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## Dynamic parameterization of soil surface characteristics for hydrological models in agricultural catchments

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1 Dynamic parameterization of soil surface characteristics for  
2 hydrological models in agricultural catchments

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18 Abstract

19 The detrimental impacts of surface runoff and soil erosion, particularly in cultivated areas, call for the  
20 use of distributed runoff and soil erosion models with a view to supporting adapted catchment  
21 management strategies. However, runoff model parameterization remains challenging in agricultural  
22 catchments due to the high spatial and seasonal variability of soil properties. Data acquisition is  
23 demanding and may not always be feasible. Therefore, model parameterization in such environments  
24 have been the subject of numerous research efforts. The combined analysis of land use management  
25 and soil surface state was proposed in literature to address this issue and demonstrated its potential  
26 for runoff analysis and modelling. However, these research findings were related to specific rainfall  
27 sequences and/or soil surface state. In this study, existing knowledge on soil surface state and its  
28 application to runoff model parameterization were synthesized and included in an easy-to-use  
29 parameterization software (PREMACHE), providing a framework for modelers lacking of means and/or  
30 data for modelling complex agricultural catchments.

31 To develop and evaluate the software, a dataset was acquired over 9 years on more than 110 plots in  
32 a 1045 ha agricultural catchment, including crop types, soil surface state, rainfall and runoff time series.  
33 Soil surface state dynamics was modeled based on crop types and daily rainfall. It was evaluated in the  
34 experimental catchment and validated in a nearby catchment. Soil hydrodynamic properties (e.g.  
35 infiltration capacity) were deduced from this framework and literature data at a daily time step, for  
36 each plots. Moreover, runoff events were measured when the modeled infiltration capacity was low,  
37 indicating that the parametrization adequately captured its temporal dynamics. The software  
38 developed in this study, as well as setup values deduced from the monitoring campaigns are provided  
39 with the manuscript for application in other ungauged catchments and explore their impact on  
40 agricultural catchment hydrological dynamics.

41 **Keywords:** Crops, Soil properties, Runoff, Agricultural catchment, Model parameterization, Soil  
42 infiltration capacity, Tillage operations

43 Highlights

- 44 • Parameterization of runoff models is challenging in agricultural catchments
- 45 • Knowledge on using soil surface state for model parameterization was synthesized
- 46 • A comprehensive field survey was performed on a 1045 ha agricultural catchment
- 47 • A simple framework for soil surface state is proposed and evaluated for common crops
- 48 • A software is provided to derive runoff model inputs from rainfall and crop types

49

## 50 1. Introduction

51 Soil erosion may generate numerous detrimental environmental impacts, including the on-site loss of  
52 fertile soil and the off-site triggering of muddy floods, resulting in the degradation of the road network  
53 and housing (Boardman et al., 1994; Boardman, 2020). Downstream, the increased fine particles load  
54 to rivers is detrimental to aquatic environment (Owens et al., 2005). Muddy floods are regularly  
55 observed in the European loess belt (Evrard et al., 2007; Boardman, 2010; Evrard et al., 2010), where  
56 the soil erodibility is high and agriculture provides the dominant land use (Cerdan et al., 2004). Models  
57 are therefore needed to design effective mitigation strategies to reduce erosion and muddy flood  
58 impacts. However, the adequate modelling of runoff and erosion in agricultural catchments requires a  
59 spatially-distributed description of the highly variable hydrodynamic properties of soil surface  
60 (Gascuel-Oudoux et al., 2011; Gumiere et al., 2011). Indeed, soil hydrodynamic properties such as  
61 infiltration capacities can exhibit large spatial variations, resulting from crop allocation decisions and  
62 management operations (Shore et al., 2013), as well as large temporal variations because of crusting  
63 and roughness evolution throughout the year.

64 Different modelling approaches have been applied to agricultural catchments, such as the spatially  
65 distributed LISEM (De Roo et al., 1996) or STREAM (Cerdan et al., 2002a; Evrard et al., 2009) models,  
66 or the widely used lumped SWAT/SWAT+ model (Arnold et al., 1998; Bieger et al., 2017). In runoff and  
67 erosion models, the parameterization used to calculate the partition of rainfall between runoff and  
68 infiltration is critical and, as such, questioned (Qi et al., 2020). The curve number approach (Ponce &  
69 Hawkins, 1996) has been used in several models, including SWAT. This approach was criticized as being  
70 an empirical formulation of runoff, which may result in an incorrect representation of hydrology (Garen  
71 and Moore, 2005; Hawkins, 2014). However, using curve number adaptations following methods such  
72 as that proposed by Martin et al. (2009) could provide an adequate formulation of infiltration and  
73 runoff calculation in agricultural environments. Finding alternative approaches to include the seasonal  
74 variability associated with the crop growth and management in these modelling approaches conducted

75 at the catchment scale remains a topic of wide scientific interest (Nkwasa et al., 2020; Msigwa et al.,  
76 *under review*).

77 Another common approach included in hydrological models to describe runoff dynamics is the use of  
78 infiltration capacity maps, which can be used to calculate the runoff and infiltration partition using e.g.  
79 the Green-Ampt formula (King et al., 1999). Measuring infiltration capacity on multiple plots during  
80 the entire crop growth and harvest period and during intercrops, which have a strong impact on runoff  
81 and erosion (Cerdan et al., 2002b), would however be time- and labor-consuming and limit their  
82 widespread application. To overcome this challenge, many experiments such as those referenced in  
83 Cerdan et al. (2002a) were performed to monitor runoff from the plot to the catchment scales in both  
84 agricultural and natural environments. These experiments demonstrated that soil surface state,  
85 particularly soil crusting, but also soil roughness and crop cover mainly controlled runoff and erosion  
86 dynamics (e.g. Duley, 1939; Auzet et al., 1993), and could be used to infer soil hydrodynamic  
87 properties. Several classifications of the soil surface state have been developed (e.g. Boiffin et al.,  
88 1988) and used to understand runoff and erosion processes in various environments such as West and  
89 Sub-Saharan Africa (Casenave and Valentin, 1992; Valentin, 1991), Australia (Moss and Watson, 1991;  
90 Foley et al., 1991), Israel (Eldridge et al., 2000), USA (Baumhardt et al., 1991; Le Bissonnais and Singer,  
91 1992), Iran (Eghbal et al., 1996) and Northern Europe (Auzet et al., 1995; Van Dijk and Kwaad, 1996;  
92 Le Bissonnais et al., 2005; Evrard et al., 2008). Numerous runoff and infiltration equations have been  
93 elaborated using these parameters (Seginer and Morin, 1969; Brakensiek and Rawls, 1983; Assouline  
94 and Mualem, 1996). Models using this approach demonstrated their ability to predict runoff and  
95 erosion in agricultural fields in various contexts on loess soils (e.g. in France and Belgium), suggesting  
96 that they adequately captured the main runoff dynamics drivers, as well as their temporal variations  
97 (Evrard et al., 2009). Most importantly, these studies provided a methodology to create soil  
98 hydrodynamic properties maps that may be used by physically based models (e.g. De Roo and  
99 Riezebos, 1992), and to account for their spatial and temporal variability. Soil surface state classes can  
100 also be directly be used to incorporate infiltration, imbibition (reflecting pre-ponding rainfall),

101 Manning's coefficient (Cerdan et al., 2002a), but also erosive parameters such as the potential  
102 suspended sediment concentration (Cerdan et al., 2002b) in expert based runoff and soil erosion  
103 models (Bartman et al., 2020).

104 However, even if monitoring soil surface state requires limited efforts and could be used to create  
105 adequate runoff model inputs, such monitoring strategies are time-consuming, which may not always  
106 be feasible (e.g. in remote catchments locations, for time and/or money constraints). The literature is  
107 therefore lacking means to account for the potentially high spatial and temporal variability of soil  
108 surface properties and to represent runoff dynamics in agricultural catchments.

