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## Performance of the HYDRUS-1D model for water balance components assessment of irrigated winter wheat under different water managements in semi-arid region of Morocco

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1 **Performance of the HYDRUS-1D model for**  
2 **water balance components assessment of irrigated winter wheat under**  
3 **different water managements in semi-arid region of Morocco**

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27

28 **Abstract**

29 The main goal of this research was to evaluate the potential of the HYDRUS-1D  
30 numerical model for estimating the soil moisture ( $\theta$ ) at different depths, actual crop  
31 evapotranspiration (ETa) and its components (crop transpiration, Ta and soil  
32 evaporation, Ea) as well as the deep percolation (DP) of irrigated winter wheat under  
33 different water managements in the semi-arid region of Tensift-basin (central  
34 Morocco). The HYDRUS-1D simulations were performed at daily time step during  
35 the two growing seasons: 2002/2003 and 2015/2016.

36 The model was firstly calibrated based on one field “denoted F1” data during the  
37 2002/2003 cropping season by using the Levenberg-Marquardt method implemented  
38 in HYDRUS-1D model for optimizing various parameters of Van Genuchten  
39 equation that provide the minimum difference between measured and simulated soil  
40 moisture at four layers of soil (0-5, 5-10, 10-20, 20-30, 30-50 cm). Afterwards, the  
41 model validation was done based on the data from four fields of wheat: two fields  
42 “denoted F2 and F3” during the 2002/2003 and two other fields “denoted F4 and F5”  
43 during the 2015/2016 cropping season. All fields were irrigated with flooding system  
44 except the field F5 where drip irrigation was undertaken. *In-situ* measurements of  $\theta$   
45 was carried out using Time Domain Reflectometry (TDR) and gravimetric method ETa  
46 was measured by the Eddy Covariance system Ta and Ea were monitored using a  
47 lysimeter in F5 field. The results showed that the HYDRUS-1D model simulates the  $\theta$ ,  
48 ETa, Ta and Ea reasonably well.

49 Additionally, the evaluation of the irrigation system on DP losses was  
50 investigated by comparing the simulation results over flood (F4) and drip (F5)  
51 irrigated fields. It was found that about 56% and 20% of seasonal supplied water  
52 were lost by DP in F4 and F5 sites, respectively. Such unexpected high amount of DP  
53 taking place in F5 field is due to the improper use of the drip irrigation system..

54 **Keywords:** HYDRUS-1D; Evapotranspiration; Eddy Covariance; deep percolation;  
55 winter wheat.

## 56 **1- Introduction**

57 In arid and semi-arid regions, water resources are currently scarce and will be one  
58 of the major challenge in the future due to the combined effect of the expected  
59 hydrological cycle alteration as a result of climate change and the sharp increase of  
60 water demand for agriculture, urban and industry (IPCC, 2009). In these regions,  
61 water scarcity is one of the main factors limiting agricultural development, and thus  
62 food security. The impact of such water scarcity is amplified by inefficient irrigation  
63 practices, especially because the irrigation system consumes more than 85% of the  
64 available water in these regions (Chehbouni et al., 2008).

65 In Morocco, cereals represent the main agricultural crops, accounting for about  
66 65% of all agricultural lands, among which common wheat constitutes about 54% of  
67 the agricultural production (MADRPM, 2010). Additionally, due to the high  
68 evaporation rate ( $\approx 1600$  mm/year) and erratic rainfall, the irrigation of cereals is  
69 inevitable under these conditions. Therefore, the monitoring of cereal water needs  
70 and consumption is a major challenge for developing rational irrigation strategy and  
71 for achieving higher water use efficiency. This requires an accurate estimation of the  
72 water consumed by evapotranspiration (ET) and its components (soil evaporation,  $E_a$   
73 and plant transpiration,  $T_a$ ) as well as the part lost through deep percolation DP (Er-  
74 Raki et al., 2010a; Khabba et al., 2013; Nassah et al., 2018) which represent the water  
75 balance components extremely difficult to quantify. It is important to mention that  
76 the loss in terms of percolation is considered in the context of agronomy. However, it  
77 is not considered as a loss with regard to hydrology since it feeds the water table. In  
78 this regard, quantifying the two loss components (soil evaporation and deep  
79 percolation) is of paramount importance for sound irrigation management especially  
80 in water shortage situation. Reducing both losses could be one of the most important  
81 water-saving strategies in semi-arid agricultural regions.

82 Recently, numerous studies have been done on either measurements or estimates  
83 of ET over the annual crops such as the wheat in the Haouz plain located in the  
84 Tensift basin near to the Marrakech city (Duchemin et al., 2006; Er-Raki et al., 2007,  
85 2010b, 2011; Ezzahar et al. 2009; Kharrou et al., 2013; Diarra et al., 2017; Ait Hssaine et  
86 al., 2018). Unfortunately, partitioning ET based on the separate measurements or

87 estimates of plant transpiration and soil evaporation is technically challenging (Rafi  
88 et al., 2019). The reasons are numerous: developed technologies including lysimeters,  
89 sap flow sensors, stable isotopes (Scott et al., 2006; Wang et al., 2010; Allen et al.,  
90 2011; Kool et al., 2014) are not suitable over the wheat crop, difficulty to install sap  
91 flow sensors which can damage the monitored stems, non-continuous measurements  
92 along the growing season, costly and require a competent staff for data processing  
93 and maintenance and the difficulty for up scaling the single measurements from  
94 plant to the field scale (Kool et al., 2014).

