IMPACT OF ANTHROPOGENIC LAND-USES ON SALINIZATION IN THE YELLOW RIVER DELTA, CHINA: USING A NEW RS-GIS STATISTICAL MODEL

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ABSTRACT:

Land salinization is threatened with secondary salinization recently because of unreasonable exploitation of natural resources and global change. However, previous assessments cannot obtain comprehensive and spatial explicit statistics and impede to develop ecologically sound policies for government. This study tries to confront these difficulties and identify key anthropogenic determinants, their extent and effectiveness (positive or negative) in the YRD. A SAR model was firstly applied to evaluate human impacts on salinity. Based on RS-GIS system, three sub-region models (LF, ST and LU) were created to normalize salinity heterogeneity. The predicted land salinity was served as the response variable in models. 12 explainable variables were elaborately selected as input into the models. The conventional OLSR model was compared simultaneously to validate performance of SAR model. SAR model fitted better than OLSR model because spatial autocorrelation in soil salinity was well dealt with. SAR modelling in sub-regions where environmental impacts were normalized had a high accuracy in determining the most influenced factors. Among established key determinants, oil exploitation, road construction and saline aquaculture were aggregative to salinization but only in originally highly saline sub-regions, such as LF_coastal zone and ST_soil III. Two agricultural activities, salt-tolerant crop plantation and fertilization, were ameliorative to salinization in most models. The most effective agricultural alleviation occurred in moderately saline sub-regions, such as LF_floodplain, ST_soil II and LU_wastland to farmland, which may benefit by the development of farm forests and farm ponds. The assessment with SAR sub-region model provides suggestions for policy makers and also has implications in other environmental assessments.

1. INTRODUCTION

The Yellow River Delta (YRD), one of China′s three major river deltas, is characterized by extensive coverage of saline soils. For recent decades, the YRD has undergone extensive development of agriculture and industry, which leads to secondary salinization and poses a threat to the food production and environment (Ye et al., 2004; Fang et al., 2005). As the Chinese Central Government has planned to restore land salinization in the YRD, assessment of anthropogenic determinants is urgently needed to develop ecologically sound policies.

Existing assessments of salinization determinants tend to bypass salinity heterogeneity in space and time due to complex interaction with environment and intensive human activities. Climate conditions, soil types, topographic and hydrologic factors determine the heterogeneity of background context where salinization occurs (Metternicht and Zinck, 2003; Cardona et al., 2004). Thus, it’s improper to assess human impacts on land salinization separately, which is highly combined with environmental complexity. A few studies concerned about the both anthropogenic and environmental factors such as climatic factors (Li et al., 2007), soil types (Bui et al., 1996; Hamed, 2008). However, these assessments may not perfectly compliant with standards in present restoration projects as they were not spatial statistical; e.g., the method used by Li et al. (2007) was land cover dynamic analysis, by Hamed (2008) was comparative analysis and by Bui et al. (1996) was GIS spatial association. Another important factor associated with the temporal heterogeneity of salinization is land-use history, which was neglected in previous studies. The human activities causing secondary salinization are mostly related to land-use change, such as overgrazing and unreasonable utilization of land and water resources (Li et al., 2007). Land cover change results in the conversion of the vegetation appearance and function (Tappeiner et al., 1998), which disturbs hydrology condition, i.e. the balance between salinity and water, and in turn alter the land salinity pattern (George et al., 1997). Land use history could be seemed as an artificial environmental factor and its impact on salinity needs to be considered. Last but not least, previous studies tend to focus on one type of anthropogenic impact on land salinity and did not comprehensively assess all potential determinants. For example, some studies concerned the impact of agricultural irrigation on salinization (Ohara, 1997; Kotb et al., 2000; de Paz et al., 2004; Schoups et al., 2005). These researches did explain the relationship between a single type of human activity and land salinity, but they may be somehow misevaluated or partial by excluding other influenced activities in the region of interest. On the other hand, human activities for various purposes bring about different salinization processes. For instance, poor land and water management in irrigated farmlands leads to secondary salinization worldwide (Metternicht and Zinck, 2003). Many approaches have then been taken to mitigate salinization such as large-scale planting of trees (Cacho et al., 2001), development of salt-tolerant crops (Omar, 2003), and appropriate water management (Misak et al., 1997). Hence, it is crucial to apply an integrated and spatial statistical model to salinization assessment, which can successfully integrate complex environment and analyze all potential anthropogenic determinants.

