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Robustness of a parsimonious subsurface drainage model at the French national scale

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Abstract - Drainage systems are currently implemented on agricultural plots subjected to temporary or permanent waterlogging issues. Drained plots account for 9% of all arable soils in France. As such, the need for accurate hydrological modeling is crucial, especially in an unstable future context affected by climate change. The aim of this paper is to assess the capacity of the SIDRA-RU hydrological drainage model in representing the variability of pedoclimatic conditions within French metropolitan areas, as well as to demonstrate the utility of this model as a long-term management tool. The model is initially calibrated using the KGE' criterion as an Objective Function (OF) on a large and unique database encompassing 22 plots spread across France and classified according to three main soil textures (silty, silty-clayey and clayey). The performance of SIDRA-RU is evaluated by monitoring the KGE' calibration values, as well as the quality of the simulations of both high and low discharges and the annual drained water balance on each plot. Next, the temporal robustness of the model is assessed by conducting the split-sample test on the selected plots that satisfy the data requirements. Results show that the SIDRA-RU model accurately simulates the drainage discharge, especially on silty soils. The performance on clayey soils is slightly weaker than that on silty soils yet remains acceptable. Similarly, the split-sample test indicates that SIDRA-RU is temporally robust on all three soil textures. Consequently, the SIDRA-RU model closely represents the diversity of French drained soil and could be used for its long-term management.

1. Introduction

Subsurface drainage is an agricultural soil management technique that controls soil water content and increases aeration on soils subjected to temporary or permanent deep-water infiltration issues (Jamagne, 1968; Baize and Jabiol, 2011). Plot water conditions are stabilized, thus ensuring better crop yields (Broadhead and Skaggs, 1982; Armstrong et al., 1988; Nijland et al., 2005; Ibrahim et al., 2013) while reducing the flood risk on plots (Henine et al., 2014; Tuohy et al., 2018b). Drained soils often belong to the hydromorphic soil category and moreover lie on a shallow and impervious layer that stops the natural waterlogging of soil (Thompson et al., 1997; Lange et al., 2011).

In France, all artificially drained soils comprise more than 2.7 million hectares of arable soils (source: “RGA - Agreste” (2010)), i.e. close to 10% of all arable land, including 20% for cereal-type field crops. In practice, several techniques exist to drain soils, such as mole drainage, a technique that involves digging a gallery into the clayey soil to collect and convey the excess water out of the plot by gravity. However, over 80% of drainage practices are conducted by introducing perforated pipes lying on the impermeable layer. The drain depth, spacing, slope and diameter of these pipes constitute the main characteristics of each design; they are constrained by the type of climate and soil found in local conditions (Mulqueen, 1998) and contribute to the large diversity of drainage configurations in France.

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Since the economic and environmental consequences of climate change are of increasing concern to stakeholders, proper drainage practice has become a major issue. Predicting the long-term behavior of these systems is even more crucial in this context of water resource protection and restoration since drainage has an impact on water quality (Tournebize et al., 2012, 2017, 2020). The literature contains studies targeting the impact of climate change on drainage practices, with an emphasis on either the increase in annual drained water balance (Pease et al., 2017) or agricultural productivity on drained plots (Jiang et al., 2020a). These issues raise concerns over the sustainability of existing drainage systems, and their need to be redesigned has come to the fore (Deelstra, 2015; Abd-Elaty et al., 2019). A common theme in all these studies is the need to properly represent drainage systems within the study area.

In this context, hydrological modeling is a widespread tool for predicting drainage discharge, with several models currently being used, e.g. DRAINMOD model (Skaggs, 1981; Skaggs et al., 2012) in the United States. This spatially-distributed model operates on various spatial scales (Konyha and Skaggs, 1992; Brown et al., 2013) and integrates many modules in order to represent different hydrological processes and solute transports (Breve et al., 1997). In Europe, the MACRO model (Jarvis, 1994; Jarvis and Larsbo, 2012) was developed by the FOCUS group (Adriaanse et al., 1996; Boesten et al., 1997) and is now commonly used to evaluate drainage system performance and contaminant transport (Jarvis et al., 1997; Beulke et al., 2001). These two models have demonstrated their effectiveness, yet they have been designed using physically-based modeling strategies, thus complicating their parameterization on a large database.

Given this complexity, the SIDRA-RU model offers an interesting alternative. This semi-conceptual model is parsimonious in terms of the number of parameters requiring a calibration (only four versus approx. twenty for MACRO), hence making it easier to configure (Perrin et al., 2003). Initially intended to simulate the drained discharge during flood periods (Lesaffre and Zimmer, 1987a), this model converts weather-dependent soil recharge into drainage discharge by solving a semi-analytical formula derived from the Boussinesq equation (Boussinesq, 1904). Various modules have been integrated to better represent infiltration (Kao et al., 1998), water flux in the unsaturated zone (Bouarfa and Zimmer, 2000) or pesticide leaching (Branger et al., 2009). The RU module was recently integrated in order to model water transfer in the unsaturated zone. This new version inputs a continuous recharge term into the SIDRA module, which then allows for the simulation of drainage discharge over the entire hydrological cycle.

Due to soil diversity within French drained areas, a model used for management purposes must initially be as general as possible and correctly calibrated to ensure model behavior matches as closely as possible the behavior of each studied site (Perrin, 2000). In this context, a relevant calibration protocol often depends on the choice of Objective Function (OF), which serves as the numerical criterion we're seeking to optimize so that the simulation better resembles reality. Many OFs can be used to calibrate a model such as NSE (Nash and Sutcliffe, 1970) or KGE (Gupta et al., 2009), depending on the purpose of the particular study. The model here is intended for use on future prediction data for long-term management. From this perspective, the model must be temporally robust, i.e. independent of the period chosen for calibration (Klemeš, 1986). Such an evaluation can be performed by means of various tests, which tend to depend on the model structure (Refsgaard and Storm, 1996; Refsgaard, 2001; Henriksen et al., 2003; Daggupati et al., 2015). Since SIDRA-RU is a simple model, the split-sample test (Klemeš, 1986) is considered to be sufficient (Refsgaard, 1997). However, the national-scale evaluation of a hydrological model requires a large database, which is not readily available in the drainage hydrology field. This lack of data would be the reason for the paucity of studies in the current literature.

The aim of this study is to assess the ability of a hydrological drainage model to simulate the observed drainage discharge across all of France. An exhaustive database, composed of 22 experimental sites and spread over the main drained regions

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in France, has been built to account for the large diversity of French drained soils on which the model was tested. Database completeness is one of this paper's main strengths and allows generalizing our results on this soil diversity. The chosen hydrological model is SIDRA-RU, a parsimonious model that yields continuous simulations and is easily run on the database. In addition, the SIDRA-RU drainage model is new in the hydrological drainage modeling community; this study therefore offers an opportunity to test its performance at the national scale, which raises another point of interest for the study. Moreover, the temporal robustness of the SIDRA-RU model is assessed in the aim of asserting whether or not the model can be used in a long-term management tool, i.e. subject to climate change.

2. Materials and methods

2.1 French classification of drained soils

A multitude of materials constitute French soils, as defined by their geological origin, textural evolution and regional climate. All of the above characteristics serve to determine the uniqueness of a soil. Agricultural drainage is applicable in this diversity, and a perfect model would consider all these characteristics in an effort to increase simulation accuracy. The purpose here however is to use the SIDRA-RU model, which as mentioned above is parsimonious and generalizable, hence unable to individually consider each soil type. Consequently, making generalizations about soil diversity and grouping them by soil category is a necessary step. Several official classifications serve to group soil types (FAO, 1988; Krogh and Greve, 1999; Driessen et al., 2000); however, the drained soil classification requires other criteria to be efficient. In this study, we are proposing to classify them by texture, making it possible to sort the database used into various categories capable of describing as many pedoclimatic contexts as possible (see Fig. 1 & Table 1).

The Lagacherie and Jamagne classification (Jamagne et al., 1977; Lagacherie and Favrot, 1987; Richer-de-Forges et al., 2008) was used to evaluate this strategy. According to Fig. 1, three distinct soil types occupy most of the regions with the highest drainage ratio (i.e. percentage of a land area that has been drained, with drainage ratio values above 50% of total arable area). First, the glossic and planolosic soils, belonging to the Luvisols, are characterized by horizontal groundwater flows and a noteworthy textural differentiation between the surface horizon, which is often silty and sometimes sandy-loamy, and a deep clayey horizon. These soil types are mainly located around the Paris Basin and in the Allier region (see Fig. 1). Second, brown acidic and leached soils, mostly distributed in the country's Western region (Fig. 1), lie on a magmatic and metamorphic substratum and are affected by the subsurface drainage as well; they are often characterized by a silty-clayey or loamy texture. Third, the pseudogley soils are also known to be subsurface drained, yet they are barely correlated with any specific soil texture. In southwestern France, where subsurface drainage is commonly used, the soil is mostly loamy or silty-sandy. In France's Eastern region (Fig. 1), soils with a silty-clayey texture and fine sediment soils with heavy clay are predominantly used for agricultural drainage. Figure 1 shows the drainage ratio of arable soil in France. Most drainage systems lie on a loamy texture according to Lagacherie and Favrot (1987), who showed that 80% of French drained soils are loamy and spatially dispersed throughout the main drained regions. Consequently, the SIDRA-RU model needs to be tested on these various soil types.