95 During the last two decades, substantial efforts (e.g. Liu et al., 2002 ; Kang et al.,  
96 2003; Balwinder-Singh et al., 2011; Zhang et al., 2002; 2011; Aouade et al., 2016, Rafi et  
97 al., 2019) have made ET partitioning of wheat crop. All of these studies were  
98 generally based on the combination of micro-meteorological measurements (Bowen  
99 ratio, eddy covariance system), eco-physiological techniques (sap flow, stable  
100 isotopes) and water balance methods (lysimeters or micro-lysimeters and soil water  
101 budget). However, these techniques are not always reliable and representative at  
102 ecosystem scale due to the heterogeneous characteristics of land use and agronomical  
103 practices. Therefore, estimation of soil evaporation and plant transpiration separately  
104 with models could be a good alternative to the above measurement methods. In this  
105 context, several models have been developed to estimate evapotranspiration and its  
106 components separately. These models are generally based on water balance and/or  
107 energy balance, and ranged from complex such as the Simple Soil Plant Atmosphere  
108 SiSPAT (Braud et al., 1995) and ISBA (Noilhan and Mahfouf, 1996) to simple ones  
109 such as FAO-56 dual approach (Allen et al., 1998), HYDRUS-1D (Šimůnek et al.,  
110 2008), HYDRUS-2D/3D (Šimůnek et al., 2016). Other crop models such as AquaCrop  
111 (Raes et al., 2009), RZWQM (Ahuja et al., 2000), APSIM (McCown et al., 1996)  
112 simulate ET and its components through the combination of a water balance with a  
113 crop growth component. These models are dynamic and generally include climate  
114 module, crop module, soil module and field management module.

115 Regarding DP component, less attention has been paid on estimating this term  
116 although it contributes to significant loss of water if irrigation system is inadequate.  
117 DP is commonly determined as a residual in water balance equation (Sammis et al.,

118 1983, Willi et al., 1997; Vázquez et al., 2006; Wang et al., 2012; Hatiye et al., 2018;  
119 Nassah et al., 2018). These studies tested this method for various crops under  
120 different irrigation techniques and for different soils texture and salinity.  
121 Nevertheless, the estimation of DP with this method was not always reliable due to  
122 the uncertainties in measuring some water balance components such as ET.

123 Other methods such as lysimeters (Kim et al., 2011; Duncan et al., 2016),  
124 fluxmeters (Deurer et al., 2008; Gee et al., 2009) can directly measured DP. However,  
125 these methods are expensive (Upreti et al., 2015), difficult to set up and the  
126 measurements take place on a limited spatial scale (Gee et al., 2009, Rafi et al., 2018).  
127 Other indirect methods are also used such as chloride mass balance modelling (Willi  
128 et al., 1997), hydraulic method (Qinbo et al., 2011), temperature measurements in the  
129 unsaturated zone (Constantz et al., 2003) and geochemical tracers (Stonestrom et al.,  
130 2003). Since the HYDRUS-1D model has been widely used to simulate soil water  
131 movement and the water balance components (mainly infiltration, soil evaporation,  
132 transpiration and deep percolation), it is often preferred due to its simplicity when  
133 compared to heavily parameterized physically-based models. Additionally,  
134 HYDRUS-1D requires relatively few inputs parameters for calibration and the  
135 obtained results are satisfactory as reported in several investigations (e.g. Wenninger  
136 et al., 2010; Sutanto et al., 2012; Li et al., 2014; Tan et al., 2014; Han et al., 2015; Zheng  
137 et al., 2017; Xu et al., 2017; Hatiye et al., 2018). Most of these investigations have  
138 applied HYDRUS-1D model for simulating soil water movement and percolation,  
139 but there are a very few studies on the ET partitioning. For instance, one can cite the  
140 works of the Sutanto et al. (2012) and Wenninger et al. (2010) which tested the  
141 potential of HYDRUS-1D to estimate ET partitioning over grass and a teff crop based  
142 on the combination of the isotope method and the water balance equation,  
143 respectively. As reported by Kool et al., (2014), these two studies were only  
144 conducted in a laboratory set-up with no conclusive partitioning results, which  
145 indicates the need for further validation by using experimental field data. In this  
146 context, the objective of this study is to calibrate and validate the HYDRUS-1D model  
147 for estimating actual crop evapotranspiration (ET<sub>a</sub>) and its components (T<sub>a</sub> and E<sub>a</sub>),  
148 as well as the temporal dynamics of soil moisture at different depths (5, 10, 20, 30 and

149 50 cm) of irrigated winter wheat under different water managements in the semi-arid  
150 region of Tensift-basin (central of Morocco). The evaluation of the irrigation system  
151 on DP losses has been also performed.

