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Temporal and Spatial Variations of Vegetation Response to Dynamic Change of Meteorological Factors and Groundwater in the Heihe River Basin, China

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The interaction of meteorological factors and groundwater depth affects vegetation coverage and growth, particularly in semi–arid regions where groundwater is extracted for human use. This paper analyzed the characteristics of temporal and spatial variations in the Normalized Difference Vegetation Index (NDVI) between 1998 and 2008 to clarify the response of NDVI to variations in meteorological factors and groundwater depth in the Heihe River Basin, China. The results indicated that: (1) there was a statistically significant response of NDVI to temperature variation, and this was greater than the response to precipitation. Partial years showed a time–lag in response to temperature and precipitation, and NDVI–temperature had a faster response time than NDVI–precipitation. (2) Groundwater depth less than 7.3 m had the greatest effect on NDVI. Salinization, the capillary height and the maximum vegetation root zone were the main factors to increase or reduce the growth of vegetation. The relationship between NDVI and groundwater depth could be fitted with a logistic correlation curve.

Key words: Heihe River Basin; Normalized Difference Vegetation Index; Meteorological factors; Groundwater depth; Correlation analysis

INTRODUCTION

Vegetation coverage refers to the percentage of project area of vegetation (including leaves, stems and branches) vertically onto the ground to the surface area. It is an important parameter in the evaluation of land desertification, soil erosion monitoring and distributed hydrological modelling (Myeong *et al.*, 2006; Rasmussen *et al.*, 1992; Li *et al.*, 2004; Wang *et al.*, 2015; Wu *et al.*, 2016).

There is a strong research demand to find the interaction between vegetation coverage and climate because it is closely related to various environmental factors such as soil moisture, surface temperature, surface energy, and the hydrological cycle. Anthes (1984) analyzed the effect of changes in vegetation coverage on precipitation in arid regions and concluded that the bands of vegetation 50–100 km wide in semi–arid regions would increase precipitation. Nicholson *et al.* (1990) analyzed the time response of the Normalized Difference Vegetation Index (NDVI) to precipitation and found a good correlation over seasonal and annual timescales. Schmidt *et al.* (2000) studied the response of vegetation to precipitation in different vegetation zones of a north and south belt in Israel using Advanced Very High Resolution Radiometer (AVHRR) NDVI and concluded that the transition zone was sensitive to precipitation.

Vegetation coverage is also closely related to the groundwater level. Using data from 12 monitoring sections in the middle reaches of the Tarim River, China, Xu *et al.* (2004) established a regression equation between the groundwater level and vegetation coverage. Quantitative researches on vegetation coverage and groundwater in Eqinaqi, in the Heihe River Basin (Zhong *et al.*, 2002; Wang *et al.*, 2014; Wang *et al.*, 2016; Yang *et al.*, 2016) considered that there was a dynamic equilibrium between vegetation growth and degradation and groundwater level. Based on NDVI, Jin *et al.* (2014) calculated the effect of groundwater on vegetation coverage in the Wutumeiren region of the Qaidam Basin and showed that the vegetation growth was closely related to groundwater.

In this study, we studied the effects of climate change and groundwater depth on the vegetation coverage in the Heihe River Basin, the second largest continental river basin in the northwest arid region in China. Drought coupled with the over–exploitation and use of the limited water resources in the river basin make the local ecosystem fragile and unstable. Understanding the effects will improve the management of vegetation coverage in arid areas and provide a scientific basis for the sustainable development of the social, economic and ecological environment.

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STUDY AREA AND DATA COLLECTION

Study area

The Heihe River Basin in the inland arid area of Gansu province encompasses an area of 1.3×10^5 km^2 between 37°41'–42°42'N and 96°42'–102°00'E, with a river length of 821 km (Fig. 1). Over–exploitation and use of limited water resources in the 1990s have gradually degraded the ecological environment (Feng *et al.*, 2002). For example, with the increase in human activities over recent years, the groundwater level has been greatly lowered, and the relationship between surface water and groundwater has become more complex. Spring water flows have sharply decreased. The unique landscape of the Heihe River Basin, and lower levels of human activity compared with the eastern regions makes the Heihe River Basin a natural laboratory for research on the effects of different natural geographical units on ground vegetation and global change responses.

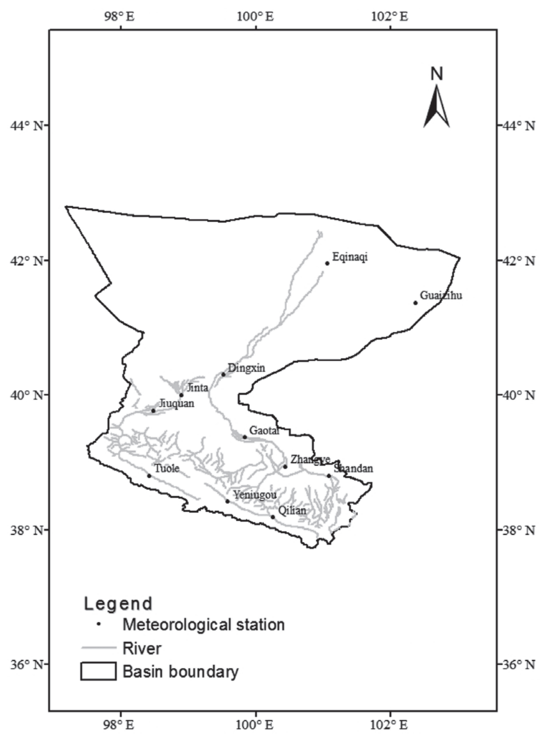

Fig. 1. Location of the Heihe River Basin and meteorological stations.

