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Variability in groundwater depth and composition and their impacts on vegetation succession in the lower Heihe River Basin, north-western China

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Abstract. Plant-community structure and groundwater attributes were investigated in Ejina Delta in north-western China to understand spatial variability of groundwater depth and composition and their impacts on vegetation succession. Geostatistical methods and ordination analysis were performed to analyse the data. In addition, we tried to obtain vegetation successional series by using an approach of spatial sequences instead of temporal sequences. The findings of the present study were as follows: (1) the coefficient of variation for groundwater depth (GWD), salinity (SAL), total dissolved solids (TDS), electrical conductivity (EC), pH, Ca^{2+}, Mg^{2+}, K^+, Na^+, SO_4^{2-}, HCO_3^-, NO_3^-, Cl^- and F^- ranged from 0.04 to 1.53; (2) GWD, Mg^{2+}, TDS, EC, Ca^{2+}, HCO_3^-, NO_3^- and pH showed strong spatial autocorrelation, whereas K^+ and SAL showed moderate spatial autocorrelation; (3) canonical correspondence analysis revealed that groundwater heterogeneity, especially GWD, followed by pH, SAL, TDS, EC and HCO_3^-, had an important impact on vegetation succession, and thus showed a prevalence of groundwater attributes-based niche differentiation among plant communities; and (4) there were two vegetation successional processes (drought and salinisation) in the lower Heihe River Basin, and salinisation processes increased with drought processes. Our results indicated that high spatial variability of groundwater attributes contributes to promoting maintenance of species and landscape diversity in the lower Heihe River Basin.

Additional keywords: canonical correspondence analysis (CCA), groundwater heterogeneity, semi-variogram.

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Introduction

Numerous mountain ranges exist in central, western and northern China, including the Himalayan mountains in the west, the Kunlun and Allun mountains in the north-west and the Qilian and Qinling mountains in central northern and eastern China (Wang *et al.* 1986). Snow and glacier melt generates rivers, some of which flow north. North of the Tibetan plateau, itself surrounded by mountains, are the Taklimakan Desert, the Mu Us Desert and the Gobi Desert (Chen *et al.* 2005). The region is arid, and reliance on ephemeral river water and perennially available groundwater resources is extensive. Oases are common features of this region, and vegetation succession is critically determined by the coming and going of surface and near-surface water resources (Zhong 2002; Cheng and Zhao 2008). In the past 50 years, population growth, increased agricultural activity and socio-economic developments have greatly affected the water budget of this region (Du *et al.* 1997; Dou 2004; Quan 2006). Desertification is proceeding rapidly, with dust storms and progressively deepening groundwater levels, as well as concomitant drying of rivers and lakes, a frequent occurrence across much of the region (Zhang *et al.* 2002; Xiao and Xiao 2004). The 'Long-term science and technology development program outline in China (2006–2020)' explicitly identifies these problems and highlights the need for ecohydrological studies linking knowledge of the hydrological cycle, productivity and ecosystem services (Song and Leng 2005).

There are groundwater-dependent ecosystems and groundwater-dependent vegetation in arid regions (Eamus *et al.* 2006). For arid inland ecosystems globally, including northern China, groundwater availability is a critical determinant of vegetation structure and function (Ma and Gao 1997). The Ejina Delta is an oasis surrounded by desert, and groundwater is a key factor determining landscape ecology and regional socio-economics (Peng *et al.* 2011). Native plant communities in this region use groundwater as their main source of water, although surface runoff can also be locally important (Zhang and Shi 2002).

Because of increased human consumption and allocation to industry (including agriculture), there have been extensive changes in regional groundwater quality and groundwater depth (Zhang *et al.* 2001), posing a serious threat to the ecology and socio-economics of these regions.

Geostatistics is an effective tool to examine problems of spatial heterogeneity of landscapes (Levin 1992). These methods can be used not only to reveal the spatial distribution, variation and related characteristics of a variable but also to associate spatial patterns with ecological processes and thereby explain the impact of spatial patterns of variability on ecological processes and functions (Rossi *et al.* 1992; Li and Reynolds 1995; Wang 1999). At present, this method has been widely applied to analyse spatial heterogeneity in soil (Imhoff *et al.* 2000; Sauer *et al.* 2006; Yavitt *et al.* 2009), vegetation (Harte *et al.* 1999; Chen *et al.* 2002; Yu *et al.* 2011) and groundwater resources (Pebesma and Kwaadsteniet 1997; Adams *et al.* 2001; Cinnirella *et al.* 2005). Canonical correspondence analysis (CCA) is a multiple direct gradient-sorting method that combines vegetation and environmental factors into an effective multivariate technique (Mucina 1997). This method has been widely used for analyses of community structures and for understanding the relationships among vegetation communities and the environment in vegetation ecology (Leps and Šmilauer 2003). In the present paper, plant community structure and groundwater attributes (composition and depth) were investigated in 31 plots in the Ejina Delta in the lower reaches of the Heihe River. Geostatistical methods (semi-variograms and Kriging interpolation) and ordination (canonical correspondence analysis, CCA) were performed to analyse the data. Meanwhile we tried to obtain vegetation successional series using an approach of spatial sequences instead of temporal sequences. Our objectives were to (1) characterise the variability in groundwater depth and composition in the lower Heihe River Basin, and (2) assess the influences of groundwater depth and composition on vegetation succession. The results of the paper can provide a scientific basis for the understanding of ecosystem restoration and reconstruction in this or similar regions.

Materials and methods

Study-area description

The study area (3×10^4 km^2) is located in the lower reaches of the Heihe River, extending between latitudes 40°20′N and 42°30′N and longitudes 99°30′E and 102° 00′E, in the county of Ejina, Inner Mongolia, north-western China (Li *et al.* 2001). This region has a continental climate, with a mean annual temperature of ~8°C, a maximum daily temperature of 41°C (July) and a minimum of −36°C (January) (Xie 1980). The long-term (1957–2003) annual average precipitation at the study site is less than 42 mm and groundwater recharge is minimal in most years and restricted predominantly to rare periods of high-intensity rainfall. Pan evaporation rates are typically 2300–3700 mm year^{-1} (Wen *et al.* 2005). No perennial runoff is generated in this region and the Heihe River sustains the only perennial flow through the area (He and Zhao, 2006). The Heihe River, which originates from the Qilian Mountain, flows through the Ejina Basin and divides into two branches at Langxinshan (Wang 1997). The two branches of the Heihe River flow into East and West Juyan Lake, and the total length of these branches in the basin is ~240 km (Feng *et al.* 2001). Before entering the terminal lakes, the East River and West River form several tributaries, such as the Nalin River, the Longzi River and the Andu River. The Heihe River is the main source of recharge and drainage for the groundwater system, and ~68% of the groundwater recharge in the Ejina alluvial fan is attributed to vertical percolation of the Heihe River (Feng *et al.* 2004; Wen *et al.* 2005).

