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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 (θ) 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 θ
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 θ ,
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 (≈ 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_a) and its components (T_a and E_a),
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⁻¹. 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 filed 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
$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K \left(\frac{\partial h}{\partial x} + 1 \right) \right] - S \quad (\text{eq. 2})$$

273 where h is the water pressure head (cm), θ is the volumetric water content (cm^3/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 θ_s is the saturated water content (cm^3/cm^3); θ_r is the residual water content
 283 (cm^3/cm^3); m , α 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:

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

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

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 (θ_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 , α , n and l were also calibrated in each layer (Table 2). The calibrated values of K_s and θ_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 (α , 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 (θ) for all depths.
 357 According to this figure, the dynamics of θ was adequately simulated and followed

358 the trend of the measured values with some under-estimation of θ 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 θ 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 (θ) 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 θ 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 θ 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 θ 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 0.4m² 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 θ 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 θ and 0.58 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 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 mm) was greater than for drip irrigation (93 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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564 **6- References**

565
566 Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shaffer, M.J., Ma, L. 2000. Root Zone Water
567 Quality Model: Modeling Management Effects on Water Quality and Crop
568 Production, Water Resources Publications, LLC, Highlands Ranch, CO (2000).
569 Allen, R.G, L.S Pereira, D Raes, M Smith. 1998. Crop Evapotranspiration. Guidelines
570 for Computing Crop Water Requirements, Irrigation and Drain, 56 (3): 42-48.
571 Allen, R. G. Pereira, L.S., Howell,T. A., Jensen, M. E.. 2011. Evapotranspiration
572 information reporting: I. Factors governing measurement accuracy. Agr. Water
573 Manage, 98, 899-920.

574 Amazirh, A., Er-Raki, S., Chehbouni, A., Rivalland, V., Diarra, A., Khabba, S.,
575 Ezzahar, J., Merlin, O. 2017. Modified Penman–Monteith equation for
576 monitoring evapotranspiration of wheat crop: Relationship between the surface
577 resistance and remotely sensed stress index. *Biosystems Engineering*.164, 68-84.

578 Aouade, G., Ezzahar, J., Amenzou, N., Er-Raki, S., Benkaddour, A., Khabba, S.,
579 Jarlan, L. 2016. Combining stable isotopes and micrometeorological
580 measurements for partitioning evapotranspiration of winter wheat into soil
581 evaporation and plant transpiration in a semi-arid region. *Agricultural Water
582 Management*. 177(1), 181-192.

583 Aouade, G., Jarlan, L., Ezzahar, J., Er-Raki, S., Napoly, A., Benkaddour, A., Khabba,
584 S., Boulet, G., Garrigues, B., Chehbouni, A., Boone, A. Evapotranspiration
585 partition using the multiple energy balance version of the ISBA-A-gs land
586 surface model over two irrigated crops in a semi-arid Mediterranean region
587 (Marrakech, Morocco). *Hydrol. Earth Syst. Sci. Discuss.*, <https://doi.org/10.5194/hess, 2020>.

589 Baldocchi DD, Law BE, Anthoni PM. 2000. On measuring and modeling energy
590 fluxes above the floor of a homogeneous and heterogeneous conifer forest.
591 *Agricultural and Forest Meteorology* 102: 187–206.

592 Balwinder-Singh, Eberbach, P.L., Humphreys, E., Kukal, S.S., 2011. The effect of rice
593 straw mulch on evapotranspiration, transpiration and soil evaporation of
594 irrigated wheat in Punjab. India. *Agric. Water Manage.* 98 (12), 1847–1855.

595 Boone, A., Samuelsson, P., Gollvik, S., Napoly, A., Jarlan, L., Brun, E., & Decharme,
596 B.: The interactions between soil-biosphere-atmosphere land surface model with
597 a multi-energy balance (ISBA-MEB) option in SURFEXv8-Part 1: Model
598 description. *Geosci. Model Dev.*, 10(2), 843-872, 2017.

599 Braud, I., Dantas-Antonino, A.C., Vauclin, M., Thony, J.L., Ruelle, P. 1995. A simple
600 soil-plant-atmosphere transfer model (SiSPAT) development and field
601 verification. *J. Hydrol.* 166, 213–250.

