EFFECT OF ALTERNATE IRRIGATION ON WATER AND SALT MOVEMENT UNDER MOISTUBE IRRIGATION

Zhan-yu Zhang\textsuperscript{1}, Wei Qi\textsuperscript{2}, Ce Wang\textsuperscript{3}

ABSTRACT

Many water-saving irrigation techniques are proposed in response to water scarcity in irrigation. Sub-surface irrigation is widely applied because it supplies water precisely and reduces surface evaporation effectively. A new type of irrigation technique—moistube irrigation was developed based on sub-surface irrigation and practiced well in China in Recent years. The major objectives of this study were to investigate the water and salt movement in soil by alternate irrigation with saline water of different mineralization degrees under moistube irrigation and to explore the potential of saline water application in moistube irrigation. Five irrigation treatments were performed using fresh water and saline water with four mineralized levels of 2, 3, 4, 6 g/L. The results showed that the mineralization degree of irrigation water had substantial effect on infiltration rate. The overall trend of infiltration could be well described by the Kostiakov empirical infiltration model despite the alternate irrigation. The propagation of wetting area in all treatments were similar, which gradually evolved from approximate circles to ellipses. The value of wetting area were in similar linear correlation with the cumulative infiltration amount in most treatments. The wetting area was significantly reduced when the mineralization degree of irrigation water was high in the first stage, which was probably due to the change of soil structure caused by high salt content. The soil moisture and salt were mainly distributed near the moistube. There was a sign that irrigating with water of low mineralization degree moved the salt near moistube to wetting edge in soil, which indicated the possibility of application of saline water in moistube irrigation and needed to be further investigated.

Keywords: Moistube irrigation, Alternate irrigation, Saline water, Wetting patterns, Water and salt distribution.

1. INTRODUCTION

Water scarcity caused by climate change has become a serious problem for irrigation. Many water-saving irrigation techniques were proposed and practiced to reduce irrigation water use and promote total crop yield. It is widely proved that sub-surface irrigation, mainly including sub-surface drip irrigation and infiltration irrigation, can conserve moisture by supplying water precisely and minimizing surface evaporation. Therefore effectively enhance the water use efficiency (Bonaiti and Borin, 2010; Cai et al., 2017; Siyal and Skaggs, 2009). However, there are still some intractable disadvantages, such as easy clogging of emitter and high energy consumption (Gil et al., 2008; Trooien et al., 2000). In attempt to overcome the shortcomings, a new type of sub-surface irrigation technique—moistube irrigation, was developed and strongly advocated by the Ministry of Water Resources of the People’s Republic of China, and has been partially popularized in China currently. The moistube, made of semipermeable membrane material in which nanoscale pores are

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densely distributed, is employed as water emitter that can hardly get clogged. The water is driven out from the pores by the difference in water potential between inside and outside the tube. Under a low pressure head during operating, moistube irrigation supplies water slowly, continuously and automatically. It achieves high consistency between the processes of water supply and water adsorption of crops and provides appropriate moisture condition for crop throughout whole growth period, which is beneficial to crop growth. Considerable lab experiments were carried out to investigate the law of water movement of moistube irrigation. Many researchers reported that the wetting front of moistube irrigation in soil profile approaches circle centered on the tube (Bi et al., 2018; Xue et al., 2013). The size of wetting body is markedly affected by many factors, such as pressure head, tube depth, initial soil water content, and so on (Fan et al., 2018; Zhang et al., 2018). The relationship between migration distance of wetting front and infiltration time follows a power function and the variation of cumulative infiltration amount versus time can be well described by the Kostiakov empirical infiltration model (Xue et al., 2013; Zhang et al., 2017). Besides, many field or pot experiments were conducted to examine the practicability of moistube irrigation. Shi et al. (2013) found that at seedling stage the plant height and stem diameter of maize were larger in moistube irrigation treatment than drip irrigation treatment.

He et al. (2012) reported that moistube irrigation was beneficial to the development of maize-seed, resulting in the increase of grain mass by comparison with drip irrigation. Wang et al. (2018b) reported that comparing with ordinary irrigation, moistube irrigation significantly promoted the growth of large leaf chrysanthemum and the irrigation water productivity. However, much work so far focused on moistube irrigation with fresh water, little attention was paid to the irrigation with saline water. Saline water has been successfully used as irrigation water as long as the salt content with root zone was controlled at a reasonable level (Flowers et al., 2005; Karlberg et al., 2007). In consequence, the main objectives of this study were to investigate the migration and distribution of water and salt in soil under moistube irrigation by alternate application of saline water and fresh water, and to further explore the potential of using saline water in moistube irrigation.