Data collection and methods

The raw data resource used in this research included 1–km spatial resolution and 10–d temporal resolution Satellite Pour l'Observation de la Terre (SPOT) Vegetation NDVI data from April 1998 to July 2008. A total of 372 scenes were available in China's long–term series SPOT Vegetation NDVI data sets from the Environment and Ecological Science Data Center for Western China of the National Natural Science Foundation of China. Digital number (DN) was stretched in value, which was ranged from 0 to 255, and true NDVI was calculated using the formula NDVI=DN*0.004–0.1 in ArcGIS (ESRI, Redlands, U.S.A., http://www.esri.com). This study used a Maximum Value Composite with the NDVI data to eliminate the interference of reflectance distortions such as clouds, atmosphere, and solar altitude angle.

Precipitation and temperature data were collected by 11 meteorological stations in the Heihe River Basin from 1998 to 2008 which are part of the National Meteorological Information Center. The data on groundwater came from the datasets of groundwater of Heihe River Basin from 1998 to 2008, which were provided by the Data Center of Arid and Cold Regions in China. The data contained average monthly groundwater level, ground elevation and the longitude and latitude of each observation point.

The trend line method for measuring temporal variation focuses on a set of average annual NDVI values that change with time and predict the future trend. Spatial variation in the average NDVI over ten years is shown in raster format. By calculating the NDVI value of each pixel, this study simulated variations in the trend of NDVI using trend line analysis, that was, the NDVI variation rate. The computational formula is as follows:

$$\text{slope} = \frac{n*\sum_{i=1}^{n}\text{NDVI}_i-(\sum_{i=1}^{n}i)*(\sum_{i=1}^{n}\text{NDVI}_i)}{n*\sum_{i=1}^{n}i^2-(\sum_{i=1}^{n}i)^2}, \quad (1)$$

where slope is slope of the trend line; i is yearly sequence number for 1 to n; NDVI is average annual NDVI on a given year. The slope greater than 0 means the increasing trend in the phase, the opposite the decreasing trend.

Based on the Z distribution, the z–score is the one of standard measures of trends, and is also called the z–value or normal score. Z–values are most frequently used to compare a sample with a standard deviation, although they can be defined without assumptions of normality. They eliminate the unit limits of data, and transform data to simple numerical values, so that different units or different orders of magnitude can be compared. The formula used to calculate the z–score is as follows:

$$z = \frac{x-\mu}{\sigma}, \quad (2)$$

where z is z–value; μ is the mean value of data; σ is the standard deviation of data.

The correlation coefficients show general correlation levels, which are formulated as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2*\sum_{i=1}^{n}(y_i-\bar{y})^2}}, \quad (3)$$

where r_{xy} is correlation coefficient between NDVI and the meteorological factors (precipitation or temperature); y_i is the annual NDVI for a given year; $\bar{y}$ is average NDVI for ten year; x_i is the annual meteorological factors (precipitation or temperature); $\bar{x}$ is average precipitation or temperature for ten years; n represents 10 years.

Partial correlation coefficients reflect the degree of correlation between two factors in the system without considering other factors.

$$r_{123} = \frac{r_{12} - r_{13} * r_{23}}{\sqrt{(1-r_{13}^2)*(1-r_{23}^2)}} , \quad (4)$$

where r_{123} is partial correlation coefficient; r_{12}, r_{13} and r_{23} are correlation coefficients between NDVI and precipitation, NDVI and temperature, precipitation and temperature, respectively.

The multiple correlation coefficient is the index of linear correlation between NDVI and meteorological factors (precipitation and temperature), reflecting the comprehensive effects of meteorological factors on NDVI. The specific calculation process is as follows: Make regression of y on x and

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 , \quad (5)$$

then

$$R = \text{corr}(y, \hat{y}) = \sqrt{\frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}} = \sqrt{\frac{SS_R}{SS_T}} , \quad (6)$$

where β_0 is y-intercept, and β_1 and β_2 are regression coefficients R is multiply correlation coefficient; y is NDVI while x_1 and x_2 are precipitation and temperature respectively.

To better quantify the correlation between NDVI and groundwater depth, the least square method (LSM) was used to reconstruct and fit the data on NDVI and groundwater depth as closely as possible. The principle of LSM is as follows:

$$\varepsilon_i = \phi(x_i) - f(x_i), \quad (7)$$

where ε_i is residual error of $\phi(x_i)$ on x_i ; x_i is from i=1,2,…,n. The point of this method can be summarized with curve fitting shape function $\phi(x_i)$ construction. Function is not required strictly to pass all points of data, which is equation of $\varepsilon_i \neq 0$. In order to the approximate curve can reflect the variation trend of the points, $|\varepsilon_i|$ is required to reach the expectation for minimum according to one metric.

