# Experimental study on the infiltration and salinity variation of saline soil under simulated rainfall

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**Abstract:** Soil salt drainage efficiency is of significant interest in quantifying soil remediation, related to external environment, soil properties, and amendment. This study mainly discusses the mechanism of slope gradients and rainfall intensities affecting water-salt transport in saline soils. Laboratory investigations were made to measure the key parameters including the wetting front, water content, and salinity in a flume of almost 1.2 m long under four slope gradients (0°, 5°, 10°, and 15°) and five rainfall intensities (10, 30, 50, 75, and 100 mm/h). The results show that the migration rate of water in soils increased with higher rainfall intensity and at lower slope gradients, in turn resulting in a substantial decrease in soil salinity. The rainfall intensity grew from 10 mm/h to 100 mm/h, and the water content growth rate and salinity decrease rate increased from 0.59%/min to 0.93%/min and 0.044%/min to 0.060%/min, respectively. The rainfall intensity has less influence on the time of salinity stabilization, which is approximately 420 to 480 min. Higher slope gradient and shorter distances from the slope top caused decrease in water-salt migration rate. The wetting front and water content showed a significant linear and exponential relationship with rainfall time respectively, while soil salinity as a function of rainfall time are piecewise functions. The results explicate the water-salt transport behavior of saline soils, and provide a scientific reference for soil remediation.
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## 1 Introduction

According to statistics, China is one of the most-affected countries by soil salinization, whose total saline soil area is about $3.6\times10^7$ hm$^2$, accounting for 4.88% of the available land area. To be specific, the saline arable land covers an area of $9.2\times10^4$ hm$^2$, accounting for 6.62% of the national arable land[1,2]. The deteriorating physical properties of these soils, such as dispersed soil particles, dense soil structure, high bulk density, and low hydraulic conductivity, are the culprits for the lower production of saline soils[3-5]. Over the past century, remediation measures, including hydraulic, physicochemical, and biological, have been extensively studied[6-9]. Salinity reduction rate is an important parameter for evaluating the validity of soil remediation practices. Rainfall intensity (RI), slope gradients (SG), and slope positions are major factors in influencing soil salt drainage efficiency, though soil texture, types, and incorporation rates of amendment, as well as underlying surface conditions, also have their impacts on soil-water-salt characteristics of saline soil. Moreover, it is noted that most of these remediation measures were carried out in the field. Previous field studies, especially those under natural rainfall conditions, not only consumed lots of resources but also took a long time to get the desired soils and rainfall conditions[2,10-12]. However, laboratory experiments using simulated rainfall have been rarely utilized to study the physicochemical properties of saline soil as well as water and salt transport processes. This is despite the fact that they possess several advantages, such as allowing a systematic replication of multiple rainfall and topographic conditions (e.g., spatiotemporal characteristics of rainfall, surface slope, and soil roughness).

Previous investigations have generally indicated that rainfall intensity and slope gradient mattered a lot to the flow velocity[13,14], although soil texture, slope length, and underlying surface conditions also affected the hydrodynamic characteristics of slope flow[15-17]. In this regard, Liu et al.[18] and Yang et al.[19] explored the influences of the incorporation of wheat straw on flow velocity and runoff under different rainfall intensities and slope gradients, respectively. Giménez and Govers[20] reported the laboratory measurement of flow velocity in rills under four slope gradients (3°, 5°, 8°, and 12°). Chen et al.[21] found that slope gradient, flow rate, and thawed soil depth had a remarkable effect on detachment rate using a laboratory simulated rainfall test. Furthermore, some surveys indicated that rainfall is considered to be an essential aspect influencing the hydrodynamics of hillside water flow[22,23]. To date, soil erosion and soil slope flow velocity under simulated rainfall conditions have been studied. However, limited research has been conducted on rainfall intensity and slope gradient despite their huge impacts on hydraulic and physicochemical properties of saline soil under simulated rainfall conditions.

In this study, laboratory investigations were made to measure the infiltration, water content, and salinity of coastal saline soil under five rainfall intensities (10, 30, 50, 75, and 100 mm/h) and four slope gradients (0°, 5°, 10°, and 15°). The study objectives are 1) to quantify the effect of the rainfall intensity and slope gradient on decrease rates of soil salinity and increase rates of water content; 2) to determine the impact of the rainfall intensity and slope

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gradient on the soil-water-salt movement process; and 3) to propose the function relationships between wetting front, water content, and salinity of soils and rainfall time, respectively, under simulated rainfall conditions. The findings of this study provide a scientific basis for the effective remediation of coastal saline-alkali soils.

## 2 Experimental materials and methods

### 2.1 Experimental materials

The experimental soils were obtained from a barren land in the eastern part of the Yellow River Delta of China (Figure 1a). The experimental saline soil had a pH value of 8.76 and a high salt content (EC=7.73 dS/m), a limiting factor for crop production. Moreover, the experimental soil was loam containing 53.56% sand, 38.20% silt, and 8.24% clay particles. Prior to the tests, the soil was screened through a sieve of 2 mm and dried in the air until the water content reached 1.97% (g/g). Basic physicochemical characteristics of the saline soil are displayed in Table 1.


Note: a. site pictures of borrow area; b. experimental apparatus (runoff erosion trough and rainfall simulator); c. experimental soil flume; d. sampling point diagram.

Figure 1 Experimental apparatus and samples

**Table 1 Characteristics of the saline soil in the Yellow River Delta of China**

| Source of variation | | Saline soil |
|---|---|---|
| pH[a] | | 8.76 |
| Bulk density/g·cm$^{-3}$ | | 1.46 |
| Electrical conductivity/(dS·m$^{-1}$)[a] | | 7.73 |
| Soluble salt/g·kg$^{-1}$ | | 21.20 |
| Cation exchange capacity/cmol·kg$^{-1}$ | | 13.21 |
| Saturated hydraulic conductivity/10$^{-5}$ cm·s$^{-1}$ | | 5.84 |
| Clay (<0.002 mm) | | 8.24 |
| Silt (0.002-0.020 mm) | | 38.20 |
| Sand (0.02–2.00 mm) | 0.02-0.20 mm | 53.54 |
| | 0.20-2.00 mm | 0.02 |

[a] Soil EC and pH were measured using 1:5 mixture of soil and water

### 2.2 Experimental equipment

The experimental device (i.e. rainfall simulator) was located in the Geotechnical Engineering and Soil Physics Laboratory, Shandong Agricultural University, Tai'an, China. In this study, the equipment was used to conduct a simulated rainfall experiment (Figure 1b). The simulator could generate a simulated rainfall of deionized water covering vast areas. Sideways projection of the simulated rainfall was carried out by using eight nozzles located at a distance of about 8 m above the ground, followed by its vertical fall towards the ground. The rainfall intensity was determined from the valves connected to pressure gauges, which automatically operated through a computer to monitor the electronic rain gauge. The speed of the raindrops simulated that of the natural rainfall after calibration.

