Soil water movement under a drip irrigation double-point source
Lizhu Hou, Jie Shang, Jiangtao Liu, Haiyuan Lu and Zhiming Qi

ABSTRACT
Particularly in dry regions, the scarcity of high-quality fresh water has heightened the importance of urban runoff water re-use, leading as well to the improvement of water use efficiency through the surface drip irrigation method. Given the limited research on wetting front migration under a surface drip irrigation emitter, soil water movement under a double-point-source irrigation emitter was investigated. An experimental soil bin was designed and filled with silt loam soil, and time domain reflectometry and tensiometers were used to measure soil moisture contents and soil water potential, respectively. The results show that under the conditions of 6 hours of irrigation with two drippers each delivering 1.05 L hr\(^{-1}\) and spaced at 45 cm, the soil moisture content of the 0–30 cm layer increased rapidly and reached 0.29 cm\(^3\) cm\(^{-3}\), and was greater than that in the 30–60 cm layer as irrigation proceeded. After 6 hours the irrigation was stopped, such that in the redistribution phase, soil moisture of the top layer gradually decreased, while that of the sublayer gradually increased. The results indicate that 6 hours of irrigation under given emitter flow conditions produced adequate soil moisture down to 30 cm for most shallow-rooted crops.

Key words | drip irrigation, rainwater utilization, soil moisture content, two-point source, wetting front

INTRODUCTION
The use of non-conventional water sources is becoming more widespread, particularly in arid regions where high-quality waters are scarce (Kazumba et al. 2010). Urban runoff water is an important non-conventional water source (Kazumba et al. 2010), which can be collected and reused for irrigation, after treatment to remove varying amounts of bacteria, heavy metals, organic matter, and nutrients (Ahammed & Meera 2006; Hou et al. 2014). Surface drip irrigation is an advanced irrigation technology, which enables the application of small amounts of water to the soil through emitters, thereby enabling a slow and precise delivery of water to chosen plants (Moncef et al. 2002).

While theoretical and experimental studies of single-point-source drip irrigation have been conducted (Bhatnagar & Chauhan 2008; Elmaloglou & Diamantopoulos 2009), in the field the intersection of adjacent emitters' wetting fronts can occur when drip emitter spacing is short, such that the zone of moist soil below individual emitters will merge to form a joint drip irrigation wetted zone that parallels the drip pipe. The characteristics of the moist body of soil beneath a single-point-source drip infiltration will therefore differ significantly from that under a two-point source. However, limited research has been carried out on the rate of soil water movement and intersection of wetting fronts under a two-point-source drip irrigation system.

With drip irrigation, farmers can achieve greater water use efficiency, while suffering less from the potential hazards of poor water quality. Adopting drip irrigation also enhances opportunities to (re)use degraded water and to improve the uniformity of water application (Revol et al. 1997).

Crop roots absorb water mainly from the moist soil zone, so that root distribution is affected by the shape of this moist zone. Therefore, comprehensive knowledge of
soil water distribution in the root zone is essential to the design and management of surface and subsurface drip irrigation systems (Elmaloglou & Diamantopoulos 2009; Kazumba et al. 2010; Elmaloglou et al. 2015). However, there has been little research using continuous time domain reflectometry (TDR) and tensiometer measurements coupled with visualization with advanced plotting software (Si et al. 2010).

A district of Beijing, Daxing (39°26′–39°50′E, 116°14′–116°43′N, elevation 15–50 m, area ≈1,030 km²), typically supports a double cropping pattern of winter-wheat/summer-maize requiring 660–920 mm yr⁻¹ (1 mm = 10⁻³ m² ha⁻¹) of water, while only receiving about 518 mm yr⁻¹ in precipitation. But annual precipitation varies unpredictably between emitters (corresponding to pro

To investigate soil water movement under double-point-source irrigation emitters, an indoor experimental soil bin was designed and filled with silt loam soil from the Daxing District. The objectives of this study were to: (i) investigate the rate of soil water movement and intersection of wetting fronts under two-point-source drip irrigation emitters; and (ii) study potential soil water availability in a silt loam soil typical of Beijing’s Daxing District, in order to provide a basis for improving irrigation for agricultural production and landscape planning.

