ISSN 1023-1072

Pak. J. Agri., Agril. Engg., Vet. Sci., 2011, 27 (1): 39-50

CROP PRODUCTION AND WATER USE EFFICIENCY UNDER SUBSURFACE POROUS CLAY PIPE IRRIGATION

A. A. Siyal[1], A. G. Siyal[2] and M. Y. Hasini[3]

[1]Department of LWM, Sindh Agriculture University, Tandojam, Pakistan
[2]Department of I & D, Sindh Agriculture University, Tandojam, Pakistan
[3]Pakistan Agricultural Research Council, Islamabad, Pakistan

ABSTRACT

Subsurface irrigation is considered well suited for arid regions due to minimal surface evaporative and deep percolation water losses because with this method required amount of water is directly applied to the root zone. However, people are reluctant to adopt subsurface drip and leaky pipe irrigation methods as they are not only expensive but are also difficult to install, operate and maintain. Therefore, there is a dire need to introduce and practice traditional irrigation methods in water scarce regions with arid climate. One of these methods is porous clay pipe irrigation method. To assess viability of the porous clay pipe irrigation as a water conservation technique under arid climate, an experimental study was conducted on an area of about 500 m^2 of a sandy loam at Sindh Agriculture University, Tandojam, Pakistan. Clay pipe segments, each of length 40 cm, were joined together and then buried in 25 trenches (laterals), each of 20 m length and 0.43 m depth. Water was supplied from an overhead tank to all the laterals via main line. When soil above laterals became visibly wet, soil moisture distribution within root zone was determined and simulated with HYDRUS-2D. Okra, Eggplant and turnip were then sown separately on moist soil above laterals. These vegetables were irrigated until harvest through buried clay pipe laterals. The experimental results revealed that with this method water savings up to 80% were achieved compared to that of surface irrigation methods. Also yield of vegetables irrigated with this system was 5 to 16% more than the normal production obtained with surface irrigation methods.

Keywords: Clay pipe, irrigation, hydrus-2D, moisture, root zone, subsurface

INTRODUCTION

Water resources play a vital role in global crop production and thus ensure food security for feeding the increasing world population. Presently, about 70% of the fresh water resources in Pakistan are being used for the agricultural production while the rest for drinking, municipal, industrial and other uses. Despite the facts that Pakistan has the largest irrigation network in the world, yet about 20–34% of

Corresponding author: siyal@yahoo.com

its population is still suffering from malnutrition (FAO, 1998). Major causes of lack of food and fiber are water shortages due to limited water availability in the system and inefficient use of the available water for agriculture (Laghari *et al.* 2008). Thus, increasing demand for food and fiber production calls for the new areas to be brought under cultivation for more crop production. For which supply of fresh water needs to be increased either by reducing seepage from canals, distributaries and watercourses (conveyance losses) or by reducing farm water losses by practicing water use efficient irrigation techniques such as sprinkler, bubbler, drip etc. It is estimated that out of total 80 percent water losses, about 20% are farm water losses because of deep percolation and surface evaporation due to practice of traditional surface irrigation methods (Siyal, 2008) . Hence there is dire need to develop and introduce simple, economical and easily installed and maintained water saving technologies for the arid and semi-arid regions.

Subsurface irrigation is said to be most efficient irrigation method in which small volume of water is supplied from below the soil surface to crop resulting in reduction of evaporative and deep percolation water losses at the farm level. It has been practiced in various forms such as pitcher or pot irrigation since ancient times (Bainbridge, 2001 and Siyal *et al.* 2009) and perforated or porous clay pipe irrigation (Ashrafi *et al.,* 2002 and Qiaosheng *et al.,* 2007). The development of plastic micro-irrigation technology in the last century led to increased use of subsurface irrigation. Today, subsurface drip irrigation is being used throughout the world to irrigate field crops, vegetables, and orchards. However, installation and maintenance of subsurface plastic drip tubing and emitters are expensive and require skilled labor for continuous monitoring and maintenance. Also plastic drip tubing and emitters sometimes clog when used in clay soil or if muddy water is used. Therefore, there is great need to practice water use efficient, simple and low cost traditional irrigation methods, such as pitcher and clay pipe for irrigation and water conservation in arid areas of Pakistan.

