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Groundwater-dependent distribution of vegetation in Hailiutu River catchment, a semi-arid region in China

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ABSTRACT

In arid and semi-arid regions, groundwater availability is one of the controls on vegetation distribution. This groundwater-dependent distribution of vegetation has been particularly observed in the Hailiutu River catchment, a semi-arid region in North China. We used remote sensing images of vegetation index (normalized difference vegetation index, NDVI) and field data of depth to water table (DWT) to assess the response of vegetation distribution on increase of DWT at the regional scale. The frequency distribution curves of NDVI with respect to different DWT were obtained. The statistical distributions of NDVI values at different DWT intervals indicate that higher vegetation coverage and more plant diversity exist at places of shallow groundwater. Both the mean and the standard deviation of NDVI values decrease with the increase of groundwater depth when DWT is less than 10 m. Beyond that depth, a low level of vegetation coverage and diversity is maintained. Comparisons of different sub-areas within the region with different dominant species showed that the NDVI of shrubs is sensitive to DWT. In contrast, NDVI of herbs is not significantly influenced by DWT. The relationship between NDVI and groundwater depth in farmlands could not be reliably determined because of disturbance by human activities. We conclude that application of this methodology may significantly improve our ability on sustainable management of land and groundwater resources. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS NDVI; groundwater; semi-arid region; *phreatophytes*; Mu Us Desert

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INTRODUCTION

Groundwater can be an important source of water for plant growth and transpiration. In arid and semi-arid regions, it is generally recognized that the density of vegetation is highly influenced by the depth to water table (DWT) (Meinzer, 1927; Naumburg *et al.*, 2005). Thus, some ecosystems in these regions are characterized as groundwater-dependent vegetation (Eamus *et al.*, 2006a). How vegetation is influenced by groundwater is species dependent. Meinzer (1927) was the first to use the term *phreatophytes* to define a group of species that use groundwater for growth. In addition, Naumburg *et al.* (2005) proposed the term *xeric phreatophytes* to refer to the species in arid and semi-arid regions that are able to not only use but also depend on groundwater. We can also use the terms 'facultative *phreatophytes*' and 'obligate *phreatophytes*' to schematically identify species, where the former use groundwater when available but can survive without it, whereas the latter must have it available to survive. However, this becomes problematic in that some plants may only need groundwater occasionally to survive, and without studying them throughout their entire lifetime, it is often difficult to establish the obligate nature of groundwater use. As a guiding principle, if groundwater is available within the rooting depth of vegetation in arid and semi-arid zones, we can safely conclude that groundwater use is occurring (Eamus *et al.*, 2006a,b). The relationship between groundwater availability and vegetation has been used previously as possible indicators of groundwater relatively close to the land surface or using groundwater depth as a driver of landscape vegetation patterns (Stromberg *et al.*, 1996; Wierda *et al.*, 1997).

At regional scales, patterns in vegetation distribution have been frequently investigated using satellite remote sensing (RS) information. In arid and semi-arid regions, such studies have been linked with analyses of the relationships between groundwater depth and vegetation distribution and structure. Thus, Gong *et al.* (2004) found a linear correlation between the normalized difference vegetation index (NDVI) and DWT in a Californian mountain meadow. With the use of MODIS NDVI and DWT data, correlations between the spatial distribution of the vegetation index and the DWT in the Ejina and Yinchuan Basins in Northwest China have also been analyzed (Jin *et al.*, 2008; Sun *et al.*, 2008; Jin *et al.*, 2011). Optimum values of DWT were found for vegetation growth (Jin *et al.*, 2011).

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For arid and semi-arid regions, the dependency of the vegetation index on groundwater depth can yield regional-scale ecohydrological information. This is helpful for the investigation of ecosystem responses to climate and land use change. However, there are uncertainties in the application of this approach because vegetation distribution is highly heterogeneous and depends on multiple factors. DWT is also highly heterogeneous when landscapes and aquifers are complex. To resolve this problem, sufficient field data and rigorous statistical approaches are required to capture the statistical patterns of both vegetation and DWT distribution. In the present study, high-resolution NDVI and groundwater depth data were used to investigate the influence of groundwater depth on distribution patterns of vegetation in a semi-arid catchment in China. Specifically, we address the following questions: how does NDVI change as a function of DWT in the semi-arid region of China; is there a lower limit to DWT beyond which vegetation does not respond to the presence of groundwater; and do different vegetation types differ in their response to changes in groundwater depth?

MATERIALS AND METHODS

Study area

The Hailiutu River catchment is located in the Ordos Plateau, in North China, and is a part of the Mu Us Desert (Figure 1, left top). The catchment area is around 2600 km^2, and the land surface gradually decreases towards the south as shown by the 25-m-resolution digital elevation model (DEM) data derived from 1:50 000 scale topographic maps (Figure 1, right). The Hailiutu River is the main river that originates in the centre of the catchment and is a tributary of the Wuding River, a branch of the Yellow River. Climate is inland semi-arid continental, with an annual precipitation that ranges from 300 to 500 mm and an annual potential evaporation that ranges from 800 to 1200 mm (estimated from observed pan evaporation multiplied by an empirical pan coefficient). The catchment is dominated by sand dunes covered with *xeric* plants such as *Artemisia desertorum* and *Salix psammophila*. The catchment also contains streams, lakes, wetlands, groves and farmlands.

