Agricultural Sciences, 3(2), 49-57 (1998)

Porous-Tube Subsurface Irrigation

F.S. Mohammad

Department of Agricultural Engineering, College of Agriculture, King Saud University, Riyadh, Saudi Arabia

الري تحت السطحي بواسطة الأنابيب المسامية

الملخص : أجري هذا البحث لدراسة العوامل التي تؤدي إلى التوزيع المنتظم للماء تحت سطح التربة عند استخدام الأنابيب المسامية . تشمل هذه العوامل عمق الأنابيب و شدة الضغط المشغل لنظام الري و عمق طبقة الأرض غير النفاذة والغلاف الحصوي المحيط بالأنبوب . ولتحديد مدى تأثير هذه العوامل مختبريا أنشئ خزان وتم ملؤه بالرمل ووضع بداخله الأنابيب المسامية ، ويمثل الخزان والأنابيب وضعا مقطعا داخل التربة . و أوضحت النتائج أن عمق الطبقة غير النفاذة يؤثر تأثيرا واضحا في ارتفاع مستوى الماء . ولم يكن للغلاف الحصوي أي أفضلية على الأنابيب المسامية غير المغلفة . وقد دلت التجارب إلى أن هذه الأنابيب لا تعمل بكفاءة في حالة الضغط المنخفض (أقل من ٨٠ كيلو بسكال) أو المرتفع جدا (أكثر من ١٥٠ كيلو باسكال) .

ABSTRACT: This research was conducted to study the factors leading to the uniform distribution of water from a subsurface irrigation system using porous tubes. The factors included the depth at which the tubes are installed, operating pressure, depth of impermeable layer, and a gravel envelope surrounding the tubes. A laboratory soil tank was constructed to determine the effect of these factors. The tank was filled with sand and fitted with porous tubes. The tank and the tubes represent a section of soil profile. The results of this study showed that the depth of the impermeable layer affected significantly the water-table rise in the soil profile. The gravel envelope did not show any advantage over tubes without an envelope in sandy soils. A separate experiment was conducted to compare the characteristics of the flow from the porous tubes with the specifications given by the manufacturer. The results of the experiment showed that porous tubes do not work efficiently either under low pressure (below 80 kPa) or very high pressure (i.e. above 150 kPa).

The increasing demand for irrigation water should be met with more efficient methods of irrigation in order to take full advantage of the available water supplies. To achieve high efficiency of water application and optimum plant growth, an adequate amount of water must be supplied to the plant roots. Water applied directly to the root zone results not only in improved efficiency but also big savings of water. Subsurface irrigation techniques enable control and direct application of irrigation water to the root zone. This method has many advantages including decreased labor requirements, extended economic life of the system, reduced evapotranspiration (ET) losses from the soil surface, less soil compaction and no interference with farm practices. Phene *et al.* (1992) listed several characteristics of subsurface irrigation systems that can maximize water efficiency. They showed that hourly application of the subsurface trickle irrigation, even when applied at 25% less than the water requirements, results in less water stress than weekly furrow irrigation with full water requirements. Lamm *et al.* (1995) found that careful management of subsurface irrigation can reduce net irrigation needs by nearly 25%. Mohammad and Al Amoud (1994) and Boggle *et al.* (1989) compared subsurface irrigation techniques with the conventional method of irrigation and found an increased water-use efficiency with subsurface irrigation. However, the approach has not been used to its full potential because of the lack of established design criteria and methodical characterization of the operation of the system in the field. Some of the comparative factors which should be considered for the development of a subsurface irrigation system are given by Criddle and Kalisvaart (1967).

Subsurface irrigation is accomplished by controlling the level of the water-table either by ditches in humid areas or by applicators in arid areas. Applicators such as perforated pipes, discreet emitters or porous tubes can distribute water underground. The principal advantage of the subirrigation porous tubes is the uniform watering of a field. The walls of these tubes contain very fine pores so that the water emits slowly over their entire surface as compared to the rapid flow through the opening of conventional drip tubing. The spacing between the tubing and depth of placement should be designed to ensure that the plants receive adequate water, avoid differential growth patterns and minimize the cost of installation (Mason, 1984).

The subsurface irrigation system has been widely employed in humid areas utilizing existing drainage systems. In arid areas, subsurface irrigation has been developed mostly through trial and error. In USA locations exist where subsurface irrigation is practiced in semi-arid and arid regions, notably California, Idaho, Colorado, Utah and Wyoming (Criddle and Kalisvaart, 1967). Subsurface irrigation is usually limited to areas where the soil is permeable at a considerable depth, surface slopes are gentle, and natural subdrainage is restricted (Van Bakel, 1988).

Design of a subsurface irrigation system, requires information on the substrata conditions by test borings. Borings should be referenced to a common datum and the boring logs and samples analyzed to determine (i) the existence of any restricting layer and its topography, and (ii) the hydraulic conductivity of the various strata above the restricting layer (Skaggs, 1991). Successful subsurface irrigation needs a restricting layer in the soil profile upon which a perched or temporary water table can be developed beneath the normal root zone of the crops. The restricting layer may be clay, bedrock, or simply natural groundwater (Massey *et al.*, 1983). Most irrigation engineers locate the subirrigation tubes near the impermeable layer. However, they do not discuss the criteria for deciding the depth of the impermeable layer. This study was carried out to provide a basis for the design of a placement of porous tubes with respect to the impermeable layer. A sand tank was used to study the conditions of water movement in soil due to surface irrigation and/or drainage. Parameters of the analysis can include drain diameter, spacing of perforations, length of pipe segments, placement of gravel envelope, and impermeable-layer depth on water table rise and drawdown (Luthin and Haig, 1971).

