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RESEARCH ARTICLE

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Effect of irrigation management on soil salinization in Manas River Valley, Xinjiang, China

Abstract The irrigated area of Manas River Valley in Northwest China is an example of the successful reclamation of massive land affected by shallow ground water levels and salinization. To determine the effect of irrigation management practices on soil salinization, soil profiles representing various soil types were sampled. The historical records on the characteristics of irrigation management practices, groundwater level and soil salts accumulation in this region at four key periods, namely: flood irrigation without drainage; flood irrigation with drainage but of low efficiency; irrigation in combination with lined irrigation canals and exploitation of groundwater; and irrigation with the application of water-saving irrigation techniques, were analyzed emphatically. In addition, the salinization status of cultivated land in 2010 and 2020 was also predicted by using analogism according to the relationship between soil salinization and irrigation practices. The results revealed that the application of the traditional irrigation methods, such as flood irrigation and ridge irrigation, resulted in a rapid rising of groundwater level and salts accumulation in soil surface layers. However, with the way of well irrigation and well drainage, the groundwater level and the desalinization in soil layers apparently lowered, leading to a substantial increase of crop yield. Currently, the application of drip irrigation under mulch decreased the salts concentration in soil layers and increased the crop yield. With the continuous application of drip irrigation, the average soil desalinization efficiency in soil layers may increase. It is predicted that the percentage of salinized land would be reduced to 35%–40% when irrigation water is utilized reasonably in 2010. With the high efficient utilization of irrigation water after 2020, the salinized land would remain below 30%. It is concluded that with the improvement of irrigation management, an obvious desalinization would appear in the soil surface layers and the area of salinized land in this study area would gradually narrow, but the land salinization problem would be hard to totally solve.

Keywords irrigated area, irrigation practices, drainage, drip irrigation, soil salinization, Manas River Valley

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1 Introduction

The agricultural production and its development rely mainly on irrigation in Xinjiang Uygur Autonomous Region, Northwest China. In this region, expansion of the irrigated area, particularly since the early 1950s, has significantly increased the agricultural output. However, it has also resulted in serious problems of soil salinity in the irrigation commands (Tian and Zhou, 2000; Fan et al., 2002). The salinity problem, as encountered in irrigated agriculture, is frequently associated with an uncontrolled groundwater table within one to two meters below the ground surface (Stuyt et al., 2000). Irrigation systems are particularly prone to salinization and it is considered to be one of the main causes of falling crop yields and the loss of land from production (Thomas and Middleton, 1993). Irrigation practices, if feasible, can lower the groundwater table and eliminate the secondary soil salinization.

There is a large body of literature on the relationship between irrigation and land secondary salinization in arid regions. O'Hara and Sarah (1997), for example, studying the problems of soil degradation, in particular waterlogging and salinization associated with irrigation systems, in Turkmenistan, outlining the nature and extent of the problem and assessing its implication for the future economic development of this state. Hachicha et al. (2000) assessed the impact of irrigation on changes of the ground water level and soil salinity throughout three periods in Northern Tunisia, also analyzed the salt balance and evaluated the future salinization risk. Luo (1985) investigated the forming process and types of salinized land in Xinjiang, China. Yuan et al. (1995) studied the environmental impacts of land development, especially pointed soil salinization problems resulting from the introduction of irrigation systems in Manas River Valley. Ji et al. (1998) investigated the salt variation of cultivated land on the different stages of salinization control in the Aral cultivated area, Xinjiang. They also discussed the existing problems and countermeasures on salinization alleviation. Fan et al. (2002) discussed the trend of salinized agricultural land in the northwest region of China and concluded that soil salinization in formerly cultivated land is reducing but it is becoming severe in the newly cultivated land. Additionally a lot of studies on water-salt dynamic changes and balance under different irrigation methods were carried out (Bingham et al., 1984; Bveese and Moshrefi, 1985; Li et al., 2001; Zhang et al., 2004; Liu and Tian, 2005; Zhou and Ma, 2005). Their experiments showed that under the same amount of water applied, drip irrigation yielded much higher dry matter than the other irrigation methods did. Additionally, under the drip irrigation, less salt was accumulated in the root zones with an increase in the amount of water applied. With the same amount of water applied, the saline level under the drip irrigation was dramatically reduced as compared with that under the other irrigation methods.

