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Water Dynamics Combined with a Supply of NPK Solutes and Urea in a 3-Layer Soil Profile under Drip Irrigation

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Abstract

The intensive and inappropriate use of water, fertilizers and phytosanitary products is sources of water and soil pollution. It is thus necessary to improve the management of irrigation water in order to optimize its use and productivity, especially in regions where water resources are becoming increasingly scarce. The water flow and non-reactive solutes' transport simulation under drip irrigation were carried out in a 3-layered soil profile distributed from top to bottom *i.e.*, sandy, sandy-silty, silty-sandy-clay. The aim of this study was thus, to provide a good practice of water management associated with solutes' application, in order to retain as much solute as possible in the root zone, which will increase the residence time of the solutes. Three treatments of water flux corresponding to 100% ET_c, 75% ET_c, 50% ET_c, combined with 100 mmol /L/ m^2 of NPK and 246 mmol/L/m^2 of urea applicable in two doses, were carried out over a period of 110 days corresponding to the duration of the cropping cycle for the intermediate variety of maize. The 100% ET_c and 75% ET_c treatments cause more loss of water and solutes, because of the sandy texture of the soil. However, a 50% ET_c water flux would reduce more water loss through drainage, and solutes' loss due to leaching beyond the root zone, which would increase the residence time of solutes in the soil profile. Application tests of the NPK solute on different days before the 15th day after sowing were also carried out according to the technical itinerary for maize production in Burkina Faso, in order to find a favorable day for application of the solute. For the different dates of solute's application, there was more loss of the solute as we approach the 15th day after sowing. To limit this loss and increase the residence time of the NPK solute, one could apply the solute without first supplying water, the day before and the day after the date of solute' injection. Or, one could amend the soil with organic matter to improve its retention capacity of water, and the solutes' residence time in the soil.

Keywords

Drip Irrigation, Hydrus 1D, Solute and Water Management, Residence Time

1. Introduction

The search for a continuous increase in agricultural productivity, the standardization of technology, and the intensification of the production led in the 1980s to negative environmental impacts on agro-ecosystems, such as erosion, reduction of biodiversity, water and soil pollution. Intensive and inappropriate use of water, fertilizers and phytosanitary products are sources of water and soil pollution [1] [2] [3]. This water and soil pollution by pesticides has become a major health problem [4]. It is thus necessary to improve the management of irrigation water in order to optimize its use and productivity, especially in regions where water resources are becoming increasingly scarce [5]. Irrigated agriculture, the main objective of which is to improve irrigation water management and increase productivity, will be used. Irrigation techniques can indeed meet the challenge of reasonable management of water resources and fertilizers. Among the existing irrigation methods, drip irrigation systems offer enormous potential as compared to other systems. Indeed, they significantly reduce evaporation, apply water and fertilizers directly to the root zone and greatly reduce loss. Due to these advantages, drip irrigation has become the most accepted method of irrigation/fertigation in order to improve the efficient use of water and nitrogen, as well as minimize nitrate leaching [6]. However, a potential problem associated with drip irrigation is the deep percolation and leaching of nutrients beyond the root zone [7] [8] [9] [10] [11], which could be a source of soil and groundwater pollution. In Burkina Faso, where the lack of water continues to increase each year, the adoption of drip irrigation as an alternative by producers is slowly taking place, despite the enormous benefits that this irrigation system could bring to producers. In order to better support producers, studies therefore need to be carried out, especially on how to manage water and fertilizers for the proper planning of irrigated agriculture with drip irrigation. The main objective of this study was thus, to propose good practices for the application of water associated with fertilizers (NPK; urea) in order to retain as many fertilizers as possible in the root zone as long as possible, for the production of corn under drip irrigation. Doing so, could maximize the residence time of solutes, which could also increase the solute's uptake by the plant. More specifically, our objective was to: 1) study the dynamics of NPK (14-23-14) and urea (46-0-0) in the soil; 2) predict the risks of leaching according to the dose and the time of application; 3) provide a good management of the soil and a good use of the crop. Proper design of drip systems requires knowledge of the wetting front distribution around the dripper. Although several studies have been carried out to investigate the dynamics of water in soil under drip irrigation (e.g. [12] [13] [14]), it is still difficult to design management strategies for the optimization of the quantity of irrigation water, its frequency, and the location of drippers, in order to achieve the highest water use efficiency [15]. Simulation models have been valuable research tools for studies taking into account the interactive and complex processes of water flow and solutes' transport in the soil, and also the effects of management practices on yields as well as the environment [16] [17]. These simulations can be used to assess the efficiency of irrigation systems over several seasons, and advise producers if this requires improvement in several aspects of the functioning of the irrigation systems [18]. Numerical simulation as a tool to optimize the management of irrigation practices is a fast and an inexpensive approach; it has been used a lot over the past ten years. Among the numerical models used, the Hydrus model, thanks to its flexibility in taking into account different boundary conditions, and the uptake of water and nutrients by the roots of the plant, and an easy-to-access user interface, was much successfully used in several studies (e.g. [7] [10] [15] [19]-[24]) to simulate the movement of water under drip irrigation. In this study, we used Hydrus 1D to simulate water flow and non-reactive solutes' transport in one dimension (vertical axis), in a 3-layer soil, and we did not take into account water and solutes' root uptake.

2. Methods and Materials

2.1. Process

The studied scenario consisted of an application of urea (46-0-0) and NPK (14-23-14) for the production of maize (intermediate variety 95 - 110 days) through a simulated drip irrigation with the Hydrus 1D software. In order to assess deep drainage, and solutes' leaching according to the day of application, the water flux and the solutes' concentration, neither the crop nor the water and solutes' uptake by roots were considered in this simulation. The two solutes applied were considered as tracers, therefore having no interaction with the environment. Also, they were provided in liquid form with the irrigation water. The water supplies were first made at 100% ET_c. This, in order to observe possible loss of water and solutes if the irrigation were scheduled daily, and then, to proceed with an irrigation planning when the water is considered as a limiting factor, or to reduce loss. The quantities of solutes supplied were in accordance with those recommended for maize production in Burkina Faso, according to J. Sanou (2004). The scenarios were simulated according to the initial and boundary conditions in order to get closer to the reality

2.2. Plot of Land Meshing

We considered a plot of land with an area of 500 m^2 (25 m × 20 m) irrigated by surface drip irrigation system, with a flow rate of 2 l/h (the most frequently used flow under in our tropics). The crop used was maize (intermediate variety) with a production cycle of 110 days. We used the recommendations of the Ministry of Agriculture in terms of inter-crop and inter-row spacing of 40 cm × 80 cm. For the area to be irrigated, there will be 31 lines of pipes and 50 drippers per line, *i.e.*, a total of 1550 drippers (pockets) are given in Figure 1.

2.3. Fertilizers Dosage

For semi-intensive agriculture, the quantities of urea (46-0-0) and NPK (14-23-14) to be used for maize production are respectively 150 kg/ha and 200 kg/ha (J. Sanou, 2004). Table 1 gives the quantities of fertilizer and their date of application. For a small village irrigation (500 m^2), we determined the concentration of urea and NPK to apply according to the area:

- **NPK concentration**

From sowing date until to the 15th day after sowing, the NPK dose to use is 200 kg/ha, *i.e.*, 0.02 kg/m^2 or 20 g/m^2. For NPK (14-23-14) or 14% of N_2, we will have 2.8 g/m^2. The concentration being the number of moles per volume quantity, we considered a liter (1 L) of solution. The molar concentration would therefore be 0.1 mol/L/m^2 or 100 mmol/L/m^2. This concentration value was considered as input data for the NPK simulation.

