

Capillary rise and saliferous groundwater evaporation: effects of various solutes and concentrations

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ABSTRACT

Capillary rise is capable of demonstrating the mechanism involved in groundwater evaporation, where the evaporation from saliferous groundwater could be quantized in accordance with fresh groundwater. The two types of experiments included 12 treatments with four solutes (KCl, NaCl, CaCl₂, and MgCl₂) that were dissolved in groundwater at three concentrations (5, 30, and 100 g/L), and one control treatment without the salt solutions. The results demonstrated that the capillary action played a dominant role only within a very short period of time at the beginning of evaporation (i.e. within 2 min). The total dissolved solids (TDS) of the groundwater that was dissolved with KCl or NaCl affected the capillary water gravity more than soil pore structure. The TDS of the groundwater that was dissolved with CaCl₂ or MgCl₂ affected both the capillary water gravity and the soil pore structure. During the groundwater evaporation process, the evaporation conversion coefficient C_{TDS} (>1.0) had the potential to calculate the saliferous-groundwater evaporation in accordance with the fresh-groundwater evaporation. The C_{TDS} values were the largest for the groundwater that was dissolved with KCl/NaCl and CaCl₂/MgCl₂ at 5 and 30 g/L, where it reached average values of 1.3530–1.3735 and 1.3257–1.3589.

Key words | capillary rise, evaporation conversion coefficient, groundwater, salt solutions

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INTRODUCTION

Groundwater is important for sustainable water resources management, where groundwater consumption is the main type of water consumption in croplands, particularly in regions that have strong evaporation and a shallow water table (Cai *et al.* 2016; Xing & Ma 2018). The soluble salts in the groundwater are absorbed by the upward water flow and finally moved into the soils. The soil water evaporates, leaving the salts gathered in the soils. This behavior ultimately causes soil salinization, which is an environmental issue that has become a large obstacle within sustainable agricultural development (Shi *et al.* 2013; Benini *et al.* 2016). Research regarding saliferous groundwater is important in evaluating groundwater resources.

Areas that lack site observation data often use empirical models, such as the Averiyarov equation or the Lei

equation, to compute groundwater evaporation (Xing *et al.* 2016). The coefficient of groundwater evaporation that is calculated as the amount of the groundwater evaporation divided by the amount of surface-water evaporation within the same time period (Xing *et al.* 2015) is commonly used to calculate groundwater evaporation. Previous studies, for example Xu *et al.* (2013), assessed the influence that the water table had on the evaporation intensity. Luo & Sophocleous (2010) measured the groundwater contributions to cropland via lysimeter observation data and a model simulation. Li & Wang (2014) quantized the phreatic water evaporation in an extra arid region. The groundwater evaporation without salts or fresh groundwater became more popular. The total dissolved solids (TDS) in groundwater is not commonly considered, which is a significant

issue in arid regions. Xing *et al.* (2013) stated that various types of salts in groundwater could cause different characteristics and processes of the groundwater flow. K^+ , Na^+ , Ca^{2+} , and Mg^{2+} may have blocking effects on the hydrochemical zoning of groundwater and the formation of saline water in groundwater systems, which also have different influences on soil properties (e.g. soil pores and soil structure), as well as on soil-water movement (Xing *et al.* 2017, 2018). Therefore, an estimation of saliferous groundwater evaporation obtained from the above methods could be inconsistent with the actual value, and under this circumstance, the evaporation conversion coefficient of saliferous groundwater was proposed, where it was thought to have significance for estimating groundwater evaporation dissolved with salts.

Groundwater evaporation could be actually reflected through the capillary rise, which could in turn reveal the mechanism involved in groundwater evaporation. Wessolek *et al.* (2011) proposed a HPTF model to estimate the annual capillary rise from groundwater. Stenitzer *et al.* (2007) assessed the capillary rise from shallow groundwater via the simulation model SIMWASER by either estimating the pedo-transfer functions or measuring the hydraulic parameters. The researchers focused more on the characteristics of capillary rise from fresh groundwater, neglecting the effects of salts found within the groundwater. Groundwater with high-TDS is extensively distributed in extremely arid regions, such as the Hexi Corridor, the Junggar Basin, and the Tarim Basin. It is necessary to quantify the capillary rise characteristics of saliferous groundwater, as this would deepen the understanding of groundwater evaporation mechanisms in extremely arid regions, while promoting the scientific management of groundwater (Wang *et al.* 2017).

