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Development of an innovative integrated model for the simulation of nitrogen dynamics in farmlands with drainage systems using the system dynamics approach

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ABSTRACT

In the subsurface drainage system, there is a high potential for nitrate leaching, causing the pollution of both surface and ground water. In this research, a simple but comprehensive process-based model was developed for simulating the water flow and nitrogen dynamics. Processes considered in this model included all the important processes involved in nitrogen transformations, as well as nitrogen transport. Nitrogen transformation processes comprised fertilizer dissolution, nitrification, denitrification, ammonium volatilization, mineralization and immobilization. The nitrogen transport processes included nitrogen uptake by the plant, soil adsorption, upward flux, surface runoff losses and drain losses in the fields with the drainage network. For model evaluation, the measured data obtained from Imam agro-industrial Company, in Khuzestan, Iran, were used. Computed RMSE of the simulated water table, the drainage discharge rate, nitrate and ammonium concentration in drainage water were determined to be 14.58 cm,1.82 mm/day,1.73 mg/L and 0.48 mg/L, respectively. The results indicated a good agreement between the observed and simulated data. This model could be, therefore, used for fertilizer management, thereby reducing the concentration of nitrate and ammonium in the drainage water and helping to prevent the environmental pollution.

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1. Introduction

Nitrate in groundwater is a public health concern (Medellín-Azuara et al., 2013). Excessive nitrate loads in surface waters are a major cause of hypoxia and eutrophication. In many places, agriculture is the single largest source of nitrogen entering the receiving waters (Ling Ng et al., 2014). The over application of nitrogen fertilizers leads to their significant leaching, thereby rendering them out of the reach and use of the plant and vegetation. The amount of nitrates in water resources can also affect the quality of our environment and the health of human and animals alike (Gu et al., 2013; Kuzmanovski et al., 2015; Shamrukh and Coropciogles, 2001; UNEP, 2003; Yang et al., 2013; Youssef et al., 2005).

In the subsurface drainage system, there is a high potential for leaching the nitrate, due to the high solubility of nitrate; this is why the amount of pollution in surface and ground water is high. The previous researches have revealed that the total drainage outflow is the major cause of nitrate losses (Chapman et al., 2001; Drury et al., 1996; Evans et al., 1995; Jaynes, 2013; Williams et al., 2015; Yang et al., 2007;). At present, a significant amount of drainage water is discharged into the river and surface water, causing the low quality of downstream water.

Due to the high potential of nitrogen in reducing the quality of groundwater and the complexity of the flow process, as well as leaching nitrogen in the soil profile, the fate of nitrogen in the soil-water-plant system is of great importance. Using modeling, we can predict the rate of the nitrate leached, transferring it into the groundwater and managing the nitrate under different conditions (Akhavan et al., 2010a; Akhavan et al., 2010b). Simulation models are considered useful tools in determining the contribution of nitrogen in the contamination of water resources and finding

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the most effective methods in reducing nitrogen leaching (Kyllmar et al., 2005). Selecting an appropriate model for estimating the effects of farming on groundwater contamination is not an easy task; therefore, their theoretical and scientific investigations, along with the determination of their applicability, is of significant importance before they are used. Today, several models are specifically presented for modeling the nitrogen transformation and nitrogen leaching in the root zone, the most important of which include ANIMO (Rijtema and Kroes, 1991), LEACHN (Wagenet and Hutson, 1989), HYDRUS (Simunek et al., 1999) and DRAINMOD-NII (Youssef et al., 2005). The problem with these models of simulating water flow and nitrate in soil profiles is that a large number of input parameters are required and measuring some of them with high accuracy at the field-scale can be really difficult, if not possible. Some of these parameters are given for DRAINMOD-NII, which are as follow:

1. Decomposition rate and C/N ratio of litter pools include surface structural, surface metabolic, surface microbes, below−ground structural and below-ground metabolic ones.
2. Decomposition rate and C/N ratio of soil organic matter pools include active, slow and passive ones.
3. Michaelis−Menten kinetics rates constants (K_{max} and V_{max}) for urea hydrolysis, nitrification and denitrification reactions.
4. Henry's coefficient (H), ammonia−N diffusion coefficient in the gaseous phase (dg), pH_{min}, pH_{max}, pH_l, $pH_{h,}$ etc.

Furthermore, the main problem with DRAINMOD-NII is that it does not consider the fertigation as the application method of fertilizer (only surface application and incorporate are considered).

