Agricultural Water Management 113 (2012) 19–29

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Application of HYDRUS-1D model for simulating water and nitrate leaching from continuous and alternate furrow irrigated rapeseed and maize fields

Arash Tafteh, Ali Reza Sepaskhah*

Irrigation Department, Shiraz University, Shiraz, Islamic Republic of Iran

ARTICLE INFO

Article history:
Received 16 February 2012
Accepted 17 June 2012
Available online 7 July 2012

Keywords:
Alternate furrow irrigation
Partial root drying irrigation
Nitrate leaching
Deep percolation
Nitrogen uptake
HYDRUS-1D

ABSTRACT

Different simulation models were used to evaluate drainage and nitrogen fertilizer movement to groundwater. The objectives of this study were to evaluate the HYDRUS-1D model for simulation of water and nitrate leaching in different nitrogen fertilization rates (as urea) and variable and fixed alternate furrow irrigation (VAFI, FAFI) and continuous furrow irrigation (CFI) of rapeseed and maize planted in 36 field lysimeters. Results indicated that seasonal drainage in rapeseed field was reduced 39% and 72% under VAFI and FAFI, respectively compared with CFI. These reductions for maize were 40% and 57%, respectively. For rapeseed, NO_3–N leaching was reduced 40% and 69% under FAFI and VAFI compared with that obtained under CFI, and it was increased up to 55% by increasing N application rate to 200–300 kg ha^{-1} compared to 0 N application rates. For maize, NO_3–N leaching was reduced similarly under VAFI and FAFI (56%) compared with CFI, and it was increased up to 67% by increasing N application rate to 300 kg ha^{-1} compared to 0 N application rates. Furthermore, for both crops, HYDRUS-1D model was able to simulate deep percolation water (NRMSE of 0.11 and 0.094 for rapeseed and maize, respectively), NO_3–N leaching (NRMSE of 0.14 and 0.18 for rapeseed and maize, respectively) with a very good accuracy even though the water and NO_3^- flow in soil surface layer was 2-dimensional. The measured and predicted crop N-uptake was different and this difference was attributed to the excluding root nitrogen uptake in the measured values and neglecting N mineralization, denitrification and microbial immobilizatrion processes.

1. Introduction

Water is an important factor for crop production especially for rapeseed and maize in arid and semi-arid regions. Partial root drying irrigation by alternate furrow irrigation (AFI) and drip irrigation is an appropriate procedure for management of deficit irrigation in these regions. In these irrigations, deep percolation and surface evaporation are reduced and less water is used (Sepaskhah and Kamgar-Haghighi, 1997; Sepaskhah and Hosseini, 2008; Ahmadi et al., 2010).

Nitrogen (N) plays an important role in crops grown with supplementary irrigation (Tavakoli and Oweis, 2004). It is important to use an optimum amount of water and nitrogen for best management of crop production in arid and semi-arid regions because the application of an excess amount of water causes nitrogen leaching below the root zone (Gheysari et al., 2009; Wang et al., 2010), and causing economic losses for farmers.

Fars province in south of Iran is the main agricultural production region with wheat, rapeseed and maize as main crops. In this region, N fertilizer applications have increased in recent years and resulted in higher N accumulation in soil. However, N fertilizer use efficiency is low in this region (Sepaskhah and Hosseini, 2008; Pirmoradian et al., 2004). Anions like NO_3^- are not adsorbed by soil clay particles and are easily leached by deep percolation water. Therefore, N fertilizer losses resulted in groundwater nitrate (NO_3^-) contamination. Many studies have reported N accumulation and leaching in soil profiles with different irrigation schedules (Li et al., 2007; Hu et al., 2006; Wang et al., 2010). However, there are few investigations on the leaching of N with different rates of fertilizer application and water saving irrigation methods. Furthermore, more knowledge on the environmental impact of fertilization and irrigation is needed to reduce the groundwater contamination and economic losses (Ersahin and Karaman, 2001).

Simulation models are appropriate tools for identifying best irrigation and N fertilization management. Different simulation models were used to evaluate the N fertilizer movement to groundwater (Li and Ghodrati, 1994; Jala et al., 1994; Ersahin and Karaman, 2001). Among different investigators, Ersahin and Karaman (2001) and Follett (1995) applied NLEAP (Nitrate Leaching and Economic Analysis Package) model to simulate N leaching in lysimeter and field with different rates of N fertilizer application and indicated that the model simulation predicted the N leaching with acceptable

* Corresponding author. Tel.: +98 711 228 6276; fax: +98 711 228 6130.
E-mail address: sepas@shirazu.ac.ir (A.R. Sepaskhah).

0378-3774/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agwat.2012.06.011

Table 1
Physical properties of soil at the experimental site.

Depth cm	Clay %	Silt %	Sand %	Organic matter	Bulk density g cm^{-3}	Field capacity cm^3 cm^{-3}	Permanent wilting point cm^3 cm^{-3}
0–15	30	35	35	2.0	1.25	0.32	0.11
15–30	30	35	35	2.0	1.32	0.36	0.12
30–50	39	38	23	–	1.36	0.36	0.14
50–70	40	39	21	0.7	1.42	0.39	0.16
70–100	40	39	21	0.7	1.42	0.39	0.16

accuracy. Stewart et al. (2006) used APSIM (Agricultural Production Systems Simulator) model to estimate the N contamination of deep percolation water in sugarcane fields and indicated that this model can be applied for proper management of water and N leaching.

HYDRUS1-D model has been used to study the leaching of accumulated N in the soil profile under heavy rainfall, high irrigation rates in growing season and different amounts of initial accumulated N (Wang et al., 2010). At regions with water scarcity, water saving irrigation like alternate furrow irrigation (AFI) is used for different crops (Sepaskhah and Kamgar-Haghighi, 1997; Samadi and Sepaskhah, 1984; Sepaskhah and Khajehabdollahi, 2005; Sepaskhah and Parand, 2006; Sepaskhah and Ghasemi, 2008; Sepaskhah and Hosseini, 2008). In furrow irrigation water infiltration in the soil surface layer occurs in horizontal and vertical directions (2-dimensional) and infiltration water front from the two adjacent furrows overlap in horizontal direction. In this irrigation method water and NO_3^- flow is occurred in 2-dimensional condition at the soil surface and HYDRUS-2D and other 2-dimensional models should be used to describe the water and NO_3^- flow. However, HYDRUS-2D model is more complicated than HYDRUS-1D model and further it is not easily accessible. On the other hand, in deep soil layer the gravitational 1-dimensional flow may be prevailed and water and NO_3^- flow in deeper soil profile might be described by HYDRUS1-D model.

Crevoisier et al. (2008) simulated water and nitrogen transfer under continuous furrow irrigation (CFI) and AFI with equal applied water depth using HYDRUS-1D and HYDRUS-2D for CFI and AFI. They indicated that 2-D model simulated water transfer better than 1-D model especially in case of AFI. Furthermore, soil nitrate simulation was acceptably precise in the case of CFI and less precise in AFI between irrigation events. On the other hand, AFI combined with reduced applied water depth has not been considered in a similar study to those reported by Crevoisier et al. (2008). Combined use of AFI and reduced applied water is considered as water saving or partial root-zone irrigation (WSI/PRI) that enhanced the water productivity as reported by Sepaskhah and Ahmadi (2010) and Ahmadi et al. (2010). Therefore, in this study we tried to simulate water and nitrogen leaching in combined uses of AFI and reduced applied water depth by using HYDRUS-1D model. This model is used due to the finding of Mailhol et al. (2007) that indicated the difference between initial N profiles measured under ridge and under furrow is reduced and 2-dimensional problem may turn to 1-dimensional especially at deep soil profile. Many investigators considered the lower boundary conditions in flow of water and N transfer in furrow irrigation as free drainage (Abbasi et al., 2004) as my occur in 1-dimensional condition. Furthermore, it is interesting to consider 1-dimensional HYDRUS model that is simpler and easier than 2-D cases where 2-D HYDRUS model has not resulted in a very accurate findings (Crevoisier et al., 2008). Therefore, HYDRUS-1D model can be considered as a non-sophisticated N leaching model for average input and output fluxes of water and nitrogen. Williams and Kissel (1991) indicated that simple N-leaching based on average percolation potential would be useful in identifying problematic irrigation system. Once a problematic irrigation system is identified, more detailed simulation model can be used to address complex fertilizer management problems.

To the knowledge of authors, there is no report on the study of HYDRUS-1D model to simulate the leaching of applied N fertilizer under continuous furrow irrigation (CFI) and alternate furrow irrigation (AFI) with reduced irrigation water depth.

The objectives of this study were to evaluate the HYDRUS-1D model for simulation of water and NO_3^- leaching at different N fertilization rates and in water saving irrigation, i.e., fixed and variable alternate furrow irrigation (FAFI, and VAFI, respectively) and full irrigation, i.e., continuous furrow irrigation (CFI) of rapeseed and maize in field lysimeters.

