Dual-Drip Subsurface Irrigation Systems: Can it Act as a Hydraulic Barrier?

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Abstract

Subsurface drip irrigation systems, compared to other irrigation systems, enhance delivery of water and chemicals directly into the root zone. However, in light-textured soils, certain quantities of water may percolate below the root zone due to the subsurface position of drip lines. The main objective of this paper is to evaluate three technologies to enhance a spatial distribution of water and solutes in the root zone and to limit downward leaching. The three technologies include a) a physical barrier, b) a dual-drip system with concurrent irrigation, and c) a dual-drip system with sequential irrigation. To achieve this objective, we performed computer simulations and field experiments. Numerical simulations were carried out using the HYDRUS (2D/3D) software for both bare and cultivated soils. The results indicate that the physical barrier is more efficient than dual-drip systems in enhancing the water distribution in the root zone while preventing downward leaching.

1. Introduction

Surface and subsurface drip irrigation systems are increasingly being used in arid regions with limited water resources to irrigate agricultural crops. The subsurface drip irrigation (SDI) systems, have an especially promising future due to their many advantages. The main advantages of SDI, compared to surface drip irrigation (DI), include: a) a significant reduction of evaporation, b) a direct injection of water and fertilizers into the root zone, and c) an easier and safer, operation of machinery.

The proper design of SDI systems requires knowledge of the water distribution patterns around the emitters that match the root extraction patterns and minimizes wetting of the soil surface and deep percolation (Kandelous et al., 2011). The exact shape of the wetted volume and water distribution depends on many factors, including soil hydraulic characteristics, initial soil conditions, discharge rate, application frequency, root characteristics, evaporation, and transpiration (Subbaiah, 2013). Additionally, the wetting pattern depends on the location of the emitter with respect to the soil surface. The wetting pattern is hemi-ellipsoidal or ellipsoidal when the dripper is located on the soil surface or in the subsurface, respectively.

Generally, plants have higher root densities in the upper part of the root zone. Majumdar (2004) indicated that in a soil profile with a uniform water content most plants extract about 40, 30, 20, and 10% of their water needs from corresponding quarters of the root zone (Figure 1a). Despite a similar wetting pattern under DI and SDI systems (Figure 1bc), a considerable amount of water escapes from the root zone by percolating downwards or dispersing laterally in the soil beyond
the reach of roots. Figure 1 indicates that the wetting pattern for the DI system is more similar to the root distribution than for the SDI system, while more water leaches below the root zone in the SDI system than in the DI system. El-Berry (1989) reported that the main avenue for water losses under SDI is deep percolation, which is highest during the seedling stage and declines with the growth of the root system.

Several investigators have tried to adjust the shape of the wetted zone to better match the root extraction pattern (e.g., Phene et al., 1987; Barth, 1995; Welsh et al., 1995; Ismail et al., 2006). Phene et al. (1987) showed that the wetted pattern around the buried emitter can be managed by adjusting the irrigation frequency and that more water moves toward the soil surface when the irrigation frequency is increased. Other investigators (e.g., Barth, 1995; Welsh et al., 1995) have suggested placing an impermeable barrier below the lateral drip lines. This barrier can be made of polyethylene (Barth, 1995) or metal (Welsh et al., 1995). However, there are some problems concerning this physical barrier. For example, there are technical and economical problems with digging a wide and deep trench to install the physical barrier.

Ismail et al. (2006) attempted to modify the wetting pattern by burying a secondary drip line beneath the primary one, and by dividing the required water volume between the two drip lines. This approach depends on the fact that water moves faster into the dry soil (due to a higher pressure head gradient) than into the moist soil, and thus, when the secondary drip line moistens the soil below the primary drip line, it forces water from the upper drip line to redistribute upward and laterally, rather than moving downward. Hence, they called this technique “a hydraulic barrier”. This technique requires no wider trenching than the normal SDI trenching. Their results showed that when applied in the field, the hydraulic barrier increased the total and marketable yields of the Jerusalem artichokes by 12 and 48%, respectively, while the physical barrier increased the yields by 131 and 138%, respectively (Ismail et al., 2006). These results clearly document the benefits of using such techniques to increase crop yields.