602 Chehbouni, A., Escadafal, R., Boulet, G., Duchemin, B., Simonneaux, V., Dedieu,
603 G.,Mougenot, B., Khabba, S., Kharrou, H., Merlin, O., Chaponnière, A., Ezzahar,
604 J., Er-Raki, S., Hoedjes, J., Hadria, R., Abourida, H., Cheggour, A., Raibi, F.,

605 Hanich, L., Guemouria, N., Chehbouni, Ah., Lahrouni A., Oliosio, A., Jacob, F.,
606 Sobrino, J., 2008. The Use of Remotely Sensed data for Integrated Hydrological
607 Modeling in Arid and Semi-Arid Regions: the SUDMED Program. *International*
608 *Journal of Remote sensing*, 29: 5161 – 5181.

609 Constantz, J., Tyler, W., & Kwicklis E. (2003). Temperature-profile methods for
610 estimating percolation rates in arid environments. *Vadose Zone Journal*, 2, 12-24.

611 Deurer, M., Clothier, B. E., Green, S. R., & Gee G., (2008). Infiltration rate, hydraulic
612 conductivity and preferential flow. In: S. D. Logsdon, D. Clay, D. Moore, & T.
613 Tsegaye (Eds.), *Soil Science: Step-by-step Field Analyses* (pp. 221-233). USA: Soil
614 Science Society of America.

615 Diarra, A.; Jarlan, L.; Er-Raki, S.; Le Page, M.; Aouade, G.; Tavernier, A.; Boulet, G.;
616 Ezzahar, J.; Merlin, O.; Khabba, S. Performance of the two-source energy budget
617 (TSEB) model for the monitoring of evapotranspiration over irrigated annual
618 crops in North Africa. *Agric. Water Manag.* 2017, 193, 71–88.

619 Duchemin, B., Hadria, R., Er-Raki, S., Boulet, G., Maisongrande, P., Chehbouni, A.,
620 Escadafal, R., Ezzahar, J., Hoedjes, J., Karrou, H., Khabba, S., Mougénot, B.,
621 Oliosio, A., Rodriguez, J.-C., Simonneaux, V., 2006. Monitoring wheat phenology
622 and irrigation in Central Morocco: on the use of relationship between
623 evapotranspiration, crops coefficients, leaf area index and remotely-sensed
624 vegetation indices. *Agric. Water Manage.* 79, 1-27.

625 Duchemin, B., Hagolle O., Mougénot B., Simonneaux V., Benhadj I., Hadria R.,
626 Ezzahar J., Hoedjes J., Khabba S., Kharrou M.H, Boulet G., Dedieu G., Er-Raki
627 S., Escadafal R., Oliosio A., Chehbouni A.G. 2008. Agrometeorological study of
628 semi-arid areas: an experiment for analysing the potential of FORMOSAT-2 time
629 series of images in the Tensift-Marrakech plain. *International Journal of Remote*
630 *Sensing*, 29: 5291-5299.

631 Duncan, M. J., Srinivasan, M. S., & Mc Millan H. (2016). Field measurement of
632 groundwater recharge under irrigation in Canterbury, New Zealand, using
633 drainage lysimeters. *Agricultural Water Management*, 166, 17–32.

634 Eugenio F. Coelho and Dani Or. 1999. Root distribution and water uptake patterns of
635 corn under surface and subsurface drip irrigation. *Plant and Soil* 206: 123–136,
636 1999.

637 Er-Raki, S., Chehbouni, A., Guemouria, N., Duchemin, B., Ezzahar, J., Hadria, R.,
638 2007. Combining FAO-56 model and ground-based remote sensing to estimate
639 water consumptions of wheat crops in a semi-arid region. *Agric. Water Manage.*
640 14, 41-54.

641 Er-Raki, S., Chehbouni, A., Boulet, G., Williams, D.G. 2010a. Using the dual approach
642 of FAO-56 for partitioning ET into soil and plant components for olive orchards
643 in a semi-arid region. *Agricultural Water Management*. 97: 1769–1778.

644 Er-Raki, S.; Chehbouni, A.; Duchemin, B. 2010b. Combining satellite remote sensing
645 data with the FAO-56 dual approach for water use mapping in irrigated wheat
646 fields of a semi-arid region. *Remote Sens.* 2010, 375–387.