In this region, the sampled vegetation is composed mainly of desert plant species, with low species diversity and vegetation cover (Zhu *et al.* 2013). Survey data (Flora of Inner Mongolia, 1977–1979; eFloras 2008) list 268 species belonging to 151 genera and 49 families in this area. Compositae (81 species), Chenopodiaceae (47 species) and Gramineae (33 species) are the dominant families, with each comprising 30 or more species. Leguminosae (15 species), Polygonaceae (11 species), Cyperaceae (11 species) and Tamaricaceae (10 species) each have 10 or more species. These seven families incorporate the 208 most dominant species, which account for 72% of the total species in the region (Zhu *et al.* 2009).

Xerophytic, extremely xerophytic and salt-tolerant desert species are also widely distributed in this region. From the distribution patterns, it is clear that mesophytes and hygrophytes, including arbours, bushes and herbs, growing in the Ejina River banks and the fluvial plain, including *Populus euphratica*, *Elaeagnus angustifolia*, *Tamarix ramosissima*, *Phragmites communis*, *Achnatherum splendens*, *Sophora alopecuroides* and *Glycyrrhiza uralensis*, are the dominant species of these groups in the region. Various types of desert shrubs and herbs, including *Haloxylon ammodendron*, *Nitraria tangutorum*, *Artemisia oxycephala* and *Agriophyllum arenarium*, are primarily distributed at the margins of oases. Some sparse and drought-tolerant desert species, such as *Reaumuria soongorica*, *Ephedra przewalskii*, *Zygophyllum xanthoxylon*, *Sympegma regelii*, *Anabasis brevifolia* and *Calligonum mongolicum* , are mainly distributed in low mountainous and hilly areas and the Gobi Desert (Si *et al.* 2005). The dominant vegetation in the study area, including *P. euphratica*, *T. amosissiman* and *S. alopecuroides*, primarily depends on groundwater for its continued presence (Zhu *et al.* 2009).

Plots and measurements

Surveys of natural vegetation were carried out in the same plots from June to August in 2010, 2011 and 2012. In total, 31 observation points were selected for water-table and salinity monitoring. Thirty-one plots, each 400 m^2 in area, and 217 quadrats (31 tree quadrats, 93 shrubs quadrats and 93 herb quadrats) were established randomly but within 20 m of the wellbore that was used to measure the depth of the water table. Height, coverage and diameter at breast height of the trees (≥5 m) were recorded individually. Three shrub quadrats, each 25 m^2 in area, and three herb quadrats (1 m^2) were also established randomly in each of the 31 plots. The species composition and the frequency, height and percentage of canopy cover were determined for each quadrat. Vegetation cover data were recorded using the method of ordinal scale. The location of observation points, including altitude, longitude and latitude,

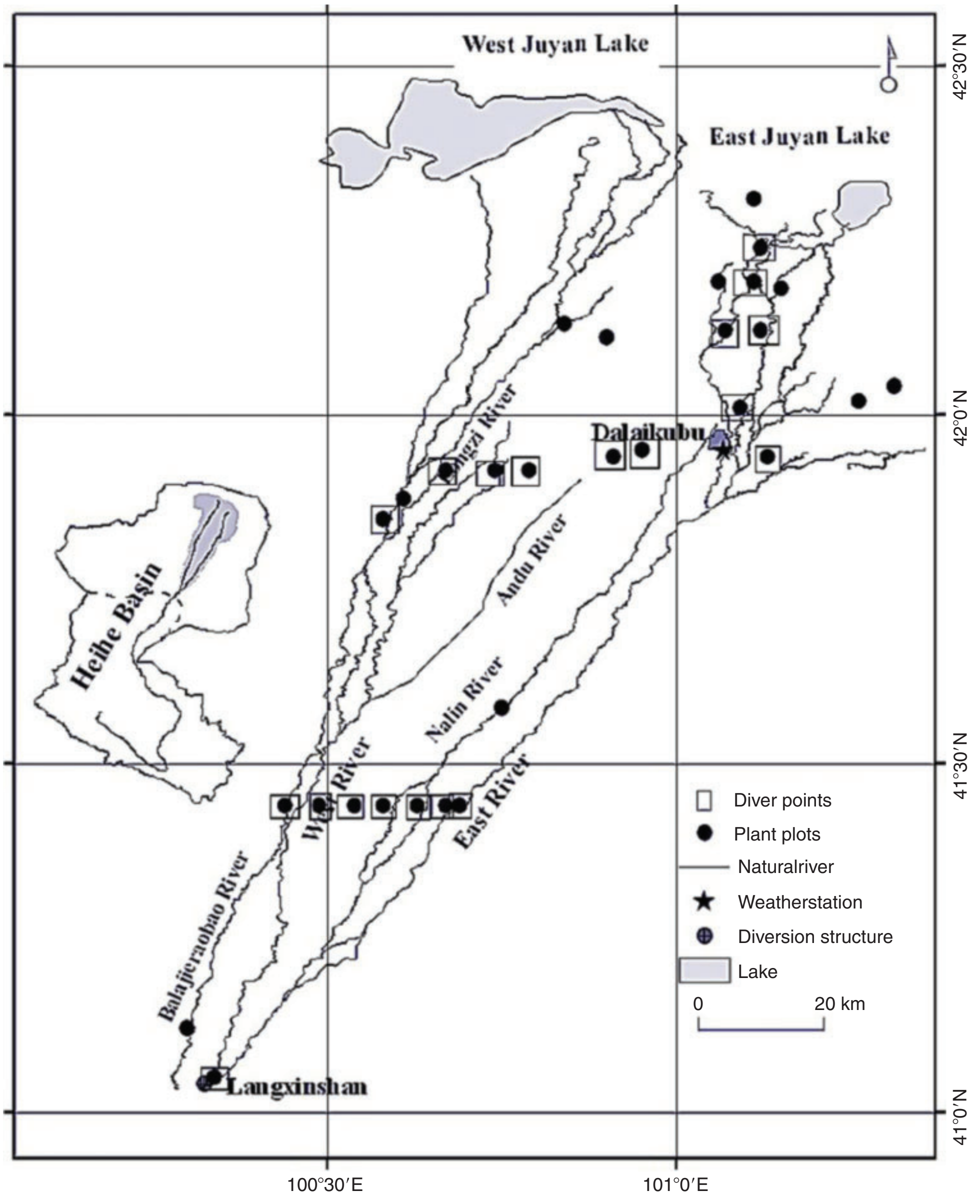

Fig. 1. The location of study area, water channels and plant plots (400 m^2).

