Study on Wetted Soil Geometry of a Negative Pressure Irrigation (NPI) System

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Abstract. The limited water resource is a main constraint on agricultural production in arid and semi-arid regions like Saudi Arabia. The Negative Pressure Irrigation (NPI) is one of the attractive irrigation systems since it consumes less water, leads irrigated water down to root zone, minimizes evaporation and prevents deep percolation than other traditional irrigation systems. The aim of this paper is to get information on the soil water dynamics, which is very essential for the design and operation of the NPI system. With this view, the water balance experiment was carried out in the NPI system for different time intervals for three different negative pressures (\(P_n = -0.02\)m, -0.07m and -0.10m). After finishing the experiment, the dry soil was removed from the column to measure the configuration of wet soil. This geometry of wetted soil represents the soil water dynamics and the wetted soil volume represents the water stored in soil at different negative pressures and elapsed time. A good relationship was obtained between the wetted soil geometry, time and negative pressure. This study reveals that for a certain negative pressure and time interval, the depth, width and volume of wetted soil can be predicted.

1. Introduction

Water loss for evaporation, deep percolation and conveyance is a common phenomenon in irrigation systems. Frost and Schwalen [1] showed that wastage of water in a sprinkler irrigation can be 45% in sunny weather. Water saving irrigation techniques are very essential to regions with inadequate water resources and severe exterior conditions for evaporation such as Saudi Arabia. Negative pressure irrigation (NPI) is a water saving irrigation system as it enables water supply directly to the root zone. Yabe et al. [2] found that water loss in the NPI is less than the water loss of the drip irrigation. NPI system is composed of a water reservoir and a porous pipe placed in soil. Negative pressure, \(P_n\) is created by placing water reservoir at a lower height than that of porous pipe. Water goes upward from the reservoir to the pipe and after that enters into the adjacent soil through the porous pipe, when the absolute value of matric potential, \(\psi\), of the soil is larger than the absolute value of negative water pressure in the porous pipe, \(P_n\). However, when \(|\psi|\) is smaller than \(|P_n|\), the water flow stops automatically as shown in in figure 1.
Although the study on the NPI system has been undertaken by many researchers [3], [4], [5] it has not made great advances. The main reasons are: (i) the production of the porous pipe is costly and (ii) there was no effective technique to remove air bubbles that interrupts the flow in the silicon tube. However, the cost of porous pipe can be reduced by using locally available material. S. M. Moniruzzaman et al. [6] was succeeded to eliminate air bubbles in the tube associated with ultra-slow flow by means of a small electric pump. On the other hand, successful management of any irrigation system depends on the soil water dynamics i.e., the wetted soil geometry. The NPI system is not an exception either. Most of the past studies on wetted soil geometry of NPI system, such as Kato et al. [7], Tanigawa et al. [8], Ashrafi et al. [9], Siyal et al. [10] were performed with water flow through a porous pipe placed horizontally in soil. Peifu et al. [11] and Akhoond et al. [12] studied the water flow around a vertically placed porous pipe. It is easily predictable that the wetted soil geometry will be dissimilar for vertically placed porous pipe than that of horizontally placed one. Therefore, the aim of this study is to observe the wetted soil geometry of the NPI technique by using a porous pipe placed vertically and develop simple methods for predicting it at various pressures.

2. Material and Method

2.1. Water balance experiment

The research was performed in a temperature (25°C) and humidity (30%) controlled room as shown in figure 2. A PVC column (diameter = 0.20 m; height = 0.21 m) was filled with Kawanishi sand. The dry density of the sand was 1410 kg/m³. A porous pipe of length, \( l = 0.1 \) m, radius, \( R_p = 12.5 \) mm and thickness, \( t_p = 6 \) mm was placed vertically at the centre of the sand column as shown in figure 2. The value of hydraulic conductivity of porous pipe, \( k \) was 6.38×10⁻⁹ m/sec. A water supply tank equipped with Marriot tube and a reservoir were used to keep \( P_n \) constant. Water moved from the reservoir to the porous pipe and the adjacent soil. Air bubbles from the pipes were removed by a small pump. Two electric balances were located below the sand column and the reservoir with water supply tank separately to measure the supplied water from reservoir, \( M_{sup} \), and the stored water in soil, \( M_{soil} \), simultaneously. The data were collected for 72 hours. Evaporation from the soil surface, \( M_{eva} \), can be estimated by the water balance equation (1);

\[
M_{sup} = M_{eva} + M_{soil} \tag{1}
\]
2.2. Observation and measurement of wetted soil geometry

After measuring $M_{sup}$ and $M_{soil}$ and finishing the experiment, dry soil adjacent the wet soil was separated from the soil column. Subsequently, the shape of the wetting front i.e., the wetted soil geometry was observed by a camera and measured by a scale.