The fitting metric is given as

$$\|e\|_1 = \sum_{i=0}^{n} |\varepsilon_i| = \sum_{i=0}^{n} |\phi(x_i) - f(x_i)| \quad (8)$$

or

$$\|e\|_\infty = \max_i |\varepsilon_i| = \max_i |\phi(x_i) - f(x_i)|$$

$$\text{for } e = [\varepsilon_0, \varepsilon_1, \ldots, \varepsilon_n]^T \quad (9)$$

where $\|e\|$ is minimized as much as possible.

$$\|e\|_2^2 = \sum_{i=0}^{n} \varepsilon^2 = \sum_{i=0}^{n} [\phi(x_i) - f(x_i)]^2 , \quad (10)$$

where $\|e\|_2^2$ is required to reach a minimum to facilitate calculation, analysis and application. Achieving the least squares fitting of the sum squares error is called the least squares method for curve fitting.

RESULTS AND DISCUSSION

Temporal and spatial variations of NDVI

Based on SPOT Vegetation NDVI data, descriptive statistics for the maximum, minimum, monthly and annual NDVI variation from 1998 to 2008 are shown in Table 1 and the temporal variation of NDVI is shown in Fig. 2. The NDVI data from each year derived from the SPOT Vegetation sensor ranged from 0.004–0.028 for $NDVI_{min}$, and 0.82–0.92 for $NDVI_{max}$, and there was a change in 2001 (Fig. 2a). The values of NDVI decreased gradually from 1998 to 2001. After 2001, the values of NDVI increased. Overall, the values of NDVI increased

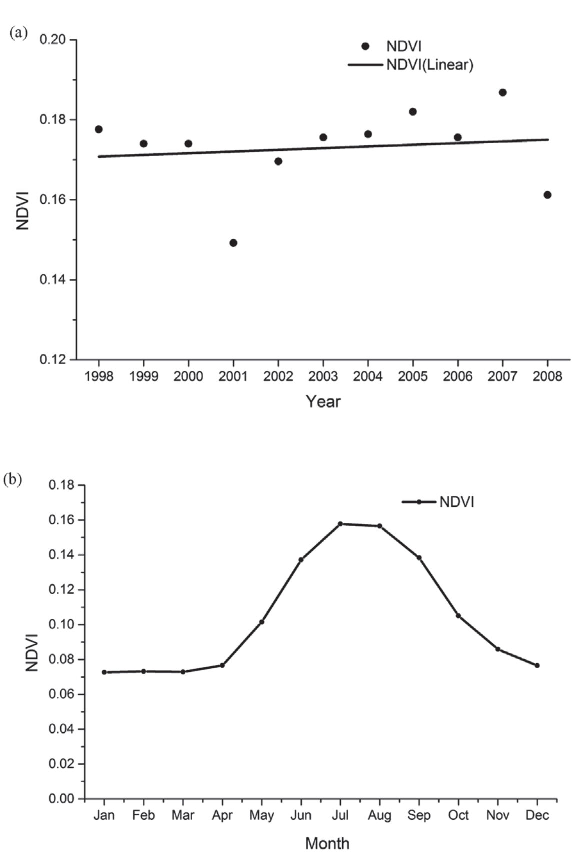

Fig. 2. Temporal variation of NDVI from 1998 to 2008; (a) Average annual NDVI; (b) Average monthly NDVI.

Table 1. Maximum, minimum and average annual NDVI from 1998 to 2008

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Max	0.920	0.920	0.920	0.820	0.860	0.856	0.856	0.864	0.884	0.892	0.836
Min	0.024	0.024	0.012	0.012	0.012	0.012	0.012	0.012	0.008	0.028	0.004
Average	0.178	0.174	0.174	0.149	0.170	0.176	0.176	0.182	0.176	0.187	0.161

slowly from 1998 to 2008 with a variation slope of 0.0004. This represented a trend of slightly increasing vegetation coverage in the Heihe River Basin, and was consistent with the results of increasing vegetation coverage over the last 20 years (Fang *et al*., 2003).

The monthly NDVI variation (Fig. 2b) revealed the process of vegetation growth over a whole year. From April, the values of NDVI showed a sharp rise, which reflected the natural vegetation growing season. In June, where conditions were suitable for the growth of all types of vegetation, the NDVI values reached to 0.14. Optimum growth for most vegetation was achieved in July and August, when the chlorophyll content peaked at 0.16. In the following months, NDVI slightly decreased as most vegetation stopped growing or even gradually withered. The maximum rate of decline appeared in October. From December to next March, the values remained low and stable at about 0.08.

With the data of NDVI from 1998 to 2008 in the Heihe River Basin, the spatial distribution of average annual NDVI (Fig. 3) was calculated. The spatial distribution of NDVI in the Heihe River Basin has significant regional differences. Vegetation coverage in the southern mountain areas was more pronounced than that in the northern mountains. High values of average annual NDVI (0.50–0.92) were concentrated in the upper Basin regions of Qilian County, southeastern Sunan County, Minle County, southern Shandan County, Zhangye City and Linze County, and scattered across the mid–Basin around Jiuquan City and southern Jinta County, which marked better vegetation coverage in these regions. NDVI values in the mid–Basin regions of northwestern Sunan County, Jiayuguan County, and part of Eqinaqi ranged from 0.25 to 0.50. Northwestern Eqinaqi was mostly desert grassland, with low NDVI values (0.10–0.25). The majority of the remaining areas, which were mostly the Gobi or other deserts, had NDVI values of < 0.10. High vegetation coverage was shown in areas close to the drainage networks.

