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1 **Coupling of a subsurface drainage model with a soil** 2 **reservoir model to simulate drainage discharge and** 3 **drain flow start**

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12 **Abstract**

13 The environmental impact of subsurface drainage and agricultural activities has been widely studied
14 in the literature. Agricultural subsurface drainage modifies the hydrological behavior and accelerates
15 the transfer of pollutants of agricultural origin into surface water during the drain flow period, which
16 is often limited to winter. The main objective of this study is to present a modeling approach allowing
17 an accurate modeling of subsurface drainage discharge and prediction of drain flow start times, by
18 integrating a new conceptual soil reservoir, managing the water flow in the unsaturated zone, to the
19 SIDRA model. A comparison of the model results with field measurements of drainage discharge at the
20 “La Jaillière” site (France) shows that such a model can efficiently simulate drainage discharge (KGE
21 values > 0.75) and predict, with good accuracy, the drain flow start time (with a median value of 5 days

22 and a standard deviation of 10 days). The split simple test conducted for the model calibration and
23 validation shows that the model is temporally robust. A sensitivity analysis conducted using the Sobol
24 method on the five model parameters reveals that the drainage discharge simulation is mainly
25 sensitive to the hydraulic conductivity and drainable porosity parameters. On the other hand, the date
26 delimiting drain flow start is sensitive to the soil reservoir parameters. The model's ability to accurately
27 predict the start of drain flow serves to avoid the application of farm inputs (pesticides or fertilizers)
28 during this critical period in order to limit their transfer to surface waters.

29 Keywords

30 Subsurface drainage, modeling, drain flow start, tile-drained field.

31 1 Introduction

32 Land improvements contribute to agricultural intensification, which in turn leads to greater crop
33 production from the same parcel. Among such improvements, subsurface drainage (SD) is practiced to
34 remove the temporary excess water from the root zone for purposes of: better aeration, higher
35 temperatures and enhanced workability of the soil in humid regions. In arid and semi-arid regions, the
36 primary function of SD is to prevent irrigation-induced waterlogging and soil salinization (Ritzema,
37 1994). In Europe, SD is mainly devoted to preventing waterlogging in specific hydromorphic soils; this
38 practice is principally employed in Northern Europe, on over 50% of arable land (from the Netherlands
39 to Finland), vs. approximately 10-20% for other European countries. In France, out of the 27 million
40 hectares of arable land, more than 10% are subsurface drained (AGRESTE, 2010; Vincent, 2020).
41 Subsurface drainage was established in France later than in other European countries, i.e. during the
42 1980's; it was promoted by European and national-level subsidies until 1992, when current water laws
43 began limiting the extent of additional SD practices.

44 Agricultural SD introduces significant modifications to the hydrological behavior and results in nutrient
45 and fertilizer losses from farmland to surface water (Blann et al., 2009; Gramlich et al., 2018). During

46 the drainage period, the application of mobile pesticides or fertilizers before a heavy rainfall increases
47 their losses toward the SD outlet and the water surface (Boithias et al., 2014; Nolan et al., 2008). The
48 temporary functioning of SD systems, mainly during the wet season, allows adapting the timing of
49 when to apply farm inputs to reduce losses, e.g. increasing the interval between an application and
50 the first drain flow of the drainage season (Brown and van Beinum, 2009; Trajanov et al., 2015; Wilson
51 et al., 2020). An accurate prediction of this first drain flow is key to optimizing the timing of farm input
52 application, thereby decreasing the risk of their transfer toward the water surface (L Jones et al., 2000;
53 Lewan et al., 2009; Nolan et al., 2008; Trajanov et al., 2015; Willkommen et al., 2019).

54 The behavior of SD systems can be simulated by means of a physical or hydraulic approach. The
55 physical approach is based on the numerical resolution of a physical law, such as the 3D Richards
56 equation. Several physically-based models propose specific conditions for considering the presence of
57 SD, e.g. in HYDRUS, SOIL, CATHY, DDM and 2D-DPERM (Al Jabri and Youngs, 2015; Boivin et al., 2006;
58 Dusek and Vogel, 2014; Gärdenäs et al., 2006; Gatel et al., 2019; Gerke et al., 2013; Mehdinejadani
59 and Fathi, 2020; Shokri and Bardsley, 2016). The hydraulic-based approach merely considers the flow
60 in a saturated zone and proposes a simplified equation, derived from both the Boussinesq equation
61 (1904) and Forchheimer's hypothesis (Guyon, 1963; Henine et al., 2014; Van Schilfgaarde, 1963), to
62 calculate drainage discharge as a function of water table height at mid-drain. The Hooghoudt drainage
63 equation (Hooghoudt, 1940), which relates steady-state drainage discharge to the water table height
64 at mid-drain, is the most widely used approach in SD modeling. When the water table rises to the soil
65 surface for relatively long periods, drainage discharge is computed using the Kirkham equation
66 (Kirkham, 1949) for ponded water. The approach proposed by Moriasi et al. (2013) couples Kirkham's
67 simplified equations with the Hooghoudt equation (Hooghoudt, 1940; Kirkham, 1949) to examine long
68 time series of subsurface drained experimental facilities; this approach offers the advantage of
69 simulating both small and peak flow discharges. The Kirkham and Hooghoudt equations were
70 integrated into the DRAINMOD model (Skaggs, 1980). The models MACRO (Jarvis and Larsbo, 2012),
71 SWAP (Kroes et al., 2008) and many others adopt different equations (such as Hooghoudt, Kirkham's

72 and Ernst equations) or use seepage potential theory by considering the drain as a sink term to take
73 into account subsurface drainage (Qi and Qi, 2016; Youngs, 1980). Guyon (1963) and Lesaffre and
74 Zimmer (1987) developed the SIDRA (*Simulation of DRAINage*) model to simulate drainage discharge
75 during the drainage season, based on the numerical integration of Boussinesq's equation between the
76 drain and mid-drain. In relying on this same Boussinesq equation, Stillman et al. (2006) proposed
77 another semi-analytical equation to simulate drainage discharge. These various simplified approaches
78 have been incorporated into several distributed hydrological and GIS-based models for the purpose of
79 integrating the SD function, e.g. SWAT (Moriassi et al., 2012), HYPE (Lindstrom et al., 2010) and ADAPT
80 (Gowda et al., 2012).

81 The models derived from the Boussinesq equation are well adapted to simulate the hydrological
82 behavior of SD, including peak flow prediction (Lesaffre and Zimmer, 1988). However, they become
83 less suitable once the goal turns to predicting the environmental impact of agricultural SD. It is
84 necessary to take into account the hydrodynamic behavior of the unsaturated zone as well as the plant
85 growth impact on water table recharge and, hence, on drainage discharge. In this context, a coupling
86 of the behavior in both saturated and unsaturated zones within a simple hydraulic approach for SD
87 behavior modeling would offer a better understanding of the underlying environmental impacts. A
88 coupled agronomic-hydrological model, namely STICS-SIDRA (Tournebize et al., 2004), was developed
89 to manage the saturated and unsaturated zones; however, this crop model requires numerous
90 parameters only available in certain fields of experimental research.

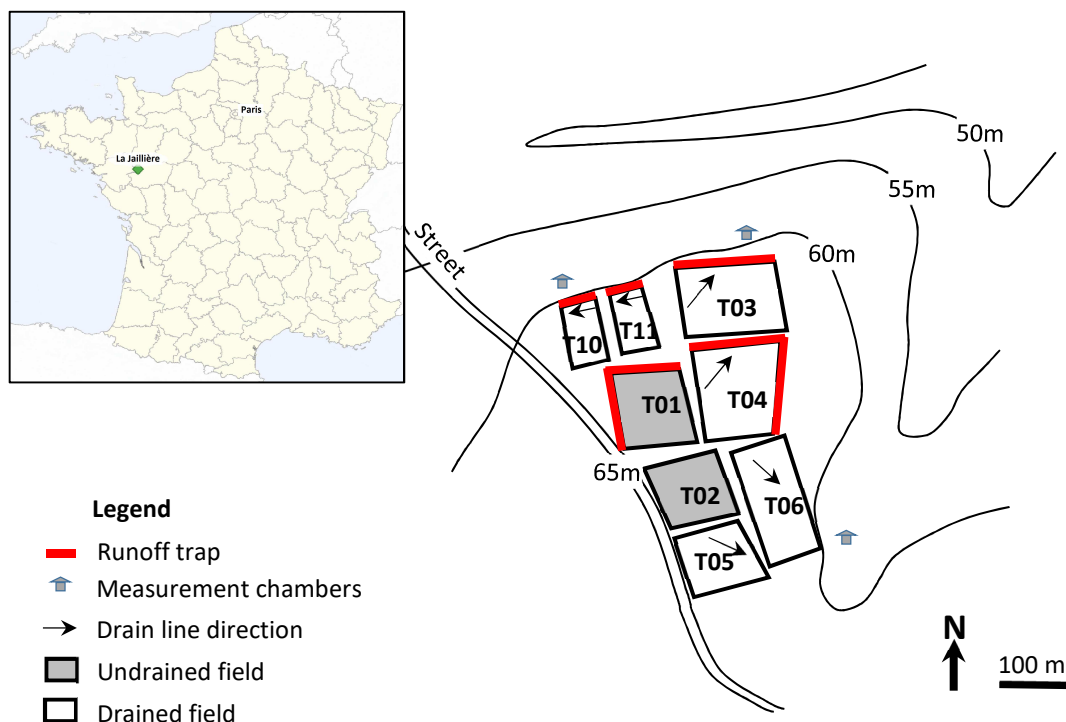
91 This paper integrates a new conceptual soil reservoir module into the hydraulic-based SIDRA model in
92 order to predict both drainage discharge and drain flow starts. The conceptual module simulates water
93 transfer in the unsaturated zone and calculates the recharge of the perched water table, which then
94 serves as SIDRA input data. To simplify the model as much as possible, this conceptualization needs to
95 be easily implemented and should improve both the prediction of drainage discharge and drain flow
96 start every hydrological year.

97 The proposed model has been calibrated and validated using the dataset collected from two
 98 experimental drained plots located at the "La Jaillière" site (western France). The model's performance
 99 evaluation criterion is based on a comparison between simulated and observed drainage discharge, as
 100 well as on the drainage season start date. A global sensitivity analysis has also been conducted to study
 101 the influence of input parameters on model performance.

102 2 Experimental set-up

103 2.1 Experimental study sites

104 The "La Jaillière" experimental site (Figure 1) is located in western France's Loire-Atlantique
 105 Department (47°27' N, 0°57' W); it has been managed by the Arvalis Institute (French agricultural
 106 institute) since 1987. The experiments and research work carried out here focus on several study
 107 objectives, in particular to achieve satisfactory control over both water quality and quantity of the SD
 108 system. Several experiments have been ongoing since its inception, thus providing a most valuable
 109 dataset covering nearly 30 years.



110

111 Figure 1: The "La Jaillière" experimental study site and its general location (Arvalis, Maine-et-Loire, France)

112 The climate in the study area is oceanic with a mean annual rainfall of 709 mm; the mean annual
 113 temperature is approximately 11°C. The mean potential evapotranspiration (PET) reaches 738 mm a
 114 year. The period of water budget deficit begins in April and continues until the end of September.
 115 Subsequent to this period, the excess net rainfall allows for a progressive saturation of the soil and the
 116 formation of a temporary perched water table, at which point the drain flow starts.

117 The soil at the La Jaillière site is a brown, hydromorphic stagnic luvisol (FAO 2006) developed on a low
 118 permeability, altered schist formation (Dairon et al., 2017). The soil surface layer (< 30 cm deep)
 119 consists of a sandy loam (16-22% clay), while the underlying layer, of variable thickness (from 30 to 90
 120 cm), is richer in clay (> 30%, clayey-silty texture). The depth of the altered schist formation is highly
 121 variable within the studied plots, ranging from 0.6 to 1.2 m, and represents a natural obstacle to water
 122 infiltration. This impervious layer is responsible for temporary waterlogging through the formation of
 123 a perched water table. For each experimental plot (Table 1), the water holding capacity (see Section
 124 3.1) was estimated from the textural soil analysis at a 0.8-m soil profile, by use of Rawls' linear
 125 regression equation (Rawls and Brakensiek, 1982).

