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ORIGINAL ARTICLE

An integrated assessment of the impact of precipitation and groundwater on vegetation growth in arid and semiarid areas

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Abstract Increased demand for water resources together with the influence of climate change has degraded water conditions which support vegetation in many parts of the world, especially in arid and semiarid areas. This study develops an integrated framework to assess the impact of precipitation and groundwater on vegetation growth in the Xiliao River Plain of northern China. The integrated framework systematically combines remote sensing technology with water flow modeling in the vadose zone and field data analysis. The vegetation growth is quantitatively evaluated with the remote sensing data by the normalized difference vegetation index (NDVI) and the simulated plant water uptake rates. The correlations among precipitation, groundwater depth and NDVI are investigated using Pearson correlation equations. The results provide insights for understanding interactions between precipitation and groundwater and their contributions to vegetation growth. Strong correlations between groundwater depth, plant water uptake and NDVI are found in parts of the study area during a ten-year drought period. The numerical modeling results indicate that there is an increased correlation between the groundwater depth and vegetation growth and that groundwater significantly contributes to sustaining effective soil moisture for vegetation growth during the long drought period. Therefore, a decreasing groundwater table might pose a great threat to the survival of vegetation during a long drought period.

Keywords Spatial–temporal analysis · Groundwater · Vadose zone · Normalized difference vegetation index · Numerical simulation · Plant water uptake · Northern China

Introduction

Increased human demand for water resources, together with the influence of climate change, has dramatically altered the water cycle and has degraded water conditions which support vegetation in many parts of the world, especially in arid and semiarid areas where the water cycle balance and vegetation ecology are fragile (Froend and Sommer 2010; De Paola and Ranucci 2012; De Paola et al. 2014). Vegetation canopy can be directly observed from space by remote sensing technology. The information of vegetation growth and distributions can be characterized from normalized difference vegetation index (NDVI) over time and across spatial scales (Seaquist et al. 2003; Gebremichael and Barros 2006; Groeneveld and Baugh 2007). The NDVI derived from remotely sensed data can effectively reveal the status of vegetation growth on the ground. It utilizes the contrast between the strong reflection of ground vegetation in the near infrared wavelength and the strong absorption by chlorophyll in the red wavelength

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(Gao and Dennis 2001). The NDVI values reflect the density and greenness of the vegetation distributions. A few studies have been done to investigate the relationships between NDVI and some separate climatic variables. The relationships were commonly interpreted using correlation analysis, transformed linear regression, and multiple-linear regression (Box et al. 1989; Schultz and Halpert 1995; Ichii et al. 2002; Ji and Peters 2004; Anyamba and Turcker 2005). A number of studies showed that precipitation and NDVI were highly correlated (Richard and Poccard 1998; Wang et al. 2001; Sarkar and Kafatos 2004). The overall relation between NDVI and precipitation is log-linear in Eastern Africa (Davenport and Nicholson 1993) and linear in semiarid regions of Northeastern Brazil. However, there is no significant correlation in the Amazon watershed (Santos and Negri 1997). These empirical equations between NDVI and precipitation vary from region to region.

Compared to the precipitation, the influence of groundwater on vegetation growth is usually less obvious and more difficult to be detected, especially during wet periods with a plentiful precipitation. Groundwater mainly gets recharged from precipitations and has great impact on the spatial and temporal distributions of soil moisture which further affects vegetation growth on the ground (Naumburg et al. 2005; De Paola et al. 2013; Dai et al. 2014). NDVI has also been used to investigate the relationship between groundwater depth and vegetation at regional scales. For example, the suitable groundwater depth for the vegetation growth is derived from NDVI on basis of the histogram of the groundwater depth and corresponding pixel numbers of NDVI (Jin et al. 2007). Jin et al. (2014) analyzed the frequency distributions of NDVI for different vegetation types with different groundwater depth. Laboratory experiments and field investigations were conducted to investigate the effects of groundwater level drawdown on the performance of vegetation species (Kotowski et al. 2001; Froend and Sommer 2010; Chen et al. 2015). Some approaches, such as the statistical model of curve-fitting regression procedure, were employed to assess the influence of groundwater on vegetation growth (Stromberg et al. 1996). Various mechanistic models, such as eco-hydrological models (Chui et al. 2011), vegetation competition models coupled with saturated-unsaturated hydrological models (Brolsma et al. 2010a, b; Condon and Maxwell 2014; Tillman et al. 2012), EDYS models (Childress et al. 2002), WAVES models (Zhang et al. 1996), and IWSV model (Cheng et al. 2011), were developed to examine those relationships. There are few studies on exploring the integrated interrelationship of groundwater depth, precipitation and vegetation at multiple scales.

This study uses an arid and semiarid area, the Xiliao River Plain of northern China, as an example to develop an integrated framework to assess the impact of precipitation and groundwater on vegetation growth at in situ and regional scales. The study area is located in Eastern Inner Mongolia of China with an area of 55,378 km^2 (Fig. 1). Forest land, grass land and cultivated land are the three major types of lands in this region. The major vegetation

