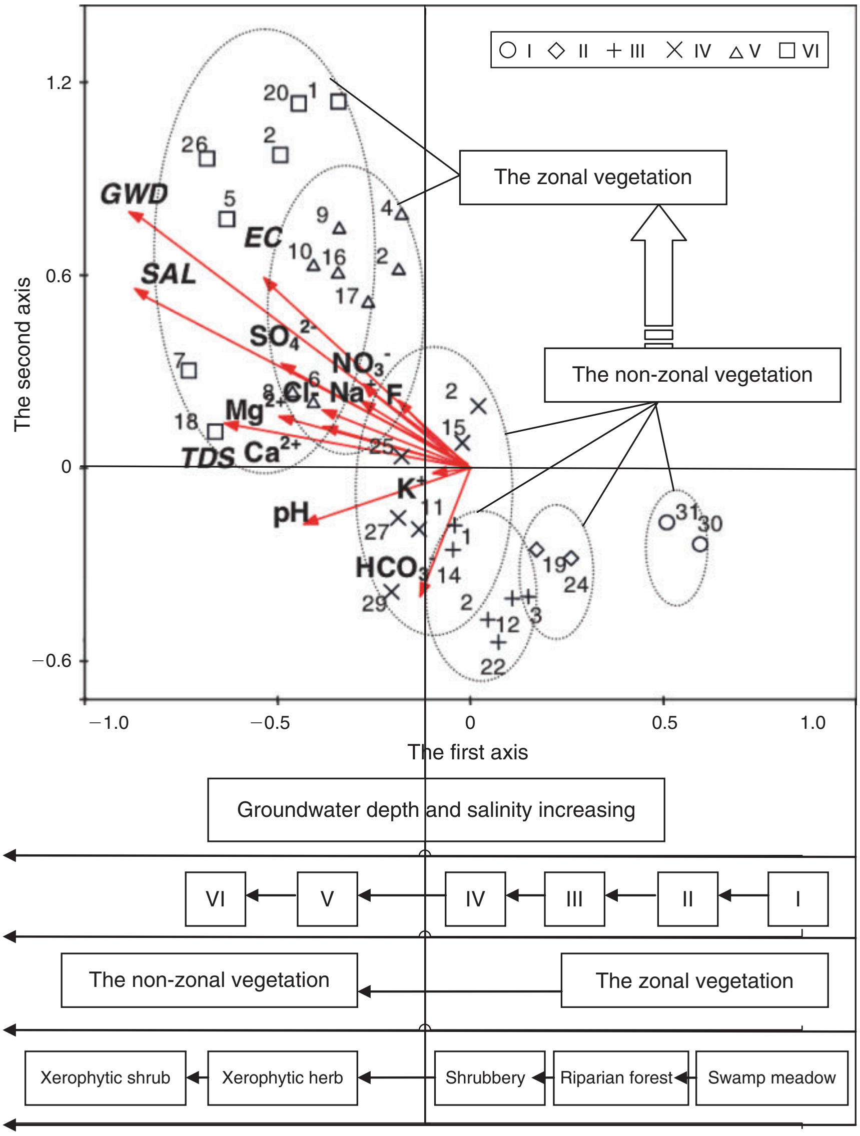

Fig. 4. Canonical correspondence analysis (CCA) ordination diagram and the sketch map of vegetation succession with groundwater depth and salinity increasing. IAss, *Phragmites australis* + herbs; IIAss, *Elaeagnus angustifolia–Tamarix ramosissima* + herbs; IIIAss, *Populus euphratica–Tamarix ramosissima* + 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

