

# Accepted Manuscript

Research papers

Exploration of warm-up period in conceptual hydrological modelling

Kue Bum Kim, Hyun-Han Kwon, Dawei Han

PII: S0022-1694(17)30769-2

DOI: <https://doi.org/10.1016/j.jhydrol.2017.11.015>

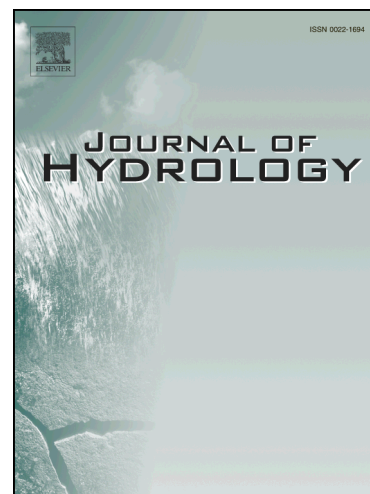
Reference: HYDROL 22373

To appear in: *Journal of Hydrology*

Received Date: 4 May 2017

Revised Date: 23 September 2017

Accepted Date: 8 November 2017



Please cite this article as: Kim, K.B., Kwon, H-H., Han, D., Exploration of warm-up period in conceptual hydrological modelling, *Journal of Hydrology* (2017), doi: <https://doi.org/10.1016/j.jhydrol.2017.11.015>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

# Exploration of warm-up period in conceptual hydrological modelling

Kue Bum Kim<sup>1</sup>, Hyun-Han Kwon<sup>2\*</sup> and Dawei Han<sup>1</sup>

<sup>1</sup> Water and Environmental Management Research Centre, Department of Civil Engineering, University of Bristol, Bristol, UK

<sup>2</sup> Department of Civil Engineering, Chonbuk National University, Jeonju-si, Jeollabuk-do, South Korea

\* Corresponding author: hkwon@jbnu.ac.kr

## Abstract

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

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).

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

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

The primary objectives addressed in this paper are to: (1) assess the effects of initial soil moisture condition, rainfall amount and simulation starting point on the warm-up period and (2) suggest guidelines for defining the initial soil moisture value depending on the hydrological model. This investigation has both practical and scientific value since it allows us to identify the importance of the initial soil moisture condition and to understand how the hydrological model responds to initial conditions. This could lead to the improvement and development of hydrological models, specifically in terms of determining soil moisture initial conditions and warm-up period. In Section 2, we describe the study area and data used and provide an outline of the hydrological models HYMOD and IHACRES. The simulation design is provided in Section 3. The effects of initial soil moisture conditions and rainfall amount on the warm-up period are presented in Section 4. The discussion and main conclusions of this study are summarized in Section 5 and 6 respectively.

## 2. Case study area and the hydrological models

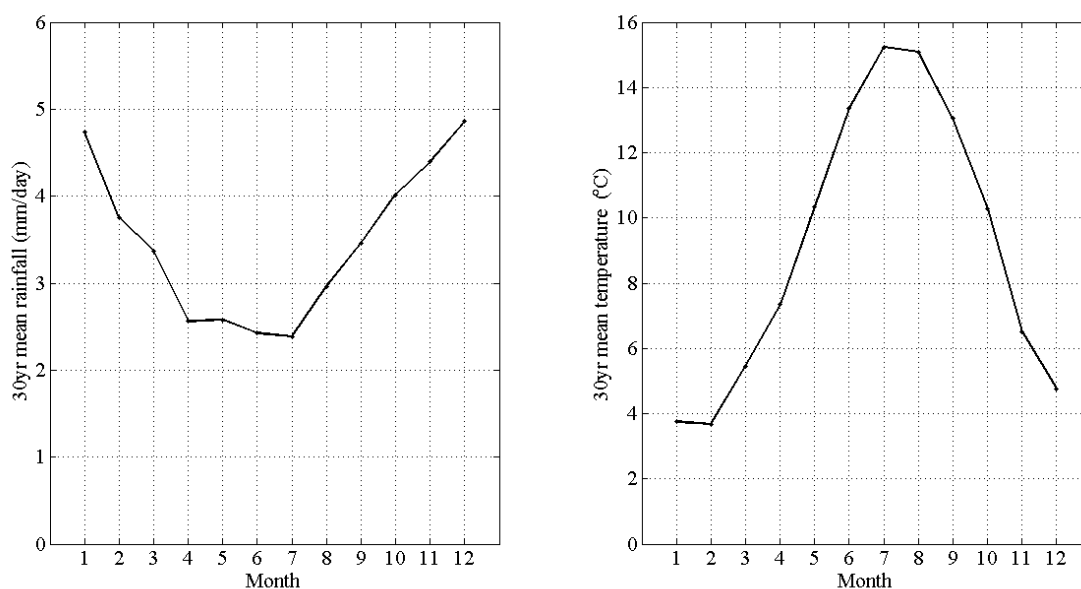
### 2.1 Study area and data

The Thorverton catchment is used in this study. It has an area of 606 km<sup>2</sup>, and is a sub-catchment of the Exe catchments. The Exe catchment is in the southwest of England and has an area of 1,530 km<sup>2</sup> and an average 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.



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 spatial distribution of the water storage,  $F(C)$ , 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  $\alpha$ . 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
$\alpha$	-	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

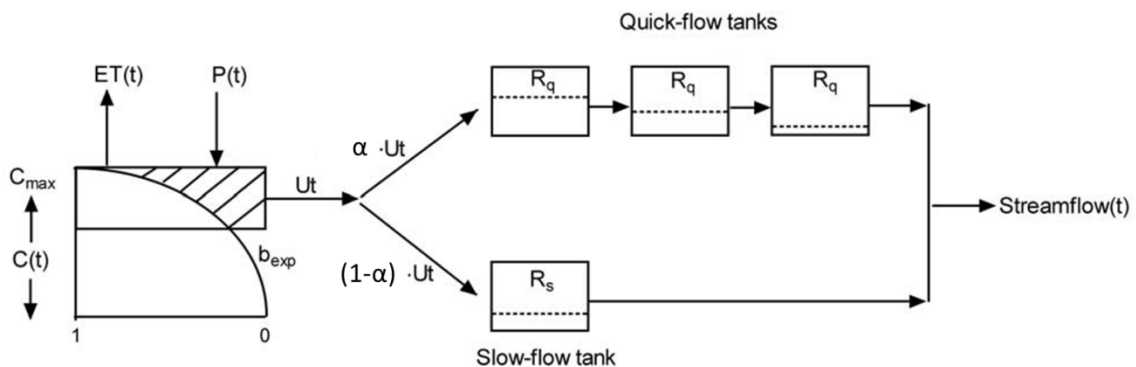


Figure 3. Structure of the HYMOD model (adopted from Vrugt et al. [2002]).