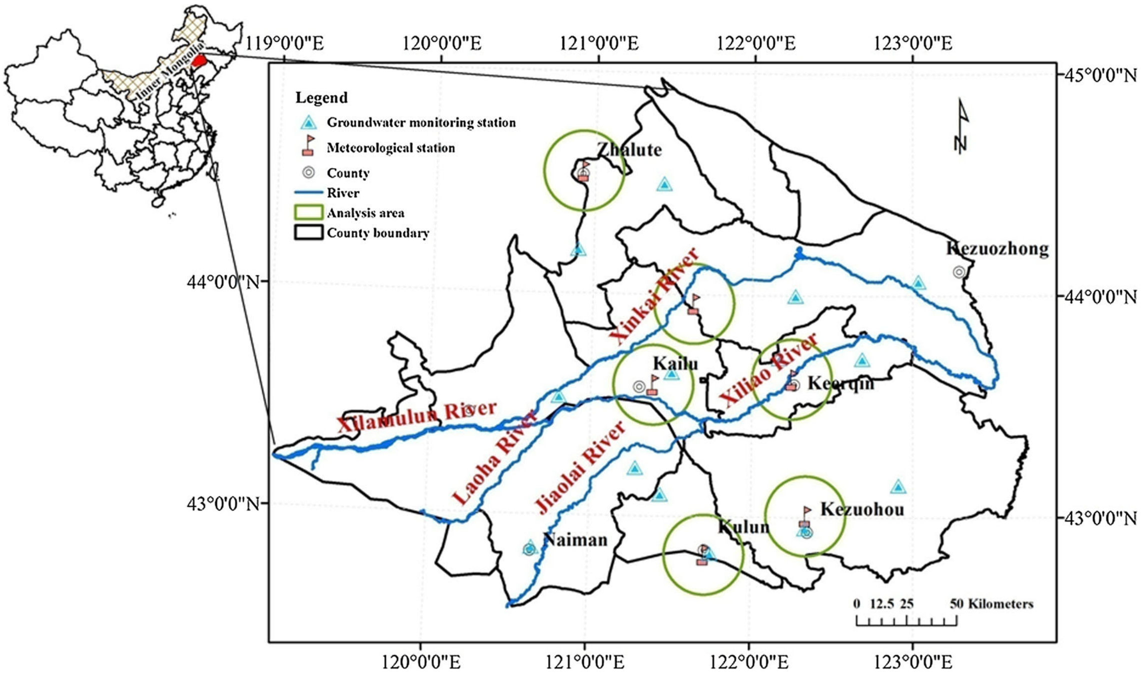


Fig. 1 Locations of six analysis areas and field data monitoring stations

types include *Stipa Baicalensis*, *Grandis* and *Aneurolepidium Chinense*, *Agropyron Cristatum*, *Ulmus Pumila* and *Artemisia Halodendron*. The average annual precipitation in the 2000 s varies from 178 mm in the western Naiman desert to 368 mm in the eastern region, while the average annual evaporation is 1900 mm for the same period. About 70 % of the annual precipitation falls between June and August each year. Average annual temperature is between 5 and 6 °C. The surface water system mainly includes the Xiliao river, Jiaolai river, Laoha river, Xilamulun river and Xinkai river. There have been relevant studies in the Inner Mongolia. Brogaard and Prieler (1998) identified land cover change using Landsat MSS satellite data (1975 and 1989) in Horqin steppe and found that there is no overall degradation and that precipitation data seem not to explain these changes. Brogaard et al. (2005) used a satellite data-driven gross primary production model to map gross primary production (GPP) from 1982 to 1999 and the results did not indicate declining biological production. Runnström (2003) found a general increase of biomass production using NDVI images between 1987 and 1996. There is little analysis between NDVI and precipitation such as Runnström (2003) found that in 1987 precipitation was delayed by almost a month causing vegetation growth to peak later. A quantitative investigation of the integrated impact of precipitation and groundwater on vegetation growth conditions is needed in this area. A better understanding of the water conditions which support vegetation growth will be helpful for a better management of the scarce water resources in this area.

This study examines the correlations among NDVI, precipitation and groundwater simultaneously using their time-series data from 1981 to 2010 at the regional scale. Numerical simulations of the interactions among precipitation, groundwater and plant water uptake at in situ scale are conducted to quantitatively evaluate the water conditions at the vadose zone of this area. The results provide insights which would help us to develop a strategy for regional water resources management and to mitigate the impact of the changing climate and the increased groundwater depth on vegetation growth.

Methodology

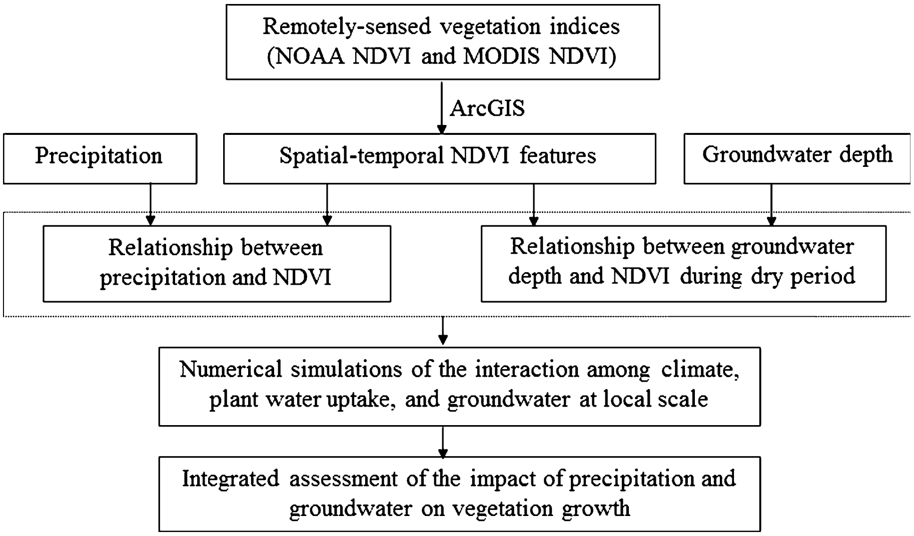
Integrated framework

Interactions between precipitation and groundwater and their contributions to vegetation growth are very complex. An integrated framework is developed to assess the relationships among vegetation, precipitation and groundwater depth, which systematically combines remote sensing technology with plant water uptake modeling in the vadose zone and the regional historical precipitation and groundwater measurements from 1981 to 2010 in the study area. The vegetation growth is quantitatively evaluated with the remote sensing data (by the NDVI) and the simulated plant water uptake rates. The correlations among precipitation, groundwater depth and the NDVI are investigated using Pearson correlation equations. Numerical simulations of plant water uptake would further quantitatively evaluate the water sources (precipitation and groundwater) which support the vegetation growth. The flowchart of the integrated framework is shown in Fig. 2.

