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Investigating the impact of calibration timescales on streamflow simulation, parameter sensitivity and model performance for Indian catchments

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ABSTRACT
Hydrological model calibration is a quintessential step in model development, and the time scale of calibration depends on the application. However, the implications of choice of time scale of calibration have not been explored extensively. Here, we evaluate the effect of the time scale of calibration on model sensitivity, best parameter ranges, and predictive uncertainty for three river basins using the Soil and Water Assessment Tool (SWAT) model. Multiple models were set up for three different catchments from southern India. Our results showed that the sensitivity of the parameters, best parameter ranges, and model performance are conditioned on the time scale of calibration. The models calibrated at coarser time scales marginally outperformed the models calibrated at fine time scale in terms of Nash-Sutcliffe efficiency and percentage bias. Transfer of parameters across scales (both from coarse to fine and from fine to coarse) have a general tendency to worsen the model performance in all three catchments, with few exceptions.

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1 Introduction

Hydrological models are essential tools for various purposes, such as understanding the water balance, estimating the impacts of anthropogenic activities, designing watershed management strategies, and flood warning and risk reduction (Zanon *et al.* 2010, Sleziak *et al.* 2015, Wu *et al.*, 2017). Hydrological models are generally classified into black-box models, conceptual models, and physics-based models (Beven and Freer 2001). Notwithstanding the type of model, their application requires calibration, i.e. estimating the model parameters so that the model closely matches the behaviour of the real system it represents (Gupta and Sorooshian 1998). Some parameters can be determined through field measurements; however, most model parameters (particularly for conceptual and black-box models) need to be estimated through calibration. In most cases, this is done by adjusting the important model parameters so that simulated and observed streamflow agree sufficiently well. Calibration methods can be classified into trial-and-error and automatic procedures. The former involves numerous trial runs with different parameter values for reducing the error between simulation and observed data. Auto-calibration uses mathematical methods, such as optimization, to find the optimal parameter set (Abbaspour 2013). The trial-and-error method becomes highly cumbersome and complex when there are numerous parameters, and it is highly subjective. In this case, auto-calibration is more efficient and effective (Madsen 2000, Getirana 2010).

Generally, auto-calibration involves estimating the best parameter values for the sensitive parameters by minimizing the objective function, which measures the closeness of the model to the observed data at a specified time and spatial scale. One of the crucial factors in model calibration is the temporal scale, i.e. the temporal resolution at which the simulations are compared with the observations. Using a conceptual model, various researchers suggested that the model should be calibrated at the computational time scale, i.e. at the time scale at which it is operated. However, models are frequently calibrated at coarser time scales, owing to (i) the lack of fine time scale data for calibration (for example, the daily streamflow data is not made available to the public for certain important rivers); (ii) model-driving input data may not be robust (for example, the climate model simulations that drive the hydrological models are less accurate at daily scales); (iii) the simulations are often required at coarser time scales, e.g. monthly or yearly simulations are desired for planning studies; and (iv) calibration at coarser time scales is computationally less intensive (Sudheer *et al.* 2007, Wang *et al.* 2009). Example studies include Novotny and Stefan (2007), Da Silva *et al.* (2017), Setti *et al.* (2018), and Lotz *et al.* (2018) where the model is calibrated at the coarser time scale, but the model simulation and result analysis is performed at a finer scale. This approach indirectly assumes that models mimic the process dynamics even at a smaller time step than the one they have been calibrated for. Even though this assumption is acceptable as long as the model is used simultaneously, the model results cannot be extended to other lower scales without

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Supplemental data for this article can be accessed here

investigation. The Soil and Water Assessment Tool (SWAT), a popular model, works at daily time steps, but a large fraction of studies perform calibration at the monthly time scale (White and Chaubey 2005, Adla *et al.* 2019, Lerat *et al.* 2020). Adla *et al.* (2019) identified more than 500 papers using SWAT that assume that a good performance at one time scale will translate into a similar performance at other time scales.

Several studies (Finnerty *et al.* 1997, Littlewood and Croke 2008, Cho *et al.* 2009, Wang *et al.* 2009, Remesan *et al.* 2010, Kavetski *et al.* 2011, Reynolds *et al.* 2018) have investigated the influence of the time scale of the input data on model parameters and model performance. However, the effect of the calibration time scale remains poorly understood, as very few studies have investigated this effect. One such study was carried out by Sudheer *et al.* (2007), who concluded that the model's performance could not be ensured at a finer time scale (such as daily) by calibrating at the monthly time scale. Troy *et al.* (2008) studied the impact of transferring parameters across scales using the Variable Infiltration Capacity (VIC) model and concluded that it is possible to calibrate at coarser time steps to save computational time. Daggupati *et al.* (2015) evaluated the parameter transfer across spatial and temporal scales for the West Lake Erie Basin and found that transferring parameters from monthly to yearly and daily time steps performed well. On the other hand, Adla *et al.* (2019) reported that the SWAT model calibrated at the monthly scale failed to characterize the streamflow simulation at the daily time scale for the Punpun River Basin, India. The results from some of the prior studies (Sudheer *et al.* 2007, Duggupart *et al.* 2015, Adla *et al.* 2019) suggest that there is a deterioration in coarse to fine transition, but these studies were based on one catchment and the analyses considered only transfer across daily and monthly scales.

Apart from the above studies on parameter transfer from one scale to another, researchers (Atkinson *et al.* 2002, Reusser *et al.* 2011, Herman *et al.* 2013, Xie *et al.* 2017) have investigated parameter sensitivity with time and have shown that model parameter sensitivities changes through time; this provides a basis for the present study in understanding how parameters are scale dependent.

In this study, three river basins of various sizes and characteristics are considered to address the following questions: (i) How does the time scale of calibration affect the sensitivity, the model parameters, and the streamflow prediction? (ii) Can we transfer the parameters calibrated at one time scale to other time scales for the simulation? The answers to these questions can be very useful for regions where data at a fine temporal scale is scarce (in terms of both availability and quality).

To understand the impact of time scale on calibration and the implications of parameter transfer on model performance, we have considered the most widely used hydrological model, SWAT, which performs water budgeting daily, but in general, calibrated at a monthly or yearly time scale. Adla *et al.* (2019) report that most studies (around 50%) calibrate the model at a monthly scale and do not report the results of daily calibration and validation statistics. Therefore, most studies inherently assume the model performing well at a coarse scale will perform well at a finer scale also. Further, it is also interesting to understand how the transfer of parameters from a finer scale to a coarser scale will be applicable in situations where the fine-scale streamflow data is only available for a certain time period. Therefore, to evaluate whether parameters obtained by calibration at one time scale can be transferred to other time scales, we applied the SWAT model for three watersheds in India, namely Vamshadhara, Kagna, and Kharkai, at three time scales (daily, monthly, and yearly) and developed different scenarios to study the changes in parameters across time scales.

2 Material and methods

2.1 Study area

We selected three river basins from the southern part of the Indian sub-continent for this study. These basins were selected for the following reasons: (i) past studies at these basins using the SWAT model have reported good performance in terms of streamflow simulation, (ii) there is no significant impact on the hydrological systems in terms of water resources infrastructure and diversions upstream of gauging points, (iii) the three selected basins have similar hydroclimate gradients but different land uses and human influence, and (iv) the catchments differ in size.

