SUSTAINABLE SUBSURFACE IRRIGATION WITH A RING-SHAPED EMITTER FOR SMALL-SCALE FARMS IN ARID REGIONS

Reskiana Saefuddin[1], Hirotaka Saito[2], and Jiří Šimůnek[3]

ABSTRACT

Introducing an irrigation technique based on indigenous materials and skills to small-scale farmers in rural areas is crucial to support food security in highly populated regions of developing countries. A simple-design affordable emitter is vital for small scale farmers. Subsurface irrigation with a ring-shaped emitter is one of the low-cost irrigation techniques that have been developed and introduced in arid regions of Indonesia for cultivating horticulture crops. The original emitter was made from a water rubber hose, which was bent into a ring-shape emitter with a 20-cm diameter. After five small holes were drilled at equal distances, the ring-shaped hose was covered entirely with a permeable textile to ensure uniform water distribution around the emitter. Our previous study investigated whether the number of holes and the covering method can be modified. As a result, an emitter partially covered by permeable textile with a reduced number of holes was proposed. In addition, proper water and nutrient management during subsurface irrigation of cultivated crops is very important to obtain sustainable yields, to save precious water, and to prevent nitrate pollution of groundwater due to deep percolation. Understanding the relationship between applications of water and nutrients, plant root water uptake, and leaching risk can be helpful in designing better irrigation practices and management. The present study was undertaken to assess long-term effects of using subsurface fertigation with a ring-shaped emitter on the subsurface environment. Two different emitter designs were used: the original fully-covered emitter with 5 holes (emitter 5F) and an alternative design of an emitter with 2 holes, which was partially covered with permeable textile (emitter 2P). The fully three-dimensional numerical model HYDRUS was used to simulate soil water movement and solute and nutrient distribution and leaching under different emitter designs. The numerical analysis extended for 10 years. The simulation results showed that by applying water and nutrients using emitter 2P, the amount of nutrient leaching can be minimized and root nutrient uptake can be increased by up to 94 %.

1. INTRODUCTION

Now a days, fresh water resources are getting scarce due to climate change, poor management, and pollution. This problem will become chronic in the near future because of the rapid increase in the world population. In many water-scarce regions, farmers need to adopt efficient irrigation methods for sustainable crop production. While in many developed countries, high-tech micro-irrigation methods such as sprinkler and drip irrigation are increasingly used, many farmers are reluctant to adopt these methods due to their high initial cost of installation, costly maintenance, and the need for highly skilled and well-trained engineers. Therefore, the use of indigenous skills and materials is crucial to promote irrigation technologies in such areas.

Subsurface irrigation with a ring-shaped emitter (Saefuddin *et al*., 2014) is one of the low-costaffordable irrigation techniques that have been developed and introduced in some arid regions of Indonesia. An emitter is made from a common rubber hose,

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1 Tokyo University of Agriculture and Technology, Japan, E-mail rezqchan@gmail.com

2 Tokyo University of Agriculture and Technology Japan, hiros@cc.tuat.ac.jp

3 University of California Riverside, United States, E-mail: jsimunek@ucr.edu

which is economically affordable, especially for small-scale farmers. To create an original design, a rubber hose is bent into a ring shape with a diameter of about 20 cm, and five 5-mm holes are drilled at even intervals. The entire ring-shaped hose is then covered with a permeable textile so that irrigated water can be distributed through the permeable textile in all directions around the emitter. Water is supplied through a supply tube connecting a water tank and a ring-shaped emitter. An emitter can be installed directly in the root zone at a given depth.