Research regarding capillary rise and saliferous groundwater evaporation is of both theoretical and practical significance. The main objective of this study was to investigate the influences of solute and concentration on the capillary rise and the groundwater evaporation, specifically: (1) to reveal the salty-groundwater evaporation mechanisms on the basis of the characteristics of capillary rise; and (2) to analyze the relationship between salty and fresh groundwater evaporation on the basis of the evaporation conversion coefficient of saliferous groundwater.

MATERIALS AND METHODS

Experimental soil samples were collected from a cultivated field on the Loess Plateau of China (approximately $34^{\circ}17' N$ and $108^{\circ}04' E$). The samples were classified as loam, with particle size distributions of 16.32%, 0–0.002 mm, 34.56%, 0.002–0.02 mm, and 49.12%, 0.02–2 mm. The experimental soils were air dried and then sieved through a 2-mm mesh. According to the rangeability of the TDS concentration of salt water ($3\text{--}10\text{ g L}^{-1}$), saline water ($10\text{--}50\text{ g L}^{-1}$), and brine water ($>50\text{ g L}^{-1}$), four common salt solutes, KCl, NaCl, $CaCl_2$, and $MgCl_2$, were each dissolved in distilled water at concentrations of 5, 30, and 100 g L^{-1} (K-5, K-30, and K-100). Distilled water was used as the control treatment (CK). Each type of solution served as the water-supply source.

For the capillary rise experiment, the influence of pipe diameter on capillary action can be ignored under conditions where the pipe diameter is much larger than the soil particle diameter and the soil porosity maintains constant (Zhang 2017). Under such circumstances, with the consideration of convenient operation and observation, a type of fine Plexiglas pipe with an inner diameter of 2.9 mm was selected, which was filled with experimental loam soils at a constant dry bulk density of 1.35 g cm^{-3} , similar to the laboratory experiments conducted by Salim (2016). A small window screen covered the bottom of each pipe, and each column was placed into a clear water tank that was connected to a Mariott bottle for continuous water supply and constant water level (Figure 1(a)). The capillary ascension height was obtained from the scales on the pipe during various time intervals.

For the groundwater evaporation experiment, the experimental soils were compacted into Plexiglas soil columns with a height of 60 cm and an inner diameter of 15 cm at 1.35 g cm^{-3} dry bulk density for the groundwater evaporation trials. Ten centimeters of gravel and sand was placed at the bottom of each soil column, acting as a filter. A Mariott bottle was connected to the bottom of soil column to maintain a steady water table at 50 cm and provided with a continuous water supply (Figure 1(b)). The existing coverage on soil surface was not removed until the visual wetting front reached the surface and the

