TECHNICAL MEMORANDUM

821

Impact of the representation of the infiltration on the river flow during intense rainfall events in JULES

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Abstract

Intense rainfall can lead to flash flooding and may cause disruption, damage and loss of life. Since flooding from intense rainfall (FFIR) events are of a short duration and occur within a limited area, they are generally poorly predicted by Numerical Weather Prediction (NWP) models. This is because of the high spatio-temporal resolution required and because of the way the convective rainfall is described in the model. Moreover, the hydrological process descriptions of Land Surface Models (LSMs) are not necessarily suitable to deal with cases of intense rainfall.
In this study different representations of infiltration into the soil were developed in the JULES land surface scheme with the aim of improving prediction of the amount of surface runoff, and thus ultimately river flow.
Infiltration and surface runoff are explored in a test case of intense rainfall with a variable maximum infiltration. The modelled hydraulic conductivity profile is modified with depth to reduce the rate of outgoing fluxes. The new infiltration scheme is then applied to different UK catchments. The resulting river flow is evaluated against a benchmark river flow calculated using default infiltration in JULES and also observations. The results demonstrate improved representation of the highest flows with this new variable maxiumum infiltration scheme in some catchments but limited improvement elsewhere. This scheme shows best improvement in the wettest areas of the UK where the annual mean precipitation is above 1200 mm. This work highlights the requirement for substantial further work on the hydrological process representation in JULES.

1 Introduction

The continuous increase in computer power enables the increase in resolution of Numerical Weather Prediction (NWP) models. The physical representation of the models needs to be adapted as a function of the resolution such as the representation of the convective rainfall in a General Circulation Model (GCM). The representation of the precipitation at a finer resolution such as 4 km or even 1 km with explicit convection leads to better forecast performance (Lean et al., 2008). Better understanding the hydrological process in Land Surface Models (LSM) is important in order to improve the forecasting of floods events. Since the water cycle in Earth System Models (ESM) is essential, the improvement of the hydrology in LSM helps to reduce the bias of hydrological exchange between atmosphere and land surface (MacLeod et al., 2016). Events such as floods can be diagnosed by improving the land surface hydrology in LSM (Stephens et al., 2015). However, LSM are usually not well parameterised to represent hydrological processes at high resolution.

Here, we work on the representation of the infiltration in order to better understand how the model is sensitive to intense rainfall at high resolution. An improvement of the representation of these intense rainfall events could lead to better forecasts of flash flood events and in turn contribute to the reduction of hydrological uncertainties in coupled model (ESM).

An experimental variable maximum infiltration scheme was developed at the University of Reading in the early parts of the UK NERC Flooding From Intense Rainfall Programme (Project SINATRA, A.Mueller, personal communication). Here this scheme is adapted to improve the physical hydrology of the soil. After studying the methods used for the calculation of the infiltration in the different land surface models, we developed a different scheme of variable maximum infiltration to improve the model for the case of intense rainfall. The surface water balance is evaluated for each of these schemes in a test case of intense rainfall. The maximum infiltration rate is compared for the different infiltration schemes along with their

variable	name in JULES	PFT name	PFT Number	default value
β_{veg}	infil_f	1	Broadleaf tree	4.00
		2	Needleleaf tree	4.00
		3	C3 grass	2.00
		4	C4 grass	2.00
		5	Shrubs	2.00
$\beta_{non-veg}$	infil_{nvg}	6	Urban	0.10
		7	Open water	0.00
		8	Bare soil	0.50
		9	Ice	0.00

Table 1: Value of the parameter β used in the maximum infiltration rate for each Plant Functional Type (PFT).

corresponding surface runoff, drainage and infiltration rates. A sensitivity test is also made to compare the river flow obtained with the two most physical schemes.

The results of the different experiments in the first part of this study leads to the selection of a different improved infiltration scheme than the one developed in SINATRA. This is then evaluated further in order to understand to what extent the modified scheme represents an improvement. The river flows of the standard and the new infiltration scheme in JULES are compared with observations for several UK catchments. For one particular catchment, we study the behaviour of the river flow for both of infiltration schemes with and without using the river routing scheme. The Ure catchment is chosen to evaluate the impact of the inclusion of the infiltration excess in the case of intense rainfall. A sensitivity study of the values used for soil physical properties as well as different magnitudes of rate of infiltration was performed.

2 Model description of surface infiltration scheme

2.1 JULES model

In this study, the trunk version 4.8 of JULES is used. JULES is a Joint UK Land Environment Simulator a component of the UKMO Unified Model. In the standard version of JULES, the actual infiltration rate is limited by the maximum infiltration rate which is independent of time and actual soil water content.

The surface infiltration is the process by which water on the ground surface enters the soil. The infiltration depends on the properties of the soils such as the moisture content at the surface and the texture of the soil. In standard JULES, the maximum infiltration I_{max} is fixed and calculated at the initialisation which is defined by equation 1 where K_{sat} represents the saturated hydraulic conductivity of a given texture of soil and a parameter β which depends on the surface type (Table 1).

$$I_{max} = \beta K_{sat} \tag{1}$$

The water reaching the soil surface is split between surface runoff and infiltration into the soil. In the presence of vegetation, the throughfall depends on the canopy as explained in Best et al. (2011). The rainfall rate is described as an exponential distribution dependent on the fractional area ε of the canopy, where R_L is the local rainfall (Eq. 2).

$$f(R_L) = \frac{\varepsilon}{R} \exp\left[\frac{\varepsilon R_L}{R}\right] \tag{2}$$

The local throughfall rate is expressed as a function of the local rainfall R_L and of the ratio of the actual water content C and the maximum water content of the canopy C_M as described in equation Eq. 3

$$T_{FL} = \begin{array}{ll} R_L \dfrac{C}{C_M} & \text{if } R_L \leq \dfrac{C}{\Delta t} \\ R_L - \dfrac{C_M - C}{\Delta t} & \text{if } R_L > \dfrac{C}{\Delta t} \end{array} \tag{3}$$

The local surface runoff S_{rL} occurs when the rate of throughfall exceed the rate of maximum infiltration (Eq. 4). From equation Eq. 3, the expression of the surface runoff also depends on the water content of the canopy.

$$S_{\mathrm{rL}} = \begin{array}{ll} T_{\mathrm{FL}} - I_{max} & \text{if } T_{\mathrm{FL}} \geq I_{\mathrm{max}} \\ 0 & \text{if } T_{\mathrm{FL}} < I_{\mathrm{max}} \end{array} \tag{4}$$

The surface runoff over the area in the grid box is expressed as $S_{\mathrm{r}} = \int_0^\infty S_{\mathrm{rL}} f(R_L) dR_L$. The calculation of this equation is described by equation 5 and depends on the precipitation rate R, the canopy water content C and the maximum canopy water content C_m, the max surface infiltration rate I_{max} , the fraction of the grid that receives rainfall f_{grid} and the timestep used Δt.

$$S_{\mathrm{r}} = \begin{array}{ll} R\frac{C}{C_m} \exp\left(\frac{-f_{\mathrm{grid}} I_{\mathrm{max}} C_m}{RC}\right) + R\left(1 - \frac{C}{C_m}\right) \exp\left(\frac{-f_{\mathrm{grid}} C_m}{R\Delta t}\right) & \text{if } I_{\mathrm{max}} \Delta t \leq C \\ R \exp\left(-\frac{f_{\mathrm{grid}}(I_{\mathrm{max}}\Delta t + C_m - C)}{R\Delta t}\right) & \text{if } I_{\mathrm{max}} \Delta t > C \end{array} \tag{5}$$

The infiltration I into the soil is determined through the integration of the contributions for each of the surface types by using the water balance at the surface taking into account throughfall T_{fall} and snow melt M:

$$I = \Sigma_{i=1}^{nPFT} (T_{fall} + M - S_{\mathrm{r}}) \tag{6}$$

In JULES, the actual infiltration is dependent on the calculation of the surface rainfall which is dependent itself on the maximum infiltration rate. Since the rainfall in the model can be interpreted as a local convective rainfall, the calculation of the surface runoff is based on the calculation of the integration by parts of the local throughfall, which makes the calculation and modification more complex. Since this, the modification of the actual infiltration cannot be carried out without changing all the previous calculation related to the hydrology of JULES. We decided to determine a variable maximum infiltration scheme which helps to better represent the exchange of water at the surface in the case of intense rainfall.

2.2 Methods used in other Land Surface Models

The infiltration methods of 10 land surface models are summarised in Table 2.2 and can be divided into 4 different methods to calculate infiltration: 1) Variable infiltration capacity (VIC), 2) according to Green Ampt (Green and Ampt, 1911), 3) using a probability distribution and 4) uses a source/sink approach where the infiltration is calculated in such way as to maintain the conservation of the Surface Water Balance (SWB), (Ashton, 2014). Most of the land surface models describe the actual infiltration into the soil which is limited by a maximum infiltration.

As can be seen in Table 2.2, most of the models use a variable maximum infiltration rate (VIC) dependent on factors such as soil moisture, texture, hydraulic conductivity and orography. The actual infiltration is based on the amount of precipitation and runoff to keep in check the surface water balance in the model. Since the JULES model calculates the actual infiltration rate in the same way and depends on the calculation of the runoff, the most straightforward potential change that can be made in order to attempt to improve the representation of infiltration, is to include a variable maximum infiltration instead of a fixed maximum infiltration. The calculation of the runoff may be adapted to the moisture content of the soil to be able to better represent the actual infiltration rate at the surface of the soil.

Model	Institution	Reference	Maximum infiltration method	Actual infiltration method
JULES	Met Office	(Best et al., 2011)	Fixed Imax rate	SWB
VIC	Princeton Uni.	(Gao et al., 2010) (Liang et al., 1996)	VIC scheme	SWB
ISBA	Meteo-France	(Decharme and Douville, 2006) (Noilhan and Mahfouf, 1996)	VIC scheme	SWB
ORCHIDEE	IPSL	(Krinner et al., 2005)	VIC I_{max}=f(θ)	probability distrib.
CLM	NCAR	(Oleson et al., 2010)	VIC I_{max}=f(texture,θ)	SWB
HTESSEL	ECMWF	(Balsamo et al., 2009)	VIC I_{max}=f(θ,orog.)	SWB
NOAH	NCEP	(Schaake et al., 1996)	VIC I_{max}=f(θ,K_{sat})	SWB
CLASS	Canada	(Verseghy, 1991)	Green-Ampt	Green-Ampt I=f(K,Ψ)
CABLE	Australia	(Haverd and Cuntz, 2010)	No I_{max}	SWB
MATSIRO	Japan	(Takata et al., 2003)	No I_{max}	SWB
G2G	CEH	(Bell et al., 2007, 2009)	VIC I_{max}=f(θ)	probability distrib.

Table 2: Table of Infiltration Methods used in a review of 10 Land Surface Models

3 Methods of maximum infiltration in JULES

The infiltration scheme is calculated from the surface runoff calculation which in turn depends on the maximum infiltration I_{max}. However, this scheme is constant in time (summarised in Table 2.2). In the case of intense rainfall, the modelled surface runoff is likely to be underestimated compared to the observations (personal communications). To better represent flooding events with the model, it is important to better represent the infiltration scheme by taking into account both the saturation excess, when the soil is saturated and the infiltration excess in the case of intense rainfall such as during flash floods. The infiltration excess has to be limited by a variable maximum infiltration rate.

The study of Mueller et al. (2016) has shown that JULES is not able to represent the surface runoff in the case of constant intense rainfall where the surface runoff does not have a gradual increase in time, which is shown in the experiments and in SWAP (Van Dam et al., 1997) and CHTESSEL (Balsamo et al., 2009).

This section explains the different development tests which have been undertaken an alternative experimental methods in order to improve the rate of surface runoff and the infiltration scheme. The first method was developed to continue the study of Mueller et al. (2016) and we develop a set of new methods of calculation (from method 2 to method 4) of a variable maximum infiltration to be in accordance with other land surface models (Table 2.2).

In the hydrology module of JULES, the surface runoff and infiltration are calculated differently according to the method of precipitation that can be calculated as average precipitation data or as point precipitation data. For the infiltration schemes we have developed, the calculation of infiltration I_{max} is taken into account for both of the two precipitation calculation methods. The variable maximum infiltration we developed has been included as an output of the JULES model.

3.1 Infiltration scheme 1: simplified CHTESSEL approach

In order to modify the infiltration of the JULES model in the case of intense rainfall, the infiltration scheme has been evaluated, during the SINATRA project, with constant rainfall rates varying from 100 mm/d to 1000 mm/d by Mueller (personal communication). The infiltration scheme follows the scheme of the CHTESSEL model without the term dependent on orography (Balsamo et al., 2009) and is assumed to be:

$$I_{max} = \beta (W_{sat} - W)/\Delta t \tag{7}$$

where the parameter β is defined in table 1, W and W_{sat} are respectively the moisture content and the saturated moisture content (in kg m^{-2}) integrated into the whole column of the soil. However, the formulation in CHTESSEL used the volumetric moisture content (m^3 m^{-3}) This scheme is applied only using point precipitation data and with the JULES flag *l_point_data* set to true.

3.2 Infiltration scheme 2: moisture content of the 1st layer

This infiltration scheme was first studied so as to continue the work of Mueller but also taking into account only the moisture content of the soil which is close to the surface. In this formulation, the moisture content W^{top} represents the moisture content of the 1^{st} layer of the soil (mc layer1) as defined in the JULES model as equation 8.

$$I_{max} = \beta(W_{sat}^{top} - W^{top})/\Delta t \tag{8}$$

3.3 Infiltration scheme 3: actual hydraulic conductivity of the soil

This scheme has been implemented through a new module called *infiltration_K_mod.F90*. This infiltration scheme is dependent on the actual hydraulic conductivity K_{top} of the top layer instead of the saturated conductivity as below:

$$I_{max} = \beta K_{top} \tag{9}$$

This module uses the calculation of hydraulic conductivity from the module *hyd_con_vg* when the Van Genuchten flag (*l_vg_soil*) is activated and uses *hyd_con_ch* when the model of Clapp and Hornberger is used (by default).

We create a flag *l_infil_K* to use the infiltration scheme based on the actual hydraulic conductivity when it is set to true and the method 2 (see section 3.2) when it is set to false.

3.4 Infiltration scheme 4: calculation of CHTESSEL

When the infiltration scheme explained in the section 3.2 is used, the results are dependent on the timestep used. To avoid this, we implement the original scheme of maximum infiltration used in CHT-ESSEL described in equation 10, where b described the standard deviation of the orography σ such as $b_0 = \dfrac{\sigma - \sigma_{min}}{\sigma + \sigma_{max}}$. Since the orography is not represented in standard JULES, we choose to set b_0 as the minimum, corresponding to a flat area, so b_0 is equal to 0.1. The dimension of the infiltration is given by throughfall T and snow melt M.

$$I_{max} = (W_{sat} - W) + max\left(0, W_{sat}\left[(1 - \frac{W}{W_{sat}})^{\frac{1}{b_0+1}} - (\frac{T+M}{(b_0+1)W_{sat}})\right]^{b_0+1}\right) \tag{10}$$

3.5 Infiltration scheme 5: calculation from Darcy's law

In this scheme, we assume the maximum infiltration rate is based on Darcy's law (Hubbert, 1957) with the hydraulic conductivity of the 1^{st} layer K_{top} and the potential gradient ψ between the first and the second layer of the soil as in equation 11.

$$I_{max} = K_{top}\frac{d\psi}{dz} \tag{11}$$

In this case, the maximum infiltration rate corresponds to the flux of water between the first and the second layer of the soil.

