Factors Affecting Water seepage Rate of Clay Pitchers in Arid lands

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ABSTRACT

A field experiment was initiated to study the effect of pitcher material, potential evaporation and soil on the seepage rate of clay pitcher. Eleven pitchers with varying shape and hydraulic conductivity were used in the experiments. Seepage rate of pitchers were measured in the atmosphere and after burying them up to their neck in a silt loam soil. Average seepage rate of pitchers were higher when buried in the soil under constant head (5500 mL/day) compared to that of variable head conditions (2700 mL/day) or atmospheric seepage (1700 mL/day). Seepage rate was directly proportional to pitchers conductance and potential evaporation. A linear relationship was found between seepage rate and potential evaporation for all pitchers showing a sign of auto-regulative capabilities. Pitcher seepage rate was also found to be directly correlated to matric potential of soil around pitcher wall suggesting that pitcher behavior is affected by soil moisture conditions.A mathematical conceptual model was used to predict the seepage rates of pitchers buried in the soil under variable and constant head conditions. The model prediction of seepage rate correlated very well with the experimental data with R^2 ***equal to 0.74 and 0.62 for variable head and constant head experiments, respectively.***

Keywords: Pitcher irrigation; Seepage rate; Seepage modeling; Water conservation.

INTRODUCTION

Water scarcity in arid and semi arid countries is the main constraint in agricultural production. Therefore, agricultural practices should be directed to methods where high saving potential for water is possible. Rainfed agriculture is very popular in semi-arid countries like Jordan and Saudi Arabia. However, the variability of rainfall and high evaporation rate limits the success of rainfed agriculture in those arid lands. Despite water shortage, irrigation agriculture is becoming the only solution for sustainable crop production in arid and semi- arid countries (Tvedt, [1]).

Great efforts have been focused to increase the efficiency of irrigation systems and reduce water losses. Government agencies in arid countries are encouraging farmers to adapt irrigation methods that have high water saving potential such as trickle irrigation. However financial and operational difficulties have prevented the wide spreading of these systems. New, inexpensive and simple irrigation methods are needed to support food production and increase farmer's income (Batchelor et al., [2]). One of these methods is pitcher irrigation.

Pitcher irrigation is an ancient technique that has been practiced originally in Iran and spread later on to many other countries in Asia and Africa (Bainbridge [3]). The technique is simple, cheap and believed to have a large water saving potential (Mondal [4]; Stein [5]). Pitcher irrigation consists, in its simplest form, of unglazed baked clay pots, which are buried up to the neck in the soil and filled with water (Gischler and Jauregui [6]). Water gradually seeps out through the pitcher's porous wall into the root zone due to hydraulic and soil matric potential. It is believed that pitchers have self-regulation capability since water seepage is controlled by moisture content in the soil matrix around the pitcher (Cliff-Hill [7]; Chigura [8]). As soil water decreases due to evapotranspiration seepage rate from pitchers increases to keep soil moisture at a specific value. Therefore, factors affecting seepage rate must be properly evaluated. Saturated hydraulic conductivity of pitcher wall material and soil pitcher surface area and evapotranspiration rate is believed to be the key factors affecting seepage rate of pitchers (Usman

[9]; Stein [10]). However, experimental verification of factors affecting pitcher seepage rate is scarce.

In an arid country with limited water resources like Jordan and Saudi Arabia, pitcher irrigation technique can be very useful due to its simplicity and large water saving potential. In addition, production of clay pitchers is a traditional profession that was practiced for thousands of years. People used clay pitchers to store water, crops and oil. Extending the use of pitchers for irrigation can maintain this profession and improve the people income and encourage the use of locally produced products. Until now, little work has been done to evaluate the potential uses of this system in Jordan and Saudi Arabia. Therefore, the objective of this research is to investigate the suitability of pitcher irrigation by evaluating seepage rate of various types of pitchers having a wide range of hydraulic conductivity under field conditions.

Materials and methods

This research was conducted at the experimental station of Jordan University of Science and Technology (JUST) during the 99/2000 and 2000/01 growing season. JUST is located in the marginal area of north Jordan 32º 27.58996 North and 35º 58.34166" East, with an altitude of 627.65 m. The annual precipitation was less than 200 mm for the two seasons. The soil in the experimental site is classified as silt loam. The soil texture, determine by hydrometer method, was 20% sand, 41% silt, and 39% clay. The following soil properties were measured in the lab: soil pH was 8.04 at 30 °C, extract electrical conductivity (EC) = 8.52 x 10-^{3} mmhos/cm, and soil bulk density (ρ) = 1.36 gm/cm^3.

