Simple Method for Determining the Emitter Discharge Rate in the Reclamation of Takyric Solonetz with Drip Irrigation

Pengfei Huang[1]; Yaohu Kang[2]; Shuqin Wan[3]; and Xiaobin Li[4]

Abstract: A laboratory experiment was conducted to study the effects of the emitter discharge rate (EDR) on the distribution of water and salt in a manipulated soil texture of a coarse soil surrounded by takyric solonetz. The objective was to develop a simple method to rapidly determine a suitable EDR for the reclamation of takyric solonetz using drip irrigation. Major influences on soil structure were observed at EDRs ≤0.5 L/h, and slight influences were observed at EDRs >0.5 L/h. This was consistent with the changing trend of irrigation amount as the EDR increased from 0.1 to 2 L/h, with the irrigation amount decreasing rapidly at first and then remaining constant during a one-time irrigation. A method is proposed to determine the EDR based on the changing trend. The method considers the EDR at the inflection point—i.e., the point at which the irrigation rate declines from quick to slow—to be the ceiling value, where a lower value is considered better. A suitable EDR below the ceiling value is then selected that satisfies the peak period of crop water consumption. **DOI: 10.1061/(ASCE)IR.1943-4774.0001678.**

Author keywords: Drip irrigation; Emitter discharge rate (EDR); Soil salinity; Takyric solonetz; Volumetric soil moisture content.

Introduction

About 1×10^9 ha of the world's surface is affected by salt, and saline-sodic and sodic soils constitute nearly 60% of this area (Tanji and Wallender 2012). Saline-sodic and sodic soils exist mainly in arid and semiarid areas across the world and are characterized by the occurrence of excessive Na^+, which adversely influences the soil structure and leads to poor aeration and infiltration (Singh 2016; Temiz and Cayci 2018). The traditional amelioration methods are the addition of soil amendments, such as gypsum and limestone, together with sufficient fresh water for leaching, which can generate good ameliorative effects (Wang et al. 1993, 2017; Temiz and Cayci 2018). The cost of soil amendments is high and they are not feasible for use in arid areas, which lack a supply of fresh water. Some researchers have proposed an economic and environmentally sustainable amelioration method based on crop and irrigation management, without the need for a soil amendment, in some sodic calcareous soils (Qadir and Oster 2004; Li and Keren 2008; Zhang et al. 2013).

Takyric solonetz is a highly saline-sodic soil (IUSS Working Group WRB 2014) that covers a large part of the northwest arid region of China (Wang et al. 1993). The saturated hydraulic conductivity of the soil is extremely low (<0.1 mm/day). Zhang et al. (2013) succeeded in planting wolfberry in takyric solonetz and obtained a good yield through the use of drip irrigation and the manipulation of soil texture. The manipulated soil texture was constructed by installing a soil water redistribution medium (RM) beneath the emitter and filling it with sand. The irrigation water initially infiltrated into the RM and was then redistributed to the soil through the interface by unsaturated soil water movement. The use of the RM had two main effects: (1) enlarging the infiltration interface, and (2) providing a suitable habitat for plants in the early growth stage, with good air and water permeability.

Recently, researchers have focused on the use of a manipulated soil texture with drip irrigation for the improvement of saline-sodic soil (Zhang et al. 2013; Feng et al. 2017; Liu et al. 2020) and the use of marginal-quality water (Berezniak et al. 2018). However, these studies have not led to the development of a practical method to determine a suitable emitter discharge rate (EDR) for a drip irrigation system.

A suitable EDR is important for a drip irrigation system because an EDR that is too high could lead to runoff, erosion, and finally secondary salinization (Darwish et al. 2005; Dastranj et al. 2018). An EDR that is too low may not meet the crop water consumption required in the rapid growth period. For soil with normal permeability, the EDR is calculated by the water requirement, number of emitters, irrigation application efficiency of the irrigation system, and irrigation duration (Wu et al. 1986). When considering differences in soil permeability, some researchers have defined the EDR through a comprehensive analysis of the soil infiltration capability, shape of the wetting volume, steady-state ponding area, emitter space, and other factors (Zur 1996; Naglic et al. 2014; Chen et al. 2015). For two kinds of coastal saline soil with different

[1]Ph.D. Candidate, Univ. of Chinese Academy of Sciences, No. 19A, Yuquan Rd., Shijingshan District, Beijing 100049, China; Ph.D. Candidate, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11A, Datun Rd., Chaoyang District, Beijing 100101, China; Assistant Research Fellow, Institute of Farmland and Irrigation, Chinese Academy of Agricultural Sciences, No. 380, Hongli Rd., Muye District, Xinxiang 453002, China. Email: huangpengfei@caas.cn

[2]Professor, College of Resources and Environment, Univ. of Chinese Academy of Sciences, No. 19A, Yuquan Rd., Shijingshan District, Beijing 100049, China; Professor, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11A, Datun Rd., Chaoyang District, Beijing 100101, China (corresponding author). Email: Kangyh@igsnrr.ac.cn; hpf2687009@163.com

[3]Associate Professor, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11A, Datun Rd., Chaoyang District, Beijing 100101, China.

[4]Associate Professor, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11A, Datun Rd., Chaoyang District, Beijing 100101, China.

Note. This manuscript was submitted on April 1, 2021; approved on January 7, 2022; published online on February 28, 2022. Discussion period open until July 28, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, © ASCE, ISSN 0733-9437.

Table 1. Chemical characteristics of the irrigation water, aqueous extracts of the original soil, and RM

Type	Ionic concentration (mmol/L)				EC (dS/m)	pH	SAR $(mmol/L)^{0.5}$
	Mg^{2+}	Ca^{2+}	K^{+}	Na^{+}			
Irrigation water	0.4	0.52	0.03	14.74	1.94	7.83	15.4
Aqueous extracts of RM	0.47	0.61	1.97	17.99	2.3	8.48	17.38
Aqueous extracts of soil	0.26	0.22	0.31	93.48	10.56	9.36	134.26

Note: EC = electrical conductivity; and SAR = sodium adsorption ratio.

permeability, Chen et al. (2015) found that there was a linear relationship between the steady-state ponding area radius and EDR, and then used it to propose a rapid method for determining the EDR in the reclamation of a coastal saline soil with drip irrigation.

The methods used to define the EDR have all been applied in homogeneous soils, with no serious problems regarding permeability. However, they have not been applied in a manipulated soil texture, in which a coarse soil is surrounded by a fine soil with extremely poor permeability. Thus, the objective of this study was to develop a rapid method to determine a suitable EDR for drip irrigation in a manipulated soil texture. The EDR selected by the method should also satisfy the crop peak demand of water.

Materials and Methods

Experiments were conducted at Xidatan Agricultural Comprehensive Development Experimental Station (38°52′N, 106°27′E; altitude 1,095 m) from 2016 to 2018. The station is located in the northern part of Ningxia Plain, China. It has a typical arid continental climate. The soil at the study site is classified as takyric solonetz (IUSS Working Group WRB 2014). The details of the soil profile are given in Table 1.