Surface water in this area is mainly derived from groundwater discharge from unconsolidated sandy sediments and semi-consolidated sandstones. The sandy sediments form an unconfined aquifer at the top of the geological basin. Recharge occurs as infiltration of sufficiently large rainfall events. Surface discharge occurs into wetlands, lakes and streams where the land surface intersects the water table. In most of the study area, groundwater depths are shallow (<10 m) and evapotranspiration is also a major discharge process.

Groundwater level contour map

During July 2010, field measurements of groundwater level in the Hailiutu River catchment were conducted at 46 sites. Groundwater levels in most of the sites were measured in wells that penetrated the upper unconfined sandy aquifer. However, the number of these observation points was small for the construction of a detailed groundwater level contour map. Consequently, historical observation data since 1970 were added to the dataset, and the number of groundwater level measurements increased to 540. A contour map of

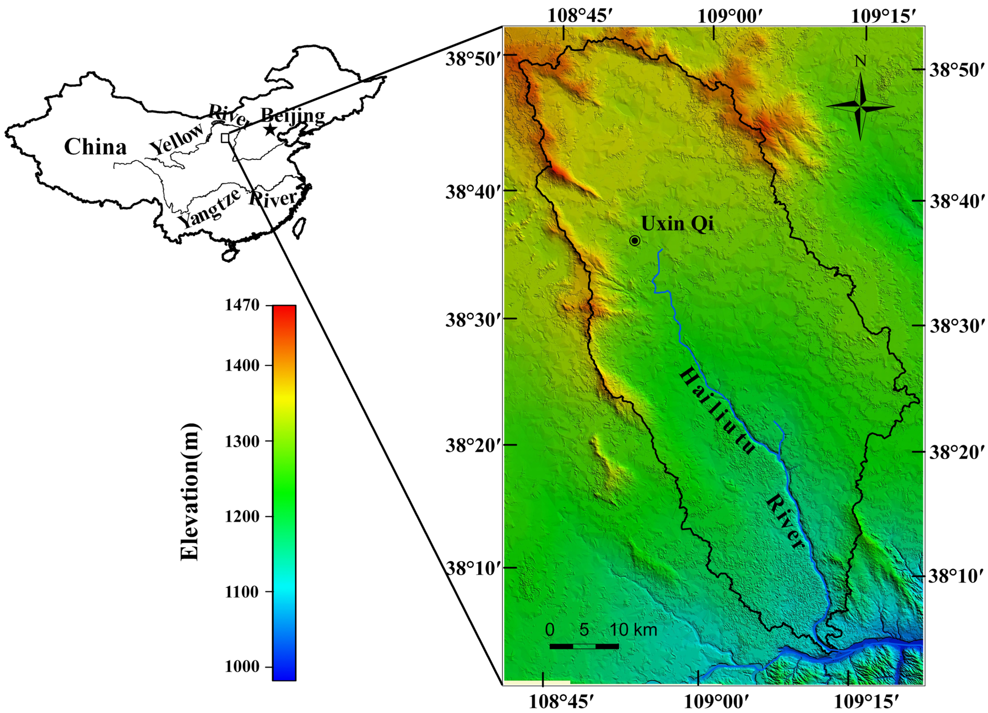

Figure 1. The study area. Resolution of digital elevation model data (right) is 25 m.

groundwater level was constructed by interpolating measured groundwater levels to a 300-m-resolution grid (Figure 2). The contour map shows that regional groundwater flow is in general towards the river; only in the northern area does the groundwater discharges to a lake.

Depth to water table map

The DEM map (Figure 1) was upgraded to the surface elevation map of the same 300-m-resolution grid as the groundwater level contour map. For one cell of 300 m by 300 m grid, there are 12 × 12 DEM pixels. The arithmetic mean of 144 DEM values was used as a representative value of the surface elevation in the cell. The difference between the surface elevation map and the groundwater level contour map yields a DWT map (Figure 3). In most part of the area, DWT is less than 10 m; only in water divide and terraces is DWT more than 10 m.

Normalized difference vegetation index map

Landsat-5 thematic mapper (TM)-derived NDVI data were applied to analyse the distribution patterns of vegetation. Surface water, soils and vegetation were identified and distinguished through the use of the TM sensor (http://eros.usgs.gov/#/Guides/landsat_tm). Landsat TM-derived NDVI were calculated using the normalized difference of the red and infrared spectral bands, as follows:

$$NDVI = \frac{DN_{NIR} - DN_R}{DN_{NIR} + DN_R} \quad (1)$$

where DN_{NIR} and DN_R represent the average reflectances measured in the visible (red) and near-infrared regions, respectively. This vegetation index can be used to quantitatively assess the status of land surface: higher positive values indicate higher vegetation coverage, non-vegetated land surfaces have small positive NDVI values and negative values are generally caused by water bodies.