126 Table 1: Characteristics of the experimental plot at the La Jaillière site: drainage design (depth and
 127 drain spacing), surface area, and Water Holding Capacity (WHC) calculated at a 0.8-m soil profile

Plot	Drain depth (m)	Drain spacing (m)	Surface area (ha)	WHC (mm)	Type of collected water
T01	-	-	0.83	97	Surface runoff
T02	-	-	0.90	96	-
T03	0.8-1.0	10	1.04	84	Surface runoff / Drainage
T04	0.8-1.0	10	1.08	104	Surface runoff / Drainage

T06	0.8-1.0	10	1.01	103	Drainage
T10	0.8-1.0	10	0.42	95	Surface runoff / Drainage
T11	0.8-1.0	10	0.42	99	Surface runoff / Drainage

128

129 To prevent soil waterlogging and improve crop growth during winter, an SD network was installed in
130 the 1980's (Table 1). Each experimental drained plot has been equipped with an individual drainage
131 network (10 m drain spacing, installed at a depth of 0.8 - 1 m), connected to a non-perforated collector
132 extending to the measurement chamber. For each field, the drainage discharge and surface runoff are
133 collected and measured separately. The surface runoff is collected using traps around each plot (Figure
134 1). The flow discharge is then measured hourly at each collector outlet using a V-notch weir. The water
135 level upstream of the weir, measured with an automatic pressure probe, is proportional to the flow
136 discharge.

137 Meteorological data are available at two stations (Trajanov et al., 2018). The former station from 1982
138 is located 1.4 km from the fields, while the new one (in operation since 2006) is located at the
139 experimental site.

140 2.2 Observation data

141 For purposes of model assessment, the dataset collected for experimental plots T03 (1.04 ha) and T04
142 (1.08 ha) is used to validate SIDRA-RU model. These datasets comprise hourly subsurface drainage
143 discharge (from 1994 to 2010) and surface runoff (from 1994 to 2004).

144 Since the meteorological data recorded at the study site contain many gaps, we have used the rainfall
145 and Potential EvapoTranspiration (PET) data from the SAFRAN meteorological reanalysis produced by
146 the Météo-France Agency (Vidal et al., 2010), defined on 8 km × 8 km grids at the national scale. While

147 these PET data can be considered as homogeneous on the 8 km × 8 km SAFRAN grid, the rainfall data
 148 should display more local variation, which can exert a rather significant impact on modeling accuracy
 149 of the two studied plots.

150 One of the mitigation solutions of pesticides losses from subsurface drained fields is to increase the
 151 time interval (of several days) between their application and first drain flow (Brown and van Beinum,
 152 2009; Trajanov et al., 2015). Thus, the SIDRA-RU model needs to be efficient and capable of accurately
 153 predict drainage discharge and drain flow start. This accuracy depends on the method or criterion used
 154 to set the drain flow start date. At the beginning of the drainage season, drain flow is often low and
 155 quick; also, several days may pass without any drain flow at all. This specificity is difficult to reproduce
 156 with acceptable accuracy by the models. To overcome the low flows that fail to indicate the actual
 157 start of the drainage season, we have introduced herein a new method using two static thresholds
 158 conditions: (1) the calculated cumulative drainage discharge must be greater than the initial threshold;
 159 and (2) the additional cumulative drainage discharge within the 5 subsequent days must be greater
 160 than the second threshold. Based on the experimental dataset, the first and second thresholds are set
 161 to 2 and 2.5 mm, respectively.

162 From the drainage discharge measurement, we defined the drain flow start dates for each season. The
 163 yearly cumulative values of meteorological data, drainage discharge and surface runoff plus the drain
 164 flow start dates used in this study are listed in Table 2.

165 Table 2: Yearly cumulative values of meteorological data (PET, rainfall), drainage discharge (Qdrain)
 166 and surface runoff, plus drain flow start dates on Plots T03 and T04. Values between parentheses (*)
 167 represent the cumulative rainfall and PET over drain flow periods (Qdrain > 0)

Drainage seasons	PET (*) (mm)	Rainfall (*) (mm)	T03 plot			T04 plot		
			Qdrain (mm)	Runoff (mm)	Drain flow start	Qdrain (mm)	Runoff (mm)	Drain flow start

1994-1995	723 (586)	947 (787)	484	64	24-Oct	500	-	23-Sept
1995-1996	763 (334)	586 (414)	134	13	22-Dec	109	10	27-Dec
1996-1997	727 (117)	606 (286)	189	16	28-Nov	165	15	29-Nov
1997-1998	675 (162)	709 (399)	221	15	11-Dec	193	22	10-Dec
1998-1999	706 (342)	779 (610)	280	34	19-Oct	290	37	24-Nov
1999-2000	634(288)	945 (764)	438	34	19-Sept	382	57	19-Sept
2000-2001	644 (292)	1128 (990)	519	76	11-Oct	512	113	16-Oct
2001-2002	631 (110)	614 (260)	156	39	18-Oct	144	14	29-Dec
2002-2003	649 (164)	887 (566)	398	46	4-Sept	328	28	2-Nov
2003-2004	681 (246)	629 (427)	247	-	14-Nov	237	29	16-Nov
2004-2005	704 (66)	506 (85)	24	-	5-Jan	10	-	20-Jan
2005-2006	739 (131)	594 (298)	122	-	4-Jan	121	-	4-Dec
2006-2007	677 (352)	1029 (778)	278	-	19-Oct	274	-	21-Oct
2007-2008	691 (279)	682 (464)	231	-	27-Nov	174	-	5-Jan
2008-2009	668 (247)	646 (353)	133	-	10-Nov	113	-	9-Dec
2009-2010	735 (231)	650 (423)	181	-	28-Nov	226	-	28-Nov
Mean	690 (247)	746 (494)	252	37	10-Nov	236	36	23-Nov
Standard deviation	40 (127)	184 (238)	141	22	-	140	32	-

168

169 Table 2 shows that the yearly drainage discharge correlates with the yearly rainfall. The PET shows a
170 small inter-annual variation (with a mean value of 690 and a standard deviation of 40 mm). In the wet
171 period (autumn and winters seasons), the PET demand is generally satisfied and the excess of rainfall
172 (P-PET) causes drainage discharge (Q_{drain}) and surface runoff. Assuming that deep infiltration under
173 the drainage network is negligible during the drain flow period, the average evapotranspiration (AET,
174 computed as Rainfall - Q_{drain} - Surface Runoff) accounts for 86% of PET. However, in the dry period,

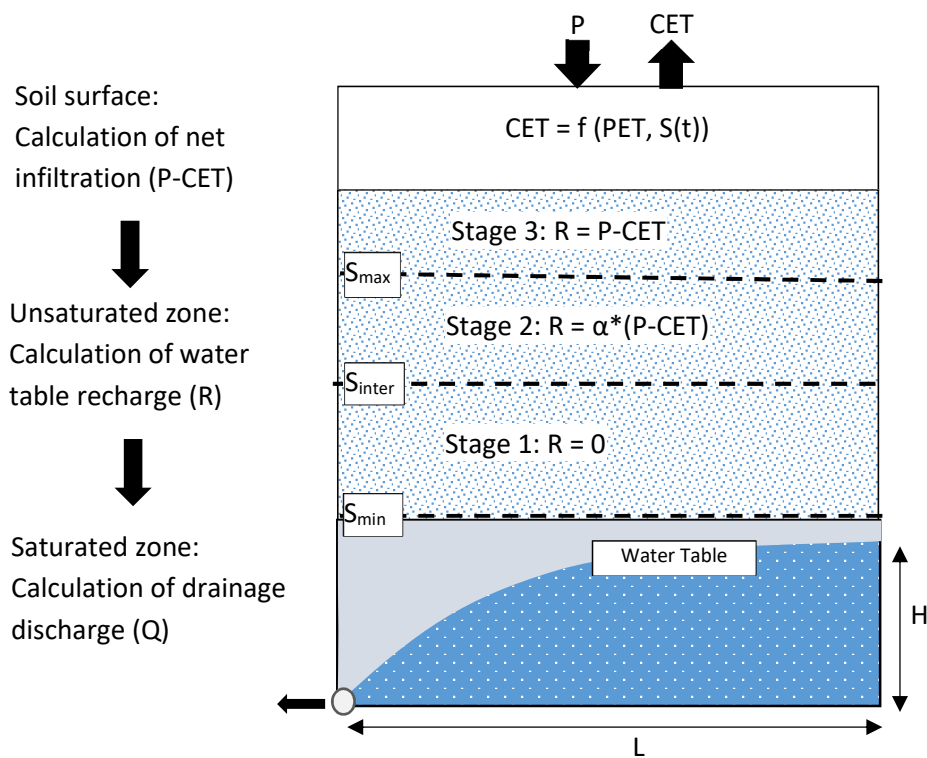
175 the PET demand is poorly satisfied and there occurs neither drain flow nor surface runoff. The yearly
176 average AET accounts for 67% of PET. The rainfall and drainage discharge dataset displays high
177 hydrological variability with respect to both dry (e.g. season 2004-05) and wet seasons (e.g. 2000-01).
178 Analysis of Table 2 suggests that the start of drainage season is highly variable from one season to
179 another. In average, the drainage season starts in mid-November, however, it can start early (in
180 September) or very late (in January). The drainage season 2004-2005 started later in January 5 and
181 presented a low cumulative drainage discharge (of 10 mm). Drain flow often starts earlier on plot T03
182 than on T04, despite their similarity during the intense drainage season. The low WHC value for plot
183 T03 (Table 1) allows filling the soil profile and generating a water table flow toward drains earlier on
184 the this plot, as compared to T04. From the data observed in Table 2, surface runoff accounts for 12%
185 and 10% of the total outflow of plots T04 and T03, respectively.

186 3 Model description

187 Drain flow occurs when the perched water table rises above the drains. The SIDRA model simulates
188 drainage discharge during the soil profile saturation period, defined as the Intensive Drainage Season
189 (IDS) by Lesaffre and Zimmer (1988). The new SIDRA-RU model presented herein allows SIDRA to
190 simulate SD discharges and hydrological behavior at the plot scale during a full hydrological year and
191 extending for several subsequent years. The proposed model has been based on three coupled
192 modules (Figure 2) managing the flow paths: in the soil surface, in the unsaturated zone, and in the
193 water table temporally perched above the drains. These three modules, integrated into the current
194 version of SIDRA-RU, are as follows:

- 195 1. Module 1: Estimation of net infiltration from climatic data, by integrating a more realistic
196 evapotranspiration algorithm that takes into account the potential evapotranspiration
197 rate (PET) and available soil water content in the soil reservoir $S(t)$. The new value
198 calculated during this step is referred to as “corrected evapotranspiration” (or CET). Net
199 infiltration is equal to rainfall (P) minus corrected evapotranspiration (CET);

- 200 2. Module 2: Management of water transfer in the unsaturated zone, in order to calculate
- 201 the net recharge into the drained water table, based on the conceptual reservoir
- 202 approach. This module calculates net recharge as a function of the available soil water
- 203 content in the soil reservoir $S(t)$, relative to three distinct soil reservoir levels, namely
- 204 minimum (S_{min}), intermediate (S_{inter}) and maximum (S_{max});
- 205 3. Module 3: Simulation of the SD discharge (Q) as a function of the mid-drain water table
- 206 height above drain (H) by applying the SIDRA model (Lesaffre and Zimmer, 1988).



207

208 Figure 2: Diagram presenting the three SIDRA-RU modules, with P : rainfall [LT^{-1}], CET : corrected

209 evapotranspiration [LT^{-1}]; $S(t)$: actual water level in the soil reservoir [L]; S_{min} : minimum soil reservoir

210 level (= 0 mm); S_{inter} : Intermediate soil reservoir level [L]; S_{max} : maximum soil reservoir level [L]; $R(t)$:

211 water table recharge [LT^{-1}]; L : distance between the drain and mid-drain [L]; H : mid-drain water table

212 height above drain [L]; and Q : drainage discharge per unit area [$L^3T^{-1}L^{-2}$]. The dashed horizontal lines

213 indicate the soil reservoir module levels. α : partition coefficient representing the part of net

214 infiltration which recharges the water table during the stage 2.