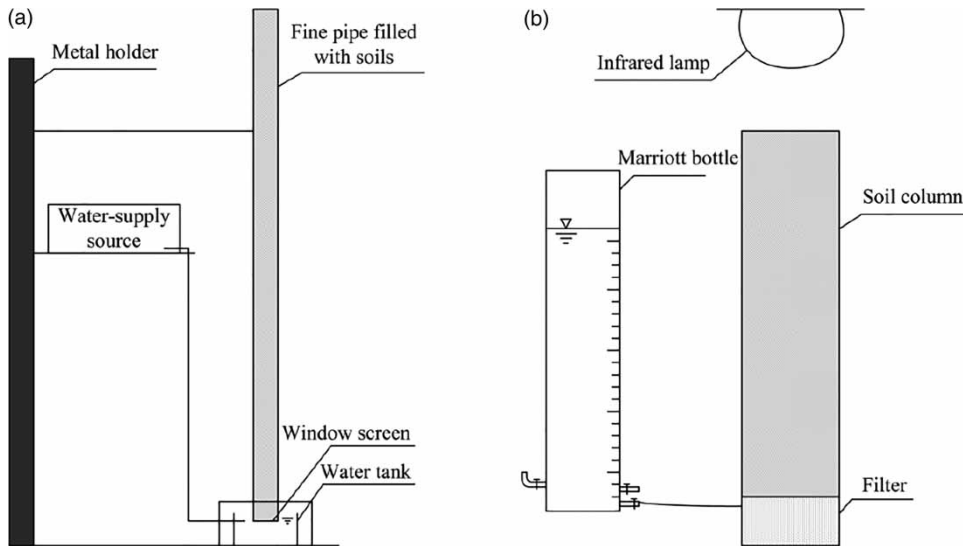


Figure 1 | Simplified experimental setup of the (a) capillary rise experiment and the (b) groundwater evaporation experiment.

upward capillary rate was constant. In order to create a steady-state evaporation (Shi *et al.* 2014; Ren *et al.* 2017), each soil column was placed beneath an infrared lamp with a constant power (e.g. 275 W) to encourage evaporation. The vertical distance between the lamp and the soil surface was maintained at 40 cm. The day-and-night illumination cycle occurred for 20 d. The water level in the Mariott bottle was recorded at 08:00 hours each day, in order to calculate the daily groundwater evaporation.

RESULTS

Capillary rise affected by the solute and TDS of groundwater

The soil close to the liquid surface trended to saturation during capillary rise (i.e. saturated zone), and a supporting capillary water zone existed above the saturated zone. The water moisture along the soil profile decreased rapidly as the height increased (Figure 1(a)). The air-water interface, as well as the vapor transport, resulted from liquid evaporation existing in the unsaturated zone. The solute in the water-supply source with high TDS gradually concentrated during evaporation, absorbing on the soil particle surface, and finally changing the soil structure.

The height of capillary rise increased with an increase in duration, but the increasing rate gradually decreased. The KCl and NaCl treatments (Figure 2(a) and 2(b)) demonstrated that the duration of capillary water that reached the surface (D_{CW}) increased as the concentration of KCl and NaCl solutions increased, in the following order: K (Na)-100 > K (Na)-30 > K (Na)-5. The D_{CW} was around 305, 335, and 390 min for the K-5, the K-30, and the K-100 treatments, and about 315, 337, and 360 min for the Na-5, the Na-30, and the Na-100 treatments, respectively. The CaCl_2 and MgCl_2 treatments (Figure 2(c) and 2(d)) did not have a monotonous relationship between the D_{CW} and the concentration, so the order was: Ca (Mg)-100 > Ca (Mg)-5 > Ca (Mg)-30. The D_{CW} was about 315, 283, and 383 min for the Ca-5, the Ca-30, and the Ca-100 treatments, and about 350, 345, and 355 min for the Mg-5, the Mg-30, and the Mg-100 treatments, respectively. The height of the capillary rise increased as a function of power alongside the duration, with a high R^2 (Table 1).

The capillary rise rate was signified as the height per unit time. The variation of the capillary rise rate during the first 30 minutes is plotted in Figure 3. The capillary rise rate tended to decrease, with a sharp decrease at the initial stage and a slow decrease after. Figure 3 shows that the capillary action played a dominant role for a short time, at the beginning of evaporation. The capillary water demonstrated a stairs-type rise phenomenon after

