Send Orders for Reprints to reprints@benthamscience.ae

The Open Hydrology Journal, 2015, *9*, 1-12 1

Open Access

Mohid Land - Porous Media, a Tool for Modeling Soil Hydrology at Plot Scale and Watershed Scale

P. Chambel-Leitão*, T.B. Ramos, T. Domingos and R. Neves

MARETEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal

Abstract: Hydrological modeling is becoming more important in water management. Soil hydrological models are increasingly being used to provide services to farmers and to water supply managers. This study tests the stability and adequability of MOHID LAND-PM in modelling soil water dynamics. Soil water flow and content was simulated in five soils with different soil textures (sand, sandy loam, clay, loam, and silt). The results were then compared with HYDRUS-1D simulations using the same input data. Soil domain was divided into 100 layers up to a depth of 2 m. Five additional simulations were carried out in MOHID LAND-PM in order to quantify the error of reducing the number of layers to 10 (instead of 100) when discretizing the soil profile. This is relevant in a watershed model like MOHID LAND-PM since the computing time is greatly reduced. MOHID LAND-PM results were compared with those of HYDRUS using Nash-Sutcliffe model efficiency (NSE) and Percent bias (PBIAS). Soil volumetric water content, pressure heads, and soil water velocity were compared for 4 depths. For the water contents, NSE was above 0.87 for sand and above 0.97 for all other soils and layers except for the clay soil (NSE≥0.01). For pressure heads, NSE >0.46 for sand and >0.98 for all other soils and layers except clay (NSE≥-23.95). Statistical analysis shows a soil water velocity of NSE below 0.0 for most sand and clay depths, and above 0.58 NSE for all other soils. PBias shows that in general, MOHID LAND-PM tends to underestimate HYDRUS soil water content and velocities.

Keywords: Infiltration, Hydrus, MOHID LAND-PM, Richards equation, soil water content, soil layer discretization.

1. INTRODUCTION

The entire world is experiencing water use changing patterns as a result of changes in land use [1]. In developing countries, the occupation of natural landscapes by agriculture is a major cause, and developed countries are facing changing cropping patterns. In both cases economic factors driven by the globalisation of world trade are involved. In both cases further global movement is expected as a result of climate change.

Water availability is essential for socio-economic activities and citizens expect water supply managers to take the necessary measures for assuring quantity and quality for direct and indirect human consumption. Some authors are raising the possibility of transforming water as a commodity [2]. In this perspective the share of the world wide soil water balance can become a measure of the prosperity of a country, and evapotranspiration can become an expense to a country. The knowledge of the processes determining water end use, actual reserves and the capacity to forecast water consumption are essential for catchment manager's decision making. For this it is essential to have the possibility to make operational the watershed model capable of modelling all fluxes in the global water cycle (precipitation, evapotranspiration, infiltration, aquifer recharge, etc.).

The estimation of evapotranspiration is very important for any hydrologic simulation. Reference evapotranspiration is normally calculated using FAO-56 method [3, 4]. Mohid_land uses the same formulation. However, more recent papers point out that newer more accurate methods exist to calculate evapotranspiration [5, 6]. However, this is not the focus of this paper, but it should be in future papers, due to the importance of evapotranspiration calculation.

MOHID LAND is a watershed model developed within the MOHID WATER framework [7, 8]. It has the advantage of being an open integrated watershed model, using an easy to read Fortran code developed for Windows and Linux environments. MOHID LAND can use standard hdf format to generate results or read input information. It has a set of tools to generate continuous grid data, based on netcdf dat and ESRI ascii data. The model is parallelized using open MP allowing a reduction in computing time. It is fully compliant with the operational Aquasafe system [9] and the Art system [10].

MOHID LAND - Porous Media (PM) was the first component of MOHID LAND, developed in 2000 using the MOHID philosophy and solved implicitly the Richards equation using "θ-modified Picard method". In its first version, MOHID LAND-PM could be used to carry out 1D, 2D or 3D simulations [11]. Later, methods to solve the Richards equation were improved and compared with field measurements and Hydrus simulations in a single soil [12]. Later "θ-modified Picard method" was replaced by the use of the Richards Equation. After these changes, MOHID LAND-PM

*Address correspondence to this author at the MARETEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal; E-mail: chambelpc@tecnico.ulisboa.pt

was again compared with soil moisture measurements and soil moisture simulations using the Hydrus and RZWQM models [13]. Comparisons were made only for one soil type and had no statistical analysis. This study presents the results for 5 different soil types and provides a statistic analysis for water content, pressure head and soil water velocity.

Simultaneously Mohid River Network (MRN) was added and MOHID LAND RunOff (RO) were included, and the first model validation of the watershed scale was made [14]. Both MRN and MOHID LAND-RO can run as standalone models. The first is suited for river simulations and the second is more appropriate for flood simulation.

No previous works with MOHID LAND-PM have tested stability and adequability of current version of MOHID LAND-PM in modelling soil water dynamics. This study analyses the MOHID LAND-Porous Media (PM) component of MOHID LAND catchment model [14]. We present a few test cases which may help model stability and adequability in future irrigation and watershed modelling studies.

2. IN METHODS

2.1. The MOHID LAND-PM Model

In MOHID LAND-PM, flow is calculated based on mass and momentum conservation equations. It is assumed that the inertial forces are nil. This generates equilibrium between pressure, gravity, and viscous forces. Using the concept of conductivity, the momentum conservation equation becomes the Darcy equation, which when replaced in the mass conservation equation becomes the Richards equation [15]:

$$\frac{\partial}{\partial t}\iiint \theta \, dV = \iint \left(-k\vec{\nabla}\left(h+z\right)\cdot\vec{n}\right) dA + S \tag{1}$$

where θ [-] is the soil volumetric water content, V [m^3] is the volume of integration whose surface is A [m^2], $\vec{n}$ is the exterior unit normal to the volume surface, k [m/s] is the hydraulic conductivity, h [m] is the pressure head, z [m] is the vertical coordinate, t [s] is time and S [m^3] represents the addition or extraction of water in the control volume (e.g., extraction by roots).