- **Urea concentration**

In total, we used 150 kg/ha of urea (46-0-0) in two applications:

On the 30th day after sowing

We used 100 kg/ha of urea (46-0-0) or 46 kg/ha or 4.6 g/m^2 of urea. The concentration being the number of moles per quantity of volume, we considered a liter (1 L) of solution. The molar concentration would therefore be 0.164 mol/L/m^2 or 164 mmol/L/m^2.

On the 45th day after sowing

The quantity envisioned is 50 kg/ha of urea (46-0-0) or 23 kg/ha of urea, which

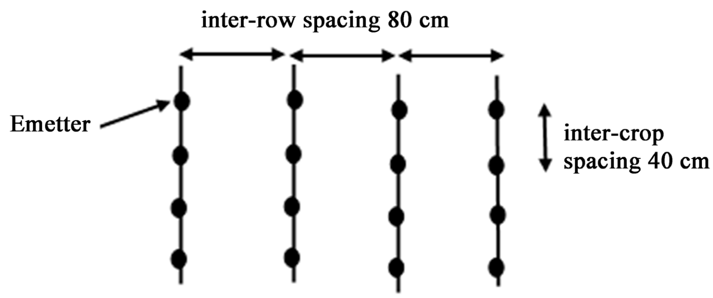

Figure 1. Row and crop spacing.

Table 1. Urea and NPK doses used for semi-intensive production [25].

Fertilizer	Base	Application date	Quantity
NPK	14-23-14	Sowing up to 15th day after sowing	200 kg/ha
Urea 1	46-0-0	At the 30th day after sowing	100 kg/ha
Urea 2	46-0-0	At the 45th day after sowing	50 kg/ha

is equivalent to 2.3 g/m^2. By going to the concentration, we obtained 0.082 $mol/L/m^2$ or even 82 $mmol/L/m^2$.

2.4. Field of Study

The study area **Figure 2** was a one meter deep soil profile, made up of 3 layers and initially dry. These three layers are distributed from top to bottom in a sandy layer, sandy-silt, and sandy-clay silt. The initial water contents in these different layers were equal to the residual water contents. In this study domain, we placed observation nodes N1, N2, N3, N4, and N5 respectively on the soil surface of 0 cm, 20 cm, 50 cm, 75 cm and 100 cm in depth.

The soil properties used for the simulation were determined experimentally thanks to a complete characterization of the physical, morphological and hydrodynamic properties in [26]. We presented the physical parameters of the 3 different layers necessary for the simulation in **Table 2**. The parameters alpha α and n were derived from particle size distribution and bulk density in [26] with the ROSETTA pedotransfer function. And the other parameters θ_s and K_s were determined experimentally by [26]. At the beginning of the simulation, the soil did not contain any solute, the irrigation water also did not. The ground surface was subject to an atmospheric boundary condition with meteorological values that were those of Burkina Faso, obtained from the National Meteorological Agency. The surface of the domain was also subjected to variable fluxes of water and solutes in order to take into account the inputs of water and fertilizer. The bottom boundary of the domain was subject to free drainage, and the side walls, to zero flux of water and solutes. The various meteorological data are shown in **Table 3**. Water supplies were made according to the plant's water

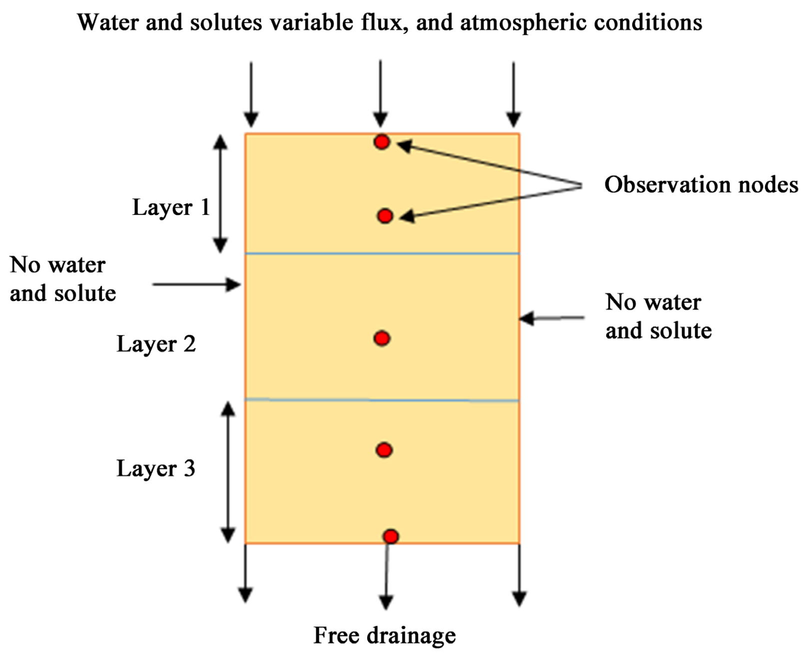

Figure 2. Domain flow and boundary conditions as well as observations nodes.

Table 2. Soil hydraulic properties.

Parameters	θ_r	θ_s	α	n	K_s	l
Layer 1	0	0.3655	0.0377	2.4559	268.932	0.5
Layer 2	0	0.37	0.0378	1.9234	28.27	0.5
Layer 3	0.0057	0.396	0.0259	1.2733	35.251	0.5
Units	$m.m^{-3}$	$m.m^{-3}$	cm^{-1}	-	$cm.jr^{-1}$	-

Table 3. Meteorological parameters used for simulation.

Time (day)	ET_0	Radiation	T_{min}	T_{max}	Humidity	Wind	Sunshine
1-21	6.8377	16.4071	19.9190	35.2428	25.3809	236.16	7.3714
22-42	6.7290	18.0452	22.5857	38.0285	29.2619	196.251	8.34761
43-63	8.1371	19.5380	24.6952	40.1857	26.5238	242.742	8.3190
64-110	6.4298	18.5943	27.6695	39.1630	45.3586	222.949	7.7
Units	mm/day	$MJ/m^2/day$	°C	°C	%	Km/day	hr

Table 4. Water flux and solutes' concentration applied at the top of the domain.

Time (day)	Flux top	Concentration of solute 1	Concentration of solute 2
1 - 21	0.266	100 NPK	
22 - 42	0.631		164 Urea 1
43 - 63	0.722		82 Urea 2
64 - 110	0.459		
Units	cm/day	$mmol/L/m^2$	$mmol/L/m^2$

requirements, which were determined by the FAO method Equation (1).

$$ET_c = ET_0 \times K_c \quad (1)$$

In which, ET_c is the crop water evapotranspiration (mm/day), ET_0 the potential evapotranspiration (mm/day); and K_c the dimensionless maize crop coefficient depending on plant growth. In Table 4 we summarize the different inputs of water and solutes during the simulation period.

2.5. Water Flow and Solutes' Transport Modeling

The Hydrus 1D software [27] was used for the one-dimensional numerical simulation of water, and solutes' transport in the soil column. The water flow in a variably saturated medium is described by the Richards equation:

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

where z is the vertical coordinate (cm); and h the soil water pressure head (cm); t the time (day); K the hydraulic conductivity function ($cm \cdot day^{-1}$); θ the volumetric water content ($cm^3 \cdot cm^{-3}$).

The hydraulic conductivity function is given by the van-Genuchten (1980) Mualem (1976) relationnships in Equation (3) [28].

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_{sat} - \theta_r} = \left[1 + (\alpha h)^n\right]^{-m} \tag{3}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{4}$$

In which S_e is the effective saturation, θ_r and θ_s respectively denote the residual and saturated water contents ($cm^3 \cdot cm^{-3}$). K_s is the saturated hydraulic conductivity ($cm \cdot day^{-1}$), α (cm^{-1}) and n (−) are empirical shape parameters, l is a pore connectivity/tortuosity parameter (−).