This study tries to disentangle the salinity heterogeneity caused

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by complex interactions with environment and human activities. As most land processes have the patterns of spatial autocorrelation, such as variations of soil nutrients (Knops et al., 1997; Li et al., 2008) and land-use change (Aguiar et al., 2007), spatial autoregression (SAR) was firstly import in salinization assessment. A GIS-based SAR model integrating related variables was performed in normalized environmental background. The conventional ordinary least square regression (OLSR) model was compared simultaneously to validate performance of SAR model. The objective was to identify key anthropogenic determinants, their extent and effectiveness (positive or negative) in the YRD, in a comprehensive and quantitative way, to provide guidelines for land use managements.

2. MATERIALS AND METHODS

2.1 Study area

The YRD is situated on the northeast coast of China (118°06′E–120°00′E, 37°15′N–38°10′N), with an area of 6622 km^2, containing 23 counties of Dongying City (Fig.1). This area is characterized by a typical continental climate. The annual average precipitation and evaporation are approximately 600 mm and 1944 mm, respectively. 70% of the total precipitation concentrated between July and August, leading to seasonal drought from October to May. Saline land covers more than 70% of the total area, where the salt content of the soil surface (0-15 cm) ranges from 0.4% to 1.5% (Shi and Zhang, 2003). Sea-water intrusion makes salt easily reach the land surface, leading to the aquifer proximate to subsurface (about 1-3 m depth) has high water salinity (5-30 g/L) (Shi and Zhang, 2003), especially in the lowland estuary of YRD. The natural vegetation in the study area is composed of halophytic plant communities predominated by grass and shrub species.

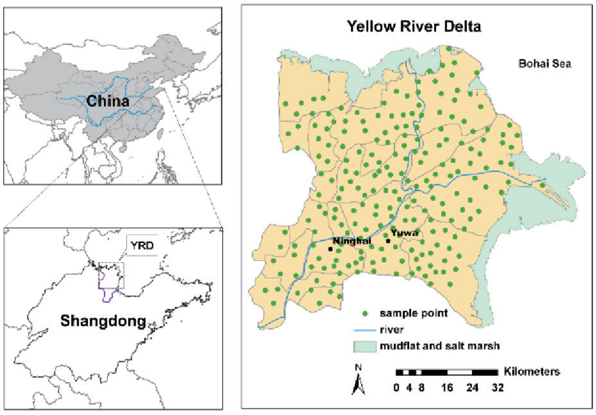


Fig. 1 The administration map of the Yellow River Delta (YRD) and the distribution of our fieldwork sampling

The YRD has been undergoing extensive and rapid development of industry and agriculture for recent decades. Shengli Oil-field, the second largest oil-field in China, has more than twenty thousand wells spread all over the YRD since the first well was excavated in 1964 (Gong et al., 2004). Large scale agricultural production has been developed simultaneously with the policy that the Chinese central government planned to develop comprehensive agriculture in the YRD (Zhou et al., 2007). Large part of grassland and wilderness has been cultivated with salt-tolerant crops and grass, such as cotton, maize, clover and date, and wide foreshore areas have been exploited as extensive shrimp ponds and salt pans (Zhou et al., 2007). Other human activities, such as the construction of irrigation system and road net work, are proceeding greatly along with the development of agriculture and industry (Zhou et al., 2007).

2.2 Field work and laboratory analysis

Total 219 ground points were selected from July 16th to August 8th 2008, by a systematic approach at the centers of 5 km^2 grids, each of which corresponds to one sample with 25 km^2 (Fig.1). Each point site was collected 3-6 repetitions of soil sample. The soil samples were taken to the laboratory for measuring saturated paste conductivity (ECe) by using 1/5 diluted extracts (the electrical conductivity (EC) of 1:5 soil-water extract) (Spies and Woodgate, 2005). According to Spies and Woodgate (2005), land salinity can be estimated from ECe value. The land salinity in this study refers to ECe value.

2.3 Model input data

Responsible variable (salinity): based on our salinity measurement, the distribution map of soil salinity (ECe) was created by using ordinary kriging (OK) interpolation technique. The predicted land salinity was served as the response variable in the model.