152

## 153 **2- Materials and Methods**

### 154 **2.1. Site description**

155 Field experiments were conducted over wheat crops in the irrigated zone R3,  
156 approximately located 40 km East of Marrakech city (centre of Morocco) (Fig. 1),  
157 during both 2002/2003 and 2015/2016 growing seasons. This area has a semi-arid  
158 Mediterranean climate, characterized by low and irregular rainfall with an annual  
159 average of about 240 mm, against an evaporative demand ( $ET_0$ ) of about 1600 mm  
160 year<sup>-1</sup>. Most of the precipitation falls during winter and spring, from the beginning of  
161 November until the end of April (Duchemin et al., 2006, 2008; Er-Raki et al., 2007).

162 The R3 zone has been managed since 1999 by a regional public agency (Office  
163 Regional de Mise en Valeur Agricole du Haouz (ORMVAH)) for crop irrigation.

164 The R3 region covers about 2800 ha and is almost flat, with deep soil of xerosol type  
165 and a fine, clay to loamy texture, developed on colluvial materials from the High-  
166 Atlas mountain range (Duchemin et al., 2006). This results in homogeneous soils and  
167 the soil hydraulic parameters have to be similar over all studied sites. The main crop  
168 grown in the region is the winter wheat (Iounousse et al., 2015). More details on the  
169 study site are provided in Duchemin et al. (2006), Er-Raki et al. (2007) and Amazirh  
170 et al. (2017).

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### 174 **2.2. Field experiments**

175 Field experiments were carried out in five fields of winter wheat: three fields  
176 denoted "F1, F2 and F3" during the 2002/2003 cropping season and two others  
177 denoted denoted respectively as field one, two and three in the growing seasons  
178 2002/2003 and in the other "denoted F4 and F5" during the 2015/2016 cropping  
179 season (Fig. 1). All fields were irrigated with flooding system except the field F5

180 where surface drip irrigation method was used. The irrigation amounts were about  
181 30 mm for F1, F2 and F3, and about 65 mm for F4 in each irrigation event, while the  
182 field F5 was randomly irrigated by applying an amount varied between 15 mm and  
183 45 mm for each water supply. Sowing dates, the lengths of wheat growth stages and  
184 the irrigation timing used in each field are provided in Table 1. The entire growing  
185 season of wheat was divided into four growth stages namely: the initial ( $l_{ini}$ ), the  
186 development ( $l_{dev}$ ), the midseason ( $l_{mid}$ ) and the late season ( $l_{late}$ ). The lengths of  
187 growth stages were computed according to the FAO-56 method (Allen et al., 1998,  
188 Er-Raki et al., 2011) as a fraction of canopy cover (CC).

189

### 190 **2.3 Data description**

191 The data used in this study were obtained from two experiments carried out  
192 on five irrigated wheat crops to monitor the different variables of the surface energy  
193 and water balances as well as soil and vegetation data during the 2002/2003 and  
194 2015/2016 cropping seasons.

195 Meteorological data were recorded very close to the five fields by using a  
196 tower installed over a well-watered clipped grass and equipped with classical  
197 automatic sensors. Measurements included incoming solar radiation (Kipp and  
198 Zonen CM5 pyranometer, The Netherlands), air temperature and vapour pressure  
199 (HMP45C, Vaisala, Finland), wind speed (A100R anemometer, R.M. Young  
200 Company, USA) and rainfall (FSS500 tipping bucket automatic rain gauge, Campbell  
201 Inc., USA). Daily averaged values of meteorological data were calculated in order to  
202 compute the daily reference evapotranspiration ( $ET_0$ ) (mm/day), according to the  
203 FAO-56 Penman–Monteith equation (Allen et al., 1998; Er-Raki et al., 2010c).

204 On each field of wheat, an Eddy Covariance system (EC) was installed to  
205 measure the actual evapotranspiration ( $ET_a$ ) using high frequency measurements of  
206 the three dimensional (3D) air velocity, temperature and water vapor fluctuations.  
207 This system consists of commercially available instrumentation: a 3D sonic  
208 anemometer (CSAT3, Campbell Scientific Ltd) and an open-path infrared gas  
209 analyzer (Li7500, Licor Inc.) or fast hygrometer (KH2O, Campbell Scientific Inc.,  
210 USA). Data loggers (Campbell Scientific Ltd) were used for the storage of raw 20 Hz

211 data. The half-hourly fluxes were later calculated off-line using Eddy Covariance  
212 processing software 'ECpack', after performing all required corrections for planar fit  
213 correction, humidity and oxygen (KH20), frequency response for slow apparatus,  
214 and path length integration (Van Dijk et al., 2004). The software is available for  
215 download at <http://www.met.wau.nl/>. More details about the description of EC  
216 measurements as well as the data processing can be found in Duchemin et al. (2006).  
217 The performance of EC measurements was assessed by checking the energy balance  
218 closure. By neglecting the term of canopy heat storage and the radiative energy used  
219 in photosynthesis (Baldocchi et al., 2000), the energy balance equation is given by:

$$220 \quad R_n - G = H + LE \quad (\text{eq. 1})$$

221 where  $R_n$  is the net radiation measured by CNR1 radiometers;  $G$  is the soil heat flux  
222 measured using soil heat flux plates;  $H$  and  $LE$  are respectively the sensible heat flux  
223 and the latent heat flux measured by eddy covariance system. By plotting the sum of  
224 the turbulent fluxes ( $H+LE$ ) against the available energy ( $R_n-G$ ) for five sites (data  
225 not shown here), it was found that the absolute error values of average closure was  
226 less than 20% (Er-Raki et al., 2011; Amazirh et al., 2017, Aouade et al. 2020). This is  
227 considered as acceptable with regards to literature (Twine et al., 2000).

