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ORIGINAL ARTICLE

Hydro-salinity balance and mobilization in oasis irrigation areas at two different scales

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Abstract Decades of intensive irrigation of farmlands in the oasis irrigated areas of Xinjiang, Northwest China has caused secondary salinization of vast areas of land since the mid-1980s. Based on the systematic analysis of the monitoring data of hydrology, soil, irrigation and salinity at two different scales in the case of Weigan River Plain Oasis in Xinjiang Province, algorithms derived from hydrosalinity balance principle were developed to estimate the salt mobilization and characteristics; salt and water mobilization and distribution were closely examined both in catchment scale and in field scale. The critical ratio of drainage to irrigation of Weigan River Plain Oasis was estimated to be 9.19%. Furthermore, analysis of the relationship between the two different scaling issues was illustrated. Finally, corresponding countermeasures for secondary soil salinization were proposed according to the different developmental stages and salinization status of water and soil resources.The findings of this paper is helpful in controlling the local hydrology, in limiting or diminishing salinization trends, as well as in providing academic and instructive meaning for the sustainable development of agriculture in oasis irrigation areas.

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Introduction

Water utilization in the past 30 years has resulted in some negative effects in oasis irrigation areas of Xinjiang Province, Northwest China. First, the natural hydrological process has temporal and spatial variation. However, most of the river water is being carried into artificial oasis, and the water flowing to lower reaches has greatly decreased. Secondly, natural vegetation has degraded while desertification area has increased. The ecological environment is getting worse because of the improper utilization of water resources. The overemphasis on inland river development and on using water to develop oasis has led to soil salinization and desertification. In arid regions with intensive irrigation agriculture, oasis irrigation areas have proved to be very vulnerable to soil salinization. Salinization of large areas of farmland constitutes to major ecological and environmental problems and threatens the continued development and sustained operation of irrigation agriculture in this area (Tang et al. 2007). In attempting to solve these problems, numerous salinity-related studies were done in the past 30 years, leading to considerable advancement in the knowledge of soil salinity. The main focuses of these studies were on the following two aspects:

(a) Qualitative analyses of the causes of salinization and its direct and associated impacts on soil–water–vegetation system and on the society. The main reasons for secondary salinization are irrational irrigation, imperfect diversion, and discharge of water works (Cui et al. 2005). The groundwater level is raised during the diversion and irrigation processes and exceeds the critical depth of evaporation. Because of the constant evaporation of groundwater, salt in groundwater is largely accumulated at the surface (Xu et al. 2005). Destruction of forests and grassland for cultivation and the diminishing of vegetation has caused the dramatic change in evapotranspiration. Economic damage due to secondary salinization is serious (Lin and Tang 1992).

(b) Simulation of water and salt quantity and mobilization either in field scale or in catchment scale. The phenomenon of salt transport through the vadose zone is affected by the temporal variation in irrigation water quality, the spatial variability of plant water uptake, and the chemical and physical properties of the soil. Examples of water and salt transport models include: UNSATCHEM (Suarez and Šimůnek 1997), HYDRUS (Simunek and Suarez 1997) LASCAM (Sivapalan et al. 1996; Viney and Sivapalan 2001) and DRAINMOD (Skaggs et al. 1995), SWAP (Van Dam et al. 2008). The simulation of soil water flow and salt transport processes requires the consideration of water and salt transport under variable soil moisture content conditions (Gibbison and Randall 2006). For example, (Moharana and Kar 2002) carried out a GIS-based simulation in a catchment in the Thar Desert. Pala (2003) used the conceptual analysis and synthesis of hydrographs (CASH) model to analyze rainfall and runoff data from the Kocadere rural catchment, Turkey. Xia et al. (2003) developed a coupled hydrology–ecology model to simulate and predict the change in water resources and environment in the Bosten Lake Basin.

Advances in soil science during the past several decades have significantly increased our understanding of many physical and chemical processes on soil, especially in the laboratory scale but, unfortunately, not always equally in the field scale. Suitable catchment-scale inventories of soil salinity do not exist, nor do practical techniques to monitor salinity or to assess the impacts of management changes upon soil salinity and salt loading in a regional scale. It is widely recognized that laboratory results generally do not reflect field experiments because of two major problems: (a) laboratory results are free from simultaneous, transient, and nonlinear effects of all major environmental factors operating under natural field conditions; and (b) soil cores in laboratory experiments are usually repacked, and hence do not represent undisturbed field conditions (Shainberg and Letey 1984).