## 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 ( $\phi_k$ ) can be written as:

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

where  $\tau_k$  is the drying rate given by:

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

Here,  $\tau_w$  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. The routing 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  $\alpha$  and  $\beta$  are the recession rate and peak response, respectively. The relative volumes of quick flow and slow flow can be calculated from:

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



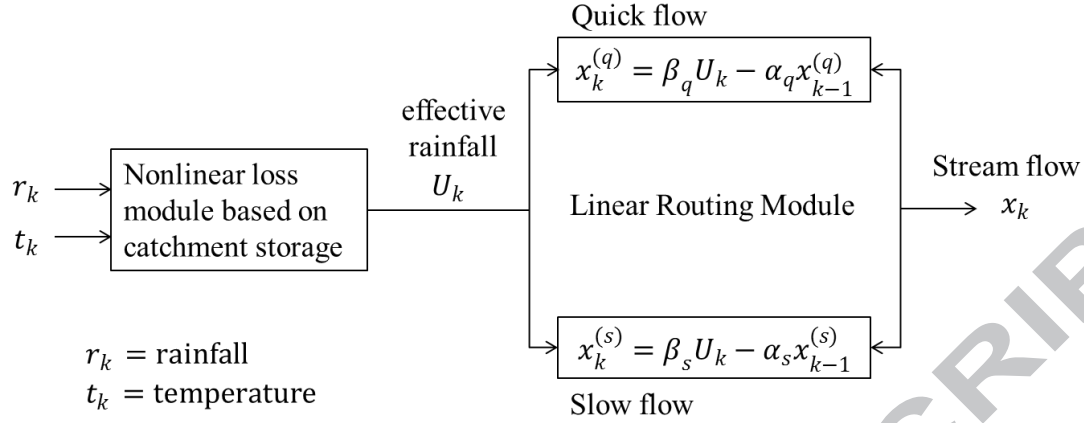


Figure 4. A schematic representation of the rainfall-runoff process in the IHACRES model.

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

Module	Parameter	Description
Non-linear	$c$	Mass balance
	$\tau_w$	Reference drying rate
	$f$	Temperature modulation of drying rate
Linear	$\alpha_q, \alpha_s$	Quick and slow flow recession rate
	$\beta_q, \beta_s$	Fractions of effective rainfall for peak response
	$\tau_s$	Slow flow recession time constant, $\tau_s = -\Delta/\ln(-\alpha_s)$
	$\tau_q$	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. It was found that values of values of NSE is greater than 0.75 for both calibration and validation periods, which can be considered to be sufficient for rainfall-runoff modeling (Motovilov et al., 1999)

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

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.

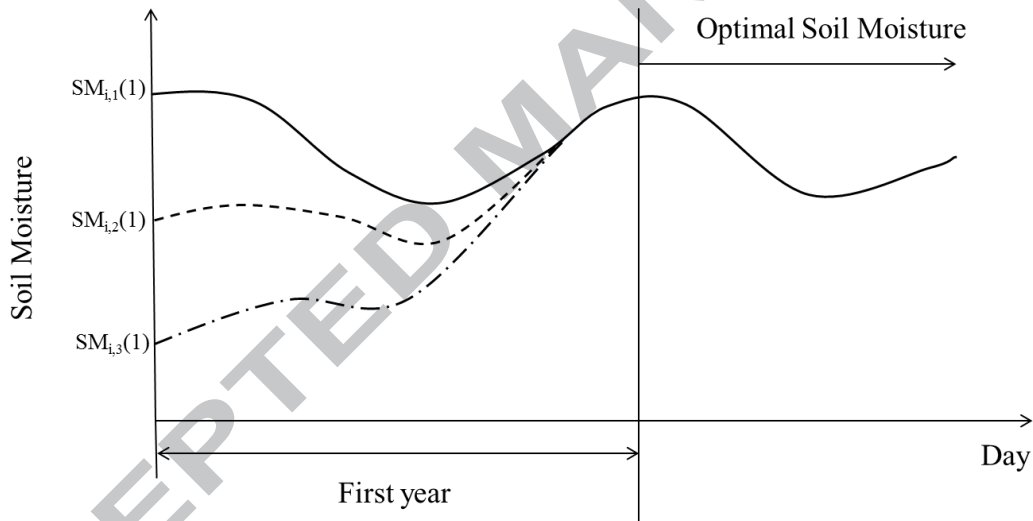


Figure 5. Illustration of the method for estimating the optimal soil moisture state with different soil moisture initial conditions.  $SM_{i,t}(1)$  points represent different soil moisture initial conditions.

### 3.2 Definition of warm-up period

Hereafter, the optimal soil moisture state is used to determine the warm-up period. Since we know the optimal value now, we can determine the warm-up period by simulating soil moisture under different initial soil moisture conditions. Figure 6 illustrates how the warm-up period is estimated. First, we know the time series of the optimal soil moisture, wherein the initial value is  $SM_{i,t}(1)$ . Next, simulations have been done with different initial soil moisture conditions (e.g.,  $SM_{i,1}(1)$ ,  $SM_{i,2}(1)$ ), and the simulated soil moisture approaches

the optimal value over time. Finally, the warm-up period (i.e., when the simulated soil moisture data becomes almost the same as the optimal value) was calculated by applying the cut-off threshold (CT) criteria (Eq. (10)). Generally, the warm-up periods are longer for higher threshold levels. The sensitivity of the warm-up period 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%, as illustrated in Table S1-2. 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).

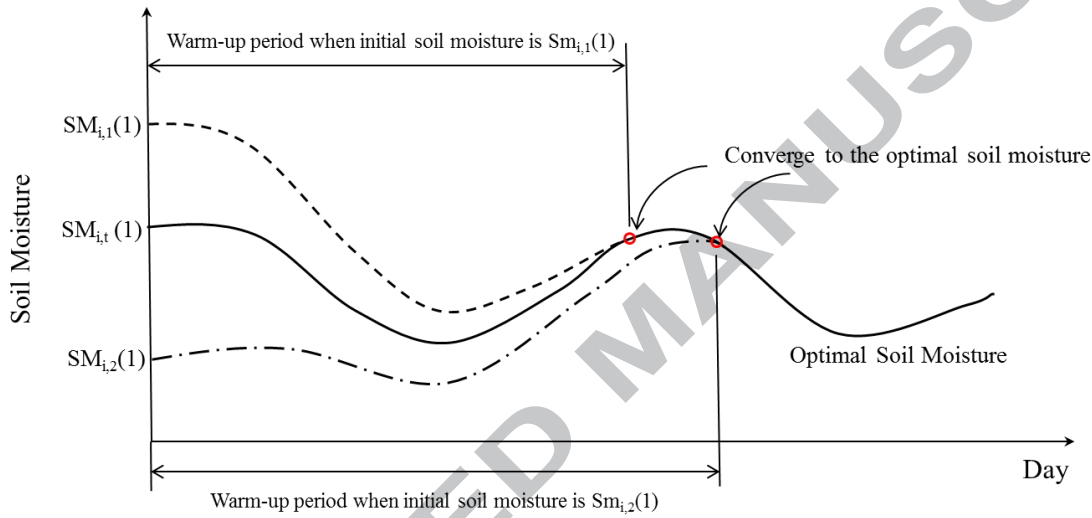


Figure 6. Illustration of the equilibrium soil moisture state under different initial soil moisture conditions.

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

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. Here, since the first year data has been removed, the rainfall is multiplied from the second-year data which is used as the optimal state.

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, 1970s and 1980s 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). For 1960s case, 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 lie on the upper part of soil moisture for 1960s and 1970s cases when soil moisture levels were high enough. On the other hand, the convergence level is between the maximum and minimum soil moisture for 1980s case when soil moisture level was relatively low in comparison with that of other periods. This result will be further discussed in Section 4.1.4.