were determined using the global positioning system. Groundwater depth (GWD) was measured three times each month in each of the 31 wells over the 3-year period. In addition, three groundwater samples were collected every 2 months at each point. Chemical components, including HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+, were measured at the Institute of Geography Sciences and Natural Resources Research, Chinese Academy of Science (Beijing, China). Concentrations of SO_4^{2-}, Cl^-, NO_3^- and F^- were analysed by ion chromatography (IC), and HCO_3^- anions were determined by titration (0.01 N H_2SO_4). Cations were analysed by inductively coupled plasma mass spectroscopy (ICPMS). TDS represents the sum of the cations and anions in the water. The major ions in water chemistry contribute to salinity, EC and pH values that were measured *in situ* using a HANNA HI 98188 (HANNA, Italy) waterproof portable conductivity meter as well as CyberScan PC300 (EUTECH, USA) waterproof portable pH–ORP–conductivity meters. To obtain exact data on the annual changes in groundwater depth and salinity in this region, 15 depth sensors and five water-quality sensors (Eijkelkamp, Netherlands) were fixed in 20 wells in April 2010 (Fig. 1) and GWD was recorded every 30 min.

Statistical analysis

Statistical characteristic evaluation and a test for normality of distribution (Kolmogorov–Smirnov test) were performed to analyse the groundwater data. A logarithmic conversion was applied when data did not conform to a normal distribution. Calculation of spatial variograms of groundwater attributes and

Table 1. Descriptive statistics of groundwater attributes
K–S, Kolmogorov–Smirnov value

Attribute	Mean	Median	Max	Min	Range	s.d.	CV	Skewness	Kurtosis	K–S	*P*
GWD (m)	3.77	3.09	11.00	1.75	9.25	2.03	0.54	2.08	4.98	0.23	0.07
SAL (%)	3.91	2.70	14.40	1.20	13.20	3.21	0.82	1.97	3.93	0.22	0.12
pH	7.82	7.77	8.74	7.22	1.52	0.33	0.04	0.89	0.75	0.11	0.16
TDS ($mg\,L^{-1}$)	1253.27	817.50	9130.00	291.00	8839.00	1333.99	1.06	3.50	16.03	0.24	0.00
EC ($\mu s\,cm^{-1}$)	2521.19	1626.50	18 250.00	612.00	17 638.00	2665.17	1.06	3.51	16.02	0.25	0.00
Cl^- ($mg\,L^{-1}$)	318.58	177.06	2513.00	51.27	2461.73	429.28	1.35	3.38	12.55	0.31	0.00
SO_4^{2-} ($mg\,L^{-1}$)	638.07	406.97	4000.00	51.44	3948.56	807.32	1.27	2.58	7.66	0.25	0.00
HCO_3^- ($mg\,L^{-1}$)	355.80	279.30	1218.48	143.35	1075.13	225.56	0.63	2.44	5.86	0.23	0.00
Na^+ ($mg\,L^{-1}$)	290.23	165.30	1376.00	59.29	1316.71	292.08	1.01	2.38	6.35	0.22	0.00
K^+ ($mg\,L^{-1}$)	15.12	9.67	106.30	4.41	101.89	20.44	1.35	3.83	15.45	0.38	0.00
Mg^{2+} ($mg\,L^{-1}$)	98.35	60.18	483.30	24.14	459.16	96.83	0.98	2.67	8.44	0.30	0.00
Ca^{2+} ($mg\,L^{-1}$)	73.79	60.52	244.50	18.55	225.95	49.24	0.67	1.80	4.15	0.22	0.00
NO_3^- ($mg\,L^{-1}$)	16.79	8.06	101.76	2.92	98.85	25.73	1.53	3.21	10.79	0.39	0.03
F^- ($mg\,L^{-1}$)	0.45	0.23	2.22	0.00	2.22	0.58	1.29	2.53	7.01	0.28	0.14

determination of their theoretical model was undertaken in the GS+7.0 software (Gamma Design Software 2002).

To obtain a measure of semi-variograms of groundwater depth and composition, we calculated the semi-variogram as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{n} [Z(\chi i) - Z(\chi i + h)]^2,$$

where $\gamma(h)$ is the value of semi-variance, $N(h)$ is the total number of spacings between points in h, $Z(\chi i)$ is the value of Property Z in χi and $Z(\chi i + h)$ is the value of a regionalised variables in $(\chi i + h)$ (Rossi *et al.* 1992). By taking $\gamma(h)$ as the vertical axis, h as the horizontal axis, and by drawing the scatter diagram of $\gamma(h)$ variation, along with the increase in a delay distance h, one can test a spherical model, exponential model and linear model, to determine which model best fits the data. Models with the largest coefficient of determination (R^2) were deemed to be the most appropriate. A semi-variogram was produced with the following three parameters: sill ($C_0 + C$), nugget (C_0) and range (a) (Wang 1999). Sill, which included C and C_0, is the maximum degree of variation in the system attributes, nugget represents the random changes that cannot be explained, showing that there are other processes having an impact at smaller scales, and a represents the scale of spatial variation, and within this range, the variable has a spatial autocorrelation. Nugget and sill are largely influenced by themselves or the measurement unit and cannot be used to compare the variation among different variables, whereas $C_0/(C_0 + C)$ reflects the variance in nugget values and can account for the ratio of the total spatial variation and show the spatial dependence of variation on groundwater attributes. Generally, the spatial variable has a strong spatial autocorrelation when $C_0/(C_0 + C) < 0.25$; and when $C_0/(C_0+C)$ ranges from 0.25 to 0.75, there is moderate spatial autocorrelation. A weak spatial autocorrelation is present when $C_0/(C_0 + C) > 0.75$, and there is no spatial variation when $C_0/(C_0 + C)$ approaches unity (Li and Reynolds 1995). After calculation of the semi-variance, Kriging interpolation was performed to analyse groundwater attributes and to produce a Kriged map of the spatial distribution probabilities of groundwater attributes. The detailed mathematical processes required to perform the semi-variance and Kriging mapping may be found in Wang (1999). The above analyses were performed using GS+ 7.0 (Gamma Design Software 2002) and ArcGIS 9.2 (ERSI, Redlands, CA, USA). The impact of groundwater attributes on the spatial pattern and succession of plant community was studied using CCA ordination; for more information, see Jongman *et al.* (1995). CCA ordination processes using the package of Vegan (Oksanen *et al.* 2010) were accomplished using the R 2.7.2 software (R Development Core Team 2010). On the basis of 3 years of vegetation survey data, we tried to obtain vegetation successional series by using an approach of spatial sequences instead of temporal sequences.