Numerous studies have been carried out to investigate the water-table drawdown during drainage and the water-table rise during subirrigation. Todd (1959), Harr (1962), Donnan (1959), van Schilfgaarde *et al.* (1963) and Glover (1964) have introduced physical and mathematical theories related to water-table drawdown and rise. Most of these studies have considered water movement through open ditches or perforated pipes and require information about the depth of the impermeable layer. In general, these equations assume a-two-dimensional flow distribution between the drains or the subirrigation tubes. This approach is easy to apply and requires few soil property inputs. However, postulates have not been tested for subsurface irrigation with porous tubes. Hence an attempt was made to test the validity of the "step method" for predicting the water rise midpoint between tubes. This method is a modification of the Bouwer and van Schilfgaarde (1963) by Skaggs (1979). This paper reports the results of a laboratory study that was designed to : (1) study the water movement in the soil using porous tubes for subsurface irrigation; (2) study the effect of an impermeable layer underneath the porous tubing on water-table movement; (3) study the effect of a gravel envelope surrounding the tubes on the water movement during subirrigation; (4) study the effect of operating pressure head on flow through the porous tubes during subirrigation; (5) study the flow characteristics of the porous tubes and (6) evaluate the validity of one of the existing numerical methods (step method) for predicting the effect of subsurface irrigation on water-table movement in the soil profile.

Materials and Methods

Experiments were conducted in the laboratory. A soil tank having dimensions of 2.4 m x 1.2 m x 1.2 m was constructed of sheet steel. An outlet was provided at the bottom of the tank to serve as a drain. The tank was packed with sand in layers of 10 cm to minimize density differences in the tank. The results of the sand size determination are given in Table 1. The mean bulk density was 1.59 g/cm^3 and the soil was considered to be uniform. The soil tank represented a section of the soil profile and its floor acted as an impermeable layer. It was also large enough to incorporate heterogeneity. Three rows of porous tubes at a spacing of 0.6 m were installed across the tank at heights of 200, 400 and 600 mm above the bottom (Figure 1). Each row was used separately to model a different depth of the impermeable layer. Tubes were connected through a system of pipes to a constant-head water tank to provide a uniform supply of water under constant pressure. The inside diameter of porous tubes was 16 mm, outer diameter 22 mm, weight 160 g/m, minimum operating pressure 40 kPa and maximum operating pressure 200 kPa. Flow rates of 2 lt/hr/m were attained at working pressures of 60 to 80 kPa.

TABLE 1

Particle-size analysis of the sand used in this work

Screen No.	Size Range (mm)	Percent Retained
40	0.48-0.42	1.91
60	0.42-0.25	32.2
80	0.25-0.18	38.9
100	0.18-0.15	22.2
< 100	0.15-0.0	4.79

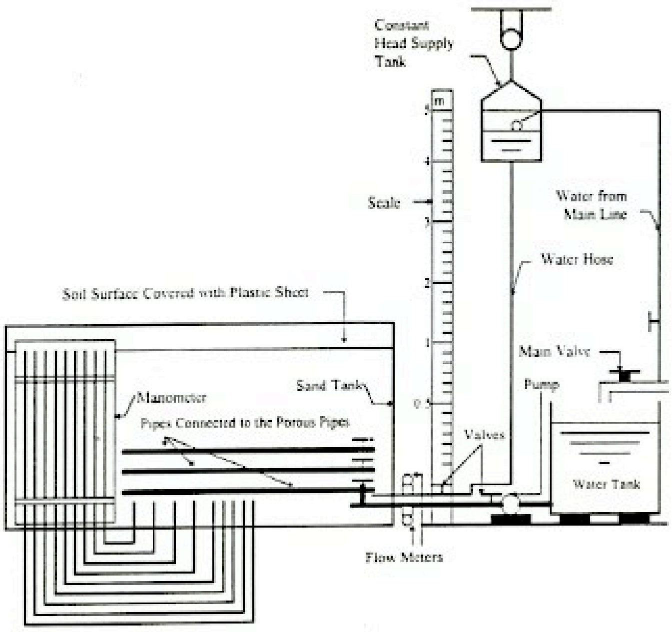

Figure 1. Schematic sketch of the main experimental setup.

Thirteen sets of piezometers were installed along the length of the sand tank at 50 mm spacing (Figure 1). The piezometers were connected to manometers to monitor the pressure head in the tank during subirrigation. Care was taken to eliminate air bubbles in the piezometer-manometer system. Before initiating the experiment, the sand tank was filled with water through the drainage outlet by pumping water from a water reservoir. It should be noted that there was no evidence of seepage along the sand tank interface in any of the experiments. The tank was drained and the process repeated twice to ensure settlement of the soil. Following the soil settlement process, the water-table was initially kept horizontal at three different elevations (200, 400 and 600 mm) and the subirrigation process was initiated by raising the water level in the constant head tank or by pumping water from a reservoir. The experiment was carried out both at low and high pressure heads. The low pressure ranged from 1 to 4.5 m head of water. A pump provided water at high pressures, i.e. from 100 to 185 kPa.