Explanatory variables (Table 1): 20 variables were considered 12 explainable variables (9 anthropogenic variables) were elaborately selected to avoid potential correlation among the explanatory factors.

2.4 Building sub-region models for normalization

Given that the impacts of environmental factors, land-use history on salinity are relative stable, sub-region partition based on these factors was applied to normalize their impacts on salinity and disentangle their complex interaction with anthropogenic factors. Three types of sub-region models were built up. The land form (LF) model classifies the region according to landform and elevation: terrace (> 6 m a.s.l.), coastal zone (< 2 m a.s.l.), and floodplain (2 – 6 m a.s.l.). The soil type (ST) model is classified as: Calcaric Fluvisols (soil I), Salic Fluvisols (soil II), and Gleyic Solonchaks (soil III). The land use (LU) model concerning land-use history: transition from wilderness to farmland (WF), permanent farming land (farmland to farmland, FF) and permanent wilderness land (wilderness to wilderness, WW). According to Fang et al. (2005), terrace, floodplain, soil I, and FF can be regarded as non-saline or slightly saline background, soil II and WF as moderately saline background, while coastal zone, soil III and WW as highly saline background. The output maps include sub-regions of soil and landform models (Fig. 2a) and sub-regions of land-use change model (Fig. 2b).

2.5 Spatial statistic models and measures of fit in models

The comparisons between OLSR model and SAR model were conducted to assess the relative importance of potential explanatory factors. In theory, the SAR model adds a term that incorporates the spatial autocorrelation structure of a given dataset in the standard OLSR model. The additional term is implemented with a ‘spatial weight matrix’, where the neighborhood weight of each location needs to be defined as Queen’s or Rook’s neighborhood (Anselin, 2001). SAR model

Table 1 The list of potential determining factors and a representative subset of selected variables

category		variable	description	selected variables	data source
natural environment		soil	reclassification of soil substrate effect	soil	*CAS*
		landf	reclassification of elevation effect	landf	STRM-90m
land use history		landu	reclassification of land cover effect (1992-2008)	landu	TM
industry and transportation		den_oilw	density of oil welll in the YRD	den_oilw	TM
		den_road	density of road in the YRD	den_road	TM
		den_chan	density of drainage channel in the YRD	den_chan	TM
agriculture	technology	fer_cons	fertilizers consumption per county	fer_cons	*DSB*
		diesel_cons	diesel consumption per county		*DSB*
		agri-power	overall agriculture power per county		*DSB*
	demography	agro_pop	population density of county labor in agriculture	agro_pop	*DSB*
		w_pop	population density of whole county labor		*DSB*
	economy	ru_income	rural per capita net income of resident in every county	ru_income	*DSB*
		agro-output ration	farming, fishing, forestry and grazing output ratio		*DSB*
	agrarian structure	a_irrig	percentage of irrigation area in every county		*DSB*
		a_grain	percentage of grain area in every county	a_grain	*DSB*
		a_cotton	percentage of cotton area in every county	a_cotton	*DSB*
		a_aquac	percentage of saline aquaculture area in every county	a_aquac	*DSB*
		a_pastu	percentage of pasture area in every county		*DSB*
		a_orch	percentage of orchard area in every county		*DSB*
		a_forest	percentage of forest area in every county		*DSB*

CAS: Chinese Academy of Sciences; TM: LANDSAT TM5; DSB: Dongying Statistic Burea

consists of the spatial lag and spatial error models. The SAR lagged model (SAR_{lag}) assumes that the autoregressive process occurs in the response variable ('inherent spatial autocorrelation'). Thus it adds a term (ρW) and takes the form:

$$Y = \rho WY + X\beta + \varepsilon \;, \varepsilon \sim N(0, \sigma^2)\,, \qquad (1)$$

where ρ is the autoregression coefficient, and the product WY expresses the spatial dependence.

The spatial error model (SAR_{err}) assumes that the autoregressive process is found in the error term. Thus, the spatial structure (λW) term is added and the SAR_{err} thus takes the form:

$$Y = X\beta + \lambda Wu + \varepsilon \;, \varepsilon \sim N(0, \sigma^2) \qquad (2)$$

where λ is the spatial autoregression coefficient.

