DOI: 10.22620/agrisci.2024.40.007

IMPLEMENTATION OF MOHID-LAND MODEL FOR SIMULATING SOIL WATER DYNAMICS FOR TOMATO CROP

Nina Philipova[1,2], Nadejda Shopova[2], Milena Kercheva[3], Mila Chilikova-Lubomirova[1]

[1]Institute of Mechanics, Sofia, Bulgaria
[2]Climate, Atmosphere, Water Research Institute, Sofia, Bulgaria.
[3]Institute of Soil Science, Agrotechnologies and Plant Protection "N. Pushkarov", Sofia, Bulgaria
***Corresponding author's Email: philipovan923@gmail.com**

Abstract

The agriculture sector on the whole planet has been subjected to abrupt climate changes, sudden floods and continuous drought. The nutrition of the planet is indangered taking into account the rate of population growth combating with water resources scarcity on some places. There is a need of developing water efficient technologies and improving their management. The MOHID-Land model has been developed in 2018 and simulates the full soil-water-plant-atmosphere transfer system and can help the improvement of agricultural water management. The current paper discussed the simulation of the soil water dynamics of drip-irrigated tomatoes cultivated in the Experimental field of the Agricultural University – Plovdiv, Bulgaria. The data by the simulations has been compared with experimental data obtained at three soil depths.

Keywords: MOHID-Land Model, 3D numerical simulations, soil water dynamics, field experiments

INTRODUCTION

Eighteen countries in the Southeastern Africa are subjected to reduced rainfall, abrupt drought and ravaging farmlands by desert locusts as a result of abrupt climate changes. Enormous damages have been caused to agriculture in these countries. The nutrition of the population is critical (The Gardian, 15th of September, 2021). The nutrition of the population in developing countries has been put in the question, that is why the agriculture on the planet is indicated as a risk sector. Many countries face increasing pressure on fresh water resources under conditions of the rate of economic development and climate change. The European Commission identifies the agriculture as a priority sector, in which measures to combat water scarcity should be considered. The fostering water-efficient technologies and practices are among the main European Commission's policies since 2007. The daily biomass production and final crop yield in relation to water supply, consumption and agronomic management and additionally based on the current plant physiological and soil water and salt budgeting concepts can be simulated by AquaCrop. The details of the simulated processes are provided in a set of three papers which were published since the model's release (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009). The Irrigation and Drainage Paper No. 66 'Crop Yield Response to Water' (Steduto et al., 2012), and the reference manual (Raes et al., 2012) are updated regularly (Vanuytrecht et al., 2014).

A Soil and Water Assessment Tool (SWAT) was developed by Dr. Jeff Amold for the United States Department of Agriculture (USDA). The SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in the large complex watersheds with varying soils, land use and management conditions over long period of time (Neitsch et al., 2011). The physical processes associated with water and sediment movement, crop growth, and nutrient cycling could be directly modeled by SWAT using the input data for weather, soil properties, topography, vegetation, and land management practices. Some of the available packages for one-dimensional simulation of water and solute dynamics are available – LEACHM (Leaching Estimating and Chemistry model; Htson and Wagenet, 1990), SWAP (Soil Water Atmosphere Plant, van Dam et al., 1997), RZWQM (Root Zone Water Quality Model, Hanson et. al., 1998), and HYDRUS-1D (Simunek et al., 2005). These models are used to investigate the soil water and salute transport processes under different boundary conditions with or without crop interactions. They are essential tools for determining agricultural management strategies under different environmental scenarios (Chen et. al., 2019). The integrative modelling operational tools capable of simulating the full soil-water-plant-atmosphere transfer system are needed to improve the agricultural water management (Ramos et al., 2017, Simionesei et al., 2016, Simionesei et al., 2020). The MOHID-Land model simulates the soil water dynamics, taking into account the soil variability, the root water uptake reductions due to water stress, the soil evaporation, the leaf area index and the total dry biomass.

In this paper has been simulated the soil water dynamics of drip-irrigated tomatoes observed in the Experimental field of the Agricultural University – Plovdiv, Bulgaria. The obtained data by the simulations has been compared with experimental data obtained at three soil depths.

MATERIALS AND METHODS

Water flow model equations

The authors have no access to the full version of the User’s Guide of the MOHID-Land model and for that reason abide to the model equations described by Simionesei et al. (2016). The Richards equation for 3D Darcian flow (linear relationship between velocity field and gradient of pressure is valid for porous media) was used for calculating the spatial distributions of transient soil water contents and volumetric fluxes:

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

where: θ is the volumetric soil water content $\left(\mathrm{m^3\ m^{-3}}\right)$, h – the soil water pressure head (m), t – time (h), x, y – horizontal space coordinates (m), z – the vertical space coordinate (m), K – the hydraulic conductivity $\left(\mathrm{mm\ h^{-1}}\right)$, S – the sink term reporting water uptake by plant roots $\left(\mathrm{m^3\ m^{-3}\ h^{-1}}\right)$

The van Genuchten-Maulem functional relationship was used for estimating the unsaturated soil hydraulic properties (van Genuchten, 1980):

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{\left[1+\alpha|h|^n\right]^m} \qquad (2)$$

$$h(\theta)=\left|\frac{\left(S_e^{-1/n}-1\right)^{1/n}}{\alpha}\right| \qquad (3)$$

$$S_e(h)=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r}=\frac{1}{\left(1+|\alpha h|^n\right)^m} \qquad (4)$$

$$K(h)=K_sS_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (5)$$

where: $K(h)$ is the unsaturated conductivity $\left(\mathrm{mm\ h^{-1}}\right)$, S_e – the effective saturation $\left(\mathrm{m^3\ m^{-3}}\right)$, θ_r, θ_s are the residual and saturated water content $\left(\mathrm{m^3\ m^{-3}}\right)$, K_s – the saturated hydraulic conductivity $\left(\mathrm{mm\ h^{-1}}\right)$, α – the inverse of air-entry value (m^{-1}), n – the pore-size distribution index $(-)$, $m = 1 - 1/n$, l – the pore connectivity parameter $(-)$.