Soil Column Experimental Design

The soil column was made of tempered glass, with a height of 63 cm. The cross section was a square, with sides of 60 cm. The bottom 10 cm of the column was filled with quartz sand and a drainage system made of PVC cylinders was applied, as shown in Fig. 1. The blended soil was filled layer by layer every 5 cm, with a density of 1.40 g/cm^3. The surface soil was slightly disturbed by a brush between layers to avoid stratification. A hemisphere of 20 cm in

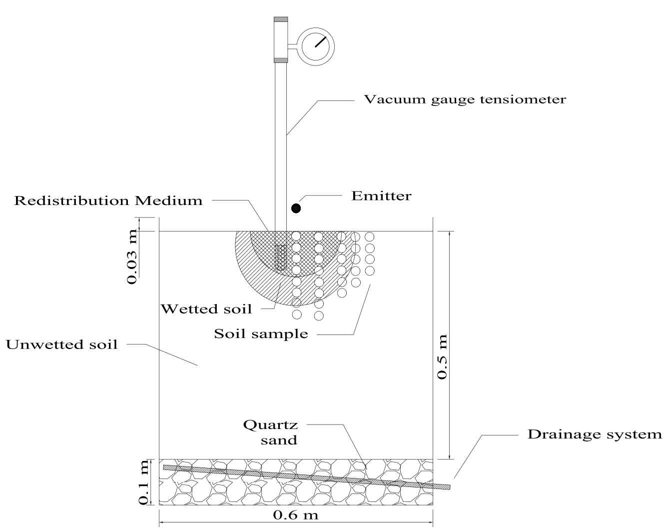

Fig. 1. Experimental equipment and the position of soil samples.

diameter in the center of the top two layers was excavated and filled with sand (the chemical properties of the aqueous extracts of the sand are shown in Table 1) at a density of 1.40 g/cm^3 as the RM. An emitter was placed directly above the RM and the pressure head was maintained by adjusting the height of a Mariotte bottle. A vacuum gauge tensiometer (WST-1, Beijing Waterstar. Tech. Co., Beijing) was installed in the RM following the method used by Kang et al. (2013). The soil matric potential (SMP) of the RM was recorded at 8:00 and 18:00 each day.

Irrigation was carried out when the SMP lower than −5 kPa. Due to the low permeability of takyric solonetz, runoff can occur rapidly in the sodic soil once the RM is saturated, which should be avoided. Therefore, the irrigation event was stopped when RM saturated. Thus, the volumetric soil moisture content (VSMC) of the RM in the experiment was controlled to be in the range of about 23.3% (the corresponding SMP of the RM is −5 kPa) to 35.6% (the RM is saturated and the ponding area radius arrives at the RM–soil interface).

In Experiment 1, eight EDRs (0.1, 0.2, 0.3, 0.4, 0.5, 1, 1.5, and 2 L/h) were selected to simulate the relationship between the EDR and quantity of irrigation water in one-time irrigation testing.

In Experiment 2, five EDRs (0.1, 0.3, 0.5, 1, and 1.5 L/h) were used to simulate the water and salt distribution. Parts of the soil columns were sampled at 0, 12, 24, 48, 72, and 96 h after the first irrigation. The rest of soil columns were sampled 72 h after 3, 6, 9, 12, and 15 irrigation phases.

The soil for the soil column experiment was collected from five random cores (0–40 cm) in undisturbed areas around the station and blended after removing impurities (Table 2). The irrigation water detailed in Table 1 was drawn from a groundwater well. The surface of the columns was covered by plastic to cut off evaporation from outside. All soil column experiments were replicated three times.

Field Experimental Design

To verify the practicability of the proposed method, a field experiment was conducted (beginning on April 23, 2017) in which wolfberry was grown on a highly saline-sodic wasteland at the station. The plowing, ridging, and planting methods were the same as those used by Zhang et al. (2013, 2019). The soil was deep plowed to a depth of 50 cm. Planting occurred along ridges with a height of 0.5 m, width of 3 m, and ridge surface width of 1 m. The RM had a semiellipsoid shape

Table 2. Main physicochemical properties in uncultivated soil

Main physicochemical properties	Soil depth (cm)					
	0–10	10–20	20–30	30–40	40–60	60–120
Bulk density (g/cm^3)	1.44	1.53	1.59	1.64	1.60	1.59
ECe (dS/m)	9.07	4.51	2.76	2.34	2.91	3.01
pH	9.11	9.73	9.68	9.72	9.62	9.40
SAR $(mmol/L)^{0.5}$	173.65	62.74	42.27	35.71	41.18	33.28

Note: ECe = electrical conductivity of the saturation paste extract; and SAR = sodium adsorption ratio.

(diameter 0.2 m, depth 0.3 m), which was dug in the center of the ridge and then filled with sand. A drip line was placed on the center of the ridge surface. A previous study observed that a crack usually formed below the emitter along with drip line in alkali soil. Thus, a trapezoidal sand tank was placed under the drip line beyond the space of RM, which also acted as a water redistribution medium. Wolfberry transplants were planted in the RM, with a row spacing of 1 m, and finally the ridge surface was mulched with plastic film.

Two EDRs were applied in field experiments. One EDR was selected by the method based on the results of soil column experiments. Another EDR was 1 L/h, which was used as a control. The area of each plot was 144 m^2, with a length of 12 m and width of 12 m. Each plot used an independent irrigation system and the EDR was controlled by a valve and pressure gauge. A total of 15 mm of water was applied 3 days before planting to reduce the salt content of the soil near the RM, and this also provided suitable moisture conditions. Two-year-old wolfberry transplants were planted. After transplanting, irrigation was guided by a vacuum gauge. The vacuum gauge was installed 0.2 m beneath the emitter nearest the fringe of the RM, following the method of Kang et al. (2013). The SMP threshold was −5 kPa in the first year based on Zhang et al. (2013). Urea and potassium dihydrogen phosphate were dissolved in a bucket and applied with the irrigation water. All field experiments were replicated three times. Samples were collected before irrigation and at the end of the growing season in the root zone (40 cm from the emitter in the horizontal direction and 60 cm in the vertical direction) to test electrical conductivity of the saturation paste extract (ECe), pH, Na^+, Ca^{2+}, and Mg^{2+}. The ECe, pH, Na^+, and sodium adsorption ratio (SAR) in the root zone before irrigation were 6.50 dS/m, 9.34, 89.57 mmol/L, and 178.26 $(\text{mmol/L})^{0.5}$, respectively.

Soil Sampling

Soil samples in soil column experiments were collected using a soil auger (diameter 2 cm, length 10 cm). In the horizontal direction, the sampling distance from the emitter was 0, 5, and 10 cm and then every 2 cm until the soil was dry. In the vertical direction, the sampling interval was every 2 cm until the soil was dry for sampling after a one-time irrigation, and every 3 cm for the other experiments.

In the field experiment, the soil samples in the root zone were collected every 10 cm in the horizontal direction to 40 cm from the drip line for layers of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–60 cm in the vertical direction.

Analysis

Soil moisture content was measured by oven-drying to a constant weight at 105°C. VSMC was converted by soil moisture content times soil bulk density.

Samples for chemical analysis were mixed from three replicates in equilibrium. Clear extracts of the saturated soil pastes were obtained by centrifugation. The ECe was measured with a conductivity meter (DDS-11A, REX, Shanghai, China) and pH was measured with a pH meter (PHS-3C, REX, Shanghai, China). The contents of Na^+, Ca^{2+}, and Mg^{2+} were measured by an inductively coupled plasma optical emission spectrometer (Optima 5300DV, PerkinElmer, Waltham, Massachusetts). The SAR was calculated according to the following formula:

$$\text{SAR} = \frac{[\text{Na}^+]}{([\text{Mg}^{2+}] + [\text{Ca}^{2+}])^{0.5}} \tag{1}$$

The irrigation amount was calculated by recording the water volume in the Mariotte bottle at the beginning and end. The positions of wetting front 96 h postirrigation in both vertical and horizontal directions were measured by a ruler. The wetting front in the horizontal direction was measured directly from the surface of the soil column. The wetting front in the vertical direction was measured by sampling right below the drip emitter and recording the wetting depth. The wetted area and the area of the low-salinity zone were measured by sampling and calculated by the grid method with kriging interpolation, which included in Surfer 13 software in the same way as Chen et al. (2015). The water stored in RM was calculated as the spatial weighted mean of all soil samples within RM in the same way as Huang et al. (2021).

Statistical Analysis

Microsoft Excel was used to statistically analyze the data. SPSS 19.0 statistical software was used to conduct an analysis of variance. Multiple comparisons among the treatments were made using Duncan's multiple range test. Differences of $p \leq 0.05$ were considered significant. Figures were created by Surfer 13 and Sigmaplot 12.5.

