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Exploration of warm-up period in conceptual hydrological modelling

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18 **Abstract**

19 One of the important issues in hydrological modelling is to specify the initial conditions of the catchment
20 since it has a major impact on the response of the model. Although this issue should be a high priority among
21 modelers, it has remained unaddressed by the community. The typical suggested warm-up period for the
22 hydrological models has ranged from one to several years, which may lead to an underuse of data. The model
23 warm-up is an adjustment process for the model to reach an ‘optimal’ state, where internal stores (e.g., soil
24 moisture) move from the estimated initial condition to an ‘optimal’ state. This study explores the warm-up
25 period of two conceptual hydrological models, HYMOD and IHACRES, in a southwestern England
26 catchment. A series of hydrologic simulations were performed for different initial soil moisture conditions and
27 different rainfall amounts to evaluate the sensitivity of the warm-up period. Evaluation of the results indicates
28 that both initial wetness and rainfall amount affect the time required for model warm up, although it depends
29 on the structure of the hydrological model. Approximately one and a half months are required for the model to
30 warm up in HYMOD for our study catchment and climatic conditions. In addition, it requires less time to
31 warm up under wetter initial conditions (i.e., saturated initial conditions). On the other hand, approximately
32 six months is required for warm-up in IHACRES, and the wet or dry initial conditions have little effect on the
33 warm-up period. Instead, the initial values that are close to the optimal value result in less warm-up time.
34 These findings have implications for hydrologic model development, specifically in determining soil moisture
35 initial conditions and warm-up periods to make full use of the available data, which is very important for
36 catchments with short hydrological records.

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40 Keywords: warm-up period, soil moisture, conceptual hydrological model, equilibrium state

1. Introduction

Hydrological modelling is an essential tool for understanding the hydrological behavior of a catchment (Madsen, 2000; Wagener et al., 2003) and is a complicated task (De Vos et al., 2010). The most common method for identifying the optimized model parameters is by calibration with historical data. Objective functions, such as Root Mean Squared Error (RMSE) and Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) are routinely used to minimize the difference between the observed and simulated flows. The calibrating scheme has been widely applied to various hydrologic models (Gan and Biftu, 1996; Gupta et al., 2009; Gupta et al., 1998; Sorooshian, 1991). In addition, validation is a standard practice in hydrological modelling (Andréassian et al., 2009) used to test the model performance with previously unprocessed data.

One of the important issues in hydrological modelling is to specify the initial conditions of the catchment since these have a major impact on the stability and convergence of the model (Berthet et al., 2009). Although this issue should be a high priority among modelers (Cloke et al., 2003), it has not been properly addressed by the community. The two important input factors that affect the response of a hydrological model are rainfall and initial soil moisture. Soil moisture is a state variable, while the rainfall is a forcing variable. Both variables have variability in space and time, which make the relationship between rainfall and runoff nonlinear. Therefore, reliable data are required to better represent the runoff. However, it is difficult to identify accurate distributions of rainfall and initial soil moisture, and this may increase the uncertainties of the hydrological model outputs (Nikolopoulos et al., 2011). There have been some studies about the sensitivity of simulated flow to rainfall variability (Bell and Moore, 2000; Nicótina et al., 2008; Sangati and Borga, 2009; Segond et al., 2007; Vivoni et al., 2006) and the effect of the initial states on the model output (Berthet et al., 2009; Castillo et al., 2003; Goodrich et al., 1994; Minet et al., 2011; Nikolopoulos et al., 2011; Senarath et al., 2000; Zhang et al., 2011). These studies explored the complicated interactions between the initial soil moisture, climatic conditions and catchment conditions.

The model warm-up is an adjustment process for the model to reach an ‘optimal’ state, wherein the internal stores (e.g., soil moisture) move from an estimated initial condition to an ‘optimal’ state. The response of the model during this process may show a drift and could be unrealistic. When the model reaches an ‘optimal’ state, the response of the model becomes realistic (or stable), and the simulated hydrologic variables are better matched to the observations (Ajami et al., 2014; Cosgrove et al., 2003; Seck et al., 2015; Yang et al., 1995).

69 Several studies have examined the warm-up behavior of land surface models (LSMs) (Cosgrove et al., 2003;
70 Rodell et al., 2005; Yang et al., 1995). However, the warm-up behavior of hydrological models has not been
71 fully explored, and there is no consensus in the literature regarding various issues including the definition of
72 an equilibrium state, the criteria of evaluating warm-up and an optimal method for warming up an LSM
73 (Shrestha and Houser, 2010; Yang et al., 1995). The typical range of the warm-up periods for LSMs is
74 anywhere from one to several years (Chen and Mitchell, 1999; Cosgrove et al., 2003; De Goncalves et al.,
75 2006; Rodell et al., 2005; Yang et al., 1995).

76 Most of the aforementioned studies have been based on different rainfall attributes (duration and intensity),
77 catchment characteristics and wetness conditions. Various results indicate that the interactions between these
78 factors are rather complicated, and it is difficult to generalize these issues. In line with this concept, the study
79 presented in this paper attempts to investigate and propose how to specify a catchment's initial conditions in
80 terms of soil moisture and to minimize the warm-up period to fully utilize the acquired data.