The Vamshadhara River Basin, with an area of 10 448 km^2, is located between the Godavari and Mahanadi major river basins in Southeast India (Fig. 1) and is located at the geographical coordinates of 18°20′59”N latitude and 84°07′59”E longitude. The Vamshadhara River originates in the Kalahandi district of Odisha state and flows around 254 km before joining the Bay of Bengal at Kalingapatnam, Andhra Pradesh. The Vamshadhara River Basin receives an average annual rainfall of 1400 mm, with 75% of the rainfall falling during the southwest monsoon months of June to September. Of the basin's total area, 78% is covered by forest and 20% by irrigated crops. Figure 2 shows the topography, the spatial distribution of land use and soils, and the location of the Kasinagar gauge station used for calibration and validation. The river basin is covered by clay soils (67%) and loam soils (34%).

The Kharkai Watershed is located in the Subarnarekha River Basin near Jamshedpur town. It covers an area of 6267 km^2 area at 21°59′56”N latitude and 86°25′29”E longitude. The Kharkai River originates at Gobardhansahi village of Mayurbhanj and flows through Jharkhand and Odisha states. The average annual rainfall is 1400 mm, of which 79% is received in the monsoon months. Major land-use/land-cover classes are forest (41%) and irrigated crops (57%). The watershed is covered by clay soils (43%), loam soils (38%), and sandy-clay-loam soils (19%). The calibration discharge gauge is Adityapur (Fig. 2).

The Kagna Watershed, with an area of 1909 km^2, is located in the Krishna River Basin and near Tanuru Mandal of Telangana state at 17°01′3”N latitude and 77° 57′30”E longitude. It receives an annual rainfall of around 800 mm, with 80% during the monsoon months. In terms of its total area, 73% is covered by clay soils and 27% by clay-loam. The majority of land use/land cover classes are irrigated crops (82%) and forest (12%). We used the Lewangi gauge discharge data for model calibration and validation (Fig. 2).

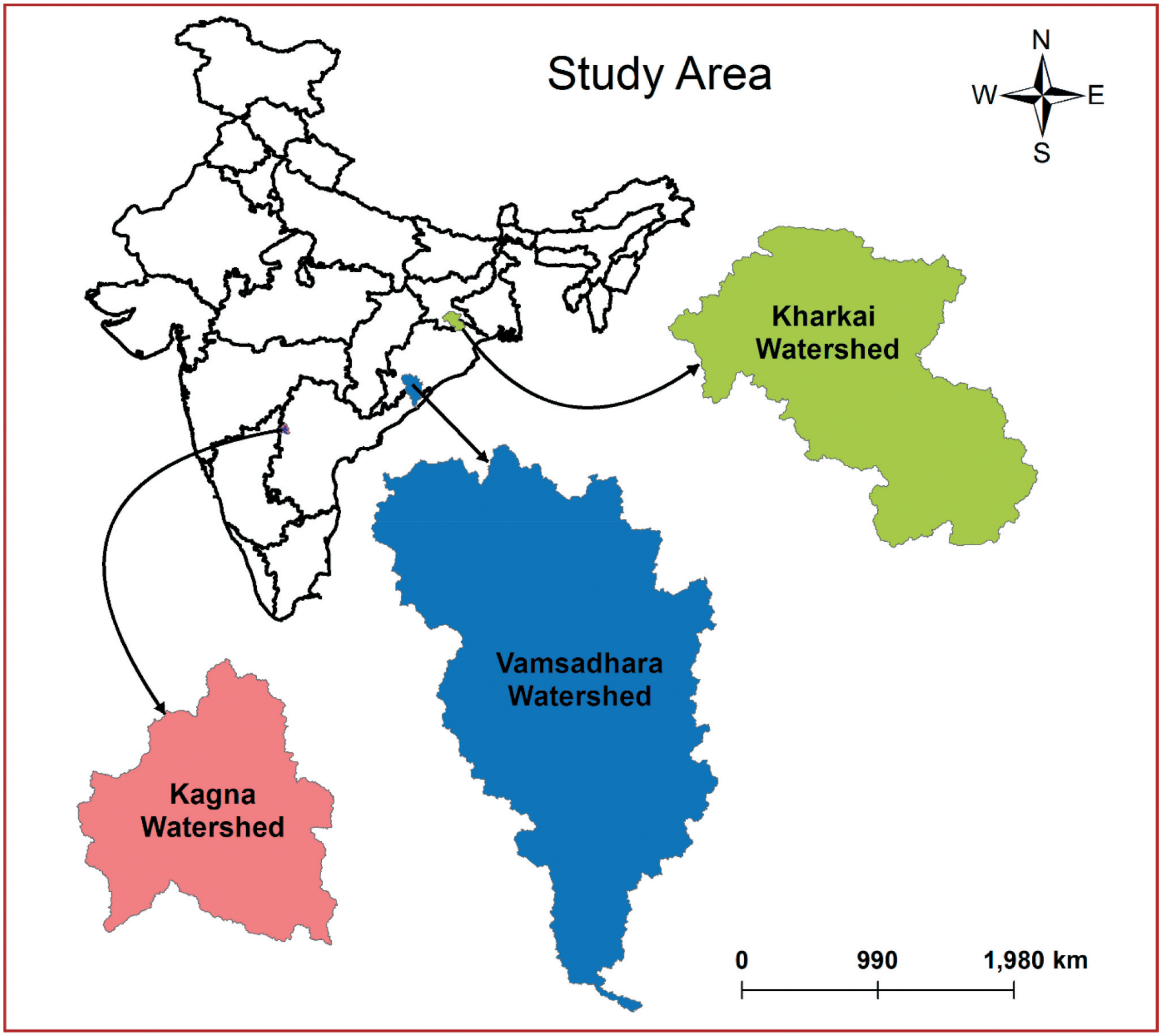

Figure 1. Index map showing the geographical location of the three catchments, namely Vamsadhara, Kharkai, and Kagna.

Spatial data, i.e. digital elevation models, land use/land cover, soil properties, and temporal data, i.e. gauge discharge and meteorological data, were used as input for the SWAT model and the detailed source of each dataset is given in Table S1 (in the Supplementary material).

2.2 SWAT model

SWAT is a continuous and semi-distributed hydrological model. It was developed by the Agricultural Research Service of the United States Department of Agriculture (USDA-ARS) (Arnold *et al.* 1998, 2012) to assist water resources management and planning. SWAT requires input data like weather, topographical, soil properties, land use, and land cover information to simulate the surface runoff and sediment yield of the river basin at daily time steps, using the water balance equation (Neitsch *et al.* 2002):

$$SW_t = SW_O + \sum_{i=1}^{t}(R_{day,i} - Q_{surf,i} - E_{a,i} - W_{seep,i} - Q_{gw,i}) \quad (1)$$

where SWt denotes the final soil water content (in mm), SW_o represents the initial soil water content on day *i* (in mm H_2O), and *t* represents the simulation period (in days). $Q_{surf,i}$, $R_{day,i}$, and $E_{a,i}$ denote the amount of surface runoff, precipitation, and evapotranspiration, respectively, on day *i*(in mm H_2O). $Q_{gw,i}$ and $W_{seep,i}$ represent the amount of groundwater return flow and percolation, respectively, on day *i* (in mm H_2O).