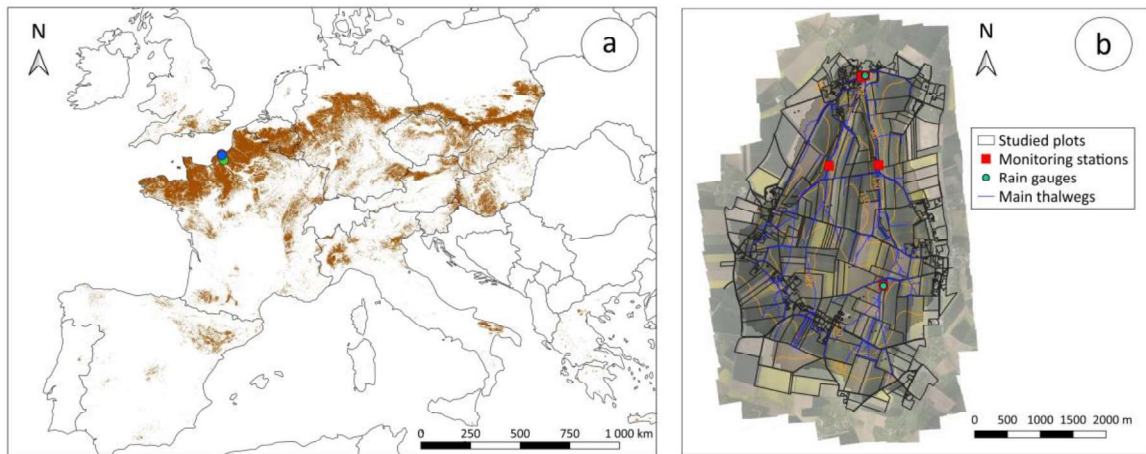
109 Accordingly, the goal of our research was to develop and evaluate a parametrization software  
110 producing runoff and erosion model inputs: the PREMACHE (Parameterization of Runoff and Erosion  
111 Models in Agricultural Catchments) software. It provides users with an easy approach when using  
112 models to address the complex hydro-sedimentary behavior of agricultural catchments. This approach  
113 is based on the use of soil surface state as proxies of soil hydrodynamic properties the validity of which  
114 was demonstrated the literature. A simple parameterization of soil surface state dynamics over  
115 common crop types is proposed, and evaluated in an agricultural catchment located in the European  
116 loess belt. Soil hydrodynamic properties, such as infiltration capacity, were deduced from the modeled  
117 soil surface state and literature data review. It was then used to analyze the impacts of the soil  
118 properties spatial and temporal heterogeneities on the catchment dynamics. Finally, the toolbox used  
119 to create runoff model inputs is provided with setup values along with the manuscript to support  
120 models parameterization for ungauged agricultural catchments.

## 121 2. Methods

### 122 2.1. Study area

123 The monitoring campaigns were performed in the Bourville catchment, located in Upper Normandy,  
124 France (Figure 1a), within the European loess belt, defined as the "Silt" and "Silt-loam" texture in the  
125 USDA classification applied to the dataset proposed by Ballabio et al. (2016). This site is a 1045 ha

126 catchment which was mainly covered, during the monitoring period of almost 9 years (September, 26<sup>th</sup>  
127 2007 - May, 31<sup>th</sup> 2016) with cropland (72%), grassland (18%), urban (6%) and forested areas (4%). The  
128 main crops were, relative to the total crops area, wheat (42%), flax (16%), rapeseed (13%), sugar beet  
129 (7%), winter barley (7%), potatoes (6%) and maize (6%).



130

131 Figure 1: a) Location of the study area in Europe. The Bourville (blue) and nearby Blosseville (red) and  
132 Austreberthe (green) catchments are located within the European loess belt (brown areas). The experimental  
133 setup of the Bourville catchment is presented in subfigure b).

134 The catchment is mainly covered with Neoluvisol and Brunisol soils. According to the USDA soil textural  
135 classification, soils are referred to as silts and silt loams, associated with a low structural stability. These  
136 soils developed on well-drained thick soils, overlying karstic geological formation. Silt and silt loam  
137 corresponded to more than 9% of the surface area of the European soil texture dataset proposed by  
138 Ballabio et al. (2016), indicating that the studied catchment soils are representative of cultivated soils  
139 across the continent. These soil types have been described as sensitive to surface crusting, affecting  
140 the soil's hydrodynamic properties. Indeed, an increase in crusting results in a decrease of the  
141 infiltration capacity (Boiffin et al., 1988; Le Bissonnais et al., 1998). Additional data were also collected  
142 from literature for the nearby Blosseville and Austreberthe catchments (section 2.2.2): they were  
143 located 10 km north and 30 km south of the Bourville catchment, respectively. Both sites are covered  
144 with silt loam soils developed on loess Quaternary deposits. These catchments included a large



145 proportion of cultivated areas: more than 90% for the Blossenville catchment (90 ha) and 60% for the  
 146 Autreberthe catchment (215 km<sup>2</sup>). Additional details on these catchments can be found in Cerdan et  
 147 al. (2002a) and Delmas et al. (2012), respectively.

## 148 2.2. Field measurements

### 149 2.2.1. Crop type and soil surface state monitoring

150 On average during the monitoring period, 110 plots were surveyed in the Bourville catchment. The  
 151 associated crops types, seeding, harvesting and tillage operations (e.g. ploughing) dates were  
 152 determined through farmers' interviews and field observations. Crusting stage, crop cover and  
 153 roughness were also monitored for 19 different crops following the procedure described in Boiffin et  
 154 al. (1988) and Ludwig (1992). Two micro-plots (50 cm x 35 cm) were delimited in each plot,  
 155 photographs were taken and observations were performed on the field to evaluate crop cover and  
 156 surface roughness. The specific procedures described in Bresson and Boiffin (1990) were used to define  
 157 the crusting stage. These procedures are based on morphological descriptions of clods size and shape,  
 158 and estimation of inter-clods patches of continuous areas where interstices disappeared. These  
 159 observations were performed at different periods to capture plant growth and crusting development.  
 160 The corresponding crops and monitoring classes were reported in Table 1.

Crop cover index		Crusting		Roughness		Monitored crop types
C1	0 – 20 %	F0	Fragmentary	R0	0 - 1 cm	Wheat x 4 (N=42)
			stage			Flax x 2 (N=24)
C2	21 – 60 %	F1	Structural	R1	1 - 2 cm	Rapeseed x 2 (N=20)
			stage			Sugar beet x 2 (N=22)
C3	61 – 100 %	F12	Intermediate	R2	2 - 5 cm	Potatoes x 2 (N=18)
			crusting			Maize x 2 (N=16)
		F2	Sedimentary	R3	5 - 10 cm	Peas x 2 (N=14)
			crust			Intercrops x 3 (N=22)

161 

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Table 1: Soil surface state, associated nomenclature and crop types monitored for their soil surface state. The  
162 number of monitored plots and total observation numbers (in parenthesis, including the two locations and the  
163 temporal observations) are indicated in the last column.

164 The monitored crops represented the most common plants cultivated in the catchment (section 2.1).  
165 Several plots were monitored to include a variety of crop rotations type. For each monitored plot, the  
166 crop cover, crusting and roughness level were assessed for the two micro-plots and during various  
167 measurement periods to capture the entire growing cycle. Measurements were performed between  
168 four and seven times (on average five times) over the monitoring period, depending on the crop  
169 growing duration. In total, 176 observations were used for this study. Depending on the crop growing  
170 cycle duration, each crop type was monitored for a period comprised between 51 and 202 days (mean  
171 126 days).