The relation between the pressure head (h) and the volumetric water content (θ) is given by the van Genuchten model [16]:

$$h(\theta) = -\left|\frac{\left(S_e^{-\frac{1}{m}} - 1\right)^{\frac{1}{n}}}{\alpha}\right| \tag{2}$$

$$m = 1 - 1/n\,,\ n>1 \tag{3}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4}$$

where θ_s and θ_r (m^3/m^3) are the saturated and residual water contents, respectively, and α (1/m) and n (-) are empirical shape parameters.

Equation (2) is non-linear, requiring an iterative process to solve a nonstationary, unsaturated flow. Hydraulic conductivity is calculated according to [16]:

$$k(\theta) = k_S S_e^L \left(1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right)^2 \tag{5}$$

where L is an empirical shape parameter (-) and k_S the saturated hydraulic conductivity (m/s).

The main difficulty in solving these equations is the non-linearity of the hydraulic soil properties and the definition of the calculation grid. The difficulty increases in tri-dimensional grids. MOHID is based on the finite volumes method. Thus, the simulation domain is divided into a group of control volumes of finite sizes (hence the name "finite volumes"). In MOHID LAND-PM these volumes are called cells. Cells are defined in the vertical direction using a layer depth. In the horizontal direction the cells are defined using a cell corner and cell length from the east-west and north-south directions.

Fig. (**1**) shows the calculation points for each of the state variables in an Arakawa C-grid [17]. θ, h and k are calculated in the centre of the volumes and the fluxes are calculated in the faces of the volumes. The k that are necessary to calculate the fluxes in the faces are obtained normally by averaging values in the adjacent cells. The hydraulic gradients of equation (1) ($\vec{\nabla}\left(h+z\right)$) are calculated with the h values of the cells adjacent to the face.

The source code and additional documentation for MOHID LAND can be accessed at the MOHID code repository website (http://mohid.codeplex.com). Modeling was done using version 88294 (http://mohid.codeplex.com/SourceControl/changeset/88294) of MOHID LAND, released on 28.02.2014. Two interfaces are available to prepare inputs and to analyse model results: (i) MOHID GIS and MOHID GUI [7], free and available at www.mohid.com; and (ii) MOHID Studio, which is the commercial interface available at www.actionmodulers.com.

2.2. The HYDRUS Model

HYDRUS is as a reference model used in vadose zone modelling [18, 19]. It has been often used in irrigation management [20-22] and aquifer recharge modelling [23]. HYDRUS also solves the Richard equation. However, HYDRUS uses nodes (finite elements) to describe the geometry of the soil in opposition to the finite volumes available in MOHID LAND-PM. The van Genuchten model is also available to describe the soil hydraulic properties [16].

HYDRUS-1D model version 4.16 used was retrieved from the HYDRUS site (http://www.pc-progress.com/en/Default.aspx?h1d-downloads).

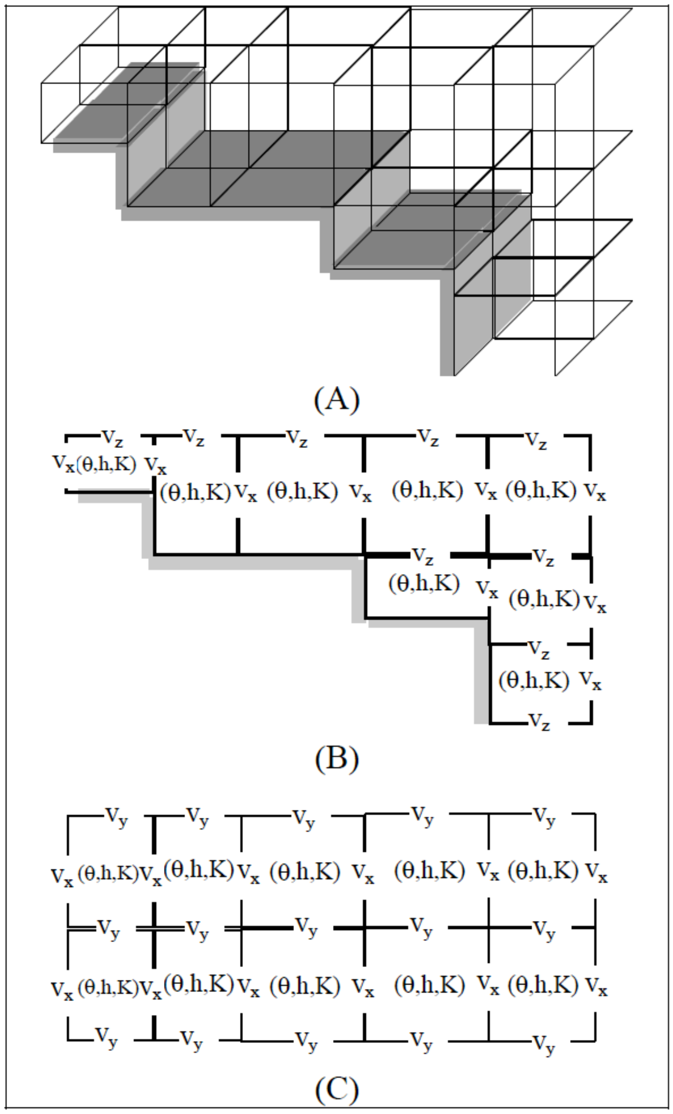

Fig. (1). Different perspectives of a MOHID LAND-PM grid: (**A**) tri dimensional view (**B**) profile view and (**C**) top view. Also the location of the state variables of the model, where θ [-] is the soil volumetric water content, k [m/s] is the hydraulic conductivity, h [m] is the pressure head in the centre of the cells V_x, V_y,V_z [m^3] are the water velocities in the cell faces in the three directions,

Table 1. Layers in MOHID LAND model.