228 Soil water content was measured over the five fields (F1, F3, F4, F5) by using a  
229 Time Domain Reflectometry (TDR) (CS616, Campbell Scientific Ltd.) at different  
230 depths (5, 10, 20, 30, 40, and 50 cm). TDR measurements were taken at 1 Hz, and  
231 averages were stored at 30 min intervals on CR23X data loggers (Campbell Scientific  
232 Ltd.). Likewise, weekly measurements of soil water content in different depths were  
233 made by using the gravimetric method over F2 field. This method was also  
234 conducted over other fields in order to calibrate the TDR measurements. This  
235 method consists of using the split tube sampler to take several soil sampling at  
236 different depths (5 cm, 10 cm, 20 cm, 30 cm and 50 cm) and under different  
237 conditions (humid, moderate and dry) with a weekly frequency. Finally, the soil  
238 moisture at the root zone (0-50 cm) was calculated based on the weighted soil  
239 moisture in each depth.

240 Additionally, on weekly basis, measurements of the canopy cover (CC) and leaf  
241 area index (LAI) over each field were made using hemispherical canopy photographs

242 (using a Nikon Coolpix 950 with a FC-E8 fish-eye lens converter, field of view 183°)  
243 and the metric method, respectively. For more details about those techniques and the  
244 software processing used for deriving CC, the reader can be referred directly to  
245 Duchemin et al. (2006) and Er-Raki et al. (2007).

246  
247 Besides all above measurements, two mini-lysimeters (30 cm in diameter) were  
248 installed over F5 field: one of 30 cm depth to measure actual soil evaporation (Ea)  
249 and another one of 90 cm depth to measure the actual evapotranspiration (ETa). Only  
250 the 90-cm depth lysimeter was seeded on the same date as the entire wheat field. The  
251 30-cm depth lysimeter was left under bare soil conditions while its immediate  
252 surroundings were kept untouched in order to reproduce the wheat field  
253 environment. To mimic the field irrigation, one single dripper per lysimeter was  
254 diverted to feed the surface soil right above the lysimeter cylinder. Both lysimeters  
255 are tension-controlled and allow for measuring the water fluxes at the surface (30 cm  
256 for Ea) and at the bottom (90 cm for ETa). Such measurements were used for  
257 validating the ETa partitioning by HYDRUS 1D model.

258

## 259 **2.4. Model description**

260 HYDRUS-1D model is a public domain Windows-based modeling environment  
261 for simulation of water, heat and solute movement (Šimůnek et al., 2008). The model  
262 numerically solves the Richards equation for variably saturated media, and the  
263 convection–dispersion equation for heat and solute transport based on Fick’s law.  
264 The water flow equation includes a sink term to account for root water uptake of  
265 plants. In the present study, this model was applied to predict the soil water  
266 movement at different depths, the main components of the water balance: plant  
267 transpiration, soil evaporation and deep percolation.

268 The governing one-dimensional water flow equation for a partially saturated  
269 porous medium is described using the modified form of the Richards equation,  
270 under the assumptions that the air phase plays an insignificant role in the liquid flow  
271 process and that water flow due to thermal gradients can be neglected:

$$272 \quad \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K \left( \frac{\partial h}{\partial x} + 1 \right) \right] - S \quad (\text{eq. 2})$$

273 where  $h$  is the water pressure head (cm),  $\theta$  is the volumetric water content ( $\text{cm}^3/\text{cm}^3$ ),  
 274  $t$  is time (day),  $x$  is the spatial coordinate (cm),  $K$  is the unsaturated hydraulic  
 275 conductivity function (cm/day), and  $S$  is the sink term in the flow equation  
 276 ( $\text{cm}^3/\text{cm}^3/\text{day}$ ) accounting for root water uptake.

277 The soil water retention,  $\theta(h)$ , and hydraulic conductivity,  $K(h)$ , functions  
 278 according to van Genuchten (1980), are given as

$$279 \quad \theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h > 0 \end{cases} \quad (\text{eq. 3})$$

$$280 \quad K(h) = K_s S_e^l \left[ 1 - \left( 1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (\text{eq. 4})$$

$$281 \quad m = 1 - \frac{1}{n}, \quad n > 1$$

282 here  $\theta_s$  is the saturated water content ( $\text{cm}^3/\text{cm}^3$ );  $\theta_r$  is the residual water content  
 283 ( $\text{cm}^3/\text{cm}^3$ );  $m$ ,  $\alpha$  and  $n$  are empirical shape factors in the water retention function,  $K_s$   
 284 is the saturated hydraulic conductivity (cm/day);  $l$  is the shape factor (the pore  
 285 connectivity parameter) in the hydraulic conductivity function; and  $S_e$  is the relative  
 286 saturation, which is expressed as:

$$287 \quad S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (\text{eq. 5})$$

288 HYDRUS-1D model uses  $LAI$  and  $ET_0$  as the basis to calculate potential transpiration  
 289 ( $T_p$ ) and potential soil evaporation ( $E_p$ ) at a daily time step using:

$$290 \quad T_p = ET_0 (1 - e^{-k * LAI}) = ET_0 * CC \quad (\text{eq. 6})$$

$$291 \quad E_p = ET_0 * e^{-k * LAI} = ET_0 * (1 - CC) \quad (\text{eq. 7})$$

292 where  $k$  is an extinction coefficient for global solar radiation; its value was  
 293 taken as 0.5 for the wheat according to Monteith and Unsworth, (1990).