4 Model experiments and methodology

4.1 Single point

The different infiltration schemes have been studied and compared using a single point simulation. We have used the Loobos FLUXNET data situated in the Netherlands for the year 1997 (Baldocchi et al., 2001). This dataset is considered as the standard study point of JULES. This database contains meteorological data at a 30 min time step. For the test cases, the rate of precipitation has been imposed as a constant rate moving from 100 mm/d to 1000 mm/d. The default timestep of the model used for this test case is 1440 seconds (study from SINATRA not published).

4.2 UK catchments

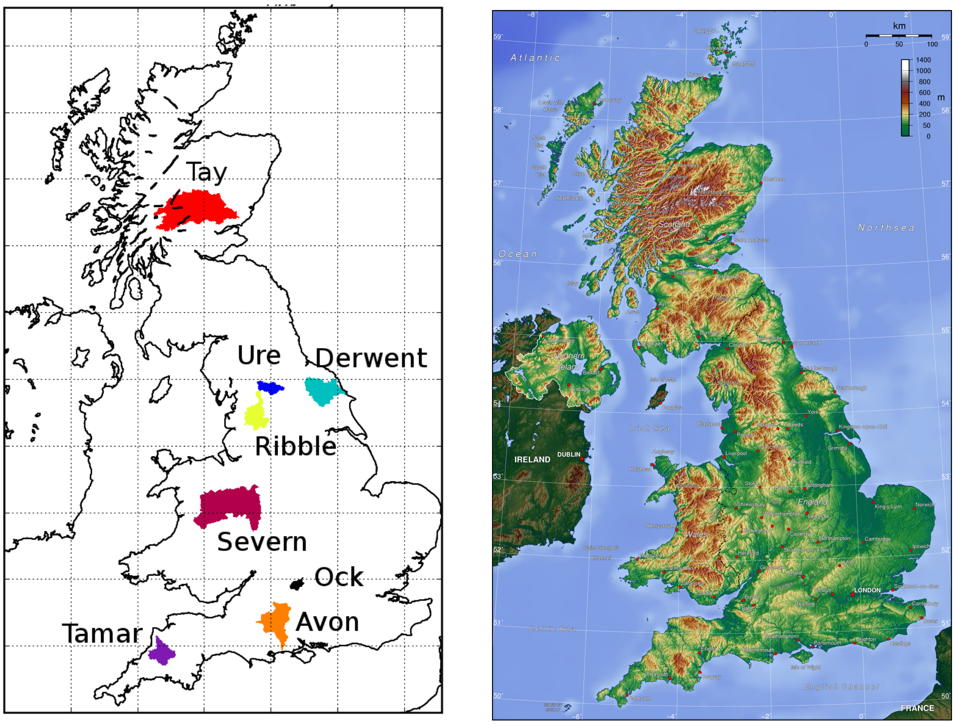
The meteorological forcing data used to drive the JULES model (jules-vn4.8) to study the river flow at the outlet of various UK catchments were taken from the CHESS data (Climate Hydrology and Ecology research Support System meteorology dataset for Great Britain) (Robinson et al., 2017). This meteorological data covers Great Britain with a spatial resolution of 1 km and uses daily precipitation from the CEH Gridded Estimates of Areal Rainfall (CEH-GEAR) (Tanguy et al., 2014) dataset which is derived from the MORECS rainfall observation and downscaled using information about topography (Thompson et al., 1981).

The simulations were performed at a 30 min time step for the period 1991-2000 with a spin up of 10 years where the CHESS dataset from 1986 to 1990 has been used twice. We evaluate the modelled river flow at the outlet of 8 catchments located in Great Britain (location and information given in Fig. 1(a) and Table 3). The default soil hydraulics formulation used is the Brooks and Corey (Brooks and Corey, 1964).

The surface runoff produced by saturation excess is based on the PDM (Probability Distributed Model) (Moore, 1985; Moore and Bell, 2002) and we used the River Flow Model (RFM) routing scheme. The modelled river flow at the outlet of catchments are compared to the observed gauged daily flow (GDF) of the National River Flow Archive (NRFA) (https://nrfa.ceh.ac.uk/).

River	Station	Area	Precip.
Tay	15006 (Ballathie)	4587	1424
Ure	27034 (Kilgram)	510	1337
Derwent	27041 (Buttercrambe)	1586	765
Ock	39081 (Abingdon)	639	639
Avon	43021 (Knapp Mill)	1706	810
Tamar	47001 (Gunnislake)	917	1215
Severn	54001 (Bewdley)	4325	912
Ribble	71001 (Samlesbury)	1145	1350

Table 3: River, station and area (km^2)s of the catchment used in this study including the annual mean precipitation over 1960-1990 period (mm).



(a) Studied catchments (b) Topography

Figure 1: (a) Location of the studied catchments and corresponding topography of the United Kingdom (from http://digimap.edina.ac.uk)

4.3 Evaluation Methodology

The modelled river flow is evaluated with the Kling Gupta Efficiency KGE (Gupta et al., 2009). This coefficient is described in equation Eq. 12, where ED is the Euclidean Distance from the ideal point. This efficiency has the advantage of taking into account the linear correlation r, the ratio of the standard deviation α and the ratio of the mean value β, between the simulated and observed flows. We define the bias of the model as (β-1)*100 (%). The ideal value of the KGE such as each of its three components is 1.

$$
\begin{aligned}
KGE &= 1 - ED \\
&= 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \\
&= 1 - \sqrt{(\frac{Cov_{sim,obs}}{\sigma_{simu}\sigma_{obs}} - 1)^2 + (\frac{\sigma_{sim}}{\sigma_{obs}} - 1)^2 + (\frac{\mu_{sim}}{\mu_{obs}} - 1)^2}
\end{aligned} \tag{12}
$$

The evaluation of the modelled river flow is made with different schemes of the maximum infiltration. In order to compare the efficiency of the two different modelled scheme compared to the observations, we use the relative KGE R_{KGE}, as formulated by Lerat et al. (2012), to evaluate the methods of maximum infiltration scheme used and diagnose the better scheme for each situation. The relative KGE R_{KGE} is described in equation Eq. 13, where m = 1 - KGE measures the discrepancies between the simulated

R_{KGE}	$m_{obs,x}/m_{obs,r}$	Interpretation
1	0	Simulated flow with scheme x is perfect
0.5	1/3	Error metric m of scheme x is 3 times smaller than with r
0.33	1/2	Error metric m of scheme x is twice smaller than with r
0.15	1/4	Error metric m of scheme x is 25 % smaller than with r
0.10	8/10	Error metric m of scheme x is 20 % smaller than with r
0.05	9/10	Error metric m of scheme x is 10 % smaller than with r
0	0	Error metric m is equal to the reference
-0.05	10/9	Error metric m of scheme x is 10 % larger than with r
-0.33	1/2	Error metric m of scheme x is twice larger than with r
-1	$+\infty$	Simulated flow with scheme r is perfect

Table 4: Interpretation of the relative performance KGE index

and the observed river flows, r is the simulation of reference (with the standard scheme) and x is the simulation with the scheme x. Here, we study only the scheme 3. For a perfect simulation, m = 0.

$$R_{KGE} = \frac{m_{obs,r} - m_{obs,x}}{m_{obs,r} + m_{obs,x}} \tag{13}$$

The range of the relative KGE is between -1 and 1, where -1 corresponds to a perfect simulation when we used the simulation of reference r and 1 is perfect when we used the simulation with the infiltration scheme x. $R_{KGE} = 0$ occurs if the metrics m of the scheme x simulation equal the metrics of the reference scheme r simulation. The interpretation of the value of R_{KGE} is detailed in Table 4 adapted from Lerat et al. (2012). In this method, R_{KGE} compared only the metric value of $m_{obs,r}$ and $m_{obs,x}$. This means, it can only distinguish when the new scheme x is an improvement on the scheme of reference r but does not discern when the value of m is low or high.

5 Results

5.1 Evaluation of the different infiltration schemes in a point

5.1.1 Infiltration scheme 1 and 2

Infiltration schemes 1 and 2 consider that the maximum rate of water which can be infiltrated into the soil corresponds to the amount of water content missing before the soil is being saturated. Scheme 1 considers the saturation of the soil of the whole depth of the soil (3 m in the standard JULES) and scheme 2 considers the saturation of the first layer of the soil only (10 cm depth in the standard JULES).

In order to compare these 2 schemes, we applied a constant rainfall of 1000 mm/d on to bare soil ($\beta = 0.5$) in dry soil conditions (10% of humidity) with a timestep of 60 seconds, to evaluate the behaviour of the surface runoff scheme which is represented in red in Fig. 2. The scheme "mc layer1"

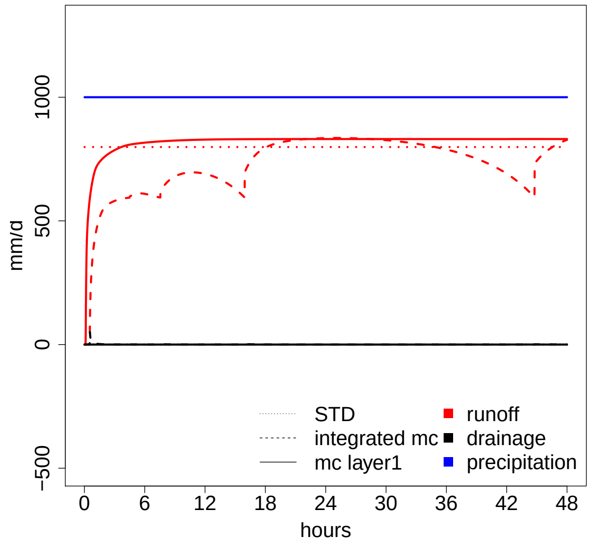


Figure 2: Surface water balance at the surface of the soil with the standard infiltration scheme of JULES (STD), the scheme 1 (integrated mc) and with the scheme 2 (mc layer1) in mm/s. 2 days of simulation expressed in minutes with a constant rainfall of 1000 mm/d.

(continuous line) shows a better trend in surface runoff and avoid gaps as opposed to the scheme 1 ”integrated mc” (dotted line). The limitation of the infiltration with taking into account the actual moisture content of the first layer of the soil slightly increases the rate of surface runoff of 830 mm/d in a steady state compared to the default infiltration ”STD” of JULES of 798.5 mm/d (dashed line). In this experiment, the saturated conductivity applied K_{sat} is set to 0.004715 kg.m^{-2}.s^{-1} (ie 407.3 mm/d).

However, this case is dependent on the timestep we use. Since the surface runoff is proportional to the exponential decrease of $I_{max}/(R\Delta t)$ (as shown in equation 5), the higher the timestep, the higher the surface runoff (see Figure 3). The I_{max} term does not necessarily have to be dependent of Δt since this is already taken into account in the calculation of the surface runoff. The term Δt has been added in the first method in order to achieve the correct dimension of a rate. In these methods, the infiltration is independent of the actual hydraulic conductivity of the soil.

5.1.2 Infiltration scheme 3

The variable maximum infiltration in scheme 3 is limited by the rate of the actual hydraulic conductivity K of the first layer which is dependent on the soil moisture content (Fig 4). In JULES, the calculation of the hydraulic conductivity can be either from the formulation of Van Genuchten (1980) (VG) or from Clapp and Hornberger (CH) (default) as described below:

$$K(\theta)_{CH} = K_{sat}\theta^{2b+1} \tag{14}$$

The behaviour of K is function of the moisture content as shown with the solid line in Fig. 4. The default value of b enhances the hydraulic conductivity which tends to zero for a fractional saturation of the soil

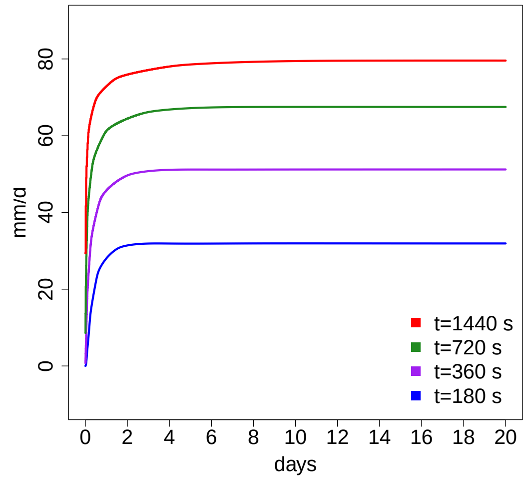


Figure 3: Surface runoff rate in mm/d when we impose an intense rainfall of 100 mm/d for 20 days. The respective blue, purple, green and red represent the timestep used of 180, 360, 720 and 1440 seconds.

moisture content lower than 80% for CH and 99% for VG. This behaviour is extreme and has been tested for different values of b. In the Loobos test point, the default parameter b is set to 6.63.

In comparison with another land surface model, the ORCHIDEE model has set this b parameter dependent on the texture of the soil from 2.12 for fine soil and 1.16 for coarse soil. For the following simulation we choose to evaluate the model with the default value of b and with the value set to 1.5.

In the case study of constant intense rainfall (100 mm/d), we evaluate the amount of surface runoff as a function of the maximum infiltration rate with different initial soil moisture conditions (5). With the standard value of b, the soil moisture of the soil has to be high in order to allow some infiltration of water into the soil. The Fig. 5 shows the profile of surface runoff as a function of the maximum infiltration rate. The soil moisture of the soil has to be $>$ 85 % to infiltrate more than 20 % of the precipitation (5).

In JULES, the actual infiltration is calculated after the surface runoff which depends on the maximum infiltration rate. In this scheme, the maximum infiltration rate is based on the value of the hydraulic conductivity of the first layer of the soil which increases with the moisture content of the soil (Fig. 4). Fig. 6 shows the variation of the actual infiltration for each simulation of constant intense rainfall of 100 mm/d for a period of 20 days by imposing different initial conditions of the fractional moisture content from 0.999 to 0.60 with the standard value of b=6.63 and with b=1.5. The reduction of the parameter b enhance an increase of the infiltration rate (See full and dashed green and red line Fig. 6).

5.1.3 Infiltration scheme 3 and 5

The maximum rate of infiltration based on Darcy's law (scheme 5) is not used since it corresponds to the transfer between soil layers and not between the air-soil interface. Scheme 3 and 5 both use the hydraulic conductivity of the top soil layer. Scheme 5 also takes advantage of the potential gradient. The

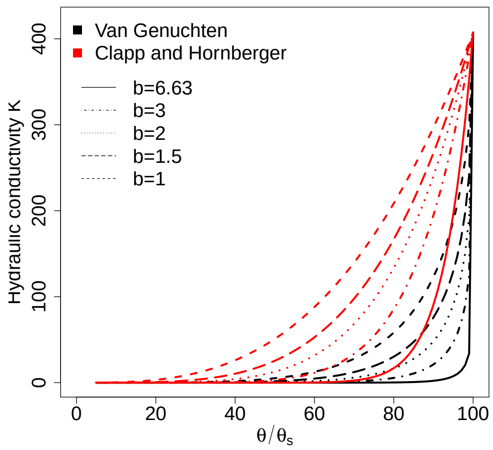


Figure 4: Hydraulic conductivity of the soil as a function of the fractional saturation of moisture content with the formulation of Clapp and Hornberger (in red) and Van Genuchten (in black) with the a set of value for the parameter b from the default value of 6.63 to 1.