The solutes' transport is represented by a convective-dispersive transport equation. Convection accounts for the macroscopic transport of solutes, which accompany the fluid. Diffusion accounts for both molecular diffusion and hydrodynamic dispersion. No nitrogen transformation was considered in the simulation process. Thus, the adsorption, precipitation/dissolution, volatilization of nitrogen were neglected. The equation governing the transport of non-reactive solutes in a homogeneous porous medium is written as:

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial z}\right) - \frac{\partial qc}{\partial z} \tag{5}$$

where c is the concentration of the species in the liquid phase ($M \cdot L^{-3}$); D the hydrodynamic dispersion coefficient of the chemical species ($L^2 \cdot T^{-1}$), and q the water flow ($L \cdot T^{-1}$).

3. Results and Discussion

We presented the results of the simulation for a 110 days duration (duration of the crop cycle) below. The first results obtained were in conformity with the technical route recommended for maize production in Burkina Faso using of fertilizers. **Figure 3** and **Figure 4** respectively gave the potential pressure head and the water content, versus time at the various observation nodes. These two **Figure 3** and **Figure 4** show how the water is distributed through the soil, from the surface (node N1: 0 cm) to the bottom of the domain (node N5: −100 cm). **Figure 4** and **Figure 5** respectively show the concentration of NPK and urea versus time at the different observation nodes. Through **Figure 5** and **Figure 6**, we saw how the solutes infiltrate and then, spread throughout the soil from the application date. By analyzing **Figure 3**, we noticed that, with a water flux of 0.266 cm/day applied to the surface (node N1) during the first 21 days, the water reached the layers N2, N3, N4, and N5 respectively 1 day, 7 day, 12 day, 17 day after application. Beyond the 40th day of irrigation, the pressure potential in nodes N4 and N5 was greater than that of nodes N1, N2, N3, which means that the quantity of water leaving the deep layers was greater than that coming from the upper layers. Beyond the 65th day, the curves of the various observation

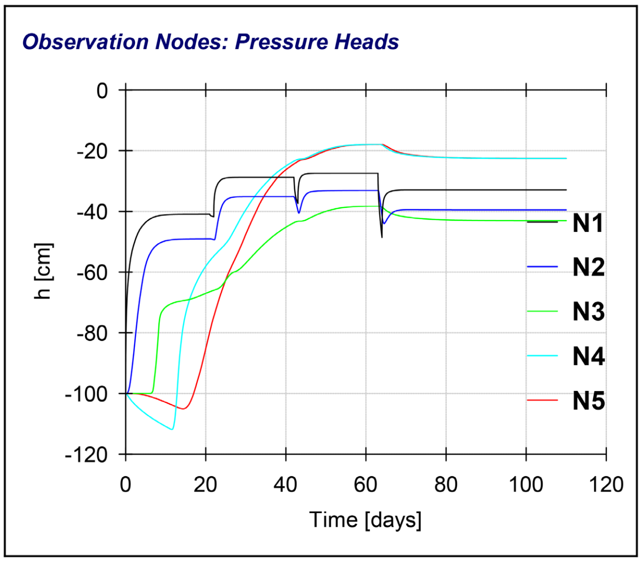

Figure 3. Pressure Head versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm).

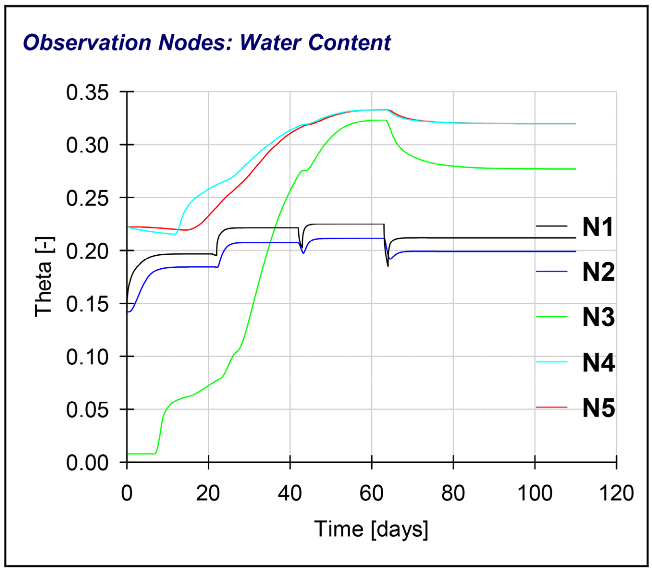

Figure 4. Water Content versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm).

nodes were almost parallel, until the end day of simulation. We therefore, saw the water flux reach an equilibrium state in the entire soil profile. We also noticed that, the water flux leaving the soil profile at node N5 was greater than the flux of water infiltrating the surface at node N1, which means a loss of water from the 40th day until the end day of the simulation (110th day). Figure 4 showing the water content versus time at the different observation nodes, looks like Figure 3, which confirmed the previous results. The observation of nodes N1, N3 and N5 in Figure 3, clearly shows that the water stock above 50 cm was greater than that in the first 50 cm of the ground.

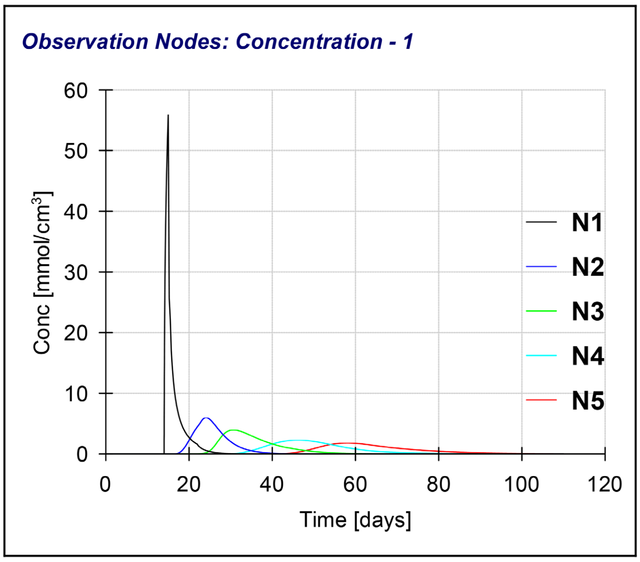

Figure 5. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm).

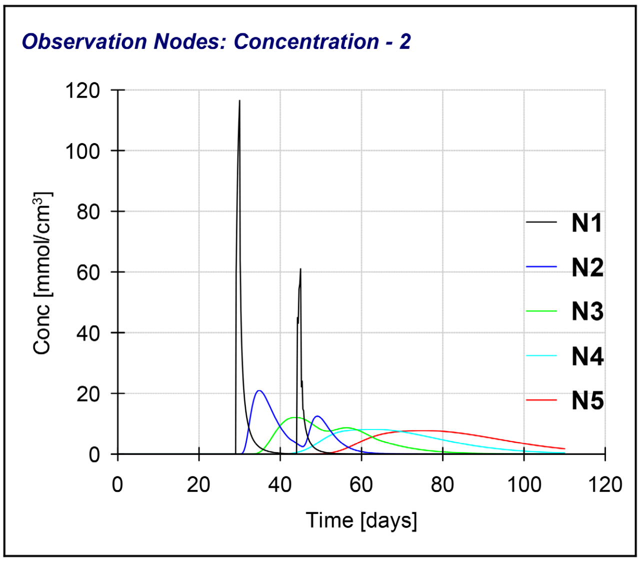

Figure 6. Solute (Urea) concentration versus time at selected ob−servation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm).