2. Materials and methods

2.1. Experimental site

This study was conducted in Bajgah area, Fars province, Iran for growing season (2008–2009). This growing season casually occurred in a drought year with an annual rainfall of 175 mm (44% of mean annual rainfall). However, a considerable portion of precipitation occurred in winter while the rapeseed crop was in dormant period in this season as it is in normal years. The physical properties of soil in the study area are shown in Table 1. The soil is a clay loam (Fine, mixed, mesic, Typic Calcixerepts) with a deep water table in the Bajgah Agricultural Experiment Station of Shiraz University located 16 km north of Shiraz (29°, 36′ N, 32° 32′ E, 1810 MSL). Chemical analysis of the soil water extract and used irrigation water is shown in Table 2. Chemical analysis of irrigation water and soil saturation extract indicated that there is no salt hazard in irrigation water that could affect the soil saturation extract. However, there is some nitrate in the irrigation water that should be considered in N balance in soil. This experiment was conducted in a cluster of water balance lysimeters contained 36 square units (9 × 4) with dimensions of 1.5 m × 1.5 m × 1.1 m each. The number of lysimeters was equal to the number of experimental treatments × replicates (i.e., 4 × 3 × 3 = 36). A layer of 0.05 m gravel was placed at the bottom of each unit and soil layer with height of 1.0 m was placed on top of the gravel layer. Therefore, soil surface was 0.05 m lower than the edge of each unit for irrigation water catchment. A drain tube was

Table 2
Chemical analysis of soil saturation extract and irrigation water.

Properties	Unit	Saturation extract	Irrigation water
pH		7.49	7.20
Electrical conductivity	dS m^{-1}	1.10	0.76
Chloride	meq L^{-1}	1.18	0.40
Calcium	meq L^{-1}	2.10	0.28
Magnesium	meq L^{-1}	3.85	0.79
Sodium	meq L^{-1}	1.01	0.35
Potassium	meq L^{-1}	0.20	0.01
Bicarbonate	meq L^{-1}	0.29	0.07
Phosphorous	meq L^{-1}	0.013	0.003
Nitrate	meq L^{-1}	–	0.11

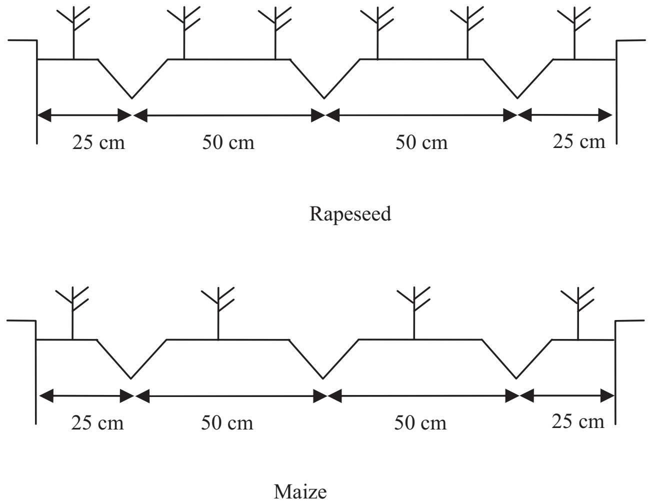

Fig. 1. Schematic diagram of planting in lysimeters.

installed under the gravel filter in each unit to drain the deep percolation water. These drains were connected to different sumps to collect the deep percolation water. The spacing between the units was 0.3 m. The wall and bottom of the units were concrete and was coated with water proof bitumen.

Total furrow length was more than 6 m that lysimeter wall divided it into 4 sections each with 1.5 m long. Two ends of each furrow were blocked by lysimeter walls. By this setup we constructed different short furrow irrigation units that simulated furrow irrigation with 2-dimensional infiltration with uniform infiltration along the 1.5 m furrow length.

2.2. Experimental design

The experimental design was complete randomized design with factorial arrangement (4 × 3) and three replications. Experimental treatments were four levels of nitrogen (0, 100, 200, and 300 kg ha^{-1}) and three furrow irrigation methods (continuous furrow irrigation, CFI, fixed alternate furrow irrigation, FAFI, and variable alternate furrow irrigation, VAFI). While CFI is considered as a full irrigation, alternate furrow irrigation (i.e., FAFI and VAFI) are considered as water saving or partial root-zone irrigation (WSI/PRI), respectively. In CFI, water was applied to every furrow at each irrigation event. In FAFI, water was applied to fixed alternate furrows throughout the growing season, and in VAFI water was applied to alternate furrows which were dry in the preceding irrigation cycle. Each unit for rapeseed (*Brassica napus* L.) contained three furrows with two complete furrow ridges of rapeseed (with two rows of plants) at middle of lysimeter and two half furrow ridges of rapeseed at left and right sides with one row of plant (Fig. 1). Furrows in each lysimeter were V-shaped with 1.5 m long and 0.5 m spacing between furrows. Each unit for maize (*Zea mays* L.) contained three V-shaped furrows similar to those for rapeseed. However, one row was planted on each furrow ridge. Furrow spacing of 0.5 m for rapeseed is a local farmer practice. However, for maize the row spacing is smaller than the common practice in order to accommodate 4 rows of plants in a lysimeter with a plant population similar to that in field practice. Therefore, wider spacing within plant row was used.

The soil in each unit was tilled by shovel. During the soil preparation phosphorous at a rate of 46 kg ha^{-1} as triple super phosphate and 30% of the N treatments for rapeseed (0, 30, 60, and 90 kg ha^{-1}) and 50% of N treatments for maize (0, 50, 100, and 150 kg ha^{-1}) as urea were mixed with the soil. The remaining N (70% and 50% of each treatment for rapeseed and maize, respectively) was applied at the initiation of the vegetative growth at late winter-early spring for rapeseed and 60 days after seed emergence for maize, respectively. The top dressing of N was applied to every furrow in CFI and to the furrows which were irrigated in FAFI and VAFI.

After the land preparation, seed of Licord cultivar was planted in two rows on top of the furrow ridges (a total six rows in each lysimeter) with spacing between rows of 0.25 m and 150 seeds per m^2 with seeding spacing on row of 0.025 m. Seeding date was 28 September in 2008. Maize seed of single-cross 704 cultivar was planted in one row on top of the furrow ridges (a total of four rows in each lysimetyer) with spacing between rows of 0.5 m and 13 seeds per m^2 with seeding spacing on row of 0.15 m. Seeding date was 18 June in 2009.

Mean air temperatures and relative humidity during the growing season were 11.1 °C and 46.6% for rapeseed and 22.1 °C and 42.9% for maize, respectively. During first and second week after seed emergence, rapeseed and maize were thinned to the given spacing on each row. Weeds were removed by hand weeding every 2-week intervals. In spring, aphids and other pests were controlled by using an appropriate pesticide every 2-week for three times for rapeseed and two times for maize. At the podding stage of rapeseed, the plots were covered by screen to prevent the pods from bird invasion.

Irrigation water was applied in 7-day interval as a local practice, and soil water in the root zone was raised to the field capacity according to following equation:

$$d_n = \sum_{i=1}^{n} (\theta_{fci} - \theta_i)\Delta z \quad (1)$$

where d_n is the net irrigation water, m, θ_{fci} and θ_i are the volumetric soil water contents at field capacity and before irrigation, respectively in layer i, m^3 m^{-3}, Δz is the soil layer thickness, m, and n is the number of soil layers. Then, the gross irrigation water was determined by dividing the d_n by irrigation application efficiency of 70% that is a common irrigation efficiency used by farmers in the well managed fields. We used E_a of 70% to mimic the more risked conditions regarding the leaching process. Volume of irrigation water for each irrigation treatment was determined by multiplying the irrigated furrow area by the respective gross irrigation water depth. The volume of gross irrigation water was applied with a flexible hose and measured with a volumetric flow meter. The applied depth of irrigation water in the lysimeters with short furrows is assumed to be equivalent to the average depth of water applied in long furrows in real practice. The water application depth is not the same under AFI and CFI due to the fact that under AFI half of the field or furrows are irrigated. The first and second irrigation events for rapeseed were applied in CFI in all irrigation treatments (about 25 mm each) to obtain uniform and vigorous seed germination and vegetation stands. For maize the first to third irrigation events were applied in CFI with a total depth of 150 mm in these three irrigation events. Figs. 2 and 3 show the amounts of crop evapotranspiration (ET_p), rainfall, irrigation water applied for each irrigation event of CFI, FAFI, and VAFI for rapeseed and maize, respectively. ET_p was determined by $K_c \times ET_o$ in which K_c is the crop coefficient and ET_o is the reference evapotranspiration.

The water content of soil in depths of 0.15, 0.3, 0.5, 0.7, and 1.0 m was measured by neutron probe before each irrigation event. A dz of 10 cm would allow a more accurate estimation of the soil water on a given soil depth, however a dz of 20–30 cm was used to reduce the frequency of neutron meter use for longer durability of the apparatus. The access tube of neutron probe was installed in the bottom of the middle furrow in CFI and in the middle and side furrows in the AFI. The mean soil water content in furrows was used in Eq. (1) to determine the irrigation water depth.

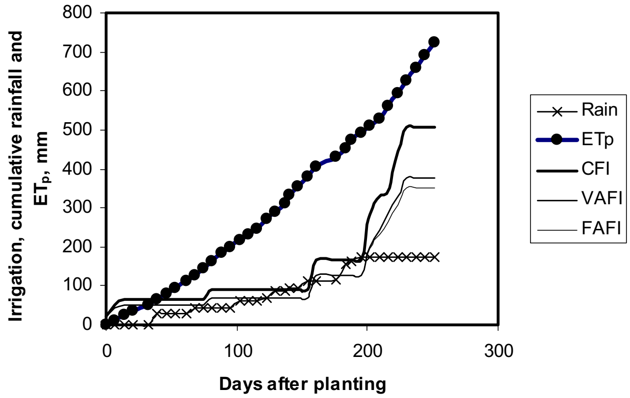

Fig. 2. Crop potential evapotranspiration (ETp), rainfall and applied irrigation (CFI, VAFI, FAFI) water during rapeseed growing season.