The experimental soil flume had a length, width, and depth of 8, 5, and 0.3 m, respectively, which was located below the rainfall simulator. Due to the large length and width of the flume, a large amount of soil was required, and the flume was constructed using steel plates and was not transparent to observe the transport of soil wetting fronts. Thus, in this study, a self-designed transparent container with length, width, and depth of 1.2 m, 0.4 m, and 0.3 m, respectively (Figure 1c), was constructed in the middle of the flume. The drainage holes were opened at the bottom of the self-designed flume to permit the escape of soil-air.

### 2.3 Experimental design

This experiment was divided into two parts with a total of 27 sets of tests. Part One was designed with a fixed slope gradient of 0° and five rainfall intensities (10, 30, 50, 75, 100 mm/h). Part Two provided a fixed rainfall intensity of 50 mm/h but four slope gradients (0°, 5°, 10°, 15°). Each treatment had three replicates. Based on the infiltration of the soil and the natural rainfall intensities, the simulated rainfall intensity was designed. Under normal conditions, rainfall intensity in the Yellow River Delta of China may reach 10-100 mm/h[24].

The self-designed experimental soil flume was supported on a mobile framework which was allowed to be set at different slope gradients, and which was used to accommodate the soils in the experimental program. While the flumes were set horizontally, the self-made soil flume was uniformly packed with air-dried soil material by pouring a specific soil mass into a specific volume of the box in the form of a layer with a thickness of 20 cm. A wooden paddle was used for tamping the materials down so that a 1.46 g/cm$^3$ bulk density was achieved, a representative bulk density of soils on the sampling sites. High porosity material having 4.75-9.50 mm particle size with a thickness of 5 cm was laid in the middle of the box, and the lower layer of the box contained 5 cm saline soil (Figure 1c). The air escaped through 2 mm holes, spaced 20 mm from each other, in the bottom of the box. The bottom of the box was covered with a thin cloth to prevent the soil contents loss.

In the process of rainfall test by changing the rainfall intensity, the wetting front transport condition was firstly recorded, and soil samples were collected from 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm layers at certain time intervals according to the wetting front so as to measure the soil's water contents and salinity, respectively. During the test by changing the slope gradient, the movements of the wetting front at 10 cm, 60 cm, 95 cm, and 115 cm from the top of the slope were recorded, and soil samples were collected at certain time intervals to measure the water content and salinity according to the movement of the wetting front, as shown in Figure 1d. The D10, D60, D95, and D115 represent a distance of 10 cm, 60 cm, 95 cm, and 115 cm to the top of the slope, respectively.

### 2.4 Data analysis

With the help of the drying method, the water contents of the samples were measured, and the salinity of the samples were converted from the electrical conductivity (EC) measured by the conductivity meter using the Equation (1) proposed by Liu et al[25]:

$$y = -0.001\,86 + 2.741\,39x \approx 2.74x \quad (1)$$

where, $y$ is the soil salinity, %, and $x$ is the soil electrical conductivity, mS/mm.

## 3 Results

### 3.1 Effects of rainfall intensity on the infiltration of saline soil

Figure 2 shows that the soil infiltration rate increased with higher rainfall intensity, and the mean migration rate of wetting front generally followed the sequence of $V_{10\ \mathrm{mm/h}}>V_{30\ \mathrm{mm/h}}>V_{50\ \mathrm{mm/h}}\approx V_{75\ \mathrm{mm/h}}\approx V_{100\ \mathrm{mm/h}}$. When the wetting front reached a depth of 200 mm (bottom of the soil flume), the duration of water infiltration was 152 min for the 10 mm/h, 116 min for 30 mm/h, 92 min for 50 mm/h, 90 min for 75 mm/h, and 88 min for 100 mm/h. The transport rate of the wetting front with 100 mm/h rainfall intensity increased by 70.58% and 30.94% as compared to the rainfall intensity of 10 mm/h and 30 mm/h, but only rose by 5.56% and 2.53% compared with that of a rainfall intensity of 50 mm/h and 75 mm/h. Table 2 implies that there was a linear relationship between rainfall duration and soil wetting front under different rainfall intensities.

### 3.2 Effects of rainfall intensity on the water content of saline soil

Figure 3 presents the variations of the soil water content for different depths under various rainfall intensities over time. Results demonstrated that the time taken for the soil to reach saturation decreased with an increasing rainfall intensity. Furthermore, with the increase in sampling depth, the impact of rainfall intensity on soil saturation time increases. Figure 3 also displays that the rainfall intensity had less effect on the soil saturated water content, which was approximately 35%, and the water content increased exponentially with the rainfall time under variable experimental parameters.

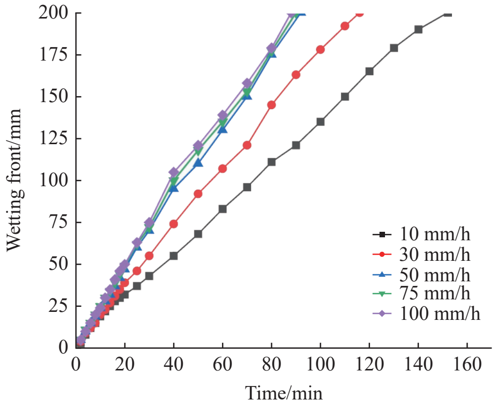



Figure 2 Relationship between wetting front and time under different rainfall intensities

