

# Combined Effects of Water Quality and Furrow Gradient on Runoff and Soil Erosion in North China<sup>\*1</sup>

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## ABSTRACT

Irrigation-induced soil erosion seriously affects the sustainability of irrigated agriculture. The effects of irrigation water quality and furrow gradient on runoff and soil loss were studied under simulated furrow irrigation in laboratory using a soil collected from an experimental station of China Agricultural University, North China. The experimental treatments were different combinations of irrigation water salt concentrations of 5, 10, 20, and 30 mmol<sub>c</sub> L<sup>-1</sup>, sodium adsorption ratios (SAR) of 0.5, 5.0, and 10.0 (mmol<sub>c</sub> L<sup>-1</sup>)<sup>0.5</sup>, and furrow gradients of 1%, 3%, and 5%, with distilled water for irrigation at 3 furrow gradients as controls. The experimental data indicated that total runoff amount, sediment concentration in runoff, and total soil loss amount generally decreased with increasing salt concentration in irrigation water but increased with its sodicity and furrow gradient. The effects of water quality and furrow gradient on soil loss were greater than those on runoff, and the increase of furrow gradient decreased the influence of water quality on soil loss. When the salt concentration increased from 5 to 30 mmol<sub>c</sub> L<sup>-1</sup> at SAR of 10.0 (mmol<sub>c</sub> L<sup>-1</sup>)<sup>0.5</sup>, total runoff amount, sediment concentration, and total soil loss amount decreased by 3.89%, 52.1%, and 53.92%, and 10.57%, 38.86%, and 42.03% at the furrow gradients of 1% and 5%, respectively. However, they respectively increased by 3.37%, 45.34%, and 55.36%, and 3.86%, 10.77%, and 13.91% when SAR increased from 0.5 to 10.0 (mmol<sub>c</sub> L<sup>-1</sup>)<sup>0.5</sup> at the salt concentration of 5 mmol<sub>c</sub> L<sup>-1</sup>. Irrigation water quality and furrow gradient should be comprehensively considered in the planning and management of furrow irrigation practices to decrease soil loss and improve water utilization efficiency.

**Key Words:** salt concentration, sediment concentration, sodium adsorption ratio (SAR), soil dispersion, soil loss

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## INTRODUCTION

Irrigation plays an important role on food and fabric supply safety (Li, 2006; Sojka *et al.*, 2007). The irrigated farmland occupies less than 40% of total arable area but supplies about 80% of total grain yield in China (Li, 2004); therefore, maintaining sustainable development on irrigated agriculture is very crucial to social stability and economic development in China. Surface irrigation is a dominant irrigation method in the world (Sojka *et al.*, 2007), and it accounts to about 95% of total irrigated area in China (Li, 2004). Of all surface irrigation methods, furrow irrigation is one of the main types.

Many experimental results have indicated that furrow irrigation might result in unsustainable soil erosion especially when irrigation furrow gradient is greater than 2% (Koluvek and Tanji, 1993; Lentz and Sojka, 1994; Sojka *et al.*, 1994; Fernández-Gómez *et al.*, 2004). Erosion induced by irrigation reduces soil potential productivity due to the loss of fertile surface soil (Carter, 1993; Koluvek and Tanji, 1993). In general, three forces are involved in furrow irrigation erosion: the shear stress of flowing

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water in irrigation furrow, cohesive force within soil particles, and stream transport capacity (Lehrsch and Brown, 1995; Fernández-Gómez *et al.*, 2004; Mailapalli *et al.*, 2009). Water quality affects soil clay dispersion, subsequently soil aggregate size, soil infiltrability, and runoff amount, and finally results in the change of soil loss amount in furrow irrigation activity (Lentz *et al.*, 1996).

Because of heavy competition in industry for fresh water, marginal water application in irrigation is an inevitable and increasing tendency in many countries and regions where fresh water resource is scarce. Irrigation with slight or moderate saline water at total dissolved salt content less than  $5 \text{ g L}^{-1}$  has been in practice in many regions in North and Northwest China (Lei *et al.*, 2003; Fang and Chen, 2007; Wan *et al.*, 2007; Wang *et al.*, 2007; Ma *et al.*, 2008). Compared with fresh water, higher salinity or sodicity level in marginal water will result in a change of soil hydraulic properties (Shainberg and Letey, 1984; Zhang and Miller, 1996; Li, 2006).

