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PAPER

Modelling the response of vegetation restoration to changes in groundwater level, based on ecologically suitable groundwater depth

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Abstract

Groundwater-level fluctuations at a large scale have a significant effect on the preservation and restoration of vegetation. This study determined suitable groundwater depth within which natural vegetation grows well, and analysed the effect of groundwater regulation on vegetation restoration in Tianjin City, northern China. Normal and lognormal distributions were used to fit the curve of the relation between vegetation and groundwater depth. The groundwater depth range corresponding to the higher frequency of vegetation distribution was regarded as the 'suitable water depth' range for vegetation growth. The suitable groundwater depth for shrub growth was 3–5 m and for grass growth 1–3 m. A groundwater flow model predicted the future changes of groundwater depths in the vegetation distribution area under the condition that the current levels of groundwater extraction are maintained. The results showed that there is potential for the extraction of groundwater in shrubland areas, but for grassland areas the water-table elevation showed a downward trend, meaning that water shortages in some areas may be more severe in the future. Finally, based on the current groundwater extraction regime, two regulation schemes were developed: (1) for shrubland, groundwater extraction was reduced by 10% in the ecological water deficit areas, and extraction was increased by 10% in the ecological water surplus and suitable areas, and (2) for grassland, groundwater recharge was increased by the restoration of the wetland areas. In conclusion, the groundwater depths in most of the area would be more suitable for vegetation growth under the regulation schemes.

Keywords Numerical modeling · Vegetation restoration · Salinization · Ecology · China

Introduction

The state of the natural vegetation is an important indicator of the health of the ecosystem, with implications for the control of desertification and preservation of biodiversity. The influence of ecological factors on natural vegetation is comprehensive because vegetation occurs in an integrated environment. The growth status of vegetation results from the combined effects of climate, soil type and landform, especially in terms of the water-table depth upon which vegetation depends (Chui et al. 2011; Mata-González et al. 2012; Sommer and Froend 2014; Comte et al. 2014; Krogulec et al. 2016).

Many scholars have carried out studies on the relationship between groundwater and natural vegetation. Xu et al. (2007) took the ecological water conveyance project that transfers water from the Bosten Lake, to Daxihaizi Reservoir, and finally to the Taitema Lake in China as a case study to analyze the dynamic change of the groundwater depth, the vegetation responses to the elevation of the water table, as well as the relationship between the groundwater depth and

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the natural vegetation in the Lower Tarim River. Loheide and Gorelick (2007) simulated hydrologic behaviour with a finite element model of variably saturated groundwater flow and analysed the effects of stream incision and restoration on vegetation type and pattern. Patten et al. (2008) drew on historic groundwater data and groundwater modelling and studied the potential effects of groundwater withdrawal and water-table decline on spring-supported vegetation. Laidig et al. (2010) developed vegetation models, which linked groundwater hydrology models and landscape level applications, and predicted the potential changes in vegetation associated with water-table declines. Cheng et al. (2011) developed an eco-hydrology model to evaluate the influence of water and salt on vegetation (IWSV) in the semi-arid desert regions and determined the suitable water and salt conditions for three plant species (*Artemisia ordosica*, *Salix psammophila* and *Carex enervis*). Goedhart and Pataki (2011) discussed the effect of groundwater depth decreases on different vegetation types in Owens Valley, California (USA), and showed that the grass cover declined at sites with deeper water tables while shrub cover remained constant. Lv et al. (2012) used remote sensing images of vegetation index (normalized difference vegetation index, NDVI) and field data of the depth to water table (DWT) to assess the response of the vegetation distribution to the increase of DWT at the regional scale. Kopeć et al. (2013) investigated the relationship between the vegetation and DWT in one of the largest wetlands in central Poland and found that restoration was possible through the limitation or a total discontinuation of agriculture, without the need for hydro-technical engineering which would result in DWT changes in the study area. Palanisamy and Chui (2013) used a spatially varying, coupled groundwater-vegetation growth model to investigate the survival mechanism of wetland herbaceous plants and demonstrated the ability of the groundwater-vegetation response model to facilitate an understanding of plant development and a hierarchy of important factors. Zhu et al. (2015) developed an integrated framework to assess the impact of precipitation and groundwater on vegetation growth in the Xiliao River Plain of northern China and found that there is an increased correlation between the groundwater depth and vegetation growth. Jin et al. (2016) evaluated moderate resolution imaging spectroradiometer (MODIS) time-series data for monitoring vegetation variation in the Qaidam Basin in northwestern China and revealed that the vegetation fluctuation depends on various attributes such as climate change, topographic elevation, water-table depth, and total dissolved solids (TDS). Koirala et al. (2017) used several high-resolution data products to show that the spatial patterns of ecosystem gross primary productivity and water-table depth are correlated during at least one season, in more than two-thirds of the vegetated area across the world. The aforementioned studies showed that vegetation growth, distribution and succession were closely related to the groundwater environment, and the most important factors affecting vegetation growth were the elevation of the water-table and groundwater mineralization. Vegetation grows well only where it occurs above the optimal water-table depth and groundwater salinity ranges (Dahlhaus et al. 2010; Wang et al. 2011; Lv et al. 2012; Sommer and Froend 2014).

The city of Tianjin is crisscrossed by irrigation canals and ditches, dotted with lakes and wetlands. The ecological environment is closely related to the groundwater depth. With the increasing demand for water, the groundwater has been over extracted, which has caused serious land subsidence issues and threatened vegetation growth in Tianjin, especially in the southern region. How to restore the vegetation effectively is an important question that managers must address; however, most studies on vegetation restoration in Tianjin are based on the ability of the soil seed bank to restore vegetation (Mo et al. 2012; He et al. 2013), and there are few studies about how to improve the vegetation growth environment by adjusting the groundwater depth. External sources of water will effectively ease water shortages in some regions south of Tianjin after the South-to-North Water Transfer Project is fully implemented, and part of the water can be used to restore the ecological environment by adjusting groundwater extraction to regulate groundwater from unsuitable depth ranges to the suitable depth ranges to ensure vegetation growth. In addition, in the north of Tianjin, groundwater recharge is more effective, and the groundwater resource is sufficient; thus, there is a potential to extract the groundwater resource. Improving the groundwater environment and utilizing water resources rationally is the focus of this paper.

Data and methods

Study area

The plain of Tianjin is located at the east longitude 116°42′05″ ~ 118°03′31″ and northern latitude 38°33′57″~ 40°00′07″; it is 172 km from north to south and 104 km from east to west, it covers approximately 11,000 km^2, and consists of 13 counties (Fig. 1). Tianjin is bounded by the Bohai Sea in the southeast and the Yanshan Mountain in the north. The terrain is flat from the piedmont plain to the coastal plain, while slightly sloping from the northwest to southeast where the piedmont flood product and alluvial fan group are at an elevation (Yellow Sea height datum of China) between 50 and 10 m. The adjacent areas are alluvial plain and fluvial plain at an elevation between 10 and 2.5 m, and the southeast region is the sea product plain at an elevation between 1 and 2 m, which is composed mainly of salt pans. The average annual

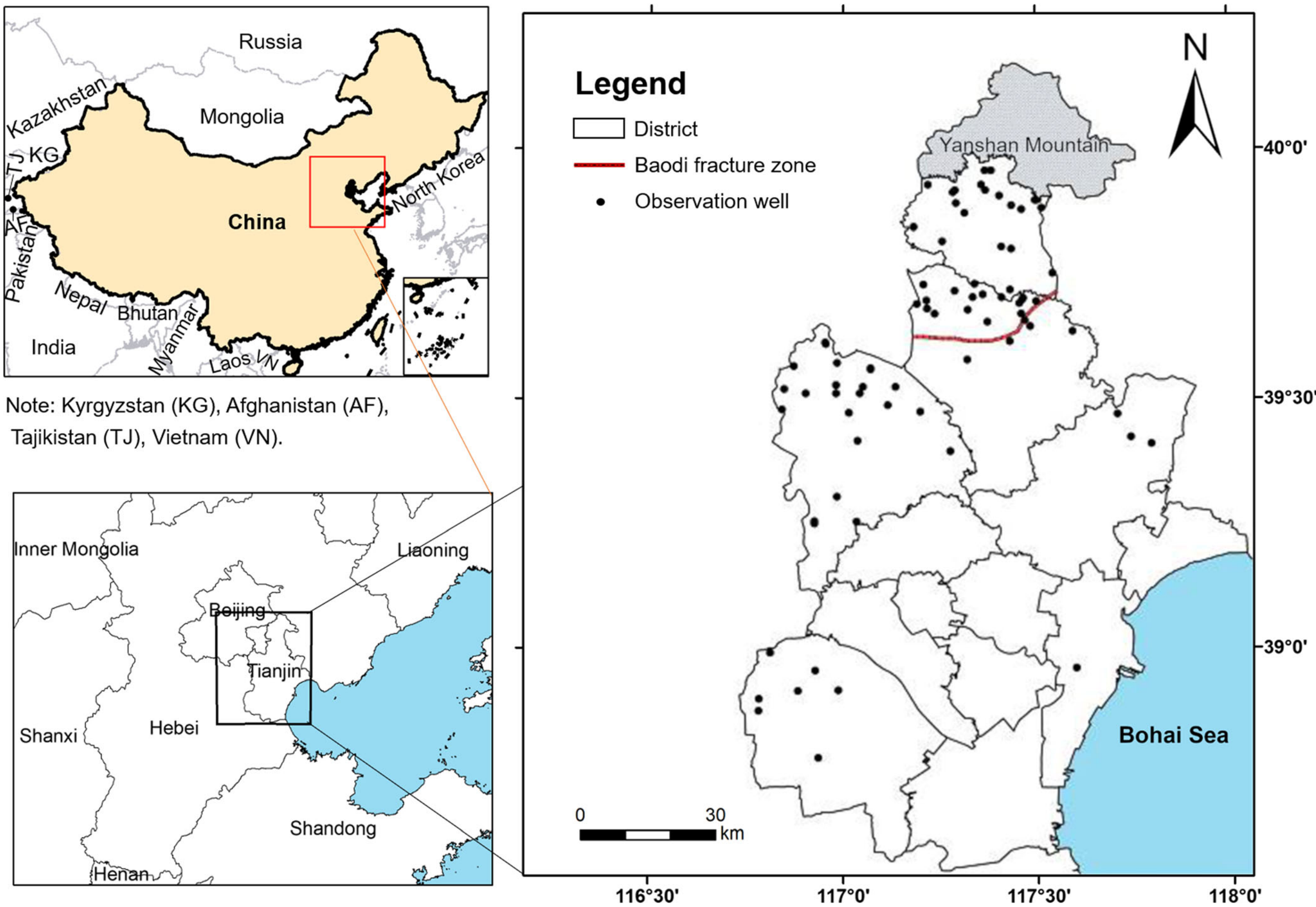

Fig. 1 The location of Tianjin in China

temperature in the study area is 11–12 °C. The average annual precipitation is 582 mm, mainly concentrated in June to October. The average annual water surface evaporation is 1,000–2,000 mm.