In this study, algorithms derived from hydro-salinity balance principle are presented for estimating the water and salt mobilization both in catchment scale and field scale. The proposed hydro-salinity balance algorithm provides an attractive alternative to the more complicated methods based on the numerical solution equations in two different scales. The main objectives of this paper are: (1) to present algorithms derived from hydro-salinity balance principle for estimating salt mobilization and characteristics in two different scales, (2) to investigate the water and salt mobilization and dynamic change in typical oasis irrigation areas at two different scales and to illustrate the scaling issues, (3) to determine countermeasures and optimum management strategy in salt and water management to reduce the risk of soil salinization in oasis irrigation areas in Xinjiang Province, Northwest China.

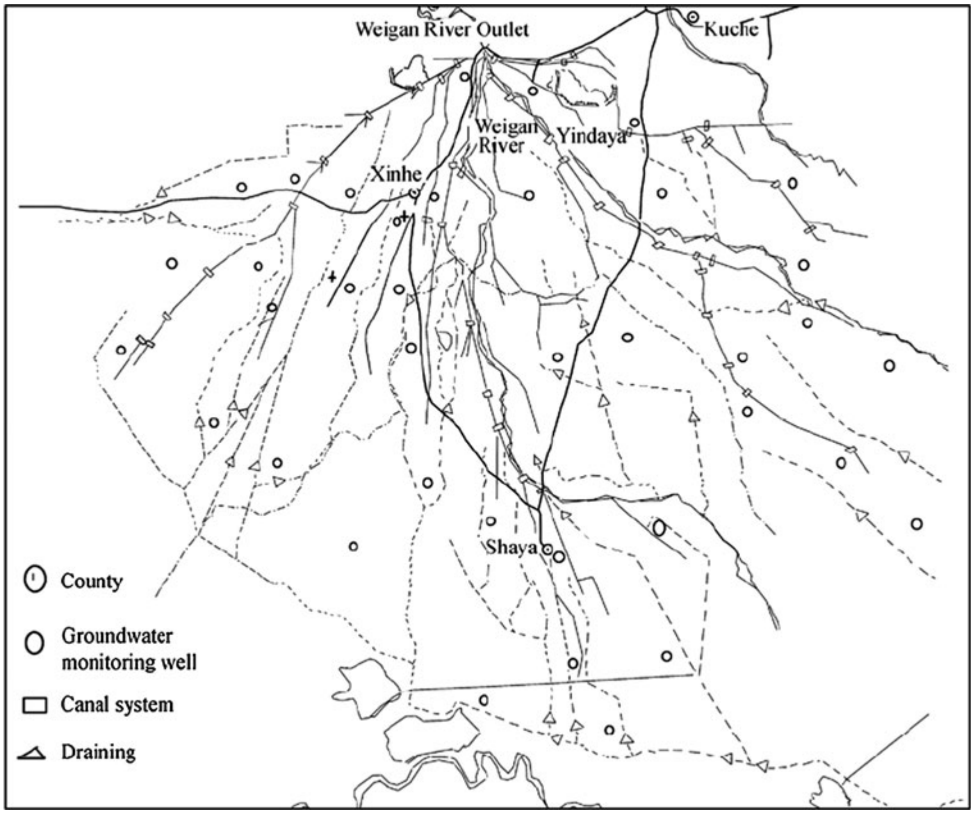
Materials and methods

Study area

The Weigan River Plain Oasis is located in the southern part of Tianshan Mountains and the northern part of Tarim River Basin (Fig. 1) with geographic coordinates of 41°06′–41.38′N, 81°26′–83°17′E (Hu et al. 2007). The river plain is a typical and complete alluvial–proluvial fan plain that covers the three counties of Kuche, Shaya, and Xinhe in Aksu region. The Weigan River is of a radial distribution after outflow from Tianshan Mountains. The fan-shaped oasis is 64 km from east to west and 160 km from north to south with low topography in the south and high topography in the north. It has a mean altitude of 920–1,100 m and an area of 8 346.5 km^2. The xeric climate is temperate continental with hot and dry summers. It has a mean annual precipitation of 51.6 mm, an evaporation of 199.20–2 863.4 mm (measured by Φ 20 cm evaporation pan), a mean annual temperature of 10.7°C, sunshine of 2 888.7 h, and a frost-free season of 209 days. The main soil texture is light loam and sandy loam, and the soil pH value is from 7.9 to 8.0, the salt content of some plough layers is between 0.3 and 0.6%. Salt content of some areas ranges from 0.6 to 1%, and the salt content of some wasteland is about 2%. Chloride and sulfate are the main components, and non-salinized soil, which is mainly distributed in upstream of the irrigation areas, watercourse and large-scale irrigation canal or the land with perfect irrigation and drainage systems accounts for 50% of the total irrigation areas. The area with high salinity soil is 26% and is mainly distributed in nonagricultural areas and wastelands.

