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Vegetation dynamics induced by groundwater fluctuations in the lower Heihe River Basin, northwestern China

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Abstract

Aims
Since 2000, the environmental flow controls project has been implemented in the lower Heihe River Basin, a typical arid inland river basin in northwest China, to restore the deteriorated ecological environment in this region. The aim of this study was to explore the impacts of groundwater fluctuations on vegetation dynamics. Our results can be used as a reference for water resources planning and management to maintain proper environmental flows in arid areas.

Methods
The location (by Global Positioning System) and depth of the monitoring wells, as well as groundwater table depth and salinity were measured in situ at each site from July to August 2009. Based on the measurements of the groundwater table depth and salinity following the implementation of environmental flow controls project (EFCP) in the lower Heihe River Basin, the groundwater fluctuations during the period from 2001 to 2009 were analyzed. Descriptive statistics and Pearson's correlation were used to analyze the relationship between vegetation changes and groundwater table fluctuations. Additionally, the spatial distributions of the groundwater table depth and salinity were interpolated using the simple kriging method. Trend analysis was applied to the time series of integrated Moderate Resolution Imaging Spectroradiometer normalized difference vegetation index data to identify interannual vegetation dynamics. The relationship between vegetation status and groundwater environment was investigated at different spatial scales by analyzing and comparing the time series and trends.

Important Findings
(i) The groundwater table and salinity increased significantly in most of the study area with spatial heterogeneity. On average, the groundwater table rose ~0.5 and 1.5 m in the upper and lower Ejina Basin, respectively, and the groundwater salinity increased across the study area by 0–4%. (ii) A notable correlation between the vegetation status and the groundwater table was revealed when the groundwater table depth fluctuated between 1.8 and 3.5 m, whereas the vegetation did not show an obvious response to groundwater table changes when the groundwater table depth was more than 5–6 m. (iii) Vegetation restoration mainly occurred in riparian areas within 500–1 000 m of from natural rivers, where the groundwater table depth varied from 2 to 4 m, and salinity was <5%, whereas vegetation degradation appeared at some locations where groundwater environment had deteriorated.

Keywords: seasonal average NDVI • groundwater table • salinity • Mann–Kendall method • arid area

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INTRODUCTION

The spatio-temporal dynamics of vegetation in arid and semi-arid regions are largely determined by water availability (Li *et al.* 2001). Groundwater is an important water source for many plants, particularly in arid and semi-arid regions, where groundwater supports a great density of vegetation by providing additional water for plant growth and transpiration (Naumburg *et al.* 2005). In addition, groundwater, as a component of total water resources, plays a dominant role in environmental protection (Zhu *et al.* 2004). Understanding the responses of vegetation dynamics to groundwater fluctuations is crucial for the sustainable improvement of ecosystems in arid regions (Wu and Hobbs 2002).

In arid and semi-arid regions, where the rainfall is particularly scarce, the direct effects of precipitation on plant functioning are very weak (Elmore *et al.* 2006). Therefore, the natural vegetation in these areas is mainly distributed along rivers or where the groundwater maintains an appropriate depth and salinity to allow for plant growth. In recent years, regional groundwater declines have threatened many riparian ecosystems in the arid and semi-arid regions of the world (Stromberg *et al.* 1996). Vegetation–groundwater interactions are becoming the focus of renewed interest related to the effects of groundwater fluctuations on plants and vegetation communities (Maitre *et al.* 1999). Recent studies have produced more and increasingly precise information on the response of vegetation cover and ecosystem functioning to groundwater fluctuations in arid and semi-arid regions. For example, Stromberg *et al.* (1996) investigated the changes in riparian vegetation due to declining groundwater levels in semi-arid regions and predicted that further declines in groundwater levels would cause a sequential 'desertification' of the riparian flora. Munoz-Reinoso (2001) reported a trend toward more xerophytic communities due to vegetation changes in response to a decline in groundwater level and a decrease in water availability from 1970 to 2000 in the Donana National Park, Spain. Using a 16-year record of plant cover derived from satellite data, Elmore *et al.* (2006) found that the plant community in the Owens Valley, USA, was groundwater dependent; however, with extensive groundwater declines, the vegetation cover became weakly correlated with the groundwater level, particularly after the groundwater level declined below the average plant rooting depth (~2.5 m).

In the arid regions of northwestern China, where the use of land and water resources has been significantly increased since the 1950s, the lower basins faced serious environmental deterioration and ecosystem degradation, such as the dry up of rivers and lakes, declines in groundwater levels and desertification (Feng and Cheng 1998; Wang and Cheng 1999). To restore the ecosystems in these regions, surface water has been transported from upper-middle to lower basins in the last 10 years (Chen *et al.* 2006, 2010). Impacts of fluctuations in groundwater levels on riparian vegetation along the Tarim River in western China have been reported in previous studies (Chen 2004; Chen *et al.* 2006, 2010; Kong *et al.* 2009; Pang *et al.* 2010). Based on the result of field campaign along 15 transects in the lower Tarim River, Chen (2004) concluded that the groundwater table depths at which *Phragmites communis*, *Tamarix* spp. and *Populus euphratica* began to experience stress were 3.5, 5 and 4.5 m, respectively. Using the field data from 40 monitoring wells and 18 vegetation survey plots during the period from 2000 to 2002, Chen *et al.* (2006) found that the groundwater level played a dominant role in determining plant species diversity in the lower Tarim River Basin. Kong *et al.* (2009) quantified the spatio-temporal variations of vegetation and landscape patterns related to groundwater fluctuations by analyzing Landsat TM images of the Tarim Basin in western China for 1986, 1999 and 2004. Pang *et al.* (2010) investigated riparian groundwater recharging and evolution in the middle Tarim by analyzing tritium, stable isotopes and water chemistry data. They confirmed the relationship between groundwater and ecosystems in this arid area. Based on a field investigation of groundwater table depth and plant species abundance along nine transects crossing the Tarim River, Chen *et al.* (2010) showed that damaged arid ecosystems were restored as far as 850 m from the river bank after considerable increases in the water level.

The Heihe River is the second largest inland river in northwestern China. In the last 50 years, increased water diversions from the Heihe River for irrigation in its middle reaches has triggered a series of ecological problems, including the disappearances of terminal lakes and a severe decline of the groundwater level in its lower basin (Chen *et al.* 2005; Feng and Cheng 1998; Feng *et al.* 2001; Wang and Cheng 2000; Zhu *et al.* 2004). Declines in the groundwater level have caused large areas of vegetation to die-off and have led to ecological deterioration and the desertification of the Ejina Oasis, which plays a protective role in blocking sandstorms in northwest China (Guo *et al.* 2009). Several studies have addressed the issue of fluctuations in groundwater levels and salinity, which affect plant growth indirectly or directly (Feng *et al.* 2004; Wen *et al.* 2005). Groundwater level variations of the Ejina region have been simulated in recent years based on experimental observation data (Xi, Feng, Liu, *et al.* 2009). Feng *et al.* (2004) investigated the distribution and evolution of water chemistry in the Heihe Basin and concluded that since the 1960s, large volume of the river water diverted for irrigation has been found to re-emerge as spring water at the edge of alluvial fans and then reintegrate into the Heihe River. After a number of reuses and re-emergences in the middle reaches of this river, the mineralization and ionic composition of the river water has doubled. Wen *et al.* (2005) found that salinity levels in groundwater were highly variable, with significant zonation from the recharge to the discharge area.

