ORIGINAL ARTICLE

A model for evaluating the influence of water and salt on vegetation in a semi-arid desert region, northern China

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Abstract A model, influence of water and salt on vegetation (IWSV), was developed to evaluate their influence on plant species. The main function of this model was to calculate a comprehensive index value for evaluating the suitability of plant growth. This model consists of five explanatory variables (vadose zone moisture content, vadose zone salinity, vadose zone lithology, depth to the water table, and groundwater mineralization) and two response variables (plant species and their cover). A set of independent data on three plant species, *Artemisia ordosica*, *Salix psammophila,* and *Carex enervis*, which are dominant species in the Mu Us Desert of northern China, were used to validate the model. Validation results show an overall correct prediction for the distribution of these three species. The results demonstrated that the IWSV model can be a useful tool for groundwater management and nature conservation in a semi-arid desert region, especially for predicting the vegetation distribution in areas with groundwater extraction.

Introduction

Several hydrology–vegetation models have been developed over the past two decades for facilitating prediction of the occurrence of plant species in relation to habitat conditions (Venterink and Wassen 1997). Each model differs in purposes and study areas from the others and with respect to the modeling methods, abiotic habitation variables, and plant species. However, the hydrology–vegetation interaction is a common subject in all of these models.

The water and flora model (WAFLO) model (Gremmen et al. 1990) is not based on actual field data, but rather on ecological indicator values of plant species, and it only predicts the disappearance of species. The abiotic variables are those related to the soil such as soil moisture, soil aeration, and nitrogen content. The hydrology–vegetation model (HYVEG, Noest 1994) predicted the probabilities of the occurrence of 100 dune slacks (between the fore dunes and the main dunes are dune slacks which are low-lying depressions) species in different habitat conditions. Changes of the habitat conditions were predicted by means of hydrological models. The vegetation data were obtained from 200 plots. The abiotic variables were related to groundwater extraction and climatic conditions. The influence of chemical and hydrobiological factors on response of species (ICHORS) model (Barendregt and Wassen 1989) was developed to predict the influence of chemical and hydrobiological factors on the response of species in aquatic and marsh ecosystems. The model predicts the probabilities

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of occurrences of species. These probabilities were determined by means of statistical analysis of data sets from vegetation plots and the abiotic variables (soil type and electrical conductivity of surface water). Venterink and Wassen (1997) compared six correlative eco-hydrological models. The primary models and their abiotic variables are shown in Table 1. All of the models include three kinds of abiotic habitat variables relevant to hydrology, climate, and soil. There is a general agreement that moisture and salt in the soil and water are key factors for vegetation performance.

Soil moisture was selected as the primary hydrological variable in all of these hydrology–vegetation models because it has a comprehensive effect on the interaction of rainfall, surface water, and groundwater. In some cases, groundwater mainly supplies the soil with moisture through the capillary fringe level and can control the distribution of vegetation in groundwater-dependent ecological systems. Moreover, much of the vegetation in arid regions has well-developed root systems which can reach to a great depth below the land surface to uptake the moisture from aquifers. Hence, groundwater is one of their moisture sources. However, in most of the models, the groundwater level was not taken into account (Table 1).

The level of the total dissolved salt (TDS or soil salinity) and the mineralization of groundwater are high in arid regions because of strong evaporation. This can reduce rain infiltrating and restrain water uptake from the soil and groundwater (Zhao et al. 1991). Thus, the TDS is another important variable for vegetation performance in arid regions. It is obvious that the influence of salinity on vegetation is not fully considered in the existing models. Some models, considering the soil salinity, however, ignore the mineralization of groundwater.

Furthermore, the thickness of the soil layer is usually less than 1 m in these models. This depth is too shallow to fully evaluate the role of vegetation because the root system of many shrubs and herbs is well developed and its length is greater than 1 m in arid areas. Consequently, it would be necessary to include the whole vadose zone in these models to insure a higher probability of producing a real result.

The objective of the current study was to develop an eco-hydrology model to evaluate the influence of water and salt on vegetation (IWSV) in the semi-arid desert regions. The IWSV model is constructed based the field survey. Its direct purpose is to predict and evaluate the influence on plant species when the water table drops with groundwater extraction in the Mu Us Desert in northern China. The model took into account five explanatory variables (abiotic habitat variables) including vadose zone moisture content, vadose zone salinity, vadose zone lithology, depth to the water table, and groundwater mineralization, and two response variables (biotic variables) including plant species and their cover. The model is useful as a tool to evaluate nature conservation policy regarding groundwater management.