215 3.1 Calculation of the corrected evapotranspiration

216 To estimate net rainfall infiltration, this module calculates a more realistic evapotranspiration value,
217 referred to here as corrected evapotranspiration (CET). This CET depends on the potential
218 evapotranspiration (PET), the available soil water content in the soil profile and the type of vegetation
219 (Hansen, 1984; Kristensen and Jensen, 1975). Depending on the type of vegetation, CET is transformed
220 into the maximum evapotranspiration rate (MET) by means of the crop coefficient, β . When the soil
221 water content lies in the range of the extractable soil water (ESW), the CET/PET ratio is equal to β . This
222 value represents the share of the WHC that allows plants to extract water from the soil without either
223 water constraints or growth limitations (Hansen, 1984; Jacquart and Choisnel, 1995). Soil WHC
224 represents the amount of water held by soil against gravity force that can be extracted either by
225 evaporation or by root plant (Bordoloi et al., 2019). Under France's agro-climatic conditions, ESW
226 varies from 0.4 to 0.6 of WHC, as a function of root depth (Jacquart and Choisnel, 1995). In this study,
227 ESW has been set equal to 0.6 of WHC. This value defines the lower limit of soil water content in the
228 soil profile, at which CET equals the maximum evapotranspiration rate (MET). When the soil water
229 content in the soil profile lies below ESW, less water is available for root extraction; Eq. 1 proposes an
230 exponential decrease of CET with water level in the soil reservoir $S(t)$. To simplify the model
231 parameterization and to take into account the non-uniformity of the soil water content in the soil
232 profile, WHC has been approximated at the intermediate soil reservoir level S_{inter} of the conceptual soil
233 reservoir model (Section 3.2 below). The module computes CET [L] as follows:

$$\begin{array}{ll} \text{Case 1: If } (S(t) > 0.6 * S_{inter}) & \text{CET} = \text{MET} = \beta * \text{PET} \\ \text{Case 2: If } (S(t) < 0.6 * S_{inter}) & \text{CET} = \beta * \text{PET} * \exp\left(-\frac{0.6*S_{inter} - S(t)}{S(t)}\right) \\ \text{Case 3: If } (S(t) < 0) & \text{CET} = 0 \end{array} \quad (\text{Eq. 1})$$

235 where $S(t)$ [L] is the actual water level in the soil reservoir, β [-] is a correction coefficient that depends
236 on the type of soil cover. In this study, β has been set equal to 1.

237 3.2 Management of water flow in the soil reservoir

238 It has been assumed herein that throughout the hydrological season, the soil water content only varies
239 under the effects of rainfall, evapotranspiration and drainage discharge.

240 Modeling soil water movement in unsaturated zone to assess water table recharge should cover
241 several complex processes (Milly, 1988; Nielsen et al., 1986; Šimůnek and Bradford, 2008; van
242 Genuchten and Jury, 1987). In the literature, numerous models describing water flow in this zone are
243 available and they use either physical-based or conceptual approach. In this study, we present a
244 conceptual calculation of the water table recharge. Downward water movement through homogenous
245 soil profile is governed mainly by both gravity and matric pressure gradients (ψ) effects. When the soil
246 is dry, the ψ gradients effect is dominating, and when the soil is very wet, gravity effect becomes
247 dominant (Nimmo, 2005). Along the soil profile (extending from the soil surface to the impervious layer
248 under the drains), the soil water content is not uniform and variable with respect to time (Zimmer and
249 Lesaffre, 1989). Indeed, the soil profile can present at the same time dry condition near the soil surface
250 and wet condition at the drain level. Thus, instead of considering this spatial variation, the soil reservoir
251 model depicts the filling of the soil profile and calculates water table recharge as a function of three
252 global thresholds (see Figure 2), i.e.:

253 1) The minimum soil reservoir level (S_{\min}) represents the lower limit of the soil reservoir, below which
254 no water moves in the soil under the effects of either evaporation or root extraction, herein set equal
255 to zero; this reflects the driest soil profile condition.

256 2) The maximum soil reservoir level (S_{\max}) represents the upper limit, at which the total net infiltration
257 recharges the water table gravitationally. In this case, the soil water content lies close to the saturation
258 condition throughout the soil profile. The SD network reaction to a rainfall event is rapid, mainly
259 occurring during the high rainfall events that generate drainage discharge peaks. This subsurface
260 drainage period is referred to as Intense Drainage Season (IDS).

261 3) Between S_{min} and S_{max} , the reservoir model includes an intermediate threshold (S_{inter}). When the soil
262 reservoir lies between S_{inter} and S_{max} , the soil water content can exhibit a saturation condition close to
263 the drain, while remaining unsaturated at the upper part of the soil profile. In this case, one portion of
264 the infiltrated water contributes to the water table recharge and flows toward drains. The other
265 portion of the infiltrated water continues to fill the soil reservoir. The distribution of net infiltration
266 between water table recharge and soil reservoir filling was conducted by means of partition coefficient
267 α . Thus, the S_{inter} defining the start of the drainage season is used as first soil reservoir parameter. The
268 soil water level difference between S_{inter} and S_{max} is referred to as the intense drainage season reservoir
269 level (S_{IDS}). As S_{max} variations are dependent on that of S_{inter} (S_{max} must be greater than S_{inter}), S_{IDS} is used
270 as second soil reservoir parameter. The two parameters S_{inter} and S_{IDS} of the conceptual soil reservoir
271 are difficult to estimate from a field measurement; they are mainly determined through model
272 calibration.

273 The model responsible for managing the behavior of the unsaturated zone is referred to as the water
274 holding capacity (WHC) concept, or RU (acronym for *réserve utile* in French). Consequently, the
275 reservoir model will be referred to hereafter as the "RU" model. The conceptual reservoir ignores the
276 deep infiltration flow, given that such contributions are often negligible during the winter period in
277 hydromorphic soils, due to the presence of clayey layers underneath the drains, which in this study are
278 assumed to be impervious.

279 In the RU module, water variations in the soil reservoir (ΔS) and water table recharge $R(t)$ at time "t"
280 both depend on the water level in the soil reservoir $S(t)$ at time "t-1". The RU module considers the
281 time variable $S(t)$ and $R(t)$ as uniform between the drain and mid-drain. The calculation algorithm can
282 then be expressed as follows:

283 - If $S(t)$ lies between S_{min} and S_{inter} : net infiltration increases or decreases the water level in the
284 soil reservoir, depending on its sign (negative or positive), hence: $S(t) = S(t-1) + (P-CET)$. The

285 minimum soil reservoir level cannot decrease below zero. During this stage, the water table
286 recharge equals zero.

287 - If $S(t)$ lies between S_{inter} and S_{max} : when net infiltration is positive, the RU module splits this
288 infiltration into two components via partition parameter α , with the first part (α) recharging
289 the water table and the second part ($1-\alpha$) continuing to fill the soil reservoir:

$$S(t) = S(t - 1) + (1 - \alpha) * (P - CET) \quad (Eq. 2)$$
$$R(t) = \alpha * (P - CET)$$

291 - If $S(t)$ is equal to S_{max} : when net infiltration is positive, the entire excess infiltration will recharge
292 the water table. Otherwise, when net infiltration is negative, the net infiltration rate will be
293 extracted from the soil reservoir.

294 3.3 Management of water table flow

295 In this study, the original SIDRA model is used to simulate water table flow toward drain. The specificity
296 of SD in France is that the drains overlay a clayey layer, assumed herein as impervious. SD flow only
297 occurs when the perched water table rises above the drain, as identified during the intense drainage
298 season. The SIDRA model is only able to simulate drainage discharge during this season. The model
299 does not consider unsaturated flow, by assuming that the net infiltration, calculated as rainfall minus
300 evapotranspiration rate, instantly reaches the water table (Bouarfa and Zimmer, 2000; Lesaffre and
301 Zimmer, 1988; Zimmer et al., 1995).

302 Water flow toward the drain is influenced by several parameters related to both the SD network
303 geometry (i.e. drain depth and drain spacing) and soil hydrodynamic characteristics. The SIDRA model
304 semi-analytically solves the Boussinesq equation according to the following basic assumptions
305 (Bouarfa and Zimmer, 2000; Lesaffre and Zimmer, 1988):

306 - The perched water table is a free (unconfined) surface that overlays the impervious horizontal
307 clayey layer. Within the saturated zone, the subsurface flow is assumed to be horizontal, in
308 accordance with Dupuit-Forchheimer (Guyon, 1963; Van Schilfgaarde, 1963);

309 - The Boussinesq equation is based on the concept of drainable porosity (De Marsily, 1986; Zhang
 310 and Zhang, 1986), which serves to relate water table fluctuations to water table recharge. This
 311 parameter is also approximated with a “specific yield” or “specific storage” value (Anderson
 312 and Woessner, 1992; Rupp and Selker, 2005).

313 In homogeneous soils, based on these assumptions, a combination of the continuity equation and
 314 Darcy's Law leads to the classical 1D nonlinear Boussinesq equation (1904):

$$315 \quad \mu \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(K_{\text{sat}} h \frac{\partial h}{\partial x} \right) + R(t) \quad (\text{Eq. 3})$$

316 where K_{sat} [LT^{-1}] is the saturated hydraulic conductivity in the horizontal direction, h [L] the water table
 317 height above the drain, μ [-] the drainable porosity, $R(t)$ [LT^{-1}] the time-dependent water table
 318 recharge, t [T] the time, and x [L] the horizontal position coordinate.

319 The Boussinesq equation simulates drainage discharge and water table variations assuming that the
 320 water table shape remains constant or slightly variable during the steady state or tail recession stages
 321 (Guyon, 1963; Van Schilfgaarde, 1963). Modeling of the transient state of a water table depends on
 322 the time step adopted (from hourly to daily). For a daily time step, the Boussinesq assumption of a
 323 constant water table shape is acceptable, as demonstrated by Tournebize et al. (2004). This
 324 assumption allows for a pseudo-separation of variables in both time and space. The spatial integration
 325 of the water table shape between drain and mid-drain, using the factor concepts developed by Guyon
 326 (1963) and Youngs (1966), results in the following equation solely dependent on the time variable:

$$327 \quad \mu C \frac{dH(t)}{dt} = -K_{\text{sat}} \frac{H^2}{L^2} + R(t) \quad (\text{Eq. 4})$$

328 where C [-] is defined as the “second water table shape factor”, L [L] the half-drain spacing, and H [L]
 329 the water table elevation above the drain at mid-drain. The term $J(H) = K_{\text{sat}} \frac{H^2}{L^2}$ [LT^{-1}] represents an
 330 equivalent Hooghoudt equation (Hooghoudt, 1940; Van Der Ploeg et al., 1999) describing the steady-
 331 state drainage discharge, in assuming that the drain lies on the impervious horizontal layer. Further

332 details of different steps establishing the model equations can be found in the publication by Bouarfa
333 and Zimmer (2000).

334 From Darcy's Law, let's now add the influence of recharge, as established by Lesaffre and Zimmer
335 (1987), which yields the following equation to calculate drainage discharge:

$$336 \qquad \qquad \qquad Q(t) = AJ(H) + (1 - A)R(t) \qquad \qquad \qquad \text{(Eq. 5)}$$

337 where A [-] is called the “third water table shape factor”.

338 The water table shape factors C and A are equal to 0.904 and 0.896, respectively, as calculated by
339 integrating $\frac{1}{4}$ of the ellipse curve, corresponding to the water table shape between drain and mid-drain
340 (Bouarfa and Zimmer, 2000). Eq. 5 reveals that during the recharge stage, drainage discharge Q(t) is
341 generated by: (i) the water table recession based on the Hooghoudt equation (the A.J(H) term), and
342 (ii) the direct contribution of net recharge (the (1-A).R(t) term). In Eq. 5, the water table shape factor
343 A enables the water table recession to contribute to drainage discharge by a factor of 86.9%, to be
344 subsequently completed with the direct recharge at 13.1% (1-A) of R(t).

345 In this study, surface runoff is calculated using a simplified approach. Several empirical models are
346 available to calculate surface runoff, such as the model by Horton, and Green and-Ampt (Musy and
347 Higy, 2004). However, most of these models are based on parameters that lack physical meaning and
348 can only be defined by model calibration. The simplest empirical approach consists of assuming that
349 surface runoff occurs when the soil reservoir reaches its maximum storage capacity (Dooge, 1959), i.e.
350 when the soil profile is totally saturated and the water table lies near the soil surface. We thus assume
351 that the generation of surface runoff is independent of the soil infiltration capacity in drained soils.
352 Observations in drained fields do indeed show that the surface runoff rate is reduced, compared to an
353 undrained field, and moreover account for roughly 10% of total outflow, thus confirming the high
354 infiltration capacity of drained soils (Augeard et al., 2005; Kao et al., 1998; Trajanov et al., 2018). In the

355 SIDRA-RU model, when the water table elevation (H) equals drain depth (d), the excess rainfall is
356 converted into surface runoff.

