

Water Dynamics under Drip Irrigation to Proper Manage Water Use in Arid Zone

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Abstract

The water resources reduction due to climate changes and also population increase, have contributed to increasing the constraint on water disponibility and accessibility. In the agricultural field, we need moderate soil and water resources management. This work aims to simulate water dynamics in soil under drip irrigation system in arid regions to better manage irrigation water. Simulations are done with soil physical properties of Burkina Faso. We assess maize plant water requirements for the whole growing season. With Hydrus 2D, we simulate water supply in the soil column. We assign atmospheric conditions on the top of the domain, zero flux of water on the lateral sides, and free drainage on the bottom boundary domain. We perform many irrigation events to analyze wetting pattern distribution around the emitter, which allowed us to contain the amount of irrigation water applied, only around the area dominated by roots, and then reduce water losses that roots cannot uptake. According to the different growing stages of the maize crop, we choose proper irrigation duration and frequency, and suggest irrigation schedule for the whole growing season.

Keywords

Drip Irrigation, Water Dynamics, Hydrus (2D/3D), Water Management

1. Introduction

The countries of sub-Saharan Africa like the other countries in the world face multiple problems linked to climate changes. These problems are: rainfall modification, season shift and the increase of extreme meteorological events such as drought or flood particularly in arid or semi-arid regions like Burkina Faso, which affect considerably water and soil resources. Water resources reduction due to climate changes, and also population increase, have contributed to in-

creasing constraint on water supply and accessibility which were already an important problem in Sahelian countries. Furthermore, we have self-food sufficiency problem. We will need irrigated agriculture to produce more food with less water and without deteriorating soil and water resources. Drip irrigation technology can face the challenge [1] [2]. It allows water and solute use more efficiently, reduces losses by allowing accurate supply of water and solutes in the crop base [3]. This work is performed in order to help farmers to improve water and soil management. The main objective of this study is to use Hydrus 2D to analyze water dynamics under drip irrigation in arid soil in Burkina Faso and guide farmers in the water management depending on the specific soil physical properties. The specific objectives are: 1) forecast infiltration, redistribution and evaporation in a soil column with Hydrus 2D; 2) forecast water losses by reducing the amount of irrigation water which reaches region unexplored by the roots; 3) and suggest efficient water use model based on the crop used. Numerical simulation is a fast and efficient tool to study optimal management of drip irrigation technic [2] [4]. Several studies have shown the importance of numerical modeling to design and manage irrigation systems and ferti-irrigation too [5]-[18].

2. Methods and Materials

2.1. Drip Irrigation

It enables water supplying into the soil, directly in the plant base with small regular amounts of water. Drip irrigation improves water use efficiency, plants growth and production yield. It also improves the application of fertilizers and solutes, it reduces the risk of salinity, weeds and energy needs [19]. Drip irrigation is the most efficient system for crop, vegetables, and fruit trees irrigation [20]. In arid regions or semi-arid regions, due to water scarcity and the increasingly use of water in agriculture drip irrigation is very important to ensure more efficient management of water resources. We distinguish surface drip irrigation system, sub-surface drip irrigation system and family drip irrigation. We called family drip irrigation system, a drip irrigation perform especially for family production, operating in small area between 500 to 1000 m². It is ideal for rural zones, where there is a water scarcity or water supply is limited, moreover no competency or expertise is required [21].

2.2. Hydrus 2D Software

Hydrus is a worldwide known software used in many fields linked to soil sciences. The software gives a modelisation scheme that allows to analyze water flow, the movement of solutes and heat in variably-saturated media [22]. Hydrus can be used as a design tool to study and design drip irrigation system management. Hydrus has been used successfully to simulate water flow under drip irrigation [4] [6] [22] [23]. The Hydrus program numerically solves the equation for water flow, heat and solutes transport [4] [6] [23]. The governing equation in

two dimension (X, Z) for water flow in a variably-saturated porous media included in Hydrus is given in Equation (1) as:

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

where x, z are the spatial coordinates (m); h is the soil water pressure head (m); t is the time (s); K is the hydraulic conductivity function ($\text{m}\cdot\text{s}^{-1}$); θ is the volumetric water content ($\text{m}\cdot\text{m}^{-3}$) and S is the root water uptake term (s^{-1}). The hydraulic conductivity function is given by the van-Genuchten (1980)-Mualem (1976) relationships in Equation (2).

$$K_r(\theta) = \left(\frac{\theta - \theta_r}{\theta_{sat} - \theta_r} \right)^{1/2} \left[1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_{sat} - \theta_r} \right)^{1/m} \right]^m \right]^2 \quad (2)$$

where θ is the volumetric water content; θ_{sat} is the saturated volumetric water content ($\text{m}\cdot\text{m}^{-3}$); θ_r is the residual water content ($\text{m}\cdot\text{m}^{-3}$) and m is a shape parameter given by the water retention curve suggested by van-Genuchten (1980).

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

Irrigation was conducted with constant flux, with water application rate of $1 \text{ l}\cdot\text{h}^{-1}\cdot\text{m}^{-1}$ and emitter radius $r = 1 \text{ cm}$. The water flux to supply is determined by Equation (4):

$$q = \frac{Q}{2\pi r} = \frac{1000 \text{ cm}^3 \cdot \text{h}^{-1}}{2\pi \times 1 \text{ cm} \times 100 \text{ cm}} = 1.59 \text{ cm} \cdot \text{h}^{-1} \quad (4)$$

q is the water flux ($\text{cm}\cdot\text{h}^{-1}$); Q is the emitter discharge rate ($1\cdot\text{h}^{-1}\cdot\text{m}^{-1}$) and r the emitter radius (cm).

2.3. Soil Physic Properties Used for Simulation

The soil physic properties used to perform the simulations, come from the west Bobo Dioulasso city. This soil has general characteristics to many soils of Burkina Faso particularly in the Sahelian zone [24]. A complete characterization has been done by [24] to determine physic, morphologic and hydrodynamic properties. Soil was dug with 1 meter depth on $2.5 \text{ m} \times 2 \text{ m}$ area. According to depth 3 layers was determined as followed: from 0 to 30 cm superficial layer; from 30 cm to 70 cm the middle layer; and deep layer from 70 cm to 100 cm. The superficial layer (30 cm depth) is used in this study. **Table 1** shows the properties used for the modelisation.

Table 1. Soil hydraulic properties used for simulations [24].

Parameters	θ_r	θ_{sat}	α	n	K_s	I
Values	0	0.3655	0.107483	1.3922	268.932	0.5
Units	$\text{m}\cdot\text{m}^{-3}$	$\text{m}\cdot\text{m}^{-3}$	cm^{-1}	-	$\text{cm}\cdot\text{day}^{-1}$	-

2.4. Field of Study and Boundary Conditions

The transport domain is a vertical two dimensional plan (XZ) of the soil layer. We assume that the soil is completely dry before the simulations and the initial water content is assume to be zero, $\theta_i = 0$. The boundaries conditions counted during the simulation are shown in **Figure 1** and presented in **Table 2**. We consider atmospheric conditions on the top of the domain; on the lateral sides far of 80 cm we assign zero flux of water; on the bottom boundary of the domain we apply free drainage that allows water which reach the bottom boundary to go free away.

2.5. The Maize Crop

As an application, we used the maize crop to optimize water supply under drip irrigation. The species of the maize crop used is the intermediate variety with a production duration of fourteen weeks. In **Figure 2**, we show the schedule to grow the maize suggested by the Ministry of Agriculture, Hydraulic and Fisheries Resources of Burkina Faso. It allows to assess the plant water requirements depending on the growth stage. The water requirements was calculated from potential evapotranspiration (ET_0) data of the Meteorology Department of Burkina Faso. ET_0 was calculated with the Penman-Monthei method.