The SWAT model simulates canopy storage, infiltration, surface runoff, lateral subsurface flow, percolation, groundwater flow, soil water content, evapotranspiration, pond recharge, snowmelt, and transmission losses (Spruill *et al.* 2000a, Arnold *et al.* 2012). Surface runoff can be modelled by (i) The Chemicals, Runoff, and Erosion from

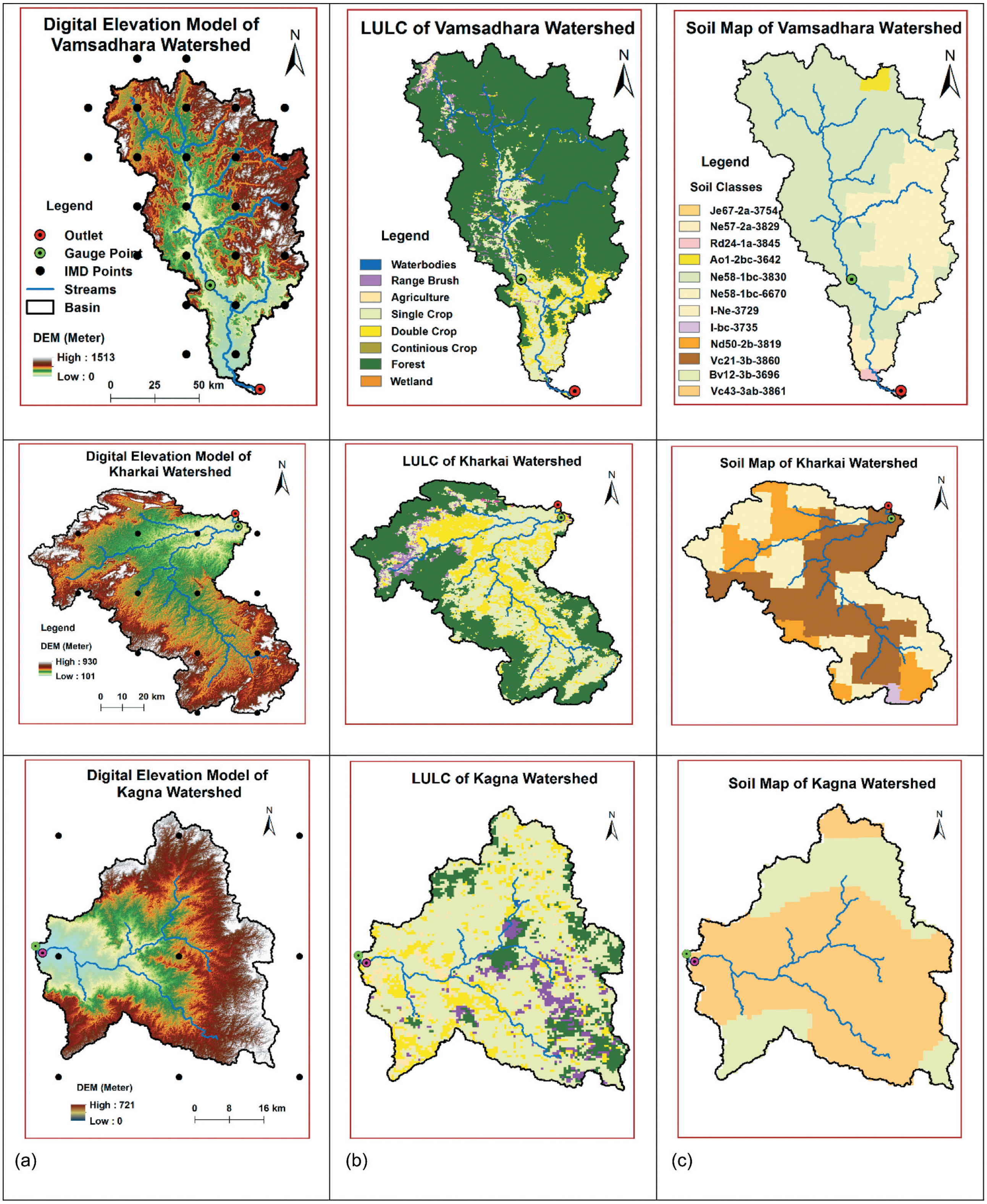

Figure 2. (a) Topography, (b) land use/land cover, and (c) soil classes for the three watersheds: Vamsadhara, Kharkai and Kagna.

Agricultural Management Systems (CREAMS) runoff model (Knisel 1980), which includes the Soil Conservation Service (SCS) curve number (CN) method; (ii) the Green and Ampt infiltration method or (iii) the modified rational formula method. In this study, we derived surface runoff from the SCS-CN method:

$$S = 254\left(\frac{CN}{100}\right) - 1 \qquad (2)$$

where S represents the retention parameter (in mm), and CN is the curve number, which depends on the soil, land use, and soil moisture conditions. Since the CN method is an infiltration loss model that does not account for evaporation and evapotranspiration, its use was restricted to modelling storm losses. However, the parameter S should be linked with the soil moisture accounting module for continuous streamflow simulation. The SWAT model links S with available soil moisture and using the CN method for continuous simulation.

Manning's formula is used to estimate the watershed time of concentration (considering both overland and channel flow). SWAT uses a storage routing technique to model the percolation and flows through each soil layer in the root zone (Spruill *et al.* 2000a), and also calculates lateral subsurface flow and recharge beyond the lowest soil layer. In SWAT, the plant growth model is used to estimate water and nutrient uptake from the root zone, transpiration, and bio-mass production (Arnold *et al.* 2012). SWAT provides three options for estimating the potential evapotranspiration (PET): the Hargreaves method (Hargreaves and Samani 1985), the Priestley Taylor method (Priestley and Taylor 1972), and the Penman-Monteith method (Monteith 1965). In this study, we applied the Penman-Monteith method. Groundwater flow is estimated by routing the shallow aquifer storage to the streams (Arnold *et al.* 1993). We used the QGIS interface (QGIS 2.6.1) and SWAT 2012 to process the input data and run the model, respectively. A detailed description of the different hydrological processes and the corresponding model parameters are shown in Table S2.

2.3 Model set-up

The streams and the sub-basin boundaries were delineated by adopting a minimum sub-basin area of 100 km^2. Each sub-basin was further disaggregated into several hydrological response units (HRUs) based on a unique combination of soil properties, land use/land cover classes, and slope (Gassman *et al.* 2012). This resulted in 26 sub-basins and 1460 HRUs, 20 sub-basins and 500 HRUs, and 14 sub-basins and 300 HRUs for Vamsadhara, Kharkai, and Kagna watersheds, respectively. Based on the cropping pattern in each of these watersheds, the model's management options were modified accordingly. Apart from minor variations, the main crops in the three watersheds were paddy and pulses during the summer and winter cropping seasons, respectively.

