SOIL COMPOSITION AND TEXTURE INFLUENCE ON THE NITROGEN TRANSPORT THROUGH UNSATURATED SOILS

Anca Marina MARINOV[1], Tudor PETROVICI[2], Viorica NISTREANU[3], Roxana IVAN[4]

The impact of fertilizers on the groundwater pollution is connected with many factors: soil composition, crops evolution, irrigation method, fertilizer's type and schedule.

The water flow through the unsaturated soil influences the nitrogen compounds transport toward the phreatic water table.

Two hydraulic parameters are very important in nitrogen transport biochemical models: the volumetric flow rate per unit of soil area and the water content in the soil profile.

We propose here a numerical approach of the soil composition and texture influence on the nitrogen transport through unsaturated soils.

Keywords: groundwater, unsaturated soils, nitrogen compounds, coupled models.

1. Introduction

High nitrate levels in soils and in groundwater endanger public water supplies. The maximum concentration of nitrates (50 mg/l) in drinking water, tolerated in the European Community, is exceeded in many Romanian aquifers.

The increase in nitrate levels found in aquifers is primarily due to a combination of fertilizer use, disposal of wastewater containing liquid manure from livestock farms, the intrusion of wastewater from sewer systems, and rainwater.

Numerous models have been proposed to describe the nitrogen transport in soils. Very important for our research have been the models proposed by Antonopoulos and Wyseure [1] evaluating the transient water movement, mass transport, and N transformations of restored and undisturbed soil, Delgado [2] considering long-term effects of crop behavior on potential nitrates leaching, Geng [3] simplifying the nitrogen cycle in unsaturated soils.

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[1] Professor., Power Engineering Faculty, University "Politehnica" of Bucharest, Romania, and researcher at the Institute of Statistical Mathematics and Applied Mathematics of Academy.

[2] Researcher, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania.

[3] Professor., Power Engineering Faculty, University "Politehnica" of Bucharest, Romania.

[4] Masterand student., Power Engineering Faculty, University "Politehnica" of Bucharest, Romania.

In this paper we consider the impact of different types of texture classes of soil, on nitrate leaching, using a mathematical coupled model.

Our model [4] describes the behavior of 1.5 m unsaturated soil polluted by three types of nitrogenous fertilizer application. The model (fig.1) contains two sub-models: the hydraulic model and the biochemical one. The hydraulic model calculates the suction in the soil pores, h, the volumetric water content, θ, the total water quantity, (RSOL), in the roots region (0-50 cm) and the total water quantity, (RNON), in the unsaturated region (50-150 cm).

RSOL, RNON, the discharges, (QI), entering the soil surface from rain and irrigation (diminish by evapotranspiration), and the discharge (QIR) flowing through the unsaturated region laying between 50 and 150 cm, influence the nitrogen transformations and the quantity of nitrates attending the water-table.