The porous clay pipe is an improved version of the traditional method of subsurface irrigation in which both conveyance and seepage of the water is done instantaneously by the same pipe. Due to negligible percolation and evaporative losses, this method of irrigation has been practised successfully in many arid and semi-arid regions of the world. Results from a series of experiment conducted by Batchelor *et al.* (1996) in Zimbabwe have shown that subsurface irrigation using clay pipes can improve both water-use efficiency and crop quality. But the viability of the porous clay pipe irrigation as a water conservation technique under arid regions of Pakistan needs to be assessed before its adoption on large scale. Considering the need for viability of locally made subsurface irrigation under arid climate of Pakistan, the present study was conducted.

MATERIALS AND METHODS

A sub-surface irrigation experiment using baked clay pipes was carried out at the experimental field of the Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam, Pakistan. The site is located at latitude 25^{o} 25’ 28” N, and longitude 68° 32' 25" E and is at an elevation of about 26 m above the mean sea level (MSL).

Installation of subsurface irrigation system

Trenches 20 m long and 0.43 m deep were excavated for burying clay pipes. Clay pipes with approximately 10 cm diameter and 40 cm length were prepared by local potters using clay soil and then baked in a kiln. The pipe wall thicknesses and outside diameters were measured with a Vernier Calliper and found to be 1.5± 0.110 cm and 13.1 ± 0.20 cm, respectively. So that the pipes could be joined, one end of the pipes tapered to a 15 cm diameter. Pipes for the terminal end of the laterals were made with a closed end, whereas pipes for the beginning of the laterals were tapered to a 6.2± 0.120 cm outside diameter on one end so that they could be connected to the steel main line using rubber pipe and hose clamps. The porosity of the pipes was determined to be 0.35±0.010 based on the difference in weights of dry and saturated pipes. Longer pipe segments were produced by cementing together four pipes. These segments were then placed in the trench and cemented together to form 20 m long pipes (Fig.1). These pipes were buried at a depth of 30 cm (measured to the top of the pipe) with soil that was removed during excavation. Water was fed to the clay pipe system from an aboveground water storage tank. A water meter and pressure gauge were installed at the beginning of the irrigation laterals, as were valves for modifying water flow and pressure. In total, 25 clay pipe lateral lines were installed at spacing of 1 m.

Figure 1. Baked clay pipes and their installation at the experimental field.

Soil sampling and soil water content distribution profiles

Water was supplied continuously to one of the laterals for five days at a hydraulic head of 100 cm. The soil around the lateral was initially dry. At the end of the five days, soil samples were taken from the depths 0, 15, 30, 45, 60, 75 and 90 cm, at distances 15, 30 and 45 cm on both sides of the pipe. The gravimetric water contents of the samples were determined by recording the weight loss of the samples after oven drying at 105 ^{0}C for 24 hours. Due to the presumed symmetry of the wetted zone, the two water contents for the same depths and distances on opposite sides of the pipe were averaged for data analysis. Wetting pattern after five days of irrigation with hydraulic head of 100 cm was subsequently obtained.

The hydrometer method was used to determine the soil particle size distribution. The texture of soil according to the USDA system was found to be loam, with the sand content ranging from 40 to 46%, silt from 30 to 45%, and clay from 15 to 24%. Soil bulk density was determined at several locations down to 90 cm depth using a core sampler with 1.5 cm diameter. The density measurements ranged from 1.25 to 1.30 g cm^{-3}. No obvious trend in the bulk density was observed, so the average value of 1.27 g cm^{-3} was used to convert the gravimetric water content data to volumetric water content.

Sowing of crop

To evaluate the performance of the subsurface clay pipe irrigation system in terms of irrigation efficiency under arid climate, three vegetable crops i.e. turnip, okra and eggplant were grown. The volume of water consumed for growing each crop was measured separately with water-meter. Before sowing, water was applied continuously to all the laterals for three days as a soaking doze. When soil surface above the laterals became visibly moist, Eggplant, okra and turnip was sown. These were drilled in rows separately at a depth of 2 cm above clay pipe laterals using hand drill.

Water application

Water was supplied continuously to clay pipe laterals via mainline from overhead tank at a pressure head of 100 cm until final harvest of the crop. The water seeped continuously out of the porous clay pipe laterals and maintained the water content of soil adjacent to pipe at field capacity. The total crop durations for turnip, okra and eggplant were 60, 90 and 160 days respectively. The volume of water delivered to each crop during entire growth period was measured separately with water-meters installed at all laterals.

