

Developing a Composite Risk Index for Secondary Soil Salinization Based on the PSR Sustainability Framework

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Abstract: Risk assessment of secondary soil salinization, which is caused in part by the way of people manage the land, is a challenge to agricultural sustainability. The objective of our study was to develop a soil salinity risk assessment model by selecting a consistent set of risk factors based on the conceptual Pressure-State-Response sustainability framework, incorporating the grey relational analysis and the Analytic Hierarchy Process methods. The development of the composite risk index for secondary soil salinization was presented through a case study in the Yinchuan Plain of China. Fourteen risk factors were selected in terms of three PSR criteria: pressure, state, and response. The results showed that the salinity risk in the Yinchuan Plain was strongly influenced by the subsoil and groundwater salinity, land use, and depth to groundwater. To maintain agricultural sustainability in the Yinchuan Plain, a suite of remedial and preventative actions were proposed to manage soil salinity in the regions that are affected by salinity at different levels and by different salinization processes. The weight sensitivity analysis results also showed that the overall salinity risk of the Yinchuan Plain would increase or decrease as the weights for pressure or response risk factors increased, signifying the importance of human activities on secondary soil salinization. Ideally, the proposed method will help us develop more consistent management tools for risk assessment, management, and control of secondary soil salinization.

Keywords: Secondary soil salinization; Salinity risk assessment; Agricultural sustainability; Pressure-State-Response framework; Grey relational analysis.

1 INTRODUCTION

Secondary soil salinization is a challenge to agricultural sustainability. Historic records have shown that salinization is to blame for the downfall of several ancient civilizations that relied on irrigation agriculture [Hillel, 2005]. In modern times, roughly half of all irrigated lands are adversely affected by salinity, especially in countries such as China, Egypt, Iran and Argentina [Ghassemi et al., 1995]. Salinization is also the second largest cause of loss of land from agricultural production. In the future, to meet the demand of an increasing world population, more lands will be converted to agricultural use. This conversion will be mainly achieved through irrigation agriculture, thus expanding the salinity risk. Impacts of salinity on environmental quality and human welfare also include deterioration of stream water quality, loss of biodiversity, increased flood risk, and increased infrastructure failure risk [Pannell and Ewing, 2006].

To promote the sustainable use of natural resources, the concept of a composite index of the quality of natural resources has been developed by many to facilitate communication among scientists, policymakers, and practitioners by providing a basis for evaluating the environmental impact of agricultural practices and also government programs and policies. One of the first composite indices for soil salinity risk assessment – the Salinity Risk Index – was developed by Eilers et al. [1997] in the context of evaluating soil quality and its impact on agricultural sustainability in the Canadian Prairies. However, the scientific basis for the risk factor selection process used in the previous soil salinity risk assessments can be significantly improved to better reflect the cause and effect relationship between the risk factors and salinity expressions [Niemeijer and de Groot, 2007] as well as the chain of causality between human activities and secondary soil salinization [Wiebe et al., 2007]. Conceptual frameworks can play an important role in the factor selection process and in developing a consistent risk factor set in the assessment of secondary salinization risk where a whole range of risk factors from biophysical to human activities needs to be considered. While many conceptual frameworks are used in sustainability development studies, the Pressure-State-Response (PSR) is one of the widely-used conceptual frameworks in the context of causal chain [OECD, 1993].

Therefore, the objective of this paper is to develop a composite risk index for secondary soil salinization based on a set of risk factors selected using the PSR conceptual framework. A calculative method incorporating the grey relational analysis (GRA) [Deng, 1982] and the Analytic Hierarchy Process (AHP) [Saaty, 1980] will also be proposed to quantitatively determine the cause and effect relationship between risk factors and salinity expression. The use of the PSR sustainability framework for salinity risk assessment will be demonstrated through a case study in an important irrigation district in northwest China. Ideally, the proposed method will help us develop more consistent management tools for risk assessment, management, and control of secondary soil salinization.