The irrigated area of Manas River Valley, which is situated in the north of Xinjiang, appears to be an example of the successful reclamation of massive land affected by shallow ground water levels and salinization. The reasons for success will be analyzed through the comparison of four periods of the area's history: flood irrigation and before drainage (1950–1960), after drainage but low efficient irrigation (1961–1980), after the combination of anti-seepage of irrigation canals and exploitation of groundwater (1981–1997), and finally, with the application of water-saving irrigation techniques which was began in 1998. In addition, an attempt will be made to predict the developing trend of land salinization for 2010 and 2020 according to the relationship between land salinization and irrigation levels.

2 Materials and methods

2.1 Location of the study area, soil and climate

The area of Manas River Valley (84°43′–86°35′E and 43°21′–45°20′N), which is located in the north of Tianshan Mountain and appears to be a representative section of the Junggar Basin of Xinjiang. It covers an area of approximately 24.3 thousand km^2, 48% which comprises the mountains confined to the south, 42% comprises oasis plain and 10% is desert. The Manas River Valley is divided into three main administrative regions: the City of Shihezi, Manasi County and Shawan County. The Manas River and the other four rivers with relatively lower runoff including Taxi, Bayingou, Jingou and Ningjia all originate from the mountains and constitute the dominant influence on the local hydrological system. Poorly developed soils were formed from quaternary sediments with characters of salinity and gradually formed alluvial fan, alluvial plain and delta (Fig. 1). The alluvial fan that derived from many different-sized alluvial fans is adjacent to piedmont, lies between 450 m and 1000 m above sea level. Fertile loam soils and better hydrogeologic conditions in this zone constitute the earliest and most important part of local industries and agriculture production. The alluvial plain, which lies between alluvial fan and delta, is the largest portion in the Manas river watershed (2–3 times the alluvial fan). The grey desert soil, which is mostly composed of the cultivated grey desert soil (approximately 80%) and the salinized grey desert soil distribute widely within the entire zone. For the alluvial plain, its flat terrain (average gradient $<0.5\%$) is very suitable for machine operation. These, coupled with abundant light and heat supply make it become the primary potential part of agriculture production. The delta lies at the lower reaches of Manas River and is adjacent to the south edge of Gurbantonggut Desert. The soils in this zone are predominantly formed from aeolian and alluvial deposits.

According to a 50-year meteorological records, average annual precipitation ranges from 400–600 mm in the south mountains, 344–428 mm in low-relief terrain, and 197.2 mm in oasis plain, to nearly 117.9 mm in the desert edge. Around 67% of precipitation occurs during spring and summer, and 33% during autumn and winter. Mean annual pan evaporation varies from 1500 mm to 2100 mm with a mean temperature of 6.0°C. The coldest months are from December to February with a mean temperature of −19.0°C, and the hottest months are from June to August with a mean temperature of 25.9°C.

2.2 Data collection and analysis methods

Data on irrigation management practices included the characteristics of irrigation techniques, the area of irrigated land, the amount of irrigation water used, the amount of pumped groundwater, the percentage of lined canal network, and the water use efficiency. This information from statistical yearbooks and documents was mainly investigated from relevant government agencies including