357 4 Model evaluation

358 The aim of this study is to validate the ability new SIDRA-RU model to address the tasks of drainage
359 discharge and drain flow start at the field scale based on the existing experimental observations. We
360 begin by assessing the model performance in order to simulate drainage discharge using the classical
361 calibration and validation criterion KGE (Gupta et al., 2009). Next, we evaluate the model by predicting
362 the drain flow start. A criterion determining the drain flow start dates from both observed and
363 simulated drainage discharge is presented. We finish by conducting an analysis to assess the sensitivity
364 of model parameters with respect to KGE and the drain flow start criteria.

365 4.1 Model calibration and validation

366 Running SIDRA-RU requires introducing input data (rainfall and evapotranspiration) as well as field
367 characteristics. The SD geometry data consist of the 0.8-m drain depth (d) and the 5-m half-drain
368 spacing (L). The correction coefficient for the CET calculation, which depends on the type of soil cover
369 (β), equals 1.

370 The water partition parameter (α) is not considered for model calibration, because its influence on
371 model calibration using observed drainage discharge is negligible (See sensitivity analysis results,
372 section 5.1). During the period when drainage season starts (delimited by S_{inter} and S_{max}), the ratio of
373 drainage discharge to rainfall is typically low. Field observations have indeed shown that during this
374 period, the ratio equals approximately 1/3 (Favrot and Lesaffre, 1984; Lesaffre, 1988; Lesaffre and
375 Morel, 1986). The partition coefficient α is thus set theoretically at 1/3.

376 The calibration model parameters are: the two soil reservoir parameters (S_{inter} and S_{DS}), and the two
377 soil hydrodynamic parameters (K_{sat} and μ). This modeling approach assumes uniform hydraulic

378 properties within the soil profile, thus leading to calibrate an average value of the parameters set for
379 each plot.

380 A performance assessment of the model must acknowledge the fact that drainage discharge is highly
381 variable during the drainage season. To account for this seasonal variability, the Kling-Gupta efficiency
382 (KGE, Gupta et al., 2009) criterion (Eq. 6) is used for model calibration and validation. This KGE criterion
383 has the advantage of incorporating drainage discharge variability throughout the simulation period by
384 combining the correlation, bias and variability between simulated and observed drainage discharges:

$$385 \quad KGE = 1 - \sqrt{(r - 1)^2 + (\varepsilon - 1)^2 + (\Delta - 1)^2} \quad (\text{Eq. 6})$$

386 where Δ denotes the ratio between the mean simulated and mean observed drainage discharges (i.e.
387 the bias), r the linear correlation between observations and simulations, and ε the measure of relative
388 variability. KGE values range from $-\infty$ to 1. The model performance is improved when the value of KGE
389 lies close 1 (Gupta et al., 2009).

390 The limited number of calibration parameters in SIDRA-RU serves to limit the equifinality problem and
391 the possibility of obtaining secondary optima (Coron et al., 2017). The optimization algorithm is based
392 on the drainage discharge results, using the KGE criterion as Objective Function (OF) combined with
393 “airGR” R package (Coron et al., 2017; Michel, 1987). First, a grid-screening algorithm explores the
394 parameters space by systematic examination and extracts the most likely convergence zone
395 (Mathevet, 2005). Second, a steepest - descent local search procedure (Michel, 1991) seeks to improve
396 the OF by refining the previously obtained parameter set. Note that each parameter is independently
397 calibrated without considering their possible correlations. The sampling procedure is based on the
398 probability distribution function (pdf) and the limits of the four calibration parameters (Table 3):

399 - K_{sat} and μ follow a log-normal distribution (Kosugi, 1999; Ren and Santamarina, 2018; Rousseva
400 et al., 2017; Schaap and van Genuchten, 2006; Suleiman and T. Ritchie, 2001). The pdf and the
401 limits of hydraulic conductivity K_{sat} and drainable porosity μ values in Table 3 were established

402 from 35 hydrodynamic measurements in different drained hydromorphic soils by means of
 403 Guyon's pumping test (Lesaffre, 1990). These experiments were carried out in the 1980's as
 404 part of the measurement campaign initiated by the French Ministry of Agriculture that allowed
 405 establishing 70 referenced soil areas (Lagacherie, 1987);

406 - The soil reservoir parameters (S_{inter} and S_{IDS}) follow a normal distribution similar to that used
 407 for maximum soil water content (Biswas, 2019; Brocca et al., 2007);

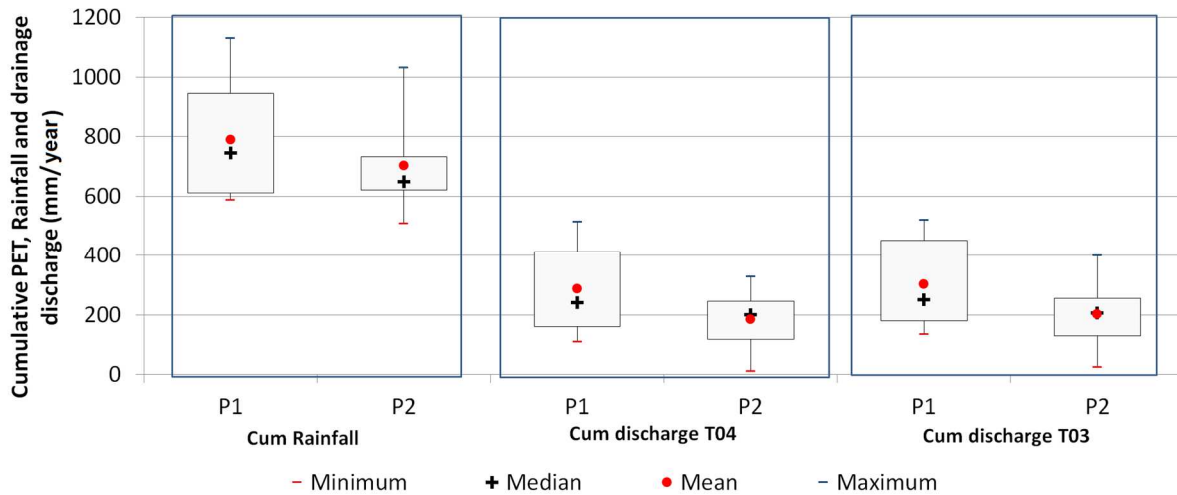
408 - Table 3: Characteristics of the pdf representing the variations in SIDRA-RU parameters

SIDRA-RU parameters	Pdf type	Limit interval		Mean	Standard deviation
		Min	Max		
S_{IDS} (mm)	Normal	10	55	33.3	17
S_{inter} (mm)	Normal	55	225	138.4	53.3
K (m/day)	Log-normal	0.03	4.63	0.9	3.17
μ (-)	Log-normal	0.015	0.13	0.031	1.926

409

410 The model evaluation is performed using the split-sample test (Klemeš, 1986), by dividing the 16
 411 seasons (Table 2) of daily drainage discharge measurements into two equivalent periods: Period P1,
 412 from 1994 to 2002, and Period P2, from 2002 to 2010. For each period, the model was run in turn for
 413 both calibration and validation of drainage discharge. Figure 3 shows the mean variations in yearly
 414 cumulative rainfall and drainage during these two periods on plots T03 and T04. Note that Period P1
 415 is wetter than P2, with a higher variation in the yearly cumulative rainfall and drainage discharge
 416 (Figure 3 displays the various box widths). It then becomes interesting to test the behavior of model
 417 calibration and validation during these two defined periods.

418



419

420

421

422

Figure 3: Comparison between periods P1 and P2 - the mean variations in yearly cumulative rainfall and drainage discharge data on plots T03 and T04.

The boxes are delimited by the 25% and 75% quartiles.

423 4.2 Assessment of drain flow start dates

424

425

426

To assess model accuracy in predicting the drain flow start, a criterion has been established in this study, based on the mean of the absolute difference between observed and simulated drain flow start dates (X_{diff}). This criterion is calculated as follows:

427

$$X_{diff} = \text{mean} [\text{abs} (\text{Date}_{\text{obs}} - \text{Date}_{\text{sim}})] \quad (\text{Eq. 7})$$

428

429

430

where Date_{sim} and Date_{obs} (in Julian days) are the determined dates of drain flow start from the observed and simulated drainage discharge, respectively, using this dynamic threshold; “abs” represent the absolute value.

431

432

433

The best date prediction occurs when X_{diff} lies near zero. This criterion, in calculating a mean value for the 8 drainage seasons for each period, is sufficient to evaluate model performance in predicting the drain flow start. It is not used however for model calibration.

434 4.3 Sensitivity analysis of the performance criteria

435 The objective of the sensitivity analysis is to identify the model input parameters exerting the greatest
436 influence on two performance criteria, namely drainage discharge (using KGE criterion) and the drain
437 flow start criterion (X_{diff}).

438 Several sensitivity analysis methods are available to analyze model effectiveness (Iooss and Lemaître,
439 2015; Saltelli, 2008). In light of the low number of input parameters, it is possible to perform a global
440 sensitivity analysis (GSA) of SIDRA-RU using the Sobol method (Sobol, 1993), based on the variance
441 decomposition principle. The purpose of this method is to allocate a fraction of the total variance in
442 the evaluation criterion to each model parameter. The main advantage of this method is its strong
443 performance with nonlinearities that can be often problematic in hydrological modeling (e.g. Gatel et
444 al., 2019; Muñoz-Carpena et al., 2007). When considering a model with several parameters, the Sobol
445 method allows quantifying their impact on the model response as well as their interactions regarding
446 the evaluation criterion (Pianosi et al., 2016; Saltelli et al., 2000).

447 The total variance of the model output, in this case the quality criteria of drainage discharge and X_{diff} ,
448 is allocated to each parameter using two sensitivity indices: the first-order sensitivity index (S_i), and
449 the total sensitivity index (TSi). The S_i index represents the direct impact of each parameter taken alone
450 on total variability, while TSi is defined as the sum of the impact of each parameter taken alone and in
451 interaction with others on total variability. Several methods exist to define the S_i and TSi index values,
452 and no single one prevails over the others. Consequently, it is recommended to use several methods
453 to compute the sensitivity indices in order to assess the robustness of GSA. In this study, we tested
454 three variance estimators from (i) Saltelli (2002), named Saltelli2002, (ii) Jansen (1999), named Jansen,
455 and (iii) Martinez (2011), named Martinez. S_i has been computed based on the same estimators as TSi,
456 plus the Roalhs estimator (Tissot and Prieur, 2015), named ROALHS.

457 The SIDRA-RU sensitivity analysis is focused on the following parameters: soil hydraulic conductivity
458 (K_{sat}), drainable porosity (μ), intermediate reservoir level (S_{inter}), the intense drainage season reservoir

459 level (S_{IDS}), and partition coefficient α . The Sobol sampling procedure is based on the probability
460 distribution function (pdf) and the limits defined for all calibration parameters presented in Table 3
461 and the partition coefficient α , which follows a uniform distribution and ranging from 0 to 1.

462 In practice, input parameter was sampled in its respective pdf, as defined in Table 3. The sampling size
463 was $n = 1,000$, and the total number of simulations for $N_p = 5$ parameters was thus: $N_{tot} = (N_p+2)*n =$
464 $(5+2)*1,000 = 7,000$. Bootstrap methods were then implemented to evaluate the uncertainty
465 associated with each estimator, considering the 95% confidence interval, and 100 bootstrap replicates.