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

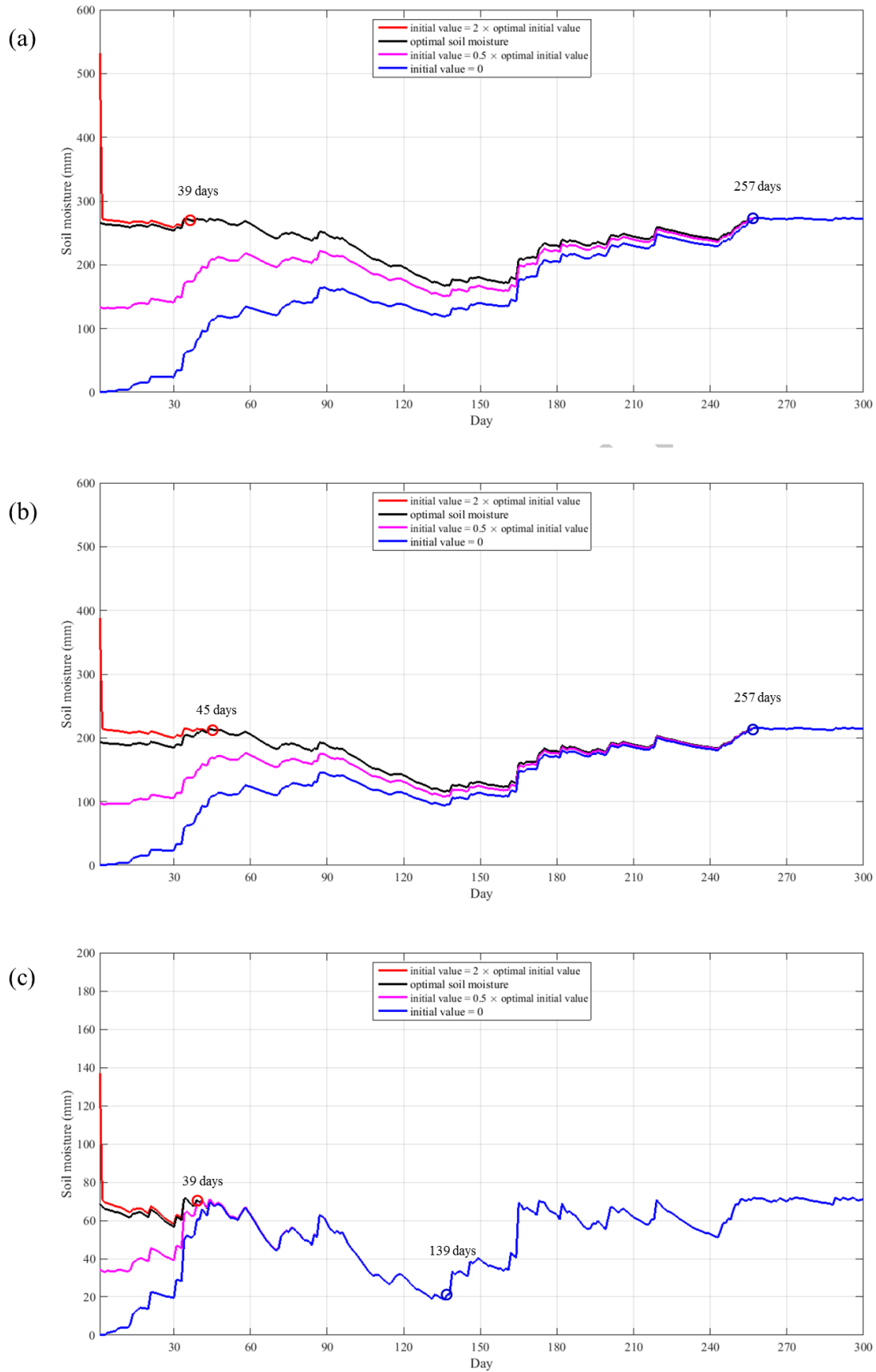


Figure 7. An illustration of warm-up periods required to converge to the optimal soil moisture for different SMICs. (a) 1960s. (b) 1970s. (c) 1980s.

#### 4.1.2 Effects of the starting point of the simulation

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

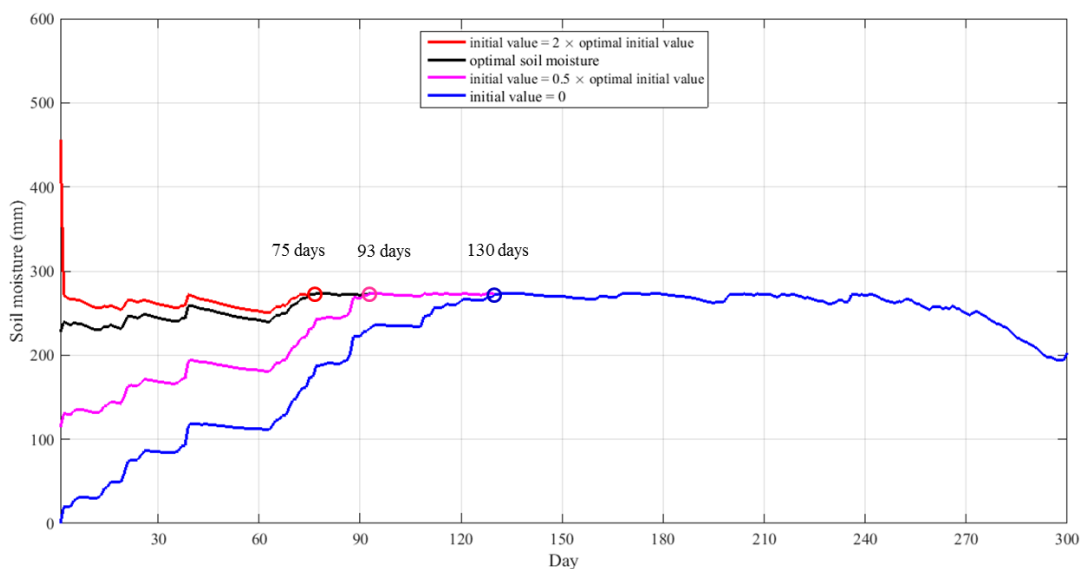


Figure 8. An illustration of warm-up periods required to converge to the optimal soil moisture for different SMICs (1960s' case with the simulation starting in the summer).

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



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

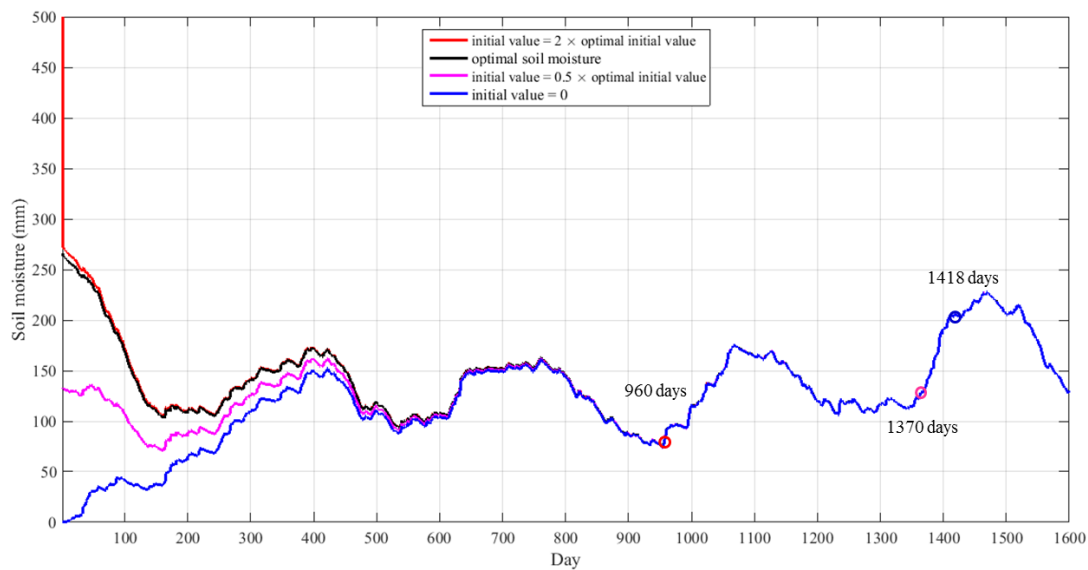


Figure 9. An illustration of warm-up periods when the rainfall is one quarter the observed rainfall.