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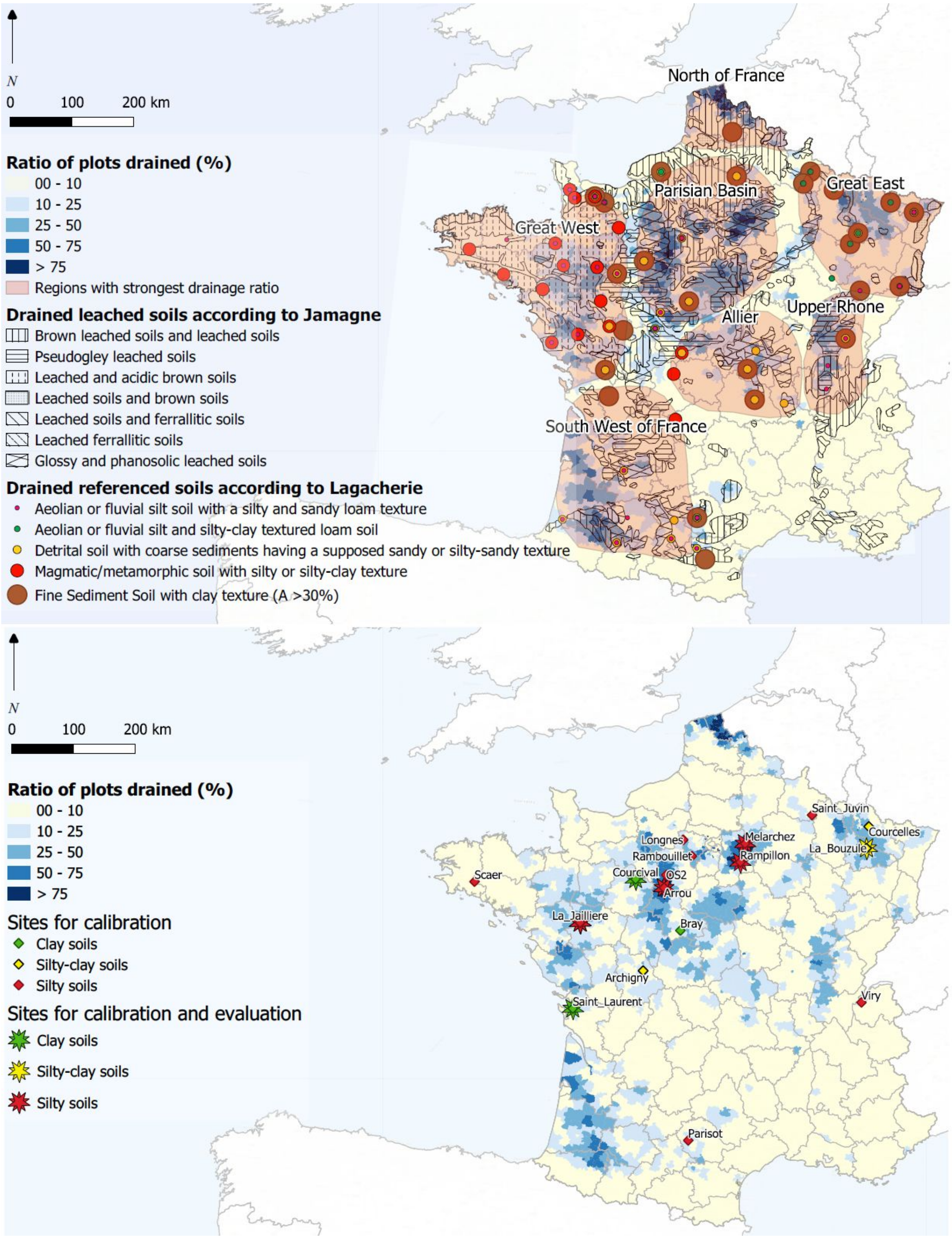

Figure 1: top) the pedologic distribution of French soils, produced by Jamagne et al. (1977) and Lagacherie and Favrot (1989), overlaid on the spatial distribution of French drainage (RGA, 2010); bottom) the spatial distribution of sites aggregated by texture with observed flow data

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Table 1: Main characteristics of the 22 plots with observed discharges and associated KGE' from the calibration process and split-sample tests

Texture	Plot name	Site Location	Chronic length (years)	Surface (ha)	Tile depth (m)	Drain (half-gap) (m)	Use	KGE' from total calibration	KGE' from the Split-Sample Test: In calibration P1	In calibration P2	In evaluation P1	In evaluation P2	Index (Fig. 9)
Clayey soil	Bray_P1	Bray	6	46.0	0.9	5.0	calibration only	0.52	-	-	-	-	-
	Courcival_P3	Courcival	10	1.3	0.9	6.0	calibration and evaluation	0.44	0.42	0.48	0.36	0.34	C1
	La_Bouzule_P1	La Bouzule	13	1.9	0.9	12.0	calibration and evaluation	0.52	0.58	0.52	0.42	0.31	C2
	Saint_Laurent_P2	Saint Laurent	15	1.2	0.9	10.0	calibration and evaluation	0.76	0.75	0.75	0.58	0.63	C3
Silty soil	Arrou_P6	Arrou	19	2.0	0.8	5.0	calibration and evaluation	0.65	0.57	0.78	0.75	0.55	S1
	Arrou_P8	Arrou	19	2.0	0.8	10.0	calibration and evaluation	0.65	0.54	0.72	0.72	0.53	S2
	Courcelles_P1	Courcelles	3	2.4	0.9	5.0	calibration only	0.70	-	-	-	-	-
	Courcelles_P2	Courcelles	3	2.4	0.9	5.0	calibration only	0.68	-	-	-	-	-
	La_Jaillière_P4	La Jaillière	16	1.0	0.9	5.0	calibration and evaluation	0.83	0.82	0.87	0.79	0.82	S3
	Longnes_P2	Longnes	6	1.0	0.9	6.0	calibration only	0.66	-	-	-	-	-
	Longnes_P3	Longnes	6	1.0	0.9	7.5	calibration only	0.58	-	-	-	-	-
	Melarchez_GP	Melarchez	39	700.0	0.9	6.0	calibration and evaluation	0.77	0.77	0.75	0.61	0.61	S4
	OS2_P1	OS2	3	2.0	1.0	5.0	calibration only	0.54	-	-	-	-	-
	Parisot_P2	Parisot	4	0.3	0.9	6.0	calibration only	0.81	-	-	-	-	-
	Rambouillet_P1	Rambouillet	3	1.0	0.9	5.0	calibration only	0.77	-	-	-	-	-
	Rampillon_GP	Rampillon	9	355.0	0.9	6.0	calibration only	0.77	0.80	0.76	0.71	0.73	S5
	Saint_Juvin_P1	Saint Juvin	3	1.4	0.9	1.5	calibration only	0.56	-	-	-	-	-
	Scaer_P2	Scaer	5	1.4	0.9	5.0	calibration only	0.61	-	-	-	-	-
	Viry_P1	Viry	4	0.8	0.9	7.5	calibration only	0.60	-	-	-	-	-
Silty-clayey soil	Archigny_P1	Archigny	2	1.0	0.9	4.0	calibration only	0.76	-	-	-	-	-
	Archigny_P2	Archigny	2	1.0	0.9	6.0	calibration only	0.76	-	-	-	-	-
	La_Bouzule_P2	La Bouzule	13	2.9	0.9	6.0	calibration and evaluation	0.54	0.50	0.60	0.45	0.56	SC1

2.2 Input data

A representative database of drainage discharge across France was specially built for this study. The data originate from various sources: (1) the ORACLE research project (Tallec et al., 2015) and artificial Rampillon wetland (Tournebize et al., 2012, 2017; Lebrun et al., 2019); (2) the partnership with the ARVALIS Institute, which monitors the *La Jaillière* experimental site; (3) data from reference drainage sites dating between the 1960's and 1980's. The data from this last source stem from monitoring experiments managed by INRAE (formerly Cemagref) that test drainage modalities. The combination of these sources yields a database of nearly 200 years of cumulative hydrological records on drained plots in diverse pedoclimatic contexts over a broad plot scale range (e.g. 0.8-700 ha). The resulting extensive dataset compiled for hydrological modeling purposes guarantees the transferability aspect of this study.

The drainage network of the various study plots is based on similar technical characteristics (see Table 1), composed of perforated and corrugated pipes lying on a depth from 0.85 m to 1 m with an inter-drain spacing of 8 to 24 m. The most widely used method for monitoring drainage discharge consists of measuring the corresponding water level at the drainage collector outlet using a calibration curve fitted at each measurement site, by designing a control section where flow is hydraulically managed. Before the 1980's and 1990's, data were recorded on a paper sheet that followed the motion of a floater linked to the water level. Nowadays, water level sensors (floating systems equipped with ultrasonic measurements) are used and data are digitally recorded. To ensure data homogeneity, a post-treatment was carried out on the longest series in order to limit uncertainties.

The 22 study plots are distributed over three distinct soil textures: silty, silty-clay, and clay. Fifteen of them are characterized by a silty soil texture covering most French regions (Fig. 1). The database is more limited as regards clayey soils, with sites like *Saint-Laurent* or *Courcival*. Some regions like Eastern France, which are strongly characterized by a clayey texture with just one clayey site, are not well represented. The SIDRA-RU performance in this region will be estimated from the SIDRA-RU global performance on the clayey soils from the database, comprising 44 years of observed discharges (Table 1). Moreover, some regions with a high drainage ratio, e.g. Southwestern France, have no observation points and are therefore not covered by this study. Lastly, the pseudogley soils are mostly correlated with the silty-clay soils, yet the database does not provide any relevant silty-clayey plots. Model performance will thus be estimated by the global performance for all such sites. Each site was defined by the aforementioned technical characteristics (drain depth, half-space between two successive drains, surface area), plus the length of available observed discharge logs and suitability to the split-sample test (Table 1).

Initially the French operation “secteur de reference” was developed to assess agronomic impacts of subsurface drainage using different drainage technics (such as pipe material, pipe spacing, …) on yields, water table management, workable days. Nevertheless, agronomic data were missing when we gathered hydrological chronics from data mining. Then we assume that the cultural practices do not affect the subsurface drainage hydrology on the study plots, excepted for no tillage technic (Dairon et al., 2017) which is not widespread in France or in the case of implemented winter cover crop (Meyer et al., 2018). This assumption is supported by 1) subsurface drainage is mainly effective during fall and winter, when actual evapotranspiration is weak; 2) significant differences in terms of soil moisture regime can be found mainly between cultivated and bare soils (Mitchelle and Genuchten, 1992). Since our study investigates drained soils in winter, and given that these are mainly used for winter crops such as wheat and maize (Zimmer, 1996), we assume the studied plots are cultivated every year over this season without a bare period. 3) these crop types similarly impact the subsurface drainage hydrology. Thus, this study is based on the hypothesis that annual crop rotation does not add significant bias to

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model calibration. 4) the cover crops effect is neglected due to the fact they are not widely used before 2012 and that for 19 out of 22 sites in the database the study periods end before 2012.

The meteorological data were provided by the SAFRAN database (Vidal et al., 2010), which provides a meteorological reanalysis over France in supplying rainfall and potential evapotranspiration (PET, based on the FAO-56 Penman-Monteith PET (Córdova et al., 2015)) data over all database-referenced plots. The data are available from 1959 to 2019 at a daily time step and a spatial resolution of 8 km, which is 1,000 times greater than the scale of the studied plots. This difference may introduce errors into the model data input that might stem from a spatial scale difference between the input data and the model output.