Study area

The Mu Us Desert, covering an area of about 40,000 km^2, is located in parts of Shaanxi Province and the Inner Mongolia Autonomous Region of northern China (Fig. 1). The desert has geomorphic features including stable or semi-stable sand dunes and dune slacks. Annual rainfall varies from 145 to 715 mm, with mean annual precipitation of 360 mm. More than 70% of rainfall occurs in July–September. The maximum and minimum temperatures are

Table 1 Current hydrology–vegetation model

| Model	Abiotic variables
Nature technique model (NTM) (Ellenberg 1974)	Trophic state, soil acidity, soil moisture
The Dos effect model for terrestrial nature (DEMNAT) (Witte et al. 1992)	Soil moisture, salinity, trophic state, soil acidity, substrata dynamic
The multiple stress model for vegetation (MOVE) (Latour and Reiling 1993)	Soil moisture, soil acidity, nitrogen deposit, groundwater, extraction
The hydrology vegetation model (HYVEG) (Noest 1994)	Groundwater extraction, climate
The influence of chemical and hydrobiological factors on response of species (ICHORS) (Barendregt and Wassen 1989)	Soil type, electrical conductivity of surface water
Influence of terrestrial site condition on the response of species (ITORS) (Ertsen 1995)	Soil type, conductivity of surface water, groundwater, water chemical, soil moisture
Water and flora model (WAFLO) (Gremmen et al. 1990)	Soil moisture, soil nitrogen availability, soil aeration, depth of open water
The distributed hydrology soil vegetation model (DHSVM) (Cuo et al. 2006)	Net radiation, surface temperature, air temperature, relative humidity, wind speed, soil temperature, soil moisture, rainfall, stream discharge
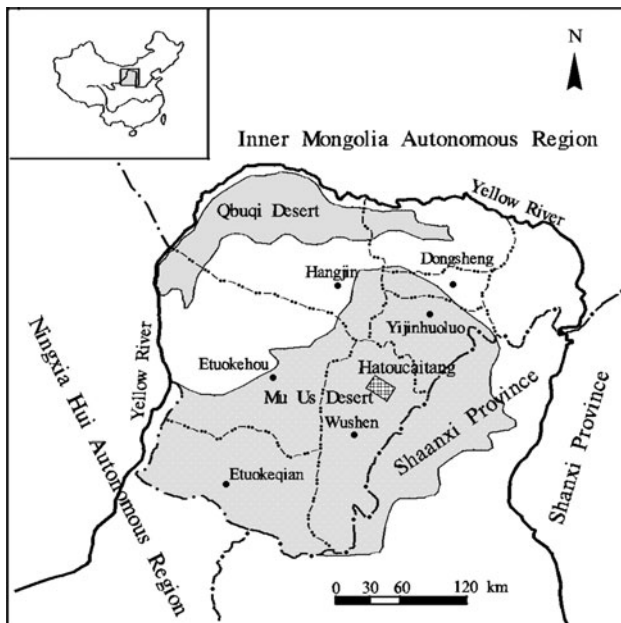
Fig. 1 Map showing the study area within the Mu Us Desert. *Gray areas* are desert, and *quadrilateral with grid* is the study area; *thick dashed* and *dotted lines* are provincial boundaries, and *thin dashed* and *dotted lines* are county borders

36.4 and −31.4°C, respectively, and the mean annual temperature is 6.4°C. The average annual evaporation is 2,343 mm. Because of the scarcity of surface water, groundwater is the primary source for industrial, agricultural, and drinking water. In recent years, with rapid development of oil and chemical industries in Odors Basin, the demand for water has increased greatly. Because of the scarcity of surface water, China Geological Survey (CGS) developed a program to survey groundwater resource since 1999 in Ordos Basin. The results demonstrated that rich groundwater is occurrent in the basin. However, the impact of groundwater extraction on vegetation was so far poorly assessed in this ecologically fragile area. In the program for groundwater survey in North Shaanxi and Inner Mongolia since 2005 and 2007, respectively, this issue was been seriously taken into account. The IWSV model is constructed based this field survey.

Hatoucaidang is part of the hinterland of the Mu Us Desert, and was chosen as the study area. It is in Wushen Qi County, Inner Mongolia. It is about 600 km² in area and has an average elevation of approximately 1,300 m above the mean sea level (Fig. 1).