#### 172 2.2.2. Additional soil surface state data

173 To increase the database robustness, the 204 observations on plots cultivated with wheat presented  
174 by Delmas et al. (2012) were used in the current research to generate the parameterization proposed  
175 in section 3.2 and 3.3. In the current research, results will be presented only for the main winter (i.e.  
176 wheat) and spring (i.e. flax) crop types observed in the Bourville catchment. Additional figures, showing  
177 parameterization performance for the other monitored crops, can be found in supplementary material  
178 for evaluation over a variety of crop types. Moreover, the parameterization was validated on  
179 measurements performed in the Blossenville catchment in section 3.4. The latter included rainfall and  
180 soil surface state observations on 20 plots at 5 to 6 dates along the entire crop cycle, corresponding to  
181 an additional 109 observations over an additional year. Results are also presented in supplementary  
182 material. In this study, 489 observations were used including 380 records for parameterization and 109  
183 for validation. This compilation relied on observations made across three different catchments and  
184 contrasted monitoring periods, corresponded to three years of monitored data. It is therefore

185 expected that this compilation would produce results that can be extrapolated to other catchments,  
186 as it included various rainfall depths, intensity, kinetic energy, as well as variations in temperatures  
187 and soil textures.

### 188 2.3. Monitoring stations and data processing

189 Rainfall and water discharge were measured in the Bourville catchment. Measurement of water  
190 discharge was contemporary to rainfall period. Rainfall was monitored with automatic rain gauges at  
191 a 6-minutes time step (Précis Mécanique 3029) from September 2007 to May 2016. Mean annual  
192 rainfall was ranging from 629 mm to 974 mm, with a mean of 769 mm over the monitoring period. The  
193 mean long-term (1981-2010) annual rainfall recorded at the nearby Le Havre station is 790 mm with a  
194 mean monthly rainfall ranged from 52 mm (February) to 89 mm (December). The monitored rainfall is  
195 therefore representing average conditions, including both dry and wet years.

196 Water discharge was measured at four locations in the catchments, including nested measurements  
197 in sub-catchments. In this study, we only used data from the station located at the catchment outlet.  
198 Discharge was measured using a calibrated flume, using water height probes (INW PT12) measuring  
199 water height at a high frequency, and recorded using a ISCO 2105G data logger. The monitoring  
200 frequency ranged from one to six minutes, depending on the monitoring period. Gauging was  
201 performed using a velocimeter (Valport 801 flat) or the salt dilution method, depending on the  
202 discharge range. Gauging was combined with water height levels to establish rating curves (Richet et  
203 al., 2021), resulting in high-frequency discharge monitoring at each station. The rating curve fitted well  
204 with the 13 measurements; the determination coefficient was 0.99 at the catchment outlet. Measured  
205 discharge ranged from  $0.04 \text{ m}^3 \cdot \text{s}^{-1}$  to  $2.7 \text{ m}^3 \cdot \text{s}^{-1}$ . 95.7% of the values recorded during the monitoring  
206 period were included in this range, indicating its representativity. Field observations lead since 1994  
207 did not revealed any spring in the catchment, and it had no watercourses, only ditches (Richet et al.,  
208 2021). Therefore, the measured discharge results only from runoff.

209 Individual rainfall events were defined from the rainfall time series measured at a 6-minutes time step.  
210 One individual event was defined as more than 1 mm of rain, separated from the following event by  
211 at least 3 hours without rainfall. Rainfall depth, duration and intensity were then calculated for each  
212 rainfall event. Individual runoff events were defined from the discharge time series as events with a  
213 peak discharge higher than  $0.03 \text{ m}^3 \cdot \text{s}^{-1}$  and a total volume higher than 0.01 mm. Runoff volume,  
214 duration, peak discharge were calculated for analyzing the catchment hydrological dynamics  
215 (performed in Richet et al., 2021). This procedure was adapted from the methodology proposed by  
216 Grangeon et al. (2021). The parametrization developed in this study made use of rainfall depth and  
217 intensity during the rainfall events, as well as rainfall depth occurring prior to runoff events, considered  
218 a proxy of soil moisture (Cerdan et al., 2002).

219 The Mood test was used at the 5% level of significance to test for median differences between groups  
220 in rainfall and runoff distributions. To assess the parameterization performance, the Kruskal-Wallis test  
221 was used at the 5% level of significance.

## 222 2.4. PREMACHE framework description

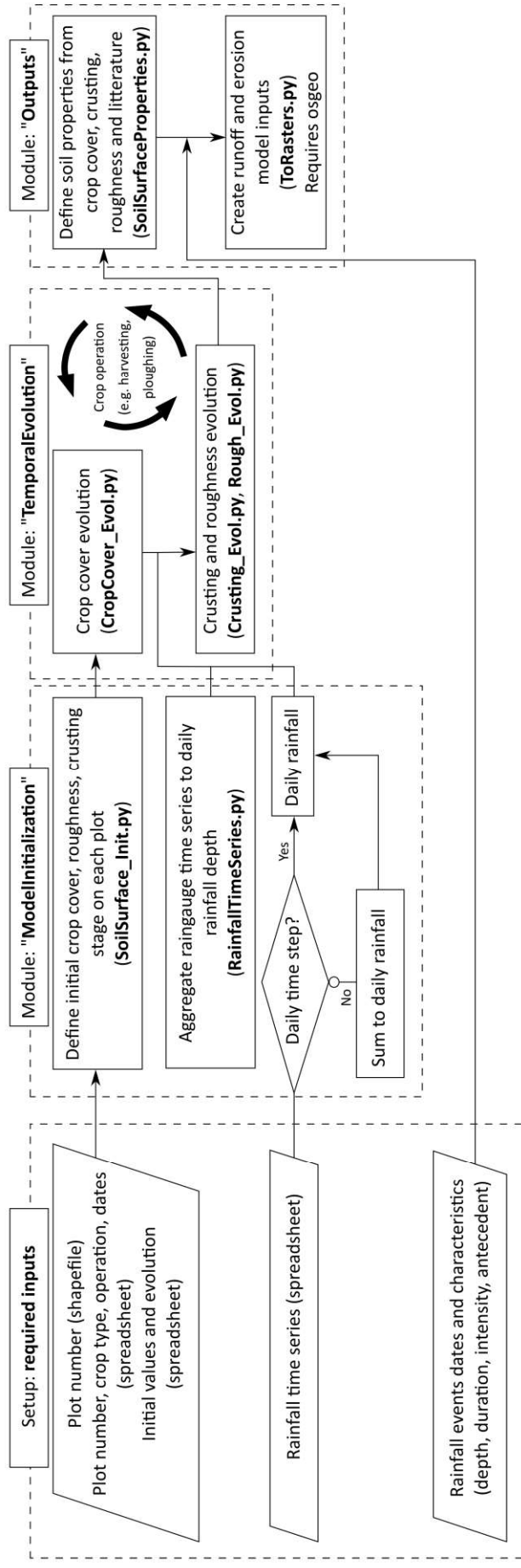
### 223 2.4.1. Model summary

224 The objective of the PREMACHE software was to generate soil hydrodynamic property maps that can  
225 be readily used as runoff and erosion models inputs. The following model inputs can be created at a  
226 daily time step: infiltration capacity, imbibition and Manning's  $n$  coefficient. Additional variables  
227 related to erosion modelling are also provided (sheet erosion concentration and soil erodibility), based  
228 on the data proposed by Cerdan et al. (2002b). However, in this study, results will focus on infiltration  
229 capacity, as it is one of the main runoff model requirements.

230 To create a spatial distribution of these parameters (maps), the soil surface state is modeled by  
231 PREMACHE at a daily time step, on each plot across the catchment. For each plot, PREMACHE initialized  
232 the crop cover, crusting and roughness based on empirical data depending on the crop type, previous  
233 shallow tillage operations and potential chemical crop destruction. Crop cover was then modeled to

234 increase with time over the modeled period, depending on the crop type. Empirical data from the  
235 current study was provided as default values for different crop type. PREMACHE then combined the  
236 crop cover with rainfall records to model soil crusting and roughness evolution. Crop operations are  
237 considered, as they may modify both crop cover (e.g. harvesting) and surface crusting and roughness  
238 through tillage operations (e.g. ploughing).