2.3 The SIDRA-RU model

The SIDRA-RU model is a semi-conceptual, lumped model that describes the hydrological processes of artificial drainage systems. This model is based on the principle of rainfall-drainage discharge conversion and uses the rainfall P and potential evapotranspiration PET to predict water table height and drainage discharge at the drainage network outlet. Three modules are integrated into the current version of SIDRA-RU (see Fig. 2):

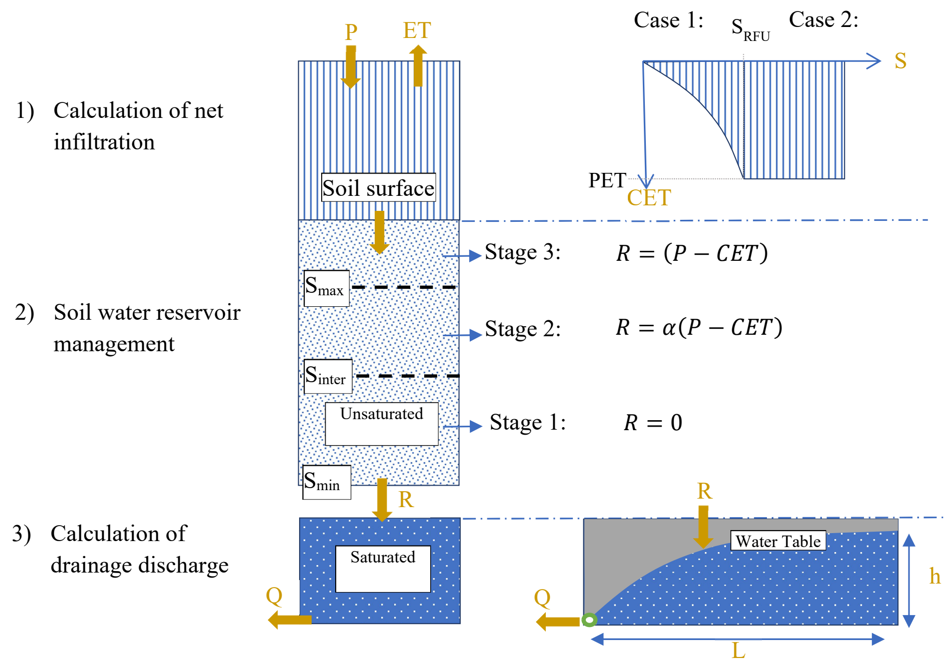

Figure 2: Diagram presenting the various modeling stages of the SIDRA-RU model

First, an evapotranspiration module converts PET into an approximate value of actual evapotranspiration, called corrected evapotranspiration CET, from the available water level S(t) in the storage to satisfy the evapotranspiration. A S_{RFU} threshold is set, thereby assigning the minimal water level to fully satisfy PET. If $S(t) \geq S_{RFU}$, CET(t) = PET(t); otherwise, CET(t) is calculated by Eq. (1). The net infiltration $P_{net}(t)$ is calculated by subtracting CET(t) from P(t).

$$CET(t) = PET(t) * e^{-\frac{S_{RFU}-S(t)}{S(t)}} \quad (1)$$

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Second, the RU module, a conceptual storage, calculates the water table recharge term R(t) (mm) from the meteorological input and water storage capacity of the soil reservoir. Two parameters control the RU module. On the one hand, the S_{inter}(mm) parameter (S_{RFU} = 0.4*S_{inter}) is an intermediate threshold of the soil reservoir defining the water quantity needed to generate flow in the reservoir before saturation of the storage. On the other hand, the S_{max} (mm) parameter represents the maximum capacity of the soil reservoir from which the net infiltration is fully converted into R(t). These two parameters reflect an approximate concept of the water holding capacity of a soil. Three stages are to be considered (see Fig. 2):

- Stage 1: $S(t) < S_{inter}$, the water level is too low to allow the formation of groundwater flows to the drains, e.g. Eq. (2):

  $$R(t) = 0\ ;\ S(t) = S(t-1) + P_{net}(t) \tag{2}$$

- Stage 2: $S(t) \in [S_{inter}; S_{max}[$, the water level is high enough to partially allow the formation of water table recharge R(t). Only proportion α, experimentally set at $1/3$, of the P_{net}(t) is converted to recharge R(t), while the remainder updates the water level, e.g. Eq. (3):

  $$R(t) = \alpha * \mathrm{P_{net}}(t)\ ;\ S(t+1) = (1-\alpha)\,\mathrm{P_{net}}(t) + S(t) \tag{3}$$

- Stage 3: $S(t) \geq \mathrm{S_{max}}$, the water storage is full, e.g. Eq. (4):

  $$R(t) = \mathrm{P_{net}}(t) = P(t) - CET(t). \tag{4}$$

Third, the calculated water table recharge R(t) feeds the original SIDRA module (Lesaffre and Zimmer, 1987b; Bouarfa and Zimmer, 2000) in order to calculate water table level h(t) and drainage discharge Q(t) (see Eqs. (5),(6)), in solving a semi-analytical formula derived from the Boussinesq equation (Boussinesq, 1904). This physically-based module is mainly controlled by two parameters: the horizontal hydraulic conductivity K(m/d), and drainage porosity μ(-).

$$\frac{dh(t)}{dt} = \frac{R(t) - \mathrm{K}\frac{\mathrm{h}(t)^2}{\mathrm{L}^2}}{A_2\mu}\ ;\ h(t+1) = h(t) + \frac{dh(t)}{dt} \tag{5}$$

$$\mathrm{Q}(t) = \mathrm{AK}\frac{\mathrm{h}(t)^2}{\mathrm{L}^2} + (1-\mathrm{A})\mathrm{R}(t) \tag{6}$$

- L: space between drain and inter-drain (m);
- A_2: second water table shape factor, $A_2 \approx 0.89$ (Lesaffre, 1989);
- A: third water table shape factor, $A = 0.869$ (Lesaffre, 1989). We are supposing here that the water table shape between the drain and the mid-drain is an ellipse. A therefore is obtained by integrating ¼ of this reference ellipse (see Fig. 2, Part 3: Calculation of drainage discharge).

Let's note that surface runoff is considered to be negligible in the model, only contributing slightly to total flow (Kuzmanovski et al., 2015). To be completely operational, SIDRA-RU requires information on technical characteristics, such as drain depth P(m) and spacing L(m) between the drain and inter-drain. Furthermore, a calibration process is required for four parameters: K and μ with the K/μ ratio describing the nervousness of the system, and S_{inter} and S_{max} from the RU module.

2.4 Methods

2.4.1 Calibration method

Parameter optimization (i.e. calibration) is commonly performed in hydrological modeling in order to adapt the hydrological model parameters to the specific study area context. This process is relevant for conceptual parameters since, by construction, they cannot be easily correlated with any physical characteristics of the studied system. Some of the physically-based parameters that are too difficult to measure can also be calibrated. In this context, the model calibration allows estimating parameters based on a comparison between observations and model simulations.

215 Model calibration is based on the algorithm implemented in the "airGR" package (Coron et al., 2017, 2020), as written in programming language R and composed of two parts. First, a systematic examination of the parameter space provides the most likely zone of convergence on the basis of a grid-screening algorithm (Mathevet, 2005), according to a given performance criterion (i.e. Objective Function, OF). Each parameter space is defined by its specific distribution and intrinsic statistical characteristics, with respect to the soil texture. Second, a steepest-descent local search procedure (Michel, 1991) seeks to improve the OF beginning with the grid-screening part and find a more accurate estimate of the parameter set, i.e. with higher model performance.

The hydraulic conductivity K and drainage porosity μ follow a log-normal distribution (Rousselot and Peyrieux, 1977; Kosugi, 1994, 1996, 1999; Rousseva et al., 2017; Ren and Santamarina, 2018). Parameters S_{inter} and S_{max} are conceptual and thus not defined by an intrinsic distribution. However, they are similar to the soil water holding capacity of a soil that follows a normal distribution (Vachaud et al., 1985; Brocca et al., 2007; Biswas et al., 2012; Biswas, 2019); consequently, in this study, both S_{inter} and S_{max} are described as following a normal distribution.

Various OFs are commonly used in hydrological calibration processes, depending in large part on the primary aim of the study. The most widespread OFs are RMSE (Anderson and Woessner, 1992), MSE (Ye et al., 2020), NSE (Nash and Sutcliffe, 1970) and, more recently, KGE' (Gupta et al., 2009). Our goal here is to evaluate model performance in order to simulate an entire hydrological cycle and represent the inter-annual variations of the study plot to produce long-term projections about drainage hydrology in the future. We thus introduce the KGE' criterion (Kling et al., 2012), an evolution of KGE and more relevant than NSE in reproducing internal flow rate variability (Santos et al., 2018). KGE' is defined by three modeling error components, as combined in Eq. (7):

$$KGE' = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \quad (7)$$

with:

- $r = \frac{cov(Q_{obs},Q_{sim})}{\sigma_{obs}{}^2\sigma_{sim}{}^2}$: the Pearson correlation coefficient, which serves to evaluate the error in both shape and timing between observed and simulated flows, with cov being the covariance between observed and simulated flows and σ their standard deviation;
- $\beta = \frac{\mu_{sim}}{\mu_{obs}}$: the bias term, which evaluates the bias between observed and simulated flows, with μ being the mean of observed and simulated discharges, respectively;
- $\gamma = \frac{\mu_{obs}\sigma_{sim}}{\sigma_{obs}\mu_{sim}}$: the ratio between observed and simulated coefficients of variation, serving to evaluate the flow variability bias.

KGE' values range from $-\infty$ to 1; a perfect model performance is obtained when KGE' = 1. During the model calibration step, the data series over the whole time period were used for each studied plot (Table 1).

2.4.2 Split-sample test

The temporal robustness of the model is designed to assess its utility when facing a different time period from that chosen for calibration, i.e. the model's capacity to perform equally well over different and contrasted time periods (Li et al., 2011). This point is particularly important in assessing robustness when the model is intended for application under future climate change scenarios (Thirel et al., 2015b).

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The choice of evaluation strategy mainly depends on model structure. For lumped conceptual models such as SIDRA-RU, a simple split-sample test (Klemeš, 1986) is sufficient to assess the robustness of such a model (Refsgaard and Storm, 1996; Daggupati et al., 2015). The split-sample test, as illustrated in Fig. 3, consists of splitting the data period into two subperiods (P1 and P2) and then calibrating the model over both of them, independently.
Thus, two optimal parameter sets are obtained (one over P1 the other over P2), with each one being tested over the other subperiod (e.g. evaluation period P2 for a calibration over period P1). If the evaluation of KGE' scores, i.e. from the evaluation period, lies close to the KGE' score calibration, i.e. from the calibration period, then the model calibration is considered as temporally robust and independent of the chosen time period.
This test was performed on the records from 9 plots showing at least 10 years of time-series data (Table 1). These time-series were split into two equal-length periods, and the KGE' scores obtained over the calibration and evaluation periods were assessed and compared.