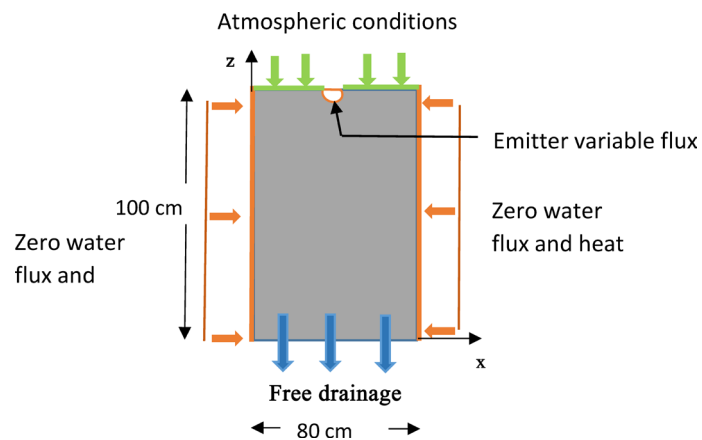


Figure 1. Transport domain and boundary conditions.

Table 2. Boundaries conditions assigned to the domain.

Applied conditions	Atmospheric conditions	Zero water flux and heat	Free drainage	Variable flux
Boundaries	Top boundary	Lateral side	Bottom boundary	Emitter
Sowing	weeding NPK	Urea1	Urea2 earthing up	flowering
↓ 0	↓ w ₁ w ₂	↓ w ₃ w ₄	↓ w ₅ w ₆ w ₇	↓ w ₈
				w ₉ w ₁₀ w ₁₁ w ₁₂
Vegetative stage		reproductive stage		late stage and maturity

Figure 2. Maize crop schedule suggest by the ministry of agriculture.

2.6. Water Requirements for Irrigation

Irrigation scheduling is done at 100% of crop evapotranspiration (ET_c). The values of potential evapotranspiration used to calculate the crop evapotranspiration are those collected by the meteorology agency. The water requirements to supply climatic needs (ET_c) was determined Equation (5), and the different values are shown in **Table 3**.

$$ET_c = ET_0 \times K_c . \quad (5)$$

where ET_c is the crop water evapotranspiration (mm/day); ET_0 the potential evapotranspiration (mm/day) and K_c is the dimensionless maize crop coefficient depending on plant growth.

3. Results and Discussion

We perform simulation according to each growing stage and we show some of these results.

3.1. Initial Stage of Growing

Considering 1 mm/day rain depth like 1 liter volume of water spreaded in an area of 1 m^{-2} , for the initial stage an irrigation event will end off after 2.5 hours of water application with flow rate of $1 \text{ l}\cdot\text{h}^{-1}\cdot\text{m}^{-1}$ to supply a crop evapotranspiration value of 2.6684 mm/day. Assuming a daily water supply frequency. **Figure 3** shows the water content distribution into the soil at $t = 1$ hour corresponding to first day and at $t = 120$ hours five days later. We notice water content value of $\theta = 0.197 \text{ m}^3\cdot\text{m}^{-3}$ at 13 cm around the emitter. This value exceeds considerably the water requirements just needed for the first days of germination. After many attempts in order to reduce the water flux, we will contain the length of the water content distribution around the emitter by spacing water flow supplying. Finally to manage water flow supplying for the initial stage, we assume 3 days frequency, which reduce water losses. We also avoid a hydric stress to the plant. We present in **Figure 4**. The water content distribution around the emitter according to the new frequency adopted.

3.2. Growth Stage

At this step, the initial condition for water content and temperature are taken to be equal to the final water content and temperature in the initial stage. Furthermore, $ET_c = 6.3176$ mm/day, thus we will need approximatively 6 hours of

Table 3. Water requirements and crop coefficient.

