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Excessive use of nitrogen (N) fertilizers is likely to be responsible for the increasing nitrate in groundwater. Thus, appropriate water and nutrient management is required to minimize groundwater pollution and to maximize the nutrient-use efficiency. In this study HYDRUS-2D software package was applied to simulate nitrate leaching from a drip-irrigated sandy agricultural soil for varying emitter discharges and various amounts of fertilizer. It was found that for small emitter discharge values free drainage increased significantly with increase in discharge, whereas the increase was leveled out at greater discharge values. Nitrate leaching increased with an increase in emitter discharge and amount of fertilizer, but the rate of increase was most significant for low emitter discharges. Based on the results, with regard to the selection of emitter discharge and the amount of appropriate fertilizer amount, nitrate leaching from a potato field can be minimized even in a sandy soil.

Keywords Drip fertigation, HYDRUS-2D, modeling, nitrate leaching

Introduction

Ammonium (NH_4^+) and nitrate (NO_3^-) are absorbed and utilized by crops and termed as available nitrogen (N). Nitrate is highly mobile and leachable because it is not adsorbed by particles in most soils. Therefore, excessive application of N might lead to nitrate pollution of ground and surface waters (Hayens 1985; Waskom 1994).

The regular excessive application of N fertilizers with irrigation water therefore is likely to be responsible for the increase in nitrate concentrations of groundwater resources

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in climatic regions where irrigation agriculture is dominated. The degree of nitrate leaching depends on soil properties, crops and crop rotation, irrigation methods, management practices, and climatic parameters. Therefore, alternative irrigation and soil management practices are needed to maximize the application efficiency of water and fertilizer, thereby minimizing leaching of N out of the root zone to the groundwater (Bar-Yosef 1999). An alternative management method is fertigation where soluble fertilizer is applied via the irrigation water, thereby improving water- and nutrient-use efficiencies, aiming at maximizing farmer's income and minimizing pollution (Bar-Yosef 1999). Wetting patterns in soil and the spatial distribution of soil water, matric potential, and nitrate concentrations depend on soil hydraulic properties, emitter discharge rates, spacing and placement of emitters, irrigation amount and frequency, crop water uptake rates, and root distribution patterns (Gardenas et al. 2005). Appropriate design of drip fertigation system requires detailed knowledge of water- and nutrient-distribution patterns in the root zone, nutrient availability in the vicinity of roots, and nutrient leaching below the root zone, which is a function of discharge of emitter and soil hydraulic and physical properties (Hanson et al. 1996).

Field experiments to investigate water and nutrient distribution for evolving appropriate design and management options is a costly and time-consuming affair. A properly calibrated and validated water flow and solute transport model can reduce time and cost required for studying the water and nutrient dynamics under a drip irrigation system. Computer models provide an understanding of the relationships among the amount and timing of water and nutrient applications, the crop root uptake, yield, soil hazard, and groundwater pollution (Antonopoulos 2001). Many researchers have demonstrated that the HYDRUS-2D package is a convenient tool for modeling and simulation of N dynamics under drip irrigation conditions. Cote et al. (2003) used HYDRUS-2D to analyze the soil wetting and solute transport in subsurface trickle irrigation under various irrigation and fertigation strategies. They demonstrated that fertigation at the beginning of the irrigation cycle might reduce nitrate leaching under specific conditions. Gardenas et al. (2005) investigated nitrate leaching from citrus, grape, tomato, and strawberry fields for various fertigation scenarios under micro-irrigation fertigation using HYDRUS-2D. They reported that seasonal leaching was the greatest for coarse-textured soils and that fertigation at the beginning of the irrigation cycle increased seasonal nitrate leaching, in contrast to fertigation at the end of the irrigation cycle. Ajdari et al. (2007) investigated modeling of N leaching from experimental onion field under drip fertigation using HYDRUS-2D. They reported that the effect of soil type on N leaching was larger than the emitter discharge rates. Dultra and Munoz (2010) investigated simulation of N leaching from a fertigated crop rotation in a Mediterranean climate using the EU-Rotate_N and HYDRUS-2D models. They found that the results of both models when predicting of N leaching were acceptable.

Potato (*Solanum tuberosum* L.) rates fourth among the world's agricultural products in production volume after wheat, rice, and corn (Fabeiro, Martin de Santa Olalla, and de Juan 2001). The area under potato cultivation in Iran is 186,000 ha, with total production of 4.8 million tons. In Iran, potato is cultivated under irrigated conditions with excessive application of N fertilizer and water due to the low cost of both. Until now, there has been no estimate of N losses from potato fields at the country level. Considering the large area under potato cultivation, the N losses from the potato field could be substantial. Leaching losses of nitrate can be minimized if fertilizer is applied through drip fertigation. Approximately 85% of the root length of the potato is concentrated in the upper 0.3 m of the soil (Kang et al. 2002). This facilitates the loss of mobile compounds such as nitrate by excessive irrigation compared to more deeply rooted crops. Therefore, water and N management in potato field is very important especially in coarse-textured soil from production and nitrate loss points of view.