647 Er-Raki, S., Chehbouni, A., Khabba, S., Simonneaux, V., Jarlan, L., Ouldbba, A.,
648 Rodriguez, J.C., Allen, R. 2010c. Assessment of reference evapotranspiration
649 methods in semi-arid regions: Can weather forecast data be used as alternate of
650 ground meteorological parameters? *Journal of Arid Environments*, 74: 1587-
651 1596.

652 Er-Raki, S., Chehbouni, A., Ezzahar, J., Khabba, S., Lakhal, E.K. Duchemin, B., 2011.
653 Derived crop coefficient for winter wheat using different reference
654 evapotranspiration estimates methods. *Journal of Agricultural Science and*
655 *Technology*, 13: 209-221.

656 Ezzahar, J., Chehbouni, A., Er-Raki, S., and Hanich, L.: Combining a Large Aperture
657 Scintillometer and estimates of available energy to derive evapotranspiration
658 over several agricultural fields in semi-arid regions. *Plant Biosystems*. 143, 209-
659 221, 2009.

660 Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of Field Water use and
661 Crop Yield. Center for Agricultural Publishing and Documentation (PUDOC),
662 Wageningen, The Netherlands, p. 189.

663 Gee, G. W., Newman, B. D., Green, S. R., Meissner, R., Rupp, H., Zhang, Z. F., Keller,
664 J. M., Waugh, W. J., van der Velde, M., & Salazar J. (2009). Passive wick

665 fluxmeters: Design considerations and field applications. *Water Resources*
666 *Research*, 45, 1–18.

667 Ghanbarian-Alavijeh, B., Liaghat, A., Guan-Hua, H., Th. Van Genuchten, M. 2010.
668 Estimation of the van Genuchten Soil Water Retention Properties from Soil
669 Textural Data. *Pedosphere*, 20(4): 456–465.

670 Grecco, K. L., de Mirandaa, J.H., Silveiraa, L.K., van Genuchten, M.Th. 2019.
671 HYDRUS-2D simulations of water and potassium movement in drip irrigated
672 tropical soil container cultivated with sugarcane. *Agricultural Water*
673 *Management* 221 (2019) 334–347.

674 Han, M., C. Zhao, J. Šimůnek, and G. Feng. 2015. Evaluating the impact of
675 groundwater on cotton growth and root zone water balance using Hydrus-1D
676 coupled with a crop growth model, *Agricultural Water Management*, 160, 64-
677 1385 75, doi:10.1016/j.agwat.2015.06.028.

678 Hatiye, S.D., Hari Prasad, K. S., Ojha, C.S.P. 2018. Deep Percolation under Irrigated
679 Water-Intensive Crops. *Journal of Irrigation and Drainage Engineering* 144(8);
680 DOI: 10.1061/(ASCE)IR.1943-4774.0001326.

681 Hssaine, B.A., Merlin, O., Rafi, Z., Ezzahar, J., Jarlan, L., Khabba, S., Er-Raki, S.
682 Calibrating an evapotranspiration model using radiometric surface temperature,
683 vegetation cover fraction an, near-surface soil moisture data. *Agric. For.*
684 *Meteorol.* 2018, 256–257, 104–115.

685 Iounousse, J., Er-Raki, S., Elmotassadeq, A., Chehouani, H. 2015. Using an
686 unsupervised approach of Probabilistic Neural Network (PNN) for land use
687 classification from multitemporal Satellite images. *Applied Soft Computing* 30:
688 1–13.

689 IPCC: Intergovernmental Panel on Climate Change (IPCC), <http://www.ipcc.ch/>,
690 2009.

691 Jyotiprava Dash, Ch., Sarangi, A., Singh, D. K., Singh, A. K., Adhikary, Partha
692 Pratim. 2015. Prediction of root zone water and nitrogen balance in an irrigated
693 rice field using a simulation model. *Paddy and water environment* 2015, 13, 281-
694 290.

695 Kang, S., Gu, B., Du, T., Zhang, J., 2003. Crop coefficient and ratio of transpiration to
696 evapotranspiration of winter wheat and maize in a semi-humid region. *Agric.*
697 *Water Manage.* 59 (3), 239–254.