Growth cycle	Initial stage	Growth stage	Middle stage	Harvest stage
Duration (weeks)	0 - 3	3 - 6	6 - 9	9 - 14
K_c	0.40	0.80	1.15	0.70
ET_0	6.671	7.897	6.2858	6.5644
ET_c	2.6684	6.3176	7.2287	4.5951

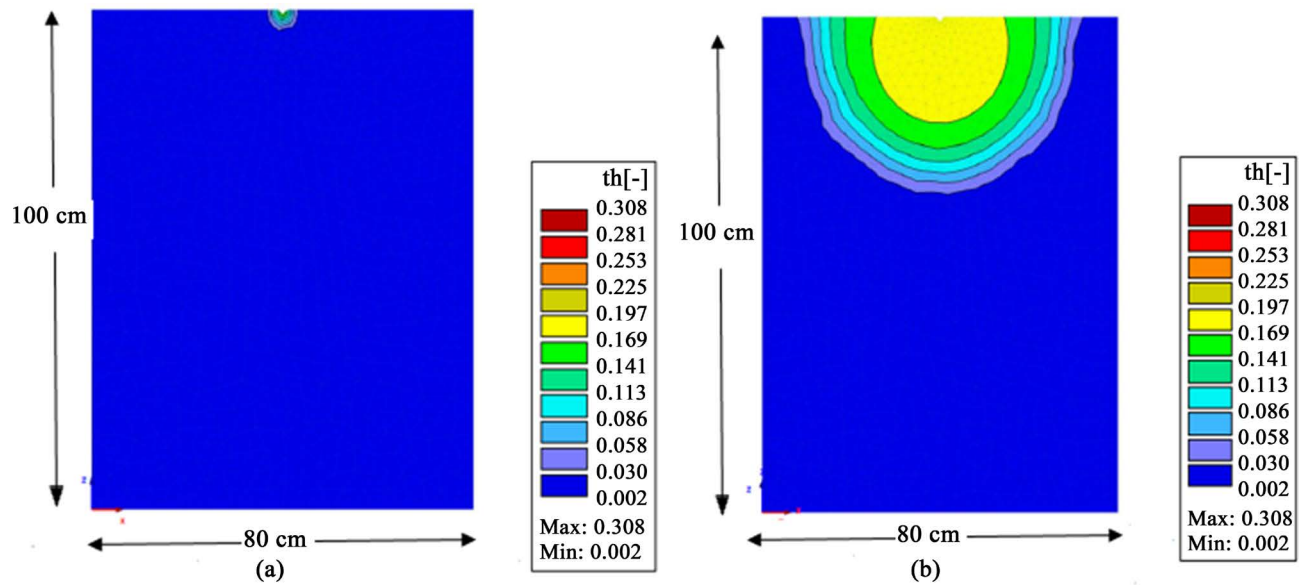


Figure 3. Water content distribution for initial stage of growing at $t = 1$ hour (a) and at $t = 120$ hours (b).