Initial soil NO_3–N was determined in soil samples at depths of 0–0.3, 0.3–0.6, and 0.6–0.9 m before N application (Chapman and Pratt, 1961). Soil samples for rapeseed at each soil depth were taken from three different replicates and a composite sample was constituted for a given depth. Samples for this measurement were taken in 23 September, 2008 and 14 June, 2009 for rapeseed and maize, respectively. The residual soil NO_3–N at each experimental treatment was determined at the same depths after harvest (14 June, 2009 and 17 October, 2009 for rapeseed and maize, respectively). The residual soil NO_3–N at harvest for rapeseed was considered as initial soil NO_3–N for maize.

After each irrigation event or rainfall, the deep percolation water was collected and its total volume was measured by volumetric cylinder. NO_3 concentration in the deep percolation water was immediately determined by spectrophotometer. Nitrate leaching at each irrigation and rainfall event was determined by multiplication of volume of deep percolation water and nitrate concentration.

Plants from two middle ridges with a length of 1.5 m (i.e., 4 rows for rapeseed and 2 rows for maize, respectively) were harvested. Finally, seeds were separated from straw and weighed. Furthermore, the oven-dried weight of straw was determined. Samples from seeds and straw were used to determine the N contents in mg kg^{-1} by Kejldahl procedure (Bremner and Mulvaney, 1982). Measured grain yield and N uptake were used in a two-way statistical

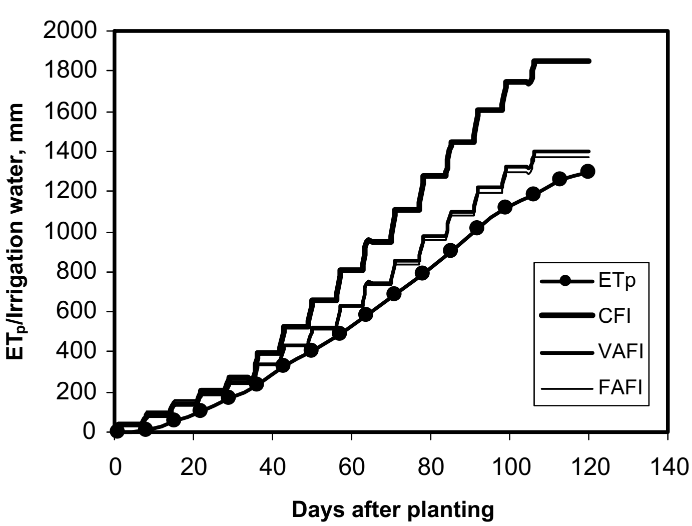

Fig. 3. Crop potential evapotranspiration (ETp) and applied irrigation (CFI, VAFI, FAFI) water during maize growing season.

analysis and the means were compared by Duncan multiple range test.

2.3. Model description

HYDRUS-1D model was developed by Simunek et al. (2008) to simulate the 1-dimensional flow of soil water, heat, solute and viruses in variably saturated-unsaturated media (www.HYDRUS.com). In the present study, this model (version 3.00) was applied to predict the leaching of nitrate from the surface-applied nitrogen as urea and excess water from surface-applied irrigation as CFI and AFI.

Furrow irrigation is governed by a 2-dimentional water transfer process. However a 1-dimensional flow model is used to describe the water and NO_3^- leaching. It is clear that 2-dimensional model should be used to describe the soil water contents, pressure heads, and NO_3^- concentration distribution in the surface layer of lysimeter. However, we tried to describe the bottom fluxes of water and NO_3^- by the 1-dimensional HYDRUS1-D model. 30% and 70% of N application for rapeseed and maize was applied uniformly before land preparation and the rest was applied to every furrow at CFI and to irrigated furrows with 1.0 m apart that is not very far. Therefore, in general HYDRUS-1D model could be suitable for simulation of N leaching at a higher soil depth (1.0 m). In this case the upper boundary of water and nitrogen on the soil surface can be considered on an average 1-dimansional as a whole. We used HYDRUS model since it is soil water and salt transfer model and it is more appropriate for simulation of leaching water and nitrogen in the rooting zone in field. Therefore, results of the present study may justify the use of HYDRUS-1D model for leaching water and nitrogen in the rooting zone. Furthermore, the role of plants in water and nitrogen uptake that grown on the all ridges, water redistribution process in the rooting zone, and simulation of the leaching water and nitrogen at a depth higher than which concerned by the 2-D process justified the use of HYDRUS-1D instead of HYDRUS-2D.

2.3.1. Soil water movement

Soil water movement for the experimental situation has been described in the model (Simunek et al., 2008) as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right] - S \tag{2}$$

Boundary and initial conditions are:

$$H = h_i(z) \quad \text{at} \quad -100 \le z \le 0, \quad t = 0 \tag{3}$$

$$-K\left(\frac{\partial h}{\partial z}+1\right) = E(t) \quad \text{at}\, z = 0, \quad t > 0 \tag{4}$$

$$\frac{\partial h}{\partial z} = 0 \quad \text{at}\, z = -100, \quad t > 0 \tag{5}$$

where θ is the soil volumetric water content (cm^3 cm^{-3}); h is the water pressure head (cm); K is the unsaturated hydraulic conductivity (cm d^{-1}); z is the vertical axis (upward positive) depending on the origin of the surface flux; $E(t)$ is the rate of infiltration or evapotranspiration (cm d^{-1}) that is time variable flux for irrigation or rainfall option in the model; S is the root water uptake rate (cm^3 cm^{-3} d^{-1}) that is considered as Feddes et al. (1978) function; h_i is the initial soil water pressure head (cm). In this study, the free drainage was used as the bottom boundary. Therefore, Eq. (5) was considered that $dh/dz = 0$. In Eq. (5), $z = -100$ was considered due to the maximum soil depth and root depth of 100 cm.

The value of S was determined by Feddes et al. (1978) equation as follows:

$$S = \alpha(h) S_{\max} \tag{6}$$

Table 3
Values of the coefficients of equation for root water uptake [Eq. (6)], cm.[a]

Plant	h_o	h_{opt}	h_{2H}	h_{2L}	h_3
Rapeseed	0	−1	−500	−900	−16,000
Maize	−15	−30	−325	−600	−8000

[a] Water uptake is assumed to be zero close to saturation (i.e., wetter than some arbitrary "anaerobiosis point" h_o). Root water uptake is also zero for pressure heads less than the wilting point (h_3). Water uptake is considered optimal between pressure heads h_{opt} and h_2, whereas for pressure heads between h_2 and h_3 (or h_o and h_{opt}) water uptake decreases (or increases) linearly with pressure head.

where S is the rate of root water uptake, S_{max} is the maximum rate of root water uptake and $\alpha(h)$ is the coefficient of root water uptake. The coefficients of Eq. (6) are presented in Table 3 (Simunek et al., 2008). In this equation, water uptake is assumed to be zero at close to saturation (i.e., wetter than some arbitrary "anaerobiosis" point, h_o). Root water uptake is also zero for pressure heads less than the wilting point (h_3). Water uptake is considered optimal between pressure head h_{opt} and h_2, whereas for pressure heads between h_2 and h_3 (h_o and h_{opt}) water uptake decreases (or increases) linearly with pressure head.

Root growth was described by the logistic growth function that is defined as follows (Simunek et al., 2008):

$$L_R(t) = L_m f_r(t) \quad (7)$$

$$f_r(t) = \frac{L_o}{L_o + (L_m - L_o)e^{-rt}} \quad (8)$$

where $L_R(t)$ is the root depth at time t (cm); L_o is the initial root depth (seeding depth, cm); L_m is the maximum root depth (cm); t is the number of days after planting; and r is the root growth ratio that is 0.03 and 0.07 for rapeseed and maize, respectively. The maximum root depth of rapeseed and maize were 100 cm and 100 cm, respectively, and seeding depths were 5 cm and 10 cm for rapeseed and maize, respectively.

Soil water hydraulic properties were the model inputs. van Genuchten (1980) and Mualem (1976) functions were represented the soil water retention, $\theta(h)$ and hydraulic conductivity, $K(h)$. Soil water hydraulic parameters are presented in Table 4.

Water and nitrogen uptake process was considered in the HYDRUS-1D version used in this study. Furthermore, crop evapotranspiration is used directly in the model with no separation of soil surface evaporation from transpiration.

2.3.2. Soil NO_3–N transport

Similar to the study of Wang et al. (2010), in this study, we assumed that soil organic N was mineralized directly into NO_3–N and ammonia volatilization was ignored due to irrigating soil immediately after nitrogen fertilizer application. Furthermore, experimental results in soils in this region showed that NO_3–N concentrations were much higher than NH_4–N concentrations (Sepaskhah and Yousefi, 2007), therefore we did not consider the NH_4–N movement.