#### 4.1.4 Summary of the HYMOD results

The warm-up period with different SMICs is illustrated in Figure 10 as a function of the rainfall amount. In this case, the rainfall is enough for the simulated soil moisture to reach a maximum value in a short time period. Figure 10(a) is the explanation of the warm-up period for the simulation starting from winter. If the SMIC is greater than the optimal soil moisture, the converging point can be at  $A_1$ , which is in the first upper stage of the optimal soil moisture, or at  $A_2$ , which is in the next higher stage. The converging point  $A_2$  may happen when the rainfall is not enough for the simulated soil moisture to reach the first upper stage, which results in a slow response to the soil moisture. Likewise, if the SMIC is excessively low (or near zero), the converging point will be either at  $B_1$  or  $B_2$ . Figure 10(b) shows the case for the simulation starting in summer,

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

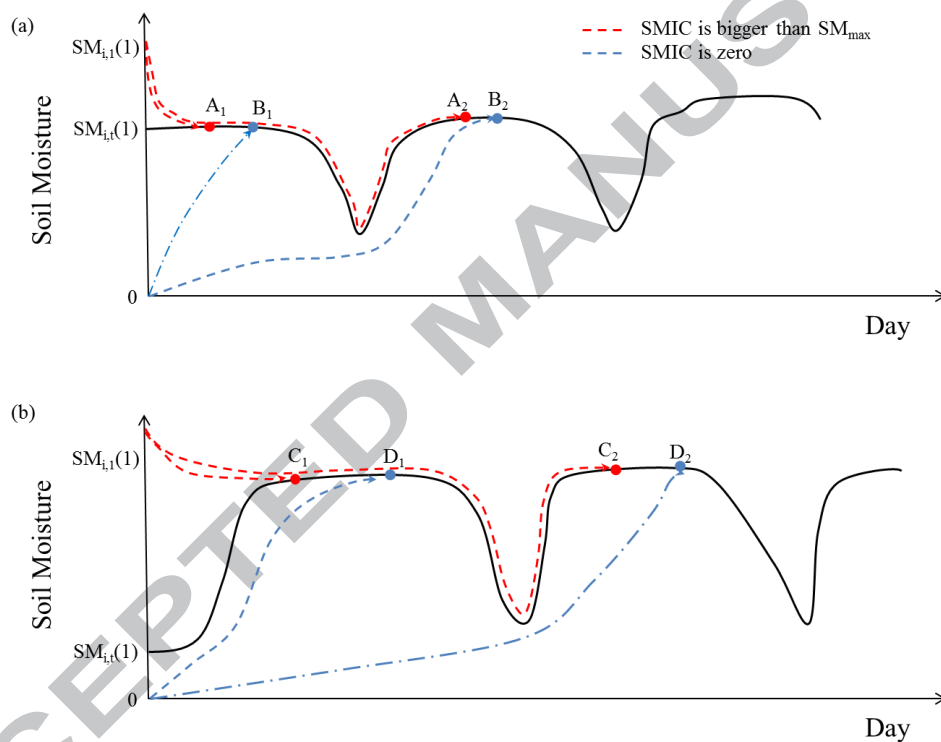


Figure 10. An illustration of the warm-up period when the rainfall is enough for soil moisture saturation.

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.

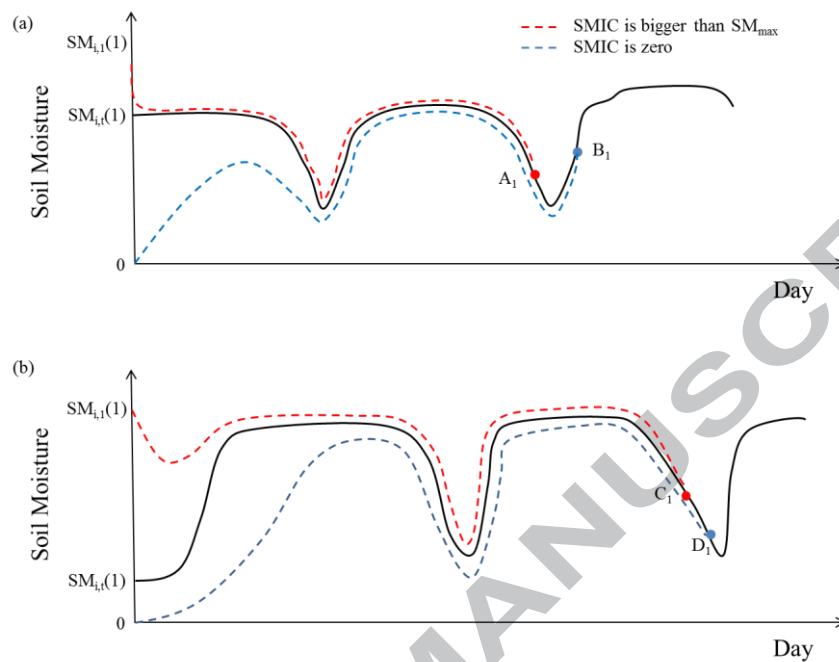


Figure 11. An illustration of the warm-up period when the rainfall is not enough for the simulated soil moisture to converge at the upper level of the optimal soil moisture.

#### 4.1.5 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.

## 4.2 IHACRES

### 4.2.1 Effects of SMICs

The same analysis has been conducted with the IHACRES model to explore the differences in SMICs between the different model structures. Table 9 shows the warm-up period with different SMICs for three time periods. Overall, the range of the warm-up period is 121-197 days, and the impact of different SMICs on the warm-up period is less than the HYMOD. Although the difference is small, less time is required for the model to come to an equilibrium state when the SMICs are close to the optimal initial soil moisture value (when  $n=1$ ). A general pattern of soil moisture under different SMICs is presented in Figure 12. As shown in Figure 12, the optimal soil moisture (black line) is obtained based on the observed data (1960’s, 1970’s, 1980’s), and the effects of different SMICs are illustrated only for two cases, when the initial values are double the optimal value (red line) and zero (blue line). It is clearly seen that the required warm-up period is proportional to the increase in SMICs. From these results and Eq. (15) in the following section 4.2.3, it is evident that the time required for convergence is related with the optimal initial soil moisture value as well as the temperature.