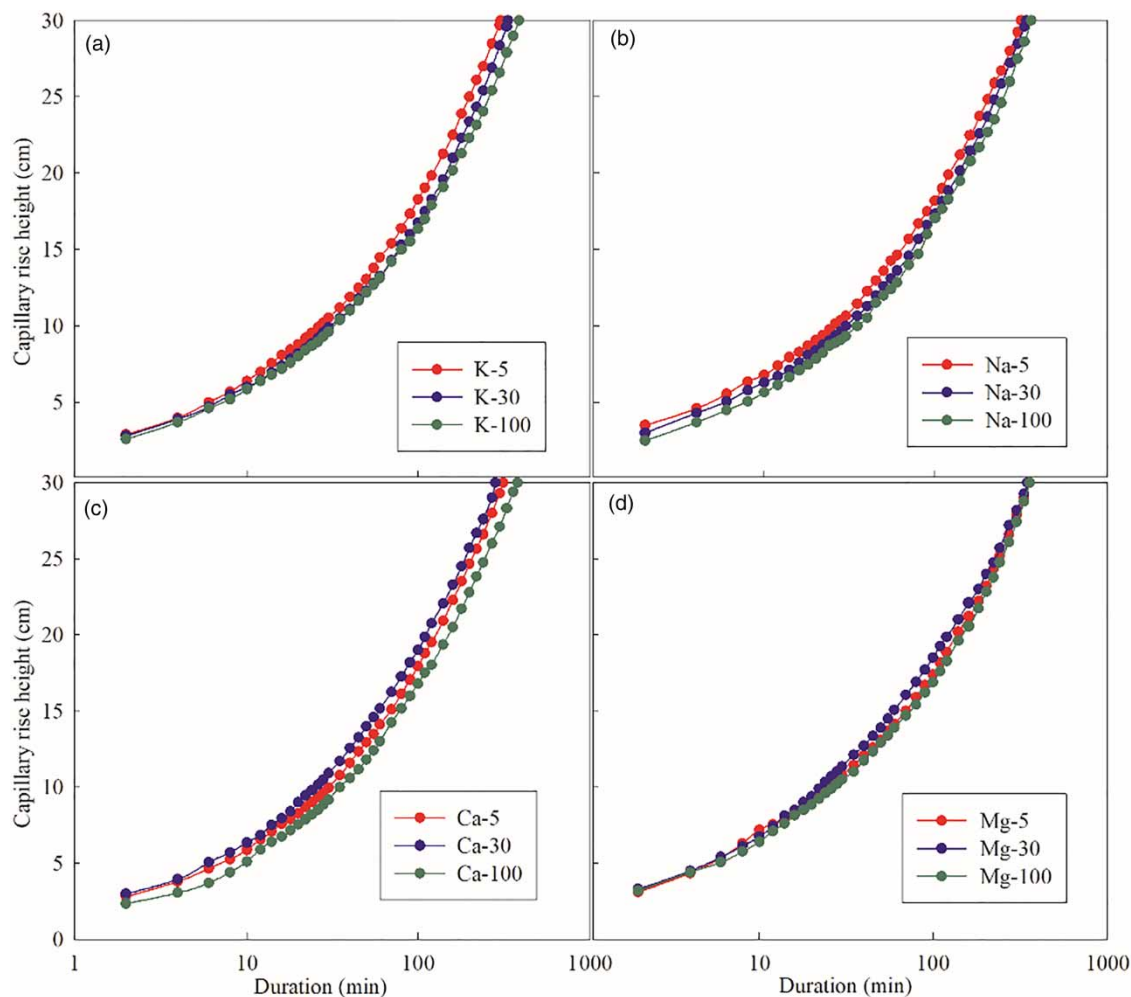


Figure 2 | Variation of the capillary rise heights under various solutes and TDS conditions.

Table 1 | Relationship between the height of capillary rise h and the duration t

Treatment TDS/(g/L)	KCl		NaCl		CaCl ₂		MgCl ₂	
	Equation	R ²	Equation	R ²	Equation	R ²	Equation	R ²
5	$h = 2.200t^{0.459}$	0.9994	$h = 2.542t^{0.428}$	0.9996	$h = 2.004t^{0.474}$	0.9997	$h = 2.557t^{0.419}$	0.9979
30	$h = 2.076t^{0.457}$	0.9997	$h = 2.224t^{0.446}$	0.9995	$h = 2.184t^{0.468}$	0.9990	$h = 2.618t^{0.422}$	0.9979
100	$h = 2.038t^{0.453}$	0.9992	$h = 1.911t^{0.469}$	0.9993	$h = 1.674t^{0.495}$	0.9974	$h = 2.453t^{0.423}$	0.9992

the KCl, NaCl, CaCl₂, and MgCl₂ treatments, where the rise of capillary water stagnated during some time intervals within the observation precision. The final height characteristics of the capillary water was inconsistent with its rate during the early period, and thus requires further investigation.