NDVI data

Two NDVI datasets for the study area are downloaded from Web sites of Earth Resources Observation System

Fig. 2 Flowchart of the integrated framework



Data Center (EROS) and Pathfinder Land Dataset (PAL). The first one is the level-3 NDVI product of Advanced Very High Resolution Radiometer (AVHRR) on National Oceanic and Atmospheric Administration satellites (NOAA). It covers the period from 1981 to 2000 at a ten-day interval and has a resolution of 8 km. The second one is the level-3 NDVI product of Moderate Resolution Imaging Spectro-radiometer (MODIS) named MOD13A3. It covers the period from 2001 to 2010 at a monthly interval and has a resolution of one kilometer. The MODIS data can be used directly, whereas NOAA data need to be processed for converting digital number (DN) to NDVI before application (Eq. 1).

$$\mathrm{NDVI} = 0.008 \times (\mathrm{DN} - 128) \tag{1}$$

The NOAA ten-day-interval NDVI data are composited into monthly NDVI data using the maximum value composite (MVC) technique which can retain the highest NDVI value for each pixel and minimize cloud contamination as well as off-nadir viewing effects (Habib et al. 2009). Correlation analyses of NDVI with precipitation and groundwater are implemented within the period from 1981 to 2000 and the period from 2001 to 2010 separately to eliminate the potential calibration bias from different sensor systems (NOAA and MODIS).

The study area is one of the major grain-growing areas in northern China. About 20 % of the area has been cultivated with well-developed irrigation facilities. Those cultivated areas have to be excluded from correlation analysis since irrigation activities will distort the natural relationship between precipitation, groundwater and vegetation. Landsat Thematic Mapper (TM) images are used to delineate the cultivated lands. Seven TM images are needed to cover the entire area. A maximum likelihood supervised classification is performed in The Environment for Visualizing Images System (ENVI) to map the cultivated land. The classification accuracy is about 94 % (Zhao and Zhu 2012). The cultivated lands are predominantly distributed along the river courses. Those cultivated areas were then excluded from correlation analysis. There are only some small towns in this area. Their impact on the NDVI values is very limited and can be ignored (Zhao and Zhu 2012).

Precipitation and groundwater data

The monthly precipitation data are collected from six meteorological stations within the study area. The groundwater depth data are collected from 14 long-term monitoring wells (Fig. 1). Here, the groundwater depth is defined as the distance from the ground surface to groundwater table. This analysis is focused on six analysis areas which are defined by the circles centred at six meteorological stations with a radius of 20 km. We focus on the time variety of the groundwater depth. From downstream to upstream, the groundwater spatial variability is small. The groundwater depth is interpolated into a grid with a resolution of 1 km using the ordinary Kriging method with a spherical semivariogram model. The groundwater depth for each circled analysis area is then extracted from the grid by averaging all cell values within the analysis area. The NDVI values are also averaged in these analysis areas.

Correlation analysis of NDVI-precipitation and NDVI-groundwater depth

The Pearson's correlation coefficient is also called Pearson product moment correlation (or PPMC), which is a measure of the strength and direction of the linear relationship between two parameters that is defined as the sample covariance of the variables divided by the product of their sample standard deviations, or

$$r = \frac{\mathrm{Cov}(x,y)}{\sigma_x \sigma_y} = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}} \tag{2}$$

where Cov is the covariance, and σ is the standard deviation of the measured data x or y. The time lags of the precipitation effect on vegetation or NDVI values vary with different shallow soil properties. In this study area, the shallow soil is mainly composed of black calcium soil, brown soil, chestnut calcium soil, and sand. The hydraulic conductivities and porosities in these soil layers are relatively large. The precipitation can be relatively quickly uptaken by the plant roots to impact on vegetation or NDVI values. Previous studies indicate that the vegetation is mainly controlled by the precipitation of current month, prior 1 month (e.g., Zhou et al. 2007; Zhang et al. 2011), and prior 2 months (e.g., Sharon et al 1990; Li et al 2007). This study adopted an empirical value of 3-month precipitations to calculate the accumulated precipitations of the maximum NDVI month. The Pearson correlation coefficient is calculated between the maximum NDVI of each circled analysis area and the accumulated precipitations of the maximum NDVI month and the prior 2 months. The correlation is also calculated between the maximum NDVI and groundwater depth at the same month to assess the relationship between groundwater depth and water condition of vegetation.

Numerical simulations of plant water uptake

The variably saturated vadose zone in this area mainly consists of alluvial–proluvial fan sediments, including