MATERIALS AND METHODS

Test equipment

The experiment was carried out using a water supply system and a test soil bin (Figure 1). The water supply system consisted of drip tapes, emitters (Rain Bird, Azusa, CA, USA) and a water supply tank. The constructed test soil bin (90 × 40 × 65 cm, length × width × height) was made of 1 cm thick plexiglass. An array of 24 holes – six, 15 cm apart lengthwise (at 7.5, 22.5, 37.5, 52.5, 67.5, and 82.5 cm, i.e., A–F in Figure 1) by four, 15 cm apart depthwise (5, 20, 35, and 50 cm below the soil surface, i.e., 1–4 in Figure 1) – were drilled in the front of the bin to accommodate the installation of tensiometers (Institute of Geographic Science and Natural Resources Research, Chinese Academy of Science, Beijing, China). The TDR (TDR100, Campbell Scientific, Inc., Logan, UT, USA) probes were installed on the back side of the bin, opposite the tensiometers. A further two holes were also drilled for drainage, one on each side of the bottom of the soil bin. Surface drip irrigation was applied from a centrally located horizontal surface line source, with a spacing of 45 cm between emitters (corresponding to profiles B and E and their TDR probes and tensiometers). The end of the drip irrigation pipe was connected by pipes to a water supply tank situated 10 m above the soil surface. Flow was controlled by a valve 1.0 m upstream from the experimental soil system.

Soil

The soil was taken from Dazang village, Beizangcun Township, Daxing District, Beijing, located at the edge of the Yongding River alluvial plain.

The natural soil profile was divided into five layers of 0–12, 12–24, 24–36, 36–48, and 48–60 cm. The different soil layers’ bulk density and texture are shown in Table 1. The soil was classified as silt loam according to Chinese soil-type designations (Li 1986).

The soil’s saturated water content (θₛ) was determined gravimetrically after elution of a volume corresponding to 100 pore volumes. The mean cross-soil-depth soil water content at saturation (θₛ) and field capacity (θₑ) were 0.39 cm³ cm⁻³ and 0.30 cm³ cm⁻³, respectively. The residual water content (θᵣ) was measured gravimetrically with triplicate samples of soil air-dried for 24 hours at 105 C. The water retention curve obtained along the soil profile was then determined using a pressure membrane apparatus (1500F1 and 1600; Soil Moisture Equipment Corp, Goleta, CA, USA), and the analytical RETention Curve (RETC) software (Hollenbeck et al. 2000) was
employed to estimate retention curve parameters and hydraulic conductivity functions for the unsaturated soil using $\theta$-h and K-\(\theta\) relationships (Kumar et al. 2013).

A ‘column’ with 4 cm layers of the native soil was extracted to a depth of 60 cm. Then the 4 cm soil layers were mixed or homogenized, respectively, and were put

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**Table 1** Physical properties in the soil profile of 0–60 cm \(\varphi_{\text{bc}}\): the bulk density, \(\theta_s\): saturated water content, \(\theta_{\text{fc}}\): the water content at field capacity, \(\theta_r\): residual water content)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>(\rho_b) (g cm(^{-3}))</th>
<th>(-1) (mm)</th>
<th>(0.1–1) (mm)</th>
<th>(0.25–0.5) (mm)</th>
<th>(0.1–0.25) (mm)</th>
<th>(0.075–0.1) (mm)</th>
<th>(0.05–0.075) (mm)</th>
<th>(-0.05) (mm)</th>
<th>Soil texture</th>
<th>(\theta_s) (cm(^3)·cm(^{-3}))</th>
<th>(\theta_{\text{fc}}) (cm(^3)·cm(^{-3}))</th>
<th>(\theta_r) (cm(^3)·cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–12</td>
<td>1.56</td>
<td>0.45</td>
<td>0.88</td>
<td>13.82</td>
<td>33.87</td>
<td>19.01</td>
<td>10.37</td>
<td>21.60</td>
<td>Silt loam</td>
<td>0.412</td>
<td>0.291</td>
<td>0.067</td>
</tr>
<tr>
<td>12–24</td>
<td>1.62</td>
<td>0.05</td>
<td>0.64</td>
<td>12.76</td>
<td>35.71</td>
<td>20.71</td>
<td>9.78</td>
<td>20.36</td>
<td>Silt loam</td>
<td>0.394</td>
<td>0.304</td>
<td>0.076</td>
</tr>
<tr>
<td>24–36</td>
<td>1.67</td>
<td>0</td>
<td>1</td>
<td>22.51</td>
<td>33.58</td>
<td>13.84</td>
<td>9.50</td>
<td>19.78</td>
<td>Silt loam</td>
<td>0.373</td>
<td>0.300</td>
<td>0.045</td>
</tr>
<tr>
<td>36–48</td>
<td>1.64</td>
<td>0</td>
<td>0.44</td>
<td>21.91</td>
<td>45.91</td>
<td>13</td>
<td>6.08</td>
<td>12.66</td>
<td>Silt loam</td>
<td>0.366</td>
<td>0.294</td>
<td>0.044</td>
</tr>
<tr>
<td>48–60</td>
<td>1.63</td>
<td>0</td>
<td>0.27</td>
<td>27.83</td>
<td>53.87</td>
<td>10.14</td>
<td>2.56</td>
<td>5.33</td>
<td>Silt loam</td>
<td>0.392</td>
<td>0.313</td>
<td>0.042</td>
</tr>
</tbody>
</table>

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**Figure 1** | Schematic diagram of the experimental soil system.
into the soil bin and adjusted to each layer’s soil water content and density in the field, respectively, to a total thickness of 60 cm. The top 5 cm of the soil bin was not filled.