A number of studies on vegetation changes following the implementation of emergency water diversion in the lower Heihe River Basin have also been conducted in recent years (Guo *et al.* 2009; Jin *et al.* 2008, 2010; Wang *et al.* 2001). An increasing trend of vegetation growth was found in the lower East River basin based on annual regional-mean normalized difference vegetation index (NDVI) data from 2000 to 2006, and the status of the vegetation was highly correlated with the preceding year's run-off entering the Ejina Basin (Jin *et al.* 2008, 2010). Previous field investigations have shown a clear relationship between vegetation coverage and groundwater table depth in the Ejina Oasis: when the groundwater table depth declines from 1 to 5 m, the vegetation coverage accordingly decreases from 80% to 10% (Wang *et al.* 2001). Guo *et al.* (2009) showed that the vegetation grew remarkably well 100–400 m away from the water channel and around terminal lakes, and the growth rates decreased with the distance from the water body, based on field survey data from 2001 to 2005. The above-mentioned studies have involved groundwater characteristics related to the water cycle and vegetation changes in the ecosystems in the lower Heihe River Basin. However, very few studies have been focused on the impact of groundwater fluctuations on the succession and change in coverage of vegetation in this region. Because groundwater is an important ecological factor in arid regions and understanding the responses of vegetation dynamics to groundwater fluctuations is crucial for the sustainable improvement of ecosystems in arid regions, the purpose of this study was to reveal the dependence of vegetation on groundwater and the effects of groundwater fluctuations on vegetation dynamics in regions of water limitation.

THE STUDY AREA

The lower Heihe River Basin (Ejina Basin) covers an area of 3×10^4 km^2 in northwest China, extending between 40°20′–42°30′N and 99°30′–102°00′E (Li *et al.* 2001; Zhang *et al.* 2005) (Fig. 1). This region is characterized by a continental climate that is extremely hot in the summer and severely cold in the winter (Xie 1980). The mean annual temperature is ~8°C, with a maximum temperature of 41°C (July) and a minimum of −36°C (January). The mean annual precipitation is only 42 mm and the mean potential evaporation rate is 2 300–3 700 mm/year (Wen *et al.* 2005). The topography of the basin inclines from southwest to northeast, with an average slope of 1–3‰, and the land surface elevation varies from 1 127 to 820 m (Akiyama *et al.* 2007). The dominant landscape of the Ejina Basin is the Gobi Desert, which is composed of wind-eroded hilly land, desert and alkaline soils. The limited vegetation that exists in the region is distributed along the Heihe River and relies on shallow groundwater for sustenance (Akiyama *et al.* 2007; Feng *et al.* 2004; Xie 1980).

The Heihe River, originating in the Qilian Mountain, flows through the Ejina Basin and splits into two branches at Langxinshan (Fig. 1). The two branches of the Heihe River flow to the East and West Juyan Lakes, respectively; the total length of the two branches in the basin is ~240 km (Feng *et al.* 2001). Before entering the terminal lakes, the East River and West River forms several tributaries, including the Nolin River, the Longzi River and the Andu River (Fig. 1). The Heihe River is the main recharge source for the groundwater system, and ~68% of the groundwater recharge in the Ejina alluvial fan occurs through vertical percolation from the Heihe River (Feng *et al.* 2004; Wen *et al.* 2005; Wu and Hobbs 2002; Wu *et al.* 2002). In general, shallow groundwater flows from south to northeast across the basin and separates into two flow directions: one toward the Juyan Lakes and the other toward Gurinai (Si *et al.* 2009; Wen *et al.* 2005; Xie 1980). The mechanisms of groundwater discharge are evaporation (accounting for more than 90% of the total discharge), transpiration and groundwater withdrawal (Feng *et al.* 2004; Si *et al.* 2009; Xi, Feng, Liu, *et al.* 2009; Xi, Feng, Si, *et al.* 2009; Xie 1980).

The Ejina Oasis is located along these rivers on the alluvial fan and is encompassed by peripheral desert, including Gobi and sandy desert. The predominant natural vegetation in oasis includes *P. euphratica*, *T. ramosissima*, *H. ammodendron* and *Sophora alopecuroides*. Sparse xerophilic vegetation, such as *Nitraria tangutorum Bobr*, also exists in the study area. The predominant vegetation in the study area, which is characterized by species such as *P. euphratica*, *T. ramosissima* and *S. alopecuroides*, mainly relies on groundwater for sustenance (Guo *et al.* 2009; Zhu *et al.* 2009). In recent decades, over-extraction of the groundwater has caused a decline in the water table, resulting in the withering of large areas of *P. euphratica*, thus creating a highly visible indicator of ecological change and desertification in the Ejina Basin (Guo *et al.* 2009). Under the combined effects of climate change and human activities, the groundwater level in the Ejina Basin had continued to decrease before 2000, thus causing further degradation of vegetation and desertification of the Ejina Basin (Feng *et al.* 2004).

To restore the seriously degraded ecosystem in the lower Heihe River Basin, 'Integrated Water Resource Management of the Heihe River Basin' was conducted by the Heihe River Bureau in 2000 (Guo *et al.* 2009). As a part of this larger conservation plan, the EFCP has been implemented since 2000 for limiting a certain amount of river water (9.5×10^8 m^3/year) into the lower Heihe River Basin to protect the Ejina Oasis from deterioration (Guo *et al.* 2009; Jin *et al.* 2008, 2010; Wang *et al.* 2001). According to observations at the Langxinshan Hydrologic Station, annual run-off increased from 1.8×10^8 m^3 in 2001 to 7.5×10^8 m^3 in 2003 and continued to increase since then (Fig. 2). The total volume of annual river run-off into East Juyan Lake, which dried up in 1992, was 2.58×10^8 m^3 from 2000 to 2008 and reached a maximal water surface of 35.7 km^2 in 2004 (Guo *et al.* 2009). The surface water of Heihe River reached West Juyan Lake, which dried up in 1961, only in 2003, with a volume of 2.7×10^7 m^3 (Guo *et al.* 2009).

MATERIALS AND METHODS

To assess the change of the groundwater environment in the study area, the groundwater dynamics was studied from 2000 to 2009 by analyzing the water table depth and salinity from four groups of water sampling points: groups A, B, C and D (Fig. 3). A field campaign was conducted in July and August 2009, during which groundwater table depths were measured at 77 wells. In addition, groundwater salinity was analyzed in situ using a HANNA HI 98188 waterproof, portable Conductivity Meter at 92 regularly pumped (drinking, irrigation and