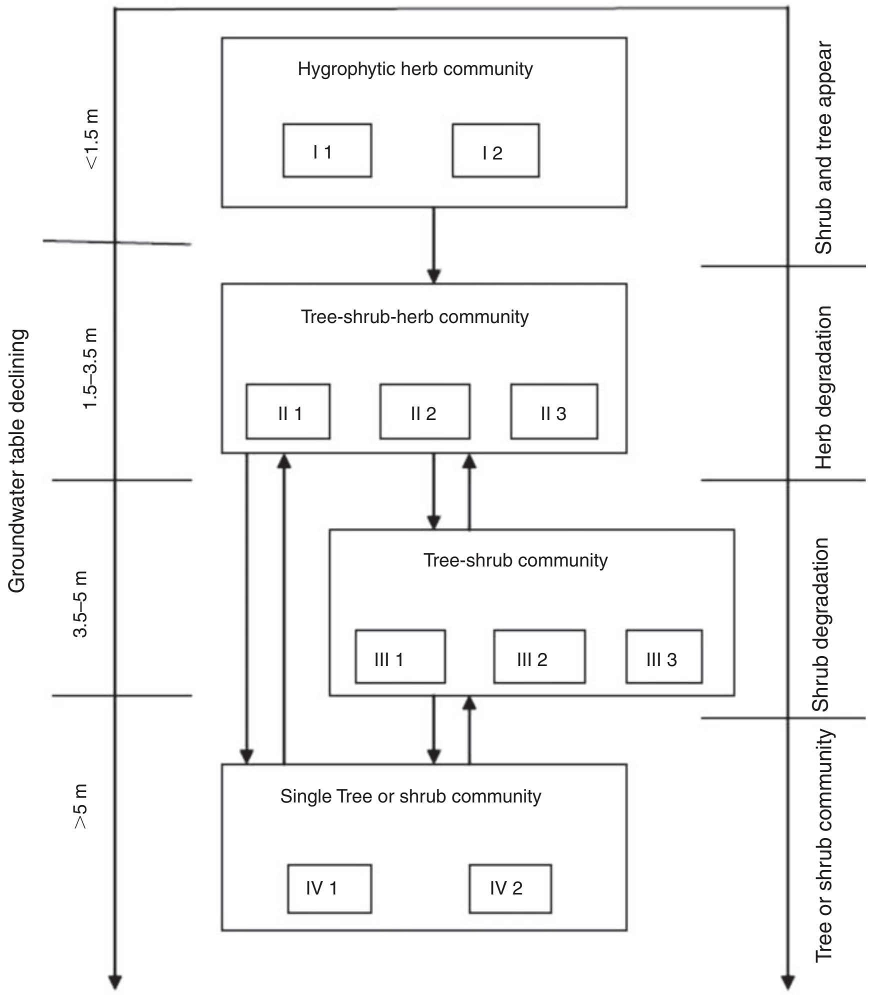

Fig. 5. The sketch map of vegetation succession (drought process) in Ejina Delta. The figure is adapted from Feng *et al.* (2009). I1, *Phragmites communis* + *Kalimeris indica* + *Leymus secalinus*; I2, *Achnatherum splendens* + *Calamagrostis epigeios* + *Elymus breviaristatus*; II1, *Populus euphratica* + *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

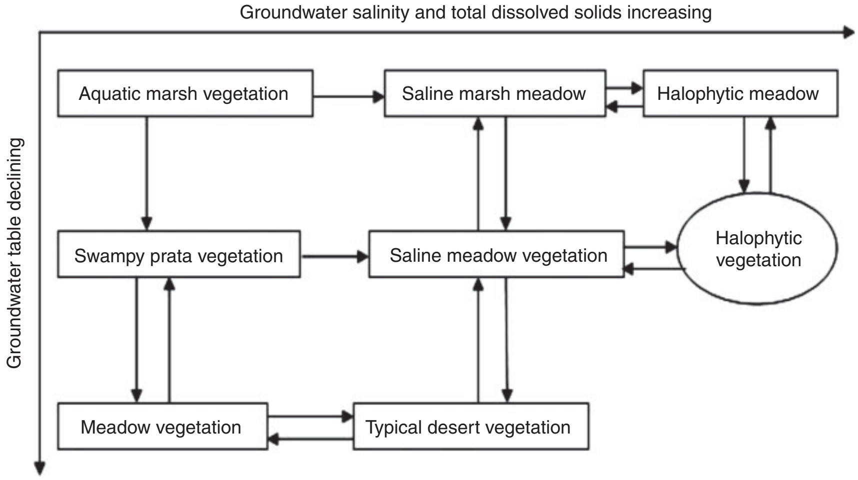

Fig. 6. The sketch map of vegetation succession (salinisation process) in Ejina Delta. The figure is adapted from Feng *et al.* (2009).

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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