2.4 Performance measures

We used the coefficient of correlation (Willmott 1981), the Nash-Sutcliffe efficiency coefficient (NSE; Nash and Sutcliffe 1970), and percent bias (Pbias) (Yapo *et al.* 1996) to evaluate the streamflow simulations:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{mean}^{obs} \right)^2} \right] \quad (3)$$

$$NSE = 1 - \left(\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{mean}^{obs} \right)^2} \right) \quad (4)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{\mathrm{n}} \left(y_i^{obs} - y_i^{sim} \right) \mathrm{X100}}{\sum_{i=1}^{\mathrm{n}} \left(y_i^{obs} \right)} \right] \quad (5)$$

Here, Y_i^{obs} and Y_i^{sim} denote the *i*th observed and simulated data points, respectively; Y_{mean}^{obs} is the mean of the observed data during the simulation period; and n denotes the number of observations. For both criteria, values close to 0 indicate unsatisfactory model performance. If NSE and R^2 are close to 1, then the model is ideal. The ideal value for Pbias is zero; if Pbias is negative, the simulated streamflow overestimates the observed streamflow; if it is positive, the model is an underestimation. These performance measures were applied at different time steps – daily, monthly, or annual – thus allowing calibration across temporal scales.

2.5 Sensitivity analysis

Sensitivity analysis is employed to identify the most important model parameters, reducing the number of parameters used in the calibration process (Arnold *et al.* 2012). It can be divided into two types: local and global sensitivity analysis (Abbaspour 2015). Local sensitive analysis (one at a time – OAT) is limited as it does not consider the simultaneous variation of parameters and thus cannot represent interactions between parameters. Hence, we used a global sensitivity analysis (all at a time – AAT) which typically leads to more robust results (Arnold *et al.* 2012). Here we estimate the parameter sensitivity using the multiple regression system, which regresses the Latin hypercube-generated parameters against the objective function values as shown in Equation (6):

$$h = a + \sum_{j=1}^{m} b_j \gamma_j \quad (6)$$

where h is the objective function value (in this study NSE (Equation 3) is used), γ_j indicates the parameter vector, a is the regression constant, and b is the regression coefficient vector. The sensitivities obtained to estimate the average changes in the objective function result from changes in each parameter, while all other parameters are changing (Abbaspour 2015). It is important to note that the above method does not consider the interaction between the model parameters such as those possible in the SOBOL method, which can be explored in future studies.

A *t*-test is used for estimating the relative significance of the parameter γ i (Abbaspour *et al.* 2007). The *t*-statistic is obtained by dividing the coefficient of a parameter by its standard error. It measures the precision with which the regression coefficient is measured. If the coefficient value is large compared to its standard error, the value will be different from zero, and the parameter is sensitive (Abbaspour 2015). The smaller the *p* values and the larger the *t*-test absolute values, the more sensitive is the parameter.

2.6 Model calibration and validation

We used an auto-calibration procedure performed by applying the Sequential Uncertainty Fitting Algorithm Version 2 (SUFI-2) of the SWAT-CUP (SWAT Calibration and Uncertainty

Programme) software. The procedure accounts for interactions between calibration parameters, as it assesses the performance of parameter sets and not the performance of individual parameters during the calibration. The SUFI-2 procedure results in the best range of parameters rather than individual values (Abbaspour *et al.* 2004). The propagation of the uncertainties in the parameters leads to the uncertainties in the model output (here, streamflow), expressed as 95% probability distributions (95-PPU). The 95-PPU has estimated at the 2.5% and 97.5% levels of the output variable obtained from the n simulations using the n set of parameters. The resulting 95-PPU envelope is the output obtained from the SUFI approach. The P-factor and R-factor measure the fit between the observed data and the output from SUFI (expressed in terms of 95-PPU).

The P-factor indicates the fraction of the observed data falling within the 95% confidence limits. For instance, a P-factor of 1 indicates that 100% of the observed data fall within the 95% band. The R-factor indicates the average width of the 95-PPU band. It is calculated as the average 95-PPU thickness divided by the standard deviation of the corresponding observed variable (Abbaspour 2015). Theoretically, the P-factor ranges from 0 to 1, and the R-factor ranges from 0 to ∞. A simulation with P-factor = 1 and R-factor = 0 corresponds exactly to the observed data. The extent to which the values of the P-factor and R-factor are near to these numbers will help us understand the calibration level. The larger value of the P-factor will be achieved at the cost of the R-factor. While we would like to capture the observed data within the 95-PPU, we would like to have a small uncertainty envelope; therefore, a compromise between the two is required. The SUFI algorithm performs several iterations, and in each iteration, the parameter ranges get narrower, zooming on the region of the parameter space, where the previous iteration obtained good results.

As a consequence, the 95-PPU becomes smaller, resulting in a smaller P-factor and R-factor. Generally, R-factor values near 1.5 are considered satisfactory (Abbaspour 2013). When satisfactory P- and R-factors are obtained, the final parameter ranges are defined as the best ranges (for details, see Abbaspour *et al.* 2007). This study has chosen the NSE (Yang *et al.* 2016) as the objective function (for Equation 6) for calibrating the models and R^2 and Pbias for model assessment of calibrated models.

Since discharge data was not available for a common time window at all three catchments, we have adopted different windows for calibration and validation for the different catchments (Table 1). The time windows are selected based on the availability of continuous discharge data. We have divided the entire time period into three parts – warm-up period, calibration period, and validation period – for the three watersheds based on available discharge data (as shown in Table 1).

Table 1. Time windows used for calibration and validation.

Watershed	Gauge location	Warm-up period	Calibration period (validation period)
Vamsadhara	Kasinagar	1979–1981	1982–2000 (2001–2010)
Kharkai	Adityapur	1982–1984	1985–2000 (2001–2010)
Kagna	Jewangi	1979–1981	1982–1992 (1993–2000)

Table 2. Details of the different model scenarios generated in this study to evaluate the impact of the calibration time scale for the three watersheds.

Scenario	Remark
D	Self-validation at daily time scale
M	Self-validation at monthly time scale
Y	Self-validation at yearly time scale
DM	Model calibrated at daily time scale then validated at monthly time scale
DY	Model calibrated at daily time scale then validated at yearly time scale
MD	Model calibrated at monthly time scale then validated at daily time scale
MY	Model calibrated at monthly time scale then validated at yearly time scale
YD	Model calibrated at yearly time scale then validated at daily time scale
YM	Model calibrated at yearly time scale then validated at monthly time scale

2.7 Impact of time scale on calibration and parameter transfer scenarios

To the answer the two research questions raised above, we developed nine parameter transfer scenarios (D, M, Y, DM, DY, MD, MY, YD, YM) as shown in Table 2. The SWAT model was calibrated using daily, monthly, and yearly streamflow data, denoted as D, M, and Y, respectively. Then these calibrated models were validated at these three time scales, creating nine scenarios, as shown in Table 2. We followed two-letter notations for each scenario, wherein the first letter denotes the scale of calibration and the second letter the scale of validation. For example, DY denotes a model calibrated at the daily scale and applied at a yearly time scale for validation.

3 Results and discussion

The results and subsequent discussion in Sections 3.1 to 3.3 would answer the following question: How does the time scale of calibration affect the sensitivity analysis, the model parameters, and the streamflow prediction?