466 5 Results

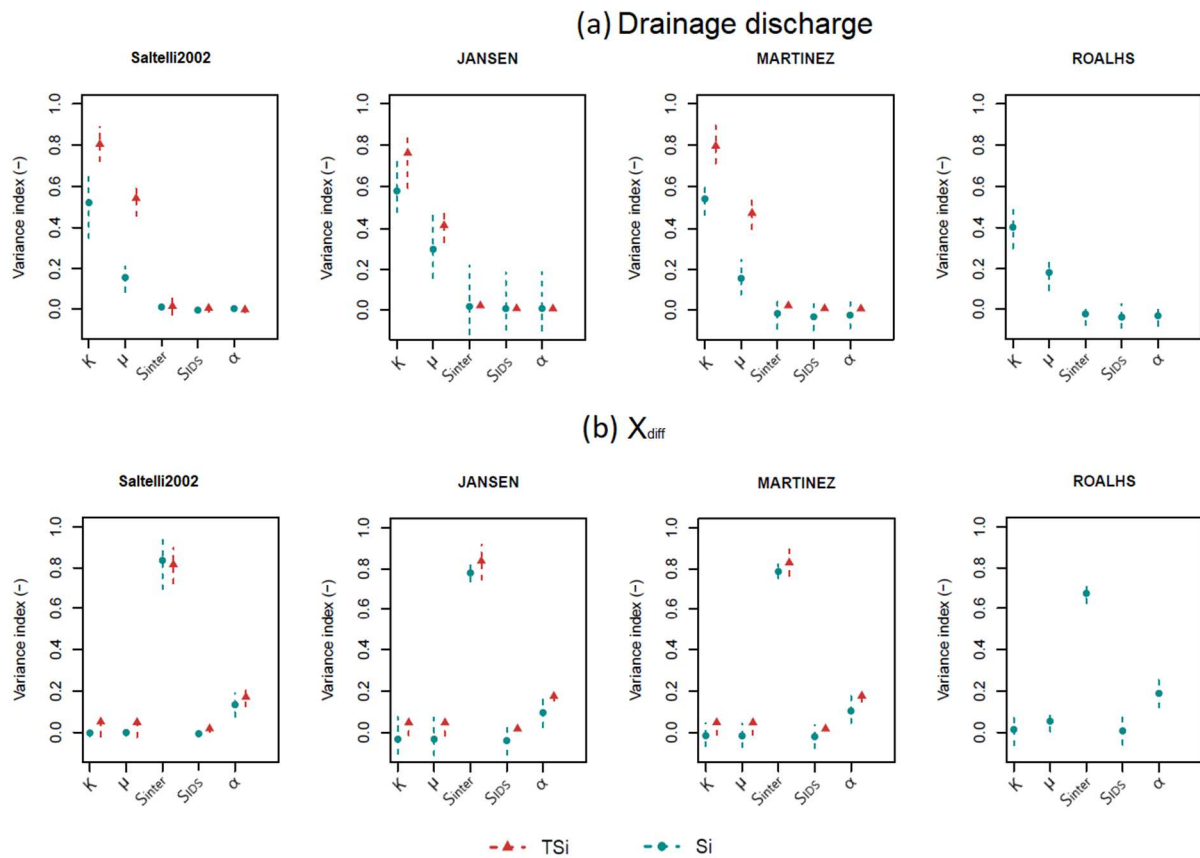
467 This section reports the results obtained by the SIDRA-RU model in terms of optimal criterion
468 performance. The first subsection will discuss the sensitivity analysis results of the five model
469 parameters (K_{sat} , μ , S_{inter} , S_{IDS} and α) with respect to the drainage discharge (by mean of KGE criterion)
470 and X_{diff} criteria. The second subsection will provide the results obtained for the calibration and
471 validation of four model parameters (K_{sat} , μ , S_{inter} and S_{IDS}) using the daily drainage discharge in the KGE
472 criterion, and analyze the results obtained for yearly cumulative of drainage discharge and surface
473 runoff. Next, the reliability of the model in predicting the drain flow start will be assessed using the
474 X_{diff} criterion. The assumption of approximating the soil WHC by S_{inter} (section 3.1) will be assessed by
475 comparing the S_{inter} values and the measured WHC for both plots T03 and T04 (Table 1).

476 5.1 Sensitivity analysis

477 Drainage discharge simulation T04_P1 (Table 4, section 5.2) has been used as a reference for the
478 sensitivity analysis of the five SIDRA-RU model input parameters (K_{sat} , μ , α , S_{inter} , S_{IDS}). This analysis
479 generated 20 first-order indices (Si) and 15 total-order indices (TSi) per criterion (using drainage
480 discharge and X_{diff}). Figure 4 shows that the various methods used, all present a similar hierarchy of
481 input effects on each criterion, with small deviations, thereby confirming the reliability of the
482 sensitivity analysis conducted. As regards the drainage discharge, hydraulic conductivity (K_{sat}) is the

483 parameter featuring the highest Si index (from 0.4 to 0.6); it explains nearly half of the total model
484 variance with respect to this criterion. Drainable porosity μ reflects values of the Si index around 0.2.
485 The TSi index exhibits an identical trend; its values for K_{sat} are close to 0.8 and for μ close to 0.5. The
486 last three parameters (α , S_{inter} , S_{IDS}) all display values for both the Si and TSi indices of close to zero and
487 have negligible influence on drainage discharge. Sobol (2002) and Martinez (2011) estimators show a
488 greater difference between Si and TSi for K_{sat} and μ , hence highlighting strong interactions between
489 them. In contrast, the TSi for α , S_{inter} and S_{IDS} parameters lie close to zero, thus indicating that taken
490 alone or interacting with others, these parameters exert no influence on drainage discharge. In
491 considering the very limited effect of parameters α , S_{inter} and S_{IDS} , it can be concluded that the
492 interactions are essentially occurring between K_{sat} and μ , thus demonstrating that these two
493 parameters are the only ones sensitive to the drainage discharge.

494 As regards the X_{diff} criterion, S_{inter} is the parameter with the highest Si and TSi indices, with values close
495 to 0.8 for both, hence the importance of this parameter in the model defining drain flow start. The TSi
496 and Si index values for S_{IDS} are nearly zero, thus demonstrating that the X_{diff} criterion is insensitive to
497 this parameter taken alone or in interaction with the other model parameters. Parameter α , reflecting
498 values of Si index around 0.1 and TSi index around 0.18, has little impact on the model performance
499 regarding the drains flow start. The hydrodynamic soil parameters K_{sat} and μ exert no influence on the
500 X_{diff} criterion.



501

502 Figure 4: Sensitivity analysis of the five SIDRA-RU model input parameters with respect to both
 503 drainage discharge and X_{diff} criteria using the Sobol method with four variance estimators
 504 (Saltelli2002, Martinez, Jansen and Roalhs). The blue points represent the first-order Sobol (Si)
 505 indices and red points the Total-order Sobol (TSi) indices; dashed lines indicate the uncertainty of
 506 each index, considering the 95% confidence interval.

507 5.2 Model performance assessment

508 The split-sample test yields calibration and validation results in two parameter sets for each plot (Table
 509 4). Simulations using either period P1 or P2 for calibration are followed by the suffix P1 or P2, for plots
 510 T03 and T04, respectively. The KGE values obtained exceed 0.81 for calibration and 0.75 for validation,
 511 thus indicating that model calibration can be considered good enough for hydrological modeling
 512 (Knoben et al., 2019). However, the calibrated parameters differ slightly depending on the selected
 513 calibration period. This variability is mainly influenced by the hydrological variability of period P1, as
 514 compared with P2 (Figure 3). For the various calibration tests, the resulting values of drainable porosity

515 μ are identical, while those of hydraulic conductivity K_{sat} range from 0.54 to 0.73 m/day. This difference
 516 is more pronounced for the soil reservoir parameters. Note that the calibrated S_{inter} values
 517 overestimate the measured WHC, calculated as water held by the soil between the drain and the soil
 518 surface (see Table 1). As the WHC has been approximated by S_{inter} (see section 3.1), this result reveals
 519 that part of the soil below the drains can contribute to water storage before the start of the drain flow.

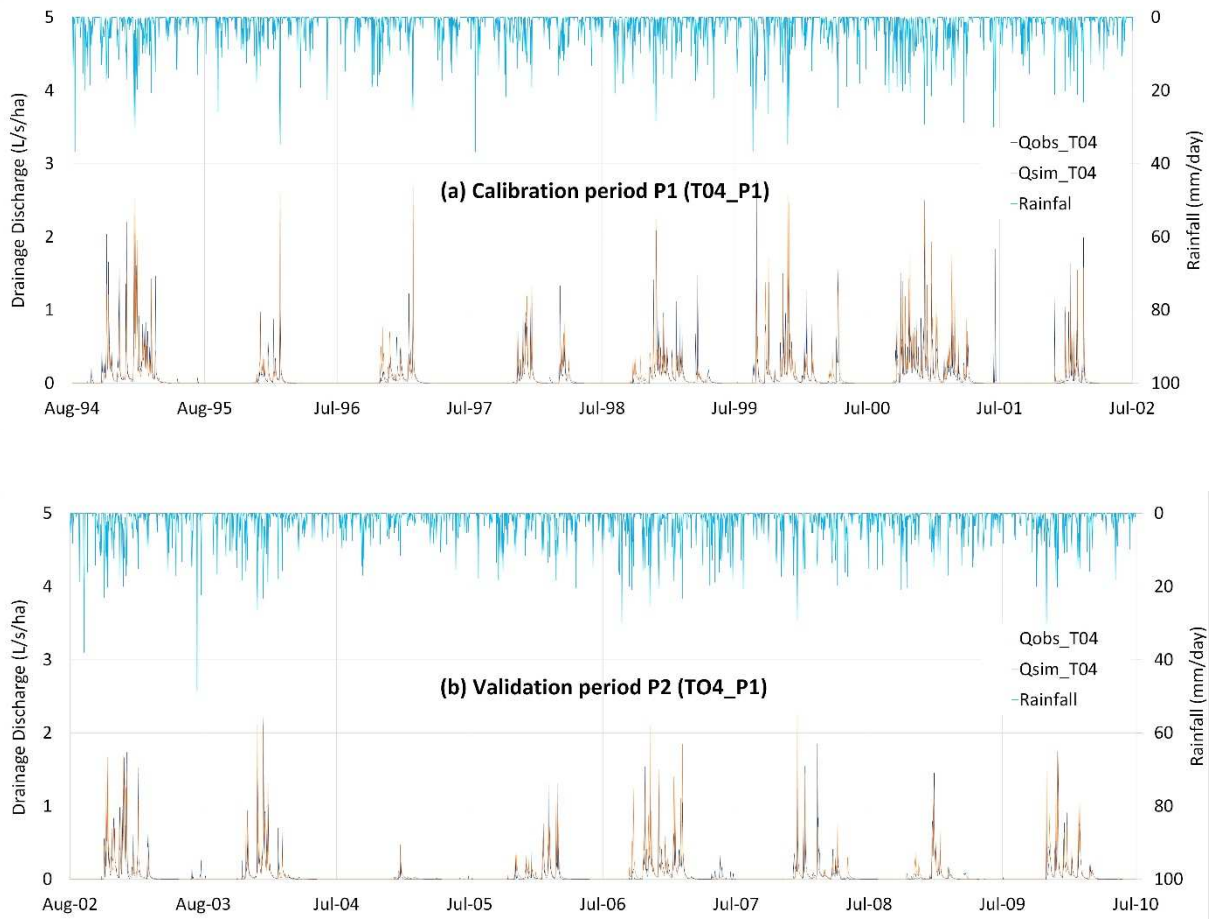
520 Table 4: Split-sample test results of model performance based on drainage discharge data
 521 from plots T03 and T04

Simulation	Calibration period	Validation period		Calibrated parameters			
	P1 (1994-2002)	P2 (2002-2010)	x_{diff} (days)	K_{sat} (m/d)	μ (-)	S_{inter} (mm)	S_{max} (mm)
T03_P1	0.846	0.751	5.5	0.73	0.05	105.5	110.6
T04_P1	0.818	0.82	8.0	0.71	0.05	119.3	127.1
	Calibration period	Validation period		Calibrated parameters			
	P2 (2002-2010)	P1 (1994-2002)					
T03_P2	0.839	0.78	7.5	0.54	0.05	102.4	130.7
T04_P2	0.871	0.785	6.0	0.73	0.05	140.0	152.9

522
 523 The graphical comparison between the measured and simulated drainage discharges of plot T04, using
 524 calibration period P1 (simulation T04_P1), is illustrated in Figure 5. The results obtained from plot T03
 525 show the same variations as from plot T04, discussed herein. The two graphs, for the calibration and
 526 validation steps, indicate that the simulated daily drainage discharge is in good agreement with
 527 observed values, during both high and low drainage seasons (Figure 5). This simulation slightly
 528 underestimates the observed peak discharge and slightly overestimates the low and medium discharge
 529 values. The model does not capture some of the observed peak flows, such as those in July 2001,
 530 August 2003 and July 2009, and does not correctly simulate the drain flow start of some drainage
 531 seasons, e.g. December 2001. These inaccuracies might be explained by the use of SAFRAN rainfall,

532 defined on an 8 km × 8 km grid instead of that measured in the field as input data, or else by drainage
 533 discharge measurement errors, which are difficult to verify. Aside from these few simulation
 534 shortcomings, the model faithfully reproduces the drainage discharge observations.