294 Estimated  $T_p$  and  $E_p$  in conjunction with the water stress responses (Feddes et al.,  
 295 1978) and the root growth distribution were then used to calculate actual plant  
 296 transpiration ( $T_a$ ) and actual soil evaporation ( $E_a$ ). In particular,  $T_a$  is calculated by  
 297 means of the following equation:

$$298 \quad T_a = \int_{Z_r} S(h, x) dx = T_p \int_{Z_r} \alpha(h) b(x) dx \quad (\text{eq. 8})$$

299 where  $Z_r$  is the root depth,  $S$  is the root water uptake rate,  $\alpha(h)$  is the water stress  
 300 response function (dimensionless) and  $b(x)$  is the distribution function of water

uptake by the root. The reader can find more details about the form of these two functions in Feddes et al. (1978) and Šimůnek et al., (2008).

Actual soil evaporation ( $E_a$ ) is calculated by the following equation:

$$E_a = -K \left[ \frac{\partial h(x,t)}{\partial x} + 1 \right] \leq E_p \quad (\text{eq. 9})$$

## 2.5. Model calibration and evaluation procedure

The HYDRUS-1D model was calibrated on one field (F1) during 2002/2003 cropping season and then validated on four other wheat fields, denoted “F2, F3” and “F4, F5” during the 2002/2003 and 2015/2016 cropping seasons respectively, by using the same calibrated parameters. As mentioned before the soil texture in the R3 zone is uniform (clay to loamy), then the soil hydraulic parameters have to be similar over all studied sites.

The calibration was performed based on the Marquardt-Levenberg technique (Marquardt, 1963; Šimunek and Hopmans, 2002) implemented in HYDRUS-1D model for inverting the soil hydraulic parameters that provide the minimum difference between measured and simulated soil moisture at different depths (5, 10, 20, 30 and 50 cm). To this end, soil is divided into five layers and the soil hydraulic parameters of Van Genuchten (1980) functions (see eqs. 2 and 3) were calibrated for each layer (Table 2). The obtained value of soil residual water content ( $\theta_r$ ) was  $0.0945 \text{ cm}^3/\text{cm}^3$  and it is similar for all layers, while the soil saturation water content differs from the shallow layer to deeply one depending on soil texture. Other parameters for soil water retention curve (Van Genuchten, 1980) such as  $K_s$ ,  $\alpha$ ,  $n$  and  $l$  were also calibrated in each layer (Table 2). The calibrated values of  $K_s$  and  $\theta_s$  are in concordance with the values found by Toumi et al., (2016) who calibrated the AquaCrop model for winter wheat over the same study area. For the other parameters of Van Genuchten equation ( $\alpha$ ,  $n$  and  $l$ ), the calibrated values are in agreement with other finding (e.g. Ghanbarian-Alavijeh et al., 2010; Li et al., 2014; Jyotiprava Dash et al., 2015; Wallor et al., 2018; Latorre and Moret-Fernández, 2019) who again calibrated the HYDRUS-1D model for different soil textures. Some of these studies (Li et al., 2014; Wallor et al., 2018) determined the soil hydraulic parameters by using the RETC software package through fitting the retention data  $\theta(h)$ .

332 Finally, the performance of the HYDRUS-1D model was evaluated using  
 333 statistical parameters: the correlation coefficient ( $R^2$ ) and the Root Mean Square Error  
 334 (RMSE), which measure the correlation and the discrepancy of simulated values  
 335 around observed ones, respectively for both the calibration/validation stages. The  
 336 correlation coefficient ( $R^2$ ) and the Root Mean Square Error (RMSE) are given by:  
 337

$$RMSE = \sqrt{\frac{1}{N} * \sum_{i=1}^N (y_{isim} - y_{iobs})^2}$$

$$R^2 = \left[ \frac{\sum_{i=1}^N (y_{isim} - \bar{y}_{isim})(y_{iobs} - \bar{y}_{iobs})}{\sum_{i=1}^N (y_{isim} - \bar{y}_{isim}) \sum_{i=1}^N (y_{iobs} - \bar{y}_{iobs})} \right]^2$$

338 where  $\bar{y}_{sim}$  and  $\bar{y}_{obs}$  are the averages of model and observations, respectively,  $N$  is  
 339 the number of available observations, and  $y_{isim}$  and  $y_{iobs}$  are the daily values of  
 340 modeled and observed variables, respectively.

### 341 **3- Results and discussions**

342 In this section, the results of the calibration and the validation processes of  
 343 HYDRUS-1D model by exploiting the data collected during two cropping seasons  
 344 (2002/2003 and 2015/2016) are presented. Since the different components for ETa  
 345 partitioning were measured on one field (F5) during 2015/2016 by using the  
 346 weighing mini-lysimeters, an attempt was made to validate the ETa partitioning  
 347 through the comparison between measured and simulated actual plant transpiration  
 348 (Ta) and soil evaporation (Ea). As HYDRUS-1D model is able to simulate deep  
 349 percolation water (DP), the evaluation of the irrigation method (drip and flood) in  
 350 terms of DP losses will be also discussed at the end of this section.