2. MATERIALS AND METHODS

2.1 Site Location and Soil Properties

The study was conducted indoors at Hohai University in Nanjing, China (31°57’ N, 118°50’ E). The soil used in this study was collected from the upper 20 cm layer of the experimental farm where rice and wheat have been alternatively cultivated during the last 10 years. The soil texture was clay loam classified as a Hapludalf (Alfisols) with an average of 43% clay (<0.002 mm), 32% silt (0.002 mm-0.02 mm) and 25% sand (≥0.2 mm). Physical soil properties is shown in Table 1.

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Clay loam</td>
</tr>
<tr>
<td>Classification</td>
<td>Hapludalf, Alfisols</td>
</tr>
<tr>
<td>Remolded dry bulk density</td>
<td>1.25 g/cm³</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.63</td>
</tr>
<tr>
<td>Sand content (≥0.02mm)</td>
<td>25%</td>
</tr>
<tr>
<td>Silt clay (0.002mm-0.02mm)</td>
<td>32%</td>
</tr>
<tr>
<td>Clay content (&lt;0.002mm)</td>
<td>43%</td>
</tr>
<tr>
<td>Antecedent moisture content</td>
<td>4.0% in gravimetric watercontent</td>
</tr>
<tr>
<td>Saturated moisture content</td>
<td>46.7% in gravimetric watercontent</td>
</tr>
</tbody>
</table>
2.2 Experimental Set-Up and Data Collection

The experimental installation is presented in Figure 1, which was mainly composed of Plexiglas box and moistube irrigation system. The box was used for containing soil specimen. The length, width and height of the box were 60 cm, 6 cm and 55 cm, respectively. The back slab was uniformly perforated with measuring apertures for TDR (Time-Domain Reflectometry) probes. A section of moistube (16 mm in diameter) was fixed in the box through the symmetrical holes in the front and back slab. The end of the moistube in back slab was connected to the Mariotte bottle. The moistube and the Mariotte bottle jointly functioned as a simple moistube irrigation system.

![Figure 1. Diagram of experimental setup from the side view and rear view.](image)

After collection from the field, the soil was air-dried, and sieved through a 2-mm mesh sieve to exclude impurities. Subsequently, the soil was uniformly filled into the box with an average soil bulk density of 1.25 g/cm³ in 10 cm height increments until 50 cm. With the exception of top layer, the surface of each layer was scrubbed after filling in order to abate the undesirable discontinuity between layers. The entire size of soil specimen was 60×6×50 cm³, under which condition the migration of water and salt in soil could be regarded as two-dimensional movement. A total of ten specimens were prepared for the infiltration experiment.

Five treatments of different alternate irrigation regimes (Table 2) with two replicates were performed. The pressure head was controlled at 1.2 m and the buried depth of moistube was 23 cm. The irrigation amount was determined as 2500 ml. The saline water with different mineralization degrees were made by mixing sodium chloride and pure water in different proportions. During infiltration experiment, the infiltration amount was recorded according to the variation of the water level in the Mariotte bottle, and the advance of wetting front in soil specimen was captured by a digital camera placed in front of the box.

After infiltration, the soil moisture (volumetric water content) and the electrical conductivity of soil were measured by TDR. The electrical conductivity $EC_a$ (mS/cm) was converted into soil salt content $SS$ (g/kg) by the empirical equation $SS = 0.0347 \times EC_a + 0.15$ that was obtained by laboratory.

### Table 2. Treatments of alternate irrigation regime

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mineralization degree of irrigation water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First stage (1250ml)</td>
</tr>
<tr>
<td>T1</td>
<td>3 g/L</td>
</tr>
<tr>
<td>T2</td>
<td>2 g/L</td>
</tr>
<tr>
<td>T3</td>
<td>4 g/L</td>
</tr>
<tr>
<td>T4</td>
<td>0 g/L</td>
</tr>
<tr>
<td>T5</td>
<td>6 g/L</td>
</tr>
</tbody>
</table>
2.3 Digital Image Processing

From the images collected in infiltration experiment, the wetting front was well visualized owing to the significant contrast between wetting and dry soils. The wetting area of soil could be recognized according to the approach proposed by Wang et al. (2018a). Firstly, the core 60×50 cm$^2$ of the original images were cropped to extract the part of soil specimen and resized to a resolution of 6000×5500 (0.1mm/pixel).