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

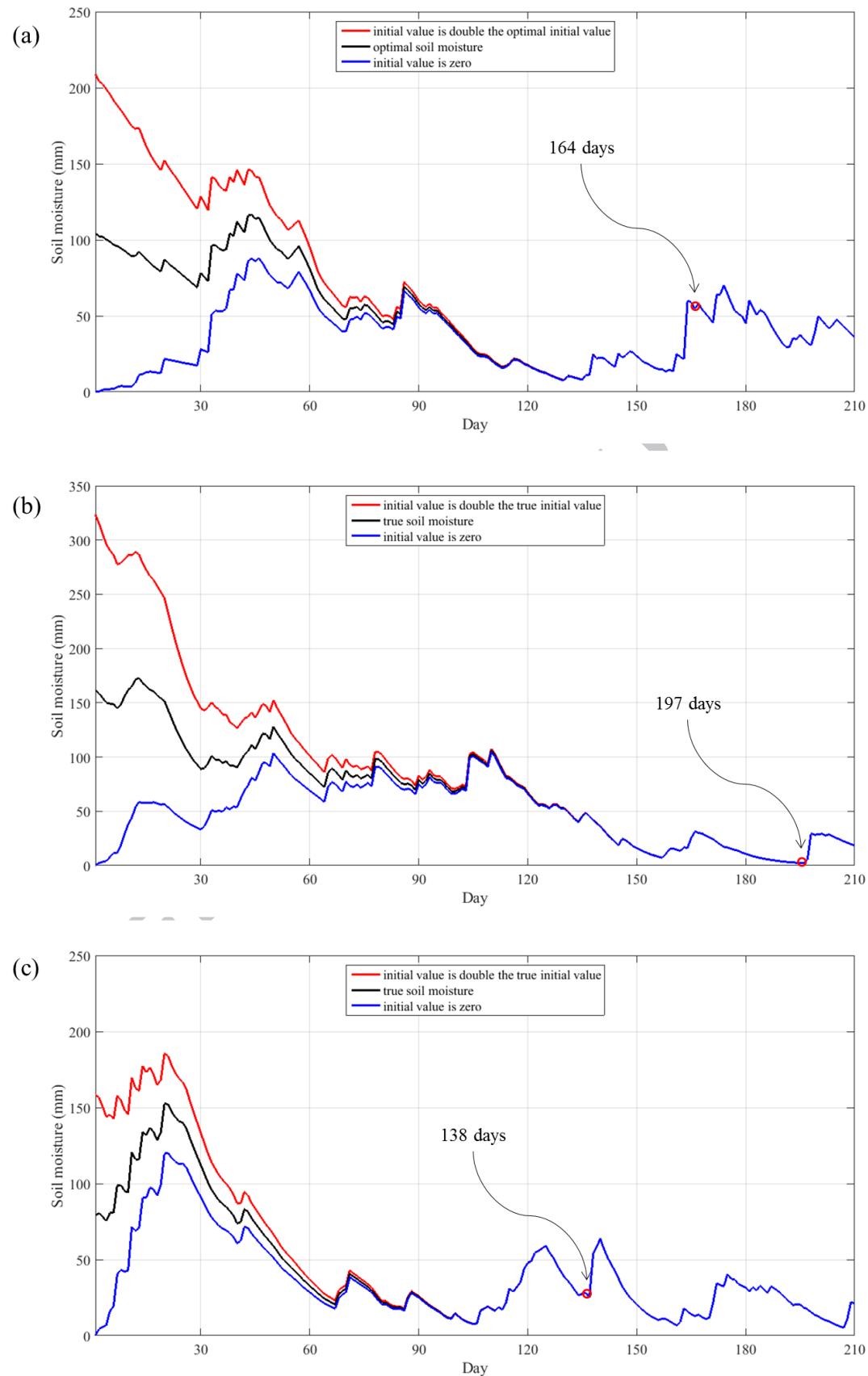


Figure 12. An illustration of the warm-up period for the observed rainfall and temperature when the SMICs are twice the optimal value and zero ((a) 1960s, (b) 1970s, (c) 1980s).

#### 4.2.2 Effects of the starting point of the simulation

Table 10 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 10. 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

#### 4.2.3 Effects of rainfall amount

Next, the effects of rainfall amount on the warm-up period were explored. The 1960's 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 11.

Table 11. 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

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

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

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

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

385  $\vdots$

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

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

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

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

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

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

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

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

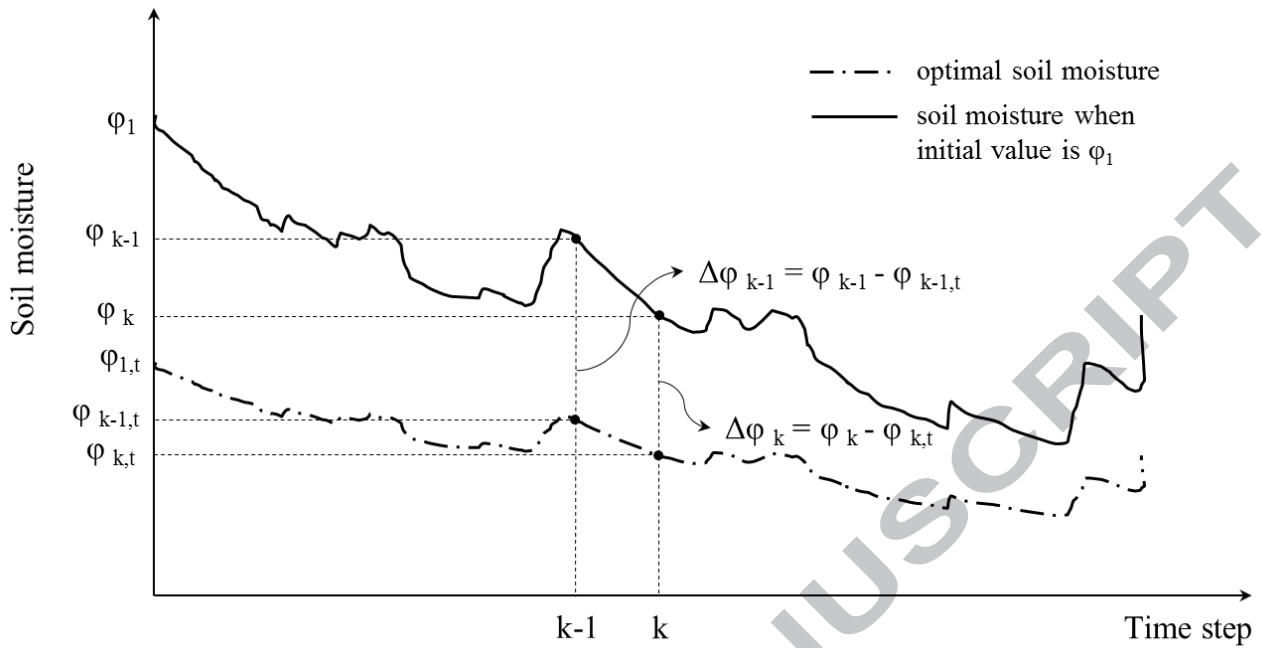


Figure 13. Illustration of the time series of soil moisture for IHACRES.

#### 4.2.4 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 km<sup>2</sup>) and Manley Hall (1013.2 km<sup>2</sup>) 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.

The warm-up periods between three different catchments have been compared. In Thorverton catchment, the estimated warm-up period ranges from 21 to 1418 days (Table 7) while the Bala and Manley Hall catchments require 4-116 days and 4-238 days respectively (Table 12 and 13). This might be due to different maximum soil moisture storage values which are discussed in the following section 5.2. The estimated maximum soil moisture storage capacity (i.e.  $C_{max}$ , mm) are 273, 30 and 54 for the Thorverton, Bala and Manley Hall catchments respectively. As expected, it is easily seen that more time is required to reach the equilibrium state for the larger maximum soil moisture storage. However, we have not attempted to explore the patterns of warm-up period in other parts of the world at this point, and will further investigate the warm-up period within this framework in more detail as part of future work.