Fertigation

The required volume of liquid fertilizer was injected in the main line from fertilizer tank. The fertilizer concentration in irrigation water was maintained by opening water and fertigation tank valves at a required level. Fertilizer concentration in water after injection of liquid fertilizer was calculated using following relation:

$$C_r = C_1 \times a + C_2 \times b \qquad (1)$$

where

C_r = Required fertilizer concentration in irrigation water (after mixing of fertilizer)
C_1 = Concentration of nitrogen already in water (before mixing)
a = proportion of water
C_2 = Concentration of liquid fertilizer in fertigation tank.
b = proportion of liquid fertilizer

Weeding

Weeds from the vegetable crops were removed manually with hand hoe whenever necessary so as to avoid any loss of water or nutrient due to weed uptake.

Harvesting

After nearly nine weeks to the drilling of seed, the turnip crop was ready to harvest. The harvested production was weighed and recorded. The first okra picking started after 7 weeks of sowing. The picking process continued twice a week throughout the crop period (90 days). Okra yield thus obtained was weighed and recorded. Similarly picking started for eggplants after 14 weeks of sowing, and continued once after every 5 days. The production was weighed recorded each time.

Soil water content simulation with HYDRUS-2D

Prediction for the dimensions of the wetting zone is important, both to ensure efficient irrigation and to avoid the seepage of precious irrigation water beyond the root zone. The HYDRUS-2D software package (Šimůnek *et al.*, 1999) is used to simulate variably saturated water flow in porous media by solving the mixed form of the Richard's equation (Celia *et al.*, 1990) using a Galerkin finite-element method. Thus, HYDRUS-2D was used to simulate water infiltration and redistribution from a subsurface porous clay pipe source. The soil hydraulic properties in HYDRUS-2D are based on the van Genuchten model (van Genuchten, 1980)

$$\theta(h) = \begin{cases} \theta_r + \dfrac{-\theta_r}{\left(1+|\alpha h|^n\right)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{2}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{3}$$

where θ_r and θ_s are the residual water content and the water content at saturation (L^3 L^{-3}), respectively; K_s is the saturated hydraulic conductivity (L T^{-1}); α is an empirical constant that is inversely related to the air-entry pressure value (L^{-1}); *n* is an empirical parameter related to the pore-size distribution (unitless); ℓ is an empirical shape parameter; m = 1–1/n (unitless); and S_e is the effective saturation given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \qquad (4)$$

Only the right side of the vertical cross section was simulated, with the clay pipe located on the left side (Fig. 2). The pipe wall was included in the flow domain, which is represented by a half circular wall with a thickness of 1.5 cm. Similar approach was also adopted by Ashrafi *et al.* (2002). The flow domain was discretized with 1333 nodes and 2553 triangular elements, using smaller spacing within the pipe wall and in the soil near the pipe. The finite element mesh was generated using the automatic triangulation algorithm that is implemented in HYDRUS-2D.

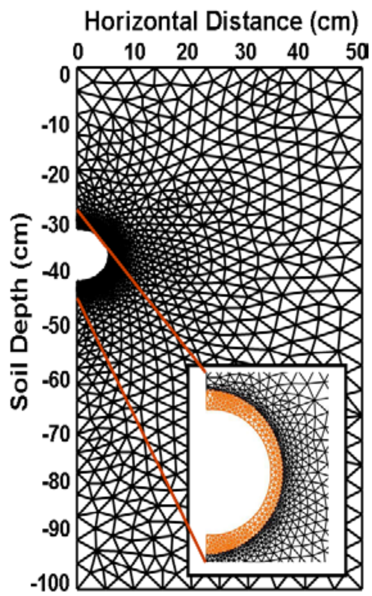

Figure 2. Typical geometry and finite element mesh used in the HYDRUS-2D simulations

Hydraulic parameters (θ_r, θ_s, α, n and ℓ) for nodes representing soil material were determined with the Rosetta pedotransfer function model (Schaap *et al.*, 2001) that is implemented in HYDRUS-2D using data of the bulk density and percentages of sand, silt and clay (Table 1). The saturate hydraulic conductivity of clay pipes was determined by adopting approach of Abu-Zreig and Atoum (2004). The hydraulic parameters for the clay pipe are also given in Table 1. The small value of α was chosen so that the pipe wall would remain saturated throughout the simulations, and thus the assumed unsaturated parameter (θ_r, θ_s, n and ℓ) values for the pipe wall material were of no consequence.