#### 351 **3-1 Model Calibration**

352 As mentioned above, the calibration of the different parameters of the hydraulic  
 353 functions of van Genuchten (1980) used in HYDRUS-1D model was based on the  
 354 comparison between measured and simulated soil moisture at different depths (5, 10,  
 355 20, 30 and 50 cm). Fig. 2 shows this comparison which showed a good agreement  
 356 between simulated and measured volumetric soil water content ( $\theta$ ) for all depths.  
 357 According to this figure, the dynamics of  $\theta$  was adequately simulated and followed

358 the trend of the measured values with some under-estimation of  $\theta$  during the peak  
359 values for upper layer (5 cm). Seemingly, the soil water content in the upper soil  
360 layers produced more changes than in the deeper soil layers when the soil was not  
361 fully covered. The same behavior of surface soils was revealed by Han et al., (2015)  
362 when applying HYDRUS-1D model over a cotton crop in northwest of the Tarim  
363 Basin in the Xinjiang province of northwestern China. However, once the canopy  
364 cover reaches its maximum, the simulated and measured soil water content becomes  
365 very close even during the irrigation and rainfall events.

366 Likewise, it can be clearly seen that the simulations as well as the measurements  
367 respond well to water supply (irrigation and rainfall). For the integrated evaluation  
368 of soil moisture simulations, the measured root-weighted soil moisture with the  
369 simulated one we compared (fig 2-f). It is clear that the model correctly simulates the  
370 integrated  $\theta$  at the root zone. The corresponding values of  $R^2$  and RMSE are 0.87 and  
371  $0.02 \text{ cm}^3/\text{cm}^3$  and, respectively.

372 The model performance was also evaluated during the calibration stage by  
373 comparing the measured and simulated actual evapotranspiration ( $ET_a$ ) values. The  
374 correspondence between measured and simulated  $ET_a$  is shown as daily time course  
375 and in the scatter plot displayed in Fig. 3. A good agreement ( $R^2=0.83$  and  
376  $RMSE=0.90\text{mm/day}$ ) between simulated and measured  $ET_a$  was found. The model  
377 produced slightly lower values of  $ET_a$  than those observed. This underestimation of  
378  $ET_a$  in field F1 is expected and is attributed to the presence of the wild oat which was  
379 randomly developed in this field (Duchemin et al., 2006) during 2002/2003 season.  
380 Generally speaking, this wild oat that invaded this field increases the Leaf Area  
381 Index (LAI) and consequently the measured  $ET_a$  by eddy covariance system. The  
382 model was driven by an average value of LAI calculated by averaging all  
383 measurements taken along several transects using the allometric method, which  
384 means that the simulated  $ET_a$  is more or less representative for the whole wheat  
385 only. In contrary, the measured  $ET_a$  is limited to the footprint of the eddy covariance  
386 system. Therefore, any extra wild oat within this footprint can increase LAI (wild and  
387 wheat) and thus measured  $ET_a$ . The same behavior has been remarked by Toumi et

388 al., (2016) when using the same data for calibrating AquaCrop model that uses CC  
389 instead of LAI for crop development monitoring over the same field.

390 Additionally, by comparing the statistical results obtained by Toumi et al. (2016)  
391 ( $R^2 = 0.69$  and  $RMSE = 1.07$  mm/day), it is clearly seen that albeit of its hydrological  
392 aspect, HYDRUS-1D simulates better  $ET_a$  than agronomical model AquaCrop. Over  
393 the same field, Aoaude et al. (2020) have calibrated new multiple energy balance  
394 (MEB) version of ISBA (Interaction Soil Biosphere Atmosphere) developed recently  
395 by Boone et al. (2017) and their results of  $R^2$  and RMSE values were about 0.73 and  
396 2.6 mm/day which are slightly less performing than those obtained by HYDRUS-1D.  
397 Consequently, one can confirm the potential of HYDRUS-1D model for estimating  
398  $ET_a$  compared to ISBA-MEB model which is very complex and requires many input  
399 parameters to run it.

400

### 401 **3-2 Validation of HYDRUS-1D model**

402 After the calibration of the HYDRUS-1D model, model validation was performed  
403 using the dataset collected over four other wheat fields: two fields named F2 and F3  
404 during the 2002/2003 and two other ones named F4 and F5 during 2015/2016  
405 cropping season.