To quantify the effect of the impervious layer depth on the water flow from the porous tubes, the soil surface in the tank was covered with a transparent plastic sheet. This prevents evaporation from the soil surface and minimizes its effect on water rise in the soil profile. Under field conditions, the vertical losses due to evaporation or deep seepage are difficult to quantify. In such cases, the drawdown measurements are usually made during low evaporation periods.

In subirrigation experiments, the water-table was initially horizontal at a distance d above the impermeable layer. In the first experiment, the impermeable layer (i.e. bottom of the tank) was kept 200 mm below the porous tubes. The soil-water hydraulic head in the tank was measured through piezometers. The test begun when the water head at each piezometer was within ± 1 mm of the approximate equilibrium value. For the low pressure experiment, the pressure head was kept constant by maintaining the water level at a height of 4.5 m. The rate of water movement in soil was determined by the difference between the measured inflow rate and the rate of outflow from the constant head reservoir. The experiment was repeated for low (viz. 1 to 4.5 m) and high pressure heads (100, 150 and 185 kPa) at various depths of the impermeable layer (200, 400 and 600 mm). The rise of water-table was measured during the initial period (0-6 hr) of subirrigation when the water was applied through the porous tubes.

An investigation was also made to study the water movement in soil using the same type of porous tubes but being surrounded by a 40-mm-thick gravel envelope. Experiments were conducted with three operating pressures (100, 150 and 185 kPa), and with the depth of impermeable layer at 600 mm.

The basic soil properties required in a subsurface irrigation design are the saturated hydraulic conductivity and the drainable porosity. These are needed to predict the rise or drawdown of the water-table using modelling. The hydraulic conductivity is a measure of the soil ability to transmit water. The effective saturated hydraulic conductivity was determined by conducting steady-state tests with a constant-supply reservoir at one end and a narrowly perforated outlet at the other end of the tank. The water-table was raised almost to the surface of the reservoir and a small gradient was established between the reservoir and the perforated outlet. The hydraulic heads in the outlet were held constant and the flow rate measured. Then the hydraulic heads in both the supply reservoir and the outlet were lowered and the test repeated at three different water-table elevations. Hydraulic gradients were determined at two horizontal positions in the soil profile and the effective hydraulic conductivity determined from Darcy's equation as follows:

$$Q = -kA \frac{dh}{dx} \quad (1)$$

where, Q = volume rate of flow (m^3/hr)
K = hydraulic conductivity (m/hr)
A = soil profile area (m^2)
dh/dx = hydraulic gradient

The drainable porosity or specific yield is the volume of water per unit area that is released when the water-table falls by a unit distance in the absence of rainfall or evaporation. The drainable-porosity experiment was conducted using three cylindrical tanks (diameter 0.6 m, height 1.72 m) filled with the sand used in the major experiment. The water-table in the soil column was raised gradually to the surface. Then it was lowered by 0.3 m in each column and the volume of the water released was measured.

Another independent experiment was carried out to test the specifications of the porous tubes given by the manufacturer. The experimental setup consisted of a porous tube 10 m in length, a pump, a pressure regulator and a water supply tank (Figure 2). Water flowing at 2 m intervals from a 0.5 m section of the tube was obtained in collectors under different operating pressures and measured. In one exercise, the outlet of the tube was plugged to allow measurement of the flow rate only through the pores of the tubes at each section (2 m). In a second exercise, the flow measurements were carried out on the tube with its outlet unplugged.

The results of the major experiments were used to verify the theoretical solution given by Bouwer and van Schilfgaarde (1963) and modified by Skaggs (1979). This was mentioned above as the step method. The method assumes a constant drainable porosity throughout the soil profile and expresses the change in water-table elevation as:

$$\frac{dh}{dt} = -\frac{q}{n} \qquad (2)$$

$$\Delta v = -q\Delta t \qquad (3)$$

where h is the water-table height above the tube at midpoint, q is the subirrigation rate at the midpoint, n is the drainable porosity, and $\Delta v = n\,\Delta h$ is the depth of water rise in time Δt. The subirrigation rate q can be determined from Hooghout's solution as:

$$q = 4C\ k\ h\ (2d_e + h)/L^2 \qquad (4)$$

where k is the hydraulic conductivity, L is the distance between the tubes, d_e is the equivalent depth used to account for the radial flow caused by exit convergence near the tubes, and C is a correction factor representing the ratio between the subirrigation flux at the midpoint and the average subirrigation. Bouwer and van

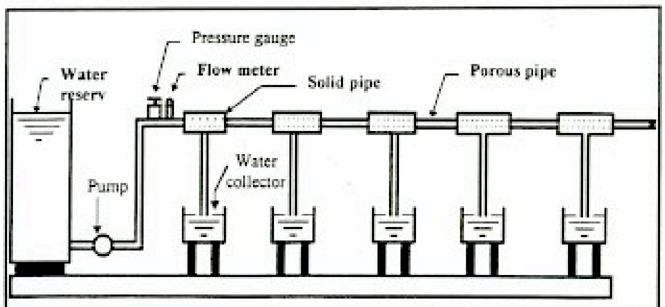

Figure 2. Experimental setup for testing the flow from the porous tubes.