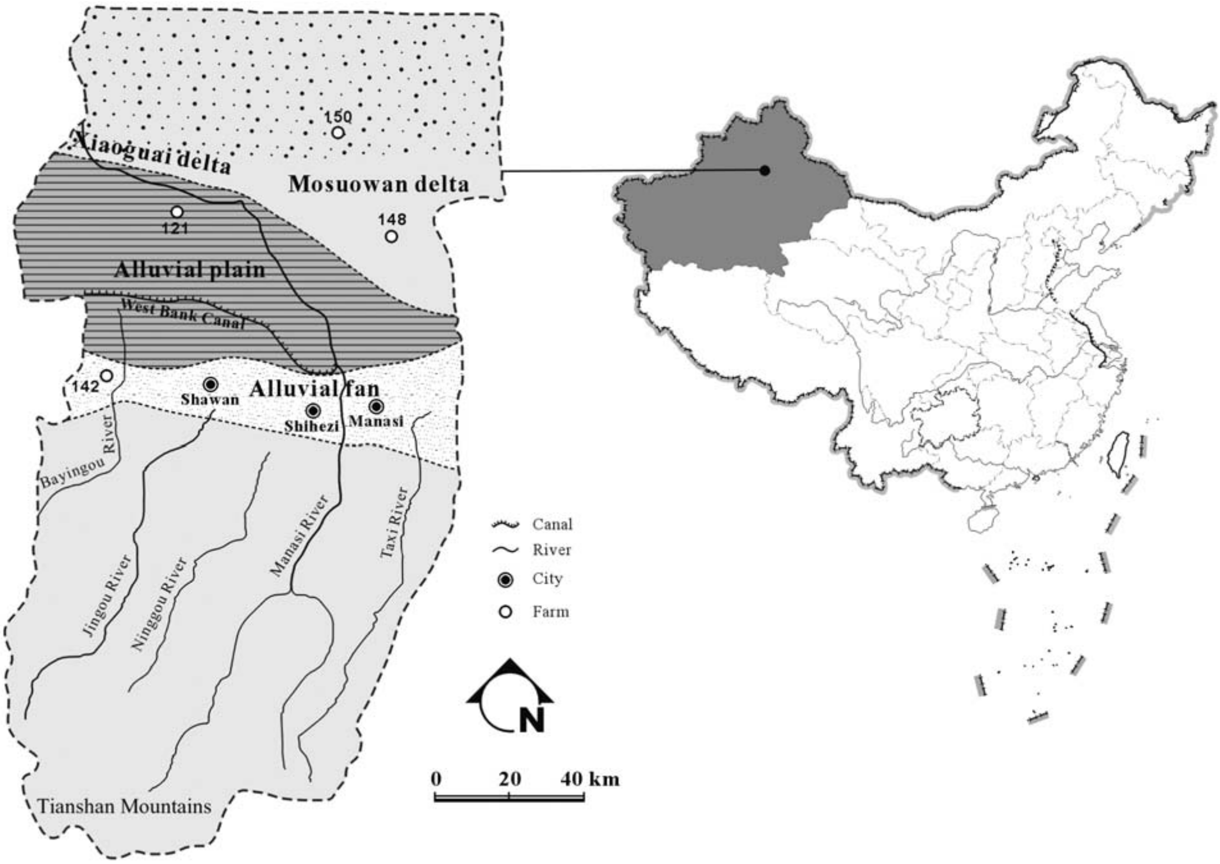

Fig. 1 Location of the Manas River Valley

bureaus of agriculture, hydroelectricity and statistics. In addition, the historical information on crop patterns, crop yield, soil salinity and fluctuations of the groundwater table were also surveyed for the past 50 years on the representative state farms.

To investigate the impact of irrigation practices on the soil salinization in this region, two typical soil profiles that were representatives of the various soil types (Cultivated grey desert soil and Salinized grey desert soil) were selected based on the soil salinity survey in 1982. The cultivated grey desert soil samples were collected at the depths of 30 cm, 48 cm, 69 cm and 115 cm, in September, 2005, and the salinized grey desert soil was sampled at the depths of 30 cm, 54 cm, 67 cm, 90 cm and 120 cm, respectively. In addition, the information on variations of salts accumulation at the 1 m soil layer under mulched drip irrigation was also collected during different application years (respectively 1, 3, 8 years and before drip irrigation). The soil samples were collected on the State Farm 121 at the depths of 30 cm, 60 cm, and 100 cm, respectively. All the soil samples were taken back to laboratories to determine the soluble salt concentration by using a salinity meter. In this study, the content of soil salinity was expressed in terms of %, meaning the mass percentage of the total amount of dissolved salts in the soil.