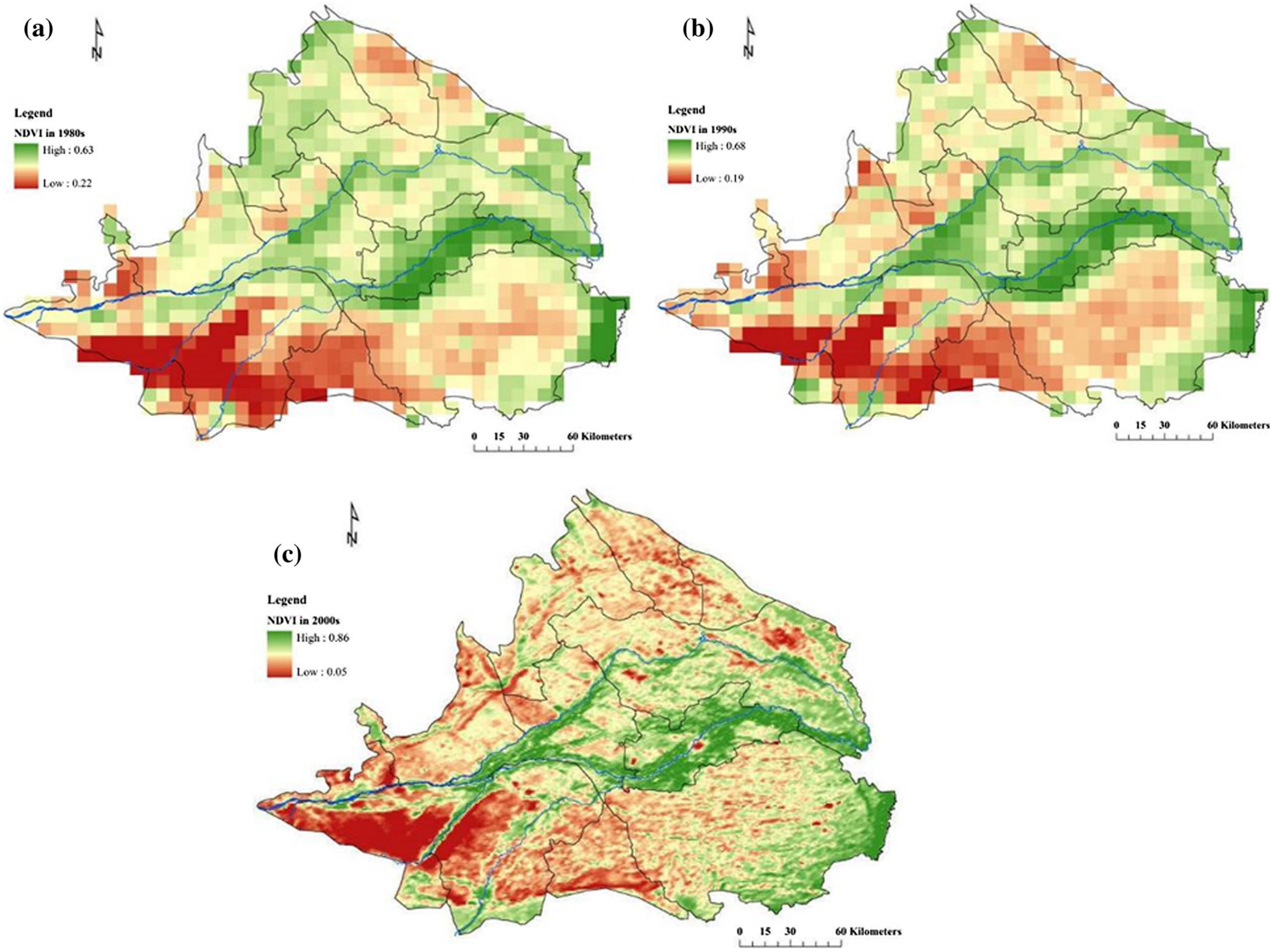


Fig. 3 Distribution patterns of the maximum NDVI in 1980s (**a**), 1990s (**b**) and 2000s (**c**)

black calcium soil, silt sand, medium-fine sand, and gravel. From upstream to downstream of the Xiliao River, the aquifer strata changes from a single thick layer to multiple thin layers and the total thickness of aquifer layers becomes thinner. The groundwater heads of this region are reducing because of the increased groundwater exploitation and the reduction of the annual precipitation in recent years. A numerical model for simulating plant water uptake is established using a geological cross section near the observation well K1 in Kulun. The model has a width of 5 m, a depth of 3 m and a thickness of 1 m. The corresponding precipitation, evaporation and transpiration data (from 1981 to 2010) are assigned at the top atmosphere boundary. The bottom boundary is a variable water head boundary, in which the boundary water head data were obtained from the long-term measurements of the well K1. We assume that the water flow in the variably saturated porous media is three-dimensional isothermal Darcian flow and the flow equation is given by a modified form of the Richards' equation (Dai and Samper 2004; Dai et al. 2008; Šimůnek et al. 2011):

$$\nabla(K_{\mathrm{r}}K\nabla h) + w = \left(\varphi\frac{\partial\,\mathrm{S_w}}{\partial\,\psi} + S_{\mathrm{w}}S_{\mathrm{s}}\right)\frac{\partial\psi}{\partial\,t}, \tag{3}$$

where h is hydraulic head which is the sum of pressure head ψ and elevation Z

$$h = \psi + Z \tag{4}$$

Hydraulic conductivity K is the product of relative conductivity K_{r} and saturated conductivity K_{s}. S_{w} is water saturation degree defined as the ratio between volumetric water content θ and porosity ϕ, or $S_{\mathrm{w}} = \theta\ /\phi$. Water saturation is related to pressure head through retention curve

$$S_{\mathrm{w}}(\psi) = S_{\mathrm{r}} + (1 - S_{\mathrm{r}})[1 + (-\alpha\psi)^{n}]^{-m} \tag{5}$$

where S_{r} is the residual water saturation and m, n and $\alpha(1/L^{-1})$ are Van Genuchten parameters usually estimated by fitting this function to observation data (van Genuchten, 1980). *w* is a source or sink term, which includes the plant (or root) water uptake, or the volume of water removed from specific volume of soil in a specific time due to plant water uptake. Feddes model (Feddes et al. 1974) and van Genuchten approach (1987) are used to calculate the root water uptake. Equation (3) is highly nonlinear because both hydraulic conductivity and saturation degree are functions of pressure head. The finite element numerical method combined with Newton–Raphson iteration scheme is used to solve the nonlinear Eq. (3) (Šimůnek and Hopmans 2009; Šimůnek et al. 2008, 2011). The numerical model computes the plant water uptake, infiltration rate, and flow rate at water table, which will be used to analyze the intrinsic water cycle and the water budget for vegetation growth in the vadose zone.