Secondly, the resized images were transformed into YUV color images and grayed by eliminating the values of Y and U. Finally, an automatic threshold algorithm named ‘OSTU’ was employed to segment the gray images into binary images in which the wetting area was white (the pixel value equals 1) while the dry area was black (the pixel value equals 0). Based on the binary images, parameters characterizing wetting patterns, including value of wetting area, advancing distance of wetting front, were computed by morphological algorithms. All these operations were performed in MATLAB R2016a using the intrinsic functions along with programmed functions on the basis of Image Processing Toolbox.

3. RESULTS AND DISCUSSION

3.1 Effect of Mineralization Degree of Irrigation Water on Infiltration Rate

Figure 2 shows the cumulative irrigation amount versus infiltration time for all treatments. Significant differences were observed in the infiltration rate in the first stage among treatments. The cumulative infiltration amount at the same time was in the order of T1> T2> T3> T4> T5, indicating that the mineralization degree of irrigation water had substantial effect on infiltration rate. In this experiment, the irrigation water with mineralization degree of 3 g/L infiltrated fastest, and the infiltration rate accelerated as the mineralization degree increased when below 3 g/L while it showed if increased beyond 3 g/L.

It was consistent with the observation of Zhang et al. (2017). With the increase of soil salt concentration, the diffused double electron layer shrinks to the surface of clay particles and the repulsion forces between particles is decreased, which enlarges the proportion of effective pores and thus promotes the soil hydraulic conductivity. However, when the soil salt concentration is very high, the exchangeable sodium percent is also high, giving rise to the expansion and dispersion of soil particles and then causes clogging of soil pores. Consequently, the soil hydraulic conductivity gets decreased (Niu and Xue, 2014).

![Figure 2. Cumulative irrigation amount versus infiltration time for all treatments.](image-url)
3.2 Effect of Alternate Irrigation Regime on Infiltration Characteristics

The total infiltration time for all treatments were 4250 min, 5100 min, 5825 min, 6286 min and 8993 min, respectively. The large differences in total infiltration time implied that the distinct alternate irrigation regime affected the infiltration rate greatly. As can be seen from Figure 2, all the curves are smooth with good continuity between two infiltration stages. The data of cumulative infiltration amount was analyzed using the Kostiakov infiltration model \( I = K t^\alpha \) (\( K \) is infiltration coefficient, \( \alpha \) is infiltration index) with the corresponding error analysis conducted. The fitting parameters are provided in Table 3. The analysis shows that the \( R^2 \) for all treatments are very close to 1, indicating that the overall trend of infiltration can also be well described by the Kostiakov empirical infiltration model despite the alternate irrigation with water of different mineralization degree. The infiltration coefficient of T1, T2 and T3 are about 1, which were markedly larger than those of T4 and T5. T4 presents the lowest infiltration coefficient 0.6864. However, there is little difference in infiltration indices among treatments.

Table 3. Fitting parameters of \( K \) and \( \alpha \) for the treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>( K )</th>
<th>( \alpha )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1.0360</td>
<td>0.9350</td>
<td>0.9990</td>
</tr>
<tr>
<td>T2</td>
<td>1.0411</td>
<td>0.9118</td>
<td>0.9995</td>
</tr>
<tr>
<td>T3</td>
<td>1.0481</td>
<td>0.8986</td>
<td>0.9996</td>
</tr>
<tr>
<td>T4</td>
<td>0.6864</td>
<td>0.9384</td>
<td>0.9997</td>
</tr>
<tr>
<td>T5</td>
<td>0.8222</td>
<td>0.8823</td>
<td>0.9990</td>
</tr>
</tbody>
</table>

3.3 Effect of Alternate Irrigation Regime on Wetting Patterns

The evolution of wetting area in all treatments were similar, hence we only selected T1 for analysis. Figure 3 displays the shape of wetting body at different times in T1. At initial moment, the shape of wetting area was close to a circle centered on the moistube. Afterwards, the shape was gradually changing to an ellipse. The downward advancing distance of wetting front was a little larger than upward advancing distance, which was due to the influence of gravity potential of soil.