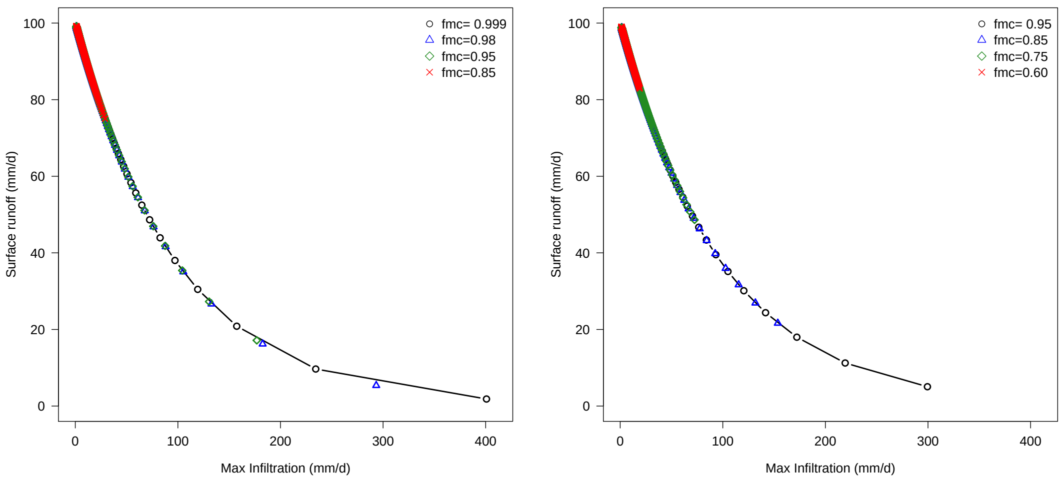


Figure 5: Surface runoff as a function of the maximum infiltration rate with a constant rainfall of 100 mm/d during 20 days. The initial conditions of the fractional moisture content (fmc) of the soil are 0.85, 0.95, 0.98 and 0.999 represented respectively in red, green, blue and black with (a) b=6.63 and with (b) b=1.5.

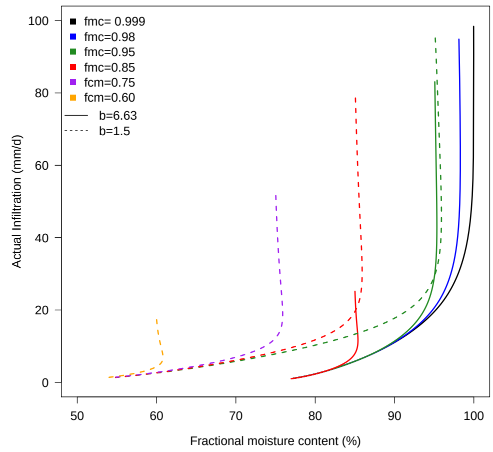


Figure 6: Actual Infiltration rate (mm/d) as a function of the fractional moisture content (fmc) (%) with initial conditions of 0.999, 0.98, 0.95, 0.85, 0.75 and 0.60 respectively in black, blue, green, red, purple and orange for a set up of b=6.63 (full line) and b=1.5 (dashed line).

comparison between these 2 schemes has been made using the annual mean river flow of the Ock and Ribble catchments as represented in Fig. 7.

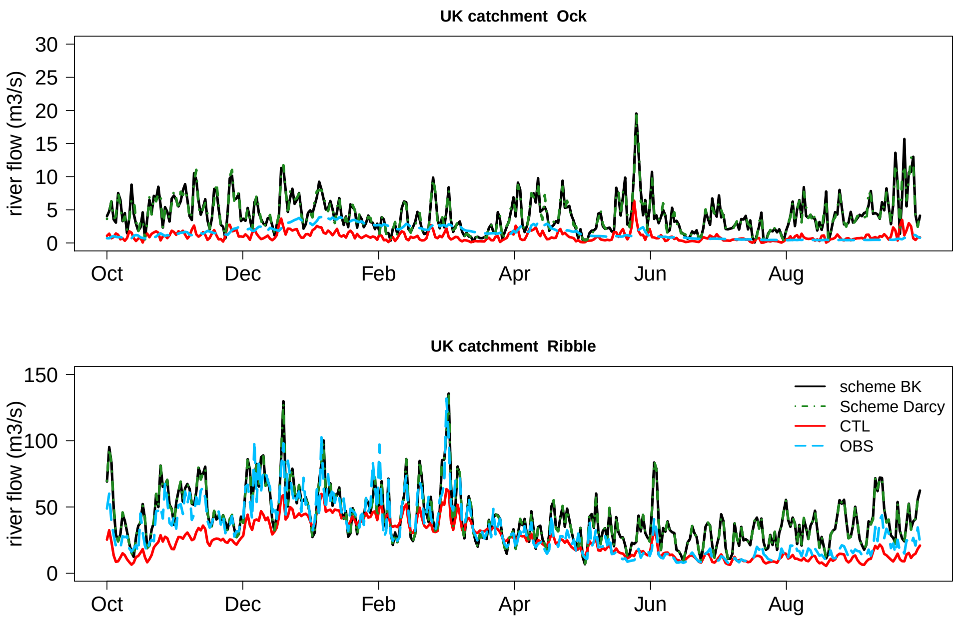


Figure 7: Annual mean river flow of the 1991-2000 period for the (top) Ock and (bottom) Ribble catchment in Great Britain. The scheme Darcy (scheme 5) is represented in dotted green line and BK scheme (scheme 3) in black in comparison with the standard scheme of JULES (CTL) in red.

These catchments have been chosen because they represent respectively a dry and a wet area (annual mean precipitation represented in Table 3). In Fig. 7, we can clearly see that river flow obtained with scheme 3 and 5 is identical. We can deduce that in these cases, the rate of infiltration is controlled directly by the hydraulic conductivity K_{top} which is really low and acts as the limiting factor. Since this has been studied in both a dry and a wet area, the scheme 5 is not considered further.

5.2 Evaluation of river flows of UK catchments

The evaluation considered here uses the configuration and optimised parameters from Martinez et al. (2016) in order to obtain the best profile and efficiency of the modelled river flow used with the default maximum infiltration used in the model. The evaluation of the river flow is made between the standard scheme (CTL) and the infiltration scheme 3 except when another scheme is specified. The configuration is the same for both of the infiltration schemes tested.

5.2.1 Evaluation for the Ure catchment

Here, we evaluate the scheme 3 (Section 3.3) of the variable maximum infiltration on the river flow of the small Ure catchment in UK using the CHESS meteorological data of 1 km^2 spatial resolution (Robinson et al., 2017). The river flow at the outlet of the Ure catchment with the new infiltration scheme is compared with the river flow obtained with the standard scheme of JULES, with and without PDM scheme which calculates the saturation excess. The simulated river flows are compared with the observed river flow from the National River Flow Archive (CEH, Wallingford, https://nrfa.ceh.ac.uk/).

We study the influence of PDM scheme on the daily annual mean modelled river flow with the two different schemes of maximum infiltration over the 1991-2000 period as shown in Fig. 8. The river flow from using the standard scheme (CTL) and scheme 3 (BK scheme), respectively represented in red and black, is compared to the observations (OBS) in blue. The new infiltration scheme is not sensitive (correlation higher than 0.9999) to the saturation excess controlled by PDM model. In that case, the annual mean and the daily river flow over the 10 year period is the same with and without PDM when we use the maximum infiltration scheme 3. This new scheme shows a large improvement in the representation of the river flow at the outlet of the Ure catchment when PDM model is not used (NO PDM). The correlation between the modelled and the observed river flow increases from 0.46 to 0.76 due to the new infiltration scheme. However, this improvement is less marked with the use of saturation excess (when PDM model is used), where the correlation of the river flow is similar (0.76 and 0.77) as shown in Table 5.

Although the KGE efficiency is slightly better with the control scheme (CTL) when PDM is used, the standard deviation of the modelled river flow with the BK scheme is closer to the observed standard deviation than for CTL scheme. Parameter a in Table 5 corresponds to the ratio of the standard deviation $\frac{\sigma_{sim}}{\sigma_{obs}}$. The BK scheme overestimates the variability whilst the CTL scheme underestimates it. For the Ure catchment, the variability of the river flow is better represented with the BK scheme.

Fig. 8 b) shows a better estimation of the winter flow than for the summer. In Fig. 8 c) and d), we have compared the river flow for the hydrological year where the highest peak of flows occurs (October 1994-1995). The trend of the two modelled river flows has the same conclusion for the year 1994-1995 than for the annual mean profile, when PDM is not used (correlation of 0.68 compared to 0.48 with the CTL scheme). However, the BK scheme is better able to represent the highest peak of the river flow (Fig. 8 d). The variability and the mean value of the river flow is closer to the observations with the

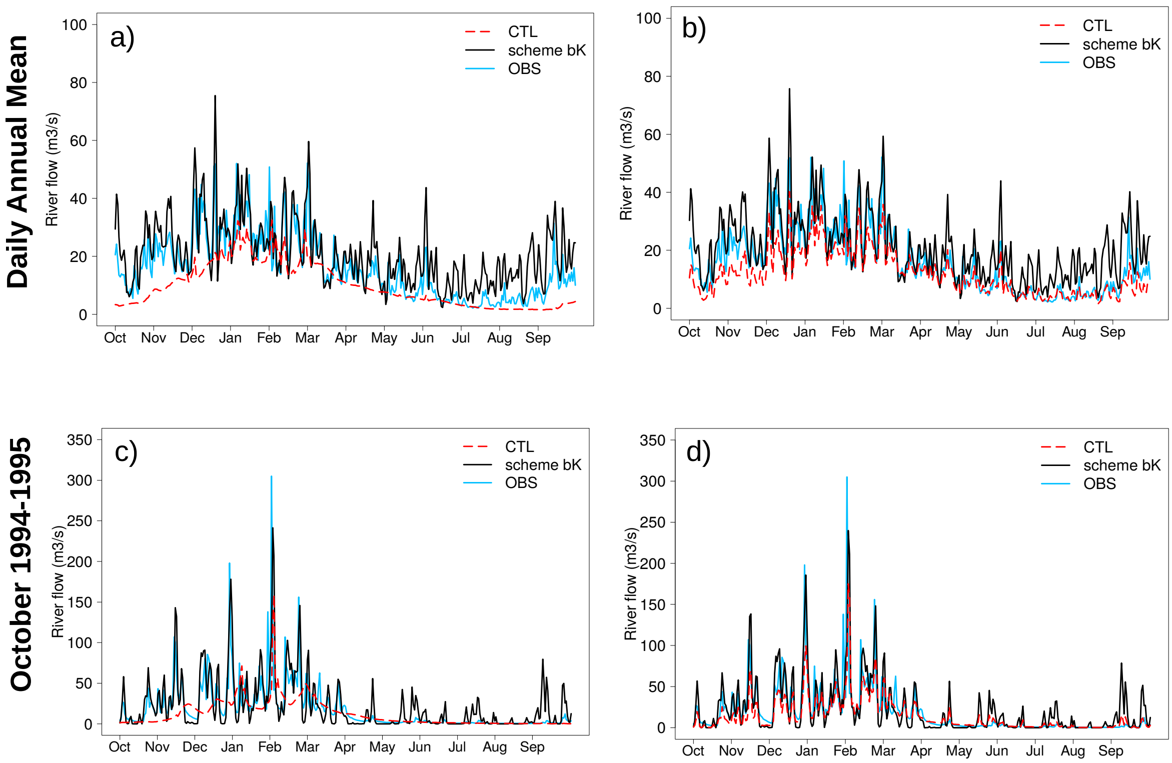


Figure 8: Observed (blue) and simulated daily river flow for the Ure catchment with the standard scheme (dashed red) and the scheme 3 of infiltration (scheme bK) (black line) with (right) and without (left) PDM scheme, (top) for the annual mean of 1991-2000 period and (bottom) for the year with the maximum river flow peak (October 1994 - October 1995)

	Annual Mean		October 1994-1995	
	NO PDM	PDM	NO PDM	PDM
Scheme BK				
KGE	0.547	0.547	0.612	0.612
ρ	0.76	0.76	0.68	0.68
a	1.26	1.26	1.12	1.12
b	1.28	1.26	1.21	1.21
Scheme CTL				
KGE	0.212	0.549	0.247	0.523
ρ	0.46	0.77	0.48	0.70
a	0.55	0.69	0.57	0.69
b	0.63	0.76	0.67	0.78

Table 5: Table of KGE efficiency and its three components ρ, a and b for the BK and CTL schemes with PDM/without PDM for the annual mean river flow 10 year period and for the hydrological year 1994-1995.

BK scheme which gives a better KGE efficiency (0.612), which corresponds to an increase of efficiency of 16 %. This trend is especially clear in winter when the highest value of river flow occurs. The KGE efficiency during winter (DJF) increases 57 % (0.516 compared to 0.327 with the CTL scheme), when the highest value of river flows occurs. The highest peak flows are well represented with the BK scheme (Tab. 5, Fig. 8 d)). In summary, the BK scheme has a better efficiency than the CTL scheme when PDM is not used for every percentile of river flow (represented by the full line in Fig. 9). When PDM is used, the KGE efficiency is similar with both schemes when we consider all value of flows. However, the efficiency of the BK scheme is higher than for the CTL scheme when we consider only the river flows values with a percentile higher than 10%. This difference increases for the highest river flows (red dotted line and black line in Fig. 9). For the Ure catchment, the scheme BK represents an improvement which is especially shown for high flows.

The different schemes of maximum infiltrations directly control the rate of surface runoff and indirectly the rate of subsurface runoff (due to a lower rate of infiltration with the BK scheme). The underestimation of the river flow with the standard CTL infiltration scheme, when PDM is not used, is mostly caused by a too small rate of surface runoff (Fig. 10). In the JULES model (CTL), the estimation of the river flow is given by the process of surface runoff due to saturation excess (test made with PDM) as shown in Fig. 10. Without the use of PDM, the surface runoff occurs only during the highest rate of precipitation of 76mm (Fig. 11). This occurs on the 1st of February 1995 with the CTL scheme (red peak in the left figure 10 at the bottom). The use of the new infiltration scheme (BK scheme) makes it unnecessary to use PDM. The daily surface runoff with the BK scheme averaged over all the Ure catchment is correlated up to 0.967 with the surface runoff with CTL scheme + PDM for the hydrological year of 1994-1995 (Fig. 10). The good representation of the modelled river flow is due to the improved calculation of runoff.