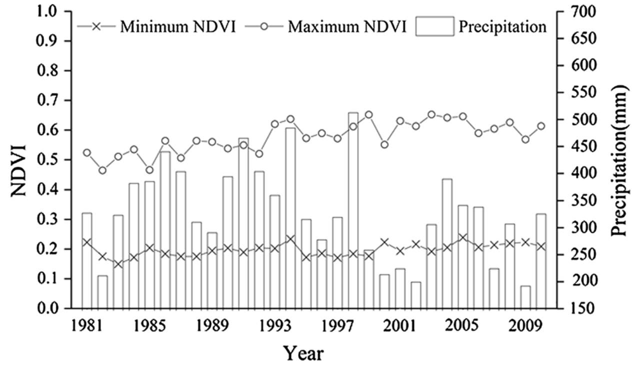


Fig. 4 The precipitation, maximum and minimum NDVI during the vegetation growing season in the whole region

Results and discussion

General pattern of NDVI, precipitation and groundwater depth

The NDVI value in the study area generally rises from west to east. This distribution corresponds to the regional precipitation pattern, which typically reflects the close relationship between vegetation and precipitation (Fig. 3). From 1981 to 2000, the regional maximum NDVI has a mild increasing trend as shown in Fig. 4, which might reflect an improved ground vegetation cover of this region. The precipitations in the 2000s, when the region experienced a dry period, are markedly lower than those in the 1980s and 1990s. The reduction of precipitations in the 2000 s does not dramatically bring down the NDVIs (Fig. 4) in the whole region. However, the lower precipitations in the 2000s apparently stop the upward trend of maximum NDVI.

Groundwater depths of the six analysis areas have a mild increase during 1981 to 2000. The increase has been sped up since early 2000s. The faster decline of groundwater table since early 2000s (Fig. 5) corresponds to the lower precipitation during this period. A lower precipitation reduces the water supplement to the groundwater and encouraged more usage of groundwater for irrigation. In addition, an expanded population in the region has certainly put more pressure on the water resources. About 63 % of the groundwater depth measurements are within 2 meters in the 1980s. In the 1990s, the dominant groundwater depth values are from 2 to 3 m while only 21.7 % of

Fig. 5 The fluctuation of groundwater depth in six analysis areas from 1981 to 2010

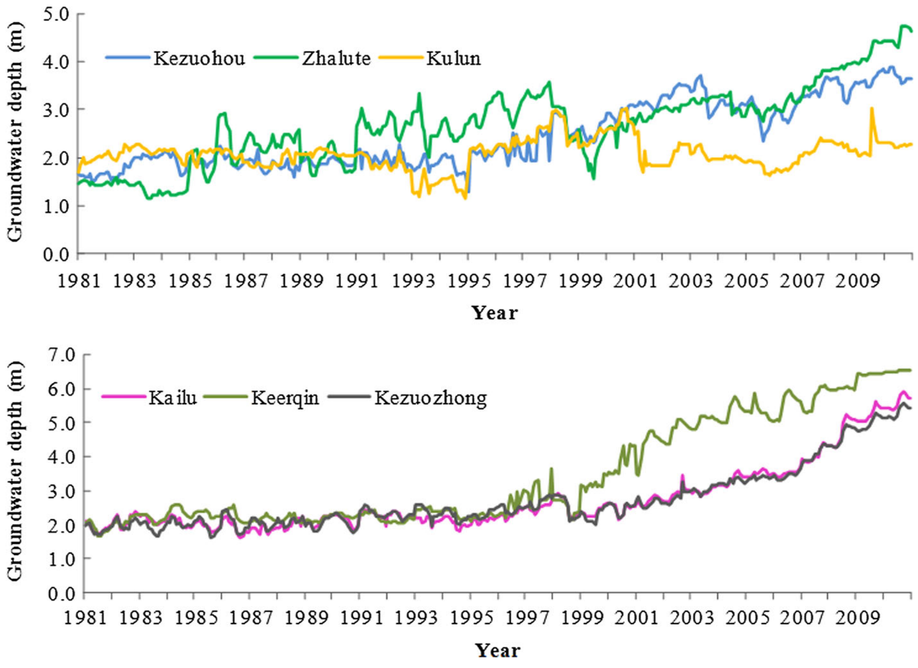


Table 1 Correlation coefficients and *p* values between three-month accumulated precipitation, groundwater depth and maximum NDVI

Relationship	Kailu	Keerqin	Kezuohou	Kezuozhong	Kulun	Zhalute
Precipitation-NDVI						
1981–2000						
Coefficients	0.27	0.34	0.36	0.45	0.32	0.31
p value	0.2496	0.1424	0.1190	0.0465	0.1690	0.1835
2001–2010						
Coefficients	0.70	0.21	0.43	0.61	0.21	0.51
p value	0.0242	0.5604	0.2149	0.0611	0.5604	0.1321
Groundwater depth-NDVI						
2001–2010						
Coefficients	−0.33	−0.60	−0.23	−0.54	−0.64	−0.22
p value	0.1763	0.0130	0.3454	0.0262	0.0077	0.3667
Monthly precipitation and groundwater depth						
1981–2000						
Coefficients	−0.60	−0.02	−0.08	−0.74	0.57	−0.73
p value	0.0052	0.9333	0.7374	0.0002	0.0087	0.0003
2001–2010						
Coefficients	0.14	0.66	−0.57	0.08	0.50	−0.08
p value	0.6997	0.0378	0.0854	0.8261	0.1411	0.8261

the groundwater depth values are less than 2 m. In the 2000s, this percentage is dropped to about 6 %.

Relationship between NDVI and precipitation

The seasonal variation patterns of NDVI and precipitation in the six analysis areas are generally similar. The NDVI values start rising in May and typically reached the maximum value in August, then gradually declines afterward. Most rain falls are in summer (June, July and August). The three-month accumulated precipitations have declined in most of analysis areas since the 1980s, while the NDVI values have slightly increased in all analysis, mostly occurs before the 2000s. A moderate increase of NDVI over a long period is a relatively common case in a well-cultivated region because of the ongoing improvement of ground vegetation coverage. The dry period during the 2000s only slightly brings down regional NDVIs. A downward trend line of three-month accumulated precipitation is mainly driven by the lower precipitation during the 2000s.