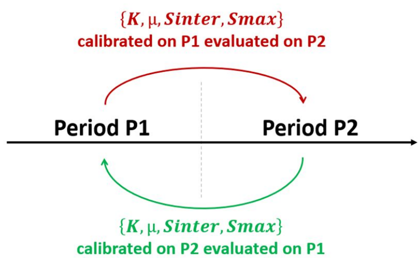

Figure 3: Functional diagram of the split-sample test

2.4.3 Numerical evaluation criteria

Evaluating and highlighting model performance limits during the calibration process using numerical scores such as NSE, RMSE or KGE criteria is often recommended, in addition to the graphical analysis (Moriasi et al., 2015). However, understanding their evolution is difficult. To avoid this difficulty, a classification of model performance by a range of numerical scores values will help to assess the calibration quality.

In this study, the KGE' score is used because of its performance regarding the seasonal variability of the subsurface drainage discharge. In the subsurface drainage modelling, the bibliography is not exhaustive regarding KGE' score ranges and the few articles that exist deal with catchment hydrology modelling (Crochemore et al., 2015; Poncelet et al., 2017). The NSE criterion is detailed more extensively (Moriasi et al., 2007; Ritter and Muñoz-Carpena, 2013; Moriasi et al., 2015) and studies dealing with the model calibration using NSE' score in subsurface drainage modelling showed that values upper than 0.5 are considered as acceptable (Helwig et al., 2002; Wang et al., 2006; Tuohy et al., 2018a). Even if the comparison between NSE and the KGE' scores is theoretically incorrect and not unequivocal (Criss and Winston, 2008; Knoben et al., 2019), we assume that the score ranges using NSE criterion can be transposed to those using KGE' criterion. We assume herein to score the KGE' values as follows: the model calibration using KGE' values greater than or equal to 0.5 leads to acceptable model performance. KGE' values ranging from 0.6 to 0.7 were considered to be a good performance, while a KGE' of greater than or equal to 0.7 was considered a very good performance (Table 2).

The model was also evaluated in terms of the capacity to reproduce annual cumulative discharges, with a direct comparison conducted between observed and simulated flow rates using the linear correlation coefficient R^2 (Bailly and Carrère, 2015) and the associated linear regression equation.

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3. Results

3.1 Model performances after the calibration

Table 1 lists performance over the entire calibration periods obtained from all 22 sites. The calibration performance differs from one site to another, with poor KGE' values, e.g. for the *Courcival* site, and some "very good" KGE' values, e.g. the *Parisot* site. For 21 of the 22 referenced plots, the calibration KGE' lie above 0.5, thus revealing at least "acceptable" KGE' values. The silty plots show values ranging from 0.54 to 0.83, including the best model performances, such as the *La Jaillière* plot, with a KGE' of 0.83. However, the silty-clayey plots show relatively homogenous KGE' values, ranging from 0.54 to 0.76. As regards the clayey plots, KGE' values display a wider range than on the silty-clayey plots, i.e. from 0.44 at the *Courcival* plot to 0.76 at *Saint Laurent*. *Courcival* is the only one indicating an "unsatisfactory" KGE' value.

Table 2 classifies model performance from each soil texture according to the score ranges. Performance is spread across the three observable soil textures, especially on the silty soils, which constitute 80% of French drainage and compose 15 of the plots. On this soil texture, the model assessment shows three "acceptable" KGE' values, reaching "good" for six of them and "very good" for another six. On the silty-clayey soil, one plot shows "acceptable" performance while the other two register "very good" performance.

Table 2: KGE' calibration scores

KGE' value range	Scores	Number of plots	Silty soils	Silty-clayey soils	Clayey soils
< 0.50	Unsatisfactory	1	-	-	1
[0.50 - 0.60[	Acceptable	6	3	1	2
[0.60 - 0.70[	Good	6	6	-	-
≥ 0.70	Very good	9	6	2	1
Total	-	22	15	3	4

The SIDRA-RU calibration on clay plots shows a weaker performance, with one "unsatisfactory" KGE' value, two "acceptable" values and one "very good" value. Nevertheless, the SIRA-RU model performance on clayey soils remains "acceptable" with three sites producing at least one "acceptable" score. The initial results indicate that the SIDRA-RU model can be well calibrated on all three main soil textures.

The *La Jaillière* plot is used as an example to illustrate the time-series temporal comparison between observed and simulated discharges over 16 years (see Fig. 4). The same graphs are available in Appendix A to illustrate the case of a silty-clayey soil at *La Bouzule_P2* and in Appendix B for the case of a clayey soil at *Saint-Laurent_P1*.

Figure 4 shows that the simulated discharges are in good agreement with observations in terms of seasonal dynamics (dry and wet season alternation) and cumulative distribution. Rainfall series are not directly correlated with discharge, thus demonstrating that a rainfall event is not converted to discharge every time, mainly due to the nonlinear processes controlling the precipitation-discharge transformation (i.e. the reservoir must first be filled to generate runoff). However, winter rains typically turn into discharge after a delay of one or two days, subsequent to which the soil water level reaches the S_{inter} value. A graphical analysis shows that simulated drainage discharges generally start in the same period as the observed discharge, with various delays depending on soil texture. The siltier the plot texture, the shorter the delay. For clayey soils, this delay can be long, up to a full month. During hydrological year 2002-03, the drainage season starts on the same day for both simulation and observation (i.e. November 1st).

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In 2002-03, the maximum observed drainage discharge lies close to 15 mm/d, versus a lower simulated peak of 12 mm/d. The SIDRA-RU model correctly predicts the temporal evolution and magnitude of drainage discharges while accurately delimiting the drainage seasons. The simulated peak flows closely match the observed ones. Peak flows often tend to be underestimated in simulation by a few mm/d, although the timing is usually well estimated.

The dry periods are on the whole well represented by the model. Drying times are a bit longer for the simulations, but typically lie within a few days. Note that spring runoffs are sometimes not well simulated, as was the case in 2001-02 or in 2006-07.

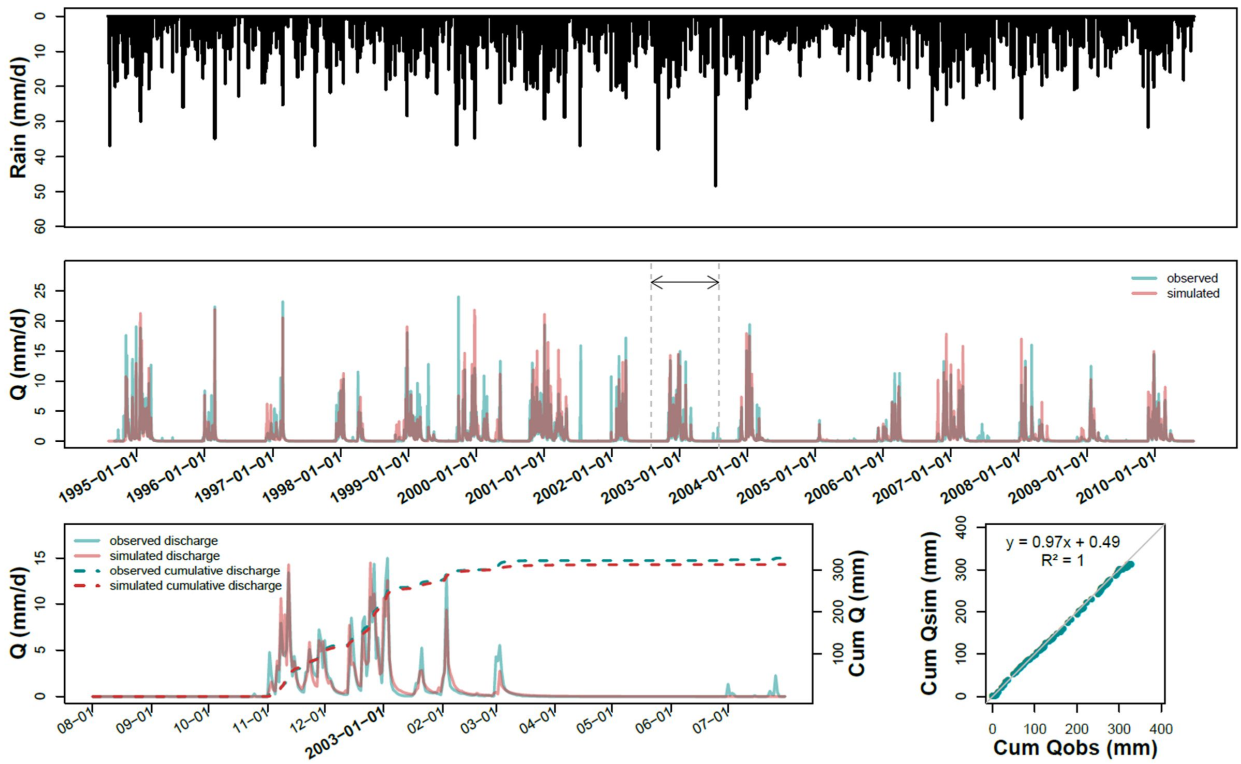

Figure 4: Hydrograph on La Jaillière after calibration over the entire available record, plus a close-up on hydrological year 2002-03 and the associated temporal and direct comparisons between observed (blue curves) and predicted (red curves) cumulative discharges

The capacity of the SIDRA-RU model to respect the water balance is also assessed. Figure 4 shows that the simulated cumulative drainage discharge over 2002-03 lies close to the observed discharge, with a slight underestimation of 10 mm, i.e. below 3% of the annual drained water balance relative to 350 mm. The linear regression between observed and simulated cumulative discharges yields an equation close to a 1:1 equation with an R^2 of 1, leading to the assessment that the water balance is fully respected over this year on the *La Jaillière* plot, in both time and total quantity.

Figure 5 shows a comparison between the predicted and observed total cumulative discharges on each plot and for each hydrological year, classified by soil texture. The linear regressions are close to the 1:1 equation with an R^2 above 0.9 for all three textures, thereby indicating that SIDRA-RU respects the water balance nearly all the time. However, Fig.5 shows significant discrepancies between prediction and observation, especially on the silty plots, with a deviation of the

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simulated cumulative discharge of 300 mm. The same observations are drawn on clay soils with the same discrepancies and a smaller dataset.