Results

Descriptive statistics of groundwater depth and composition

The results of descriptive statistics of groundwater attributes (Table 1) showed that the mean and median of GWD, pH and F^- exhibited minimal variation across the 31 plots, with pH having the smallest coefficient of variation (0.04). Intermediate ranges of variation were observed for SAL (0.82), HCO_3^- (0.63) and Ca^{2+} (0.67), whereas larger coefficients of variation were observed for the remaining attributes (0.98–1.53). The degree of variation for different attributes decreased in the following order: $NO_3^- > Cl^- = K^+ > F^- > SO_4^{2-} >$ TDS = EC $> Na^+ > Mg^{2+} >$ SAL $> Ca^{2+} > HCO_3^- >$ GWD > pH. A Kolmogorov–Smirnov test showed that other attributes did not meet the normal distribution, except for GWD, SAL, pH and F^- ($P > 0.05$). Therefore, logarithmic conversions were used, thus ensuring that normal distributions were obtained and were appropriate for geostatistics and Kriging interpolation.

Variability in groundwater depth and composition

The optimal model of spatial heterogeneity for GWD, pH, HCO_3^-, Mg^{2+} and Ca^{2+} was an exponential model, whereas a spherical model was more appropriate for SAL, TDS, EC and

Table 2. Fitted model types and parameters for semi-variograms of groundwater attributes
RSS, (residual sum of squares)

Attribute	Model	Nugget (C_0)	Sill (C_0+C)	C_0/(C_0+C) (%)	Rang (A_0) (°)	R^2	RSS
GWD (m)	Exponential model	0.0001	0.2132	0.0469	0.08	0.443	0.0311
SAL (%)	Spherical model	0.1773	0.3636	48.7624	0.25	0.375	0.0460
pH	Exponential model	0.0230	0.1100	20.9091	0.01	0.000	4.756E–03
TDS (mg L^{-1})	Spherical model	0.001	0.3950	0.2532	0.05	0.031	0.0898
EC (μs cm^{-1})	Spherical model	0.001	0.3700	0.2703	0.06	0.053	0.0818
Cl^- (mg L^{-1})	Linear model	0.5282	0.5282	100	0.68	0.395	0.202
SO_4^{2-} (mg L^{-1})	Linear model	0.5620	0.7240	77.6243	0.68	0.110	0.261
HCO_3^- (mg L^{-1})	Exponential model	0.0184	0.2008	9.1633	0.03	0.075	0.045
Na^+ (mg L^{-1})	Linear model	0.5259	0.5259	100	0.68	0.270	0.149
K^+ (mg L^{-1})	Spherical model	0.0924	0.3578	25.8245	0.18	0.195	0.150
Mg^{2+} (mg L^{-1})	Exponential model	0.001	0.4960	0.2016	0.03	0.079	0.145
Ca^{2+} (mg L^{-1})	Exponential model	0.001	0.3300	0.3030	0.04	0.216	0.0439
NO_3^- (mg L^{-1})	Linear model	0.1007	0.8617	11.6862	0.55	0.097	2.12
F^- (mg L^{-1})	Linear model	0.0976	0.0976	100	0.55	0.201	0.0519

K^+. A linear model was more suitable for Cl^-, SO_4^{2-}, Na^+, NO_3^- and F^-, and the spatial structure characteristics of groundwater attributes were suitably represented by the theoretical models (Table 2, Fig. 2). The nugget effects of groundwater attributes were all positive, and SO_4^{2-}, Cl^- and Na^+ had larger nugget values. $C_0/(C_0 + C)$ in GWD, Mg^{2+}, TDS, EC, Ca^{2+}, HCO_3^-, NO_3^- and pH was smaller (0.0469–20.9091%), showing strong spatial autocorrelation (the variation ranges are 0.08°, 0.03°, 0.05°, 0.06°, 0.04°, 0.03°, 0.55° and 0.01°, respectively.); the ratio of K^+ and SAL ranged from 0.25 to 0.75, showing moderate spatial autocorrelation; the ratio of SO_4^{2-} was larger (>75%), showing weak spatial autocorrelation; whereas Cl^-, Na^+ and F^- presented a constant spatial autocorrelation because the ratio was equal to 1. The variation range of Cl^-, SO_4^{2-}, Na^+, NO_3^- and F^- was larger (0.55–0.68°), showing good spatial continuity; the value of pH, HCO_3^-, Mg^{2+} and Ca^{2+} was smaller (0.01–0.04°), showing poor spatial continuity.

Mapping of groundwater depth and composition

Groundwater depth was largest (9–11 m; Fig. 3) at the northern edge of the basin, on the southern edge of the cold and arid Gobi. The shallowest depths to groundwater occurred at the southern and central regions of the basin (1–3 m deep). The north-western and north-eastern regions of the catchment had intermediate depths to groundwater (3–6 m). Thus, there was a general trend with a south–north gradient of increasing depth to the water table. Groundwater salinity was lowest (0–2%) in the south-western part of the catchment and highest (10–14%) in the north-east. This pattern was also observed in the spatial patterns of TDS and EC (Fig. 3). The lowest values of SAL, TDS and EC occurred at the southern end of the transect (Fig. 3).

Vegetation succession determined by groundwater depth and composition

CCA ordination showed that the eigenvalues of the first two axes, namely, 0.547 and 0.162, were larger than those of the other axes. These two axes explained 55.8% and 16.5%, respectively, of the variance in the data (Fig. 4). Thus, the first two axes accounted for 72.3% of the environmental information. Among all the environmental factors measured, GWD exhibited the largest influence on community distribution, followed by pH, SAL, TDS, EC and HCO_3^-. In the CCA ordination diagram, the first axis represented variation in GWD, whereas the second axis was related to pH values. As a result, it is not difficult to show that GWD was the most important factor influencing community distribution. With increasing GWD, SAL, TDS and EC, there was also a clear increasing trend along the first axis. The spatial pattern of plant communities varied along the first axis, with transitions from community Type I (Ass. *Phragmites australis* + herbs) through to community Type VI (Ass. *Ephedra przewalskii* – *Reaumuria soongorica* + *Nitraria tangutorum* + *Alhagi sparsifolia*) (a more detailed description of each community type can be found in Zhu *et al.* 2012) across the axis (from right to left); accordingly, the landscape type changed from swamp meadow to xerophytic shrub, and finally, the zonal vegetation replaced the non-zonal vegetation.