3 Results and discussion

3.1 Impact of irrigation management practices on soil salinization

3.1.1 The period of flood irrigation and before drainage (1950–1963)

Before the reclamation of irrigated area of Manas River Valley, the groundwater levels generally ranged between 4.0 m and 7.0 m below the soil surface, and the groundwater salinity was lower. Therefore, the soil salinification in these areas was generally not very severe. The reason was mainly that the percentage of farmland was relatively lower and most of water losses through the conveyance and in-field system were discharged to the lowland (Lai et al., 2004). Since the early 1950s, the massive land in this region was cultivated. As the restriction of financial capability and irrigation management levels, the majority of irrigation canals were unlined (Table 1), and total efficiency of the irrigation system in this region was approximately 30%–43%. During the irrigation season, almost the total land area was irrigated from the surface with furrow irrigation predominating and the gross irrigation amount per unit area reached 1.50×10^4–2.25×10^4 $m^3 \cdot hm^{-2}$. Like the conveyance system, considerable amount of

Table 1 Variations of lined water-carriage system in Shihezi cultivated area

period	arterial canal		lateral canal		sublateral canal		field canal	
	length of canal/km	percent of canal lined/%	length of canal/km	percent of canal lined/%	length of canal/km	percent of canal lined/%	length of canal/km	percent of canal lined/%
1960	213.55	38.40	1063.00	31.81	1922.00	16.72	4591.80	0
1985	387.28	57.45	1087.60	51.60	3124.60	17.85	9665.00	5.46
2001	535.60	82.29	1032.00	80.12	3501.00	39.39	14517.66	9.60

water was lost by seepage and evaporation, which considerably replenished the groundwater. In addition, the drainage systems to control ground water levels were almost absent at that time. Therefore, all these resulted in a distortion of the natural salt balances in the soil-water system and, hence, a marked increase in ground water levels. For example, in the State Farm 142 the groundwater table sharply rose from 4.46 m in 1956 to 1.85 m in 1959. At the same time, the groundwater salinity (almost sulphates and chlorides) in this zone increased from 2.19 $g \cdot L^{-1}$ to 13.6 $g \cdot L^{-1}$. In the State Farm 121, the groundwater depth was observed to have risen to the level between 1.0 m and 2.5 m in some parts of the zone until 1960, and the salt content in topsoil layer was above 16.67 $ms \cdot cm^{-1}$. Figure 2 showed the variations of irrigated land area under different groundwater depth in the State Farm 147. It indicated that with the rapid rising of groundwater table, the area of irrigated land under the zone of the critical groundwater depth was also rising.

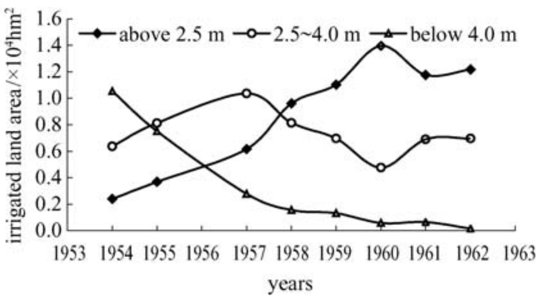

Fig. 2 Variations of irrigated land area with different groundwater levels in the State Farm 147 of Shihezi cultivated area

At that time, the control of soil salinity was managed through the leaching of over-irrigation and growing rice. It is worth noting that at the early period of reclamation, the effect of controlling soil salinity practices was obvious. However, with the increasing groundwater, the salts leached in lower-horizon soil were accumulated in the surface soil again due to the absence of effective drainage (Ji et al., 1998). Therefore, the salinized soil conditions in the irrigated land resulted in a general simple crop pattern and lower crop production. Over this period, the cropping pattern mainly included wheat and oil crops in this region. Wheat accounted for approximately 20% of the total cultivated area, oil crops stood at over 14%, while cotton as a cash crop remained only a contribution of 7%. The yield of lint cotton in Shihezi cultivated area was only 350 $kg \cdot hm^{-2}$ during the period of flood irrigation without drainage (Table 2).