The physical properties of the three soil layers of the Experimental field of the Agricultural University - town of Plovdiv were assumed according the data pointed by Kojnov et al. (1998). Their hydraulic characteristics were calculated according to the pedotransfer functions proposed by Wösten et al. (1999) (Table 1).

Table 1. Physical and hydraulic characteristics of the soil layers

Soil layers			
Depth (m)	**0-0.30**	**0.30-0.60**	**0.60-1.00**
Coarse sand, 2000-200 μm (%)	7.1	9.7	10.1
Fine sand, 200-20 μm (%)	53.5	58.0	60.6
Silt, 20-2 μm (%)	13.3	16.7	15.5
Clay, <2 μm (%)	26.1	15.6	13.8
USDA			
Sand, 2000-50 μm (%)	49.4	51.7	51.1
Silt, 50-2 μm (%)	24.5	32.6	35.0
Clay, <2 μm (%)	26.1	15.6	13.8
Texture	Sandy Clay Loam (SCL)	Loam (L)	Loam (L)
Organic matter $(\%)$	1.78	1.12	0.64
Bulk density $(g\ \text{cm}^{-3})$	1.52	1.52	1.3
Van Genuchten-Maulem parameters			
Residual water content θ_r $(\text{m}^3\ \text{m}^{-3})$	0.025	0.025	0.025
Saturated water content θ_s $(\text{m}^3\ \text{m}^{-3})$	0.402	0.406	0.474
Inverse of air-entry value α (m^{-1})	6.538	5.303	3.898
Pore-size distribution index n $(-)$	1.1588	1.2159	1.2686
Pore connectivity parameter l $(-)$	-3.6	-1.9	-0.8
Saturated hydraulic conductivity K_s (mm h^{-1})	7.69	5.55	12.45

Potential and actual evapotranspiration rates

The daily value of reference evapotranspiration ET_0 was calculated according to FAO Penman-Monteith equation (Allen et al., 1998). The single crop coefficient approach was applied for determining K_c.

$$ET_c = K_c ET_0 \quad (6)$$

$$T_p = ET_c\left(1 - e^{(-\lambda LAI)}\right) \quad (7)$$

$$E_p = ET_c - T_p \quad (8)$$

where: ET_c – the crop evapotranspi-ration (mm day^{-1}), K_c – the crop coefficient $(-)$, E_p – the potential evaporation (mm day^{-1}), T_p – the potential transpiration (mm day^{-1}), LAI – the leaf area index $(\text{m}^2\ \text{m}^{-2})$, λ – the extinction coefficient of radiation attenuation within the canopy (set to 0.463)

The sink term S in Eq.1 was calculated according to the macroscopic approach of Feddes et al. (1978) and Feddes et al. (2004). Actual transpiration rate T_a (mm day^{-1}) was computed from potential transpiration T_p (mm day^{-1}) as a function of root distribution and soil water availability.

$$S = w_{strs} S_p = w_{strs} \beta T_p A_t \quad (9)$$

$$w_{strs} = \begin{cases} 0 & h \le h_4, h > h_1 \\ (h - h_1)/(h_2 - h_1) & h_2 \le h < h_1 \\ 1 & h_3 < h < h_2 \\ (h - h_4)/(h_3 - h_4) & h_4 < h \le h_3 \end{cases} \quad (10)$$

where: S, S_p – the actual and potential volume of water removed from a unit volume of soil per unit time $\left(\mathrm{m^3\ m^{-3} day^{-1}}\right)$, respectively; w_{strs} – a prescribed dimensionless stress respond function of soil water pressure head h, $w_{strs}(h)$ – defined using a piecewise linear function introduced by Feddes et al .(1978) and Feddes et al. (2004); β – a normalized root density distribution function $\left(\mathrm{m^3}\right)$, A_t – the area of soil surface associated with transpiration $\left(\mathrm{m^2}\right)$, T_a was obtained by integrating Eq. (9) over the root domain R $\left(\mathrm{m^3}\right)$:

$$T_a = T_p \int_R w_{strs} \beta \, dR \quad (11)$$

Plant development

MOHID-Land model is based on EPIC (Erosion – Productivity Impact Calculator) to simulate crop growth (Williams et al., 1989). The heat unit theory is applied for calculating the plant growth and it takes into account that all heat units above the base temperature accelerate the crop growth and development. The total number of heat units for a plant necessary to reach maturity was calculated as:

$$PHU = \sum_{i=1}^{m} HU = \sum_{i=1}^{m} \left(T_{\mathrm{av}} - T_{\mathrm{base}}\right) \quad (12)$$

when $T_{\mathrm{av}} > T_{\mathrm{base}}$

where: PHU – total heat units required for plan maturity (°C), HU – the number of heat units accumulated on day i (°C), $i = 1$ corresponds to the day of planting, m – the number of days required for a plant to reach maturity $(-)$, T_{av} – the mean daily temperature (°C), T_{base} – the minimum temperature for plant growth (°C).