Schilfgaarde (1963) used the reciprocal C as the correction factor and presented arguments for its determination in terms of the water-table height at the midpoint. However, most applications of the equation have used a constant value of C=1.

The equivalent depth to the impermeable layer, d_e, can be calculated from an equation presented by Moody (1966):

$$d_e = \frac{d}{1 + \frac{d}{L}\left[\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - 3.4\right]} \qquad (5)$$

where r is the radius of subirrigation tubes and d is the height of the irrigation tube above the impermeable layer. Equation 5 assumes an elliptical water-table and cannot be used for the initial stages of water rise or drawdown when the water-table is changing from horizontal to a curved shape. The time lag prior to rise of the water-table at the midpoint is determined from constant nondimensional parameters obtained from numerical solutions to the Boussinesqe equation (Skaggs, 1979):

$$t_i = 0.015\ \frac{n}{kh_0} \qquad (6)$$

The time required for a water-table rise of Δh from a midpoint elevation $h=h_1$ to $h=h_2$ may be computed from a mass balance at the midpoint as :

$$n\Delta h = \bar{q}\Delta t + s\Delta t \qquad (7)$$

where s is the evapotranspiration (ET) and/or the deep seepage rate, and q is the average flow for a midpoint water-table rise of Δh. This average flux may be determined using the following equation:

$$\bar{q} = \frac{2kC[h_1(2d_e + h_1) + h_2(2d_e + h_2)]}{L^2} \qquad (8)$$

The time required for the water-table drawdown from h_1 to h_2 at the midpoint can be approximated using equation 8. Then Δt can be computed from equation 7 for each incremental rise of the water-table elevation.

Results and Discussions

The mean effective hydraulic conductivity determined from steady-state experiments through the soil profile was 73 cm/hr. Contributions from the unsaturated zone above the water table were considered in the calculation of hydraulic conductivity by determining the effective thickness of the capillary fringe (Bouwer, 1978). The unsaturated zone was 4 cm/hr, a result which influenced significantly measurements of the effective hydraulic conductivity. This is because the rate of water transmission is a function of the unsaturated hydraulic conductivity which, in turn, is dependent on the distribution of pore sizes.

The average drainable porosity determined from the soil columns was 0.35. This value was obtained from the relationship established between the drainage volume and the water-table depths. However, this value is far from constant since it depends on the proximity of the water-table to the soil surface and on the rate and direction of the water-table movement.

Table 2 reproduces the rise in the water elevation from the porous tubes (i.e. $x=0$) and a point midway between the subirrigation tubes ($x=300$ mm) under different operating pressures and depths of the impermeable layer. Clearly, the rise of water over the tube is higher than that at the midpoint. This is the result of the rapid rise of the water-table near the tubes during the inital stages of irrigation. The difference in elevation increases with the depth of the impermeable layer. Thus it changes after 6 hr of irrigation from 22 mm for an impermeable layer 200 mm deep to 61 and 144 mm for an impermeable layer 400 and 600 mm deep (operating pressure of 150 kPa in Table 2). Similar results were noticed at the operating pressure of 185 kPa, where the difference increases from 38 mm for an impermeable layer 200 mm deep to 139 mm for an impermeable layer 600 mm deep. Therefore, it is concluded that the water-table elevation is quite high when the depth of the impermeable layer is 600 mm as compared with elevations at layers 200 and 400 mm deep. The difference is minor between layer depths of 200 and 400 mm. Differences could be due to the radial and exit losses combined with lateral flow at the porous openings of the irrigation tubes. This effect is less pronounced for the 200 and 400 mm impermeable-layer depths.

At low pressure (45 kPa), the water-table elevation in the soil profile is relatively flat. Differences between the water elevation directly over the tubes and a point midway between them after 25 days of continuous irrigation are minor, which means that the effect of the impermeable layer is minimal. Differences are 30 mm in the case of 200 mm depth, 41 mm at 400 mm depth, and 32 mm at 600 mm depth (Table 2 Part C). This result argues that water level in the soil between the tubes rises almost simultaneously at all points after long periods of irrigation at low pressure. Further, the rate of water movement in the horizontal direction at low pressures is higher than that at high pressure. Thus the process of irrigation under low operating pressures is slow and will take a long time to complete. In this process, the driving force is the soil-water potential difference in the pores of saturated and unsaturated soil. This is ineffective in the vertical direction since the pores of the sand particles are large. Water movement in the soil profile takes place primarily in the horizontal direction than in the vertical.

The difference in the water-table elevation between the subirrigation tubes and the point midway between the tubes is important because it results in uneven distribution of irrigation water. In general, the amount of water necessary for the root zone depends on the elevation of the water-table midway between the subirrigation tubes. If the depth and spacing of the tubes are not properly chosen, the water depth at this critical location will not be adequate and severe soil water defficiencies will occur.