The pipe internal boundary nodes were allocated a constant pressure head equal to the pressure head imposed in the experimental trial (100 cm). The remaining portion of the left boundary was set as a zero flux condition (due to the symmetry of the profile). The surface was specified as an "atmospheric boundary condition". The bottom boundary was specified as a free drainage condition while the right boundary was a zero flux condition. The computational domain was made sufficiently large such that these right hand and bottom boundaries did not affect water flow (50 cm x 100 cm).

The initial soil profile water content was specified based on the measured water content of soil samples taken when the clay pipes were buried. These water content measurements were converted to pressure head values using the soil water retention characteristic given by equation (2) with the loam soil parameter values given in Table 1. Consistent with these observed values, the initial conditions were specified such that the pressure head increased linearly with depth in the profile, from -3000 cm at the top (z = 0) to -2000 cm at the bottom (z = -100 cm). The initial profile was assumed uniform in the horizontal direction. The clay pipe wall was assumed to be initially saturated (Ashrafi *et al*., 2002).

Table 1. Hydraulic parameters estimated with Rosetta pedotransfer function model.

Material	θ_r $cm^{-3}\,cm^3$	θ_s $cm^{-3}\,cm^3$	α cm^{-1}	n	K_s $cm\,d^{-1}$	ℓ
Loam soil	0.078	0.43	0.036	1.56	24.96	0.5
Clay pipe	0.042	0.35	0.000001	1.30	0.05	0.5

RESULTS AND DISCUSSION

Comparison of measured and simulated soil wetting pattern

Fig. 3 shows measured and simulated water content profiles for subsurface clay pipe irrigation with line pressure head of 100 cm, after five days of irrigation. Figure shows measured and predicted water contents along selected profile transects, as well as contour plots of the observed and simulated water content profiles. The contour plots were drawn using a kriging interpolation algorithm. The contour plot given in Fig. 3 shows that the predicted soil water distribution is in good agreement with the observed; the depths and widths of the wetted area are very close as are the spatial distributions of the water content. The transect plots also indicate good agreement between the experimental and simulated results.

To further evaluate quantitatively the accuracy of the model predictions, the coefficient of determination (R^2) was calculated for observed and predicted water contents. The coefficient of determination (R^2) was 0.96, indicating a good model fit. Overall, the observed level of accuracy for the model predictions confirms that HYDRUS-2D is suitable tool for investigating the design of subsurface clay pipe irrigation systems.