239 Finally, conversion of soil surface states into hydrodynamic properties was performed using the  
240 procedure described in the STREAM model (Cerdan et al., 2002a). The Manning coefficient was derived  
241 from the experimental data proposed for various crop types by Gilley et al. (1991) and Morgan (2005).  
242 These values can also be modified on the corresponding input spreadsheet. The software functioning  
243 is summarized in Figure 2.



245 Figure 2 : Flowchart of the PREMACHE software and associated individual scripts.

246 Values acquired in the current study are provided with the toolbox and may be used as default values  
247 in similar although unmonitored catchments. Otherwise, values can be modified in the spreadsheets  
248 to reflect changes in soil properties for instance.

249 The GIS files were processed using QGIS (QGIS, 2022; V.3.10 - A Coruña). The toolbox was developed  
250 as a sequence of scripts using Python V.3.8.5 and is available at <https://github.com/BRGM/premache>

#### 251 2.4.2. Required inputs

252 The required inputs are:

- 253 • A raster providing the expected resolution and extent, such as the Digital Elevation Model  
254 (DEM).
- 255 • A shapefile corresponding to the catchment plots. Each plot should be associated with a plot  
256 (arbitrary) number. As the plot sizes and locations may change over time, multiple shapefiles  
257 can be used to reflect the land use temporal evolution. Monitored data, national databases  
258 providing annual maps or statistics can be used to fill in this spreadsheet.
- 259 • A spreadsheet file indicating the land use (including crop type and farming operations) at each  
260 measurement period, with the associated plot numbers.
- 261 • A two-column file including the rain gauge records. Rainfall records should be provided with a  
262 daily time step. If a higher resolution is available, the toolbox can be used to decrease the  
263 resolution to a daily time step in order to avoid high frequency variations while conserving an  
264 adequate temporal resolution regarding the timescales involved in the control of soil surface  
265 state evolution.
- 266 • A file including rainfall events characteristics for which runoff model inputs will be generated.  
267 Users should provide one or multiple dates of interest in a specific file, corresponding to  
268 rainfall events that should be modeled, with their associated characteristics: rainfall depth,  
269 duration maximum intensity and rainfall depth over the past two days before the rainfall  
270 event.

- 271       • Three different tables describing the evolution of:
- 272             ○ Crop cover increase as a function of time and crop cover decrease dynamics under
- 273             different farming operation types. In the current research, ploughing and chemical
- 274             destruction were considered separately, as described below (section 3.2).
- 275             ○ Surface roughness and crusting as a function of both cumulative rainfall and crop cover
- 276             (section 3.3).

#### 277             2.4.3. Limitations and adaptations

278     In the toolbox, crops are assumed to grow independently from rainfall and temperature. Our dataset,

279     and the corresponding parameterization, should therefore need additional calibration for catchments

280     undergoing severe dry or wet periods. We are also aware that process-based approaches were

281     proposed in the literature (Peñuela et al., 2018; Boas et al., 2021), for instance to model crop growing

282     at various scales. However, the goal of the current research was to provide measurement data and a

283     simple parameterization to obtain reliable estimates of soil surface evolution, based on limited input

284     requirements. Moreover, the software made use of simple spreadsheets; values can therefore be

285     easily modified according to the scientists' knowledge, or using dedicated measurements or more

286     detailed crop growing modelling.

287     This toolbox was developed for agricultural fields on soils prone to surface crusting, and may therefore

288     need additional calibration to describe soil surface evolution in catchment located in a different

289     climate context and on different soils (i.e. loess-derived silt-sized soils) than those typically found in

290     the European loess belt, for instance following the methodology proposed in Ludwig (1992) or Evrard

291     et al. (2009). While it should help modelers in representing soils hydrodynamics properties, they

292     should adapt the proposed values depending on the dominant processes occurring in the modeled

293     catchment. It should also be noted that this approach was successfully adapted by Gascuel-Odoux et

294     al. (2009) and Evrard et al. (2009) for catchments of Western France, Southern France and Belgium,

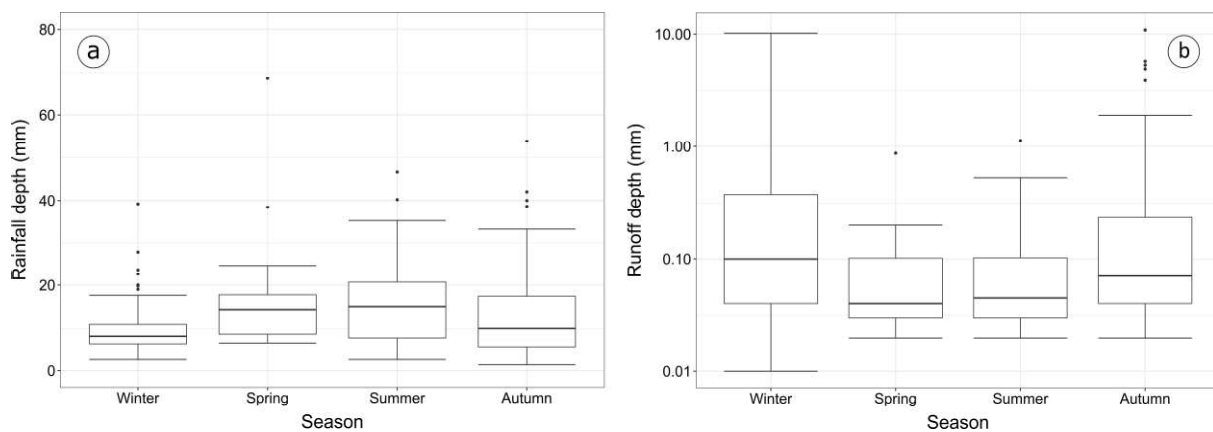
295     suggesting that it may be implemented in catchments located in other regions.



296 3. Results and discussion

297 3.1. Rainfall and crop types variations over the monitoring period

298 During the monitoring period, 227 runoff events were recorded. Among them, 40 (18%) events  
299 occurred after a rainfall depth lower than 5 mm, 187 events (82%) took place in response to rainfall  
300 depths higher than 5 mm, including 104 (47%) runoff events occurring following rainfall depths higher  
301 than 10 mm (Figure 3).



302

303 Figure 3: Boxplots of a) rainfall depth that resulted in runoff events and b) corresponding runoff depth  
304 (logarithmic scale in the y-axis).

305 Most runoff events (Figure 3b) occurred during autumn (49%) and winter (31%). Runoff events were  
306 also recorded during summer (14%) and spring (6%). Interestingly, a significantly higher rainfall depth  
307 was required to generate runoff event in summer than in winter: the corresponding median rainfall  
308 depths amounted to 15 mm and 8.2 mm, respectively (Figure 3a), and the median runoff depth  
309 amounted 0.05 mm and 0.1 mm, respectively (Figure 3b). In this case, runoff occurrence is related to  
310 the high variability in infiltration capacity over seasons resulting from surface crusting, with infiltration  
311 rates ranging from 2 mm.h<sup>-1</sup> to 50 mm.h<sup>-1</sup> (Cerdan et al., 2002a).