Total biomass was calculated from the solar radiation intercepted by the crop leaf area by using Beer's law (Monsi & Saeki, 1953):

$$\begin{aligned} \mathrm{Bio_i} &= \sum_{i=1}^{m} \Delta \mathrm{Bio_i} \gamma_{\mathrm{reg,i}} = \sum_{i=1}^{m} \mathrm{RUE\ \ PAR_{phosyn,\,i}} \gamma_{\mathrm{reg,i}} \\ &= \sum_{i=1}^{m} \mathrm{RUE}\ \left(0.5 \mathrm{PAR_{day,i}} \left(1 - e^{(-k_l LAI)}\right)\right) \gamma_{\mathrm{reg,i}} \end{aligned} \quad (13)$$

where: $\mathrm{Bio_i}$ – the total biomass on a given day i $\left(\mathrm{k}g\ \mathrm{ha^{-1}}\right)$, RUE – the radiation-use efficiency of the plant $\left(\left(\mathrm{k}g\ \mathrm{ha^{-1}}\right)\left(\mathrm{MJ\ m^{-2}}\right)^{-1}\right)$, $\mathrm{PAR_{phosyn,\,i}}$ – the daily amount of intercepted photosynthetic active radiation $\left(\mathrm{MJ\ m^{-2}}\right)$, $\mathrm{PAR_{day,i}}$ – the daily incident photosynthetic active radiation $\left(\mathrm{MJ\ m^{-2}}\right)$, $\mathrm{k_l}$ – the light extinction coefficient $(-)$. It depends on foliage characteristics, sun angle, row spacing, row direction and latitude. The value used in the model $\mathrm{k_l} = 0.65$ is representative of crops with narrow row spacing. A smaller value $\mathrm{k_l} = 0.4 - 0.6$ might be appropriate for tropical areas where average sun angle is higher and for wide row spacing (Williams et al., 1989);

$\gamma_{\mathrm{reg,i}}$ is the daily plant growth factor $(0.0 - 1.0)$ which reported water and temperature stresses.

RUE was calculated by using the approach proposed by Stockle et al. (1992) while $\gamma_{\mathrm{reg,i}}$ was estimated as follows:

$$\gamma_{\mathrm{reg,i}} = 1 - \max\left(w_{\mathrm{strs,\,i}}, t_{\mathrm{strs,\,i}}\right) \quad (14)$$

where: $w_{\mathrm{strs,\,i}}$, $t_{\mathrm{strs,\,i}}$ are the water and temperature stresses for a given day $(-)$, respectively;

Water stress, $w_{\mathrm{strs,\,i}}$ was calculated according to Neitsch et al. (2011)

$$w_{\mathrm{strs,\,i}} = 1 - \frac{T_{a\,cum,\,i-1}}{T_{p\,cum,\,i-1}} \quad (15)$$

Temperature stress was calculated as temperature diverged from the optimal by applying a sigmoid function (Neitsch et al., 2011):

$$t_{\text{strs, i}} = 1 \quad \text{when} \quad T_{\text{av}} \le T_{\text{base}} \qquad (16)$$

$$t_{\text{strs, i}} = 1 - \exp\left[\frac{-0.1054\left(T_{\text{opt}} - T_{\text{av}}\right)^2}{\left(T_{\text{av}} - T_{\text{base}}\right)^2}\right] \qquad (17)$$

when $T_{\text{base}} \le T_{\text{av}} \le T_{\text{opt}}$

$$t_{\text{strs, i}} = 1 - \exp\left[\frac{-0.1054\left(T_{\text{opt}} - T_{\text{av}}\right)^2}{\left(2T_{\text{opt}} - T_{\text{av}} - T_{\text{base}}\right)^2}\right] \qquad (18)$$

when $T_{\text{opt}} < T_{\text{av}} \le 2T_{\text{opt}} - T_{\text{base}}$

$$t_{\text{strs, i}} = 1 \quad \text{when} \quad T_{\text{av}} > 2T_{\text{opt}} - T_{\text{base}} \qquad (19)$$

where: T_{opt} is the optimal air temperature for a given day (°C).

Leaf area index is calculated as a function of heat units, crop stress and development stages. The leaf area added on day i was estimated as:

$$\Delta\text{LAI}_{\text{act, i}} = \Delta\text{LAI}_{\text{i}}\ \sqrt{\gamma_i} = \left(fr_{\text{LAImax, i}} - fr_{\text{LAImax, i-1}}\right)\text{LAI}_{\text{max}}\left(1 - e^{\left(5\left(\text{LAI}_{\text{i-1}} - \text{LAI}_{\text{max}}\right)\right)}\right)\sqrt{\gamma_i} \qquad (20)$$

where: $\Delta\text{LAI}_{\text{act, i}}$, $\Delta\text{LAI}_{\text{i}}$ – the actual and potential leaf area added on day i $\left(\text{m}^2\ \text{m}^{-2}\right)$, respectively;

LAI_{i}, $\text{LAI}_{\text{i-1}}$ – the leaf area indices for day i and i - 1 $\left(\text{m}^2\ \text{m}^{-2}\right)$, respectively;

$fr_{\text{LAImax, i}}$, $fr_{\text{LAImax, i-1}}$ are the fraction of the plant's maximum LAI for day i and i - 1 (-), respectively.

LAI_{max} – the maximum LAI for the plant $\left(\text{m}^2\ \text{m}^{-2}\right)$.