Layer Number	1	2	65	82	91	(…) 95	96	97	98 (…)	100
Depth of the center of layer [cm]	198.5	196	70	36	18	10	8	6.5	5	1
Depth of layer bottom [cm]	200	197	71	37	19	11	90	7	6	2

2.3. General Model Setup

A vertical 1D geometry was defined In MOHID LAND-PM. The soil was divided into 100 layers up to a depth of 2 m (Table **1**). The time step was variable, with a maximum of 3600 and a minimum of 0.001 seconds. The average time step was 50 seconds. The average number of iterations, for convergence in each time step, was 5. Simulations were carried out between 2013-05-01 and 2013-10-15 (168 days). The model was run on a CPU Intel® Core™ i7-2600 Processor with 8 GB RAM. The simulation took 63.76 seconds with a total CPU time of 62.70 seconds. The results of the simulation occupied 1.5 MB of disk space (excluding the 50 MB of the DT log).

Atmosphere boundary conditions was defined using historical hourly data from the meteorological model available at http://meteo.tecnico.ulisboa.pt/. Atmospheric properties used were precipitation (mm), air temperature (ºC), solar radiation (W/m^2), relative humidity (-) and wind modulus (m/s).

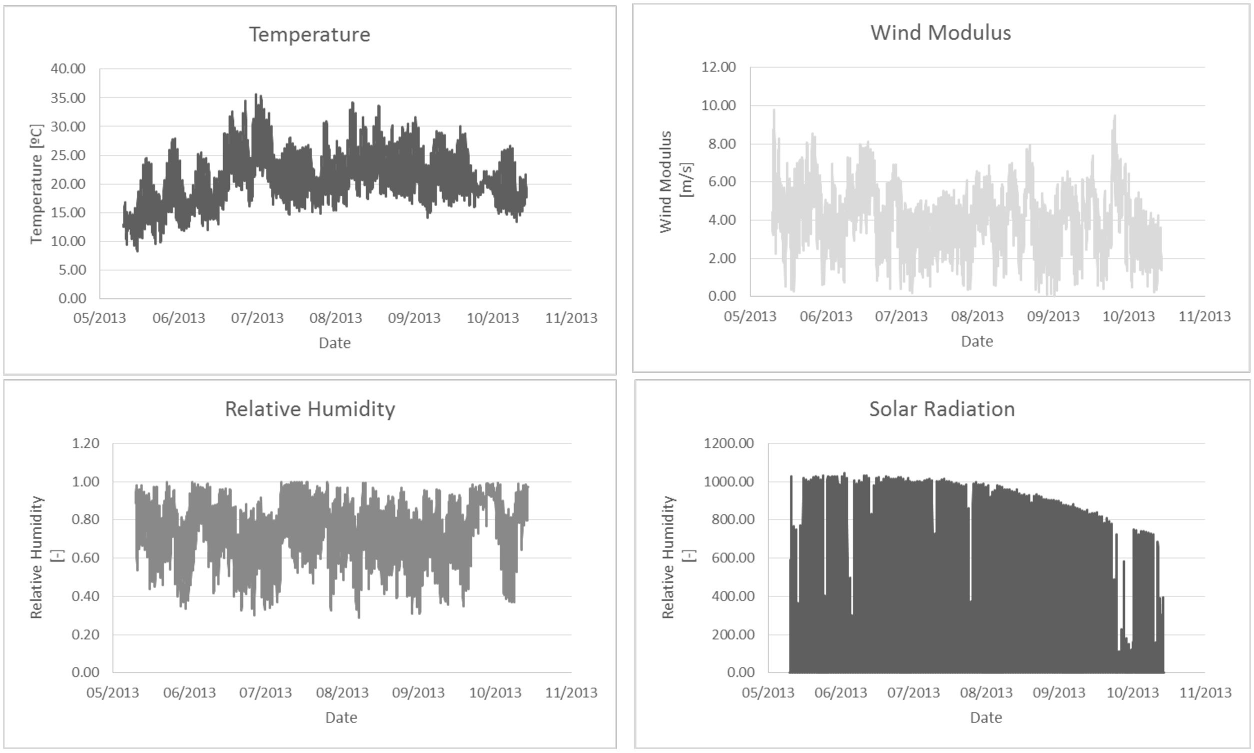

Fig. (2). Meteorological data for the simulated period.