The oasis economy has caused agriculture to depend on irrigation. The characteristic of the water resource utilization in the Weigan River Plain Oasis is its single water resource structure. The Weigan River is its exclusive source of irrigation water. The average annual runoff is

Fig. 1 Sketch map of study area



2.21×10^9 m^3, and the variation coefficient is 0.119. The coefficient of water resource utilization is high, but the utilization efficiency is low. Irrigation and drainage are in chaos so that the soil salinization is serious in this catchment (Hu et al. 2007). The oasis water is consumed for various purposes, and ecological water consumption plays an important part.

Data resource

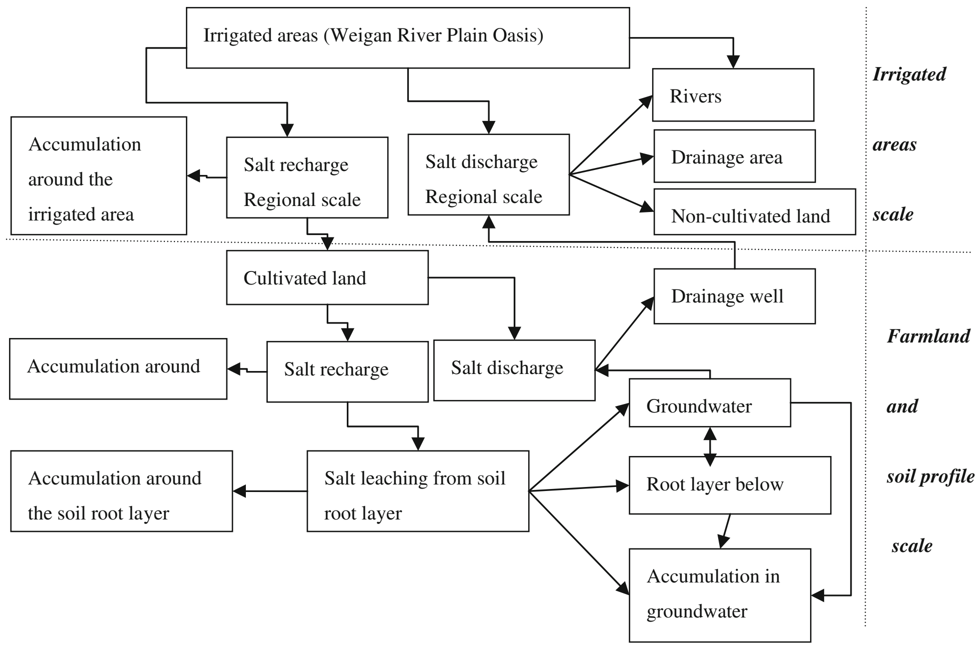
Water resource and salt content data in Weigan River Plain Oasis, as far back as the 1990s, can be found in annual Chinese hydrological yearbooks and statistics yearbooks compiled for Xinjiang Province. The original records from each gauging station in this catchment included geo-referenced coordinates (latitude and longitude), catchment area, mean monthly surface-water flow, precipitation, river flow rates, river level, lake volumes, storage capacity of reservoirs, plus agricultural and industrial water requirements. Groundwater information was from the hydrological geology survey conducted in this area. A basin-wide soil salinity survey was conducted on different farmlands. One experimental field (5 cultivated farmland sites and 5 uncultivated farmland sites) is located in a 500 ha national agricultural farm in Weigan River oasis irrigation areas in Xinjiang. Soil salinity and basic soil physics property measurements were made for different layers (0–10, 10–20, 20–30, 30–50, 50–70, 70–100 cm) of the soil profile. Ground-water depth was automatically monitored at five groundwater monitoring wells in this irrigation areas since 1990.

Hydro-salinity balance schematic diagram at two different scales

Scaling and its impacts are directly related to heterogeneities which can be traced to two major sources. The principal sources of heterogeneities are differences in climate, topography, soil, and geology which govern water and salt transport. The other source is the discontinuities or boundaries separating soil types, geologic formations, or land covers. This leads to defining a scale as a size of a cell or sub-catchment within which the water and salt transport process can be treated as homogeneous. There are two aspects for the scaling issues for hydro-salinity balance in oasis irrigation areas (Fig. 2). The first one is in irrigation areas scale. The other one deals with field scale.

The first one is at catchment scale. The accumulated salt in the catchment increases as the amount of irrigation water goes up. Some of the salt is drained out of the irrigation catchment with the drainage water. However, most of the salt would stay in the catchment in different ways, such as flowing into uncultivated farmland, leaching into the soil plant layer and permeating into groundwater. The accumulated salt in irrigation areas is called dry drainage.