Results and Discussion

Relationships between Irrigation Amounts and EDRs

The mean values of irrigation time for EDRs increasing from 0.1 to 1.5 L/h were 15.7, 5.9, 3.8, 2.2, 1.8, 0.84, 0.57, and 0.4 h. The corresponding irrigation amounts are shown in Fig. 2. The irrigation amount initially decreased rapidly and then declined slowly as the EDR increased. The irrigation was stopped once RM saturated. Therefore, the irrigation amount was different for each EDR treatment. The high level of Na^+ in soil will lead to the slaking, swelling, and dispersion of clay minerals, which were responsible for permeability deterioration (Qadir and Schubert 2002). Previous studies showed that the aggregates are more stable and less susceptible to sodicity when exposed to a small wetting rate (Shainberg et al. 2001; Mamedov et al. 2002). Therefore, the soil structure is more stable for small EDRs, which helps water infiltration. The relationship between the EDR and quantity of irrigation water in a one-time irrigation could be expressed by the following equation:

$$Y_{qi} = 0.69 + 0.15\text{EDR}^{-0.82}, \quad R^2 = 0.77 \tag{2}$$

The term Y_{qi} represents the quantity of irrigation water in a one-time irrigation. The absolute rate of decline was >1 when the EDR ranged from 0 to 0.32 L/h. For an EDR >0.32 L/h, the absolute rate was <1 and had a tendency to approach 0.

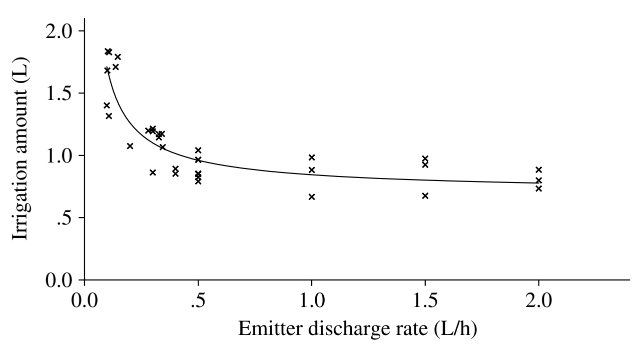

Fig. 2. Relationship of irrigation amount and EDR for a one-time irrigation.

Redistribution Process of Soil Water

Fig. 3 indicates that the position of the region with a high VSMC changed similarly for all EDRs. The highest VSMC was recorded at the RM once irrigation finished. Twenty-four hours later, the highest water content was around the interface of the two differently textured soils. At 48 h, the region with a high VSMC had moved to the boundary layer of the sodic soil and there was little change until 96 h. The matric potential gradient and the gravitational gradient are the two main effects on the rate of water movement. The gravitational gradient remains constant while the matric potential gradient decreases with time, which explains why the high-VSMC region moves fast in the first 48 h and then changed little.

As Fig. 4 shows, the wetted front in both the vertical and horizontal directions decreased as the EDR increased from 0.1 to 1.5 L/h 96 h postirrigation. The absolute rate of decrease of the vertical wetted front was greater than that of the horizontal wetted front, which indicated that an increase in the EDR would have a strong influence on the vertical wetted front. The ratio of the horizontal to vertical wetted front was <1.

For the wetted areas in Table 3, there were no significant differences at 0 h. With the continuous soil water redistribution, the wetted areas with EDRs of 0.1, 0.3, and 0.5 L/h were significantly larger than those of the 1 and 1.5 L/h treatments 48 h later ($p < 0.05$). At 96 h postirrigation, the wetted areas under the 0.1 and 0.3 L/h treatments were 430.18 and 378.06 cm^2, with both being significantly larger than the values of the other three treatments ($p < 0.05$).

The ratio of water stored in the RM to the full quantity of irrigation (R/F) was calculated to evaluate the infiltration rate of water from the RM to soil (Fig. 5). At 0 h, the R/F ranged from 0.36 to 0.77 and the ratio increased as the EDR increased. The R/F values under the 0.1 and 0.3 L/h treatments were 0.36 and 0.52, respectively, which means that almost half of the irrigation water entered the soil once irrigation stopped. In the first 24 h, the R/F fell quickly and was lower than 0.5 for all treatments except 1.5 L/h. Then the R/F changed slowly. At 72 h, the R/F values were 0.15, 0.27, 0.28, 0.35, and 0.48 for the five EDRs from 0.1 to 1.5 L/h, respectively. At 96 h postirrigation, only the R/F value of the 1.5 L/h treatment was higher than 0.3. Most of the water was stored in RM and little seeped into soil once irrigation stopped for the poor soil permeability. Therefore, R/F was higher initially and then decreased gradually for water seeping into the soil by the force of hydraulic gradient in redistribution process. One reason for larger R/F in more EDR was because the lasting hours of the irrigation event were shorter for more EDR. Another reason was that a low wetting rate helps the stability of aggregates, which was better for the soil permeability (Shainberg et al. 2001; Mamedov et al. 2002).

Spatial Distribution of VSMC

In Fig. 6, it is apparent that the highest VSMC in the profile was still concentrated in the margin of the soil, while the mean VSMC of the whole profile increased markedly over time. The boundary of the dry and wet soil slowly faded. Sampling was stopped until the soil was dry. The VSMC of the dry soil was higher than 3% after nine irrigations; thus, a VSMC of 6% was selected as the boundary of the wetted front in the following analysis. In the horizontal direction, the wetted front arrived at 30 cm (the wall of the soil column) after 12 irrigations under the 0.1 L/h treatment and 15 irrigations under the 0.3 L/h treatment. The wetted fronts under the 0.5, 1, and 1.5 L/h treatments after 15 irrigations were 25.81, 23.92, and 26.17 cm, respectively.

The cumulative experiment time was also important for soil water redistribution. The 15 irrigation events were completed in 125 days for the 1 L/h treatment and 119 days for the 1.5 L/h treatment. Over similar amounts of time, under the 0.1 L/h treatment there were 11 irrigation events in 130 days, under the 0.3 L/h treatment there were 12 irrigation events in 125 days, and under the 0.5 L/h treatment there were 14 irrigation events in 123 days. Because sampling was not conducted after 11 and 14 irrigations, the proximate irrigation events of 12 for the 0.1 L/h treatment and 15 for the 0.5 L/h treatment were selected to compare the soil water redistribution at the same experimental time. The wetted areas with a VSMC >6% were 1,000.94, 748.80, 778.06, 753.32, and 713.27 cm^2 for the five EDRs increasing from 0.1 to 1.5 L/h, respectively. The 0.1 L/h treatment had a wetted area that was significantly larger than that of the other treatments ($p < 0.05$). The horizontal wetted front under the 0.1 L/h treatment was >30 cm and the value for the 0.3 L/h treatment was 27.02 cm. Both were larger than the values under the 0.5, 1, and 1.5 L/h treatments ($p < 0.05$). In the vertical direction, the wetted front under the 0.1 L/h treatment extended for 37.93 cm, which was significantly larger than that for the other treatments ($p < 0.05$). Previous studies showed that the adverse effect of irrigation on soil permeability was less for small wetting rate (Shainberg et al. 2001; Mamedov et al. 2002). Small EDRs contributed to water seeping from RM to alkali soil for lower R/F. Both help the downward moving of wetted front with small EDRs.

The relationship between the quantity of irrigation water and time in Fig. 7 could be described by an exponential function. The quantity of irrigation water declined substantially during the initial three irrigation events under all treatments. Then the quantity used tended to vary around certain values. The values were 0.85, 0.68, 0.55, 0.55, and 0.51 L as the EDR increased from 0.1 to 1.5 L/h. The values under the 0.1 and 0.3 L/h treatments were higher than the values under the other treatments ($p < 0.05$). The quantity of irrigation water included the increase in the amount of water stored in the RM and the water that infiltrated into the soil. The increase in the amount of water stored in the RM was about 0.26 L for each irrigation event. Thus, the amounts of irrigation water infiltrated into the sodic soil were 0.59, 0.42, 0.29, 0.29, and 0.25 L as the EDR increased from 0.1 to 1.5 L/h and the corresponding proportions of irrigation water infiltrated into the sodic soil to per irrigation event were 70%, 62%, 53%, 53%, and 49%, respectively.