535

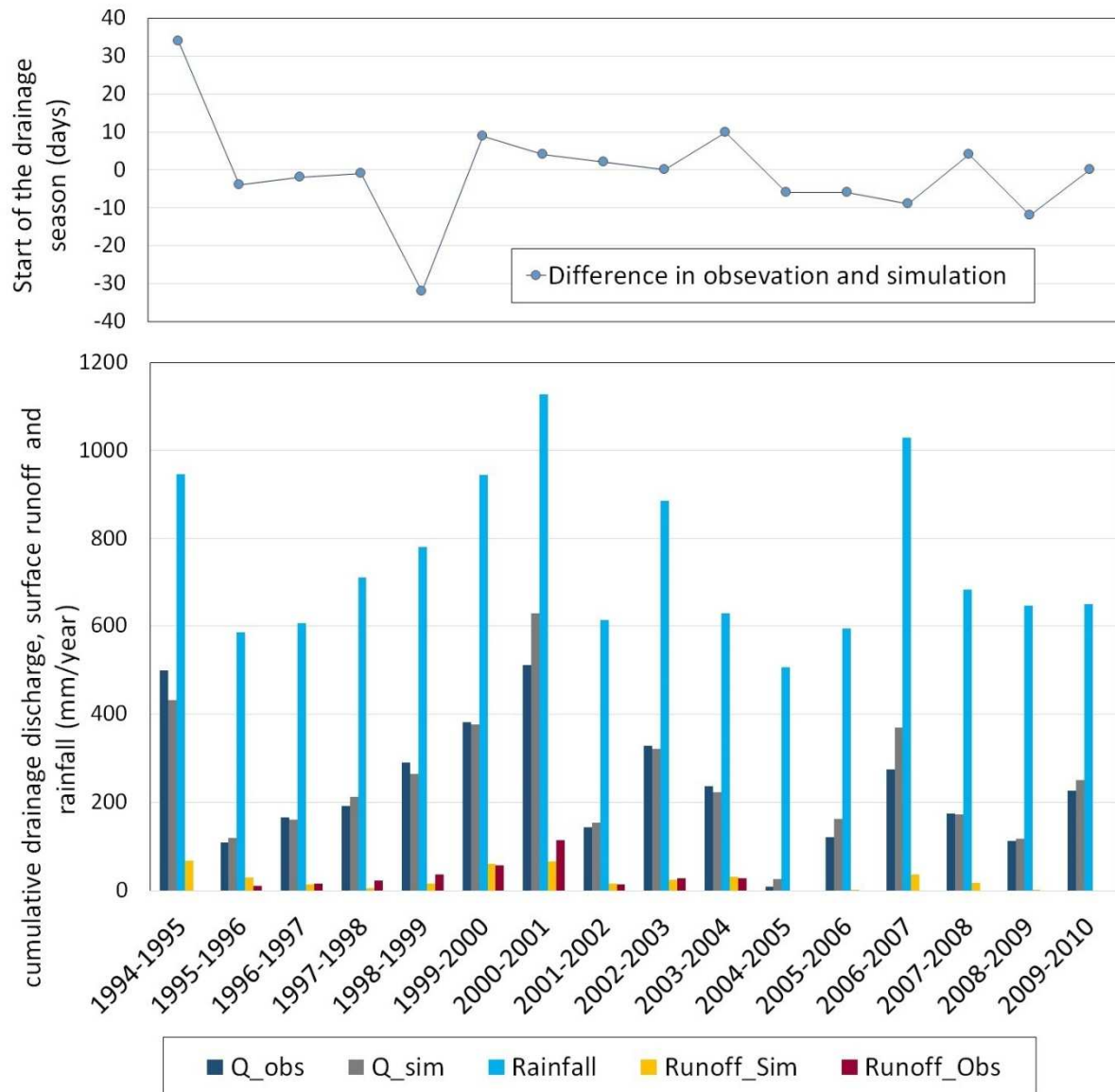


536

537 **Figure 5: Calibration (period P1) and validation (period P2) of the SIDRA-RU model**

538 **using observation data from plot T04**

539 For simulation T04_P1, Figure 6 shows the variations in yearly cumulative rainfall, the measured and
 540 simulated drainage discharge and surface runoff (mm/season), and the drainage flow start time
 541 differential (days). At the scale of a hydrological season, except for a few wet years, the simulated
 542 cumulative drainage discharge lies close to the observed values (to within 10%). The mean simulated
 543 drainage discharge of 250 mm/season is in good agreement with the observed volume of 236
 544 mm/season (Table 2). The yearly simulation of surface runoff (calculated by the model as excess
 545 rainfall) is of the same order of magnitude as the available data observations (from 1995 to 2004).



546

547 Figure 6: Comparison between yearly cumulative observation and simulation results for plot T04,
 548 using the parameter set of calibration period P1 (T04_P1): rainfall, simulated and observed drainage
 549 discharge and surface runoff [mm/year], and the difference in simulated and observed drainage flow
 550 start times [days].

551 The reliability of the SIDRA-RU model in predicting drain flow start was also assessed using the X_{diff}
 552 criterion (Eq. 7). The median values of X_{diff} are less than 8 days for both plots (Table 4). For simulation
 553 T04_P1, Figure 6 shows that the model accurately simulates the drain flow start, except for seasons
 554 1994-95 and 1998-99, when the difference in simulated and observed drain flow start times was equal
 555 to 34 and -32 days, respectively. For the entire simulation period, the model output a median X_{diff} value

556 of 5 days with a standard deviation of 10 days. These results demonstrate that model calibration based
557 on the drainage discharge observation does not reduce the large discrepancies between drain flow
558 start observation and simulation.

559 6 Discussion

560 The main objective of integrating a soil reservoir module (RU) into the SIDRA model consists of
561 simulating a continuous drainage discharge over several hydrological years, as opposed to the original
562 SIDRA model, which is only applied during the intense drainage season and *a priori* qualified by users.

563 The SIDRA-RU performance analysis has been based on optimizing the four model parameters (K_{sat} , μ ,
564 S_{inter} , S_{DS}) to maximize calibration criterion KGE, based on drainage discharge. The comparison between
565 daily observation and simulation of drainage discharge proves to be satisfactory in most seasons
566 examined. Simulations reveal good flow dynamics, with KGE values greater than 0.75, which are
567 efficient in hydrological modeling (Knoben et al., 2019). The peak flows have been correctly simulated,
568 yet some events have been slightly under- or overestimated. These small deviations might be related
569 to the input data or the model's simplifying hypothesis, e.g. neglecting deep infiltration and
570 preferential flow (Pleur et al., 2020). In terms of yearly cumulative drainage discharge and surface
571 runoff, these results show that the simulations lie very close to the observations. As for the
572 observations themselves (Table 2), the simulated surface runoff is less than 12% of total outflow.

573 The model evaluation demonstrates that for most drainage seasons, the observed drain flow start
574 times are predicted with good accuracy. However, large gaps can be noticed when predicting the drain
575 flow start times for certain seasons; the main cause may be related to the rainfall regime. Indeed,
576 continuous rainfall does in fact cause a progressive rewetting of the soil profile until formation of the
577 perched water table. Any heavy rainfall on dry soil can generate preferential flow toward the drains
578 before total saturation of the soil profile (Zimmer, 1992). Since this process is neglected in SIDRA-RU,
579 the prediction of drain flow start time gets delayed. Despite such simulation differences, the model is
580 still capable of predicting drain flow start with a relatively acceptable standard deviation of 10 days.

581 Thus, the model can offer farmers and agricultural operators accurate critical period to avoid the
582 application of pesticides and fertilizers, other than changing or limiting their application to the autumn
583 or winter period (Brown and van Beinum, 2009; Lewan et al., 2009).

584 The sensitivity analysis of SIDRA-RU parameters, according to the Sobol method, indicates that model
585 performance with respect to the drainage discharge (using KGE Criterion) solely depends on
586 hydrodynamic parameters K_{sat} and μ . The soil reservoir parameter S_{inter} , which describes the threshold
587 when the soil reservoir is capable of recharging the drained water table, has negligible impact on model
588 sensitivity, as regards drainage discharge. Meanwhile, model performance relative to the drain flow
589 start (as described by the X_{diff} criterion) mainly depends on the parameter S_{inter} .

590 In our modeling approach, the soil hydrodynamic parameters K_{sat} and μ , governing the water table
591 flow, have zero impact on the determination of the drain flow start dates. Indeed, the water table only
592 starts to form when water storage in the soil reservoir lies above the S_{inter} threshold in the RU module
593 (Section 3.2). This module considers the unsaturated zone as a single reservoir system defined by its
594 storage level parameters (S_{inter} and S_{IDS}), with instantaneous input (net infiltration) and output (water
595 table recharge). Thus, the RU module does not take into account dynamic flow in the unsaturated zone
596 (e.g. (Niswonger et al., 2006)) nor any influence of the soil hydrodynamic parameters.

597 The sensitivity analysis has also shown that model parameter α has a negligible impact on the model
598 performance regarding the drainage discharge, thus confirming the assumption to set this parameter
599 to 1/3, within the limit of the SIDRA-RU model proposed in this study (Section 3.2). However, this
600 parameter has a little influence when defining the drain flow start.

601 *In situ*, the soil hydrodynamic parameters (K_{sat} , μ) can be estimated using Guyon's pumping test
602 (Chossat, 1995; Guyon and Lesaffre, 1986; Lesaffre, 1990). However, the field estimation of the soil
603 reservoir parameters (S_{inter} and S_{IDS}) is difficult. Theoretically, their values lie close to the measured
604 WHC of the soil profile, which is available from farming professionals. We would suggest determining
605 these values by means of model calibration based on the drain discharge observations.

606 7 Conclusion

607 This study has presented a modeling strategy based on the integration of a new module (RU) in order
608 to manage the behavior of the SIDRA model's soil reservoir. This novel concept allows calculating the
609 recharge of the perched water table. Integration of the RU module makes it possible to simulate the
610 flow of soil water through the drainage system. This model is run with four parameters, serving to
611 control the behavior of both soil water storage and hydrodynamic flow of the perched water table,
612 both of which are determined by means of model calibration.

613 Application of SIDRA-RU at the "La Jaillière" experimental site has revealed its efficiency in simulating
614 drainage discharge during both wet and dry seasons. Simulation output is in good agreement with the
615 observed daily drainage discharge and yearly cumulative volume in most of the seasons studied; in
616 addition, the model correctly identifies the drain flow start, i.e. accurate to within a median value of 5
617 days and a standard deviation of 10 days.

618 The sensitivity analysis conducted for five model parameters (K_{sat} , μ , α , S_{inter} , S_{IDS}) indicates various
619 dependencies on the performance criteria tested. The calibration of drainage discharge is mainly
620 sensitive to hydraulic conductivity and drainable porosity, whereas the determination of drain flow
621 start time is sensitive to the soil reservoir parameter S_{inter} . To reduce simulation uncertainties, it is
622 recommended to calibrate S_{inter} and S_{IDS} independently of the K_{sat} , μ calibration using the observed
623 drainage discharges.

624 The model's ability to predict drain flow start times with good accuracy allows preventing the transfer
625 of agricultural pollutants into the water surface. Predicting the first drainage flows, using 6-days
626 weather forecasts, allows farmers and agricultural operators to plan for the critical application timing
627 and, hence, reduce the level of pesticide transfer. Moreover, this new model simulates the drained
628 yearly volume with a good level of approximation, thus offering the potential for realistic estimations
629 of the annual transfer of various pollutants of agricultural origin by means of SD systems.

