SEEPAGE RATE FROM CERAMIC PITCHERS UNDER POSITIVE AND NEGATIVE HYDRAULIC HEAD

M. Abu-Zreig, A. Zraiqat, M. A. M. Abd Elbasit

ABSTRACT. *Picher irrigation is a traditional technique used to supply water to plants under drought conditions in arid regions. Laboratory experiments were conducted to evaluate water seepage rates from ceramic pots/pitchers, made from baked clay-sand local materials, under various environmental and hydraulic conditions. Seven ceramic pots (simulating ceramic emitters) with various dimensions were used in the experiments. Handmade ceramic pots of about 1 L in volume and 26 cm tall were used in the experiment. The hydraulic conductivities of the pots were measured using falling head method and the values ranged from 0.275 to 0.704 mm/d. Seepage rate from ceramic pots were measured in the air and when buried in the soil under constant and falling head method inside a temperature and humidity-controlled chamber. Results indicated that seepage rate is affected by various conditions including potential evaporation, soil suction pressure and moisture condition, and hydraulic head. Seepage rate from ceramic pots were higher under constant head condition and when buried inside soil than that under falling head or in the air. Seepage rates were found to increase steadily with potential evaporation but decrease gradually with increased soil moisture around ceramic pots. The value of hydraulic head seemed to have the largest effect on pitchers' seepage rate. The seepage rate under a constant head of 30 cm above the mouth of the ceramic pot tested in the experiment was 2500 mL/d but decreased to only 114 mL/d under a constant head of -25 cm below the mouth of the pot. The experiments revealed that ceramic pitchers can be used to supply water even under negative head thus eliminating the need for pressurized flow inside irrigation pipes.*

Keywords. *Arid regions, Drylands, Evaporation, Hydraulic head, Pitcher irrigation, Subsurface irrigation.*

Methods of irrigation used worldwide are surface irrigation, sprinkler irrigation, and trickle irrigation. Surface irrigation has the lowest efficiency of about 60%, whereas the efficiency of trickle irrigation can reach up to 90%. However, trickle irrigation requires more investment, more management, and operational cost that limits its use by many traditional farmers. Therefore, there are great needs to modify trickle systems and adapt new and simple irrigation methods with high water-saving potential such as trickle irrigation with ceramic emitters.

Pitcher irrigation is an old-new irrigation method that has been practiced in many part of the world such as India, Iran, Africa and South America (Mondal, 1974; Dubey et al., 1991). The technique is simple, cheap, and could have large water-saving potential. Pitcher-irrigation utilizes clay pots which are baked at high temperature to produce walls of the desired porosity. Pitchers are buried up to their neck in the soil and filled with water at various time intervals to keep soil water at a level favorable to plant growth. Water gradually seeps out into the root zone in the soil due to the pressure head gradient across the wall of the pitcher resulting from the positive pressure head inside the pitcher and the conditions on the outside pot surface. It is claimed to be a self-regulative system with very high water saving potential and good capabilities for irrigation of various types of crops (Chigura, 1994). Many researchers found that using clay pots can save up to 70% of water compared to watering with buckets and sprinkler irrigation. Despite its apparent simplicity, factors affecting the system performance have not been well described and proven in the literature (Stein, 1990).

Few efforts have been made lately to understand the performance of pitcher irrigation and the factors affecting water flow out of the pitcher (Abu-Zreig et al., 2006, Vasudevan et al., 2014, Ansari et al., 2015). It seems that water seepage is affected by many factors including saturated hydraulic conductivity of pitcher materials, wall thickness, surface area, and rate of evapotranspiration. Stein (1997) found that the seepage rate from pitchers is significantly affected by varying pan evaporation, the hydraulic conductivity and surface area of the pitcher. Chigura (1994) reported that seepage rate of some African and Ecuadorian pitchers were

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directly proportional to saturated hydraulic conductivity and rate of evapotranspiration. He found, however, that only one pitcher was able to supply water in accordance to plant needs. Abu-Zreig and Atoum (2004) and Abu-Zreig et al. (2006) have conducted field and laboratory experiments and proved the auto regulative capability of pitchers. Pitcher's seepage rate is directly and linearly related to potential evaporation. However, those studies were carried out under controlled atmospheric conditions and did not consider the effect of hydraulic head and/or the soil moisture on seepage rate.