In the initial period $fr_{\text{LAImax, i}}$ was estimated as:

$$fr_{\text{LAImax, i}} = \frac{fr_{\text{PHU,i}}}{fr_{\text{PHU,i}} + e^{\left(l_1 - l_2\ fr_{\text{PHU,i}}\right)}} \qquad (21)$$

where: $fr_{\text{PHU,i}}$ – the fraction of PHU accumulated for the plant up to day i in the growing season (-); l_1, l_2 – the shape coefficients (-);

Once LAI_{max} is reached, it remains constant until the senescence begin. Then it is obtained for $\Delta\text{LAI}_{\text{act, i}}$:

$$\Delta\text{LAI}_{\text{act, i}} = \text{LAI}_{\text{i}}\ \sqrt{\gamma_i} = \text{LAI}_{\text{max}}\frac{\left(1 - fr_{\text{PHU,i}}\right)}{\left(1 - fr_{\text{PHU,,sen}}\right)}\sqrt{\gamma_i} \qquad (22)$$

where: $fr_{\text{PHU,,sen}}$ – the fraction of growing season at senescence (-);

The canopy height was computed as:

$$h_{c,i} = h_{\text{c, max}}\sqrt{fr_{\text{LAImax, i}}} \qquad (23)$$

where: $h_{c,i}$ – the canopy height for a given day i (m);

$h_{\text{c, max}}$ – the plant maximum canopy height (m).

Once the maximum canopy height is reached, h_c remains constant until harvest.

The fraction of total biomass partitioned to root system is 30-50% in seedlings and 5-20% in mature plants. The model decreases the fraction of total biomass in roots linearly from 0.4 at emergence to 0.2 at maturity (Williams et al., 1989).

Root depth increases linearly, reaching the maximum depth at mid-season stage $\left(fr_{\text{PHU,i}} > 0.4\right)$, as follows:

$$Z_{\text{root,i}} = 2.5\ fr_{\text{PHU,i}}\ Z_{\text{root, max}} \qquad fr_{\text{PHU,i}} \le 0.4 \qquad (24)$$

$$Z_{\text{root,i}} = Z_{\text{root, max}} \qquad fr_{\text{PHU,i}} > 0.4 \qquad (25)$$

where: $Z_{\text{root,i}}$ – the root depth for a given day i (m);

$Z_{\text{root, max}}$ – the maximum root depth (m).

RESULTS AND DISCUSSION

Model setup

The period under investigation was from the 1st to 31st of July 2021 and the observed crop - tomato. The following modules have been incorporated in the model structure so the soil water dynamics was simulated by means of the MOHID-Land model: Atmosphere, Discharges, Drainage Network, Basin, Geometry, Irrigation, Model, Porous Media and Vegetation, as well as databases such as Crop Growth Database and Feddes's Parameters Database (Figure 1). All necessary Boundary and Initial Conditions are coded by using Fortran 95. The observed soil profile was 1m depth, including three soil horizons. Arkawa C-grid type (Purser and Leslie, 1988) was used for determining one vertical column discretized into 100 grid cells with 1cm width, 1cm length and 1 cm thickness each. These data were put in Geometry data file. Parameters θ, h and K were calculated in the center of the volumes and fluxes were calculated on the faces of the volumes. The parameter K is necessary for calculations of fluxes on the faces and it is usually obtained by averaging the values in the adjacent cells. The hydraulic gradients $\vec{\nabla}(h+z)$ were calculated with the h values of the cells adjacent to the face (Chambel-Leitão et al., 2015).