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633 References

634 AGRESTE, 2010. Agricultural census, Ministry of agriculture, food and forestry, France.

635 Al Jabri, S.A., Youngs, E.G., 2015. Steady-State Water Tables in Drained Lands Modeled Using the
636 HYDRUS Package and Compared with Theoretical Analyses. *Journal of Irrigation and Drainage*
637 *Engineering*, 141(9). DOI:doi:10.1061/(ASCE)IR.1943-4774.0000881

638 Anderson, M.P., Woessner, W.W., 1992. *Applied Groundwater Modeling: Simulation of Flow and*
639 *Advective Transport*

640 Augeard, B., Kao, C., Chaumont, C., Vauclin, M., 2005. Mechanisms of surface runoff genesis on a
641 subsurface drained soil affected by surface crusting: A field investigation. *Physics and Chemistry of*
642 *the Earth*, 30(8-10): 598-610.

643 Biswas, A., 2019. Joint multifractal analysis for three variables: Characterizing the effect of topography
644 and soil texture on soil water storage. *Geoderma*, 334: 15-23.
645 DOI:https://doi.org/10.1016/j.geoderma.2018.07.035

646 Blann, K.L., Anderson, J.L., Sands, G.R., Vondracek, B., 2009. Effects of Agricultural Drainage on Aquatic
647 Ecosystems: A Review. *Critical Reviews in Environmental Science and Technology*, 39(11): 909-
648 1001. DOI:10.1080/10643380801977966

649 Boithias, L., Sauvage, S., Srinivasan, R., Leccia, O., Sánchez-Pérez, J.-M., 2014. Application date as a
650 controlling factor of pesticide transfers to surface water during runoff events. *CATENA*, 119: 97-
651 103. DOI:https://doi.org/10.1016/j.catena.2014.03.013

652 Boivin, A., Šimůnek, J., Schiavon, M., van Genuchten, M.T., 2006. Comparison of Pesticide Transport
653 Processes in Three Tile-Drained Field Soils Using HYDRUS-2D. *Vadose Zone J*, 5(3): 838-849.
654 DOI:10.2136/vzj2005.0089

655 Bordoloi, R., Das, B., Yam, G., Pandey, P. K., and Tripathi, O. P., 2019. Modeling of Water Holding
656 Capacity Using Readily Available Soil Characteristics. *Agricultural Research* 8, 347-355.

657 Bouarfa, S., Zimmer, D., 2000. Water-table shapes and drain flow rates in shallow drainage systems.
658 *Journal of Hydrology*, 235(3-4): 264-275.

659 Boussinesq, J., 1904. Recherches théoriques sur l'écoulement des nappes d'eau infiltrées dans le sol et
660 sur le débit des sources. *Journal de Mathématiques Pures et Appliquées*, 10: 5-78.

661 Brocca, L., Morbidelli, R., Melone, F., Moramarco, T., 2007. Soil moisture spatial variability in
662 experimental areas of central Italy. *Journal of Hydrology*, 333(2): 356-373.
663 DOI:<https://doi.org/10.1016/j.jhydrol.2006.09.004>

664 Brown, C.D., van Beinum, W., 2009. Pesticide transport via sub-surface drains in Europe. *Environmental*
665 *Pollution*, 157(12): 3314-3324. DOI:<https://doi.org/10.1016/j.envpol.2009.06.029>

666 Chossat, J.C., 1995. Qualité des sols : méthode de mesure de la conductivité hydraulique horizontale
667 équivalente et de la porosité de drainage in situ. Méthode de Guyon. Norme NF X 31-504.

668 Coron, L., Thirel, G., Delaigue, O., Perrin, C., Andréassian, V., 2017. The suite of lumped GR hydrological
669 models in an R package. *Environmental Modelling & Software*, 94: 166 - 171.
670 DOI:<https://doi.org/10.1016/j.envsoft.2017.05.002>

671 Dairon, R., Dutertre, A., Tournebize, J., Marks-Perreau, J., Carluier, N., 2017. Long-term impact of
672 reduced tillage on water and pesticide flow in a drained context. *Environmental Science and*
673 *Pollution Research*, 24(8): 6866-6877. DOI:10.1007/s11356-016-8123-x

674 De Marsily, G., 1986. *Quantitative hydrogeology*. Academic Press, Inc., Orlando, FL, 464 pp.

675 Dooge, J.C.I., 1959. A general theory of the unit hydrograph. *Journal of Geophysical Research* (1896-
676 1977), 64(2): 241-256. DOI:<https://doi.org/10.1029/JZ064i002p00241>

677 Dusek, J., Vogel, T., 2014. Modeling Subsurface Hillslope Runoff Dominated by Preferential Flow: One-
678 vs. Two-Dimensional Approximation. *Vadose Zone J*, 13(6). DOI:10.2136/vzj2013.05.0082

679 Favrot, J.C., Lesaffre, B., 1984. *Science du sol et drainage agricole, Livre jubilaire du cinquanteaire*
680 AFES (Association Française pour l'Etude du Sol) 1934-1984. AFES, Paris, pp. 309-319.

681 Gärdenäs, A.I., Šimůnek, J., Jarvis, N., Van Genuchten, M.T., 2006. Two-dimensional modelling of
682 preferential water flow and pesticide transport from a tile-drained field. *Journal of hydrology*, 2006
683 v.329 no.3-4(no. 3-4): pp. 647-660. DOI:10.1016/j.jhydrol.2006.03.021

684 Gatel, L. et al., 2019. Global evaluation and sensitivity analysis of a physically based flow and reactive
685 transport model on a laboratory experiment. *Environmental Modelling & Software*, 113: 73-83.
686 DOI:<https://doi.org/10.1016/j.envsoft.2018.12.006>

687 Gerke, H.H., Dusek, J., Vogel, T., 2013. Solute Mass Transfer Effects in Two-Dimensional Dual-
688 Permeability Modeling of Bromide Leaching From a Tile-Drained Field. *Vadose Zone J*, 12(2).
689 DOI:10.2136/vzj2012.0091

690 Gowda, P., Mulla, D., Desmond, E., Ward, A., Moriasi, D., 2012. ADAPT: Model use, calibration and
691 validation. *Transactions of the ASABE (American Society of Agricultural and Biological Engineers)*,
692 55: 1345-1352. DOI:10.13031/2013.42246

693 Gramlich, A., Stoll, S., Stamm, C., Walter, T., Prasuhn, V., 2018. Effects of artificial land drainage on
694 hydrology, nutrient and pesticide fluxes from agricultural fields – A review. *Agriculture, Ecosystems*
695 & *Environment*, 266: 84-99. DOI:<https://doi.org/10.1016/j.agee.2018.04.005>

696 Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and
697 NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*,
698 377(1): 80 - 91. DOI:<https://doi.org/10.1016/j.jhydrol.2009.08.003>

699 Guyon, G., 1963. Considérations sur l'hydraulique des nappes de drainage par canalisations
700 souterraines.

701 Guyon, G., Lesaffre, B., 1986. Mesures expérimentales au champ utilisées pour caractériser le
702 fonctionnement hydraulique d'une réseau drainé en sol à pseudo-gley. *Zeszyty problemowe*
703 *postepow nauk rolniczych*(132): 187-215.

704 Hansen, S., 1984. Estimation of Potential and Actual Evapotranspiration: Paper presented at the Nordic
705 Hydrological Conference (Nyborg, Denmark, August - 1984). *Hydrology Research*, 15(4-5): 205-212.
706 DOI:10.2166/nh.1984.0017

707 Henine, H., Nédélec, Y., Ribstein, P., 2014. Coupled modelling of the effect of overpressure on water
708 discharge in a tile drainage system. *Journal of Hydrology*, 511(0): 39-48.
709 DOI:<http://dx.doi.org/10.1016/j.jhydrol.2013.12.016>

710 Hooghoudt, S.B., 1940. General consideration of the problem of field drainage by parallel drains,
711 ditches, watercourses, and channels, Bodemkundig Instituut, , Groningen, Netherlands.

712 looss, B., Lemaître, P., 2015. A review on global sensitivity analysis methods. In: Meloni, C., Dellino, G.
713 (Eds.), *Uncertainty management in Simulation-Optimization of Complex Systems: Algorithms and*
714 *Applications*. Springer.

715 looss, B., Veiga, S.D., Alexandre, J., Gilles, P., 2020. sensitivity: Global Sensitivity Analysis of Model
716 Outputs

717 Jacquart, C., Choisnel, E., 1995. Un modèle de bilan hydrique simplifié à deux utilisable en
718 agrométéorologie, Association Météo et Climat, .

719 Jansen, M.J.W., 1999. Analysis of variance designs for model output. *Computer Physics*
720 *Communications*, 117(1): 35-43. DOI:10.1016/S0010-4655(98)00154-4

721 Jarvis, N., Larsbo, M., 2012. MACRO (v5.2): Model Use, Calibration, and Validation. *Transactions of the*
722 *ASABE*, 55(4): 1413-1423. DOI:<https://doi.org/10.13031/2013.42251>

723 Kao, C., Nedelec, Y., Zimmer, D., 1998. Surface runoff mechanisms and modeling in subsurface drained
724 fields, 7th international drainage symposium in the 21st century : food production and the
725 environment, Orlando, USA, 8-10 March 1998, pp. 258-266.

726 Kirkham, D., 1949. Flow of ponded water into drain tubes in soil overlying an impervious layer. Eos,
727 Transactions American Geophysical Union, 30(3): 369-385. DOI:10.1029/TR030i003p00369

728 Kjær, J. et al., 2011. Transport modes and pathways of the strongly sorbing pesticides glyphosate and
729 pendimethalin through structured drained soils. Chemosphere, 84(4): 471-9.
730 DOI:10.1016/j.chemosphere.2011.03.029

731 Klemeš, V., 1986. Operational testing of hydrological simulation models. Hydrological sciences journal,
732 1986 v.31 no.1(no. 1): pp. 13-24. DOI:10.1080/02626668609491024

733 Knoben, W., Freer, J., Woods, R., 2019. Technical note: Inherent benchmark or not? Comparing Nash–
734 Sutcliffe and Kling–Gupta efficiency scores. Hydrology and Earth System Sciences, 23: 4323-4331.
735 DOI:10.5194/hess-23-4323-2019

736 Kosugi, K., 1999. General Model for Unsaturated Hydraulic Conductivity for Soils with Lognormal Pore-
737 Size Distribution. Soil Science Society of America Journal, 63(2): 270-277.
738 DOI:10.2136/sssaj1999.03615995006300020003x

739 Kristensen, k.J., Jensen, s.E., 1975. A MODEL FOR ESTIMATING ACTUAL EVAPOTRANSPIRATION FROM
740 POTENTIAL EVAPOTRANSPIRATION. Hydrology Research, 6(3): 170-188.
741 DOI:10.2166/nh.1975.0012

742 Kroes, J.G., Van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Jacobs, C.M.J., 2008. SWAP version 3.2.
743 Theory description and user manual, Alterra, Wageningen, Netherlands

744 Kronvang, B., Strøm, H.L., Hoffmann, C.C., Laubel, A., Friberg, N., 2004. Subsurface tile drainage loss of
745 modern pesticides: field experiment results. Water science and technology : a journal of the
746 International Association on Water Pollution Research, 49(3): 139-47.

747 L Jones, R. et al., 2000. Processes affecting movement of pesticides to drainage in cracking clay soils.
748 Pesticide Outlook, 11(5): 174-179. DOI:10.1039/B007951K

749 Lagacherie, P., 1987. Synthèse générale sur les études de secteur de référence drainage.

750 Lesaffre, B., 1988. Fonctionnement hydrologique et hydraulique du drainage souterrain des sols
751 temporairement engorgés. Thèse de doctorat Thesis, Université Pierre et Marie Curie, Paris VI, 334
752 pp.

753 Lesaffre, B., 1990. Field measurement of saturated hydraulic conductivity and drainable porosity using
754 Guyon's pumping test. Transactions of the ASAE, 33(1): 173-178.

755 Lesaffre, B., Morel, R., 1986. Use of hydrographs to survey subsurface drainage : networks ageing and
756 hydraulic operating. In: Van Wijk, A.L.M., Wesseling, J. (Eds.), Symposium on agricultural water
757 management, Arnhem, NLD, 18-21 June 1985, pp. 175-189.