698 Kim, Y., Jabro, J. D., & Evans R. G. (2011). Wireless lysimeters for real-time online soil
699 water monitoring. *Irrigation Science*, 29 (5), 423–430.

700 Khabba, S., Jarlan L., Er-Raki S., Le Page M, Ezzahar J., Boulet, G., Simonneaux, V.,
701 Kharrou, M.H., Hanich, L. Chehbouni, G. 2013. The SudMed program and the
702 Joint International Laboratory TREMA: A decade of water transfer study in the
703 Soil-Plant- Atmosphere system over irrigated crops in semi-arid area. *Procedia*
704 *Environmental Sciences.* 19: 524-533.

705 Kharrou, M.H., Le Page, M., Chehbouni, A., Simonneaux, V., Er-Raki, S., Jarlan, L.,
706 Ouzine, L., Khabba, S., Chehbouni, G. 2013. Assessment of Equity and Adequacy
707 of Water Delivery in Irrigation Systems Using Remote Sensing-Based Indicators
708 in Semi-Arid Region, Morocco. *Water Resources Management.* 27(13): 4697-
709 4714.

710 Kool, D., Agam, N., Lazarovitch, N., Heitman, J.L., Sauer, T.J., Ben-Gal, A., 2014. A
711 review of approaches for evapotranspiration partitioning. *Agric. For. Meteorol.*
712 184, 56–70.

713 Latorre, B., Moret-Fernández, D. 2019. Simultaneous estimation of the soil hydraulic
714 conductivity and the vanGenuchten water retention parameters from an upward
715 infiltration experiment. *Journal of Hydrology*, 572, 461-469.

716 Li, Y., Šimůnek, J., Jing, L.F., Zhang, Z.T., Ni, L.X., 2014. Evaluation of water
717 movement and water losses in a direct-seeded-rice field experiment using
718 Hydrus-1D. *Agric. Water Manag.* 142, 38–46

719 Liu, C., Zhang, X., Zhang, Y., 2002. Determination of daily evaporation and
720 evapotranspiration of winter wheat and maize by large-scale weighing lysimeter
721 and microlysimeter. *Agric. For. Meteorol.* 111 (2), 109–120.

722 MADRPM, 2010. L’agriculture Marocaine en chiffres. Ministère Marocain de
723 l’Agriculture, du Développement Rural et des Pêches Maritimes, plan Maroc
724 vert, Rapport interne, pp. 15.

725 Marquardt, D. W. 1963. An algorithm for least-squares estimation of nonlinear
726 parameters. *SIAM J. Appl. Math.* 11(2): 431-441.

727 McCown, R.; Hammer, G.; Hargreaves, J.; Holzworth, D.; and Freebairn, D. 1996.
728 APSIM: A novel software system for model development, model testing and
729 simulation in agricultural systems research. *Agric. Syst.* 1996, (50), pp. 255-271.

730 Monteith, J.L. and M.Unsworth, (1990). *Principles of Environmental Physics*, 2nd
731 Edition Edward, Arnold, London.

732 Noilhan, J., Mahfouf, J.F. 1996. The ISBA land surface parameterisation scheme.
733 *Global and Planetary Change*, 13:145-159.

734 Nassah, H., Er-Raki, S., Khabba, S., Fakir, Y., Raibi, F., Merlin, O., Mougnot, B. 2018.
735 Evaluation and analysis of deep percolation losses of drip irrigated citrus crops
736 under non-saline and saline conditions in a semi-arid area. *Biosystems*
737 *Engineering*.165, 10-24.

738 Phogat, V., Skewes, M.A., Cox, J.W., Sanderson, G., Alam, J., Šimůnek, J. 2014.
739 Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated
740 mandarin (*Citrus reticulata*) and assessing management options for drainage
741 and nitrate leaching. *J. Hydrol.*, 513 (2014), pp. 504-516.

742 Qinbo, C., Chen, Xi., Xunhong, C., Zhicai, Z., & Minhua L. (2011). Water infiltration
743 underneath single-ring permeameters and hydraulic conductivity
744 determination. *Journal of Hydrology*, 398 (1-2), 135-143.