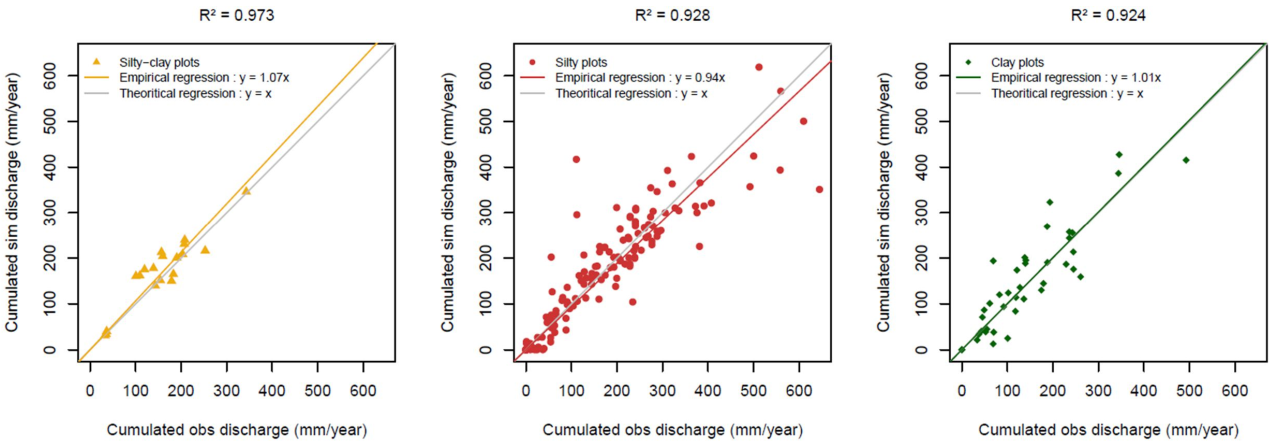

Figure 5: Comparison of the drained annual discharges between simulation and observation - each point represents the drained water quantity from a hydrological year for a given site, and all points have been classified by texture

In order to use the SIDRA-RU model for a long-term prediction of agricultural drainage management in France, for example through coupling with pesticide or nitrate leaching modules, the model must first be able to reproduce both high and low drainage discharge. Figure 6a depicts the differences in the Q05 quantile between observed and simulated drainage discharge. This quantile represents the values under which the annual drainage discharge occurs 5% of the time, in order to evaluate low flows. The Q95 analysis (Fig. 6b) value under which the annual drainage discharge occurs in 95% of the cases serves to evaluate high flows. Figure 6c displays an analysis of the average discharges (Q_{mean}). This Q_{mean} analysis is applied to each hydrological year of each plot on the non-zero flows, thus reducing the predicted drainage discharges by the observed ones; results are classified by texture using boxplots (Tukey, 1977).

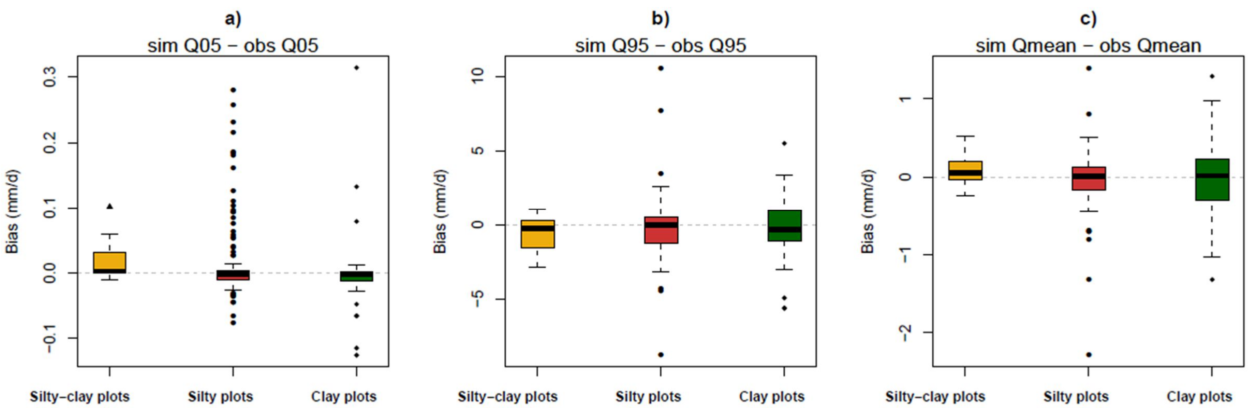

Figure 6: Differences between prediction and observation of low (Q05), high (Q95) and average (Q_{mean}) flows. Each hydrological year from each site is independently considered. Results are compiled by soil texture: 142 points for silty soils, 17 for silty-clayey soils, and 44 for clayey soils.

Regarding the Q05 quantiles (Fig. 6a), results show that for the three textures, the Q05 ranges are all very close to 0, with some extreme points (mainly on the silty texture). The medians all lie close to zero as well, revealing that the model correctly predicts low flows. Regarding the Q95 quantiles (Fig. 6b), the median values of the boxplots are again near 0;

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however, the Q95 ranges lie above those of the Q05 quantiles. On silty soils, 50% of the deviations range from -1 mm to +1 mm, and 98% of deviations range between -3 mm and +3 mm. Similarly, for silty-clayey soils, drainage discharges range from -3 mm to -2 mm; the discrepancies are larger on clayey soils, where the Q95 varies from -4 mm to +4 mm. According to Fig. 4, the SIDRA-RU model accurately predicts high flows yet with significant bias for some extremely high rainfall events. Figure 6c shows that the boxplot medians for the Q_{mean} also lie close to zero. Q_{mean} ranges from -0.5 mm to +0.5 mm for silty soils, from -0.3 mm to +0.6 mm for silty-clayey soils and from -0.8 mm to +0.9 mm for clay soils. SIDRA-RU performs at a level of good agreement with respect to the average discharges. The deviation on Q_{mean} is higher on clayey soils, thus reflecting the difficulties of the SIDRA-RU model in simulating Q_{mean} on this soil texture. This finding is consistent with previous observations made on the annual cumulative discharges and KGE' values for clayey soils, which exhibit slightly lower values than those for the other two textures.

3.2 Model robustness

The KGE' values obtained during the evaluation period are then compared to those obtained during the calibration period, as illustrated in Fig. 7. For starters, this figure shows that all points are located under the line y = x, relating therefore that all evaluation KGE' values from a specific period are always less than calibration KGE' values from the same period. This result seems to be normal because an evaluation parameter set will normally always yield a lower KGE' value than that obtained from the calibration parameter set, thus corresponding to the best result depending on the chosen objective function, which here is the KGE' criterion. Moreover, Fig. 7 indicates that the deviations differ according to soil texture.

On silty soils, the maximum variation is observed at *Melarchez*, with KGE' values varying from 0.66 to 0.55 over the second subperiod (Table 1), but the evaluation and calibration KGE' values are similar in four of the silty plots, over both

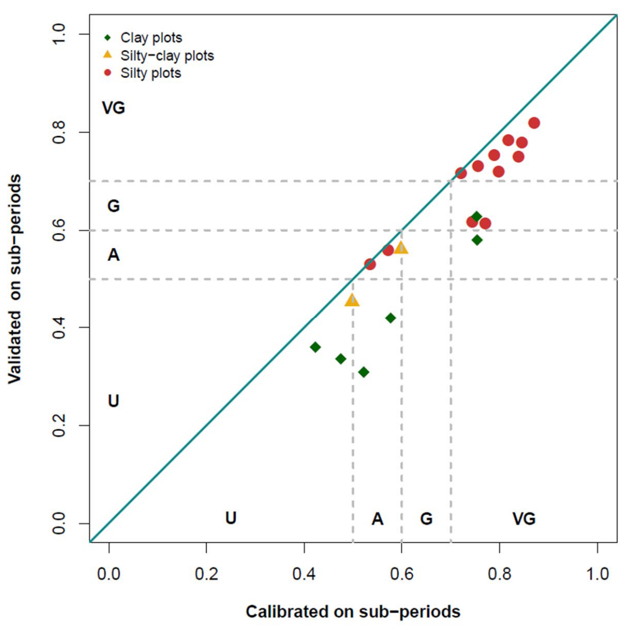

Figure 7: Comparison between the KGE' values assessed on the calibration and evaluation period at the 9 plots used for the split-sample test: (U) Unsatisfactory, (A) Acceptable, (G) Good, and (VG) Very Good

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subperiods. Furthermore, the evaluation KGE' values on silty soils remain at least "acceptable". Results are similar for the silty-clayey soils, which feature validated KGE' values close to the calibration values.

The deviations in KGE' values are more significant on clayey soils. Indeed, KGE' varies from 0.75 to 0.58 at the *Saint Laurent* site, i.e. a score somewhere between "very good" and "acceptable". *Saint Laurent_P2* is the only clay plot that remains at least "acceptable" according to Table 2. On the *La Bouzule_P1* plot, the KGE' value is reduced from 0.52 in calibration to 0.31 in validation. However, the results of Fig. 7 show that the KGE' deviations on clayey soils are less than 0.21. These performances are noteworthy when considering the difficulties the model experiences on clayey soils during calibration. A comparison between calibration and evaluation KGE' values confirms that the SIDRA-RU model is temporally robust, especially on silty soils.

A graphical comparison between the predicted drainage discharges calculated using the evaluation parameter set and the observed discharges helps assess model robustness, as depicted in Fig. 8 at *La Jaillière* during the 2002-03 hydrological year. The calibration simulations use the parameter set calibrated over subperiod P2 (including the 2002-03 season) while the evaluation simulations use the parameter set calibrated over subperiod P1. Figure 8 shows that both calibration and evaluation drainage discharges lie close to the observed levels. The peak flows from both simulation curves have been superimposed on the main part of the drainage season, hence the evaluation parameter set performs well over the studied time period.

Differences between the two simulations only exist at the beginning of the drainage season, as strongly controlled by the RU module. The drainage season seems to start the same day from both simulation curves, but the discharge magnitude during the first few days differs from one simulation to another. The same graphical approach is used on a clayey soil available in Appendix C for *Saint Laurent_P2* in the 1982-83 season. These observations are similar to the previous ones on *La Jaillière*.