81 The primary objectives addressed in this paper are to: (1) assess the effects of initial soil moisture condition,
82 rainfall amount and simulation starting point on the warm-up period and (2) suggest guidelines for defining
83 the initial soil moisture value depending on the hydrological model. This investigation has both practical and
84 scientific value since it allows us to identify the importance of the initial soil moisture condition and to
85 understand how the hydrological model responds to initial conditions. This could lead to the improvement and
86 development of hydrological models, specifically in terms of determining soil moisture initial conditions and
87 warm-up period. In Section 2, we describe the study area and data used and provide an outline of the
88 hydrological models HYMOD and IHACRES. The simulation design is provided in Section 3. The effects of
89 initial soil moisture conditions and rainfall amount on the warm-up period are presented in Section 4. The
90 main conclusions of this study are summarized in Section 5.

91

92 **2. Case study area and the hydrological models**

93 **2.1 Study area and data**

94 The Thorverton catchment is used in this study. It has an area of 606 km², and is a sub-catchment of the Exe
95 catchments. The Exe catchment is in the southwest of England and has an area of 1,530 km² and an average
96 annual rainfall of 1,088 mm. Figure 1 shows an overview of the Thorverton catchment area. A daily time

97 series of the observed precipitation, potential evapotranspiration and flow data (1961-1990) over the
98 Thorverton catchment was obtained from the UK Met Office. Daily temperature data were acquired from the
99 UKCP09 gridded observation data sets. Thirty year (1961-1990) mean rainfalls and temperatures for this
100 catchment are presented in Figure 2.

101
102 Figure 1. Map showing the location of the Thorverton catchment in the UK.
103

104
105 Figure 2. The 30-year mean monthly rainfall and temperature for the Thorverton catchment.
106
107

2.2 Hydrological model

2.2.1 HYMOD

The first conceptual rainfall-runoff model used in this study is HYMOD, and it has five parameters. The model consists of a simple rainfall excess model based on the probability distributed principle (Moore, 1985) and was applied by several recent studies (Boyle, 2001; De Vos et al., 2010; Vrugt et al., 2003; Wagener et al., 2001). The model parameters are described in Table 1, and the model structure is illustrated in Figure 3. The cumulative distribution function of the water storage capacity, C , has the following form.

$$F(C) = 1 - \left(1 - \frac{C(t)}{C_{max}}\right)^{b_{exp}}, \quad 0 \leq C(t) \leq C_{max}, \quad (1)$$

where C_{max} is the maximum soil moisture storage capacity in the catchment, and b_{exp} controls the degree of spatial variability of the soil moisture capacity. The excess rainfall is transformed into runoff, which is divided into quick and slow flow based on the partitioning factor α . The runoffs are routed through three identical quick flow tanks and a parallel slow flow tank. The flow rates are determined by the recession coefficient for the quick flow tank (R_q) and slow flow tank (R_s).

Table 1. Model parameters considered in the HYMOD model.

Parameter	Unit	Range	Description
C_{max}	mm	1-500	Maximum soil moisture storage capacity
b_{exp}	-	0.01-1.99	Spatial variability of soil moisture capacity
α	-	0.01-0.99	Quick/slow flow distribution factor
R_s	day	0.01-0.99	Recession coefficient for slow flow tank
R_q	day	0.01-0.99	Recession coefficient for quick flow tank

Figure 3. Structure of the HYMOD model (adopted from Vrugt et al. [2002]).

2.2.2 IHACRES

Another conceptual rainfall-runoff model used in this study is IHACRES (Jakeman and Hornberger, 1993), which has eight parameters. The IHACRES model has been widely applied to a variety of catchments for hydrological analysis and climate impact studies (Jakeman et al., 1993; Kim and Lee, 2014; Kim and Han, 2016; Kim et al., 2016; Letcher et al., 2001; Littlewood, 1999). The model is composed of a linear module and a nonlinear module as shown in Figure 4, and the model parameters are listed in Table 2. The nonlinear module converts rainfall to effective rainfall, which is calculated from the following equations.

$$U_k = [C(\phi_k - l)]^p r_k \quad (2)$$

Here, r_k is the observed rainfall, C is the mass balance factor, l is the soil moisture index threshold, and p is the power on soil moisture. The soil moisture (ϕ_k) can be written as:

$$\phi_k = r_k + (1 - \frac{1}{\tau_k})\phi_{k-1}, \quad (3)$$

where τ_k is the drying rate given by:

$$\tau_k = \tau_w \exp[0.062f(t_r - t_k)]. \quad (4)$$

Here, τ_w is the drying rate at the reference temperature, f is the temperature modulation, t_r is the reference temperature, and t_k is the observed temperature. This module assumes that there is a linear relationship between the effective rainfall and runoff. Two components in the module (quick flow and slow flow) can be connected in parallel or in series. In this study, two parallel storages in the linear module are used to simultaneously consider the catchment conditions and the streamflow (x_k) at time step k as follows:

$$x_k = x_k^{(q)} + x_k^{(s)}, \quad (5)$$

$$x_k^{(q)} = \beta_q U_k - \alpha_q x_{k-1}^{(q)}, \quad (6)$$

$$x_k^{(s)} = \beta_s U_k - \alpha_s x_{k-1}^{(s)}. \quad (7)$$

Here, $x_k^{(q)}$ and $x_k^{(s)}$ are the quick flow and slow flow, respectively, and α and β are the recession rate and peak response, respectively. The relative volumes of quick flow and slow flow can be calculated from:

$$V_q = 1 - V_s = \frac{\beta_q}{1 + \alpha_q} = 1 - \frac{\beta_s}{1 + \alpha_s}. \quad (8)$$

Figure 4. A schematic representation of the rainfall-runoff process in the IHACRES model.

Table 2. Parameters considered in the IHACRES model and their descriptions.