745 Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009a. AquaCrop-the FAO crop model
746 to simulate yield response to water. II. Main algorithms and software
747 description. *Agron. J.* 101, 438-447.

748 Rafi, Z.; Merlin, O.; Le Dantec, V.; Khabba, S.; Mordelet, P.; Er-Raki, S.; Amazirh, A.;
749 Olivera-Guerra, L.; Ait Hssaine, B.; Simonneaux, V.; et al. Partitioning
750 evapotranspiration of a drip-irrigated wheat crop: Inter-comparing eddy
751 covariance-, sap flow-, lysimeter- and FAO-based methods. *Agric. For. Meteorol.*
752 2019, 265, 310-326.

753 Sammis, T. W., Evans, D. D., & Warrick A. W. (1983). Comparison of methods to
754 estimate deep percolation rates. *Water Resources Bulletin*, 18 (3), 465-470.

755 Scott, R.L., Huxman, T.E., Cable, W.L., Emmerich, W.E., 2006. Partitioning of evapo-
756 Transpiration and its relation to carbon dioxide exchange in a Chihuahuan
757 Desert shrubland. *Hydrol. Process.* 20, 3227–3243.

758 Silva Ursulino, B.; Maria Gico Lima Montenegro, S.; Paiva Coutinho, A.; Hugo
759 Rabelo Coelho, V.; Cezar dos Santos Araújo, D.; Cláudia Villar Gusmão, A.;
760 Martins dos Santos Neto, S.; Lassabatere, L.; Angulo-Jaramillo, R. 2019.
761 Modelling Soil Water Dynamics from Soil Hydraulic Parameters Estimated by
762 an Alternative Method in a Tropical Experimental Basin. *Water* 2019, 11, 1007.

763 Šimůnek, J., van Genuchten, M.Th., Šejna, M. 2016. Recent developments and
764 applications of the HYDRUS computer software packages *Vadose Zone J.*, 15 (7),
765 p. 25, 10.2136/vzj2016.04.0033.

766 Šimůnek, J., M.Th. van Genuchten, and M. Šejna. 2008. The HYDRUS-1D software
767 package for simulating the one-dimensional movement of water, heat, and
768 multiple solutes in variably-saturated media. Version 4.0. HYDRUS Software
769 Ser. 3. Dep. of Environmental Sciences, Univ. of California, Riverside.

770 Šimůnek, J., and J. W. Hopmans. 2002. Chapter 1.7: Parameter optimization and
771 nonlinear fitting. In *Methods of Soil Analysis: Part 1. Physical Methods*, 139-157.
772 J. H. Dane and G. C. Topp, eds. 3rd ed. Madison, Wisc.: SSSA.

773 Stonestrom, D. A., Prudic, D. E., Laczniak, R. J., Akstin, K. C., Boyd, R. A., &
774 Henkelman K.K. (2003). Estimates of deep percolation beneath irrigated fields,
775 native vegetation, and the Amargosa River channel, Amargosa Desert, Nye
776 County, Nevada: U.S. Geological Survey Open-File Report 03–104, 83 p.

777 Sutanto, S.J., Wenninger, J., Coenders-Gerrits, A.M.J., Uhlenbrook, S., 2012.
778 Partitioning of evaporation into transpiration, soil evaporation and interception:
779 a comparison between isotope measurements and a HYDRUS-1D model.
780 *Hydrol. Earth Syst. Sci.* 16, 2605–2616.

781 Tafteh, A, Sepaskhah, A.R. 2012. Application of HYDRUS-1D model for simulating
782 water and nitrate leaching from continuous and alternate furrow irrigated
783 rapeseed and maize fields. *Agricultural Water Management* 113, 19-29.

784 Tan, X., Shao, D., Liu, H., 2014. Simulating soil water regime in lowland paddy fields
785 under different water managements using HYDRUS-1D. *Agric. Water Manag.*
786 132, 69–78.

787 Toumi, J., Er-Raki, S., Ezzahar, J., Khabba, S., Jarlan, L., Chehbouni, A. Performance
788 assessment of AquaCrop model for estimating evapotranspiration, soil water
789 content and grain yield of winter wheat in Tensift Al Haouz (Morocco):
790 Application to irrigation management. *Agricultural Water Management.*
791 163(1):219-235.