The highest flows of the 1991-2000 period are better represented with the BK scheme (Fig 8 d), where this scheme produces the highest average rate of surface runoff (Fig. 10). This high rate of runoff is due to a higher frequency of grid cells (1 km of resolution) of the Ure catchment where the rate of surface

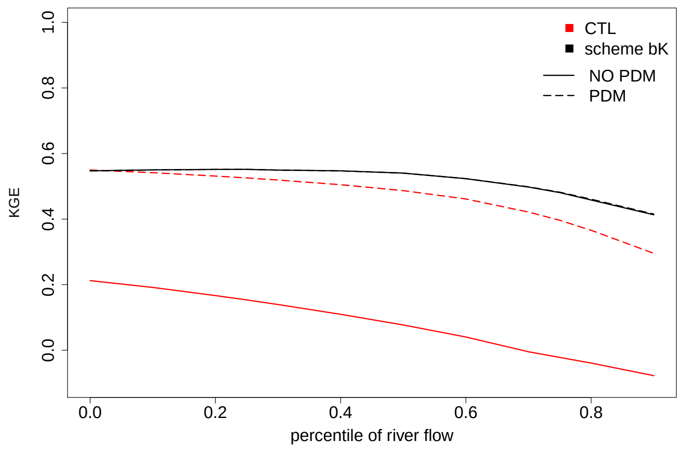


Figure 9: KGE efficiency as a function of the percentile of the modelled river flow. Scheme BK is represented in black and the standard (CTL) in red, when PDM model is used (full line) and when it is deactivated (dotted line).

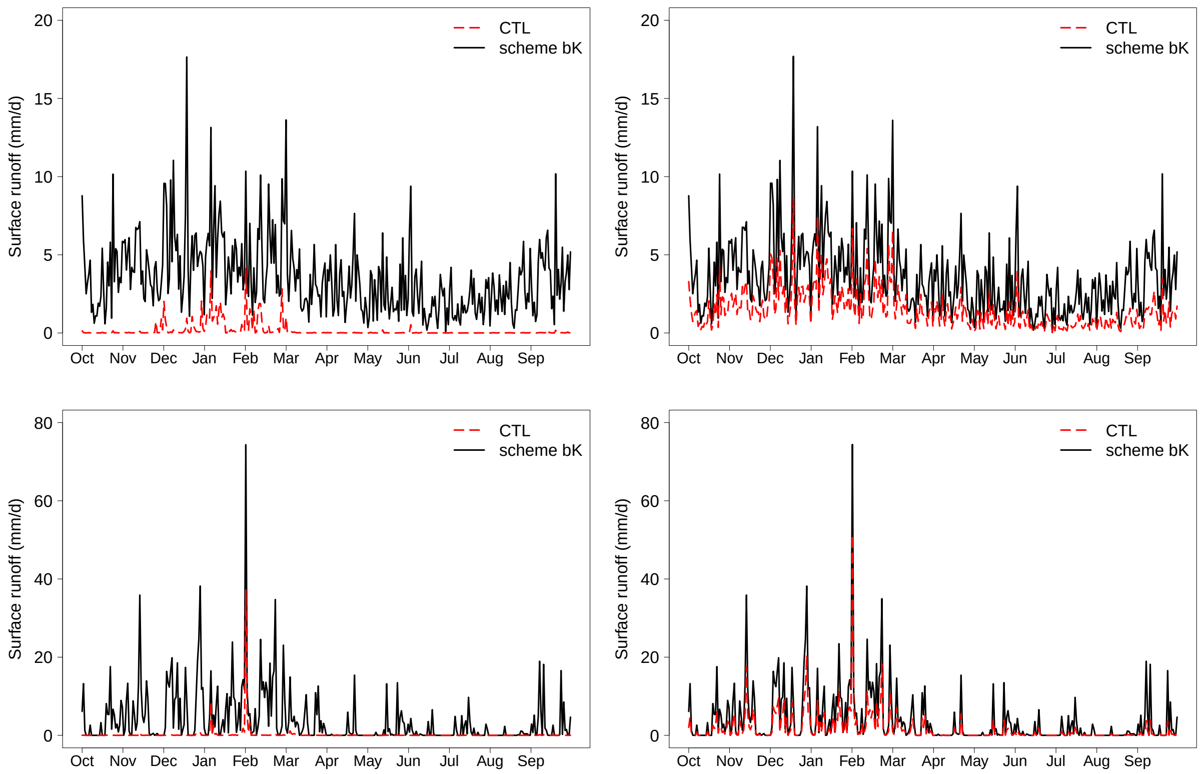


Figure 10: Observed (dotted blue) and simulated surface runoff (mm/d) averaged over all grid cells of the Ure catchment with the standard CTL scheme (dashed red) and the scheme 3 of infiltration (scheme BK) (black line) with (right) and without (left) the PDM scheme, (top) for the annual mean of the 1991-2000 period and (bottom) for the year with the maximum river flow peak (October 1994 - October 1995).

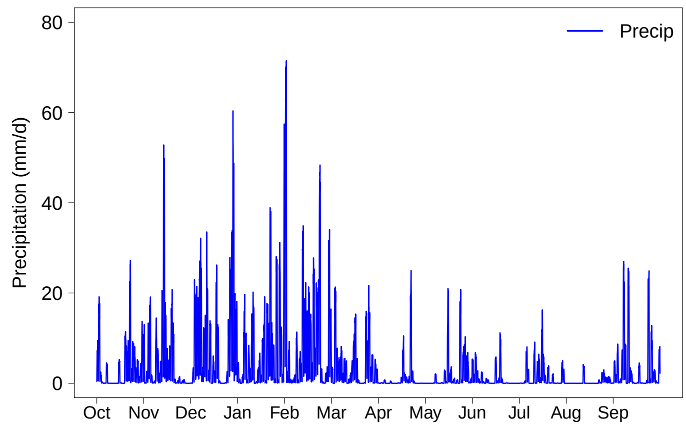


Figure 11: Average hourly precipitation (expressed in mm/d) over the Ure catchment from October 1994 to October 1995.

runoff per grid is higher than 60 mm/d during the day of the peak of precipitation (Fig. 12). The peak of the river flow on the 1st February 1995 is explained by the high rate of the precipitation on this day (Fig. 11), since the rate of the surface runoff is relatively low during the 2 days before as it is shown in Fig. 12. However, the new BK scheme (left on Fig. 12) creates a higher frequency of grid cells where the surface runoff reaches at least 10 mm/d for the days which precede the river flow peak.

This study has shown that infiltration scheme 3 (BK scheme) has induced an increase of surface runoff which helps to better represent the river flow at the outlet of the Ure catchment, especially during high flow periods. This scheme now has to be studied in other catchment settings and over different time scales.

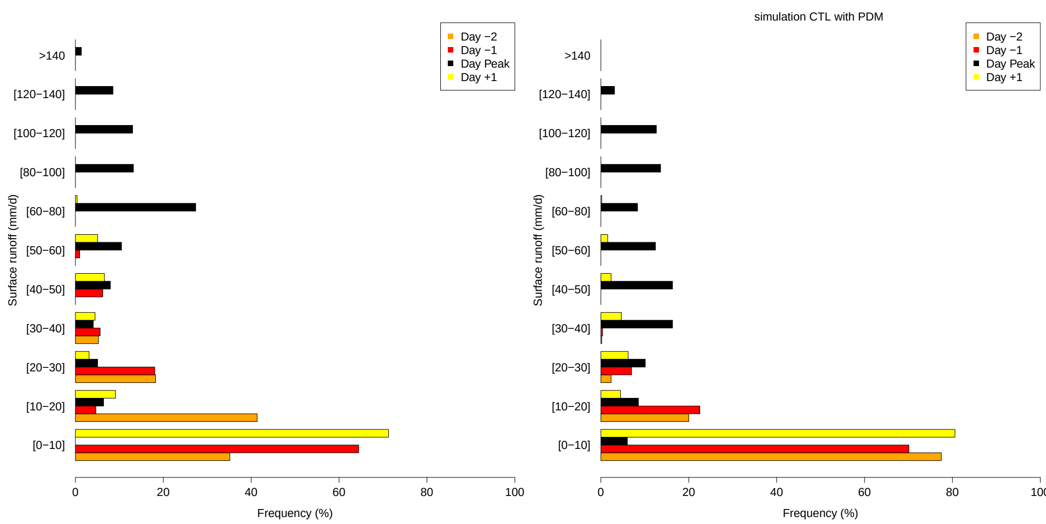


Figure 12: Frequency of grid cells of the Ure catchment classed by surface runoff rate (mm/d) for the day of the peak river flow on the 1st February 1995 (in black), for the days before (days -2) (orange) and (day -1) (red) and the day after (day +1) (yellow) with the maximum infiltration scheme 3 (left) and with the standard simulation CTL (right) with using the river routing scheme PDM.

5.2.2 Evaluation with 8 UK catchments

The evaluation of the new infiltration scheme has been made with the STD scheme (CTL) with PDM. Fig 9 has shown significant increases in efficiency of the river flow when PDM is used. Here, Fig. 13 confirms this improvement for all the catchments studied, where the average improvement for all the catchments is set to a relative KGE of 0.29. We remind the reader that a value of the relative KGE of 0.33 indicates that the error metric *m* of PDM is twice smaller than for the reference NO-PDM. The level of flow has no significant impact on the value of Relative KGE, except for the highest 20% of flows (percentile 0.80).

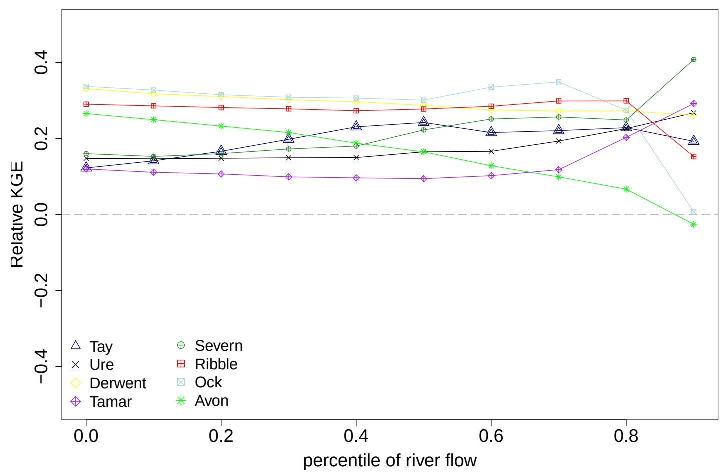


Figure 13: Relative KGE of the daily river flow of each catchment for the 1991-2000 period modelled with the standard model CTL with PDM compared to NO-PDM as a function of the percentile of the river flow

We evaluate the monthly mean river flow for the UK catchments as described in Table 3 in order to compare the trend of the river flow with the different BK and CTL schemes (Fig. 14). The mean value of the model with the BK scheme is on average 59 % higher (26.5 % lower with CTL scheme) than the mean observed value. For the 20% highest values of flow, this bias is reduced to 22 % with the BK scheme, which is closer to observations than with the CTL scheme, where the mean value is 34% lower than observations (absolute value of the bias represented in Fig. 16). In average for the 8 catchments, the new BK scheme is better able to represent the highest flow than the CTL scheme.

The monthly profile of the flow is well represented for the catchments located in the most humid regions of Great Britain, such as Tay, Ure, Tamar and Ribble. The corresponding mean KGE efficiencies are 0.77, 0.70, 0.43 and 0.69 respectively. The improvement of the daily river flow is significant only for the Ribble and Ure catchment, where the Relative KGE is on average of 0.38 and 0.28 respectively compared to the CTL scheme NO-PDM, and 0.13 and 0.10 respectively with CTL PDM (Fig. 17). The improvement is also visible in Fig. 17 for the Tamar catchment where we consider all the river flows except the 20% lowest flows. Although the Tay catchment predictions are not improved, the correlation with observations is higher than 0.87 (Fig. 14). This can be explained by a river flow too sensitive to precipitation, which is visible in the annual mean profile represented in Fig. 15. The standard CTL scheme however underestimates the variability of the river flow of this catchment (B=1.15 with BK and B=0.81 with CTL). The Fig. 19 shows the relative KGE component r (Pearson correlation) as a function

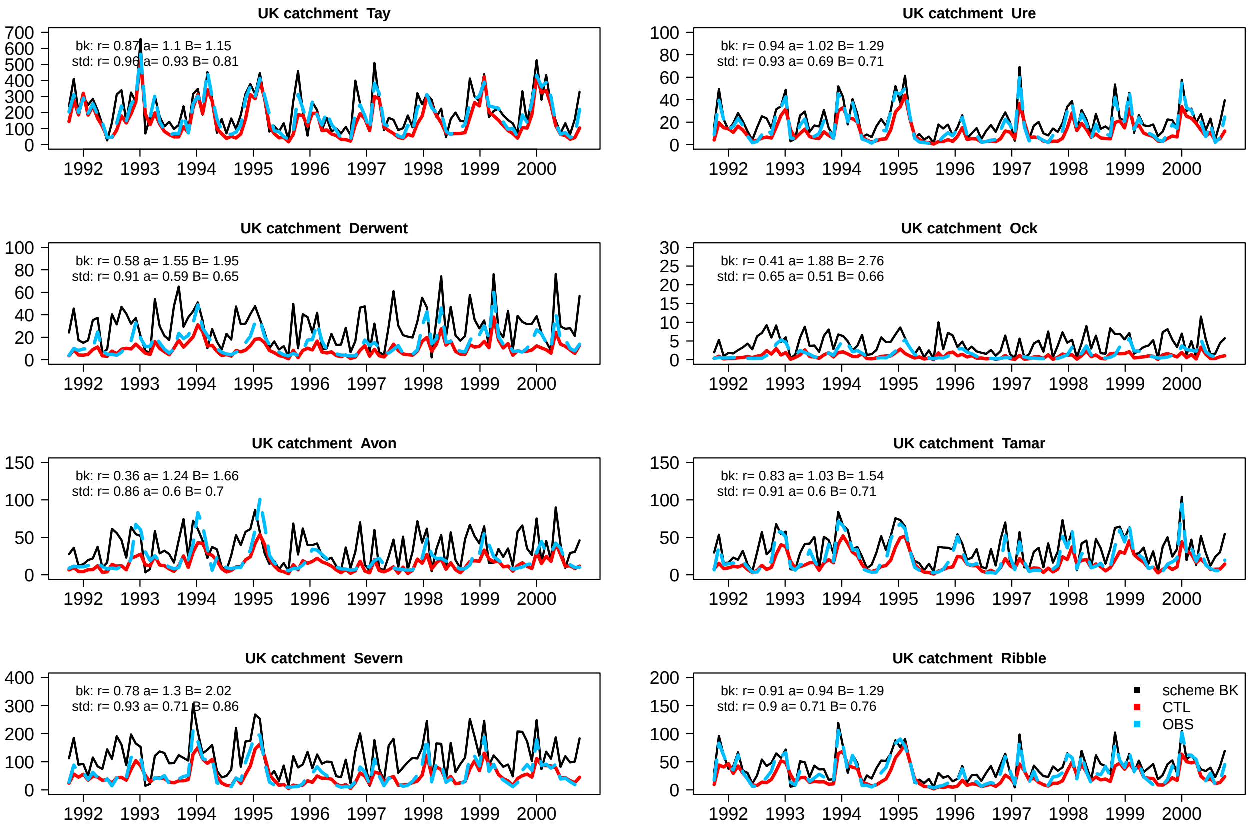


Figure 14: Monthly mean river flow of UK catchments of the NRFA observations (blue) and of the model with BK scheme (black) and with CTL scheme (red) with corresponding correlation r, variability ratio a and ratio of means B