Although ring-shaped emitters have been successfully used for subsurface irrigation of cultivated annual and perennial crops on an island of Indonesia (Saefuddin *et al*., 2014; Sumarsono *et al*., 2018) where precipitation is limited, the current design does not allow easy detection of malfunctions because the ring is fully covered with a permeable textile. In our previous study, an alternative ring-shaped emitter design (Saefuddin *et al*. 2018) with a reduced number of holes and a different covering method was proposed. In the alternative ring-shaped emitter design, the ring was partially covered only around the holes to increase usability and facilitate maintenance. The performance of the original and alternative ring-shaped emitter designs was then evaluated numerically using the HYDRUS (2D/3D) software package (Šimůnek *et al*. 2016) for various soil textures. The numerical results showed that, depending on the soil texture, the partially-covered ring-shaped emitter with fewer holes had better performance in providing suitable conditions for plant roots to uptake water in the root zone.

In addition, the performance of the alternative ring-shaped emitter design, which had 2 holes and was partially covered only around the holes (referred to as emitter 2P) and of the original emitter design (referred to as emitter 5F) was farther evaluated experimentally during bell pepper cultivation (Saefuddin *et al*., 2018). The experimental results showed that the alternative ring-shaped emitter produced higher irrigation water productivity and water use efficiency compared to the original one.

Increase in irrigated areas for intensive horticulture cultivation in arid lands can contribute to increase in nitrate concentrations in shallow aquifers because of nitrate leaching (Siemens *et al*., 2008; Ramos *et al*., 2012). Excessive applications of N fertilizers and poor management of water lead to nitrate pollution of groundwater.

Thus, the monitoring of nitrate concentrations in aquifers needs to be complemented with the control of nitrate leaching below the root zone. Even though subsurface irrigation has many advantages such as saving of irrigation water, one of the potential problems associated with this irrigation technique is nutrient leaching due to deep percolation below the root zone (Ajdary *et al*., 2007; Doltra and Munoz, 2010).

Therefore, proper management of water and nutrients during subsurface irrigation of cultivating crops is very important to obtain a sustainable yield, to save precious water, and to prevent nitrate pollution of groundwater due to deep percolation. Understanding the relationships between the amount of water and nutrient applications, crop root water uptake, and leaching risk can be helpful in providing better irrigation practices and management. In addition, to provide sustainable irrigation with ring-shaped emitters, it is crucial to evaluate the long-term effects of subsurface irrigation with ring-shaped emitters on the root zone and the aquifer.

Direct measurements of simultaneous water and solute movement around a buried ring-shaped emitter at the field scale are labor-intensive, time-consuming, and expensive. Simulation models have been showed to be valuable tools for assessing and predicting the long- and short-term effects of subsurface irrigation on soil properties, crop yield, nitrate leaching, and groundwater environment (Hanson *et al*., 2006; Ajdary *et al*., 2007, Doltra and Munoz, 2010; Wang *et al*., 2014). The interactions between soil water, solutes, and plant root water uptake areconsidered in the HYDRUS software package (Šimůnek *et al*., 2012; 2016). This model is therefore selected in the present study to simulate water movement and solute transport during subsurface irrigation with a ring-shaped emitter under field conditionsduring a long period.

In this study, the effects of long-term use of an alternative ring-shaped emitter for subsurface irrigation in the cultivated arid land East Lombok, Indonesia, were assessed numerically. HYDRUS (2D/3D) was used to investigate soil water movement, solute distribution, and deep percolation.

2. MATERIALS AND METHODS

2.1 Study Area

The study area was located in Pringgabaya village, in the East Lombok of West Nusa Tenggara, Indonesia (8^{o}31’58.32”S, 116^{o}37’44.85”E). Hot pepper (*Capsicum frutences* L.) was cultivated during the dry season from June to November (Sumarsono et al., 2018). The original ring-shaped emitter design was used in the field experiment. The climate is continental, arid, and temperate with annual average precipitation of 1042 mm from 2008 to 2017. Most precipitation occurred from November to February. Annual reference average evapotranspiration was 1675 mm from 2008 to 2017. Fluctuations in precipitation and potential evapotranspiration during ten years is shown in Figure1. The lowest and the highest temperatures were about 22.5^{o}C in January and 36.3^{o}C in August, respectively. Soil texture in the study area was characterized as sandy clay loam. The main soil properties are presented in Table no.1