The NPK (concentration 1) was injected on the 15th day. As the water seeps into the soil, it carries the solutes with it through the entire soil profile. The concentration of solute available on the surface of the soil gradually decreased until it was completely leached on the 30th day. The solute, respectively reaches a depth of 20 cm (node N2) and 50 cm (node N3) on the 17th day and 22nd day after sowing, which means respectively, 2 days and 7 days after application of the NPK. The NPK continues its distribution and reaches the bottom of the domain (node N5: 100 cm) on the 47th day. As the water continues to seep into the soil, all of the solute concentration applied to the soil surface will be leached, and thus, returning the soil profile to its initial state of zero concentration. What occurred after the 75th day, with the solute concentration in all layers being zero, the soil was completely leached. The solute concentration in the different layers of the soil remained low, a peak of around 6 mmol/cm^3 was reached at a depth of 20 cm on the 25th day. The concentration beyond 20 cm of depth remained lower than the observed peak. In **Figure 6**, two supplying of urea (concentration 2) were made on the 30th and 45th day after sowing, which is observable at node N1: 0 cm. Because of the dispersion, this concentration of solute progressively reaches respectively nodes N3: −50 cm and N4: −75 cm on the 32nd and 40th day. The solute concentration not being zero at node N5 at the end of the simulation, we deduced that the solute remains in the soil at the end of the simulation. These analyzes show that, a large part of the water and solutes used, was lost through drainage and leaching beyond the root zone, especially in the early stages of the crop development. As for the volume of water and the quantity of solute stored in the soil, the quantity (NPK in particular) would be unusable by the crops, because they was stored beyond a certain depth (−60 cm) of the non-colonized soil by the roots at the first stage of the crop development. We performed different simulations in order to limit the volume of water, and a certain high concentration of solutes in the first half of the soil, where the root density is higher for the first phase of corn growth between 1 and 21 days. As the root volume is still growing until the maturity of the maize during which time, urea was applied in two doses, the urea could still be absorbed by the roots even beyond 60 cm depth. It was therefore necessary to optimize the application of NPK, as it can be applied from seedling to the 15th day after sowing, a period included in the initial phase of growth, for which root development is not important.. In order to reduce the water loss by drainage as well as NPK loss, we carried out water supplies at 100% ET_c, 75% ET_c, and at 50% ET_c with new treatments for NPK's inputs and thus found a favorable day in which there would be less loss and longer residence time, as compared to other days of application.

3.1. 100% ET_c and NPK Applied Either on the 1st, 5th, 10th or 15th Day after Sowing

When the NPK was applied the 1st day after sowing **Figure 7**, we can see through the various observation nodes that the solute concentration was watched out from the surface (node N1) of the soil on the 25th day after application, and the maximum concentration was 60 mmol/cm^3. The solution continues its distribution and reached the N2 node 2 days after application, with a maximum (6 mmol/cm^3) reached on the 20th day. The solute left the 20 cm depth on the 39th day. After 9 days, the solute then reached a depth of 50 cm (node N3) for which, peak concentration was 5 mmol/cm^3, and beyond the 60th day, it leached over the depth of 50 cm. The N4 node was reached on the 15th day with a peak concentration of 3.75 mmol/cm^3. The solute left the N4 horizon on the 75th day.

For an NPK treatment on the 5th day after sowing **Figure 8**, all the solute

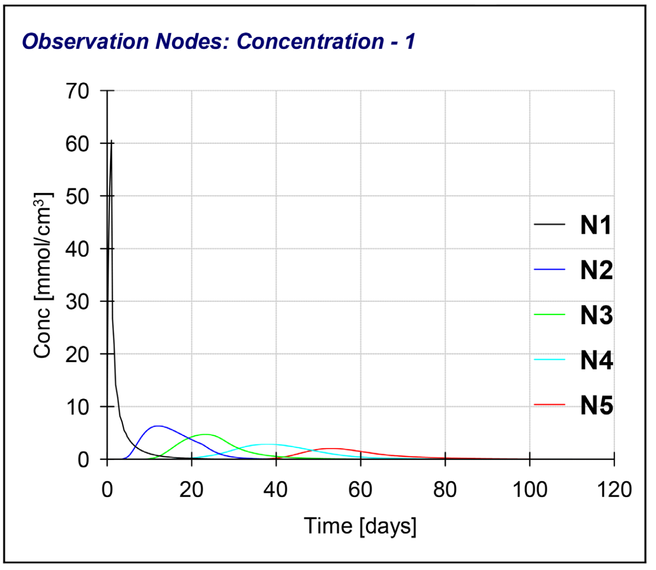

Figure 7. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 1.

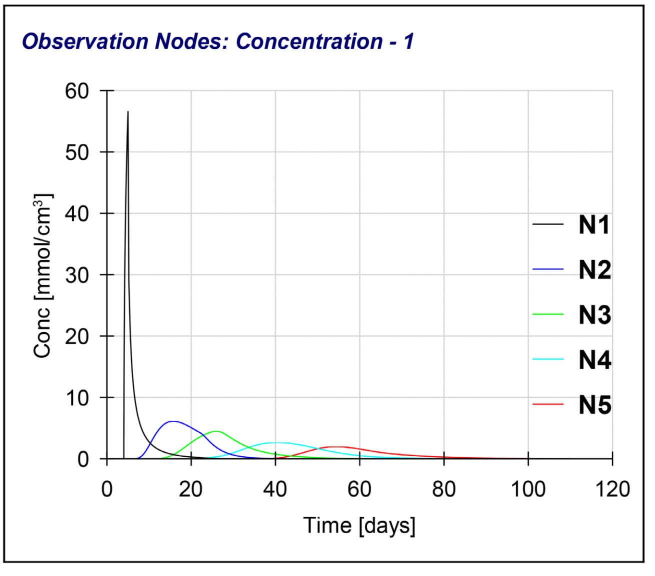

Figure 8. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 5.

disappeared from the soil surface on the 28th day. The maximum concentration observed at this level was 56 mmol/cm³. The solute front reached N2 on the 7th day with a maximum concentration of 7.75 mmol/cm³ on the 15th day. The solute was leached to the depth of 20 cm on the 40th day.

The water continuing its infiltration carried the solute with it to node N3 on day 12, and leaves the depth on the 60th day. On the 20th day, the solute reached node N4 and leaves this depth on the 75th day.

Figure 9 (NPK applied on the 10th day after sowing) on the soil surface, the solute was leached before the 30th day. The solute continues to progress until it reached node N2 on the 12th day with a maximum concentration of 6 mmol/cm^3; the solute leaves this region of the soil on the 43rd day. Node N3 was reached on the 17th day, and the solute was leached from this horizon on the 65th day. 10 days after reaching node N3, the solute then reaches node N4 in order to flow past N4 by the 90th day.

The application of NPK on the 15th day after sowing Figure 10 shows a disappearance of the solute from the soil surface (N1) on the 32nd day. The solute front continues to distribute and reached N2 on the 17th day and then vanished on the 46th day. Nodes N3 and N4 were reached after the 22nd and 30th day

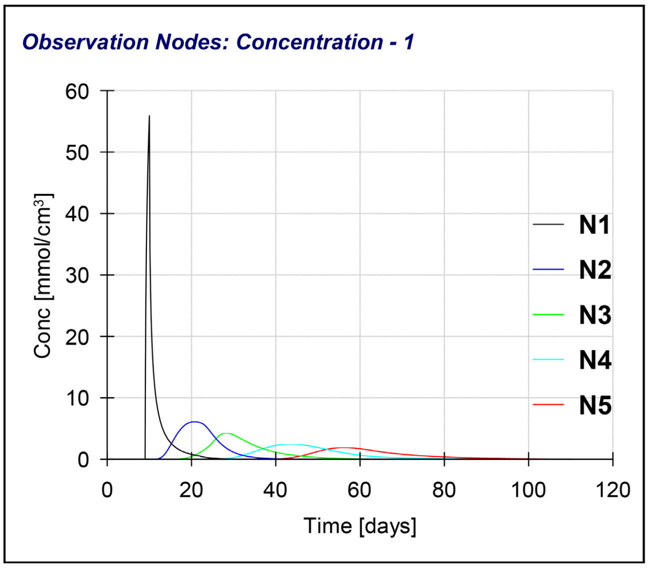

Figure 9. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 10.