The rate of capillary rise during the second minute was investigated (Figure 4) in order to determine how the TDS affected capillary rise. The rate of capillary rise during the KCl and NaCl treatments decreased as the solution concentration increased from 5 to 100 g/L, indicating that the TDS had a major effect on the capillary water gravity, but few

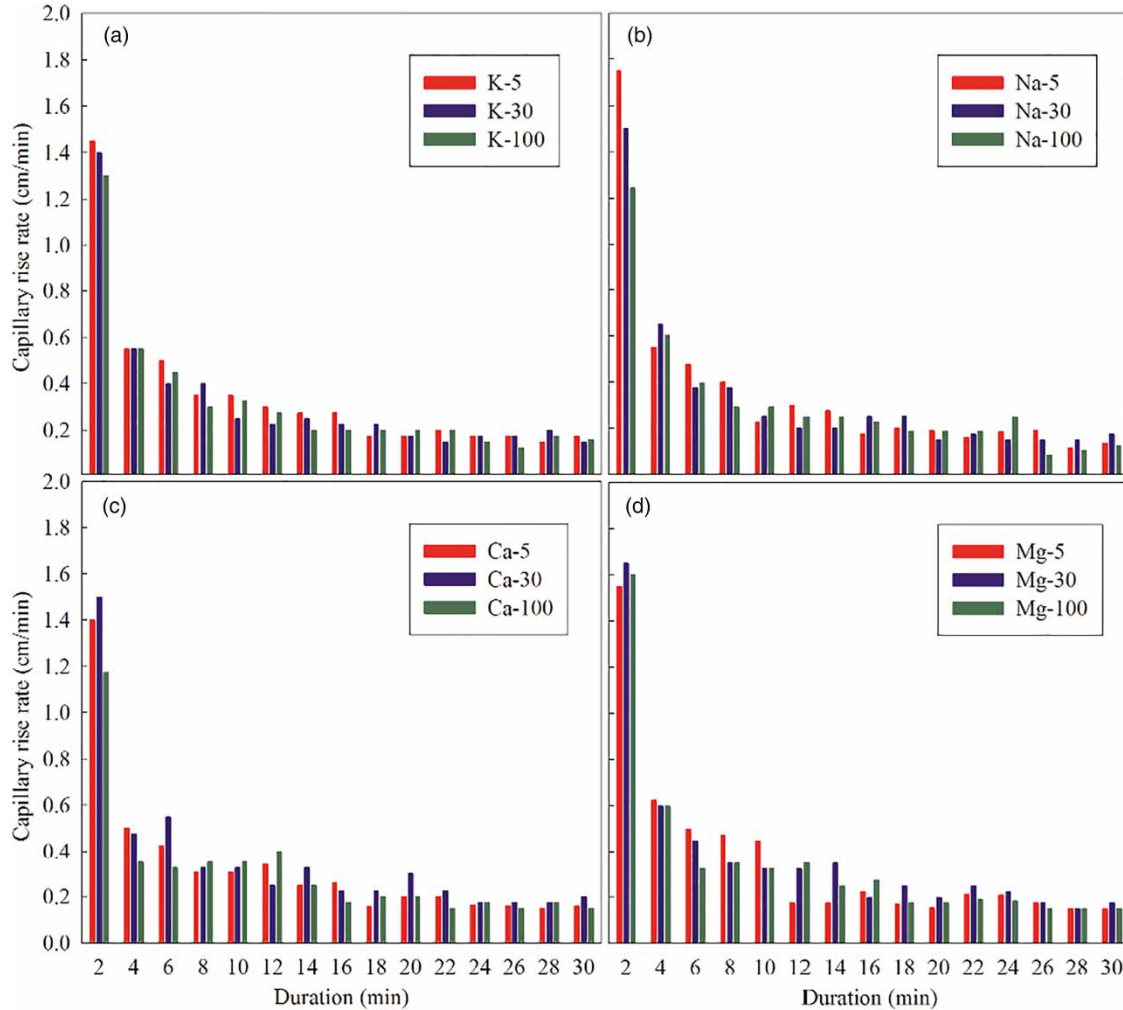


Figure 3 | Variation of the capillary rise rate during the first 30 minutes, under various solutes and TDS conditions.