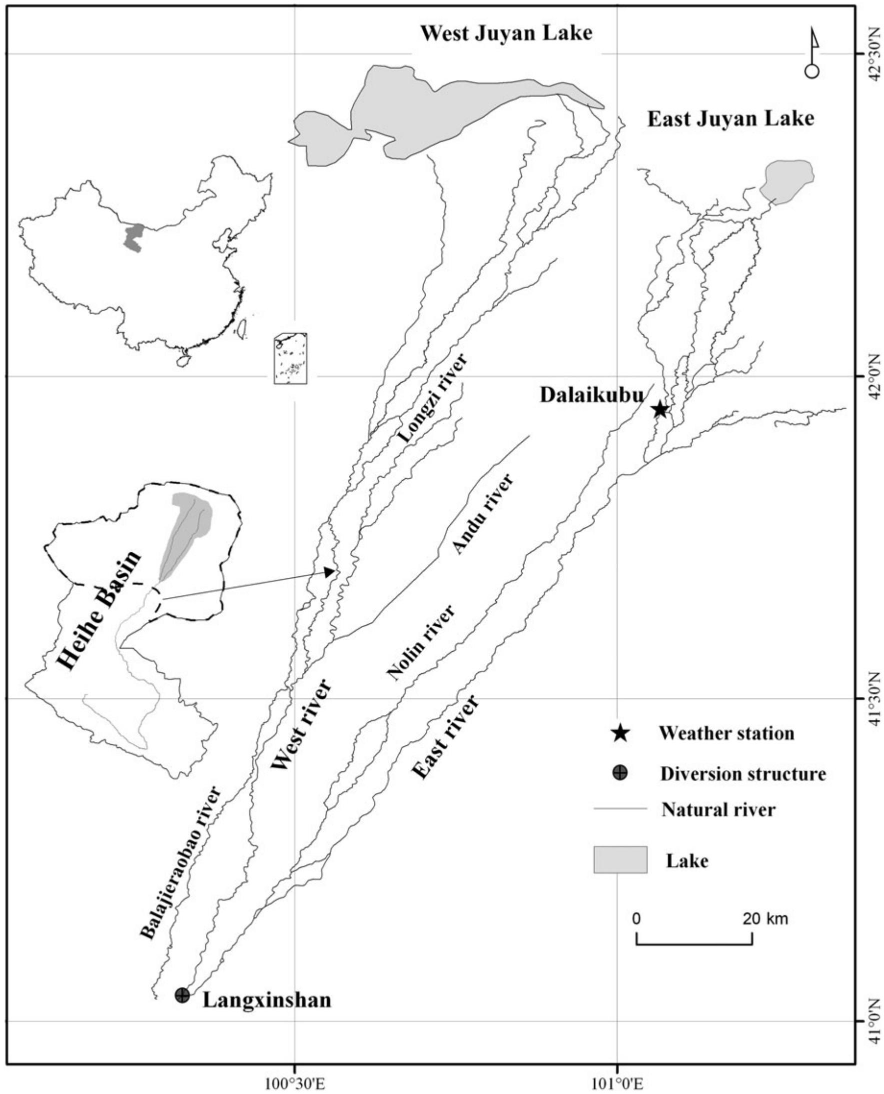

Figure 1: location of study area and water channels.

industrial) wells or boreholes (group A in Fig 3). Another field campaign was conducted by Lixin Wang and Yushu Zhang (Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences) in September 2001 from 59 wells (group B in Fig 3), including groundwater table depths measurements at 56 locations and 47 salinity samples. Moreover, groundwater table depths at the monitoring wells of in groups C and D (Fig. 3) were regularly measured once every 10 days during 2001–03 and 2000–09, respectively, by Hongwei Yang and Maoyun Qiao (Ejina Water Affairs Bureau). Data from all of the wells in group D were used later to investigate the relationship between vegetation dynamics and groundwater changes, except for wells d2 and d7, where continuous measurements are absent.

The NDVI derived from satellite sensor data at high temporal resolutions have been very widely used to investigate vegetation dynamics, particularly for arid and semi-arid areas (Fabricante *et al.* 2009; Jarlan *et al.* 2008; McGwire *et al.* 2000; Pouliot *et al.* 2009). In this study, NDVIs from the Moderate Resolution Imaging Spectroradiometer/Terra L3 16-day composite at 250 m resolution (i.e. MOD13Q1) were used to derive the seasonally averaged NDVIs (SAN) over the period of April–October. The SAN values were then used to indicate the annual vegetation state and investigate the temporal variation of the vegetation changes.

The SAN time series data were then compared with the mean groundwater table depth (MGTD) for 2000–08. To represent the status of the groundwater environment, the MGTD was calculated by averaging the 10-day records of the wells in group D over the period of April–October, which. For the investigation of relationships between vegetation dynamics and groundwater changes, SANs from the cells at which the wells are located were extracted for each year. This corresponds to an area of 250 × 250 m

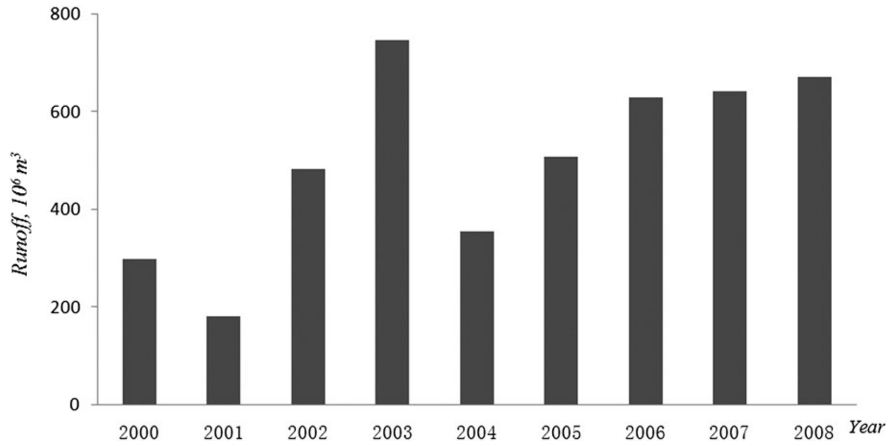

Figure 2: annual run-off into the lower Heihe River Basin.

from which the SAN values were compared with the MGTD data.

The Mann–Kendall method (Hipel and Mcleod 2005; Mann 1945) was used to test for trends in the SAN time series. A significance level of $\alpha = 0.05$ was adopted. The spatial distribution of groundwater table depth and salinity was interpolated using the simple kriging method in ArcGIS 9.2. The relationship between MGTD and SAN was determined using Pearson's correlation (Swan and Sandilands 1995).

RESULTS AND DISCUSSION

Vegetation dependence on groundwater

Groundwater is a key factor controlling the vegetation dynamics in this arid area. Additionally, fluctuations of the groundwater table were often accompanied by enhanced salinity of groundwater, which might offset vegetation restoration benefiting from alleviated water stress through the increase in salt stress to plants (Chen *et al.* 2004). As the vegetation in desert is very sparse, our study only took into account the vegetation in the oasis region. Based on the fact that the NDVI for the oasis is much higher than that in the desert during growing seasons, the pixels with mean SAN values >0.077 during 2000–09 were treated as oasis regions and the other pixels were designated as desert regions. The oasis region in the study area covers ~2 129 km^2 and consists of two regions, which locate along the West River and the East River, respectively. Several narrow strip-shaped oases within these regions have formed along five relatively independent tributaries, including the Longzi River, the Andu River and the Nolin River. These green belts run in the same north–south direction and serve as multilevel shelters to prevent sandstorms from the northwest. A flat-shaped oasis, which is different from the strip-shaped oases in other regions of the study area, forms in the lower East River, where the tributaries spread radially.

According to the field investigation, the predominant natural vegetation in the oasis includes *P. euphratica*, *T. ramosissima*, *H. ammodendron* and *S. alopecuroides*. These species play a very important role in maintaining the ecosystem function in the arid area because of their tolerance to severe drought and to high salinity and alkalinity in soils (Chen *et al.* 2004). Previous studies have suggested that the accumulation of proline in individuals of *P. euphratica*, which is the main community-building species of the desert riparian forests, is closely related to the change of the groundwater level gradient under drought stress (Chen *et al.* 2003, 2008). In the lower Tarim River, the groundwater stress depth for normal growth and the critical depth for the survival of *P. euphratica* are below 4.5 and 9–10 m, respectively (Chen 2004; Chen *et al.* 2003, 2004). In the study area, the depth of the groundwater table is mainly controlled by the topography and groundwater run-off features (Xie 1980). According to the field investigation conducted in July–August 2009, the measured groundwater table depth ranged from 0.80 to 8.29 m, with an average value of 3.33 m and a median of 2.90 m. As shown in Fig. 4, the groundwater table depth varies from 2 to 4 m, with an exception in the northeastern area, where the groundwater table depth was more than 4 m. Therefore, the current groundwater table depth in the majority of the area (2–4 m) is sufficient for the growth of desert riparian vegetation, such as *P. euphratica*.