Soil NO_3–N movement is described as follows (Simunek et al., 2008):

$$\frac{\partial(\theta \cdot C)}{\partial t} = \frac{\partial}{\partial z}\left[\theta \cdot D\left(\frac{\partial C}{\partial z}\right)\right] - \frac{\partial(q \cdot C)}{\partial z} + S_c \quad (9)$$

In case of no nitrogen application treatment, boundary and initial condition are:

$$C = C_o(z) \quad \text{at} \ -100 \le z \le 0, \quad t = 0 \quad (10)$$

$$\frac{\partial C}{\partial z} = 0, \quad \text{at}\, z = -100, \quad t > 0 \quad (11)$$

where C is the NO_3–N concentration in soil solution (mg L^{-1}); D is the effective dispersion coefficient of the soil matrix (cm^2 d^{-1}); and S_c is the sink term that includes mineralization, microbial immobilization and denitrification and is shown as follows:

$$S_c = S \times C_r + k_{\min} - k_{im} \times C - k_{den} \times C \quad (12)$$

where k_{min} is the mineralization rate constant (μg cm^{-3} d^{-1}); k_{im} is the microbial immobilization rate constant (d^{-1}); k_{den} is the denitrification rate constant (d^{-1}); S is the plant water uptake (cm d^{-1}) and C_r is the outflow nitrogen concentration that is a function of soil nitrogen concentration (C) and maximum root nitrogen uptake coefficient (C_{RM}). The values of C_{RM} for rapeseed and maize were 0.03 and 0.01, respectively that were obtained by model calibration. In concept, the rhizosphere dynamics of water and nutrient uptake is very complex, and may have to consider differentiation between passive and active N uptake, N mineralization and denitrification (Bar-Yosef, 1999). In order to avoid these complications of which the relative magnitude and relevance is yet to be determined, this study makes the typical assumption that root uptake of ammonium and nitrate is strictly passive and assumes that the other listed mechanisms are not occurring (Hanson et al., 2006). Therefore, nitrogen uptake is considered as the multiplication of plant water uptake by the soil mineral nitrogen concentration.

NO_3–N movement was considered a few days after irrigation events, therefore microbial immobilization and denitrification processes are ignored. The model is used to simulate the transport of NO_3–N while N was applied in form of urea. In this study we assumed that the urea is instantaneously nitrified to NO_3^-. This is justified by the fact that nitrification is fast compared to other process and it takes a few days (Havlin et al., 2006). Furthermore, there is some residual NO_3^- in soil before urea application that can be leached.

In case of nitrogen application treatments, the boundary conditions are as follows:

$$-\theta \cdot D\left(\frac{\partial C}{\partial z}\right) + q \cdot C = q_o \cdot C_o(t), \quad \text{at}\, z = 0, \quad t > 0 \quad (13)$$

where $C_o(t)$ is the nitrogen application rate at different times. Therefore, in model application, the concentration boundary conditions and free drainage were options that were used in the model.

Table 4
Soil hydraulic properties used in the HYDRUS-1D model.[a]

Soil layer(cm)	Texture	Particle fraction (%)			BD (g cm^{-3})	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	l	K_s (cm d^{-1})
		Clay	Silt	Sand							
0–15	Clay loam	30	35	35	1.25	0.11	0.47	0.0109	1.480	0.5	22.16
15–30	Clay loam	30	35	35	1.32	0.12	0.45	0.0110	1.474	0.5	15.24
30–50	Clay loam	39	38	23	1.36	0.14	0.46	0.0122	1.414	0.5	12.16
50–70	Clay	40	39	21	1.42	0.16	0.45	0.0122	1.399	0.5	8.58
70–100	Clay	40	39	21	1.42	0.16	0.45	0.0122	1.399	0.5	8.58

[a] BD is the soil bulk density, θ_r is the soil residual water content, θ_s is the soil saturation water content, α, n, and l are the parameters of soil hydraulic functions, and K_s is the soil saturated hydraulic conductivity.

2.4. Model calibration

In this model, soil is divided in different layers and physical properties are used as inputs (Table 4). In order to use minimum number of data as input in running the model, the parameters for soil water retention curve (van Genuchten, 1980) were estimated by the HYDRUS-1D model by using the soil particle fractions, bulk density (Table 4) and soil residual water content as 0.16 $cm^3\ cm^{-3}$. The estimated values of α, n and K_s (Table 4) are close to those determined by Mahbod and Zand-Parsa (2010) as 0.014 cm^{-1}, 1.33 and 20.6 cm d^{-1}, respectively. Furthermore, initial soil water content, residual soil mineral nitrogen content, and cropping duration are used in the model. Initial soil water contents for rapeseed and maize in different soil depths were 0.25–0.29 $cm^3\ cm^{-3}$ (mean value of 0.28 $cm^3\ cm^{-3}$) and 0.24–0.30 $cm^3\ cm^{-3}$ (mean value of 0.275 $cm^3\ cm^{-3}$), respectively. Mean initial soil mineral nitrogen (SMN) for rapeseed was 80.9 kg ha^{-1} and the residual soil mineral nitrogen (SRMN) at N application rates of 0, 100, 200, and 300 kg ha^{-1} for rapeseed were 70.6, 89.3, 119.5, and 117.7 kg ha^{-1}, respectively. These values were considered as the initial SMN for maize. The cropping duration of rapeseed and maize were 256 and 118 days, respectively. Amounts of rainfall, irrigation water, root depth, nitrogen fertilizer application rate at different times are inserted in the model. Nitrate concentration in irrigation water is also given as input (6.6 mg L^{-1}). By using single crop coefficient (K_c) of rapeseed and maize from Shaabani (2007) and Shahrokhnia (2009), respectively and daily reference evapotranspiration (ET_o), the daily crop evapotranspiration (ET_p) was calculated $K_c \times ET_o$ (Allen et al., 1998) and used in the model. The values of daily ET_o were determined by using modified Penman–Monteith equation (Razzaghi and Sepaskhah, 2012) and daily measured weather parameters in a nearby weather station. The values of ET_p and irrigation water at different treatments are presented in Figs. 2 and 3 for rapeseed and maize, respectively.

Soil solute transport parameters were the model inputs. They were modified to calibrate the model. The modified longitudinal dispersivity and molecular diffusion coefficient of NO_3–N in free water (D_o) were used as 1.0 cm and 1.65 $cm^2\ d^{-1}$, respectively.

2.5. Model performance criteria

Outputs of the model were drainage water (deep percolation), nitrate concentration of drainage water (NO_3–N) and crop nitrogen uptake. The outputs of the model were compared by the measured values using following statistical parameters:

$$\mathrm{RMSE} = \left\{1/n\left[\sum_{i=1}^{n}(X_i - Y_i)^2\right]\right\}^{0.5} \tag{14}$$

$$\mathrm{NRMSE} = \frac{\left[1/n\sum_{i=1}^{n}(X_i - Y_i)^2\right]^{0.5}}{O} \tag{15}$$

where RMSE and NRMSE are the root mean square error and normalized root mean square error, respectively, n is the number of observations, X is the measured values, Y is the estimated values and O is the mean values of measured data.

$$d = 1 - \left\{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(|X_i - O| + |Y_i - O_e|)^2}\right\} \tag{16}$$

where d is the index of agreement and O_e is the mean value of estimated data. The value of NRMSE and d approaches 0.0 and 1.0, respectively, for the accurate estimation. The closer the NRMSE is to 0, the model is more accurate. The value of d varies between 0 and 1.0 and the closer its value to 1.0, the model is more accurate.

3. Results and discussion

3.1. Yield

Grain yield for rapeseed and maize are shown in Table 5. At N application rates of 200 and 300 kg ha^{-1}, grain yields of rapeseed were statistically similar at CFI and VAFI. However, their values were statistically lower at FAFI. At N application rates of less than 200 kg ha^{-1}, grain yields of rapeseed at CFI were higher than those at VAFI and FAFI and FAFI resulted in lower grain yields of rapeseed than VAFI ($p < 0.05$). These results indicated that at lower N application rates, higher water application is needed to obtain higher yield, while N application rate of 200 kg ha^{-1} is the optimum and in this N application rate, VAFI with lower water application resulted in similar yield of rapeseed to CFI (7% reduction) with lower water application (25%).

At N application rates of 200 and 300 kg ha^{-1}, grain yields of maize were statistically similar at VAFI and FAFI. However, they were statistically lower at N application rates of 0 and 100 kg ha^{-1}. At CFI, their yields increased as a function of N application rates. Grain yields of maize decreased at CFI, VAFI and FAFI, respectively at 0–200 kg ha^{-1}. However, they were statistically similar at VAFI and FAFI at N application rate of 300 kg ha^{-1}. In general, for maize it is indicated that under water shortage, if VAFI is going to be used, lower N application rate is appropriate to be used (i.e., 200 kg ha^{-1}), while under full irrigation condition, higher N application rate (i.e., 300 kg ha^{-1}) is appropriate

3.2. Deep percolation

Predicted and measured values of cumulative deep percolation (DP) at different days after planting for different irrigation treatments are presented in Figs. 4 and 5 for rapeseed and maize, respectively. Cumulative DP values for rapeseed increased rapidly at around 190 days after planting. This is obtained due to higher irrigation water depth applied at irrigation events after this time because of rapid growth of rapeseed crop that is occurred due to increase in air temperature at this time. In general, the cumulative DP is lower at VAFI and FAFI compared with CFI. This occurred because of lower volume of irrigation water in VAFI and FAFI that was distributed in a given volume of soil compared with CFI. Therefore, the DP is reduced in VAFI and FAFI.