3.1.2 The period after drainage and low efficiency irrigation (1964–1981)

In the middle 1960s, the soil salinization was mainly controlled or prevented by extension of drainage canals, by manual labor or digging machines and application of plastic film or clay and straw plaster as lining materials of conveyance canals to reduce irrigation water seepage. Until 1970, the total efficiency of the irrigation system in this region increased to approximately 57%. In the early 1970s, irrigation wells were only applied in small experimental farms with better economical conditions. In addition, the traditional irrigation method (flood irrigation) was gradually improved and other methods including ridge or furrow irrigation were practiced to reduce the groundwater recharge, but at that time, the gross irrigation amount per unit area was still high, reaching 0.75×10^4–1.25×10^4 $m^3 \cdot hm^{-2}$. Although the introduction of many advanced irrigation management practices contributed to controlling groundwater table and soil salinization to some degree, the groundwater level was still rising (i.e. in some parts of the region, the groundwater table varied from 0.5 m to 1.0 m below the surface). Consequently, these lead to secondary soil salinization on a large scale until the early 1980s. It is roughly

Table 2 Variations of irrigated land, crop yield and water use efficiency at different periods in Shihezi cultivated area

period	area of land irrigated/ 10^3 hm^2	yield of cotton/$kg \cdot hm^{-2}$	increase in yield/kg cotton·hm^{-2}	water use efficiency of cotton/$kg \cdot m^{-3}$
flood irrigation and before drainage	73.83	352.60	–	0.04
after drainage but low efficient irrigation	143.33	607.80	255.2	0.07
beginning of pumping and well-irrigation	152.96	1141.20	533.4	0.15
since the application of water-saving irrigation techniques	162.59	1736.80	595.6	0.29

estimated that until 1980, the total area of abandoned farmland caused by secondary soil salinization varied between 3.5×10^4 hm^2 and 4.0×10^4 hm^2 in this area (Lai et al., 2004). Figures 3 and 4 showed the evolution of soil salinity of two typical soil types in this region from 1982 to 2005. It can be clearly seen that severe salt accumulation occurred in the soil layers, especially in the subsoil layers in 1982. Thereafter, clearly identifiable desalinization occurred in these soils with better irrigation and drainage systems.

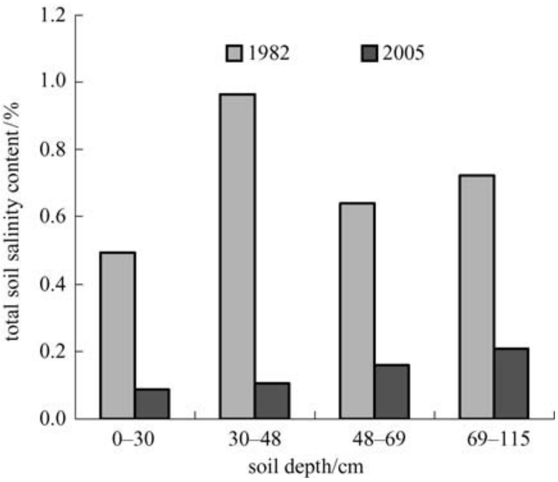

Fig. 3 Variations of soil salinity in the irrigated grey desert soil profile from 1982 to 2005