Data

Meteorological data (precipitation and evaporation) from 1998 to 2008 are used to build the three-dimensional (3D) groundwater model for shallow aquifers and come from China's meteorological data sharing service system (China Meteorological Administration 2017). The data from 1998 to 2008 used in the model, including irrigation water consumption, river and reservoir-infiltration-water consumption, and groundwater extraction consumption, are provided by the Water Resources Survey and Management Center of Tianjin (WRSMC). The data on groundwater depths and degree of mineralization for 74 groundwater observation wells from 2006 to 2008 are provided by WRSMC (Fig. 1). The remote sensing data for the vegetation of Tianjin for 2008 (resolution is 100 m) provided by the Institute of Remote Sensing Application Chinese Academy of Sciences (RSACAS) is used to extract vegetation distribution data.

Methods

The determination of optimal groundwater depth for vegetation growth

The groundwater depth range in which natural vegetation grows well is called the suitable groundwater depth, and beyond this range, vegetation will wilt or die; therefore, the groundwater depth should be controlled within a suitable range. There are many factors that influence the distribution of vegetation. Generally, these factors can be divided into two categories—one category contains natural factors such as topography, climate, CO_2 concentration, groundwater salinity and groundwater depth factors; while the other category contains human activities such as afforestation, reclamation, grazing, agricultural modernization and urbanization. For a small-scale area such as the Tianjin Plain, where climate, topography and CO_2 concentration do not change substantially across the region, these factors have a minimal impact on the vegetation distribution. There have been no large-scale afforestation, grazing or other human activities in recent years; thus, human activities have minimally impacted the vegetation distribution.

However, the groundwater depth and salinity change considerably across the region. The groundwater depth in Tianjin decreases from north to south. The groundwater depth in the northern plain region of Tianjin is 10–15 m, the middle plain region is 4–10 m, the south plain region is less than 4 m, and the eastern coastal region is less than 2 m. The salinity of the groundwater increases from north to south, from the piedmont plain to the coastal plain. Except for the northern plain region, the salinity is larger than 1 g/L, which does not meet standards for drinking water quality of China (GB 5749–2006)—for example, the salinity of groundwater in the midwestern region is in the range 1–3 g/L, the southern region is 3–5 g/L, the eastern coastal region is more than 5 g/L, and the ocean-front region is more than 10 g/L and can be as high as 81.8 g/L. Given the aforementioned, the groundwater salinity in these regions is more than 1 g/L, which does not meet standards for drinking water quality of China (GB 5749–2006). Therefore, the study selected groundwater depth and salinity as the main factors affecting the distribution and abundance of vegetation. Groundwater depth can be an indicator used to identify land-surface vegetation patterns (Goedhart and Pataki 2011; Jin et al. 2016), and the stress of salinity on vegetation inhibits vegetation growth. When the salinity is between 0.5 and 5.5 g/L, vegetation grows well; when the salinity is more than 6 g/L, most vegetation cannot grow.

Compared with the groundwater depth data, the observations of salinity in space are sparse. If the salinity raster map is plotted by using these observations, the space difference error will be a large. Moreover, it is also difficult to regulate salinity in the short term; thus, the regulation and control schemes associated with future trends as part of this study (years 2020 and 2030) do not consider salinity as a regulatory factor. Additionally salinity is only used to discern the different vegetation distributions according to its current distribution. According to the vegetation density map and groundwater salinity map, the optimal groundwater salinity ranges for shrubland and grassland were ascertained.

To eliminate the impacts of abnormal water-table-elevation fluctuations on the determination of suitable vegetation water depth, this study used the monthly average data of shallow groundwater observation wells from 2006 to 2008. The groundwater-depth-raster map was plotted by the Kriging interpolation function of a geographic information system (GIS). Kriging is most appropriate when a spatially correlated distance or directional bias in the data is known, and it is often used for applications in soil science and geology (Varouchakis and Hristopulos 2013). For comparison and analysis, the groundwater-depth-raster map had the same resolution (100 m) as the vegetation-remote-sensing data. The groundwater depth data were divided into different groups at intervals of 0.1 m, and then the numbers of forest and grassland vegetation grids within the intervals were counted and called vegetation abundance.

Several ecological studies (Chapman 2010; Cai et al. 2011; Bullock et al. 2017) showed that plants and environmental elements often conform to the nonlinear quadratic curve model, which is known as the unimodal model, especially in normal distributions. The study used a normal distribution (Eq. 1) and a lognormal distribution (Eq. 2) to match the shrub and grass vegetation data by using R software. It was concluded that the groundwater depth range corresponding to the higher frequency of vegetation distribution was regarded as the vegetation suitable water depth range.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (1)$$

$$f(x) = \frac{1}{x\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{\ln(x)-\mu}{\sigma}\right)^2} \quad (2)$$

where x is the environmental factor (groundwater depth in this study, m); $f(x)$ is the biomass reflecting vegetation growth status (vegetation abundance in this study, %); μ and σ are the parameters of the normal distribution and lognormal distribution, represent mean and variance, respectively.

The effect of groundwater regulation on the vegetation

Each type of vegetation has its suitable groundwater depth range. Within this range, the vegetation can achieve the best growth, while outside of this range, vegetation growth can be restricted; therefore, it is necessary to manage groundwater depth, from unsuitable depth ranges to the suitable depth ranges, to ensure vegetation growth. To achieve this, a groundwater flow model was built. The groundwater flow model is an effective tool to simulate and predict groundwater depths by changing inputs of the model. The established groundwater flow model of the shallow aquifer in Tianjin (Li et al. 2016) was used to simulate shallow groundwater-level variation under different regulation and control schemes.

The groundwater flow in the city of Tianjin was modelled using the MODFLOW package (Harbaugh 2005), developed by the US Geological Survey (USGS). The pre- and post-processor GMS package (Owen et al. 1996), developed by the Environmental Modeling Research Laboratory at Brigham Young University (USA), was used to input data and output results. The study area is represented using cells that are 500 m × 500 m. The established groundwater flow model of the shallow aquifer in Tianjin (Li et al. 2016) has high accuracy (Figs. 2 and 3). The model grid consists of 346 rows and 248 columns, with a total of 42,628 active cells. Based on the available data, the period from January 2006 to December 2008 was selected as the identification and