For the study area, an RS image of 10 July 2010, with a 30-m resolution, was obtained from a shared dataset provided by the International Scientific Data Service Platform, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn/) (Figure 4). The image was selected for the same date of field survey on groundwater level. No disturbance by clouds was present in the RS data. The NDVI values were converted to land cover classes shown in Table I. It shows that the catchment is mainly covered by low-density (67%) and high-density (27%) shrublands. The meadow and farmland accounts only for 4%.

Processing normalized difference vegetation index map

For correlation analysis with DWT, the NDVI map was also upgraded to the same 300-m-resolution grid using the arithmetic mean. The new NDVI map matches the DWT map. For each grid cell, a pair of NDVI and DWT values can be read. There are in total 29 159 pairs of NDVI and DWT values. The scatter plot NDVI against DWT is shown in Figure 5. Although NDVI values vary between 0 and 0·6 and DWT values range from 0 to 95 m, a dark cloud of data points concentrate in the area of DWT < 15 m and NDVI < 0·3.

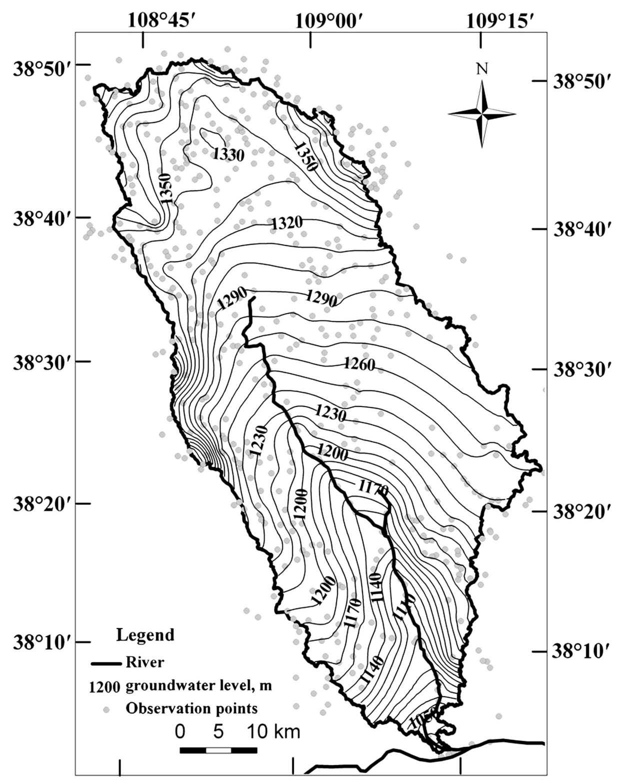

Figure 2. Contour map of groundwater level in July 2010, based on observation points (grey circles). Resolution of the grid is 300 m.

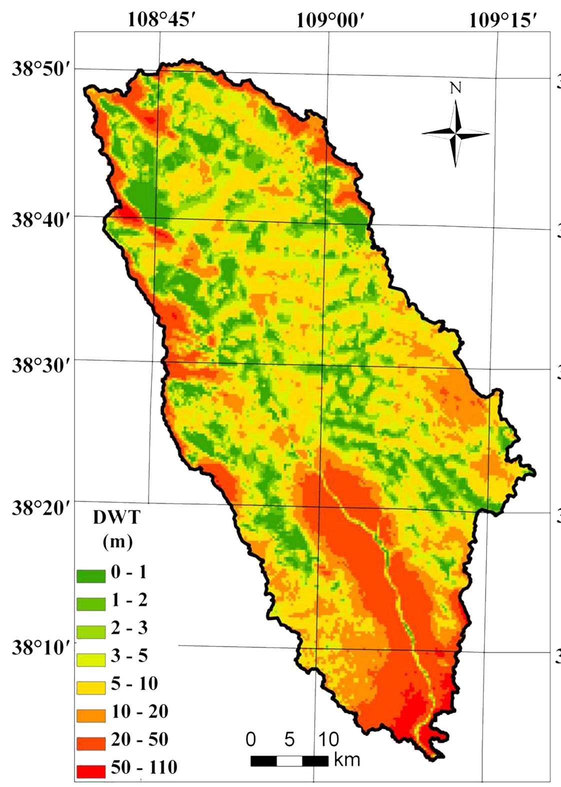

Figure 3. Distribution of depth to water table (DWT) in July 2010, in Hailiutu River catchment, in China. Resolution of the grid is 300 m.