Groundwater salinity, which is another important factor that directly or indirectly affects plant growth, varied from 1.2% to 9.8% during the study period. The coefficient of variation (CV), as a statistical measure commonly used for comparing the diversity of a series of numbers, represents the ratio of the standard deviation to the mean (Swan and Sandilands 1995). The CV of the groundwater salinity was 0.58, which indicates a relatively high degree of variation. As shown in Fig. 4, the groundwater exhibits a significant zonation in salinity along the direction of regional flow from the recharge to the discharge area (Wen *et al.* 2005). The low-salinity groundwater zone ($S \leqslant 3\%$) is mainly distributed in the foreland of diluvial fan, which suggests improved recharge and cycling conditions. Groundwater in this area is characterized as the Cl–HCO$_3$–Mg–Na water type. The medium-salinity

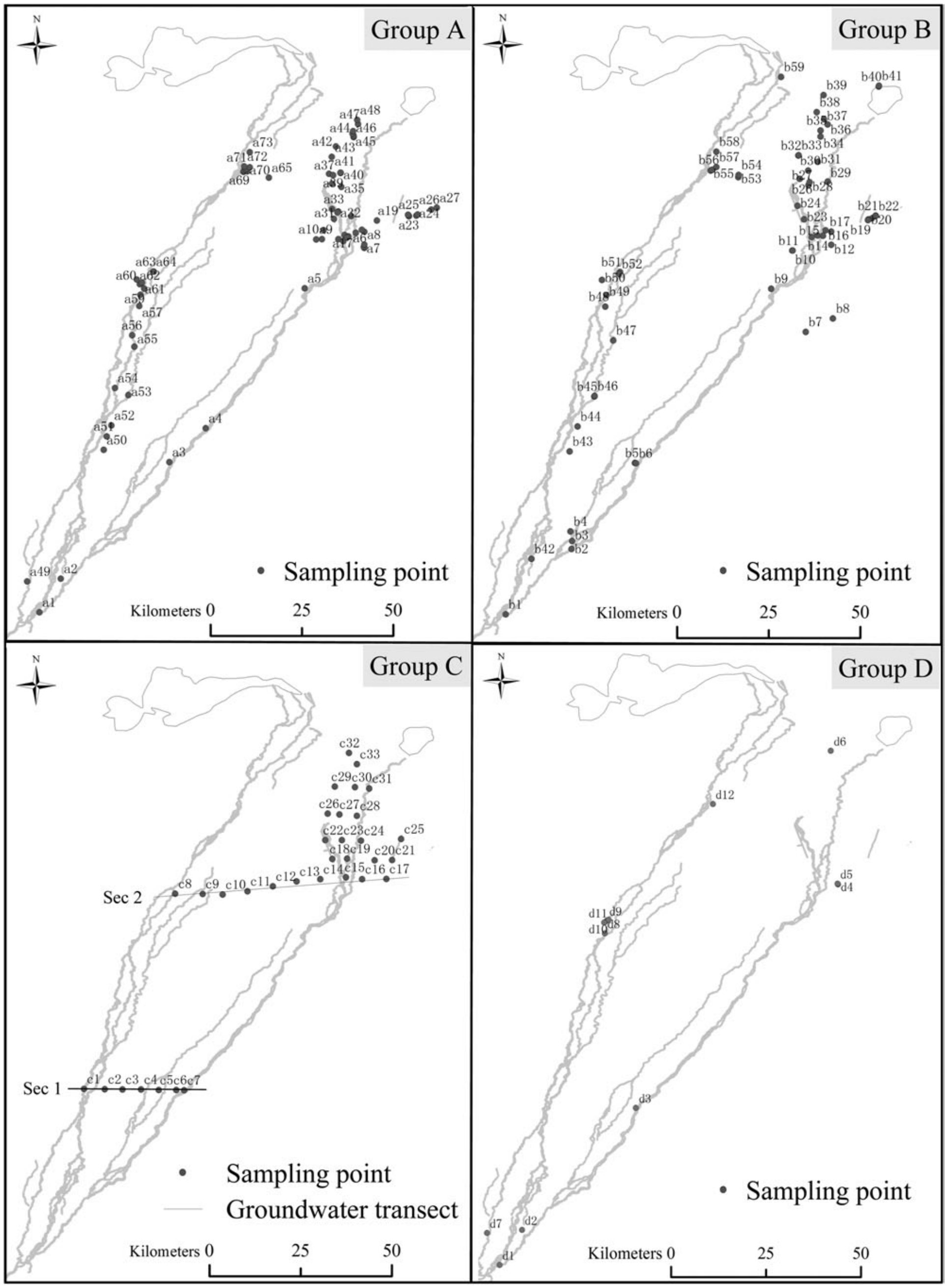

Figure 3: location of groundwater sampling.

groundwater zone (3% < $S \leqslant$5%) is mainly distributed in the central region and northern plain of the Ejina Basin, and groundwater in this area is characterized as the SO_4–Cl–Mg–Na water type. The high-salinity groundwater zone (S > 5%) is distributed to the northeast of Dalaikubu and overlaps with the Quaternary sedimentary center. This area has a low elevation and is a discharge sector of the groundwater system in the Ejina Basin. In this area, mineral dissolution and evapotranspiration are the main mechanisms of salt accumulation in groundwater (Pang *et al.* 2010; Wen *et al.* 2005). Environmental flows have resulted in a distinctive zoning pattern in groundwater salinity. Riparian vegetation is mainly distributed in the areas with lower salinity due to modern groundwater recharge.

Relationship between vegetation changes and groundwater table fluctuations

Because the percentage of cultivated land in the grid cells associated with the wells was not beyond 15% (Table 1), the SAN mostly reflected the status of natural vegetation in these