312 The evolution of crop types over the monitoring period is provided in Figure 4.

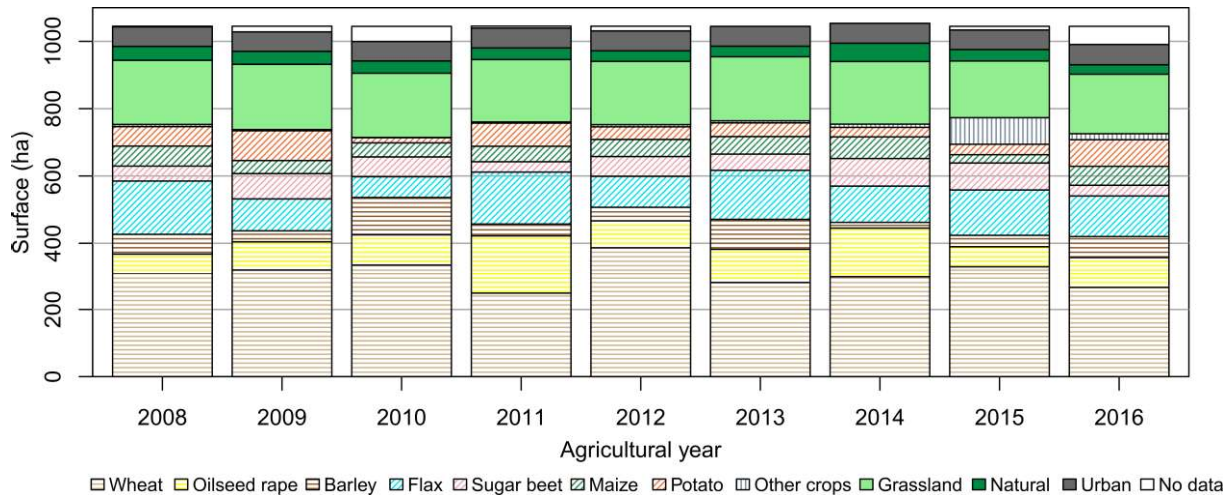


Figure 4: Crop type evolution during the monitoring period. Each year is corresponding to agricultural years, starting in September, e.g. “2008” is corresponding to 1<sup>st</sup> September 2007 to 31 August 2008. Intercrops were not included in this analysis. No data values corresponded to periods when it was not possible to collect data from landowners.

The cultivated areas were dominated by winter crops (60%), including wheat, rapeseed and winter barley. Spring crops, including flax, sugar beet, maize and potatoes, represented 35% of the cultivated area. These crops were also the most widely cultivated plants crops in Europe for the period 2009-2019, and including common wheat, maize and corn-cob mix, barley, oats and rye (Eurostat, 2019). The observed crops are therefore representative of the most commonly cultivated plants in Europe.

The current study took advantage of extensive field measurements obtained with the active cooperation of landowners. Consequently, a unique long-term monitoring of crop types and shallow tillage operations was available for this study. At large scales, such data are usually not available, but interesting approaches such as crop rotation simulations (Schönhart et al., 2011; Sietz et al., 2021) may contribute to improve such shortcomings. The proposed database from our study may be used to validate such approaches.

329 3.2. Crop cover evolution

330 Crop cover evolution was evaluated over the entire catchment based the soil surface state observation.

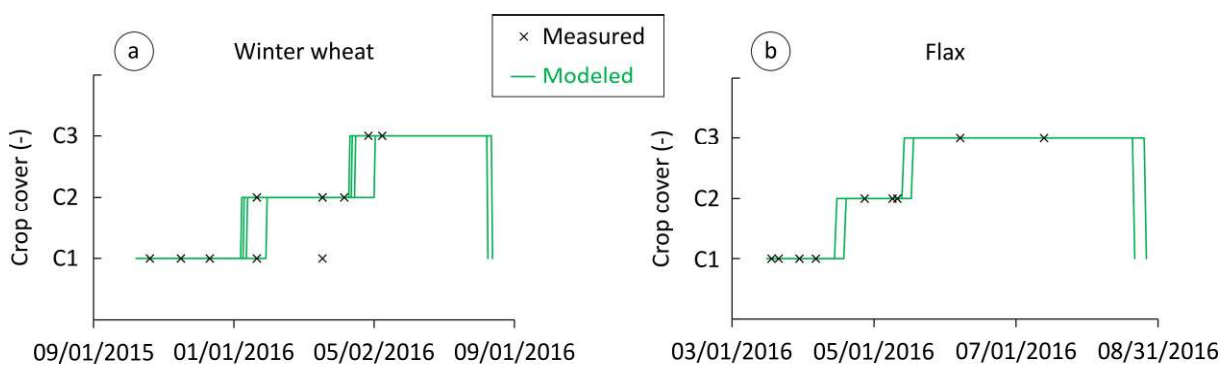
331 The mean seeding date corresponded to mean values obtained from the farmers' interviews. The

332 resulting crop cover evolution is proposed in Table 2.

<b>Crop cover</b>	<b>Mean seeding date</b>	<b>20%</b>	<b>40%</b>	<b>60%</b>	<b>80%</b>	<b>100%</b>
<b>Crop cover class</b>	<b>(0 %)</b>					
	<b>C1</b>	<b>C2</b>		<b>C3</b>		
Crop type	Crops growing (days)					
Sugar beets, cabbages, spinach	April 15 <sup>th</sup>	44	75	83	102	107
Maize	April 25 <sup>th</sup>	66	82	92	114	124
Flax, alfalfa	March 15 <sup>th</sup>	29	48	58	76	81
Peas, faba beans, beans	March 30 <sup>th</sup>	55	76	87	93	103
Potatoes	April 15 <sup>th</sup>	45	65	72	88	93
Oats, rye, radish	April 10 <sup>th</sup>	25	45	55	61	66
Wheat	October 20 <sup>th</sup>	92	136	186	193	203
Barley	October 5 <sup>th</sup>	77	154	176	198	208
Rapeseed	September 5 <sup>th</sup>	61	77	207	210	215
Ryegrass, clover	September 5 <sup>th</sup>	40	57	71	73	107
Intercrops with mustard	September 5 <sup>th</sup>	30	45	55	57	64
Intercrops with phacelia	September 1 <sup>st</sup>	39	54	64	72	82
Intercrops: mustard or faba bean		d+50	d+30	d+20	d+10	d
Intercrops: other types		d+50	d+35	d+25	d+15	d

333 Table 2 : Soil cover parameterization deduced from the field survey. Numbers indicate the days required to reach  
 334 the corresponding crop cover. The “d” letter corresponded to crops destruction.

335 Crop cover was divided into 5 segments (0% to 100% in 20% increments) to allow for a smoother  
 336 transition between classes, particularly for crusting and roughness evolutions (see section 3.3 below).  
 337 However, they were aggregated in three classes (0%-20%; 21%-60%; 61%-100%) for comparison with  
 338 measurements. After the progressive crop cover increase during the growing period, different  
 339 operations were considered for explaining the crop cover decrease: chemical destruction, harvesting,  
 340 mechanical destruction, and ploughing. Intercrop chemical destruction was estimated to result in a  
 341 progressive decrease from a fully developed crop or intercrop to a limited cover in 50 days (Martin,  
 342 1997). Conversely, harvesting and ploughing resulted in a quick decrease from a maximal to a limited  
 343 crop cover. The initial crop cover of the following crop type was therefore defined based on the  
 344 previous crop type and latest farming operation. An illustration of the modeled and observed crop  
 345 covers for the two most common winter and spring crops is provided in Figure 5. For evaluation over  
 346 other crop types and on the Blosseville catchment, additional figures were provided as supplementary  
 347 material.