In the Hatoucaidang area, the first bed of unit beneath Holocene eolian sands is the Upper Pleistocene Salawusu Group consisting of fluvio-lacustrine deposits of medium-fine sand, silty sand, and sandy clay. The base of the group is in unconformity with the Zhidan Group of Lower Cretaceous age. This group is composed of sandstones in the

color of purplish red and celadon. The outcrops of eolian sand of the Holocene Series occur widely and their base is the Salawusu Group (Hou et al. 2006, 2008).

The study area has two aquifers; the upper one is unconfined and is composed of the eolian sand and the underlying Salawusu Group and beneath this is a confined aquifer consisting of the Zhidan Group. The recharge of the unconfined aquifer mainly comes from the infiltration of precipitation (Yin et al. 2010). Groundwater flows from west to east in the study area, and its discharge types include groundwater extraction and evapotranspiration. The chemical type of groundwater belongs to Ca–Mg–HCO₃ (Hou et al. 2006, 2008).

Evaluation method

This study evaluated the IWSV using a comprehensive index modelthat includes the response variables and the explanatory variables.

Response variables

The occurrence of plant species at regional scales is controlled by climatic factors. However, water and salt can obviously influence the distribution of these species in local areas (Zhou and Shao 2008). For this reason many models select plant species as a response variable to hydrological factors (Austin et al. 2006; Venterink and Wassen 1997; Gremmen et al. 1990). In the study area, plant species vary with the depth to the water table (Cheng et al. 2010a, b). This phenomenon shows that the depth to the water table is an important factor controlling the distribution of plant species.

The response of overall vegetation cover to water and salt is not as sensitive as that of individual plant species because the vegetation cover is also influenced by other factors, such as nutrients and sunshine [e.g. the vegetation cover in positive and negative sides of a slope is different (Cuo et al. 2006)]. In the local areas, the vegetation cover may respond to the moisture under the condition that nutrients and sunshine can be regarded to be identical (Song et al. 2010). The transpiration rate and the respiration of vegetation can be used as the response variables (Li et al. 2009); however, collecting the data on these variables is difficult. In this paper, the plant species and their cover, which are acquired easily, were selected as the response variables.

Explanatory variables

In the subsurface, the primary explanatory variables in relation to the water and salt usually are the depth to the

water table, groundwater mineralization, vadose zone moisture content, and vadose zone salinity.

The depth to the water table and the vadose zone moisture content are related to the growth of vegetation. The influence of depth to the water table on dependent vegetation has been documented by many studies (Song et al. 2010; Xu et al. 2007; Yang et al. 2006; Munoz-Reinoso and De Castro 2005; Zhao et al. 2005; Lammerts et al. 2001; Munoz-Reinoso 2001; Noest 1994). The suitable moisture content of the vadose zone is beneficial to the growth of vegetation. There is a critical value in moisture content for vegetation. When moisture content is lower than the critical value, the water cannot enter the root system of plants because the negative pressure in the vadose zone is higher than the penetrating pressure of the root system (Ball and Oosterhuis 2005), and some researches demonstrated its mechanism from the point of view of molecular-level gene expression (Shao et al. 2008a, b).

The groundwater mineralization and the vadose zone salinity are salinity factors. When their levels are extremely high, root water uptake will be counteracted by the penetration pressure (Ma et al. 2009; Skilhagen et al. 2008). Actually, groundwater mineralization and vadose zone salinity represent the relationship between vegetation and moisture content indirectly. Because strong evaporation leads to high groundwater mineralization and vadose zone salinity in the study area, its influence on plant species and cover must not be ignored.

In addition, vadose zone lithology is a comprehensive element that influences the root environment, including the aeration, the nutrients, etc. (Ertsen 1995; Gremmen et al. 1990; Ellenberg 1974). The vadose zone lithology in the study area can be divided into two types: eolian sand and sandy loam. Eolian sand is distributed widely; however, sandy loam occurs only in dune slacks. Results of the field investigation suggest that thick eolian sand is favorable to root growth and development (Cheng et al. 2010a, b). Consequently, the five factors mentioned above were selected as explanatory variables.