Eleven pitchers with variable shape, volume and hydraulic conductivity (K_s) were evaluated in the experiment. The average physical characteristics of the experimental pitchers are shown in Table 1. The pitchers were randomly collected from various local producers and the pitchers properties cannot be replicated because of differences in the production materials, firing temperature and manual manufacturing.

The saturated hydraulic conductivity of pitchers was determined with a modified falling head permeameter. The whole pitcher was first saturated in a water bath for three days and then placed in a water bucket submersed to its neck. Submersion of pitchers for three days should be adequate to saturate them since similar procedure was recommended to saturate ceramic plates used in pressure plate apparatus (Klute [10]). The water level in the bucket was kept constant by overflow. A manometer tube was inserted into a rubber stopper and fitted tightly to the opening of the pitcher. The hydraulic head, that is the water level in the manometer tube above free water surface in the bucket, was monitored with time. Schematic diagram of the experimental setup is shown in Figure 1. Pitchers Ks were calculated by applying the falling head equation as follows (Stein [11]):

$$K_s = \frac{aL}{A}\frac{\ln(h/h_o)}{(t)} \tag{1}$$

Where; h_o is the initial height of water level in the manometer tube above the free water surface, mm; h is the height of water in the manometer tube at time t, mm; A is the surface area of the pitcher, mm^2; a is the cross sectional area of the manometer tube, mm^2; L is the average wall thickness of the pitcher, mm; Ks is the saturated hydraulic conductivity, mm/d; and t is the cumulative time, day.

The thickness of the pitcher (L) was estimated by breaking up three similar pitchers and measuring the thickness of the fractured pieces with a caliper. The average wall thickness of pitchers was about 6.5 mm. Pitcher’s surface area was measured by using a flexible nylon rope with a diameter of a bout 5 mm. The whole pitcher was wrapped tightly with the rope. Measuring the total length of the rope gives the surface area of the pitcher which is equal to the length of the rope multiplied by its diameter.

Clay pitchers were randomly placed in a silt loam soil at two meters distance in a field planted with 3 years old olive trees, which are about two meters away from the center of the pitchers line. The saturated hydraulic conductivity of the soil was measured with Guelph permeameter

(Soil Moisture Corp [12]) and is equal to 2.5 mm/day. Pitcher's were buried to their neck below soil surface. A 2-cm thick sand layer was placed around pitchers wall to prevent direct contact of pitcher's wall with the surrounding soil in orders to prevent mud formation around pitcher's wall. A schematic diagram of the experimental set up is shown in Figure 2.

Seepage rate from pitcher was monitored under variable and constant head condition over a two-month period each starting in May, 2001. In the variable head experiments pitchers were filled with water and left for 24 hours then filled again. In the constant head experiments a Mariotte bottle was used to keep a constant water level in pitchers as shown in Figure 2. The loss in the water volume inside Marriott bottle due to seepage from pitchers was daily monitored from May to July 2001. Two tensiometers for each pitchers were installed around pitchers A1 and B1 at a radial distance of 7 and 15 cm away from the wall of the pitchers. For all other pitchers, one tensiometer was installed at 7 cm from pitchers wall. The tensiometer readings were monitored daily to determine the variation of pitcher seepage rate with soil suction pressure. Pan evaporation was daily collected from a Class A pan installed at the Ramtha weather station located about 1 km away from the experimental area. Crop reference evapotranspiration (ET_o) was estimated by multiplying pan evaporation by the pan constant, which was found to be 0.75 for the climatic conditions prevailing at the experimental area (Wanielista et al. [13]).

Linear regression analyses were performed between variables to determine the coefficient of determination, standard error of estimate and the correlation significance at 95% probability level. Testing of means of seepage rate cannot be performed since pitchers cannot be replicated in the field due to manual production process. Linear regression was also performed on predicted versus observed seepage rates of pitchers. A regression line having an interception of 0.0 and slope of 1.0 would exhibit zero bias between predicted and observed values. Hypothesis testing was performed, on the slope equal to 1.0 and intercept equal to 0.0 of regression lines, to detect any bias between predicted and observed values at 95% probability level.