3.1 Parameter sensitivity

We analysed the sensitivity of the model response, i.e. catchment runoff, to variations in 18 parameters (Table S2). These parameters were selected based on the previous literature (Murty *et al.* 2014, Narsimlu *et al.* 2015, Abbaspour *et al.* 2017). The initial parameter range was obtained from the SWAT database and is consistent with the physics of the process modelled. Using the global sensitivity analysis approach, we determined the sensitivity of these parameters and the corresponding ranks when calibrated at the three time scales for each watershed (Table 3).

Significant variations in the sensitive parameter ranking at each time scale and for each watershed can be observed. The ranks are highly dependent on the calibration time scale. For example, soil evaporative demand (ESCO) was a dominant parameter for all watersheds at the yearly and monthly time scale but not at the daily scale. In contrast, the alpha baseflow factor (ALPHA_BF) was one of the sensitive parameters in all watersheds at daily and monthly time scales but not at the

Table 3. Results of sensitivity parameter rank and p(t) values for Vamsadhara, Kharkai and Kagna watersheds corresponding to three time scales during 1979–2010.

S. no.	Parameter name	Vamsadhara						Kharkai						Kagna					
		Daily		Monthly		Yearly		Daily		Monthly		Yearly		Daily		Monthly		Yearly	
		R	p(t)	R	p(t)	R	p(t)	R	p(t)	R	p(t)	R	p(t)	R	p(t)	R	p(t)	R	p(t)
1	1:V__ESCO.hru	7	0.00(−4.61)	2	0.00(−5.81)	1	0.00(−29.44)	15	0.73(−0.34)	2	0.00(−2.97)	5	0(−8.53)	8	0(−3.11)	2	0(−6.51)	1	0(−9.74)
2	15:R__CN2.mgt	1	0.00(−18.84)	12	0.38(−0.89)	2	0.00(−16.27)	4	0(20.24)	1	0.00(30.99)	1	0(21.76)	7	0(−3.51)	3	0(−5.06)	2	0(4.58)
3	5:V__SLSUBBSN.hru	6	0.00(5.94)	10	0.14(1.49)	3	0.00(6.88)	6	0(−15.4)	5	0.00(−2.83)	7	0(−3.35)	4	0(−12.52)	17	0.96(−0.05)	8	0.37(0.9)
4	4:R__SOL_AWC(.).sol	14	0.04(2.09)	6	0.01(2.61)	4	0.00(6.04)	10	0.19(1.3)	17	0.39(0.86)	12	0.89(−0.14)	16	0.53(0.63)	8	0.09(1.7)	4	0(3.56)
5	3:V__HRU_SLP.hru	8	0.00(−3.92)	8	0.10(−1.64)	5	0.00(−6.08)	7	0(12.64)	3	0.00(3.35)	4	0(6.1)	6	0(6.24)	13	0.39(0.85)	13	0.63(0.48)
6	9:V__OV_N.hru	16	0.19(1.31)	13	0.45(−0.76)	6	0.04(−2.06)	5	0(−15.96)	9	0.69(0.4)	17	0.24(−1.19)	3	0(−12.65)	12	0.38(−0.88)	11	0.44(0.78)
7	7:V__EPCO.hru	15	0.10(1.66)	18	0.97(0.03)	7	0.08(1.75)	17	0.93(0.09)	15	0.1(1.66)	8	0.81(0.24)	15	0.49(0.7)	7	0.04(2.03)	5	0(3.54)
8	14:V__SURLAG.bsn	5	0.00(−9.97)	15	0.73(0.35)	8	0.41(0.83)	13	0.65(−0.45)	16	0.49(0.69)	15	0.83(0.21)	14	0.48(0.71)	16	0.94(−0.08)	18	0.97(−0.04)
9	12:V__CH_K2.rte	2	0.00(14.09)	7	0.01(−2.50)	9	0.39(−0.86)	2	0(−32.92)	12	0.00(−4.06)	3	0.35(0.93)	1	0(−37.65)	6	0.03(−2.19)	10	0.43(−0.78)
10	6:V__RCHRG_DP.gw	9	0.00(3.26)	1	0.00(−9.01)	10	0.32(1.04)	16	0.9(−0.13)	4	0.21(1.25)	11	0(5.24)	11	0.24(−1.17)	5	0.02(−2.35)	3	0(−3.9)
11	2:V__LAT_TTIME.hru	10	0.00(3.15)	16	0.81(−0.24)	11	0.21(1.25)	9	0.15(−1.43)	11	0.19(−1.32)	10	0.33(0.97)	13	0.34(0.95)	11	0.33(0.97)	17	0.97(−0.04)
12	16:V__ALPHA_BF.gw	3	0.00(−12.53)	3	0.00(5.69)	12	0.94(0.07)	1	0(46.91)	7	0.00(25.63)	2	0.19(1.32)	2	0(19.67)	1	0(19.74)	6	0.03(2.15)
13	10:V__GW_REVAP.gw	13	0.02(2.35)	5	0.01(2.80)	13	0.42(−0.81)	14	0.67(0.43)	6	0.4(−0.83)	13	0(−3.01)	9	0.1(−1.67)	9	0.1(−1.65)	16	0.85(0.19)
14	11:V__CH_N2.rte	4	0.00(11.68)	11	0.22(1.22)	14	0.33(−0.97)	3	0(−21.05)	13	0.00(−2.83)	6	0.44(−0.76)	5	0(−11.91)	4	0(−4.04)	7	0.1(−1.67)
15	18:V__GWQMN.gw	12	0.02(2.43)	4	0.00(3.95)	15	0.59(0.55)	11	0.3(1.05)	8	0.59(0.54)	16	0.23(−1.2)	10	0.2(−1.29)	15	0.92(0.1)	9	0.4(0.85)
16	13:R__SOL_K(.).sol	17	0.20(1.29)	9	0.13(1.53)	16	0.73(−0.35)	18	0.99(0.01)	18	0.45(0.76)	14	0.93(−0.09)	12	0.33(0.98)	10	0.17(1.36)	12	0.54(0.61)
17	17:V__GW_DELAY.gw	11	0.01(2.65)	17	0.94(0.08)	17	0.30(1.04)	12	0.59(0.54)	10	0.94(−0.07)	18	0.26(−1.14)	17	0.76(−0.3)	14	0.69(−0.39)	14	0.69(0.4)
18	8:V__REVAPMN.gw	18	0.86(0.17)	14	0.60(−0.52)	18	0.70(0.39)	8	0.13(1.51)	14	0.11(1.61)	9	0.71(−0.37)	18	0.87(0.17)	18	1(0)	15	0.79(−0.26)