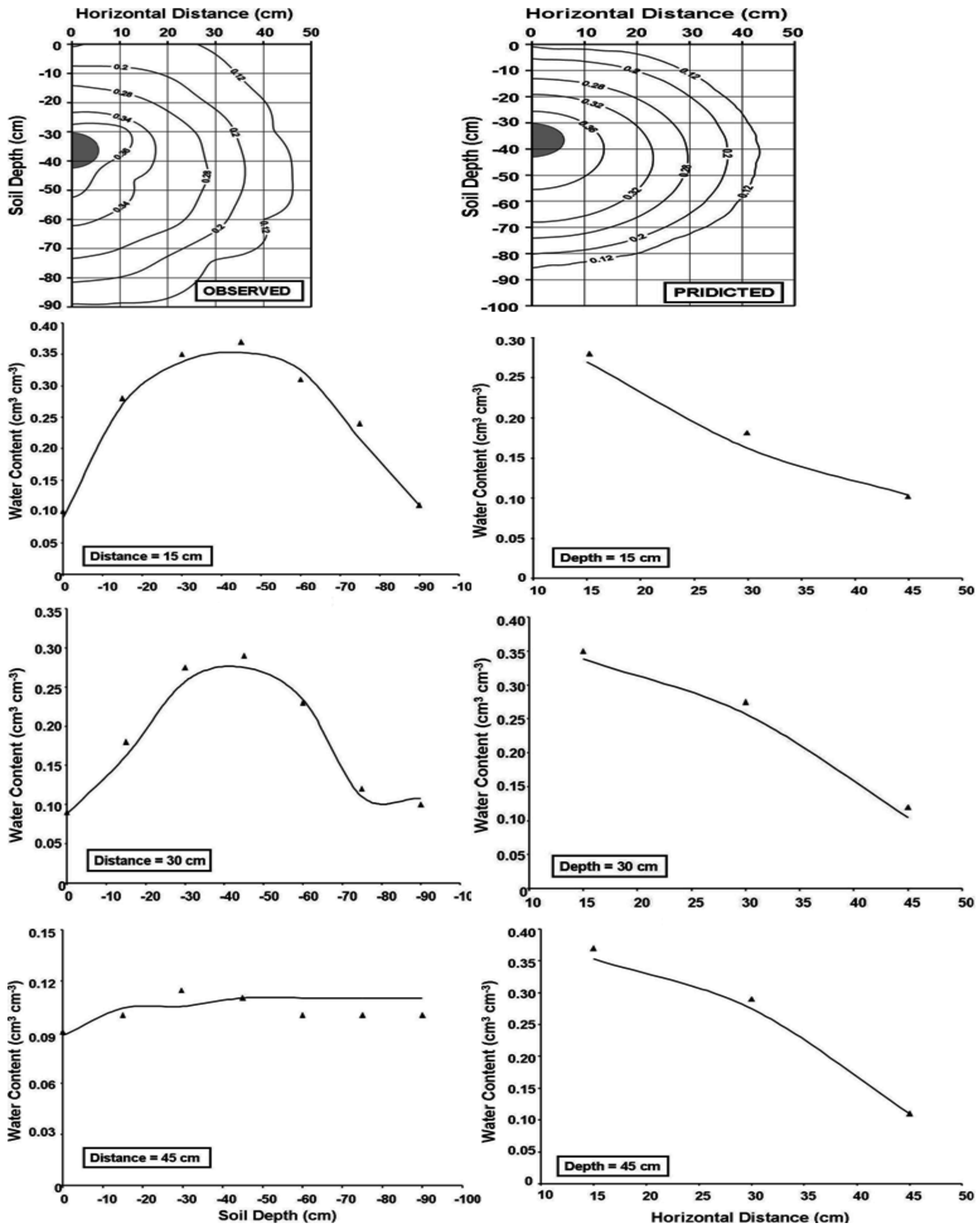

Figure 3. Measured and predicted water contents after five days of irrigation with a constant pipe pressure head of 100 cm.

Crop production

Plant germination with subsurface clay pipe irrigation was above 90% for all the three considered vegetables. After nearly nine weeks to seed drilling, the turnip crop was ready to harvest. The turnip crop production was weighed and recorded. The comparison of crop yield with subsurface clay pipe irrigation method to typical yield obtained with conventional surface flooding method is shown in Fig. 4. The total yield of turnip obtained from each lateral was 52 kg or 26 tons/ha which is 16% more than that of obtained with conventional methods of irrigation and fertigation. The total yield of okra obtained from each lateral was 7.7 kg or 4 tons/ha which is 5% more than that of obtained with surface flooding method. Similarly the yield of eggplant per laterals was 20 kg or 10 tons/ha which is 4% more than production obtained with conventional surface flooding method. Thus, the crop production with subsurface irrigation is 4 to 16% higher than that of obtained with surface flooding method. Similar results were reported by Batchelor *et al.* (1996) who found subsurface clay pipe method effective in improving yields, crop quality and water use efficiency as well as being cheap, simple and easy to use. The higher yield with clay pipe method can be contributed to steady seepage from the porous pipe which maintained water content in the root zone at field capacity throughout the entire plant growth period. At field capacity, plants are usually capable of extracting 100% of their water requirements. Also direct and uniform application of fertilizers to plant roots with clay pipe method eliminated the risk of nutrient loss due to deep percolation resulting in improved crop yield.

