominant species abundance, species richness, and vegetation coverage were selected as the main indicators to assess the initial degeneration, qualitative change, and disastrous change of groundwater ecological function, as elaborated below.

(1) Degenerative stage

In this stage, the general groundwater table depth was greater than 5 m, exceeding the optimal growth water table depth and the main root depth of most common natural vegetation in the northwest arid zone of China (Guo et al. 2005; Jin et al. 2010). As a result, most herbs, shrubs, and trees supported by groundwater begin to deteriorate in growth, and herbs and small shrubs even begin to wither (except for drought-tolerant herbaceous shrubs that rely on summer precipitation). This stage was generally characterized by a vegetation coverage less than 35% and species richness less than four species in poor growth conditions, thus retaining only a few relatively abundant dominant species. Therefore, groundwater table depth greater than 5 m was defined in the present study as a major indicator of the degeneration of groundwater ecological function. However, in areas where groundwater ecological function was in a degenerative stage, the surface vegetation would still gradually return to a good ecological status by itself as the groundwater table moved toward the surface.

(2) Qualitative change stage

In this stage, groundwater table depth was greater than 7 m, exceeding the groundwater table depth suitable for most desert vegetation species, including *Elaeagnus angustifolia*, *Tamarix chinensis*, and other small trees (Xu et al. 2004; Ma et al. 2005; Cao et al. 2020). Vegetation species were distributed sparsely and most of them were in an inhibited growth state, withered and dying, leaving only herbs that were sustained by temporarily increased soil moisture originating from precipitation, or *Elaeagnus angustifolia* and *Haloxylon ammodendron* with a dead branch rate exceeding 80%. Therefore, this stage was characterized by generally having only two or less than two species, NDVI of less than 0.1, and vegetation coverage of less than 20%.

(3) Disastrous change stage

In this stage, groundwater table depth was greater than 10 m, but this depth represents the limit that the root system of main desert trees can reach (Guo et al. 2005; Jin et al. 2010; Cao et al.

2020). Therefore, most of the desert vegetation species died at this stage. Vegetation coverage reduced nearly to zero and the surface had mostly been desertified, generally with less than 5% vegetation coverage and NDVI of less than 0.08. The remaining species generally consisted of only herbs maintained by single rainfall events or *Nitraria tangutorum*, which is not strongly dependent on groundwater (Yang et al. 2000; Jin et al. 2016).

3.5 Comprehensive evaluation of groundwater ecological function

(1) Indicator selection and confirmation

The groundwater table depth and natural vegetation quadrat joint survey and the analysis in Sections 4.1-4.4 revealed that groundwater table depth, NDVI, vegetation type, species richness, vegetation coverage, and dominant species abundance are the main indicators for use in investigating and evaluating groundwater-dependent vegetation ecosystems. However, given the high correlation between NDVI and vegetation coverage, we selected groundwater table depth, NDVI, vegetation type, species richness, and dominant species abundance as five independent indicators for evaluating the groundwater ecological function in the Shiyang River watershed. These five important indicators, independent of each other, constitute the indicator set *U*.

(2) Critical values and membership calculation of indicator

Groundwater ecological function evaluated in terms of each of the five indicators was divided into four grades V_1, V_2, V_3, and V_4, all of which constitute the judgment set *V*, where V_1 represents a good state of groundwater ecological function, V_2 represents mild deterioration or degeneration of groundwater ecological function, V_3 represents moderate deterioration or qualitative change of groundwater ecological function, and V_4 represents severe deterioration or disastrous change of groundwater ecological function. Moreover, to quantify the degree of influence of each factor on groundwater ecological function, the four grades V_1, V_2, V_3, and V_4 were scored between 0 and 1 (1, 0.7, 0.5 and 0.3, respectively), with a higher score indicating better groundwater ecological function. The values of groundwater table depth, NDVI, species richness, and dominant species abundance corresponding to the grades V_1–V_4 are shown in Table 2.