The experimental results of Lentz *et al.* (1996) demonstrated that irrigation water with electrical conductivity (EC) of  $0.5 \text{ dS m}^{-1}$  and sodium adsorption ratio (SAR) of  $12 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  resulted in a greater soil loss amount than that with EC of  $2 \text{ dS m}^{-1}$  and SAR of  $0.7 (\text{mmol}_c \text{ L}^{-1})^{0.5}$ . However, the effects of salinity and sodicity levels in irrigation water on runoff, soil erosion, and their interaction with furrow gradient are not studied systematically, and there is not enough information to reasonably manage furrow irrigation practices when water quality and furrow gradient are comprehensively considered.

Irrigation water quality not only affects the shear stress of runoff (erosivity) but also changes soil susceptibility to shear stress (erodibility). Meanwhile, the gradient of irrigation furrow also imposes an influence on both erosivity and erodibility because of the change of gravity components on fluid and soil particles (Li *et al.*, 2003). In addition, irrigation water quality and furrow gradient interact with each other, and they may exert a combined effect on irrigation erosion especially for loose soil surface in the cultivated fields. To test this hypothesis, the objectives of present study were: 1) to evaluate the effects of water quality on runoff and soil erosion at various furrow gradients under furrow irrigation; and 2) to investigate the combined effects of water quality and furrow gradient on runoff and soil loss in North China.

## MATERIALS AND METHODS

The tested soil was collected from the upper layer of 0–0.3 m of a cultivated field in the Yongledian Experimental Station of China Agricultural University, Beijing, China, which is located at the southeast plain of Beijing City ( $39^\circ 47' \text{ N}$ ,  $116^\circ 47' \text{ E}$ , 12 m above sea level). This region belongs to the semihumid continental monsoon climate, and the averaged annual precipitation is 595 mm. The soil was sandy loam with  $691.9 \text{ g kg}^{-1}$  sand,  $174.0 \text{ g kg}^{-1}$  silt, and  $134.1 \text{ g kg}^{-1}$  clay. Of the clay fraction, the dominant clay minerals were illite and montmorillonite ( $800 \text{ g kg}^{-1}$  together), and some kaolinite and chlorite were also present. The collected soil samples were air-dried and crushed to pass through a 4-mm sieve. The initial and the saturated gravimetric water contents for the tested soil were about 30 and  $325 \text{ g kg}^{-1}$ , respectively. The extract with soil to water ratio of 1:2 had an EC of  $0.265 \text{ dS m}^{-1}$ , with SAR of  $1.1 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  and pH of 7.21.

The experiment was conducted with plexiglass miniflumes with length  $\times$  width  $\times$  height of  $1.0 \text{ m} \times 0.1 \text{ m} \times 0.22 \text{ m}$ . Transition segments of V-shaped troughs with a  $90^\circ$  angle, each 0.2 m long, were connected to each of the two ends of the miniflume to facilitate water flow. The prepared soil samples were evenly packed into the miniflume, layer by layer, at the bulk density of  $1.4 \text{ Mg m}^{-3}$  until the top of the miniflume sides. A  $90^\circ$  V-shaped furrow with top width  $\times$  depth of  $4.4 \text{ cm} \times 2.2 \text{ cm}$  was made in the soil to simulate irrigation furrow. The gradient of irrigation furrow was adjusted to the designed value by hand.

The designed gradients of irrigation furrow were 1%, 3%, and 5%, the salt concentrations of irrigation water were 5, 10, 20, and  $30 \text{ mmol}_c \text{ L}^{-1}$ , and the SAR values of irrigation water were 0.5, 5.0, and  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$ . The designed salinity and SAR levels in irrigation water were obtained by mixing  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$  and NaCl (analytical reagents) with distilled water according to their calculated amounts.