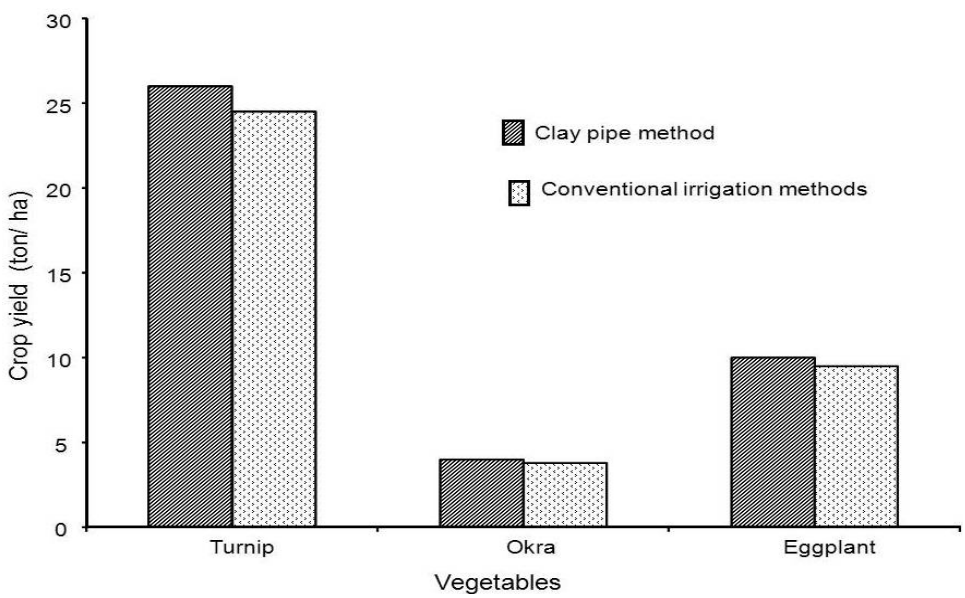

Figure 4. Crop yield obtained with subsurface clay pipe irrigation method compared to that of with conventional surface flooding method.

Water consumption

Table 2 shows depth of water used for growing vegetables with subsurface clay pipe irrigation method compared to that of surface flooding method. The volumes of water consumed for growing turnip okra and eggplant with clay pipe irrigation method were 700 m^3/ha (70 mm), 1000 m^3/ha (100 mm) and 1500 m^3/ha (150 mm) respectively compared to 3200 m^3/ha (320 mm), 5000 m^3/ha (500 mm) and 6500 m^3/ha (650 mm) respectively typically consumed with surface flooding method. Thus, 76 to 80% water savings were obtained with subsurface clay pipe irrigation system. The subsurface irrigation method eliminates water losses due to surface evaporation and deep percolation through the soil. This leads to very high efficiency--much better than drip irrigation and as much as 8 times more efficient than conventional surface irrigation.

Crop water productivity is important for understanding water-food relationships. It is defined as amount of water required per unit of crop yield. Water productivity is dependent on several factors, including crop genetic material, water management practices and the economic and policy incentives to produce. The crop productivity of vegetables grown with subsurface clay pipe irrigation system is shown in Fig. 5. The higher water productivity of all three vegetables can be contributed to the better water management through clay pipe irrigation method.