**Test method and measurements**

Irrigation began at 12:15 p.m. on 24 May 2009, with each emitter operating at a flow rate of 1.05 L h\(^{-1}\), and ended at 18:15 p.m. on the same day. The soil surface was open to evaporation but the indoor air flow was slow. To speed up evaporation, a fan was set over the soil bin to drive air flow and promote soil evaporation. The variation in soil moisture content and soil water potential served in calculating the migration rate of the wetting front.

The soil matric potential \(\psi_m\), in cm H\(_2\)O, was calculated as:

\[
\psi_m = 12.6(h + \Delta h) - H
\]  

(1)

where \(h\) is the increasing height of the mercury column (cm); \(\Delta h\) is the drop in height of the mercury surface in the pond due to the mercury column rising (cm); and \(H\) is the height between the center of the tensiometer and the mercury pond surface (cm).

The horizontal and vertical migration rates of the wetting front were calculated as

\[
v_h = \frac{L_h}{t_2 - t_1}
\]  

(2a)

\[
v_v = \frac{L_v}{t_5 - t_1}
\]  

(2b)

where \(v_h\) is the horizontal migration rate of the wetting front (cm min\(^{-1}\)); \(v_v\) is the vertical migration rate of the wetting front (cm min\(^{-1}\)); \(L_h\) is the distance between two horizontal points (cm); \(L_v\) is the distance between two vertical points (cm); and \(t_1, t_2, t_3\) are the times at a particular point when (1) the soil water content changed significantly, (2) the soil water content of the adjacent horizontal sampling point's soil water content changed significantly, and (3) the soil water content of the sampling point immediately below changed significantly (min), respectively.

Graphical analysis of data was performed using the plotting software Surfer (ver. 8.0; American Golden Software Company, Golden, CO, USA).

**RESULTS AND DISCUSSION**

**Soil water movement during the irrigation phase**

The soil moisture content distribution and its change with respect to soil depth during the irrigation phase and the redistribution phase are shown in Figure 2. The irrigation-induced rise in moisture content measured by the probes at positions A1, C1, D1, and F1 lagged significantly behind those measured at positions B1 and E1 (75 minutes vs 15 minutes, respectively; Figure 2(a)). Therefore, under the experimental conditions, at 5 cm below the soil surface, the migration rate in the horizontal direction was roughly 0.25 cm min\(^{-1}\).

The soil water content profile at profile B increased with time after the onset of irrigation (Figure 3). Comparing Figures 2 and 3(a), the moisture content of each profile of the soil can be seen to begin to change after irrigation commenced, with the soil water content at all measured depths, except 50 cm, increasing. Soil water content at depths of 5 and 20 cm below the soil surface changed significantly, and were higher than at other depths. Teasdale & Abdul-Baki (1995) found that most tomato root length was in the upper 30 cm of the bed, with only 12% below this level. Wang et al. (2006) found that 63–82% of potato root weight density under drip irrigation was in the upper 10 cm of the bed. Therefore, the observed soil water distribution following the irrigation event tested would have met the vegetable crop demand for this particular soil and crop situation.

**Soil water movement during the redistribution phase**

Redistribution of the soil moisture at profile B, 360 minutes after the onset of irrigation is illustrated in Figures 2 and 3(b). After irrigation ended, soil water content at depths of 5 and 20 cm decreased immediately and after half an hour, then decreased asymptotically as the experiment proceeded. However, the soil water content at a depth of 35 cm began
rising 1.5 hours after irrigation ended, reaching a maximum at 8.75 hours after irrigation ended. The soil water content at 50 cm remained unchanged over the course of the experiment.

The magnitude of changes in the soil water content at a depth of 5 cm was significantly greater than at depths of 20 or 35 cm (Figure 3(b)). After quickly reaching a maximum value at depths of 5 and 20 cm, the water content became relatively stable as irrigation progressed. Changes in moisture content in each section of the soil profile led to the soil water content being more evenly distributed during the redistribution phase. The difference in moisture values between soil depths of 20 and 35 cm reduced gradually over time.