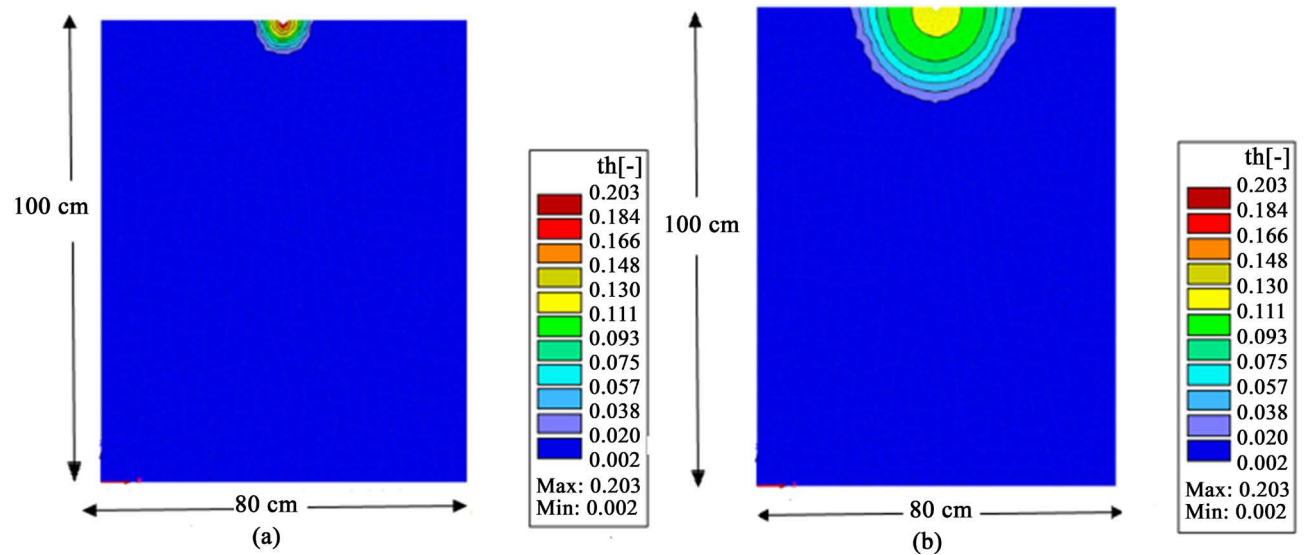


Figure 4. (a) Water content distribution 1st day, and 21 day later (b), irrigation frequency 3 day.

irrigation to supply the plant water requirements. In **Figure 5**, we show the water content distribution corresponding to the first experiments.

For water content value $\theta = 0.113 \text{ m}^3 \cdot \text{m}^{-3}$, the wetted area extend to 14 cm around the emitter concerning the first day. At the last day of the simulation the wetted area reach 35 cm around the emitter for the same water content. The area reached by the water strongly exceed the area hold by roots. We can then reduce the quantities of water supplied by keeping the wetted area to the zone colonized by roots. The irrigation frequency kept is 3 days, we obtain a wetted zone of 25 cm around the emitter with water content $\theta = 0.111 \text{ m}^3 \cdot \text{m}^{-3}$. The water volume is restricted to the optimum volume hold by the roots. In **Figure 6** we present the water content new distribution for the new frequency chosed.

For the last two growth stages, we take into account root water uptake parameter to perform simulations.

3.3. Middle-Stage of Growth

At this growth stage, crop water requirements raised again with $ET_c = 7.2287$ mm/day. An irrigation event will take approximately 7 hours per day to supply plant water requirement. The initial water content and initial temperature correspond respectively to the final water content and temperature of the previous growth stage. **Figure 7** shows the corresponding water content distribution in the soil.

We notice that the wetting zone reach an area of 30 cm around the emitter concerning the first day and 36 cm area at the 21st day of the stage. The available water in soil after roots uptake is so important. At the end of the simulation $\theta =$