Variation trends of NDVI

The variation trends of NDVI in the Heihe River Basin from 1998–2008 were characterized and quantified from the thresholds using a regression trend line method. As shown in the variation table (Table 2) and vegetation coverage variation trend map (Fig. 4), stable NDVI values ($-0.001 < \text{Slope} \leq 0.001$) accounted for the largest proportion, occupying 45.48% of the total area. However, the area of vegetation degradation ($-0.010 \leq \text{Slope} \leq -0.001$ occupied 30.28%) was greater than the area of vegetation improvement ($0.001 < \text{Slope} \leq 0.010$) which occupied 20.56%. Overall, the Heihe River Basin was in the state of degradation over the 10–year period. The areas of slight vegetation degradation were distributed in southwest and parts of the middle of the upper Basin as well as in the west of the lower Basin. Several patches of the upper Basin were also classed as serious degradation ($\text{Slope} \leq -0.010$).

The regions with vegetation improvement were mostly distributed in the northwest of the upper Basin,

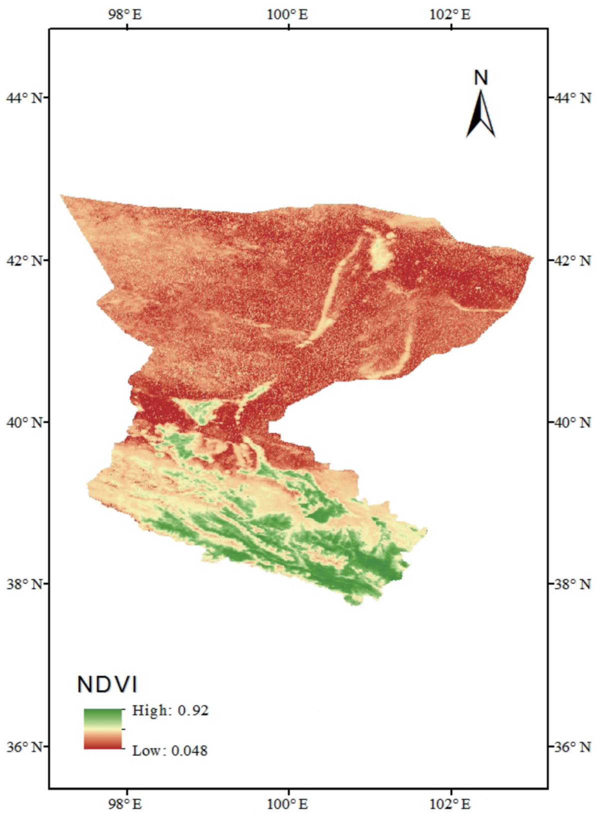

Fig. 3. Average annual spatial distribution of NDVI from 1998 to 2008.

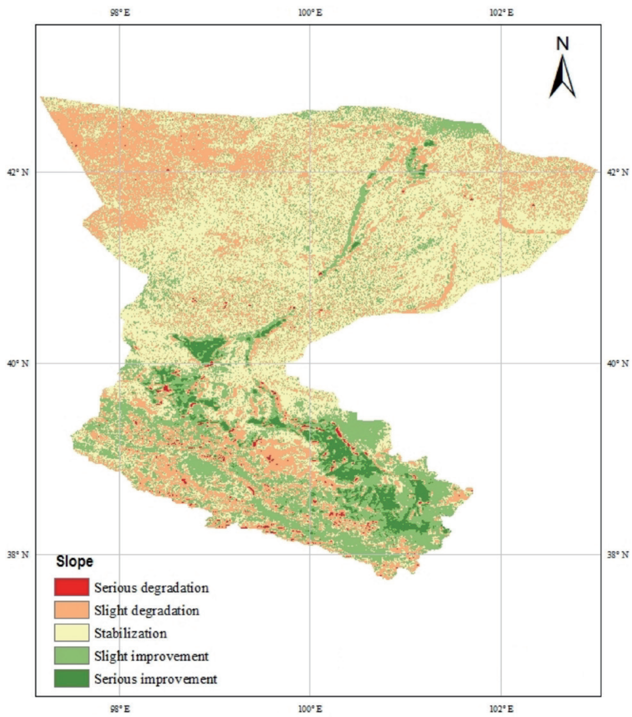

Fig. 4. Vegetation coverage variation trend from 1998 to 2008 (Serious degradation: slope < –0.010; slight degradation: –0.010 ≤ slope ≤ –0.001; stabilization: –0.001 < slope ≤ 0.001; slight improvement: 0.001 < slope ≤ 0.010; serious improvement: 0.010 < slope).