The treatments were different combinations of furrow gradients, salt concentrations, and SAR levels, totaling 36. Irrigation with distilled water (salt concentration near  $0.05 \text{ mmol}_c \text{ L}^{-1}$ ) also was carried out at three tested gradients as controls. The inflow rate of irrigation water was  $1 \text{ L min}^{-1}$ . Before the experiment, the inflow rate was adjusted and maintained at the designed value by Mariotte bottles. The time that inflow water entered into irrigation furrow and outflow began to discharge at the end of the furrow was recorded. The outflow was collected and its volume was measured every 2 min during the experimental period. The experiment stopped until the runoff rate became approximately steady (20 min). The collected outflow samples were dried in oven at  $105 \text{ }^\circ\text{C}$  for 10 h, and the eroded soils were weighed. All treatments were carried out with three replicates, and the experimental data between treatments were analyzed by paired t-test according to SPSS 12.0.

## RESULTS

### Total runoff amount

Total runoff amounts at the furrow gradients of 1% and 5% at various tested salt concentrations and SAR levels of irrigation water are given in Fig. 1. The data at the furrow gradient of 3% are not presented because its variation tendency was similar to those at the gradients of 1% and 5%. The runoff amount generally decreased with salt concentration but increased with SAR level of irrigation water at various tested furrow gradients.

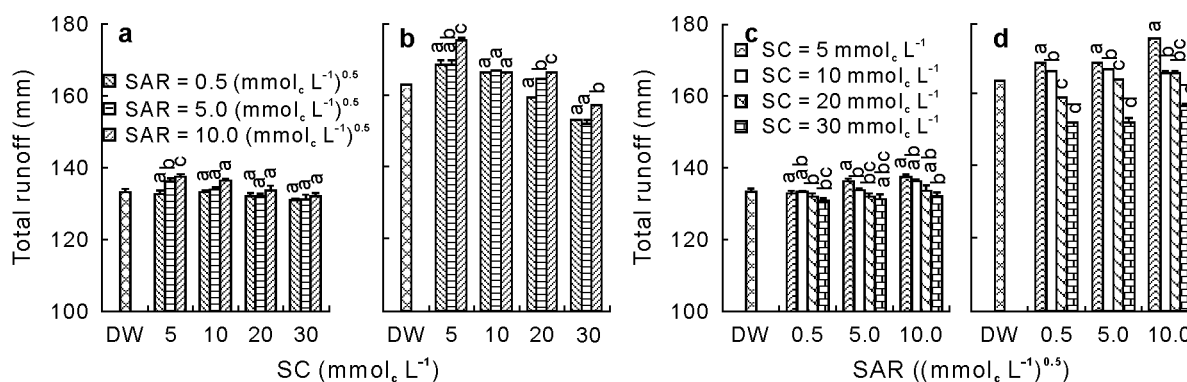


Fig. 1 Variation of total runoff amount with salt concentration (SC) and sodium adsorption ratio (SAR) value of irrigation water at the furrow gradients of 1% (a and c) and 5% (b and d). DW refers to distilled water (control). Columns labeled by the same letter(s) within groups do not differ significantly at the 0.05 probability level. Bars represent standard deviation.

Total runoff amount increased with the increased gradient of irrigation furrow (Fig. 1), which is in agreement with the results of Santos *et al.* (2003) measured under sprinkler irrigation. The total runoff amount followed an exponential function relationship with furrow gradient at 0.001 probability level ( $R^2 = 0.88$ ). In addition, the variation range of total runoff amount under various tested water quality conditions increased with furrow gradient; that is, the influence of water quality on soil permeability increased with furrow gradient.

Total runoff amount in the control was smaller than that in the treatments with the combination of low salt concentration and/or high SAR level, but it generally was greater than that in the treatments with salt concentrations of 20–30  $\text{mmol}_c \text{ L}^{-1}$  at various tested SAR levels and gradients (Fig. 1). This phenomenon indicated that the distilled water imposed certain adverse influence on the permeability of tested soil.

### Sediment concentration in runoff

The sediment concentration in runoff generally decreased with time first and then increased and approached to a steady state (data not shown), which was similar to the result of Kim and Miller

(1996) measured under rainfall simulator. The higher sediment concentration at the initial period of the experiment was because of loose and dry soil on the newly formed furrow, and the increased sediment concentration in the late period of the experiment possibly was a result of increased runoff amount and subsequently higher erosivity.