Two vegetation successional processes (drought process and salinisation process)

On the basis of the combined results of the quantitative classification and ordination on community structure and groundwater attributes (Zhu *et al.* 2012), using the method of spatial information to extend time series, two vegetation successional processes (drought process and salinisation process) were proposed for Ejina Delta (Figs 5, 6). In the drought process, plant communities first experienced a positive stage of aquatic successional series, from hygrophytic herb community to woody plant community, then experienced a negative stage of xerophytic successional series, and successively experienced a period of herb degradation, shrub degradation and tree degradation (Fig. 5). Community successional processes could be divided into the following four stages: hygrophytic-herb community stage, tree–shrub–herb community stage, tree–shrub community stage, and single tree or shrub community stage. In the processes of succession, the various stages were not wholly separated, but overlapped to some extent. Meanwhile, according to the differences in community types and structural characteristics, each stage could be divided into several smaller stages. These are briefly described as follows (Zhu *et al.* 2012):

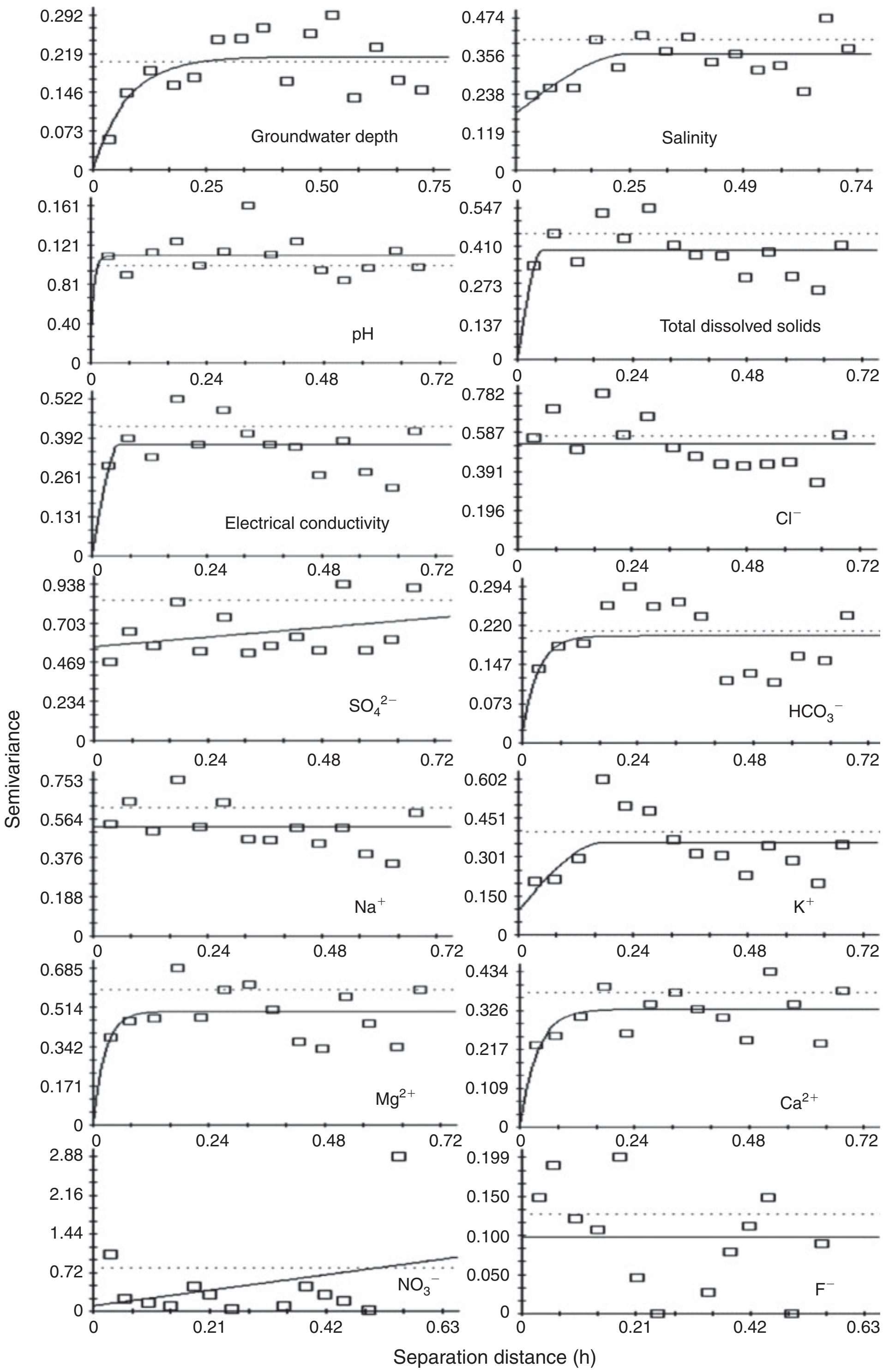

Fig. 2. Semi-variograms of groundwater depth and composition.

I – Hygrophytic-herb community stage

Hygrophytic-herb community stage was the initial stage of plant community succession in Ejina Delta. During this stage, the plant community was mainly composed of salt-tolerant herbaceous plants, and community appearance was described as swamp meadow, and groundwater level was generally less than 1.5 m. With the decrease in groundwater level, shrubs and trees gradually appeared, and finally the hygrophytic habitat developed into the mesophytic habitat. The following two community types were observed at this stage: I1 *Phragmites*