Results and discussion

The average daily seepage rate of pitchers in the atmosphere and in the soil under variable and constant head conditions are summarized in Table 2. Seepage rates were lowest in the atmosphere and increased when pitcher buried in the soil due to soil suction pressure. Seepage rates under constant head were higher than that under variable head due to an increase in the hydraulic head of water inside pitchers. The average seepage rate for all pitchers in the atmosphere was about 1700 mL/day compared to 2700 mL/day inside soil with variable head and 5500 mL/day inside soil with constant head.

Seepage rate of pitchers increases with an increase in pitcher's surface area and saturated hydraulic conductivity. The combined effect of these two factors along with the wall thickness of pitchers is lumped together in a property called conductance. Conductance is equal to K_s multiplied by the surface area divided by the wall thickness of pitchers, as shown in Table 2 (Chigura [8]). Seepage rate of pitchers was directly and significantly related to conductance ($P<0.01$). As shown in Figure 3, a linear relationship was found between seepage rates and conductance with R^2 equal to 0.74, 0.90 and 0.90 for seepage experiment of pitcher in the soil with constant head, in the soil with variable head and in the atmosphere with variable head, respectively. The corresponding Standered Error of Estimate (SEE) were 1357, 357 and 267 mL/d, respectively. Similar results were reported by Abu-Zreig and Attom [14] who found a linear relationship between seepage rate of pitchers in the atmosphere and conductance.

A modified physically based seepage model that predicts daily seepage rate, Q_p, from the pitcher conductance has been used to predict daily seepage rate of pitchers buried in the soil under variable and constant head conditions. The model was validated by Abu-Zreig and Attom [14] using data from pitcher's seepage experiments in the atmosphere. The model calculated seepage rate from the summation of basal and side wall seepage. Slight modifications in the model have to be done to take into account the soil suction on the pitcher's wall. The modified model is as follows:

$$Q_p = (\frac{A_b}{A_s})CD(fh + hs) + (1 - \frac{A_b}{As})CD(fh + h_s) \qquad (2)$$

Where A_s is the total surface area of pitcher; A_b is the basal area which is equal to 7900 mm^2 in average for all pitchers, base diameter = 100 mm; *CD* is pitchers conductance which is equal to (K_s x As / L); *h* is the measured pitcher's height; and *f* is the fraction of pitchers height and *f* h is the effective water head that depends on pitchers geometry and experimental conditions; and h_s is the soil suction at the outer surface of pitcher's wall that was estimated from tensiometer's readings installed near pitchers wall.

The model was successful in predicting seepage rate of buried pitchers under both variable and constant head conditions and the results are shown in Figures 4 and 5, respectively ($P<0.01$). Regression analysis was performed between the predicted versus observed seepage rate and the resultant coefficients of determination R^2 equal to 0.74 and 0.62 for variable head and constant head experiments, respectively. The line slope values were 1.06 and 0.95 and they are not significantly different than 1.0 using 95% confidence interval indicating a good model prediction. The value of height fraction *f* used in the model, Equation 2, was equal to 0.1 and 0.4 for variable head and constant head condition, respectively being within the range recommended by Abu-Zreig and Attom [14].

The average cumulative seepage volume from four pitchers was plotted with cumulative time during two months period as shown in Figure 6. Cumulative seepage volume varied steadily among pitchers. After about 55 days (1320 hr) the volume of seepage were about 90, 300, 360 and 520 liters for pitchers A5, A1, C1 and B1, respectively. Pitcher's seepage seemed to increase with pitcher conductance except in the case of pitcher C1 compared to pitcher A1. The cumulative seepage volume for C1 is higher than that of A1 despite the fact the A1 has a higher conductance. This is because of the outer shape of C1 having larger surface area compared to A1. An increase in the soil pressure at the outer surface of clay pots would increase the seepage volume at a rate correlated to their surface area, according to Darcy's law.