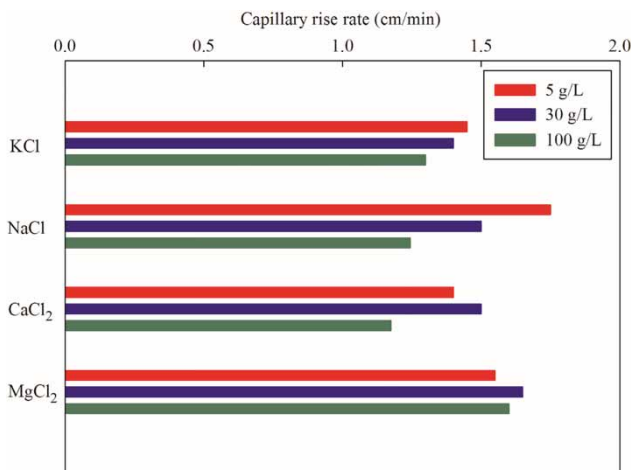


Figure 4 | Variation of capillary rise rate during the second minute, under various solutes and TDS conditions.

effects on the soil pore structure. The TDS changes the capillary water gravity and the soil pore structure during the CaCl₂ and MgCl₂ treatments, demonstrating that the soil capillary suction was affected. The combined influences lead to a complicated variation of the rate of capillary rise, where a monotonous relationship was not observed between the capillary rise rate and the concentration of the CaCl₂ or MgCl₂ solutions.

Evaporation conversion coefficient of saliferous groundwater

The evaporation conversion coefficient of the saliferous groundwater (C_{TDS}) was defined as the ratio of the

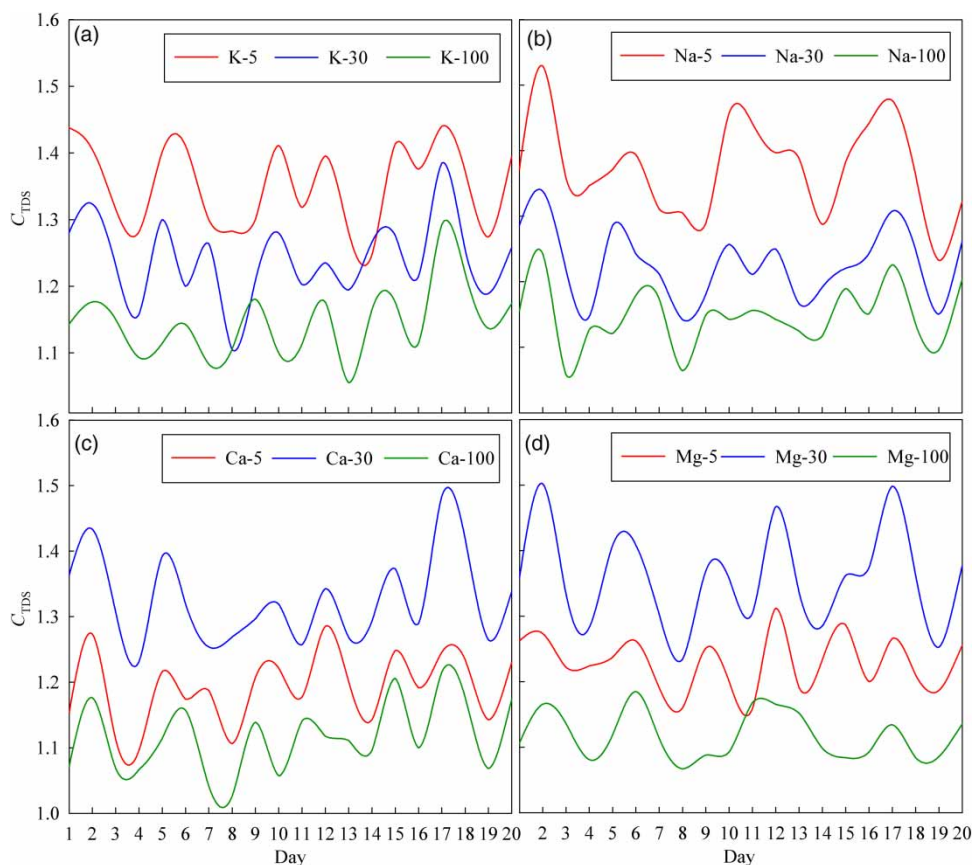


Figure 5 | Variations of the C_{TDS} over various treatments, during the experimentation period.