After irrigation ended, the soil moisture content of the upper layers initially began to decline sharply, but as time passed, the rate of decrease slowed, as did the rate of water movement. By water moving from an upper moist
layer to a dry lower layer, the water content in the moist layer decreased while that of the drier lower layer increased. The moisture content at each depth tended to be uniform, and the hydraulic gradients between adjacent layers were reduced, leading to decreased water flux. Conversely, evaporation led to the water near the soil surface moving upwards and being lost into the air. When the moisture content was reduced to a certain level, the hydraulic gradient between the soil surface and the layer below increased, such that soil water then moved up to the surface, resulting in further soil water redistribution.

Spatial distribution of soil water movement

Point-source infiltration is three-dimensional in space with the matric and gravitational potentials being the main potentials driving the migration and redistribution of soil moisture in an unsaturated soil.

The soil moisture spatial distribution curves under the point-source emitters at different times (Figure 4) show that soil water at the upper and lower layers shows an asymmetric increase during the irrigation phase, followed by an asymmetric decrease during the redistribution phase. The moisture content under the two point sources is not distributed symmetrically under the experimental conditions, which may be because of asymmetry in the initial moisture content of the soil and the effect of heterogeneity of hydraulic conductivity in the soil profile.

Soil water content at positions D2 (52.5 cm, −0.20 m) and F2 (82.5 cm, −20 cm) began to increase after 4 hours of irrigation (Figure 4), but the range in moisture content increase at D2 was greater than at F2, indicating that intersection of the wetting fronts from the two emitters had occurred at 20 cm below the surface. This may be explained by the migrating wetting fronts overlapping and migration rate of the moisture increasing. The soil moisture content
Figure 4 | Distribution of soil water content during the irrigation phase and the redistribution phase.
at D3 (52.5 cm, –35 cm) increased by 0.068 cm$^3$ cm$^{-3}$, 550 minutes after irrigation, whereas that at F3 (82.5 cm, –35 cm) began to increase but lagged behind that of the D3 position, increasing only by 0.058 cm$^3$ cm$^{-3}$. This shows that intersection of the two wetting fronts and migration of the combined moisture front made water movement faster, and increased the rate of change in soil moisture.

For irrigation, high amounts of water supplied always induce deep water percolation and fertilizer seepage. Proper drip irrigation could be a reliable means of preventing such occurrences and enable drip irrigation managers to reduce water and nutrient losses (Moncef et al. 2002).

Aina & Fapohunda (1986) found that at different stages of plant growth most of the maize roots, as much as 70% of the total, were concentrated in the top 22.5 cm of a sandy loam soil profile. Similarly, at two silty clay loam sites in Argentina, maize root abundance was stratified in the top 20 cm of soil (Taboada & Alvarez 2008).

Currently the roots of the main fruit and vegetable crops that use drip irrigation extend to about 30 cm (Weaver & Bruner 1987). Teasdale & Abdul-Baki (1995) found that most tomato (Lycopersicon esculentum Mill.) roots occurred in the upper 30 cm of the bed, with only 12% extending beyond this depth. Aside from the high density of primarily structural roots adjacent to the plant, roots were distributed relatively uniformly throughout the upper 30 cm of the bed (Teasdale & Abdul-Baki 1995). A lower density of roots extended beyond 30 cm to a hard pan at 40–50 cm depth (Teasdale & Abdul-Baki 1995). Others have reported significant tomato root growth to depths beyond the upper 30 cm of a bare soil (Weaver & Bruner 1927) and under mulches (Tindall et al. 1991). Therefore, for the roots of tomato, potato and other vegetables, the irrigation tested would have met the crop demand for this particular soil and crop situation.

**CONCLUSIONS**

To alleviate problems associated with seasonally rain-fed agriculture, drip irrigation using treated urban runoff can play a vital role. In this study, the study of soil water movement under a double-point drip irrigation source was conducted. Time domain reflectometers were buried in the bin with a homogeneous soil to measure soil moisture automatically, and the plotting software was used to draw soil water isobars.

(i) Under given emitter flow conditions, as irrigation proceeded, the wetting front gradually spread out at a rate of roughly 0.25 cm min$^{-1}$ in the horizontal direction at 5 cm below the soil surface. The soil moisture content of the 0–30 cm layer increased rapidly and reached 0.29 cm$^3$ cm$^{-3}$ during the irrigation phase.

(ii) During the redistribution phase (after the irrigation was stopped), the surface soil moisture content reduced due to evaporation and downward movement of soil water. The moisture content of the 0–30 cm layer was more uniform at between 0.23 and 0.29 cm$^3$ cm$^{-3}$ during redistribution of the soil moisture.

(iii) The application of 6 hours of irrigation with two drippers each delivering 1.05 L hr$^{-1}$ and spaced at 45 cm produced adequate soil moisture down to 30 cm for most shallow-rooted crops.

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