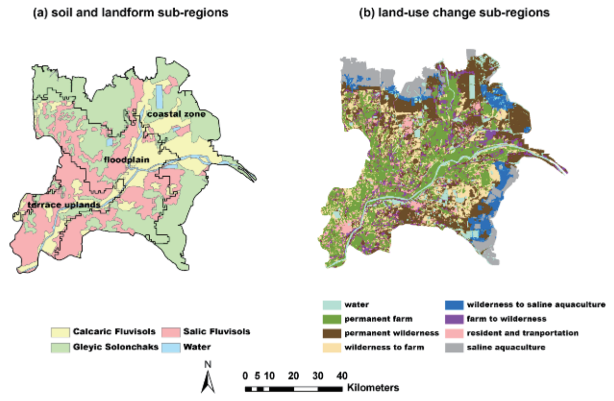


Fig. 2 sub-regions of (a) soil and landform model; and (b) land-use change model during 1992-2008

To compare the relative importance of determinants in each model, the standardized regression coefficients (β') and associated significance level (*p*-level) for each variable should be presented (Aguiar et al., 2007). In the presence of spatial autocorrelation, the traditional R^2 or R^2_{aj} based on the OLSR model, is not an appropriate measure of fitness for the SAR models. To avoid biased models and make the OLSR model and the SAR models comparable, Akaike Information Criterion (AIC) (Akaike, 1974) was applied. The lower AIC the measure, the better the model fit. The analysis process, including construction, selection and evaluation of SAR, were implemented by using a freeware Anselin's GeoDa package (GeoDa, 2003).

3. RESULTS AND DISCUSSION

3.1 The spatial validity of assessment

We tested the spatial autocorrelation of land salinity of all models, including the whole YRD and three sub-region models (ST, LF and LU models) [Table 2(a)]. The spatial coefficient (ρ or λ) of all SAR models, measuring the extent of spatial autocorrelation in the salinization process, are significantly high (>0.90). This indicates land salinity of the YRD has strong spatial autocorrelation, in agreement with previous study (Wang et al., 2007). Thus, OLSR model is not an appropriate application as the results may produce spatial-correlated residuals, biased estimation of error variance and t-test significance levels, or overestimation of regression coefficient (Kissling and Carl, 2008). Meanwhile, a comparison of measure of fit (MOF) between OLSR and SAR models shows that all SAR models fit better than OLSR models (lower AICs in SAR models) [Table 2(b)], verifying that SAR models fit better and well solve spatial autocorrelation (Jetz and Rahbek, 2002; Overmars et al., 2003; Meyfroidt and Lambin, 2008).

Model MOF comparisons also show that both OLSR and SAR than the whole region models [Table 2(b)]. The results support that it is of great necessity to normalize the combined impacts of non-anthropogenic factors. Among all tested models, the SAR sub-region model fits best. For instance, oil-well exploration, as well as saline aquaculture, severely aggravates salinization in only the coastal zone or soil III, incorporating with the distribution of oil-fields or saline-fishery. Agro-labor population is the main determinant in densely populated area (e.g., terrace, floodplain, soil I, and soil II). The grain and cotton plantation play important roles in all sub-region models, which attribute to rapid development of crop cultivation in the whole YRD (Zhou et al., 2007). Therefore, it can be concluded that the SAR sub-region models can obtain spatial explicit results. This corroborates with our earlier proposal on solving problems of salinity heterogeneity and spatial autocorrelation in salinization assessment.

3.2 Anthropogenic effects on salinization in the YRD

As SAR model performed better than OLSR model and sub-region model better than whole region model, SAR sub-region models were chosen to assess key anthropogenic determinants. Fig.3 shows the key determinants and their effectiveness across three SAR sub-region models among nine variables. The negative β' in regression model means the effect of salinization curbing and the positive β' means the effect of salinization aggravation. Saline aquaculture (a_auqac) and oil-well exploration (den_oilw) are the most important aggravators to salinization. Most agro-variables, such as cotton and grain plantation (a_cotton and a_grain), fertility consumption (fer_cons) and irrigated channel construction (den_chann) are alleviators to salinization in their respective models. It is noted that the absolute β' of a_cotton is often higher than that of a_grain in models, indicating that cotton plantation is more important than the grain plantation in ameliorating salinization. On the other hand, the key determinants (bold β' in Fig. 3) are different among sub-region models, indicating causes and impacts of secondary salinization have sub-regional differences. Saline aquaculture and oil-well exploration aggravate severe salinization in highly saline area, such as the coastal zone or the soil III. The key determinants in slightly or moderately saline areas (terrace, floodplain, soil I, soil II, FF and WF) are dominated by a_cotton, a_grain and fer_cons. Other obtained determinants, such as road and channel constructions (den_road and den_chann), limit in a few sub-regions and their influences are minor (low absolute β').