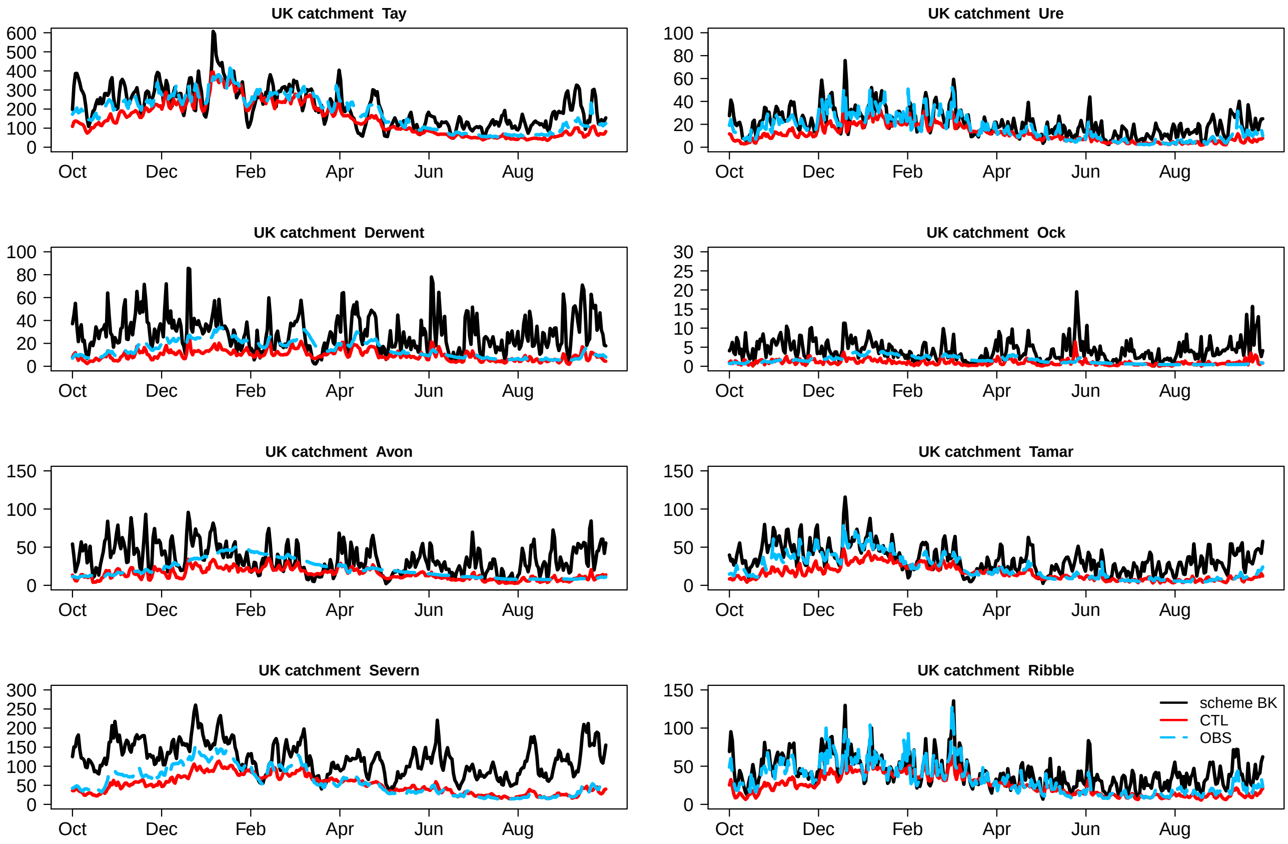


Figure 15: Annual mean river flow of UK catchments of 1991-2000 period of the NRFA observations (blue) and of the model with BK scheme (black) and with CTL scheme (red).

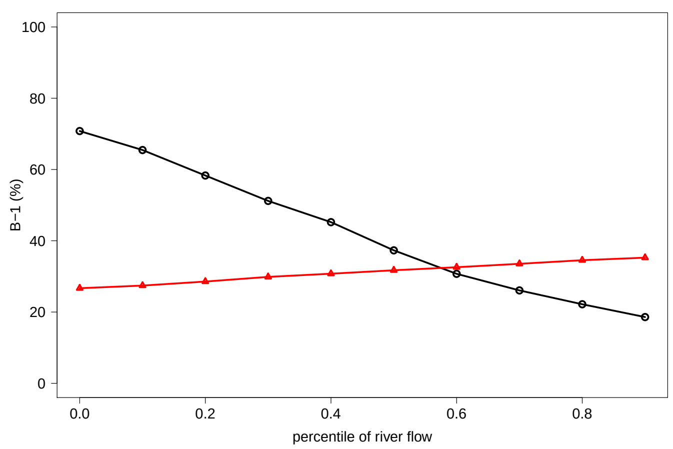


Figure 16: Average of the mean absolute bias value for the 8 studied catchments with the BK scheme (black) and the CTL (red). All the bias values are negative for the CTL scheme and positive with BK, corresponding respectively to an underestimation and an overestimation.

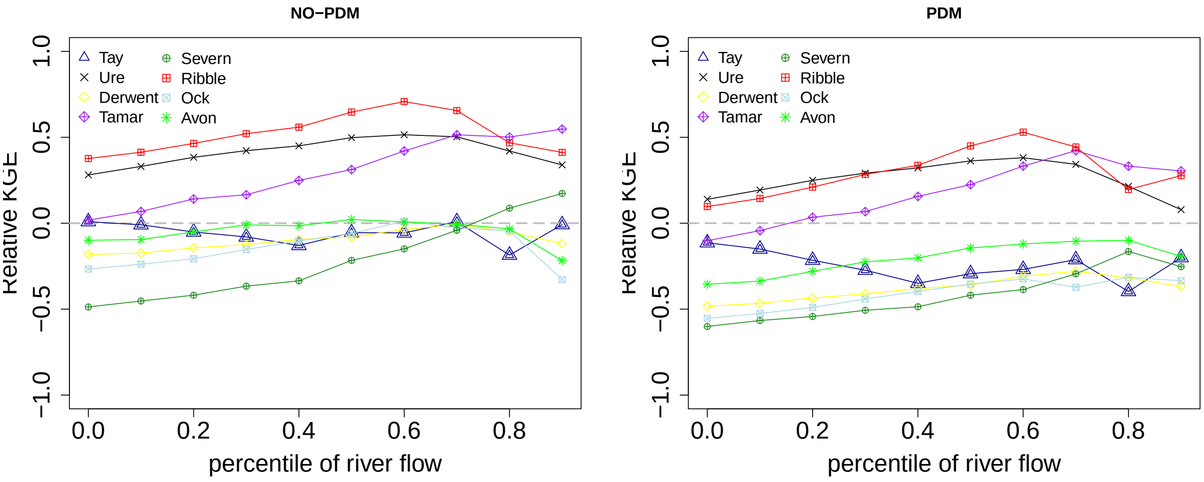


Figure 17: Relative KGE of the daily river flow of each catchment of the 1991-2000 period modelled with the BK scheme compared to the reference CTL scheme as a function of the percentile of the river flow.

of the percentile of the river flow. For high river flow in the Severn and Tay catchment, the correlation between the modelled flow with BK scheme and observations is better than with the CTL scheme.

The improvements of the river flow of the Ribble and Tamar catchments with the BK scheme are due to the improvement in the highest peak flow which occurs between November and March (Fig. 15). Fig. 18 shows the relative KGE of each catchment separated for each season of the year. The Tamar catchment represented in purple in Fig. 18 performs better with the BK scheme only during DJF and MAM for medium flow levels. It is important to note that the percentile of the river flow in Fig 18 splits the flow level of the corresponding season. This means that the highest percentile of flow during SON corresponds to a lower flows that the mean percentile during the MAM flows. We can deduce from the results presented in Fig. 18 that the BK scheme is not able to well represent the flow during SON where the level is relatively small, compared to higher flow levels such as during the spring (MAM) where the improvement is visible for 5 of the 8 tested catchments. Here, we can see in Fig. 18 that the improvement of the wettest catchments (Ribble, Ure, Tamar) does not occur for the driest season of SON. However, the trend of the river flow of the Tamar, Ribble and Ure catchment with the BK scheme seems to better match with observations from October (Fig. 15). The BK scheme is mainly unable to represent the SON flows (Fig. 18) due to the poor performance for the period of September.

5.2.3 Sensitivity study

The river flow is well represented with the BK infiltration scheme for the wettest catchments and during the highest flow periods. However, the use of the standard CTL scheme is better for the lower flow periods and the regions with less precipitation. In order to understand the river flow level response of these schemes, we have undertaken a sensitivity study of the maximum infiltration rate.

The overestimation of the river flow of the BK scheme is due to the overestimation of the surface runoff

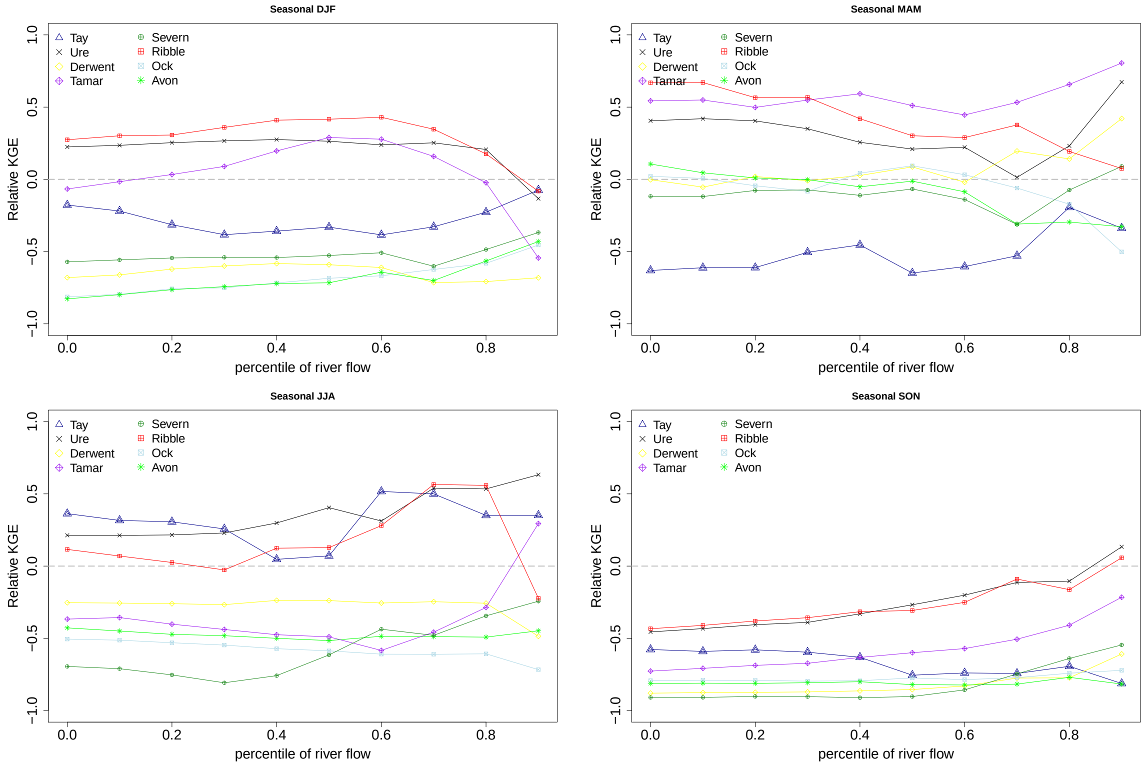


Figure 18: Relative KGE efficiency as for Fig. 17, represented for each season from Winter (DJF) at the left top to Autumn (SON) at the right bottom.

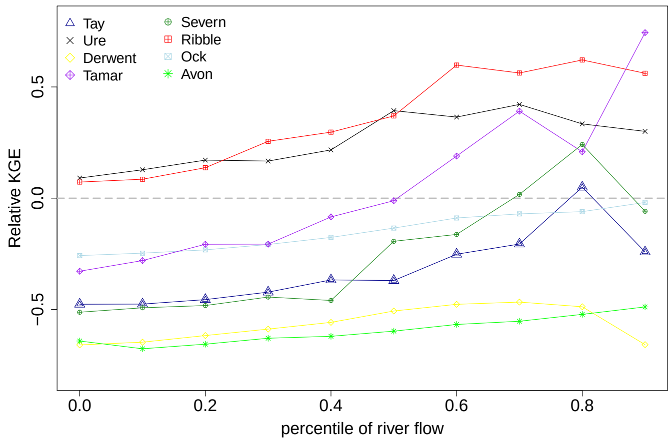


Figure 19: Relative KGE of the r component (Pearson correlation) between the daily river flow of each catchment of the 1991-2000 period modelled with the BK scheme compared to the reference CTL scheme as a function of the percentile of the river flow.

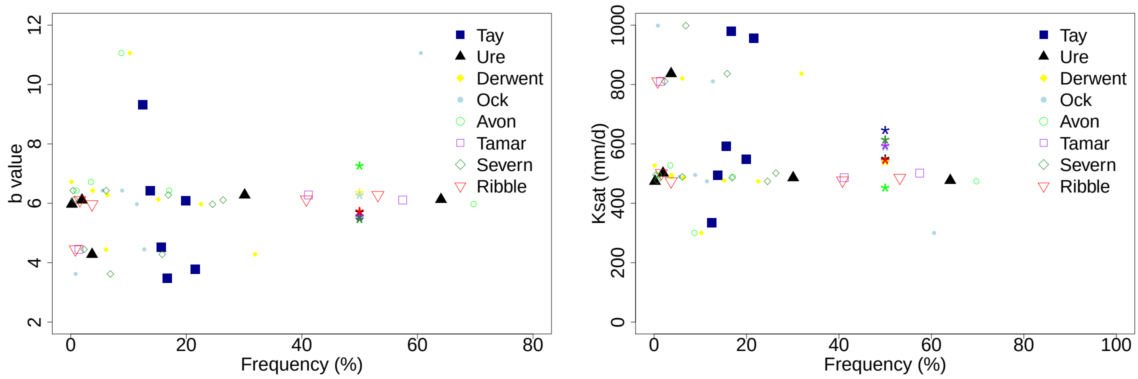


Figure 20: Frequency of the b (left) and Ksat in mm/d (right) value over all the grid cells considered for each catchment. The mean value is represented with the * symbol for each catchment.

corresponding to an underestimation in the infiltration rate. The actual infiltration rate is too low and does not allow the water to be infiltrated into the soil. This leads to a too dry soil and enhances a low value of the hydraulic conductivity (10^{-5} - 10^{-12} kg.m^{-1}.s^{-1}) as a function of time and catchment. To ensure that the low value of the hydraulic conductivity is not due to a poor representation of the *b* value parameter used in the calculation of the hydraulic conductivity where the values are represented in Fig. 4, we have done several sensitivity tests of the river flow with the BK scheme.

The sensitivity study of the *b* parameter has already been tested at the point location of Loobos (Fig 6). Now this is repeated for the catchment scale. We have chosen the Ock catchment which has a low mean annual precipitation (639 mm) in order to see if the poor representation of flow with the new scheme could be improved. The mean value of the *b* parameter for the all the grid cells of the Ock catchment is 6.32 where the range is between 3.6 and 11 and the mean saturated hydraulic conductivity is 594.6 mm/d (Fig. 20). The change of *b* has no significant impact on the river flow at the outlet of the Ock catchment (Figure not shown). The relative change of the river flow when the *b* value is divided by 2 is no more than 0.058 %.