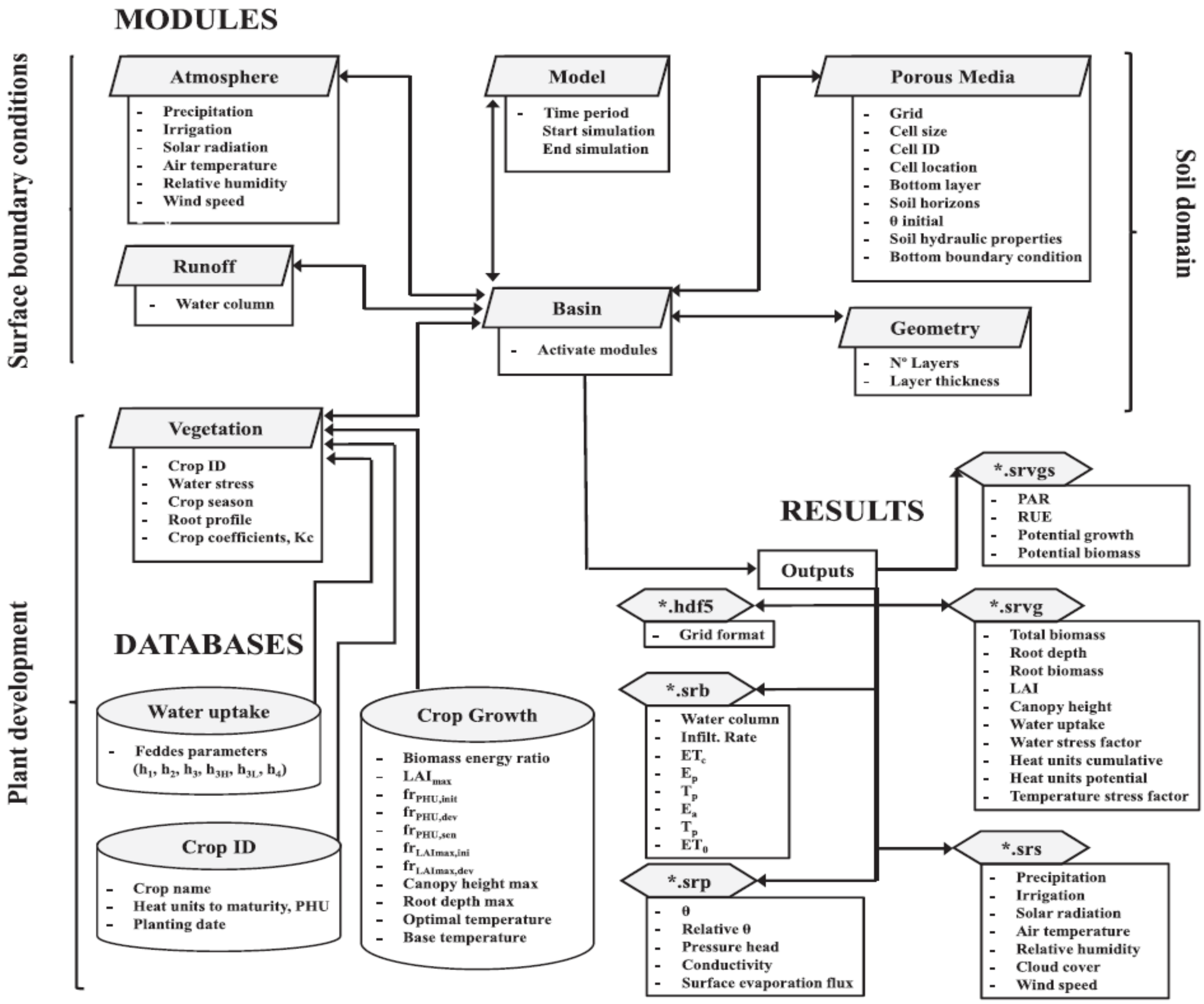

Fig.1. Conceptual model of MOHID-Land after Simionesei et al. (2016)

Initial and Boundary Conditions

The Richard's Equation 1 is a partial differential equation with two variables – the soil pressure head h and the hydraulic conductivity K. For equation solving empirical equation of van Genuchten – Maulem (Equation 5) was applied. A modified Picard iteration algorithm was implied according to Galvão (2004). Water content or soil pressure head at the soil surface $(z = L)$ and at $t = 0$ should be specified as initial condition:

$$\theta(x, y, z, t) = \theta_0(x, y, z), \qquad z = L,\ t = 0 \quad (26)$$

$$h(x, y, z, t) = h_0(x, y, z) = h_{atm} \qquad z = L,\ t = 0 \quad (27)$$

where $\theta_0(x, y, z)$ is the initial soil water content, $(\mathrm{cm^3 cm^{-3}})$;

$h_0(x, y, z) = h_{atm}$ – the atmospheric pressure, (cm).

The boundary conditions at the soil surface $(z = L)$ or at the base $(z = 0)$ of the soil profile were expressed as specified pressure head, specified flux or specified gradient boundary conditions.

$$h(x, y, z, t) = h_0(t) \qquad z = 0 \text{ or } L,\ t > 0 \quad (28)$$

$$K\left(1 - \frac{\partial h}{\partial z}\right) = q_0(t) \qquad z = 0 \text{ or } L,\ t > 0 \quad (29)$$

$$\frac{\partial h}{\partial z} = 0, \quad h = const \qquad z = 0,\ t > 0 \quad (30)$$

where: $h_0(t)$, (cm) and $q_0(t)$, $(\mathrm{cm\,day^{-1}})$ – the pressure head and soil water flux. The upper boundary condition was specified by the actual evaporation and transpiration rates, irrigation and precipitation fluxes. The lower boundary was set up as free drainage (Chen et al., 2019).

The following data are taken from the closest meteorological weather station: maximum daily temperature $T_{\max}$ (°C), minimum daily temperature $T_{\min}$ (°C), relative humidity RH (%), wind speed $\mathrm{u_2}$ $(\mathrm{m\,s^{-1}})$, solar radiation $\mathrm{Rs}(\mathrm{W\,m^{-2}})$ and precipitation (mm). The daily evapotranspiration was calculated according to FAO Penman-Monteith method. The crop evapotranspiration ET_c values were calculated from the daily reference evapotranspiration ET_0 by using the crop coefficient K_c values of 1.15 for the midseason stage of tomato (Allen et al., 1998). The upper boundary condition was specified by the actual evaporation and transpiration rates, irrigation and precipitation fluxes. The following parameters of Feddes were applied in water uptake initial conditions: $h_1 = -15$, $h_2 = -30$, $h_3 = -800$ to -1500, $h_4 = -8000$ cm in order to compute the potential transpiration T_p reductions due to the water stress (Kroes et al., 2003).

The porous media initial conditions include soil horizons, initial soil water content, soil hydraulic properties, and bottom boundary conditions. The initial soil water content was specified to field capacity. The soil hydraulic properties $\theta_s, \alpha, \eta, K_s$ were calculated for the Experimental field of Agricultural University - Plovdiv (Bulgaria) according to the pedotransfer functions proposed by Wösten et al. (1999) (Table.1). The crop growth parameters in Arnold et al. (2012) crop database were also used as default settings and the crop growth data for tomato are pointed out in Table. 2.

All initial conditions were set in GrowthDatabase.dat.

MOHID-Land Model allows triggering the irrigation process and a system-dependent boundary condition was used for that purpose. The irrigation is triggered when a certain threshold pressure head, h_t is obtained in some grid cells of the observed root zone domain and then it will be stopped when the pressure head reaches the field capacity. The system-dependent boundary condition includes, as well, constraints that prevent the application of meaningless irrigation amounts and countless irrigation events. The minimum irrigation rate, $I_{\min}$, maximum irrigation rate, $I_{\max}$ and the minimum irrigation interval, I_{int} were set up in the model.