438 Table 12. The estimated warm-up period (days) with different SMICs and rainfall amounts while using the  
439 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

441 Table 13. The estimated warm-up period (days) with different SMICs and rainfall amounts while using the  
442 fixed, observed PET for the Manley Hall catchment.  
443

		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

444 Table 14. The estimated warm-up period (days) with different SMICs and rainfall amounts while using a fixed,  
445 observed temperature for Bala catchment.  
446

		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

Table 15. The estimated warm-up period (days) with different SMICs and rainfall amounts while using a fixed, 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 × Obs.	132	130	130	111	111	130	130	132
	0.50 × Obs.	132	130	130	111	111	130	130	132
	0.75 × Obs.	132	130	130	111	111	130	130	132
	Obs.	132	130	130	111	111	130	130	132
	1.25 × Obs.	132	130	130	111	111	130	130	132
	1.50 × Obs.	132	130	130	111	111	130	130	132
	1.75 × Obs.	132	130	130	111	111	130	130	132

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

To investigate the effects of maximum soil moisture capacity,  $C_{max}$ , on the warm-up period, an experiment study is described in which the maximum soil moisture capacity was varied in 100 mm increment, from 100 to 2000 mm, with the same increment on the SMICs ranging from 100 to 2000 mm using a grid context, while using the fixed, observed rainfall and potential evapotranspiration. As shown in Tables 16 to 18, accordingly, more time is required to reach the equilibrium state for the larger maximum soil moisture storage. More specifically, the range of warm-up period under different maximum soil moisture storage values becomes less (e.g. 35-385 days for Thorverton catchment) when the SMICs are larger than the parameter  $C_{max}$  and greater (e.g. 252-1386 days for Thorverton catchment), and vice versa. These results are logical in terms of a model since the model requires relatively more time away from the SMICs to reach the ‘optimal’ state with a larger soil moisture storage. More generally, the warm-up period can be significantly shortened by the SMICs beyond the maximum soil moisture capacity. As already seen in Tables, the SMICs exert a strong influence on warm-up period directly with the interaction of the maximum soil moisture capacity, thus, the uncertainty associated with the SMICs needs to be reduced for a reliable calibration of the rainfall-runoff model.

Table 16. The estimated warm-up period (days) for different maximum soil moisture capacity  $C_{max}$  and SMIC for Thorverton catchment.

Warm-up Period		SMIC (mm)																				
		2000	1900	1800	1700	1600	1500	1400	1300	1200	1100	1000	900	800	700	600	500	400	300	200	100	
$C_{max}$ (mm)	2000	386	658	758	760	1056	1057	1058	1058	1059	1059	1064	1231	1382	1385	1385	1385	1385	1385	1386	1386	
	1900	385	385	441	758	758	760	1056	1057	1057	1058	1058	1059	1064	1067	1381	1381	1382	1385	1385	1385	
	1800	384	384	384	390	708	758	759	800	1056	1056	1057	1058	1058	1059	1062	1066	1381	1381	1381	1381	
	1700	384	384	384	384	388	707	708	758	760	1056	1056	1056	1056	1057	1058	1059	1060	1064	1275	1381	
	1600	382	382	382	382	382	386	647	707	722	758	760	1052	1056	1056	1056	1056	1058	1058	1059	1062	
	1500	357	357	357	357	357	357	385	555	641	707	736	758	760	1050	1051	1052	1056	1056	1056	1058	
	1400	357	357	357	357	357	357	357	384	396	640	641	707	736	758	760	1050	1050	1050	1052	1056	
	1300	349	349	349	349	349	349	349	349	382	388	636	640	641	707	736	758	760	1042	1043	1050	
	1200	348	348	348	348	348	348	348	348	348	357	386	422	634	637	641	676	708	758	758	1023	
	1100	315	315	315	315	315	315	315	315	315	315	350	384	390	634	634	635	641	647	707	736	
	1000	314	314	314	314	314	314	314	314	314	314	314	348	381	386	422	634	634	634	637	641	
	900	311	311	311	311	311	311	311	311	311	311	311	311	315	357	384	388	422	633	634	634	
	800	292	292	292	292	292	292	292	292	292	292	292	292	292	311	348	379	385	396	444	633	
	700	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	310	314	349	381	385	390
	600	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	292	310	314	349	357
	500	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	274	292	308	311
	400	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	268	268	289	
	300	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	257	257	
	200	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	252	
	100	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	

470 Table 17. The estimated warm-up period (days) for different maximum soil moisture capacity  $C_{max}$  and SMIC for Bala catchment.

Warm-up Period		SMIC (mm)																			
		2000	1900	1800	1700	1600	1500	1400	1300	1200	1100	1000	900	800	700	600	500	400	300	200	100
$C_{max}$ (mm)	2000	1505	1552	1850	2004	2104	2130	2188	2210	2271	2280	2330	2374	2393	2451	2465	2473	2490	2512	2548	2556
	1900	1454	1454	1502	1799	1899	2031	2099	2119	2138	2188	2205	2215	2276	2280	2317	2343	2374	2386	2429	2456
	1800	1434	1434	1434	1457	1740	1827	1916	1988	2074	2104	2117	2131	2161	2188	2200	2211	2226	2273	2279	2280
	1700	1369	1369	1369	1369	1441	1644	1776	1829	1890	1958	2007	2059	2086	2106	2114	2121	2135	2151	2184	2189
	1600	1317	1317	1317	1317	1317	1378	1558	1690	1775	1810	1857	1890	1931	1970	2007	2048	2076	2086	2104	2108
	1500	1259	1259	1259	1259	1259	1259	1334	1495	1593	1681	1745	1786	1810	1830	1864	1888	1916	1946	1966	1975
	1400	1184	1184	1184	1184	1184	1184	1184	1265	1445	1513	1578	1644	1690	1741	1759	1786	1802	1813	1829	1854
	1300	1112	1112	1112	1112	1112	1112	1112	1112	1185	1389	1452	1501	1533	1578	1611	1653	1682	1713	1742	1755
	1200	1083	1083	1083	1083	1083	1083	1083	1083	1083	1111	1310	1405	1444	1454	1494	1517	1536	1558	1583	1609
	1100	1055	1055	1055	1055	1055	1055	1055	1055	1055	1055	1082	1218	1311	1360	1413	1439	1445	1453	1466	1494
	1000	972	972	972	972	972	972	972	972	972	972	972	1052	1115	1209	1270	1311	1350	1362	1404	1429
	900	866	866	866	866	866	866	866	866	866	866	866	866	954	1082	1111	1152	1201	1230	1268	1277
	800	740	740	740	740	740	740	740	740	740	740	740	740	740	848	1019	1077	1083	1109	1112	1119
	700	679	679	679	679	679	679	679	679	679	679	679	679	679	679	696	893	972	1021	1056	1077
	600	602	602	602	602	602	602	602	602	602	602	602	602	602	602	602	602	703	838	867	925
	500	474	474	474	474	474	474	474	474	474	474	474	474	474	474	474	474	541	639	686	696
	400	349	349	349	349	349	349	349	349	349	349	349	349	349	349	349	349	349	454	501	547
	300	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	237	349	422
	200	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	240
	100	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26

474 Table 18. The estimated warm-up period (days) for different maximum soil moisture capacity  $C_{max}$  and SMIC for Manley Hall catchment.

Warm-up Period		SMIC (mm)																						
		2000	1900	1800	1700	1600	1500	1400	1300	1200	1100	1000	900	800	700	600	500	400	300	200	100			
$C_{max}$ (mm)	2000	1349	1438	1691	1838	1920	2026	2104	2132	2173	2199	2213	2271	2280	2304	2330	2371	2381	2433	2463	2480			
	1900	1275	1275	1402	1607	1799	1879	1923	1981	2079	2113	2133	2172	2194	2210	2224	2271	2278	2280	2315	2330			
	1800	1225	1225	1225	1349	1556	1714	1808	1879	1900	1964	2026	2079	2108	2121	2138	2173	2190	2202	2212	2228			
	1700	1112	1112	1112	1112	1318	1518	1609	1743	1803	1852	1885	1905	1958	1979	2047	2080	2106	2120	2132	2142			
	1600	1100	1100	1100	1100	1100	1100	1244	1468	1552	1628	1722	1786	1812	1854	1883	1890	1917	1957	1973	2015	2056		
	1500	1100	1100	1100	1100	1100	1100	1100	1179	1444	1505	1552	1594	1676	1742	1779	1803	1824	1854	1881	1887	1891		
	1400	1076	1076	1076	1076	1076	1076	1076	1076	1115	1389	1457	1505	1526	1561	1594	1650	1692	1743	1775	1800	1810		
	1300	1015	1015	1015	1015	1015	1015	1015	1015	1015	1084	1305	1435	1454	1495	1516	1524	1552	1566	1591	1622	1663		
	1200	897	897	897	897	897	897	897	897	897	897	1069	1218	1353	1433	1448	1464	1492	1505	1516	1522	1524		
	1100	866	866	866	866	866	866	866	866	866	866	866	925	1124	1230	1334	1377	1435	1445	1453	1464	1469		
	1000	697	697	697	697	697	697	697	697	697	697	697	697	863	1110	1161	1209	1268	1314	1357	1405	1432		
	900	555	555	555	555	555	555	555	555	555	555	555	555	555	808	1073	1111	1119	1162	1186	1218	1245		
	800	447	447	447	447	447	447	447	447	447	447	447	447	447	447	447	695	936	1073	1097	1111	1115	1119	
	700	260	260	260	260	260	260	260	260	260	260	260	260	260	260	260	260	260	809	905	1016	1069	1082	
	600	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	491	684	734	817	863
	500	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	445	509	609	679
400	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	357	445	458	
300	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	260	355	
200	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	49	
100	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	