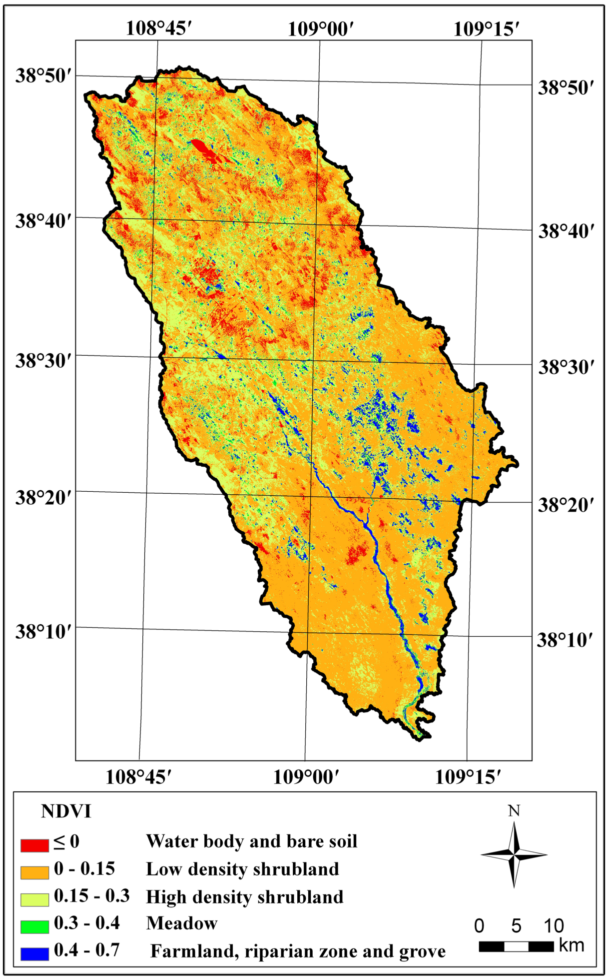

Figure 4. Distribution of normalized difference vegetation index (NDVI) in July 2010 with resolution of 30 m, in Hailiutu River catchment, in China.

RESULTS

Statistical characteristics of normalized difference vegetation index distribution

The NDVI distribution was analysed with frequency distribution curves. Figure 6 plots the histogram and cumulative frequency curves of NDVI for different DWT. All NDVI distributions are skewed. When groundwater is shallow (DWT < 6 m), the frequency distributions of NDVI are less skewed with a wider distribution, indicating the presence of more variety of vegetation types. When groundwater is getting deeper (DWT > 6 m), the frequency distributions of NDVI are more skewed and becomes narrower, indicating less varieties of vegetation covers.

Changes of statistical characteristics of normalized difference vegetation index with depth to water table

In order to analyse the dependency of NDVI characteristics on DWT, arithmetic mean, geometric mean, harmonic mean, standard deviation and coefficient of skewness were calculated with increase of groundwater depth. When DWT is less than 20 m, 1-m intervals of DWT were applied to capture a group of NDVI values. However, to ensure the number of values in each interval is sufficiently large for calculating statistical characteristics, larger intervals were used when DWT is greater than 20 m. The results are shown in Table II and Figure 7.

It can be seen that the arithmetic mean (Figure 7a), geometric mean (Figure 7b) and harmonic mean (Figure 7c) decrease with the increase of groundwater depth and approximately approach constants when DWT is greater than 10 m. This relationship can be described by the empirical equation

$$NDVI_a = NDVI_c + (NDVI_m - NDVI_c)\exp(-\beta \cdot DWT), \quad (2)$$

where $NDVI_a$ is the average NDVI value for a given depth of the water table, $NDVI_c$ and $NDVI_m$ are the minimum and maximum average values of NDVI, respectively, and β indicates the rate of the decrease of NDVI with the increase of groundwater depth.

The least squares method was used to fit Equation (2), and the identified equations are plotted as the solid curves in Figure 7a–c. Although the minimum and the maximum of different average NDVI values are different, the rate of decrease is more or less the same. The geometric mean values of NDVI were more representative because the statistical distributions of NDVI were skewed.

The standard deviation also decreases with the increase of groundwater depth but approaches a constant value when DWT is greater than 10 m (Figure 7d). However, the coefficient of skewness exhibits an increasing trend at the shallow groundwater depth (DWT < 10 m) and fluctuates afterwards (Figure 7e). They both indicate that the dependency of the vegetation on the water table depth

Table I. Change of statistical characteristics of NDVI distribution with depth to water table.

NDVI	≤0·01	0·01–0·15	0·15–0·3	0·3–0·4	>0·4
Zone Index	Null	A	B	C	D
Landscape	Water body (NDVI<0) and bare soil	Low-density shrubland	High-density shrubland	Meadow	Farmland, riparian zone, grove
Dominant plants	Reed for shallow water body	*Artemisia desertorum*, *Salix psammophila*		Herbs	Crops (*Maize*), *Salix matsudana*, *Populus tomentosa*
Area proportion (%)	2·56	66·79	26·66	2·78	1·22

NDVI, normalized difference vegetation index.