Figure 3. Evolution of wetting area with infiltration time in T3.

Figure 4 and Figure 5 respectively present the value of wetting area related to the cumulative infiltration amount and the average advancing distance of wetting front versus infiltration time for all treatments. For T1 to T4 treatments, the values of wetting area were in similar linear correlation with the cumulative infiltration amounts and the terminal values were close to each other. The wetting area in T5 was significantly less than those in other treatments. The propagation of wetting body in T5 could be divided into two stages synchronized with irrigation stages. The first stage was similar to that in other treatments. However, in the second stage the slope of the line is markedly decreased, indicating that the advancing distance of wetting front was reduced though same amount of water was applied when irrigating with fresh water. From Figure 5, the average advancing distances of wetting front were similar among T1 to T4, while in T5 the average advancing distance was significantly less than others, and the advancing velocity was much slower, especially in the
second stage. Those were due to the change of water conductivity and water retention of soil caused by irrigating with highly mineralized water.

![Figure 4. Value of wetting area as related to cumulative infiltration amount.](image1)

![Figure 5. Average advancing distance of wetting front versus infiltration time. The average advancing distance is the average value of wetting distance in up, down, left and right directions.](image2)

### 3.4 Water and Salt Distribution in Soil Profile

The average soil moisture and soil salt content at different soil depths in all treatments is shown in Figure 6. The variation of average soil moisture with soil depth for all treatments was similar. The soil moisture reached maximum value about 30% at the depth of near 26 cm and then decreased with the increasing distance away from that depth. Owning to the effect of gravity potential of soil, the depth with the maximum average water moisture was lower than the moistube depth and the total moisture below the moistube depth was more than that above the moistube depth. However, it could be seen that the effect was limited in T5, which was probably attributed to the low infiltration rate. Therefore, to reduce water pressure or moistube depth may help to restrict the effect of gravity potential and thus decrease the risk of deep percolation in moistube irrigation.
The soil salt content reached the maximum values at the similar depth to soil moisture. The maximum values were respectively 0.773, 0.969, 0.859, 1.165, 1.039 g/kg in T1 to T5. In T1, the salt moved with the water. Consequently, similar to water distribution, most salt was accumulated in soil below the moistube. In T3, the soil salt content at the depth of 11 cm and 41 cm were higher than that in other treatments, implying that a considerable amount of salt was carried to the edge of wetting area by the water (2 g/L) applied in the second infiltration stage. Comparing with T1 and T3, salt was more concentrated in soil layer near the moistube in T2, T4 and T5. There was no similar sign that the salt was transferred to soil far from the moistube when applying fresh water in T5. It was probably due to the low infiltration rate in the second stage. These findings indicate the potential application of saline water in moistube irrigation. By irrigating with water of low mineralization degree, the salt in soil can be removed from the root zone and thus a low salt zone that is suitable for crop growth can be formed. However, further experimental works are necessary to investigate whether the accumulation of salt at wetting edge in long-term moistube irrigation has obvious side effect on soil and crop.

4. CONCLUSIONS

(1) The mineralization degree of irrigation water greatly affected infiltration rate. Water of mineralization degree less than 4 g/L could promote infiltration rate and the water of 3 g/L infiltrated fastest. The Kostiakov empirical infiltration model could successfully describe the relationship between cumulative infiltration amount and infiltration time despite the alternate irrigation with differently mineralized water.

(2) Due to the effect of gravity potential, the wetting area transited from approximate circles at the initial time to ellipses with the downward wetting front farther than the upward wetting front at the later stage. The value of wetting area were in linear correlation with the cumulative infiltration amount. Irrigating with highly mineralized water may have substantial effect on water conductivity and water retention, resulting in less wetting area.

(3) The soil moisture and salt were concentrated near the moistube. Owning to the influence of gravity potential of soil, the total moisture was higher in soil below the moistube depth than above the depth. The salt near moistube can be transferred to wetting edge by irrigating with water of low mineralization degree under moistube irrigation and a low salt zone can therefore be formed near moistube, which bears beneficial recommendation for using saline water in moistube irrigation.
5. ACKNOWLEDGEMENTS

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6. REFERENCES