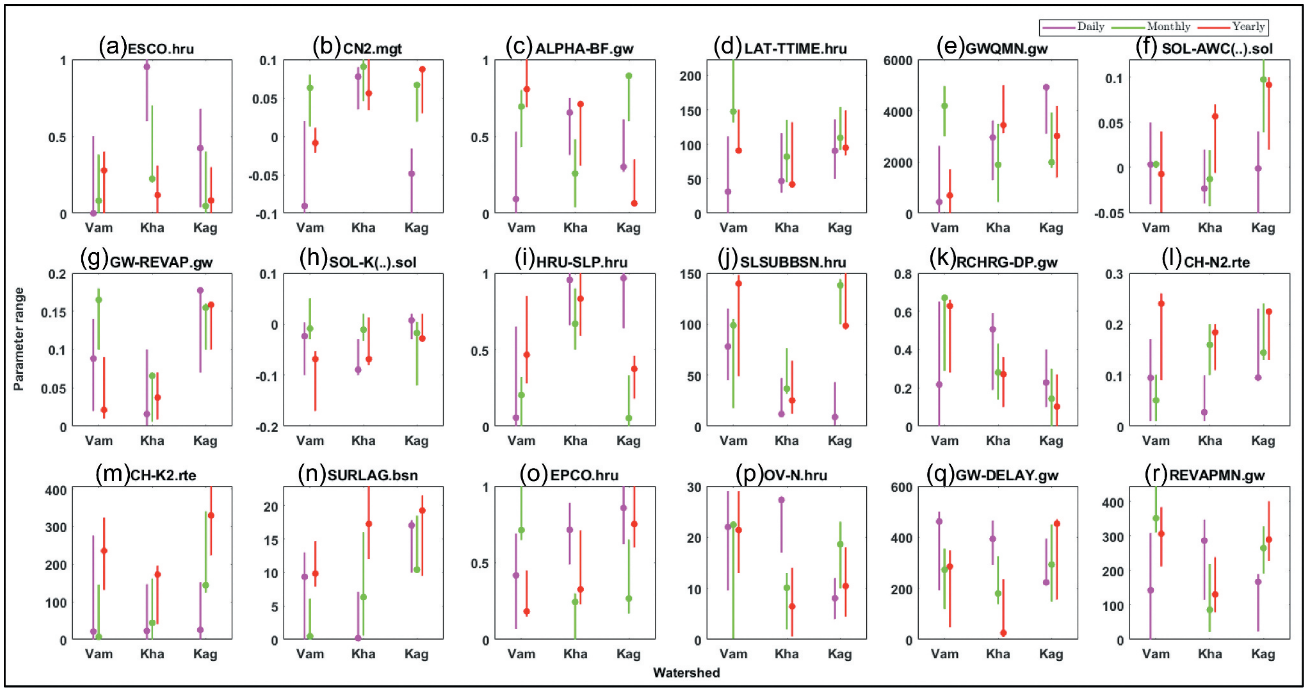

Figure 3. Best parameter values and best parameter ranges resulting from the calibration at different time scales for Vamsadhara, Kharkai, and Kagna watersheds using an auto-calibration procedure by applying the Sequential Uncertainty Fitting Algorithm Version 2 (SUFI-2). Lines and dots represent the best parameter range and best-fitted values, respectively.

yearly time scale. There is also variation between watersheds. For instance, for the Vamshadara River Basin, the curve number (CN2) was sensitive only at the daily and yearly time scales.

On the other hand, for the Kharkai basin, CN2 was sensitive at all time scales. Overall, the results suggest a significant impact of the calibration time scale on the parameter sensitivity. However, there is no clear pattern emerging from the results for these three watersheds.

3.2 Best parameter range

The calibration using the SUFI-2 optimization algorithm starts with a wide parameter range and ends with a narrower range, i.e. the best parameter range. We have used 18 parameters for calibration of the model. For the first iteration, the parameter uncertainty is expressed by a uniform distribution. The optimal parameter value and the best parameter ranges resulting from the calibration at different time scales varied significantly (Fig. 3). An analysis of some of the parameters that directly affect the water balance is given below.

3.2.1 ESCO

For the Vamsadhara River Basin, the best ESCO parameter values range between 0 and 0.5. ESCO is the coefficient that can be used to alter the depth distribution which is linked with the evaporative demand. The lower the values of ESCO, the deeper the layers that can contribute to the evaporation, resulting in more evaporation and a decrease in streamflow. From the results, the best parameter values were lower for daily and higher for monthly and yearly time scales, indicating the fine-scale model allows evaporation from deeper levels of soils than the models at monthly and yearly scales.

In the Kharkai River Basin case, there is a significant difference between the best parameter and the range of ESCO values. The daily scale values are close to 1, indicating lower evaporative demand, and the monthly and yearly scale values were close to 0.2, indicating higher demand. For the Kagna River Basin, daily scales values are higher than the coarser time scales, indicating the lower demand.

The difference in the ESCO values can be attributed to the idea that when we calibrate a hydrological model at coarse time steps, say monthly or annual, the model only needs to reproduce the total streamflow correctly and the overall water balance. This would not give importance to variations of the other processes, such as evapotranspiration. Further, the difference in the pattern across the catchments can be attributed to the corresponding dominant land use and land cover. For example, the Vamshadara River Basin covered by forests (80%) allows higher evaporative demand from deeper soil layers. In contrast, Kagna is dominantly covered by agricultural land (75%), which allows lower evaporative demand from the deep soil layers.

3.2.2 CN2

CN2 is an important parameter as it directly controls the amount of excess runoff generated and its travel through the system. The values in Fig. 3b represented the percentage increase or decrease concerning the initial CN value. For example, 0.1 indicates a 10% increase in the CN in comparison with the initial value. In the Vamsadhara watershed, the values are in the low range (−0.1 to 0.02) at daily calibration, 0.0–0.07 at monthly calibration and −0.02 to 0.01 at yearly calibration. The decrease in the CN2 value from the default value shows that the model allowed more surface runoff. In the case of Kharkai, the range of CN2 is similar at daily, monthly, and yearly calibrations, and the range is positive, indicating the model underestimated the runoff at all three windows. For the Kagna watershed, the range of CN2 is similar for both monthly and yearly calibration; however, the range of CN2 is different and negative in the daily calibration, which indicates that the model overestimates the surface runoff at the daily scale.

3.2.3 ALPHA-BF

The ALPHA-BF has a smaller value for the Vamsadhara River Basin than in the monthly and yearly calibration, indicating a quicker baseflow recession at the coarse scale than in the daily calibrated model. For the Kharkai watershed, daily and yearly calibrations have a similar range of parameters, and the values are higher, indicating a quick recession. Still, at the monthly calibration, the range is 0–0.5, indicating the slow movement of baseflow and sustained flow in the river. For the Kagna watershed, the ALPHA-BF is sensitive at daily, monthly, and yearly calibration but has a dissimilar range, indicating the baseflow movement varies at all three time scales.

The results discussed here are directly dependent on the choice of objective function used for calibration and sensitivity analysis. If one was to use NSE on Box-Cox transformed streamflow time series to give equal weight to high and low flows, or any another statistical metric, the results might become quite different.

3.3 Performance of models calibrated at different time scales

The SWAT model was individually calibrated for the three watersheds and the three time scales. The results for the calibration periods are summarized in Table 4 (performance measures) and Figs 4–6 (discharge time series). In general, good to very good results were obtained at all time scales.

The model performance, quantified by R^2 and NSE, improved at coarser time scales for all three basins. It is essential to understand that even while the model is calibrated at coarser scales, SWAT simulates the flow at a daily time step. The daily values are then time-averaged to monthly and annual values, respectively. The improvement can be attributed to this time-averaging, as overestimations may compensate for underestimations and vice versa. Time-delay errors at the daily time scale typically do not play a role at monthly and annual time scales (Adla *et al.* 2019).