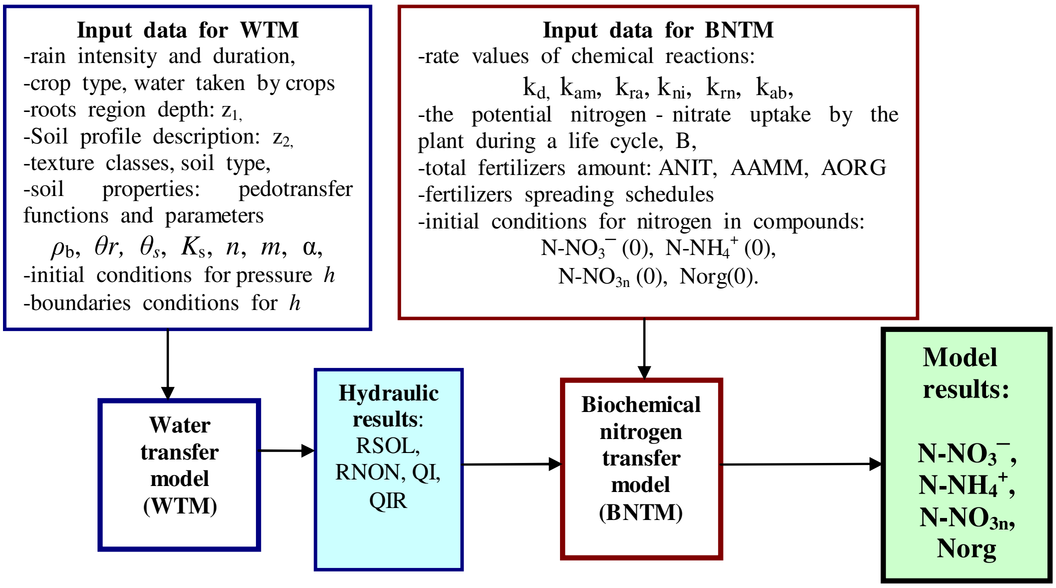

Fig.1. Model flowchart.

The biochemical model describes the simplified chain of nitrogen proposed by Geng [3], considering the transformations between different nitrogenous forms, in unsaturated soil, taking into account the plant needs and the hydrodynamic regime. We are using the model presented in [4], to analyze the influence of soil texture on the nitrogen transport through the unsaturated soil, toward the groundwater.

2. Mathematical model for the flow through unsaturated soils

The mathematical model to describe an isothermal one-dimensional fluid flow in the unsaturated porous soil can be obtained by combining the mass conservation equation with the generalized Darcy's law. One of its forms is known as Richards' equation:

$$\frac{\mathrm{d}\theta}{\mathrm{d}h}\frac{\partial h}{\partial t}=\frac{\partial}{\partial \mathrm{z}}\left[K(h)\left(\frac{\partial h}{\partial z}-1\right)\right], \tag{1}$$

where: $\theta(z, t)$ [$\mathrm{L}^3\ \mathrm{L}^{-3}$] is the volumetric water content, $h\ (z, t)$ [L] is the soil water pressure head (h<atmospheric pressure), $K(h)$ [L T^{-1}] is the hydraulic conductivity, z [L] is soil depth taken positive downwards, and t [T] is time. If we consider the atmospheric pressure like reference, the pressure into an unsaturated soil is always negative: $h<0$. Defining the specific soil water capacity:

$$\frac{\mathrm{d}\theta}{\mathrm{d}h}=C(h) \tag{2}$$

Richards' eqn. (11) can be writen as:

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial \mathrm{z}}\left[K(h)\left(\frac{\partial h}{\partial z}-1\right)\right], \tag{3}$$

where $C(h)$ and $K(h)$ are functions of the local soil water pressure head, $h(z,t)$, at a given moment.

We solved numerically Richards' equation, using a fully implicit finite differences, stable and convergent scheme.

The initial condition for the equation (1) may be any arbitrary function $h(z,0)=hi(z)$ or $\theta(z,0)=\theta i(z)$.

The upper boundary conditions can be described as a known $q_0\ (t)$ [LT^{-1}] water flux density through the soil surface (precipitation, irrigation, snowmelt, evaporation), or as a given pressure head, during ponding: $h(0,t)=h_0(t)\geq 0$. Three conditions can be imposed at the lower boundary ($z=L$): a known net fluid flux density, the pressure head, $h(L,t)=h_L(t)$, when a water table is present, or a gradient of pressure head $\frac{\partial h}{\partial z}=0$, for a free-draining soil profile.

In our example we considered initial conditions $\theta(z,0)=\theta i(z)$, for upper boundary a known $q_0\ (t)$, and for lower boundary: $\frac{\partial h}{\partial z}=0$**.** We neglected the soil hydraulic functions' hysteresis and the effect of the air phase on water flow.

The unsaturated hydraulic conductivity $K(\theta)$ can be expressed as a function of the volumetric water content, θ.

Mualem–van Genuchten [5] soil water retention and hydraulic conductivity relationships have been used in our hydraulic model:

$$\theta(h)=\theta_r+(\theta_s-\theta_r)\left[\frac{1}{1+(\alpha|h|)^n}\right]^m, \tag{4}$$

where: θ (cm^{3}cm^{-3}) is the soil volumetric water content, θ_r (cm^{3}cm^{-3}) – the residual soil water content θ_s (cm^{3}cm^{-3}) – saturated soil water content, α, n, m are parameters defining the moisture retention characteristic's (MRC) shape, and h (cm) is the pressure head in the soil's pores, $m = 1 - \frac{1}{n}$ (Mualem approximation).

$$K(\theta) = K_S \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1}{2}} \left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1}{m}} \right)^m \right]^2 . \tag{5}$$

K_s, θr, θ_s, α, n, m are parameters which have to be estimated from observed soil water retention data. Table 1 gives these parameters for different texture classes.