Table 2. NDVI variation trend statistics

Classification Criterion	Variation Trend	Area Percentage (%)
Slope < –0.010	Serious degradation	0.49
–0.010 ≤ Slope ≤ –0.001	Slight degradation	30.28
–0.001 < Slope ≤ 0.001	Stabilization	45.48
0.001 < Slope ≤ 0.010	Slight improvement	20.56
Slope > 0.010	Serious improvement	3.19

including Shandan County, Minle County and Zhangye City; the mid–Basin, covering Jiuquan City and southern Jinta County; and downstream of Ejinaqi Prairie. Compared with the spatial pattern of drainage (Fig. 1), both the regions classed as serious vegetation improvement (0.010 < Slope) (especially the section from Yingluo Gorge to Zhengyixia Gorge, Liqiao Reservoir, Wafangcheng Reservoir and Yuanyangchi Reservoir) and the regions in serious degradation were along the drainage lines and around the reservoirs. This illustrated that both the improvement and degradation of vegetation coverage were affected by changes to streams and lakes or by environmental transition.

Correlation analysis with NDVI and meteorological factors

In addition to temporal analysis of NDVI and meteorological factors in the Heihe River Basin, we also calculated the correlation coefficients between NDVI and meteorological factors. The correlation coefficients, partial correlation coefficients and multiple correlation coefficients were calculated pixel by pixel across the Heihe River Basin using monthly data (NDVI, precipitation and temperature) from 1998 to 2008. The increased values of NDVI and meteorological factors in the growing seasons affected the correlation analysis to some extent, so the NDVI, temperature and precipitation data were expressed as anomalies, which were the subtraction of the original values from the average of each month (Table 3) (Mao *et al.*, 2008).

According to the data from 11 meteorological stations in the Heihe River Basin, the correlations between average temperature from six meteorological stations and the corresponding NDVI were significant ($p < 0.05$), with correlation coefficients greater than 0.45. With precipitation, only Eqinaqi station showed a statistically significant level at $p < 0.05$. These results suggest that the correlation between NDVI and meteorological factors was not high, but the temperature was more influential on NDVI than the precipitation. Same trend was also demonstrated in the partial correlation analysis. Under the condition of fixed precipitation, the relationship between NDVI and temperature at six stations all passed the significance level ($p < 0.05$). Under the condition of fixed temperature, the significance levels of NDVI and rainfall were all above $p < 0.01$. The statistical relationship in multiple correlation coefficients between precipitation, temperature and NDVI was significant only for Ejinaqi station. This indicated that the temperature combined with precipitation data did not have a linear relationship with NDVI. Therefore, except for the interaction between temperature and precipitation, the response of NDVI was most sensitive to temperature variation in the study area. This result is similar to other researches in the Heihe River Basin and northwest China (Guo *et al.*, 2008; Mao *et al.*, 2007).

The monthly average temperature, monthly precipitation and the maximum monthly NDVI from each meteorological station over the 10–year period were computed and standardized using z–scores in SPSS (IBM, Armonk, U.S.A., http://www–01.ibm.com/software/analytics/spss/), which extracted the paired relationships between NDVI, precipitation and temperature variations (Fig. 5). The variation trends of temperature were basically consistent with that of precipitation, high (low)

Table 3. Linear correlations between NDVI, concurrent precipitation and temperature. Precipitation (*P*), Temperature (*T*); partial correlation analysis (*T*/*P*) is temperature and NDVI correlation analysis under the fixed precipitation conditions, and partial correlation analysis (*P*/*T*) is precipitation and NDVI correlation analysis under the fixed temperature conditions.

Meteorological Station	Correlation		Partial Correlation		Multiple Correlation	
	P	*T*	*T*/*P*	*P*/*T*	*R*	*F* value
Ejinaqi	–0.687*	0.365	0.447	–0.716	0.760*	5.461
Dingxin	–0.245	0.291	0.368	–0.334	0.433	0.921
Jinta	0.087	0.466*	0.511*	–0.254	0.517	1.458
Jiuquan	0.000	0.656*	0.688*	–0.274	0.688*	3.579
Gaotai	–0.115	0.267	0.268	–0.118	0.290	0.368
Tuole	0.432	0.466*	0.393*	0.349	0.559	1.818
Yeniugou	0.116	0.642*	0.635*	0.003	0.642	2.801
Zhangye	0.074	0.42*	0.415*	–0.013	0.420	0.859
Qilian	0.099	–0.162	–0.162	0.099	0.190	0.149
Shandan	–0.012	0.643*	0.653*	0.154	0.653	2.981
Guaizihu	0.060	0.316	0.316	0.060	0.321	0.461