The cumulative reference evaporation (ET_0) during the whole test period was also shown in Figure 6. Pitcher B1 was able to supply water above the reference evaporation and therefore it is suitable for irrigation since its cumulative daily seepage was always higher than ETo. Pitcher C1 and A1 can also be suitable for irrigation since the water supply is slightly below that of potential evaporation. Such type of pitcher could be appropriate for deficit irrigation because there was a constant supply rate of water just below that of potential evaporation. Obviously, seepage volume from pitcher A5 was far below that of potential evaporation, thus can’t meet crop water demand and therefore is not suitable for irrigation.

To further analyze the relationship between potential evaporation and seepage rate of pitchers the daily seepage rate for 4 pitchers was plotted against the daily potential evaporation as shown in Figure 7. There was a week but positive linear relationships between (ET_0) and daily seepage for all pitchers with R^2 ranging from 0.17 to 0.45, as shown in Figure 7. These results indicated that clay pitchers showed sign of auto-regulative capability, as they were slightly responsive to ET_0. As ET_0 increased pitcher seepage rate increased accordingly, a necessary condition for a good irrigation system. The seepage rate of pitcher B1 showed however a slightly different behavior (Figure 8). Seepage rate of B1 seemed to be constant when ETo values were less than 8 mm/day. However, as ETo values increased beyond 8 mm/day seepage rate increased rapidly. This is because of the large conductance of pitcher B1 resulting in large seepage rate irrespective of ET_0. However, as ET_0 became higher than 8 mm/day B1 pitcher became more responsive and seepage rate increased accordingly.

Conclusion

Field experiments have shown that clay pitchers were capable of supplying water at a rate directly proportional to crop need represented by crop reference evapotranspiration (ET_0) and soil moisture level.

Application of pitcher irrigation in the field can be achieved by connecting a series of pitcher through a network of pipe that can fill the pitcher in regular basis. This research has shown that water seepage from pitchers is an auto regulative process and is a function of soil moisture conditions which in turns affected by evapotranspiraton rate.

The seepage rate of pitchers is also affected by its physical properties including saturated hydraulic conductivity, surface area and wall thickness which are lumped together in a property called conductance. A linear and significant relationship ($P<0.01$) was found between seepage rate and conductance with R^2 of 0.74 for buried pitchers under constant head and 0.90 for pitchers in the atmosphere. A modified conceptual model was used to predict seepage rate of pitchers in the soil under variable and constant head conditions. The model was successful in predicating seepage rate of pitchers with R^2 equal to 0.74 for variable head and 0.62 for constant head experiments ($P<0.01$). Predicting seepage rate of pitchers from conductance and water head will help quantify the amount of seepage water from a pitcher when buried in the soil that determine its suitability for irrigation before field installation.

Seepage rate of pitchers was affected by potential evapotranspiration (ETo) indicating an auto-regulative capability. Some pitchers were able to supply water at a rate greater than ET_o, such as B1, while other pitchers, i.e. C1 & A1 with moderate conductance values seemed to supply water at a rate slightly below that of ETo, indicating their suitability for irrigation. In addition, seepage rate of pitchers seemed to be affected by soil matric potential around pitcher indicating that seepage rate is affected by soil moisture level. These results indicted that pitchers can release higher quantities of water in dry soil compared to that in wet soil, indicating that pitchers can auto-regulate water supply to plants. Further investigations are needed to confirm this result.

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Caption of Figures

- **Figure 1.** Schematic diagram of the falling head permeameter used to measure the saturated hydraulic conductivity of pitchers.
- **Figure 2.** Schematic diagram of the experimental setup in the field.
- **Figure 3.** Relationship between seepage rates and conductance. SEE is the Standard Error of Estimate; P value indicates the regression significance.
- **Figure 4.** Predicted versus experimental seepage of pitchers buried in the soil under variable head conditions. SEE is the Standard Error of Estimate; P value indicates the regression significance
- **Figure 5.** Predicted versus experimental seepage of pitchers buried in the soil under constant head condition. SEE is the Standard Error of Estimate; P value indicates the regression significance
- **Figure 6.** Cumulative seepage rate of pitchers and cumulative crop evapotranspiration over the experimental period.
- **Figure 7.** Influence of daily potential evaporation on daily seepage rate of pitchers uses in this experiment.
- **Figure.8.** Influence of ET_o on seepage rate of B1 pitcher.