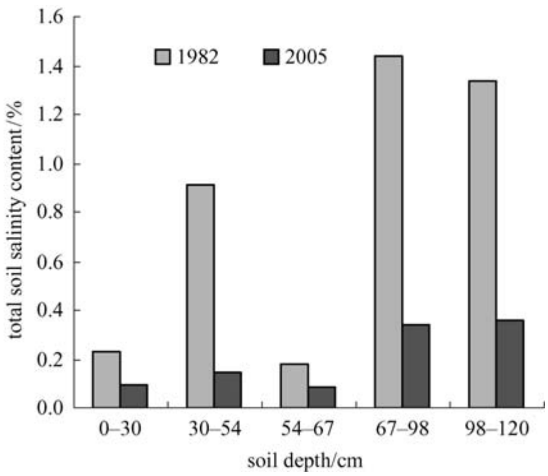

Fig. 4 Variations of soil salinity in the salinized grey desert soil profile from 1982 to 2005

3.1.3 The period after the beginning of the pumping and well-irrigation (1982–1997)

In the early 1980s, main conveyance canals including arterial were almost lined with cement plates on a large scale. Total efficiency of the irrigation system in this region was increased to approximately 70%. In addition, planned pumping began at the same time, providing large quantities of groundwater from the selected water source to irrigate crops. It was estimated that the amount of pumped groundwater significantly reached 3.15×10^8 m^3 and accounted for 70% of the total permissible exploitation volume in Shihezi region, which substantially decreased the groundwater levels and reduced the secondary soil salinization hazards (Li and Han, 2004). Therefore, these irrigation management practices substantially resulted in declined groundwater level in most of the region and it stabilized at 2.0 m below the soil surface (Fig. 5), although this groundwater table was still high, averaging 1.0 m below the surface in some parts of this region (i.e. the alluvial fan formed by Bayingou River), due to the long-term irrigation without drainage and especially to the blocking of groundwater flow towards downstream zone caused by the "West Bank Canal" (Feng, 2005).

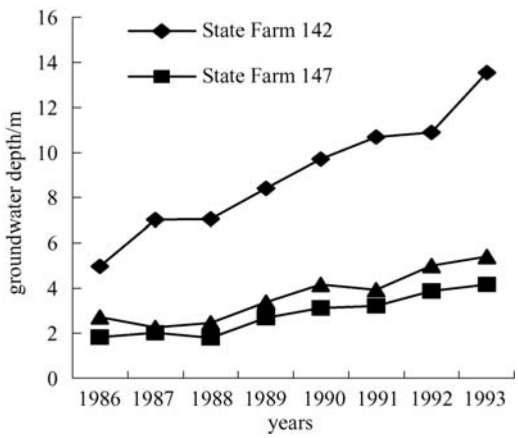

Fig. 5 Variations of the groundwater level in different irrigated areas of Shihezi cultivated area

Figure 6 showed the correlation between the number of wells and cotton yield in the period of 1975 to 2000 in Shihezi cultivated area. It indicated that with the increasing number of pumping wells, the cotton yield was also showing the same rising trend. This has mainly resulted to the development of pumping systems which effectively lowered the groundwater levels and reduced the soil salinization hazards, and therefore increased the crop yield.

3.1.4 The period for the application of water-saving irrigation techniques (1998-present)

From the late 1990s, the level of in-field drainage to remove excess water was relatively improved, the connection between arterial, secondary and tertiary drainage canals in this area was almost finished, and the total efficiency of the irrigation system in this region was increased to approximately 72%. Therefore, the high level of drainage effectively reduced the groundwater table in this

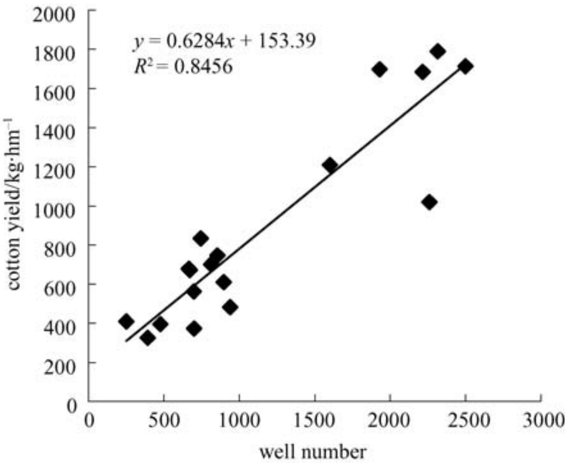

Fig. 6 Correlation between the number of wells and cotton yield in the period of 1975 to 2000 in Shihezi cultivated area