Table 1

Mualem-van Genuchten parameters of class pedotransfer functions

	texture	θ_r	θ_s	α	n	m	K_s
topsoil	Coarse	0.025	0.403	0.0383	1.3774	0.2740	60.0
	Medium	0.010	0.439	0.0314	1.1804	0.1528	12.061
	Medium-fine	0.010	0.430	0.0083	1.2539	0.2025	2.272
	Fine	0.010	0.520	0.0367	1.1012	0.0919	24.800
	Very fine	0.010	0.614	0.0265	1.1033	0.0936	15.000
subsoil	Coarse	0.025	0.366	0.0430	1.5206	0.3424	70.000
	Medium	0.010	0.392	0.0249	1.1689	0.1445	10.755
	Medium-fine	0.010	0.412	0.0082	1.2179	0.1789	4.000
	Fine	0.010	0.481	0.0198	1.0861	0.0793	8.500
	Very fine	0.010	0.538	0.0168	1.0730	0.0680	8.235
	Organic	0.010	0.766	0.0130	1.2039	0.1694	8.000

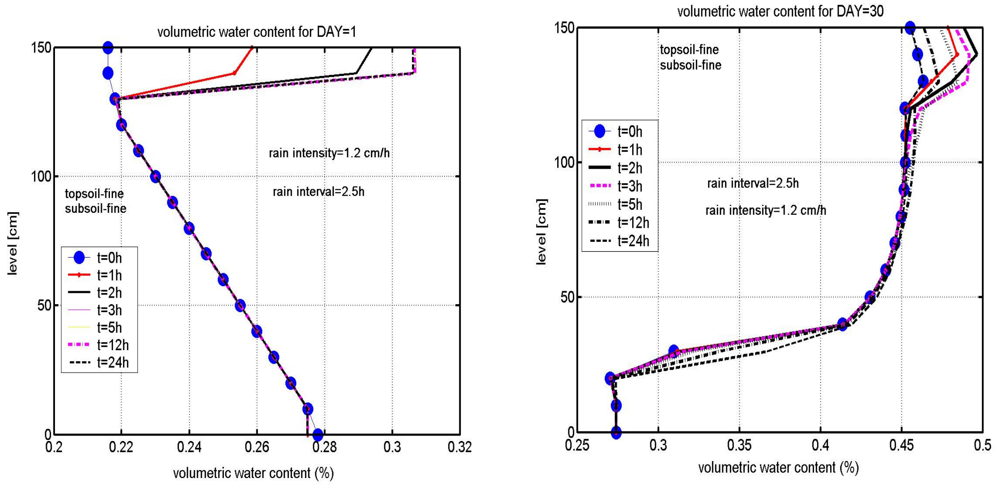

Fig.2. Volumetric water content profile for a soil with a fine texture class (topsoil-fine, subsoil-fine), after one day and after 30 days of rain with intensity=1.2cm/hour, 2.5 hours/day.

The figures 2 and 3 show the simulation results concerning water flow in unsaturated soil profile. We considered the hydraulic regime corresponding to 90 days, the rain intensity being 1.2 cm/hour, 2.5 hours/day, during 30 days. The last 60 days the rain intensity vanishes.

Richards equation with van-Genuchten pedotransfer parameters corresponding to different soil profiles (Table1) has been integrated.