Data collection

In 2007–2009, the CGS developed this groundwater survey program in the Ordos Basin in the Inner Mongolia Autonomous Region of northern China. The data for the study were obtained from the field work in this program. The field wok was conducted five times: April, June, August, September, and November 2009. The data on plant species and their cover were obtained by plots and section investigations. A total of 20 plots with an area of 100 m × 100 m in each plot were delineated, and the six transects of investigation with a total length of 80 km were selected to collect data.

Forty wells were used to monitor groundwater levels and mineralization. Ninety boreholes, each 42 mm in diameter, were drilled into the vadose zone to investigate soil moisture using a neutron instrument inserted each hole. The soil samples were collected at different depths for the analyses of the total dissolved solids using the conductivity method.

Field observations

There are seven primary plant species (Artemisia ordosica, Salix psammophila, Hedysarummaxim, Caragana korshinskii, Sabina Vulgaris, Achnatherum splendens, and Carex enervis) in the Mu Us Desert (Zhao 2006). The investigation results indicate that the vegetation is dominated by Artemisia ordosica, Salix psammophila and Carex enervis in the study area. The xeromorphic plant, Artemisia ordosica, is independent of the groundwater, while Salix psammophila and Carex enervis are groundwater-dependent.

The suitable depth to the water table for Salix psammophila is in the range of 2.0–5.0 m, and that for Carex enervis is in the range of 0.5–2.0 m. The suitable moisture content in the vadose zone for Artemisia ordosica, Caragana, and Hedysarummaxim is in the range of 12–25%, and for Salix psammophila and Carex enervis, it is more than 25%, which is equal to the average moisture content within the capillary fringe. The suitable salinity of the vadose zone for Artemisia ordosica and Carex enervis is less than 0.1% and in the range of 0.4–1.0%, respectively, and that for Salix psammophila is that between the suitable salinity of Artemisia ordosica and Carex enervis. The suitable groundwater mineralization for Artemisia ordosica and Salix psammophila is less than 500 mg/l and that for Carex enervis is in the range of 500–900 mg/l (Cheng et al. 2010a, b).

The plant species are sensitive to the depth to the water table and moisture content of the vadose zone. Vadose zone salinity and groundwater mineralization are insensitive indicators. The cover of vegetation which is groundwater dependent is more sensitive to the depth to the water table, while the total coverage is an insensitive indicator because the distribution of xeromorphic vegetation is much wider than the groundwater-dependent vegetation.

Model description

Weighting coefficient values of explanatory variables

The vegetation in Hatoucaidang comprises not only xeromorphic and aquatic species, but also shrubbery and herbage. The five explanatory variables exercise various influences on different plant species and their cover. The weighting coefficient values of explanation variables are

Table 2 Weighting coefficient values of explanatory variables

Explanatory variables	Weighting coefficient values					
	Artemisia ordosica		Salix psammophila		Carex enervis	
	Species	Cover	Species	Cover	Species	Cover
Depth to water table	0.10	0.13	0.30	0.40	0.35	0.30
Groundwater mineralization	0.10	0.10	0.10	0.10	0.05	0.15
Vadose zone lithology	0.40	0.20	0.30	0.10	0.20	0.10
Vadose zone moisture content	0.30	0.40	0.20	0.30	0.35	0.30
Vadose zone salinity	0.10	0.17	0.10	0.10	0.05	0.15

confirmed by the investigation results and the knowledge of our colleagues (Table 2).

According to the results of the investigation, the moisture related to *Artemisia ordosica* mainly derives from the vadoze zone, which is rarely dependent on the groundwater, and is less likely affected by groundwater mineralization (Yu 2005). Moreover, it is a typical sand plant species, so it is very sensitive to the lithology of the vadose zone. The sequence of the weighting coefficient values for the five explanatory variables for *Artemisia ordosica* is vadose zone lithology > vadose zone moisture content = vadose zone salinity = depth to the water table = groundwater mineralization, and for their cover the sequence of the weighting coefficient values is vadose zone moisture content > vadose zone lithology > vadose zone salinity > depth to the water table > groundwater mineralization.

The *Salix psammophila* and arbor species distribute widely at edges of dune slacks with small depth to the water table, and thus the depth to the water table is the most important factor. Considering that it rarely grows on sand dunes due to its root development, vadose zone moisture is an important water resource for it. In addition, this species grows not only in eolian sand but also in sandy loam, so both salinity and vadose zone lithology are insensitive variables for it (Zhao et al. 1991).