**Table 2 Fitting of relationship between soil wetting front and rainfall time under different rainfall intensities**

| RI/mm·h⁻¹ | Fitting function (1) | | Fitting function (2) | |
|---|---|---|---|---|
| | Power function | $R^2$ | Linear | $R^2$ |
| 10 | $F=1.85t^{0.93}$ | 0.998 | $F=1.36t$ | 0.999 |
| 30 | $F=2.20t^{0.95}$ | 0.998 | $F=1.77t$ | 0.999 |
| 50 | $F=2.75t^{0.95}$ | 0.997 | $F=2.20t$ | 0.999 |
| 75 | $F=3.09t^{0.92}$ | 0.998 | $F=2.27t$ | 0.999 |
| 100 | $F=3.24t^{0.92}$ | 0.997 | $F=2.32t$ | 0.999 |

The calculated growth rates in soil water content under increasing rainfall intensities and sampling depths are listed in Table 3. The soil water content increase rate increased significantly with higher rainfall intensity ($p$<0.05). The growth rates of the water content ranged from 0.44 %/min to 0.89 %/min, 0.54 %/min to 0.88 %/min, 0.74 %/min to 1.09 %/min, 0.75 %/min to 1.13 %/min, and 0.72 %/min to 1.17 %/min under 10, 30, 50, 75, and 100 mm/h rainfall intensity, respectively. Furthermore, compared to other soil layers, the increase rate in soil water content was highest in the top soil (0-5 cm), ranging from 0.88%/min to

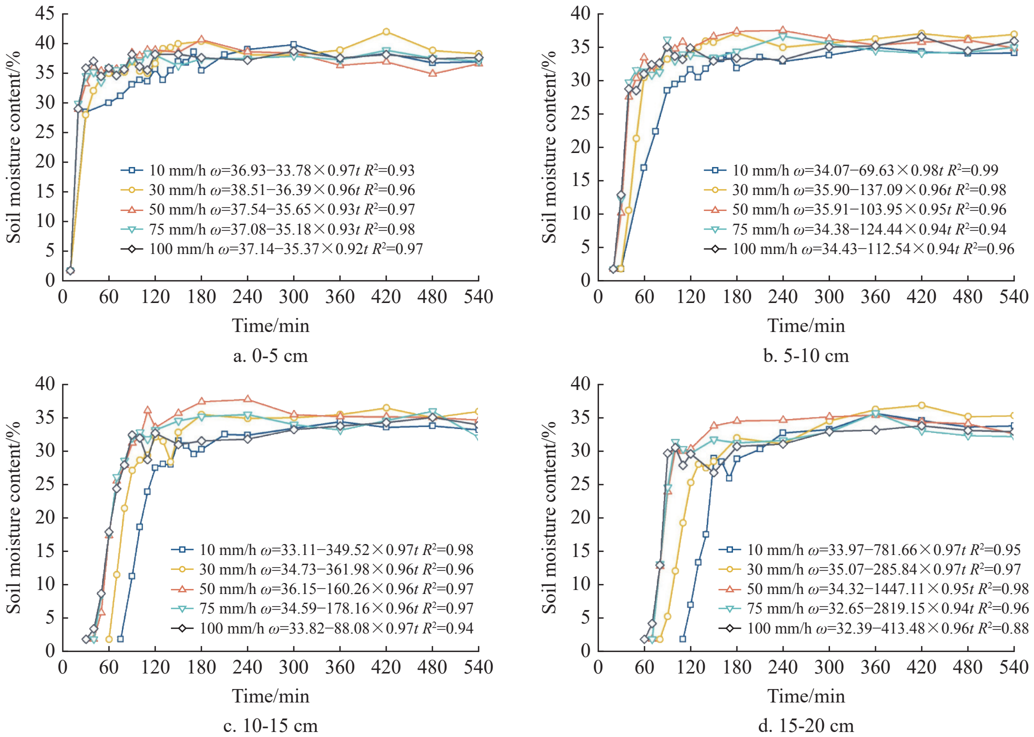



Figure 3 Relationship between soil water content and time under different rainfall intensity

1.17%/min. This can be attributed to the fact that when the water content of the lower layer starts to change, the upper layer is close to saturation and water starts to infiltrate steadily.

**Table 3 Rising rate of soil water content under different rainfall intensities**

| Soil layer/cm | Rising rate of soil water content/%·min$^{-1}$ | | | | |
|---|---|---|---|---|---|
| | 10 mm/h | 30 mm/h | 50 mm/h | 75 mm/h | 100 mm/h |
| 0–5 | 0.89 | 0.88 | 1.09 | 1.13 | 1.17 |
| 5–10 | 0.44 | 0.78 | 1.03 | 1.07 | 1.07 |
| 10–15 | 0.50 | 0.69 | 0.83 | 0.82 | 0.72 |
| 15–20 | 0.52 | 0.54 | 0.74 | 0.75 | 0.76 |
| Mean value | 0.59 | 0.72 | 0.92 | 0.94 | 0.93 |

When the rainfall intensity increased from 10 mm/h to 50 mm/h, the increase rates of soil water content increased by 22.47%, 134.09%, 66%, and 42.31% for the sampling depths of 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm. However, at the rainfall intensity of 50-100 mm/h, the rainfall intensity had the least influence on the increase rates of water content.

### 3.3 Effects of rainfall intensity on soil salinity

As observed in Figure 4, the salinity of the surface soil (0-5 cm) decreases exponentially with rainfall time. Apart from the surface soil, the soil salinity is a piecewise function of rainfall time. The first section of the function is a straight line that increases linearly with rainfall time, and the second section is a curve that decreases exponentially with rainfall time. Thus, the soil salinity increased and then decreased with rainfall time, and the salinity in the soil was ultimately reduced to near 0 under the continuous rainfall drenching effect. Moreover, the $y$-coordinate of the intersection point of the two functions is denoted as the peak salinity. The peak salinity of soil increased prominently with the increase in soil depth.