The main objective of our study was to determine the nitrate leaching below the root zone from a sandy soil under different irrigation intensities and fertilizer amounts using the solute transport model HYDRUS-2D. The study involved field experiments, modeling of water transport, and nitrate leaching. Field data were used to calibrate and validate the solute transport model. We hypothesis that potato cultivators can benefit from these results by selecting appropriate irrigation and fertilizer techniques to minimize nitrate leaching and obtain greater yields.

Materials and Methods

Experimental Details and Measurements

The experiment was conducted at an agricultural experimental station in the city of Jiroft in Kerman Province located in the southern part of Iran (26° to 29° N and 56° to 59° E) during 2009–2010. The climate is semi-arid with a mean annual temperature of 27.8 °C and a mean annual rainfall of 175 mm. Prior to planting of the potato, field was heavily irrigated twice to remove excess salts from the root zone. Soil samples were collected from different layers from surface to a depth of 1.2 m before planting the potatoes. The samples were analyzed in the laboratory to determine physical and chemical properties (Tables 1 and 2). Soil texture of all the soil layers was sandy according to the USDA classification system.

Irrigation and Fertigation Schedule. Distance between each emitter was 20 cm, and the distance between each row was 60 cm. Irrigation water was applied on alternate days during the crop growing period based on crop water demand and growth stage of potatoes at a rate of 1 L h^{-1} through drip emitters placed at the soil surface parallel to and within the crop row. The amount of water applied during each irrigation varied with the water requirement of the potato and was regulated by increasing or decreasing the interval and the duration of the irrigation events. The duration of irrigation events varied from 2 to 4 h. Potassium nitrate (KNO_3) was used as a fertilizer in the fertigation system and applied through the irrigation water. Fertigation was started immediately after the emergence of the potato plants. Total amounts of 600 mm irrigation water and 200 kg N ha^{-1} were applied

Table 1
Physical properties of soil of the experimental field

Depth (cm)	Soil texture (g/100 g) Sand	Silt	Clay	Textural class	Bulk density (g/cm^3)	Fc (%vol)	Pwp (%vol)
0–20	81.6	15	3.4	Sand	1.47	15.1	5.2
20–40	80.2	14.4	5.4	Sand	1.59	14.96	5.1
40–60	77	17.6	5.4	Sand	1.6	14.8	5
60–80	82.4	13.2	4.4	Sand	1.6	14.9	5.1
80–100	81	13.2	5.8	Sand	1.6	14.78	4.96
100–120	77	17.2	5.8	Sand	1.61	14.8	4.9

Table 2
Chemical properties of soil of the experimental field

Depth (cm)	pH	EC ($dS\ m^{-1}$)	Organic carbon (%)	Available P (ppm)	Available K (ppm)
0–20	8.4	0.64	0.25	11	163
20–40	8.5	0.66	0.04	3	82
40–60	8.7	0.67	0.13	3	89
60–80	8.9	0.61	0.08	2	82
80–100	8.8	0.67	0.08	1	74
100–120	8.8	0.63	0.02	1	79

through the fertigation system during the entire growing season. Nitrogen fertilizer was applied six times during the growing season in equal amounts. During each fertigation, fertilizer was applied at the start of the last hour of irrigation for 0.166 h. We used the irrigation and fertigation schedule typically practiced by the farmers in the region who cultivate potato under drip fertigation.

Observations and Analysis. Soil samples were collected from different depths (0–0.2, 0.2–0.4, and 0.4–0.6 m) at a horizontal distance of 0, 15, and 30 cm from the emitter using a tube auger to determine spatial and temporal distribution of water and nitrate during the growing season. The samples were collected before the beginning of the fertigation events and before selected irrigation events through the growing season. In the laboratory, soil samples were analyzed to determine the gravimetric moisture content. Nitrate concentration was measured using the spectrophotometer method (Page, Miller, and Keeny 1982).

Water and Nutrient Transport Modeling

Nitrate leaching from the potato field under drip fertigation was modeled using the computer simulation HYDRUS-2D software package (Simunek, Sejna, and van Genuchten 1999). This software package can simulate the transient two-dimensional movement of water and nutrients in soils. The model can implement a wide range of boundary conditions, irregular boundaries, and soil heterogeneities.

Considering two-dimensional soil water flow, the water flow equation is written as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial r}\left(K_r \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(Kz \frac{\partial h}{\partial z}\right) - \frac{\partial k}{\partial z} - WU\,(h, r, z) \tag{1}$$

where θ is the volumetric soil water content ($L^3\ L^{-3}$), K is the unsaturated hydraulic conductivity function (LT^{-1}), h is the soil water pressure head (L), r is the lateral coordinate, z is the vertical coordinate (positive downward), t is time (T), and $WU(h, r, z)$ denotes root water uptake (T^{-1}).Both K and WU are functions of θ and/or h. The subscripts r and z allow for the possibility of including soil anisotropy to simulate water flow with the unsaturated hydraulic conductivity function being different for the r and z directions. Equation (1) was solved using the Galerkin finite-element method based on the mass-conservative iterative scheme proposed by Celia, Bouloutas, and Zarba (1990). The root water uptake *WU* in Eq. (1) was computed from

$$WU(h, r, z) = \gamma(h)\, RDF(r, z)\, WT_{pot} \tag{2}$$

where $\gamma(h)$ is the soil water-stress function (dimensionless) of Feddes, Kowalik, and Zaradny (1978), *RDF* is the normalized root water uptake distribution (T^{-1}), T_{pot} is the potential transpiration rate (LT^{-1}), and *W* is the radius of the soil surface (L) associated with the transpiration process. For the present study, the root distribution was assumed to be uniform in time.