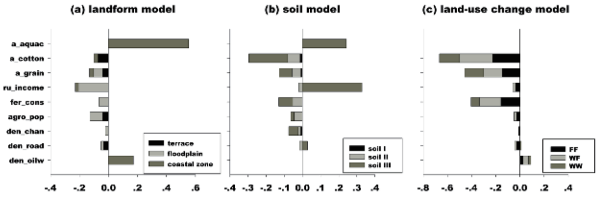
On the basis of integrated and spatial statistical assessment, the key anthropogenic determinants and their effectiveness can be identified. The effectiveness of key determinants is a double-edged sword to salinization process. On the one hand, salt-water balance is vulnerable to the aggravated anthropogenic activities. For example, the oil-field exploitation directly destructs vegetation cover and plant diversity (Yue et al., 2003), and once the vegetation gets sparse or bare land occurs, the level of saline groundwater rises as most rain water is not being used effectively and flow into groundwater table, then salt concentrates at the surface owing to evaporation and sub-region models have much larger value in AIC and fit better capillarity (Spies and Woodgate, 2005). Saline aquaculture is a pure process of salt accumulation, therefore the rapid land use transition from wilderness and marsh of foreshore to saline aquaculture reported by Zhou et al.(2007) will be seriously hazardous in the future. On the other hand, most agro-variables, including cotton and grain plantation, fertility consumption and irrigated channel construction, seem to be ameliorators for salinization in the YRD. The results are not consistent with the previous findings in irrigated area or in semi- / arid area (i.e., Rodriguez et al. (1993) in Spain, Lemly (1994) in the western United States, Ohara (1997) in central Asia, Cacho et al. (2001) in Australia, and Cardona et al. (2004) in Mexico). These areas have high water-tables and saline groundwater resources, but they are lack of fresh water and drainage, therefore, great demands for the agricultural water may produce drainage problem and lead to salinization (Schoups et al., 2005). However, the situation in the YRD is different; the region has been traversed by the Yellow River, the second longest river in China. Although the groundwater is highly saline, the irrigation network has been developed and the Yellow River can meet the irrigation demand. Moreover, the sediment in the Yellow River brought by the irrigation channels could improve the saline soil. Another reason for agricultural amelioration is that large scale cultivation of salt-tolerant crop cotton, which is more important than the ordinary grain, such as wheat and corn, in curbing salinization. The advantages and benefits of salt-tolerant crop cultivation in salt-impacted lands were also emphasized in previous paper (Omar, 2003). Besides, a large quantity of fertility consumption accompanied with large scale agricultural production can also reduce the deleterious effects of salinity by improving the crop productivity (Kant et al., 2007). Thus, the policy of developing salt-tolerant crop plantation should be continued to encourage as it is one of the most effective alleviation activities. With reasonable management, other alleviators related to large scale crop cultivation could be considered in salinization restoration, such as fertility consumption and channel construction.

The influenced extent of anthropogenic determinants can also be derived from such assessment, which provides spatially explicit guidelines for spotting the hazardous area. Saline aquaculture and oil-well exploration pose no serious threat to the YRD temporarily except the highly saline areas (the coastal zone or the soil III). These areas are characterized by newly formed marsh land where salt-water balance in is vulnerable to be broken (Yue et al., 2003). Therefore, we suggest that it should be carefully treated when implementing policies of large-scale oil-development and saline aquaculture in highly saline areas, although these activities can bring huge economic benefits. Agricultural activities largely alleviate salinization in slightly and moderately saline areas (terrace, floodplain, soil I, soil II, FF and WF). Compared to slightly saline areas, agricultural alleviation in moderately saline areas is more effective in salinization restoration. This effectiveness may benefit from some improving methods were adopted by farmers in the moderately saline areas. In terms of our field survey, the main improvements are developments of farm forestry (trees inter-planted in the farmland) and farm ponds (digging ponds

Table 2 The spatial autocorrelation (ρ or λ) and goodness test of SAR model in the whole YRD, three sub-region models. (a) the spatial coefficient; and (b) the AIC, compared with the linear models