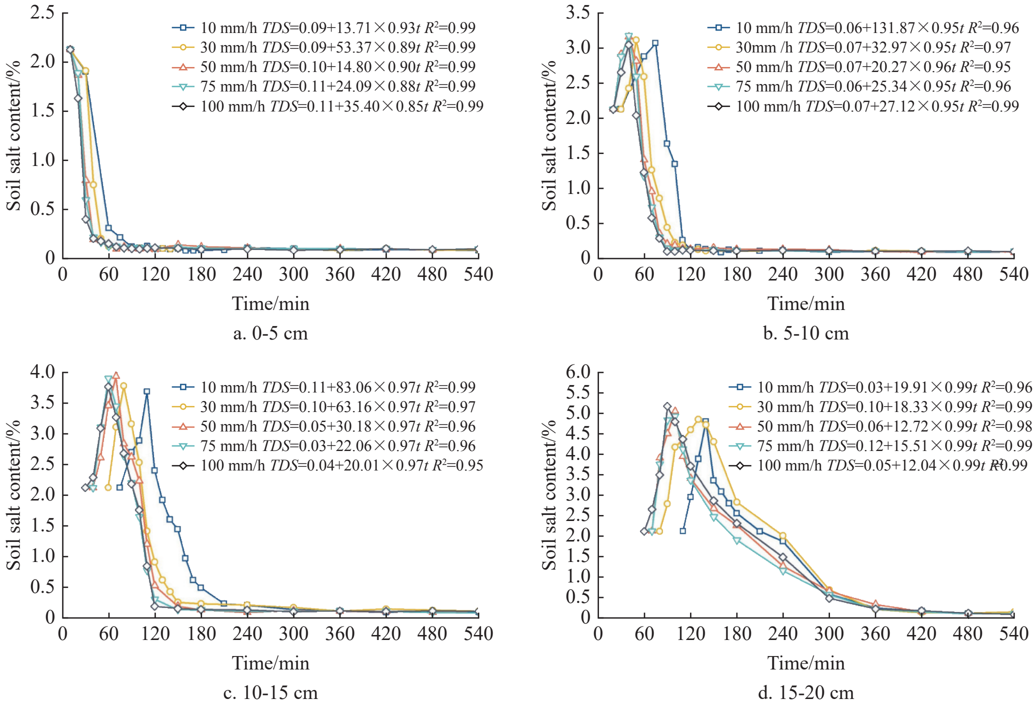



Figure 4 Relationship between soil salinity and time under different rainfall intensity

For the soils in the 0 to 15 cm depth range, rainfall intensity had a positive effect on the time to reach stabilization of the soil salinity. When the rainfall intensity was 10 mm/h, the time for soil salinity stabilization at 0-15 cm depth was greatly longer than that for other rainfall intensities. However, the rainfall intensity had less effect on the time for soil salinity stabilization at a depth of 15-20 cm, which was about 420 to 480 min (Figure 4d).

Based on the experimental data, the computed decrease rates in soil salinity under increasing rainfall intensities and sampling depths are listed in Table 4. The decrease rates of salinity in the surface soil (0-5 cm) were significantly more than those of soil salinity at other depths, ranging from 0.051 %/min to 0.086 %/min. Also, the rates of soil salinity reduction significantly decreased with increasing soil depth at the same rainfall intensity. Additionally, this study also displays that as the rainfall intensity increased, the mean decrease rates of soil salinity also gradually increased. The mean decrease rates of soil salinity were 0.044 %/min, 0.055 %/min, 0.056 %/min, 0.057 %/min, and 0.060 %/min under rainfall intensities of 10, 30, 50, 75, and 100 mm/h, respectively.

**Table 4 The decreasing rate of soil salinity under different rainfall intensities**

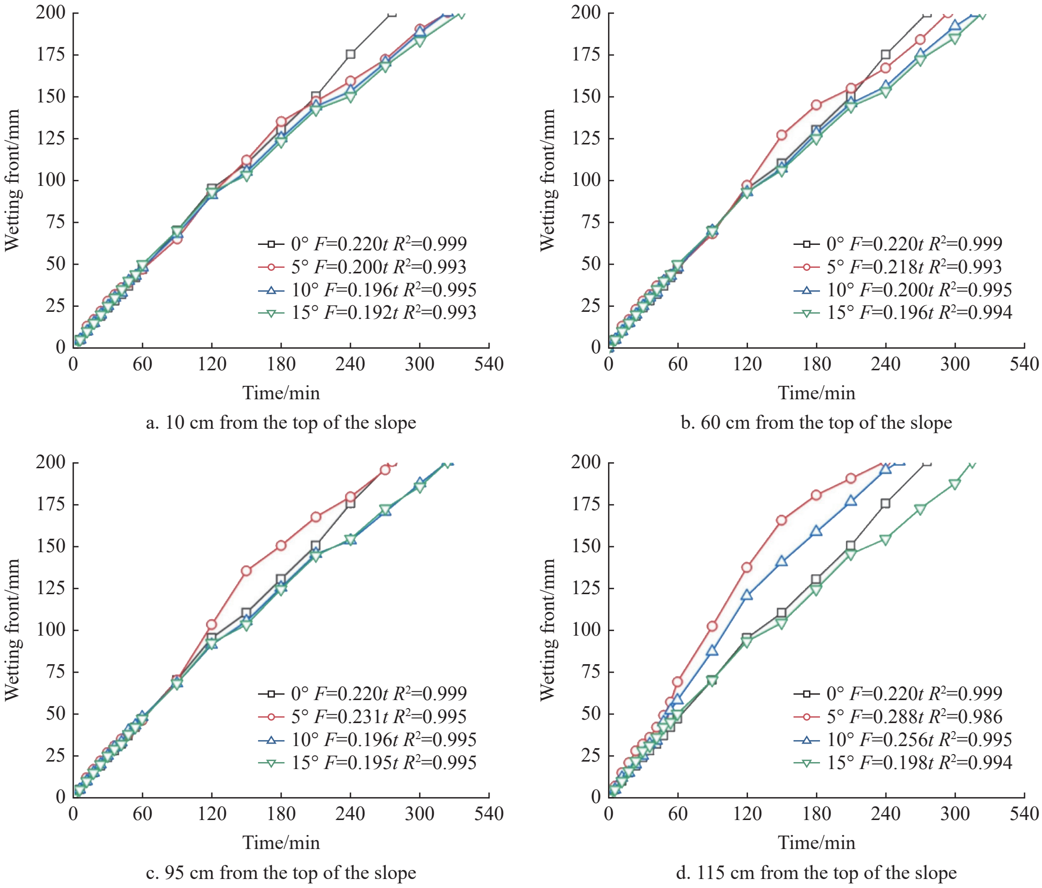
| Soil layer/cm | Salinity reduction rate/%·min$^{-1}$ | | | | |
|---|---|---|---|---|---|
| | 10 mm/h | 30 mm/h | 50 mm/h | 75 mm/h | 100 mm/h |
| 0–5 | 0.051 | 0.085 | 0.083 | 0.084 | 0.086 |
| 5–10 | 0.067 | 0.061 | 0.064 | 0.064 | 0.070 |
| 10–15 | 0.041 | 0.053 | 0.058 | 0.061 | 0.062 |
| 15–20 | 0.015 | 0.019 | 0.019 | 0.020 | 0.022 |
| Mean value | 0.044 | 0.055 | 0.056 | 0.057 | 0.060 |