Fig. 2 Schematic diagram for salt drainage and hydro-salinity balance in different scales



The next aspect deals with field scale. The irrigation water for farmland is from rivers and channels. When salt flows into farmland with the irrigation water, some of the salt remained in the water would be transported to the soil layer and groundwater, and the salt accumulates in the tilled layer and groundwater. Therefore, the most important thing for hydro-salinity regulations is in reducing the salt content in the plant layer and groundwater to the maximum limit.

The salt balance equation at catchment scale can be expressed as:

$$\Delta S = S_\mathrm{i} - S_\mathrm{o} \quad (1)$$

and

$$S_\mathrm{i} = V_\mathrm{i} C_\mathrm{i} \quad (2)$$

$$S_\mathrm{o} = S_\mathrm{d} + S_\mathrm{p} = V_\mathrm{d} C_\mathrm{d} + A_\mathrm{c} S_\mathrm{c} + A_\mathrm{n} S_\mathrm{n} \quad (3)$$

where, ΔS is the change of salt content; S_i, S_o, V_i are the total recharge salt content (10^4 t), the total discharge salt content (10^4 t), and the total irrigation water amount (10^8 m^3) respectively; C_i is the average salt concentration for irrigation water (g L^{-1}); V_d, C_d and S_d are the total discharge water amount (10^8 m^3), the average salt concentration for discharge water (g L^{-1}) and the total salt amount in discharge water (10^4 t); A_c, A_n are the area for cultivated land and non-cultivated land in the irrigation area (hm^2); S_p is the total salt amount absorbed by plant (10^4 t); S_c and S_n are the salt amount absorbed by cultivated land and non-cultivated land in united area (10^4 t). It can be clearly seen that during salinity increase stage (salification), the change of salinity in irrigation scale is bigger than zero. It stays stable and keeps at stable stage if there is zero change. Moreover, it is at salinity decrease stage (desalinization) when the change of salinity in irrigation scale is smaller than zero. ΔS can be used as an indicator not only for soil salinization, but also as a necessary standard for discharge and irrigation in oasis irrigation systems.

The field scale salt mobilization in farmland is described by a simplified Soil Water and Salt Transport Model (SWSTM) The SWSTM model is one-dimensional model developed for the use at the field scale. In the model, the soil profile is divided into homogeneous layers characterized by their physical properties. The SWSTM model describes unsaturated water flow in vadose zone using the one-dimensional Richards' equation. The governing equation of one-dimensional convective–dispersive transport under transient water flow conditions in partially saturated porous medium is taken as

$$\frac{\partial(\rho s)}{\partial t} + \frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial Z} - qc\right) - \Psi \quad (4)$$

where ρ is soil bulk density (g cm^{-3}), ψ is sink or source for salt (g cm^{-3} T^{-1}), q is the volumetric flux density given by Darcy's law (cm^3 cm^{-2} day^{-1}), c is the solute concentration associated with the solid phase of the soil (g cm^{-3}), and D is the effective dispersion coefficient (cm^2 day^{-1}). A more detailed description of the SWSTM water balance model and its underlying conceptualisations and parameters can be found in Xu et al. (2008) and Xu et al. (2005).

Current approaches to the estimation of catchment scale water and salt mobilization require a dense network of water and salt probes located throughout the catchment to provide a large number of samples. The most efficient way of reducing this burden is to find a way to predict large-scale salt averages from only a few sensors located at 'representative' fields. This fact enables them to be used at the catchment scale assuming that the catchment consists of different fields that do not interact. This investigation shows that one-dimensional model SWSTM may be used at the catchment scale after adaptation. To adjust the SWSTM models to the catchment scale, some procedures have been proposed. The influence of relief and river network has been taken into account. The differences between the small homogeneous fields and the heterogeneous catchments are quite significant. The soil profile with a thin zone of aeration will be saturated very quickly and will start producing surface runoff. Conversely, the soil profile with a thick zone of aeration needs much more water for saturation and very rarely produces surface runoff. The discharge at the catchment outlet depends on the performance of the river system. For large catchments, more time is needed for water to reach the outlet. This leads to differences in the time lag between water flow to the outlet of a small field and flow to the outlet of the entire catchment. Moreover, the river system usually acts as a chain of reservoirs that modulate variations in water flow and quality. In this study, this approach is tested for the couple of the one-dimensional model SWSTM, which are used very often to simulate water and salt mobilization. This couple of models takes less computer time for calculations but does not simulate water and salt exchange between micropores and macropores.