2 DEVELOPING A PSR-BASED SALINITY RISK INDEX

2.1 Cause and Effect Chain of Secondary Salinization under the PSR Framework

The PSR model divides the component factors in terms of pressure, state, and response, following the logic that “*pressure* on the environment from human and economic activities, lead to changes in the *state* (or environmental conditions) that prevail as a result of that pressure, and may provoke *responses* by society to change the pressure and state of the environment” [OECD, 1993]. Figure 1 illustrates a cause and effect chain of secondary soil salinization under the PSR sustainability framework. For any specific region, the risk factors to be included in the PSR framework are mainly dependent upon salt mobilization processes and data availability for that specific landscape. Therefore, there is no universal set of risk factors that should apply to all regions or countries [Huang et al., 2010]. In principle, the selected risk factors should be policy-relevant, understandable, easily available, and measurable [Niemeijer and de Groot, 2007]. The biggest advantage of selecting the risk factors of soil salinization under the PSR framework is to select a *set* of risk factors rather than *individual* factors so that the selected set of risk factors will reflect all aspects of the soil salinization process and avoid unnecessary redundancy. In this study, the biophysical factors are also included in the pressure category of the PSR model because pressure sources for secondary salinization are not only from human activities, but also from biophysical development of the landscape.

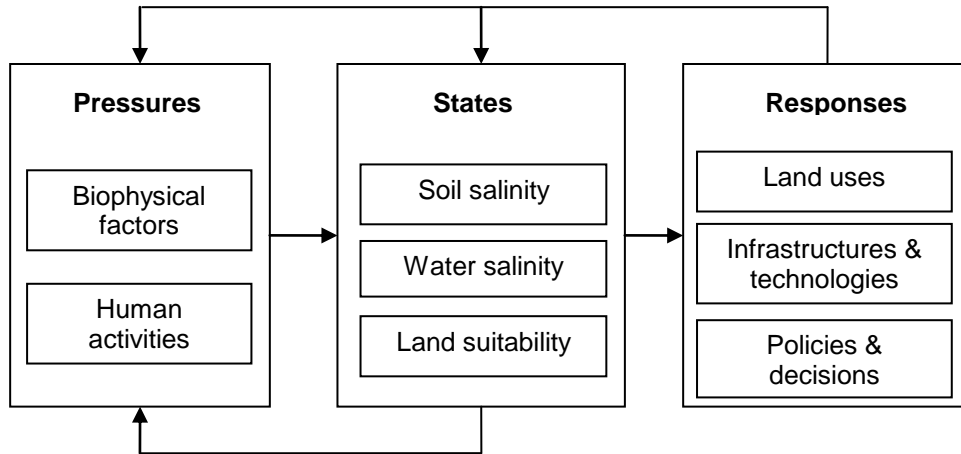


Figure 1. Schematic of the cause and effect chain of secondary salinization under the PSR framework.

2.2 Calculating Grey Relational Coefficients and Weights for Risk Factors

Once a set of risk factors are selected for a specific study area under the PSR framework, a composite risk index (CRI) for secondary salinization at assessment units (or grid cell) i can be calculated using a weighted linear model [Eilers et al., 1997]:

$$CRI_i = \sum_{j=1}^m r_{ij} \times w_j \quad (1)$$

where m is the total number of risk factors selected; w_j is the weight assigned to the j th risk factor; and r_{ij} is the so-called grey relational coefficient between two normalized comparing sequences x_{i0} and x_{ij} [Deng, 1982]. The grey relational coefficients reflect the degree of closeness between the two sequences. In the grey relational analysis of a grey theory model, x_{i0} is often called the reference (or parent) sequence and x_{ij} is referred to as the generated (or offspring) sequence. In the context of salinity risk assessment, x_{ij} is the normalized sequence of the j th risk factor that is thought to affect soil salinity; x_{i0} is the normalized sequence of soil salinity or a surrogate variable of soil salinity, the measurements of which across a large region are easier to obtain than those of soil salinity. In ecological risk assessment, x_{i0} is also referred to as the risk receptor.