348 Figure 5: Measured (black crosses) and modeled (green continuous line) crop cover for the two most common  
 349 crops observed in the catchment: a) winter wheat (four plots were monitored) and b) flax (two plots were  
 350 monitored). The different lines corresponded to different modeled plots. The differences between lines is linked  
 351 to differences in seeding dates.  
 352

353 The modeled crop cover over the eight crop types detailed in Table 1 matched the observation for 73%  
354 of the records, indicating a good parameterization performance. The agreement between modeled  
355 and measured values was statistically significant. It should however be noticed that some temporal  
356 variability was observed. For instance, the measured crop cover for winter wheat varied between C1  
357 (0% - 20%) and C2 (21% - 60%) from 21<sup>st</sup> January to 18<sup>th</sup> March (Figure 5a), depending on the monitored  
358 plots. It indicated some inherent variability in crop cover that was only partly explained by the  
359 differences in seeding dates, reflected by the modeled variability between plots (e.g. maize;  
360 supplementary material). Interestingly, the proposed values were in agreement with data collected in  
361 the literature in various contexts. For instance, Tang et al. (2018) measured that the crop cover was  
362 maximal for winter wheat approximately 180 days after sowing, while our measurements indicated a  
363 corresponding period of approximately 190 days. Deng et al. (2012) indicated that the maximal plant  
364 growth was measured after 90 days for flax and 140 days for maize, while we found in our study values  
365 of 80 and 130 days, respectively. The agreement in ranges between the values proposed in this study  
366 and the results reported in the literature suggest that the simple approach proposed in this study may  
367 be applied to other catchments to obtain reliable although rough estimates of crop growing.

### 368 3.3. Soil crusting and roughness evolution

369 The initial values for roughness and surface crusting depend on the previous (inter-)crop type and crop  
370 operation. For instance, ploughing results in a high surface roughness (i.e. > 10 cm), a value that may  
371 also be observed for potato crops. Therefore, for each crop type, the initial surface roughness and  
372 surface crusting were assumed to be controlled by the previous crop operation (e.g. ploughing,  
373 mechanical destruction) and the current crop type. In addition to this temporal evolution, initial values  
374 for crusting and roughness were therefore proposed and included as inputs for each crop type.

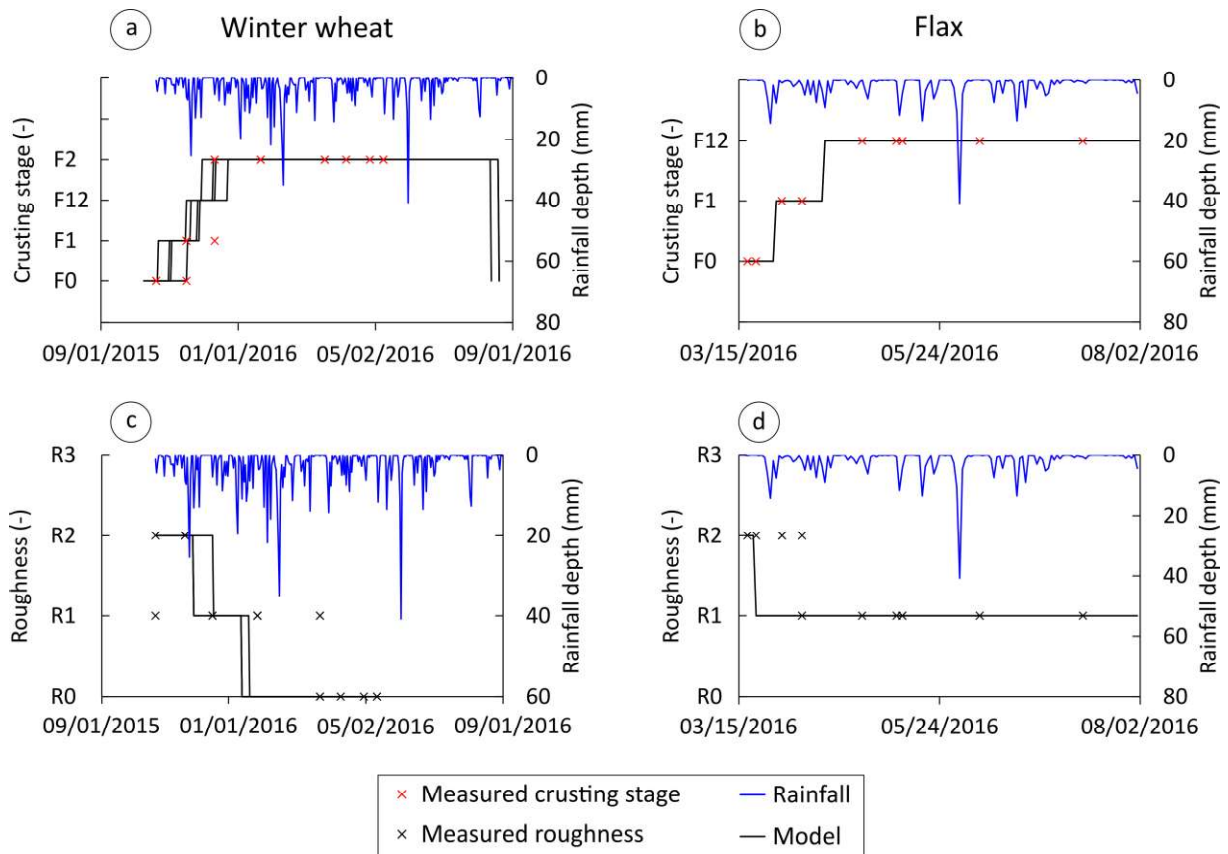
375 In this study, a parameterization of crusting and roughness evolution based on daily rainfall data  
376 (Ndiaye et al., 2005; Vinci et al., 2020) was proposed, taking into account the protective effects of the  
377 crop cover. Indeed, increasing the soil cover by vegetation was demonstrated to reduce the rainfall

378 kinetic energy (e.g. Brandt et al., 1989) and, therefore, the soil aggregate breakdown, limiting crusting  
 379 and roughness decrease. The parameterization, including Table 2 and Table 3, was initially based on  
 380 expert knowledge acquired in this region during the past decades (e.g. Auzet et al., 1990; Ouvry and  
 381 Ligneau, 1993, Martin et al., 2010), and was then adapted using the measurements acquired during  
 382 this study and collected from Delmas et al. (2012). The resulting parameterization is proposed in Table  
 383 3 to define roughness and crusting evolution over time and rainfall for various crop covers (as defined  
 384 in section 3.2).

Crop cover		0%-20%	20%-40%	40%-60%	60%-80%	80%-100%
	R4 → R3	150	190	225	300	375
<b>Surface roughness</b>	R3 → R2	120	150	180	240	300
	R2 → R1	120	150	180	240	300
	R1 → R0	120	150	180	240	300
<b>Surface crusting</b>	F0 → F1	30	45	90	115	120
	F1 → F12	35	50	100	125	130
	F12 → F2	90	130	265	335	350

385 Table 3: Soil roughness and crusting evolution under rainfall. The numbers indicate the rainfall depth (mm)  
 386 required to reach the corresponding roughness or crusting stage, for each crop cover class (columns).

387 An illustration of the proposed parameterization and comparison with measurements for crusting  
 388 stages and soil roughness is presented in Figure 6. Additional figures presented as supplementary  
 389 material presented the parameterization results for other crop types.



390

391 Figure 6: Measured (crosses) and modeled (continuous line) crusting stage (a and b, red crosses) and soil  
 392 roughness (c and d, black crosses) for winter wheat and flax. The continuous blue line represents daily rainfall.

393 The agreement between observed and modeled values reached 63% for the crusting stage and 74%  
 394 for the roughness, and was statistically significant. The limited performance for crusting is partly  
 395 explained by the poor performance obtained for fields cultivated with potatoes (22%, p-value=0.24).

396 This is related to the limited crop cover in the early stages of plant growth, the modeled crusting stage  
 397 quickly increased to reach the stage of crusted soil with sedimentary crust (F2). However, crusting is  
 398 assumed to remain limited on inter-rows, as reflected by measurements indicating the occurrence of  
 399 a structural stage (F1) during 72% of the monitoring period, ranging from April to August for this crop  
 400 type, and that of intermediate crusting (F12) as maximal observed crusting stage. Therefore, the  
 401 parameterization performance remained low for this crop type. Consequently, crusting evolution for  
 402 soil surface with high initial roughness (R4) should be considered with caution, and further  
 403 developments should include a relationship between crusting and roughness.