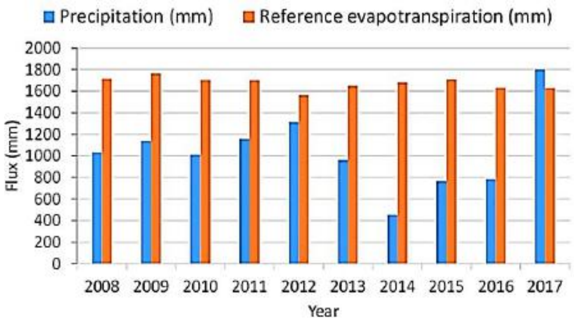

Figure 1. Annual precipitation and evapotranspiration in East Lombok Regency, West Nusatenggara, Indonesia during 10 years.

Table 1. Measured soil properties inthe study area

Parameters	Unit	Plot 1		Plot 2	
		0-15 cm	15-30 cm	0-15 cm	15-30 cm
Available water content	$cm^3\ cm^{-3}$	0.12	0.09	0.11	0.09
Field water content	$cm^3\ cm^{-3}$	0.35	0.32	0.38	0.41
Porosity	$cm^3\ cm^{-3}$	0.61	0.6	0.66	0.52
Bulk density	$g\ cm^{-3}$	0.96	0.98	0.88	1.18
Particle density	$g\ cm^{-3}$	2.44	2.48	2.56	2.47
Ks	$cm\ h^{-1}$	5.34	3.76	7.86	4.87
Ks	$cm\ day^{-1}$	128.16	90.24	188.64	116.88

(Source data ; Saptomo *et al*., 2014)

2.2 Long-Term HYDRUS Simulations of Solute Distribution

In order to predict the long-term effects of a long-term application of the alternative ring-shaped emitter for subsurface irrigation in the cultivated arid land East Lombok, Indonesia, the standard 3D module of the HYDRUS software (Šimůnek *et al*., 2012; 2016) was used for simulations. We refer to the HYDRUS technical manual (Šimůnek *et al*., 2012) for a detailed description of governing equations describing variably-saturated water flow using the Richards equation, the solute transport using the advection-dispersion equation, root water, and nutrient uptake, as well as of various implemented initial and boundary conditions. Since the alternative ring-shaped emitter design was partially covered with permeable textile only around the hole, the numerical simulations were carried out in a full three-dimensional domain (Figure 2) so that the asymmetry in the hole configurations of the emitter could be modeled without any simplifications.

The dimension of the transport domain was 100 cm in depth, 80 cm in width, and 100 cm in length. The transport domain was discretized into a finite element mesh with 12,586 nodes and 50,753 three-dimensional finite elements. The ring-shaped emitter was located at a depth of 20 cm below the soil surface. The mesh refinement of 1 cm was used around the buried ring-shaped emitter where rapid changes in flux occur. In order to describe solute distributions in soil profiles, 4 observation points were located in the center of the ring-shaped emitter at different depths (i.e., 10, 30, 50, and 70 cm).

An atmospheric boundary condition was set at the top of the transport domain. Precipitation, evaporation, and evapotranspiration were accounted for by the atmospheric boundary condition during the simulation. It was assumed that during cultivating hot peppers (*Capsicum frutences* L.), the soil surface was covered by rice straw mulch, and the potential evapotranspiration was thus taken equal to potential crop transpiration while evaporation was neglected.

Since cultivation was conducted only once a year and there was no crop rotation, evaporation which occurred from the bare soil surface was considered in the model by the atmospheric BC during non-cultivation periods. No-flux boundary condition was considered along the vertical side of the transport domain. In the present study, the water table was situated far below the transport domain. Therefore,the free drainage boundary condition at the base of the soil profile was used.