In order to efficiently design and manage SDI systems, several models (analytical and empirical) have been developed to describe water flow from an emitting source (a point or line source) in the soil (surface or subsurface) (e.g., Brandt et al., 1971; Warrick, 1985; Khalifa et al., 2004; Sing et al., 2006). One of the most complete packages for simulating water, heat, and solute movement in both two- and three-dimensional, variably-saturated, porous media is the HYDRUS software package (Šimůnek et al., 2008). Many investigators have used this model to evaluate
either field or laboratory experiments, or other mathematical models (e.g., Skaggs et al., 2004; Provenzano, 2007; Kandelous et al., 2011). The HYDRUS model enables its users to trace the movement of water and solutes and the wetting patterns in both simple and complex geometries for homogeneous or heterogeneous soils, and for different combinations of initial and boundary conditions.

The main objectives of this study therefore are (a) to simulate water flow for an SDI system while considering both the physical barrier and the dual-drip system using the HYDRUS package, (b) to numerically evaluate how these alternative techniques affect the movement of water, and (c) to evaluate whether or not the dual-drip system can act as a hydraulic barrier for movement of water.

2. Material and Methods

2.1. Modeled Scenarios

To address our main objectives, we have chosen to evaluate the following alternative scenarios:
1. Two soil textures (sand and loam).
2. Different water applications:
   a. A single emitter without a physical barrier
   b. Two emitters operating concurrently
   c. Two emitters operating sequentially
   d. A single emitter with a physical barrier

Simulations were carried out for soils representing two textural classes: sand and loam. Soil hydraulic parameters for the two textural classes were taken from the soil catalog provided by the HYDRUS software (Carsel and Parish, 1988).

![Figure 2. Location of the emitters and the physical barrier in the transport domain considered in Hydrus simulations: a domain around a dripper is magnified in excerpts.](image)

2.2. Initial and Boundary Conditions

The Hydrus (2D/3D) software package (version 2.02) (Šimůnek et al., 2008) is used in numerical simulations for all modeled scenarios. The transport domain for all scenarios was considered to be axisymmetrical around a vertical axis. Figure 2 shows the detail of the upper left corner of the
transport domain, in which the emitters and a physical barrier are located. The transport domain was 100 cm wide (radius) and 130 cm deep (depth). The (upper) emitter was located 15 cm below the soil surface (Figure 2, left), while the secondary emitter (in scenarios b and c) was 25 cm below the soil surface (Figure 2, center). The physical barrier (when considered, scenario d) was placed 27 cm below the soil surface and was considered to have a radius of 25 cm (Figure 2, right).

Figure 3 shows the boundary conditions (BCs) considered in different scenarios in this study. Boundary conditions that are placed in parenthesis are used only in some cases. In all simulated scenarios, the upper boundary of the transport domain was subjected to atmospheric conditions, while the lower boundary of the domain was free drainage. Boundaries at both vertical sides were assigned a “No Flux” boundary condition. Emitters were represented in all cases as half circles with a radius of 1 cm, located on the left vertical boundary of the transport domain. The upper emitter was assigned a “Variable Flux 1” BC. In scenarios b and c, in which two emitters were considered, the second emitter was assigned a “Variable Flux 2” BC. In scenario d, the physical barrier was simulated as a 1-cm thick impermeable barrier 25 cm wide with a “No Flux” BC, (Figure 2d and Figure 3). Simulations were carried out for 2,880 minutes (i.e., 2 days).

Time-variable boundary conditions were used to simulate drip irrigation. The dripper discharge \(Q\) was considered to be 7.5 L/h, which is equivalent to a boundary flux \(q\) of about 10 cm/min. In scenarios with a single emitter (cases a and d), the irrigation flux was 10 cm/min. In scenarios with two emitters (cases b and c), the irrigation flux at each emitter was 5 cm/min, thus maintaining the same total discharge in all scenarios.

The operation sequence of different emitters in different scenarios is shown in Figure 4. In cases a and d with only one emitter, this emitter operates for 60 minutes every two days. In case b with two emitters, the two emitters have the same duration of operation, but with only 50% flux applied to each of them. Finally, for cases c, c_u, and c_d with two emitters operating sequentially, Figure 4 shows the pattern of each sequential operation. The secondary (deeper) emitter starts operating either 30 or 120 minutes before the main (upper) emitter in cases c and c_u, respectively, or 120 minutes after the upper emitter in case c_d. Again, in these sequential scenarios, the irrigation flux to each emitter is half of the flux in cases a and d.
In the 'Results and Discussion' section below, we will provide graphical outputs for pressure heads along vertical and horizontal cross-sections throughout the transport domain. Five horizontal cross-sections are at depths of 5, 10, 15, 25, and 35 centimeters, while seven vertical cross-sections are at distances of 5, 10, 15, 20, 30, 40, 50, and 60 cm away from the axis of symmetry.