Grey relational coefficient (r_{ij}) of a grey model is calculated as follows:

$$r_{ij} = r(x_{i0}, x_{ij}) = \frac{\min_i \min_j \{|x_{ij} - x_{i0}|\} + b \max_i \max_j \{|x_{ij} - x_{i0}|\}}{|x_{ij} - x_{i0}| + b \max_i \max_j \{|x_{ij} - x_{i0}|\}} \quad (2)$$

It is apparent that r_{ij} takes values between 0 and 1, with greater values indicating a stronger relationship between the two sequences. The parameter b is a distinguishing coefficient with a value range of (0, 1). Its purpose is to weaken the effect of the maximum absolute difference between the two sequences (i.e., $\max_i \max_j \{|x_{ij} - x_{i0}|\}$ in (2)) when the difference becomes too large. The b is assigned a value of 0.5 in many studies.

Weights (w_j 's) for the risk factors in (1) can be calculated by applying the AHP method based on the relative importance of the risk factors on secondary soil salinization as perceived by experts in the field. A typical AHP procedure uses a three-level hierarchy – goal, criteria, and alternatives. In this study, the “goal” is soil salinization risk; the “criteria” are the three PSR categories (i.e., pressure, state and response); and the “alternatives” are the selected risk factors [Wang et al., 2010].

As a result, a weight vector of normalized relative importance weights is developed with one weight for each risk factor.

3 A CASE STUDY IN NORTHWEST CHINA

3.1 Study Area and Data Availability

The Yinchuan Plain (6500 km²) is an artificial oasis in northwest China under the influence of continental climate (Figure 2). Annual precipitation ranges from 180 mm to 200 mm, with 75% of the total precipitation falling during the summer (June to September). Annual evapotranspiration ranges from 1000 mm to 1800 mm [Zhang et al., 2010].

Irrigation agriculture in the Yinchuan Plain has lasted for more than 2,000 years. Water from the Yellow River irrigates a vast stretch of farmland along its course traversing the plain. The Yinchuan Plain is one of the major agricultural areas in China. The major crops are rice, wheat and corn, and the cash crops are matrimony vine, rape, benne and soybean. The Yinchuan Plain has been undergoing extensive and rapid agricultural development in the recent decades, and soil salinization has become a threat to sustainable agriculture in the region. Since 2001, some remedial actions have been taken to improve soil conditions and parts of the plain have shown signs of improving. However, some areas are still suffering from severe soil salinization due to poor natural condition and unsustainable agricultural practices.

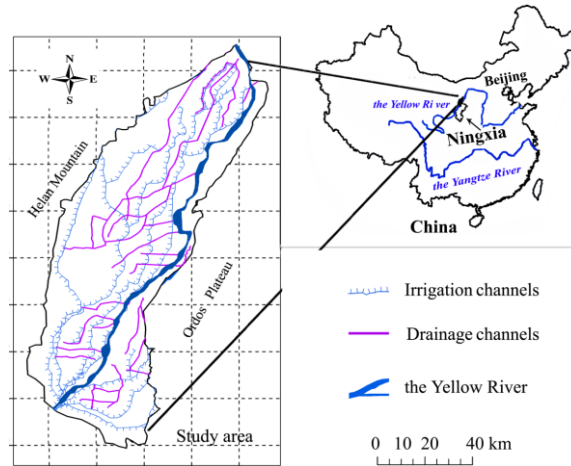


Figure 2. The Yinchuan Plain in northwest China.

The data sets that are available for the Yinchuan Plain's salinization risk assessment include the following: monthly averages of precipitation and evapotranspiration at seven weather stations, total soluble salt (TSS) of topsoil (0-60cm) and subsoil (60-100cm) measured at 101 sampling sites, TSS of groundwater measured at 253 monitoring wells, topographic maps and remote sensing images for the entire plain, and county-level data for cropping index, population density, organic fertilizer inputs, and the percentages of cultivation areas for paddy rice, wheat, and corn. The point and county-level data were interpolated using ordinary kriging to create raster maps for the corresponding risk factors. All raster data were further normalized and stored in an ArcGIS relational database.