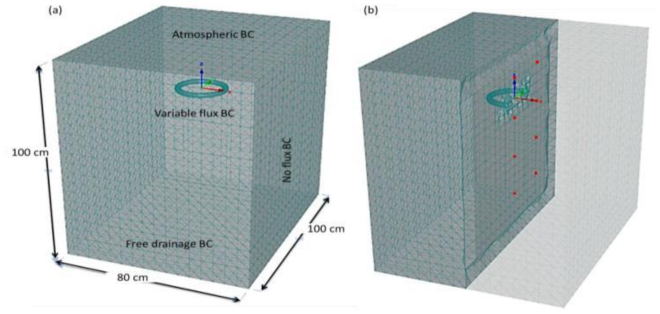

Figure 2. Conceptual geometry of the simulated area showing the location of the ring-shaped emitter and the boundary conditions used in the HYDRUS (2D/3D) simulations (a).Red dots represent the location of observation points in the

A time-variable flux boundary condition along the buried ring-shaped emitter surface was considered during irrigation and no flux otherwise. The constant flux in the aforementioned boundary condition was defined based on the amount of 1500 cm^3 water applied in each irrigation event, which corresponded to the irrigation flux rate of 9.14 cm day^{-1}. The irrigation period was 8 h per day. Since it is common to irrigate vegetables every 2-3 days (e.g., Allen *et al*., 1998), irrigation water was applied every 3 days with a duration of 8 h. A third-type Cauchy boundary condition along the emitter surface was used to evaluate the effects of nitrogen applications via fertigation on nutrient uptake and distribution in the soil during a given fertigation event. In the simulation, fertigation was applied every 2 weeks with the NO_3-N concentration of 1.07 mmol L^{-3} (Phogat *et al*., 2014). The total of 10 fertigation events was considered in one cultivation period. The fertigation involved applying fresh water for the first 4 h and fertilizer with irrigation water for the next 4 h. The initial conditions of soil water content and solute concentration were assumed uniform throughout the soil profile with values of 0.103 cm^3 cm^{-3} for the soil water content and zero for the initial solute concentration.

The reduction of root water uptake due to the water stress, α_1 (h), was modeled based on the Feddes approach (Feddes *et al*., 1978), which is implemented in HYDRUS. The reduction in root water uptake due to the salinity stress, α_2 (h) was described by adopting the Maas and Hoffmann (1977) salinity threshold and slope function. The parameters of the water stress reduction function of Feddes *et al.* (1978) and osmotic reduction parameters of Maas and Hoffman (1977) are listed in Table 2. The parameters of the spatial root distribution based on Vrugt *et al.* (2001) model were considered in the simulation.

The roots of the hot pepper were assumed to be concentrated mainly below the buried ring-shaped emitter where the water and nutrient were applied and expanded horizontally into all available space between crop lines. The parameters of the root distribution are summarized in Table 3 while the spatial root distribution is shown in Figure 3.

Table 2. Root water uptake saturation and osmotic reduction parameters (from Feddes et al. (1978) and Maas and Hoffman (1977), respectively)

Po (cm)	-10		Osmotic Reduction	
Popt (cm)	-20		Threshold (DS/m)	2.5
P_2H (cm	-800		Slope (%)	9.9
P_2L (cm)	-1500		Osmotic coefficient	1
P_3 (cm)	-3000		cRoot	0.2
r_2H (cm/day)	0.5			
r_2L (cm/day)	0.1			

The van Genuchten-Mualem model (van Genuchten, 1980) was used to describe soil hydraulic properties. Soil hydraulic parameters (Table 4) were estimated initially from a limited number of laboratory and field measured retention data points using the RETC program (van Genuchten *et al*., 1991). The Crank-Nicholson and Galerkin finite element schemes were used to solve the advection-dispersion equations of solute transport with the recommended value of the stability criterion in the simulation. A non-reactive tracer was considered in solute transport simulations. The longitudinal dispersivity equal to one-tenth of the profile depth and the transversal dispersivity equal to one-tenth of the longitudinal dispersivity, which are recommended in many studies (Ajdary *et al*., 2007; Ramos *et al*., 2012 and Doltra and Muňoz, 2010), were used.