In Figure 3, the water-table elevation at the point midway between the subirrigation tubes is plotted as a function of pressure ranging from 45 to 185 kPa for the three depths of impermeable layer. It is seen that the water-table elevation increases with time under all pressures. The influence of the impermeable layer at 45 kPa is observed in Figure 3a, which shows that elevation was minimum under low operating pressure. The water-table elevation after 400 hr of irrigation was 45, 264 and 536 mm for the impermeable layers with a depth of 200, 400 and 600 mm, respectively. At this pressure, water starts to rise at the midpoint after 100 hr of irrigation for an impermeable layer 200 mm deep. This implies that no water rises and no irrigation takes place for a long time of water application for the impermeable layers 400 and 600 mm deep. Thus, increasing the impermeable layer depth from 200 to 400 mm would have a significant influence on water rise in the soil profile.

In Figure 3b is also noted that the water rise is highly restricted in a soil profile with a shallow impermeable layer even under high pressure. After 3 hours of irrigation, the water rise under a pressure of 150 kPa is 17, 22 and 280 mm for the impermeable layer depths of 200, 400 and 600 mm, respectively. Application of 185 kPa for 3 hours yields a water

TABLE 2

Best fit of the water-table elevation (mm) during subirrigation using different conditions of pressure and impermeable-layer depth

A

Time	P=150 kPa D=200 mm			P=150 kPa D=400 mm			P=150 kPa D=600 mm		
(Hr)	at tube R^2=0.97	midway R^2=0.99	diff (mm)	at tube R^2=0.99	midway R^2=0.92	diff (mm)	at tube R^2=0.97	midway R^2=0.96	diff (mm)
0	200	200	0	400	400	0	600	600	0
1	209	206	3	417	407	10	716	692	24
2	219	211	8	435	414	21	832	784	48
3	228	217	11	452	422	30	948	876	72
4	237	222	15	470	429	41	1064	968	96
5	246	228	18	487	436	51	1180	1060	120
6	256	234	22	504	443	61	1296	1152	144

B

Time	P=185 kPa D=200 mm			P=185 kPa D=400 mm			P=185 kPa D=600 mm		
(Hr)	at tube R^2=0.94	midway R^2=0.95	diff (mm)	at tube R^2=0.97	midway R^2=0.99	diff (mm)	at tube R^2=0.99	midway R^2=0.99	diff (mm)
0	200	200	0	400	400	0	600	600	0
1	215	208	7	437	429	8	764	741	23
2	229	216	13	473	458	15	929	882	47
3	244	224	20	509	487	22	1093	1023	70
4	258	233	25	544	516	28	1258	1164	94
5	273	241	32	578	546	32	1422	1306	116
6	287	249	38	616	575	41	1586	1447	139

C

Time	P=45 kPa D=200 mm			P=45 kPa D=400 mm			P=45 kPa D=600 mm		
(Hr)	at tube R^2=0.97	midway R^2=0.97	diff (mm)	at tube R^2=0.94	midway R^2=0.94	diff (mm)	at tube R^2=0.89	midway R^2=0.88	diff (mm)
0	200	200	0	400	400	0	600	600	0
100	215	210	5	583	576	7	676	671	5
200	231	220	11	765	751	15	753	742	13
300	246	231	15	948	927	21	829	813	16
400	261	241	20	1130	1103	27	905	884	21
500	276	251	25	1313	1279	34	982	955	27
600	291	261	30	1495	1454	41	1058	1026	32

D

Time	P=100 kPa D=600 mm			P=150 kPa D=600 mm			P=185 kPa D=600 mm		
(Hr)	at tube R^2=0.98	midway R^2=0.98	diff (mm)	at tube R^2=0.96	midway R^2=0.90	diff (mm)	at tube R^2=0.97	midway R^2=0.92	diff (mm)
0	600	600	0	600	600	0	600	600	0
1	610	603	7	625	614	11	680	666	14
2	619	606	13	650	628	22	761	731	30
3	629	609	20	674	643	31	841	797	44
4	638	612	26	699	657	42	921	863	53
5	648	616	32	724	671	53	1002	929	73
6	658	619	39	749	685	64	1082	994	88

R^2 = coefficient correlation, P = operating pressure, D = depth of impermeable layer, diff. = water level difference, at tube = water level above subirrigation tube, midway = water level midway between the tubes