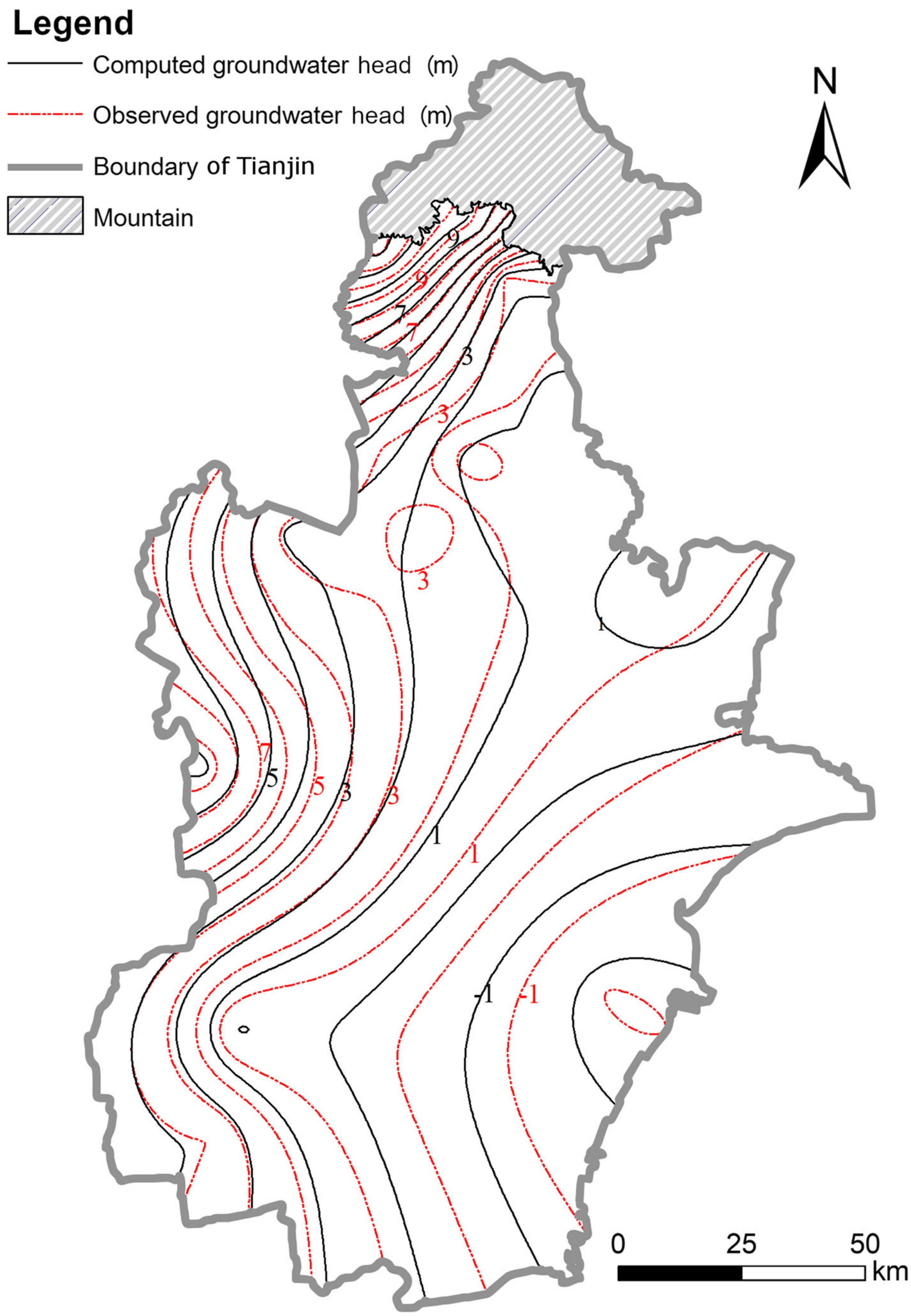

Fig. 2 Comparison of the simulated and observed water-table elevations in 2008

calibration period for the model, in which 1 month was used as a stress period that was divided into two time steps (total of 36). The hydrogeology parameters used in groundwater flow models are mainly divided into two categories. One category includes the parameters used for calculating source and sink terms such as the precipitation infiltration coefficient and the irrigation regression coefficient. The other category contains the hydrogeology parameters for an aquifer such as horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield. The initial values of these parameters were derived from the pumping tests. It was assumed also that horizontal hydraulic conductivity is 10 times larger than the vertical hydraulic conductivity. The detailed description of the MODFLOW model parameters are in the literature (Li et al. 2016). To validate the model, the model results were compared with a 3D numerical groundwater flow model established by Li et al. 2012. It was concluded that the accuracy of the current model was higher than the model established by Li et al. 2012 (see also Li et al. 2016).

Therefore, the established groundwater flow model can be used to simulate future groundwater depths under different regulation schemes. First, the groundwater depth in

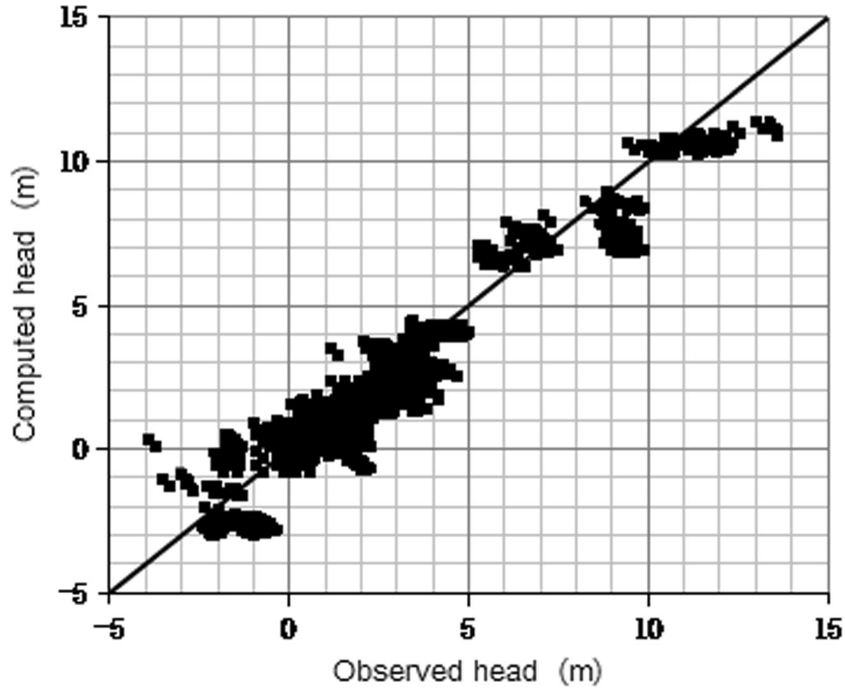

Fig. 3 Comparison of the observed groundwater heads and the heads simulated by the transient-state calibration

late December 2008 was used as the initial groundwater depth. Second, the mean annual precipitation, irrigation, evaporation, and lateral inflow from 1998 to 2008 (Table 1) were used as the fixed parameters of the model, and the amount of groundwater extraction from the shallow aquifer and wetland infiltration were the variables parameters. Third, the parameter data derived from the calibration of the model were used as the fixed parameters of the prediction model; thus, the groundwater model can be used to simulate and predict the future groundwater scenarios. Finally, the mean annual precipitation, irrigation, evaporation, and lateral inflow from 1998 to 2008 were input into the preceding model, and the groundwater regulation schemes, which were set by changing the amount of groundwater extraction and increasing wetland infiltration, were inputs into the model; thus, the prediction results for the future planning period can be obtained.

In some areas where the groundwater depth was shallower than the suitable depth, the amount of groundwater extraction can be increased; in other areas, the groundwater depth was deeper than the suitable depth, and more water was needed to raise the water level. The ecological water supplement scheme was achieved by restoring the wetland areas, and the increasing infiltration of wetlands as a result of the scheme can be calculated by Eq. (3).

$$Q_i = \lambda \cdot A \cdot 10^3 \qquad (3)$$

where Q_i is the additional infiltration of water in the wetlands (m^3/day); λ is the rate of natural wetland infiltration (mm/day); and A is the area of wetland restoration (km^2).

Results

The determination of optimal groundwater depth for vegetation growth

Based on the vegetation distribution and salinity zoning, the distribution areas of shrub (Fig. 4) and grass (Fig. 5) vegetation were determined. From the two figures, it can be seen that the groundwater salinity in the distribution area of shrub vegetation was less than 3 g/L, and the salinity in the distribution area of grass vegetation was greater than 3 g/L. The normal distribution and lognormal distribution were used to fit the curve of the relation between shrub vegetation and groundwater depth and the relation between grass vegetation and groundwater depth (Figs. 6 and 7). The parameter values (μ, σ) of the normal distribution and lognormal distribution are shown in Table 2.

The normal distribution is symmetrical, and the lognormal distribution is a right skew distribution with many small values and fewer large values. Based on Figs. 6 and 7, the normal distribution is best suited for the data, and the lognormal distribution does not fit well for both endpoints. The conclusion is consistent with several other ecological studies (Chapman 2010; Cai et al. 2011; Bullock et al. 2017).

It was observed that the shrub vegetation probability density curve peak appeared in the 3–5 m range, which showed that shrub vegetation appeared most frequently within the groundwater depth range, namely, the range for suitable groundwater depth of shrub vegetation growth was 3–5 m. When the groundwater depth is more than 7 m, shrub vegetation does not grow well and it depends mainly on

Table 1 The model input data

Year	Precipitation (mm)	Evaporation (E601) (mm)	Irrigation (10^6 m^3)	Lateral inflow (10^6 m^3)	Groundwater extraction (10^6 m^3)
1998	623	968	1,049	698	12,245
1999	418	1,059	1,295	698	14,188
2000	448	1,151	1,191	698	22,305
2001	484	1,095	997	698	22,500
2002	340	1,160	1,071	698	21,900
2003	724	1,043	1,132	698	19,900
2004	526	1,135	1,218	698	19,383
2005	621	1,081	1,378	698	25,308
2006	324	1,068	1,332	698	25,801
2007	565	1,052	1,371	698	26,012
2008	644	1,061	1,200	698	23,591

E601, a modified GGI-3000 pan, appears to have consistently good performance when compared to the 20-m^2 evaporation tanks