The increase of salt concentration or the decrease of SAR level in irrigation water decreased the averaged sediment concentration (Fig. 2). For example, when furrow gradient was 1%, the averaged sediment concentration in outflow was  $1.13 \text{ g L}^{-1}$  in the treatment with salt concentration of  $5 \text{ mmol}_c \text{ L}^{-1}$  and SAR of  $0.5 (\text{mmol}_c \text{ L}^{-1})^{0.5}$ . However, it decreased to  $0.38 \text{ g L}^{-1}$  when the salt concentration increased to  $30 \text{ mmol}_c \text{ L}^{-1}$  at the SAR value of  $0.5 (\text{mmol}_c \text{ L}^{-1})^{0.5}$ ; or it increased to  $1.65 \text{ g L}^{-1}$  when the SAR increased to  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  at the salt concentration of  $5 \text{ mmol}_c \text{ L}^{-1}$  (Fig. 2).

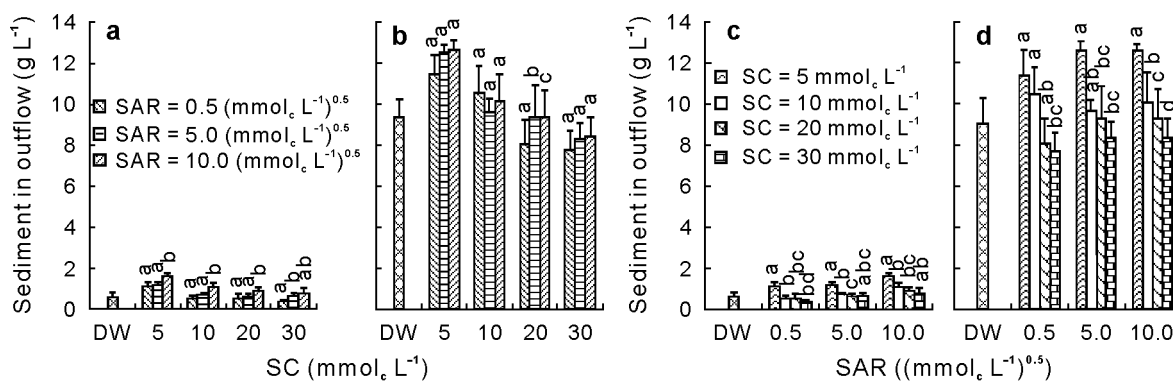


Fig. 2 Variation of averaged sediment concentration in runoff with salt concentration (SC) and sodium adsorption ratio (SAR) of irrigation water at the furrow gradients of 1% (a and c) and 5% (b and d). DW refers to distilled water (control). Columns labeled by the same letter(s) within groups do not differ significantly at the 0.05 probability level. Bars represent standard deviation.

It can be found in Fig. 2 that the sediment concentration significantly increased with the increase of furrow gradient, following a power function at 0.001 probability level ( $R^2 = 0.932$ ). When furrow gradient increased from 1% to 5%, the variation range of averaged sediment concentrations at various tested sodicity levels increased from  $1.13$ – $1.65$  to  $11.40$ – $12.63 \text{ g L}^{-1}$  and from  $0.38$ – $0.79$  to  $7.73$ – $8.35 \text{ g L}^{-1}$  for the salt concentrations of  $5$  and  $30 \text{ mmol}_c \text{ L}^{-1}$ , respectively.

The sediment concentration in the control was significantly lower than that in the treatments with salt concentration of  $5 \text{ mmol}_c \text{ L}^{-1}$  or SAR of  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  at the gradient of 1% or with salt concentration of  $5 \text{ mmol}_c \text{ L}^{-1}$  for various tested sodicity levels at the gradient of 5% (Fig. 2). However, it was equivalent to or slightly greater than that in the other treatments. This demonstrated that the effect of distilled water on sediment concentration was not very significant for the tested soil.

#### Total soil loss amount

Soil erosion was significantly affected by irrigation water quality and furrow gradient (Fig. 3). Similar to the sediment concentration, total soil loss amount generally decreased with salt concentration in irrigation water but increased with its SAR level under various furrow gradients. For example, the total soil loss amount at the gradient of 1% decreased by 53.92% when the salt concentration of irrigation water increased from  $5$  to  $30 \text{ mmol}_c \text{ L}^{-1}$  at the SAR level of  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$ . However, when the SAR of irrigation water increased from  $0.5$  to  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  at the salt concentration of  $5.0 \text{ mmol}_c \text{ L}^{-1}$ , it increased by 55.36%.