* means $p < 0.05$

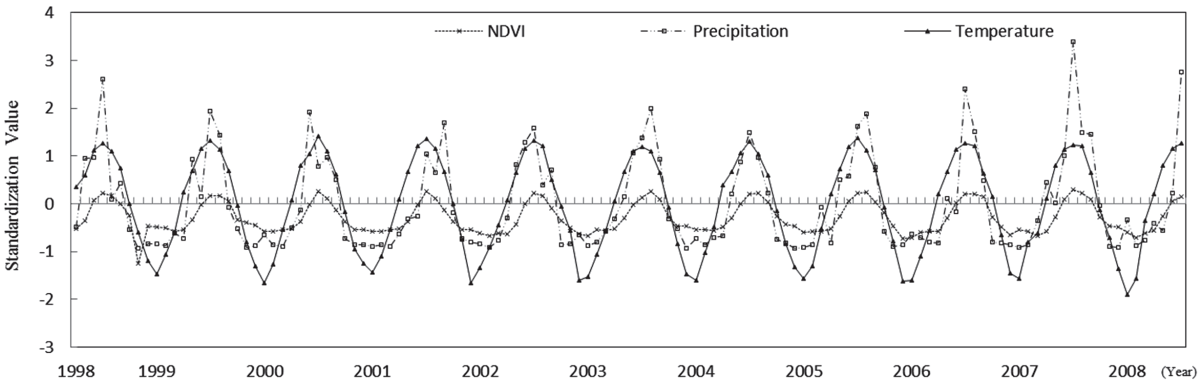

Fig. 5. Correlation between NDVI, precipitation and temperature from 1998 to 2008.

temperature periods broadly corresponding to high (low) rainfall periods in the Heihe River Basin. Average monthly temperature ranged over a small scale, while the values of average annual temperature were fairly constant across the 10 years, leading to a smooth periodic variation. The Heihe River Basin had relatively higher ranges of annual precipitation values and higher variation over the time period than that of temperature. The intra–annual distribution of precipitation was non–uniform and was mainly concentrated in June and August. The variation of NDVI values was similar to the general trend of temperature and precipitation, but the timing of peaks and troughs in NDVI did not correspond to that of temperature and precipitation. This suggests that partial years had a lagged response to temperature and precipitation. The NDVI, temperature and precipitation indicated an interactive coupling mechanism between regional NDVI–temperature and NDVI–precipitation.

To discuss the time lag (TL) effect of NDVI on the changes in temperature and precipitation, the previous 0–6 months for the growing season was regarded as the temporal gradient. The NDVI–temperature and NDVI–precipitation correlation analysis was carried out between each 10–day period of NDVI and the temperature, and each 10–day period of NDVI and the precipitation, respectively. As shown in Table 4, the time gradient corresponding to the maximum correlation coefficient (R_{max}) was used as the time lag.

The results were as followed: (1) without considering the lag effect, the correlation of NDVI–temperature and NDVI–precipitation in 11 meteorological stations was poor. By contrast, when the lag effect was considered, all the variables at the site were significantly correlated ($p < 0.05$). (2) The maximum response of NDVI to temperature and NDVI to precipitation had a lag ranging from 0–60 days and 0–150 days, respectively. In general, NDVI–temperature had a faster response time than NDVI–precipitation. (3) The response time for temperature and precipitation varied at different meteorological stations. There were five stations (Gaotai, Yeniugou, Zhangye, Qilian and Guaizihu) with the same lag time between NDVI and temperature and precipitation, four stations (Ejinaqi, Jinta, Tuole and Shandan) with a greater lag time of NDVI to precipitation than that of NDVI to temperature, and Dingxin and Jiuquan stations with a greater lag time of NDVI to temperature than that of NDVI to precipitation.

Table 4. The maximum correlation coefficient and time lag of NDVI–precipitation and NDVI–temperature

Meteorological Station	Precipitation		Temperature	
	R_{max}	TL (month)	R_{max}	TL (month)
Ejinaqi	0.454	4	0.964	1
Dingxin	0.652	0	0.927	1
Jinta	0.615	4	0.962	1
Jiuquan	0.705	0	0.903	1
Gaotai	0.604	1	0.930	1
Tuole	0.837	1	0.918	0
Yeniugou	0.932	1	0.933	1
Zhangye	0.728	1	0.926	1
Qilian	0.834	1	0.891	1
Shandan	–0.095	5	0.418	0
Guaizihu	0.721	2	0.991	2

Correlation analysis with NDVI and groundwater depth

Based on the measured data of the groundwater depth, the values of groundwater depth in each pixel (resolution consistent with SPOT Vegetation NDVI) were calculated by inverse distance weighted interpolation. The values of groundwater depth were taken to correspond with those of NDVI, thus, in the same pixel, two values of NDVI and groundwater depth could be obtained, respectively. In this study 13,873 data–pairs were obtained. To indicate the vegetation growth status in relation to groundwater depth, the scatter plots were examined (Fig. 6) and an average values treatment for NDVI was adopted when the corresponding groundwater depth was the same. As shown in Fig. 6, there were many high density points, and the discreteness of points was large as well. The correlation between groundwater depth and the corresponding values of NDVI was plotted for 183 data sets and connected in line in Fig. 7, with a depth interval of 0.1 m. The geometric mean of the

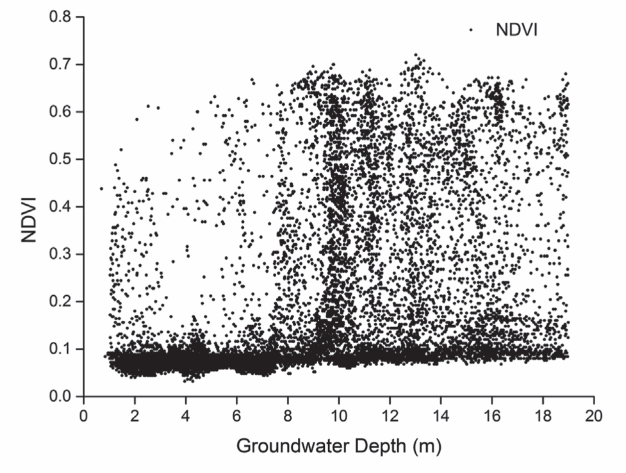

Fig. 6. Scatter plots between groundwater depth and NDVI.