Spatial Distribution of Salinity

The contour map of soil salinity in Fig. 8 shows that the salinity was concentrated at the edge of the wetted volume. Under the 0.1 and 0.3 L/h treatments, the horizontal boundary of the concentrated salt area extended to 30 cm (the wall of the soil column) after 12 irrigations and started to leach downward throughout the whole section. At the same cumulative experiment time, the horizontal distances under the 0.5, 1, and 1.5 L/h treatments were around 25 cm. In the vertical direction, the lowest point to which the concentrated salt area extended was around 40 cm for all EDRs and there were no distinct differences. After 15 irrigations, the lowest points of the concentrated salt area were 45.56, 43.72, 41.50, 41.23, and 40.22 cm as the EDR increased from 0.1 to 1.5 L/h in the five respective treatments. At both the same experiment and irrigation times, the soil salinity was more likely to be leached farther by low EDRs of 0.1 and 0.3 L/h.

The traditional defined threshold for salinity is 4 dS/m (Richards 1954), which has been shown to be harmless to most plants that are insensitive to salt (Qadir et al. 2001). In this study, the area with a soil salinity <4 dS/m was defined as a low-salinity zone and was used to analyze the effect of the EDR on the spatial distribution of salinity. The variation trend of the low-salinity zone was similar for different irrigation events. The low-salinity zone decreased in size as the EDR

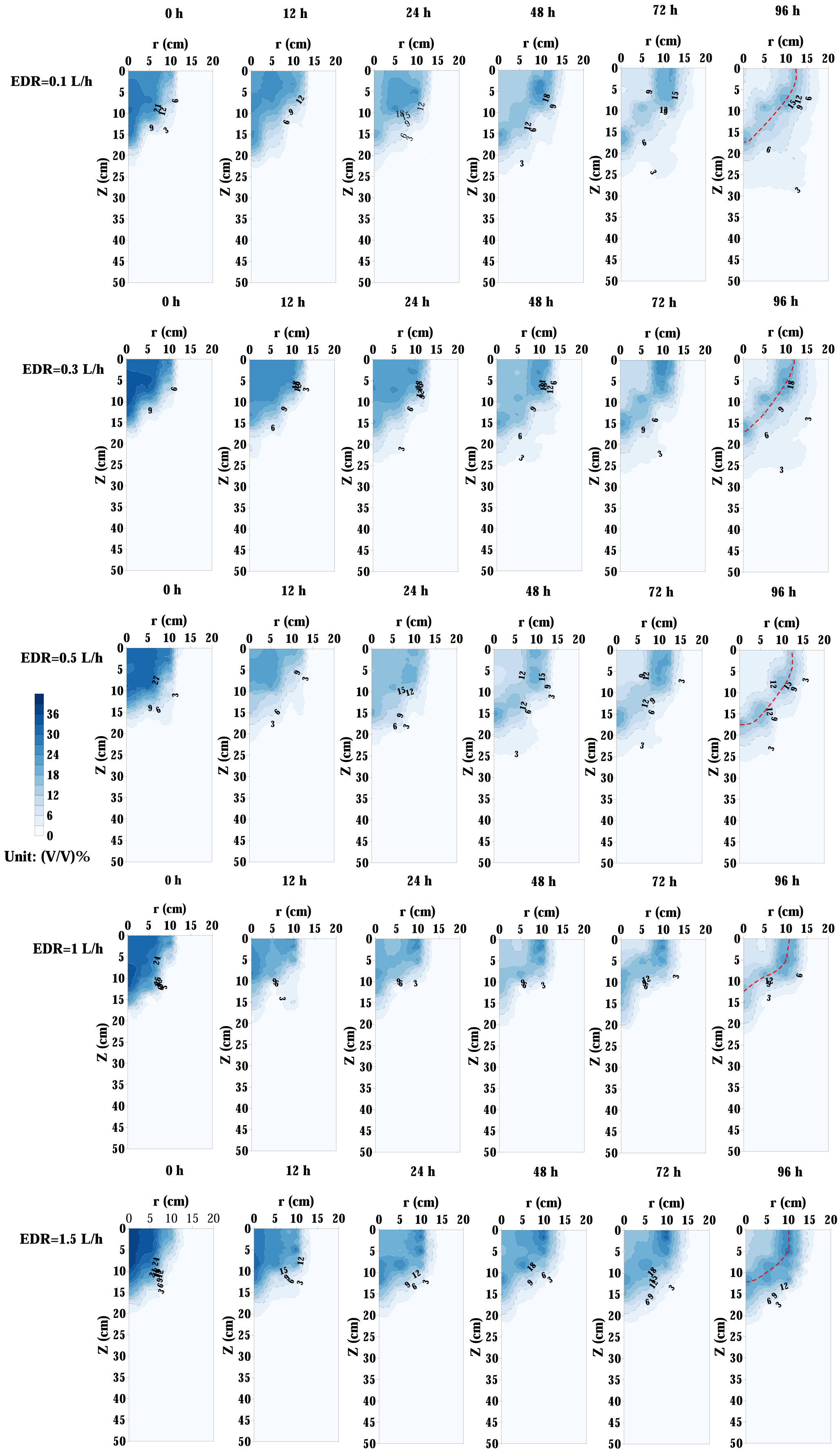

Fig. 3. Spatial distribution of VSMC in redistribution process. r = horizontal distance from emitter; and Z = vertical depth.

moved from 0.1 to 0.5 L/h and then increased slightly as the EDR increased from 0.5 to 1.5 L/h, as shown in Fig. 9. The slight increase in the size of the low-salinity zone was probably influenced by the high irrigation frequency of the 1 and 1.5 L/h treatments.

Simple Method for Determining EDR

After the first irrigation, the results indicated that a low EDR corresponded to a large irrigation amount, high infiltration rate, and large wetted area. In long-term irrigation, both the wetted area and the average irrigation amount under steady-state conditions increased with the increase of EDR, while the opposite pattern was observed for irrigation frequency. These indicators all changed dramatically among the EDRs of 0.1, 0.3, and 0.5 L/h and were slightly influenced by the EDR increasing from 0.5 to 1.5 L/h.

The manipulated soil texture of the RM surrounded by takyric solonetz can be considered to represent a coarse-texture soil surrounded by a kind of fine-texture soil with poor permeability. Remediation of fine-texture soil via leaching is often limited by the permeability of the soil and timely remediation relies on the maintenance of maximum soil hydraulic conductivity (Callaghan et al. 2014). Berezniak et al. (2018) reported that finer soil particles obtain a higher matric potential, and thus a higher capillary rise of the water into the soil and higher water retention values than coarse-texture soil. The process of soil water infiltration in an RM diffusing to sodic soil can be regarded as soil water infiltration from a coarse-texture soil to fine-texture soil. The infiltration rate will decline immediately once the wetting front arrives at the interface and there will be a constant decrease in the impermeability of the fine-texture soil (Shao et al. 2006).

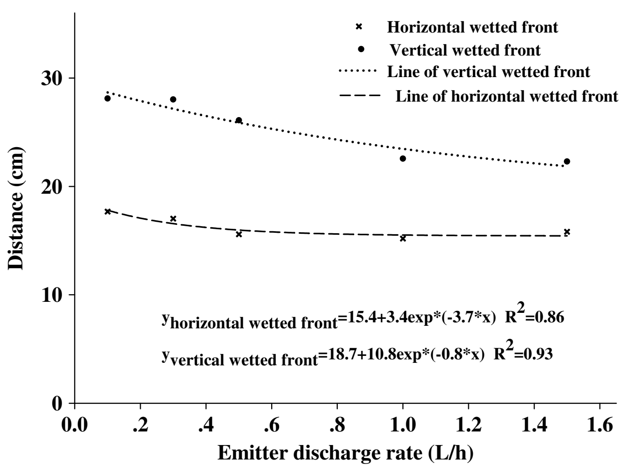

Fig. 4. Horizontal and vertical wetted depth in soil profile 96 h postirrigation.