#### 404 3.4. Evaluation of the parameterization extrapolation abilities

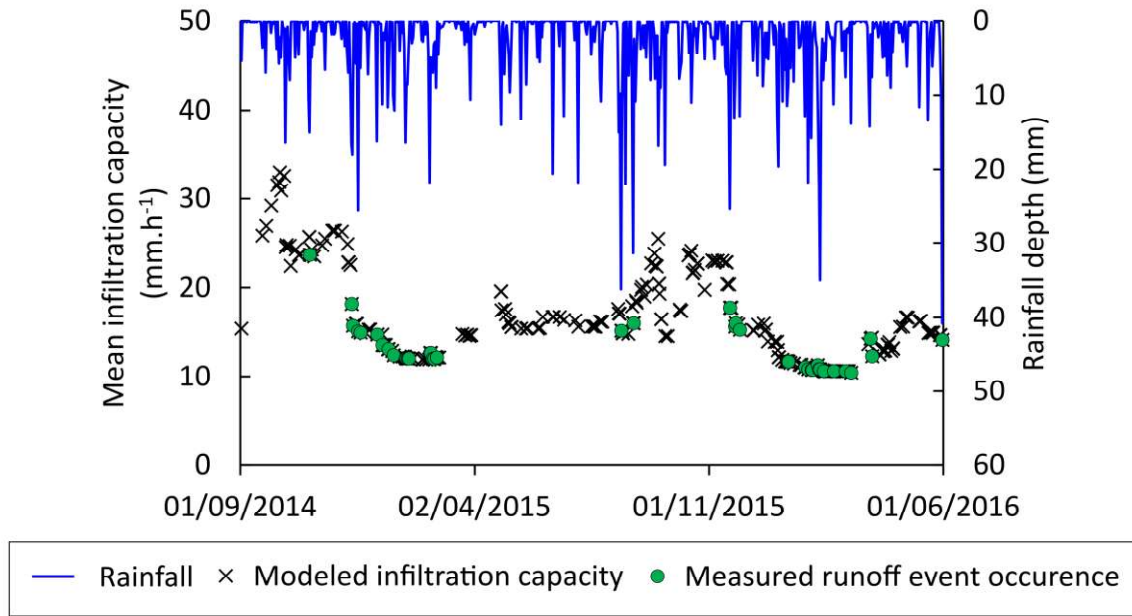
405 In addition to parameterization evaluation as performed in sections 3.2 and 3.3, we assessed whether  
406 the PREMACHE framework could be applied to other catchments by using the 109 observations of the  
407 Blosseville catchment. Results from the Blosseville catchments are presented in supplementary  
408 material. For the 20 monitored plots covered with wheat (7 plots), flax (2 plots), peas (3 plots) and  
409 winter barley (3 plots), the predicted crop cover was good. The modeled values corresponded to  
410 measurements in 91% of the cases. Errors were observed regarding the occurrence of intermediate  
411 crop cover (C2) on fields planted with peas and wheat. For crusting, only data for fields cultivated with  
412 flax and peas were available, and the parameterization matched the observations in 87% of the cases,  
413 with the few errors occurring regarding the prediction of the structural crusting stage (F1). Finally, for  
414 roughness, the parameterization performance was acceptable, with 82% of agreement between  
415 observations and modeled values, mainly due to errors to predict the roughness early stages for fields  
416 planted with wheat and winter barley: after seeding (occurring the 8<sup>th</sup> October) the observations  
417 indicated a limited roughness (R1) while the parameterization predicted a slightly higher roughness  
418 (R2) until mid-December. However, given the variations observed in the measurements, the model  
419 performance could be considered as acceptable.

#### 420 3.5. Implications for runoff modelling

421 Adequately representing the variability of soil hydrodynamic properties, such as infiltration capacity,  
422 is a long-standing issue for runoff modelers. Moreover, in agricultural catchments, the significance of  
423 shallow tillage operations can dramatically change these properties within a very short period of time  
424 (Martin et al., 2004). The PREMACHE software proposes an alternative method to account for these  
425 variations in runoff modelling, which may be crucial in understanding catchments hydrological  
426 behavior (Wagner et al., 2019). As an illustrative example of the approach, the Bourville catchment  
427 mean infiltration capacity was modeled over two entire crop cycles. Calculations were performed from  
428 1<sup>st</sup> September 2014 to 1<sup>st</sup> September 2016. For readability purpose, results are presented for 1<sup>st</sup>  
429 September 2014 to 1<sup>st</sup> June 2016, corresponding to a total of 253 rainfall events, as no significant runoff



430 event was recorded after 1<sup>st</sup> June 2016. For each of these rainfall events, the mean infiltration capacity,  
 431 weighted by the plot surface, was reported. The link between infiltration capacity and runoff was  
 432 visually suggested by indicating periods when runoff events were measured at the catchment outlet  
 433 (Figure 7).



434  
 435 Figure 7: Modeled mean weighted infiltration capacity (black crosses) for each measured rainfall event and daily  
 436 rainfall (blue continuous line) in the Bourville catchment. Green circles indicate when rainfall events generated  
 437 a runoff event that was measured at the catchment outlet.

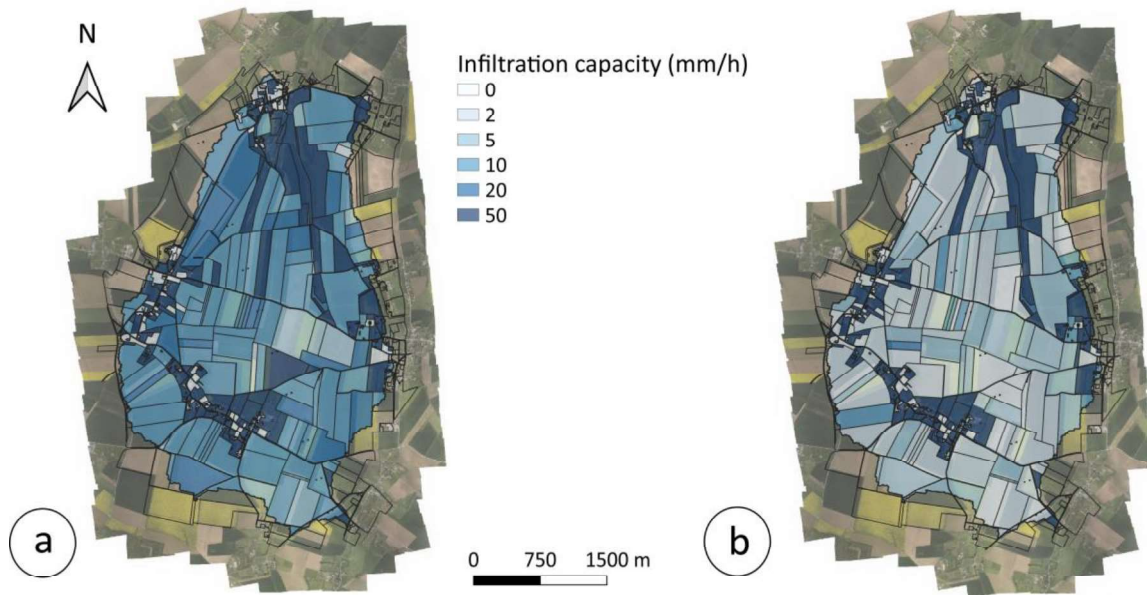
438 This result illustrated the dynamics of soil infiltration capacity and its impact on the catchment runoff  
 439 dynamics. From November 2014 to February 2015, 41 rainfall events with a rainfall depth higher than  
 440 1 mm were recorded over 92 days. Consequently, soil crusting progressively increased, resulting in a  
 441 decreased infiltration capacity, from 33 mm.h<sup>-1</sup> to 12 mm.h<sup>-1</sup>, with direct implications for runoff  
 442 generation (Ndiaye et al., 2005). This decrease occurred mainly because of three major storm events  
 443 accumulating 60.2 mm. On some cultivated fields, infiltration capacity dropped from 50 mm.h<sup>-1</sup> in  
 444 November 2014 to 2 mm.h<sup>-1</sup> in February 2015. This indicated that the soils were crusted with the  
 445 occurrence of a sedimentary crust, resulting in a very limited infiltration capacity. After harvesting and  
 446 spring crops seeding, crop cover decreased and crusting removal through shallow tillage operations

447 resulted in an increased infiltration capacity, up to 26 mm.h<sup>-1</sup> (November 2015). This increase  
448 underlined the importance of shallow tillage operations in controlling the infiltration rates of the  
449 catchment and, more generally, on soil properties (Strudley et al., 2008). Future developments may  
450 include the effects of the tillage type (Osunbitan et al., 2005) and long-term farming methods (Basche  
451 and DeLonge, 2019).