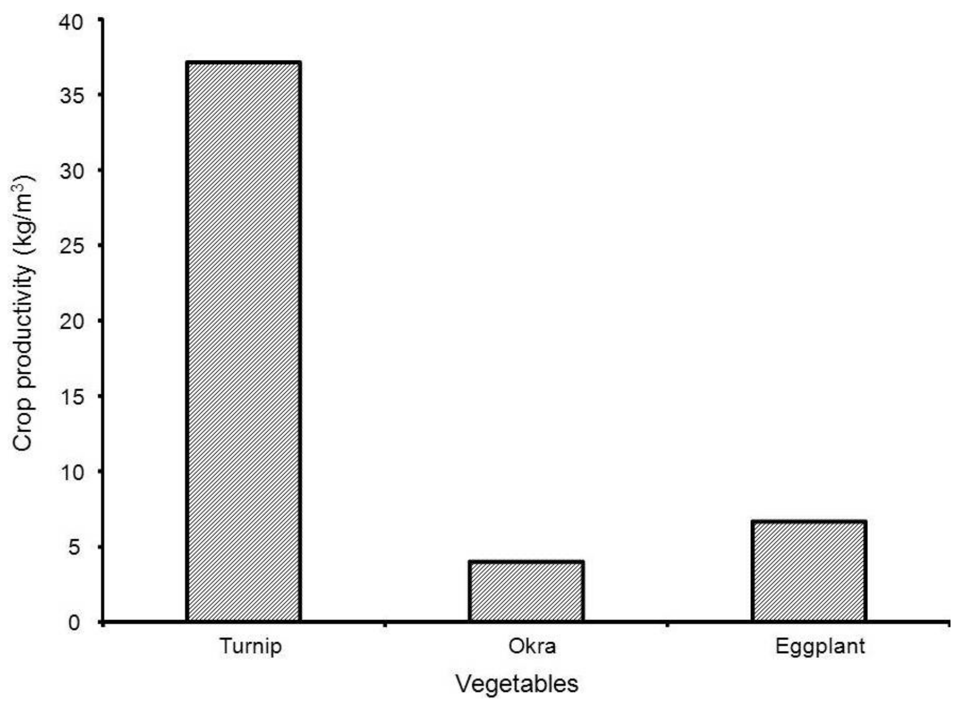

Figure 5. Crop productivity of various vegetables with subsurface clay pipe irrigation method.

Table 2. Irrigation water used and water savings with subsurface clay pipe irrigation system.

Type of crop	Water consumption with subsurface clay pipe method		Water consumption with traditional methods		Percentage of water savings
	mm	m^3/ha	mm	m^3/ha	
Turnip	70	700	320	3200	78.12
Okra	100	1000	500	5000	80.00
Egg plant	150	1500	650	6500	76.92

CONCLUSION

Experiment on growing Okra, Eggplant and turnip with subsurface clay pipe irrigation method showed water savings up to 80% compared to that of surface flood irrigation method. Also crop production of vegetables irrigated with this method was 5 to 16% more than that of obtained with conventional surface flood irrigation method.

ACKNOWLEDGMENT

The Higher Education Commission (HEC) of Pakistan is gratefully acknowledged for funding the project “Use of subsurface irrigation system to meet the water crisis in the country” under the National Research Program for Universities (NRPU).

REFERENCES

Abu-Zreig, M. and F. M. Atoum. 2004. Hydraulic characteristics of clay pitchers produced in Jordan. Can. Biosyst. Eng., 46 (1): 15-20.

Ashrafi, S., A. Gupta, M. B. Singh, N. Izumi and R. Loof. 2002. Simulation of infiltration from porous clay pipe in subsurface irrigation”. Hydrol. Sci. J., 47 (2): 253-268

Bainbridge, D. A. 2001. Buried clay pot irrigation: a little known but very efficient traditional method of irritation. Agric. Water Manage, 48 (2): 79-88.

Batchelor, C., L. Christopher and M. Murata. 1996. Simple micro irrigation techniques for improving irrigation efficiency on vegetable gardens. Agric. Water Manage, 32: 37-48.

Celia, M. A., E. T. Bouloutas and R. L Zarba. 1990. A general mass conservative numerical solution for the unsaturated flow equation. Water Resources Research, 26: 1483-1496.

FAO. 1998. Crop evapo-transpiration, guidelines for computing crop water requirements. FAO Paper No. 56, Rome.

Laghari, Q. K., B. K. Lashari and H. M. Memon. 2008. Perceptive research on wheat evapotranspiration in Pakistan. Irrigation and Drainage, 57: 571-584.

Qiaosheng, S., L. Zuoxin, W. Zhenying and L. Haijun. 2007. Simulation of the soil wetting shape under porous pipe sub-irrigation using dimensional analysis. Irrig. Drain., 56: 389-398.

Schaap, M. G., F. J. Leiji and M. Th. van Genuchten. 2001. ROSETTA: a computer program for estimating soil hydraulic properties with hierarchical pedotransfer functions. J. Hydrol., 251: 163-176.

Šimůnek, J., M. Sejna and M. Th. van Genuchten. 1999. The HYDRUS-2D software package for simulating the two-dimensional movement of water, heat, and multiple solutes in variably-saturated media. IGWMC-TPS 53, Version 2.0, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.

Siyal, A. A. 2008. Water-saving clay pipe irrigation system. Daily Dawn. http://www.dawn.com/2008/12/22/ebr6.htm.

Siyal, A. A., M. Th. van Genuchten and T. H. Skaggs. 2009. Performance of pitcher irrigation systems. Soil Science, 174 (6): 312-320.

van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Am. J., 44: 892-898.

(Received 09 June, 2011; Revised 31 October, 2011)