An important modification to trickle systems is to replace manufactured emitters with ceramic emitters. Ceramic emitters, similar to pitchers, are made of baked clay that can be fitted to lateral lines. Those emitters are expected to supply water to the surrounding soil with minimal or even negative head. Water seeps out of ceramic emitters due to the hydraulic gradient between the surface of emitters in contact with soil and the surrounding soil. Negative pressure head would develop when the water supply system connected to ceramic emitters kept in air tight conditions. This is of great importance for practical application, where the water supply-emitter system could operate for a long time without interruption. The objective of this study is to explore the possibility of using ceramic emitters for irrigation in small and large scale using baked clay pots. Ceramic emitters and clay pitchers are made of similar porous materials and their seepage hydraulics are comparable. This study adds to the knowledge, presented by the author and others, through studying seepage rate of pitchers buried inside soil and the subsequent effect of soil moisture of the surrounding soil on the seepage rate of pitchers. In addition, we explored the variation of seepage rates in pitchers operated under positive and negative head conditions. The effect of hydraulic head on seepage from clay pots has not been experimentally explored in the literature.

MATERIALS AND METHODS

Seven handmade clay pots/pitchers were selected from local producers in Jordan. A preliminary report for the study has been presented by Abu-Zreig et al. (2012). The average volume, height, and maximum outside diameter were about 1120 mL, 26 cm, and 14 cm, respectively. The surface area was calculated by digitizing the pitchers outside border and numerically integrating the surface area (as shown in figure 1 and described by Abu-Zreig et al., 2006) and found to be equal to 713 cm^2 with standard deviation equal to 16 cm^2. Table 1 summarizes the geometrical dimensions of pitchers.

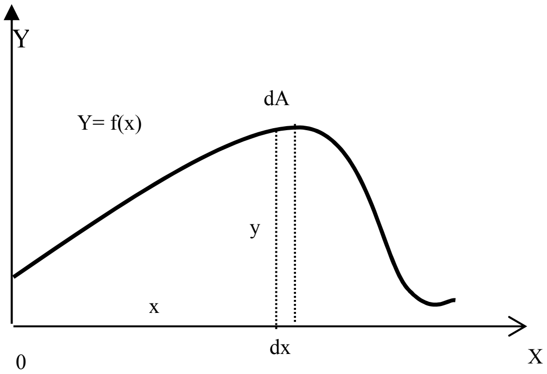

Figure 1. A diagram shows the numerical integration of pitcher surface area; A is the surface area; Y is the outside radius; x is the depth of water.

Table 1. Summary of physical characteristics of pitchers used in this study.

Name of Pitcher	Volume (mL)	Surface Area (cm^2)	Height (cm)	Maximum Outside Diameter[a] (cm)	Neck & Base Diameter[a] (cm)
P-1	1281	713	25.8	14.0	5.6
P-2	1220	699	25.4	14.0	5.4
P-3	1279	710	26.5	14.1	5.4
P-4	1286	710	25.9	13.1	5.0
P-5	1330	730	26.6	14.1	5.5
P-6	1366	737	26.6	14.2	5.7
P-7	1197	691	25.7	13.2	5.6

[a] Neck and base diameters are approximately equal, thickness ≈ 6 mm.

Saturated hydraulic conductivities, porosities, and bulk densities of the pitchers were measured by standard methods as described by Abu-Zreig and Atoum (2004) and Abu-Zreig et al. (2006). The average bulk density of the material used to construct the seven pitchers was equal to 2167 kg m^{-3} and the average material porosity is equal to 38%.

SEEPAGE MEASUREMENTS

Seepage Rate in the Atmosphere

We conducted a set of experiments to estimate the free seepage rate of the pitchers in the atmosphere (fig. 2) and inside a chamber under controlled temperature and humidity. The free seepage volume of pitchers can be correlated to seepage volume through soil under field conditions. The pitchers were filled with water and placed inside the chamber under specific temperature and humidity and the loss of water in the pitchers was measured by measuring the refilling volume of each pitcher. The volume was recorded at 24 h interval for at least four consecutive days. The procedure was repeated for each climatic condition in which temperature was varied from 10°C, 15°C, 20°C, 25°C, and 30°C whereas the humidity was kept constant at 40% resulting in varying pan evaporation from 0.3 to 5.7 mm/day. Small steel circular pan was placed in the chamber to determine the pan evaporation, E_p, under each climate condition.