### 3.4 Effects of slope on the infiltration of saline soils

Figure 5 displays the dynamic changes of soil wetting front at various distances from the slope top with different slope gradients. As the distance from the slope top increases, there is more critical influence of slope gradient on the migration of wetting fronts. For D10, the wetting fronts moved the greatest at a slope gradient of 0°, 10.01%, 12.29%, and 14.50% faster than those at a slope gradient of 5°, 10°, and 15°, respectively (Figure 5a). For D60, the wetting fronts moved 0.87%, 9.98%, and 12.11% faster at 0° than at 5°, 10°, and 15°, respectively (Figure 5b). For D95, the wetting fronts moved fastest at 5°, 5.01%, 17.94%, and 18.21% faster than at 0°, 10°, and 15° (Figure 5c). For D115, the wetting fronts moved 31.28%, 12.84%, and 45.76% faster at a slope gradient of 5° than at 0°, 10°, and 15°, respectively (Figure 5d).

### 3.5 Effects of slope on the water content of saline soils

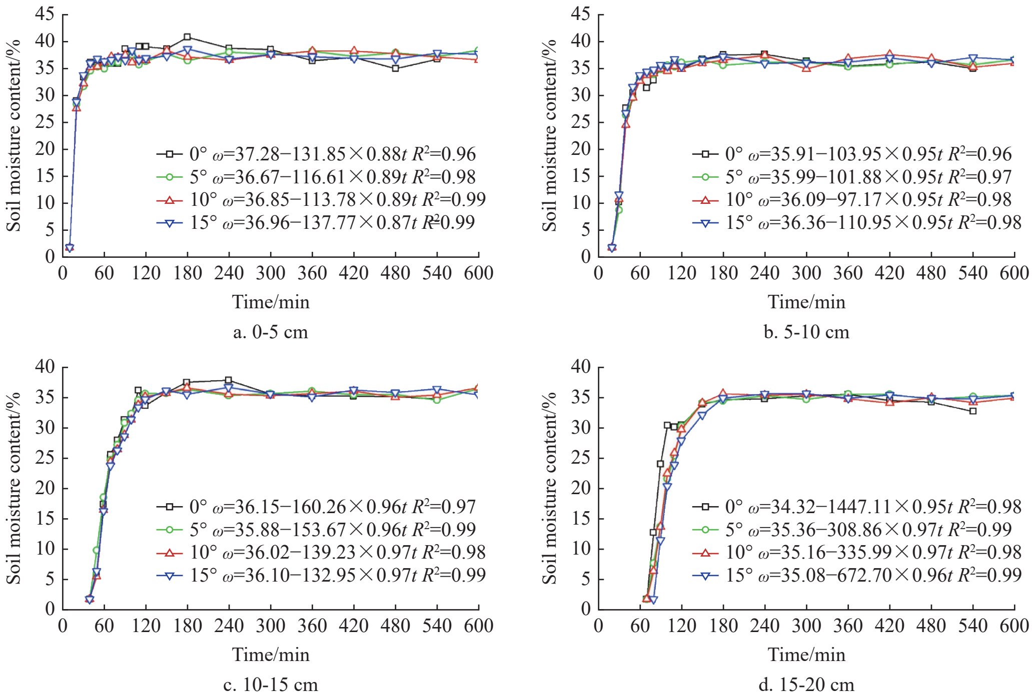
Figure 6 presents the curves of soil water content versus rainfall time for different slope gradient at 10 cm from the slope top. As shown in Figure 6, the soil water content increased dramatically over time and then stabilized, and the experimental function was used to express the correlation between soil water content and time. No significant difference was identified in the effect of slope gradient on the time for the soil to reach saturation water content. It was notable that the relationship curves between water content and rainfall time at 60, 90, and 115 cm from the slope top for different slope gradient conditions presented similarly.




a. 10 cm from the top of the slope b. 60 cm from the top of the slope

c. 95 cm from the top of the slope d. 115 cm from the top of the slope

Figure 5 Relationship between wetting front and time




a. 0-5 cm b. 5-10 cm

c. 10-15 cm d. 15-20 cm

Figure 6 Relationship between soil water content and time at 10 cm from the top of slope

The increase rates in soil water content under various slope gradients and slope positions are listed in Table 5. Under the same slope position, the growth rate of water content increased at greater slope gradient, and the maximum value of 0.922 %/min was obtained at 0°. Furthermore, the experimental data demonstrated that apart from the slope gradient of 0°, the further away from the slope top, the higher the increase rate of water content. The mean increase rate of water content at 10, 60, 90, and 115 cm from the slope top ranged from 0.648-0.689 %/min, 0.680-0.778 %/min, 0.674-0.792 %/min, and 0.685-0.923 %/min, respectively.

It can also be observed in Table 5 that increasing sampling depth causes a decrease in the increase rates of the water content. When the soil depth increased from 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, and 15 to 20 cm, respectively, the increase rate of water content ranged from 1.011 %/min to 1.104 %/min, from 0.656 %/min to 1.123 %/min, from 0.414 %/min to 0.929 %/min, and from 0.408 %/min to 0.552 %/min.

### 3.6 Effects of slope on soil salinity

Since the trend of soil salinity in relation to time was consistent for different slope positions, the change in soil salinity for D10 was used to express this trend, as displayed in Figure 7. As shown in Figure 7, the salinity of the surface soil decreased exponentially with increasing time, and the salinity of the other soil layers increased linearly and then decreased exponentially. The peak soil salinity increased dramatically with increasing sampling depth, from 2.2% in the surface layer to 5.4% in the bottom layer. The time to stabilization of soil salinity was not significantly related to slope gradient, while slope position had a certain impact on it. The stabilization time of the soil salinity was 9-10 h for D10, 8-9 h for D60, 8-9 h for D95, and 7-8 h for D115. Thus, the further away from the top of the slope, the faster the time required for the soil salinity to stabilize.