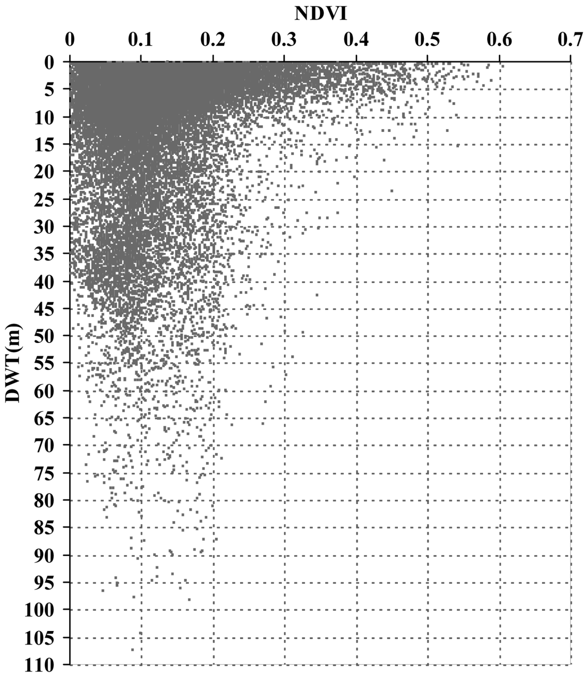

Figure 5. Scatter plot of normalized difference vegetation index (NDVI) and depth to water table (DWT) at 29 159 pixels on a 300-m-resolution grid in the study area. NDVI data on the grid is extracted from the original 30-m-resolution data with window average method.

occur within a depth of around 10 m. The shallower the water table, the higher is the diversity of vegetation.

DISCUSSION

Vegetation composition and NDVI

NDVI is an index of the average vegetation cover derived from the entire canopy at each location. Thus, it is a composite index that is influenced by all species present at a site. Therefore, the relationship between NDVI and DWT reflects the average behaviour of all species to groundwater depth. Some of the species present may be very sensitive to groundwater depth whereas others may be relatively insensitive. To examine differences between species, the vegetation covers were classified. In arid and semi-arid regions, the range of species present tends to be limited and generally quite different from each other with respect to leaf area index, which significantly influences NDVI. Thus, we classify the types of vegetation across our study area using NDVI intervals as shown in Table I according to the scheme proposed by Fang *et al.* (2009). Five land covers were classified, each with dominant species (Table I).

For each type of land cover in Table I, the arithmetic mean NDVI for every 1-m interval of DWT was calculated, as well as the total area occupied by each type (Figure 8). Analysis was restricted to sites where DWT is less than 10 m because vegetation was insensitive to groundwater at larger depths (Figures 7). More than 90% of the study area is covered by shrubland dominated by *A. desertorum* and *S. psammophila* (Table I, zones A and B). As shown in Figure 8, for zones A and B, there were similar trends of declining NDVI values with increasing DWT. This agrees well with field observation: in lowlands where groundwater is shallow, the density and height of shrubs are significantly larger than those observed in the upper lands. These shrubs can be considered as facultative *phreatophytes* because they may use both soil water and groundwater. In contrast, the trends of NDVI with DWT in zones C and D (Figure 8) were not significant. Zone C represents the meadow; the nearly constant average NDVI indicates that herbs in the meadow land cover were almost independent of groundwater depth. The root zone of herbs is shallow (less than 1 m) so that the density of herbs is highly dependent on soil water near the land surface. The relationship between vegetation and groundwater in zone D was more complex because the zone is a mixture of farmlands, riparian zone and groves of trees. Two relative larger NDVI values occur: one at the water table depth between 2 and 3 m and another between 7 and 8 m. The first peak may correspond to the crop land. The crops are irrigated and have higher NDVI values. A small part of the farmlands is located in the riparian zone of the Hailiutu River; the others are located in flat plains or local lowlands. Irrigation channels and pumping wells were constructed for irrigation. The second peak may reflect on trees. Trees, such as *Salix matsudana* and *Populus tomentosa*, are commonly planted around the crop area to reduce wind speed. In some places, the trees are dense enough to form groves. *S. matsudana* and *P. tomentosa* can extend roots to a depth of 10 m or more in the sand sediments. Even in the sandstone underlying the sandy sediments, the roots of the trees can penetrate into a depth between 2 and 3 m (Figure 9).

Comparison between sites

In the semi-arid Hailiutu River Catchment of China, the distribution of vegetation is highly dependent on groundwater availability when groundwater was less than 10 m, as shown in Figures 5 and 7. Below that depth, NDVI was independent of DWT. Therefore, 10 m may be considered as the limit of the root zone in this catchment. It is noteworthy that an upper limit of groundwater access of 8–10 m has been established in Australia at multiple sites (Zencich *et al.*, 2002; Benyon *et al.*, 2006; O'Grady *et al.*, 2006a,b). Because only a small proportion of total root mass of a tree will be located within the capillary zone of a water table and the deepest roots incur the largest resistance to water flow to the canopy, 10 m may represent a common upper limit to extensive groundwater use.