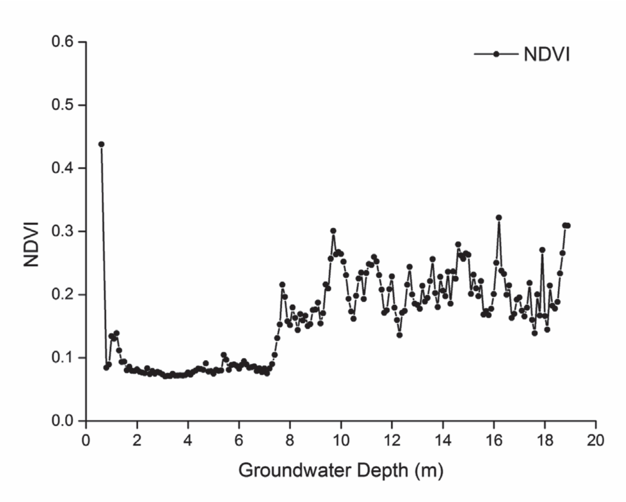

Fig. 7. Line chart between groundwater depth and NDVI.

NDVI was carried out in the depth range of the groundwater.

The values of NDVI declined sharply from 0.44–0.10, when the groundwater table was between the ground surface and 1 m below the ground, with the maximum value of NDVI being 0.44 at a groundwater depth of 0.6 m (Fig. 5). This suggests that some vegetation in the Heihe River Basin has roots in the capillary fringe of groundwater. Vegetation with high NDVI was also found in the most suitable external environments. The average annual precipitation was 99 mm while the average annual evaporation was 1923 mm in the Heihe River Basin, where the strong transpiration consumed substantial amounts of water. Because of scarce precipitation in the Heihe River Basin, a considerable part of the water consumption comes from groundwater. Consequently, groundwater discharge has an important effect in Heihe, along with soil salinity occurring at the ground surface. The values of NDVI fluctuated around 0.10 when the groundwater depth ranged from 1–7.3 m, which showed the poor development and low coverage of the vegetation. When the groundwater depth was larger than 7.3 m, the values of NDVI rose to 0.2, followed by random fluctuations. Deeper groundwater may weaken salinization effects, allowing vegetation recovery. The random fluctuations meant that groundwater depth had little impact on vegetation coverage.

It is reasonable that NDVI was affected by groundwater when the value of groundwater depth was less than 7.3 m. Therefore, this significant decline, with groundwater depths of < 7.3 m, as shown in Fig. 8, was fitted with a logistic correlation curve. The following correlation equation was obtained:

$$y = 0.083 + \frac{3.334}{1+(\frac{x}{0.427})^{6.387}}\ , \tag{11}$$

where x is groundwater depth; y is the value of NDVI, the regression analysis between NDVI and groundwater depth resulted in R^2=0.8955.

Based on the relationship of the change trend of NDVI on groundwater depth, the correlation between groundwater depth and NDVI conformed to a logistic function when the groundwater was less than 7.3 m. Moreover, the results provide good support for quantitative evaluation of the Heihe River Basin for the influence of groundwater depth on vegetation coverage. A similar logistic relationship was found in Li's (2005) research in the lower reaches of the Heihe River Basin.

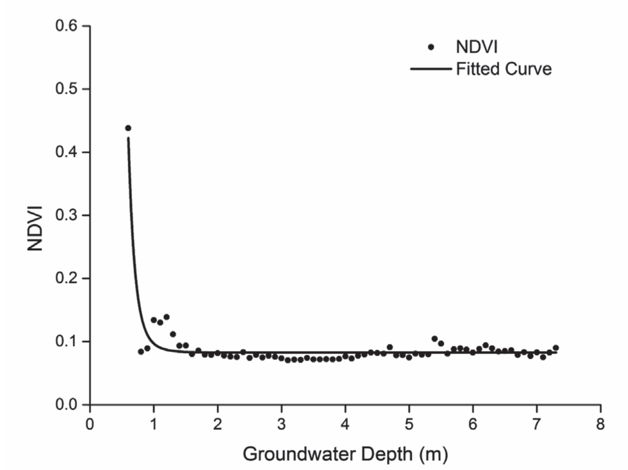

Fig. 8. Fitted curve between groundwater depth and NDVI below 7.3 m when the groundwater depth was lower than 7 m.

Influence of meteorological factors and groundwater depth on vegetation coverage

In order to analyze the quantitative relations among the three factors, average value of regions processed by Kringing Interpolation was used for the groundwater data, while average annual value was used for both NDVI and temperature. Here, the following steps were used.

(1) Normalization processing of each variable (Table 5).