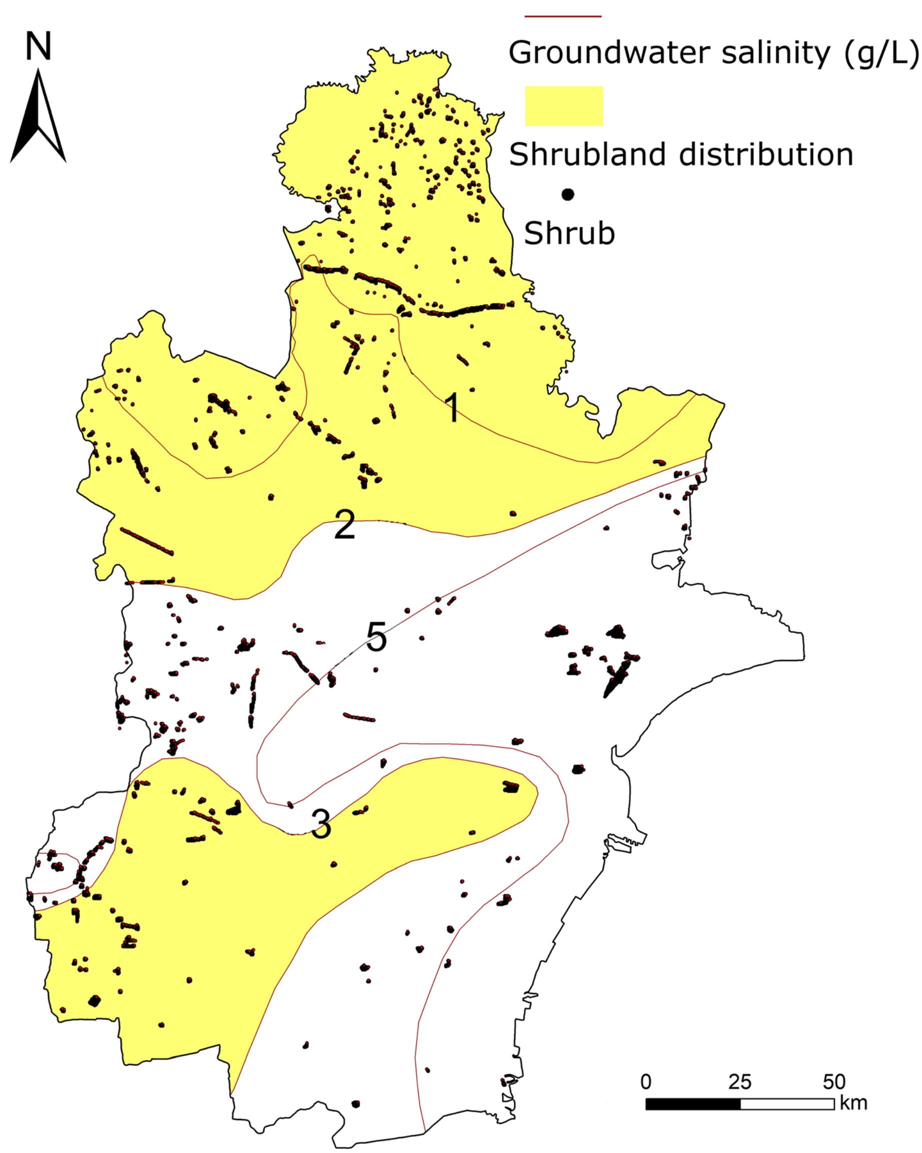

Fig. 4 The distribution of shrub vegetation in the study area

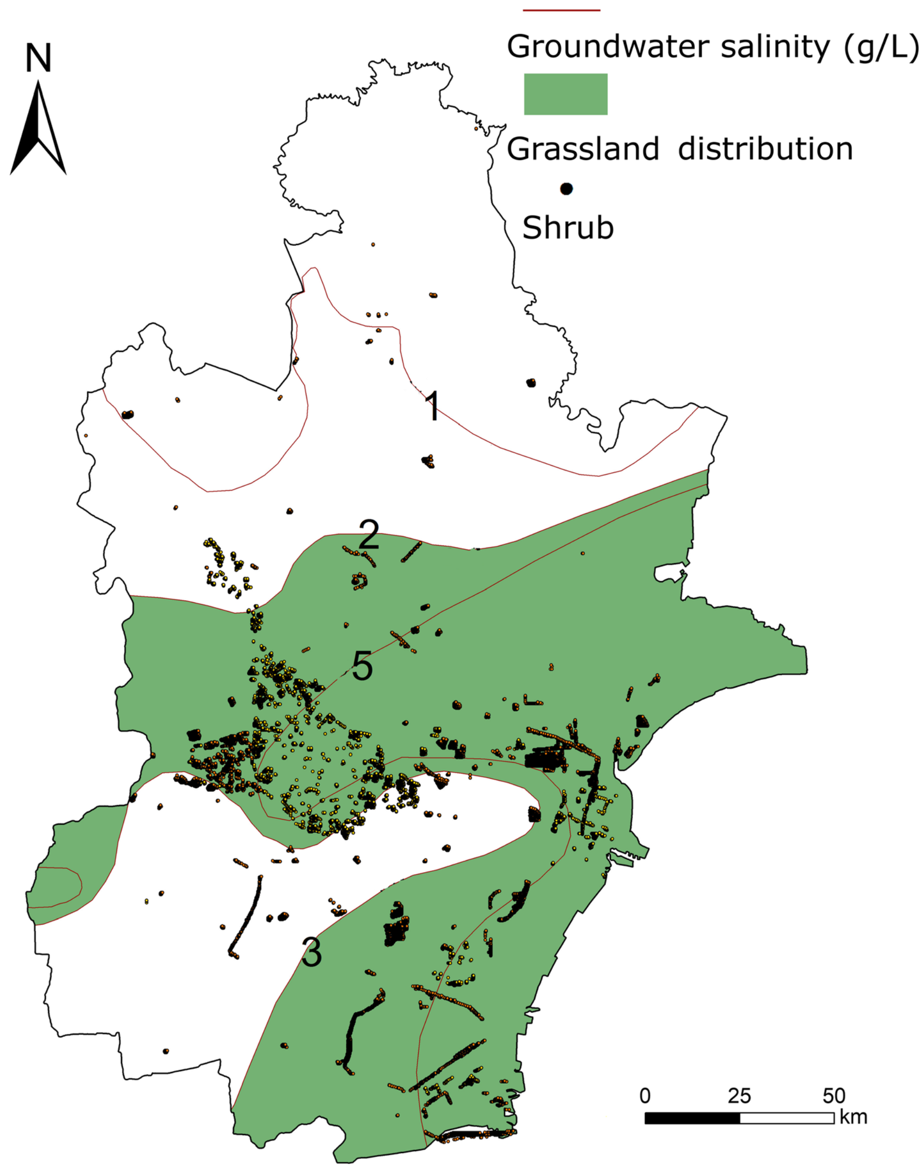

Fig. 5 The distribution of grass vegetation in the study area

precipitation; when the groundwater level falls to 10 m depth, shrub vegetation reaches its growth limit. Similarly, the grass vegetation probability density curve peak appeared in the 1–3 m range, which illustrated that the range for suitable groundwater depth of grass vegetation growth was 1–3 m. When the groundwater depth is more than 4 m, most grass vegetation will stop growing or die, and only a few deep-rooted grasses can survive.

Using groundwater depth regulations to restore vegetation

Classification of ecological zoning

Using the shallow groundwater observation wells data from 2008, the shallow groundwater depth in Tianjin was interpolated by the Kriging interpolation function of GIS. The groundwater depth distribution was superposed with the vegetation distribution, and the groundwater depth distributions in the shrubland and grassland areas were determined (Fig. 8).

Based on the concept of suitable depth range for shrub and grass growth, ecological zones were classified. The regions where the groundwater depth was greater than the suitable depth were classified as ecological water deficits, the regions where the groundwater depth was in the suitable depth range were classified as ecological water optima, and the regions where the groundwater depth was less than the suitable depth were classified as ecological water surpluses. Figure 8 shows that the groundwater depth was more than 5 m in most areas of the northern shrubland distribution, which was in a state of severe water shortage and not suitable for shrub growth.

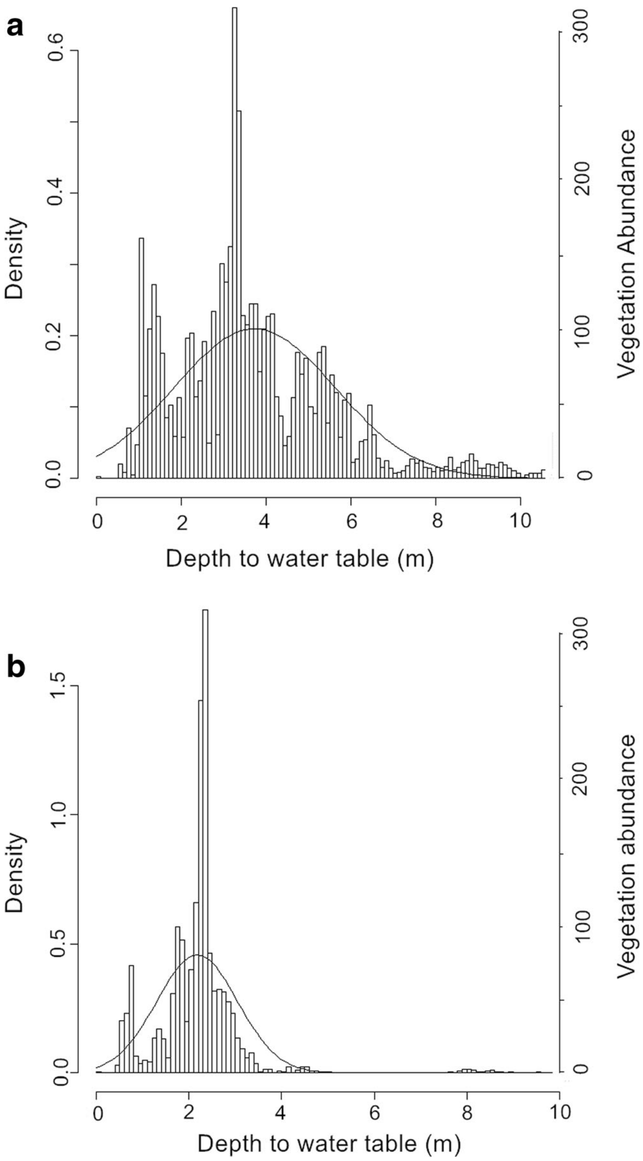

Fig. 6 The probability density curves of vegetation by a normal distribution for: **a** shrubs; **b** grass