However, the dependency of vegetation on groundwater is significantly different in the arid Ejina area in China (Jin *et al.*, 2011). In the Ejina area, a suitable DWT interval (2·8 to 5 m) was found for the vegetation growth, and a peak of NDVI occurs at a water table depth of around 3·4 m. In the Hailiutu River catchment, the large value of the NDVI occurs when groundwater is very shallow and almost linearly decreases with the increase of DWT (Figure 8) for dominant bushes. These differences may attribute to multiple factors such as climate, soil cover and hydrogeology. First, the Ejina area is much drier than the Hailiutu River catchment. The annual

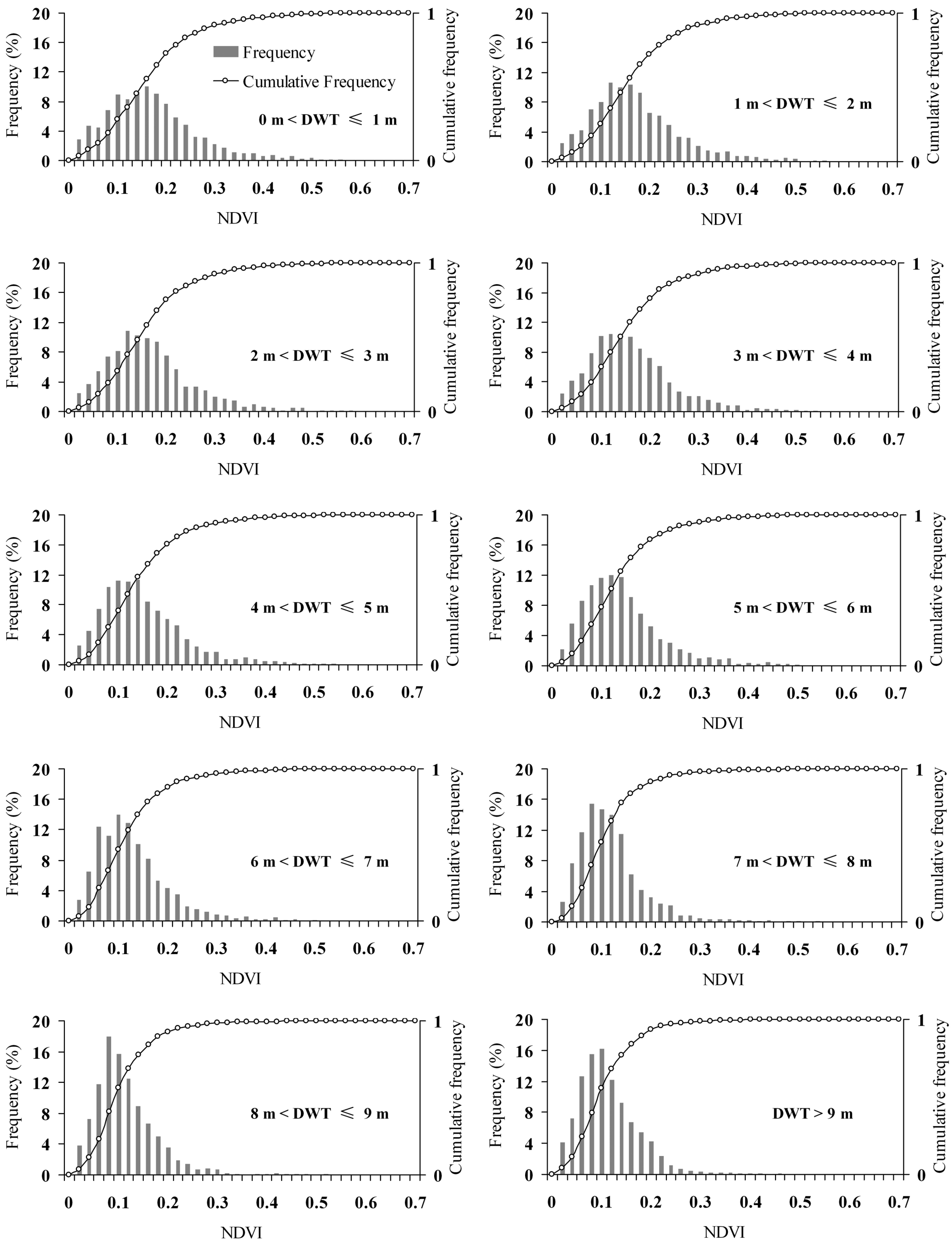

Figure 6. Statistical distribution of normalized difference vegetation index (NDVI) for different intervals of depth to water table (DWT).

rainfall in the Ejina area is only 40 mm and potential evaporation is ten times larger, whereas at the Hailiutu River catchment, the average annual rainfall is 350 mm and potential evaporation is only five times larger. Second, top soils are different. The Ejinan area is covered by saline soil whereas the Hailiutu River catchment is covered by desert sand. Sand has higher permeability and larger pores. Therefore, sand cover is good for the infiltration and percolation of rainfall but prevents evaporation. It has been found that only the top 10 cm sand is dry and sand below 10 cm is always wet in the Hailiutu River catchment. The Ejina area is subject to significant soil salinity. The top saline soils also contain high clay content. Third, the hydrogeology condition is different. The Ejina area is a part of a terminal lake catchment where land surface is flat and groundwater is shallow (ranging from 2·6 to 5·2 m). The main groundwater recharge comes from underground flow from the upstream basin and the dominant groundwater discharge is through evapotranspiration, whereas in the Hailiutu River catchment, land surface is undulating with small hills in water divide and a U-shape valley in the downstream area. Groundwater depth varies largely and is deeper (ranging from 1 to 110 m). Groundwater recharge is only from local precipitation infiltration (input little salt), whereas groundwater discharges to river (release salt out) and evapotranspiration. All of these differences result in not only the different dominant vegetation species but also their dependency on groundwater depth. In the Ejina area, more dry-tolerant and salt-tolerant vegetation species are dominant, such as *Populus*

Table II. Land cover classification scheme for the Hailiutu River catchment.