Similar observations are also recorded on the cumulative discharges (Fig. 8), which display an identical behavior, except for a gap between two predicted flows appearing at the start of the drainage season, and tend to remain so throughout the year. A direct comparison of the cumulative flows between observation and simulation yields linear regressions near the 1:1 equation, with an R^2 of 0.999 in evaluation and 1 in calibration. This result attests to the water balance in the calibration being close to that in the evaluation. The same results are shown in Appendix C for *Saint Laurent_P2*. With the exception

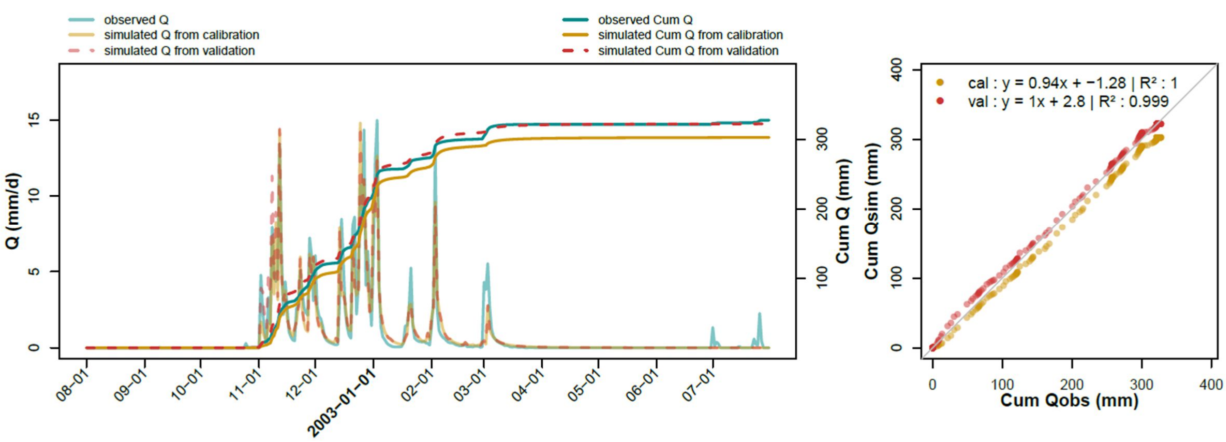

Figure 8: Hydrographs of observed and predicted discharges on calibration (parameter set derived from subperiod P2) and evaluation (parameter set from subperiod P1) scoped at La Jaillière in 2002-03. Predicted cumulative discharges are directly compared to observations.

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of the deviation at the beginning of the curves due to an early evaluation start, the curves are parallel. The water balances are similar when using either parameter set.

The use of the split-sample test for model calibration raises the question of parameter set similarity between the two calibration periods across all sites studied. Figure 9 illustrates the evolution of each of the four parameters (K, μ, S_{inter}, S_{max}) based on the two calibration periods. Each study site has been labeled in Fig. 9 with the available corresponding index from Table 1.

Results indicate that hydraulic conductivity K is the least-changing parameter between the two periods. One of the two extreme outlier points corresponds to *Melarchez* (Point S4), where K changes from 1.46 m/d for subperiod P1 to 1.75 m/d for subperiod P2, showing that hydraulic conductivity values remain within the same order of magnitude. Similar results are found for drainage porosity μ, with 7 of the 9 sites lying very close to the 1:1 line, thus confirming the similarity of both calibrated μ values. *La Bouzule_P1* (i.e. C1, see Fig. 9) displays the strongest deviation, i.e. from 0.03 in P1 to 0.01 in P2, which is nonetheless a small variation and acknowledges that μ is conserved between both subperiods.

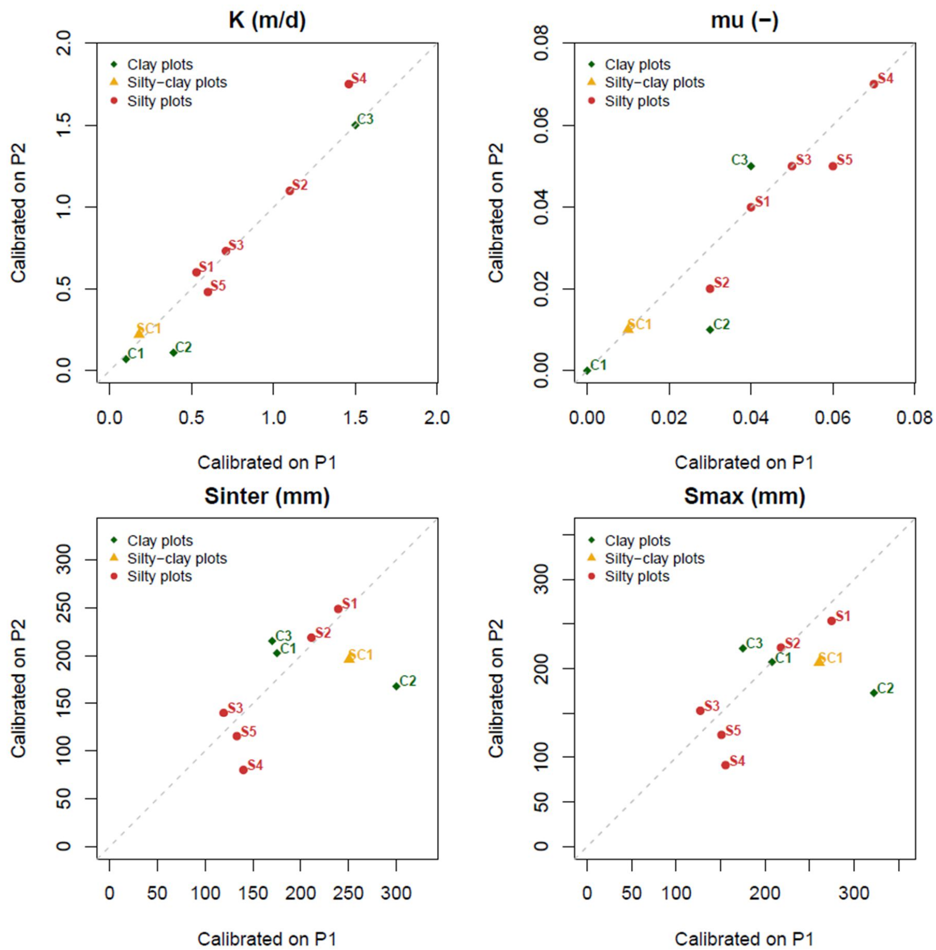

Figure 9: Comparison of parameter sets from both calibration periods (sites are referenced by their associated index assigned from Table 1)

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Soil reservoir parameters S_{inter} and S_{max} are those exhibiting the greatest change between the two calibrated parameter sets, and in a way that remains very similar. Among the 9 sites, 6 show a deviation of less than 40 mm on S_{max}, which seems to be acceptable. However, for the three other sites, i.e. *Melarchez* (S4), *La Bouzule_P1* (C2) and *Saint Laurent_P2* (C3), deviations range from 50 mm to 150 mm, indicating larger deviations for both conceptual parameters especially on clayey soils. These observations are consistent with those derived from Fig. 8 for *La Jaillière* as well as those from Appendix C. The RU parameters are slightly less stable between calibration subperiods than are the SIDRA parameters.

4. Discussion

4.1 A representative database

The literature (Perrin, 2000; Coron et al., 2012; Montanari et al., 2013; Thirel et al., 2015a) suggests that when assessing generalizable hydrological models, the aim typically consists of determining the ability of a model to reproduce the hydrological behaviors of various study areas. The larger the database, the more reliable the study because the model is being evaluated on a wider diversity of geological and climatic contexts. To the best of our knowledge however, in drainage modeling, models are often evaluated on a short-term database, with just a few years on a few sites, e.g.: DRAINMOD (Skaggs et al., 2012), MACRO (Jarvis and Larsbo 2012), ADAPT (Gowda et al., 2012), SWAT (Arnold et al., 2012). The lack of data limits the opportunities to test models in various soil types and moreover prevents assessing the relevance of models over a large range of spatial scales.

The database used in this study was specifically built to assess the performance of a drainage discharge model on a larger dataset. 22 experimental sites were compiled, accounting for nearly 200 hydrological years spread over the main drainage areas in France, on contrasted soil types and in different pedoclimatic settings with an extensive plot scale range. This database has been classified according to three main soil textures (silty, silty-clayey and clayey) using available drainage discharge data. All regions with a high drainage rate are not well represented; however, 80% of French drained soils do have silty soil textures, as represented by 15 of the 22 plots in the database. The real advantage of this database is the ability to apply the model to referenced sites that represent a large majority of France's drainage diversity. This topic constitutes both the originality and a key contribution of this study.

4.2 A parsimonious hydrological model

The diversity of the database introduced requires a model that operates correctly and in accordance with each site's specific conditions, i.e. as generalizable as possible. As such, the simplicity of the SIDRA-RU model offers a major advantage. Among the more common subsurface drainage models, SIDRA-RU is distinguished by virtue of a simple design. The model is lumped and requires the calibration of four parameters. Compared to the original SIDRA model version (Lesaffre and Zimmer, 1987a), the current version simulates continuous discharges over several hydrological years, thus simulating both wet and dry periods. The calibration process only requires brief rudimentary knowledge of soil texture, used here as *a priori* input data to establish the model parameter distributions. Regarding input variables, the model requires rainfall and PET data at a daily time step to predict the drainage discharge. Managed along with the SAFRAN climate database to provide data needed throughout France, SIDRA-RU can easily be launched on all drained areas across the territory.

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4.3 SIDRA-RU model performance

Once calibrated, results show that the model performance ranges from "acceptable" to "very good" on all sites according to KGE' value, with an exception for clayey soil. The model provides accurate simulations on small plots (0.8 ha at *Parisot*) as well as on large plots (700 ha at *Melarchez*). In comparing the SIDRA-RU performance with that of other models tested in more local studies, SIDRA-RU is just a small step behind. For a vast majority of simulations carried out by the model, the annual water balance is indeed respected. These performances are close to those obtained using pure physical approaches, like the models RZWQM (Ma et al., 2007) and ADAPT (Sands et al., 2003). Moreover, this congruence in annual cumulative water quantity between observation (integrating drained discharge and runoff) and simulation (without runoff) validates the assumption that considers runoff to be negligible, according to the conclusions of Kuzmanovski et al. (2015). This result also supports the assumption made on the fact that the effect of the current culture is neglected as long as subsurface drainage occurs mainly in winter on non-bare soil. Similarly, the SIDRA-RU model respects the temporal variation between dry and wet periods; moreover, flood peaks are simulated on time as well as recession periods, which is comparable to more complex models, e.g. DRAINMOD (Skaggs et al., 2012), CATHY (Muma et al., 2017) and RZQWM (Jiang et al., 2020b). Overall, the simple design of the SIDRA-RU model allows achieving a performance at least as good as that found in current models, like MACRO on the *La Jaillière* plot (Kuzmanovski et al., 2015) or WEPP (Revuelta-Acosta et al., 2021).

Let's note however that some peak flows are slightly underestimated; one explanation might be that the SIDRA-RU model is calibrated on both high and low drainage discharges, as represented by a unique parameter set, which introduces biases. These biases become more significant on the two extreme discharges. Furthermore, the missed variations sometimes lead to missing the beginning of the drainage season. During some hydrological years, the observed drainage discharge starts before water level in the soil reservoir reaches the S_{inter} threshold in simulation. This phenomenon might stem from assumptions related to SIDRA-RU, like neglecting lateral communication with other plots of land, potentially causing a problem in choosing the appropriate perspective at the beginning of the drainage season as a hydrological indicator in long-term studies. This early start might also prevent completely filling the annual water balance. However, deviations in this indicator remain minor in the large majority of the cases, from 5% to 10%, and produce no significant consequences on long-term studies.