region. Since 1998, water-saving irrigation techniques such as drip irrigation under mulch have been introduced. For example, in Shihezi region, the area of drip irrigation under mulch increased from only 0.20×10^4 hm^2 in 1999 to 8.67×10^4 hm^2 in 2004, which accounted for 53.3% of the total irrigated land. Table 3 showed the variations of salts concentration at 0–100 cm soil layer under mulched drip irrigation in different application years. It was clearly seen that the application of mulched drip irrigation decreased the salt concentration in soil layers, and substantial soil desalinization occurred in 1 m soil layers with the continuous application of drip irrigation. The average soil desalinization efficiency in the top 1 m soil layers was 35.9%, 61.4%, and 74.0% in 1, 3 and 8 years, respectively.

Improved soil conditions in the irrigated land allowed farmers to gradually grow more remunerative or cash crops. For example, in Shihezi region, 78% of the grown area was planted with remunerative crops, of which cotton accounts for 71%, while the percentage of wheat declined to about 6%, oil crops remain only as low as 1%. Of course, the ever-increasing importance of cotton in the area may be more likely explained by pointing at the favorable market conditions. The effect of improved irrigation management practices on crop yields and water use efficiency is also substantial. It is about 1750 kg·hm^{-2} under the drip irrigation system, which is equivalent to 5 times that of the previous production levels. The water use efficiency of cotton has increased by 0.25 kg·m^{-3} over this period. These indicate that the adoption of modern irrigation technologies has improved the general soil conditions around that area.

3.2 Prediction of developing trends of land salinization in Manas River Valley

Low efficient irrigation technologies were considered to be one of the main causes of salinization problems (Hachicha et al., 2000; Darwish et al., 2005). Fan et al. (2002) concluded that nearly 80% of the total saline land in this area occurred due to the secondary soil salinization caused by irrigation, and the developing trend of land salinization in the future will to a great extent depend on irrigation technologies. For the above reasons, an analogism method was used to evaluate the land salinization status in 2010 and 2020 by considering the relationship between the percentage of salinized land and irrigation levels. Five indexes determining irrigation levels were chosen including the volume of groundwater exploited, the percentage of canal network lined, the coefficient of irrigation water use, the irrigation applications and the water use efficiency of crops. The results of trends of land salinization are as follows.

3.2.1 The period for reasonable use of irrigation water in most of the irrigated area (2010)

When compared with Shihezi region which was subjected to high irrigation levels and relatively low land salinity (Table 4), measures must be taken to improve the irrigation efficiency in other parts of the area. According to the

Table 3 Variations of salt concentration at 0–100 cm layer under mulched drip irrigation in different application years

application years under mulched drip irrigation	total soil salinity concentration/%				seed cotton yield/kg·hm^{-2}
	0–30 cm	30–60 cm	60–100 cm	0–100 cm	
before drip irrigation	2.91	2.37	1.62	2.23	0
1 year	1.35	1.76	1.23	1.43	804.0
3 years	0.80	0.91	0.88	0.86	3564.0
8 years	0.63	0.72	0.55	0.58	4200.0

Table 4 Relationship between salinized land and irrigation levels in Manas River Valley

region	percent of salinized land/%	percent of groundwater exploited/%	percent of canal network lined/%	irrigation water use coefficient	irrigation requirement/m^3·hm^{-2}	water use efficiency/kg·m^{-3}
Shihezi	38.36	69.7	21.9	0.64	0.79	0.16
Manasi	47.20	48.5	15.0	0.59	0.89	0.14
Shawan	57.73	35.9	11.7	0.55	0.94	0.12