Results and discussion

Salt mobilization and accumulation characteristics at catchment scale

The total salt loading (Table 1) and critical ratio of drainage to irrigation (Fig. 3) were computed by a number of monitoring locations in the Weigan River Plain Oasis from 1993 to 2001. It is helpful in evaluating the stability of drainage system based on the statistical analysis of the elements of salt balance. The statistical results are

Table 1 Salt balance calculation in Weigan River Plain Oasis

Year	V_i (10^8 m^3)	C_i (g L^{-1})	S_i (10^4 t)	V_d (10^8 m^3)	C_d (g L^{-1})	S_d (10^4 t)	ΔS (10^4 t)	V_d/V_i (%)
1993	19.92	0.39	77.75	1.65	3.91	64.55	11.98	8.28
1994	24.80	0.37	91.86	2.60	4.10	106.56	−15.92	10.48
1995	23.79	0.37	87.83	3.12	4.79	149.40	−62.79	13.11
1996	25.66	0.39	98.85	3.56	5.22	185.91	−88.28	13.87
1997	27.82	0.43	119.61	3.81	3.94	150.07	−30.46	13.70
1998	26.63	0.34	90.28	4.30	4.84	208.53	−118.25	16.15
1999	25.15	0.40	101.77	4.89	4.91	204.18	−138.41	19.44
2000	22.38	0.40	89.49	3.31	5.45	180.43	−90.94	14.79
2001	25.07	0.41	102.62	3.46	6.00	207.50	−104.88	13.80

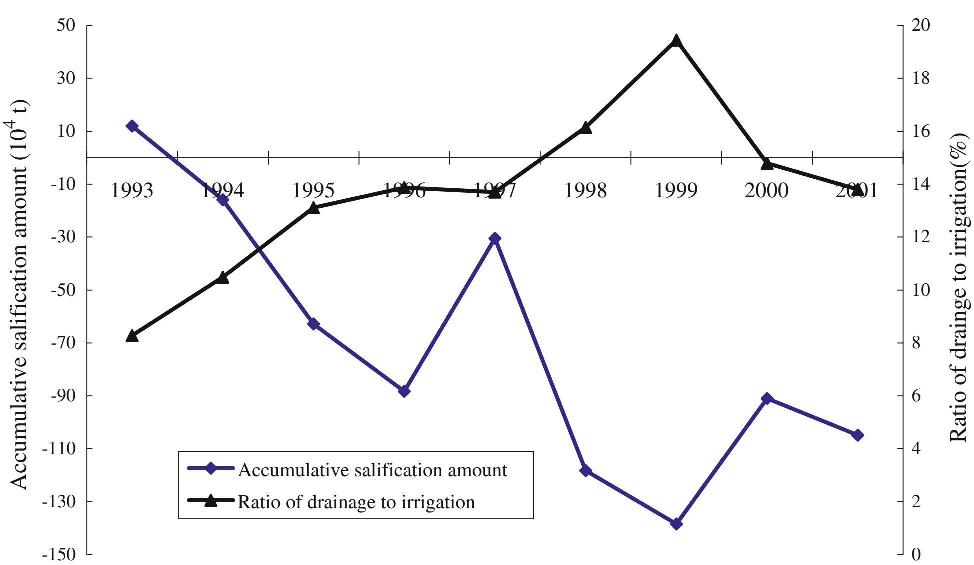


Fig. 3 Relationship between soil salt accumulative salification and the ratio of drainage to irrigation

Table 2 Eigenvalue of salt balance elements statistics in irrigated oasis area

Statistics	V_i	C_i	S_i	V_d	C_d	S_d	ΔS	V_d/V_i
Average values	24.18	0.38	92.56	3.36	4.90	163.38	−75.94	13.73
Standard deviation	2.13	0.02	8.30	0.99	0.68	52.97	51.29	3.39
Coefficient of variation (%)	8.82	5.90	8.97	29.40	13.90	32.42	67.54	24.66

V_i is the total irrigation water amount (10^8 m^3); C_i is the average salt concentration for irrigation water (g L^{-1}), S_i is the total recharge salt content (10^4 t), V_d, C_d and S_d are the total discharge water amount (10^8 m^3), the average salt concentration for discharge water (g L^{-1}) and the total salt amount in discharge water respectively (10^4 t); ΔS is the change of salt content

Table 3 Land use change from 1993 to 1996 in Weigan River irrigation areas

Type of land use	1993		1994		1995		1996	
	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)
Water	153.5	3.72	139	3.37	124.5	3.01	109.8	2.66
Farm, forest	1,276	30.89	1,366	33.07	1,456	35.25	1,546	37.43
Grass beach, depression	257.6	6.24	272.1	6.59	286.6	6.94	301.3	7.29
Fallow	1,300	31.47	1,210	29.30	1,120	27.12	1,030	24.94
Uncultivated farmland	913	22.10	913	22.10	913	22.10	913	22.10
Urban land	230.2	5.57	230.2	5.57	230.2	5.57	230.2	5.57

presented in Table 2. The salt balance from 1993 to 2001 indicated that desalinization began in 1993 and the amount of desalinization has increased with the passage of time (Table 1). It can be seen that the coefficient of variation of salt content change is around 50% which accounts for middle scale variation.