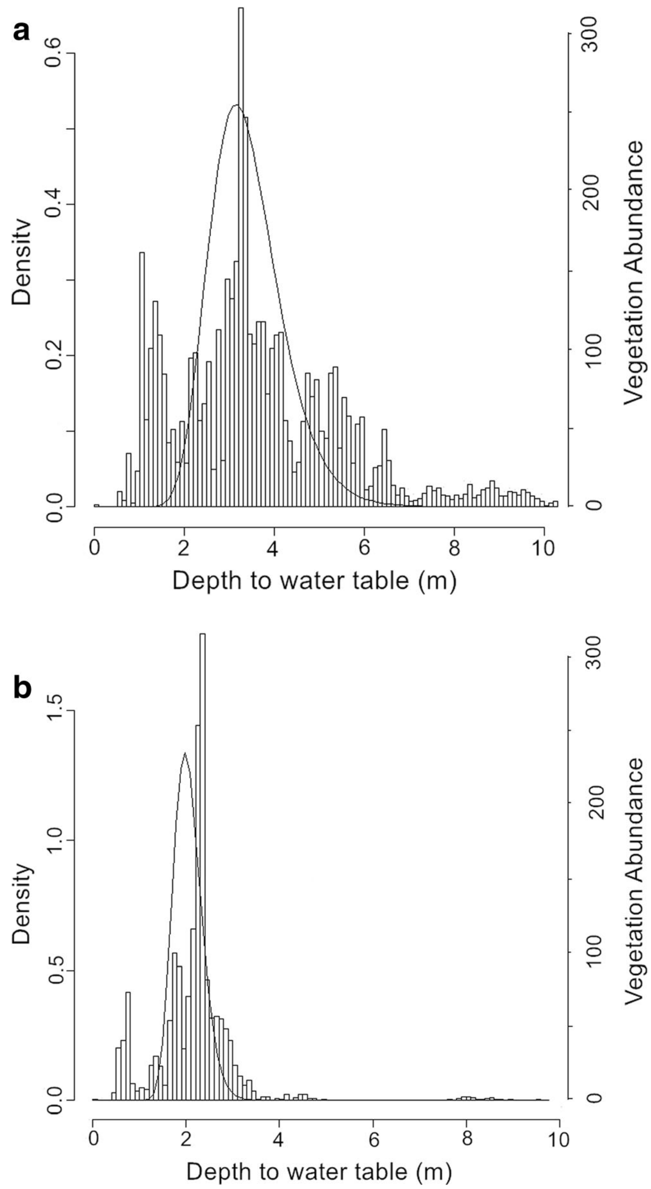

Fig. 7 The probability density curves of vegetation by lognormal distribution for: **a** shrubs; **b** grass

However, the majority of the groundwater depth in the central and southwestern regions was less than the suitable depth for shrubs; thus, these areas were an ecological water surplus. Most of the areas were categorized as the ecological water optima regions for grass (Fig. 8), and only a small number of regions in the southwest were categorized as ecological water deficit.

Future vegetation restoration under the present groundwater extraction conditions

The groundwater extraction data from 2008 were used as the input variables of the groundwater flow model to predict groundwater depth changes in vegetation distribution areas in 2020 and 2030 (Fig. 9a,b) and to calculate the changes in the ecological zone areas (Table 3).

For the shrubland regions, from 2008 to 2020, the area of ecological water deficit decreases by 73.6%, while the area of ecological water optima increases by 232%, and the area of

Table 2 The parameters of the normal distribution and lognormal distribution

Parameter	Normal distribution		Lognormal distribution	
	Shrub	Grass	Shrub	Grass
μ	3.73	2.10	1.20	0.70
σ	1.90	0.87	0.23	0.15

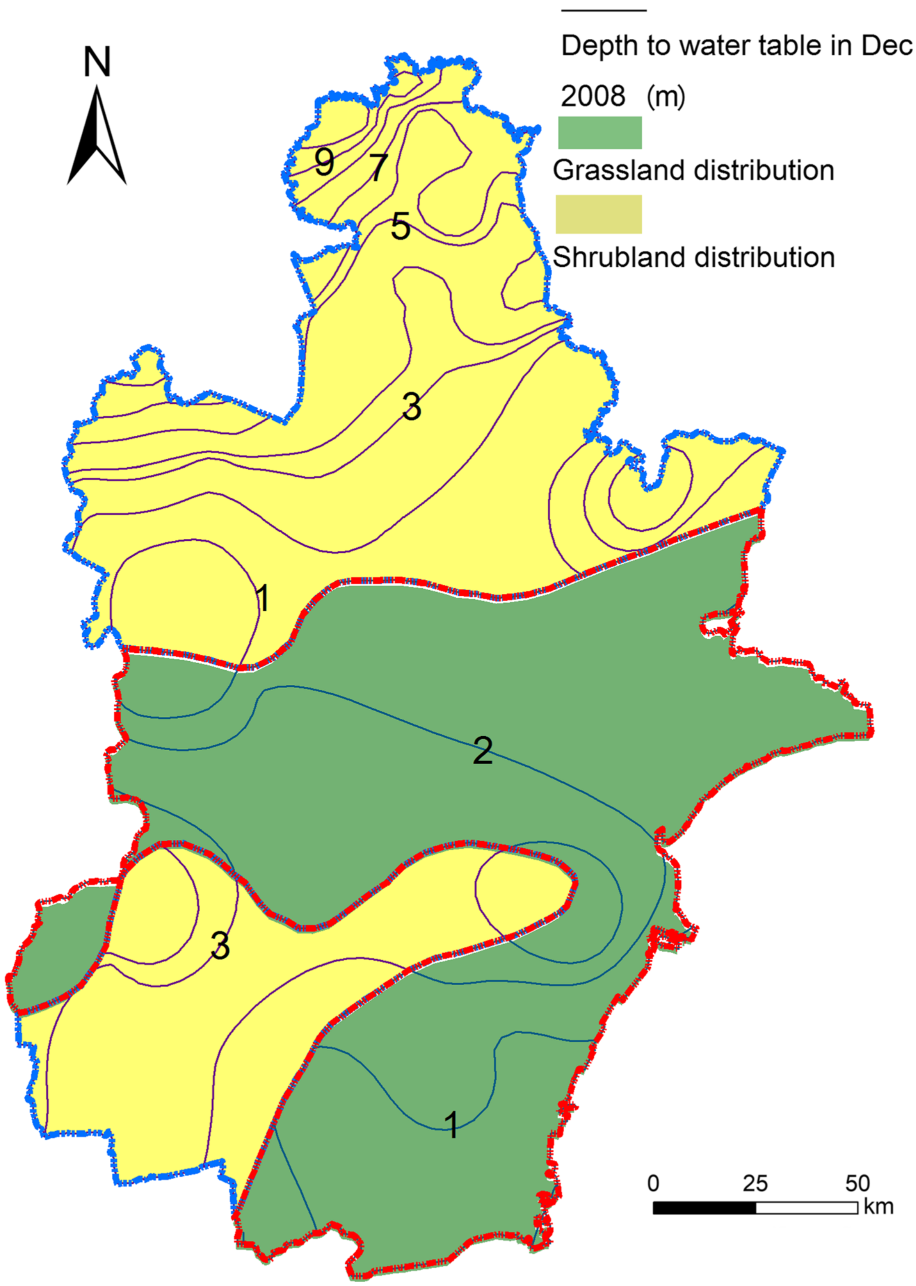

Fig. 8 Water-table depth distribution for shrubland and grassland areas in 2008

ecological water surplus decreases by 67.9%; however, from 2020 to 2030, the area of ecological water deficit decreases by 54.9%, the area of ecological water optima increases by 2.5%, and the area of ecological water surplus increases by 1%. The ecological water deficit and surplus regions transform into ecological water optima continuously, and the ecological zoning area gradually reaches a stable state in the future. This is because groundwater extraction is mainly concentrated in the ecological deficit area. It also suggests that the present extraction condition is relatively feasible in the shrubland regions, but the groundwater surplus regions have certain capacity for extraction; thus, groundwater extraction can be appropriately increased in parts of the shrubland area.

For grassland regions (Fig. 9a,b and Table 3), from 2008 to 2020, the area of ecological water deficit increases by 997%, the area of ecological water optima decreases by 30.1%, and the area of ecological water surplus decreases by 100%. Due to the falling water table, the ecological zoning areas of grassland change rapidly, and the ecological water deficit area increases significantly from 2008 to 2020. This increase is mainly because grassland regions are in areas with high groundwater use. Meanwhile, the water table is shallow (less than the evaporation-limit depth of 3 m), and the discharge of phreatic water by evaporation is relatively large, thereby increasing the groundwater depth. From 2020 to 2030, the area of ecological water deficit decreases by 1.6%, the area of ecological water

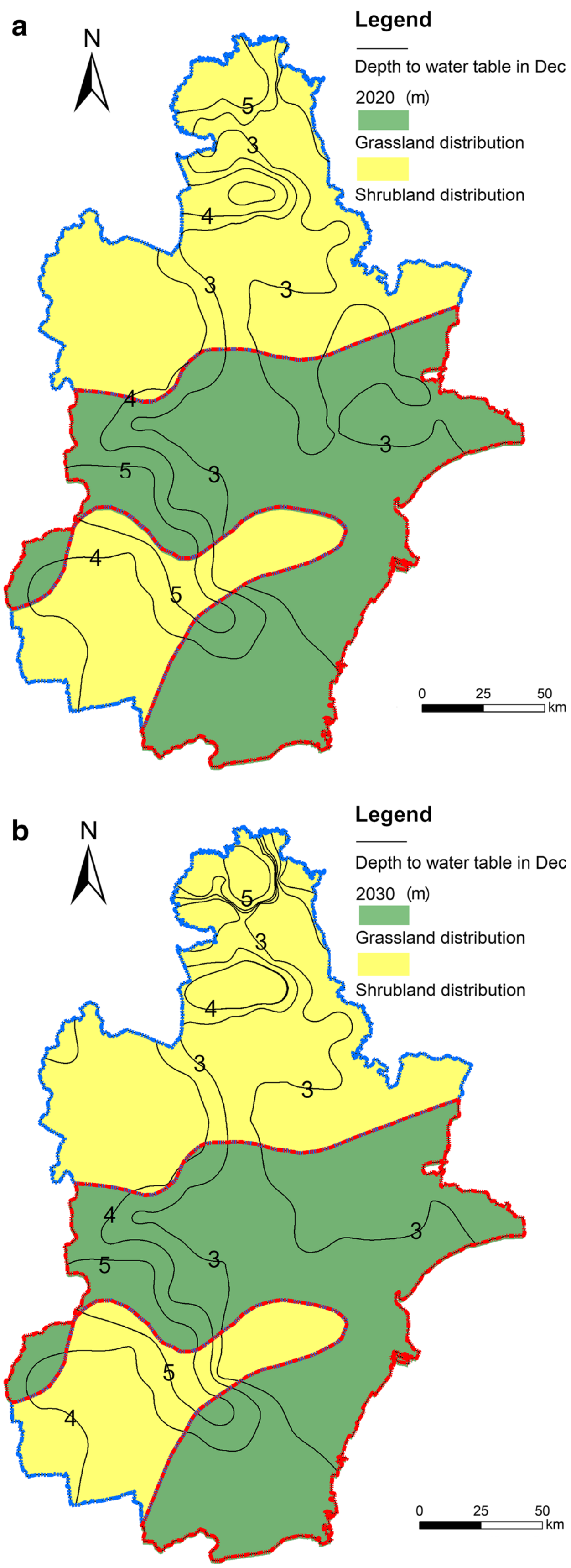

Fig. 9 Water-table depth distribution for shrubland and grassland areas in **a** 2020 and **b** 2030