The split-sample test shows that performances using calibration parameters from both subperiods are similar across all sites, with the evaluation KGE' values being close to the calibration values and moreover remaining quite good, especially on silty soils and silty-clayey soils. Performance is slightly lower on the clayey soils yet remains acceptable. The drainage discharge behaviors are similar as well, as logs from both evaluation and calibration simulations do merge on most occasions with equal water balances. These results assess the temporal robustness of the SIDRA-RU model on the studied textures, which represent the largest proportion of drained areas in France.

4.4 Calibration consistency

Another important analysis is the consistency of model calibration. Indeed, the SIDRA module solves a simplified formula derived from the Boussinesq equation and requires a good estimation of both hydraulic parameters, namely hydraulic conductivity K and drainage porosity μ. Thus, model calibration is only relevant if the calibrated K and μ are probable according to the case study soil type. Figure 10 compares the distribution of calibrated values of silty plots with the distribution obtained using the measured values of K and μ during tests conducted on reference silty drainage sites. The

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theoretical curves have also been drawn according to these distributions using the mean and standard deviation of each sample while following a log-normal law. The database provided only allows assessing the quality of the calibration on silty soils since 15 sites are referenced for this particular texture. On both of the other soil textures, only three sites are available for silty-clayey soils and four for clayey soils, which is insufficient to compare the calibrated values to a reference base, thus constituting a limitation of this study.

Regarding hydraulic conductivity K, some divergences exist between the reference base and the calibrated values, especially for the highest hydraulic conductivity values, i.e. close to 2 m/d. However, over the remaining range of values, the histograms are consistent. The theoretical laws are also similar between the reference base and calibrated values even though the curve from the calibrated value shows a higher standard deviation, due to high hydraulic conductivity values. Despite some discrepancies, the distribution of calibrated K values for silty soils seems to be relevant based on soil type. As for μ, the same method is applied (see Fig. 10); the histograms and theoretical laws do match, thereby concluding that the calibration process reliably estimates μ as well. The split-sample test confirms this analysis, in showing that K and μ from silty sites are conserved from both calibration subperiods. Each K and μ value seems to be calibrated with a robust and consistent value, hence attesting to the relevance of calibration on the physically-based module.
Regarding S_{inter} and S_{max}, these parameters are conceptual and no observed data can be used as a reference to define statistical distributions. Furthermore, even if they were to constitute a conceptual approach of water holding capacity, the soil texture is insufficient as a description, and no distributions can be determined based on the classification of the database employed. One solution might be to compare S_{inter} and S_{max} of each site with the associated real value of the water holding capacity; however, the database does not provide this information for every experimental site and measuring it *in situ* is very expensive, thus making such a study infeasible.

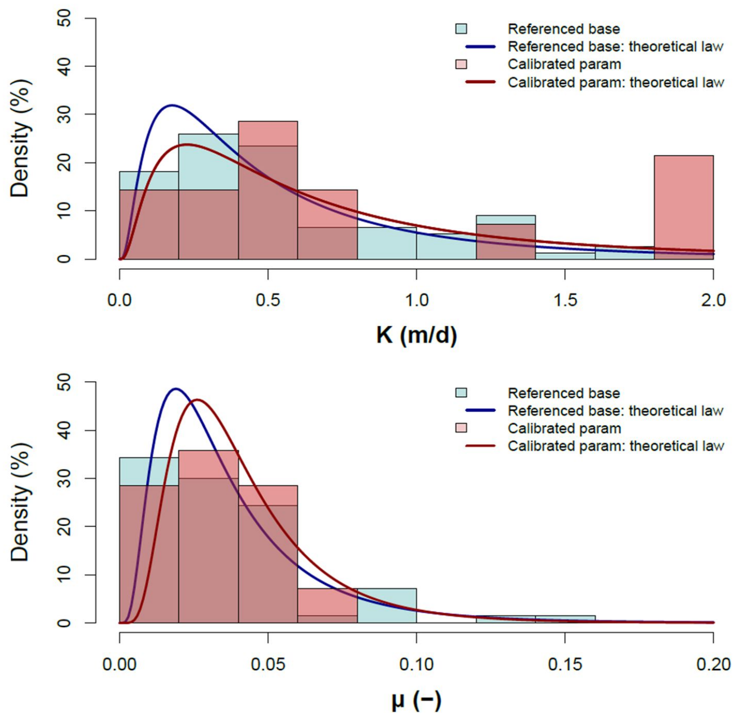

Figure 10: Distribution of K and μ from calibrated values on silty soils vs. values extracted from reference drainage sites placed on silty soils

4.5 Weaker performance on clayey soils

The literature identifies clayey soils as a recurring problem for drainage modeling (Robinson et al., 1987; Snow et al., 2007), especially in mole drainage, as currently practiced on heavy clayey soils and swelling clays (Jarvis and Leeds-Harrison, 1987; Tuohy et al., 2016). In this respect, SIDRA-RU is not an exception and shows a weaker performance on clayey soils. This finding is mainly due to a difference in hydraulic characteristics between clayey and silty soils, on which the model design is primarily based. Clay soils are characterized by natural pedological deformations, like soil surface fracturing, that lead to preferential flow zones before saturation (Beven and Germann, 1982; Jarvis and Leeds-Harrison, 1987). This problem is particularly acute at the *Courcival* site, where the drains lie on a heavy clay soil layer, at a depth varying from 20 cm to 30 cm. The horizontal soil profile is no longer homogeneous, which contradicts one of the main hypotheses of SIDRA. Moreover, agricultural practices like plowing exacerbate this phenomenon and therefore affect soil porosity.

Another critical assumption of the SIDRA module is the elliptical shape of the water table; this assumption facilitates the numerical resolution of the Boussinesq equation. As regards heavy clayey soils, this hypothesis is no longer suitable since the water table shape evolves towards a rectangular structure (Fig. 11).

This phenomenon is due to the very low hydraulic conductivity (Robinson and Rycroft, 1999; Skaggs et al., 1999), which for SIDRA-RU is difficult to integrate. Furthermore, the water table level drops when approaching the drain because the soil has been turned over on this profile in order to bury the drain, as is similar to the aforementioned natural pedological deformations.

A likely consequence of these phenomena is a drainage discharge occurring before total soil saturation, which SIDRA-RU fails to correctly detect. The RU module design partially addresses this problem, in generating a soil profile recharge before saturation, but this remains a major limitation of the model, i.e. the more clayey the soil, the poorer the model performance. A soil is considered to be mainly clayey with a clay fraction above 35% (Richer-de-Forges et al., 2008), which can be defined as the limit beyond which good model performance is no longer guaranteed.

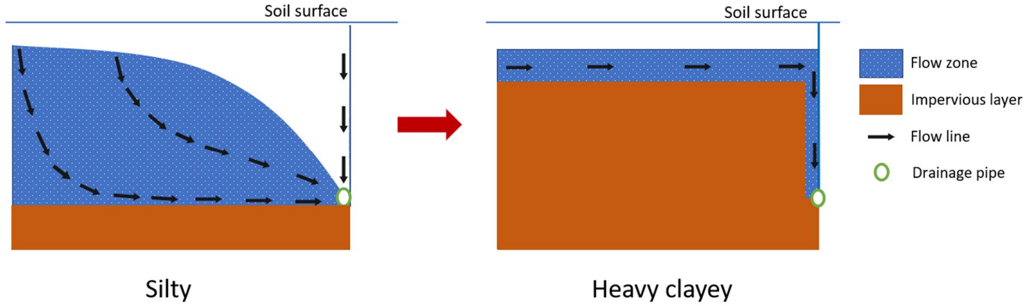

Figure 11 : Evolution of the water table shape between a silty and a heavy clayey drained soil, adapted from Bouarfa and Zimmer, 2000 and Branger et al., 2009

4.6 A less robust RU module

Another limitation of this model is the lack of robustness in the RU parameters, which are less stable between the calibration subperiods than the SIDRA parameters. This issue might originate from dependencies of the RU module on interannual meteorological variations. The S_{inter} parameter represents the soil storage threshold allowing the model to initiate each drainage season. If the calibration period is mainly characterized by dry events, S_{inter} values increase relative to a conventional period, hence the model stores a larger quantity of water, delaying the start of the drainage season.

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Conversely, a wet calibration period will tend to decrease S_{inter} and S_{max} in anticipation of the start of the drainage season. Consequently, if the two subperiods are meteorologically contrasted, S_{inter} and S_{max} will differ from the two calibrated parameter sets. One solution might be to consider the S_{inter} parameter as a variable adjusted according to the meteorological conditions of the previous year as well as to soil parameters, e.g. actual water holding capacity defined as a new parameter. Clayey soils intensify this robustness issue due to weather fluctuations exacerbating the formation of preferential flow zones.

Furthermore, the RU module intends to be an approximate concept of the water holding capacity, soil property which interacts with the current crops. Indeed, the increasing water holding capacity generates an increasing crop yield (He and Wang, 2019). Consequently, the lack of data regarding the crop practices such as the use of cover crops on the study plots might also be behind this robustness issue. However, it remains unclear whether having these data would solve the problem as for example cover crops do not significantly influence the water holding capacity value (Irmak et al., 2018).

4.7 Interpretations bounded by choices

The last point we wish to discuss deals with the dependency of the aforementioned interpretations on the conditions and choices involved in conducting this study. We noted above the lack of data in the database used for certain French regions. Adopting assumptions about model performance is then a relevant alternative yet depends on arbitrary decisions. Adding reference sites could complete and significantly improve the SIDRA-RU model robustness analysis.

Furthermore, the choice of calibration process drives the calibration results, based on study goals. We have implemented herein a grid-screening algorithm that assigns the best combination of parameters according to their respective distributions, coupled with a step-by-step algorithm. This approach has the advantage of being entirely automatic theoretically and thus eliminates the subjective aspect of calibration; however, external decisions influencing the results are still necessary.

As an example, in order to track the main purpose of this study, SIDRA-RU is calibrated using the KGE' criterion as its OF, in combining three criteria (Kling et al., 2012), for a relevant approach to properly representing the interannual variability of drainage discharge. However, if the SIDRA-RU model is to be used for another purpose, like predictions of drainage season initiation, then the KGE' criterion might be not the most efficient OF. This statement highlights the fact that the SIDRA-RU model is robust with respect to KGE', yet nothing proves the same for other OFs or purposes.