The relationship between salification and the ratio of drainage to irrigation (Fig. 3) demonstrated that the ratio of drainage to irrigation was at its peak values in 1999 before decreasing slowly in 2001. The average critical ratio of drainage to irrigation of Weigan River Plain Oasis was estimated to be 9.19%. Moreover, the coefficient of variation of irrigation water and salinity in Weigan River Plain Oasis was below 10% which accounted for weak variation. Therefore, the salt brought into the Weigan River Oasis would be stable. It is generally accepted that there are many factors that control the drainage of farmland, such as climate, geomorphology, geology, and land use. However, it is mainly determined by the initial salt content in the soil and the land use when the climate, geomorphology, soil property, and incoming irrigation water are not changeable in specific areas. The change in salt content has an obviously increase in 1997 that is because the input water from upstream got its peak in 1999. It brought the largest salt into the irrigated area. Therefore, the amount of input water from upstream should be kept relatively constant in the control of soil salinization in irrigated area, except to meet the crop water requirement; the other part is used for leaching water requirement. Therefore, it is obvious that the coefficient of variation of drainage water and drainage salt content is much higher (Table 2).

Table 1 also demonstrated that the salinity of drainage water had been steadily increasing from 1993 to 2001. One of the most important reasons was that the salt in newly cultivated farmlands was being drained out as more and more drainage systems were constructed during this period. Furthermore, the high salinity phreatic water was drained out resulting in the increase in salt content in drainage water. Correspondingly, the decrease in fallow land and water area ration from 1993 to 1996 (Table 3) verified this point of view. Owing to its simplicity of hydro-salinity balance equation in oasis irrigation area, the salt balance results only showed a macroscopic change. They did not reflect the actual salt content or distribution spatially. It was inevitable to consider the salt transport and accumulation characteristics in small scale before a comprehensive evaluation for soil salinization was made.

Salt mobilization and accumulation characteristics at field scale

The salt content was uneven not only in different parts of the Weigan River Plain Oasis, but also on the soil profile. The amount of irrigated water should be bigger than the plant demand so as to avoid desalinization in the root layer. The excess water from the plant would guarantee that the salt in the root layer be leached into the soil layer underneath. The volume of water leached is determined by the salinity and salt concentration allowed by plant. One experimental field was conducted (5 cultivated farmland sites and 5 uncultivated farmland sites) in a 500 ha national agricultural farm in Weigan

Table 4 Results of soil salinity content in two farmland in Weigan River irrigation areas

Soil depth (cm)	Non-cultivated farmland			Cultivated farmland		
	Bulk density (g cm^{-3})	Average salt content (%)	Salt storage (kg m^{-2})	Bulk density (g cm^{-3})	Average salt content (%)	Salt storage (kg m^{-2})
0–10	1.27	1.40	1.77	1.30	0.05	0.07
10–20	1.43	1.16	1.66	1.43	0.07	0.11
20–30	1.69	1.03	1.74	1.60	0.07	0.11
30–50	1.65	1.20	3.95	1.56	0.05	0.14
50–70	1.75	0.84	2.93	1.54	0.07	0.20
70–100	1.58	0.67	3.17	1.54	0.09	0.39
Average/sum	1.56 (average)	1.05 (average)	15.22 (sum)	1.50 (average)	0.07 (average)	1.02 (sum)

River oasis irrigation areas in Xinjiang in 2001. The soil salinity distribution and basic soil physics properties (0–10, 10–20, 20–30, 30–50, 50–70, 70–100 cm) of two different soil types were investigated and compared. Furthermore, soil salt storage is calculated in Table 4.

The following results can be seen from Table 4: (a) cultivated soil displayed significantly lower salinity with higher uniformity compared to uncultivated soil. The salt storage under cultivated farmland was small (1.02% for the whole soil profile). Hence, it is practical to determine the amount of drainage water under zero salification condition. Actually, the salinity of irrigation in this farmland is 0.14 g L^{-1} and the net irrigation demand amount in cultivated farmland is 5,700 m^3 hm^{-2}, the measured salt salinity in drainage water is 3–4 g L^{-1}. The ratio between irrigation and drainage would be around 8%. The preferential flow phenomenon was less apparent in cultivated soil. This is mainly due to tillage that disrupts the structure of the soil, so that deep cracks are no longer connected to the soil surface. This reduced the risk for groundwater contamination through preferential flow. (b) The salt storage under non-cultivated farmland was much higher (15.22% for the whole soil profile). It can be calculated that the salt storage (0–100 cm) in each hectare is as high as 180 t. If we set the net irrigation water demand at 6,750 m^3 hm^{-2}, the salt content in drainage water at 7–8 g L^{-1}, and the ratio between irrigation and drainage at 30%, then the salt content drained out would be 18 t per hectare. In cultivated farmlands, it would take 10 years to decrease the salt storage to 0.11%. The study also recommended that careful and continuous monitoring of the salinity status is needed now and in the future.