Module	Parameter	Description
Non-linear	c	Mass balance
	τ_w	Reference drying rate
	f	Temperature modulation of drying rate
Linear	$\alpha_q, \alpha_s,$	Quick and slow flow recession rate
	β_q, β_s	Fractions of effective rainfall for peak response
	τ_s	Slow flow recession time constant, $\tau_s = -\Delta/\ln(-\alpha_s)$
	τ_q	Quick flow recession time constant, $\tau_q = -\Delta/\ln(-\alpha_q)$

3. Simulation design for determination of the warm-up period

3.1 Overview of the optimal soil moisture state

The hydrological models were first calibrated by using 10-year hydrologic data to find a set of the optimized parameters in three different periods (e.g., 1960s, 1970s and 1980s). The calibration was performed to minimize the difference between the observed and simulated flow by using a single objective function based on the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). At the same time, the optimized parameters were tested in the validation period.

$$NSE = 1 - \frac{\sum_{i=1}^N (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^N (Q_{obs,i} - \overline{Q_{obs}})^2} \quad i = 1, \dots, N_{day} \quad (9)$$

Here, Q_{sim} , Q_{obs} , $\overline{Q_{obs}}$ are the simulated runoff, the observed runoff and the mean of the observed runoff, respectively, in the calibration period. During the optimization process, the initial soil moisture value was set to zero. To estimate the warm-up period, we needed to know the optimal soil moisture value, which is

generally unknown, due to a lack of observed soil moisture data for the sites. Therefore, in this study, we tested several different soil moisture initial conditions with the optimized parameters to explore the optimal initial soil moisture. The optimal soil moisture is defined as the point when trajectories from all the different initial conditions reach an equilibrium soil moisture state. This took less than one year, so the soil moisture from the second year was considered to be the optimal state. Hence, the simulated first-year data may be removed, and instead the second-year data is used as the optimal state. Figure 5 presents how the optimal soil moisture is defined by using different soil moisture initial conditions.

172

173 Figure 5. Illustration of the method for estimating the optimal soil moisture state with different soil moisture
174 initial conditions. $SM_{i,t}(1)$ points represent different soil moisture initial conditions.

175

176 3.2 Definition of warm-up period

177 Hereafter, the optimal soil moisture state is used to determine the warm-up period. Since we know the optimal
178 value now, we can determine the warm-up period by simulating soil moisture under different initial soil
179 moisture conditions. Figure 6 illustrates how the warm-up period is estimated. First, we know the time series
180 of the optimal soil moisture, wherein the initial value is $SM_{i,t}(1)$. Next, simulations have been done with
181 different initial soil moisture conditions (e.g., $SM_{i,1}(1)$, $SM_{i,2}(1)$), and the simulated soil moisture approaches
182 the optimal value over time. Finally, the warm-up period (i.e., when the simulated soil moisture data becomes
183 almost the same as the optimal value) was calculated by applying the cut-off threshold (CT) criteria (Eq. (10)).
184 Generally, the warm-up periods are longer for higher threshold levels. The sensitivity of the warm-up period
185 to different cut-off thresholds was investigated, and the results showed that the warm-up period gradually

increased as the threshold became smaller until the threshold was reached at approximately 0.1%. For these reasons, the CT in this study was set to 0.01%, and the required time for the model to reach an ‘optimal’ state was calculated by Eq. (10).

Figure 6. Illustration of the equilibrium soil moisture state under different initial soil moisture conditions.

$$CT = \left| \frac{SM_{i,n}(k) - SM_{i,t}(k)}{SM_{i,t}(k)} \right| \times 100 < 0.01\% \quad (10)$$

Here, CT is the cut-off threshold, $SM_{i,t}(k)$ is the optimal soil moisture, and $SM_{i,n}(k)$ is the simulated soil moisture when the time step is k .

3.3 Specification of simulation process

First, the effects of different soil moisture initial conditions (SMICs) on the warm-up period were explored. The soil moisture was simulated by the two hydrological models using nine different SMICs, including the optimal value ($SM_{i,t}(1)$). The SMICs were set based on the optimal value; that is, nine factors ($n = 2, 1.75, 1.5, 1.25, 1, 0.75, 0.5, 0.25$ and 0) were multiplied by $SM_{i,t}(1)$. The details are given in Table 3. The largest number of factors was twice the optimal moisture value ($SM_{i,1}(1)$), and the lowest one is zero, ($SM_{i,9}(1)$). In between, the values decreased proportionally.

Second, we conducted the simulation starting in winter and compared the result with the simulation starting in summer by assuming that different starting points of the simulations also affected the warm-up period. Third, we further investigated the effects of rainfall amount on the warm-up period. In this regard, an experiment was

conducted by increasing (or decreasing) the observed rainfall (R_{obs}) proportionally, while using the fixed, observed potential evapotranspiration (PET_{obs}) as summarized in Table 4.

Table 3. Nine cases of the soil moisture initial conditions for the experimental study.

Case	$SM_{i,1}(1)$	$SM_{i,2}(1)$	$SM_{i,3}(1)$	$SM_{i,4}(1)$	$SM_{i,5}(1)$
Initial soil moisture value	$2 \times SM_{i,t}(1)$	$1.75 \times SM_{i,t}(1)$	$1.5 \times SM_{i,t}(1)$	$1.25 \times SM_{i,t}(1)$	$1 \times SM_{i,t}(1)$
Case	$SM_{i,6}(1)$	$SM_{i,7}(1)$	$SM_{i,8}(1)$	$SM_{i,9}(1)$	
Initial soil moisture value	$0.75 \times SM_{i,t}(1)$	$0.5 \times SM_{i,t}(1)$	$0.25 \times SM_{i,t}(1)$	0	

Table 4. Different rainfall conditions.