YRD and sub-region model	YRD	landform			soil			land-use change		
		terrace	floodplain	coastal	soil I	soil II	soil III	FF	WF	WW
(a) spatial coeff.	0.98	0.92	0.99	0.95	0.95	0.98	0.97	0.97	0.95	0.98
(b) AIC OLSR	66 293	5434	35 297	38 009	12 114	21 602	28 917	25 206	16 564	29 460
AIC in SAR	36 792	2709	11 727	17 094	5195	7874	14 651	6028	7725	9372

and with dredged soil to stack farm uplands sideward). The dominate tree planted in farmland is Nitraria sibirica, which could effectively refrain soil from accumulation of salt in the surface soil, decrease salt content and increase soil nutrient (Zhang et al., 2004). Cacho et al. (2001) also reported strategic or large-scale planting of trees can control salinization. The farmland by stacked dredged soil makes the elevation raised, whose height saline groundwater is much harder to reach. Hence, it is understandable that the development of farm forestry and farm ponds is an effective improvement for mitigating salinization. Finally, the impacts of road and channel construction are minor or locally limited as their developments have not formed into dense networks yet. Administrators still need to have a close eye on such kind of development in the future.



	terrace	floodplain	coastal	soil I	soil II	soil III	FF	WF	WW
a_aquac	--	--	**0.55***	--	--	**0.24***	--	--	--
a_cotton	**-0.07***	-0.01	-0.03*	**-0.01***	**-0.07***	**-0.21***	**-0.23***	**-0.27***	**-0.17***
a_grain	**-0.04***	**-0.06***	-0.03*	**-0.01***	**-0.05***	-0.07*	**-0.15***	**-0.15***	**-0.16***
ru_income	-0.01	**-0.21***	-0.02*	-0.00	-0.02*	**0.33***	-0.04*	-0.02*	-0.07
fer_cons	-0.01	**-0.06***	-0.08	-0.01	**-0.05***	-0.08*	**-0.16***	**-0.18***	-0.07*
agro_pop	**-0.04***	**-0.09***	0.24	-0.01	**-0.05***	-0.02*	-0.03*	-0.02*	-0.03
den_chan	-0.01	-0.02*	-0.00	**-0.01***	-0.01*	-0.05*	-0.01*	-0.00	-0.01
den_road	**-0.03***	-0.02*	0.01	0.00	-0.02*	0.03*	-0.03*	-0.02*	0.01*
den_oilw	0.01	0.00	**0.17***	0.01	0.00	0.00	0.03*	0.06*	0.02*

Fig. 5 Comparisons of main salinization determinants across sub-regions in (a) landform model; (b) soil model; and (c) land-use change model
"*" means significant beta′ (β') coefficients, bold values are the significantly important. "-" represents the variables were filtered out.

4. CONCLUSION

Our research provides a comprehensive and quantitative assessment of intensive anthropogenic activities impacts on salinity in the YRD. The modelling process in assessment is not complicated and applicable. The key anthropogenic determinants, their extent and effectiveness can be well identified from the SAR sub-region model. This is attributed to SAR sub-region model as it captures the spatial dependency in the salinization process and normalizes the impacts of non-anthropogenic factors on land salinity. Several key anthropogenic determinants were established from such SAR sub-region models. The established relationships of anthropogenic impacts on land salinity confirm that activities of vegetation destruction and salt accumulation are aggregative to salinization, such as oil exploitation and saline aquaculture. However, the influenced areas of these activities are only distributed in highly saline areas, such as the LF_coastal zones or ST_soil III. Therefore, it is suggested that policies of large-scale oil-development and saline aquaculture should be carefully treated in highly saline areas, although these activities can bring huge economic benefits. On the other hand, the agricultural activities are proposed to be ameliorative to salinization and the most effective alleviation occurred in moderately saline sub-regions, such as LF_floodplain, ST_soil II and LU_wastland to farmland. Salt-tolerant crop plantation, fertilizer consumption, irrigated channel construction and the development of farm forests and farm ponds were analyzed as alleviators to land salinization. Policies referred to these activities were advised to continue implementing in salinization restoration. Ultimately, the SAR sub-region model is spatially explicit and helpful to spot the hazardous area, and thus the recommended policies are more likely to be accepted by the local governments and communities.

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