Seepage Rate of Pitchers Buried in Soil

A set of experiments was conducted to measure the seepage rate of pitchers buried inside soil pots (fig. 3). The pitchers were placed in the middle of a 30-L plastic soil pot then filled with air dry Tottori sand dune soil (sand= 96.1%, silt=0.4%, clay=3.5%) and placed in a chamber to measure seepage rates under controlled temperature and humidity. The pitchers were filled up to their neck with water and left in the chamber for 24 h. After that, the pitchers were refilled again measuring the seepage rate in mL day^{-1}. The weights of soil buckets were also recorded every 24 h to measure the rate of evaporation under various pitchers. Two soil moisture sensors (5TE Decagon, Meter Group, Inc. Pullman, Wash.) were installed at 5 and 15 cm below surface and 5 cm away from the surface of the pitchers, in each bucket and the soil

Figure 2. General view for the experimental setup. Measurement of seepage rate from the ceramic emitters (pitchers) in the atmosphere under constant head.

moisture content was monitored during the experiments. The sensors were connected to a data logger and the soil volumetric water content was recorded at 30 min interval.

Seepage Rate of Pitcher Under Positive and Negative Hydraulic Head

Two sets of experiments were carried out to examine the influence of hydraulic head on the seepage rate of pitchers (fig. 4). Constant positive or negative hydraulic head relative to the pitchers mouth was applied by increasing or decreasing the Marriott bottle level relative to pitchers mouth. Seepage rates of two pitchers in the atmosphere were measured one at a time under each head values that varied from -25 cm to +30 cm. Each experiment lasted for 2 to 3 days in which seepage volume under each head was measured every 12 h to ensure steady state conditions under each head value. The final four measurements were averaged out to determine the daily seepage rate in mL day^{-1} for each pitcher-head combination.

Figure 3. Ceramic pitchers buried in the soil pins inside controlled chambers.

RESULTS AND DISCUSSION

The physical characteristics of ceramic pitchers used in this study are summarized in tables 1 and 2. The volumes of the pitchers are about 1220 mL with average height and outside diameter of 26 and 14 cm, respectively. We measured the saturated hydraulic conductivity of pitchers that were varied from 0.28 to 0.7 mm/day. The behavior of these pitchers is similar to ceramic emitters that can be commercially manufactured in smaller size. In this study, we used large size emitters, called pitchers, because they are easier to study and commercially available from the ceramic pottery sellers.

The atmospheric free seepage of ceramic pitchers under constant and falling head conditions is shown in figure 5. Seepage rate under variable head is always lower than that for constant head method (Abu-Zreig and Atoum, 2004; Abu-Zreig et al., 2006). This is because water seepage is controlled by the hydraulic gradient across the wall of pitchers. Under constant head condition, the hydraulic gradient is maintained at higher value during the experimental duration. In the case of falling head procedure, the water depth inside pitchers is decreased steadily with seepage thus decreasing hydraulic gradient and water seepage accordingly. Figure 5 shows that seepage rate under variable head conditions for the seven pitchers under study varied from 166 to 384 mL d^{-1}, whereas the corresponding range of seepage under constant head condition were from 392 to as high as 1001 mL d^{-1}; approximately 2.5 fold. This is because seepage rate increased with hydraulic head which has been found by Abu-Zreig and Atoum (2004) and Abu-Zreig et al. (2006) using other types of pitchers. In either case, the seepage rate of pitchers was linearly and significantly related to the hydraulic conductivity (Ks) of pitchers wall material as shown in