Another observation is that the model performance increased with increasing catchment area for all calibration time scales. For instance, NSE at the daily time scale increased from 0.60 for the Kagna watershed (1902 km^2) to 0.63 for the Kharkai watershed (6267 km^2) and 0.75 for Vamsadhara watershed (10 448 km^2). A similar conclusion was drawn by Poncelet *et al.* (2017) and Merz *et al.* (2009). Using conceptual lumped models on hundreds of catchments in Europe, they found an increase in modelling efficiency with increasing catchment size. Based on the results from a lumped data-driven model, Maheswaran and Khosa (2012) showed that the nonlinearity and complexity of the catchment processes are lower for a larger catchment due to damping effects.

Interestingly, the improvement in model performance with spatial scale has been observed for very different modelling concepts, from lumped data-based (Maheswaran and Khosa 2012) through lumped conceptual-model-based (Merz *et al.* 2009, Poncelet *et al.* 2017) to semi-distributed process-based (our study). However, when we compare the uncertainty (P- and R-factors) in the simulation across the three basins, it is observed that the uncertainty is lower for the Kagna watershed (smallest area, less variability in land use) and higher for the Vamsadhara River Basin (largest area and greater variation in land use). The uncertainty in streamflow simulation seems to be a function of the catchment size and the variability in soil, land use/land cover, and topography. Hence, although larger catchments tend to have good model performance, they still can show large uncertainties in their estimations.

The P-factor increases for all three catchments from the finer to the coarser time scales. This is explained by the smoother variation of streamflow at coarser time scales; hence, it is easier to capture the variations within the 95-PPU. R-factor values, which represent the thickness of the 95 PPU curves and generally lower values, are desired. The pattern of variation of the R-factor concerning the calibration scale is similar for the three basins considered. For example, for all the basins, the R-value is highest for daily and lowest for monthly. This could be due to the higher levels of uncertainty at the daily calibration scale.

The calibration at different time scales resulted in different sensitive parameters and best parameter ranges. Overall, the model performance in terms of R^2, NSE, P-factor, and R-factor improves when models are calibrated and validated at coarser time scales. This is due to the smaller streamflow variability due to time averaging and the fact that model errors tend to cancel each other out at coarser time scales.

Table 4. NSE, R^2, P- and R-factor values for Vamsadhara, Kharkai, and Kagna watersheds for the calibration period for three time scales.

Watershed/time scale		Daily	Monthly	Yearly
Vamsadhara	R^2	0.77	0.9	0.92
	NSE	0.75	0.9	0.91
	Pbias	−31.4	−4.1	−1.7
	P-factor	0.49	0.82	0.95
	R-factor	0.47	0.57	0.91
Kharkai	R^2	0.66	0.86	0.84
	NSE	0.63	0.84	0.79
	Pbias	27.9	−3.1	−0.7
	P-factor	0.65	0.61	0.81
	R-factor	0.11	0.46	0.58
Kagna	R^2	0.65	0.82	0.79
	NSE	0.63	0.79	0.76
	Pbias	19.1	5.2	4.6
	P-factor	0.29	0.2	0.45
	R-factor	0.18	0.17	0.34

3.4 Effect of parameter transfer across time scales

The influence of transferring the best calibration parameter set across time scales is summarized in Table 5 for the nine transfer scenarios. The results and subsequent discussion answer the following question: Can we transfer the parameters calibrated at one time scale to other time scales for the simulation?

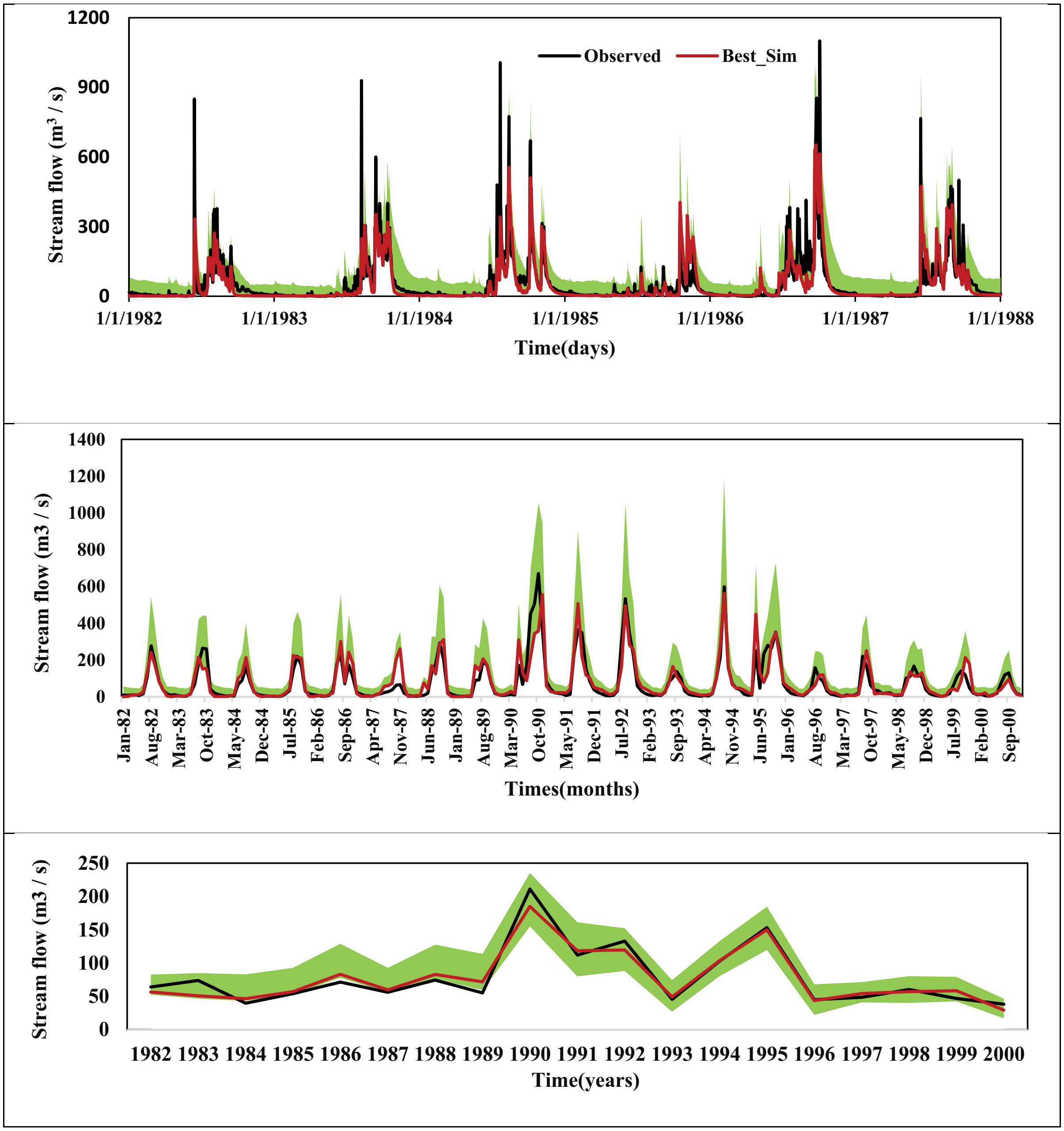

Figure 4. Streamflow simulation for Vamshadara watershed during the calibration period daily, monthly, and yearly time scales (top to bottom) using the best parameter compared with the observed flow and the 95-PPU bands shown in green. For clarity, the results at the daily scale are shown only for a small time window.