Vegetation type is scored according to the diversity of vegetation types and the dominant species. Community succession causes the total energy of the community to increase, leading to an increase in the number of species types, as well as an increase in the community structure complexity and stability, with trees appearing and dominating the community at the highest stage of community succession. In the present study, vegetation type was given a score of 1 only when the following two conditions were both met: (1) trees, shrubs, and herbs were all present; and (2) their abundance decreased in the order trees > shrubs > herbs. Vegetation type score decreased as the number of vegetation types decreased and/or the dominant species changed, as shown in Table 3.

After determining the evaluation indicators and their critical values, the membership of each factor to the judgment set was calculated using the fuzzy transformation matrix R according to Equation (2). The matrix element corresponding to a given evaluation factor and a given judgment (i.e. a grade of groundwater ecological function) can be calculated by comparing the observed value of the factor with its critical values. The membership calculation was conducted in a fuzzy manner to avoid a "jump" phenomenon in which two slightly different judgment scores point to two different grades (differing by one grade) of groundwater ecological function, thereby allowing the scores to smoothly change from one grade to another. For an indicator whose observed value fell between two critical values, its grade score was calculated according to the linear ratios of the observed value to two adjacent critical values. The grade score of a factor value less than the critical value of V_4 was calculated in a linear decreasing manner. However, given that surface

Table 2 Grading value of comprehensive evaluation index of groundwater ecological function

Index	V_1	V_2	V_3	V_4
Groundwater level depth/m	2-4	5	7	10
NDVI	> 0.7	0.2	0.13	0.08
Species richness	≥ 5	4	3	2
Abundance of the dominant species	≥ 5	4	3	2
Rating value	1	0.7	0.5	0.3

Note: when groundwater table depth was less than 2 m, its score was calculated in a linearly decreasing manner. For dominant species abundance, it may be scored 7 indicating "extremely abundant", 6 "highly abundant", 5 "abundant", 4 "fairly many", 3 "not many", 2 "sparse", and 1 "only one plant."

Table 3 Grading value of vegetation type index of groundwater ecological function

Vegetation type	Value
Arbor > Shrub > Herb	1.00
Shrub > Arbor > Herb	0.83
Arbor > Herb	0.67
Arbor > Shrub	0.83
Shrub > Herb	0.67
Shrub only	0.57
Herb > Shrub	0.50
Herb only	0.33

soil salinization affects vegetation growth when groundwater table depth is less than 2 m, the grade score of groundwater table depth in such cases was also calculated in a linear decreasing manner.

(3) Determination of evaluation indicator weights

The relative weights of the five indicators are determined by combining the hierarchical method and expert scoring method, which are 0.45, 0.15, 0.15, 0.15 and 0.1 for groundwater table depth, NDVI, vegetation type, species richness, and dominant species abundance, respectively. For a given factor at a given site or plot, its observed value and its critical values were compared to determine its grade score, which was multiplied by the weight to give a weighted score. The weighted score of each factor was then summed to give an overall score for the investigated site or plot. An overall score of less than 0.7, 0.5 and 0.3 indicates mild, moderate, and severe degeneration of groundwater ecological function, respectively.

(4) Comprehensive evaluation results

The observed values of the indicators were interpolated to grid cells with a spatial resolution of 30 m. For each grid cell, we calculated the overall score of groundwater ecological function according to the aforementioned grade scores and weights of the factors. Finally, the evaluation results of the groundwater ecological function were compiled to generate a map of the oasis–desert transition