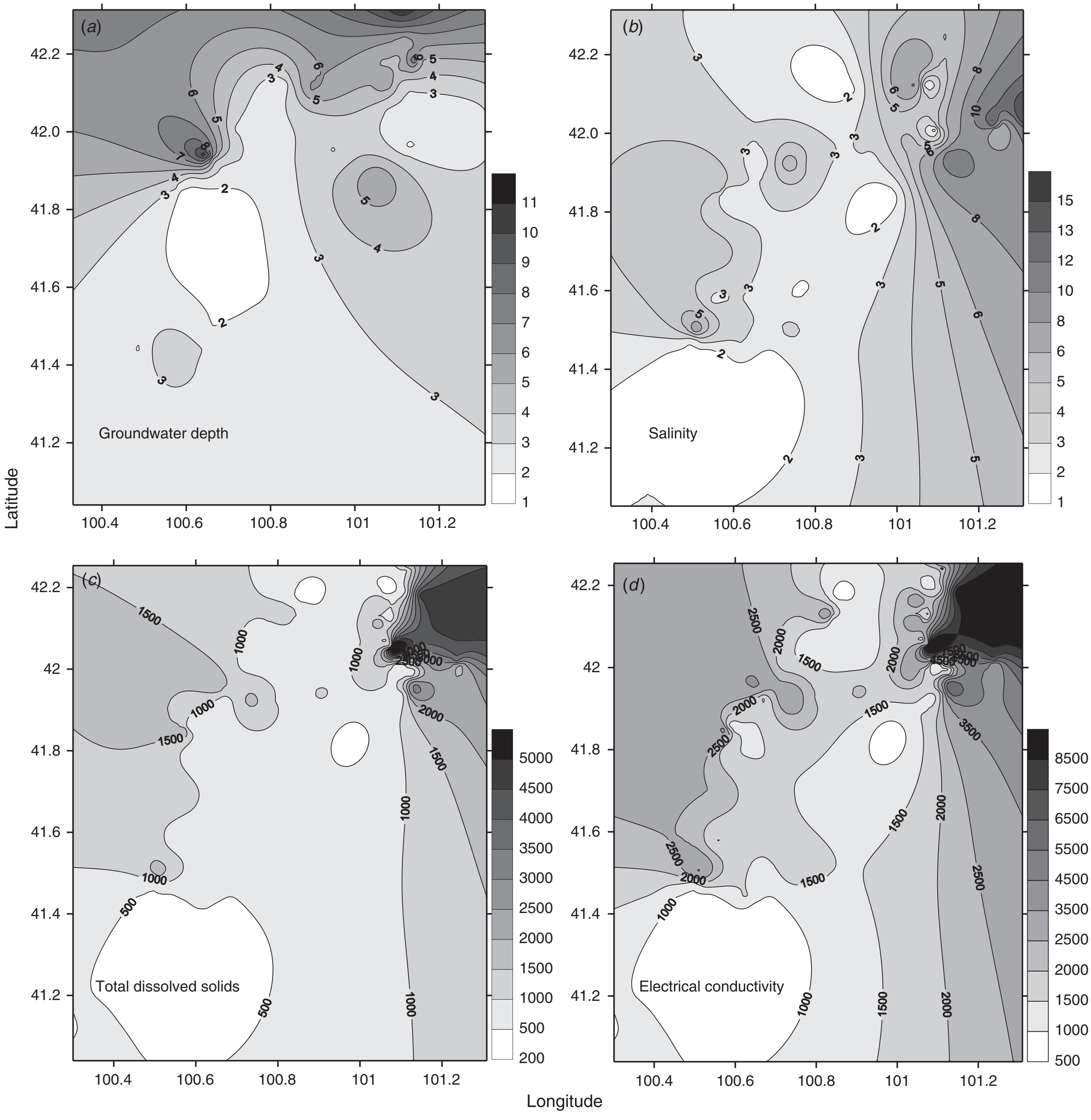

Fig. 3. Kriging maps, showing spatial distribution of groundwater depth and composition.

communis + *Kalimeris indica* + *Leymus secalinus*, and I2 *Achnatherum splendens* + *Calamagrostis epigeios* + *Elymus breviaristatus*.

II – Tree–shrub–herb community stage

The tree–shrub–herb community stage was the second stage, where plant communities consisted of trees, shrubs and halophilous herbaceous plants, and community appearance was described as *P. euphratica* forest; groundwater level ranged from 1.5 to 3.5 m. During this stage, with the increase in GWD and soil mineralisation, herbaceous plants primarily presented degradation. The plant community could be divided into the following three types: II1 *Populus euphratica* + *Tamarix ramosissima* + *P. communis* + *Sophora alopecuroides*, II2 *P. euphratica* + *T. ramosissima* + *Nitraria tangutorum* + *P. communis*, and II3 *T. ramosissima* + *P. communis*.

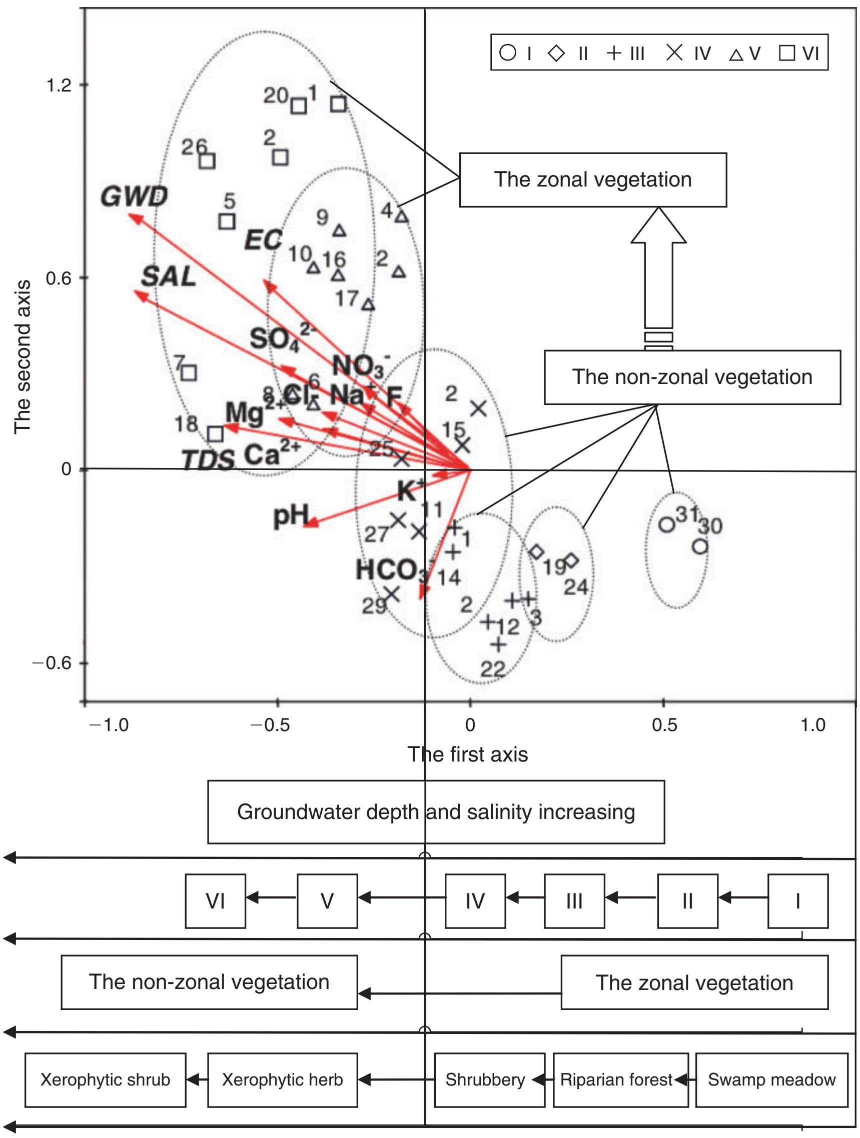

Fig. 4. Canonical correspondence analysis (CCA) ordination diagram and the sketch map of vegetation succession with groundwater depth and salinity increasing. IAss, *Phragmites australis* + herbs; IIAss, *Elaeagnus angustifolia–Tamarix ramosissima* + herbs; IIIAss, *Populus euphratica–Tamarix ramosissima* + herbs; IVAss, *Tamarix ramosissima*–herbs; VAss, *Karelinia caspica–Nitraria tangutorum* + *Artemisia* sp. + *Calligonum* sp.; and VIAss, *Ephedra przewalskii–Reaumuria soongorica* + *Nitraria tangutorum* + *Alhagi sparsifolia*.