3.2 Risk Factors and Weight Sensitivity Analysis

Based on data availability and their relevance to different categories of the PSR framework, a set of fourteen risk factors (x_1 - x_{14} in Table 1) were selected to develop a composite risk index for irrigation salinity in the Yinchuan Plain. In addition, total soluble salt in topsoil (x_0 in Table 1) was defined as the risk receptor. In the subsequent grey relational analysis, TSS in topsoil served as the reference sequence and the fourteen risk factors as the generated sequences to develop the grey relational coefficients (r 's) between the risk factors and the risk receptor. The raster maps of some risk factors are displayed in Figure 3.

Table 1. Risk factors for salinization risk analysis in the Yinchuan Plain.

PSR category	Risk factor	Symbol	Weight
Biophysical pressures	Evapotranspiration to precipitation ratio (-)	X_1	0.1162
	Relative elevation (m)	X_2	0.0499
Human-induced pressures	Depth to groundwater (m)	X_3	0.1300
	Cropping index (%)	X_4	0.0131
	Population density (# km ⁻²)	X_5	0.0114
States	Total soluble salts in subsoil (g kg ⁻¹)	X_6	0.1780
	Groundwater salinity (g L ⁻¹)	X_7	0.2296
Responses	Distance to irrigation channels (m)	X_8	0.0861
	Distance to drainage channels (m)	X_9	0.0614
	Organic fertilizer inputs (t km ⁻²)	X_{10}	0.0097
	Normalized difference vegetation index (-)	X_{11}	0.0395
	Percentage of paddy rice area per county (%)	X_{12}	0.0315
	Percentage of wheat area per county (%)	X_{13}	0.0243
	Percentage of corn area per county (%)	X_{14}	0.0194
Total soluble salts in topsoil (g kg ⁻¹)		X_0	—
Total weight			1.0000

The baseline weight scenario derived using AHP is denoted as W1 (the last column in Table 1). To explore the sensitivity of the risk factors in affecting salinization risk, the weights for the risk factors in the pressure or response categories were increased by 25%, while maintaining the total weights equal to 1. Under the W2 scenario, the sum of the weights for the pressure factors was increased by 25% and the sum of the weights for the response factors was decreased by 25%, while the weights for the state factors were kept unchanged. The magnitude of the weight change for each risk factor was proportional to its baseline weight [Wang et al., 2010]. The same principle was also applied to the W3 scenario where the sum of the weights for the response factors was increased by 25%.

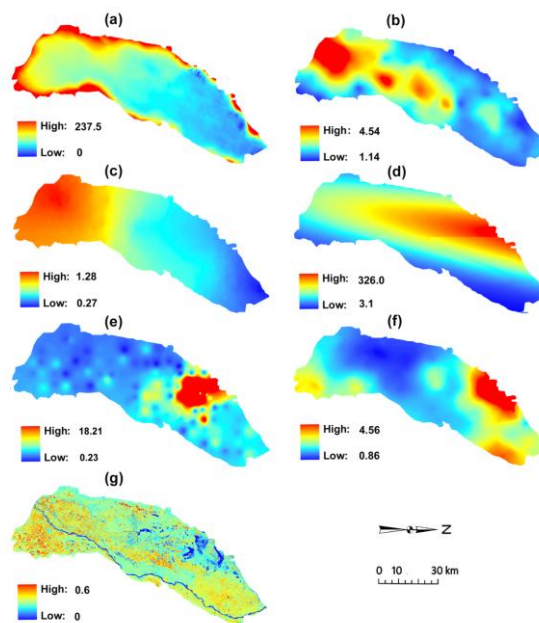


Figure 3. Raster maps of risk factors: (a) relative elevation (x_2 , m); (b) depth to groundwater (x_3 , m); (c) cropping index (x_4 , %); (d) population density (x_5 , # km⁻²); (e) total soluble salt in subsoil (x_6 , g kg⁻¹); (f) groundwater salinity (x_7 , g L⁻¹); (g) normalized difference vegetation index (x_{11} , -).