The *Carex enervis* is aquatic and salt-tolerant. It is distributed widely in the dune slacks and is scattered in the sand dunes with a great depth to the water table. Thus, groundwater is more important than the vadose zone moisture. Furthermore, salinity including groundwater mineralization and vadose zone salinity plays an important role in controlling its distribution, while the vadose zone lithology is the least sensitive among the five groundwater variables for *Carex enervis*.

Explanatory variable classes

Each explanatory variable was graded by means of the investigation results, as shown in Table 3. The depth to the water table was divided into four classes for different vegetations. The depth in the range of 2–5 m represents the

suitable depth to the water table for *Salix psammophila*, and it is in the range of 0.5–2 m for *Carex enervis*. Groundwater mineralization is divided into two classes, and the mineralization less than 0.5 g/l represents the groundwater mineralization in the sand dune areas, and the mineralization between 0.5 and 0.9 g/l represents that in dune slacks. The vadose zone has three groups of lithology with respect to thin eolian sand, thick eolian sand, and sandy loam. The three classes of vadose zone moisture content represent the moisture contents in the vadose zone, in the capillary fringe and in the saturated zone, respectively. Vadose zone salinity is divided into four classes. The salinity less than 0.1% and between 0.1 and 0.4% represent the salinity in sand dunes, while the salinity between 0.4 and 1.0% and greater than 1.0% represent the salinity in dune slacks.

Scores of each class

This paper adopted the tripartite ordinal scale (0–2, lowest to highest values) to score for explanatory variables classification. For plant species, zero, one, and two represent absence, appearance, and suitable growth of a given species, respectively, when the scores represent the cover of some species, the scores of 0, 1, and 2 indicate the plant cover is less than 20%, between 20 and 40% and great than 40%, respectively. The ordinal scales of *Salix psammophila*, *Artemisia ordosica*, and *Carex enervis* are shown in Table 3.

Calculation of comprehensive index value

The comprehensive index value may be defined as the sum of the index value for plant species and their cover such that

$$V = V_s + V_c \tag{1}$$

with

$$V_s = \sum_{i=1}^{n} (W_i \cdot SS_{ij}) \qquad V_c = \sum_{i=1}^{n} (W_i \cdot CS_{ij})$$

where V is the comprehensive index value, dimensionless; V_s is the index value for plant species, dimensionless; V_c is

Table 3 Explanatory variables classification and ordinal scale value for three plant species

Variables	Classification	Tripartite ordinal scale					
		Artemisia ordosica		*Salix psammophila*		*Carex enervis*	
		Species	Cover	Species	Cover	Species	Cover
Depth to water table	<0.5 m	0	0	0	0	2	2
	0.5–2.0 m	1	1	2	2	1	2
	2.0–5.0 m	2	2	2	2	1	1
	>5.0 m	2	1	1	0	0	0
Groundwater mineralization	<0.5 mg l^{-1}	2	2	1	2	1	0
	0.5–0.9 mg l^{-1}	1	1	2	1	2	2
	>0.9 mg l^{-1}	0	0	1	0	2	1
Vadose zone lithology	Thick eolian sand (>3 m)	2	2	2	2	1	0
	Thin eolian sand (<3 m)	1	1	1	1	1	0
	Sandy loam	0	0	1	1	2	2
Vadose zone moisture content	<12%	1	1	1	0	1	0
	10–25%	2	2	2	2	2	1
	>25%	0	0	1	1	2	2
Vadose zone salinity	<0.1%	2	1	1	1	1	0
	0.1–0.4%	1	2	2	2	1	1
	0.4–1.0%	1	1	2	1	2	2
	>1.0%	0	0	1	0	2	1

the index value for plant cover, dimensionless; W is the weighting coefficient values of groundwater variables; SS is the scores for species; CS is the scores for cover; i is the explanatory variable number; j is the classification number of some explanatory variables, $j = 1, 2,…, 4$ for the depth to the water table and the vadose zone salinity and $j = 1, 2, 3$ for other explanatory variables. The maximum and minimum values of the comprehensive index are four and zero, respectively.

The groundwater variables and vegetation variables were investigated in eight plots, and the results are shown in Table 4. The comprehensive index in these eight plots was calculated according to Eq. 1 and the results are summarized in Table 5.

Critical index value of suitable environment for vegetation

As shown in Tables 3, 4, and 5 if the conditions of occurrence of plant species and of their cover that is greater than 40% are used to judge the basis of the vegetation suitability, the corresponding comprehensive index value will be about 2.5. This is the critical index value of suitable water and salt conditions for *Artemisia ordosica*, *Salix psammophila* and *Carex enervis*. If the comprehensive index is greater than the critical index, the water and salt

environment is suitable for some plant species; otherwise, it is not suitable.