III – Tree–shrub community stage

Tree–shrub community stage was a product of plant community succession developing to a certain stage. During this stage, groundwater level generally ranged from 3.5 to 5 m, and shrubs primarily presented degradation. In Ejina Delta, *P. euphratica* was the predominant tree, and the predominant shrub was *T. ramosissima*. With the increase in GWD and TDS, except for tree species, herbaceous plants almost died out; only drought-resistant and salt-tolerant shrub communities survived. The following three community types were observed at this stage: III1 *P. euphratica* + *T. ramosissima*, III2 *P. euphratica* + *T. ramosissima* + *N. tangutorum*, and III3 *T. ramosissima*.

IV – Single tree or shrub community stage

When groundwater level continued to decline to more than 5 m, tree height growth almost stopped in the half-mature forest of *P. euphratica*, and in mature and over-mature forest, the branches and stems were growing slowly, with crown shrinkage, lower crown density and simple community structure; *T. ramosissima* was piled up by the quicksand, gradually forming a package; only retrogressive *P. euphratica* forest or single *T. ramosissima* bushwood existed. The following two community types were observed at this stage: IV1 *P. euphratica*, and IV2 *T. ramosissima*.

Vegetation succession in Ejina Delta was also closely related to salinity conditions. With the increase in salinisation, aquatic

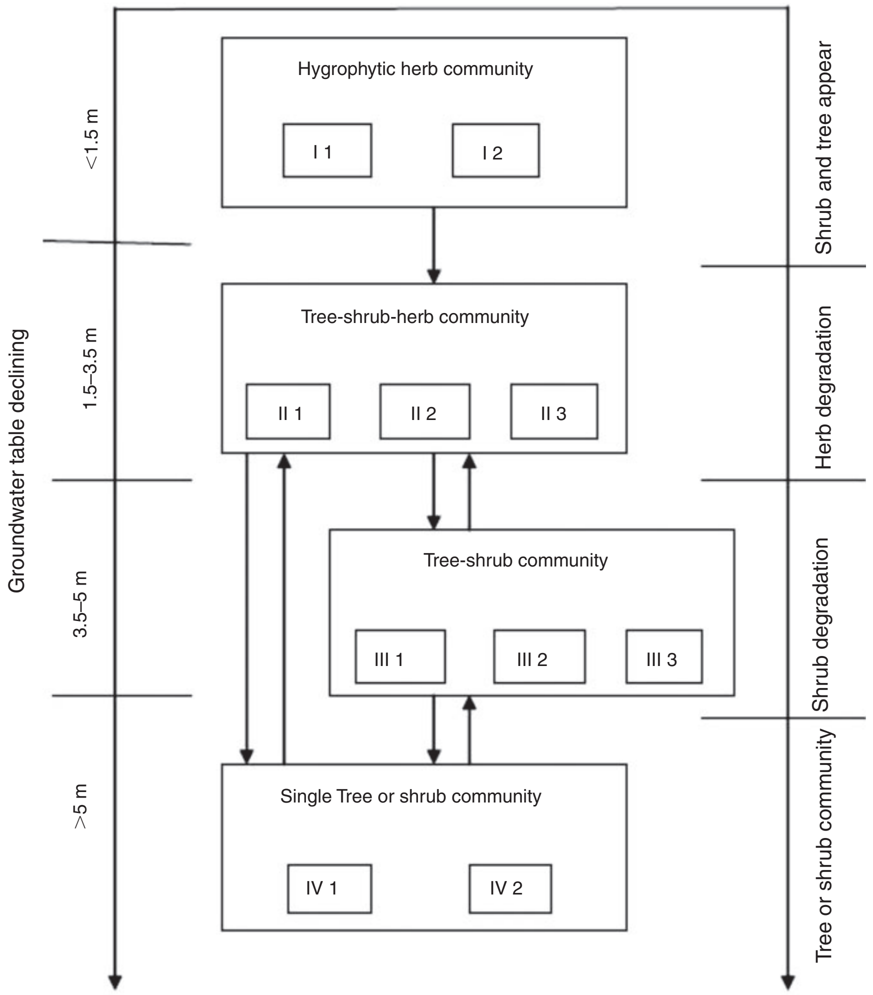

Fig. 5. The sketch map of vegetation succession (drought process) in Ejina Delta. The figure is adapted from Feng *et al.* (2009). I1, *Phragmites communis* + *Kalimeris indica* + *Leymus secalinus*; I2, *Achnatherum splendens* + *Calamagrostis epigeios* + *Elymus breviaristatus*; II1, *Populus euphratica* + *Tamarix ramosissima* + *Phragmites communis* + *Sophora alopecuroides*; II2, *Populus euphratica* + *Tamarix ramosissima* + *Nitraria tangutorum* + *Phragmites communis*; II3, *Tamarix ramosissima* + *Phragmites communis*; III1, *Populus euphratica* + *Tamarix ramosissima*; III2, *Populus euphratica* + *Tamarix ramosissima* + *Nitraria tangutorum*; III3, *Tamarix ramosissima*; IV1, *Populus euphratica*; and IV2, *Tamarix ramosissima*.

marsh vegetation changed into saline marsh meadow or halophytic meadow (Fig. 6). Salinisation would be further intensified with the increase in drought process, with halophytic vegetation and saline desert forest as predominant components at this stage, finally developing into saline desert and saline and alkaline land. Salinisation processes increased with drought processes. A reduction in water resources in the middle and lower reaches, which would inevitably lead to a decline in the water table, saw salinity concentrated in the soil surface and the dry beds of the rivers.

Discussion and conclusions

The descriptive statistics of groundwater attributes showed weak spatial variability in pH, moderate variability in GWD, SAL, HCO_3^-, Mg^{2+} and Ca^{2+}, and strong spatial variability in TDS, EC, Cl^-, SO_4^{2-}, Na^+, K^+, NO_3^- and F^-. The variability decreased in the order of $NO_3^- > Cl^- = K^+ > F^- > SO_4^{2-} >$ TDS = EC > $Na^+ > Mg^{2+} >$ SAL > $Ca^{2+} > HCO_3^- >$ GWD > pH. Such results are consistent with those of Xi *et al.* (2011), who showed moderate spatial variability in GWD, whereas Dai *et al.* (2010) found that there was strong spatial variability in TDS in a similar region.