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

Name of pitcher	Volume (mL)	Surface area $mm^2 \times 10^{-2}$	Height (mm)	Diameter† (mm)	Saturated hydraulic conductivity †† (mm/d)	Conductance‡, cm^2/d
A1	3360	1150	260	183	0.914	161.96
A2	3060	1121	250	180	0.539	92.97
A3	3150	1118	255	185	1.007	173.22
A4	3170	1123	265	180	1.020	176.21
A5	3210	1120	265	180	0.219	37.78
A6	3080	1120	265	180	0.952	164.02
A7	3090	1154	260	180	1.171	207.87
A8	3000	1194	240	183	1.678	308.17
B1	6450	1665	300	205	2.220	568.54
B2	6400	1653	310	203	2.370	602.86
C1	6770	1835	270	245	0.442	124.78

† Maximum outside diameter

†† Saturated hydraulic conductivity measured by falling head method

‡ Conductance = $(K_s \times A) / L$; A is the surface area and L is the wall thickness of pitcher

Table 2. Experimental and predicted seepage rate of pitchers under variable and constant head conditions.

Name of pitcher	Variable head seepage of pitches in the atmosphere §, (mL)	Variable head seepage of pitchers inside soil (mL)	Predicted variable head seepage inside soil (mL)	Constant head seepage inside soil§§ (mL)	Predicted constant head seepage inside soil (mL)
A1	1290.0	2350	2066	5939	3501
A2	960.0	1590	2900	2200	3696
A3	1300.0	2380	2099	5780	3611
A4	1350.0	2360	2149	5450	3743
A5	600.0	1090	1896	1265	2239
A6	1300.0	2400	2924	5050	4925
A7	1910.0	2900	2538	4500	4381
A8	2370.0	3100	3075	5200	5589
B1	3050.0	4550	4866	9430	10471
B2	3200.0	4600	5183	9670	11326
C1	1500.0	2750	2706	6538	3804

§ Outflow volume when pitcher is filled with water and left in the air for 24 h.

§§ Seepage volume when the water level in the pitchers is kept constant.

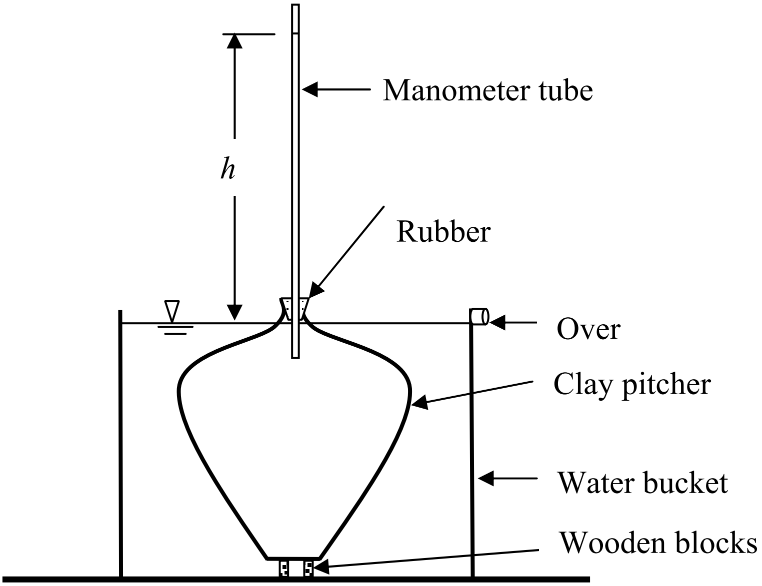

Figure 1. Schematic diagram of the falling head permeameter used to measure the saturated hydraulic conductivity of pitchers