The model was developed to produce the index value. The development process illustrates that this model computes the comprehensive index value for plant species and that the critical value is the key indictor for evaluating the suitability of plant species.

Validation of the model

Achatu with an area of 50 km^2 in Hatucaidang was chosen as the area for model validation. This area was chosen because sufficient data sets about groundwater and vegetation were available for model validation.

First, the evaluation zone was divided into grids with cells of 2×2 km according to the spatial distribution of the field data; the class of every explanatory variable at each cell was confirmed by means of field data; then the class zone was delineated using the same class cells for each explanatory variable in the validation area.

Second, the class zones for the five explanatory variables were superimposed in order to form the calculation units for the comprehensive index values for *Artemisia ordosica*, *Salix psammophila* and *Carex enervis*. The comprehensive index value was calculated according to Eq. 1 for each plant species, and it was then determined

Table 4 Explanatory variables and vegetation data in eight plots

Plots	Geomorphology	Groundwater depth (m)	Moisture content (%)	Vodose zone salinity (%)	Vodes zone lithology	Groundwater mineralization (g/l)	Cover (%) Artemisia ordosica	Salix psammophila	Carex enervis	Species
1	Dune slacks	0.4	26.30	0.58	Sandy loam	0.62	0	0	80	Carex enervis
2	Dune slacks	0.3	28.50	0.63	Sandy loam	0.72	0	0	85	Carex enervis
3	Edge of dune slacks	2.1	17.42	0.34	Eolian sand	0.42	0	70	5	Salix psammophila, Salix cheilophila, Salix matsudama Koidz, other herbs
4	Edge of dune slacks	2.3	15.30	0.32	Eolian sand	0.38	25	40	15	Salix psammophila, Artemisia ordosica, Carex enervis, other Herbs
5	Dune slacks	1.5	19.39	0.21	Eolian sand	0.18	5	45	40	Salix psammophila, Salix cheilophila, Herb
6	Gentle sand dunes	3.5	14.89	0.18	Eolian sand	0.21	40	20	10	Salix psammophila, Artemisia ordosica, Carex enervis, other Herbs
7	Gentle sand dunes	5.5	9.34	0.11	Eolian sand	0.23	70	0	5	Artemisia ordosica, Carex enervis, other Herbs
8	Gentle sand dunes	8.5	11.47	0.08	Eolian sand	0.15	45	0	0	Artemisia ordosica, Cynanchum komarovii Al.Iljinski

Table 5 Comprehensive index value for vegetation in eight plots

Plots	Comprehensive index values (dimensionless)		
	Artemisia ordosica	Salix psammophila	Carex enervis
1	0.47	1.50	4.00
2	0.47	1.50	4.00
3	3.67	3.90	2.40
4	3.70	3.90	2.45
5	1.07	3.00	3.10
6	3.20	3.10	1.45
7	3.07	2.00	0.80
8	3.00	1.80	0.65

which vegetation is suitable according to the critical index value of 2.5.

Suitable zones for *Artemisia ordosica*, *Salix psammophila*, and *Carex enervis* were then delineated. Finally, the predicted suitable zone for *Artemisia ordosica*, *Salix psammophila*, and *Carex enervis* was validated by the field data of vegetation distribution. The last three steps were performed using geographical information system (GIS).

The class zones for each explanatory variable are shown in Fig. 2a–e, and the calculation units of five explanatory variable zones are generated by GIS spatial analysis (Fig. 3). The comprehensive index value for each evaluation unit is shown in Table 6. After overlapping the level zone for each explanatory variable, eight evaluation units were noted. The comprehensive index value is identical in the second and the eighth unit, as well as in the fourth, fifth, sixth, and seventh unit for each plant species.

The evaluation results of suitable water and salt conditions for the three plant species are shown in Fig. 2f–h. The predictive distribution of *Artemisia ordosica*, *Salix psammophila*, and *Carex enervis* are similar to the field distribution (Table 7). Water and salt condition in sand dunes and the transitional area between the sand dunes and dune slacks are suitable for *Artemisia ordosica*. Those conditions in the edge of dune slacks are suitable for *Salix psammophila*, and those in dune slacks are suitable for *Carex enervis*. This proved that the five explanatory variables (depth to the water table, vadose zone moisture content, vadose zone salinity, vadose zone lithology, and groundwater mineralization) can correctly predict the distribution for *Artemisia ordosica*, *Salix psammophila,* and *Carex enervis* in a semi-arid desert area.