In this study, irrigation was finished once the surface of the RM was saturated. When the EDR was very high, the RM was rapidly saturated and the irrigation amount was approximately the same as the water stored in the RM when there was little water deep in the fine soil. If the EDR was low enough and the infiltration rate at the interface was approximately equal to the saturated hydraulic conductivity of the fine soil, the infiltration process was in a stable infiltration stage. This explains why the irrigation amount gradually increased to infinity as the EDR decreased close to 0, and tended toward a constant value as the EDR increased, as Eq. (2) shows.

It is widely accepted that structural problems are caused by excessive Na^+ through certain physical processes (slaking, swelling, and dispersion of clay) and specific conditions (surface crusting and hardsetting) (Oster and Shainberg 2001; Qadir et al. 2007). Soil permeability depends on the amount and continuity of soil macropores in soil, and when macroaggregates (>250 μm) break into microaggregates ($20-200$ μm) the soil permeability will be reduced (Kemper and Koch 1966). The use of RM to enlarge the sand–soil interface and enhance infiltration via unsaturated soil water movement avoids the disruption of soil pores. Fig. 7 shows that the quantity of irrigation water decreased dramatically over the initial three irrigation events. For the same increase in the water volume in the RM in each irrigation event, there was a decrease in irrigation quantity due to the decrease in macroaggregates from the swelling and dispersion of the sodic soil particles. Previous studies have shown that aggregates are more resistant to sodicity when wetting rates are less than 10 mm/h and the effect of the wetting rate is greater for clay soils than sandy soils (Shainberg et al. 2001; Oster and Shainberg 2001; Shainberg et al. 2002). The quantity of irrigation water tended to remain stable after three irrigation events and decreased at higher EDRs, indicating that a higher EDR impairs the amount and continuity of soil macropores and reduces the soil infiltration capacity.

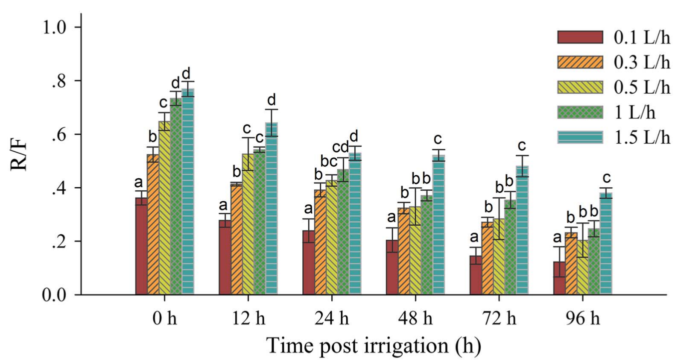

Fig. 5. R/F for each EDR treatment in redistribution process. Different lowercase letters indicate significant differences ($p \leq 0.05$) among treatments.

Table 3. Wetted area for each EDR treatment in redistribution process (cm^2)

	Time (h)					
EDR (L/h)	0	12	24	48	72	96
0.1	176.7 ± 10.7 a	204.1 ± 4.1 a	238.8 ± 9.1 a	270.0 ± 29.6 a	323.9 ± 23.2 a	430.2 ± 57.8 a
0.3	165.1 ± 10.1 a	216.15 ± 3.7 a	247.7 ± 42.0 a	292.5 ± 6.7 a	312.4 ± 12.3 ab	378.1 ± 32.6 a
0.5	172.2 ± 21.3 a	215.6 ± 11.6 a	242.1 ± 3.2 a	273.7 ± 15.5 a	288.3 ± 7.9 b	307.1 ± 12.0 b
1	155.5 ± 13.2 a	172.8 ± 6.0 b	188.7 ± 4.8 b	197.4 ± 2.6 c	214.9 ± 12.2 d	241.1 ± 24.5 b
1.5	185.4 ± 40.1 a	212.4 ± 35.0 a	217.3 ± 20.1 ab	229.1 ± 10.6 b	247.7 ± 25.1 c	298.5 ± 30.2 b

Note: Values followed by the same lowercase letters are not significantly different at $p \leq 0.05$.

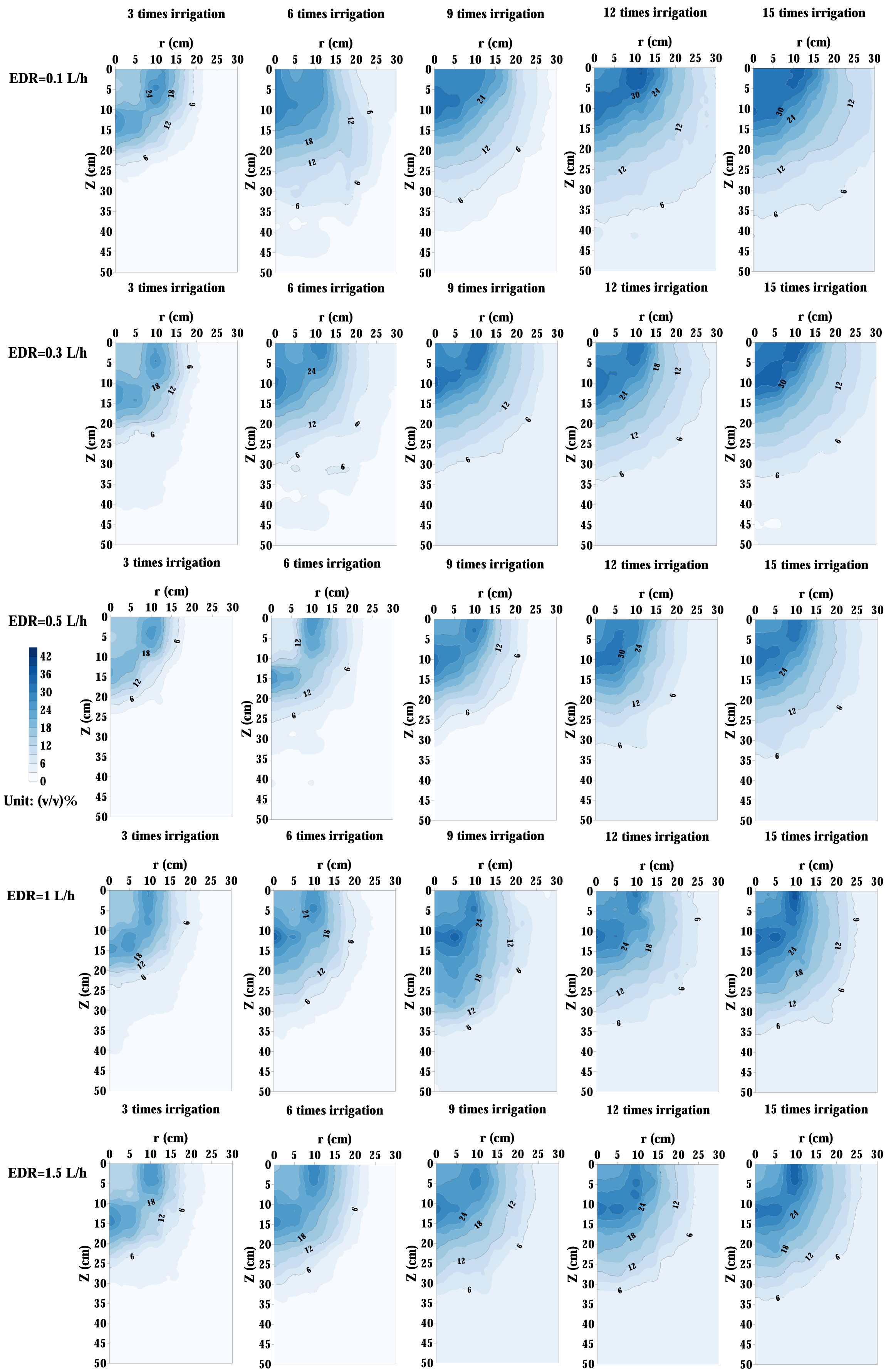

Fig. 6. Spatial distribution of VSMC for each EDR treatment with different irrigation times. r = horizontal distance from emitter; and Z = vertical depth.