In HYDRUS-2D (Simunek, Sejna, and van Genuchten 1999), solute transport is described by

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij} \frac{\partial c}{\partial x_i}\right) - NU(c, r, z, t) \tag{3}$$

where the subscripts *i* and *j* denote either *r* or *z* and *c* denotes the nitrate concentration in the soil solution (ML^{-3}). The first term on the right side represents the solute flux due to dispersion, the second term is the solute flux due to convection with flowing water, and the third term represents root nutrient uptake. D_{ij} is the dispersion coefficient ($L^2\ T^{-1}$), and *NU* defines the local passive nitrate uptake ($ML^{-3}\ T^{-1}$) by plant roots, which is a function of time and the spatial coordinates:

$$NU(r, z, t) = C(r, z, t)\, WU(r, z, t) \tag{4}$$

Calibration and Validation. The HYDRUS-2D model was calibrated with respect to hydraulic conductivity and dispersivity in the experimental area in relation to water and nitrate contents at the various point observations in the root zone during the growing season. During calibration runs, simulation period was kept to 267 h, which included two fertigation and six irrigation events. Model predicted values were compared with observed values and values of calibrated parameters were selected from the run when evaluation criteria value was acceptable. After calibration, the model was validated with the data excluded from the calibration in order to examine its predictability. The validation period included 12 points in time where soils were sampled in different depths and thereafter analyzed in the laboratory. This included 11 time points during the growing season and one at harvest.

System Geometry. Assuming symmetry of the water front under the emitters and assuming that the emitters discharge water at the same flow rate, the entire field was subdivided into identical volume elements with an emitter placed at the surface of a vertical plane. Water and nitrate patterns in the entire field can be described by analyzing the flow in this single volume element irrigated by a single emitter. The infiltration process can be viewed as a vertical flow with the length *l* (L) and the depth *z* (L) as key variables. Because of the multiple outlets along the tape, the simulation was done using the line-source model with a rectangular geometry. In the present study, the length of rectangle was taken as 60 cm (the distance between lateral spacing) and depth *z* as 60 cm. This was done because potato is a shallowly rooted crop and nutrient leaching below 60 cm depth will not be available to the plant. Figure 1 shows the conceptual diagram of the simulated domain.

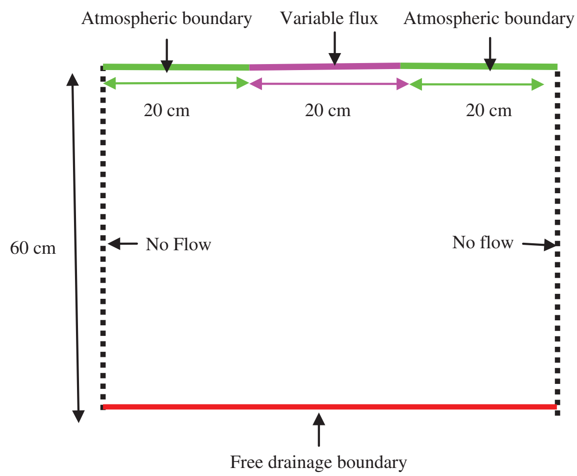

Figure 1. Conceptual diagram of simulated area (color figure available online).

Initial and Boundary Conditions. Initial condition for the water content of the soil was given as initial water content in different soil layers within the flow domain measured in the experimental field. Initial nitrate concentration as observed in various soil layers within the flow domain was given as initial condition for solute concentration. For all simulations, on the sides of the flow domain, it was assumed that no flow of water and nitrate took place and hence no flux boundary condition was chosen, which in HYDRUS-2D is specified for impermeable boundaries where the flux is zero perpendicular to the boundary. The water table was situated far below the domain of interest and therefore free drainage boundary condition at the base of the soil profile was considered. The whole simulated region was divided into elements of 1 cm $\times$ 1 cm. To account for the emitter discharge during irrigation, a flux-type boundary condition with constant volumetric application rate of emitter for irrigation duration was considered. During no irrigation period, evapotranspiration potential with positive sign was implemented. Solute was applied with irrigation water and a third-type Cauchy boundary condition was used to describe the concentration flux along flux variable at the top boundary. In the case of drip fertigation, solute flux is the product of water infiltration and dissolved nitrate concentration. Cumulative nitrate leaching below the root zone (i.e., lower boundary of flow domain) is controlled by nitrate concentration at depth and the corresponding water flux. Root distribution was assumed to be constant throughout the growing season. Simulation depth and maximum root depth was taken as 60 cm. For all simulated scenarios, the crop evapotranspiration was computed from the product of reference evapotranspiration (using weather data) and crop coefficient. This was bifurcated into evaporation and transpiration as required by HYDRUS-2D from the procedure described by Supit and van der Goot (2003). In this procedure, evaporation from soil is estimated as a function of leaf area index (Ritchie 1971, 1972; Goudriaan 1977).