Case	Increase / decrease in rainfall (keep the PET unchanged)	
	Rainfall	PET
Case 1	$0.25 \times R_{obs}$	PET_{obs}
Case 2	$0.5 \times R_{obs}$	
Case 3	$0.75 \times R_{obs}$	
Case 4	$1 \times R_{obs}$	
Case 5	$1.25 \times R_{obs}$	
Case 6	$1.5 \times R_{obs}$	
Case 7	$1.75 \times R_{obs}$	

4. Results

4.1 HYMOD

4.1.1 Effects of initial soil moisture

Table 5 presents the warm-up periods with different SMICs for the three calibration periods. The calibrations were conducted starting in the winter season (January for each time period). Overall, when the SMIC was higher than the optimal state (i.e., $n>1$), the estimated warm-up period ranged from 35 to 45 days for the catchment to reach an ‘optimal’ state according to the 0.01% threshold level criterion. On the other hand, when the SMIC was lower ($n<1$), the warm-up period was extended and ranged from 41 to 257 days. The warm-up period for each calibration period with $n>1$ was the same because the SMICs for these cases are larger than the parameter C_{max} , which is the maximum soil moisture capacity in the catchment. Specifically,

any initial soil moistures exceeding C_{max} will quickly spill out as runoff, which immediately results in soil saturation. From this result, it is apparent that less time is required for the model to reach the equilibrium state when the SMIC is higher than the parameter C_{max} . This is because more rainfall (i.e., more time) is required for the simulated soil moisture to be the optimal soil moisture state if the SMIC is very low, as displayed in Figure 7. In this figure, the time series of 1960s soil moistures for the three cases of SMICs ($n = 2, 0.5$ and 0) were compared against those of the optimal state (i.e., black line solid line). When the SMIC was double the optimal initial soil moisture value, the soil is fully saturated at the initial stage of modelling, and the soil moisture rapidly converged to the optimal soil moisture at 39 days (red line). However, when the SMICs were one-half (or zero), the required warm-up periods are then both 257 days (i.e., magenta and blue lines), which take longer than the high SMIC. Therefore, we concluded that longer warm-up times are generally required for smaller SMICs. Another interesting feature is that the converging levels always lie on the upper part of soil moisture for this catchment and rainfall amount. This result will be further discussed in Section 4.1.3.

Table 5. The estimated warm-up period with different SMICs for three calibration periods starting from winter.

	Factor n , which is multiplied by the optimal initial soil moisture							
	2	1.75	1.5	1.25	0.75	0.5	0.25	0
1960s	39	39	39	39	255	257	257	257
1970s	45	45	45	45	257	257	257	257
1980s	35	35	35	35	41	44	45	139

Figure 7. An illustration of warm-up periods required to converge to the optimal soil moisture for different SMICs (1960s case with simulation starting in winter).

241

242 4.1.2 Effects of the starting point of the simulation

243 Table 6 shows the warm-up period when the simulation is conducted beginning in July (i.e., the summer
 244 season). As previously mentioned, 35-45 days of warm-up period are needed when the SMICs are high
 245 enough and the simulation begins in the winter. For simulations beginning in summer, the estimated time is
 246 38-91 days, which is relatively longer than the simulations beginning in winter. However, when the SMIC is
 247 low, for example when it is zero, the range of warm-up periods are 139-257 days and 45-130 days for winter
 248 and summer cases, respectively. Overall, less time is required for the simulation starting in the summer. Since
 249 the rainfall in the study catchment is high in winter and low in summer, the soil moisture conditions in the
 250 beginning part of the simulation are more likely to be wet (high) in winter and dry (low) in summer, which
 251 makes the convergence quicker in winter when the SMIC is high, and vice versa. This is because the
 252 simulated soil moisture converges to the optimal value near the upper part of soil moisture, as mentioned
 253 previously. However, when the SMIC is very low, the warm-up period (i.e., 257 days) in winter is longer than
 254 that in summer (i.e., 130 days) for the equilibrium state (Figure 7 and 8). This can mainly be explained by the
 255 fact that the rainfall in winter may not be enough to reach the equilibrium state at the beginning stage (before
 256 60 days) of the optimal soil moisture state so that the simulated soil moisture converges later in the period.

257

258

259 Figure 8. An illustration of warm-up periods required to converge to the optimal soil moisture for different
 260 SMICs (1960s' case with the simulation starting in the summer).

Table 6. The estimated warm-up period (days) with different SMICs for three calibration periods starting in summer.

	Factor n , which is multiplied by the optimal initial soil moisture							
	2	1.75	1.5	1.25	0.75	0.5	0.25	0
1960s	75	75	75	75	88	93	112	130
1970s	91	91	91	91	91	93	103	103
1980s	38	38	38	38	38	38	41	45

4.1.3 Effects of the rainfall amount

The impact of the rainfall amount on the warm-up period under different SMIC conditions were explored next. Here, the analysis was carried out with the simulation using hydrologic data in the 1960s, starting in the winter season. As shown in Table 7, less time is required to reach the equilibrium state as more rain falls because the soil quickly becomes saturated. Moreover, the soil moisture at the convergence point was examined and is summarized in Table 8. When enough rain falls (larger than $0.75 \times$ observed rainfall), the converging point is either at the beginning or at the end of the optimal moisture state (approximately 272mm). In this case, the rainfall is enough for the simulated soil moisture to converge around the saturated level. However, when the rainfall is low (less than $0.5 \times$ observed rainfall), the soil moisture does converge to the relatively lower values and takes longer to reach its ‘optimal’ state, as shown in Figure 9. More specifically, the converging point was obtained between the minimum and maximum soil moisture for the given SMICs. The converging soil moisture values were 91 mm at 960 days, 132 mm at 1370 days and 206 mm at 1418 days. This may be because the small rainfall is not enough for the simulated soil moisture to reach the ‘optimal’ state at the upper level.