3. Results and Discussion

3.1. Simulation Results for Water Flow

In this section, we will discuss the results of numerical simulations for scenarios a, b, c, and d, for both the loam- and sand-textured soils. For each soil texture we will discuss both water content profiles along horizontal and vertical cross-sections. Each figure will show water content profiles for nine output times at an increasing time interval, i.e., 1, 5, 20, 60, 90, 360, 720, 1440, and 2880 min after the beginning of infiltration. These water content profiles thus cover both the infiltration and redistribution parts of the numerical experiment.

3.1.1. Bare Loamy Soil

Water Distribution along Vertical Cross-Sections

Figure 5 shows the vertical water content distributions at five vertical cross-sections at distances of 5, 10, 15, 25, and 35 cm from the emitter(s) for the bare loamy soil for four analyzed scenarios (a, b, c, and d). Multiple curves represent outputs at different times.

The irrigation scheme can be clearly identified from the water content profiles after 1 min in the 5 cm from the emitter cross-section (Fig. 5; left). While water content profiles for cases a and d clearly show infiltration from a single emitter, for case b they show infiltration from two emitters, and for case c only from the bottom emitter, since the upper emitter starts operating only after 30 minutes. In case a, the area around the emitter (depths of 8-25 cm) at a distance of 5 cm reached saturation before 5 min. This area (at a 5-cm distance from the emitter) continues to widen until almost the entire root zone is saturated at the end of irrigation. The water content profile after 60 min already reflects the redistribution process, since the irrigation flux stops at 60 min in all cases except c (as shown in Figure 4).
Figure 5. Vertical water content distributions at different distances (5, 10, 15, 25, and 35) away from the dripper for different irrigation scenarios for a bare loamy soil.

Water content profiles are quite similar at a 10-cm distance from the emitter, except in case d, which shows some small differences in the upper 25 cm. Maximum water contents are reached in case c at times of 60 and 90 min. At a 15-cm distance from the emitter, the highest water contents are reached in case d in the upper 25 cm, while the three other cases are quite similar. At a 25-cm distance, only small increases in water contents can be observed over time. While the first increase in the water content is observed only after 60 min in cases b and c, this occurs earlier (after 20 min) in cases a and d, due to the higher irrigation flux from a single emitter.

Interestingly, at a 25-cm distance, water content values appear in reverse order versus time compared to water content values at shorter distances. While at this distance, water contents are increasing for larger times, at shorter distances they are decreasing. This is due to the redistribution process, which both vertically and laterally drives water to distances further from emitters. Finally, notice that water did not reach the 35-cm distance, except in case d between depths of 10 and 25 cm.

Water Distribution along Horizontal Cross-Sections
Water content distributions for four analyzed cases are shown in Figure 6 at seven horizontal cross-sections and at depths of 5, 10, 20, 30, 40, 50, and 60 cm. The same output times as in Figure 5 are shown. The highest water contents are found at a depth of 20 cm, i.e., between the main and secondary emitters, which are placed at depths of 15 and 25 cm, respectively. In this depth, the soil stays saturated to a horizontal distance of about 20 cm for up to about 90 min in case c. In case d, water contents are highest compared to other scenarios at all times at depths of 5, 10, and 20 cm, while only a small amount of new water appears at a 30-cm depth at the far end of the physical barrier at later times (at about 360 min). This is due to the redistribution process, which is demonstrated in Figure 7. Figure 7 shows that the physical barrier is very effective in
preventing leaching of water to deeper depths, as only small quantity of water flows around the barrier.

Figure 6. Horizontal water content distributions at different depths (5, 10, 20, 30, 40, 50, and 60) for different irrigation scenarios for a bare loamy soil.

Figure 7. Water content distributions at different times for case d for a bare loamy soil.