Moreover, the distribution functions of each model parameter are required for the calibration, which in this case depends on the decision to classify soils based on their texture. Regarding K and μ, these distributions are established from measured data extracted from the reference drainage tests conducted in the 1980's, as mentioned above. The measurements are subjected to uncertainty, depending on both the number of measurements and the method employed; they constitute a significant source of error. We also mentioned above that classifying a soil by soil texture alone is a major assumption and one that distorts the distributions. Consequently, the calibrated parameters might be biased, due to an overly wide range of referenced values biasing the mean and standard deviation, as shown in Fig. 10 on silty sites. This problem is particularly worrisome since both those parameters are physical, making it prohibitive to set outliers.

Driving the distribution with realistic value ranges at each site can prove to be a relevant solution. For example, if we consider that on a specific soil K might be included within a smaller value range, according to information obtained from the study site, then the calibration might lead to a more realistic value of K. This strategy reduces the risk of extracting parameters with secondary optima, and the calibration accuracy is refined. However, better knowledge of the soil characteristics is required, with the assumption that knowing the reliable ranges and calibration becomes semi-automatic,

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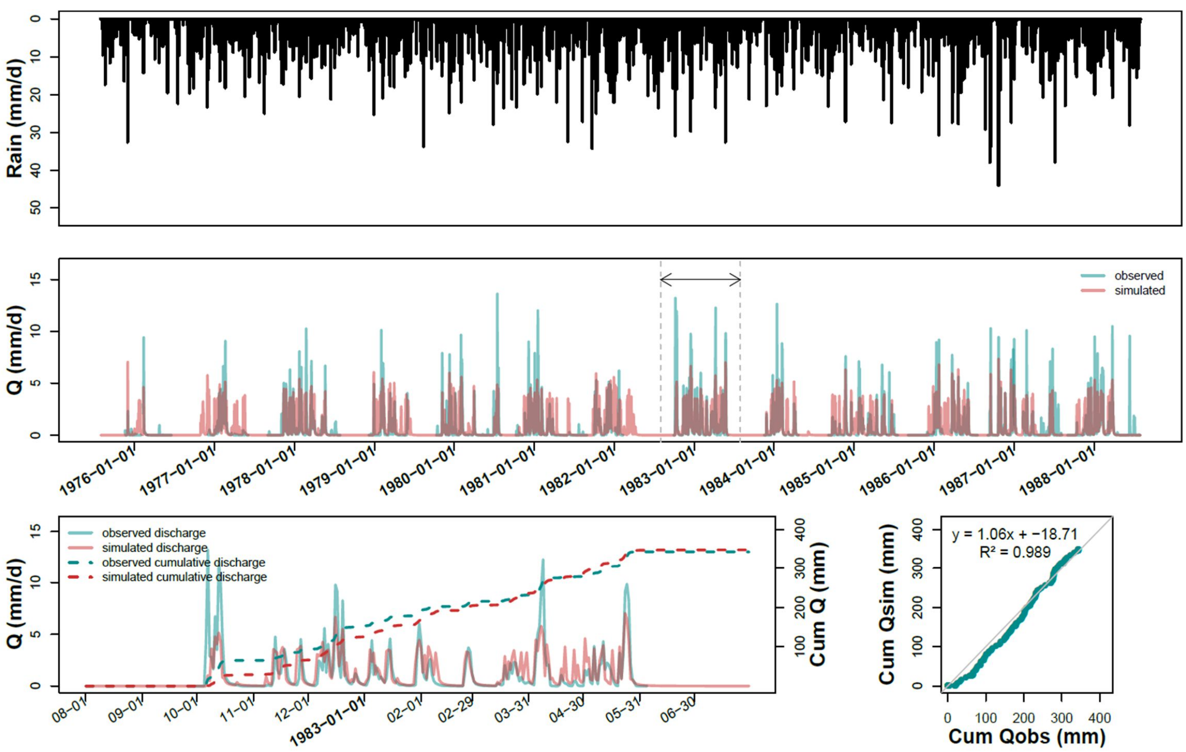
introducing an arbitrary decision-making factor into the process. In addition, this supplementary knowledge requires relatively complete databases of drained plots, which as previously discussed constitutes a persistent issue.

5. Conclusion

The aim of this study has been to implement an exhaustive database characterizing the main drainage areas throughout France, so as to assess the performance and robustness of the SIDRA-RU model. A database comprising 22 drained sites was built to represent French soil diversity and describe the three main soil textures from France's main drained parts (i.e. silty, silty-clayey and clayey). Results indicate that the SIDRA-RU model yields satisfactory drainage discharge simulations on nearly all studied sites. The model shows especially good performance on silty soils, which account for 80% of all drained plots in France. Despite a number of limitations, particularly for clayey soils, the model was found to be temporally robust at the national scale, which enables conducting long-term impact studies. Once calibrated, this model can indeed be used to assess the resilience of drainage systems under climate change according to climate scenarios like those from the CMIP5 project (Eyring et al., 2007; Taylor et al., 2011) or the upcoming CMIP6 project. Moreover, the model could also be coupled with pesticide leaching modules like PESTDRAIN (Branger et al., 2009) in order to assess the risk of pollution transfer through drains during the wet season as well as for use as a policy evaluation tool.

6. Appendices



Appendix A: Illustration of observed and simulated discharges calibrated over the total period for the plot of La_Bouzule_P2

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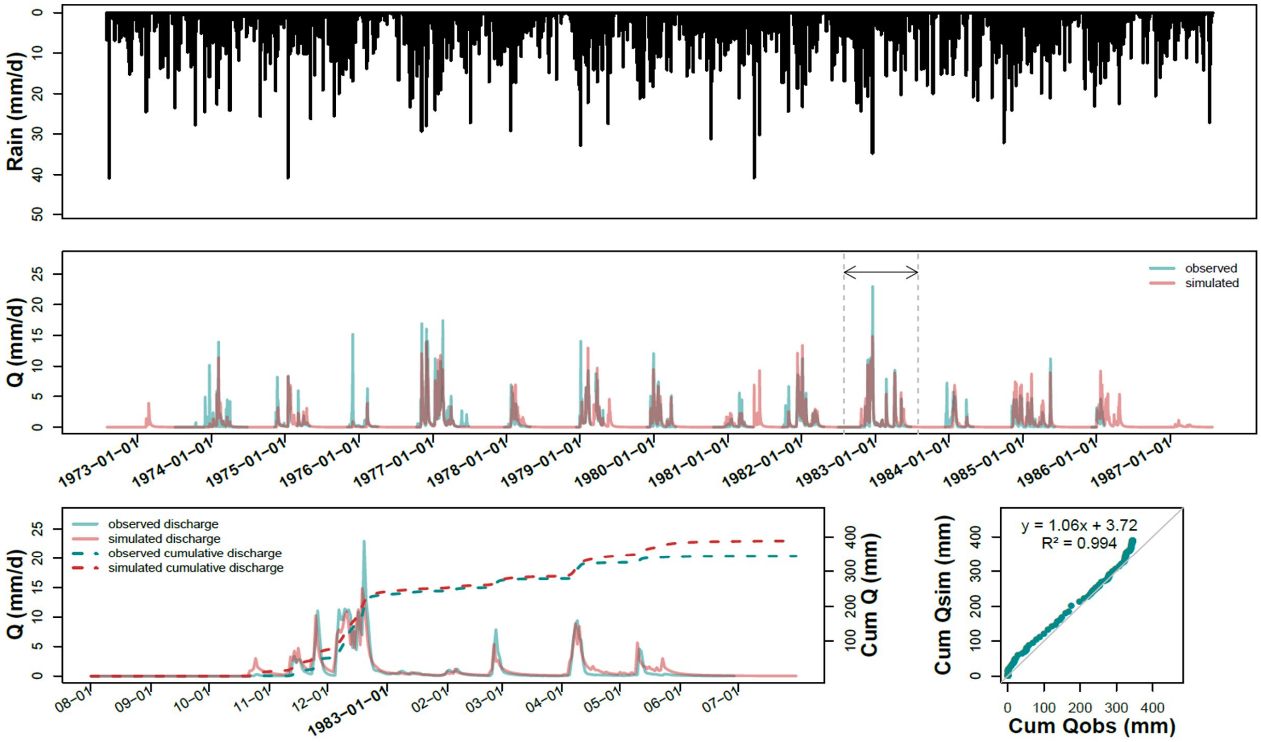

Appendix B: Illustration of observed and simulated discharges calibrated over the total period for the plot of Saint_Laurent_P2

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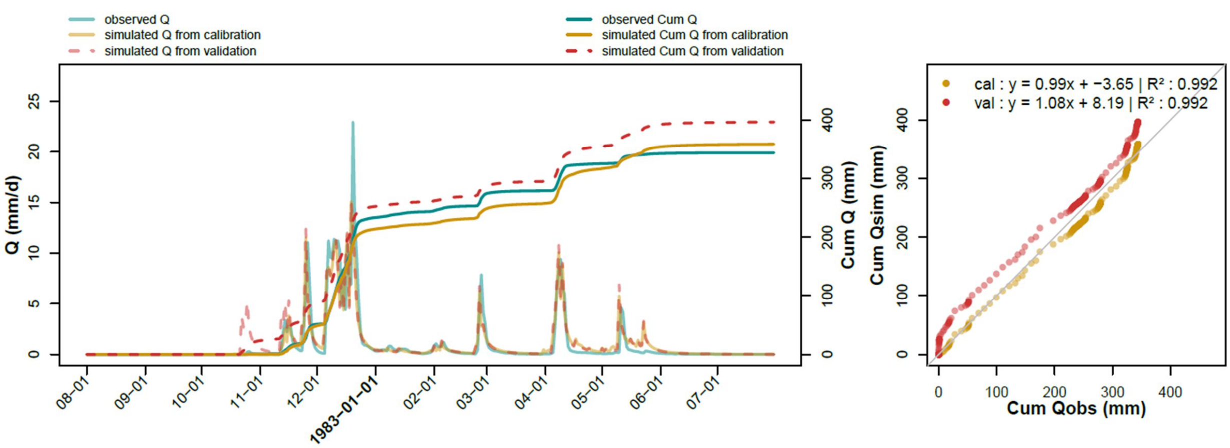

Appendix C: Illustration of observed and simulated discharges for the plot of Saint_Laurent_P1 in calibration vs. validation over 1982-83

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Author's contributions. AJ, HH and JT conceptualized the work. LC and GT provided methodological guidelines. CC, HH and JT collected data and rendered them sustainable. AJ drafted the paper. HH, CC, LC, GT and JT revised the paper and contributed to analyses and discussions.

Competing interests. The authors hereby declare that they have no conflict of interest as regards the present work.

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