**Table 5 Rising rate of soil water content in different soil layers under different slope gradients and slope positions**

| Distance from top of slope/cm | Soil layer/cm | Rising rate of water content/%·min⁻¹ | | | |
|---|---|---|---|---|---|
| | | 0° | 5° | 10° | 15° |
| 10 | 0-5 | 1.093 | 1.011 | 1.044 | 1.071 |
| | 5-10 | 1.029 | 0.671 | 0.656 | 0.835 |
| | 10-15 | 0.826 | 0.654 | 0.465 | 0.414 |
| | 15-20 | 0.740 | 0.421 | 0.425 | 0.410 |
| | Mean value | 0.922 | 0.689 | 0.648 | 0.683 |
| 60 | 0-5 | 1.093 | 1.040 | 1.037 | 1.071 |
| | 5-10 | 1.029 | 0.889 | 0.792 | 0.826 |
| | 10-15 | 0.826 | 0.653 | 0.483 | 0.415 |
| | 15-20 | 0.740 | 0.530 | 0.421 | 0.408 |
| | Mean value | 0.922 | 0.778 | 0.683 | 0.680 |
| 95 | 0-5 | 1.093 | 1.043 | 1.051 | 1.046 |
| | 5-10 | 1.029 | 0.903 | 0.790 | 0.815 |
| | 10-15 | 0.826 | 0.670 | 0.478 | 0.415 |
| | 15-20 | 0.740 | 0.551 | 0.432 | 0.420 |
| | Mean value | 0.922 | 0.792 | 0.688 | 0.674 |
| 115 | 0-5 | 1.093 | 1.089 | 1.104 | 1.042 |
| | 5-10 | 1.029 | 1.123 | 0.864 | 0.858 |
| | 10-15 | 0.826 | 0.929 | 0.553 | 0.417 |
| | 15-20 | 0.740 | 0.552 | 0.508 | 0.421 |
| | Mean value | 0.922 | 0.923 | 0.757 | 0.685 |

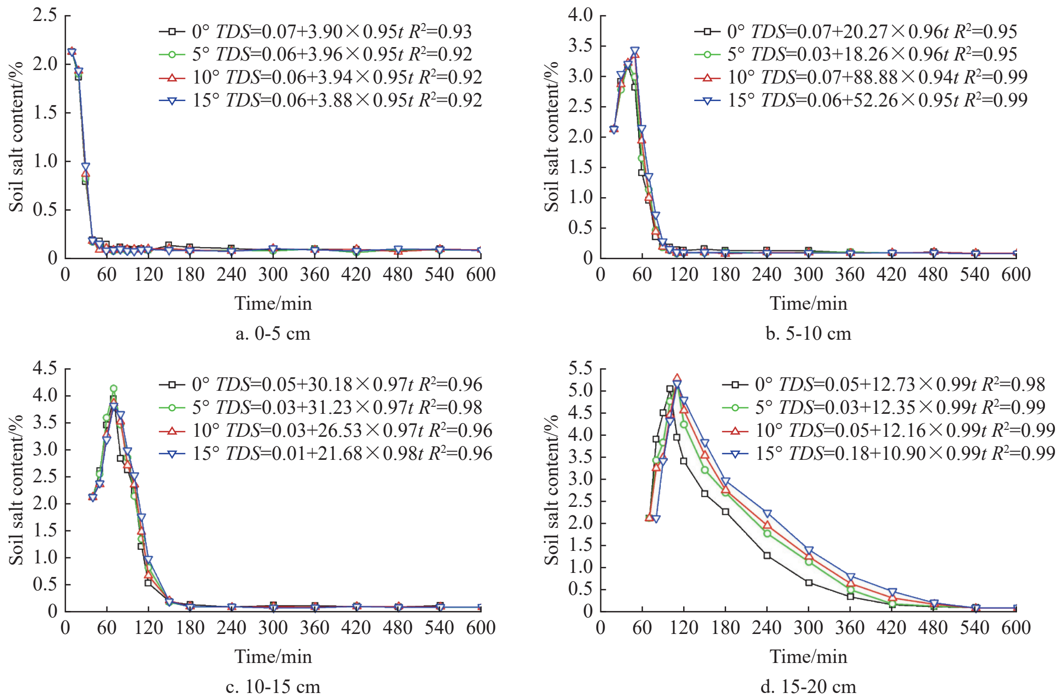



Figure 7 Relationship between soil salinity and time at 10 cm from the top of slope

The computed decrease rates in soil salinity at different sampling depth under different slope gradients and positions are listed in Table 6. Both slope gradient and position had an effect on the decrease rate of soil salinity. Under the same slope gradient, the mean decrease rate of soil salinity with increasing distance from the top of the slope, first remained basically stable and then increased dramatically at the foot of the slope. The decrease rates of soil salinity ranged from 0.046 %/min to 0.056 %/min, 0.047 %/min to 0.056 %/min, 0.046 %/min to 0.056 %/min, and 0.050 %/min to 0.070 %/min for 10 cm, 60 cm, 90 cm, and 115 cm from the top of the slope, respectively.

Apart from D115, the reduction rate of soil salinity decreased with increasing slope gradient. It is noteworthy that the impact of slope gradient on soil salinity decrease rate was significant in the slope gradient range from 0° to 5°. When the slope gradient increased from 0° to 5°, the mean reduction rate of salinity decreased from 0.056 %/min to 0.051 %/min, 0.056 %/min to 0.050 %/min, and 0.056 %/min to 0.050 %/min for D10, D60, and D90, respectively. For D115, there was no significant function between the slope gradient and the decrease rate of soil salinity. The decrease rates of salinity were 0.056 %/min, 0.070 %/min, 0.061 %/min, and 0.050 %/min when the slope gradients were 0°, 5°, 10°, and 15°, respectively. This condition could be the reason that when the rainfall intensity was stronger than the soil infiltration capacity, surface runoff appeared on the cultivated land. Due to the slope gradient, a large amount of rainwater gathered at the slope toe, resulting in a decreased rate in soil salinity at the slope toe independent of the slope gradient.