Table.2. Crop growth parameters for tomato used on model simulations after Arnold et al. (2012)

Crop parameter	**Value**
Potential heat unit, PHU (°C)	1900
Sowing date (Julian days)	136
Optimal temperature for plant growth T_{opt} (°C).	25.0
Minimum temperature for plant growth T_{base} (°C).	8.0
Plant radiation-use efficiency, RUE $\left((\text{kg ha}^{-1})(\text{MJ m}^{-2})^{-1}\right)$	30.0
Maximum leaf area index, $\text{LAI}_{\max}$ $(\text{m}^2\ \text{m}^{-2})$	3.0
Fraction of PHU to reach the end of the initial crop stage, $fr_{\text{PHU,init}}$ (-)	0.20
Fraction of PHU to reach the end of the crop development stage, $fr_{\text{PHU},dev}$ (-)	0.40
Fraction of PHU to reach crop senescence, $fr_{\text{PHU},sen}$ (-)	0.70
Fraction of $\text{LAI}_{\max}$ at the end of the initial crop stage, $fr_{\text{LAI}_{\max,\text{init}}}$ (-)	0.05
Fraction of $\text{LAI}_{\max}$ at the end of the crop development stage, $fr_{\text{LAI}_{\max,dev}}$ (-)	0.95
Maximum canopy height, $h_{\text{c,max}}$ (m)	0.5
Maximum root depth, $Z_{\text{root,max}}$ (m)	0.60
Potential harvest index for crop at maturity, HI_{opt} (-)	0.33
Minimum harvest index allowed, $HI_{\min}$ (-)	0.15

Field Experiments

The field experiments were conducted at the Experimental field of the Agricultural University –Plovdiv (Bulgaria) during the summer season of 2021 with tomato as cultivated crop. The crop scheme of planting was 0.50 x 1.60 m. The applied application requirement was 2 mm/h via drip-irrigation technology. The measuring device was the SENTEK Drill & Drop Bluetooth Probe. The soil water content was measured at several depths: 15, 25, 35 cm. The data were adopted via bluetooth technology and using the creative cloud program IrriMax Live. The experimental data of soil water content were retrieved every one hour of twenty-four hours of 7 day period, averaged over every day and compared with the numerical simulations performed by the MOHID- Land Model.

Numerical Results

The numerical simulations were performed by means of MOHID- Land Model. The soil water dynamics has been simulated under above mentioned initial and boundary conditions. The irrigation schedule was set up as discussed above as well. The calculated results by MOHID- Land Model were compared with the results obtained by the field experiments. The simulated and measured soil water content at the three soil depths: 15 cm, 25 cm, 35 cm are presented in Figure 2, Figure 3 and Figure 4. As could be seen, there is a good agreement between the simulated and the measured data.