792 Twine TE, Kustas WP, Norman JM, Cook DR, Houser PR, Meyers TP, Prueger JH,
793 Starks PJ, Wesly ML. 2000. Correcting Eddy-Covariance Flux Underestimates
794 over a Grassland. *Agricultural and Forest Meteorology* 103: 279-300.

795 Upreti, H., Ojha, C. S. P., & Hari P. K. S. (2015). Estimation of Deep Percolation in
796 Sandy-Loam Soil using Water balance Approach. *Irrigation Drainage Systems*
797 *Engineering*. S1:002. doi:10.4172/2168-9768.S1-002.

798 Van Dijk, A., Moene, A.F. and De Bruin, H.A.R., 2004. The principles of surface flux
799 physics: theory, practice and description of the ECPACK library. Internal Report
800 2004/1, Meteorology and Air Quality Group, Wageningen University,
801 Wageningen, The Netherlands, 99 pp. Van Genuchten, M. Th., A closed-form
802 equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci.*
803 *Soc. Am. J.*, 44, 892-898, 1980.

804 Vázquez, N., Pardo, A., Suso, M. L., & Quemada M. (2006). Drainage and nitrate
805 leaching under processing tomato growth with drip irrigation and plastic
806 mulching. *Agriculture Ecosystems and Environment*, 112 (4), 313–323.

807 Wang, P., Song, X. F., Han, D. M., Zhang, Y. H., & Zhang B. (2012). Determination of
808 evaporation, transpiration and deep percolation of summer corn and winter
809 wheat after irrigation. *Agricultural Water Management*, 105, 32–37.

810 Wang, L., Caylor, K.K., Villegas, J.C., Barron-Gafford, G.A., Breshears, D.D.,
811 Huxman, T.E., 2010. Partitioning evapotranspiration across gradients of woody
812 plant cover: assessment of a stable isotope technique. *Geophys. Res. Lett.* 37,
813 L09401.

814 Wallor, E., Rosskopf, N., Zeitz, J. 2018. Hydraulic properties of drained and
815 cultivated fen soils part I - Horizon-based evaluation of van Genuchten
816 parameters considering the state of moorsh-forming process. *Geoderma*, 313, 69-
817 81.

818 Wenninger, J., Beza, D.T., Uhlenbrook, S., 2010. Experimental investigations of water
819 fluxes within the soil-vegetation-atmosphere system: stable isotope mass
820 balance approach to partition evaporation and transpiration. *Phys. Chem. Earth*
821 *Parts A/B/C* 35, 565-570.

822 Willis, T.M.; Scott Black, A. & Meyer, S.W. 1997. Estimates of deep percolation
823 beneath cotton in the Macquarie Valley. *Irrig. Sci.*, 17:141-150, 1997.

824 Xue Q., Zhu Z., Musick, J.T., Stewart, B. A., Dusek, D. A. 2003. Root growth and
825 water uptake in winter wheat under deficit irrigation. *Plant and Soil* 257: 151-
826 161.

827 Xu, B., Shao, D., Tan, X., Yang, X., Gu, W., Li, H. 2017. Evaluation of soil water
828 percolation under different irrigation practices, antecedent moisture and
829 groundwater depths in paddy fields. *Agricultural Water Management*, 192
830 (2017) 149-158.

831 Zhang, Y., Liu, C., Shen, Y., Kondoh, A., Tang, C., Tanaka, T., Shimada, J., 2002.
832 Measurement of evapotranspiration in a winter wheat field. *Hydrol. Processes*
833 16 (14), 2805-2817.

834 Zhang, Y., Shen, Y., Sun, H., Gates, J.B., 2011. Evapotranspiration and its partitioning
835 in an irrigated winter wheat field: A combined isotopic and micrometeorologic
836 approach. *J. Hydrol.* 408 (3), 203-211.

837 Zheng, C., Lu, Y., Guo, X., Li, H., Liu, X. 2017. Application of HYDRUS-1D model for
838 research on irrigation infiltration characteristics in arid oasis of northwest
839 China. *Environ Earth Sci* 76, 785 (2017). [https://doi.org/10.1007/s12665-017-](https://doi.org/10.1007/s12665-017-7151-2)
840 7151-2.