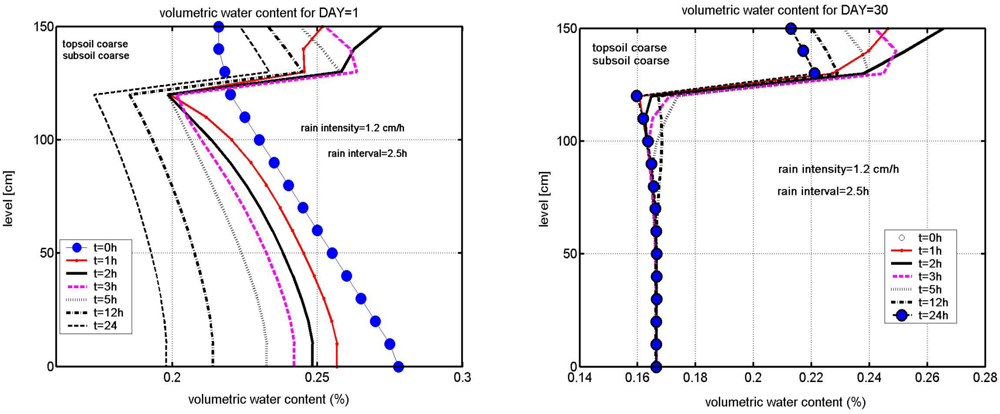

Fig.3. Volumetric water content profile for a soil with a coarse texture class (Tc-Sc), after one day and after 30 days of rain with intensity=1.2cm/hour, 2.5 hours/day.

The influence of soils' texture class on the water content and on the discharges is very important. In the same rainfall conditions for a fine soil the discharges through the unsaturated profile are smaller then in a coarse texture. The nitrogen leaching risk under the same precipitation conditions is greater in a coarse soil. The volumetric water content in a fine structure (Fig.2) is greater then for a coarse soil (Fig.3), and the nitrates dilution will be highly influenced (Fig.4).

3. Modelling the transport of nitrogen compounds in unsaturated soils

We computed the concentration of each constituent N-NO_3^-, N-NH_4^+, Norg, in the roots' region and N-NO_{3n}^- in the unsaturated, without roots, region. NO_{3n} is the nitrate concentration that reaches the groundwater surface.

The nitrogen concentrations in each component are related with the chemical entrances (fertilizers concentrations: AORG, AAM, ANIT), and with the water dynamic in the soil. The rain or irrigation intensity, P (cm/hour), the surface runoff QR (cm/hour), and the moisture retention characteristic of the soil influence the discharges values QI, QIR, the water content in the unsaturated roots' region RSOL (cm), and the water content in the unsaturated, without roots, region RNON (cm). The nitrogen concentrations in each component are obtained integrating the system (6)-(9):

$$\frac{d\left(NO_3^-\right)}{dt} = (1-QR/P)ANIT - (QI/RSOL)(NO_3^-)+[k_{ni}/(1+k_d)](NH_4^+)-$$
$$k_{rn}(NO_3^-)-B[(NO_3^-)/((NO_3^-)+k_{ab})]f_{pp}{}'(t/T), \qquad (6)$$

$$\frac{d\left(NH_4^+\right)}{dt} = AAM+k_{am}(Norg)-[k_{ni}/(1+k_d)](NH_4^+)-[k_{ra}/(1+k_d)](NH_4^+), \qquad (7)$$

$$\frac{d(Norg)}{dt} = AORG+k_{rn}(NO_3^-)+[k_{ra}/(1+k_d)](NH_4^+)-k_{am}(Norg), \qquad (8)$$

$$\frac{d\left(NO_{3n}^-\right)}{dt} = (QI/RSOL)(NO_3^-)-(QIR/RNON)(NO_{3n}^-), \qquad (9)$$

where: k_{am}, k_{ra}, k_{ni}, k_{ad}, k_{rn} are the rate values of chemical reactions, obtained by model calibration, ANIT, AAM, AORG are nitrogenous fertilizers (kg ha^{-1}), on the soil surface, entering through the surface in the unsaturated soil, B is the potential (maximum) nitrogen-nitrate uptake by the plant during a life cycle.