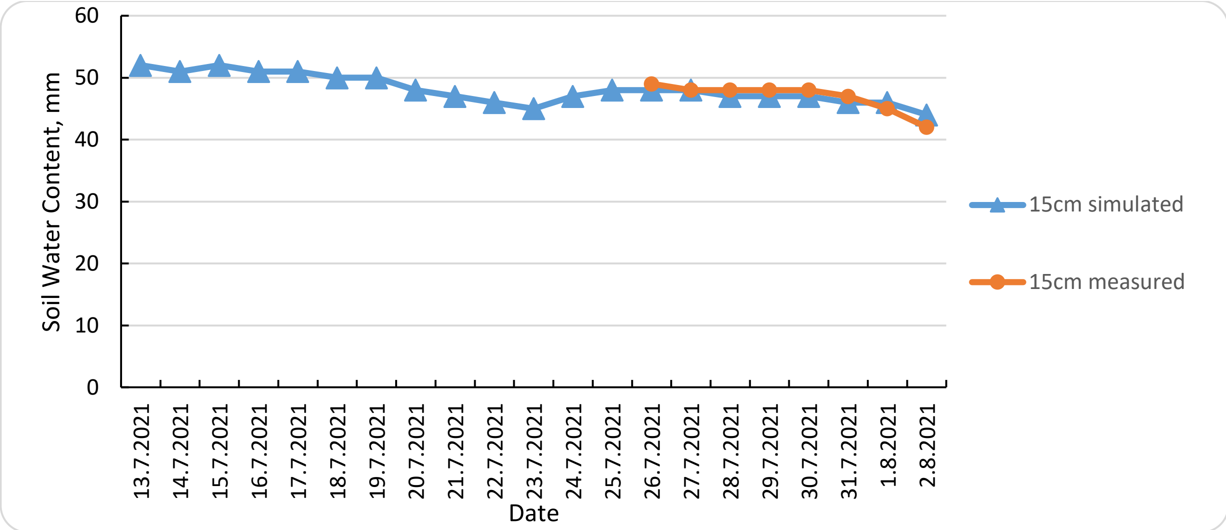

Figure 2. Soil water content at 15 cm depth

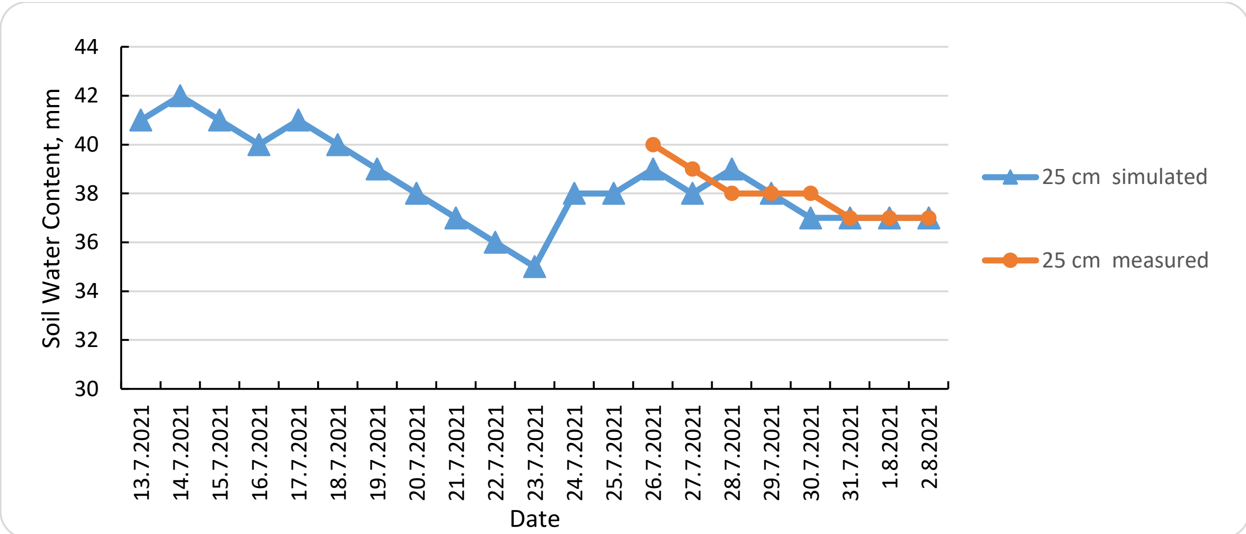

Figure 3. Soil water content at 25 cm depth

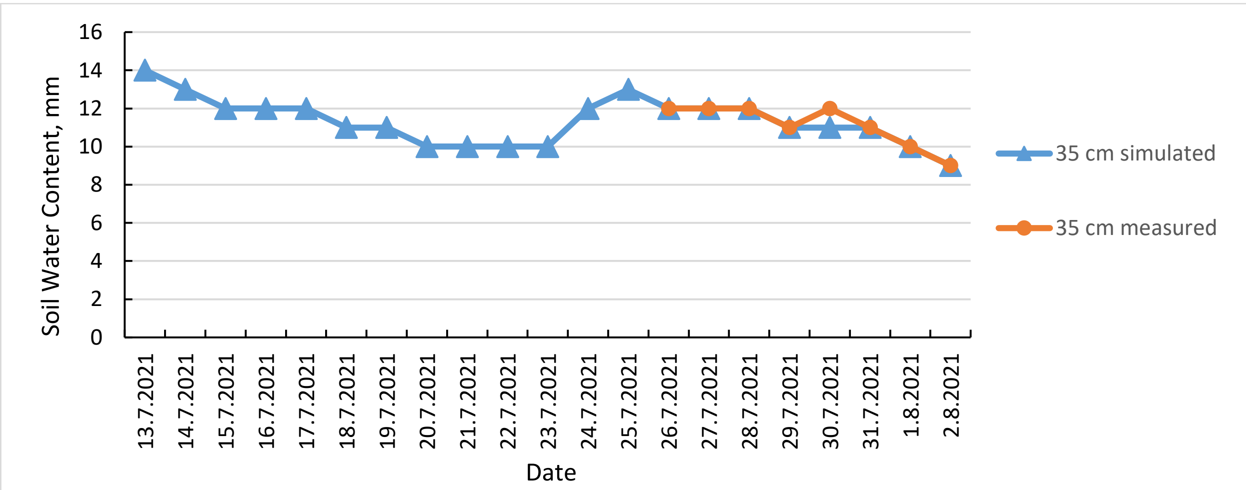

Figure 4. Soil water content at 35 cm depth

CONCLUSION

In this paper MOHID- Land Model has been investigated as one of the newest models. The numerical simulations of soil water dynamics has been performed and the field experiments have been conducted at the Experimental field of the Agricultural University – Plovdiv (Bulgaria) during the 2021 summer season. The period of simulations was July 2021. The calculated results by MOHID-Land Model were compared with the results obtained by the field experiments. They showed a good agreement between the simulated and the measured soil water content. The model permits the irrigation to be triggered when a certain threshold pressure head, h_t is obtained in some grid cells of the observed root zone domain and then it will be stopped when the pressure head reaches the field capacity. In such manner, the model can help the improvement of irrigation practices. This study is an initial stage of a deeper investigation for implementing of the MOHID- Land Model under conditions of Bulgarian agriculture. That will helps for better predicting, observing and controlling the soil moisture of cultivated crops.

DECLARATION

Conflict of Interest. The authors declare that have no conflict of interest.

ACKNOWLEDGEMENTS

This work was supported by the Bulgarian Ministry of Education and Science under the National Research Program “Smart crop production” approved by Decision of the Ministry Council №866/26.11.2020 г. The authors would like to acknowledge the Agricultural University-Plovdiv for permitting to conduct the field experiments on the Experimental field. The authors of this study are opened for future collaborations with other Bulgarian scientists. We can share the coded initial and boundary conditions of the model (for tomato, pepper or other crop). They are coded in FORTRAN 98. We can give assistance for further investigations and implementations of the MOHID-Land model under conditions of Bulgarian agriculture.

REFERENCES

Allen, R., Pereira, L., Raes, D., & Smith, M. (1998). Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements- FAO Irrigation and Drainage Paper No 56, Food and Agriculture Organization, Rome, Italy. http://www.fao.org/3/x0490e/x0490e0b.htm (Last accessed in July 2021)

Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., Haney, E., Neitsch, S.(2012). Soil & Water Assessment Tool, Input/Output Documentation, Version 2012, Appendix A, Texas Water Resources Institute, TR -439.

Chambel-Leitão, P., Ramos, T., Domingos, T., & Neves, R. (2015). Mohid Land-Porous Media, a tool for modeling soil hydrology at plot scale and watershed scale. *The Open Hydrology Journal*, 9, 1-12.

Chen, S., Mao., X., Barry, D., & Yang, J. (2019). Model of crop growth, water flow, and salute transport in layered soil. *Agricultural Water Management*, 221, 160-174.