evaporation of saliferous groundwater (i.e. with TDS) to the evaporation of the fresh groundwater (i.e. without TDS). This coefficient was introduced to make a comparative analysis of the two types of evaporation, to further reflect the relationships between them. The groundwater evaporation was measured through the corresponding setup (Figure 1(b)), and then used to calculate the C_{TDS} . A similar variation tendency of the C_{TDS} over the three concentrations of the KCl, the NaCl, the $CaCl_2$, or the $MgCl_2$ treatments were observed (Figure 5), although with some fluctuations. Figure 5 shows that the C_{TDS} values for all treatments was larger than 1.0, indicating that the saliferous groundwater evaporation was greater than fresh groundwater evaporation.

The KCl and NaCl treatments (Figure 5(a) and 5(b)) demonstrated decreased C_{TDS} as the solution concentration increased, with the average C_{TDS} values of 1.3530, 1.2414, and 1.1457 for the K-5, the K-30, and the K-100 and 1.3735, 1.2282, and 1.1479 for the Na-5, the Na-30, and

the Na-100, respectively. This indicated the evaporation of the higher-TDS groundwater was smaller than the lower-TDS groundwater. The C_{TDS} for the 30 g/L treatments were the largest with the $CaCl_2$ and $MgCl_2$ treatments (Figure 5(c) and 5(d)), followed by the 5 and 100 g/L treatments, which had average C_{TDS} values of 1.1923, 1.3257, and 1.1162 for the Ca-5, the Ca-30, and the Ca-100 and 1.2293, 1.3589, and 1.1178 for the Mg-5, the Mg-30, and the Mg-100, respectively. The value of groundwater evaporation reached its maximum at a concentration of 30 g/L.

DISCUSSION

Understanding the capillary rise for soil affects various industries such as environmental remediation and farming. Specifically, when a site has experienced pollution, the capillary rise must be known to define the soil capillary

fringe for the places where there is groundwater. The water evaporation from groundwater is actually the process of capillary rise. The mechanism of water evaporation can also be understood through the characteristics of the capillary rise. Therefore, a combination of the experiments of groundwater evaporation and capillary rise is of theoretical significance. Besides, knowing the capillary rise for cultivated soils is essential for water irrigation management (Lockington & Parlange 2004), which can also affect the salinity of soil used for farmland. If the water at the water table is brackish, capillary rise may bring the capillary fringe close to the surface and finally cause salt deposits under evaporation. Therefore, the research regarding upward water flow from saliferous groundwater is of practical significance.

Similar variations of the D_{CW} and the C_{TDS} were observed throughout all treatments (Figures 2 and 5), which was consistent with the actual situation. The smaller the evaporation intensity, the longer wetting front reached the soil surface. Both the D_{CW} and the C_{TDS} varied monotonically with the concentrations of KCl and NaCl solutes in groundwater. The D_{CW} for the very high-TDS treatments (i.e. 100 g/L in this study) were the largest, without obvious differences. At the high TDS condition, the selected four types of soluble salts concentrated and absorbed on the capillary wall. This behavior reduced the amount of large pores, which enhanced the capillary force (Bergstad *et al.* 2017), and during the later stage, the salt continued to precipitate, which blocked the smaller pores in the saturated zone and inhibited capillary rise. This behavior resulted in the smallest evaporation and the largest D_{CW} . For the $MgCl_2$ and $CaCl_2$ treatments, the D_{CW} at TDS concentration of 30 g/L was the smallest, which was different from the KCl and NaCl treatments. From the viewpoint of the changes in capillary, this phenomenon may be due to the generated suitable capillary tube diameter. Specifically, the precipitated $MgCl_2$ or $CaCl_2$ at 30 g/L reduced the original diameter of capillary tube, exactly forming a suitable diameter that is neither too large nor blocked, which promoted upward movement and water loss (Li *et al.* 2011, 2016). This could be more likely caused by the interactions between Ca^{2+} or Mg^{2+} and the ions in soils, which requires further exploration within the soil colloid and the interface chemistry.