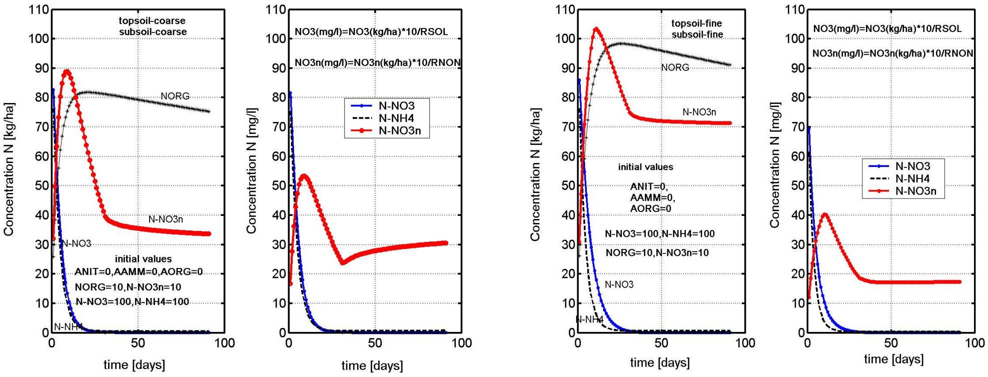

Fig. 4. Nitrogen concentration N-NO_3, N-NH_4, Norg, N-NO_{3n}, in kg/ha and mg/l, for two soil profiles (topsoil-coarse, subsoil-coarse) and (topsoil-fine, subsoil-fine).

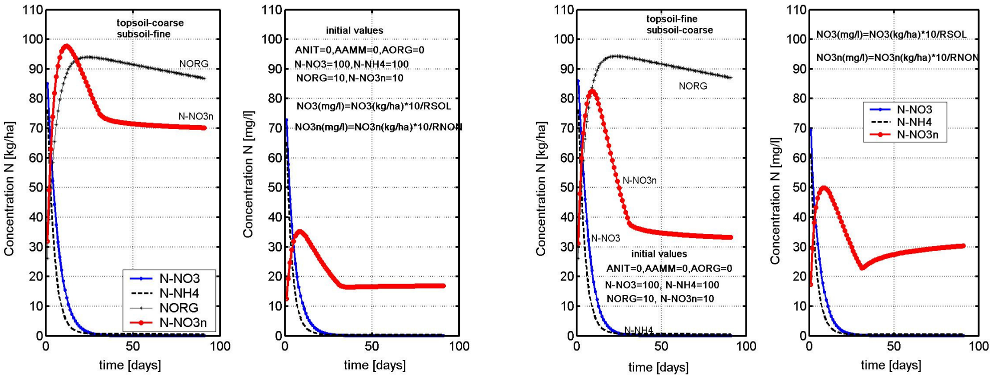

Fig. 5. Nitrogen concentration N-NO_3, N-NH_4, Norg, N-NO_{3n}, in kg/ha and mg/l for two soil profiles (topsoil-coarse, subsoil-coarse) and (topsoil-fine, subsoil-fine).

The simulations assumed the same rainfall regime with rain intensity, P=1.2 cm/hour, 2.5 hours/day, during 30 days and P=0 for the next 60 days, in four scenarios differing by the soil texture. Considering the Topsoil (20cm underlying the soil surface) and the Subsoil (between 20 cm and 150 cm depth), the four analyzed profiles are (Tc-Sc) = (Topsoil-coarse, Subsoil-coarse), (Tf-Sf) = (Topsoil-fine, Subsoil-fine), (Tf-Sc) = (Topsoil-fine, Subsoil-coarse), (Tc-Sf) = (Topsoil-coarse, Subsoil-fine). For each texture class, Mualem-van Genuchten parameters (Table 1) differentiate the soil behavior. The fertilizer influence has been introduced only by initial conditions for the nitrogenous compounds:
$N\text{-}NO_3$=100 kg/ha, $N\text{-}NH_4$=100 kg/ha, $N\text{-}NO_3n$=10 kg/ha, Norg=10 kg/ha.

The figures 4 and 5 show the daily variation of nitrogen concentration: Norg, $N\text{-}NO_3$, $N\text{-}NH_4$, $N\text{-}NO_3n$, in the analyzed soil profiles, during 90 days.