Maize was planted immediately after rapeseed harvest. Therefore, the initial soil water content was higher than those occurred in rapeseed field at initiation of vegetative growth at late winter or early spring. Due to low amount of rainfall in autumn and winter in rapeseed growing season (175 mm) the soil water content at the initiation of vegetative growth at late winter or early spring was

Table 5
Grain yield (kg ha^{-1}) of rapeseed and maize in different irrigation and N treatments.

Nitrogen application rate, kg ha^{-1}	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
Rapeseed			
0	1889c*	1351d	844f
100	2208b	1800c	1054e
200	3444a	3210ab	1812c
300	3420a	3200ab	1850c
Maize			
0	4326f*	2087h	1390i
100	6969c	3337g	2314h
200	10553b	6419cd	5747e
300	11274a	6468cd	5987e

* Means followed by the same letters in each crop are not significantly different at 5% level of probability.

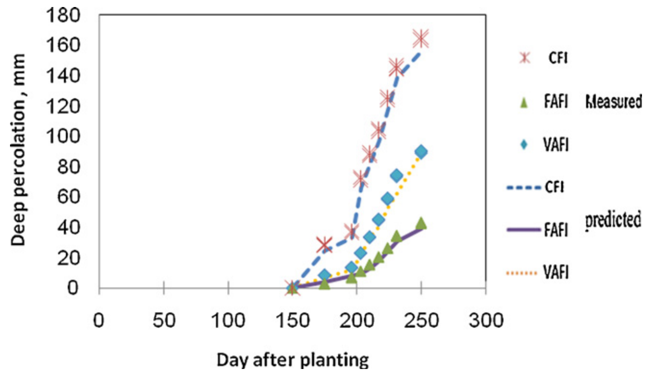

Fig. 4. Deep percolation at different days after planting under different irrigation methods for rapeseed.

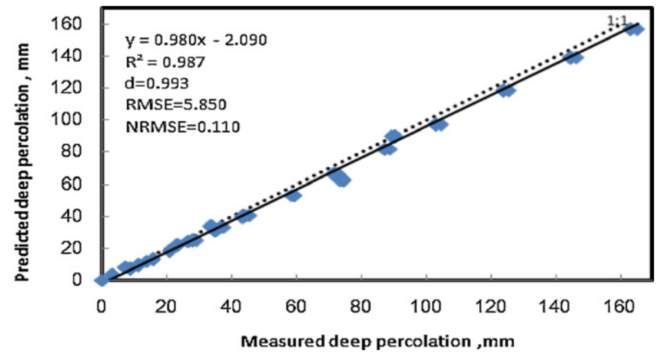

Fig. 6. Relationship between predicted and measured values of deep percolation for rapeseed.

lower than those for maize. Therefore, DP losses for maize were higher than those occurred in rapeseed (Figs. 4 and 5). This difference among two crops occurred because of higher initial soil water content in maize field at planting compared to soil water content of rapeseed field at initiation of vegetative growth at late winter or early spring.

Different irrigation treatments received very different irrigation doses that could explain the different amount of DP and nitrate leached between the different treatments. Although these differences would be more attributable to the irrigation amounts than to the irrigation practice itself, however for rapeseed grain yields were similar at CFI and VAFI. This indicates that with reduction in irrigation water dose in VAFI, DP and leached NO_3–N decreased while grain yield was not reduced for rapeseed. Therefore, the irrigation method in practice is important in irrigation and nitrogen management to reduce the water and nitrogen losses with no yield loss.

The measured values of DP matched well the predicted values. This indicated that the HYDRUS-1D model is capable to predict DP at different irrigation regimes. These evaluations for rapeseed and maize are shown in Figs. 6 and 7, respectively by comparing linear relationship between the predicted and measured values of DP with the 1:1 line. The slope of the linear relationship is statistically equal to 1.0 and the values of NRMSE and d are 0.11 and 0.993 for rapeseed, and 0.094 and 0.994 for maize that are close to 0.0 and 1.0. These indicated a high accuracy of the prediction of DP by HYDRUS-1D model for rapeseed and maize.

3.3. NO_3–N leaching

Values of measured and predicted cumulative leached NO_3–N at different days after planting for different irrigation methods and nitrogen application rates are shown in Figs. 8 and 9 for rapeseed and maize, respectively. For rapeseed, maximum leached NO_3–N at CFI was 7.5 and 11.0 kg ha^{-1} at 0 and 300 kg ha^{-1} N application, respectively. These values were 2.0 and 3.5 kg ha^{-1} for FAFI and 4.0 and 6.5 kg ha^{-1} for VAFI, respectively. In general, leached NO_3–N is lower at VAFI and FAFI compared with those at CFI. Furthermore, these values are lower at lower N application rates.

For maize, maximum leached NO_3–N at CFI was 16.0 and 55.0 kg ha^{-1} at 0 and 300 kg ha^{-1} N application rates, respectively. These values were 8.0 and 24.0 kg ha^{-1} for FAFI and 9.0 and 25.0 kg ha^{-1} for VAFI, respectively. In general, leached NO_3–N is lower at VAFI and FAFI compared with those at CFI. This occurred as a result of lower DP in VAFI and FAFI compared with CFI (Figs. 4 and 5). These values are lower at lower N application rates. In general, the NO_3–N leaching in this study is much lower than those reported by Wang et al. (2010) in a loam to silt loam soil with mean annual rainfall of 560 mm and flooding surface irrigation. Therefore, lower NO_3–N leaching in the present study was due to higher irrigation efficiency, low seasonal rainfall and heavier soil texture.

Figs. 8 and 9 indicated that the HYDRUS-1D model predicted the leached NO_3–N accurately. To show the accuracy of prediction of leached NO_3–N, it was compared with the measured values in Figs. 10 and 11 for rapeseed and maize, respectively. The linear relationship between the measured and predicted values of leached NO_3–N was compared with the 1:1 line. The slope of the linear relationship is statistically equal to 1.0 and the values of NRMSE and d are 0.14 and 0.992 for rapeseed and 0.18 and 0.992

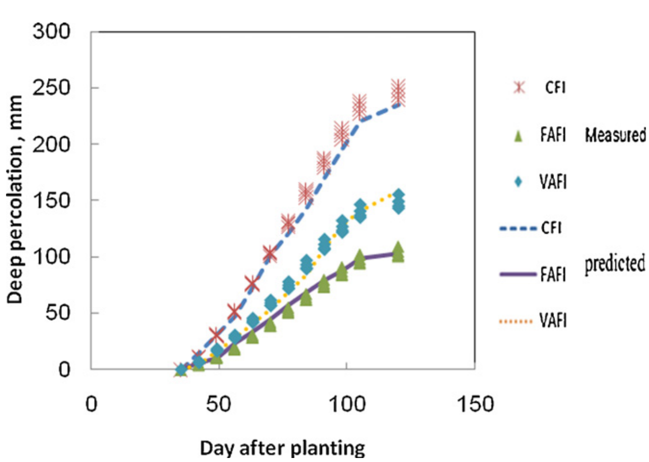

Fig. 5. Deep percolation at different days after planting under different irrigation methods for maize.

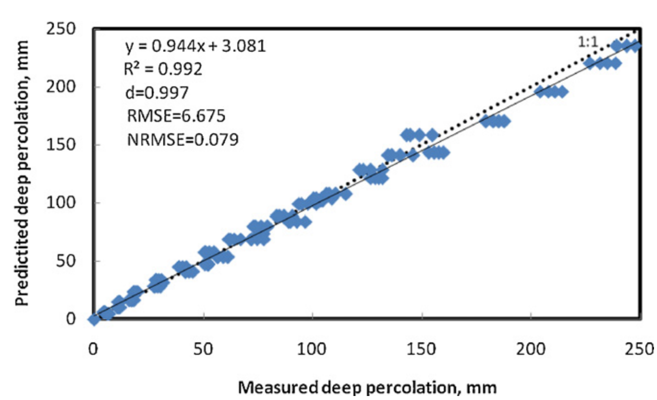

Fig. 7. Relationship between predicted and measured values of deep percolation for maize.

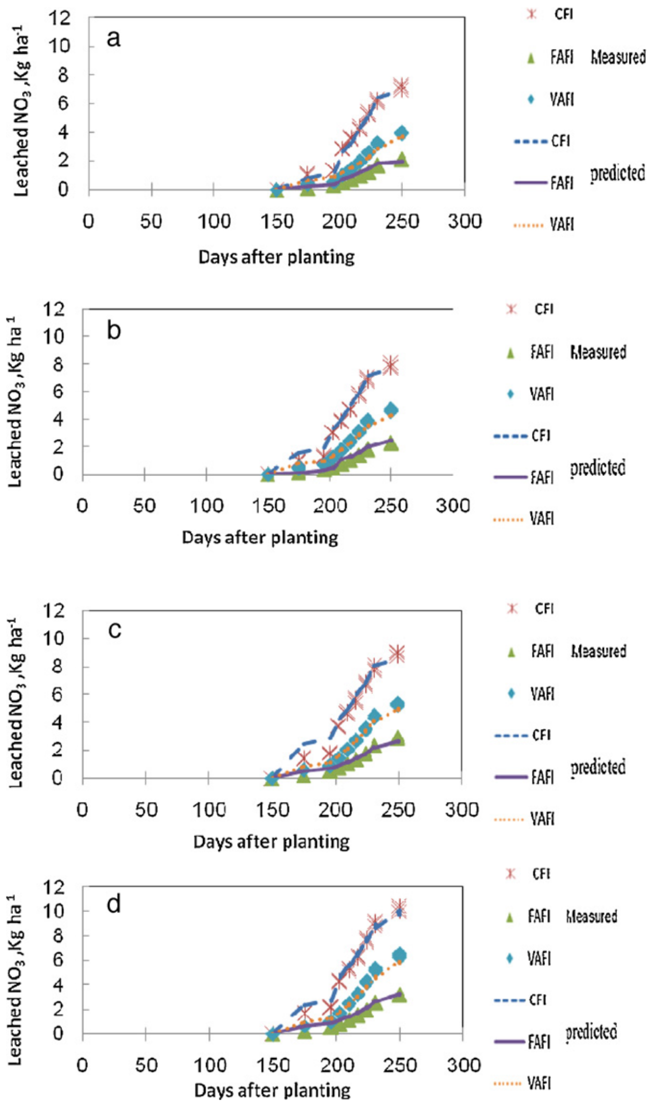

Fig. 8. Nitrate leaching at different days after planting under different irrigation methods and N application rates for rapeseed: (a) 0 kg ha^{-1}, (b) 100 kg ha^{-1}, (c) 200 kg ha^{-1}, (d) 300 kg ha^{-1}.