Table 3 The changes of vegetation ecological zoning (km^2) under the present groundwater extraction conditions

Vegetation type	Zoning	Year		
		2008	2020	2030
Shrub	Ecological water deficit	807	213	96
	Ecological water optima	1,262	4,189	4,295
	Ecological water surplus	3,432	1,099	1,110
Grass	Ecological water deficit	209	2,293	2,255
	Ecological water optima	4,089	2,859	2,897
	Ecological water surplus	854	0	0

optima increases by 1.3%, and the area of ecological water surplus is 0 km^2. With the water-table elevation dropping, the evaporation decreases continuously, and total recharge and total emissions tend to equilibrium in most grassland regions. The groundwater-depth increases just occur in the case of ecological water deficit, and this has no effect on the area of ecological zoning; thus, each ecological zoning remains relatively stable from 2020 to 2030. The ecology experienced deficit conditions in parts of the grassland area, could not

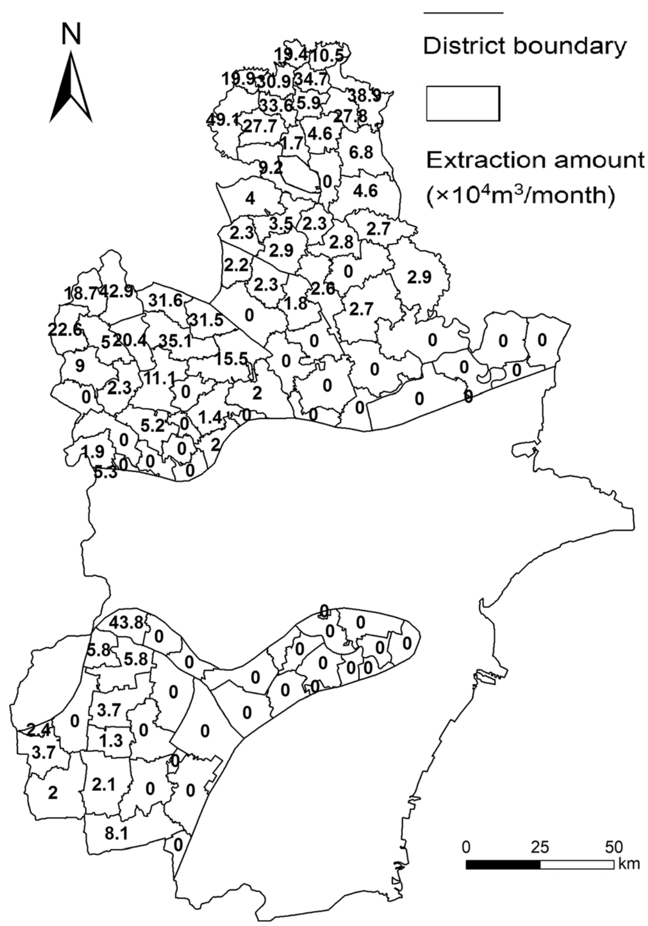

Fig. 10 The average groundwater extraction of 2008 in shrubland

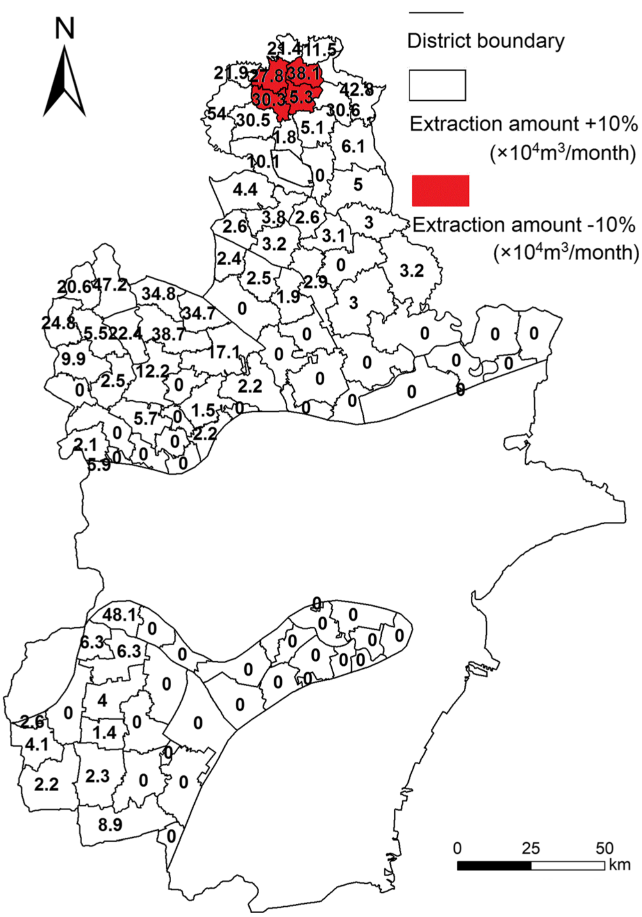

Fig. 11 The average groundwater extraction under the regulation schemes in shrubland. Note: Groundwater extraction amounts are shown on a per district basis

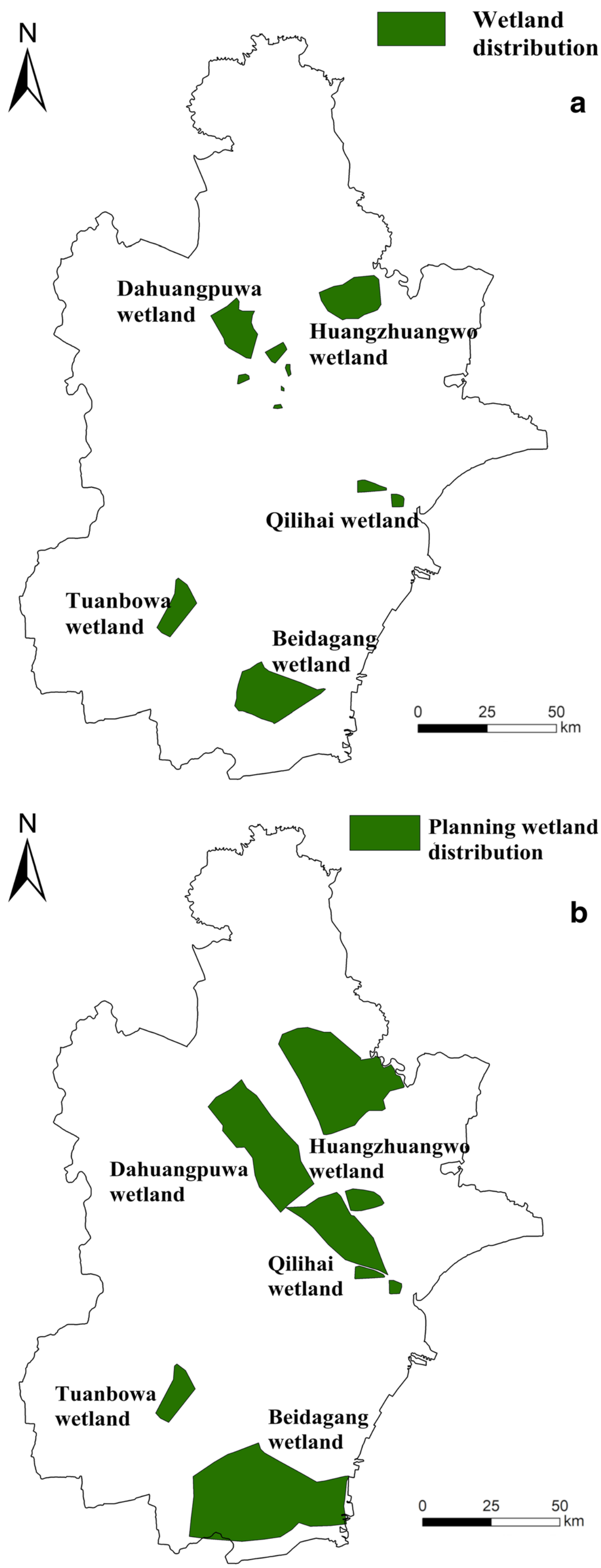

Fig. 12 The distribution of wetlands in **a** 2008 and **b** 2020

recover under the present extraction conditions, and needs more water supplement to achieve the suitable depth.

Future vegetation recovery under the regulation schemes

The regulation schemes for future vegetation recovery were formulated based on the aforementioned scenarios. Starting from the present groundwater extraction (Fig. 10), extraction is reduced by 10% in the shrubland ecological water deficit area, and extraction is increased by 10% in the shrubland ecological water surplus and optima areas (Fig. 11). For grassland, the deficit area will increase significantly under the present extraction condition in the planning years and will need more water supplement to achieve the suitable depth. Therefore, according to the wetland restoration planning projects in Tianjin (WRSMC), the central and southern wetlands in Tianjin (Dahuangpuwa, Huangzhuangwa, Qilihai, Tuanbowa, and Beidagang; Fig. 12a) will be restored to the wetland area of the 1960s by the end of 2020 (Fig. 12b). The data for restoring the wetlands area were provided by WRSMC (Table 4).