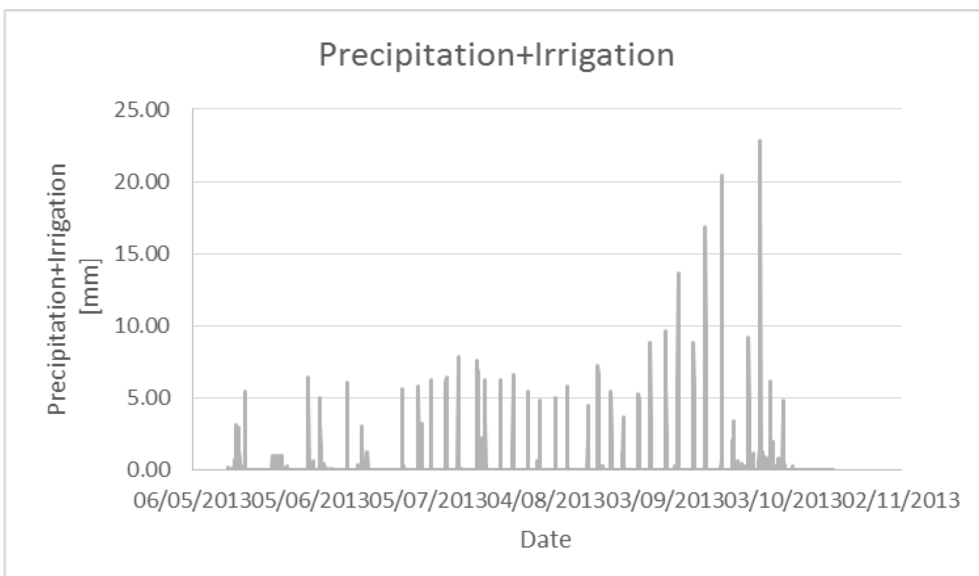

Fig. (3). Precipitation + irrigation for simulated period.

The model also included values of irrigation, measured in a field test located in the same region where the meteorological data was obtained (Fig. **3**). Fig. (**2**) presents the meteorological data used in this study. Hourly reference evapotranspiration was calculated using the FAO-56 method [3, 4] and used in model simulations, i.e., crop coefficients were set to 1. No plant growth was considered effectively assuming that all water evaporated was taken from the surface soil layer (and not from different layers has it is the case when roots are calculated). No evaporation was computed from the water column. The lowest boundary condition was set to zero flux. Output of the model was set to daily. The accumulated error was 2.9E-11 m^3 after the 168 days of simulation. This corresponds to 3.9E-09 % of the total soil water available in the end of the simulation.

Models were run for soils with five different soil textures: sand, sandy loam, clay, loam and silt. Soil hydraulic properties were obtained from [24]. The soil hydraulic properties used are shown in Table **3**.

Table 2. Layers in HYDRUS model.

Node Number	101	100	36	19	10	6	5	4	3	2	1
Node depth [cm]	200	198	70	36	18	12	8	5	3	1	0

Table 3. Van Genuchten soil hydraulic properties used to run models.

Texture	ThR (-)	ThS (-)	Alfa (1/m)	N (-)	Ks (m/s)	L (-)
Clay	0.068	0.38	0.8	1.09	5.56E-07	0.5
Loam	0.078	0.43	3.6	1.56	2.89E-06	0.5
Sand	0.045	0.43	14.5	2.68	8.25E-05	0.5
Sandy loam	0.065	0.41	7.5	1.89	1.23E-05	0.5
Silt	0.034	0.46	1.6	1.37	6.94E-07	0.5

Table 4. Layers in MOHID LAND model with 10 layers.

Layer Number	1	2	3	4	5	6	7	8	9	10
Depth of the center of layer [cm]	170	115	70	36	18	12	8	5	3	1
Depth of layer bottom [cm]	200	140	90	50	22	14	10	6	4	2

In HYDRUS-1D, geometry was defined with 101 nodes (Table **2**) Time step was variable and had a maximum time step of 3600 and minimum of 0.001 seconds. The average time step was 1600 seconds and the average number of iterations, for convergence in each time step, were 3. Period of simulation was the same as the one used in MOHID LAND-PM simulations. The simulation took 2.6 seconds with a total CPU time of 2.6 seconds. HYDRUS output files occupied 6 MB of space. Output of the model was set to daily. The accumulated error was 1.6E-06 m^3 after the 168 days of simulation. This corresponds to 3.9E-09 % of the total soil water available in the end of the simulation.

As HYDRUS-1D does not calculate reference evapotranspiration, the same atmospheric input data used in MOHID LAND-PM was used as input in HYDRUS-1D simulations. This means that it provided the same precipitation and evaporation to both models. Evaporation was the one calculated by MOHID-LAND model. The option used on the surface boundary of HYDRUS-1D was “Atmospheric Boundary Condition with surface layers”. This means that a water column can be formed on the surface when precipitation plus irrigation flux exceeds infiltration flux. Bottom boundary condition was set to zero flux.

Both model outputs were set at 8, 18, 36, and 70 cm depth.

Model simulation results were compared on an hourly basis. All comparisons were carried out for 4000 instants, except for the clay soil texture. HYDRUS-1D was unable to converge after 2600 instants were considered, because of a 40 mm irrigation in one day. This was expected to happen due to the low velocities considered the in clay soil texture and due to the large pressure head variations. We did many changes to the convergence criteria but they were all unsuccessful in achieving a complete HYDRUS run. In MOHID LAND-PM there was no need to change the convergence criteria to have a complete run.

2.4. 10 Layers Simulations

In watershed modelling it is necessary to reduce the number of layers in the soil in order to reduce the computing time. This results in an increased error. To quantify this error the same simulations were produced assuming 10 layers in MOHID LAND-PM (Table **4**). The 10 layers simulation of MOHID LAND-PM were compared with the 100 layers simulation of MOHID LAND-PM.

2.5. Statistical Analysis

The Nash-Sutcliffe model efficiency (NSE) [25] was used to evaluate the performance of the MOHID LAND-PM in reproducing HYDRUS-1D simulations of the soil water dynamics. NSE indicates how well the plot of observed versus simulated data fits the 1:1 line (trends) and it is determined as follows:

$$NSE = 1 - \left[\sum_{i=1}^{n} (Y^{obs}{}_i - Y^{sim}{}_i)^2 \Big/ \sum_{i=1}^{n} (Y^{obs} i - Y^{mean})^2 \right] \quad (6)$$

Table 5. Soil water content (m3/m3) comparison between HYDRUS and MOHID LAND-PM.