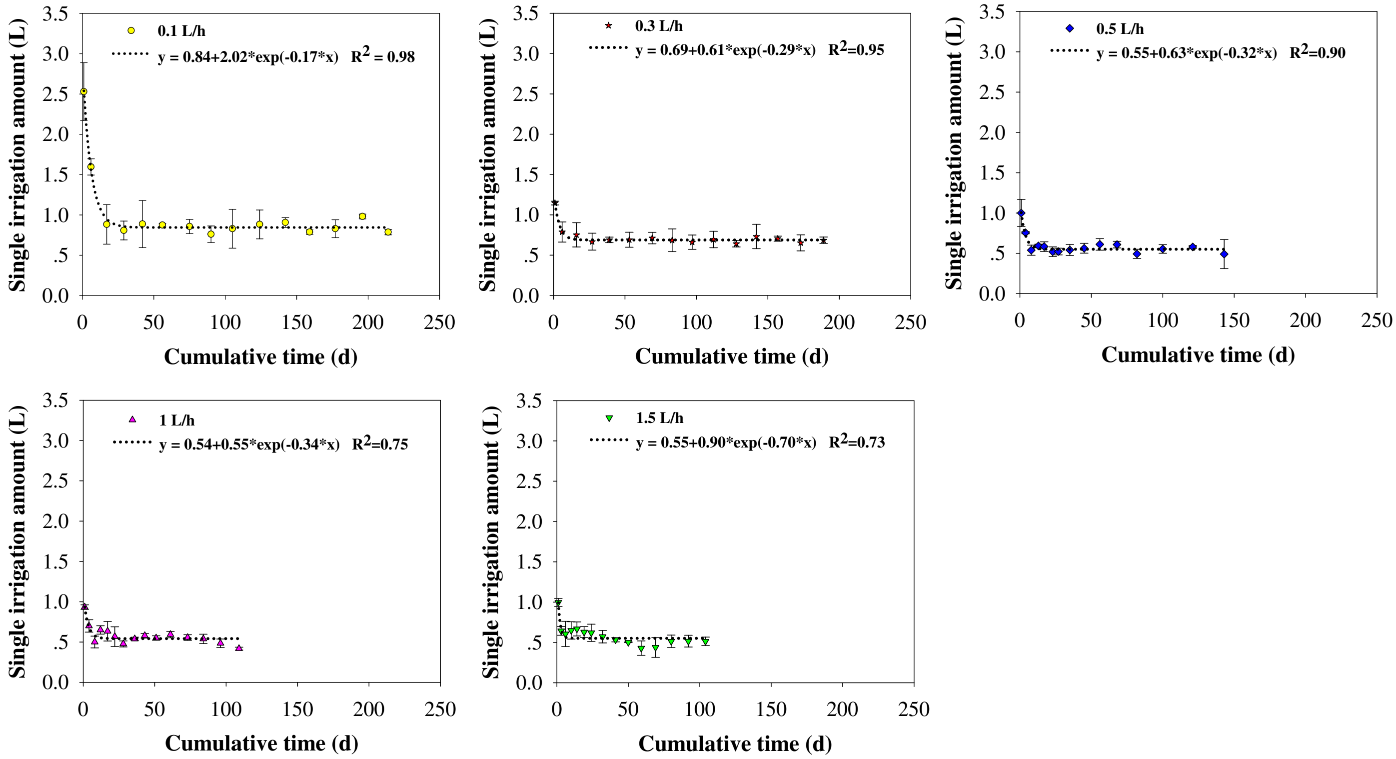

Fig. 7. Relationship of single irrigation amount and cumulative experiment time for each EDR treatment.

A comprehensive consideration of the soil water and salt distribution in profile revealed major differences in the soil water infiltration and salt leaching for an EDR ≤0.5 L/h. There was only a slight influence for EDRs ranging from 0.5 to 1.5 L/h. This concurred with the variation tendency determined from Eq. (1), which showed that the quantity of irrigation water initially declined substantially and then slowed as the EDR increased. An EDR with an absolute rate of decline of 1 can be defined as the inflection point at which the rate of irrigation water applied falls from rapid to slow. Thus, the inflection point could be regarded as the EDR ceiling for EDRs higher than the inflection point, which made a slight difference to the spatial distribution of soil water and salinity.

At the same time, the drip irrigation system is designed to provide irrigation water efficiently and uniformly, meeting the requirements of evapotranspiration (Naglic et al. 2014), and especially to meet the practical needs of peak period water consumption. The EDR selected from the range of 0 to the inflection point should therefore simultaneously meet the peak period water consumption, and the lower the value the better.

Based on the preceding analysis, a simple method is proposed to determine a suitable EDR as follows:

1. Level the land and excavate 15 or more hemispheres as the RM. The size and shape of the RM is determined by the plant species. Fill the RM with material that is appropriate as a planting medium.
2. Select at least five EDRs ranging from 0 to 1.5 L/h to drip water into the RM. Record the quantity of irrigation water when the RM is saturated. Each EDR should be repeated at least three times.
3. Use the EDR data and the corresponding quantity of irrigation water to fit a regression equation. Find the inflection point of the slope (the value of the slope for the inflection point is defined by the operator). A suitable range of EDRs is from 0 to the inflection point.
4. Select an EDR from the suitable range and meet the peak period water consumption in 24 h.

Field Validation of the Method

The peak water consumption of the wolfberry in the study area was found to be 6 to 8 mm/day. The distance between the two drip lines and the emitter interval were 3 and 0.3 m, respectively. An EDR of 0.3 L/h was selected using the method proposed, which could satisfy the peak period water consumption over 24 h. An EDR of 1 L/h was selected for the control treatment. The soil properties in the root zone and plant survival rate in October 2017 are shown in Table 4. The ECe, Na^+, and SAR decreased significantly for both treatments. The 0.3 L/h treatment was the most beneficial for the leaching of Na^+, although there was no obvious difference between the two treatments. With no soil amendments, the pH for both treatments changed only slightly in the first growing season. Wolfberry is a saline-alkali-tolerant plant and the RM also provided a suitable soil environment for its roots. The survival rates were >96% and the 0.3 L/h treatment was the best. The results showed that the newly designed EDR was suitable for field application.

Conclusion

In a manipulated soil texture representing a sandy soil in an RM surrounded by takyric solonetz, the EDR clearly influenced the spatial distribution of soil water and salt. Low EDRs contributed to the requirement of a large quantity of irrigation water, large wetted front, and large low-salinity zone. An EDR ≤0.5 L/h made a major difference, while only a slight influence was observed for an EDR >0.5 L/h. Similar results were also observed with the changing trend of EDR as the quantity of irrigation water changed.