Table 4 The leakage amount of wetlands

Zoning	Rate of infiltration (mm/day)	Area (km^2)	Restoration area (km^2)	Restoring leakage amount (m^3/day)
Qilihai	0.180	19.3	163.3	29,394
Dahuangpu	0.026	98.3	298.3	7,756
Huangzhuangwa	0.047	96.6	188.7	8,869
Beidagang	0.320	149.5	533.9	170,848

The purpose of restoring wetlands is to recharge the shallow groundwater by infiltration. The Tuanbowa Reservoir area will remain the same, but the other wetland areas will change greatly in the future. The infiltration amounts (Table 4) were calculated by Eq. (3), using the infiltration rate (Sun et al. 2008). Wetland infiltration was input as a planar recharge source in the model.

The groundwater depth distribution for shrubland and grassland (Figs. 13 and 14) and the changes in the ecological zoning areas (Table 5) in 2020 and 2030 were simulated and

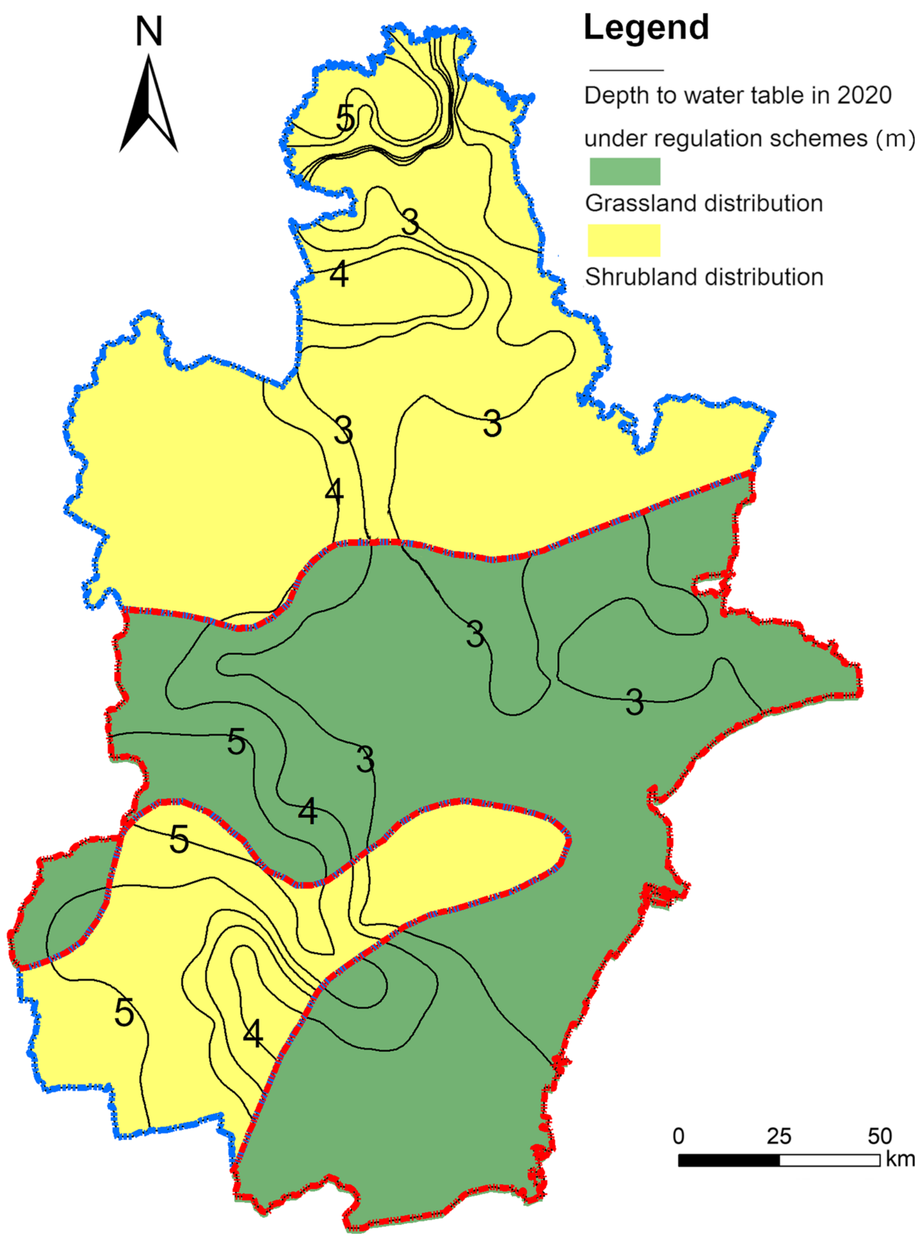

Fig. 13 The water-table depth distribution in shrubland and grassland in 2020 under the regulation schemes

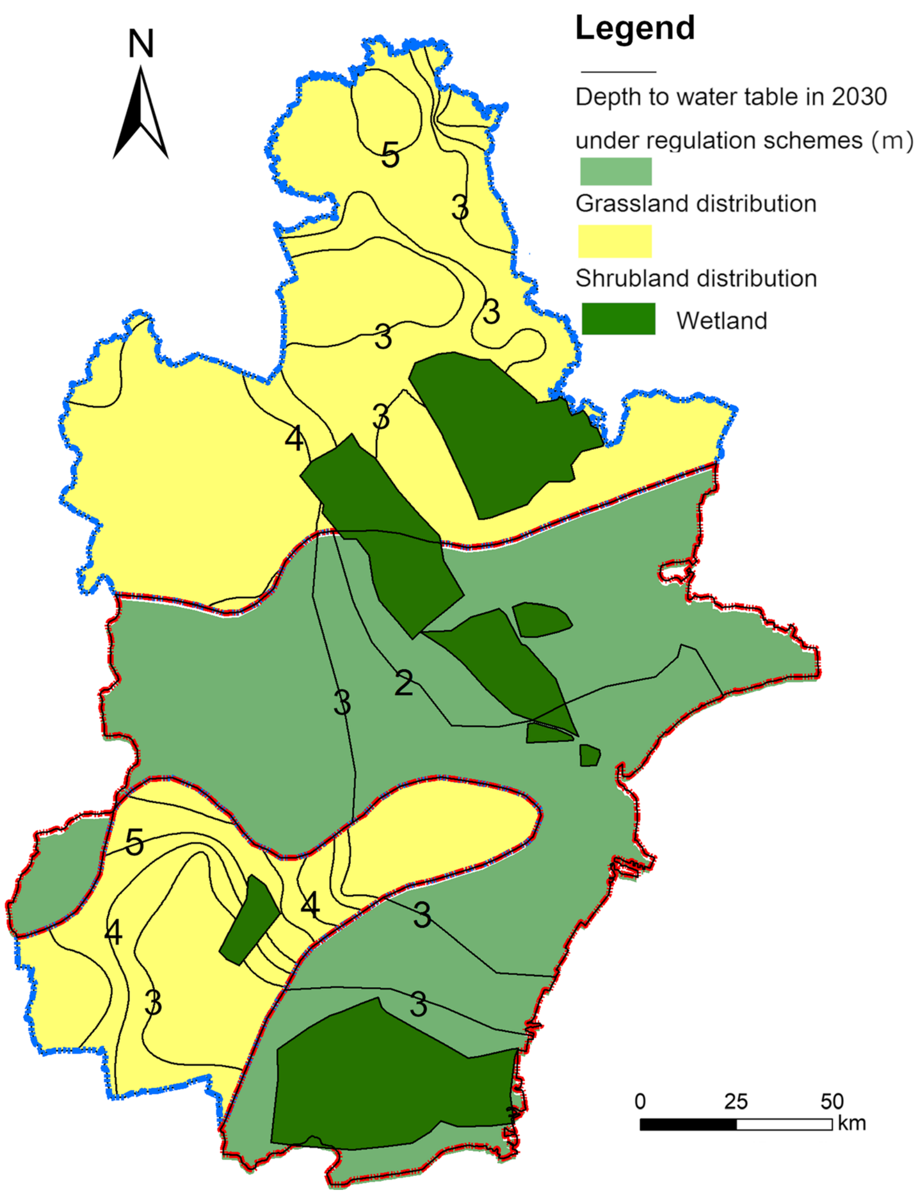

Fig. 14 The water-table depth distribution in shrubland and grassland in 2030 under the regulation schemes

quantified by the groundwater flow model. For shrubland (Fig. 13), the ecological water surplus area and ecological water deficit area are continuously decreasing, and the ecological water optima area is increasing after increased groundwater extraction. From 2008 to 2020, the ecological water deficit area decreases by 82.3%, the ecological water optima area increases by 307%, and the ecological water surplus area decreases by 93.5%. From 2020 to 2030, the ecological water deficit area decreases by 100%, the ecological water optima area increases by 3.9%, and the ecological water surplus area decreases by 26.1%. The results show that there is no ecological water deficit area for shrubland, the ecological water optima area reaches the maximum value, and the entire region is more suitable for shrub growth under the regulation scheme. The results also suggest that the regulation scheme is appropriate for the shrubland regions.