3.3 Spatial Distribution and Classification of Soil Salinity Risk

Figure 4(a) displays the spatial distribution of the CRI values calculated using the proposed PSR-based model for the Yinchuan Plain. The CRI values ranged from 0.26 to 0.42. To simplify the visualization of these CRI values, the continuous CRI values were classified into five classes (very low risk, low risk, moderate risk, high risk and very high risk) using the classification methods provided in ArcGIS 9.2. The spatial distribution of salinity risk classes under the baseline scenario (W1) is shown in Figure 4(b) and those under the W2 and W3 scenarios are shown in Figure 4(c) and 4(d), respectively. When looking at the spatial distributions, it is

evident that salinity risk in the Yinchuan Plain has regional characteristics. The salinity risk is generally higher in the regions far away from the Yellow River because the areas near the Yellow River were irrigated with water from the Yellow River that has low salinity and the areas far away from the Yellow River had to rely on the reused irrigation water that has high salinity content [Xiong et al., 1996]. Salinity risk is highest in the northwest region (Regions I and II), the region with the shallowest ground water table, lowest normalized difference vegetation index (NDVI) values, and highest population intensity, subsoil TSS, and groundwater salinity (referring to Figure 3).

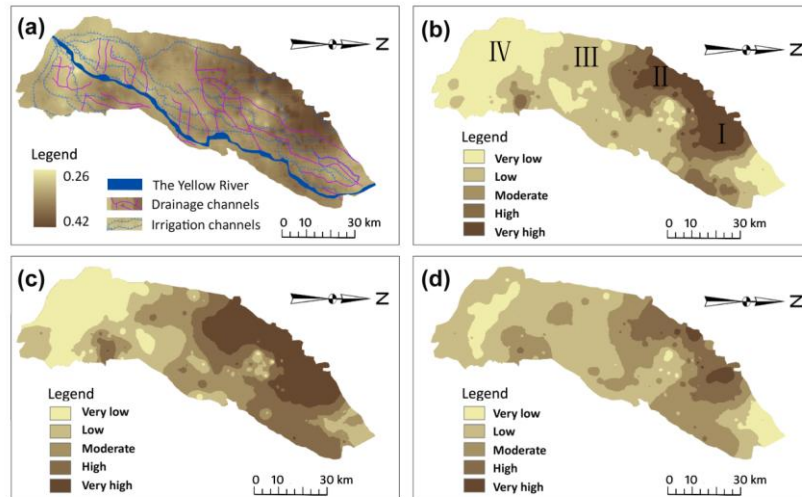


Figure 4. Spatial distribution in the Yinchuan Plain for (a) composite risk index (CRI), (b) CRI classes under the W1 scenario, (c) CRI classes under the W2 scenario, and (d) CRI classes under the W3 scenario.

3.4 Implications to Salinity Management

The results of the salinity risk assessment have profound implications for the regional salinity management in the Yinchuan Plain. The most important implication is that the local government and authorities may apply different salinity control measures for different regions that are affected by salinity at different levels and for different reasons. Specifically, our analysis demonstrated that the “high” and “very high” salinity risk regions in the western plain (Region II) had fewer irrigation and drainage channels. To further expand the existing irrigation and drainage network into this region may be the most effective measure to lower the salinity risk and to reclaim the lands in this region. For the “very high” risk region in the northwest plain (Region I), a careful comparison of Figure 3(a, b, e, f) and Figure 4(b) indicated that its high salinity risk might be caused by a combination of flat and low terrain, shallow groundwater depth, high subsoil TSS, and high groundwater salinity. In addition, the region has the highest population density (Figure 3(d)) and the lowest NDVI values (Figure 3(g)). This suggests that it may be very difficult and not economically feasible to reclaim the lands in this region. The best approach may be to live with the problem and plant salt-tolerant perennials [Pannell and Ewing, 2006].

Salinity accumulation in the Yinchuan Plain typically takes place after the fall harvest when soils are bare and exposed to high rates of evaporation due to windy and arid environmental conditions. Therefore, agroforestry – planting trees and shrubs in farmlands – may be a suitable salinity control practice for the regions with the “moderate” to “high” salinity risk (Region III). Matrimony vine, a salt-tolerant shrub species, is an important cash plant for the farmers in the Yinchuan Plain, due to its uses in Chinese nutritional diets. Intercropping matrimony vine with major crops should be helpful in reducing evaporation from the soil surface after fall harvesting and may prevent the salinity situation in this region from worsening.