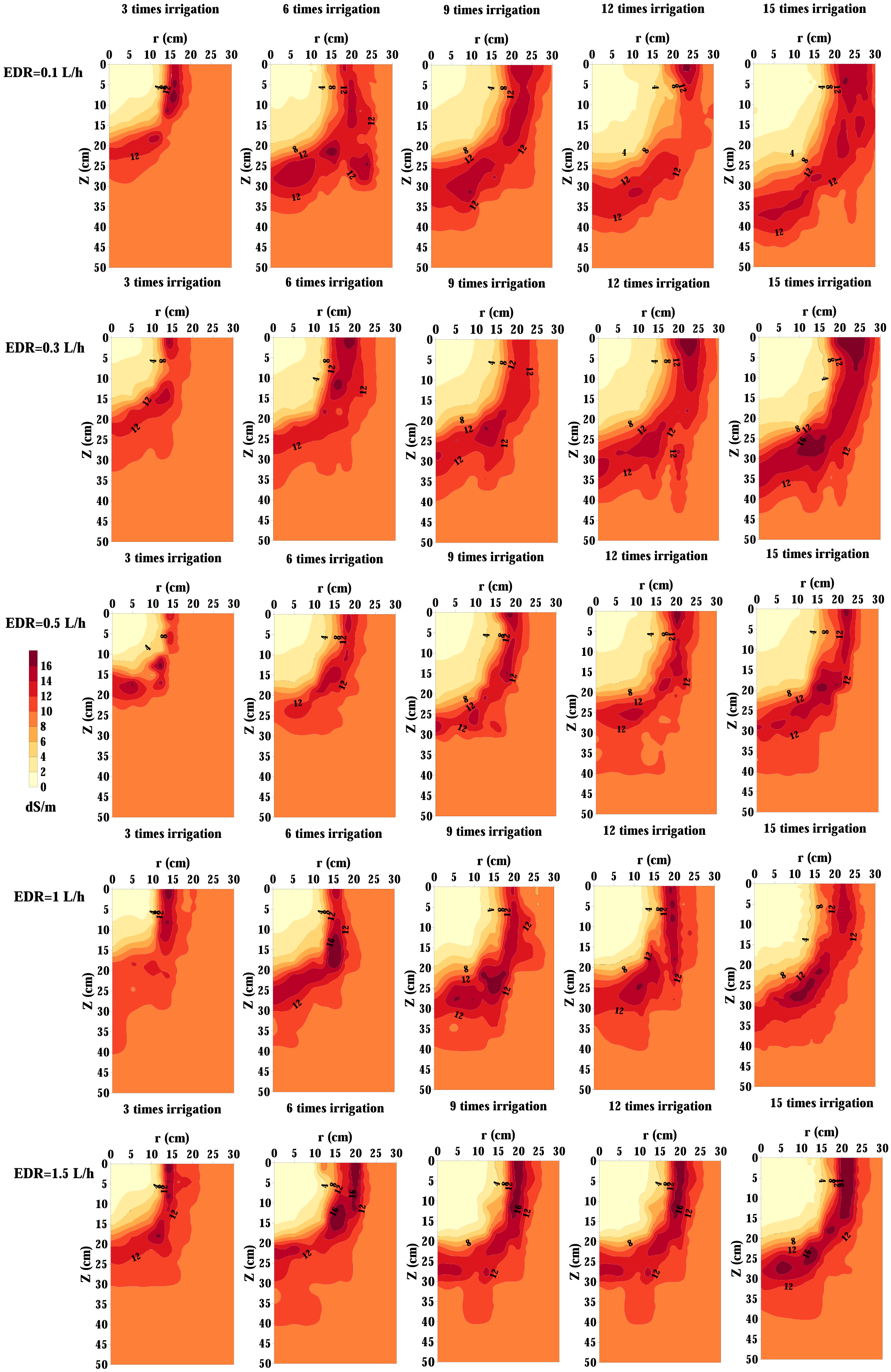

Fig. 8. Spatial distribution of soil salinity for each EDR treatment with different irrigation times. r = horizontal distance from emitter; and Z = vertical depth.

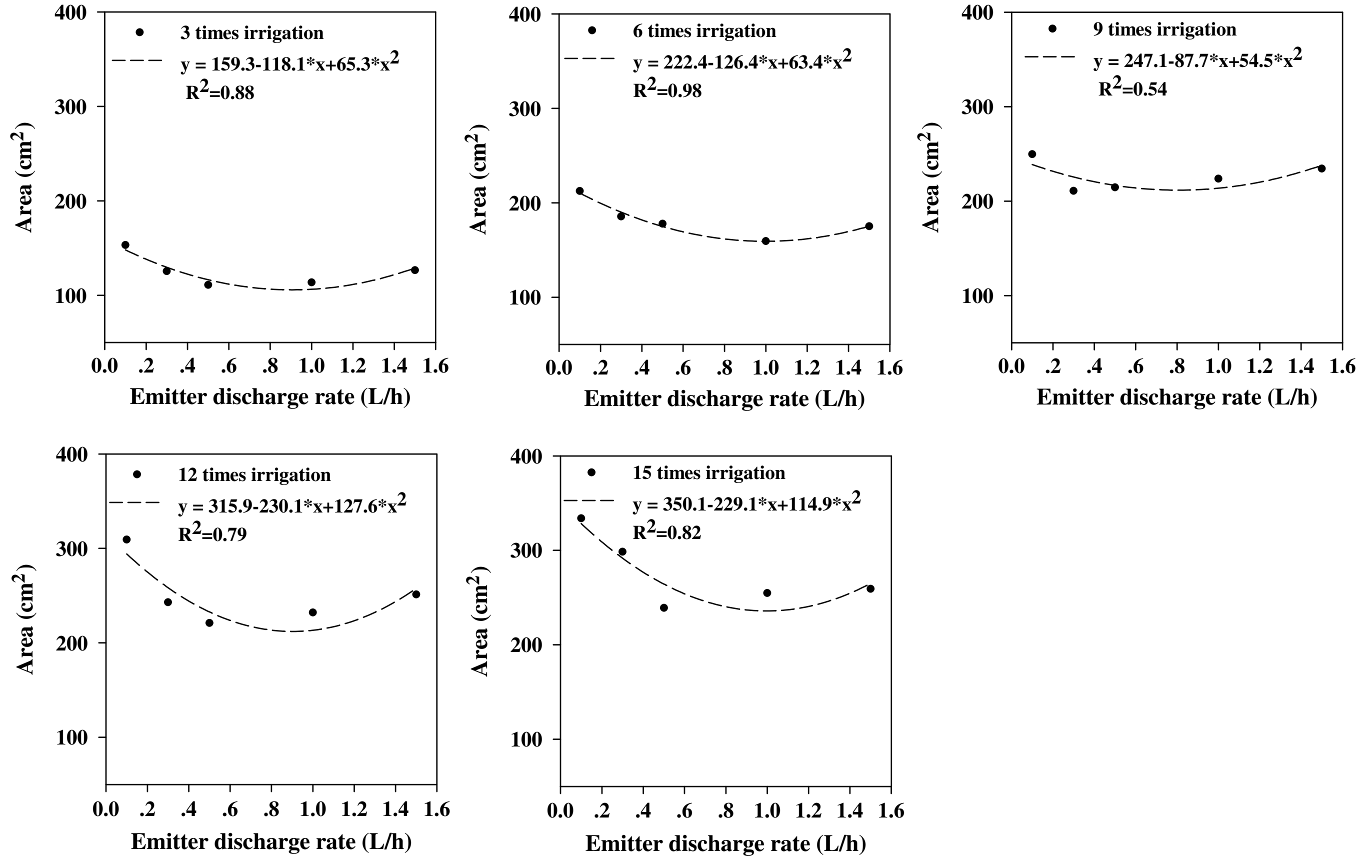

Fig. 9. Area of low-salinity zone in soil profile in response to EDR for different irrigation times.

Table 4. Plant survival rate, ECe, pH, Na^+, and SAR after field experiment

EDR (L/h)	ECe (dS/m)	Desalination rate (%)	pH	Na^+ (mmol/L)	Na^+ reduction rate (%)	SAR $(mmol/L)^{0.5}$	SAR reduction rate (%)	Survival rate (%)
0.3	4.42	32.0	9.33	37.30	58.4	92.3	48.3	98.3
1	4.70	27.7	9.40	52.91	40.9	125.7	29.5	96.6

The quantity of irrigation water initially declined substantially, but the decline then slowed as the EDR increased.

The flex point on the changing curve of irrigation amount with EDR was selected as the upper limit of suitable EDR. A rapid method of determining EDR was proposed considering the peak period water consumption and based on the premise that a lower EDR is better. Using this method, 0.3 L/h was selected as a suitable EDR in a field study. The selected EDR resulted in improved salt leaching, Na^+ induction rate, and plant survival rate compared to previous studies.

The method is simple and convenient, and takes into consideration the water requirements of the crop. The method would also be suitable for other sodic soils with a low saturated hydraulic conductivity.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

This study was supported by the Key Research Program of Frontier Sciences of the Chinese Academy of Sciences (Grant No. QYZDJ-SSW-DQC028) and the National Key Research and Development Program of China (Grant Nos. 2016YFC0501304 and 2016YFC0501305).

References

Berezniak, A., A. Ben-Gal, Y. Mishael, and U. Nachshon. 2018. “Manipulation of soil texture to remove salts from a drip-irrigation root zone.” *Vadose Zone J.* 17 (1): 170019. https://doi.org/10.2136/vzj2017.01.0019.