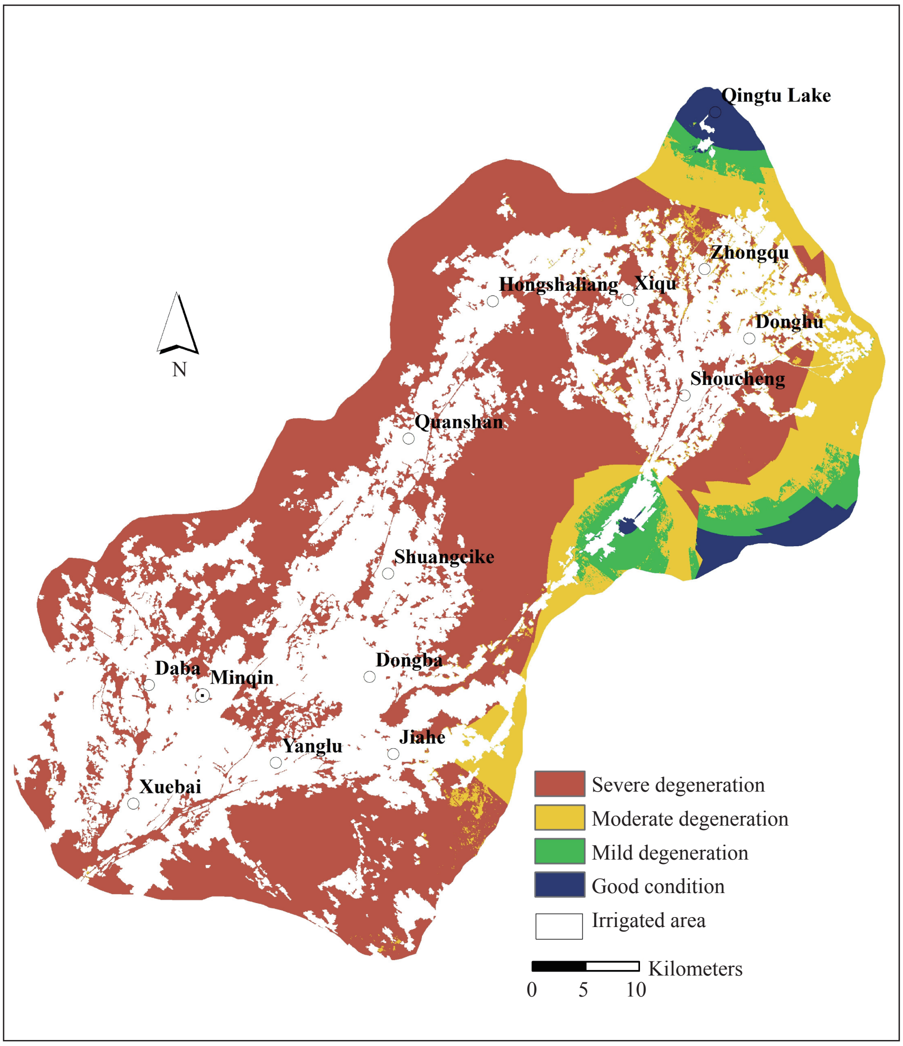

Fig. 7 Evaluation of groundwater ecological function in the Oasis-dessert area of the lower Shiyang River Basin

zone of Minqin basin in the lower Shiyang River watershed (Fig. 7). The overall score-based grading criteria and their interpretations are presented in Table 4.

As shown in Fig. 7, groundwater ecological function was generally poor in the study area. The areas with good state of groundwater ecological function accounted for only 3.5% of the total area, and they were mainly distributed in the Qingtu Lake area and the southeast area of Shoucheng township. The areas with mild and moderate degeneration of groundwater ecological function accounted for 5.5% and 16.3%, respectively, and were mainly distributed in the southern part of the Qingtu Lake area and part of the eastern transition zone of Minqin. Most of the areas have undergone severe degeneration of groundwater ecological function. Severe degeneration areas covered 1 397.9 km^2 and account for 74.7% of the total area. In particular, the area (477 km^2) along the edge of the transition zone in the west side of the Minqin basin is located downwind of Badain Jaran Desert and is the key area for the ecological protection of the oasis–desert transition zone of Minqin basin, and it is also the priority area for ecological restoration and management in the Shiyang River watershed.