(2) Linear regression modeling (Matlab), in which NDVI was the dependent variable, average groundwater depth processed by normalization was x_1, and average annual temperature processed by normalization was x_2. With the precondition that the significance

Table 5. Normalization of NDVI, temperature and groundwater depth

Year	NDVI	Temperature	Groundwater Depth
1988	0.989	0.920	0.808
1989	1.003	0.941	0.776
1990	0.976	0.963	0.776
1991	1.000	0.941	0.860
1992	0.989	0.865	0.918
1993	0.974	0.837	0.911
1994	0.982	0.980	0.949
1995	1.000	0.837	0.828
1996	0.984	0.863	0.975
1997	0.979	0.996	1.019
1998	0.937	1.187	1.000
1999	0.971	1.236	1.015
2000	0.955	0.961	0.838
2002	0.997	1.092	1.084
2003	1.010	0.982	1.106
2004	1.011	1.071	1.129
2005	1.112	1.009	1.552
2006	1.141	1.139	1.675
2007	1.135	1.133	1.197
2008	0.983	0.979	1.220

Table 6. Regression model calculation results

Regression Coefficient	Coefficient Estimates	Confidence Interval
β_0	0.8695	[0.6505 1.0885]
β_1	–0.0634	[–0.3123 0.1855]
β_2	0.1940	[0.0752 0.3128]
R^2= 0.5997 F=12.732 p<0.01s^2=0.0013		

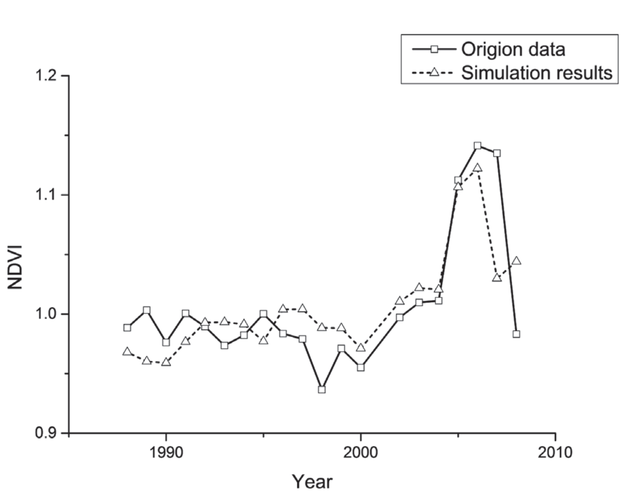

Fig. 9. Comparison between the model calculation and the original result of NDVI.

level was 0.01, the parameter S was analyzed, while the second item F was 12.732 (F0.01 (2, 20–2–1=17) =6.11, F > F0.01 (2, 17)), and the third item was 0.0015. With $p < \alpha$=0.01, the following effective regression model (R=0.774) was obtained (Table 6):

$$y = 0.8695–0.0634x_1+0.194x_2 , \quad (12)$$

where y is the value of annual NDVI, x_1 is the normalized average depth of groundwater, x_2 is the normalized average annual temperature.

The multiple linear regression model indicated that NDVI was positively related with temperature, while negatively related with groundwater depth, which agreed with the previous researches. Through the multiple linear regression model, the quantitative formula between NDVI, temperature and groundwater depth was given. This was the scientific basis for the quantitative assessment of the regional ecological environment by calculating and analyzing the process of temperature change and the change of groundwater depth, which is mainly characterized by the vegetation coverage. The vegetation index was higher in comparison with the original results, which was obtained by the model operation, the mean relative error of 7.3% Fig. 9.

CONCLUSION

The results of this study have contributed to the analysis and understanding of the characteristics of temporal and spatial variation trends of NDVI from 1998 to 2008, and clarified the response of NDVI to the variation of meteorological factors and groundwater depth in the Heihe River Basin.

It can be concluded from the correlation analysis with meteorological factors that the response of NDVI was more sensitive to temperature variation than to precipitation. The analysis of monthly values of NDVI, temperature and precipitation showed that partial years had a lagged response to temperature and precipitation. The maximum responses of NDVI to temperature and NDVI to precipitation had a lag ranging from 0–60 days and 0–150 days respectively. In general, NDVI–temperature had a faster response time than NDVI–precipitation.

Quantitative analysis between the depth of groundwater and NDVI in the Heihe River Basin revealed that depths less than 7.3 m had the greatest effect on NDVI. Salinization, the capillary height and the maximum vegetation root zone are like to be the factors that increase or reduce the growth of vegetation. The relationship between NDVI and groundwater depth could be fitted with a logistic correlation curve to establish a quantitative relationship. This offered good support for a quantitative evaluation of the Heihe River Basin of the effect of groundwater depth on vegetation coverage.

Based on the relationship between the changing trend of NDVI, meteorological factors and the groundwater depth, monadic linear regression model was used to establish the quantitative formula: $y = 0.8695 –0.0634x_1+0.194x_2$. The correlation coefficient was contented; the results provided scientific basis for the quantitative assessment of regional ecological environment.

AUTHOR CONTRIBUTIONS

Guoqiang Wang, Xianwei Zhao and Jingshan Yu contributed to the conception of the study, Xianwei Zhao and Zhiyuan Fu performed the data analyses and the manuscript preparation, Guoqiang Wang performed the analysis with constructive discussions, and Kyoichi Otsuki and Haotian Sun joined the discussions and revised the manuscript. All the authors assisted in editing of the manuscript and approved the final version.

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