The correlations between maximum NDVIs and the accumulated precipitations are shown in Table 1. The correlation coefficients are relatively weak, especially in Kulun and Keerqin with the coefficients of about 0.2 in 2000s and 0.3 from 1981 to 2000, which suggests that the precipitation is not a dominant factor and that the groundwater may have played an active role in those areas to maintain an effective water condition for vegetation growth. However, the role played by precipitation may have been enhanced in the dry period of the 2000s when the four analysis areas had higher correlations between maximum NDVI and the three-month accumulated precipitation than those in the 1980s and 1990s (Table 1). For example, the coefficient in Kailu changed from 0.27 to 0.7, while the value in Kezuozhong changing from 0.45 to 0.61. The ground vegetation is more responsive to precipitation events under a depressive dry condition.

Generally, precipitation infiltration is the main recharge for groundwater. The correlation coefficients between monthly precipitation and groundwater depth (Table 1) in Kailu, Kezuozhong and Zhalute are bigger than 0.6 from 1981 to 2000, which reflects the relative strong relationship of the two elements. This relationship is weakened during the period from 2001 to 2010 in the dry years, in analysis areas except for Kezuohou. The relationship between groundwater and vegetation can be observed more obviously in dry years.

Relationship between NDVI and groundwater depth

Some of the vegetation species are very sensitive to groundwater depth and others may be insensitive. The relationship between NDVI and groundwater depth can reflect the average behavior of all vegetation types to groundwater depth (Jin et al. 2014). There is a strong correlation between the maximum NDVI and groundwater depth in Keerqin and Kulun during the 2000s dry period, as shown in Table 1, while both areas have the weakest correlations (with a coefficient of about 0.2) between precipitation and NDVI during this period, which suggests that

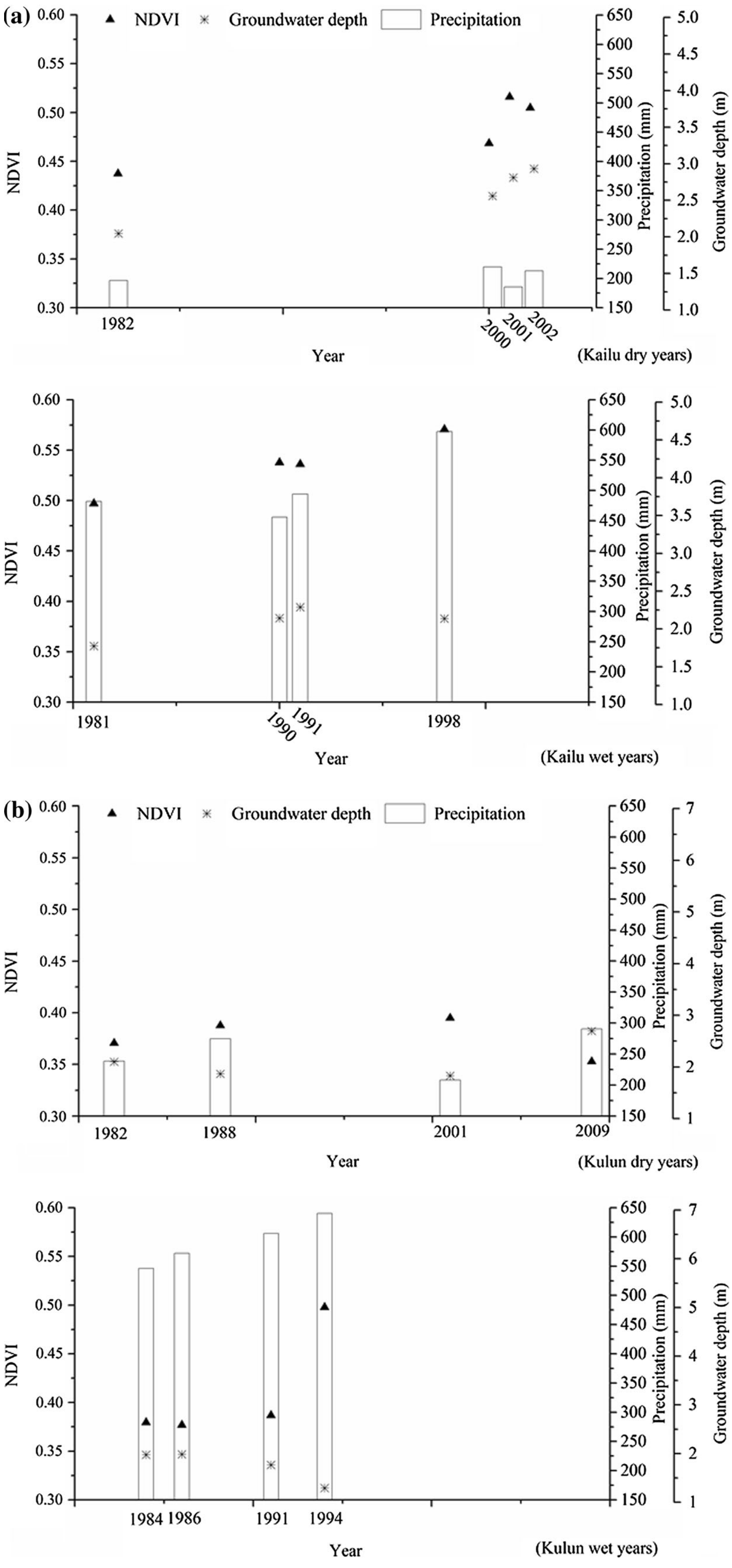


Fig. 6 Annual precipitation, groundwater depth and the maximum NDVI in dry and wet years (**a** Kailu, **b** Kulun)