758 Lesaffre, B., Zimmer, D., 1987. Modélisation du comportement hydraulique d'un sol drainé : débits de
759 pointe et tarissements. Science du sol, 25(4): 231-246.

760 Lesaffre, B., Zimmer, D., 1988. Subsurface Drainage Peak Flows in Shallow Soil. Journal of Irrigation and
761 Drainage Engineering, 114(3): 387-406.

762 Lewan, E., Kreuger, J., Jarvis, N., 2009. Implications of precipitation patterns and antecedent soil water
763 content for leaching of pesticides from arable land. Agricultural Water Management, 96(11): 1633-
764 1640. DOI:<https://doi.org/10.1016/j.agwat.2009.06.006>

765 Lindstrom, G., Pers, C., Rosberg, J., Stromqvist, J., Arheimer, B., 2010. Development and testing of the
766 HYPE (Hydrological Predictions for the Environment) water quality model for different spatial
767 scales. Hydrology Research, 41(3-4): 295-319.

768 Martinez, J.-M., 2011. Analyse de sensibilité globale par décomposition de la variance, Journée des
769 GdR Ondes & Mascot Num, Institut Henri Poincaré, Paris.

770 Mehdinejadiani, B., Fathi, P., 2020. Analytical solutions of space fractional Boussinesq equation to
771 simulate water table profiles between two parallel drainpipes under different initial conditions.
772 Agricultural Water Management, 240: 106324. DOI:<https://doi.org/10.1016/j.agwat.2020.106324>

773 Michel, C., 1987. Hydrologie appliquée aux petits bassins ruraux. Centre national du machinisme
774 agricole du génie rural des eaux et des forêts. Antony, Papier, 429 p. pp.

775 Milly, P. C. D., 1988. Advances in modeling of water in the unsaturated zone. Transport in Porous Media
776 3, 491-514.

777 Moriasi, D.N. et al., 2013. Evaluation of the hooghoudt and kirkham tile drain equations in the soil and
778 water assessment tool to simulate tile flow and nitrate-nitrogen. J Environ Qual, 42(6): 1699-710.
779 DOI:10.2134/jeq2013.01.0018

780 Moriasi, D.N., Rossi, C.G., Arnold, J.G., Tomer, M.D., 2012. Evaluating hydrology of the Soil and Water
781 Assessment Tool (SWAT) with new tile drain equations. Journal of Soil and Water Conservation,
782 67(6): 513-524. DOI:10.2489/jswc.67.6.513

783 Muñoz-Carpena, R., Zajac, Z., Kuo, Y.-M., 2007. Global Sensitivity and Uncertainty Analyses of the
784 Water Quality Model VFSMOD-W. Transactions of the ASABE, 50. DOI:10.13031/2013.23967

785 Musy, A., Higy, C., 2004. Hydrologie 1 : Une science de la nature. Presses Polytechniques et
786 Universitaires Romandes, Lausanne, 314 pp.

787 Nielsen, D. R., Th. Van Genuchten, M., and Biggar, J. W., 1986. Water flow and solute transport
788 processes in the unsaturated zone. Water Resources Research 22, 89S-108S.

789 Niswonger, R.G., Prudic, D.E., Regan, R.S., 2006. Documentation of the Unsaturated-Zone Flow (UZF1)
790 Package for modeling Unsaturated Flow Between the Land Surface and the Water Table with
791 MODFLOW-2005. 6-A19. DOI:10.3133/tm6A19

792 Nimmo, J. R., 2005. Unsaturated Zone Flow Processes. In "Encyclopedia of Hydrological Sciences".

793 Nolan, B.T. et al., 2008. Identification of key climatic factors regulating the transport of pesticides in
794 leaching and to tile drains. *Pest Management Science*, 64(9): 933-944.
795 DOI:<https://doi.org/10.1002/ps.1587>

796 Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., and Wagener, T., 2016.
797 Sensitivity analysis of environmental models: A systematic review with practical workflow.
798 *Environmental Modelling & Software* 79, 214-232.

799 Pluer, W. T., Macrae, M., Buckley, A., and Reid, K., 2020. Contribution of preferential flow to tile
800 drainage varies spatially and temporally. *Vadose Zone Journal* 19, e20043.

801 Qi, H., and Qi, Z., 2016. Simulating phosphorus loss to subsurface tile drainage flow: a review.
802 *Environmental Reviews* 25, 150-162.

803 Rawls, W.J., Brakensiek, D.L., 1982. Estimating Soil Water Retention from Soil Properties. *Journal of*
804 *the Irrigation and Drainage Division*, 108(2): 166-171. DOI:[doi:10.1061/JRCEA4.0001383](https://doi.org/10.1061/JRCEA4.0001383)

805 Ren, X.W., Santamarina, J.C., 2018. The hydraulic conductivity of sediments: A pore size perspective.
806 *Engineering Geology*, 233: 48-54. DOI:<https://doi.org/10.1016/j.enggeo.2017.11.022>

807 Rouseva, S. et al., 2017. Chapter Two - Soil Water Characteristics of European SoilTrEC Critical Zone
808 Observatories. In: Banwart, S.A., Sparks, D.L. (Eds.), *Advances in Agronomy*. Academic Press, pp. 29-
809 72. DOI:<https://doi.org/10.1016/bs.agron.2016.10.004>

810 Rupp, D.E., Selker, J.S., 2005. Drainage of a horizontal Boussinesq aquifer with a power law hydraulic
811 conductivity profile. *Water Resources Research*, 41(11). DOI:[10.1029/2005wr004241](https://doi.org/10.1029/2005wr004241)

812 Saltelli, A., 2002. Making best use of model evaluations to compute sensitivity indices. *Computer*
813 *Physics Communications*, 145(2): 280 - 297. DOI:[https://doi.org/10.1016/S0010-4655\(02\)00280-1](https://doi.org/10.1016/S0010-4655(02)00280-1)

814 Saltelli, A., 2008. *Global sensitivity analysis : the primer*. Wiley, Chichester.

815 Saltelli, A., Tarantola, S., and Campolongo, F., 2000. Sensitivity Anaysis as an Ingredient of Modeling.
816 *Statist. Sci.* 15, 377-395.

817 Schaap, M.G., van Genuchten, M.T., 2006. A Modified Mualem–van Genuchten Formulation for
818 Improved Description of the Hydraulic Conductivity Near Saturation. *Vadose Zone J*, 5(1): 27-34.
819 DOI:10.2136/vzj2005.0005

820 Shokri, A., Bardsley, W.E., 2016. Development, testing and application of DrainFlow: A fully distributed
821 integrated surface-subsurface flow model for drainage study. *Advances in Water Resources*, 92:
822 299 - 315. DOI:<https://doi.org/10.1016/j.advwatres.2016.04.013>

823 Šimůnek, J., and Bradford, S. A., 2008. *Vadose Zone Modeling: Introduction and Importance* All rights
824 reserved. No part of this periodical may be reproduced or transmitted in any form or by any means,
825 electronic or mechanical, including photocopying, recording, or any information storage and
826 retrieval system, without permission in writing from the publisher. *Vadose Zone Journal* 7, 581-586.

827 Skaggs, R.W., 1980. Drainmod Reference Report. Methods for Design and Evaluation of Drainage-
828 Water Management Systems for Soils with High Water Tables., United States Department of
829 Agriculture, North Carolina state University, Raleigh, North Carolina.

830 Stillman, J.S., Haws, N.W., Govindaraju, R.S., Suresh C. Rao, P., 2006. A semi-analytical model for
831 transient flow to a subsurface tile drain. *Journal of Hydrology*, 317(1-2): 49-62.

832 Suleiman, A.A., T. Ritchie, J., 2001. Estimating Saturated Hydraulic Conductivity from Soil Porosity.
833 *Transactions of the ASAE*, 44(2): 235. DOI:<https://doi.org/10.13031/2013.4683>

834 Tissot, J.Y., Prieur, C., 2015. A randomized orthogonal array-based procedure for the estimation of first-
835 and second-order Sobol' indices. *Journal of Statistical Computation and Simulation*, 85(7): 1358-
836 1381. DOI:10.1080/00949655.2014.971799

837 Tournebize, J., Kao, C., Nikolic, N., Zimmer, D., 2004. Adaptation of the STICS model to subsurface
838 drained soils. *Agronomie*, 24(6-7): 305-313.

839 Trajanov, A. et al., 2015. Estimating Drainage Periods for Agricultural Fields from Measured Data: Data-
840 Mining Methodology and a Case Study (La JailliÈRe, France). *Irrigation and Drainage*, 64(5): 703-
841 716. DOI:<https://doi.org/10.1002/ird.1933>

842 Trajanov, A. et al., 2018. Modeling the risk of water pollution by pesticides from imbalanced data.
843 *Environmental science and pollution research international*, 25(19): 18781-18792.
844 DOI:[10.1007/s11356-018-2099-7](https://doi.org/10.1007/s11356-018-2099-7)

845 Van Der Ploeg, R.R., Horton, R., Kirkham, D., 1999. Steady Flow to Drains and Wells. In: Skaggs, R.W.,
846 Schilfgaard, J.V. (Eds.), *Agricultural Drainage. Agronomy*. American Society of Agronomy, Inc. Crop
847 Science Society of America, Inc. Soil Science Society of America, Inc., Madison, Wisconsin, USA, pp.
848 213-263.

849 Van Schilfgaard, J., 1963. Design of Tile Drainage for Falling Water Tables *Journal of the Irrigation and*
850 *Drainage Division*, 89(2): 1-12.

851 Vidal, J.-P., Martin, E., Franchistéguy, L., Baillon, M., Soubeyroux, J.-M., 2010. A 50-year high-resolution
852 atmospheric reanalysis over France with the Safran system. *International Journal of Climatology*,
853 30(11): 1627-1644. DOI:[10.1002/joc.2003](https://doi.org/10.1002/joc.2003)

854 Vincent, B., 2020. TPrincipes techniques et chiffres du drainage agricole De la tuyautique à l'hydro-
855 diplomatie. *Sciences Eaux & Territoires*(32): 8-15. DOI:[10.14758/set-revue.2020.2.02](https://doi.org/10.14758/set-revue.2020.2.02)

856 Van Genuchten, M. T., and Jury, W. A., 1987. Progress in unsaturated flow and transport modeling.
857 *Reviews of Geophysics* 25, 135-140.

858 Willkommen, S., Pfannerstill, M., Ulrich, U., Guse, B., Fohrer, N., 2019. How weather conditions and
859 physico-chemical properties control the leaching of flufenacet, diflufenican, and pendimethalin in
860 a tile-drained landscape. *Agriculture, Ecosystems & Environment*, 278: 107-116.

861 Wilson, G.L. et al., 2020. Effects of fertilizer timing and variable rate N on nitrate–N losses from a tile
862 drained corn-soybean rotation simulated using DRAINMOD-NII. *Precision Agriculture*, 21(2): 311-
863 323. DOI:10.1007/s11119-019-09668-4

864 Youngs, E.G., 1966. Horizontal seepage through unconfined aquifers with non-uniform hydraulic
865 conductivity. *Journal of Hydrology*, 4(C): 91-97.

866 Youngs, E. G., 1980. The analysis of groundwater seepage in heterogeneous aquifers / Analyse de
867 l'infiltration des eaux souterraines dans les aquifères hétérogènes. *Hydrological Sciences Bulletin*
868 25, 155-165.

869 Zhang, W., Zhang, Y., 1986. Methods for Estimating the Drainable Porosity in Nonsteady Drainage
870 Formulas. *Hydraulic Design in Water Resources Engineering: Land Drainage*. Springer Berlin
871 Heidelberg, Berlin, Heidelberg, pp. 373-382.

872 Zimmer, D., 1992. Drainage flow patterns and modeling in a seasonally waterlogged heavy clay soil,
873 6th international drainage symposium "Drainage and water table control", Nashville, USA, 13-15
874 December 1992, pp. 80-87.

875 Zimmer, D., Lesaffre, B., 1989. Subsurface drainage flow patterns and soil types, ASAE-CSAE
876 International Summer Meeting, Québec, CAN, 25-28 June 1989, pp. 17.

877 Zimmer, D., Lorre, E., Lesaffre, B., 1995. Parameter sensitivity and field evaluation of SIDRA model.
878 *Irrigation and Drainage Systems*, 9(3): 279-296.

879