475

### 5.3 Soil moisture behavior in HYMOD and IHACRES

As presented in the previous sections, the two conceptual hydrological models, HYMOD and IHACRES, have different structures and here an attempt has been made to highlight the similarities and differences in the models. The soil moisture accounting module of HYMOD uses Pareto distribution function of storage elements of varying sizes. The storage elements of the catchment are distributed according to a probability density function defined by the maximum soil moisture storage  $C_{max}$  and the distribution of soil moisture store  $b_{exp}$  (Wagner et al., 2001). On the other hand, IHACRES model utilizes a threshold parameter ( $I$ ) and a nonlinear relationship (power law with exponent parameter  $p$ ) between the soil moisture index and the fraction of rainfall that becomes effective rainfall. Note that unlike HYMOD, the soil-water storage capacity parameter is not explicitly considered. It was found that there were positive and comparable behavior changes in the soil moisture parameters of hydrological models, HYMOD and IHACRES. As illustrated in Figure 14, the cross correlations between the simultaneously estimated soil moisture parameters were found to be similarly symmetrical about the 0.6. A noticeable difference in the time series is that an upper limit is encountered in HYMOD, due to the parameter associated with the soil moisture capacity. Moreover, as discussed in previous section, the warm-up period of HYMOD is substantially affected by the maximum soil moisture capacity.

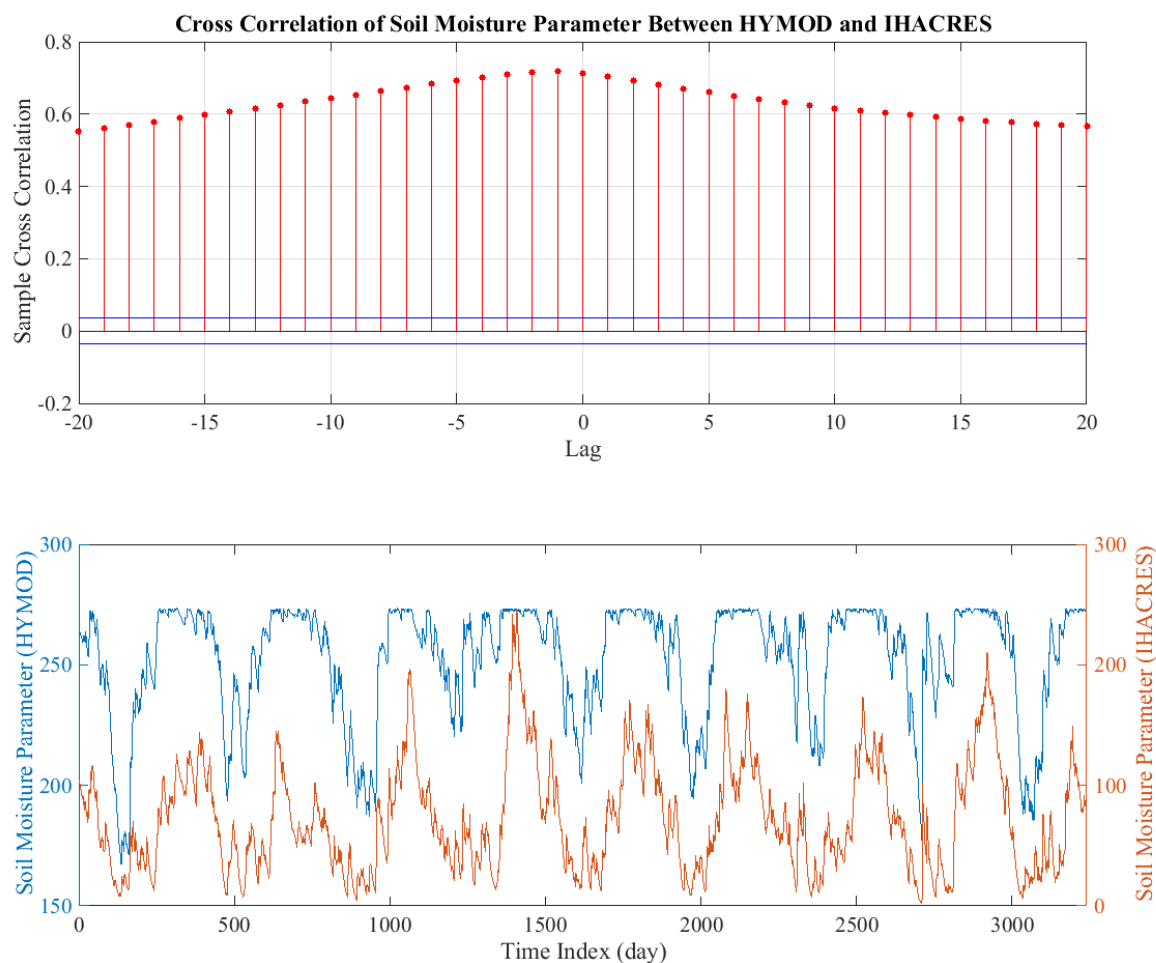


Figure 14. Time series of the estimated soil moisture parameters of HYMOD and IHACRES, and their Cross correlations over lags.

## 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.

522 Acknowledgments

523 The second author was supported by a grant (17AWMP-B127568-01) from the Water Management Research  
524 Program funded by Ministry of Land, Infrastructure and Transport of Korean government. The data used in  
525 this study are available upon request from the corresponding author via email (hkwon@jbnu.ac.kr)