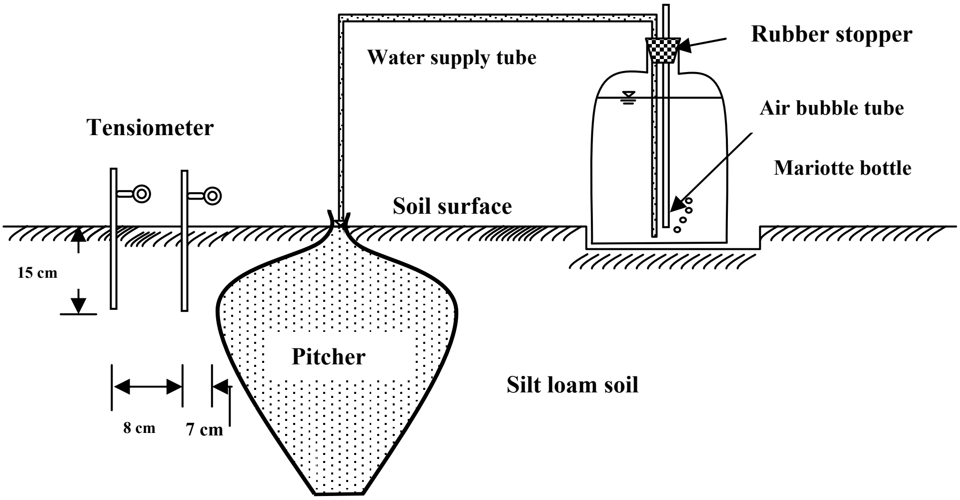

Figure 2. Schematic diagram of the experimental setup in the field.

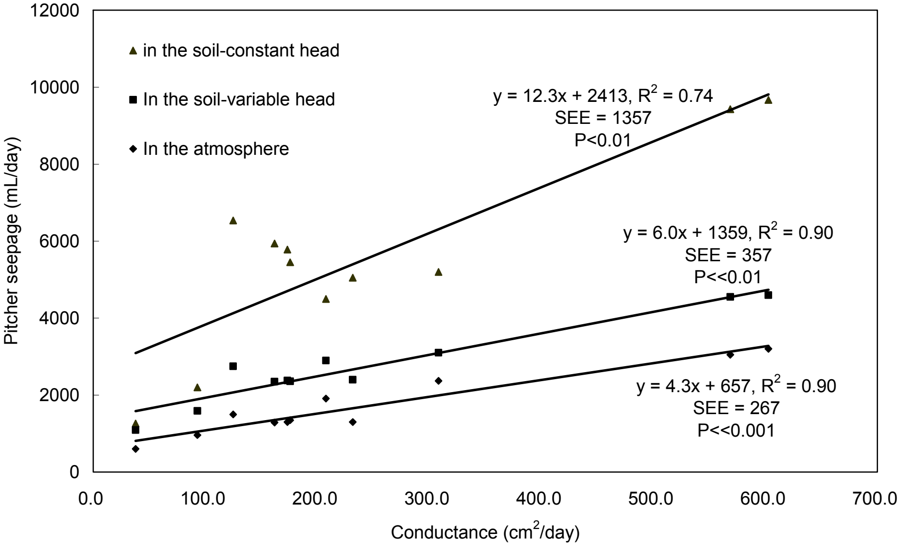

Figure 3. Relationship between seepage rates and conductance. SEE is the Standard Error of Estimate; P value indicates the regression significance

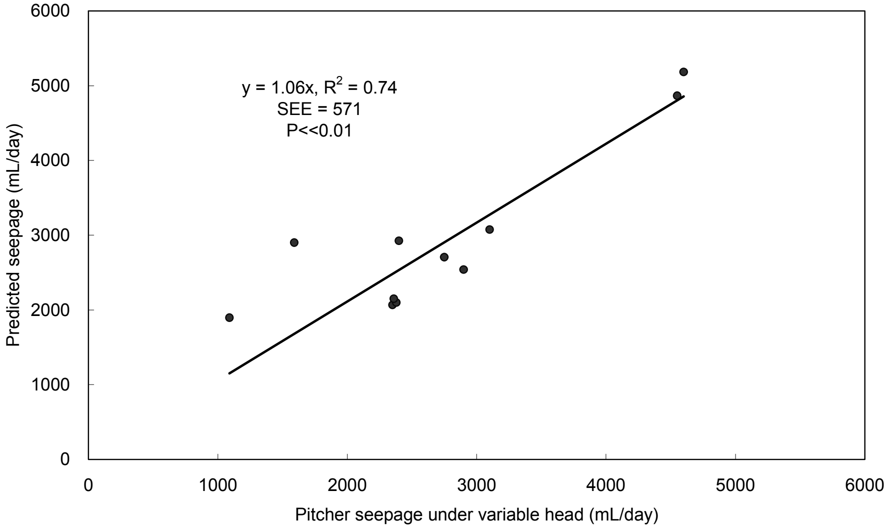

Figure 4. Predicted versus experimental seepage of pitchers buried in the soil under variable head conditions. SEE is the Standard Error of Estimate; P value indicates the regression significance