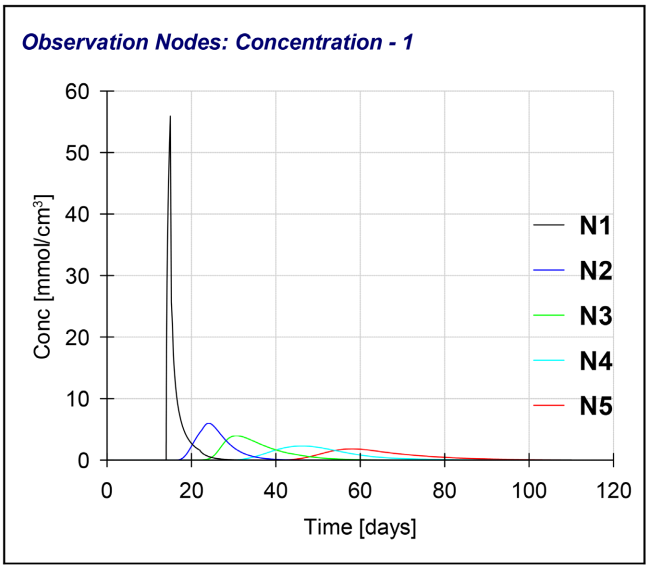

Figure 10. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 15.

respectively. The solute front leaves the N3 and N4 horizon on the 67th and the 95th day, respectively.

Note that for 100% ET_c, regardless of the period of application of NPK to the soil surface, the residence time of NPK on the soil surface did not exceed 25 days, which was the longest stay in the surface when the solute was applied on the 1st day after sowing. For each date of application, the solution reached nodes N2 and N3 respectively, 2 days and 7 days after application. On the other hand, the concentration in the various observation nodes decreases as one approaches the 15th day in order to carry out the solute's intake. All solute in the soil was lost on the 110th day after sowing, regardless of when the solute was supplied.

3.2. Water Flux 75% ET_c and NPK Applied Either on the 1st, 5th, 10th or 15th Day after Sowing

For a treatment of 75% ET_c as water supply, we considered the same treatments as above for the solutes' supply. By observing the pressure head curve in the soil at different observation nodes, we noticed that the quantity of water stored in the soil and lost at node N5 was less as compared to the quantity stored and lost for a treatment of 100% ET_c. 75% ET_c therefore reduced water loss through drainage. To save space, we did not present the figure giving the pressure head potential.

Supply of solute on the 1st day of simulation **Figure 11**: the concentration reached a peak of 55 mmol/cm³, the solute made approximately 30 days on the soil surface (Node N1). On the 4th day, the solute has reached node N2 with a peak concentration of 5 mmol/cm³, the solute has left this horizon on the 46th day after application. At 11 days of the application, the solute has reached node N3 with a peak of 4 mmol/cm³, and left this depth on the 72nd day. Node N4 was reached on the 20th day and cancels itself out on the 106th day. All the concentration

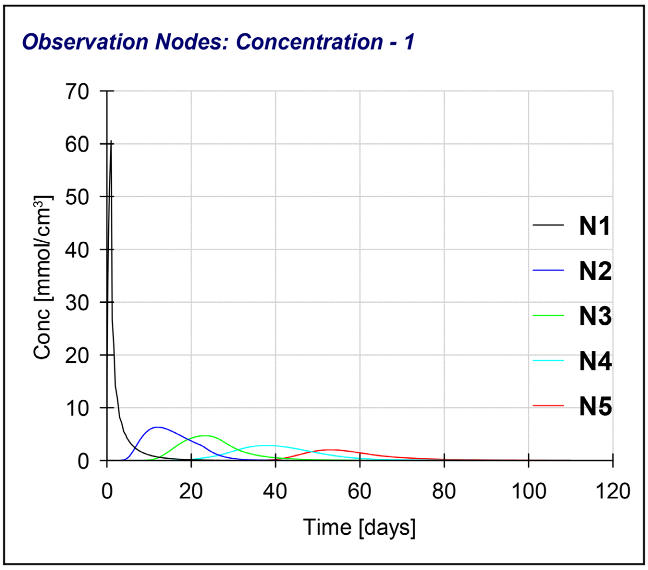

Figure 11. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 1.

has left the profile after 110 days of application.

Figure 12 shows us a solute supply made on the 5th day of simulation. A further peak of 52mmol/cm³ was observed and the solute remained on the surface until the 32nd day. The N2 horizon was reached on the 7th day with an approximate peak of 5mmol/cm³, and was washed out of this horizon on the 48th day. On the 15h day the solute reached node N3 with a peak of 4mmol/cm³ and then vanished on day 75. Node N4 was reached on the 24th day with a concentration of 2mmol/cm³ and was canceled on the 110th day.

For an application dose made on day 10 Figure 13, the solute front disappears

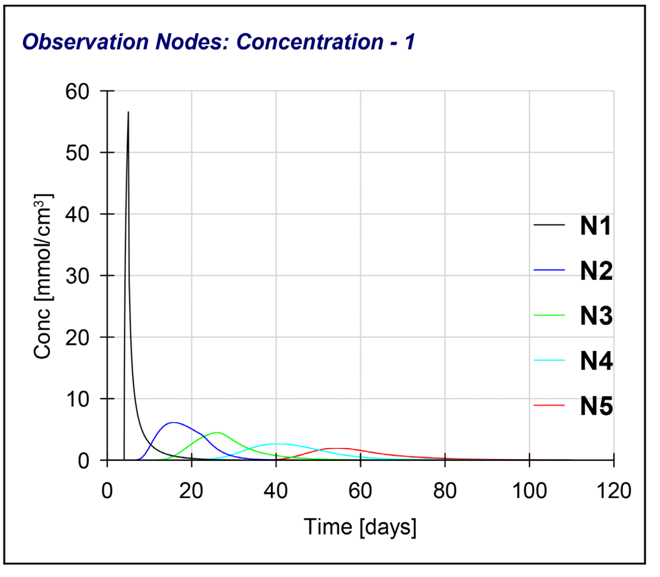

Figure 12. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 5.

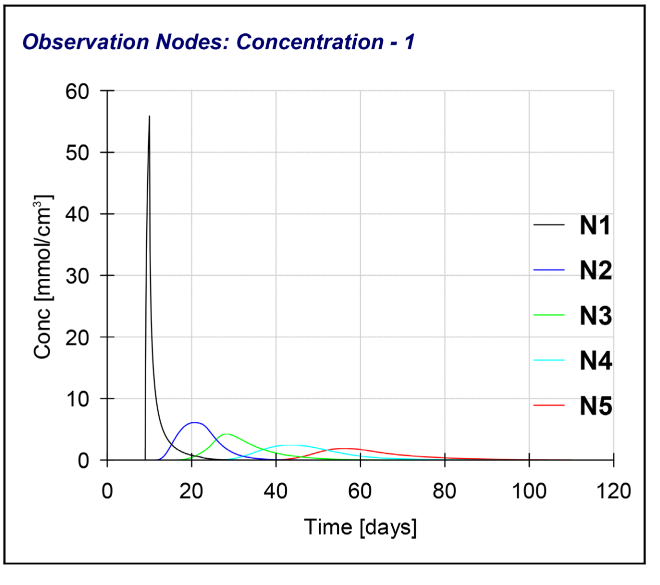

Figure 13. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 10.

com pletely from the surface on day 34. The N2 layer was reached on the 12th day with the same peak of 5 mmol/cm^3, this layer then loses the solute on the 50th day. The solute front reached the N3 level on the 19th day with a peak concentration of 4 mmol/cm^3. The solute has left this horizon on day 76, reaching the N4 layer on day 28 and canceling out on day 110.