Callaghan, M. V., E. E. Cey, and L. R. Bentley. 2014. “Hydraulic conductivity dynamics during salt leaching of a sodic, structured subsoil.” *Soil Sci. Soc. Am. J.* 78 (5): 1563–1574. https://doi.org/10.2136/sssaj2014.03.0106.

Chen, X., Y. Kang, S. Wan, L. Chu, and X. Li. 2015. “Simple method for determining the emitter discharge rate in the reclamation of coastal saline soil using drip irrigation." *J. Irrig. Drain. Eng.* 141 (10): 04015011. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000894.

Darwish, T., T. Atallah, M. El Moujabber, and N. Khatib. 2005. "Salinity evolution and crop response to secondary soil salinity in two agro-climatic zones in Lebanon." *Agric. Water Manage.* 78 (1–2): 152–164. https://doi.org/10.1016/j.agwat.2005.04.020.

Dastranj, M., M. Noshadi, A. Sepaskhah, F. Razzaghi, and R. Ragab. 2018. "Soil salinity and tomato yield simulation using SALTMED model in drip irrigation." *J. Irrig. Drain. Eng.* 144 (2): 05017008. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001243.

Feng, D., S. Wan, Y. Kang, Z. Xue, and T. Zhang. 2017. "Drip irrigation scheduling for annual crops in an impermeable saline-sodic soil with an improved method." *J. Soil Water Conserv.* 72 (4): 349–358. https://doi.org/10.2489/jswc.72.4.351.

Huang, P., Y. Kang, S. Wan, and X. Li. 2021. "Amelioration of takyric solonetz using drip irrigation with soil-water-redistribution medium." *Irrig. Drain.* 71 (1): 108–119. https://doi.org/10.1002/ird.2644.

IUSS Working Group WRB. 2014. *World reference base for soil resources 2014*. World Soil Resources Rep. No. 106. Rome: Food and Agriculture Organization of the United Nations.

Kang, Y. H., S. Q. Wan, S. F. Jiang, and F. Q. Yin. 2013. *A method of vacuum gauge tensionmeter used in saline-alkali soil*. China, 200910075194.0[ZL]. 2013-1. CN101629944 B. Beijing: Intellectual Property Publishing House.

Kemper, W. D., and E. J. Koch. 1966. *Aggregate stability of soils from western USA and Canada*. USDA Technical Bulletin 1355. Washington, DC: USDA.

Li, F., and R. Keren. 2008. "Native $CaCO_3$ mineral dissolution and its contribution to sodic calcareous soil reclamation under laboratory conditions." *Arid Land Res. Manage.* 22 (1): 1–15. https://doi.org/10.1080/15324980701784225.

Liu, A., Z. Qu, and U. Nachshon. 2020. "On the potential impact of root system size and density on salt distribution in the root zone." *Agric. Water Manage.* 234 (May): 106118. https://doi.org/10.1016/j.agwat.2020.106118.

Mamedov, A. I., I. Shainberg, and G. J. Levy. 2002. "Wetting rate and sodicity effects on interrill erosion from semi-arid Israeli soils." *Soil Tillage Res.* 68 (2): 121–132. https://doi.org/10.1016/S0167-1987(02)00115-0.

Naglic, B., C. Kechavarizi, F. Coulon, and M. Pintar. 2014. "Numerical investigation of the influence of texture, surface drip emitter discharge rate and initial soil moisture condition on wetting pattern size." *Irrig. Sci.* 32 (6): 421–436. https://doi.org/10.1007/s00271-014-0439-z.

Oster, J. D., and I. Shainberg. 2001. "Soil responses to sodicity and salinity: Challenges and opportunities." *Aust. J. Soil Res.* 39 (6): 1219–1224. https://doi.org/10.1071/SR00051.

Qadir, M., and J. D. Oster. 2004. "Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture." *Sci. Total Environ.* 323 (1–3): 1–19. https://doi.org/10.1016/j.scitotenv.2003.10.012.

Qadir, M., J. D. Oster, S. Schubert, A. D. Noble, and K. L. Sahrawat. 2007. "Phytoremediation of sodic and saline-sodic soils." *Adv. Agron.* 96 (Jan): 197–247. https://doi.org/10.1016/S0065-2113(07)96006-X.

Qadir, M., and S. Schubert. 2002. "Degradation processes and nutrient constraints in sodic soils." *Land Degrad. Dev.* 13 (4): 275–294. https://doi.org/10.1002/ldr.504.

Qadir, M., S. Schubert, A. Ghafoor, and G. Murtaza. 2001. "Amelioration strategies for sodic soils: A review." *Land Degrad. Dev.* 12 (4): 357–386. https://doi.org/10.1002/ldr.458.

Richards, L. A. 1954. *Diagnosis and improvement of saline and alkali soils*. Agriculture Handbook No. 60. Washington, DC: USDA.

Shainberg, I., G. J. Levy, D. Goldstein, A. I. Mamedov, and J. Letey. 2001. "Prewetting rate and sodicity effects on the hydraulic conductivity of soils." *Aust. J. Soil Res.* 39 (6): 1279–1291. https://doi.org/10.1071/SR00052.

Shainberg, I., G. J. Levy, and A. I. Mamedov. 2002. "Prewetting rates and sodicity effects on soil permeability and surface sealing." *Acta Hortic.* 573 (573): 21–28. https://doi.org/10.17660/ActaHortic.2002.573.1.

Shao, M. A., Q. J. Wang, and M. B. Huang. 2006. *Soil physics*. [In Chinese.] Beijing: Higher Education Press.

Singh, K. 2016. "Microbial and enzyme activities of saline and sodic soils." *Land Degrad. Dev.* 27 (3): 706–718. https://doi.org/10.1002/ldr.2385.

Tanji, K. K., and W. W. Wallender. 2012. "Nature and extent of agricultural salinity and sodicity." In *Agricultural salinity assessment and management*, 2nd ed., edited by W. W. Wallender and K. K. Tanji. 1–25. Reston, VA: ASCE.

Temiz, C., and G. Cayci. 2018. "The effects of gypsum and mulch applications on reclamation parameters and physical properties of an alkali soil." *Environ. Monit. Assess.* 190 (6): 1–12. https://doi.org/10.1007/s10661-018-6669-4.

Wang, S. J., Q. Chen, Y. Li, Y. Q. Zhou, and L. Z. Xu. 2017. "Research on saline-alkali soil amelioration with FGD gypsum." *Resour. Conserv. Recycl.* 121 (Jun): 82–92. https://doi.org/10.1016/j.resconrec.2016.04.005.

Wang, Z. Q., S. Q. Zhu, R. P. Yu, L. Q. Li, G. Z. Shan, W. R. You, X. X. Zeng, C. W. Zhang, L. J. Zhang, and R. H. Song. 1993. *Salt affects soil in China*. [In Chinese.] Beijing: Science Press.

Wu, I. P., H. M. Gitlin, K. H. Solomon, and C. A. Saruwatari. 1986. "Design principles." Chap. 2 in *Trickle irrigation for crop production*, edited by F. S. Nakayama and D. A. Bucks, 68–69. Amsterdam, Netherlands: Elsevier.

Zhang, T., Q. Dong, X. Zhan, J. He, and H. Feng. 2019. "Moving salts in an impermeable saline-sodic soil with drip irrigation to permit wolfberry production." *Agric. Water Manage.* 213 (Mar): 636–645. https://doi.org/10.1016/j.agwat.2018.11.011.

Zhang, T., Y. Kang, and S. Wan. 2013. "Shallow sand-filled niches beneath drip emitters made reclamation of an impermeable saline-sodic soil possible while cropping with *Lycium barbarum* L." *Agric. Water Manage.* 119 (Mar): 54–64. https://doi.org/10.1016/j.agwat.2012.12.016.

Zur, B. 1996. "Wetted soil volume as a design objective in trickle irrigation." *Irrig. Sci.* 16 (3): 101–105. https://doi.org/10.1007/BF02215617.