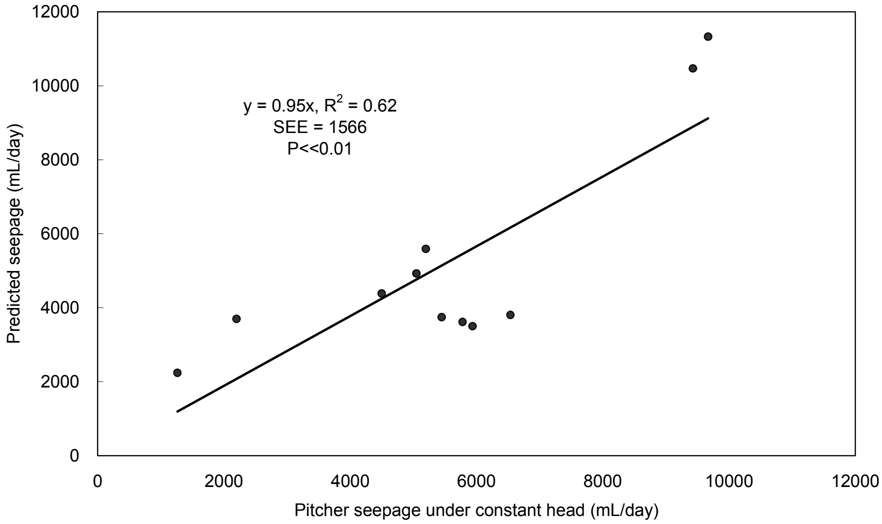

Figure 5. Predicted versus experimental seepage of pitchers buried in the soil under constant head condition. SEE is the Standard Error of Estimate; P value indicates the regression significance

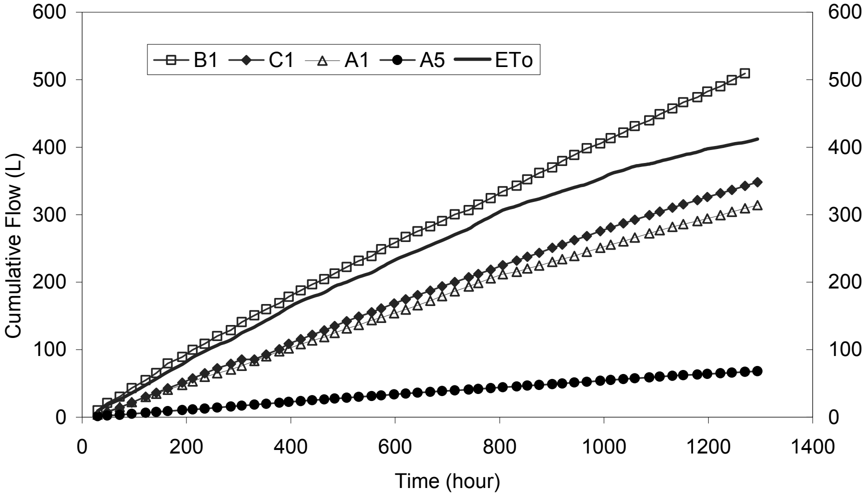

Figure 6. Cumulative seepage rate of pitchers and cumulative crop evapotranspiration over the experimental period.

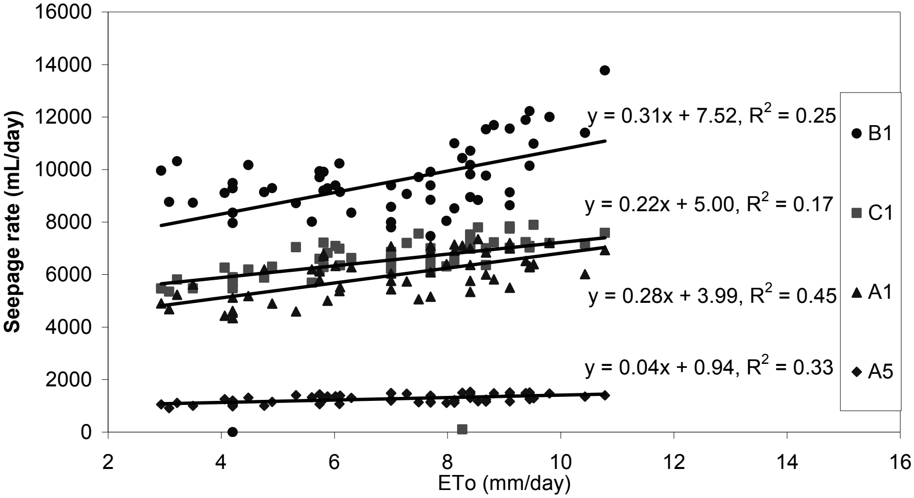

Figure 7. Influence of daily potential evaporation on daily seepage rate of pitchers uses in this experiment.