452 Then, an unusually wet period occurred in September 2015 resulted in widespread soil crusting. The  
453 mean infiltration capacity decreased again to 15 mm.h<sup>-1</sup>. Rainfall depth was 87.8 mm in September  
454 2015 while the measured mean was 56 mm. Shallow tillage operations performed across multiple  
455 fields had a strong influence on the catchment-scale infiltration capacity (Martin et al., 2010). It  
456 increased soil infiltration capacity to 24 mm.h<sup>-1</sup> in October 2015, followed by another progressive  
457 decrease during winter. This high-frequency result indicated that the soils' hydrodynamics might  
458 exhibit quick variations due to the combination of rainfall and tillage operations and may be taken into  
459 account with the simple parameterization proposed in the current research.

460 Interestingly, this result illustrates the dominance of infiltration-excess runoff. Runoff events, as  
461 defined in section 2.3 (i.e. based on a threshold on runoff volume and discharge peak), occurred mainly  
462 when rainfall increased crusting, resulting in a mean infiltration capacity below 20 mm.h<sup>-1</sup>. The  
463 PREMACHE software may therefore be used to provide inputs for runoff and erosion models and to  
464 increase their performance by taking into account the fast (e.g. progressive crusting in winter and  
465 tillage operations) and long-term (cycles over multiple years) dynamics of soil infiltration capacity. It  
466 therefore offers a possibility to quantify the infiltration-runoff partition and could therefore  
467 complement existing modelling approaches such as that including curve number variations in models  
468 (Mehdi et al., 2015). This may be useful in agricultural catchments, as both infiltration-excess and  
469 saturation-excess may be involved in generating flood events in such environments (Saffarpour et al.,  
470 2016; Grangeon et al., 2021).

471 In addition to the temporal dynamics, it is also important to consider the spatial variations of  
472 infiltration capacity at the catchment scale (Figure 8).



473  
474 Figure 8: Spatial distribution of infiltration capacity in the Bourville catchment, as simulated by the PREMACHE  
475 software in a) November 2015 (mean infiltration capacity:  $33 \text{ mm}\cdot\text{h}^{-1}$ ) and b) February 2016 (mean infiltration  
476 capacity:  $12 \text{ mm}\cdot\text{h}^{-1}$ ).

477 Plot-to-plot variations was mainly related to differences in crop types and soil surface states. These  
478 spatial variations have important implications for runoff triggering. In particular, grasslands,  
479 characterized by a high infiltration capacity (in this study,  $50 \text{ mm}\cdot\text{h}^{-1}$ ), were located in a talweg in the  
480 northern part of the Bourville catchment, concentrating runoff at locations with a high infiltration  
481 capacity. It will therefore decrease runoff volumes recorded at the outlet regardless the considered  
482 season. Depending on the considered rainfall events, it might affect the areas producing runoff and  
483 those infiltrating the runoff volumes, therefore affecting the hydrological connectivity (Darboux et al.,  
484 2001), which was previously demonstrated to be affected by landscape patchiness (e.g. Baartman et  
485 al., 2020). Of note, specific cases such as the effects of grazing on pastures infiltration capacity  
486 (Joannon, 2004) were not included in this analysis. However, they can be accounted for by creating a  
487 dedicated field in the toolbox.

488 The current study proposed an approach to account for spatiotemporal variations in soil hydrodynamic  
489 properties in complex catchments including agricultural areas. Based on simple inputs, it is  
490 complementary to existing modelling approaches in that it can also incorporate other knowledge or  
491 model inputs.

#### 492 4. Conclusions

493 In the current research, existing knowledge on soil surface state and a unique database were compiled.  
494 The database included the monitoring of crop types and soil surface state, as well as the high-  
495 resolution measurement of rainfall and runoff. Although the monitored sites corresponded to loamy  
496 soils sensitive to surface crusting under temperate climatic conditions, they may be representative of  
497 the conditions observed in other cultivated regions where hydrological processes are dominated by  
498 infiltration-excess runoff.

499 A framework describing the soil surface state dynamics was developed and included in a software  
500 made available for download. It made use of limited field data inputs: crop types and tillage operations  
501 at different observation dates, and rainfall time series. It was demonstrated to adequately reproduce  
502 the changes in crop cover, soil crusting and roughness on various crop types, in two different  
503 catchments. Previous research results were used to convert these soil surface states into  
504 hydrodynamic properties such as infiltration capacity. The software used in this study was made  
505 available for download and can be used to support runoff modelling in agricultural catchments where  
506 experimental data are lacking, using either the proposed default values or modifications based on  
507 modeler's knowledge.

508 When applied to the studied catchment, results demonstrated the high variability of soil infiltration  
509 capacity between crop types, depending on the sequences of tillage operations and rainfall dynamics.  
510 The variations in infiltration capacity at the catchment scale and for various time scales, from the  
511 rainfall event to the inter-annual scale, and its strong implications for runoff modelling were illustrated.  
512 The proposed approach allows representing this variability in runoff models by creating runoff model

513 inputs, based on a large database proposed along with the manuscript. It may therefore be useful for  
514 applications in unmonitored agricultural areas in general and more specifically on loamy soils,  
515 susceptible to crusting. It will help representing the temporal and spatial variability of soils  
516 hydrodynamic properties for different crops and a sequence of hydrological years, which will  
517 ultimately contribute to a better understanding of runoff pathways and hydrological connectivity at  
518 the catchment scale.

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534 **Author contributions:** JFO initiated the data acquisition on the Bourville catchment and secured the  
535 essential, yet uncommon, long-term funding needed to acquire representative measurements. JFO,  
536 LTP and JBR performed the crop observations, soil surface state measurements and farmers’  
537 interviews. PM and OC provided additional experimental data for model calibration and validation.  
538 JFO, OC and JBR created the model parameterization, further modified by TG, RV and OC. TG, RV and  
539 LTP processed the rainfall and runoff data. RV wrote the first model version, further modified by TG.  
540 TG wrote the manuscript. All co-authors commented the manuscript.

541 **Software and data availability:** The data used in this study (Excel spreadsheets and shapefiles) and the  
542 PREMACHE toolbox are available at <https://github.com/BRGM/premache>.

543 PREMACHE is licensed under GPL V3.0. It was developed by Rosalie Vandromme and Thomas Grangeon  
544 (r.vandromme@brgm.fr and t.grangeon@brgm.fr) in early 2021 under Python 3.8.5, using Windows  
545 10, a 2.5 GHz i5-7300HQ CPU with 16 Go memory. Using this configuration, the model processed the  
546 dataset proposed with the manuscript (a shapefile including approximately 1200 polygons monitored  
547 over 9 years) and exported rasters at a 5 m resolution for a subset of 50 rainfall events in approximately  
548 15 minutes.

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