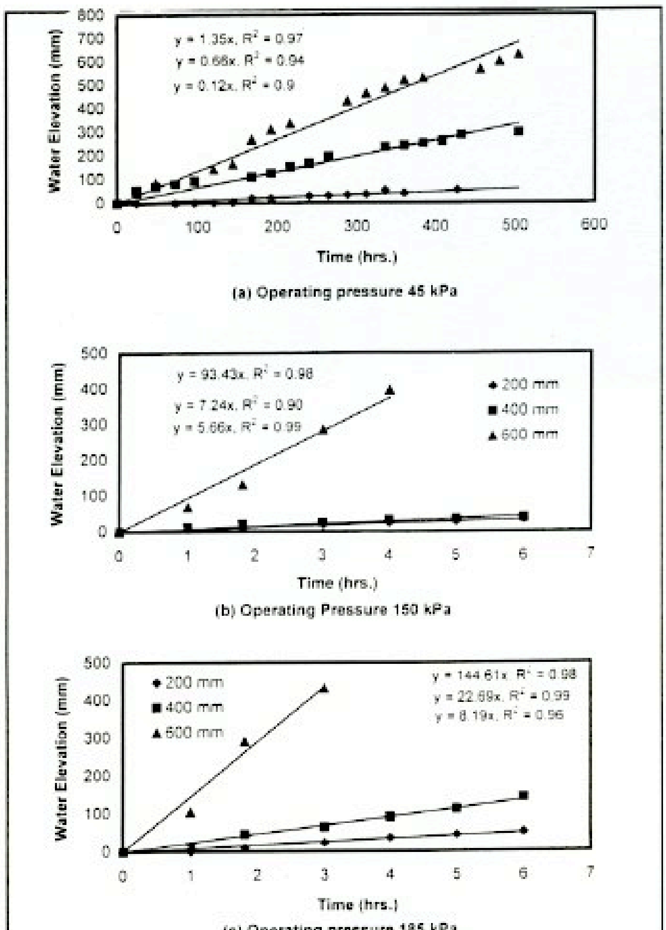

Figure 3. Water-table response to subirrigation midway between porous tubes in relation to operating pressure and depth of impermeable layer.

elevation of 25, 68 and 432 mm for the impermeable-layer depths of 200, 400 and 600 mm (Figure 3c). Under high pressures the governing force is mainly the pressure head. This head causes water to be transmitted in the upward direction more rapidly than the horizontal direction. In this case, the soil-water potential difference in the pores of saturated and unsaturated soil is not effective. To visualize the effect of the impermeable layer on water rise, a schematic diagram is presented in Figure 4 for the pressure of 185 kPa.

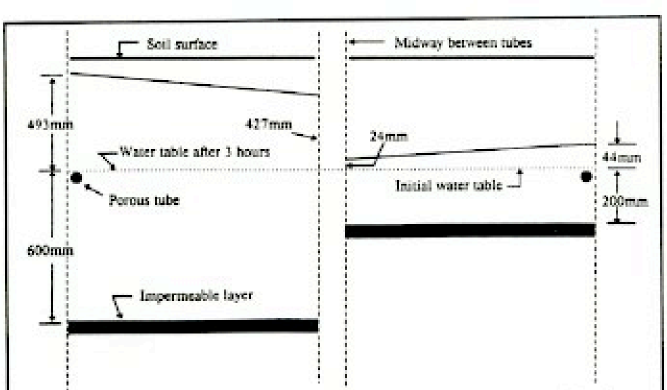

Figure 4. Sketch of the effect of the impermeable-layer depth on water rise for two soil profiles.

Two identical symmetric sections of the soil profile extend from the center of the porous tubes to the point midway between the tubes for the impermeable layer depths of 200 and 600 mm. The Figure also shows the initial and final water-table levels after the application of pressure (185 kPa) for three hr. Variations in the water-table rise could be due to the high exit velocity of flow from the pores of tubes which causes energy losses. The radial flow from the pores causes a disproportional loss of hydraulic head in the case of shallow depth, as compared to a deeper impermeable layer.

The water-rise directly over the tubes and midway between the tubes in the presence of a gravel envelope is presented on Table 2, part D. The water-rise at the tube operating under pressure of 100, 150 and 185 kPa was 638, 699 and 921 mm after 4 hours of irrigation (impermeable depth of 600 mm). Water-rise at the operating pressure of 150 kPa and impermeable layer of 600 mm decreased from 968 to 657 mm for tubes without a gravel envelope as compared with tubes with gravel envelopes (4 hours of irrigation). At 185 kPa, the water-table rise decreased from 1164 to 863 mm after 4 hours of subirrigation. Thus, the gravel envelope is not an effective measure to increase the water-table rise midway between the tubes under high pressure conditions. These results are in contrast to

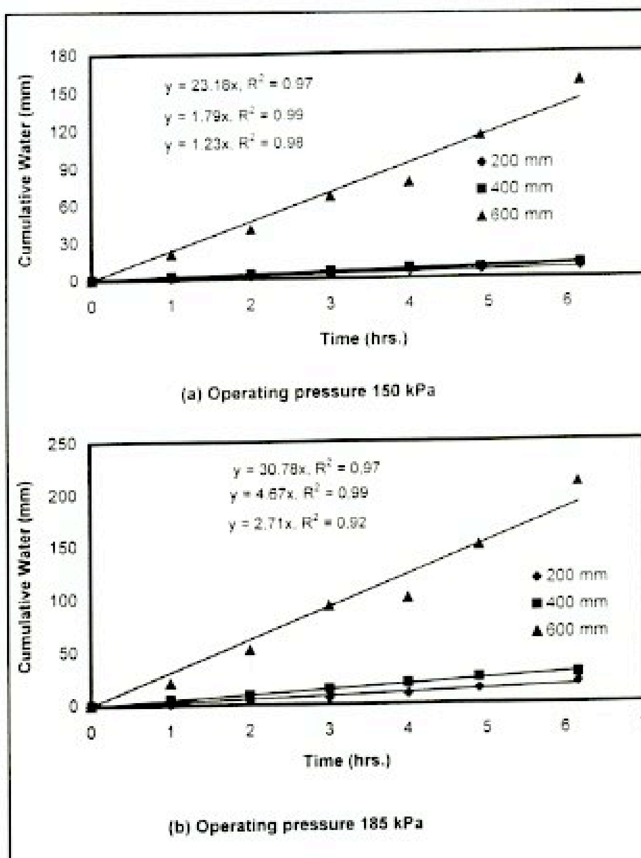

Figure 5. Cumulative irrigation of water for 6 hr in relation to operating pressure and impermeable-layer depth.

those reported by Mohammad and Skaggs (1984) where the gravel envelope had a significant effect on the rate of water-rise during subirrigation. Therefore, it can be concluded that the improved flow conditions provided by tubes with gravel envelopes are met by tubes without an envelope in sandy soils.