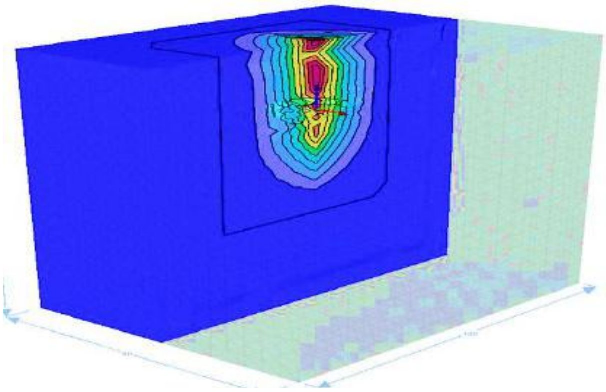

Figure 3. A spatial root distribution used in the simulation based on Vrugt *et al*. (2001) parameters

Table 3. Root distribution parameters from Vrugt et al. (2001) for hot pepper

Zm (cm)	*Z** (cm)	*Xr* (cm)	*Yr* (cm)	*Pz*	*Px*	*Py*
60	35	25	25	1	1	1

Table 4. Soil hydraulic parameters used in HYDRUS (2D/3D) water flow simulations

Soil texture	*θr* ($cm^3\ cm^{-3}$)	*θs* ($cm^3\ cm^{-3}$)	*α* (1/cm)	*n*	*Ks* (cm day^{-1})	*l*
Sandy clay loam	0.09	0.524	0.045	1.623	90.27	0.5

Thus, the longitudinal and transversal dispersivities were set to 10 cm and 1 cm, respectively. Since the effect of long-term subsurface irrigation with a ring-shaped emitter on water and solute distributions in the soil was the main concern in this study, chemical interactions and biological processes of solute degradation were ignored. The maximum solute concentration allowed to be taken up from the flow region by root uptake (cRoot) was set to 0.2 (Doltra and Muňoz, 2010). No nitrogen reactions or transforming processes were considered, assuming chemicals were either taken up by the crops and/or transported by water flow in the soil (a fraction of nitrogen will thus be lost through leaching).

To evaluate the long-term effect of subsurface irrigation with the ring-shaped emitter, a long-term simulation was conducted for 10 years using the series meteorological data from 2008 to 2017. Th e series of meteorological data used in the study area such as precipitation, air temperature, relative humidity, wind speed, and solar radiation, were downloaded from the website of National Oceanic and Atmospheric Administration (http://www.1.ncdc.noaa.gov.) Two emitter designs were compared, the emitter 5F as the original design and the emitter 2P as the alternative design (Figure 4). The simulations were done by considering the same amount of water and nitrogen applied by both emitters 5F and 2P.

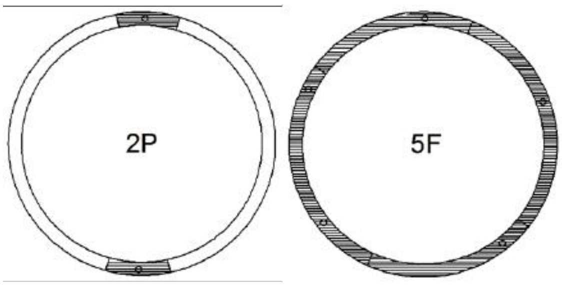

Figure 4. Ring-shaped emitter designs used in the present study

3. RESULTS AND DISCUSSIONS

3.1. The Long-Term HYDRUS Simulations

Simulated spatial nitrogen distributions in the soil profiles under different emitter designs from 2008 to 2017 are depicted in Figure 5. The figure reveals that the difference in nitrogen concentrations was more at adepth of 10 – 30 cm, which is near the emitter location. The nitrogen concentration increased with depth down to 30 cm, and thereafter decreased as the plant roots actively took up nutrient during the growing season. The fluctuation of the solute concentration in the deeper layer was smaller than in the upper layer.