Texture	Depth [cm]	NSE	Pbias (%)	HYDRUS [-]	Mohid [-]
sand	8	0.87	6.3	0.10	0.09
	18	0.97	4.0	0.13	0.12
	36	0.99	1.7	0.16	0.16
	70	0.99	2.1	0.20	0.20
sandy loam	8	0.99	0.5	0.16	0.16
	18	1.00	0.0	0.17	0.17
	36	1.00	0.1	0.18	0.18
	70	0.94	1.4	0.19	0.18
clay	8	0.76	5.9	0.32	0.32
	18	0.63	8.1	0.32	0.32
	36	0.45	11.1	0.29	0.30
	70	0.01	15.9	0.25	0.27
loam	8	0.99	0.7	0.23	0.23
	18	1.00	0.5	0.24	0.24
	36	1.00	0.5	0.24	0.24
	70	1.00	0.7	0.23	0.23
silt	8	0.99	1.1	0.28	0.28
	18	0.99	1.1	0.28	0.28
	36	0.99	1.5	0.27	0.26
	70	0.97	2.2	0.23	0.23

where $Y^{obs}{}_i$ = i^{th} observation for the constituent being evaluated, $Y^{sim}{}_i$ = i^{th} simulated value for the constituent being evaluated, Y^{mean} = mean of observed data for the constituent being evaluated, and n = total number of observations. NSE ranges between -∞ and 1.0 (1 inclusive) with NSE = 1 being the optimal value. Values ≤ 0.0 indicate that the mean observed value is a superior predictor than the simulated value, which indicates unacceptable performance.

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts [26]. The optimal value of PBIAS is 0.0 with low magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. PBIAS is computed as:

$$PBIAS = \left[\sum_{i=1}^{n} (Y^{obs}{}_i - Y^{sim}{}_i) * (100) / \sum_{i=1}^{n} (Y^{obs}{}_i) \right] \quad (7)$$

where PBIAS = deviation of data being evaluated, expressed as a percentage.

3. RESULTS

Model simulations were compared for soil water content (Table **5**) soil pressure head (Table **6**) and vertical velocity (Table **7**). In HYDRUS-1D, soil water content and soil pressure head were calculated per node (finite element) while in MOHID LAND-PM were calculated per cell (finite volume). In HYDRUS, water velocity was calculated in the nodes but in MOHID LAND-PM were calculated in the faces of the cells. This means that velocities presented for MOHID LAND-PM refer to depth plus 1cm (i.e., 9, 19, 37 and 71 cm). As a consequence the compared velocities are 1cm deeper in MOHID LAND-PM than in HYDRUS.

Statistical analysis shows an NSE for water content above 0.87 for sand and above 0.97 for all other soils and

Table 6. Soil pressure head (m) comparison between HYDRUS and MOHID LAND-PM.

Texture	Depth [cm]	NSE	Pbias (%)	HYDRUS [m]	Mohid [m]
sand	8	0.98	0.1	-0.3	-0.3
	18	0.98	0.1	-0.2	-0.2
	36	0.83	-11.2	-0.2	-0.2
	70	0.46	-143.1	-0.1	-0.2
sandy loam	8	0.99	-0.7	-0.7	-0.7
	18	1.00	0.7	-0.5	-0.5
	36	1.00	0.6	-0.5	-0.5
	70	0.99	-0.5	-0.4	-0.4
clay	8	-23.95	-289.9	-28.0	-63.6
	18	0.98	-3.2	-155.6	-5.0
	36	0.02	-61.5	-6661.8	-7002.3
	70	0.14	-28.6	-11991.1	-10040.7
loam	8	1.00	-1.5	-1.5	-1.5
	18	1.00	-0.7	-1.2	-1.2
	36	1.00	-0.8	-1.2	-1.2
	70	1.00	-1.2	-1.3	-1.3
silt	8	1.00	-0.8	-3.9	-3.9
	18	1.00	-0.9	-3.7	-3.7
	36	1.00	-1.7	-4.5	-4.6
	70	0.98	-2.6	-6.1	-6.3

Table 7. Soil water velocity (m/s) comparison between HYDRUS and MOHID LAND-PM.

Texture	Depth [cm]	NSE	Pbias (%)	HYDRUS [m/s]	Mohid [m/s]
sand	8	0.87	0.6	-3.0E-08	-3.0E-08
	18	-7827.30	-183.7	-2.9E-08	-8.3E-08
	36	-18359.59	1613.8	-2.6E-08	4.0E-07
	70	-8942.96	2517.4	-2.1E-08	5.0E-07
sandy loam	8	0.86	7.6	-1.9E-08	-1.8E-08
	18	0.94	5.4	-1.9E-08	-1.8E-08
	36	0.98	3.6	-1.9E-08	-1.8E-08
	70	0.98	2.1	-1.8E-08	-1.8E-08

Table 7. contd…

Texture	Depth [cm]	NSE	Pbias (%)	HYDRUS [m/s]	Mohid [m/s]
clay	8	-11.13	71.0	-2.1E-08	6.1E-10
	18	-0.07	79.9	-3.8E-08	-2.5E-09
	36	0.00	99.9	-2.5E-06	3.0E-09
	70	0.00	100.1	-8.7E-07	6.0E-09
loam	8	0.87	6.0	-1.3E-08	-1.2E-08
	18	0.92	7.3	-1.2E-08	-1.1E-08
	36	0.99	5.7	-1.1E-08	-1.0E-08
	70	0.99	7.3	-9.4E-09	-8.8E-09
silt	8	0.63	27.2	-1.2E-08	-8.4E-09
	18	0.58	13.1	-1.1E-08	-9.2E-09
	36	0.95	14.4	-8.7E-09	-7.5E-09
	70	0.93	23.1	-5.1E-09	-3.9E-09