Feddes, R., Kowalik, P., & Zarandy, H. (1978). Simulation of field water use and crop yield. Simulation Monograph Pudoc. Wagenigen, the Netherlands.

Feddes, R., & Raats, P. (2004). Parameterizing the soil-water-plant root system. In Feddes, R., de Rooij, G., van Dam, J. (Eds.). *Unsaturated zone modeling*: Progress, challenges and applications, (pp.95-141). Dordrecht: Kluwer Academic Publishers.

Galvão, P., Chambel-Leitão, P., Neves, R., & Leitao, P. (2004). A different approach to the modified Picard method for water flow in variably saturated soil. *Developments in Water Science*, 55(1), 557-567.

Hanson, J., Ahuja, L., Shaffer, M., Rojas, K., DeCoursey, D., Farahani, H., & Johnson, K. (1998). RZWQM: simulating the effects of management on water quality and crop production. *Agric. Syst*. 57(2), 161–195.

Hsiao, T., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., & Fereres, E., (2009). AquaCrop - The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agron. J.*, 101, 448-459.

Hutson, J., & Wagenet, R. (1990). An overview of LEACHM: a process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Chemical Equilibrium and Reaction Models. Proceedings San Antonio, 409–422.

Kojnov, V., Kabakchiev, I., & Boneva, K. (1998). Atlas na bulgarskite pochvi. [Atlas of Bulgarian soils]. Zemizdat. [in Bulgarian].

Kroes, J., & van Dam, J., Reference Manual SWAP version 3.0.3, Alterra-rapport 773, Wageningen University, Department of Water Resources.

Monsi, M., & Saeki, T. (1953). Über den Lichtfactor in den Pflanzengeselschaften und seine Bedeutung für die Stoffproduction, *Japanese Journal of Botany*, 14, 22-52.

Neitsch, S., Arnold, J., Kiniry, J., & Williams, J. (2011). Soil Water Assessment Tool, Theoretical Documentation Version 2009, Texas Water Resources Institute, Technical Report No 406.

Purser, R. J., & Leslie, L. M. (1988). A semi-implicit, semi-lagrangian finite-difference scheme using high-order spatial differencing on a non-staggered grid. *Mon. Weather Rev.* 116, 2069–2080.

Raes, D., Steduto, P., Hsiao, T., & Fereres, E. (2009). AquaCrop - The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agron. J.*, 101, 438-447.

Raes, D., Steduto, P., Hsiao, T., & Fereres, E. (2016). Reference Manual AquaCrop (Version 4.0). AquaCrop Website 2016, http://www.fao.org/nr/water/aquacrop.html (Last accessed in July 2021)

Ramos, T., Simionrsel, L., Jauch, E., Almeida, C., & Neves, R. (2017). Modelling soil water a nd maize growth dynamics influenced by shallow groundwater conditions in the Sorraia Valley region, Portugal, *Agricultural Water Management*, 185, 27-42.

Simionrsei, L., Ramos, T., Brito, D., Jauch, E., Letao, P., Almeida, C., & Neves, R. (2016). Numerical simulation of soil water dynamics under stationary sprinkler irrigation with MOHID-Land, *Irrig. and Drain.*, 65(1), 98-111.

Simionrsel, L., Ramos, T., Palma, J., Oliveira, A., & Neves, R. (2020). IrrigaSys: A web-based irrigation decision support system based on open source data and technology, *Computers and Electronics in Agriculture*, 178, 1-9.

Simunek, J., van Genuchten,M., & Sejna, M. (2005). The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutesin Variably-Saturated media Version 4.0. Dep. of Environmental Sciences, Univ. of California Riverside, California. https://www.ars.usda.gov/ARSUserFiles/20360500/pdf_pubs/P2119.pdf (Last accessed in July 2021)

Steduto, P., Hsiao, T., Raes, D., & Fereres, E. (2009). AquaCrop - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agron. J.*, 101, 426-437.

Steduto, P., Hsiao, T., Fereres, E., & Raes, D. (2021). Crop Yield Response to Water, FAO Irrigation and Drainage Paper Nr. 66. 2012, Rome, Italy (Download pdf from website: http://www.fao.org/docrep/016/i2800e/i2800e00.htm (Last accessed in July 2021)

Stockle, C., Williams, J., Rosenberg, N., & Jones, C. (1992). A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part 1Modification of the EPIC model for climate change analysis. *Agricultural Systems*, 38, 225-238.

The Guardian, Drought puts 2.1 million Kenyans at risk of starvation, 15th of September, 2021.

van Dam, J., Huygen, J., Wesseling, J., Feddes, R., Kabat, P., van Walsum, P., Groenendijk, P., & van Diepen, C. (1997). Theory of SWAP Version 2.0. DLO Winand Staring Centre, Wageningen, Netherland. http://www.swap.alterra.nl/DownloadHistory/swap207d/Swap207d%20theory%20(TechDoc%2045).pdf (Last accessed in July 2021)

Van Genuchten, M. (1980). A closed form equation for predicting hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44, 892-898.

Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T., Fereres, E., Heng, L., Garcia Vila, M., Mejias & Moreno, P. (2014). AquaCrop: FAO's crop water productivity and yield response model, Environmental Modelling & Software, 62, 351-360.

Weiss, M., Baret, F., & Jay, S. (2020). S2ToolBox Level e products, LAI, FAPAR, FCOVER, Version 2.0.

Williams, J., Jones, C., Kiniry, J., & Spanel, D. (1989). The EPIC crop growth model. *Transactions of ASAE*, 32, 497-511.

Wösten, J., Lily, A., Nemes, A., & Le Bas, C. (1999). Development and use of a database of hydraulic properties of European soils. *Geoderma*, 90, 169-185.