The spatial structural characteristics of groundwater attributes were replicated well by semi-variance fitting models. The optimal model for GWD, pH, HCO_3^-, Mg^{2+} and Ca^{2+} was an exponential model, whereas a spherical model was more appropriate for SAL, TDS, EC and K^+, and a linear model for Cl^-, SO_4^{2-}, Na^+, NO_3^- and F^-. Also Xi *et al.* (2011) found that the optimal model for GWD was an exponential model in this region, whereas Peng *et al.* (2011) considered that the optimal

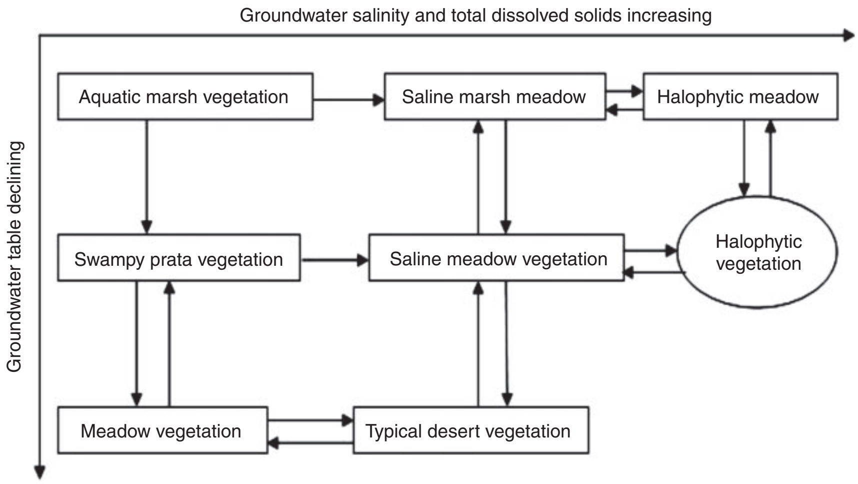

Fig. 6. The sketch map of vegetation succession (salinisation process) in Ejina Delta. The figure is adapted from Feng *et al.* (2009).

model was spherical, as the exponential model was confirmed in the present study. GWD, Mg^{2+}, TDS, EC, Ca^{2+}, HCO_3^-, NO_3^- and pH showed strong spatial autocorrelation (the variation ranges were 0.08°, 0.03°, 0.05°, 0.06°, 0.04°, 0.03°, 0.55° and 0.01°, respectively.), which suggests that random factors had a minor role in causing spatial heterogeneity and that variability was mainly caused by structural factors (topographic, geological, climatic factors). Xi *et al.* (2011) observed that GWD showed moderate spatial autocorrelation in this region. However, there were some differences apparent between their study and the present one. Thus, heterogeneity of GWD was affected by structural (i.e. topographic, geological and climatic factors) and random factors (e.g. exploitation of groundwater). Dai *et al.* (2010) also found that TDS had a strong spatial autocorrelation in a study conducted in a similar region. K^+ and SAL showed moderate spatial autocorrelation, which was caused by a combination of structural and random factors, including the impact of the spatial variation on a small scale and natural vegetation growth on groundwater attributes. SO_4^{2-} showed weak spatial autocorrelation, suggesting that the spatial variation was mainly caused by random factors. Any future analyses of patterns in SO_4^{2-} will require a more frequent sampling regime than was undertaken in the present study. The present results indicated that variability in groundwater depth and composition depends on the spatial scale of the analysis; in the meantime, hydrochemistry and groundwater depth are controlled by geochemical and physical processes that should be understood in the context of the environment that is being studied.

Habitat heterogeneity existed at different scales, which influenced the formation, distribution and physical and chemical properties of soil and changed the allocation and transfer of water and heat, and this, consequently, controlled the complex changes of species composition and distribution (Lundholm and Larson 2003). Soil moisture content and groundwater salinity both influenced vegetation growth and distribution, and both were closely related to GWD (Fan *et al.* 2004). Consequently, spatial heterogeneity of GWD was particularly important in these arid areas. In the Ejina Delta, the various landforms and geological structures, together with a complex hydrometeorology and land use, led to strong spatial variation of GWD at the meso-scale, and this resulted in differences in microhabitat and soil physical and chemical properties. This then further influenced the composition and distribution pattern of the plant community (Song *et al.* 2010). The results of the CCA ordination suggested that GWD exhibited the largest influence influence on vegetation distribution and succession among all environmental factors, followed by pH, SAL, TDS, EC and HCO_3^-. With increased GWD, the landscape type changed from swamp meadow to xerophytic shrub, and finally the zonal vegetation replaced of the non-zonal vegetation. Such results are consistent with those of Zhang *et al.* (2000), who found that vegetation distribution and succession laws were significantly affected by groundwater, especially groundwater depth and composition, and vegetation distribution and succession showed a close correlation with the groundwater (Zhang *et al.* 2000; Zhu *et al.* 2012). From the river basin to peripheral Gobi, the groundwater quality also changed accordingly, and the vegetation made the transition from desert riparian forests to sparse zonal vegetation (Zhang *et al.* 2000).

In arid areas, GWD, SAL and TDS were the main factors restricting plant community types, vegetation distribution patterns and successional processes (Zhang *et al.* 2005; Wang *et al.* 2007; Zhu *et al.* 2012). Because of higher groundwater spatial heterogeneity in this region, there were several kinds of vegetation types. In Ejina Delta, the non-zonal vegetation included species such as, for example, *P. australis*, *E. angustifolia*, *P. euphratica* and *T. ramosissima*, the growth and development of these species depending mainly on groundwater, and the zonal vegetation consisted of species such as *K. caspica*, *Calligonum* sp., *E. przewalskii* and *R. soongorica*, with atmospheric precipitation and condensation water supplying the necessary water for them (Zhang *et al.* 2000; Wang *et al.* 2002). Therefore, it was convenient to study vegetation successional processes, using spatial information (groundwater and vegetation) to extend time series, and we concluded that plant community first experienced a positive stage of aquatic successional series, from hygrophytic herb community to woody plant community, and then experienced a negative stage of xerophytic successional series, and successively experienced a period of herb degradation, shrub degradation and tree degradation. The stages of vegetation succession were different from Liu and Chen (2002) and Si *et al.* (2005), and we found a positive stage of aquatic successional series in drought process. There were two vegetation successional processes (drought and salinisation), and the salinisation process increased with the drought process. Halophytic or salty vegetation was a product of the dual role of drought and salinisation processes throughout, and was also widely distributed in the lower Heihe River Basin. The results of the present study on groundwater spatial heterogeneity and vegetation successional processes could provide the scientific basis for the future ecological threshold of each successional stage in this or similar region.

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