Applying a solute dose on day 15 after sowing **Figure 14** shows a solute front that persisted at the surface until day 36. The front continues its distribution to reach level N2 on the 18th day and remained there until the 52nd day. The N3 layer was then reached on the 25th day, the solute continues its progression to leave the N3 horizon on the 80th day. The N4 layer was reached by the 32nd day and the solute finally drains from the horizon on the 110th day.

With a flux corresponding to 75% ET_c, the residence time of the solute on the soil surface decreased as one approaches the date recommended for the application of the solute (15th day after sowing).The solute remained on the soil surface 30, 28, 25, 22 days respectively for a solute applied on the 1st, 5th, 10th and 15th day after sowing. It then took an average of 3 days to reach the N2 horizon and 11 days to reach the N3 layer. The concentration of solutes in the different layers decreased with the decrease in the inflow of water. With a lower water flux (compared to that of 100% ET_c), the solute front distributed more slowly and therefore took longer to reach the other layers (N2, N3, N4 and N5) and would reduce the leaching loss. The solute's stay in the soil was even longer before reaching the bottom limit of the domain.

3.3. Water Flux 50% ET_c and NPK Applied Either on the 1st, 5th, 10th or 15th Day after Sowing

For a 50% ET_c treatment, the curve giving the pressure head potential in the soil,

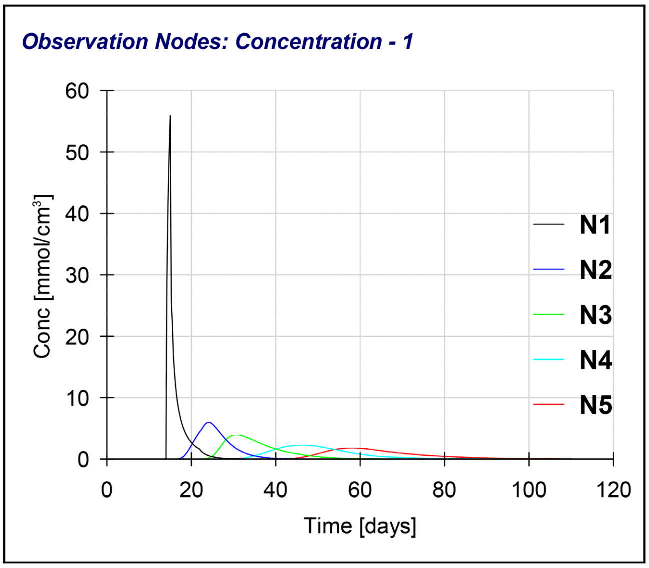

Figure 14. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 15.

showed an equilibrium-state of the water in the soil from the 70th day until the end of the simulation. The pressure head potential being constant in all observation nodes. Referring to the water mass balance, it can be seen that there was no more water loss in the soil profile after the 66th day but rather water storage in the soil profile.

For a supply of solutes on the 1st day of the simulation Figure 15 the solute spent approximately 49 days on the soil surface (node N1) with a peak concentration of 37.5 mmol/cm³ before disappearing. It then arrived at node N2 on day 9 to stay there for 86 days before leaving horizon N2; the maximum concentration for N2 being 2.5 mmol/cm³. Node N3 was reached on the 22nd day, at this level, the solute has left horizon N3 on the 110th day of the simulation. On the 35th day, the solute reached node N4 and leaved this horizon on the 110th day. The bottom of the domain (node N5) was reached on the 59th day, at this layer, the concentration of the solute did not cancel out even after the 110th day.

For an NPK treatment on the 5th day after sowing Figure 16 the solute has spent 50 days on the soil surface (node N1) before dispersing inside the soil. Continuing its progression through the soil, the solute arrived at node N2 on day 12 and canceled out on day 96. The distribution of the solute being done with the water infiltration, node N3 was reached on the 25th day; the solute has left the N3 horizon on the 110th day. 10 days after reaching node N3, the solute has arrived at node N4 and was no longer washed out of this horizon, even after the 110th day of simulation. Likewise, after reaching node N5 on the 59th day, the solute remained at the bottom of the domain after the 110th day, but at low concentration.

Figure 17 shows us a supply of solutes made on the 10th day, we observed through node N1 that the solute has made 52 days at the surface of the soil with

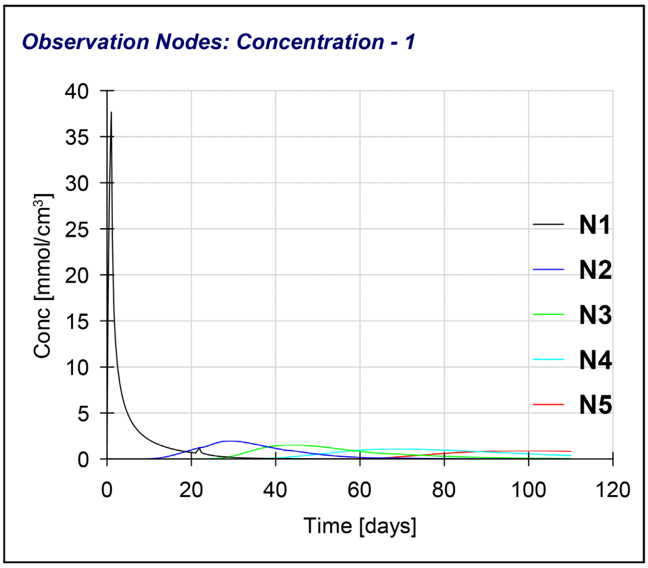

Figure 15. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 1.

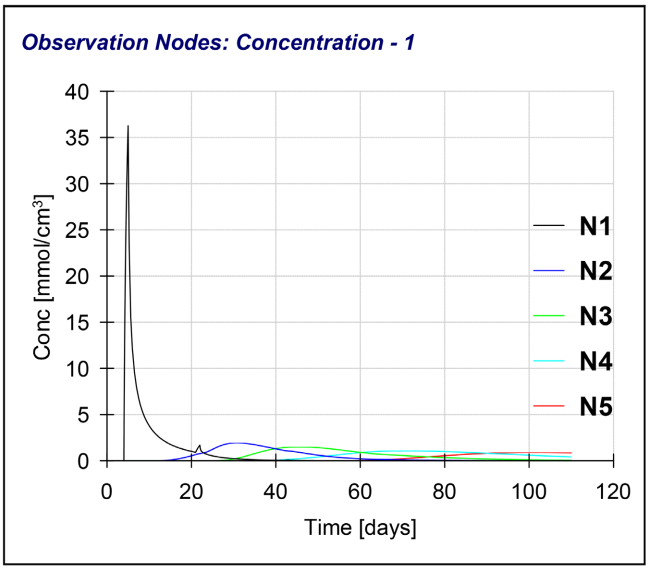

Figure 16. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 5.