Moreover, they cannot be used in artificial drained lands for the accurate modeling of the drainage rate and the nitrate losses from the drain pipes; this is because the subsurface drainage hydraulics related to drains has not been taken into consideration. The drainage water is the result of two input flows to the drain pipe: the vertical and horizontal flows from the losses resulting from the deep percolation of the irrigation water toward the drains; 2- the subsurface radial flows toward drains that, again, result from entering the losses of irrigation and groundwater.

The input of nitrate to the drain pipe also consists of two parts: 1- nitrate in the irrigation water and in the upper soil of the drain pipe that enters into the drain from the top by vertical and horizontal flows; 2- nitrate existing in the groundwater that enters into the drain from the lower part of the drain by radial flows. Therefore, the quality and quantity of the drainage water depend on the depth and distance of the drains and the amount of nitrate at the top and bottom of the drain pipe.

Nitrogen dynamics in Soil-Water-Plant- Drainage Systems (SWPD) are a complex process resulting from a number of interactions of the physical, chemical and biological processes. In order to represent these complex relations, we need new tools. One of the most effective methods for evaluating complex systems is the use of System Dynamics approach (SD).

The SD was first developed by Forrester (1961) to understand strategic issues in complex dynamic systems. The models developed based on this method contribute to a better understanding of the dynamic behavior of the systems through the feedback process for the users during the time. Every dynamic system is determined by interdependency, interaction, information feedback and the causal diagram. In SD, the relation between structure and behavior of each system is based on the concept of information feedback and the interaction of stock and flow variables (Neuwirth et al., 2015; McKnight et al., 2010; Simonovic, 2000). System dynamics modeling, known as a well-established methodology specially designed for studying complex feedback systems, has been used to address a variety of environmental/ecological studies including agricultural production systems (Walters et al., 2016), penguin population (Weller et al., 2014), carbon cycle (Mukherjee et al., 2013), competition between submerged macrophytes (Han et al., 2009), sustainable coral reef management (Chang et al., 2008), and management of the gooseneck barnacle (Bald et al., 2006).

The first objective of the present study was to develop a simulation model for nitrogen dynamics in shallow water table soils under a subsurface drainage system based on the system dynamic approach. This model is formed according to the internal structure of nitrogen dynamics and the behavior resulting from the feedback of this structure. It also calculates the quality and quantity of the drainage outflow based on the hydraulic flow toward drains in the field scale. The second objective was to evaluate the developed model through the measured- field data. So, the novelties of this research are: (1) the first nitrogen dynamic and hydrological cycle model has been developed for the first time for forecasting the drainage water quality by the system dynamic approach in the filed-scale, (2) subsurface drainage system has been considered as the sub-model in the hydrological cycle, (3) modeling of nitrate and ammonium movement into the drain pipes is considered based on the hydraulic flow toward drains, (4) system dynamics is used as a suitable instrument for understanding the nonlinear behavior of complex systems over time using stocks, flows and internal feedback loops, and (5) the developed model can be used for modeling fertilizer management to reduce environmental pollution.

2. Materials and methods

The model structure developed for nitrogen dynamic under drainage system, based on the system dynamic approach, consisted of two essential sub-models of the hydrological and nitrogen cycle as follows:

2.1. Hydrological sub model

2.1.1. Unsaturated zone

In this part of model, we used the similar method of Nozari and Liaghat, 2014. The water balance model was formulated for the unsaturated conditions. In this model, the unsaturated zone was divided into two layers and each layer was defined as a stock variable in which the rate of moisture was changed during the time.

The first layer was related to the root development zone in which the soil microorganisms were active. The second one was the distance between the end of the root development zone to the depth of the installation of drain pipes in the soil.

The model in each layer implemented the amount of evapotranspiration water and the amount of the infiltrated water reaching the groundwater. Meanwhile, the fluctuations of water table and infiltration of groundwater to the root zone are shown. The input of the upper layer included the rainfall or irrigation water and the upward flux from the groundwater table; the output consisted of evapotranspiration, runoff and deep percolation (Eq. (1)). Therefore, the amount of the stored water in the first layer could be estimated by:

$$S_j = S_{j-1} + IR_j + R_j + UF_j - ET_{aj} - DP_j - RF_j \tag{1}$$

where S_j and S_{j-1} refer to water stored in the soil at the end of day j and $j-1$, respectively, IR_j is the value of irrigation water,R_j is the value of rainfall on day,UF_j is the upward flux value from the water table, depending on the water table depth, $ET_{a\ j}$is the actual evapotranspiration value, DP_j is the value of deep percolation water to the underlying layer, and $RF_j$is the runoff value. The unit of all parameters is the same; it is expressed as millimeter per day.

The inflow water to the lower layers includes the deep percolation of the upper layer and the upward flux from the groundwater table. The outflow comprises evapotranspiration, deep percolation

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