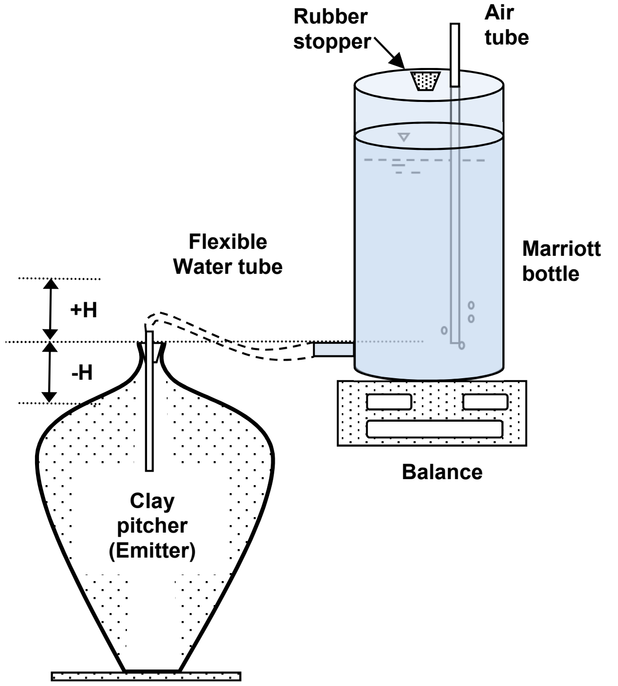

Figure 4. Schematic diagram for the experimental setup used for measurements of seepage rate under various positive and negative head relative to pitcher's mouth.

figure 6. Regression tests revealed that a strong relation exists between seepage rate and Ks with R^2 equal to 0.998 and SE = 14.6 mL day^{-1} for constant head condition and R^2 = 0.71 and SE = 43 mL d^{-1} for variable head experiments. The intercepts for both tests were also significantly equal to zero (P<0.01). These results confirmed findings found by several researchers in the literature (Stein, 1997; Abu-Zreig and Atoum, 2004; Abu-Zreig et al., 2006; Siyal et al., 2009)

Table 2. The hydraulic properties of ceramic pitchers used in this study.

Name of Pitcher	Bulk Density (kg/m^3)	Porosity (%)	Saturated[a] Hydraulic Conductivity (mm/d)
P-1	2131	34.7	0.424
P-2	2314	38.8	0.275
P-3	2197	39.7	0.497
P-4	2055	36.7	0.704
P-5	2230	39.7	0.549
P-6	2199	39.1	0.655
P-7	2046	34.8	0.283

[a] Saturated hydraulic conductivity measured by falling head method.

The seepage rate of ceramic pitchers when buried in soil is expected to be higher than that in the atmosphere because soil suction pressure at the outer surface of a pitcher increases the hydraulic gradient across the wall thus increasing seepage rate. Figures 7 and 8 confirms that seepage rate of ceramic pitcher when buried inside soil were about two-fold higher in average compared to that in the atmosphere. The highest seepage rates were found for P6 of which the seepage rates in the atmosphere and soil were 380 and 757 mL d^{-1}, respectively. Similar results were found of all other pitchers. A plot of seepage rate of pitchers inside soil versus that in the atmosphere, shown in figure 8, revealed a linear and significant (P<<0.01) relationship ($Q_{soil} = 1.9\ Q_{air}$) with coefficient of determination R^2 = 0.98. These results are useful because it enables us to estimate the expected amount of water seepage of pitchers before installing it inside the soil with simple test in the atmosphere.

However, seepage rate from ceramic pitchers inside soil is expected to decrease as soil moisture increases with time. Indeed, seepage rate was found to decrease steadily with an increase in the soil moisture around emitters as shown in figure 9. This happens when soil moisture around ceramic emitters increases the soil suction pressure also decreases and may reach to zero when soil around pitchers is fully saturated