Here, we have considered the range of the saturated hydraulic conductivity K_{sat} and the value of the *b* parameter used in the calculation of the actual hydraulic conductivity for each catchment. The *b* and K_{sat} values depend on the soil type described for each grid cell. Fig. 20 shows different values of *b* and K_{sat}, that occur in each grid cell for each catchment, as a percentage of the total amount of grid cell for each catchment. This figure demonstrates that the representation of the river flow with the BK scheme cannot be explained by the soil properties. In fact, the Tay, Ure, Tamar and Ribble catchment do not have similar soil hydraulic properties. The good representation of the river flow for these catchments is mainly due to the high precipitation in these regions.

Sensitivity studies have applied a multiplicative factor to the rate of maximum infiltration of the BK and CTL schemes. Several simulation have been launched with applying a multiplicative factor from 4 to 1000 to the hydraulic conductivity in the BK scheme. This sensitivity test has been made for the Ure catchment during the hydrological year where the maximum river flow occurs for the 1991-2000 period. The daily river flow is found not to be sensitive to these multiplicative factors (Figure not shown). The relative change between the river flow with the infiltration scheme $I_{max} = \beta K$ and with $I_{max} = \beta K \times 1000$ does not exceed 2 %. This sensitivity has been confirmed with the Ock catchment where the change of

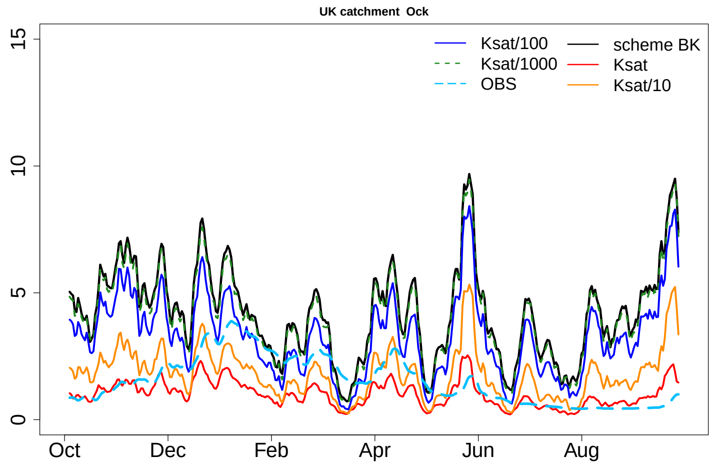


Figure 21: Weekly mean profile of the annual mean river flow at the outlet of Ock catchment for the period of 1991-2000 with BK scheme (black), CTL scheme (red), CTL scheme $K_{sat}/10$ (orange), $K_{sat}/100$ (blue), $K_{sat}/1000$ (green) and the NRFA observation (light blue).

the river flow where the maximum infiltration rate is fixed with $I_{max} = \beta K \times 10000$ does not exceed 0.031 %. This can be explained by the hydraulic conductivity value which is too low to allow sufficient water to be infiltrated so that the decreases of surface runoff are visible in the river flow.

The sensitivity of the river flow level in the Ock catchment was undertaken by applying a multiplicative factor with the standard scheme (CTL), where I_{max} is divided by 10, 100 and 1000 respectively represented in orange, blue and green in Fig. 21. The flow level when $I_{max} = \beta K_{sat}/1000$ corresponds to flow level when $I_{max} = \beta K$. The value of I_{max} with a range from 10^{-5} to 10^{-7} is already too low to allow sufficient infiltration of water into the soil. However, Fig. 21 illustrates that the river flow behaves similarly with the precipitation for each of the different values of I_{max}. The seasonal river flow when $I_{max} = \beta K_{sat}/10$ is underestimated during winter (from January to March) although this scheme overestimates for the dry season (from June to September). Fig. 21 clearly shows that the representation of I_{max} in the model cannot be realistic for all seasons. The maximum observed river flow at the outlet of the Ock catchment occurs in January. To fit with the maximum river flows, the I_{max} value should be according to the range of river flow with using $I_{max} = \beta K_{sat}/10$ and $I_{max} = \beta K_{sat}/100$.

The Brooks and Corey (1964) calculation of the hydraulic conductivity is used per default in JULES and has been used in this study. In order to evaluate the behaviour of the river flows and the results obtained with this default calculation, we have launched the same simulation with both the BK and CTL scheme for the 8 catchments in Great Britain using the Van Genuchten (1980) calculation of the hydraulic conductivity instead. Fig. 22 compares the KGE for simulations with the Brooks and Corey (1964) (BC) and the Van Genuchten (1980) (VG) formulations. The VG formulation slightly better represents the river flow than the BC formulation with the default scheme of maximum infiltration used in JULES (CTL scheme). The relative KGE reaches 0.14 for the Derwent catchment when the VG is used. This means that the VG formulation is able to reduces the error metrics up to almost 25 % compared to the BC formulation (see Table 4 for the meaning of R_{KGE}). On average for all the catchments, the use of the VG formulation enhances a reduction of the error metrics of almost 15 % (mean R_{KGE}=0.73 for the CTL scheme) compared to the use of BC (Fig. 22). However, the choice of the formulation used does not

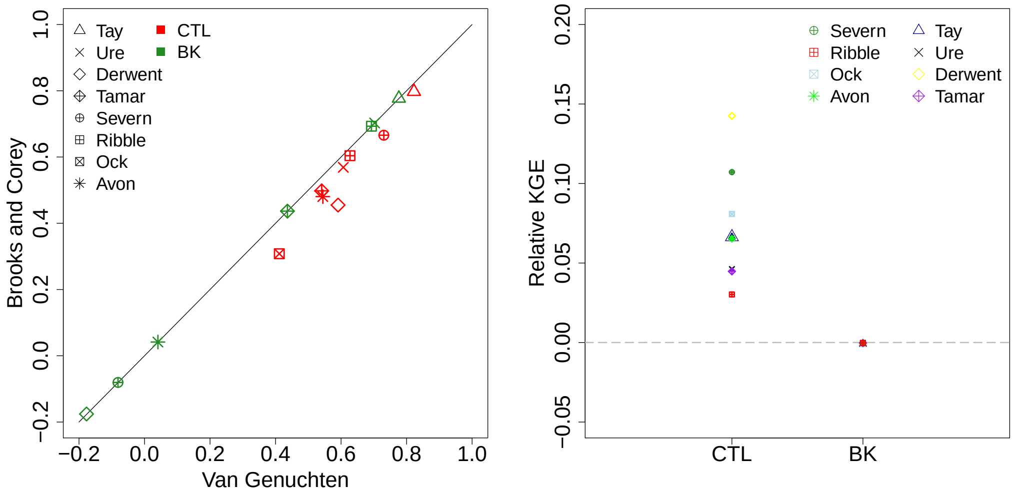


Figure 22: Left: Performance of KGE of all river level with the formulation of Brooks and Corey (1964) (BC) on the y-axis and Van Genuchten (1980) (VG) on the x-axis. Right: Relative KGE between the default BC calculation and VG for the 8 Great Britain catchments with using the CTL scheme and BK.

impact the results obtained with the BK scheme where the error metrics are equal for BC and VG (Fig. 22).

The KGE efficiency of each catchment has been shown as a function of the annual average rainfall in Fig. 23. This study highlights the fact that the efficiency of the representation of the modelled river flow with the BK scheme increases with the rainfall amount of the catchment. The use of the BK scheme provides an improvement for the wettest catchment of the UK. However, Fig. 24 shows that almost all the precipitation is routed directly to the surface runoff both for a dry (Ock) and a wet (Ribble) catchment. This highlights the lack of water for the wettest catchment, where the amount of surface runoff is well represented but the amount of infiltration is underestimated. This scheme dries the soil.

6 Discussion

Goal of the study

In this section, we summarise the results and the approach which has been used in this study in order to better discuss the results. The maximum rate of infiltration used in JULES is fixed and corresponds to the saturated hydraulic conductivity multiplied by a multiplicative factor dependent on the soil type (described in Table 1). A constant flux of water is infiltrated in this method and it does not consider the actual properties of the soil at a specific time. The process of infiltration excess is not represented in this configuration. This phenomenon could lead to an overestimation of the flux of water to be infiltrated and then underestimate the outgoing flux of water from surface runoff. In order to reduce the lack of outgoing water which can lead to an underestimation of the potential flooding event, this study has focused on representing infiltration in a different scheme. Use of variable maximum infiltration was selected because of the construction of the hydrological module in JULES. This choice has been reinforced since most other land surface models also use a variable maximum infiltration capacity.

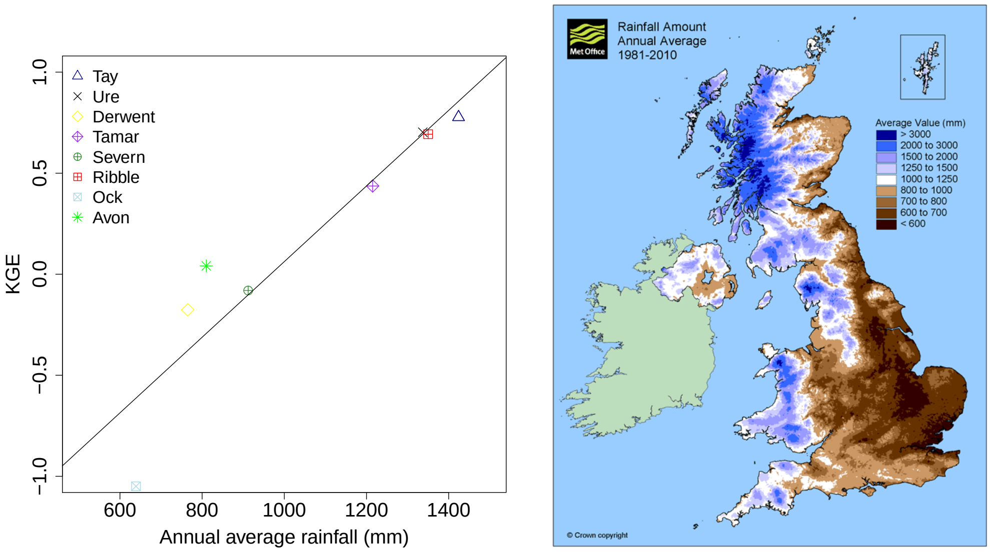


Figure 23: Left: KGE efficiency of every modelled river flows with BK scheme compared to the annual average rainfall of the corresponding catchment. Right: Annual average rainfall amount (mm) of 1981-2010 period over the UK.

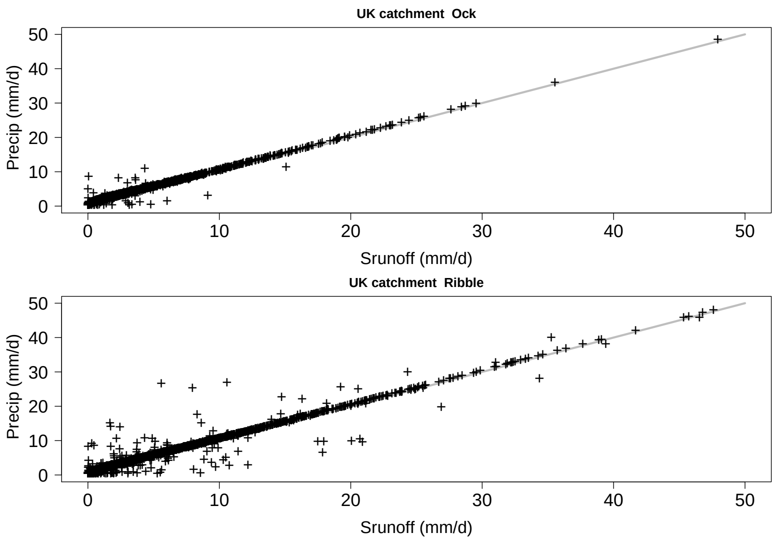


Figure 24: Mean rate of daily surface runoff (mm/d) as a function of the mean rate of daily precipitation (mm/d) over the area of the dry Ock (top) and wet Ribble (bottom) catchment.

Representations of infiltration

Section 3 described the different variable maximum infiltration schemes tested. Scheme 1 is excluded for a reason of non-linearity 2 and, as scheme 2 does not have a different result as a function of the time step used in the model. This study is based on the choice of representing the rate of infiltration in the most parsimonious and physical way such as that provided by scheme 3 and 5. We have chosen scheme 3 (explained in section 3.3) since scheme 5 represents the flux between the first and the second layer of the soil instead of the interface between atmosphere/canopy and soil. However, due to the large time step (30 min) used in the model, the contribution of the potential gradient Ψ is weak compared to the hydraulic conductivity K_{top}. This results in a substantially identical river flow pattern observed in the outlet of the Ock catchment (seen Fig. 7). The evaluation of the river flow has been made between the default representation of infiltration (CTL scheme) and the variable maximum infiltration such as represented in the scheme 3 (BK scheme) in the Eq. 9 (BK scheme).

Effect of the BK scheme on river flow prediction

The modelled river flow with the BK scheme is not sensitive to the use of PDM. This can be explained by the fact that the infiltration excess in this case is more restrictive than the saturation excess. The role of the infiltration-excess and saturation-excess generation of runoff remains uncertain. In general, the runoff is mainly produced by infiltration excess in arid regions (Niu et al., 2014). However, in wet soils such as peat in UK, the infiltration rate is high enough to prevent infiltration excess. The saturation excess is the dominant mechanism for these soils (no events where high discharge are associated with low water tables) (Evans et al., 1999). In addition, the study of Winchell et al. (1998) has shown that the infiltration-excess runoff is much more sensitive than the saturation excess, which have no significant sensitivity to the temporal and spatial resolution. This study made with high resolution overestimates the role of infiltration excess where the value chosen in the BK scheme is too low.

Small Ure catchment

For the Ure catchment, the river flow pattern obtained using BK scheme is similar to the CTL scheme once PDM is used. For the standard CTL scheme, the correlation between modelled and observed river flow reaches $\rho = 0.76$ compared to $\rho = 0.46$ when PDM is not used. The relative efficiency of the modelled river flow with the BK scheme is better when it is compared to the the CTL scheme when PDM is not used rather than when PDM is used (shift observed Fig. 18). The better representation of the river flow at the outlet of the Ure with the BK scheme is explained by the increase of the rate of the surface runoff observed in Fig 10. During high precipitation event, the increase of the surface runoff is explained by the increase of the rate as well as the frequency (in term of grid cells) of high rates of surface runoff with the BK scheme compared to the CTL with using PDM (Fig. 12). Comparing the different efficiencies of each simulation as a function of the river flow level, the BK scheme for the Ure catchment has proved to be better able to represent the flow (higher KGE) when the lowest flows are not taken into account. For the 10 % highest flows, the KGE is 0.42 with BK scheme compared to 0.30 with CTL (seen in Fig. 9).

8 UK catchments

The evaluation of the river flow is studied for 8 different catchments in Great Britain. The higher efficiency is seen in all the catchment when PDM is used with the default infiltration scheme, with a mean relative KGE of 0.29 (Fig. 13). For this reason, the comparison of the river flow with the 2 different schemes is evaluated with the use of PDM. The default CTL scheme well represents the lowest flow. The too restrictive BK scheme is able to represent the right level of flow for the catchment situated in the wettest area (west of Great Britain as shown in the righ of Fig. 23) such as Tamar, Ribble, Tay and Ure catchment. This improvement is particularly shown during the seasonal high flows (Fig. 15).