Discussion

In the current vegetation–hydrology models, the response variable is plant species. So they only evaluate the absence
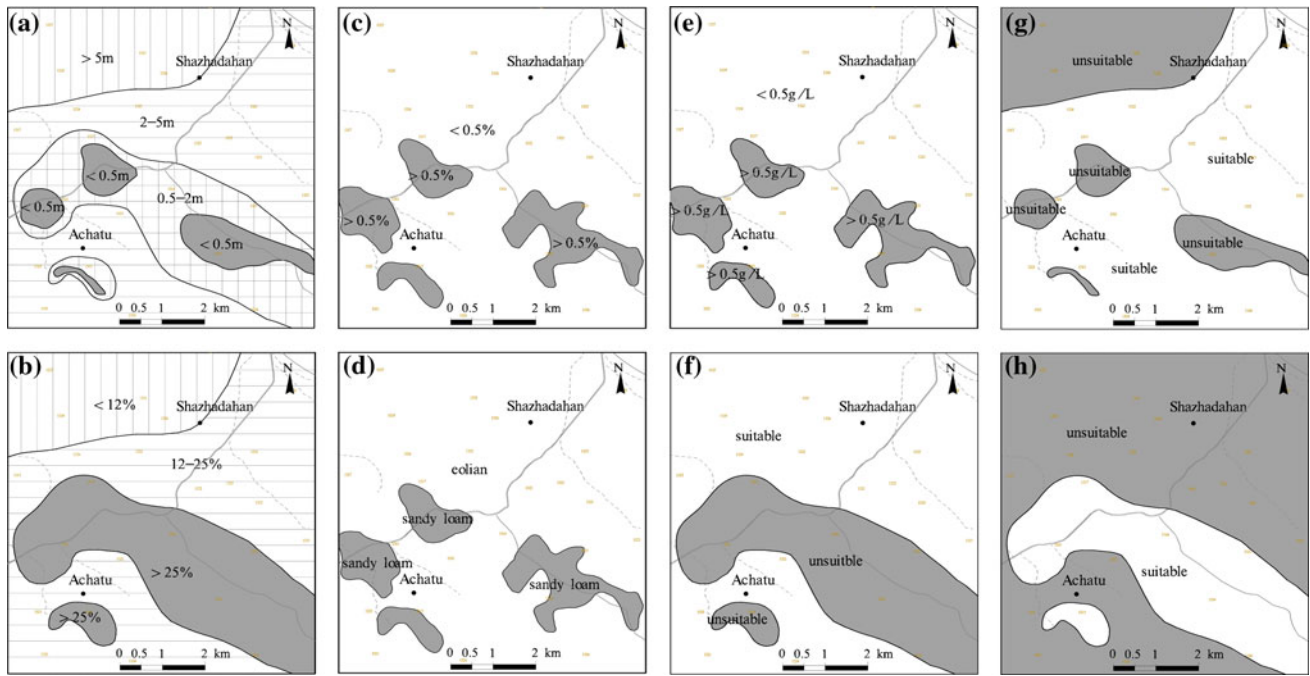
Fig. 2 Class zones of each explanatory variable. **a** depth to the water table, **b** moisture content of vadose zone, **c** vadose zone salinity, **d** vadose zone lithology, and **e** groundwater mineralization and

evaluation maps of suitable water and salt conditions for, **f** for *Artemisia ordosica*, **g** for *Salix psammophila*; and **h** for *Carex enervis*. *Gray areas* represent unsuitable, and *white areas* represent suitable
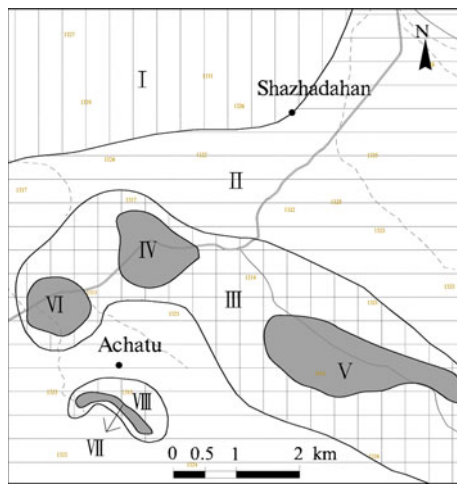