local water conservancy department planning and developing trends of irrigation levels, until 2010 the total amount of groundwater pumped is estimated to range between 60% and 70% of the permissible exploitation volume in most of the irrigated area. The percentage of lined irrigation canals can be averagely expected to vary from 25% to 30%. The total efficiency of the irrigation system in this region can be increased to about 75%. More traditional irrigation methods can be increasingly transformed to water-saving irrigation techniques which may account for 20%–30% of the total irrigated land in both Manasi and Shawan counties. Over the same period, the gross irrigation application of crops will decline to 7500–8000 $m^3 \cdot hm^{-2}$ and the water use efficiency for cotton will vary between 0.16 $kg \cdot m^{-3}$ and 0.25 $kg \cdot m^{-3}$ respectively. Therefore, it can be estimated that the percentage of total salinized land can be reduced to 35%–40% in this area.

3.2.2 The period of irrigation water use with high efficiency (2020)

High irrigation levels must be combined with modern irrigation management practices. Until 2020, it is estimated that the percentage of groundwater pumped may range from 80% to 90% of the permissible exploitation volume. About 30%–45% of lined irrigation canals can be realized. Total coefficients of irrigation water use in this area can rise to 0.80. Water-saving techniques such as drip irrigation can averagely be applied to 40%–50% of the total irrigated land. For the same period, the gross irrigation application of crops can stabilize between 7500 $m^3 \cdot hm^{-2}$ and 5000 $m^3 \cdot hm^{-2}$ and the water use efficiency for cotton can remain an average level between 0.25 $kg \cdot m^{-3}$ and 0.30 $kg \cdot m^{-3}$. In these cases, the percentage of total salinized land can be estimated to remain below 30%. However, it is necessary to indicate that, as an inland enclosed area, salts were not exported from the irrigated region. It is conceivable that, as more land in the oasis regions was reclaimed, soil salinization may still occur in the newly cultivated land taking into account the rise of the ground water levels. All in all, although in the future irrigation efficiency appears quite high, it is not sufficient to ensure that the development of secondary soil salinization can be completely controlled.

4 Conclusion

In this work, we reported the impact of irrigation management on soil salinization in the irrigated area of Manas River Valley throughout four periods: flood irrigation without drainage; flood irrigation with drainage but of low efficient; irrigation in combination with lined irrigation canals and exploitation of groundwater; and irrigation with the application of water-saving irrigation techniques. The developing trend of land salinization was also predicted by using analogism according to the relationship between land salinization and irrigation levels. It is concluded that the direct and indirect effectiveness of irrigation management over a period of 50 years has been immense in this area. On one hand, it has contributed to lowering the water table levels and decreasing the area of salinized land. On the other hand, the implications for crop production are significant that cropping patterns have been changed in favour of more remunerative crops, bringing about an increase in crop yields and water use efficiency. Of course, problems about soil salinization in this area still exist. For example, with the expansion of oasis, soil salinization may still occur in the newly cultivated land taking into account the rise of the ground water levels. Continuous salts accumulation may occur in these lower areas of alluvial plain and delta lying adjacent to the edge of deserts, as considerable discharge water containing large quantities of salts from upper irrigated areas is transported to the zones (Cheng et al., 2005). Hence, unless irrigation management practices be efficient in this area, salinity will rise to concentrations which will interfere with cropping patterns. Additionally, long term monoculture of cotton is common in this area, which has changed previous crop rotation (e. g. rice-wheat with succession of green manure-cotton-alfalfa). For example, the area of cotton growth has reached nearly 70% of that of cropland in Shihezi cultivated area. Currently, these problems such as difficulties of leaching salt in continuous cropping land have not been observed, which may emerge in 5–10 or more years (Ji et al., 1998). Because of water shortage, farmers have implemented water-saving irrigation techniques such as drip irrigation under mulch despite high cost. However, the use of drip irrigation may bring about a potential threat of the secondary soil salinization because no salt can be discharged from soil profile and salt build-up on the soil surface may be on the rise after long-term application of drip irrigation (Tian and Zhou, 2000; Zhou and Ma, 2005).

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