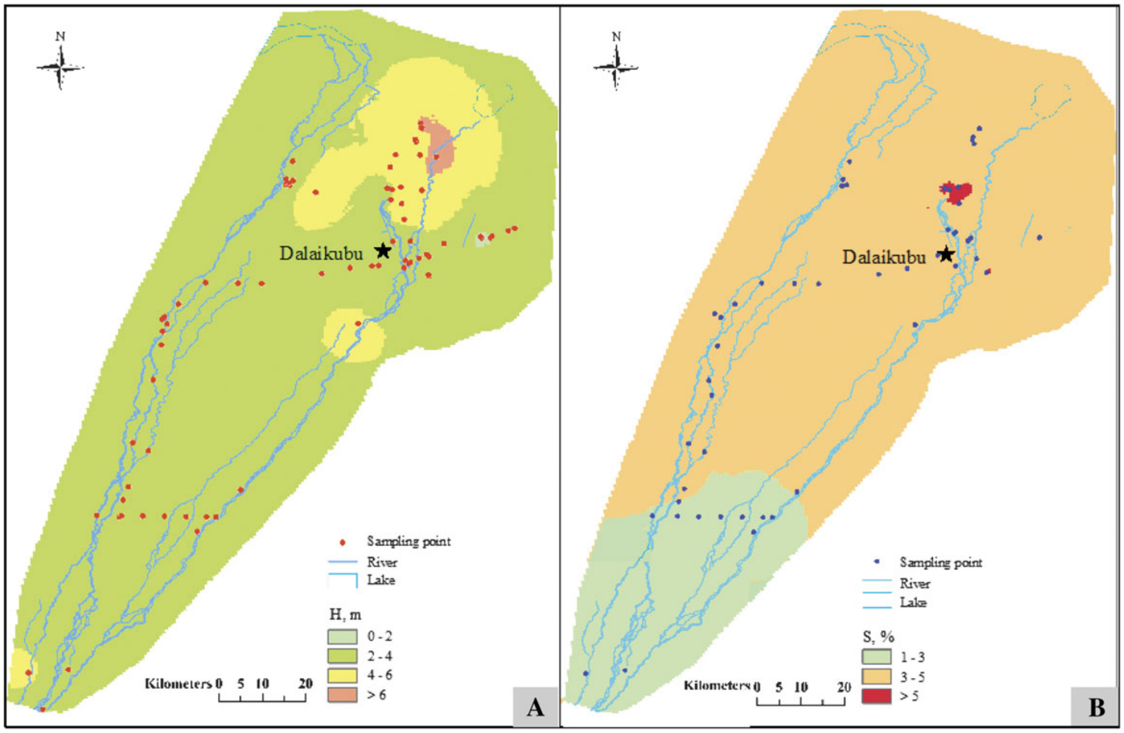

Figure 4: spatial variation of groundwater table depth (*H*, m) (**A**) and salinity (*S*, %) (**B**), 2009.

Table 1: the percentage of cultivated land in pixels (*P*, %) involving the wells

Well No.	d1	d3	d4	d5	d6	d8	d9	d10	d11	d12
P, %	0	0	10	10	5	10	10	0	0	15

areas. Pearson's correlation is used to find a correlation between two or more continuous variables. Values of the correlation coefficient (r) range from -1 to $+1$. The absolute value of the correlation coefficient indicates the strength of the linear relationship between the variables, with larger absolute values indicating stronger relationships. In geosciences, an absolute value of correlation coefficient >0.7 (i.e. $|r| > 0.7$) suggests strong correlation, whereas $|r| = 0.5$–0.7 indicates a moderate correlation (Swan and Sandilands 1995). According to Table 2, SAN correlates with MGTD, though the relationship between them varies for different wells and periods. A strong negative correlation ($r < -0.7$) between SAN and MGTD was found for wells d1 and d4 and a moderate negative correlation ($-0.7 < r < -0.5$) was found for wells d9 and d5 (group A in Fig. 5), which indicated that the vegetation got better or worse with the groundwater table rising or declining, respectively. It is found that the apparent response of vegetation to groundwater fluctuations takes place when the groundwater table depth varies between 1.8 and 3.5 m (Fig. 5). This is consistent with results of previous field studies: ~2–4 m has been found to be the range of the functional groundwater table depth for vegetation functioning (Chen 2004; Chen *et al.* 2008).

It should be pointed out that there was no notable relationship ($|r| < 0.5$) between SAN and MGTD for wells d11, d10 and d8 (group B in Fig. 5), although the groundwater table depth for these wells fluctuated in the range of 2–4 m. The disagreement of a strong correlation between vegetation change and groundwater dynamics at these sites showed that the fluctuations of the groundwater table was no longer the dominant factor driving vegetation changes, although the groundwater table depth is within the optimal range for vegetation growth. However, from Landsat ETM images, it could be observed that wells d8, d10 and d11 are located near natural rivers and are frequently submerged by surface water every year. The exposure to surface water would lead to rapid changes of the grassland, which contributes to the interannual variability in SAN.

The groundwater table depths at wells d6 and d12 (after 2003) were generally lower than 4.5 m with a declining trend, whereas the SAN showed an increasing trend. This indicates that when the groundwater table is lower than a critical level, its influence on vegetation is very limited. It should be mentioned that a concrete-lined channel has replaced the previous natural river near well d6 in recent years. The building of the channel prevented the streamflow from recharging the groundwater and caused the groundwater level to decrease,

Table 2: Pearson's correlation matrices showing marked correlations (*r*) and *P*-values between Mean Groundwater Table Depth and Seasonally Averaged NDVI

Well No.	Well d1	Well d3	Well d4	Well d5	Well 6	Well 8	Well d9	Well 10	Well 11	Well d12
r	−0.86	0.56	−0.71	−0.52	0.56	0.13	−0.66	−0.16	−0.25	0.03
P-value	0.003	0.145	0.031	0.148	0.115	0.742	0.054	0.682	0.518	0.934

though it irrigated nearby vegetation through the lateral channels extending from it. For well 12, the derelict land in its grid cell was reclaimed after 2004 due to irrigation during the implementation of EFCP.

Changes in groundwater table and salinity after the implementation of EFCP

In the arid area, vegetation degradation is mainly related to the reduced recharge to riparian groundwater, a decreased groundwater table and increased salinity of the groundwater system (Pang *et al.* 2010). Due to changes in surface hydrological processes and groundwater exploitation, the groundwater table in the lower Heihe River has markedly declined in the last decades (Su *et al.* 2007). However, this situation changed following the implementation of EFCP in 2000. The groundwater table in the upper basin (d1, d3 and d10 in Fig. 3) increased continuously during the implementation of EFCP (Fig. 6); however, the groundwater table in the lower basin (wells d6 and d12 in Fig. 3) exhibited an obvious decreasing trend due to water pumping for seasonal irrigation (Fig. 6), which is quite different from the conditions in the upper basin. It should be mentioned that the groundwater table showed intensive fluctuations in the first 2 years (2000–01) after the implementation of EFCP; e.g. 2–3 m fluctuations were observed for well d8.

The response of the groundwater table to environmental flows is also determined by the distance to the river. For example, the groundwater table depths ranged from 1.19 to 1.85 m in well c2, 2.94–3.47 m in well c3, 2.41–3.29 m in well c4 and 1.79–2.41 m in well c7 along Sec 1 (Fig. 3) during the period from 2002 to 2003. The groundwater table depths in wells c2 ($\bar{x}$ = 1.61 m, s = 0.23 m, where $\bar{x}$ is the mean of the groundwater table depth and s is the standard deviation of the groundwater table depth) and c7 ($\bar{x}$ = 2.01 m, s = 0.18 m) were much lower than in wells c3 ($\bar{x}$ = 3.23 m, s = 0.15 m) and c4 ($\bar{x}$ = 3.02 m, s = 0.17 m) (Fig. 7), which indicated that environmental flows mostly affected the groundwater in areas adjacent to the river. During this period, the groundwater table depth varied from 1.17 to 2.46 m in well c14, from 2.81 to 3.32 m in well c13 and from 3.07 to 3.54 m in well c12 along Sec 2 (Fig. 7). The groundwater table fluctuations in well c14 (1.29 m) were much greater than in wells c13 (0.51 m) and c12 (0.47 m) (Fig. 7), which indicated a rapid response of the groundwater along the river, and the response in the groundwater table is reduced with increasing transverse distance away from the river.