Ranges of DWT (m)		Arithmetic mean	Geometric mean	Harmonic mean	Standard deviation	Coefficient of skewness
Min.	Max.					
0	1	0·1630	0·1343	0·1003	0·0946	1·0656
1	2	0·1634	0·1370	0·1057	0·0919	1·0919
2	3	0·1590	0·1331	0·1035	0·0910	1·1894
3	4	0·1551	0·1297	0·1010	0·0893	1·1988
4	5	0·1422	0·1187	0·0942	0·0847	1·3218
5	6	0·1337	0·1107	0·0867	0·0812	1·3479
6	7	0·1202	0·0996	0·0795	0·0746	1·5038
7	8	0·1099	0·0921	0·0744	0·0678	1·8544
8	9	0·1056	0·0889	0·0723	0·0636	1·7961
9	108	0·1056	0·0893	0·0722	0·0611	1·4867

DWT, depth to water table.

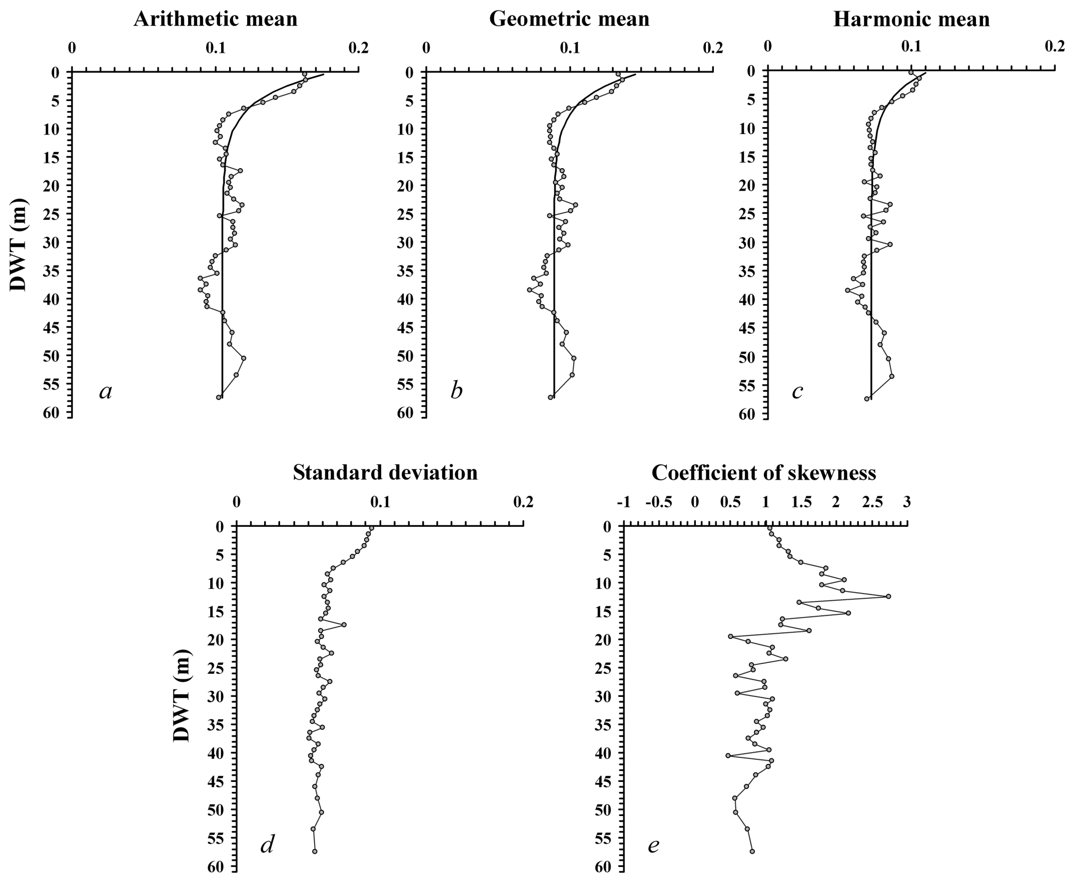

Figure 7. Change of statistical characteristics of normalized difference vegetation index (NDVI) distribution with depth to water table (DWT). Solid lines in (a) and (b) are fitted empirical trends described in Equation (2): for arithmetic mean, $NDVI_c = 0{\cdot}105$, $NDVI_m = 0{\cdot}184$ and $\beta = 0{\cdot}228\,m^{-1}$; for geometric mean, $NDVI_c = 0{\cdot}089$, $NDVI_m = 0{\cdot}153$ and $\beta = 0{\cdot}236\,m^{-1}$; for harmonic mean, $NDVI_c = 0{\cdot}072$, $NDVI_m = 0{\cdot}115$ and $\beta = 0{\cdot}219\,m^{-1}$.

euphratica and *Haloxylon ammodendron*. Because the shallow soil is very saline and groundwater depth is shallow, the roots of the vegetation are developed below the saline soil and above the water table, resulting in a distribution of NDVI values between 2·8 to 5·0 m. In the Hailiutu river catchment, there is no soil salinity problem, and relative large precipitation can maintain a wet soil profile. Therefore, shallow-rooted bushes are widely presented and also deep-rooted trees can be dependent on the deep fresh groundwater.