The seasonal relative efficiency study between the simulated flow from BK and CTL scheme has shown that the new BK scheme improves the representation of the river flow especially during spring (MAM) where the mean improvement except for the Tay (correlation of 0.23). For the Tay catchment, the correlation between observed and modelled flow with BK scheme is 0.91 for this season, which means the representation of this flow is good. In the annual mean, the improvement is visible for almost each level of flows for the Ribble, Tay and Ure catchment both when we compare with PDM and NO-PDM as shown in Fig. 17. This is due to the high coefficient during winter (DJF), spring (MAM) and summer (JJA) for these catchments. The seasonal study showed the inability of the new BK scheme to represent the flow level during the Autumn (SON) where the variability of the flow for this period is overestimated (Fig. 18 and Fig. 15). It is important to note that this is mainly due to the river flow values in September, where the period from August to September corresponds to the lowest flows levels. The variability of flow with the BK scheme is usually better than the flows with the standard CTL scheme for the Ribble, Tamar, Ure and Avon (interpretation from coefficient a shown in Fig. 14). The efficiency study includes both correlation, variability and ratio of mean value of flows. The Fig. 19 highlights the fact that the highest river flows modelled with BK scheme are much more correlated with observations than the CTL scheme up to 3 times better (Relative KGE above 0.5 for the highest flow of the Ribble and Tamar catchment). Fig. 16 summarises the capacity of the BK scheme to represent the high flows well; where the mean bias of the modelled flow with the BK scheme of the 8 studied catchments is lower for the highest 20 % of flows than for the default infiltration CTL scheme.

Sensitivity tests

The good representation of the river flow with the BK scheme is dependent and proportional to the amount of the rainfall of the catchment (Fig. 23). There is no significant sensitivity of the b and K_{sat} value (Fig. 20) where the mean value for each catchment is between 457 and 651 mm/d for K_{sat} and 5.5 and 7.3 for mean b value. A sensitivity study with the Ock catchment have shown that the change of the river flow is not more than 0.058 % when the b value is divided by 2 for each grid cell of the catchment. Even though the default CTL scheme is sensitive to the formulation used to calculate the hydraulic conductivity, the performance of the river flow modelled with BK scheme is strictly the same for Brooks and Corey than for Van Genuchten (Fig. 22).

The behaviour of the river flow profile has been evaluated as a function of different values of the rate of maximum infiltration I_{max}. Fig. 22 shows that the river flow when $I_{max}=\beta K_{sat}/1000$ is equivalent to that obtained by $I_{max}=\beta K$ (BK scheme). On the other hand, a multiplicative factor of 10^4 to the rate of maximum infiltration of the BK scheme is insufficient to see a change in the river flow values. This means that the surface runoff occurs almost permanently when the I_{max} value is below a range of 10^{-5} 10^{-7}. The sensitivity of the I_{max} value from the CTL scheme has proved that any value of I_{max} is able to improve the river flow for all seasons. The difference of I_{max} values enhance a change of the mean value but does not influence the variability of the river flow as seen in Fig. 22 (component α=0.48, 0.64 and 0.90 between I_{max} and $I_{max}/10$, $I_{max}/10$ and $I_{max}/100$ and between $I_{max}/100$ and $I_{max}/1000$). Thereby, the range of value of I_{max} which is better able to represent the river flow at the outlet of the Ock catchment is bounded between $\beta K_{sat}/10$ and $\beta K_{sat}/100$. In summer, the profile is better with $I_{max}/10$ while this underestimated the profile during the winter season which is better represented with $I_{max}/100$. The formulation of the surface runoff and the infiltration rate as described in the hydrology of JULES is not able to well represent the river flow for every condition. In fact, JULES uses the I_{max} rate to describe the profile of the surface runoff where the amount of infiltration is deduced from the residual value, namely precipitation minus surface runoff, to ensure the conservation of water in the model. The role of the infiltration excess process in determining the correct surface runoff can only be exercised properly if the hydrology of JULES determined first the right amount of water which can be infiltrated and deduced the surface runoff amount in order to conserve the surface water balance. In order to progress the representation of the hydrological consequences of convective and other intense rainfall events further work on the hydrological representativivty of JULES is required.

The BK scheme produces a rate of surface runoff which effectively corresponds to the rate of precipitation as shown in Fig. 24. Even though the representation of the river flow is quite good for the wettest catchment of the United Kingdom the soil moisture content is underestimated. Again this points to the requirement for substantial further work on the hydrological representation in JULES.

7 Conclusions

This study assesses the impact of the methods used to represent surface infiltration in the JULES land surface scheme on the calculated river flow, particularly during intense rainfall events. This report first describes the surface infiltration scheme used in JULES and in other land surface models. The easiest and most used scheme in land surface models considers the representation of variable maximum infiltration and different versions of this have been developed and tested in this study. The infiltration scheme selected for further evaluation of calculated river flow at the outlet of UK catchments is scheme 3 where $I_{max} = \beta K$, which is called here the BK scheme. The limitation rate in this scheme plays the role of the infiltration excess process where the rate is limited by the hydraulic conductivity of the top layer of the soil.

The evaluation has been made using the saturation excess from PDM and using the formulation of Brooks and Corey (1964). These choices have been found not to be sensitive to the formulation used for this scheme and also showed a better improvement when PDM is not taken into account. The BK scheme has proved to be particularly suitable for periods of high flows where the default rate underestimated the flow level. This scheme represents an improvement for the wettest catchments such as Tamar, Ure, Ribble and Tay. This scheme is particularly suitable for the spring season where the river flow is the highest. The efficiency of the BK scheme increases as a function of the average annual precipitation as summarised in Fig. 23.

The value of I_{max} is too low which leads to the lowest moisture content of the soil and leads again to a lower value of the hydraulic conductivity which is transferred to I_{max} in turn. In fact, the rate of surface runoff is almost as big as the precipitation rate (Fig 24).

This study has shown that there is no value of I_{max} that could be suitable to improve the river flow in all seasons. The sensitivity study of the I_{max} value in Fig. 22 has shown that the variability of the river flow remains constant and only differs by the mean value of the flow. In average, the CTL scheme is good enough to be able to represent the variation of the flow according to different periods of time and area. Fig. 23 showed the improvement of the BK scheme when we consider areas with an annual precipitation from 1100 mm/year. Therefore, the BK scheme is better able to represent the flow especially during intense rainfall periods.

Recommendations for changes within JULES

This study highlights that there remains much work to do in order to improve the hydrological functioning of JULES, particularly considering its applicability for representing flooding from intense rainfall. In particular, we have shown the difficulty of representing the river flow and have shown that the representation of a variable maximum rate I_{max} alone is not able to overcome the deficiencies in modelling river flow compared to observations. This study suggests that there may be a need to reformulate the hydrological module of JULES in order to calculate the rate of infiltration before the rate of surface runoff. This change would also have the advantage of overcoming problems of supersaturation reported in similar studies. Another option could be to reduce the duration of the rainfall in the model using a rate of water to calculate infiltration which is divided into sub-time steps.

Code availability

This study used the UK Met Office land surface model version 4.8 of JULES. The documentation can be found here: http://jules-lsm.github.io/vn4.8/. The development made in this study corresponds to the revision 9430 (from rev. 8542) and uses the 4.8 releases (work undertaken Jan 2017-Jan 2018). The full code can be found in the vn4.8_vn48_Imax_Chloe repository (registration required):
https://code.metoffice.gov.uk/trac/jules/browser/main/branches/dev/chloelargeron/

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Annex A:

Evaluation of 8 UK catchments with two scheme I_{max} corresponding to K_{m10} and K_{m20}

The use of the hydraulic conductivity as the maximum infiltration rate is too restrictive and does not allow to infiltrate the water. However, the evaluation of the 8 catchments have shown that the highest peak of the river flow are well defined if we consider all the precipitation going directly to the surface runoff. The results in section 5.2.3 show that the profile of the modelled river flow at the outlet of the Ock catchment the closest to observations is obtained with a rate of infiltration between $I_{max}= \beta\ K_{sat}/10$ and $I_{max}= \beta\ K_{sat}/100$.

In addition, the infiltration as defined in the land surface model of IPSL is considered as equation Eq. 15 where flux_infil is based on the potential flux of infiltration at each time step and K_m corresponds to the maximum of infiltrability.

$$I = K_m \times \exp^{-}\left(\frac{\text{flux\_infil}}{K_m}\right) \tag{15}$$

In this model, the calculation of the rate of infiltration is made first and the excess is then going to the surface runoff. However, we can consider K_m as the I_{max} as defined in JULES. Following this structure, we have tried to define I_{max} as the calculation of K_m described in equation below as dependent of the maximum and actual hydraulic conductivity K_{sat} and K, as a factor depending of the vegetation $k_{\text{fact\_root}}$ and k_{fact} a factor due to the depth of the soil :

$$K_m = K + K_{\text{sat}} \times k_{\text{fact}} \times \frac{k_{\text{fact\_root}}}{2} \tag{16}$$

In the JULES model, the factor of the vegetation is taken into account by the β factor. The maximum value of $k_{\text{fact\_root}}$ is set to 1. So the beta is slightly higher than this factor. For this reason, we decide to conserve the ratio 2 for one of the cases. k_{fact} is bounded from 1/10 to 1. This section shows the profile of the modelled river flow using the following value of I_{max}:

$$\begin{aligned} I_{max} &= \beta(K + K_{sat}/20) = K_{m20} \\ I_{max} &= \beta(K + K_{sat}/10) = K_{m10} \end{aligned} \tag{17}$$

The annual mean profile of the river flow using $I_{max}=K_{m10}$ and K_{m20} is represented respectively in green and black in Fig. 25 in comparison to the default modelled river flow (CTL scheme) and observations. The highest flows during winter season are slightly better represented with the use of K_{m10} and K_{m20} although the BK scheme is closer to observations during this period for Ribble, Tamar and Ure catchment. This infiltration scheme overestimates the variation and the mean value of the flow during summer as found for the Derwent and Ock catchment where the modelled peak of June is not observed.

The difference of the mean modelled flows between K_{m10} and K_{m20} is not significant. The Fig. 26 highlights the difference of performance between these schemes through the relative KGE efficiency of all

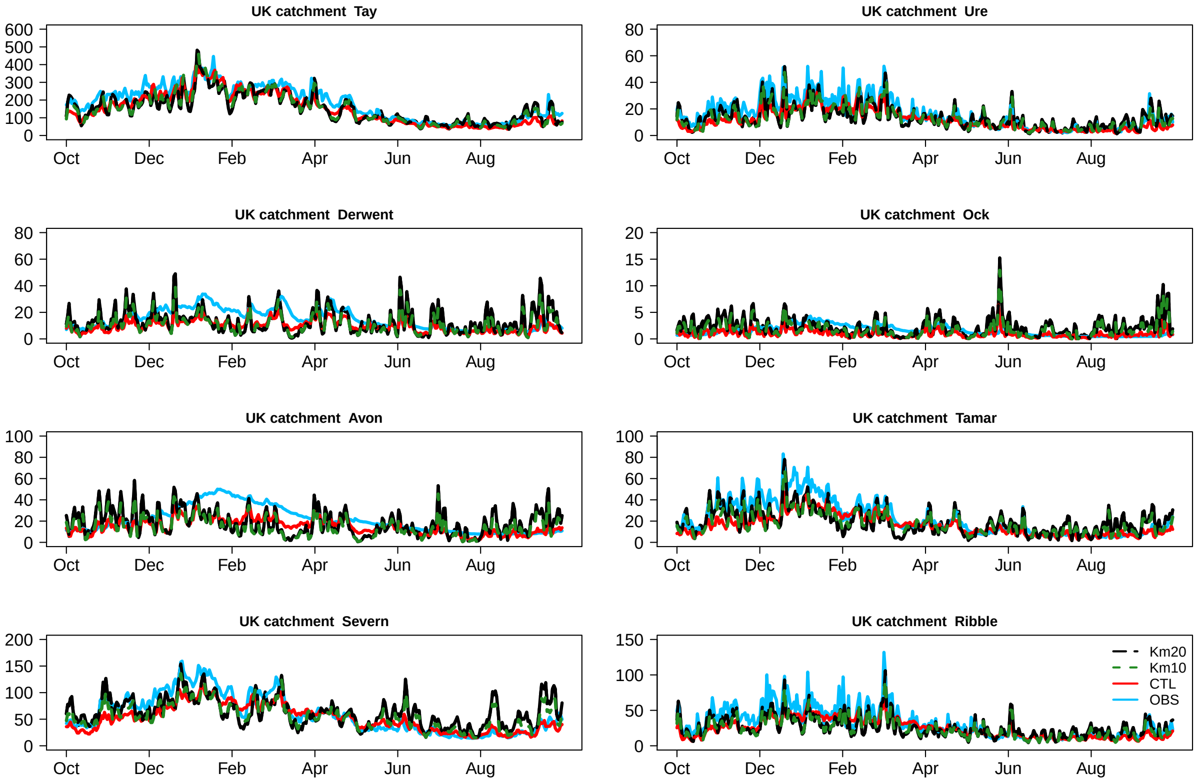

Figure 25: Monthly mean river flow profile with using the maximum rate of infiltration K_{m20} (dashed black line) and K_{m10} (dashed green line) in comparison with observations (blue) and default modelled river flow (CTL) (red).

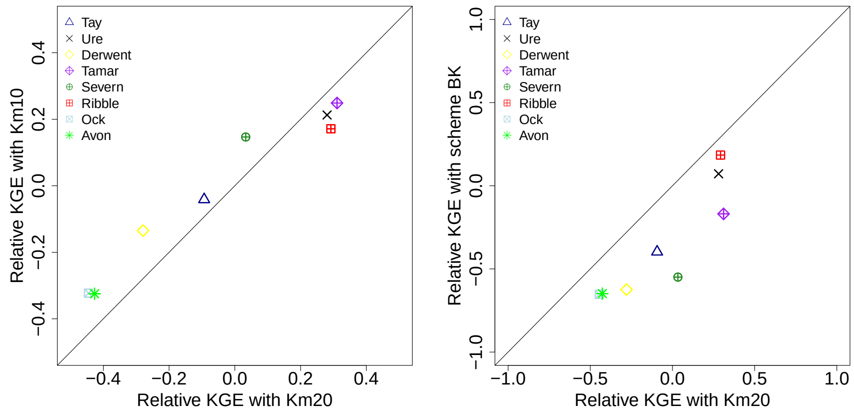

Figure 26: Performance of the different scheme through the KGE efficiency between K_{m20} and (left) K_{m10} and (right) BK scheme.

value of river flow compared with the default modelled flow (CTL scheme). For the catchments where this scheme does not represent an improvement, the degradation is less important with K_{m10}. The improvement of using this scheme compared to the default infiltration is better with K_{m20} (Relative KGE of Ribble, Ure and Tay are localised at the right of line in the left of Fig. 26). The use of scheme K_{m20} is then favorable to better improve the highest flows. To quantify the performance between the modelled river flow with the scheme K_{m20} and BK, we have also used the relative KGE for all values of the river flow. Fig. 26 shows that the efficiency of scheme K_{m20} is better for all of the catchments. This conclusion is also true for the 20 % highest flows.