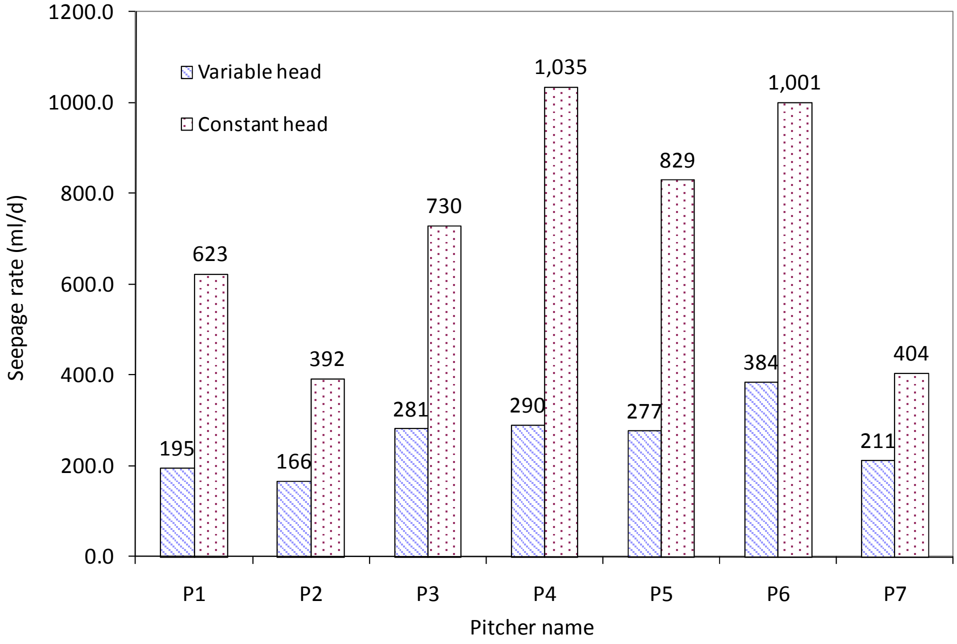

Figure 5. Seepage rate from ceramic pitchers under variable head and constant head conditions in the atmosphere under room temperature (Ep=0.4 mm/d).

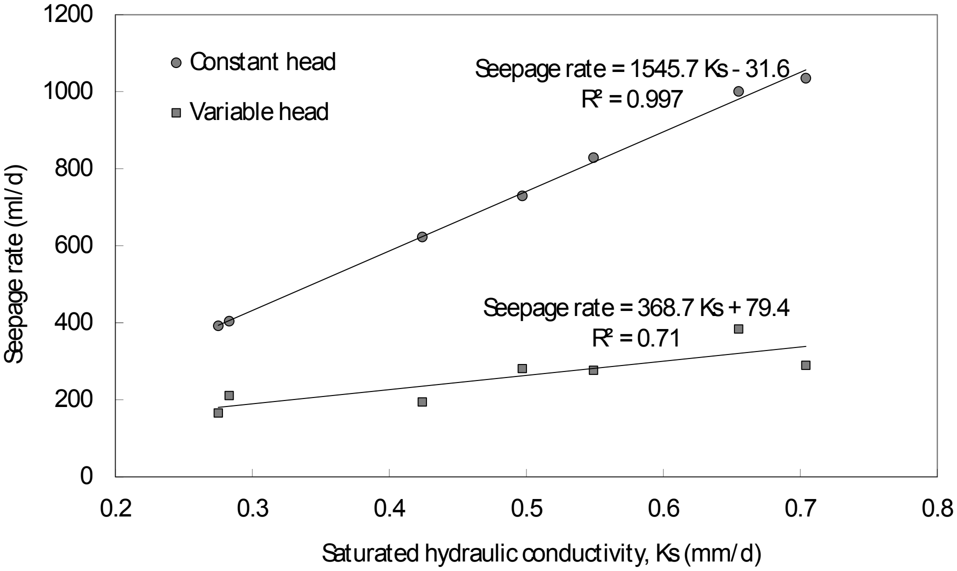

Figure 6. The relationship between seepage rate of pitchers under constant or variable head conditions in the atmosphere and hydraulic conductivity.

resulted in a decrease in the hydraulic gradient across pitchers wall thus decreasing seepage rate. Figure 9 shows a significant and linear negative relationship between seepage rate and soil moisture around pitchers with relatively acceptable R^2 value of 0.32. Regression test revealed that slope is significantly negative and less than zero ($P<0.5$).

But we also found that evaporation is another important driving force for seepage from ceramic pitchers inside soil profile. Soil moisture decreased with evaporation thus increasing soil suction pressure and therefore increases seepage rate from pitchers. Figure 10 shows that seepage rate is positively correlated to evaporation rate for all ceramic pitchers under study. For example, the seepage rate of pitcher 6 increased from 400 mL/d to about 550 mL d^{-1} when the evaporation rate increased from 0.5 to 6 mm d^{-1}. Similar increase in the seepage rates for all other pitchers were observed (fig. 10). Previous research done by Abu-Zreig et al. (2006) have shown that seepage rate of pitchers in the atmosphere increased with pan evaporation. This research showed that when pitchers are buried in the soil, seepage rate is also directly and positively related to potential evaporation and the relationship is significant for all pitchers tested ($P<0.01$).