Input Parameters. For the various input parameters required in HYDRUS-2D, namely saturated water content (θ_s), residual water content (θ_r), empirical factors (α, n), and saturated hydraulic conductivity (Ks), the neural network prediction option available in HYDRUS-2D was used by assigning the values of bulk density, field capacity, permanent wilting point, and clay, silt, and sand percentages. Values of longitudinal and transverse dispersivity were estimated through the calibration procedure and were set to 8 and 0.8 cm,

Table 3
Mean value for hydraulic parameters of soil of the experimental field

Textural class	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm h^{-1})
Sand	0.041	0.363	0.03	1.6	6

respectively. Molecular diffusion was 0.068 cm^2 h^{-1} (which is the value of the diffusion coefficient of NO_3^- in solution at 25 °C, Weast 1978) to mimic nitrate diffusion. Values of the hydraulic parameters are presented in Table 3. Duration of irrigation varied from 2 to 4 h to meet crop water requirement. During fertigation events, the duration of nitrate application was kept equal to 0.166 h. The van Genuchten–Mualem (Mualem 1976; van Genuchten 1980) analytical model without hysteresis was used for the soil hydraulic properties. Galerkin finite-element method was adopted to solve the water flow equation. Feddes's root water uptake model with no solute stress was adopted. Potassium nitrate was applied as the source of N.

Simulation of Nitrogen Leaching and Distribution under Different Scenarios

After calibration and validation, the model was used to predict the nitrate leaching below the root zone. Different scenarios were modeled: Emitter discharge rates were varied from 0.5 to 8 L h^{-1} with increments of 0.5 L h^{-1} and the amounts of potassium nitrate were varied from 950 to 2550 kg ha^{-1} with increments of 50 kg ha^{-1}, yielding a total of 528 scenarios to evaluate nitrate leaching out of the root zone of the soil.

Evaluation Criteria

The root mean square error (RMSE) and correlation coefficient (R) between the measured values and the output of the model were used to evaluate the performance of HYDRUS-2D model for prediction of nitrate concentration and moisture content. The RMSE and R statistics are denoted as

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[Y(pi) - Y(oi)\right]^2} \tag{5}$$

$$R = \frac{\sum_{i=1}^{n}(Y(p_i) - \overline{Yp})(Y(o_i) - \overline{Yo})}{\sqrt{\sum_{i=1}^{n}(Y(p_i) - \overline{Yp})^2(Y(o_i) - \overline{Yo})^2}} \tag{6}$$

where *Y(pi)* and *Y(oi)* are HYDRUS-2D outputs and the measurement respectively, $\overline{Yp}$ and $\overline{Ya}$ are the means of HYDRUS outputs and measurement respectively, and n is the number of data points.

Results and Discussion

Calibration and Validation

Results of the calibration for water content at depth 0–20 cm are presented in Figure 2 together with the irrigation events. because of the limitation of space, the results are

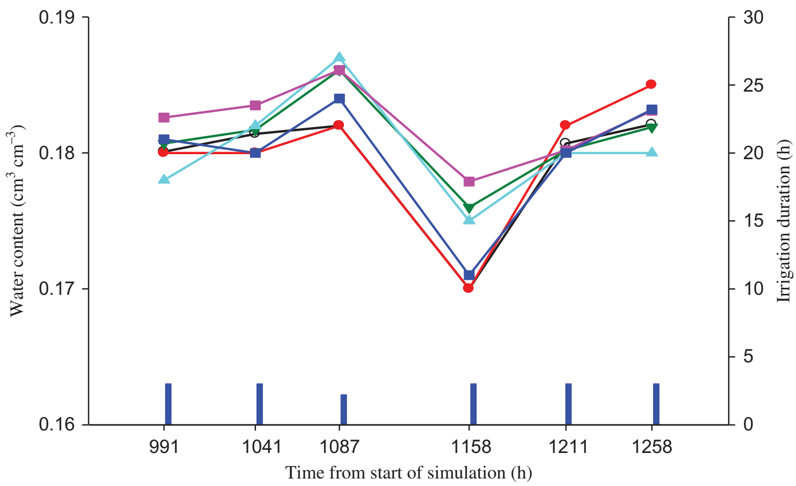

Figure 2. Simulated and observed water contents during the calibration period at a depth of 0–20 cm (color figure available online).

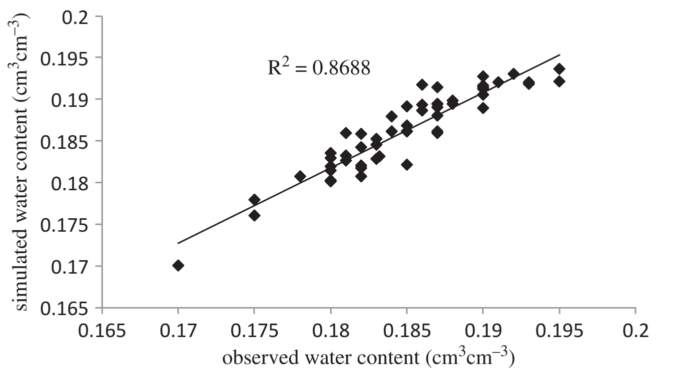

Figure 3. Scatter plot and line 1:1 between simulated and observed water contents during the calibration period.

presented for 0–20 cm deep only. Figure 2 shows that results of the model and measured water contents follow similar trends without much difference. The greatest interval between irrigation events during calibration period was occurred between time 1087 and 1158. The lowest water content during this period in both simulated and observed is observed at hour 1158. The R coefficient between observed and simulated water content has a value of 0.93 (Figure 3). The RMSE between the simulated and observed water content was 0.0023 mg. In general the results show that HYDRUS-2D can simulate water movement in the sandy soil with good accuracy.