The cumulative water depth versus time is plotted in Figure 5 for application pressures of 150 and 185 kPa. After 6 hrs, the cumulative water reaches the value of 7.5 mm under a pressure of 150 kPa and an impermeable layer 200 mm deep, while it is around 11 and 144 mm for impermeable layers 400 and 600 mm deep. At 185 kPa, the cumulative water increases to 16, 28 and 191 mm for impermeable layers 200, 400 and 600 mm deep, respectively. Hence, it is obvious that the water profile requires longer times to develop in the case of shallow depths (200, 400 mm) as compared to the deep impermeable layer (600 mm). This could be due to the turbulent flow taking place near the porous tubes of the former. Data in Figure 5 were fit using simple linear regression and results are listed on Table 2.

The results of these experiments will not directly apply to field situations. This is because there is an emphasis on the differences occurring between porous tubes at various impermeable-layer depths. However, findings can be used to test theorethical methods which describe the effects of tube pores on transient subsurface irrigation processes. Postulates can then be applied directly to field situations.

The water-table rise midway between tubes determined from the Bouwer and van Shilfgaarde equation was plotted along with the measured water-table rise in Figure 6. Experimental results were in good agreement with the predictions of the equation during the initial period of irrigation for all impermeable layer depths under 150 kPa operating pressure. At longer times, the water-table rise deviated from the predicted values which overshot due to the assumption that the water rise attains equilibrium after the subirrigation process is ceased. The theoretical method

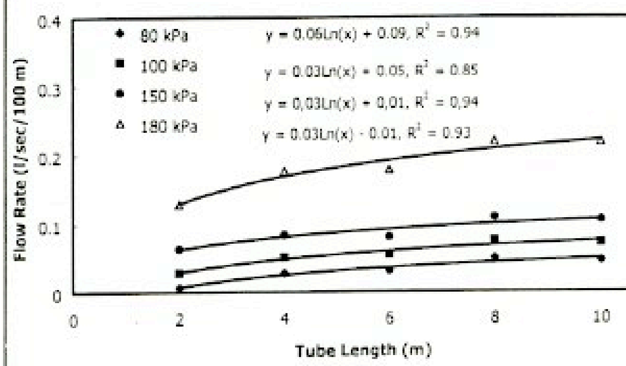

Figure 7. Measured and predicted water-table rise during subirrigation characterized by an impermeable layer 200 mm deep and an operating pressure of 150 kPa.

also assumes a constant drainable porosity in the soil profile. This is not a valid assumption since the drainable porosity is a function of soil depth. In addition, the equation was developed for tubes with circular perforations or slots, which behave differently from pores. The equation is further compromised by assuming that the stream lines at small inclinations of the free-water surface are horizontal and the velocities associated with them are proportional to the slope of the free surface. Definitely, this does not hold for regions close to the tubes since stream lines are horizontal only over short distances between tubes. Agreement between experiment and the predictions of the Bouwer and van Shilfgaarde equation can be improved by considering variable drainable porosity, the characteristics of the pores of the tube, and the conditions of the operating pressure.

Tests on the characteristics of the porous tubes were performed. Figure 7 shows the flow at different sections of the tube. The flow rate is almost uniformly distributed along the tube under different operating pressures. This is due to the pressure build-up in the tube resulting from plugging its end. The flow rate from the porous tubes increased from 120 to 326 lt/hr/100 m with increasing the operating pressure

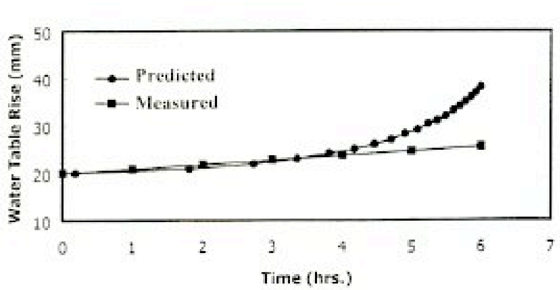

Figure 6. Flow rate from the tube-pores as a function of distance along the tubes under different operating pressures.

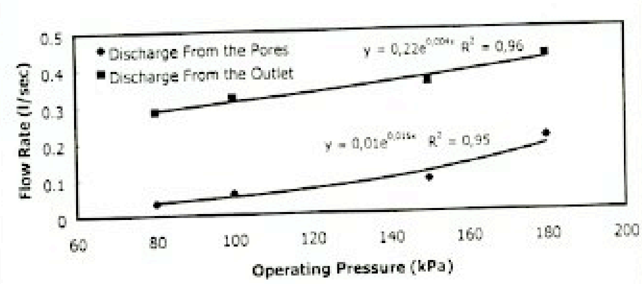

Figure 8. The effect of operating pressure on flow rates from the pores and the outlet of the tube.