SEEPAGE RATE UNDER POSITIVE AND NEGATIVE HEAD

Seepage rate from ceramic pitchers are highly affected by the hydraulic head. In theory, water flow in pipes, soil and through ceramic media and porous materials increases with hydraulic head. However, water flow through pipes and soil

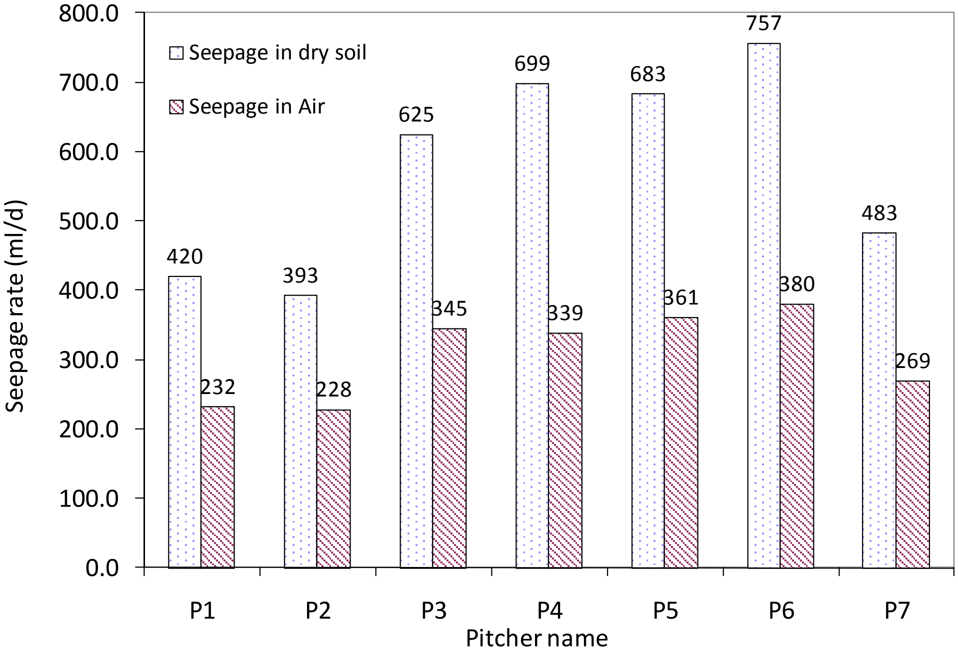

Figure 7. Seepage rate from ceramic pitchers when buried in the soil or under atmospheric pressure in controlled chamber (Ep = 2.8 mm/d).

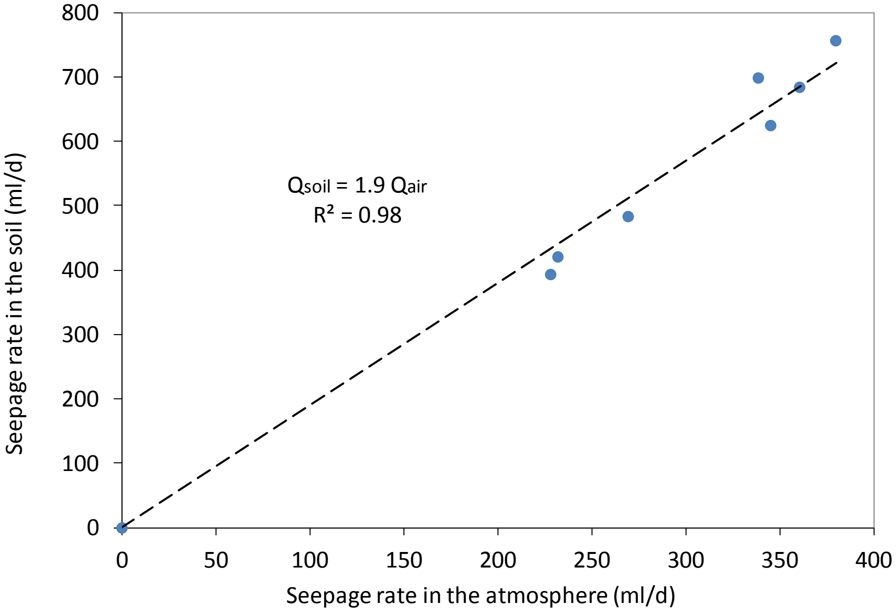

Figure 8. Relationship between seepage rate of pitchers inside the soil to that in the atmosphere.