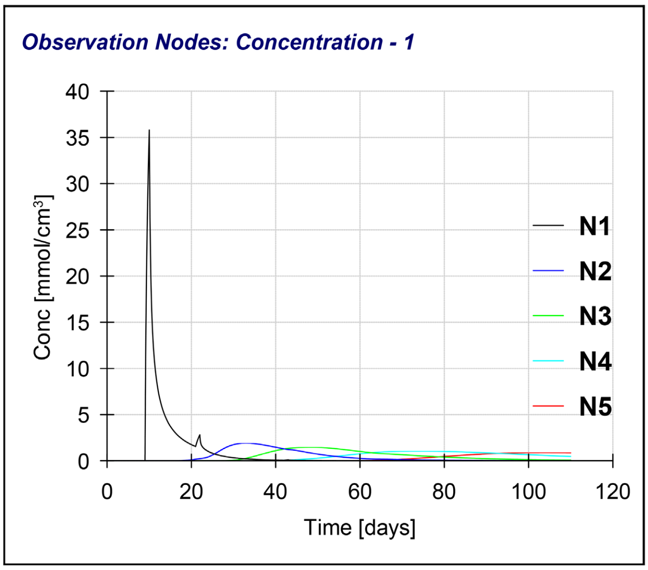

Figure 17. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 10.

a peak concentration of 36 mmol/cm^3. Horizon N2 was reached on the 18th day, the solute left this horizon on the 98th day of simulation. Continuing its progression inside the ground, the solute arrived at node N3 on the 28th day and was washed away from this horizon on the 110th day. The two nodes N4 and N5 were reached by the solute respectively on the 38th and 62nd day. At these last two nodes, the solute was no longer leached even after the last day of simulation. But concentrations remained low at these horizons.

Applying a dose of solute on day 15 **Figure 18**, the solute remained on the soil surface until the 54th day. The solute front has continued its distribution to reach

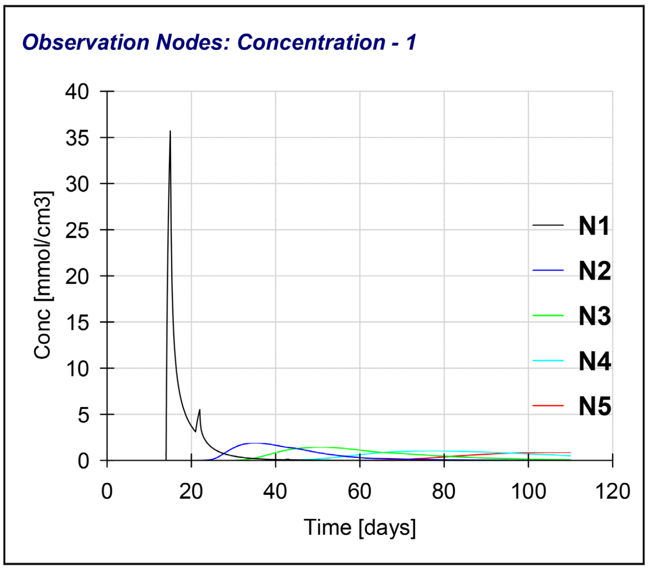

Figure 18. Solute (NPK) concentration versus time at selected observation points (N1: 0 cm; N2: −20 cm; N3: −50 cm; N4: −75 cm; N5: −100 cm) applied at day 15.

node N2 on the 24th day and left this horizon on the 102nd day. Then, the solute reached the observation node N3 on the 31st day of simulation and was washed out of this horizon on the 110th day. Nodes N4 and N5 were crossed respectively on the 40th and 62nd days of simulations. The solute's concentration on those nodes was no longer vanished indicating that the solute remains present at the bottom of the domain, even after the simulation has ended.

With a 50% ET_c treatment, the time that the solute did on the soil surface decreases as one approaches the recommended day for the application of the solute (15th day after sowing). The same observation was made for the flows corresponding to 100% ET_c, and 75% ET_c. The solute remained on the surface of the soil 49, 46, 43, 40 days respectively for a solute applied on the 1st, 5th, 10th and 15th day after sowing. It then took an average of 8 days to reach the N2 horizon and 19 days to reach the N3 layer. The concentration of solutes in the different layers decreased with the decrease in the inflow of water. With a lower water flow (compared to that of 75% ET_c, or 100% ET_c), the solute front distributed more slowly and therefore took longer to reach the other horizons (N2, N3, N4 and N5) and reduced leaching loss. With 50% ET_c, the residence time of the solute on the surface was significantly longer. No solute was lost at the bottom edge of the domain for the various treatments on the last day of simulations.

The first two layers of the soil being sandy, this explains the fairly rapid leaching towards the last layer for high water flux (100% ET_c, and 75% ET_c). Only the 50% ET_c treatment made it possible to gain water and solutes (no deep drainage or leaching beyond the limit of the bottom of the domain). An addition of solute on the 1st or 5th day after sowing regardless of the water flux provided (100% ET_c, 75% ET_c, or 50% ET_c) will not have a great impact on the absorption of solute by the crop because the roots are not yet developed at this stage. We analyzed the solute inputs on the 10th and 15th day after sowing. The closer we got to the 15th day, the more we have got a loss of solutes, probably due to the gradual storage of water, as it adds up. A favorable day for solute supply would therefore be between the 10th and 14th day after sowing. To reduce the solute infiltration velocity into the soil layers, one could inject solute without first supplying water the day before or the day after application. By simulating such a process, we realized that this treatment in addition to reducing the solute infiltration rate in the soil, also increases the concentration of the solute in the different horizons of the soil. This would increase the availability of the solute for the roots of the crop.

4. Conclusion

We simulated water and non-reactive solutes' transport into a 3-layered soil profile, with the Hydrus 1D software. For the simulation, we evaluated the doses of solutes that should be provided for the production of the intermediate variety of maize, the crop cycle of which was estimated at 110 days over an area of 500 m^2. Different simulations were performed at 100% ET_c, 75% ET_c, and 50% ET_c in terms of water supplies combined at the doses of 100 mmol/L/m^2 NPK and 246 mmol/L/m^2 of urea for the solute inputs, referring to the technical itinerary for maize production in Burkina Faso. For the three simulated treatments, there was more deep drainage for water flux at 100% ET_c or 75% ET_c, leading at the same time to loss of solutes beyond a certain depth of the soil not colonized by roots. The water flux at 50% ET_c further reduced the loss of water by drainage and of solutes by leaching, this flux hardly caused any loss beyond the bottom of the domain. It has also improved the residence time of solute in the soil. The closer one gets to the 15th day after sowing, the greater the risk of loss, because the soil has already absorbed water. This loss can be reduced by spacing the water supply and the solute supply, or by amending soil with organic matter in order to increase its retention capacity, which could improve the residence time of the solute.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zhu, Z.L. and Chen, D.L. (2002) Nitrogen Fertilizer Use in China—Contributions to Food Production, Impacts on the Environment and Best Management Strategies. *Nutrient Cycling in Agroecosystems*, **63**, 117-127. https://doi.org/10.1023/A:1021107026067

[2] Sansoulet, J. (2007) Transfert d'eau et des ions potassium et nitrate dans un sol à

capacité d'échange anionique sous un couvert redistributeur de la pluie: Etude expérimentale et modélisation dans une bananeraie fertilisée sur un andosol. Thèse de Doctorat, Institut National Agronomique Paris Grignon, Paris.