406 In order to limit the number of figures, only results for the weighted soil moisture  
407 at the root zone layer (0- 50 cm) are presented in Fig. 4 for four validation fields (F2,  
408 F3, F4 and F5). It should be noted that the weighted soil moisture over F2 field was  
409 calculated based on the measurements of the gravimetric method. As the calibration  
410 stage, HYDRUS-1D model was also able to simulate accurately the soil water content  
411 ( $\theta$ ) for all fields at different depths (data not shown here). Indeed, the simulated  
412 values of the weighted volumetric soil water content are in agreement with observed  
413 values for all fields, and their dynamics consistently reflected the rainfall and  
414 irrigation events (Fig. 4). However, some discrepancies between measured and  
415 simulated  $\theta$  were observed, particularly for high values where the model cannot  
416 effectively capture the observed data during some periods for some fields (14 to 22  
417 April for F2 and around DOY 74 for F3). The same observation was revealed by Silva  
418 Ursulino et al., (2018) and Grecco et al., (2019) when applying HYDRUS-1D and

419 HYDRUS-2D models, respectively, for predicting soil water content dynamics in two  
420 experiments in Brazil. A possible explanation for this underestimation of  $\theta$  by the  
421 model may be due to the overestimation of evapotranspiration rates, which can  
422 reduce the soil moisture rates as reported by Silva Ursulino et al., (2018). Additional  
423 explanation of the difference between measured and simulated  $\theta$  values is related to  
424 the assumption of a constant value for the root depth in HYDRUS-1D/2D, which  
425 considered an important limitation of the model (Grecco et al., 2019).

426 One can also note that the soil water content for drip field (F5), decreased rapidly  
427 within a few days after irrigation (e.g. March 23 to April 07), whereas it decreased  
428 slightly for flood irrigation (F4) during the same period. This can be explained by the  
429 rapid soil drying linked to the limited wetted fraction of soil, compared to the flood  
430 system where the soil is completely wetted which promotes the horizontal diffusion  
431 of water. Another factor that may partly explain this difference is the root water  
432 uptake (S) patterns under two irrigation systems. In the same context, Xue et al.,  
433 (2003) and Eugenio and Dani (1999) investigated the effect of available soil water and  
434 irrigation type on root distribution and water uptake patterns over wheat and corn  
435 crops, respectively. They found a significant correlation between the root water  
436 uptake and the irrigation system (flood and drip) as well as the available soil water.  
437 It can be seen also that the simulated and the measured soil water content remained  
438 almost above field capacity (about  $0.32 \text{ cm}^3/\text{cm}^3$ ) for most of time especially for field  
439 F5 due to the high amounts of delivered irrigation. Consequently, the excess water  
440 can percolate to deep soil layers (see § 3.4).

441 Based on the values of RMSE (0.06, 0.04, 0.02 and  $0.01 \text{ cm}^3/\text{cm}^3$  for F2, F3, F4 and  
442 F5, which represents a relative error of 22, 16, 6.66 and 3.44%, respectively), it can be  
443 concluded that the model performed well in simulating volumetric soil water  
444 content.

445 Concerning the validation of HYDRUS-1D simulations of  $ET_a$ , Fig. 5 shows the  
446 comparison between the daily simulated and measured  $ET_a$  for two validation fields  
447 (F2 and F3) during 2002/2003 and two other validation fields (F4 and F5) during  
448 2015/2016 cropping seasons. The scatter plot reveals a good agreement between  
449 simulated and measured  $ET_a$ . The RMSE ( $R^2$ ) values were

450 0.44 (0.83), 0.40 (0.87), 0.68 (0.69) and 0.55 (0.76) mm/day for F2, F3, F4 and F5,  
451 respectively. The slope of the linear regression is about 0.96, 0.84 and 1.05 for F2 and  
452 F3, F4 and F5 fields, meaning that the model underestimates ETa by about 4% and  
453 16% for F2 and F3, F4 and overestimates ETa by about 5% for F5. According to those  
454 statistical results, it can be concluded that although its relative simplicity, the  
455 HYDRUS-1D model can estimate very well ETa through the sum of the transpiration  
456 calculated with the root water uptake function (eq. 8) and soil evaporation (eq. 9), as  
457 shown by many authors (e.g. Li et al., 2014; Phogat et al., 2010). The question  
458 addressed after is how efficiently this model simulates the two components of  
459 evapotranspiration individually: plant transpiration (Ta) and soil evaporation (Ea).

460

461

462

### 463 **3.3 Performance of the HYDRUS-1D model for partitioning of soil evaporation and** 464 **plant transpiration**

465 As HYDRUS-1D model computes separately actual transpiration (Ta) and soil  
466 evaporation (Ea), it is of interest to investigate how well these individual components  
467 are simulated. To achieve this objective, we used the measurements of two mini-  
468 lysimeters in F5 field: one installed beneath the crop in order to measure ETa and  
469 another one under the bare soil to get the measurements of Ea. Plant transpiration  
470 (Ta) was derived as the difference between ETa and Ea. Fig. 6 presents the  
471 comparison between the measured and simulated ETa, Ta and Ea. Daily patterns of  
472 the simulated and measured values of each term are similar. The magnitude of daily  
473 Ta (Ea) was the lowest (highest) at the beginning of the season and it increased  
474 (decreased) continuously up to full development following the LAI increase.  
475 Instantaneous clear rise in Ea values respond well to water supply events (Fig. 6-b).  
476 The results showed that HYDRUS-1D model gives an acceptable estimate of plant  
477 transpiration and soil evaporation separately. In addition to the good performance of  
478 the model in terms soil moisture dynamics, the result indicates that the water uptake  
479 described in Eq. (8) is robust enough to capture the transpiration component. The  
480 associated RMSE between measured and simulated values of ETa, Ea and Ta were

481 0.54, 0.73 and 0.65 mm/day, respectively. The performance of HYDRUS-1D model in  
482 simulating ETa was similar when compared to different systems measurements  
483 (eddy covariance and lysimeter) which confirms an accurate calibration and  
484 validation of the model. For soil evaporation (Fig. 6-b), the difference between the  
485 measurements and the simulations is attributed to the fact that the lysimetre was  
486 over-irrigated because the dripper is intended to irrigate a surface of 0.4m<sup>2</sup> bigger  
487 than the area of lysimetre. This results that the lysimetre receives a larger quantity of  
488 irrigation water.