cannot occur under negative head conditions. In the case of ceramic emitters and pitchers, water flow can occur if the suction pressure at the outer surface of pitchers resulted from either soil suction or water evaporation, exceeds the pressure head at the inner surface, thus creating positive hydraulic gradient across the wall of pitchers. The influence of positive water head on the seepage rate of pitchers could be envisaged from figure 5 where the hydraulic head, and therefore seepage rate, under constant head condition is higher than that under variable head condition. But the relationship between seepage rate and negative hydraulic head that could be created inside tightly closed system of pitchers has not been studied in the literature. Therefore, we created a negative pressure head inside a pitcher by lowering the Marriott bottle level below the pitchers mouth (fig. 4). Figure 11 shows the influence of variable head ranging from -25 to +30 cm on the seepage rate of two pitchers named as P1 and P5.

Seepage rate from ceramic pitchers as expected increases with an increase in the hydraulic head. But the interesting result is that seepage rate occurred even under negative head. Under negative head of -25 cm, seepage rate of P5 is about 100 mL/d and increased to 170, 350, 425, 830 mL day^{-1} under hydraulic head values of -20, -15, -10, and 0 cm relative to the mouth of pitchers, respectively. This is a major finding since seepage rate varied widely under negative pressures. The implications are that ceramic emitters can supply water to plants without creating a positive pressure in the irrigation

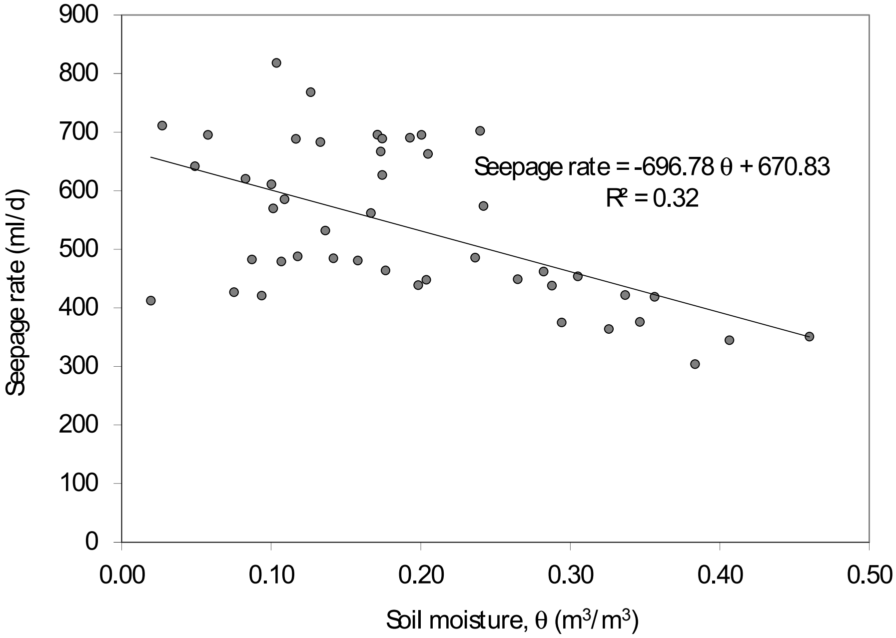

Figure 9. The influence of soil moisture around buried ceramic pitchers on their seepage rate.