Table 7. The estimated warm-up period (days) with different SMICs and rainfall amounts while using the fixed, observed PET.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rainfall	$0.25 \times$ Obs.	960	960	960	960	1257	1370	1393	1418
	$0.50 \times$ Obs.	540	540	540	540	760	870	938	966
	$0.75 \times$ Obs.	292	292	292	292	292	292	300	310
	Obs.	39	39	39	39	255	257	257	257
	$1.25 \times$ Obs.	34	34	34	34	219	219	219	219
	$1.50 \times$ Obs.	34	34	34	34	44	173	174	175
	$1.75 \times$ Obs.	21	21	21	21	40	57	156	173

285 Table 8. The soil moisture (mm) at the convergence point for different SMICs and rainfall amounts.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rainfall	$0.25 \times \text{Obs.}$	91	91	91	91	123	132	173	206
	$0.50 \times \text{Obs.}$	164	164	164	164	262	169	140	168
	$0.75 \times \text{Obs.}$	273	273	273	273	273	273	273	273
	Obs.	272	272	272	272	272	273	273	273
	$1.25 \times \text{Obs.}$	273	273	273	273	272	272	272	272
	$1.50 \times \text{Obs.}$	272	272	272	272	273	271	271	271
	$1.75 \times \text{Obs.}$	272	272	272	272	271	272	215	271

287
288 Figure 9. An illustration of warm-up periods when the rainfall is one quarter the observed rainfall.

289

290 The warm-up period with different SMICs is illustrated in Figure 10 as a function of the rainfall amount. In

291 this case, the rainfall is enough for the simulated soil moisture to reach a maximum value in a short time

292 period. Figure 10(a) is the explanation of the warm-up period for the simulation starting from winter. If the

293 SMIC is greater than the optimal soil moisture, the converging point can be at A_1 , which is in the first upper

294 stage of the optimal soil moisture, or at A_2 , which is in the next higher stage. The converging point A_2 may

295 happen when the rainfall is not enough for the simulated soil moisture to reach the first upper stage, which

296 results in a slow response to the soil moisture. Likewise, if the SMIC is excessively low (or near zero), the

297 converging point will be either at B_1 or B_2 . Figure 10(b) shows the case for the simulation starting in summer,

298 where the converging point will be at C_1 (or C_2) and D_1 (or D_2) under the different SMICs. Therefore, when

299 the SMIC is high, a combination of the converging points can be at (A_1, C_1) , (A_1, C_2) , (A_2, C_1) or (A_2, C_2) .

When the SMIC is relatively low, a combination of converging points may occur at (B_1, D_1) , (B_1, D_2) , (B_2, D_1) or (B_2, D_2) for the different rainfall amounts. Hence, there are no clear significant relationships between the starting season of the simulation and the warm-up period. On the other hand, the warm-up period depends on the SMICs and the rainfall amount. However, the results presented in this section could be a specific case for this catchment and climatic conditions.

Figure 10. An illustration of the warm-up period when the rainfall is enough for soil moisture saturation.

Figure 11 explains the case when the rainfall is not enough for the simulated soil moisture to converge at the first stage of the optimal soil moisture. Figure 11(a) shows the warm-up period for the simulation starting in the winter. Although the SMIC is greater than the optimal soil moisture, the convergence point will not be around the upper level of the optimal moisture state, but instead somewhere between the maximum and minimum soil moisture (A_1). In addition, the simulation may take longer to converge than the previous case (Figure 10) due to the small rainfall. Likewise, if the SMIC is zero, the convergence point will be at B_1 . Figure 11(b) shows the case for the simulation starting in summer, and the converging point will be around C_1 and D_1 depending on the SMIC.

Figure 11. An illustration of the warm-up period when the rainfall is not enough for the simulated soil moisture to converge at the upper level of the optimal soil moisture.

4.1.4 Guidelines for practical applications

From the analyses, the following conclusions were made for HYMOD.

1. A SMIC exceeding the parameter C_{max} (the maximum soil moisture capacity in the catchment), results in less time to warm-up the model than the small SMIC. In other words, the model requires less time to reach the ‘optimal’ state under saturated initial conditions.
2. For this catchment and climatic conditions (rainfall and PET), the convergence point always lies on the upper part of the optimal soil moisture state. This is due to the model structure, which constrains the maximum soil moisture capacity. Therefore, unless the rainfall is not very low, the simulated soil moisture meets the optimal soil moisture value around the upper state.
3. However, as presented in the experiment, if the rainfall is very low, the convergence point can be between the upper or lower part of the soil moisture.
4. Therefore, unless the catchment is a semi-arid or arid catchment, we recommend setting the SMIC greater than the maximum capacity of the catchment when the HYMOD model is used. Approximately one and a half months are required for the model to reach the ‘optimal’ state for the study catchment when the SMIC is greater than 273 mm.