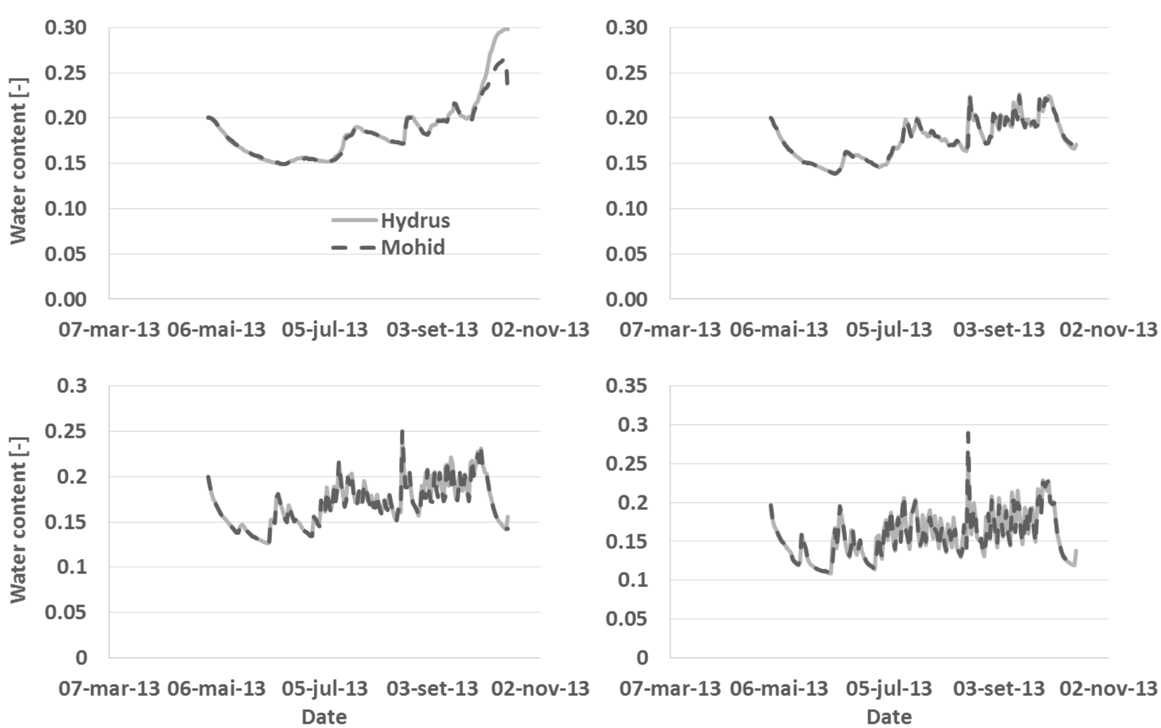

Fig. (4). Example result for water content with MOHID LAND-PM and HYDRUS in Sandy Loam.

layers except clay (Table **5**). PBias shows that MOHID LAND-PM tends to underestimate HYDRUS because all PBias are positive. PBias values are less than 6.3% in sand; less than 2.2 % in the remaining soils; while for clay maximum PBias value is 15.9%, Fig. (**4**) shows example result for water content with MOHID LAND-PM and HYDRUS in Sandy Loam.

Statistical analysis shows a pressure head of above 0.46 NSE for sand and above 0.98 NSE for all other soils and layers except clay (Table **6**). PBias shows that MOHID LAND-PM tends to underestimate HYDRUS because most PBias are negative. Highest absolute value of PBias is 2.6 % in sandy loam, loam and silt soil. For clay maximum PBias value is 289.9%. High values of PBias and low values of

Table 8. Soil water content (m3/m3) comparison between different number of layers in MOHID LAND-PM.

Texture	Depth [cm]	NSE	Pbias (%)	100 layers [-]	10 layers [-]
clay	8	0.96	-1.0	0.322	0.325
	18	0.96	-0.6	0.319	0.321
	36	0.85	-4.3	0.298	0.311
	70	0.72	-7.6	0.267	0.287
loam	8	0.93	-4.0	0.231	0.240
	18	0.86	-3.8	0.241	0.250
	36	0.85	-5.2	0.240	0.252
	70	0.80	-5.4	0.231	0.244
sand	8	-3.89	-39.4	0.092	0.128
	18	0.65	-13.8	0.124	0.141
	36	0.83	-6.2	0.155	0.165
	70	0.84	-3.6	0.200	0.207
sandy loam	8	0.92	-4.1	0.158	0.164
	18	0.82	-2.7	0.171	0.175
	36	0.26	-5.3	0.176	0.185
	70	-3.69	-13.9	0.183	0.208
silt	8	0.92	-4.9	0.280	0.294
	18	0.86	-6.1	0.280	0.297
	36	0.84	-7.7	0.262	0.282
	70	0.57	-9.7	0.227	0.249

NSE are related with the exponential variation of the head particularly in clay soils. This can be confirmed by the average values of head in each depth. It is possible to see for Hydrus that head increases one order of magnitude in each depth, while water content decreases a maximum of 0.04 between depth 36 and depth 70.

Statistical analysis shows an NSE for soil water velocity of 0.0 for sand and clay (except for first layer in sand), and above 0.58 for all other soils. In soil water velocity negative values mean upward velocity and positive values indicate downward velocity. The average values show that velocities are mostly upwards. PBias shows that MOHID LAND-PM tends to underestimate HYDRUS soil water velocity because all PBias are positive. The worst results in depths 18, 36 and 70 are related with saturation conditions that happen at the end of a run. For Saturation MOHID LAND-PM calculates velocities while HYDRUS assumes velocities to be zero between saturated layers. If we analyse only the velocities just until 22 of August for example for sand at 70 cm the NSE goes from -8942.96 to 0.90.