[3] Siyal, A.A., Bristow, K.L. and Simunek, J. (2012) Minimizing Nitrogen Leaching from Furrow Irrigation through Novel Fertilizer Placement and Soil Surface Management Strategies. *Agricultural Water Management*, **115**, 242-251. https://doi.org/10.1016/j.agwat.2012.09.008

[4] Cabioche, Y.M., Clermont-Dauphin, C., Lafont, A., Sansoulet, J., Cattan, P., Achard, R., Caron, A. and Charbier, C. (2006) Stockage dans les sols à charges variables et dissipation dans les eaux de zoocides organochlorés autrefois appliqués en bananeraies aux Antilles: Relation avec les systèmes de culture. Rapport final de contrat de recherche, AP "Pesticides" 2002 MEDD. APC INRA Antilles-Guyane.

[5] Pereira, L.S., Cordery, I. and Iacovides, I. (2012) Improved Indicators of Water Use Performance and Productivity for Sustainable Water Conservation and Saving. *Agricultural Water Management*, **108**, 39-51. https://doi.org/10.1016/j.agwat.2011.08.022

[6] Bar-Yosef, B. (1999) Advances in Fertigation. *Advances in Agronomy*, **65**, 1-77. https://doi.org/10.1016/S0065-2113(08)60910-4

[7] Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J. and Thorburn, P.J. (2003) Analysis of Soil Wetting and Solute Transport in Subsurface Trickle Irrigation. *Irrigation Science*, **22**, 143-156. https://doi.org/10.1007/s00271-003-0080-8

[8] Gärdenäs, A.I., Hopmans, J.W., Hanson, B.R. and Simunek, J. (2005) Two Dimensional Modeling of Nitrate Leaching for Various Fertigation Scenarios under Micro-Irrigation. *Agricultural Water Management*, **74**, 219-242. https://doi.org/10.1016/j.agwat.2004.11.011

[9] Rajput, T.B.S. and Patel, N. (2006) Water and Nitrate Movement in Drip-Irrigated Onionunder Fertigation and Irrigation Treatments. *Agricultural Water Management*, **79**, 293-311. https://doi.org/10.1016/j.agwat.2005.03.009

[10] Ajdary, K., Singh, D.K., Singh, A.K. and Khanna, M. (2007) Modelling of Nitrogen Leaching from Experimental Onion Field under Drip Fertigation. *Agricultural Water Management*, **89**, 15-28. https://doi.org/10.1016/j.agwat.2006.12.014

[11] Doltra, J. and Munoz, P. (2010) Simulation of Nitrogen Leaching from a Fertigated Crop Rotation in a Mediterranean Climate Using the EU-Rotate_N and Hydrus-2D Models. *Agricultural Water Management*, **97**, 277-285. https://doi.org/10.1016/j.agwat.2009.09.019

[12] Hussein, F., Janat, M. and Yakoub, A. (2011) Assessment of Yield and Water Use Efficiency of Drip-Irrigated Cotton (*Gossypium hirsutum* L.) as Affected by Deficit Irrigation. *Turkish Journal of Agriculture and Forestry*, **35**, 611-621.

[13] Ityel, E., Lazarovitch, N., Silberbush, M. and Ben-Gal, A. (2011) An Artificial Capillary Barrier to Improve Root Zone Conditions for Horticultural Crops: Physical Effects on Water Content. *Irrigation Science*, **29**, 171-180. https://doi.org/10.1007/s00271-010-0227-3

[14] Badr, A.E. and Abuarab, M.E. (2013) Soil Moisture Distribution Patterns under Surface and Subsurface Drip Irrigation Systems in Sandy Soil Using Neutron Scattering Technique. *Irrigation Science*, **31**,317-332. https://doi.org/10.1007/s00271-011-0306-0

[15] Kandelous, M.M., Kamai, T., Vrugt, J.A., Šimunek, J., Hanson, B. and Hopmans, W. (2012) Evaluation of Subsurface Drip Irrigation Design and Management Parame-

ters for Alfalfa. *Agricultural Water Management*, **109**, 81-93. https://doi.org/10.1016/j.agwat.2012.02.009

[16] Pang, X.P. and Letey, J. (1998) Development and Evaluation of ENVIRO-GRO, an Integrated Water, Salinity, and Nitrogen Model. *Soil Science Society of America Journal*, **62**, 1418-1427. https://doi.org/10.2136/sssaj1998.03615995006200050039x

[17] Li, R., Ma, J. and Zhang, R. (2003) Estimating Nitrate Leaching with a Transfer Function Model Incorporating Net Mineralization and Uptake of Nitrogen. *Journal of Environmental Quality*, **32**, 1455-1463. https://doi.org/10.2134/jeq2003.1455

[18] Phogat, V., Skewes, M.A., Cox, J.W., Sanderson, G., Alam, J. and Simunek, J. (2014) Seasonal Simulation of Water, Salinity and Nitrate Dynamics under Dripirrigated Mandarin (*Citrus reticulata*) and Assessing Management Optionsfor Drainage and Nitrate Leaching. *Journal of Hydrology*, **513**, 504-516. https://doi.org/10.1016/j.jhydrol.2014.04.008

[19] Skaggs, T.H., Trout, T.J., Šimunek, J. and Shouse, P.J. (2004) Comparison of Hydrus-2D Simulations of Drip Irrigation with Experimental Observations. *Journal of Irrigation and Drainage Engineering*, **130**, 304-310. https://doi.org/10.1061/(ASCE)0733-9437(2004)130:4(304)

[20] Lazarovitch, N., Pollton, M., Furman, A. and Warrick, A.W. (2009) Water Distribution under Trickle Irrigation Predicted Using Artificial Neural Networks. *Journal of Engineering Mathematics*, **64**, 207-218. https://doi.org/10.1007/s10665-009-9282-2

[21] Abou Lila, T.S., Berndtsson, R., Persson, M., Somaida, M., Ei-Kiki, M., Hamed, Y. and Mirdan, A. (2013) Numerical Evaluation of Subsurface Trickle Irrigation with Brackish Water. *Irrigation Science*, **31**, 1125-1137. https://doi.org/10.1007/s00271-012-0393-6

[22] Dabach, S., Lazarovitch, N., Simunek, J. and Shai, U. (2013) Numerical Investigation of Irrigation Scheduling Based on Soil Water Status. *Irrigation Science*, **31**, 27-36. https://doi.org/10.1007/s00271-011-0289-x

[23] Ramos, T.B., Simunek, J., Gonçalves, M.C., Martins, J.C., Prazeres, A. and Pereira, L.S. (2012) Two-Dimensional Modeling of Water and Nitrogen Fate from Sweet Sorghum Irrigated with Fresh and Blended Saline Waters. *Agricultural Water Management*, **111**, 87-104. https://doi.org/10.1016/j.agwat.2012.05.007

[24] Bof Bufon, V., Lascano, R.J., Bednarz, C., Booker, J.D. and Gitz, D.C. (2012) Soil Water Content on Drip Irrigated Cotton: Comparison of Measured and Simulated Values Obtained with the Hydrus-2D Model. *Irrigation Science*, **30**, 259-273. https://doi.org/10.1007/s00271-011-0279-z

[25] Sanou, J. (2004) Grille variétale de maïs vulgarisé et fertilisation minérale recommandée au Burkina Faso. Département de Productions Végétaeles, INERA.

[26] Kebre, M.B. (2013) Gestion des Ressources en Eau dans les Régions Arides: Analyse Expérimentale d'un Sol Type du Burkina Faso et Modélisation Numérique des Transferts d'Eau. Thèse de doctorat, Civil Engineering, Université Montpellier II—Sciences et Techniques du Languedoc, Montpellier.

[27] Simunek, J., Sejna, M., Saito, H., Sakai, M. and van Genuchten, M.T. (2013) The HYDRUS-1D Software Package for Simulating the Onedimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media: Version 4.16. Department of Environmental Sciences, University of California, University of California, Riverside.

[28] van Genuchten, M.T. (1980) A Closed Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, **44**, 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x