While water content profiles for the first three cases a, b, and c are quite similar in the top 30 cm (Figure 6), substantial differences occur at a depth of 40 cm and below. While in case a, at a depth of 40 cm the maximum water content is only about 0.2, in both cases b and c, water contents are as much as 0.38 at 90 min and 0.3 at 360 min. Only cases b and c show increases in
water contents (up to 0.20) at later times due to the redistribution process (at times of 720, 1440, 2880 min). None of the analyzed cases delivered water down to a 60-cm depth.

3.1.2. Bare Sandy Soil

Water Distribution along Vertical Cross-Sections
Sandy soils have significantly higher hydraulic conductivities and infiltration rates than loamy soils and significantly lower macroscopic capillary length. This causes water to move deeper and much less laterally into the sandy soil profile than in the loamy soil. Our simulations clearly show that in Figure 8. In cases b and c, water infiltrated down to 60 and 90 cm at a 5-cm distance at times of 60 and 2880 min, respectively. On the other hand, the rest of the profile is much less saturated. Although water contents around emitters are higher than 0.40, water quickly redistributes when irrigation stops. The highest water contents around the emitter at all times can be observed in case d, because of the physical barrier, which prevents redistribution of water downwards, while physical properties of the sandy soil prevent lateral redistribution. In case c, the highest water contents are reached at 90 min when irrigation from the primary emitter stops.

There are only small differences in water content profiles between the first three cases after 360 min. This shows that none of the analyzed cases, except case d, improve the wetting pattern once redistribution in the sandy soil starts. The same phenomena can be observed at cross-sections at distances of 10 and 15 cm. On the other hand, in case d one can observe accumulation of water above the physical barrier, as well as its bypassing during the redistribution process (at the 25- and 35-cm cross-sections). This shows that the physical barrier indeed enhances water redistribution in the root zone.

Figure 8. Vertical water content distributions at different distances (5, 10, 15, 25, and 35) away from the dripper for different irrigation scenarios for a bare sandy soil.

Water Distribution along Horizontal Cross-Sections
One of the main benefits of the subsurface drip irrigation is that it keeps a dry soil surface. This helps to reduce the loss of water due to evaporation and prohibits the growth of weeds at the soil surface. Cases b and c have the lowest water contents in the top 5 cm of the soil profile (Figure
This is caused mainly by the lower value of the discharge (5 cm/min) of the upper emitter in the case of the dual-drip system compared to the single-drip system (10 cm/min). This may be considered one of the benefits of the dual-drip system.

![Horizontal water content distributions](image)

Figure 9. Horizontal water content distributions at different depths (5, 10, 20, 30, 40, 50, and 60) for different irrigation scenarios for a bare sandy soil.

At a 10-cm depth, the highest water contents for cases a and d occur at 20 min, while for case c the highest water contents occur at times of 60 and 90 min. No noticeable differences are visible between cases a, b, and c from time 360 min to 2880 min. In case d water laterally spreads laterally both above (at higher values) and below the physical barrier, moving more than 40 cm at times of 1440 and 2880 min, while in other cases the lateral spreading is at most 30 cm. At a 20-cm depth, the highest water contents were obtained in case d at almost all times. This reflects the role of the physical barrier. Case c has the second highest water contents with a near-saturation state for up to 90 minutes. This reflects the effect of the sequential operation of the dual-drip system. At depths of 30 and 40 cm, the highest water contents were obtained in case c at 90 min, while the lowest water contents were obtained in case d due to the existence of the physical barrier at a depth of 27 cm. In case d, there was almost no water content increase at a depth of 50 cm and no increase at all at a depth of 60 cm. On the other hand, the dual-drip scenarios (cases b and c) show a better distribution of water at a depth of 50 cm than case a.

4. Conclusions

Numerical simulations carried out in this study show that the application of a dual-drip system or the installation of a physical barrier can significantly alter both the wetting pattern and spatial distribution of applied solutes. Physical barriers simply prevent downward movement of all substances (e.g., water, nutrients, and other chemicals) and thus their usefulness depends on
whether we want to retain these substances in the root zone or if we prefer to flush them out. A dual-drip system represents a powerful tool for manipulating the distribution of solutes in the root zone, especially if the two emitters can be operated sequentially. Such a system allows growers to control which solute to retain in the root zone and which one to discard by simply altering the operation of the two drippers. However, this technology requires much more research through the evaluation of larger numbers of possible scenarios involving different solutes, different soils, and different operation scenarios, and especially, through evaluation under field conditions.

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