Table 2 Numerical modeling parameters in the cross section (modified from

Cross section layers	Thickness (m)	Residual water content	Saturated water content	α (1/m)	*n*	*Ks* (m/d)
Black calcium soil	0.5	0.1	0.43	0.5	1.5	0.3
Silt sand	1	0.08	0.41	0.8	1.6	0.5
Fine sand	1	0.06	0.38	1.2	1.8	1
Sandy clay	0.5	0.09	0.4	1.1	1.4	0.2

there is a close connection between the groundwater depth and vegetation growth in these two areas. Ground vegetations have the ability to adapt to the water conditions by changing its composition. The vegetation root's ability of absorbing capillary water may be strengthened. The groundwater apparently plays an effective role to sustain a soil moisture condition for vegetation growth of these areas during this long dry period. In Kezuozhong, NDVI is negatively correlated to groundwater depth with a coefficient of −0.54, which suggests that there is also a connection between the groundwater condition and vegetation growth in this area. No significant correlation is found between groundwater depth and NDVI in the rest three analysis areas (Kailu, Kezuohou and Zhalute).

Annual precipitation, groundwater depth and the maximum NDVI

Annual precipitation, groundwater depth and the maximum NDVI are investigated in wet years (The precipitation data are sorted from high to low, then precipitation events occurring at less than 15th percentile of all precipitation events are wet years) and in dry years (precipitation events occurring exceeding 85th percentile of all precipitation events are dry years) to make a further assessment of the complex relationships among these three elements. Since the impact of the precipitation on the vegetation can be decreased in dry years, it is not difficult to detect the relations between the groundwater and vegetation.

Precipitation is usually the principal supplier of soil moisture and is, therefore, the major factor to affect the water supply for vegetation growth. The maximum NDVI values in wet years are greater than those in dry years in Kailu (Fig. 6a) and Zhalute areas. More precipitation could raise the NDVI under the similar groundwater depth condition. For example, the NDVI values in 1982 and 1998 were 0.43 and 0.57 with the similar groundwater depth of about 2.1 m in Kailu. This phenomenon also occurs in Kezuohou and Kezuozhong. In addition, precipitation is the main source for groundwater recharge; higher precipitation raises the groundwater tables in Kailu, Keerqin and Kezuohou. The groundwater depths in these regions during wet years are shallower than those in dry years.

Groundwater can supply a certain amount of water to sustain soil moisture conditions for support of vegetation growth and survive even through a long dry period. Under these conditions, lower annual precipitation sometimes does not bring down the NDVI values, such as in Keerqin and Kulun areas (Fig. 6b). Groundwater has played an active role in these two areas particularly during the prolonged drought of the 2000s. Both areas had a considerably lower NDVI in year 2009 as these two areas suffered a significant reduction of groundwater heads by the end of the drought.

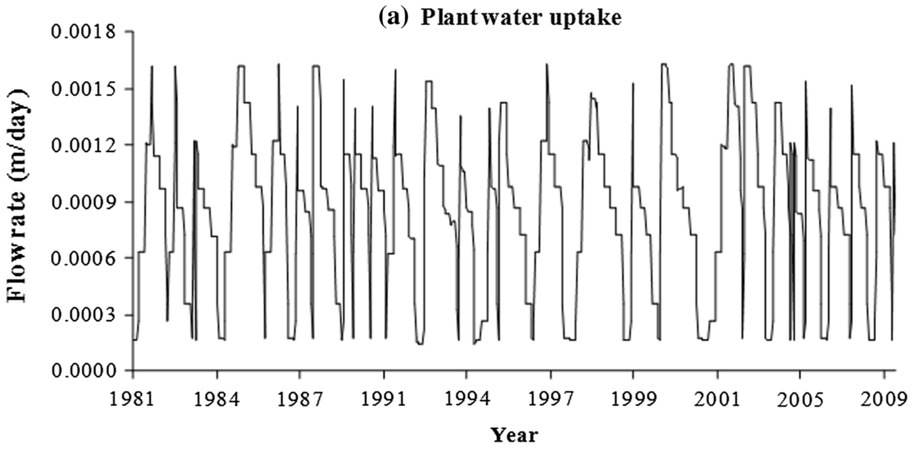
Plant water uptake modeling

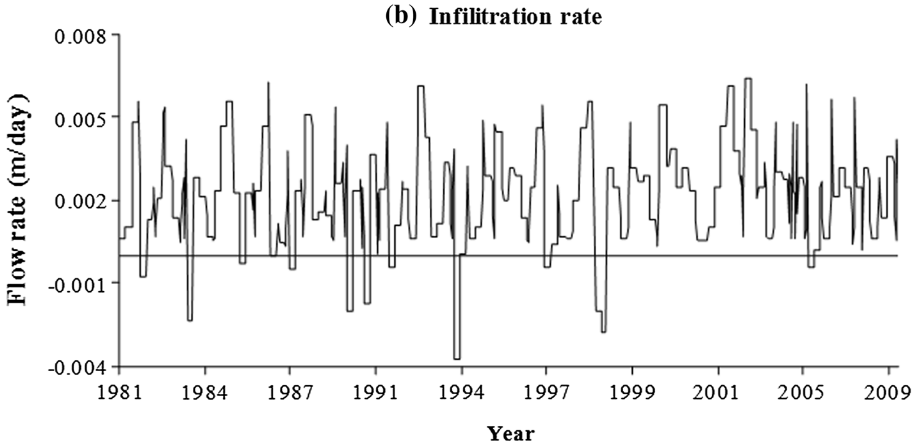
An obvious correlation between the NDVI and groundwater depth is observed in Keerqin and Kulun during the dry period. While Keerqin is the most cultivated area in the study region, the influence of the irrigation may not be totally removed due to the resolution of the TM image. Kulun has been chosen as a typical place to build the numerical model for quantitatively assessing the plant water uptake and the recharge water sources (i.e., precipitation and groundwater). The model heterogeneous structure is established using a geological cross section near an observation well (K1) in Kulun. The van Genutchten parameters and hydraulic conductivities listed in Table 2 are collected from local infiltration experiments and literature (Dai et al. 2008; Šimůnek et al. 2011).