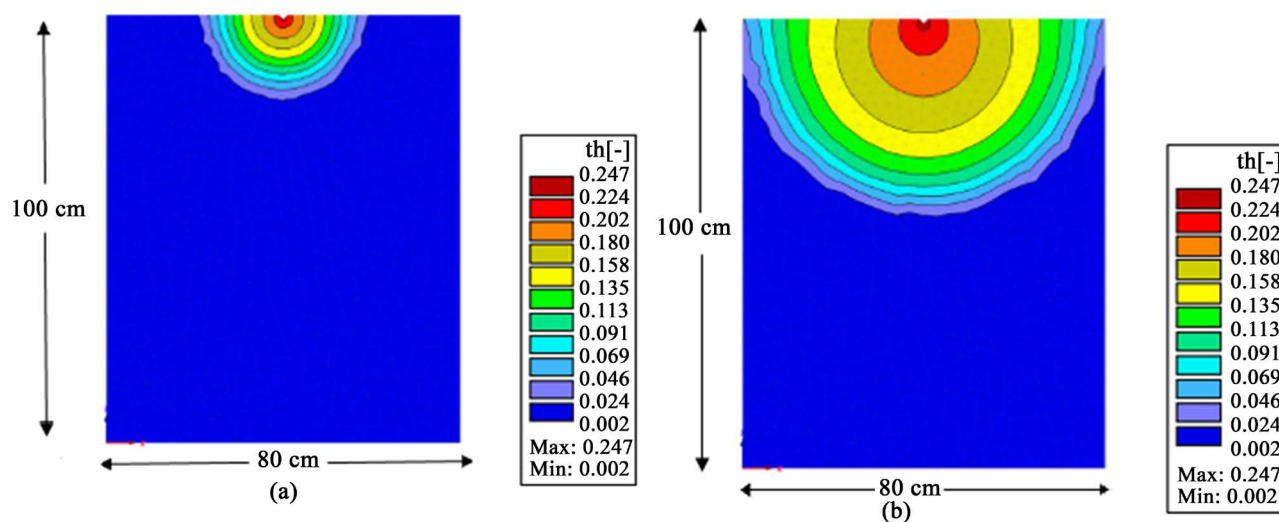


Figure 5. (a) Water content distribution 1st day, and 21 day later (b), daily irrigation frequency.

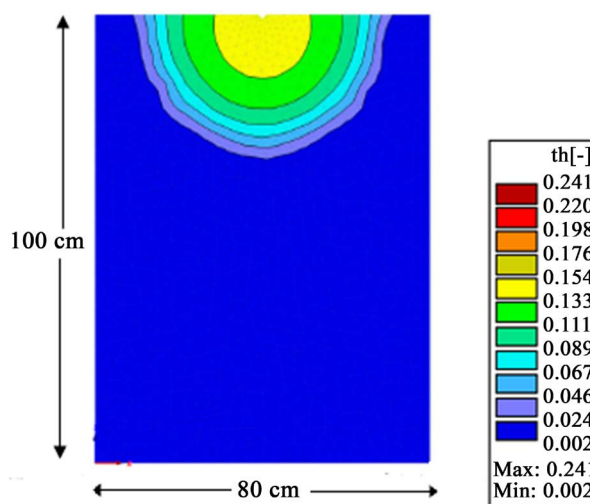


Figure 6. Water content distribution, growth stage at t = 21 day, irrigation frequency 3 days.

0.124 $\text{m}^3 \cdot \text{m}^{-3}$ for 36 cm depth. To reduce the quantities of water used to simulate this phase, we space the water supplying. And then reduce water stored in soil and the quantities of water non-uptake. To avoid water stress condition by using less water to supply the plant, we chose an irrigation frequency of 3 days. **Figure 8**. The water content distribution in the soil with the new frequency.

3.4. Harvest Stage

To compare with the middle-stage, we get a diminution of water requirements with $ET_c = 4.5951/\text{day}$. Nevertheless, to supply crop water requirements, an irrigation event will take 5 hours. We simulated water flux to supply during 35 days. In **Figure 9**, the wetting zone extend to 14 cm depth at the first day of water