For the “very low” risk region in the southern plain (Region IV), further expansion of irrigation and drainage channels may even increase salinity risk due to channel bank seepage. When the weights for the response factors were increased, the risk level for this region actually increased from “very low” to “low” risk. Figure 3(c) and Figure 4(a) indicate that this region has higher cropping index and lower salinity risk. The most effective approach to preventing salinity from worsening in this region may be to reduce the use of irrigation water in order to decrease deep percolation and maintain groundwater table depth, for example, through converting paddy rice cultivation to paddy rice and dryland crops rotation.

4. DISCUSSION

The methodology proposed in this study integrates the PSR framework, the GRA, and the AHP for the risk assessment of secondary salinization. The use of the PSR framework in the proposed risk assessment model not only provides a protocol to select a set of risk factors for salinity risk assessment, but also allows one to describe secondary salinization as a problem of agricultural sustainability [Eilers et al., 1997]. A whole range of factors needs to be considered in the process of assessing secondary salinization risk. The PSR framework provides a systematic way to select a *set* of risk factors across the entire spectrum rather than a few *individual* risk factors that only represent a portion of the salinization process [Grundy et al., 2007]. In addition, Describing soil salinity as a problem of sustainability enables us to shift our focus of risk assessment from the direct measurements of salinity to its broad impact on agricultural productivity, biodiversity, infrastructure, and other ecosystem services when the data for these environmental qualities (or ecological risk receptors) become available.

The proposed model is also unique in that it combines the uses of the GRA of the grey systems theory and the AHP to derive a calculative method for developing a composite index for salinity risk. The GRA is used to empirically (i.e., data-driven) calculate the grey relational coefficients between individual risk factors and soil salinity based on spatially explicit observations. Although the causality between the selected risk factors and soil salinity is sometimes obvious, the quantitative estimate of such a cause and effect relationship is confounded by the effects from other factors. Therefore, the data-driven grey relational coefficients provide a realistic representation of the relationship between the risk factors and soil salinity. On the other hand, the relative importance of risk factors perceived by experts in affecting soil salinity is subsequently estimated using AHP. The lack of transparency of the data-based GRA is compensated by the knowledge-based AHP, which provides an elegant way of taking into account expert knowledge and experience about the local salinity problem. Therefore, our proposed method strikes a balance between the data-based approach and the knowledge-based approach.

The main limitation associated with the use of the PSR framework for risk index development is the availability and compatibility of suitable data [Wang et al., 2010]. The PSR framework requires at least one risk factor from each of the three categories – pressure, state, and response. While the data for pressure risk factors are normally easy to access, it is not always easy to obtain equivalently high quality data for the state and response risk factors. Another limitation is that the grouping of risk factors in terms of pressure, state, and response is subject to the user’s own understanding of the problem. For example, NDVI can be considered as a state risk factor if it is perceived to reflect the severity of salinity or as a response factor if it is considered to reflect the farmers’ response to the severity of salinity.

5. CONCLUSIONS

A PSR-based model was proposed to develop a composite risk index for secondary salinization. The proposed methodology treated the secondary soil salinization as

an agricultural sustainability problem and integrated the uses of the conceptual PSR framework, the data-driven GRA, and the knowledge-based AHP method. The proposed method was demonstrated through developing the salinity risk index maps for the Yinchuan Plain, China. The results showed that the current soil salinization in the Yinchuan Plain is generally at low risk, with approximately 65% of the plain classified as “low” or “very low”. The salinity risk in the plain was strongly influenced by the subsoil and groundwater salinity, land use, and depth to groundwater. To maintain agricultural sustainability in the Yinchuan Plain, a suite of remedial and preventative actions were proposed for managing soil salinity in the regions that are affected by salinity at different levels and for different reasons. The weight sensitivity analysis results also showed that the overall salinity risk of the Yinchuan Plain would increase or decrease as the weights for pressure or response risk factors increased.

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