CONCLUSION

The dependency of vegetation on groundwater in the Hailiutu River catchment, a semi-arid area in North China, was investigated with NDVI data and observation data of groundwater depth at a regional scale. The statistical characteristics of NDVI values (mean, standard deviation and coefficient of skewness) change in response to the increase of groundwater depth. A decreasing trend of both mean and standard deviation of NDVI values with

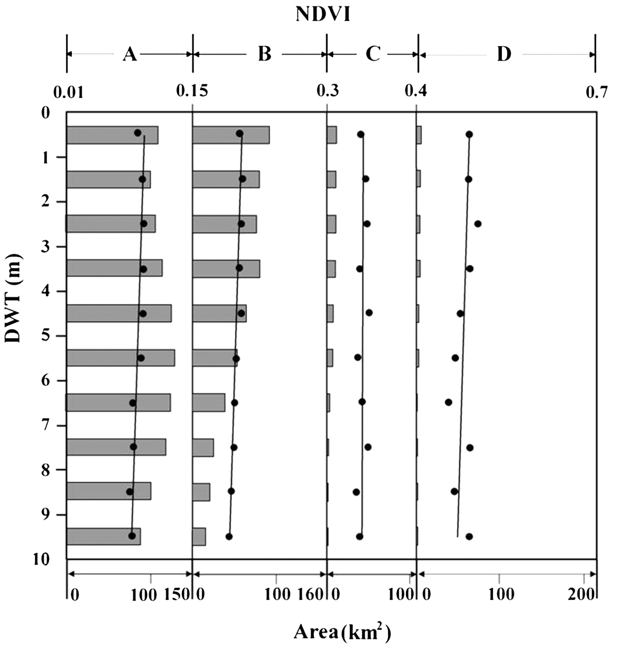

Figure 8. Relationship between average normalized difference vegetation index (NDVI) (black circles) and depth to water table (DWT) for zones of land surface with different types (from A to D) of vegetation as classified in Table I. Grey bars indicate the sub-area corresponding to the DWT intervals. Straight lines show linear correlation: A, $NDVI = -0{\cdot}0016DWT + 0{\cdot}098$, $R^2 = 0{\cdot}86$; B, $NDVI = -0{\cdot}0016DWT + 0{\cdot}208$, $R^2 = 0{\cdot}95$; C, $NDVI = -0{\cdot}0003DWT + 0{\cdot}3413$, $R^2 = 0{\cdot}08$; D, $NDVI = -0{\cdot}0014DWT + 0{\cdot}4611$, $R^2 = 0{\cdot}18$.

increasing DWT was shown. When DWT is greater than 10 m, vegetation coverage and diversity are significantly reduced and not sensitive to change of groundwater depth.

The responses of different vegetation types to groundwater depth were found different in this study area. It was indicated that the NDVI value of shrubs decreases almost in a linear pattern with increasing of DWT. However, the NDVI value of herbs in meadow land cover was not sensitive to groundwater depth because of the short roots. The relationship between NDVI and groundwater in farmlands was more complex because of the influences of human activities. *S. matsudana* and *P. tomentosa* are the dominant species in groves of trees, and they can access deep groundwater with their deeply extending roots.

The vegetation–groundwater relationship in this study area is significantly different from that found in the Ejina area (Jin *et al.*, 2011).

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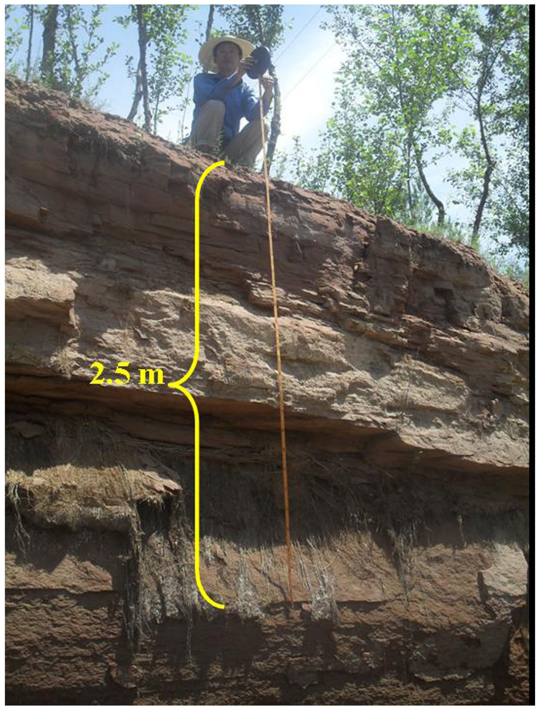

Figure 9. A picture of exposed roots of *Populus tomentosa* in a sandstone profile on the bank of Hailiutu River.

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