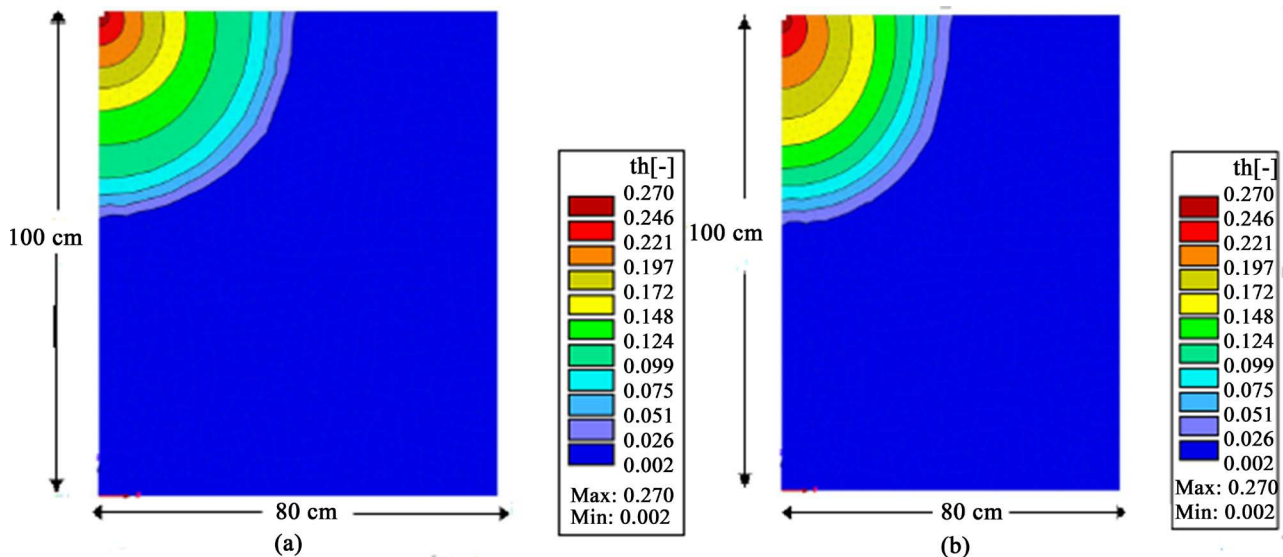


Figure 7. Water content distribution : middle-stage of growth, daily irrigation frequency, (a) $t = 1$ day and (b) $t = 21$ day later.

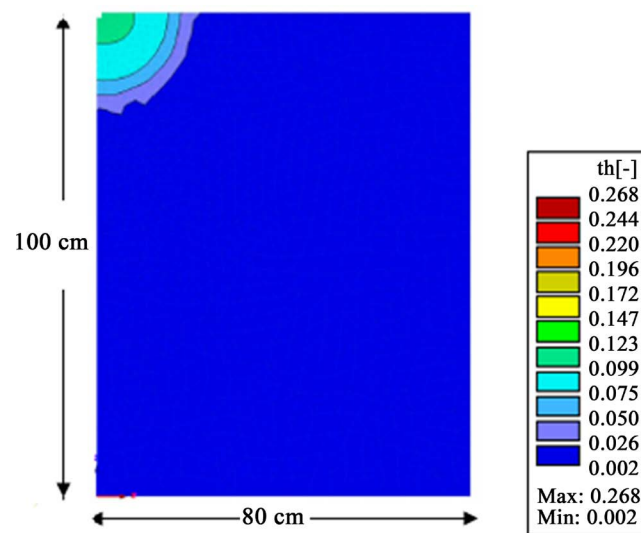


Figure 8. Water content distribution, middle-stage of growth at $t = 21$ st day, irrigation frequency 3 days.

supplying and reach 25 cm depth at 30th day and remain at this depth until 35th day. Analyzing the wetting zone on the 35th day we get an important available water content in 25 cm area around the emitter. For better use of water provide to the maize crop, we will space water supplying. Adopting 3 days of irrigation frequency, we present the corresponding wetting shape in the soil. Water content is about $\theta = 0.068 \text{ m}^3 \cdot \text{m}^{-3}$ at 12 cm around the emitter that shows a reduction of available water. We keep this frequency to supply water at the harvest stage. **Figure 10** show the water content distribution for new frequency adopted. The different simulations lead us to manage water supplying depending on