Results of the calibration for nitrate concentration during calibration period at depths 0–20 cm together with the irrigation and fertigation events are presented in Figure 4. It is seen that values of simulated and observed nitrate concentration follow similar trends without much difference. Here, due to space limitations, the results are presented for 0–20 cm deep only. The lowest nitrate concentration during calibration period was observed at 990 hour and when fertilizer was added nitrate concentration increased. The greatest

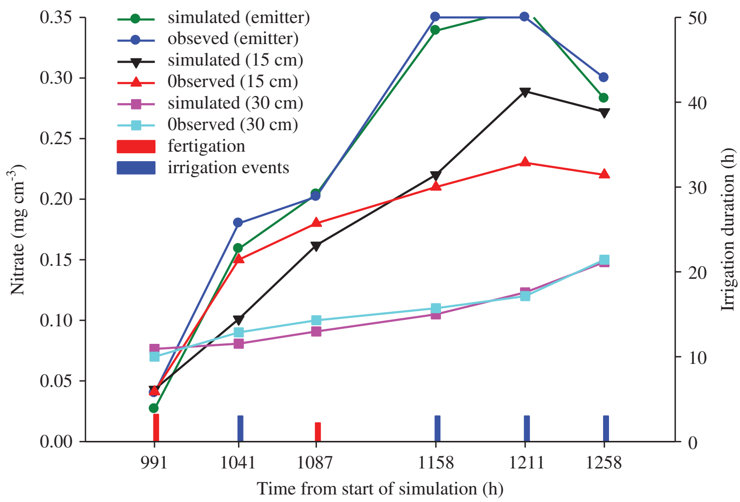

Figure 4. Simulated and observed nitrate concentrations during the calibration period at a depth of 0–20 cm (color figure available online).

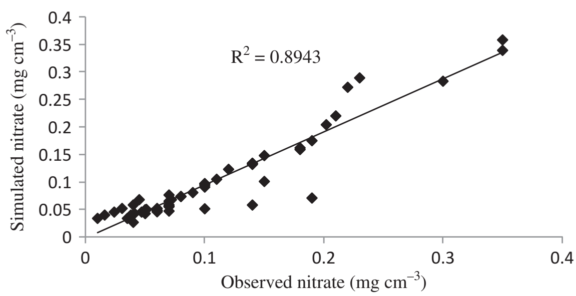

Figure 5. Scatter plot and line 1:1 between simulated and observed nitrate concentrations during the calibration period.

nitrate concentrations both simulated and observed occurred at 1157 hour, since before this time there are two fertigation events. Concentration of nitrate decreases horizontally from the emitter. Sampling for measuring nitrate was done before irrigations, and fertilizer was applied at the last hour of irrigation. Nitrate concentrations reached the depth and distance from the emitter with delay. The R coefficient (Figure 5) and the RMSE value between simulated and observed nitrate concentration were 0.95 and 0.027 mg, respectively. In general the results show that HYDRUS-2D can simulate the nitrate distribution in the sandy soil with good accuracy.

To validate the model we used the results of the 12 points in time measurement of water content and nitrate concentration at different depths during the simulation period. The results of validation with respect to the water content at different depths together with irrigation events show that the values of measured water content follow similar trends as the simulated water content with an increase in water content at depth (Figures 6a–c). Every time that the interval between irrigation events is high and the amount of applied irrigation water is low, the water content is low and vice versa (Figures 6a–c). The greatest water content is seen at hour 1466, whereas before this hour there are two irrigation events with