336 **4.2 IHACRES**

337 **4.2.1 Effects of SMICs**

338 The same analysis has been conducted with the IHACRES model to explore the differences in SMICs
 339 between the different model structures. Table 9 shows the warm-up period with different SMICs for three time
 340 periods. Overall, the range of the warm-up period is 121-197 days, and the impact of different SMICs on the
 341 warm-up period is less than the HYMOD. Although the difference is small, less time is required for the model
 342 to come to an equilibrium state when the SMICs are close to the optimal initial soil moisture value (when
 343 $n=1$). A general pattern of soil moisture under different SMICs is presented in Figure 12. As shown in Figure
 344 12, the optimal soil moisture (black line) is obtained based on the observed data (1960's), and the effects of
 345 different SMICs are illustrated only for two cases, when the initial values are double the optimal value (red
 346 line) and zero (blue line).

347
 348 Table 9. Warm-up period (days) with different SMICs for the calibration starting in winter.

	Factor n , which is multiplied by the optimal initial soil moisture							
	2	1.75	1.5	1.25	0.75	0.5	0.25	0
1960s	164	164	161	159	159	161	164	164
1970s	197	197	176	165	165	176	197	197
1980s	138	138	131	121	121	131	138	138

349

350

351 Figure 12. An illustration of the warm-up period for the observed rainfall and temperature when the SMICs
 352 are twice the optimal value and zero.

4.2.2 Effects of rainfall amount

Next, the effects of rainfall amount on the warm-up period were explored. The rainfall amounts were proportionally increased (or decreased) while using the fixed, observed temperature. Unlike the HYMOD, the warm-up period does not depend on the rainfall amount and is only affected by the SMICs as summarized in Table 10.

Table 10. The estimated warm-up period for different SMICs with proportionally increased (or decreased) rainfall while using a fixed, observed temperature.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rain	$0.25 \times \text{Obs.}$	164	164	161	159	159	161	164	164
	$0.50 \times \text{Obs.}$	164	164	161	159	159	161	164	164
	$0.75 \times \text{Obs.}$	164	164	161	159	159	161	164	164
	Obs.	164	164	161	159	159	161	164	164
	$1.25 \times \text{Obs.}$	164	164	161	159	159	161	164	164
	$1.50 \times \text{Obs.}$	164	164	161	159	159	161	164	164
	$1.75 \times \text{Obs.}$	164	164	161	159	159	161	164	164

This can be theoretically explained by the following equations and Figure 13. The simulated soil moisture (ϕ_k) and rainfall (r_k) at each time step k can be expressed as shown in Eq. (11).

$$\phi_2 - \phi_1 = r_2 - \frac{\phi_1}{\tau_2} \quad (11a)$$

$$\phi_3 - \phi_2 = r_3 - \frac{\phi_2}{\tau_3} \quad (11b)$$

$$\phi_4 - \phi_3 = r_4 - \frac{\phi_3}{\tau_4} \quad (11c)$$

$\vdots$

$$\phi_k - \phi_{k-1} = r_k - \frac{\phi_{k-1}}{\tau_k} \quad (11d)$$

Equation (12) is formulated by summing Eq. (11a) to Eq. (11d).

$$\phi_k - \phi_1 = \sum r_k - \sum \frac{\phi_{k-1}}{\tau_k} \quad (12)$$

Therefore, the optimal soil moisture at time step k ($\phi_{k,t}$) can be expressed as Eq. (13).

$$\phi_{k,t} - \phi_{1,t} = \sum r_k - \sum \frac{\phi_{k-1,t}}{\tau_k} \quad (13)$$

Equation (14) is estimated by subtracting Eq. (13) from Eq. (12), and the difference between the simulated and the optimal soil moisture can be expressed as Eq. (15). This has no rainfall terms, and is only dependent on the initial soil moisture, the soil moisture of the previous time step and the drying rate.

$$\phi_k - \phi_{k,t} - (\phi_1 - \phi_{1,t}) = - \sum \frac{(\phi_{k-1} - \phi_{k-1,t})}{\tau_k} \quad (14)$$

$$\Delta\phi_k = \Delta\phi_1 - \sum \frac{\Delta\phi_{k-1}}{\tau_k} \quad (15)$$

Figure 13. Illustration of the time series of soil moisture for IHACRES.

4.2.3 Effects of the starting point of the simulation

Table 11 shows the warm-up period for the simulation starting in July, the summer season. As previously presented, a warm-up period of 121-197 days is required for the simulation starting in winter. For the simulation starting in summer, the estimated warm-up period was about 86-200 days. Unlike the HYMOD, the IHACRES did not converge around the upper part of the optimal soil moisture state since the model does not constrain the maximum soil moisture value. In addition, the warm-up period in IHACRES has nothing to do with the rainfall, and there are no clear significant correlations between the starting season of the simulation and the warm-up period.

Table 11. Warm-up period (days) with different SMICs for the calibration starting in summer.

	Factor n , which is multiplied by the optimal initial soil moisture							
	2	1.75	1.5	1.25	0.75	0.5	0.25	0
1960s	200	198	169	131	131	169	198	200
1970s	113	106	102	86	86	102	106	113
1980s	109	107	91	81	81	91	107	109

4.2.4 Guidelines for practical applications

From the analyses, the following conclusions were made for IHACRES.