There was a significant difference between capillary rise rate within the first 2 minutes and after the first 2 minutes

(Figure 3). This was because capillary water rose under both the capillary action and gravity, so the capillary force was far larger than gravity at the beginning of the initial stage (i.e. 2 min), resulting in a rapid ascent. As the capillary rise height continuously increased, the capillary force gradually decreased until it was at equilibrium with gravity, resulting in a slow ascent. How soluble salts affect soil pores, and thus further affect the capillary rise, requires further revelations. The scanning electron microscope method could be adopted to study the microstructure of these soils (She *et al.* 2018).

The saliferous groundwater evaporation was greater than fresh groundwater evaporation (refer to Figure 5, i.e. $C_{TDS} > 1$). This phenomenon was related to the soil structure and could be explained via the soil capillary. The soluble salts in groundwater moved into the soils, crystallized and finally deposited. The volume of the moderate pores subsequently became smaller and thus resulted in an increased capillary rise height. The evaporative surface where the soil water vaporized to the air moved closer to the soil surface, resulting in more groundwater evaporation (Xing *et al.* 2015). During this process, the number of channels carrying water and vapor decreased, due to the small volume of soil pores. Theoretically, this behavior inhibited water loss. The effect of the reduction of groundwater evaporation caused by the decrease in soil channel was less than the increment of groundwater evaporation caused by the capillary rise which was caused by the decreasing soil pore. This ultimately contributed to a larger evaporation of the saliferous groundwater.

The present experiment was conducted in room-temperature conditions, and the soils were considered to be in the unfreezing period. These conditions are different from the freezing period, where the temperatures would be lower and the characteristics of the water-salt migration of frozen soil become more complex. Besides, the water evaporation in the present study was processed under steady evaporation conditions, which is different from natural conditions (i.e. day-night cycle). The characteristics of water evaporation under the conditions of alternation of day and night should be further explored on the present foundation achieved under the conditions of steady evaporation. Furthermore, the relationship between the capillary rise height and groundwater evaporation needs to be further quantified. For the areas with polluted groundwater the

height of capillary rise can be estimated according to the evaporation and, under this circumstance, appropriate irrigation scheduling, for example, can be determined and applied to the farmland avoiding soil pollution.

CONCLUSIONS

The present indoor soil-column evaporation experiment demonstrated that the solute and the TDS of groundwater had different effects on the capillary rise and the evaporation of saliferous groundwater, as well as the C_{TDS} .

During capillary rise, the D_{CW} for the groundwater that was dissolved with KCl or NaCl showed a $K(Na)-100 > K(Na)-30 > K(Na)-5$ order. The D_{CW} for the groundwater that was dissolved with $CaCl_2$ or $MgCl_2$ showed a $Ca(Mg)-100 > Ca(Mg)-5 > Ca(Mg)-30$ order. The height of the capillary rise increased as a function of power along with the duration. The rate of capillary rise obtained a decreasing trend, with a sharp decrease at the initial stage. The capillary action played a dominant role within a short period of time at the beginning of evaporation. The TDS of the groundwater dissolved with KCl or NaCl showed major effects on the gravity of capillary water, but few effects on the soil pore structure. However, the TDS of the groundwater that was dissolved with $CaCl_2$ or $MgCl_2$ had effects on both the gravity of capillary water and on the soil pore structure.

During groundwater evaporation, the evaporation intensity of the saliferous groundwater was larger than the fresh groundwater, resulting in a C_{TDS} that was greater than 1.0. The C_{TDS} for the groundwater dissolved with KCl or NaCl showed a $K(Na)-100 < K(Na)-30 < K(Na)-5$ order, where the C_{TDS} for the groundwater that was dissolved with $CaCl_2$ or $MgCl_2$ showed a $Ca(Mg)-100 < Ca(Mg)-5 < Ca(Mg)-30$ order.

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