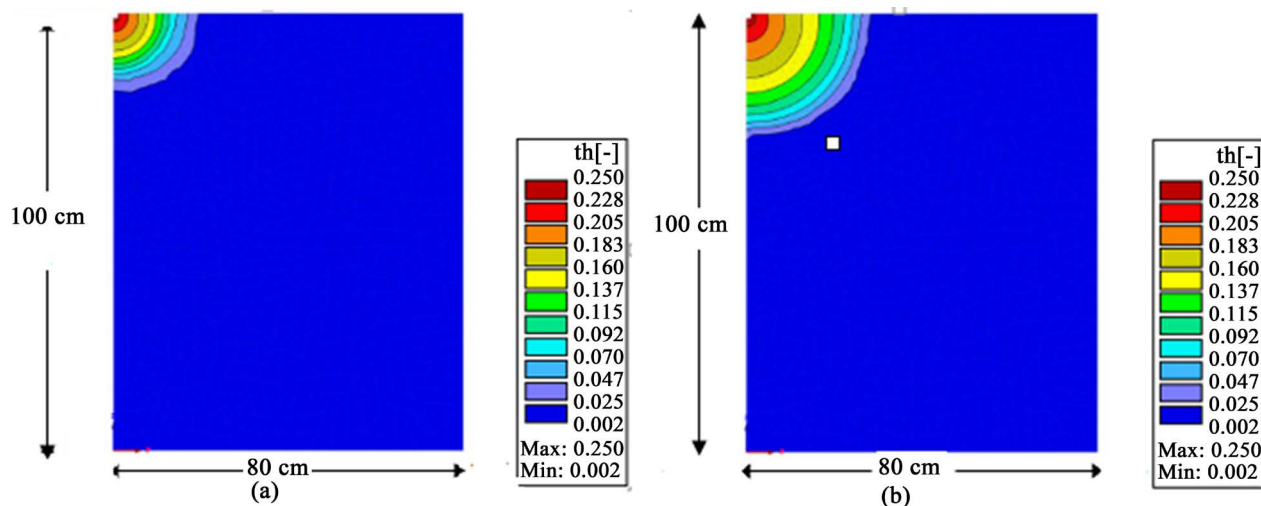


Figure 9. Water content distribution, harvest stage, daily frequency; (a) $t = 1$ st day, (b) at $t = 35$ th later.

Table 4. Irrigation scheduling of maize cycle production for fourteen weeks.

		Growth stage	Initial stage	Growth stage	Middle stage	Harvest stage
Flow rate $Q = 1 \text{ l} \cdot \text{h}^{-1} \cdot \text{m}^{-1}$	Irrigation duration		2.5 hours	6 hours	7 hours	5 hours
	Frequency		3 days	3 days	3 days	3 days

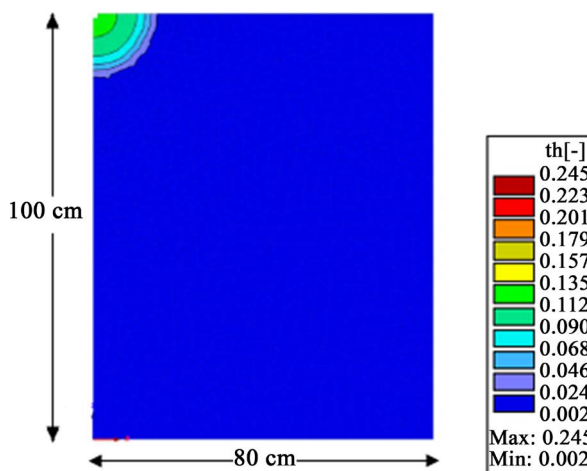


Figure 10. Water content distribution, harvest stage at $t = 35$ th day, irrigation frequency 3 days.

different growth stage, to compensate crop water requirements. Taking into account all these irrigation frequencies chosen, we suggest an irrigation scheduling in **Table 4**.

4. Conclusion

The purpose of this study was to analyze water dynamics in soil under drip irrigation in arid zone and, hence to manage properly irrigation water according to soil physical properties. Therefore we assessed water requirements 500 mm/day to supply for maize crop production and carried out many simulations with Hydrus 2D. The study of the wetting zone dimensions, allowed us to schedule water supply by taking irrigation duration and frequency according to crop growth stages. So we restricted the amount of irrigation water applied around the root zone and then reduced also water losses. Finally, we suggest irrigation scheduling for the whole maize growing season. Nevertheless, it could be interesting to carry out some experiments to assess the crop yield depending on the amount of irrigation water used, in order to enhance production yield and water management under drip irrigation.

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Conflicts of Interest

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

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