Total soil loss amount increased linearly with furrow gradient, being significant at 0.001 probability level ( $R^2 = 0.874$ ). As compared with the gradient of 1%, the total soil loss amount increased by 4.9–11.8 times and 8.9–23.5 times when furrow gradients were 3% and 5%, respectively.

At the furrow gradient of 1%, the total soil loss amount in the control was significantly smaller than

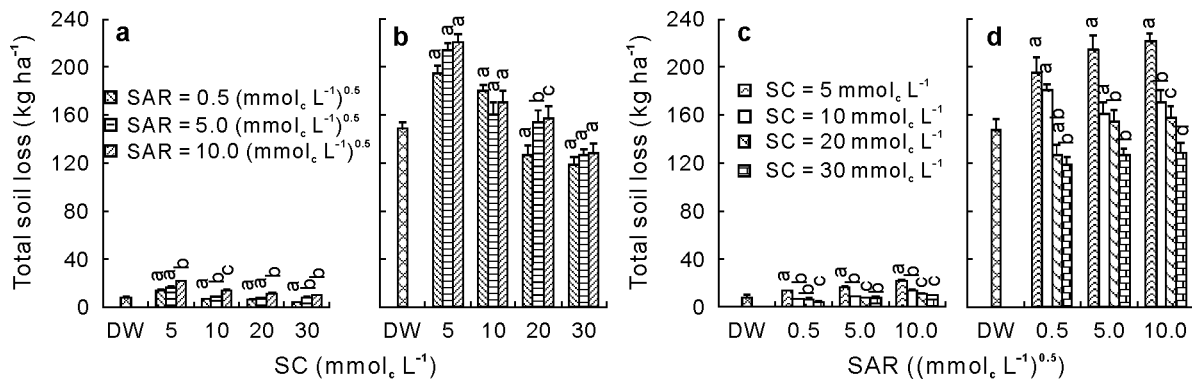


Fig. 3 Variation of total soil loss amount with salt concentration (SC) and sodium adsorption ratio (SAR) of irrigation water at the furrow gradients of 1% (a and c) and 5% (b and d). DW refers to distilled water (control). Columns labeled by the same letter(s) within groups do not differ significantly at the 0.05 probability level. Bars represent standard deviation.

that in the treatments with the salt concentration of 5 mmol<sub>c</sub> L<sup>-1</sup> or the SAR value of 10.0 (mmol<sub>c</sub> L<sup>-1</sup>)<sup>0.5</sup> at 0.05 probability level, but it was equivalent to or greater than that in the other treatments (Fig. 3). However, when the furrow gradient was 5%, the total soil loss amount in the control was smaller than that in the treatments with the salt concentrations of 5–10 mmol<sub>c</sub> L<sup>-1</sup> but equivalent to or greater than that in the other treatments (Fig. 3). These suggested that the adverse effect of distilled water on soil loss was enlarged with the increase of furrow gradient. In order to get a similar soil loss level, a higher salt concentration or lower sodicity was required when furrow gradient was great.

#### Relative runoff and soil loss amounts

The treatment with salt concentration of 30 mmol<sub>c</sub> L<sup>-1</sup> and SAR of 0.5 (mmol<sub>c</sub> L<sup>-1</sup>)<sup>0.5</sup> caused the smallest runoff amount and soil loss amount (Figs. 1 and 3); therefore it was taken as a base to calculate relative runoff amount and relative soil loss amount in all treatments (Fig. 4). The data in Fig. 4 clearly showed that the influences of salt concentration and SAR level in irrigation water on soil loss amount were much greater than those on runoff amount under various tested gradients.