2.3. Measurement of water use efficiency

The efficiency, $E_f$ was obtained by the ratio of cumulative water stored in soil, $M_{soil}$ to cumulative supplied water, $M_{sup}$ which were obtained from water balance experiment.

3. Results and Discussions

3.1. Wetted soil geometry

The wetted soil volume after irrigation has significant practical importance for calculating the water stored in soil. The wetted soil volume of NPI system was observed like a truncated ellipsoid. The total wetted zone (volume of the ellipsoid) was estimated by the following method used by B. Acar et.al [13]. The equation of an ellipsoid in $r$-$z$ plane whose origin is o, radius is $R_m$ and $B$ as shown in figure 3 can be written as follows

$$\frac{r^2}{R_m^2} + \frac{(z + H)^2}{B^2} = 1$$

(2)

The volume ($V_e$) of total wetted zone can be found from the area in figure 3 by rotating $360^\circ$ around the $z$ axis.

$$V_e = \pi \int_{-B-H}^{0} R_e^2(z)dz$$

(3)

By solving equation (3) and subtracting the porous pipe volume from it, wet soil volume, $V_{wet}$ was obtained.

$$V_{wet} = \frac{R_w^2 \pi}{3B^2}(B + H)\times \left(2B^2 - H^2 + HB\right) - \pi R_e^2 l$$

(4)

Here, $V_{wet}=$ volume of wetted soil (m$^3$), $R_w=$ maximum radial advance of wetting front (m), $B=$ depth between maximum radial wetting front expansion and vertical wetting front expansion (m) and $H=$ depth between maximum radial wetting front expansion and soil surface (m). Figure 3 shows wetting front.
after 24 hours water supply at different negative pressures. The wetting front advances more with decrease of negative pressure and increase of time. The wetted soil volume was dependent on the maximum radial and vertical expansion of wetting front. The maximum radial and vertical expansion of wetting front was affected by the negative pressure difference and by the elapsed time. Time variation of the geometric parameters \((H, R_m, B)\) of wetted soil volume at different negative pressures \((P_n = -0.02m, -0.07m, -0.1m)\) from top to bottom for each parameter) are shown in figure 4. The experimental results showed that all the parameters increase with time and decrease of negative pressure and can be expressed by the Eq. (5) to Eq. (10) in figure 4. Now inserting Eq. (5) to Eq. (10) into equation (4) wetted soil volume at different negative pressure after different elapsed time was calculated. By inserting the measured values of \(H, R_m, B\) into equation (4) wetted soil volume was estimated at different negative pressures after different elapsed time. Both the observed values and calculated values of \(V_{wet}\) have good agreement with each other.

Figure 3. Expansion of wetting font after 24 hours water supply
Figure 4. Time variation of wetted soil geometry

Figure 5. Time variation of observed and calculated wetted soil volume
3.2. Water use efficiency

Time variations of efficiency at different $P_n$ are shown in figure 6. The efficiency of NPI system was found very high and it varied from 0.92 to 0.97 depending on negative pressure at the end of the experiment.

![Figure 6. Time variation of water use efficiency](image)

4. Conclusions

The major conclusions of the study are as follows:

i) All the geometric parameters of the wetted soil increase with time. However, the geometric parameters increase with decrease of negative pressure.

ii) The wetted soil volume has been evaluated as a truncated ellipsoid. A good relationship between wetted soil, negative pressure and time has been developed.

iii) Both the calculated values and the observed values of wetted soil volumes have good agreement with each other.

iv) The efficiency of the NPI system is very high and varies from 92% to 97%, depending on negative pressure.

5. References

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