526

## References

- Ajami, H., McCabe, M.F., Evans, J.P., Stisen, S., 2014. Assessing the impact of model spin-up on surface water-groundwater interactions using an integrated hydrologic model. *Water Resour Res*, 50(3): 2636-2656.
- Andréassian, V. et al., 2009. Crash tests for a standardized evaluation of hydrological models. *Hydrology and Earth System Sciences Discussions*(13): p. 1757-p. 1764.
- Bell, V., Moore, R., 2000. The sensitivity of catchment runoff models to rainfall data at different spatial scales. *Hydrology and Earth System Sciences Discussions*, 4(4): 653-667.
- Berthet, L., Andréassian, V., Perrin, C., Javelle, P., 2009. How crucial is it to account for the antecedent moisture conditions in flood forecasting? Comparison of event-based and continuous approaches on 178 catchments. *Hydrology and Earth System Sciences Discussions*(13): p. 819-p. 831.
- Boyle, D.P., 2001. Multicriteria calibration of hydrologic models.
- Castillo, V., Gomez-Plaza, A., Martinez-Mena, M., 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. *Journal of Hydrology*, 284(1): 114-130.
- Chen, F., Mitchell, K., 1999. Using the GEWEX/ISLSCP forcing data to simulate global soil moisture fields and hydrological cycle for 1987-1988. *Journal of the Meteorological Society of Japan*, 77(1 B): 167-182.
- Cloke, H. et al., 2003. The effect of model configuration on modelled hillslope-riparian interactions. *Journal of Hydrology*, 279(1): 167-181.
- Cosgrove, B.A. et al., 2003. Land surface model spin-up behavior in the North American Land Data Assimilation System (NLDAS). *Journal of Geophysical Research: Atmospheres*, 108(D22).
- De Goncalves, L. et al., 2006. Toward a South America Land Data Assimilation System: Aspects of land surface model spin-up using the Simplified Simple Biosphere. *Journal of Geophysical Research: Atmospheres*, 111(D17).
- De Vos, N., Rientjes, T., Gupta, H., 2010. Diagnostic evaluation of conceptual rainfall-runoff models using temporal clustering. *Hydrol Process*, 24(20): 2840-2850.
- Gan, T.Y., Biftu, G.F., 1996. Automatic calibration of conceptual rainfall-runoff models: Optimization algorithms, catchment conditions, and model structure. *Water Resour Res*, 32(12): 3513-3524.
- Goodrich, D. et al., 1994. Runoff simulation sensitivity to remotely sensed initial soil water content. *Water Resour Res*, 30(5): 1393-1405.
- Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, 377(1): 80-91.
- Gupta, H.V., Sorooshian, S., Yapo, P.O., 1998. Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information. *Water Resour Res*, 34(4): 751-763.
- Jakeman, A., Hornberger, G., 1993. How much complexity is warranted in a rainfall-runoff model? *Water Resour Res*, 29(8): 2637-2649.
- Jakeman, A., Littlewood, I., Whitehead, P., 1993. An assessment of the dynamic response characteristics of streamflow in the Balquhider catchments. *Journal of Hydrology*, 145(3): 337-355.
- Kim, H., Lee, S., 2014. Assessment of a seasonal calibration technique using multiple objectives in rainfall-runoff analysis. *Hydrol Process*, 28(4): 2159-2173.
- Kim, K.B., Han, D., 2016. Exploration of sub-annual calibration schemes of hydrological models. *Hydrology Research: nh2016296*.
- Kim, K.B., Kwon, H.-H., Han, D., 2016. Hydrological modelling under climate change considering nonstationarity and seasonal effects. *Hydrology Research*, 47(2): 260-273.
- Letcher, R., Schreider, S.Y., Jakeman, A., Neal, B., Nathan, R., 2001. Methods for the analysis of trends in streamflow response due to changes in catchment condition. *Environmetrics*, 12(7): 613-630.
- Littlewood, I., 1999. Improved unit hydrograph characterisation of the daily flow regime (including low flows) for the River Teifi, Wales: towards better rainfall-streamflow models for regionalisation. *Hydrology and Earth System Sciences*, 6(5): 899-911.

- Madsen, H., 2000. Automatic calibration of a conceptual rainfall–runoff model using multiple objectives. *Journal of hydrology*, 235(3): 276-288.
- Minet, J., Laloy, E., Lambot, S., Vanclooster, M., 2011. Effect of high-resolution spatial soil moisture variability on simulated runoff response using a distributed hydrologic model. *Hydrology and Earth System Sciences*, 15(4).
- Moore, R., 1985. The probability-distributed principle and runoff production at point and basin scales. *Hydrological Sciences Journal*, 30(2): 273-297.
- Motovilov, Y. G., L. Gottschalk, K. Engeland, and A. Rodhe. 1999. Validation of distributed hydrological model against spatial observations. *Agric. and Forest Meteorology* 98: 257-277.
- Nash, J., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, 10(3): 282-290.
- Nicótina, L., Alessi Celegon, E., Rinaldo, A., Marani, M., 2008. On the impact of rainfall patterns on the hydrologic response. *Water Resour Res*, 44(12).
- Nikolopoulos, E.I., Anagnostou, E.N., Borga, M., Vivoni, E.R., Papadopoulos, A., 2011. Sensitivity of a mountain basin flash flood to initial wetness condition and rainfall variability. *Journal of Hydrology*, 402(3): 165-178.
- Rodell, M., Houser, P., Berg, A., Famiglietti, J., 2005. Evaluation of 10 methods for initializing a land surface model. *Journal of Hydrometeorology*, 6(2): 146-155.
- Sangati, M., Borga, M., 2009. Influence of rainfall spatial resolution on flash flood modelling. *Natural Hazards and Earth System Science*, 9(2): 575-584.
- Seck, A., Welty, C., Maxwell, R.M., 2015. Spin-up behavior and effects of initial conditions for an integrated hydrologic model. *Water Resour Res*, 51(4): 2188-2210.
- Segond, M.-L., Wheeler, H.S., Onof, C., 2007. The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK. *Journal of Hydrology*, 347(1): 116-131.
- Senarath, S.U., Ogden, F.L., Downer, C.W., Sharif, H.O., 2000. On the calibration and verification of two-dimensional, distributed, Hortonian, continuous watershed models. *Water Resour Res*, 36(6): 1495-1510.
- Shrestha, R., Houser, P., 2010. A heterogeneous land surface model initialization study. *Journal of Geophysical Research: Atmospheres*, 115(D19).
- Sorooshian, S., 1991. Parameter estimation, model identification, and model validation: conceptual-type models, Recent advances in the modeling of hydrologic systems. Springer, pp. 443-467.
- Vivoni, E.R. et al., 2006. Extending the predictability of hydrometeorological flood events using radar rainfall nowcasting. *Journal of Hydrometeorology*, 7(4): 660-677.
- Vrugt, J.A., Gupta, H.V., Bouten, W., Sorooshian, S., 2003. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. *Water Resour Res*, 39(8).
- Wagener, T. et al., 2001. A framework for development and application of hydrological models. *Hydrology and Earth System Sciences Discussions*, 5(1): 13-26.
- Wagener, T., McIntyre, N., Lees, M., Wheeler, H., Gupta, H., 2003. Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis. *Hydrol Process*, 17(2): 455-476.
- Yang, Z., Dickinson, R., Henderson-Sellers, A., Pitman, A., 1995. Preliminary study of spin-up processes in soil-vegetation-atmosphere transfer schemes with the first stage data of PILPS phase 1 (a). *J Geophys Res D*, 100: 16553-16578.
- Zhang, Y., Wei, H., Nearing, M., 2011. Effects of antecedent soil moisture on runoff modeling in small semiarid watersheds of southeastern Arizona. *Hydrology and Earth System Sciences*, 15(10): 3171-3179.

## Supplementary Material

Table S1. The estimated warm-up period with different cut-off thresholds for HYMOD.

Cut-off threshold	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
1.00%	34	34	34	34	178	252	255	257
0.50%	35	35	35	35	217	255	257	257
0.10%	39	39	39	39	255	257	257	257
0.05%	39	39	39	39	255	257	257	257
0.01%	39	39	39	39	255	257	257	257

Table S2. The estimated warm-up period with different cut-off thresholds for IHACRES.

Cut-off threshold	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
1.00%	131	120	116	89	89	116	120	131
0.50%	137	136	131	116	116	131	136	137
0.10%	145	145	138	138	138	138	145	145
0.05%	156	148	145	138	138	145	148	156
0.01%	164	164	161	159	159	161	164	164

**Highlights**

- This study attempts to consider the initial conditions in hydrological modelling.
- Investigated the warm-up period of two conceptual hydrological models.
- Both initial wetness and rainfall amount affect the time required for model warm up.
- Suggested guidelines for defining the initial soil moisture value depending on the model.