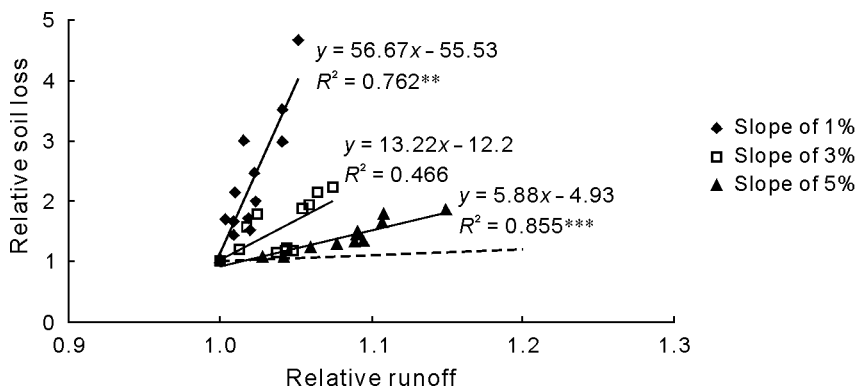


Fig. 4 Relative runoff amount and soil loss amount, by taking the treatment with salt concentration of 30 mmol<sub>c</sub> L<sup>-1</sup> and sodium adsorption ratio of 0.5 (mmol<sub>c</sub> L<sup>-1</sup>)<sup>0.5</sup> in irrigation water as a base, at the furrow gradients of 1%, 3%, and 5%. The dash line refers to the 1:1 line, which presents the same effects of salt concentration and SAR in irrigation water on runoff amount as those on soil loss amount.

## DISCUSSION

### Effect of irrigation water quality

After irrigation water enters into irrigation furrow, it flows mainly in two directions: the vertical

infiltration into soil and the movement along soil surface. Under a certain inflow rate, *i.e.*, irrigation rate, runoff amount in irrigation furrow depends on soil infiltration rate. Irrigation water quality affects soil clay dispersion and soil structure stability, and subsequently soil permeability and runoff amount if the soil solution concentration is below the critical flocculation concentration of soil clay (Shainberg and Letey, 1984; Kim and Miller, 1996; Hillel, 1998; Emdad *et al.*, 2004).

The salinity and sodicity of soil solution impose opposite effects on soil hydraulic properties. An increase of sodicity level in soil solution decreases soil permeability because of the blockage or narrowing of conducting pore passages, following soil clay dispersion or swelling, but the increase of salt concentration in soil solution counteracts the adverse influence of sodicity on it (Shainberg and Letey, 1984; Levy, 2000). Therefore, the decreased salinity and/or the increased sodicity in irrigation water resulted in a greater runoff amount (Fig. 1), a higher sediment concentration (Fig. 2), and more soil loss (Fig. 3). Under the experimental conditions, the treatment with salt concentration of  $5 \text{ mmol}_c \text{ L}^{-1}$  and SAR of  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  resulted in the greatest runoff amount (Fig. 1) and soil loss amount (Fig. 3). On the contrary, the treatment with salt concentration of  $30 \text{ mmol}_c \text{ L}^{-1}$  and SAR of  $0.5 (\text{mmol}_c \text{ L}^{-1})^{0.5}$  caused the smallest runoff amount and soil loss amount (Figs. 1 and 3), showing that this treatment was the most favorable combination of water quality parameters for soil structure stability under the experimental conditions.

The similar response tendencies of total runoff amount (Fig. 1) and total soil loss amount (Fig. 3) to salt concentration and sodicity in irrigation water demonstrated that runoff erosivity was the predominant factor influencing soil erosion. The possible decrease of soil erodibility resulting from the formation of a dense layer on soil surface under low salt concentration and/or high SAR was relatively small under the experimental conditions.

The much greater influences of salt concentration and SAR level in irrigation water on soil loss amount than those on runoff amount under various tested gradients (Fig. 4) were possibly due to the changes of both runoff erosivity and soil erodibility. First, runoff transport capability increased after dispersion occurrence. With the increase of runoff amount, the kinetic energy of water flow, *i.e.*, runoff erosivity, increased, dislodging bigger soil particles and resulting in a higher soil erosion rate. Second, soil erodibility also increased because of soil aggregate disintegration. Fine soil particles are more prone to be translocated than big soil aggregates at the same hydrodynamic conditions (Kim and Miller, 1996). The increased runoff erosivity and soil erodibility together resulted in a more significant effect of irrigation water quality on soil loss. For example, total runoff amount at the furrow gradient of 1% decreased only by 3.89% when the salt concentration of irrigation water increased from 5 to  $30 \text{ mmol}_c \text{ L}^{-1}$  at the SAR of  $10.0 (\text{mmol}_c \text{ L}^{-1})^{0.5}$ ; however, total soil loss amount decreased by 53.92% at the same conditions.