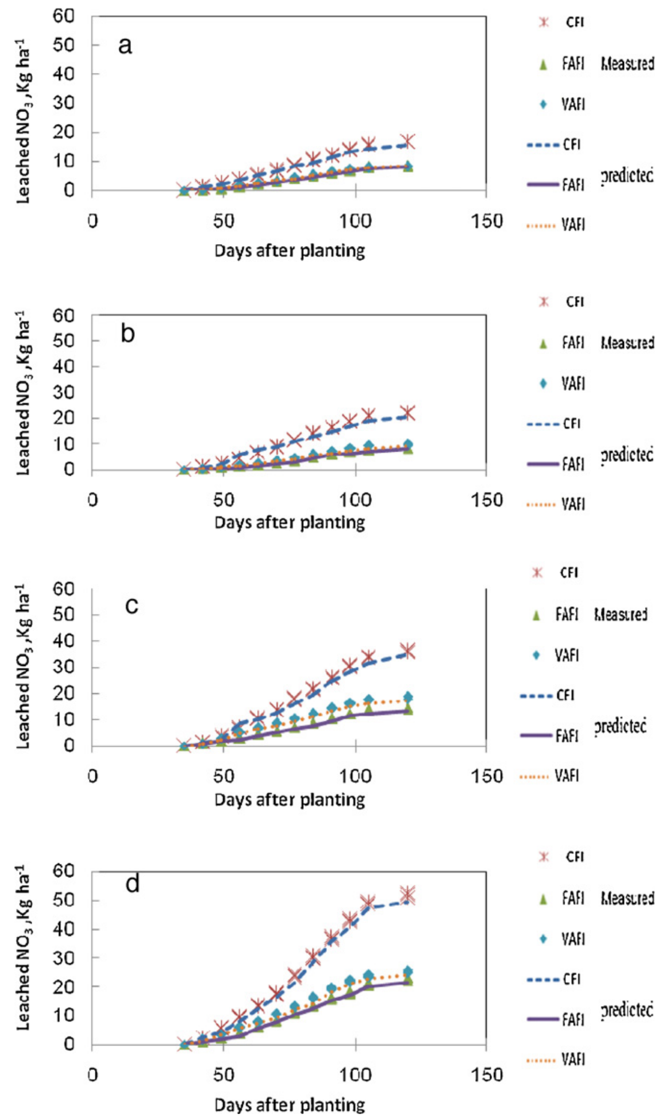

Fig. 9. Nitrate leaching at different days after planting under different irrigation methods and N application rates for maize: (a) 0 kg ha^{-1}, (b) 100 kg ha^{-1}, (c) 200 kg ha^{-1}, (d) 300 kg ha^{-1}.

for maize, respectively that are close to 0.0 and 1.0. These indicated a high accuracy of the prediction of leached NO_3–N by HYDRUS-1D model for rapeseed and maize. It seems that although we used 1-dimensional model for 2-dimnsional problem, it was able to describe the bottom fluxes reasonably well. Although it is anticipated that at some depth the bottom fluxes of water and NO_3^- can be 1-dimensional, however we do not have experimental evidence or comparison of results with 1- and 2-dimensional models to sustain that hypothesis.

3.4. Crop N uptake

Predicted cumulative crop N uptake for rapeseed and maize as a function of days after planting (DAP) and different irrigation methods and N application rates are presented in Figs. 12 and 13. N uptake in Figs. 12 and 13 are given in mg cm^{-2}, however the cumulative N uptake at the harvest are converted to kg ha^{-1} and presented in Table 6. Tafteh (2010) reported that potential dry matter yields of 28.8 t ha^{-1} and 7.6 t ha^{-1} for maize and rapeseed, respectively are associated with N application rates of 200–300 kg ha^{-1} that could result in N uptake of those given in Table 6. It is indicated that for rapeseed up to 170 DAP the rate of N uptake (slope of

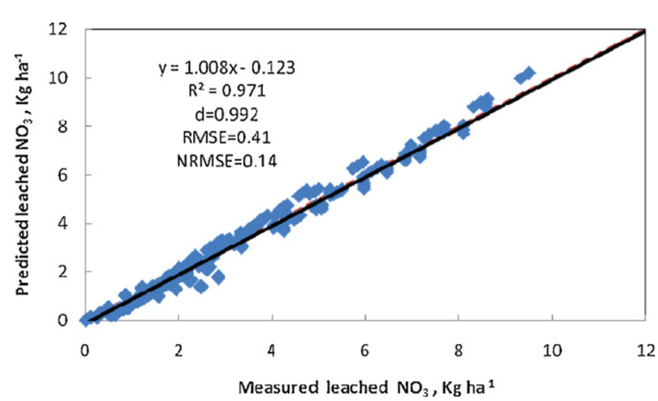

Fig. 10. Relationship between predicted and measured nitrate leaching for rapeseed.

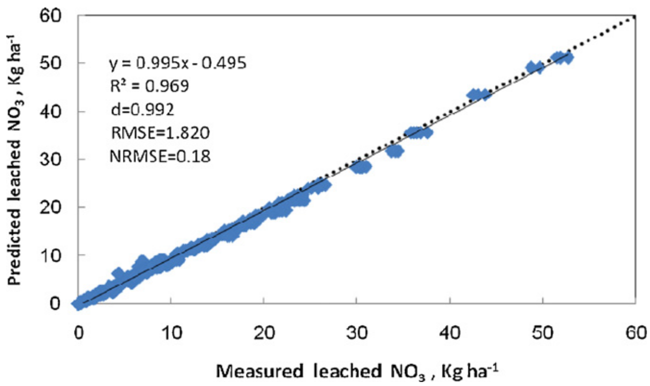

Fig. 11. Relationship between predicted and measured nitrate leaching for maize.

curves in Fig. 12) was lower and it increased at a higher rate later on (Fig. 12). This occurred due to application of second half of N fertilizer at 165 DAP and occurrence of reproduction stage of rapeseed. The values of measured and predicted N uptake for rapeseed at harvest as kg ha^{-1} are shown in Table 6. Predicted values of N uptake at harvest are the end point of curves in Figs. 12 and 13. Mean values of N uptake were compared by using Duncan multiple range test at probability level of 5%. There is no statistically significant difference between crop N uptake in different irrigation methods at 0 N application rate ($p < 0.05$). At N application rates of 100–300 kg ha^{-1}, there is no statistically significant difference between N uptake in CFI and VAFI, however it was decreased at FAFI ($p < 0.05$). N uptake in FAFI was reduced 35% compared with CFI. In general, at all irrigation methods, N uptake increased as N application rate increased.

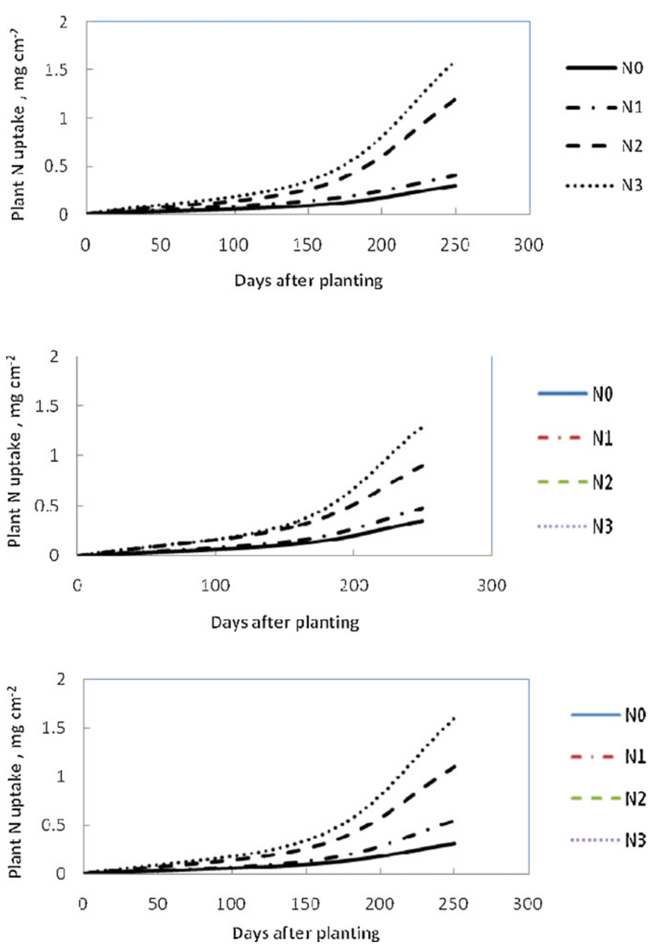

Fig. 12. Predicted crop N uptake at different days after planting under different irrigation methods (upper CFI, middle FAFI, lower VAFI) in different N application rates for rapeseed.