TABLE 3

Discharge rates from the pores of the tubes

Pressure kPa	Discharge from the pores l/hr/100m	Discharge from the pores l/s/100m	Discharge from outlet l/s	Discharge ratio
80	114.8	0.032	0.284	8.9
100	201.2	0.056	0.319	5.7
150	316.4	0.088	0.357	4.1
180	661	0.184	0.425	2.3

from 80 to 150 kPa while it changed to 728 lt/hr/100 m when the operating pressure increased further by 30 kPa. Flow characteristics of porous tubes are entirely different from those through tube openings, slots or orifices. The flow through the outlet of the porous tubes and the pores under different operating pressures is shown on Table 3. The outlet flow is raised from 0.28 to 0.42 lt/s with increasing pressure from 80 to 180 kPa, whereas the flow from the pores increases from 0.03 to 0.18 lt/s under the same conditions (Figure 8). Thus when the pressure is increased by 100 kPa, the outlet flow is increased by 50% while the flow through pores increases at least ten times as much. The huge increase in the flow rate from the pores could be due to the enlargement of pores, which reduces their ability to control the water emission. Porous tubes behave differently when they are embedded in soil. In this case, the physical properties of the soil and the operating pressure will be the dominant factors controlling the water flow from the tubes. In general, the specifications given by the manufacturer were in agreement with the results obtained in the present study.

Conclusions

Results given in this paper show that the impermeable layer has a large effect on the transient state of subirrigation. Both the subirrigation flow rate and the water-table rise with an increase in the impermeable-layer depth. A gravel envelope has no advantage over tubes in sandy soils without an envelope. The Bouwer and van Schilfgaarde equation does not predict reliably the water rise in subirrigation with porous tubes.

References

Boggle, C.R., T.K. Hartz. and C. Nunez. 1989. Comparison of subsurface trickle and furrow irrigation on plastic mulched and bare soil for tomato production. *J. Am. Soc. Hort. Sci.* 14:40-43.

Bouwer, H. 1978. Groundwater hydrology. In: *Water Resources and Environment Engineering*. p. 241-242.

Bouer, H. and J. van Schilfgaarde, 1963. Simplified method of predicting fall of water-table in drained land. *Transactions of the ASAE*. 6:288-296.

Criddle, W.D. and C. Kalisvaart. 1967. Subirrigation systems. In: *Irrigation of Agricultural Lands*. Hagan, R.M., H.R. Haise and T. W. Edminster (Eds.). ASA Monograph No. 11, *Am. Soc. Agro.* Madison, WI. U.S.A. 905-921.

Donnan, W.W. 1959. Drainage of agricultural lands using interceptor lines. *ASCE Proc. of Irrigation and Drainage Division*. (IRI). 13-23.

Glover, R.E. 1964. Groundwater movement. US Bureau of Reclamation Eng. Monograph 31. p. 315.

Harr, M.E. 1962. Groundwater and seepage. McGraw-Hill. New York 315.

Lamm, F.R., H.L. Mangoes, L.R. Stone, A.H. Khan, D.H. Rogers. 1995. Water requirements of subsurface drip irrigated corn in North-West Kansas, *Transactions of ASAE*. 38:441-448.

Luthin, J.N. and A. Haig. 1972. Some factors affecting the flow into drain pipes. Hilgardia. 41:235-245.

Mason, J.W. 1984. Automatic subsurface irrigation. In: Drilling and Irrigation International. Article directed from the next generation in automatic irrigation systems. International irrigation Exposition and Conference, Kansas City, MO. Oct. 21-25. 31-33.

Massey, F.C., R.W. Skaggs and R.E. Sneed. 1983. Energy and Water Requirements of Subirrigation Versus Sprinkler Irrigation. *Transactions of the ASAE*. 26:126-133.

Mohammad, F.S. and A.I. Al-Amoud. 1994. Response of tomato crops to subirrigation with porous tubes in greenhouses. *Al-Azhar J. Agric. Res.* 19:153-167.

Mohammad F.S. and R.W. Skaggs. 1984. Effect of drain tube opening on drainage and subirrigation. *Transaction of the ASAE*. 27:14-62.

Moody, W.T. 1966. Nonlinear differential equation of drain spacing. *J. Irr. and Drain Div.* ASCE 92. 1-9.

Phene, C.J. , R.B.B. Hutmacher. J.E. Ayers, K.R. Davis, R.M. Mead and R. A. Schoneman. 1992. Maximizing water use efficiency with subsurface drip irrigation. *Transactions of the ASAE*. 92-2090. St. Joseph, Michigan, U.S.A.

Phene, C.J., R.A. Radulovich, J.L. Rose and M.F. Blume. 1982. The effect of high frequency trickle irrigation on water stress of tomatoes. *Transactions of the ASAE*. 82-2521. p. 21.

Skaggs, R.W. 1979. Factors affecting hydraulic conductivity determinations from drawdown measurements. ASAE 79-2075. Paper presented at the 19 summer meeting Univ. of Manitoba, Winnipeg, Canada. P. 22

Skaggs, R.W. 1991. Modeling water-table response to subirrigation and drainage. *Transactions of the ASAE*. 28:815-818.

Todd, D.K. 1959. Groundwater Hydrology. John Wiley, New York. P 336.

Van Bakel, P.J.T. 1988. Using drainage systems for supplementary irrigation. In: *Irrigation and Drainage Systems*. 2:125-137. Kluwer Academic Publisher, Netherlands.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling watertables. *J. Irr. And Drain. Div.* ASCE 89:1-11.