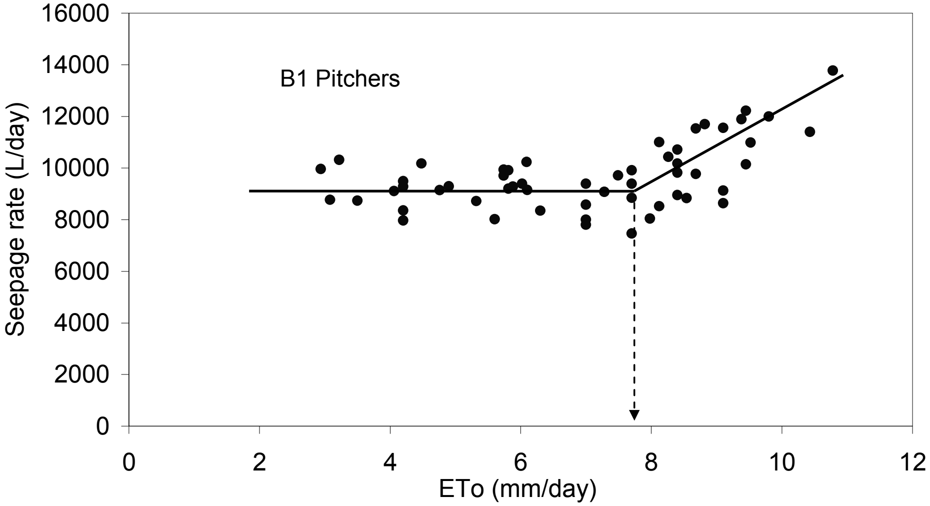

Figure. 8 Influence of ETo on seepage rate of B1 pitcher.

العوامل المؤثرة في انسياب الماء
من الجرار الفخارية في الأراضي الجافة

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الخلاصة

لقد أجريت تجربة حقلية لدراسة العوامل المؤثرة على انسياب الماء من الجرار الفخارية في الحقل مثل المواد المستعملة في صناعة الجرار، وقيم التبخر والنتح القصوى ونوع التربة. لقد تم قياس كمية الماء المنساب من (١١) جرة عندما تركت في الهواء ثم بعدما غمرت بالتراب إلى العنق وقد وجد أن كمية الماء المنساب عندما تركت الجرار في الهواء ي ١٧٠٠ ملم مقارنة بـ ٥٥٠٠ ملم بعد ما غمرت الجرار في التربة، مما يدل على أن التربة لها تأثير كبير على انسياب الماء يتناسب طرديًّا وبشكل خطي مع القيمة القصوى للتبخر بالإضافة إلى القيمة ألتوصيله للجرار وهي تساوي رياضيا (السماحية X مساحة الجرة الخارجية | سمك جدار الجرة). وهذا يدل على قدرة الجرار الفخارية على التنظيم الذاتي لانسياب المياه حسب قيمة التبخر وبالتالي حسب حاجة النبات.

لقد تم استعمال نموذج رياضي فيزيائي لحساب كمية الماء المنساب من الجرار بالاعتماد إلى عدة عوامل بنجاح حيث إن العلاقة بين كمية الماء المنسابة من الجرار وجدت قريبة من تلك المحسوبة بواسطة النموذج وبمعامل ارتباط بلغ ٧٤٪ عندما كان مستوى الماء في الجرة ثابتاً و ٦٢٪ عندما ترك مستوى الماء في الجرة يتناقص مع الزمن.

إن النتائج التي خَلُصَ إليها البحث تدل على أنه يمكن استخدام الجرار الفخارية لري الأشجار والغرس حيث تبين إن حجم الماء المنساب يتناسب مع قيمة التبخر وبالتالي مع حاجة النبات.