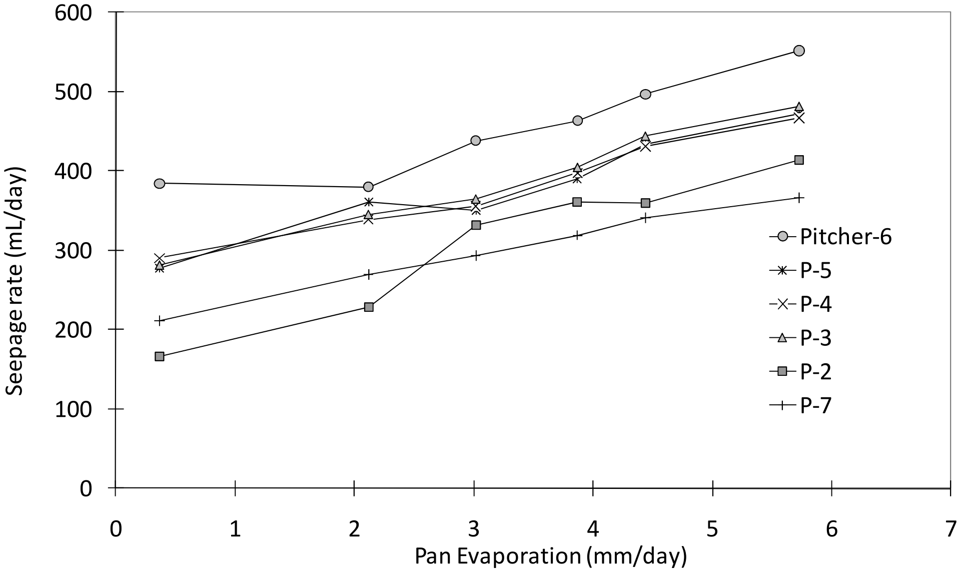

Figure 10. Variations of seepage rate of pitchers in the atmosphere with pan evaporation inside a controlled chamber.

line and one can also control how much water is released by controlling the hydraulic head of ceramic emitters. When the water supply-emitters system is kept in an air tight condition, negative pressure will develop in the system and in that case the system is shown to continue releasing water to the surrounding soil at diminishing rates. Therefore, the system can be successfully utilized for deficit irrigation where water is released at smaller quantities just below crop-water requirements. In addition, eliminating the need for pressure will eliminate the energy required to operate the irrigation lines.

CONCLUSIONS

Seepage rate from pitchers is affected by various variables including the positive hydraulic head due to water depth inside pitchers and negative suction head at the pitchers' outer surface. Seepage rates from pitchers increased by about three-fold under constant head compared to that of variable head conditions and also increased by two-fold when pitchers buried inside soil compared to that in the atmosphere. In addition, seepage rates from pitchers have increased with an increase in the evaporation rate or a decrease in the soil moisture around pitchers' wall. We have found also that seepage rates of pitchers can occur even under negative hydraulic head indicating the possibility of using pitcher irrigation systems for deficit irrigation.

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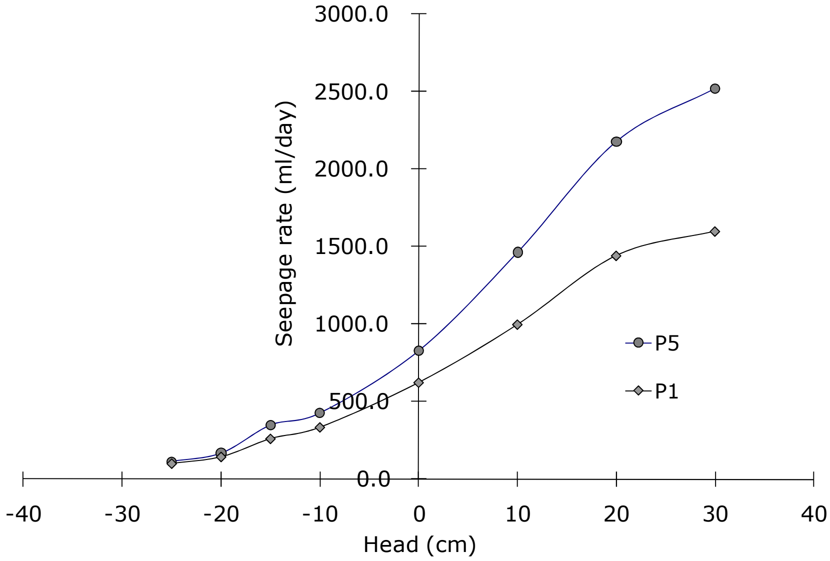

Figure 11. Variations of seepage rate of pitcher in the atmosphere under room temperature with hydraulic head.

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