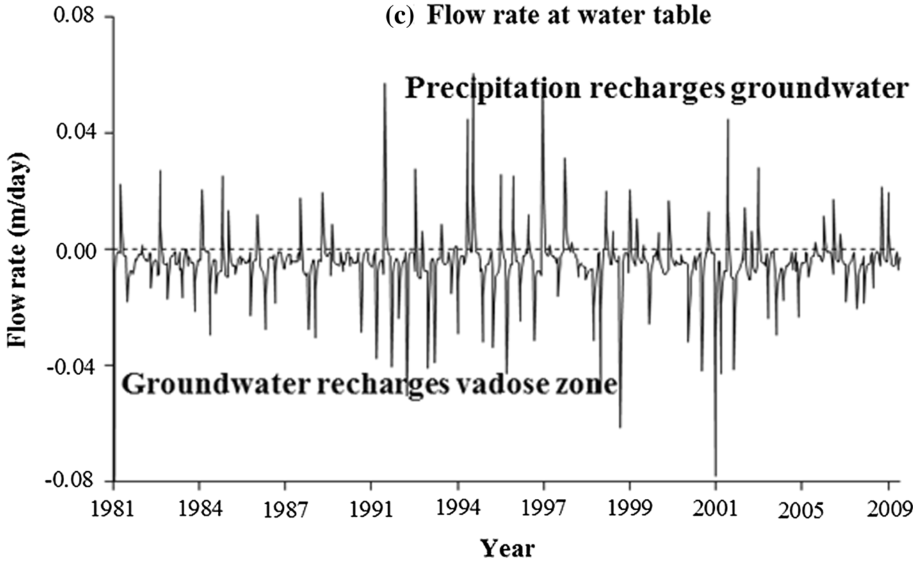
Figure 7 shows the numerical simulation results. The computed actual plant water uptake (Fig. 7a) is from two sources: actual infiltration from precipitation (Fig. 7b) and recharge from groundwater (Fig. 7c). Note that the infiltration rates (precipitation minus surface flow and evaporation) are actual water infiltrated into the vadose zone. It is obvious that the infiltration water from precipitation is directly uptaken by plant roots. If there is more infiltration than plants can uptake, it may recharge groundwater (Fig. 7b).

Figure 7c shows the water budget at the water table from 1981 to 2010. The positive flow rates indicate that the infiltration water recharges groundwater while the negative flow rates indicate that groundwater recharges to the vadose zone where it sustains the soil moisture needed for

Fig. 7 The numerical simulation results for **a** plant water uptake, **b** actual infiltration rate, and **c** flow rate at groundwater table


(a) Plant water uptake


(b) Infiltration rate


(c) Flow rate at water table

vegetation growth. In particular, during the low precipitation periods (from 2001 to 2010, Fig. 7c) groundwater recharged the vadose zone, thus preserving efficient soil moisture to sustain the growth of vegetation through a drought. A correlation analysis result indicates that groundwater had greatly contributed to plant water uptake during that drought period (Table 1). For example, the correlation coefficient between groundwater depth and the NDVI in Kulun is −0.64.

On the other hand, the contribution from groundwater to the vegetation growth would be reduced when precipitation is plentiful or the groundwater table has fallen. The supplemented water from groundwater storages would be reduced to a negligible level when the groundwater table has fallen below a certain level, where the plant root cannot reach. Therefore, a low groundwater table may pose a threat to the survival of vegetation during a prolonged drought. Maintaining proper groundwater depth is vital to vegetation growth, in particular to vegetation survival during a long dry period in arid and semiarid regions. This is a more crucial issue when there is an increasingly volatile precipitation pattern due to a changing climate.

Conclusions

An integrated investigation of remotely sensed data, precipitation and groundwater data can help us to achieve a better understanding of the relationships among precipitation, groundwater and ground vegetation in arid and semiarid regions. This study has developed an integrated framework for quantitatively assessing those relationships using the field data of precipitation, groundwater depth and NDVI collected from 1981 to 2010 in the study area. The spatial distribution of NDVI generally matches the regional spatial pattern of precipitation, which indicates that precipitation is a major factor for governing the distribution of natural vegetation in the region.

Obvious correlations between groundwater depths and NDVIs existed in parts of the study area during the prolonged drought of the 2000s, which reflects a close connection between the groundwater depth and vegetation growth in these areas. The numerical simulation results of the plant water uptake quantitatively demonstrate that precipitation infiltration and groundwater alternatively provide water for vegetation growth in different seasons. The infiltration water from precipitation is directly uptaken by plant roots. If there is more infiltration than plants can uptake, it may recharge groundwater. During low precipitation periods, groundwater can preserve efficient soil moisture which sustains the growth of vegetation through a drought. The contribution from groundwater to vegetation growth would be reduced as groundwater depth increases. Maintaining proper groundwater depth is vital for vegetation growth in arid and semiarid regions. This is a more crucial issue with the increasingly volatile precipitation pattern because of changing climate. The derived results provide information for the local government and policy makers to improve the management of water resources in the study area.

A more detailed interpolation of the spatial precipitation surface from more precipitation gauges will deliver a more accurate precipitation value at each analyzing location, while a denser groundwater monitoring well network will provide more accurate groundwater measurements for the study area. This will improve the accuracy and reliability of the correlation analysis between NDVI, precipitation and groundwater. In addition, different vegetation types may respond to regional water conditions differently. For instance, while bush land and grassland typically have a rapid and strong response to a precipitation event, permanent vegetation, such as forests, will not have such a quick and obvious response. Note that water is the key factor in vegetation growth but is not the only factor. Other environmental and climatic conditions (such as temperature and surface elevation) also influence vegetation growth. Our next study will include more environmental factors in the integrated assessment.

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