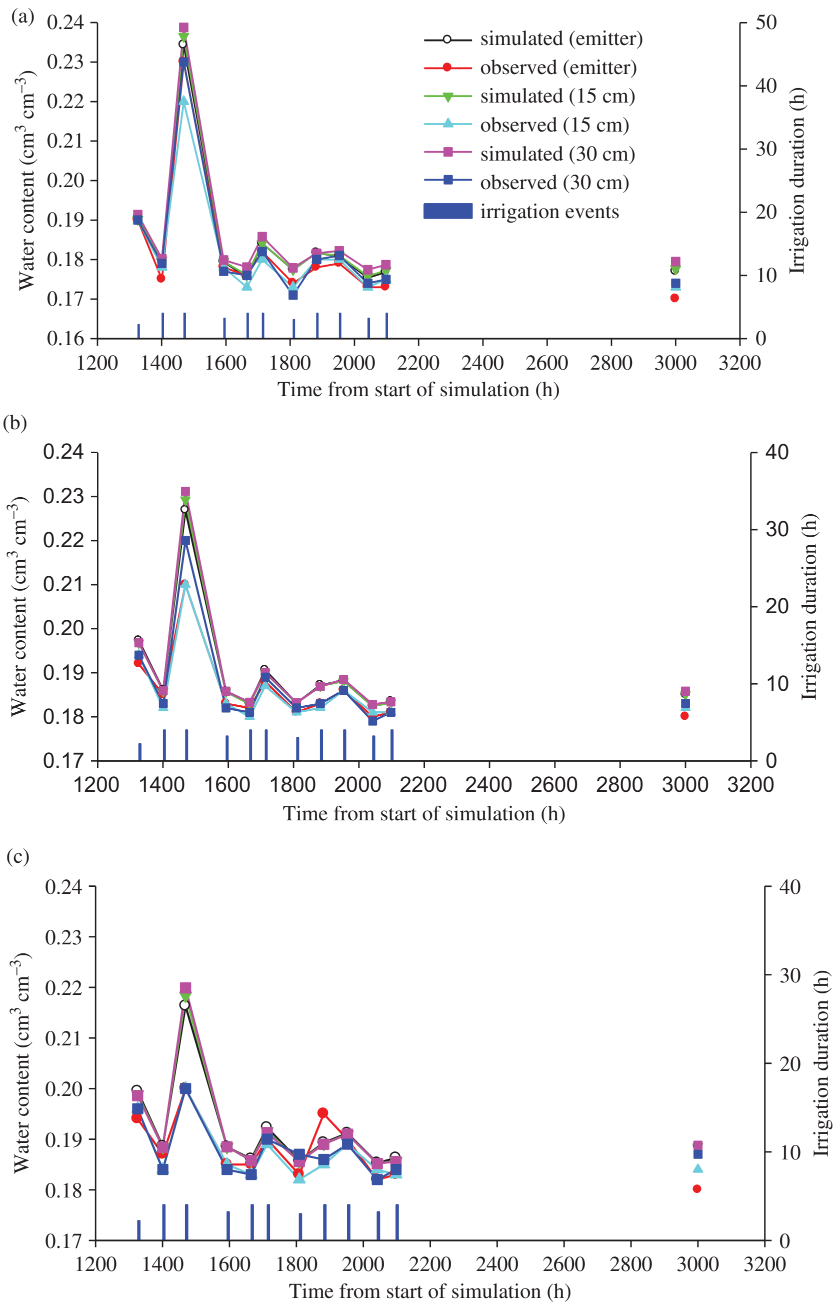

Figure 6. Simulated and observed water contents during validation period at depths of (a) 0–20 cm, (b) 20–40 cm, and (c) 40–60 cm (color figure available online).

long time and low interval between them. The R coefficient value between observed and simulated water content is 0.96 (Figure 7), and the RMSE between simulated and observed water contents was 0.0054 mg. Values of evaluation criteria therefore show that the model can simulate water content in the soil with good accuracy.

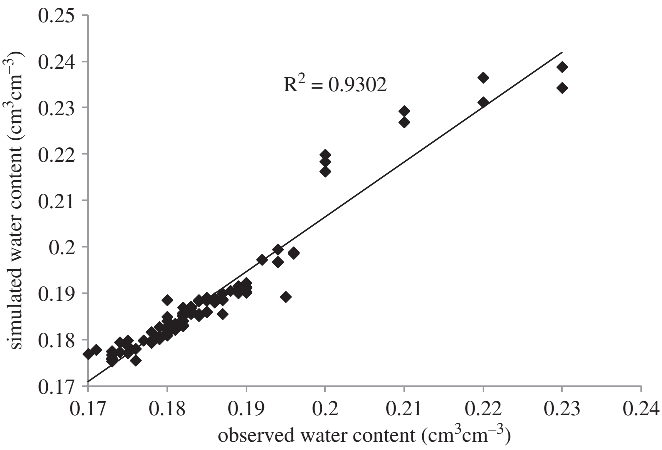

Figure 7. Scatter plot and line 1:1 between simulated and observed water contents during the validation period.

Results of simulated and observed nitrate concentrations during the validation period show that simulated and measured nitrate concentrations follow similar trends without much difference (Figures 8a–c). Considering the fact that fertigation occurred during the last hour of irrigation after each fertigation, nitrate concentration of surface layer changed immediately but nitrate concentration of deeper layer changed with delay. By increasing the distance from emitter the nitrate concentration change decreases. The R coefficient between simulated and observed nitrate concentration during validation period is 0.9678 (Figure 9). The RMSE between simulated and observed values was 0.01351 mg. These results show that the model can simulate nitrate concentration in the soil with good accuracy.