Table 2

Temporal changes of nitrogen concentration for different texture classes of soil

D	Soil	RSOL cm	RNON cm	NO3 kg/ha	NO3 mg/l	NH4 kg/ha	NH4 mg/l	NO3n kg/ha	NO3n mg/l	NORG kg/ha
0	Tc-Sc	11.02	25.49	100	90.74	100	90.74	10	3.92	10.00
	Tf-Sf	11.02	25.49	100	90.74	100	90.74	10	3.92	10.00
	Tc-Sf	11.02	25.49	100	90.74	100	90.74	10	3.92	10.00
	Tf-Sc	11.02	25.49	100	90.74	100	90.74	10	3.92	10.00
1	Tc-Sc	10.13	19.14	82.65	81.60	76.96	75.99	32.04	16.74	25.91
	Tf-Sf	12.38	25.47	85.97	69.44	76.96	62.16	30.83	12.10	26.24
	Tc-Sf	11.68	25.47	85.04	72.81	76.96	65.89	31.84	12.50	26.15
	Tf-Sc	12.39	17.98	85.98	69.37	76.96	62.10	31.18	17.35	26.24
10	Tc-Sc	9.49	16.63	8.29	8.74	6.03	6.36	86.66	52.12	78.43
	Tf-Sf	20.39	25.56	21.12	10.36	7.73	3.79	103.1	40.31	87.32
	Tc-Sf	16.59	27.91	18.53	11.17	7.72	4.65	97.03	34.76	85.07
	Tf-Sc	14.97	16.59	18.12	12.11	7.72	5.16	82.34	49.62	86.15
20	Tc-Sc	9.48	16.60	0.80	0.84	0.94	0.99	61.24	36.88	81.83
	Tf-Sf	22.49	31.60	3.90	1.73	1.16	0.51	91.97	29.10	97.72
	Tc-Sf	17.74	34.64	2.82	1.59	1.13	0.64	89.87	25.94	93.69
	Tf-Sc	14.98	16.68	2.35	1.57	1.14	0.76	61.64	36.96	94.13
30	Tc-Sc	9.48	16.60	0.15	0.16	0.57	0.60	39.51	23.80	81.19
	Tf-Sf	22.83	39.26	0.60	0.26	0.69	0.30	76.28	19.43	98.22
	Tc-Sf	18.11	42.19	0.39	0.22	0.66	0.37	76.09	18.03	93.72
	Tf-Sc	14.98	16.68	0.31	0.21	0.66	0.44	39.85	23.89	93.93
60	Tc-Sc	7.19	12.03	0.046	0.063	0.524	0.729	34.78	28.91	78.23
	Tf-Sf	20.66	41.81	0.057	0.027	0.634	0.307	71.78	17.17	94.75
	Tc-Sf	15.32	42.51	0.054	0.035	0.605	0.395	71.05	16.71	90.37
	Tf-Sc	13.02	11.10	0.054	0.041	0.606	0.466	34.18	28.48	90.55
90	Tc-Sc	6.71	11.01	0.048	0.071	0.504	0.751	33.64	30.57	75.30
	Tf-Sf	20.30	41.13	0.059	0.029	0.611	0.301	71.29	17.33	91.21
	Tc-Sf	14.72	41.58	0.056	0.038	0.582	0.396	70.23	16.89	86.99
	Tf-Sc	12.61	10.96	0.056	0.044	0.584	0.463	33.21	30.31	87.17

4. Conclusions

The changes between Norg, NO_3, NH_4, NO_3n, and the nitrates leaching depends on the hydraulic regime in the soil profile (amount of precipitation and irrigation, volumetric water content, seepage flux, the plant uptake dynamics), and that one is well imposed by the soil texture class.

The maximum values for N-NO_3, and N-NH_4, (100 kg/ha, respectively 90.744 mg/l) at the beginning of the first day (initial conditions for the biochemical system (6)-(9), decrease rapidly in the first ten days (Table 2). After 10 days N-NO_3 is 8.74 mg/l in a (Tc-Sc) profile and 12.11 mg/l in a (Tf-Sc) one. For the nitrate plant uptake the Topsoil –fine, Subsoil –coarse can be considered an advantageous profile but the nitrate concentration in the layer underlying the roots region, NO_3n, leaching towards the groundwater is 49.62 mg/l after 10 days.

The minimum value for NO_3n, after 10 days, producing the least groundwater pollution is 34.76 mg/l, corresponds to Topsoil –coarse, Subsoil – fine profile. In the coarse (Tc-Sc) soil the higher seepage solute flux implies the maximum values of nitrates concentration leaching towards groundwater (53.35 mg/l in the 9 th day). The minimum concentration of N-NO3n is obtained for fine soil (Tf-Sf) (17.12 mg/l in the 49 th day) because the water content is greater in a fine soil and the nitrate dilution will increase.

The proposed model can be used to predict the nitrogen-nitrate concentration leaching toward the groundwater, for different soil profile and to optimize the fertilization schedule.

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