Annex B:

Evaluation of 8 UK catchments with Imax= β (W_{sat}-W)/Δt

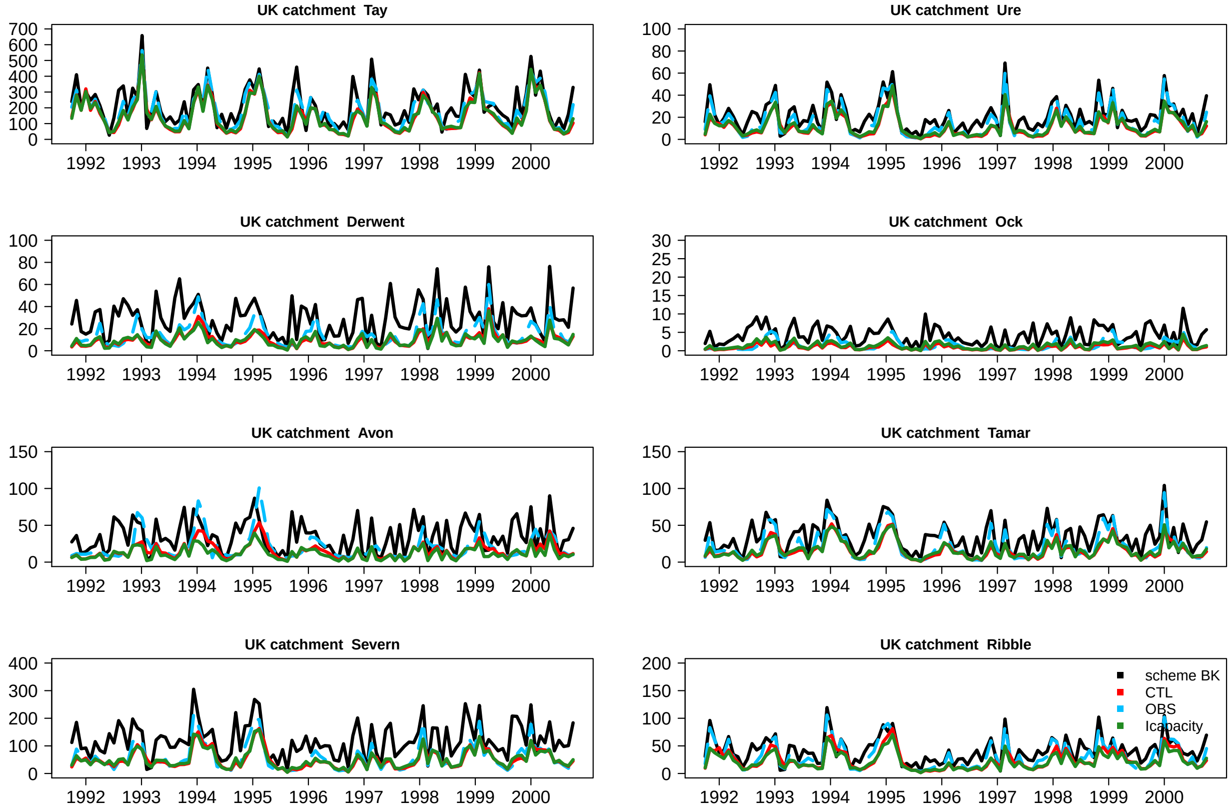

Figure 27: Monthly mean river flow profile with the infiltration scheme 2 (black) compared with the standard CTL scheme (red) and observations (blue).

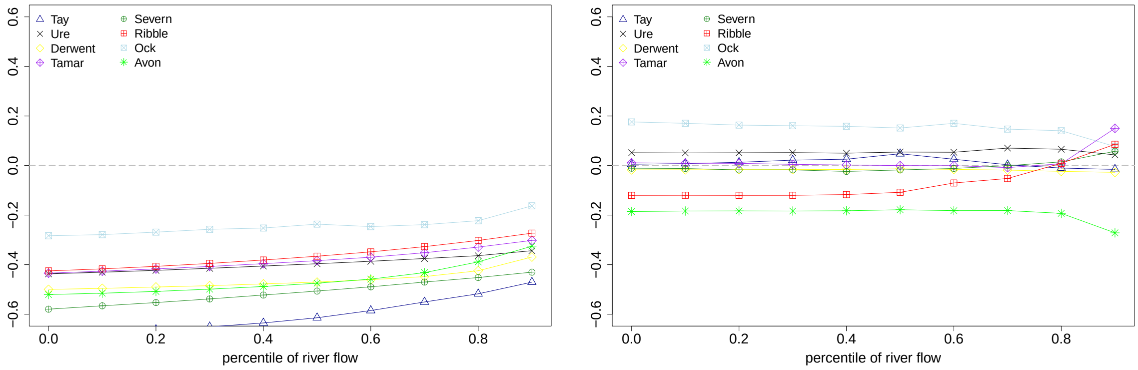

Figure 28: Relative KGE between the (left) daily and (right) monthly river flow of each catchment of the 1991-2000 period modelled with the scheme β(W$_{sat}$-W)/Δt) and the reference CTL scheme as a function of the percentile of the river flow.

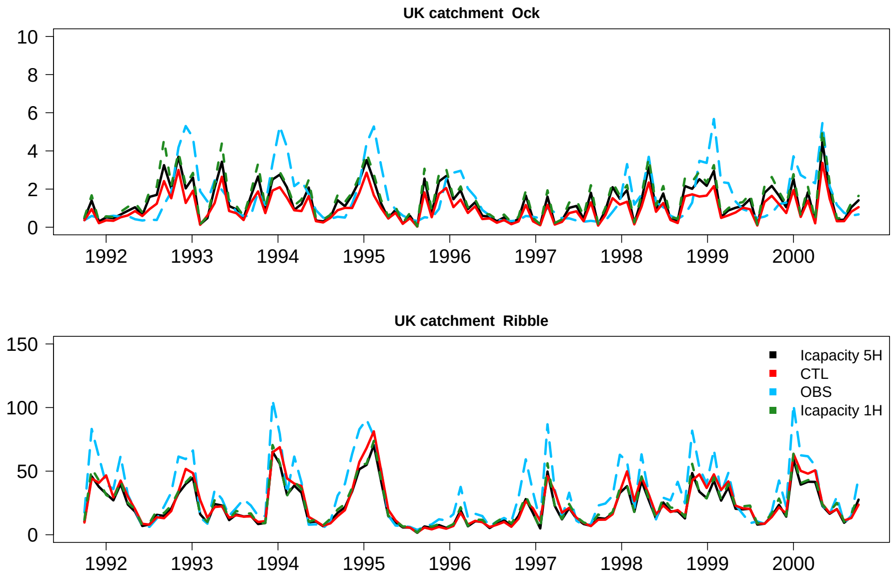

Figure 29: Monthly mean river flow profile with the infiltration scheme 2 (I$_{capacity}$) with rainfall duration of 5 h (black) and 1 H (green) compared to CTL 5 h duration (red) and observations (blue).

Annex C:

Sensitivity of the duration of the driving rainfall on the river flow

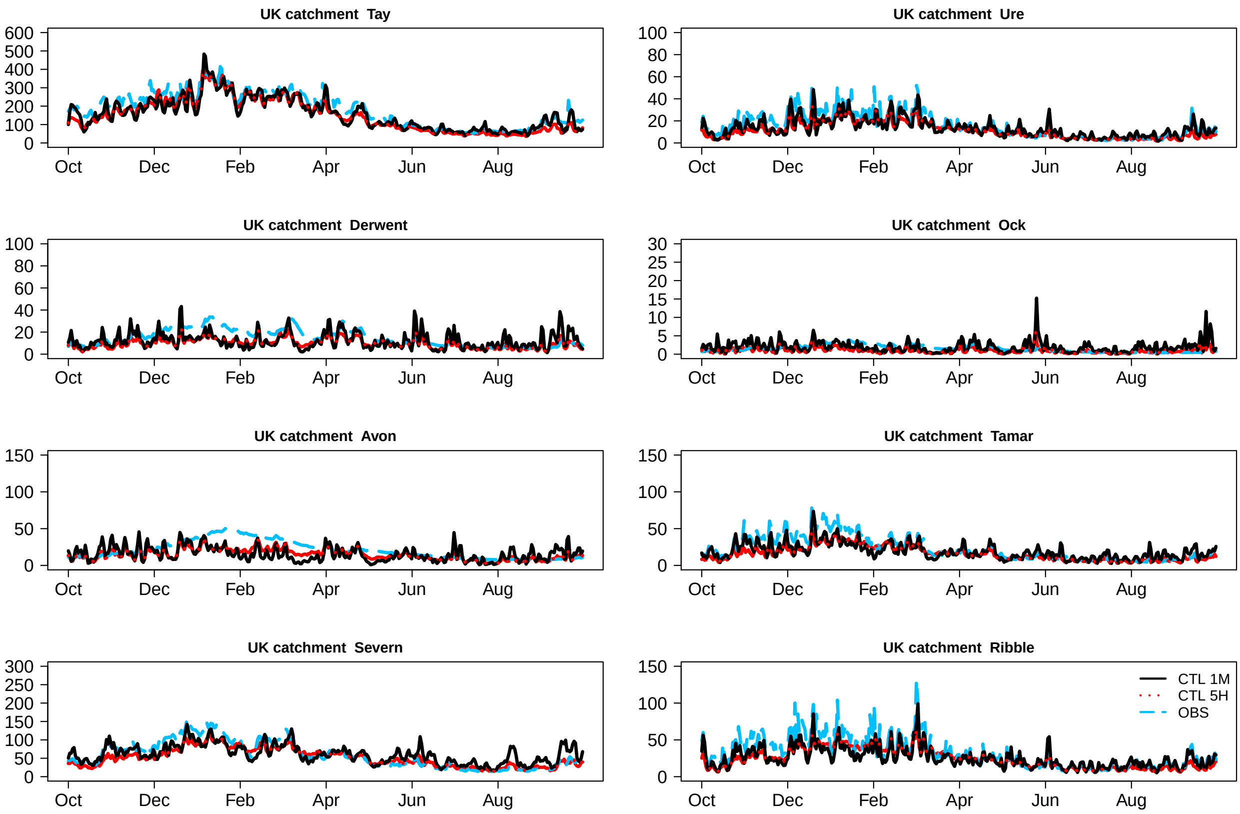

Figure 30: Monthly mean river flow profile with the default configuration of infiltration with a rainfall duration of 5 h standard configuration (red) and 1 min (blue)

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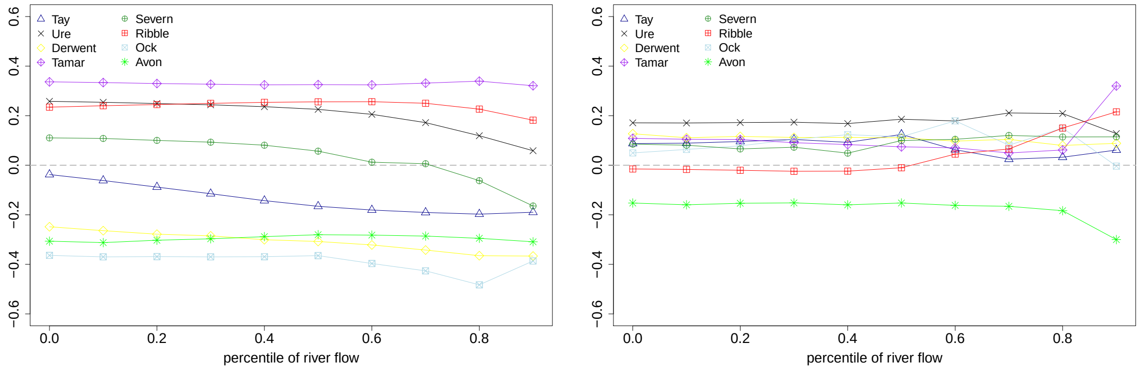

Figure 31: Relative KGE between the (left) daily and (right) monthly river flow of each catchment over the 1991-2000 period modelled with the reference CTL scheme with 1 min rainfall duration compared to 5 h as a function of the percentile of the river flow.

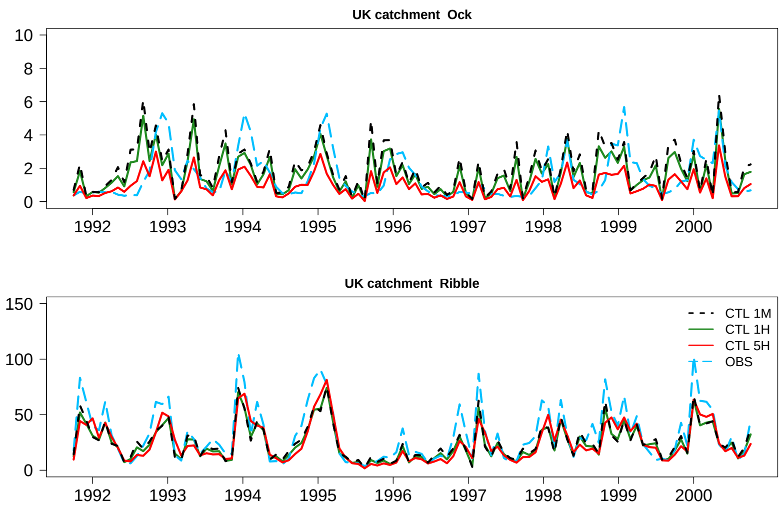

Figure 32: Monthly mean river flow profile with the default infiltration CTL scheme with rainfall duration of 1 min (black) 1 h (green) compared to CTL 5 h duration (red) and observations (blue).

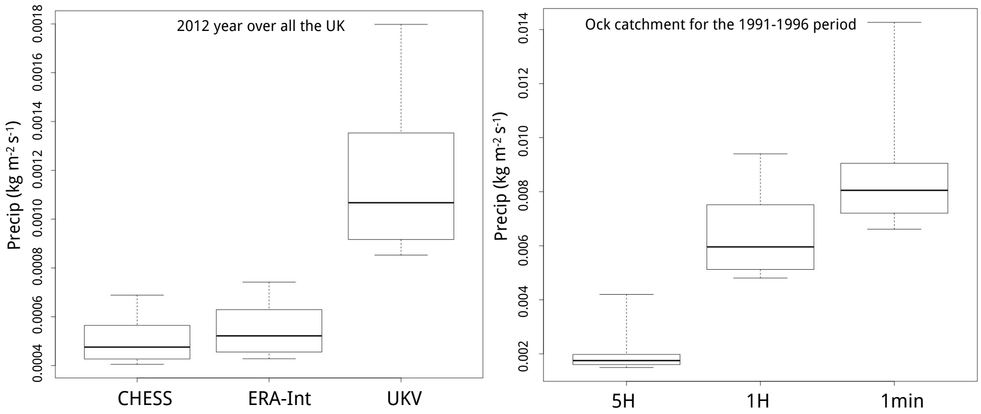

Figure 33: Boxplot of 1% highest rate of precipitation (kg m^{-2} s^{-1}) of (a) the highest grid cell located in the Ock catchment with the CHESS dataset of 5H, 1H and 1 min daily disaggregation for the 1991-1996 period and (b) the daily maximum rate of each grid cell over the whole UK compared between the dataset of the daily CHESS dataset, and every 3 hours ERA-Interim and UKV datasets respectively of 2012. The rate of precipitation is then highly dependent on the timestep of the weather data.

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