Nitrate Leaching at the End of Growing Season

The amount of nitrate leached below the root zone (60 cm) under different emitter discharges and various amounts of fertilizer is displayed in Figure 10. With an increase in emitter discharge nitrate leaching is increased. However, this increase is more pronounced at low emitter discharges compared to high emitter discharges. Ajdari et al. (2007) reported that with an increase in emitter discharge the amount of N leached out of the root zone increased. However, the amount and percentage that they reported were less than in our study. This might be related to the source of N between the two studies. Ajdari et al. (2007) used urea whereas we used potassium nitrate, and the fates of urea and nitrate in soil are different because urea at first converts to NH_4^+ and the mobility of NH_4^+ in soil is less than NO_3^-. Another reason may be that Ajdari et al. (2007) applied a constant volume of water regardless of emitter discharge compared to our study, where the volume of water increased with an increase in emitter discharge. With an increase in the amount of fertilizer the nitrate leaching was therefore increased as well. There are several reasons for this. First, our studied soil was sandy, so it had less capacity to adsorb elements; second, nitrate is an anion that does not adsorbed to soil particles and due to high permeability of the sandy soils nitrate was leached out root zone proportionally with the amount of added nitrate. Gardenas et al. (2005) also found that nitrate leaching in a drip-fertigated sandy

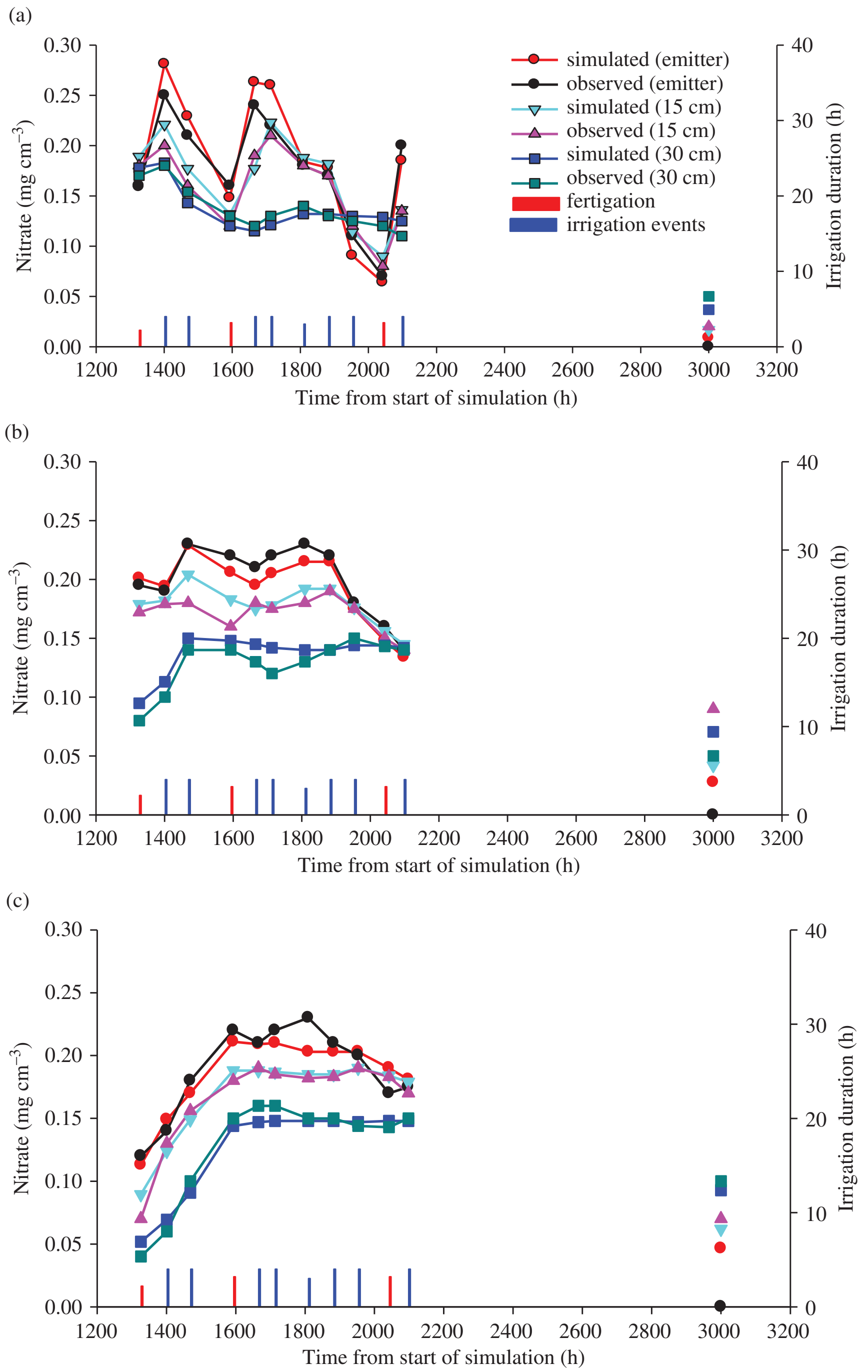

Figure 8. Simulated and observed nitrate concentrations during the validation period at depths of (a) 0–20 cm, (b) 20–40 cm, and (c) 40–60 cm (color figure available online).

loam was greater than in more clayey soils. In our work, the greatest and least nitrate leaching occurred at emitter discharges of 8 l h^{-1} and 2550 kg ha^{-1} fertilizer and 0.5 l h^{-1} and 950 kg ha^{-1} respectively.