There are no changes in the vegetation ecological zoning for grassland under the proposed regulation scheme in 2020,

Table 5 The changes of forest and grassland ecological zoning (km^2) under the regulation schemes

Vegetation type	Zoning	Year		
		2008	2020	2030
Shrub	Ecological water deficit	807	143	0
	Ecological water optima	1,262	5,136	5,337
	Ecological water surplus	3,432	222	164
Grassland	Ecological water deficit	209	2,293	274
	Ecological water optima	4,089	2,859	4,878
	Ecological water surplus	854	0	0

compared with current groundwater extraction conditions (Fig. 14). This lack of change in the vegetation ecological zoning is mainly because the wetland areas in 2020 are the same as the wetland areas in 2008. The wetland areas will be restored to the wetland area of the 1960s by the end of 2020; however, after 2020, changes in ecological zoning are expected due to water-table rise. The ecological water deficit area decreases by 88.1%, the ecological water optima area increases by 70.6%, and the ecological water surplus area remains unchanged. Most of the grassland regions will be suitable for grass growth after wetlands restoration (from 2020 to 2030). The results also suggest that restoring wetlands has an important effect on changes in ecological zoning, and the regulation scheme is appropriate in the grassland regions.

Conclusions

The groundwater suitable depth for shrub growth in the study area is from 3 to 5 m, and the suitable depth for the grass growth is from 1 to 3 m. The vegetation distribution regions were divided into ecological water surplus, optima and deficit regions. For shrubland, most of the northern region was categorized as ecological water deficit area, and most of the central and southwest regions were categorized as ecological water surplus areas. For grassland, most of the regions were categorized as ecological water optima areas, and only a small number of regions in the southwest were categorized as ecological water deficit areas.

Under the current groundwater extraction conditions, the ecological water deficit and surplus areas in the shrubland regions convert to ecological water optima areas continuously, and the ecological water optima areas increase substantially in the future. For the grassland, ecological water deficit areas increase significantly from 2008 to 2020, and each area tends to be stable by 2030. Therefore, the grassland areas need more water supplement to achieve the suitable depth.

Under the regulation schemes, ecological water surplus and deficit areas for shrubland are continuously decreasing, and the ecological water optima area is increasing. There are no ecological water deficit areas of shrubland, the ecological water optima area reaches the maximum value, and the entire region is more suitable for shrub growth. For grassland, there are no changes in vegetation ecological zoning for grassland under the proposed regulation scheme in 2020, compared to current groundwater extraction conditions. After 2020, changes in ecological zoning are expected, due to water-table rise. Most of the grassland regions are suitable for grass growth after wetlands restoration (from 2020 to 2030).

Many groundwater numerical models have been developed in different parts of the world, which have provided the foundation for implementation of vegetation restoration. Several appropriate vegetation restoration schemes can be achieved using these numerical models and the regulation processes presented in this paper. Therefore, the findings of this study are also useful to other regions that have similar hydrologic and hydrogeological settings.

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References

Bullock JM, Gonzalez LM, Tamme R, Gotzenberger L, White SM, Paetel M, Hooftman DAP (2017) A synthesis of empirical plant dispersal kernels. J Ecol 105(1):6–19. https://doi.org/10.1111/1365-2745.12666

Cai JH, Golzarian M, Miklavcic S (2011) Novel image segmentation using Gaussian mixture models: application to plant phenotypic analysis. Energy Procedia 13:2005–2014

Chapman DS (2010) Weak climatic associations among British plant distributions. Glob Ecol Biogeogr 19(6):831–841. https://doi.org/10.1111/j.1466-8238.2010.00561.x

Cheng DH, Wang WK, Chen XH, Hou GC, Yang HB, Li Y (2011) A model for evaluating the influence of water and salt on vegetation in a semi-arid desert region, northern China. Environ Earth Sci 64(2):337–346. https://doi.org/10.1007/s12665-010-0854-2

China Meteorological Administration (2017) China meteorological data sharing service system. http://www.cma.gov.cn/2011qxfw/2011qsjgx. Accessed 1 July 2017

Chui TFM, Low SL, Liong SY (2011) An ecohydrological model for studying groundwater–vegetation interactions in wetlands. J Hydrol 409(1):291–304. https://doi.org/10.1016/j.jhydrol.2011.08.039

Comte JC, Join JL, Banton O, Nicolini E (2014) Modelling the response of fresh groundwater to climate and vegetation changes in coral islands. Hydrogeol J 22(8):1905–1920. https://doi.org/10.1007/s10040-014-1160-y

Dahlhaus PG, Evans TJ, Nathan EL, Cox JW, Simmons CT (2010) Groundwater-level response to land-use change and the implications for salinity management in the west Moorabool River catchment, Victoria, Australia. Hydrogeol J 18(7):1611–1623. https://doi.org/10.1007/s10040-010-0616-y

Goedhart CM, Pataki DE (2011) Ecosystem effects of groundwater depth in Owens Valley, California. Ecohydrology 4(3):458–468. https://doi.org/10.1002/eco.154

Harbaugh AW (2005) MODFLOW-2005, The U.S. Geological Survey modular ground-water model: the Ground-Water Flow Process. US Geol Surv Techniques Methods 6-A16

He MX, Mo XQ, Li HY (2013) Study on soil seed bank and its vegetation restoration ability in Tianjin (in Chinese). Modern Landscape Architecture 10(11):38–44

Jin XM, Liu JT, Wang ST, Xia W (2016) Vegetation dynamics and their response to groundwater and climate variables in Qaidam Basin, China. Int J Remote Sens 37(3):710–728. https://doi.org/10.1080/01431161.2015.1137648

Koirala S, Jung M, Reichstein M, Graaf IEM, Camps-valls G, Ichii K, Papale D, Raduly B, Schwalm CR, Tramontana G, Carvalhais N (2017) Global distribution of groundwater-vegetation spatial covariation. Geophys Res Lett 44(9):4134–4142. https://doi.org/10.1002/2017GL072885

Kopeć D, Michalska-Hejduk D, Krogulec E (2013) The relationship between vegetation and elevation of the water tables as an indicator of spontaneous wetland restoration. Ecol Eng 57:242–251. https://doi.org/10.1016/j.ecoleng.2013.04.028

Krogulec E, Zabloki S, Sawicka K (2016) Changes in groundwater regime during vegetation period in groundwater dependent ecosystems. Acta Geol Pol 66(3):525–540. https://doi.org/10.1515/agp-2016-0024

Laidig KJ, Zampella RA, Brown AM, Procopio NA (2010) Development of vegetation models to predict the potential effect of groundwater withdrawals on forested wetlands. Wetlands 30(3):489–500. https://doi.org/10.1007/s13157-010-0063-5

Li WY, Cui YL, Su C, Zhang W, Shao JL (2012) An integrated numerical groundwater and land subsidence model of Tianjin (in Chinese). J Jilin Univ 42(3):805–813

Li FW, Li X, Zhao Y, Qiao JL, Feng P (2016) A refined groundwater flow model of the shallow aquifer in Tianjin municipality, China. Water Sci Tech Water Supply 17(4):1231–1242. https://doi.org/10.2166/ws.2016.046

Loheide SP, Gorelick SM (2007) Riparian hydroecology: a coupled model of the observed interactions between groundwater flow and meadow vegetation patterning. Water Resour Res 43(7):W07414. https://doi.org/10.1029/2006WR00523

Lv JJ, Wang XS, Zhou YX, Qian KZ, Li W, Eamus D, Tao ZP (2012) Groundwater-dependent distribution of vegetation in Hailiutu River catchment, a semi-arid region in China. Ecohydrology 6(1):142–149. https://doi.org/10.1002/eco.1254

Mata-González R, McLendon T, Martin DW, Trlica MJ, Pearce RA (2012) Vegetation as affected by groundwater depth and microtopography in a shallow aquifer area of the Great Basin. Ecohydrology 5(1):54–63. https://doi.org/10.1002/eco.196

Mo XQ, Wang XM, Meng WQ, Li HY (2012) Soil seed bank and vegetation succession in a confined space of wetland in Tianjin region (in Chinese). Bull Soil Water Conserv 32(4):219–224

Owen SJ, Jones NL, Holland JP (1996) A comprehensive modeling environment for the simulation of groundwater flow and transport. Eng Comput 12(3–4):235–242. https://doi.org/10.1007/BF01198737

Palanisamy B, Chui TFM (2013) Understanding wetland plant dynamics in response to water table changes through ecohydrological modeling. Ecohydrology 6(2):287–296. https://doi.org/10.1002/eco.1268

Patten DT, Rouse L, Stromberg JC (2008) Isolated spring wetlands in the Great Basin and Mojave deserts, USA: potential response of vegetation to groundwater withdrawal. Environ Manag 41(3):398–413. https://doi.org/10.1007/s00267-007-9035-9

Sommer B, Froend R (2014) Phreatophytic vegetation responses to groundwater depth in a drying Mediterranean-type landscape. J Veg Sci 25(4):1045–1055. https://doi.org/10.1111/jvs.12178

Sun SH, Pan ZC, Sun SH (2008) Study on calculation of ecological water demand for reservoir wetland (in Chinese). J Tianjin Agricultural Univ 15(3):29–32

Varouchakis EA, Hristopulos DT (2013) Comparison of stochastic and deterministic methods for mapping groundwater level spatial variability in sparsely monitored basins. Environ Monit Assess 185(1):1–19. https://doi.org/10.1007/s10661-012-2527-y

Wang P, Zhang YC, Yu JJ, Fu GB, Ao F (2011) Vegetation dynamics induced by groundwater fluctuations in the Lower Heihe River basin, northwestern China. J Plant Ecol 4(1–2):77–90. https://doi.org/10.1093/jpe/rtr002

Xu H, Ye M, Song Y, Chen Y (2007) The natural vegetation responses to the groundwater change resulting from ecological water conveyances to the Lower Tarim River. Environ Monit Assess 131(1–3):37–48. https://doi.org/10.1007/s10661-006-9455-7

Zhu L, Gong HL, Dai ZX, Xu TB, Su XS (2015) An integrated assessment of the impact of precipitation and groundwater on vegetation growth in arid and semiarid areas. Environ Earth Sci 74(6):5009–5021. https://doi.org/10.1007/s12665-015-4513-5