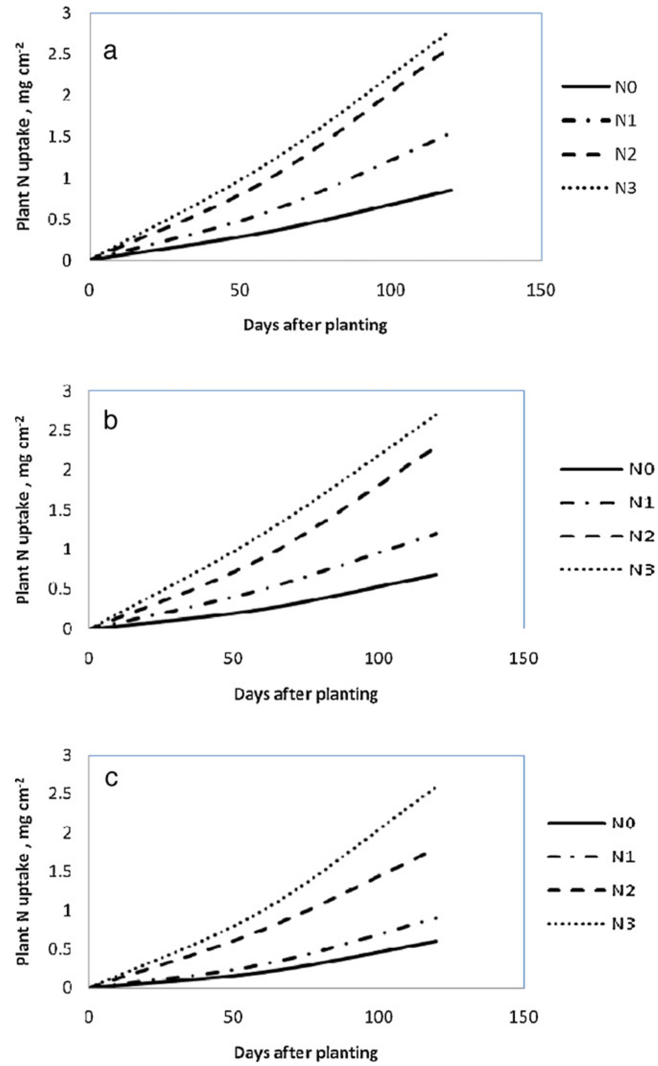

Fig. 13. Predicted crop N uptake at different days after planting under different irrigation methods (a: CFI, b: FAFI, c: VAFI) in different N application rates for maize.

Table 6
Seasonal measured and predicted crop N-uptake (kg ha^{-1}) by HYDRUS-1D model for rapeseed and maize under different irrigation methods and N application rates.

N application rates, kg ha^{-1}	OFI[a]		VAFI		FAFI	
	Meas.	Predic.	Meas.	Predic.	Meas.	Predic.
Rapeseed						
0	22.6fg[*]	30.0	19.8fg	31.0	15.3g	35.0
100	37.7e	40.0	35.0e	55.0	25.3f	48.0
200	104.6b	120.0	99.2b	110.0	68.8d	90.0
300	145.5a	163.0	147.9a	160.0	90.6c	130.0
Maize						
0	89.3efg	85.0	32.8g	62.0	52.2fg	68.0
100	157.0e	155.0	63.2fg	91.0	88.0efg	120.0
200	237.0ab	260.0	164.8cd	180.0	185.2c	234.0
300	279.0a	282.0	206.4bc	263.0	224.6ab	271.0

[*] Means followed by the same letters in each trait are not significantly different at 5% level of probability.
[a] OFI is ordinary furrow irrigation, VAFI is variable alternate furrow irrigation, and FAFI is fixed alternate furrow irrigation.

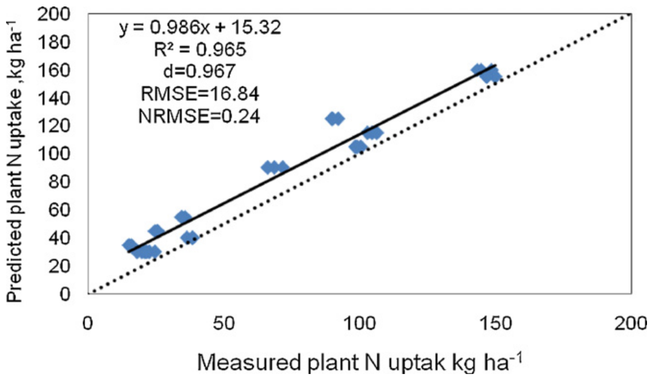

Fig. 14. Relationship between predicted and measured crop N uptake for rapeseed.

For rapeseed, N uptake order is CFI > VAFI > FAFI and their differences are statistically significant ($p < 0.05$) (Table 6). The lower N uptake in FAFI than that in VAFI is due to the considerable reduction in top dry matter in FAFI as reported by Tafteh (2010). However, N uptake order for maize is CFI > FAFI > VAFI, although the differences in FAFI and VAFI are not statistically significant ($p < 0.05$). Not considerable higher N uptake in FAFI occurred due to not considerable lower top dry matter and higher N content in FAFI (Tafteh and Sepaskhah, 2012).

For maize, up to 50 DAP the rate of N uptake increase was lower and it increased at a higher rate later on (Fig. 13). This occurred due to application of second half of N fertilizer at 50–60 DAP, and occurrence of reproduction stage. The values of measured and predicted N uptake for maize are shown in Table 6. There is no statistically significant difference between N uptake in different irrigation methods at 0 N application rate. At N application rates of 100–300 kg ha^{-1}, there is no statistically significant difference between N uptake at FAFI and VAFI. However it was higher at CFI. N uptake in AFI (mean value at VAFI and FAFI) was reduced 31% compared with CFI. In general, at all irrigation methods, N uptake increased as N application rates increased and this increase was 77% at 300 kg N ha^{-1} compared with 0 kg N ha^{-1}.

At harvest, predicted crop N uptake by HYDRUS-1D model at different irrigation methods and N application rates are compared with the measured values in Figs. 14 and 15 for rapeseed and maize, respectively. The relationship between measured and predicted crop N uptake at harvest is compared with the 1:1 line. The slope of this line is not different from 1.0. However, the intercept is about 15 and 25 kg ha^{-1} higher than 0.0 for rapeseed and maize, respectively. These are obtained due to not considering the root N uptake in the measured values, and neglecting N mineralization, denitrification and microbial immobilizatrion processes. Therefore, if 10–15% of top N uptake were included in the top N uptake the intercepts would have been equal to 0. Similar results were reported for rapeseed by Zlatko and Zdenko (2005) that indicated a root N uptake of rapeseed is about 18–26% of total crop N uptake. Furthermore, Biernath et al. (2008) reported that N uptake for maize root was 5–20% of total N uptake that is in correspondence to those obtained in this study.

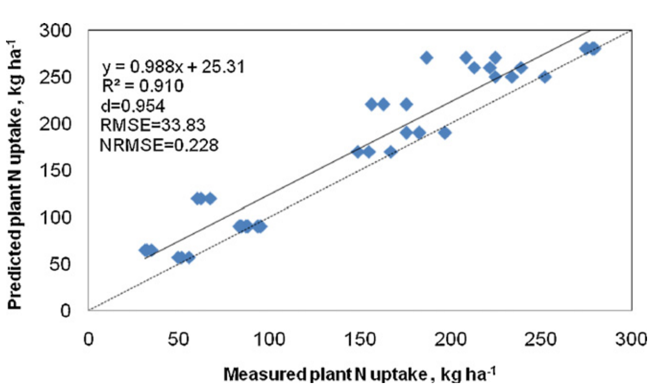

Fig. 15. Relationship between predicted and measured crop N uptake for maize.

The values of NRMSE and d for total crop N uptake are 0.24 and 0.967 for rapeseed and 0.228 and 0.954 for maize, respectively. The values of d are close to 1.0. However, the values of NRMSE are not close to 0.0 that indicated a fair accuracy of HYDRUS-1D model in prediction of crop N uptake for rapeseed and maize that might be due to not considering root N uptake in total crop N uptake. The overall crop N uptake was determined in plants that are sampled from the furrows irrigated and not irrigated in VAFI and FAFI. Therefore, 1-dimensional HYDRUS-1D model was able to describe the N uptake as well.

4. Conclusions

HYDRUS-1D model was used to simulate the transport of NO_3–N of the applied N fertilizer with different rates under CFI and AFI (PRD). For rapeseed, the amounts of NO_3–N leaching in 1.0 m soil profile under CFI, FAFI and VAFI were 8.7, 5.2 and 2.7 kg ha^{-1}, respectively and it was increased from 4.7 kg ha^{-1} for no N application to 7.3 kg ha^{-1} for 200–300 kg ha^{-1} N application rates. For maize, the mean amounts of NO_3–N leaching in 1.0 m soil profile under VAFI and FAFI were similar (13.8 kg ha^{-1}) and it was higher under CFI (31.1 kg ha^{-1}). It was increased from 10.3 kg ha^{-1} in no N application rate to 31.4 kg ha^{-1} in 300 kg ha^{-1} N application rate.