489

### 490 **3-4 Deep percolation losses**

491 Deep percolation (DP) is an important component of water balance, but it is rarely  
492 quantified for different types of irrigation. For that, we propose to evaluate the DP  
493 losses over two irrigated wheat plots: flood (F4) and drip (F5), by using both  
494 HYDRUS-1D and direct measurements with mini-lysimeter. Firstly, we analyze the  
495 effect of the irrigation type on DP by using HYDRUS-1D simulations (Fig. 7-a). Then,  
496 the validation of the DP estimation has been performed over drip plot (F5) where the  
497 measurements are available at two depths (30 and 90 cm) (Fig. 7-b).

498 According to Fig. 7-a , the simulations of DP for both fields (F4 and F5) respond  
499 well to water supply (irrigation and rainfall). After irrigation or rainfall, as expected,  
500 DP increased in two fields, but with different increasing magnitudes. In general, DP  
501 is higher for flood irrigation (F4) compared with drip irrigation (F5). This is expected  
502 because with flooding technique, the soil was completely wetted with higher amount  
503 of irrigation. Then, more amount irrigations in each water supply resulted in more  
504 water loss by DP. The cumulated simulated DP values of the entire experimental  
505 period are 93 and 347 mm for drip (F5) and flood (F4) irrigation, respectively. This  
506 amount represents about 20 and 56 % of water supply (irrigation and rainfall). This  
507 difference could be attributed to the fact that the amount of flood irrigation for each  
508 supply was higher (about 64 mm) which promotes the DP. Another factor that may  
509 partly explains this difference is that the irrigation in plot F4 coincides with some  
510 rainfall events (February 19th, March 22th) and that might have increased the DP.  
511 The lowest magnitude of DP observed after the end of March could be explained by

512 the high crop evapotranspiration (linked to the crop maturity and root growth)  
513 which was closely associated with the root water uptake (Tafteh and Sepaskhah,  
514 2012). Similar results were obtained by Jyotiprava Dash et al., (2015) and Xu et al.,  
515 (2017) when they applied HYDRUS-1D model for DP evaluation under different  
516 irrigation practices for rice crop, and they found an important amount (about 55%)  
517 of the applied water percolate below the root zone.

518 As mentioned above, DP simulations were compared to the measurements over  
519 drip plot (F5) where the measurements are available at two depths (30 and 90 cm)  
520 (Fig. 7-b). Missing data in some days is associated to power supply failures.  
521 According to Fig. 7-b, the DP at 90 cm depth is almost zero which might be related to  
522 the soil texture (more clay) that avoid the irrigated water to reach this depth. For  
523 other depths, both simulated and measured increased (with different magnitude)  
524 after water supply have decreased quickly and equal to zero in dry conditions  
525 (absence of irrigation and rainfall). As the measurements of DP with lysimeter are  
526 not complete and sometimes uncertain due to lack of spatial representativeness of the  
527 lysimeter irrigation, it is difficult to discuss more deeply about the comparison  
528 between the measurements and the simulations. Then, further effort would be  
529 necessary for more accurate measurements of DP in order to correctly validate the  
530 HYDRUS-1D simulations.

531

## 532 **4- Conclusions**

533 Good agreement was achieved to estimate  $\theta$  and  $ET_a$  between the HYDRUS-1D  
534 simulations and field measurements for winter wheat under different water  
535 managements, indicated by low average values of RMSE, which are  $0.03 \text{ cm}^3/\text{cm}^3$  for  
536  $\theta$  and  $0.58 \text{ mm/day}$  for  $ET_a$ . Validation of  $ET_a$  partitioning by the model based on  
537 lysimeters measurements showed that the model gives acceptable estimates of  $E_a$   
538 and  $T_a$ , with associated RMSE equal to  $0.73$  and  $0.65 \text{ mm/day}$ , respectively.

539 .

540 Deep percolation (DP) losses was also evaluated under drip and flood irrigations..  
541 As expected, the simulation results showed that a seasonal amount of DP losses for  
542 flood irrigation (about  $347 \text{ mm}$ ) was greater than for drip irrigation ( $93 \text{ mm}$ ), which

543 represent about 56% and 20% of water supply (irrigation and rainfall). DP  
544 simulations were also compared to the measurements taking place in drip field at  
545 two depths (30 and 90 cm). The results showed that the measured DP at 90 cm depth  
546 is almost close to zero indicating that the irrigation water does not infiltrates deeply  
547 which may be related to the heavy soil texture (clay). While for the other depth, both  
548 measured and simulated DP were noteworthy during the wetting events.

549 Finally, this study can be considered as the basis for future assessment of  
550 irrigation efficiency under drip and flood systems, and for irrigation scheduling in  
551 order to avoid the DP and Ea losses. However, further effort will be necessary for  
552 accurate measurements of DP by mini-lysimeter in order to correctly validate the  
553 HYDRUS-1D simulations.

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