1. The impact of different SMICs on the warm-up period is less than that for HYMOD. The time required for convergence decreases as the SMIC becomes closer to the optimal soil moisture value.
2. Rainfall amount has no effect on warm-up period.
3. For our catchment, a period of approximately six-months is required for the model to reach the ‘optimal’ state.
4. Since we do not know the optimal soil moisture value in practical situations, it is not possible to set the initial value close to the optimal value. Therefore, we recommend defining an initial value as the mean value of that particular day for the calibration period. For example, if the model is calibrated by a ten-year data set from January 1961 to December 1970, we first set the initial soil moisture value to zero and do the initial calibration. The initial value is then defined by averaging the soil moisture on the first day of each year, which will be used for the final calibration.

5. Discussion

5.1 Application to different catchments

To further explore potential implications of our recommendations for different catchments, we have included two more catchments of Bala (261.6 km²) and Manley Hall (1013.2 km²) in the River Dee basin in the west of England. As shown in Tables 12 and 13, we observed that the following characteristics for the warm-up periods of the HYMOD for the two catchments are largely the same as those found in the Thorverton catchment.

- Substantially, less time is required to reach the equilibrium state as more rain falls because the soil quickly becomes saturated
- For the case that the SMICs are larger than the parameter C_{max} (i.e. the maximum soil moisture capacity), the warm-up period is the same, irrespective of the rainfall amount received in a day.
- As expected, longer warm-up period is generally required for smaller SMICs

Similarly, as summarized in Tables 14 and 15, the following characteristics for the warm-up periods of the IHACRES for the two catchments are nearly the same as those observed in the Thorverton catchment.

- Again, less time is required for the model to be in an equilibrium state when the SMICs are close to the optimal initial soil moisture value
- The warm-up period is largely independent of the rainfall amount but significantly dependent on the SMICs.

Table 12. The estimated warm-up period (days) with different SMICs and rainfall amounts while using the fixed, observed PET for the Bala catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rainfall	$0.25 \times \text{Obs.}$	94	94	94	94	98	101	104	116
	$0.50 \times \text{Obs.}$	17	17	17	17	21	24	26	27
	$0.75 \times \text{Obs.}$	15	15	15	15	16	16	17	17
	Obs.	14	14	14	14	16	16	15	15
	$1.25 \times \text{Obs.}$	4	4	4	4	14	15	15	15
	$1.50 \times \text{Obs.}$	4	4	4	4	4	12	14	15
	$1.75 \times \text{Obs.}$	4	4	4	4	4	4	12	12

Table 13. The estimated warm-up period (days) with different SMICs and rainfall amounts while using the fixed, observed PET for the Manley Hall catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rainfall	$0.25 \times \text{Obs.}$	115	115	115	115	201	224	228	238
	$0.50 \times \text{Obs.}$	14	14	14	14	17	26	26	29
	$0.75 \times \text{Obs.}$	4	4	4	4	15	17	18	22
	Obs.	4	4	4	4	15	16	17	17
	$1.25 \times \text{Obs.}$	4	4	4	4	15	15	15	17
	$1.50 \times \text{Obs.}$	4	4	4	4	11	15	15	15
	$1.75 \times \text{Obs.}$	4	4	4	4	5	14	15	15

433
434

435 Table 14. The estimated warm-up period (days) with different SMICs and rainfall amounts while using a fixed,
 436 observed temperature for Bala catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rainfall	$0.25 \times \text{Obs.}$	89	89	74	66	66	74	89	89
	$0.50 \times \text{Obs.}$	89	89	74	66	66	74	89	89
	$0.75 \times \text{Obs.}$	89	89	74	66	66	74	89	89
	Obs.	89	89	74	66	66	74	89	89
	$1.25 \times \text{Obs.}$	89	89	74	66	66	74	89	89
	$1.50 \times \text{Obs.}$	89	89	74	66	66	74	89	89
	$1.75 \times \text{Obs.}$	89	89	74	66	66	74	89	89

437
 438 Table 15. The estimated warm-up period (days) with different SMICs and rainfall amounts while using a fixed,
 439 observed temperature for Manley Hall catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
Rainfall	$0.25 \times \text{Obs.}$	132	130	130	111	111	130	130	132
	$0.50 \times \text{Obs.}$	132	130	130	111	111	130	130	132
	$0.75 \times \text{Obs.}$	132	130	130	111	111	130	130	132
	Obs.	132	130	130	111	111	130	130	132
	$1.25 \times \text{Obs.}$	132	130	130	111	111	130	130	132
	$1.50 \times \text{Obs.}$	132	130	130	111	111	130	130	132
	$1.75 \times \text{Obs.}$	132	130	130	111	111	130	130	132

440

441 5.2 Effects of maximum soil moisture capacity on the warm-up period for HYMOD

442 To investigate the effects of maximum soil moisture capacity, C_{max} , on the warm-up period, an experiment
 443 study is described in which the maximum soil moisture capacity was varied in 0.25 steps from 0.25 to 1.75,
 444 with factors on the SMICs ranging from 0 to 2, while using the fixed, observed rainfall and potential
 445 evapotranspiration. As shown in Tables 16 to 18, accordingly, more time is required to reach the equilibrium
 446 state for the larger maximum soil moisture storage. More specifically, the range of warm-up period under
 447 different maximum soil moisture storage values becomes less (e.g. 35-41 days for Thorverton catchment)
 448 when the SMICs are larger than the parameter C_{max} and greater (e.g. 35-314 days for Thorverton catchment),
 449 and vice versa. These results are logical in terms of a model since the model requires relatively more time
 450 away from the SMICs to reach the ‘optimal’ state with a larger soil moisture storage.