N uptakes for rapeseed were similar under CFI and VAFI (71.5 kg ha^{-1}) and it was increased from 19.2 kg ha^{-1} to 128.0 kg ha^{-1} in N application rates from 0 to 300 kg ha^{-1}. For maize, N uptakes were similar under VAFI and FAFI (127 kg ha^{-1}) and it was higher under CFI (200 kg ha^{-1}). Furthermore, it was increased from 50 kg ha^{-1} to 250 kg ha^{-1} in 0 to 300 kg ha^{-1} N application rates.

Seasonal deep percolation in rapeseed field was reduced 39% and 72% under VAFI and FAFI, respectively compared with CFI. These reductions for maize were 40% and 57%, respectively. It is concluded that for both crops, HYDRUS-1D model was able to simulate deep percolation, and NO_3–N leaching with a very good accuracy (NRMSE of 0.11 and 0.094 for DP of rapeseed and maize, and 0.14 and 0.18 for NO_3–N leaching of rapeseed and maize, respectively). However, difference between the measured and predicted N-uptake was occurred and it was attributed to the excluding root nitrogen uptake in the measured values.

Acknowledgements

This research was supported in part by Grant No. 91-GR-AGR-42 of Shiraz University Research Council, Drought National Research Institute, and Center of Excellence on Farm Water Management.

References

Abbasi, F., Feyen, J., van Genuchten, M.Th., 2004. Two-dimensional simulation of water flow and solute transport below furrows: model calibration and validation. Journal of Hydrology 290, 63–79.
Ahmadi, S.H., Andersen, M.N., Plauborg, F., Poulsen, R.T., Jensen, C.R., Sepaskhah, A.R., Hansen, S., 2010. Effects of irrigation strategies and soils on field grown potatoes: yield and water productivity. Agricultural Water Management 97, 1923–1930.
Allen, R.G., Perrier, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56, Rome, Italy.
Bar-Yosef, B., 1999. Advances in fertigation. Advances in Agronomy 65, 1–75.
Biernath, C., Fischer, H., Kuzyakov, Y., 2008. Root uptake of N-containing and N-free low molecular weight organic substances by maize. Soil Biology and Biochemistry 40, 2237–2245.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen: total. In: Page, A.L., et al. (Eds.), Methods of Soil Analysis: Part 2. Agronomy Monograph , 2nd ed. ASA, ASSA, Madison, WI, pp. 595–641.

Crevoisier, D., Popova, Z., Mailhol, J.C., Ruelle, P., 2008. Assessment and simulation of water and nitrogen transfer under furrow irrigation. Agricultural Water Management 95, 354–366.

Chapman, H.D., Pratt, P.F., 1961. Methods of Analysis for Soil, Plants and Water. University of California, Division of Agricultural Sciences, pp. 1–309.

Ersahin, S., Karaman, M.R., 2001. Estimating potential nitrate leaching in nitrogen fertilized and irrigated tomato using the computer model NLEAP. Agricultural Water Management 51, 1–12.

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of Field Water use and Crop Yield. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, The Netherlands, p. 189.

Follett, R.F., 1995. NLEAP model simulation of climate and management effects on N leaching for corn grown on sandy soil. Journal of Contaminant Hydrology 20 (3–4), 241–252.

Gheysari, M., Mirlatifi, S.M., Homaee, M., Asadi, M.S., Hoogenboom, G., 2009. Nitrate leaching in a silage maize field under different irrigation and nitrogen fertilizer rates. Agricultural Water Management 96, 946–954.

Hanson, B.R., Simunek, J., Hopmans, J.W., 2006. Evaluation of urea–ammonium–nitrate fertigation with drip irrigation using numerical modeling. Agricultural Water Management 86, 102–113.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2006. Soil Fertility and Fertilizers, 7th ed. Prentice Hall of India, New Delhi.

Hu, C.S., Saseendran, S.A., Green, T.R., Ma, L.W., Li, X.X., Ahuja, L.R., 2006. Evaluating nitrogen and water management in a double-cropping system using RZWQM. Vadose Zone Journal 5, 493–505.

Jala, D.J., Toth, D.T., Zhengxia, D., Richard, H.F., Daniel, D.F., 1994. Evaluation of nitrogen version of LEACHM for predicting nitrate leaching. Soil Science 160 (3), 209–217.

Li, Y., Ghodrati, M., 1994. Preferential transport of nitrate through soil column containing root channel. Soil Science Society of America Journal 58, 653–659.

Li, X.X., Hu, C.S., Delgado, J.A., Zhang, Y.M., Ouyang, Z.Y., 2007. Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in North China Plain. Agricultural Water Management 89 (1–2), 137–147.

Mahbod, M., Zand-Parsa, Sh., 2010. Prediction of soil hydraulic parameters by inverse method using genetic algorithm optimization under field conditions. Archives of Agronomy and Soil Science 56 (1), 13–28.

Mailhol, J.C., Crevoisier, D., Troki, K., 2007. Impact of water application conditions on nitrogen leaching under furrow irrigation: experimental and modeling. Agricultural Water Management 87, 275–284.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12 (3), 513–522.

Pirmoradian, N., Sepaskhah, A.R., Maftoun, M., 2004. Deficit irrigation and nitrogen effects on nitrogen efficiency and grain protein of rice. Agronomie 24 (9–11), 143–153.

Razzaghi, F., Sepaskhah, A.R., 2012. Calibration and validation of four common ET_o estimation equations by lysimeter data in a semi-arid environment. Archives of Agronomy and Soil Science 58 (3), 303–319

Sepaskhah, A.R., Kamgar-Haghighi, A.A., 1997. Water use and yields of sugarbeet grown under every-other-furrow irrigation with different irrigation intervals. Agricultural Water Management 34, 71–79.

Samadi, A., Sepaskhah, A.R., 1984. Effects of alternate furrow irrigation on yield and water use efficiency of dry beans. Iran Agricultural Research 3, 95–116.

Sepaskhah, A.A., Ahmadi, S.H., 2010. A review on partial root-zone drying irrigation. International Journal of Plant Production 4 (4), 241–258.

Sepaskhah, A.R., Ghasemi, M.M., 2008. Every-other-furrow irrigation with different irrigation intervals for grain sorghum. Pakistan Journal of Biological Sciences 11 (9), 1234–1239.

Sepaskhah, A.R., Hosseini, S.N., 2008. Effects of alternate furrow irrigation and nitrogen application rates on yield and water- and nitrogen-use efficiency of winter wheat (*Triticum aestivum* L.). Plant Production Science 11 (2), 250–259.

Sepaskhah, A.R., Yousefi, F., 2007. The effects of zeolite application on nitrate and ammonium retention of a loamy soil under saturated conditions. Australian Journal of Soil Research 45, 368–373.

Sepaskhah, A.R., Parand, A.R., 2006. Alternate furrow irrigation with supplemental every furrow irrigation at different growth stages of maize (*Zea mays* L.). Plant Production Science 9 (4), 415–421.

Sepaskhah, A.R., Khajehabdollahi, M.H., 2005. Alternate furrow irrigation with different irrigation intervals for maize. Plant Production Science 8 (5), 592–600.

Shaabani, A., 2007. Effect of water stress on different growth stages of oil seed rape (*Brassica napus* L.). M.Sc. Thesis. Irrigation Department, Shiraz University, p. 192 (in Persian).

Shahrokhnia, M.H., 2009. Determination of crop coefficients and potential evapotranspiration for wheat and maize by weighing lysimeter in Kooshkak region, Fars province. M.Sc. Thesis. Irrigation Department, Shiraz University, Shiraz, Iran.

Simunek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M.Th., 2008. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media Version 4.0. Department of Environmental Sciences, University of California Riverside, California.

Stewart, L.K., Charlesworth, P.B., Bristow, K.L., Thorburn, P.J., 2006. Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. Agricultural Water Management 81, 315–334.

Tafteh, A., 2010. The study of interaction effects between alternate furrow irrigation and different levels of nitrogen on canola and maize in volumetric lysimeters. M.Sc. Thesis. Irrigation Department, Shiraz University.

Tafteh, A., Sepaskhah, A.R., 2012. Yield and nitrogen leaching in maize field under different nitrogen application rates and partial root drying irrigation. International Journal of Plant Production 6 (1), 93–114.

Tavakoli, A.R., Oweis, T.Y., 2004. The role of supplemental irrigation and nitrogen in producing bread wheat in the highlands of Iran. Agricultural Water Management 65, 225–236.

van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.

Wang, H., Ju, X., Wei, Y., Li, B., Zhao, L., Hu, K., 2010. Simulation of bromide and nitrate leaching under heavy rainfall and high-intensity irrigation rates in North China Plain. Agricultural Water Management 97, 1646–1654.

Williams, J.R., Kissel, D.E., 1991. Water percolation: an indicator of nitrogen-leaching potential. In: Luxmore, R.J. (Ed.), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am. Inc., Madison, WI, USA, pp. 59–83.

Zlatko, S., Zdenko, R., 2005. Canola cultivars differ in nitrogen utilization efficiency at vegetative stage. Field Crops Research 97, 221–226.