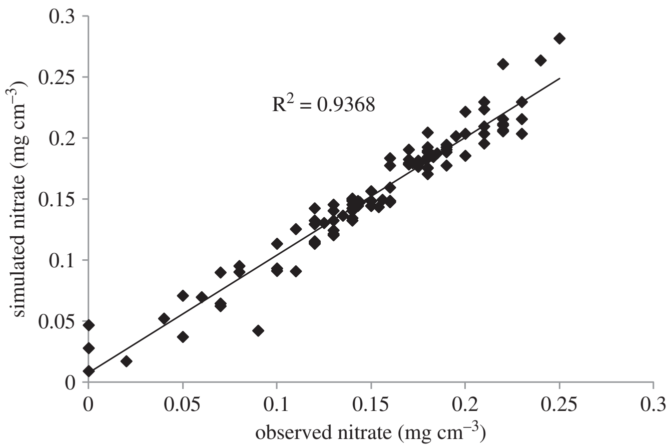

Figure 9. Scatter plot and line 1:1 between simulated and observed nitrate concentrations during the validation period.

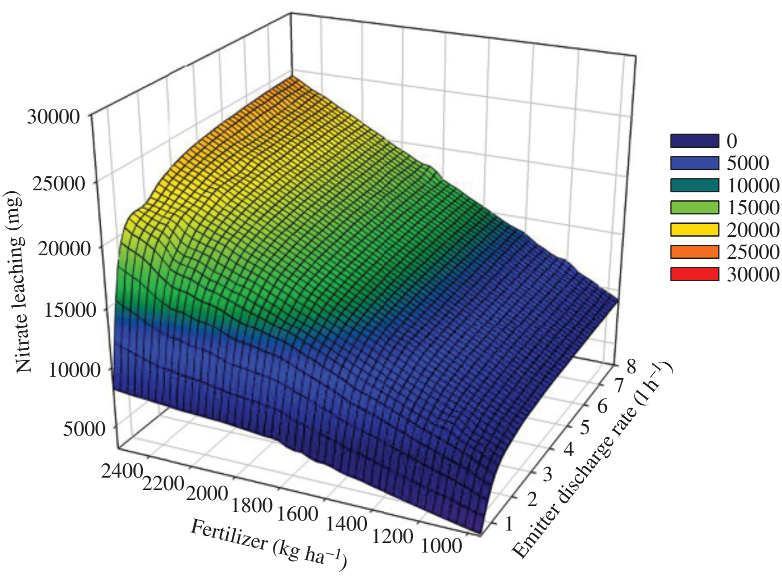

Figure 10. Amount of nitrate leaching below the 60-cm depth in the entire growing season under different scenarios (color figure available online).

Free Drainage

The total amount of water drained from the lower boundary of the domain during the entire growing season for different emitter discharges obtained from the simulation is shown in Table 4. With an increase in emitter discharge rate, the volume of water drained out of the domain was increased. Because of the large fractions of large pores in the sandy soil, water 305
is drained out of the soil easily. With an increase in emitter discharge from 0.5 to 1 l h^{-1} the free drainage increased sharply, but after that the rate of increase levels off with a further

Table 4
Cumulative free drainage below 60 cm under various emitter discharges

Emitter discharge ($l\ h^{-1}$)	Free drainage (cm^3)	Free drainage (%)
0.5	14,160	25.28
1	39,000	32.63
1.5	64,600	35.20
2	91,000	36.47
2.5	116,400	37.18
3	142,200	37.66
3.5	168,200	38.05
4	194,000	38.41
4.5	220,000	38.59
5	246,000	38.74
5.5	272,000	38.85
6	298,000	38.95
6.5	324,000	39.03
7	350,000	39.1
7.5	376,000	39.16
8	402,000	39.2

increase in discharge up to 8 $l\ h^{-1}$. Also, Ajdari et al. (2007) found that with an increase in emitter discharges in coarse-textured soils free drainage water increased as well. However, they reported lower amounts and percentages of drainage water compared to this study. This can be explained by the fact that Ajdari et al. applied a constant volume of water regardless of emitter discharge, in contrast to our study. Another reason is coarse-textured soil we use in our experiment. One of the most important factors in solute transport and water movement is soil texture. Permeability of sandy soil is high and water drains easily and quickly out of the root zone.

Conclusions

Results presented in this article describe the effect of different emitter discharge rates and various amounts of fertilizer on nitrate leaching under a potato field in a sandy soil. It is expected that a significant amount of nitrate potentially can be leached out of the root zone because the texture of the soil is coarse, the source of N fertilizer is nitrate, and the potato plant has a shallow root system. Our results showed that the lowest total amount of water percolation and nitrate leaching out of the root zone during growing season was seen at an emitter discharge of 0.5 $l\ h^{-1}$. Only a small increase in emitter discharge from this low discharge rate showed a significant increase in both water percolation and nitrate leaching. For this sandy soil we recommend that the farmer decrease the irrigation time or increase the interval between irrigation events slightly when growing potatoes to minimize nitrate leaching and to conserve water. We also found that with an increase in the amount of fertilizer the amount of nitrate leaching increased as well. With the selection of an appropriate fertilizer amount well distributed during over the growing season at an appropriate emitter discharge, nitrate leaching can be minimized.

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