The variation of total runoff amount with salt concentration or sodicity level of irrigation water generally was gradual under the experimental conditions, and there seemed no existence of a concentration threshold on runoff for the tested soil (Fig. 1). However, the total soil loss amount diminished significantly when salt concentration was greater than some critical value such as 10 or  $20 \text{ mmol}_c \text{ L}^{-1}$  for various tested sodicity levels and furrow gradients (Fig. 3). Therefore, soil permeability and soil erosion seemed having different responsivities to the “critical flocculation concentration” of soil clay, and soil erosion was more sensitive to the devastation of soil structure.

#### *Effect of furrow gradient*

The gradient of irrigation furrow affected runoff hydrodynamics. With the increase of furrow gradient, the gravity component imposing on runoff water body along with furrow direction increased; therefore, the flow velocity of runoff and its kinetic energy became greater and greater. In addition, soil aggregates at a great gradient were easier to be moved because of greater gravity component on soil granules along the furrow direction. The distribution of particle sizes of sediments in outflow, measured by Kim and Miller (1996), testified this inference. It explained the increase of runoff amount (Fig. 1) and

soil loss amount (Fig. 3) with the increased furrow gradient. Maybe it also contributed to the result of the gradient effect on soil loss amount greater than on runoff amount (Fig. 4). For example, when furrow gradient increased from 1% to 5%, total runoff amount in the treatment with the salt concentration of  $30 \text{ mmol}_c \text{ L}^{-1}$  and SAR of 0.5 ( $\text{mmol}_c \text{ L}^{-1}$ )<sup>0.5</sup> increased by 16.8% and corresponding total soil loss increased by 22.6 times.

#### *Combined effect of water quality and furrow gradient*

As discussed above, both water quality parameters and furrow gradient affected runoff erosivity and soil erodibility. However, their influences on runoff amount and soil loss amount were interactive. For runoff, the influence of water quality increased with the increased furrow gradient because of easier flowing of water along with irrigation furrow at a great gradient. Therefore, the variation degree of runoff amount caused by water quality became great with the increase of furrow gradient (Fig. 1). However, the influence of water quality on soil erosion was weakened due to easier movement of soil particles at a great gradient, so the variation degree of soil loss amount caused by water quality decreased with the increase of furrow gradient (Fig. 3). For example, when irrigation water quality changed from the salt concentration of  $30 \text{ mmol}_c \text{ L}^{-1}$  and SAR of 0.5 ( $\text{mmol}_c \text{ L}^{-1}$ )<sup>0.5</sup> to the salt concentration of  $5 \text{ mmol}_c \text{ L}^{-1}$  and SAR of 10.0 ( $\text{mmol}_c \text{ L}^{-1}$ )<sup>0.5</sup>, total runoff amount increased by 5.1%, 7.4%, and 15.0% at the furrow gradients of 1%, 3%, and 5%, respectively. However, total soil loss amount increased by 365.8%, 122.7%, and 87.1% at the gradients of 1%, 3%, and 5%, respectively, under the same water quality. The opposite variation tendencies of runoff amount and soil loss amount with furrow gradient should be attributed to the interactive result of water quality and gradient.

## CONCLUSIONS

Total runoff amount, sediment concentration in runoff, and total soil loss amount generally decreased with salt concentration but increased with sodicity level of irrigation water. The effect of irrigation water quality on soil loss amount was greater than on runoff amount. The runoff amount, sediment concentration, and soil loss amount significantly increased with furrow gradient because of greater runoff erosivity and the easier movement of soil particles. Similar to the irrigation water quality, the furrow gradient also had a much greater influence on soil loss amount than on runoff amount. Irrigation water quality and furrow gradient imposed an obvious combined influence on runoff amount and soil loss amount due to their interaction. The increase of furrow gradient enhanced the effect of water quality on runoff but constrained its effect on soil erosion. Runoff and soil erosion were obviously related with irrigation water quality and irrigation furrow gradient. Therefore, irrigation water quality and furrow gradient should be considered together in the planning and management of furrow irrigation practices so as to maximize the utilization efficiency of irrigation water, minimize soil loss, and hence maintain a sustainable irrigated agriculture.

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