The spatial patterns of groundwater table depths after EFCP are evaluated. Fig. 8 shows the difference in the groundwater table depth between September 2001 and September 2003, as well as between September 2003 and July–August 2009. As shown in Fig. 8, the changes in the groundwater table depth between 2001 and 2003 varied from −6 (increased) to +2 m (declined), which indicated a great influence of environmental flows on groundwater dynamics. During this period, the groundwater table increased in most of the area, particularly in the northeastern region of Dalaikubu. However, a slight decline in the groundwater table along the river was caused in non-infiltrated areas as a result of the construction of drainage channels (Guo *et al.* 2009). Comparing the groundwater table depth between 2003 and 2009, it is clear that the groundwater table increased by 0–1 m in general, although declines in the groundwater level persisted in areas characterized by the construction of drainage channels and irrigation areas with groundwater withdrawals (i.e. in northeastern region of Dalaikubu) (Fig. 8).

Generally, the regional increase of the groundwater table in the study area remained following the implementation of EFCP. However, irregular fluctuations in the groundwater table depth were observed in the irrigation areas. The groundwater table in these areas was significant increasing during the first 2–3 years of water diversion and then slightly declined. Water withdrawals for irrigation and the construction of drainage channels to transport water to the East Juyan Lake and the Ejina Oasis (Guo *et al.* 2009), exert an important influence on the groundwater regime, including on the dynamics of groundwater recharge.

Salinity is one of the most important factors affecting the growth of vegetation. Vegetation degradation in arid regions is related to the declination in water table, as well as the increase in salinity in the groundwater system (Pang *et al.* 2010). The spatial patterns of groundwater salinity in the study area were compared in terms of spatial distribution between July–August 2009 and September 2001. As shown in Fig. 9, the salinity level in the groundwater increased by a total of 0–4% during the implementation of EFCP. This increasing groundwater salinity resulted from the dissolving action that occurs in the process of groundwater flowing from recharge to discharge areas. Salt dissolution, deposition, ion exchange, evaporation and other chemical and physical reactions tend to cause groundwater to evolve from a dilute calcium bicarbonate type in recharge areas toward a more concentrated sodium chloride or calcium chloride type in discharge areas (Feng

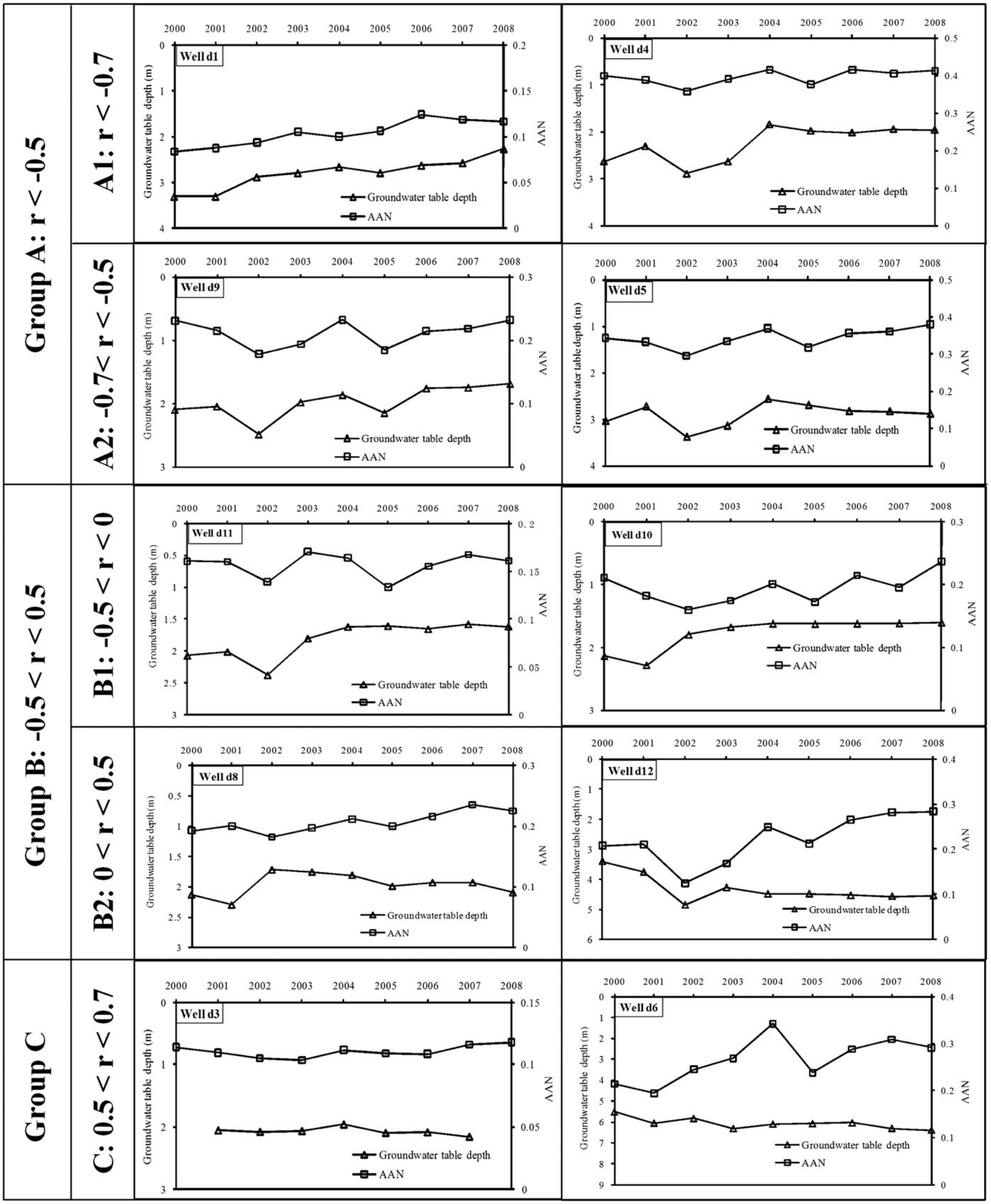

Figure 5: relationship between the groundwater table depth and SAN.

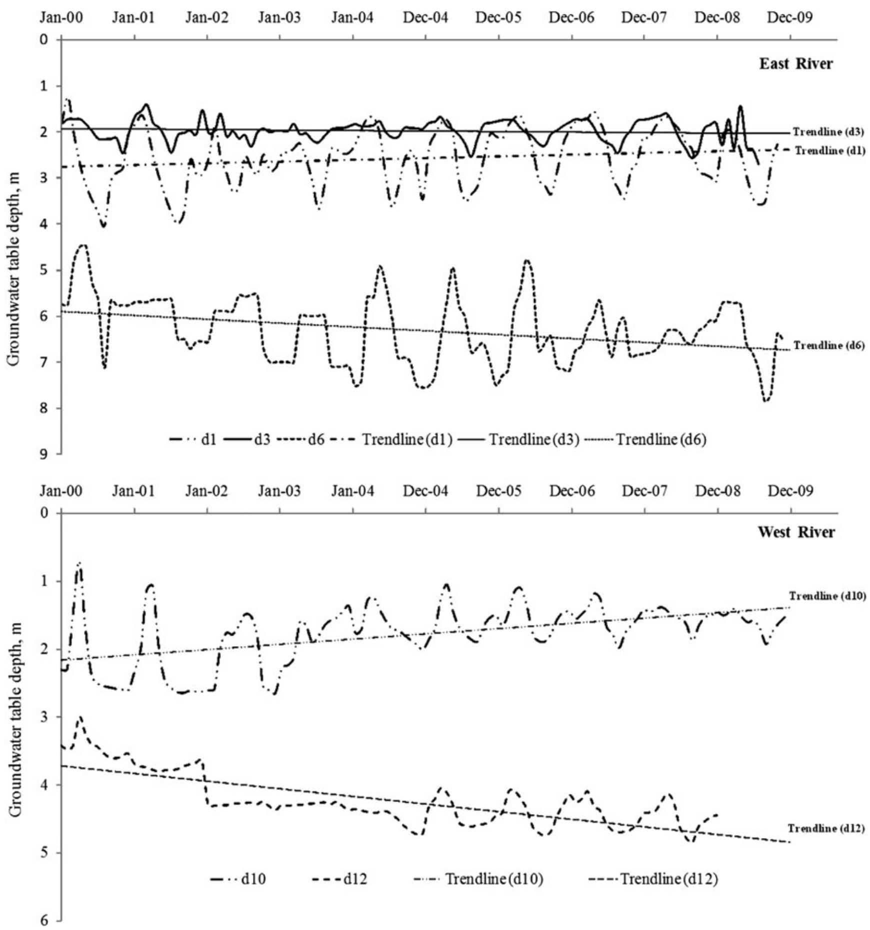

Figure 6: groundwater fluctuations in monitoring wells from 2000 to 2009.