3.1. 10 Layers Simulations

The 10 layers simulation of MOHID LAND-PM was compared with the 100 layers simulation of MOHID LAND-PM. Parameters compared were soil water content (Table **8**), soil pressure head (Table **9**) and vertical velocity (Table **10**).

PBias shows that MOHID LAND-PM with 10 layers tends to overestimate water content when compared with MOHID LAND-PM with 100 layers because all PBias are negative.

Statistical analysis shows for water content an NSE above 0.57 for all except two layers in a sandy loam and one layer in sand (Table **8**). PBias values are all less than 39.4 % in sand and less than 13.9 % in the remaining soils.

Table 9. Soil pressure head (m) comparison between different number of layers in MOHID LAND-PM.

Texture	Depth [cm]	NSE	Pbias (%)	100 layers [m]	10 layers [m]
clay	8	0.98	4.1	-1878.71	-1800.95
	18	0.66	36.8	-3932.67	-2487.38
	36	0.30	44.1	-7002.32	-3913.86
	70	0.22	38.0	-10040.75	-6228.00
loam	8	0.88	14.1	-1.50	-1.28
	18	0.86	10.7	-1.22	-1.09
	36	0.84	13.3	-1.21	-1.05
	70	0.81	12.2	-1.32	-1.16
sand	8	0.67	14.1	-0.30	-0.26
	18	0.83	3.7	-0.23	-0.22
	36	0.27	-10.3	-0.20	-0.22
	70	-2.10	-71.6	-0.16	-0.28
sandy loam	8	0.83	11.6	-0.66	-0.58
	18	0.84	5.4	-0.52	-0.49
	36	0.61	9.1	-0.48	-0.43
	70	0.08	11.3	-0.45	-0.40
silt	8	0.90	18.1	-3.92	-3.21
	18	0.85	18.8	-3.74	-3.04
	36	0.80	19.2	-4.57	-3.69
	70	0.35	19.9	-6.31	-5.05

Table 10. Soil water velocity (m/s) comparison between using different number of layers in MOHID LAND-PM.

Texture	Depth [cm]	NSE	Pbias (%)	100 layers [m/s]	10 layers [m/s]
clay	8	0.11	2171.6	6.1E-10	-1.3E-08
	18	-0.06	-559.4	-2.5E-09	-1.6E-08
	36	-0.29	614.6	3.0E-09	-1.5E-08
	70	-0.15	322.0	6.0E-09	-1.3E-08
loam	8	0.97	-31.5	-1.2E-08	-1.6E-08
	18	0.87	-34.8	-1.1E-08	-1.5E-08
	36	0.87	-30.1	-1.0E-08	-1.4E-08
	70	0.90	-28.4	-8.8E-09	-1.1E-08

Table 10. contd…

Texture	Depth [cm]	NSE	Pbias (%)	100 layers [m/s]	10 layers [m/s]
sand	8	-207.82	-1837.7	-3.0E-08	-5.8E-07
	18	-0.08	-668.4	-8.3E-08	-6.4E-07
	36	-0.54	651.1	4.0E-07	-2.2E-06
	70	-2.60	1042.3	5.0E-07	-4.7E-06
sandy loam	8	0.98	-29.9	-1.8E-08	-2.3E-08
	18	0.89	-27.9	-1.8E-08	-2.2E-08
	36	0.51	-20.5	-1.8E-08	-2.2E-08
	70	-5355.01	-2279.3	-1.8E-08	-4.3E-07
silt	8	-0.15	-66.7	-8.4E-09	-1.4E-08
	18	0.34	-35.5	-9.2E-09	-1.2E-08
	36	0.90	-25.9	-7.5E-09	-9.4E-09
	70	0.91	-28.4	-3.9E-09	-5.0E-09

Statistical analysis shows an NSE above 0.22 for all except one layer in a sandy loam and one layer in sand (Table **8**). PBias values are all less than 71.6 % in sand and less than 44.1 % in the remaining soils.

Statistical analysis shows for soil water velocity an NSE below zero for 9 out of 16 depths analysed (Table **10**). PBias values are all less than 35.5% for 10 out of 16 of the depths analysed. In soil water velocity negative values mean upward velocity and positive values downward velocity. In general the 10 layer simulation tends to overestimate the soil water velocity.

DISCUSSION AND CONCLUSION

Results show that modelling soil water dynamics using a finite volumes model like MOHID LAND-PM and a finite elements model like HYDRUS produces similar results.

The main uncertainty in these models is the estimation of the infiltrated water. In fact, when HYDRUS calculates infiltration it returns different results from MOHID LAND-PM. The simulation in the clay soil was the one which resulted in the biggest differences between models. This simulation did not manage to converge to a solution after a certain point in time. This was due to an application of about 40 mm of water in 1 day.

Some previous studies compared different models. A study carried out in Texas showed that there were differences in infiltration between the different models tested (including HYDRUS) which resulted in different soil water contents [27].

Infiltration is in fact one of the most critical variables in hydrology models and also one of the most difficult to determine. Infiltrated water can be evapotranspirated, percolated to the aquifer or carried laterally along the soil profile until it reaches the channel. The water that reaches the aquifer is lost to the stream, stored in deep aquifer or returned to the atmosphere through capillary rise followed by evapotranspiration. The water that is not infiltrated is either converted into run-off, directed to the basin river network or it can be directly evaporated from the leaves and from the surface water column. Percolation transports nitrate to aquifer and surface waters. Run-off transports phosphorous and sediments to surface waters. Evaporated water promotes soil salinity more than transpiration. Percolation to aquifers reduces soil salinity. In this perspective, we believe that these results can have a positive impact on future infiltration assessments that can be made with MOHID LAND model.