While plant uptake decreased at the end of the crop cultivation season, excess water leached nitrogen below the root zone, as is evident from 300 DOY and beyond. At the end of cultivation, the amount of solute remained in the soil profile. The accumulated nitrogen may be leaching out to the deeper layer when precipitation occurs and become a potential pollutant to groundwater environment. On the other hand, when the evaporation rate increased at the soil surface, the accumulation of nitrogen increased at the soil surface.

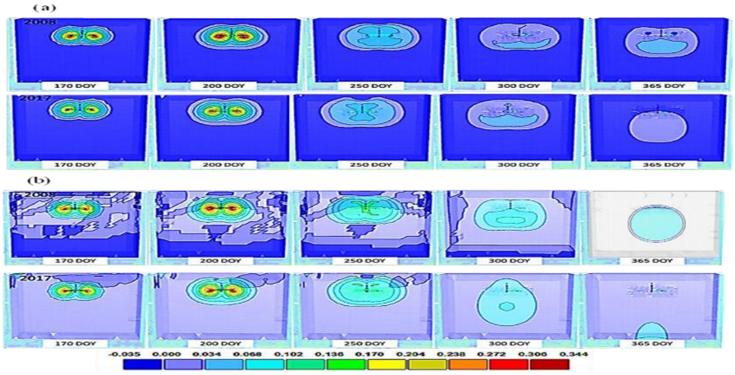

Figure 5. HYDRUS simulation

Although the same amount of fertilizer was injected during each fertigation event, the HYDRUS simulation results showed that the emitter design evidently affected the nitrogen distribution (Figure 5). As for the emitter 2P, nitrogen moved less downward as the water was applied slowly from the emitter 2P. It indicated that more nitrogen was taken up by plant roots when nitrogen remained in the active root zone. At the end of the crop cultivation, as nitrogen remained in the soil profile, nitrogen did not leach to the deepest layer.

On the other hand, the nitrogen in the root zone for the emitter 5F was higher in the early fertigation event and moved down to a deeper soil layer immediately due to the high discharge rate of emitter 5F. The amount of solute leached below the root zone was about 7,755 mmol higher than that of emitter 2P (2,565 mmol) over 10 years. It indicated that more solute leaching occurred to shallow groundwater when the emitter 5F was used. Thus, potential groundwater pollution was more pronounced foremitter 5F.

3.2. Crop Nutrient Uptake and Solute Leaching

The cumulative nutrient uptake was computed by adjusting the same amount of nutrient applied for all emitter designs. Figure 6 shows cumulative nutrient root uptake during the cultivation season for different emitter designs. The figure shows that root nutrient uptake was high and solute leaching was virtually eliminated when the emitter 2P was used. The ratio of cumulative nutrient uptake to cumulative nutrient applied for the emitter 2P was about 93.6 %, which is higher than that for emitter 5F (82.1%). Despite the lower irrigation discharge rate for the emitter 2P, allowing the plant roots to uptake more nutrient in the active root zone.

At the same time, it reduced nutrient leaching from the root zone due to excess water from irrigation events. However, cumulative nutrient uptake was lower than the amount of nutrient applied every year, indicating that the plant was not able to uptake all nutrients applied through fertigation events. On the other hand, when the nutrient was applied through emitter 5F, the nutrient uptake by plant roots was lower than for emitter 2P. Although the same amount of water and nutrient was applied in all emitter designs, cumulative nutrient uptake was low for emitter 5F. This may be because the higher emitter discharge rate facilitated more water and nutrient movement in downward directions.

Therefore, more nutrients leached below the root zone. Furthermore, because of the high intensity of precipitation during the growing season of 2010 and 2016, more nutrients leached below the root zone.