**Table 6 Reduction rate of soil salinity in different soil layers under different slope gradients and slope positions**

| Distance from top of slope/cm | Soil layer/cm | Salinity reduction rate/%·min$^{-1}$ | | | |
|---|---|---|---|---|---|
| | | 0° | 5° | 10° | 15° |
| 10 | 0-5 | 0.083 | 0.069 | 0.058 | 0.057 |
| | 5-10 | 0.064 | 0.066 | 0.078 | 0.064 |
| | 10-15 | 0.058 | 0.052 | 0.050 | 0.049 |
| | 15-20 | 0.019 | 0.015 | 0.014 | 0.015 |
| | Mean value | 0.056 | 0.051 | 0.050 | 0.046 |
| 60 | 0-5 | 0.083 | 0.068 | 0.057 | 0.056 |
| | 5-10 | 0.064 | 0.066 | 0.077 | 0.066 |
| | 10-15 | 0.058 | 0.050 | 0.051 | 0.051 |
| | 15-20 | 0.019 | 0.015 | 0.013 | 0.015 |
| | Mean value | 0.056 | 0.050 | 0.050 | 0.047 |
| 95 | 0-5 | 0.083 | 0.070 | 0.057 | 0.056 |
| | 5-10 | 0.064 | 0.068 | 0.075 | 0.062 |
| | 10-15 | 0.058 | 0.046 | 0.049 | 0.050 |
| | 15-20 | 0.019 | 0.014 | 0.013 | 0.015 |
| | Mean value | 0.056 | 0.050 | 0.049 | 0.046 |
| 115 | 0-5 | 0.083 | 0.098 | 0.067 | 0.056 |
| | 5-10 | 0.064 | 0.088 | 0.082 | 0.077 |
| | 10-15 | 0.058 | 0.075 | 0.079 | 0.051 |
| | 15-20 | 0.019 | 0.020 | 0.017 | 0.015 |
| | Mean value | 0.056 | 0.070 | 0.061 | 0.050 |

## 4 Discussion

Water-salt transport characteristics in saline soils were impacted by soil texture, bulk density, total porosity, and pore size distribution[25-27]. Further, the external environment including rainfall intensity, temperature, additive and slope gradient also are the major influencing factors for soil water infiltration and salinity[28,29]. In the present investigation, the influences of rainfall intensity and slope gradient on the water-salt transport characteristics of saline soil under simulated rainfall conditions were discussed using laboratory simulations.

### 4.1 Impact of rainfall intensity and slope on soil wetting front

The mechanisms of rainfall intensity on soil infiltration capacity are as follows: 1) When the rainfall intensity is less than that of soil infiltration capacity, all rainwater can be absorbed by the soil, and the infiltration rate is determined by the rainfall intensity at this time; 2) when the rainfall intensity is greater than the soil infiltration capacity, the infiltration rates are more dependent on soil properties than on rainfall intensity[30,31]. In other words, there is a critical value of rainfall intensity; when the rainfall intensity exceeds a threshold, surface runoff occurs, and the rainfall intensity is not the primary element affecting the soil infiltration rate at this time. In this experiment, with increasing rainfall intensity, the migration rate of wetting fronts increased. Compared with the RI10, rainfall intensity decreased the time for the wetting front to reach the bottom of the soil flume by about 23.68% for RI30, 39.47% for RI50, 40.79% for RI75, and 42.11% for RI100 (Figure 2). It can be observed that with a rainfall intensity higher than 50 mm/h, the effect of rainfall intensity on the transport rate of the wetting front decreased significantly. These results are supported by other investigations that have reported that water flow velocity increased as higher rainfall intensity and slope gradient were applied[18,19].

The effect of slope gradient on soil wetting front depended on the slope position[31]. The experimental data of this study, in general, supported this conclusion that the transport rate of the wetting front decreased with the increase of slope gradient for D10 and D60; while for D95 and D115, the migration rates of the wetting front demonstrated an increase followed by a decrease as the slope gradient increased, with the maximum under the slope gradient of 5° (Figure 5). Thus, slope position and slope gradient collectively affect soil-water-salt transport. Most studies showed that there is a power function relationship between the wetting front and time in soil column tests[26,32]. In contrast, this case found that there was a significant linear relationship between the wetting front and the time under simulated rainfall conditions (Figure 2 and Figure 5).

### 4.2 Impact of rainfall intensity and slope on soil water content

The main forms of water movement in the soil under rainfall include infiltration, interflow, surface runoff, and even preferential flow[33-35]. The previous studies of the research team have shown that the saline soils in the area have a dense structure with a concentrated pore size distribution and good homogeneity of the soil[36,37]. Therefore, water in the soils of the region mainly transports in the form of infiltration and runoff, and there is no preferential flow and interflow.

In this study, rainfall intensity and slope gradient had an effect on the soil water content. Among these, the increased rate of soil water content rose with the height of rainfall intensity, which was consistent with the experimental results of Yang et al.[23]. They demonstrated that higher rainfall intensity was not suitable for the formation of crusts, thus the resulting soils have greater initial infiltration rates. Besides, this study demonstrated that smaller rainfall intensities (10-50 mm/h) had a notable influence on the soil water content as the sampling depth increased, while the extent of this effect was decreasing at higher rainfall intensities (50-100 mm/h) (Table 3). This is consistent with the findings of studies on soil wetting fronts. From this, it can be seen that there may be a critical rainfall intensity, which in this study was at 50 mm/h. Fang et al. also found that there was no statistically considerable improvement in the runoff from the 90 mm/h and 120 mm/h.

The slope gradient, sampling location, and sampling depth together affect the variation of the water content[38]. At 50 mm/h rainfall intensity, the surface soil saturated swiftly during the early rainfall, thus there was little difference in the increase rates of water content at the 0-5 cm soil layer under the influence of different slope gradients and slope positions. At each layer within 5-20 cm, apart from the location of the slope foot, the increase rate of water content decreased with the increase of slope gradient. For D115, the increase rate of water content was the highest when the slope gradient was 5°, and the change of slope gradient had a more significant effect on the increase rate of water content on this slope position (Table 5). It follows that the slope toe has a different effect on soil water content than the other slope positions, which is explained by the appearance of soil surface runoff at the experimental design rainfall intensity, resulting in a large amount of rainwater collected at the slope toe.