4 Conclusions and recommendations

4.1 Conclusions

The ecological groundwater table of the oasis–desert transition zone in the Shiyang River watershed is positioned at 2-4 m from the surface. At this depth range, vegetation species are diverse, with NDVI, species richness, and vegetation coverage reaching the maxima. Indicators for the degeneration, qualitative change, and disastrous change of groundwater ecological function mainly consist of groundwater table depth, NDVI, vegetation type, dominant species abundance, species richness, and vegetation coverage. The groundwater table depth corresponding to the degeneration, qualitative change, and disastrous change of groundwater ecological function was approximately 5 m, 7 m and 10 m, respectively. As groundwater ecological function degenerated, there was a decrease in surface vegetation coverage and species richness, with vegetation types and dominant species becoming less diverse until only a single species was dominant. When groundwater table depth exceeded 10 m, there was generally no clear correlation between surface vegetation and groundwater.

A comprehensive multi-indicator evaluation method was established for groundwater ecological function in the Shiyang River watershed based on the characteristic indicators of groundwater ecological function. It was found that the overall groundwater ecological function in the lower Shiyang River watershed was poor. The areas with no, mild, and moderate degeneration of groundwater ecological function accounted for 3.5%, 5.5%, and 16.3% of the total study region, respectively, mainly distributed in the Qingtu Lake area and the southeast area of Shoucheng Township. Degeneration of groundwater ecological function occurs in most areas, covering 1 397.9 km^2 or 74.7% of the study region. In particular, the area (477 km^2) along the west side of the basin is located downwind of Badain Jaran Desert and is the key area for the ecological protection of the Minqin oasis. It is also an area with severe degeneration of groundwater ecological function. It is urgent to restore the groundwater ecological function in the Shiyang River watershed.

4.2 Recommendations

The sharp increase in population, human activities and agricultural irrigation area has caused overexploitation of groundwater resources in the Shiyang River watershed and a considerable lowering of the groundwater table. This is the main reason for the degeneration and shrinkage of natural vegetation in the oasis–desert transition zone, severely affecting the harmonious and sustainable development of soil and water resources, the ecological environment, and the social economy. The oasis–desert transition zone plays an important role in oasis stabilization and desertification control, and it is also an ecologically sensitive zone. Moreover, it represents a key target for human-controlled oasis protection and restoration, and restoring the groundwater table is the key to restoring groundwater ecological function in the watershed and achieving ecological rehabilitation.

The expected next step involves consideration of the mountain–river–forest–farmland–lake–

Table 4 The total score of groundwater ecological function comprehensive evaluation and its indication

Grading	V_1	V_2	V_3	V_4
The total score	>0.7	0.7-0.5	0.5-0.3	<0.3
Indication	Good condition	Mild degermation	Moderate degeneration	Severe degeneration

grass–sand system to restore groundwater table and develop site-specific, targeted measures for restoring groundwater ecological function at different groundwater levels. In areas of initial degenerated groundwater ecological function, irrigation wells should be closed and crop-planting activities should be prohibited to elevate the groundwater table and allow the surface vegetation to gradually restore to its normal state. In areas where groundwater ecological function has undergone qualitative or disastrous change, such as the oasis–desert transition zone on the west side of Minqin basin, most groundwater-dependent vegetation species have died, and thus, it is necessary to combine irrigation restriction with grain-for-green projects as well as artificial afforestation and seeding to restore natural vegetation ecology. For example, it is desirable to increase the number of small trees (e.g. *Haloxylon ammodendron* and *Elaeagnus angustifolia*) and conduct ecological forest and grass planting, to allow the vegetation to eventually serve as an effective barrier against the three major wind belts of the Badain Jaran Desert. In the Qingtu Lake area, it is necessary to continue the existing water delivery measures and gradually increase their impact on the vegetation ecology around the wetlands. When implementing policies of closing irrigation wells, prohibiting crop-planting activities, returning farmland to forest and grassland, and diverting water from other areas, it is necessary to consider water resources are the key factor determining the geographic scope of urban, agricultural, and residential land use as well as the magnitude of socioeconomic production. This approach could achieve sustainable development of the Shiyang River watershed in terms of its population, economic, resources, and ecological aspects. In this way, the oasis could gradually become an effective barrier blocking the convergence of the Badain Jaran Desert and the Tengger Desert.

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