et al. 2004; Si *et al.* 2009; Wen *et al.* 2005; Zhu *et al.* 2009). In addition, decades of irrigation have resulted in fluctuations of the groundwater table, which has accelerated salt accumulation in the groundwater and surface soils. Moreover, the inappropriate exploitation of groundwater resources has, to some extent, exacerbated the process of the salinization of groundwater in this region (Guo *et al.* 2009; Su *et al.* 2007). Mixing environmental flows with groundwater could also lead to a controlling influence on salinization process of groundwater, although compared to groundwater, environmental flows generally have a lower salinity (Wen *et al.* 2005).

The spatial response of vegetation dynamics to the implementation of EFCP

From 2000 to 2009, the areas with increasing trends, no trend and decreasing trends occupied 89.8, 1 138.8 and 901.1 km^2, representing 4.2%, 53.5% and 42.3% of the whole oasis region (Fig. 10). The large area characterized by increasing trends and no trend for SAN showed that the condition of vegetation had been improved in general. The areas with increasing trends were distributed along natural rivers (e.g. East and West Rivers) and usually appeared within 500–1 000 m away from these rivers. Meanwhile, many rivers recovered after 2000, including the lower East and West Rivers, which has been verified by local governments and can be detected on Landsat TM images. This should be attributed to the guidelines of EFCP, which specified conveying a certain amount of water to the lower Heihe River. With the recovery of rivers, the condition of the groundwater environment has improved, as shown by the increases of the groundwater level observed in many locations, as mentioned above. It is clear that the universal improvement of groundwater conditions is the most crucial factor for vegetation restoration.

Decreasing trends of the SAN, specifically vegetation degradation, mainly appeared in several floodplains along the West River, the Nolin River and the East River. Field investigations showed that the deterioration of the water environment around these floodplains occurred in recent years. As mentioned above, to convey water in the Heihe River as far as possible, some tributaries have been artificially cut off in the upper West River, and many channels have been built to replace previous natural rivers along the entire extension of the study area. These measures have directly prevented surface water from reaching nearby floodplains and recharging groundwater

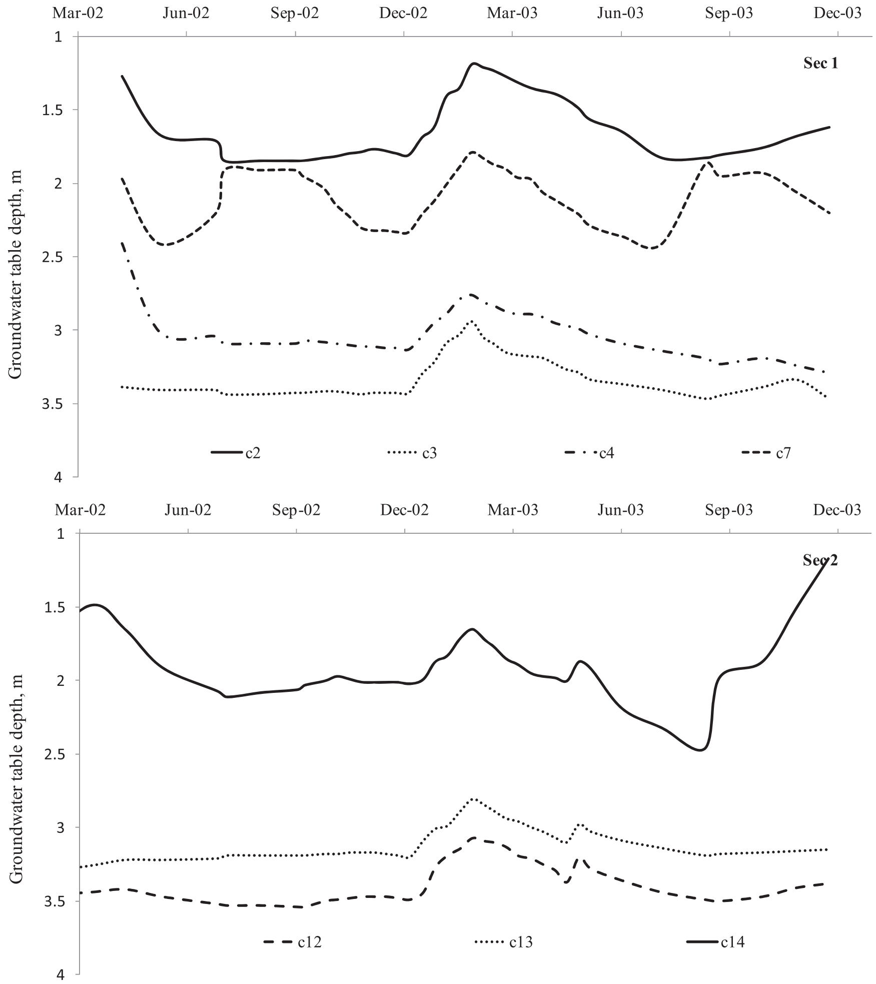

Figure 7: groundwater fluctuations in transects 1 and 2 from 2002 to 2003.

as it did prior to channel construction, though this situation mainly occurred in the upper and middle West River and the lower East River. Additionally, they have indirectly degraded the water environment far from the channels. For example, the Dongganqu, a concrete-lined channel, gradually replaced the East River to become the main water channel in this region after 2003, before entering the Ejina Basin. Because the Dongganqu was built across the upper reach of the Nolin River, the Nolin River was cut off and completely dried up. It was certain that the reduction or vanishing of surface water remarkably decreased the groundwater recharge in this area. The deterioration of the local groundwater environment further resulted in this vegetation degradation.

CONCLUSION

The vegetation dynamics induced by groundwater fluctuations were investigated through the analysis of long-term groundwater dynamics and satellite images during the implementation of EFCP in the lower Heihe River in northwestern China. The following conclusions can be drawn from this study.