Fig. 3 Calculation units for the comprehensive index generated by GIS spatial analysis

Table 6 Comprehensive index value of three plant species in evaluation units

Evaluation units	Comprehensive index values (dimensionless)		
	Artemisia ordosica	*Salix psammophila*	*Carex enervis*
I	3.07	2.00	0.80
II, VIII	3.90	3.90	2.10
III	0.70	2.90	3.65
IV, V, VI, VII	0.47	1.50	4.00

Table 7 Plant species and cover in the area of model validation

Evaluation units	Primary species	Cover (%)	Total cover (%)
I	*Artemisia ordosica*	30–40	40–50
	Caragana korshinskii	10	
	Cynanchum komarovii	<5	
II, VII	*Artemisia ordosica*	40	50–60
	Caragana korshinskii	<5	
	Cynanchum komarovii	<5	
	Salix psammophila		
III	*Artemisia ordosica*	10	60–70
	Caragana korshinskii	<5	
	Cynanchum komarovii	<5	
	Salix psammophila	40	
	Carex enervis	10	
IV, V, VI, VII	*Carex enervis*	50–60	80–90
	Carex duriuscula	20–30	

or appearance of species (Noest 1994; Gremmen et al. 1990; Barendregt and Wassen 1989). In the IWSV model, plant species and their cover were chosen as response variables. Therefore, it is possible to quantify the response variable, and thus evaluate suitable habitat condition using quantifiable classes. The five habitat variables were

specially chosen as explanatory variables in the IWSV model, which strongly focuses on the water and salt-vegetation interactions. This functional process also exists widely in other regions, such as in the Tarim Basin and the Junggar Basin in northern China, where drought and high salinity are common, and where the water and salt control the occurrence of plant species temporally and spatially. Thus, the IWSV could extend to evaluate suitable vegetation environments in arid and semiarid regions besides desert.

The critical index value varies with different plant species theoretically. In this research, the critical index values for *Artemisia ordosica*, *Salix psammophila,* and *Carex enervis* were identical. This can be explained by the wide grading, short intervals of ordinal scale, and small number of investigation plots. However, in the same plot, the comprehensive index value of the three plant species is in a sharp contrast, and this index value is thus a good indicator to distinguish the vegetation suitability.

Obviously, the more heterogeneous the water and salt variable, the more sensitive the comprehensive index value. Therefore, the model is applicable in desert regions, where the depth to the water table has great variations because of frequent migrations of sand dunes. This also leads to more heterogeneity for the vadose zone moisture content, vadose zone salinity, and groundwater mineralization. The comprehensive index values for plant species are directly related to the three kinds of topography, the dune slacks, the sand dunes, and the transitional area between sand dunes and dune slacks. So the partial topographic factors are implicitly included in these five variables.

The following are the main limitations of the IWSV model:

1. The model is validated based on only three plant species and others species are not included.
2. The vegetation retardation behavior responding to the explanatory variables is not considered.
3. The model is applicable to the local environment evaluation for vegetation because only the water and salt variables are considered in the model. For regional evaluation, the climatologic and geomorphologic variables must also be taken into account.

In future studies, progress could be made by the establishment of a set of water and salt modules, and each module should combine causal dose–effect relationships linked with mechanistic models, such as a groundwater model for depth to the water table, a geohydrochemical model for groundwater mineralization, and an unsaturated model for vadose zone moisture and salinity. Incorporation of mechanistic models can increase the functional prediction greatly. In addition, the model should be extended to evaluate the suitable groundwater environment for more plant species in semi-arid desert regions. Incorporating the model into GIS will provide an easier way for data input, calculation, zone delineation, and evaluation for the analysis of the spatial pattern from the model outputs.

Conclusion

The IWSV model focuses on the water and salt influence on the vegetation and evaluates the suitable habitats related to the subsurface conditions for vegetation in saturated zone and in the vadose zone. Despite its limitations, it can be a useful tool for groundwater management and nature conservation in semi-arid desert areas, especially for delineating the vegetation distribution in areas with groundwater extraction. The input data for this model are easy to obtain from field work. The prediction results are fairly accurate for the distribution of *Artemisia ordosica*, *Salix psammophila*, and *Carex enervis*.

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