Different scaling issues and discussion for hydro-salinity balance in oasis irrigation areas

The discussion above the hydro-salinity balance and transport relationship at two different scales was based on the net drainage salinity. The pattern, the characteristics, and the process for water and salt transport will change with different scales. The transport process is different because of the discrepancy of control factors for water and salt transport in different scales. In fact, the water and salt transport between different scales are mutually restricted and relative. The salinization in irrigation areas is related to the water and salt transport in field scale. Similarly, the change in salinization in irrigation districts will affect the regime of water and salt transport in field scale. It is highly recommended that the water and salt transport and characteristics from macroscopic to microcosmic (basin—irrigation areas—farmland—soil profile) be investigated. However, it is best to study salt accumulation and regulation from microcosmic to macroscopic (soil profile—farmland—irrigation areas—basin). To evaluate the salification trend correctly, multiple scales for water and salt balance must be developed. It is also helpful to regulate and control salinization trends as well as to provide academic and instructive meanings for sustainable development of agriculture in oasis irrigation area. Owing to the data resource, the focus of this paper was on the irrigation areas scale. As for the farmland and field scale, emphasis was on the qualities and theory analysis.

Driving force analysis and corresponding countermeasures for soil salification

There are 1.26 million hectares of secondary salinization farmland making up 31.1% of the total farmland in Xinjiang Province. The regional distribution is 69.4% in South Xinjiang, 27.1% in North Xinjiang and 3.5% in East Xinjiang. Therefore, the saline problem is serious. It is the destroyed hydro-salinity balance that causes the salinization. The three driving forces for soil salinization are detailed as follows:

1. *Economic boom and population increase*. In the past 30 years, because of a large increase in population and

an irrational development of water, soil, and biotic resources, the ecological balance is violated. This has affected not only economic development but will seriously endanger future human life. Owing to extensive growing of cotton crops with excessive use of fertilizers in oasis irrigation areas, nitrogen, and salinization pollution has become increasingly serious.

2. *Improper use of water*. As large amount of river water was carried to irrigation areas, a lot of salt also entered into the farmlands. When the irrigation technology and management were unsuitable, or when the irrigation quota was set too high, a lot of water end up underground, causing groundwater table to rise and salt to accumulate in the upper soil layer.
3. *Irrigation and drainage canal system mal-arranged*. When there was a lack of drainage system or when the drainage outlets were poor, the salt and water in the farmland and could not drain out and salt accumulated in the inner oases. Large-scale low lying lands were reclaimed. Previously, this land could be a salt accumulated area for dry salt drainage. It restrained salt movement horizontally and only had vertical transport with soil moisture. Salt could easily accumulate in the surface soil layer.

However, the Weigan River irrigation areas in Xinjiang Province still have great advantages in environment and resources, and there are great potentials in developing the economy. Thus, studying and solving the problems of ecological environmental geology have important theoretical value and practical significance. The ecological environment in Xinjiang Province is complicated and differs from place to place, and there is not any uniform study or administration model. Taking the ecological environment in the Weigan River irrigation areas as an example; a comprehensive administrative strategy should be proposed and must be paid close attention to the key factors of water resources in arid and semiarid areas. Specifically, the following countermeasures to deal with the problem of secondary soil salinization in oasis irrigation areas should be highlighted:

1. Promoting water-saving irrigation methods and establishing consummate irrigation and drainage systems. Less-developed methods and impeded drainage can lead to over-irrigation, the rise of groundwater level, and secondary salinization. It is, therefore, important to promote advanced water-saving irrigation techniques, decrease the irrigation quota, and reduce the seepage of canals in the near future. Thus, in the long run, the amount of drainage water and the disposal of the irrigation return flow are to be reduced in such a way that it will prevent the pollution of water resources downstream. These are the key issues to be taken into consideration in a strategy to prevent salinization.
2. Ensuring water resource for ecological usage and coordinating water usage between production and ecology. The limited water resource is diverted into irrigation areas to develop agriculture, resulting in a significant decrease in the amount of water for maintaining natural vegetation in the lower reaches, resulting in natural vegetation deterioration and an increase in the amount of land desertification. These pose great threats on artificial oasis. To maintain the natural vegetation and attain ecological balance, it is important to ensure necessary amount of water in lower reaches.
3. Limiting wasteland reclamation and attaining zero increase in irrigation water. Large-scale water-reclamation has resulted in the following: (1) natural vegetation was destroyed; (2) bare land greatly increases; (3) the diverted water constantly increases. All these have negative effects on the ecological environment. Therefore, the future expansion of irrigation areas should mainly depend on tapping the potentialities of irrigation water, increasing groundwater usage, and improving water application efficiency.