1) Under the regional groundwater flow systems, the groundwater table depth in the study area varied from 2 to 4 m, except in regions of irrigated farmland (up to 6–8 m). Along the groundwater flow path, the salinity level in the groundwater increased continuously from 1.2% to 9.8%.
2) A notable correlation between the vegetation status and the groundwater table was identified when the latter fluctuated between 1.8 and 3.5 m. When the groundwater table depth was more than 5 and 6 m, the vegetation conditions did not show an obvious response to groundwater table fluctuations.
3) After environment flow controls were implemented for the lower Heihe River, the groundwater table fluctuated significantly in most of the study area, with spatial heterogeneity. Generally, the groundwater table rose by ~0.5 m in the upper and 1.5 m in the lower Ejina Basin. Fluctuations in the groundwater table caused the temporal and spatial variability of salinity, which increased throughout the study area by 0–4%.
4) Implementation of EFCP led to universal vegetation recovery, though they have also caused local vegetation

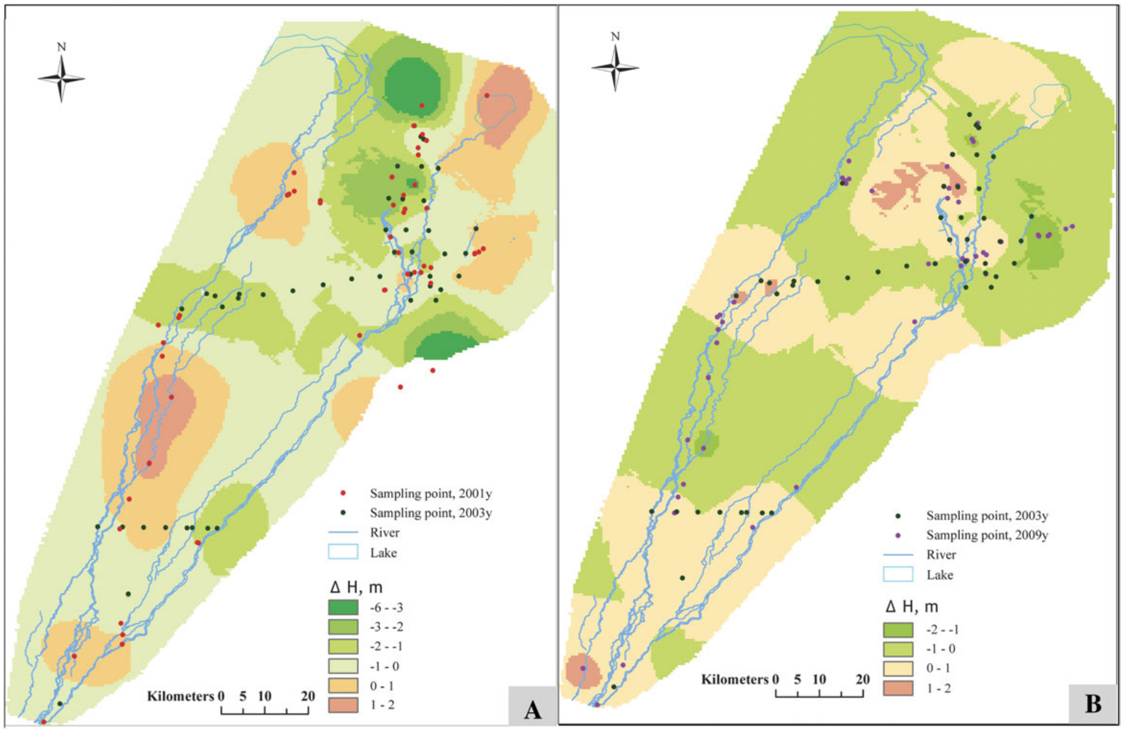

Figure 8: spatial variation of changes in groundwater table depth (ΔH, m) between 2001 and 2003 (**A**) and between 2003 and 2009 (**B**).

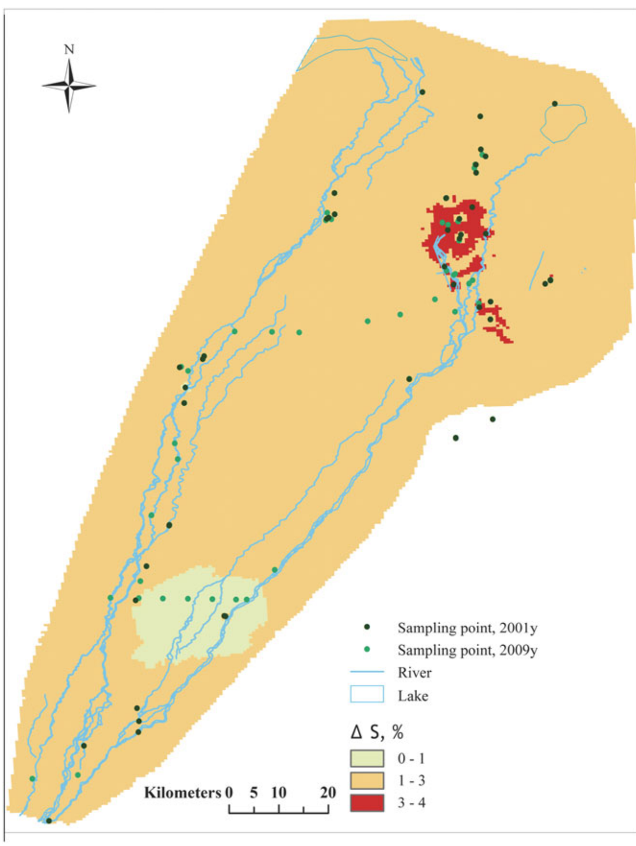

Figure 9: spatial variation of changes in groundwater salinity (ΔS, m) between 2001 and 2009.

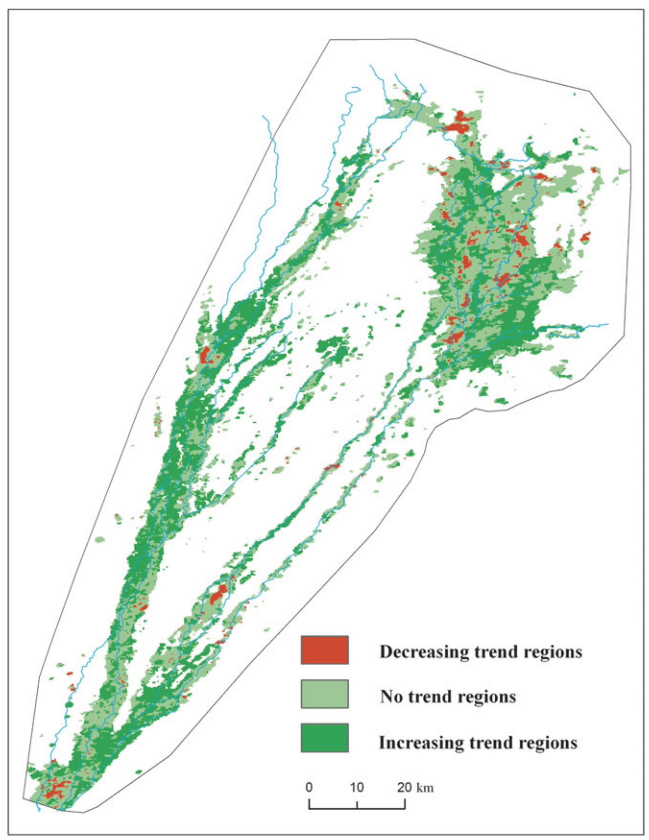

Figure 10: the spatial distribution of vegetation change analyses in 2000–09.

degradation. The areas of vegetation restoration were mainly distributed in riparian areas within 500–1 000 m of the natural rivers, where the groundwater table depth varied from 2 to 4 m, and salinity was <5%.

After the implementation of EFCP in an arid area, the accumulation of groundwater salinity will eventually offset vegetation restoration benefiting from alleviated water stress through the increase in salt stress to plants, despite the fact that the groundwater table might be raised. In this case, the mechanism of vegetation responses to groundwater fluctuations, both in the water table and in the salinity, appears to be particularly complicated. Therefore, there is a need for further scientific research with the aim of maintaining salt and water balances for the purpose of vegetation restoration.

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