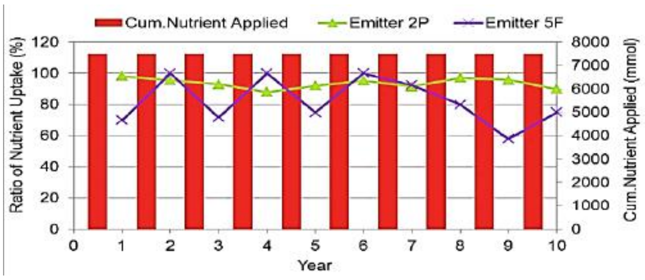

Figure 6. Proportion of nutrient uptake to nutrient applied under different emitter designs

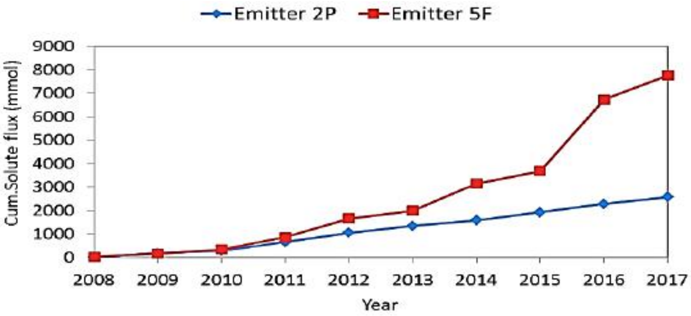

Figure 7. Cumulative solute leaching over 10 years when the same amount of fertigation was injected in emitter 2P and emitter 5F

The amount of solute leached below the root zone was determined by computing the amount of solute flux at the bottom boundary (i.e., 100 cm depth). The cumulative solute leaching under different emitter designs is plotted in Figure 7. The leached solute was considerably higher when the emitter 5F was used. Nutrient leaching most likely occurred following a fertigation event for emitter 5F. This might be because the larger emitter discharge rate pushed the nutrient below the root zone. Wang *et al*. (2014) reported that larger emitter discharge rates resulted in larger deep percolation and nutrient leaching rates. An increase in nutrient leaching was also greatly dependent on precipitation. Larger precipitation events during the growing season produced more drainage. This fact was confirmed by simulating deep drainage in 2010 and 2016 when precipitation was higher during the irrigation season. Arbat *et al*. (2013) indicated that nutrient leaching during the irrigation season was considerably higher when heavy precipitation events occurred and water consumption of crop roots was relatively small.

On the other hand, there was only limited leaching below the root zone, and fertilizers remained accessible to the plant roots when the emitter 2P was used. As for the emitter 2P, water infiltrated slowly because of the low emitter discharge rate, resulting in less nutrient moving downward during the growing season. The lower irrigation discharge rate facilitated root nutrient uptake and minimized the nutrient losses due to deep percolation. For the emitter 2P, the nutrient manning in the root zone at the end of the crop season leached out during the rainy season. Therefore, the nutrient leaching was mainly due to high precipitation instead of excess water from irrigation events.

4. CONCLUSIONS

The long-term effect of subsurface irrigation with the ring-shaped emitter on water movement and solute distribution was evaluated numerically using HYDRUS. Two emitter designs were compared: the emitters 2P and 5F. The simulation results were extended to 10 years in order to understand the effects of applied irrigation and nutrient on the shallow groundwater environment. The simulation results showed that potential solute leaching was higher when emitter 5F was used over 10 years. It can have a negative impact on the groundwater environment as it increases pollutant leaching from chemical fertilizer applications. On the other hand, by applying fertigation through emitter 2P, which had alow discharge rate, the amount of nutrient leaching can be minimized. The simulation results confirmed that 93.6% of nutrient applied was taken up by plant roots. Therefore, in order to minimize leaching losses in the fertigation cycle, the use of emitters with low flow discharge rates should be considered. In this study, the assessment of irrigation and fertigation for a long period is important to evaluate the design and management of subsurface irrigation with a ring-shaped emitter in arid regions by considering climate conditions, crop, and soil types, besides controlling environmental contaminations.

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