Conclusion

The principal conclusions from this study are

1. The critical ratio of drainage to irrigation of Weigan River Plain Oasis was estimated to be 9.19% and cultivated soil displayed significantly lower salinity with higher uniformity as compared to uncultivated soil.
2. If the irrigation culture is to survive as an economically viable and environmentally sustainable activity, irrigation–drainage management activities have to be planned in the regional scale to minimize the environmental impact of salinity upon groundwater resources. For this purpose, regional water and salt balance models would provide an insightful and a better conceptual understanding of the problems. The models would also serve as interpretative tools in making vital decisions on managing agriculture in the irrigation area of Weigan River. To evaluate soil salification trend correctly and to provide practical counter measures to solve the problem in the arid zone, multiple scales on water and salt balance must be developed, and the relationship among different scales should be interpreted quantitatively.
3. Scaling and its impacts are directly related to heterogeneities which can be traced to two major sources.

The principal sources of heterogeneities are differences in climate, topography, soil, and geology which govern water and salt transport. The other source is the discontinuities or boundaries separating soil types, geologic formations, or land covers. In essence, the development or the flourishing of oasis irrigation agriculture depends on rational allocation and utilization of the water resources at regional scale in the long term, and the water resources for a given region are relatively deterministic.

4. This investigation has shown that the one-dimensional models SWSTM can be used at the catchment scale after adaptation. However, the catchment scale do not consider the interaction between micropores and macropores. Accordingly, in the next stage of research, it is foundational to determine the suitable scale for the irrigation areas of Weigan River Plain Oasis and to couple the interaction between each field sections.

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References

Cui YL, Shao JL (2005) The role of ground water in arid/semiarid ecosystems, Northwest China. Ground Water 43:471–477

Gibbison GA, Randall J (2006) The salt water intrusion problem and water conservation practices in southeast Georgia, USA. Water Environ J 20:271–281

Hu SJ, Song YD, Tian CY, Li YT, Li XC, Chen XB (2007) Suitable scale of Weigan River plain oasis. Sci China Series D Earth Sci 50(Suppl):56–64

Lin NF, Tang J (1992) Synthetical study on eco-geological environment in the west of Tarim basin in Xinjiang. Jilin University Press (in Chinese), Changchun

Moharana PC, Kar A (2002) Catchment simulation in a sandy terrain of the Thar Desert using GIS. J Arid Environ 51:489–500

Pala A (2003) Runoff modelling of rural catchments in Turkey. J Arid Environ 54:505–512

Shainberg I, Letey J (1984) Response of soils to sodic and saline conditions. Hilgardia 52:1–55

Simunek J, Suarez DL (1997) Sodic soil reclamation using multicomponent transport modeling. J Irrig Drain Eng ASCE 123:367–376

Sivapalan M, Viney NR, Jeevaraj CG (1996) Water and salt balance modelling to predict the effects of land-use changes in forested catchments. Hydrol Process 10:429–446

Skaggs RW, Breve MA, Gilliam JW (1995) Predicting effects of water table management on loss of nitrogen from poorly drained soils. Eur J Agron 4:441–451

Suarez DL, Šimůnek J (1997) UNSATCHEM: unsaturated water and solute transport model with equilibrium and kinetic chemistry. Soil Sci Soc Am J 61:1633–1646

Tang QH, Hu HP, Oki TK, Tian FQ (2007) Water balance within intensively cultivated alluvial plain in an arid environment. Water Res Manage 21:1703–1715

Van Dam JC, Groenendijk P, Hendriks RFA, Kroes JG (2008) Advances of modeling water flow in variably saturated soils with SWAP. Vadose Zone J 7:640–653

Viney NR, Sivapalan M (2001) Modelling catchment processes in the Swan-Avon river basin. Hydrol Process 15:2671–2685

Xia J, Zuo QT, Shao MC (2003) Theory, method and practice on water resources sustainable utilization in Lake Bosten. Chinese Science and Technology Press, Beijing, pp 13–19 (in Chinese)

Xu LG, Yang JS, Zhang Q, Liu GM (2005) Salt-water transport in unsaturated soils under crop planting: dynamics and numerical simulation. Pedosphere 15:634–640

Xu LG, Yang JS, Zhang Q, Niu HL (2008) Modeling water and salt transport in soil-water-plant system under different groundwater tables. Water Environ J 22(4):265–273