451

452

453 Table 16. The estimated warm-up period for different maximum soil moisture capacity C_{max} for Thorverton
454 catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
C_{max}	$0.25 \times C_{max}$	35	35	35	35	35	39	40	44
	$0.50 \times C_{max}$	35	35	35	35	44	201	219	219
	$0.75 \times C_{max}$	35	35	35	35	253	253	253	253
	C_{max}	39	39	39	39	255	257	257	257
	$1.25 \times C_{max}$	39	39	39	39	267	268	268	268
	$1.50 \times C_{max}$	41	41	41	41	268	271	289	292
	$1.75 \times C_{max}$	41	41	41	41	273	292	310	314

455
456 Table 17. The estimated warm-up period for different maximum soil moisture capacity C_{max} for Bala
457 catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
C_{max}	$0.25 \times C_{max}$	4	4	4	4	4	4	4	4
	$0.50 \times C_{max}$	4	4	4	4	4	4	4	4
	$0.75 \times C_{max}$	4	4	4	4	12	15	15	15
	C_{max}	14	14	14	14	16	16	15	15
	$1.25 \times C_{max}$	14	14	14	14	16	16	16	17
	$1.50 \times C_{max}$	15	15	15	15	16	17	17	17
	$1.75 \times C_{max}$	15	15	15	15	17	21	21	21

458
459 Table 18. The estimated warm-up period for different maximum soil moisture capacity C_{max} for Manley Hall
460 catchment.

		Factor n , which is multiplied by the SMIC							
		2	1.75	1.5	1.25	0.75	0.5	0.25	0
C_{max}	$0.25 \times C_{max}$	4	4	4	4	4	4	4	4
	$0.50 \times C_{max}$	4	4	4	4	4	12	15	16
	$0.75 \times C_{max}$	4	4	4	4	15	15	16	16
	C_{max}	4	4	4	4	15	16	17	17
	$1.25 \times C_{max}$	4	4	4	4	15	17	17	18
	$1.50 \times C_{max}$	4	4	4	4	16	17	18	22
	$1.75 \times C_{max}$	4	4	4	4	17	18	22	22

461 462 5.3 Soil moisture behavior in HYMOD and IHACRES

463 As presented in the previous sections, the two conceptual hydrological models, HYMOD and IHACRES, have
464 different structures and here an attempt has been made to highlight the similarities and differences in the
465 models. The soil moisture accounting module of HYMOD uses Pareto distribution function of storage
466 elements of varying sizes. The storage elements of the catchment are distributed according to a probability

467 density function defined by the maximum soil moisture storage C_{max} and the distribution of soil moisture store
 468 b_{exp} (Wagener et al., 2001). On the other hand, IHACRES model utilizes a threshold parameter (I) and a
 469 nonlinear relationship (power law with exponent parameter p) between the soil moisture index and the fraction
 470 of rainfall that becomes effective rainfall. Note that unlike HYMOD, the soil-water storage capacity parameter
 471 is not explicitly considered. It was found that there were positive and comparable behavior changes in the soil
 472 moisture parameters of hydrological models, HYMOD and IHACRES. As illustrated in Figure 14, the cross
 473 correlations between the simultaneously estimated soil moisture parameters were found to be similarly
 474 symmetrical about the 0.6. A noticeable difference in the time series is that an upper limit is encountered in
 475 HYMOD, due to the parameter associated with the soil moisture capacity. Moreover, as discussed in previous
 476 section, the warm-up period of HYMOD is substantially affected by the maximum soil moisture capacity.

477 Figure 14. Time series of the estimated soil moisture parameters of HYMOD and IHACRES, and their Cross
 478 correlations over lags.
 479

6. Conclusions

In this study, we investigated the warm-up period of two conceptual hydrological models (HYMOD and IHACRES) for a southwestern England catchment. Nine different initial conditions of soil moisture were used to estimate the time for the model to reach an equilibrium state. Further, two different starting seasons (winter and summer) of the simulations have been considered to better understand these effects on the warm-up period. Additionally, we explored the impact of rainfall amount on the warm-up period based on the proportionally increased (or decreased) observed rainfall. Our analysis illustrates that the determination of the warm-up period depends on the structure of the hydrological model. For HYMOD, we recommend using a SMIC greater than the maximum soil moisture capacity of the catchment, since the model requires less time to warm-up under saturated initial conditions. For the Thorverton catchment and climatic condition, approximately one and a half months are generally required for the model to reach the 'optimal' state when the SMIC is greater than 273mm. In addition, the converging point lies on the upper stage of the optimal soil moisture state. However, an experiment with a small amount of the rainfall showed a different pattern (i.e., not always converging at the top), which indicates that more research is necessary in hot-arid or semi-arid catchments. For IHACRES, the rainfall amount has no effect on the warm-up period, and less time is required when the SMIC is close to the optimal value. For the Thorverton catchment, a period of approximately six months was required for warm-up.

These findings have implications for hydrologic model development, specifically in determining soil moisture initial conditions and the warm-up period. Based on this study, it is apparent that the estimation of warm-up period could be helpful in fully utilizing the available information, especially under conditions where data are scarce because unnecessarily long warm-up times would waste valuable hydrological data. However, only one catchment has been explored in this study, since the purpose of this study was mainly as a proof of concept to provide a methodology for analysis of the warm-up period with conceptual hydrological modelling. Further studies under different conditions (e.g., different hydrological models, catchment size, climatic conditions, land use and terrain) would be needed to obtain useful guiding patterns for setting up appropriate warm-up periods for hydrological models in different catchment conditions.

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511

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