### 4.3 Impact of rainfall intensity and slope on soil salinity

Researchers have observed that the process of soil salt leaching is top-down, which is the same as for the infiltration of soil[39-41]. This investigation found that the peak soil salinity rose, and the time required to reach the peak increased with increasing sampling depth (Figure 4). For example, with a rainfall intensity of 10 mm/h, the peak salinity in the 15-20 cm soil layer increased by 36.06% and 23.08% compared to the 5-10 cm and 10–15 cm layers, respectively (Table 4). The experimental results confirmed the principle for the “salt moving with water”; that is, these salts normally flow into the comparatively deeper soil with rainwater owing to the effect of gravity[42,43].

It is well known that rainfall intensity, slope and rainfall duration, and soil properties affect the soil salinity[44-48]. This study found that the rainfall intensity affected the decrease rate of soil salinity at each layer (Figure 4). Compared with the RI10, rainfall intensity increased the mean decrease rate of soil salinity by about 19.27%, 21.43%, 23.14%, and 26.67% for RI30, 50, 75, and 100 respectively (Table 4). The efficiency of salt discharge increased with rainfall intensity, and the decrease rate of soil salinity slowed down when the rainfall intensity increased to the range of 50-100 mm/h. Additionally, the results of the experiment also suggested a positive relationship between the stabilization time of soil salinity and the rainfall intensity at 0 to 15 cm depth, while no such relationship was observed in the bottom layer. This may be due to the long sampling interval in the latter part of the experiment.

This study also found that the soil salinity drainage efficiency was affected by slope gradient and slope position under constant rainfall intensity (Figure 7). The mean decrease rate of soil salinity at the slope toe was higher than that at the slope top under the same rainfall intensity and slope gradient. Thus, the slope top should perhaps be given more attention in soil restoration. For D10, D60, and D95, the decrease rate of salinity at 0-5 cm, 10-15 cm, and 15-20 cm soil layers showed a downward trend with increasing slope gradient (Table 6), which may be associated with the increased length of water infiltration channels under the influence of slope gradient. For D115, the salinity decrease rates rose first and then slowed down, and the highest decrease rate of salinity was 0.070 %/min when the slope gradient was 5°. This might be due to the collection of water flow at the slope toe after the generation of surface runoff and the increase of rainwater, resulting in a larger decreasing rate of soil salinity. According to Table 6, the mean decrease rate of soil salinity was 0.056 %/min, 0.055 %/min, 0.052 %/min, and 0.047 %/min for slope gradients of 0°, 5°, 10°, and 15°, respectively, with a small difference between 0° and 5°, and all greater than 10° and 15°, suggesting that the optimal slope gradient range for saline land is 0° to 5°.

### 4.4 Implications, limitations, and future work

The application of additives such as biochar, desulfurization gypsum, plant residues, and dredged sediment in soil is considered an effective measure of remediating high salt content soil since it increases water infiltration into the soil and improves soil macro-porosity and soil texture[49,50]. While these studies have provided various references for the remediation of saline soils, factors such as cost and high levels of heavy metals limited their extensive applications[1,27]. This work highlights that the determination of optimal cultivated land slope gradient and the interpretation of the soil-water-salt migration mechanism are essential before repairing saline soil using these measures. Besides, previous studies have demonstrated that soil erosion characteristics under extreme conditions may be well simulated using laboratory simulated rainfall experiments[39-41]. Thus, it is feasible to study the dynamic mechanisms of water content and salinity in saline soil under different natural conditions with indoor simulated rainfall experiments. Since amendments are not available for application to the soil on site in large amounts[1], to bring out the maximum efficiency of these measures, this study determined the optimal soil slope gradient range from 0° to 5° and preliminarily illustrates the soil-water-salt transport characteristics under simulated rainfall conditions, which have practical implications for saline soil remediation.

There are some limitations to this study. First, this study indicates that when the rainfall intensity varies from 50 mm/h to 100 mm/h, the rainfall intensity has little effect on the wetting front, increase rate of water content, and decrease rate of salinity. However, Fang et al.[51] found that high-intensity rainfall severely damaged the surface crust, and the rill development resulted in increasing soil infiltration. It is thus clear that when the rainfall intensity continues to increase, it will further increase infiltration, and owing to the limitations of the experimental conditions, another critical rainfall intensity was not found in this study. Second, the methods for measuring water content and salinity under simulated rainfall conditions still have room for improvement. In this study, these parameters were estimated using the drying method. However, this method disturbed the soil and was not consistent with the actual field conditions, which might affect the soil water and salt migration characteristics. The present work has also attempted to determine the soil EC by a pre-buried conductivity sensing chip, but its results were not satisfactory. Hence, there is room for consideration as to how dynamic measurements of soil physicochemical parameters should be conducted without disturbing the soil and ensuring the experimental data accuracy. Third, in the present work, only the effects of slope gradient and rainfall intensity on soil infiltration capacity and salinity have been considered, since the primary purpose of this study was to explore soil-water-salt transport mechanisms and to determine the appropriate slope, based on the salt discharge rate as the major indicator. However, it might be worth considering the effect of other variables, such as temperature and total rainfall amount, on the soil-salt discharge efficiency. Future work could expand the proposed study to other soil textures and be directed toward further elucidating the mechanisms of soil-water-salt dynamics with varying slope gradients and rainfall intensities.

## 5 Conclusions

This study compared the variations of wetting front, water content, and salinity under different rainfall intensities and slope gradients by simulated rainfall experiments. It was found that rainfall intensity, slope gradient, and position were crucial factors affecting soil-water-salt transport behavior. First, the growth rate of soil water content and reduction rate of salinity increased dramatically when the rainfall intensity increased from 10 mm/h to 50 mm/h. However, this trend became less significant when the rainfall intensity was higher than 50 mm/h. Second, lower slope gradient is conducive to the soil salt discharge, and the efficiency of salt discharge at the slope top is considerably weaker than at the slope foot. Third, a linear, exponential, and piecewise function relationship between wetting front, water content, salinity, and time for saline soils is observed, respectively.

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