Accurate estimates of infiltration are paramount to know the soil water content. This paper shows that MOHID LAND calculates soil water dynamics as well as HYDRUS, which is a very well tested model in detailed percolation studies. Future studies should compare MOHID LAND infiltration with infiltration in HYDRUS-1D and other models.

This paper also evaluates the impact on the reduction of the number of layers. In watershed, simulation can be used to reduce the number of layers because of computation time. Results show that it is reasonable to make a 10 layer simulation. However, we suggest to make the comparison presented here for the soils and meteorology included in a watershed simulation whenever MOHID LAND is setup.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

The work presented is part of the FP7-EU project FIGARO - "Flexible and Precision Irrigation Platform to Improve Farm Scale Water Productivity.

REFERENCES

[1] Foley JA, DeFries R, Asner GP, *et al.* Global consequences of land use. Science 2005; 309(5734): 570-4.
[2] Kaufman F. Wall Street's thirst for water. Nature 2012; 490(7421): 469-71.
[3] Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome 1998; 300: 6541.
[4] Allen RG, Pruitt WO, Wright JL, *et al.* A recommendation on standardized surface resistance for hourly calculation of reference ET< sub> o</sub> by the FAO56 Penman-Monteith method. Agric Water Manage 2006; 81(1): 1-22.
[5] Valipour M. Importance of solar radiation, temperature, relative humidity, and wind speed for calculation of reference evapotranspiration. Arch Agron Soil Sci 2015; 61(2): 239-55.
[6] Valipour M. Investigation of Valiantzas' evapotranspiration equation in Iran. Theor Appl Climato 2014: 1-12.
[7] Braunschweig F, Leitao PC, Fernandes L, Pina P, Neves RJJ. The object-oriented design of the integrated water modelling system MOHID. Dev Water Sci 2004; 55: 1079-90.
[8] Miranda R, Braunschweig F, Leitao P, Neves R, Martins F, Santos A. MOHID 2000 - A coastal integrated object oriented model. Wat Stud Ser 2000; 7: 393-401.
[9] Leitão P, Galvão P, Aires E, Almeida L, Viegas C. Fecal contamination modeling in coastal waters using a web service approach. Environ Eng Manag J 2012; 11(5): 889-905.
[10] Campuzano F, Fernandes R, Leitão P, Viegas C, de Pablo H, Neves R. Implementing local operational models based on an offline downscaling technique: the Tagus estuary case. 2 as Jornadas de Engenharia Hidrográfica 2012: pp. 105-8.
[11] Neves R, Chambel-Leitão P, Leitão P. Numerical modeling of water circulation in the soil - MOHID model. Modelação Numérica Da Circulação Da água no solo-o modelo MOHID. Pedologia 2000; 28(1): 46-55.
[12] Galvão P, Chambel Leitão P, Neves R, Leitao PC. A different approach to the modified Picard method for water flow in variably saturated media. Develop Water Sci 2004; 55: 557-67.
[13] Barão L, Leitão PC, Braunschweig F, *et al.* Simulation of water dynamics in two irrigated soils. Revista de Ciências Agrárias 2010; 33(1): 346-57.
[14] Trancoso AR, Braunschweig F, Leitao PC, Obermann M, Neves R. An advanced modelling tool for simulating complex river systems. Sci Total Environ 2009; 407(8): 3004-16.
[15] Celia MA, Binning P. A mass conservative numerical solution for two-phase flow in porous media with application to unsaturated flow. Water Resour Res 1992; 28(10): 2819-28.
[16] Vangenuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 1980; 44(5): 892-8.
[17] Arakawa A, Lamb VR. Computational design of the basic dynamical processes of the UCLA general circulation model. Methods Comput Phys 1977; 17: 173-265.
[18] Martinez G, Pachepsky YA, Vereecken H, Hardelauf H, Herbst M, Vanderlinden K. Modeling local control effects on the temporal stability of soil water content. J Hydrol 2013; 481: 106-18.
[19] Simunek J, van Genuchten MT. Modeling nonequilibrium flow and transport processes using HYDRUS. Vadose Zone J 2008; 7(2): 782-97.
[20] Ramos TB, Simunek J, Goncalves MC, Martins JC, Prazeres A, Pereira LS. Two-dimensional modeling of water and nitrogen fate from sweet sorghum irrigated with fresh and blended saline waters. Agric Water Manage 2012; 111: 87-104.
[21] Ramos TB, Goncalves MC, Castanheira NL, *et al.* Effect of sodium and nitrogen on yield function of irrigated maize in southern Portugal. Agric Water Manage 2009; 96(4): 585-94.
[22] Forkutsa I, Sommer R, Shirokova YI, *et al.* Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: I. Water dynamics. Irrigation Sci 2009; 27(4): 331-46.
[23] Vithanage M, Villholth K, Engesgaard P, Jensen KH. Vulnerability analysis of the coastal sandy aquifers in the east coast of sri lanka with recharge change consideration. Open Hydrology J 2010; 4: 173-183.
[24] Carsel RF, Parrish RS. Developing joint probability distributions of soil water retention characteristics. Water Resour Res 1988; 24(5): 755-69.
[25] Nash J, Sutcliffe J. River flow forecasting through conceptual models part I—A discussion of principles. J Hydrol 1970; 10(3): 282-90.
[26] Gupta HV, Sorooshian S, Yapo PO. Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J Hydrol Eng 1999; 4(2): 135-43.
[27] Scanlon BR, Christman M, Reedy RC, Porro I, Simunek J, Flerchinger GN. Intercode comparisons for simulating water balance of surficial sediments in semiarid regions. Water Resour Res 2002; 38(12): 1323.

Received: October 01, 2014 Revised: January 13, 2015 Accepted: February 07, 2015