3.5 Self-validation of the models

When the models are validated at the time scale for which they have been calibrated, the validation results (Table 5) are close to the calibration results (Table 4) for all basins. This indicates that the models are calibrated adequately.

3.6 From finer to coarser time scales

Referring to Table 5, calibrating the model at a fine scale and validating at a coarser scale resulted in deterioration of the model results compared to the model calibrated and validated at a coarser scale. For example, in Vamshadara River Basin, the NSE for calibration and validation was found to be 0.91 and 0.72, respectively; however, NSE for the MY and DY scenarios was found to be 0.24 and 0.44, respectively. Similar behaviour was observed for the other two river basins. It is interesting to note that transfers from daily to monthly have better performance than the transfer from daily to yearly. For example, in the Vamshadara basin, DM scenarios yielded NSE = 0.71, whereas DY produced results with NSE = 0.24. Overall, it is observed that the good performance of the fine-scale calibrated models does not warrant a similar performance at the coarse scale.

One possible reason for this behaviour could arise from the choice of objective function used for calibration. In this study, we have used the widely used NSE as the objective function; however, Schaefli and Gupta (2007) caution that in the case of monthly time scale, a model that captures the seasonal features but not the small fluctuations will still have good NSE values; however, for predictions at the daily time scale, this (high) value will be misleading. Lerat *et al.* (2020), based on their study using four different objective functions, found that the

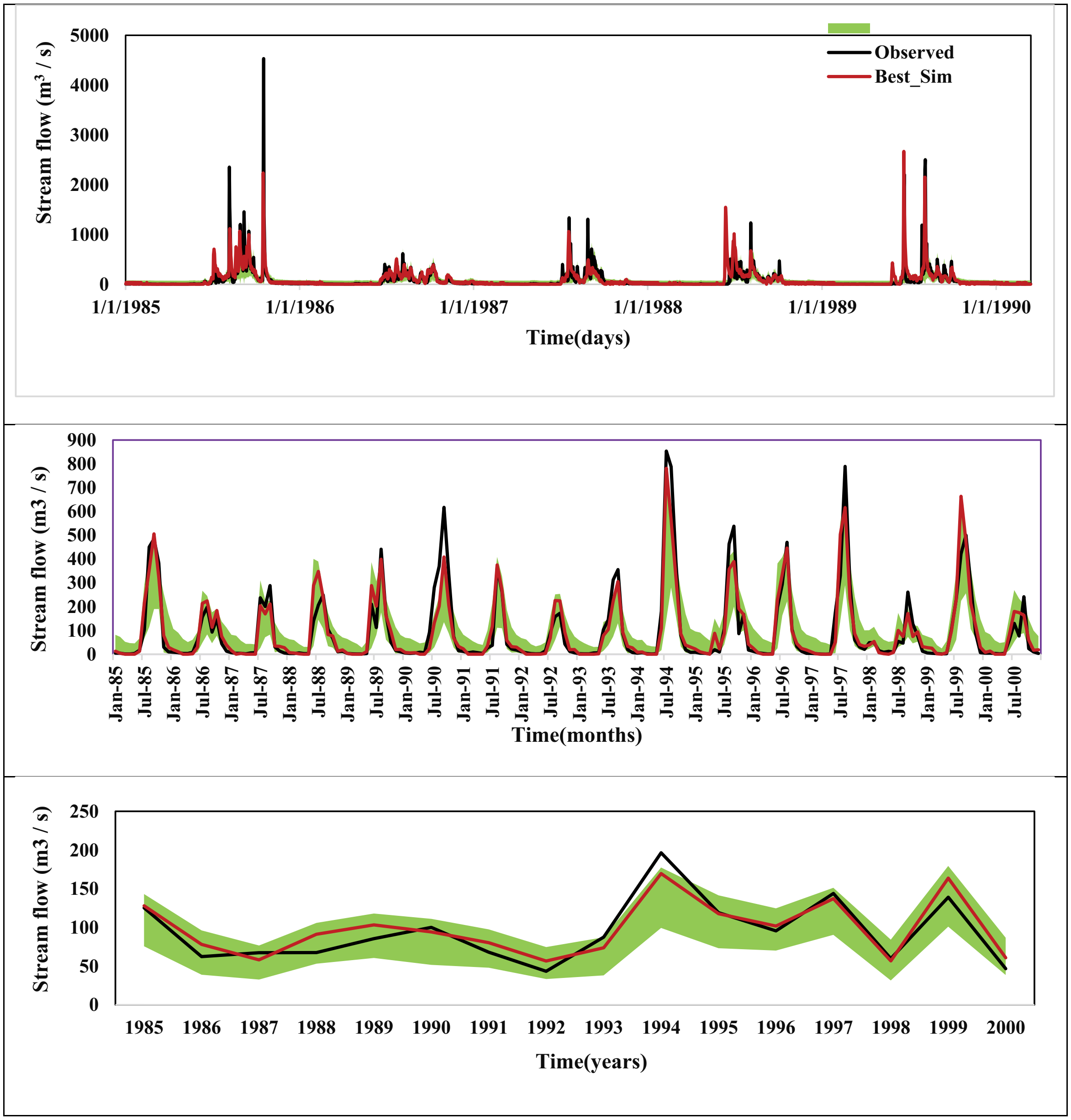

Figure 5. Streamflow simulation for Kharkai watershed during the calibration period daily, monthly, and yearly time scales (top to bottom) using the best parameter compared with the observed flow and the 95-PPU bands shown in green. For clarity, the results at the daily scale are shown only for a small time window.

performance of monthly scale models at the daily time step is a function of the objective function used and reporting it in models using NSE results in a loss of information. In a related study, Rathinasamy *et al.* (2014) emphasized the importance of model assessment and calibration using scale-wise decomposition of the observed discharge rather than using the single-scale observation. From this, it is clear that the choice of the objective function will add another dimension of uncertainty not only in model performance, as shown by Setti *et al.* (2020), but also in the transfer of parameters.

3.7 From coarser to finer time scales

Transferring parameters from the coarser to the finer scale (YD, MD, and YM) also decreased NSE in 8 of the 9 cases considering all basins; however, comparatively better results were obtained. For example, in the Vamsadhara River Basin, when the model was calibrated at the monthly scale and applied at the daily scale, only a negligible difference (NSE decreasing from 0.56 (DD) to 0.46 (MD)) in performance was obtained. Further, the scenario YD led to a comparatively better result than MD for this catchment. For the Kharkai basin, the loss in performance when transferring parameters from the coarser to the finer scale is relatively small, with values between −0.01 and −0.05. Surprisingly, for Kagna, the smallest catchment, YD and MD scenarios yielded very poor results (NSE for YD: 0.15 and for MD: 0.31) compared with the DD scenario (NSE: 0.55).

Interestingly, for the Kharkai and Vamshadara basins, the application of parameters from the yearly model produced better results than those obtained using the monthly model. We analysed the parameter ranking, and the parameter ranges for the Kharkai basin, to understand this effect. We computed the correlation between the parameter ranks of the time scales (shown in Table 3), which is 0.37 between the yearly and daily

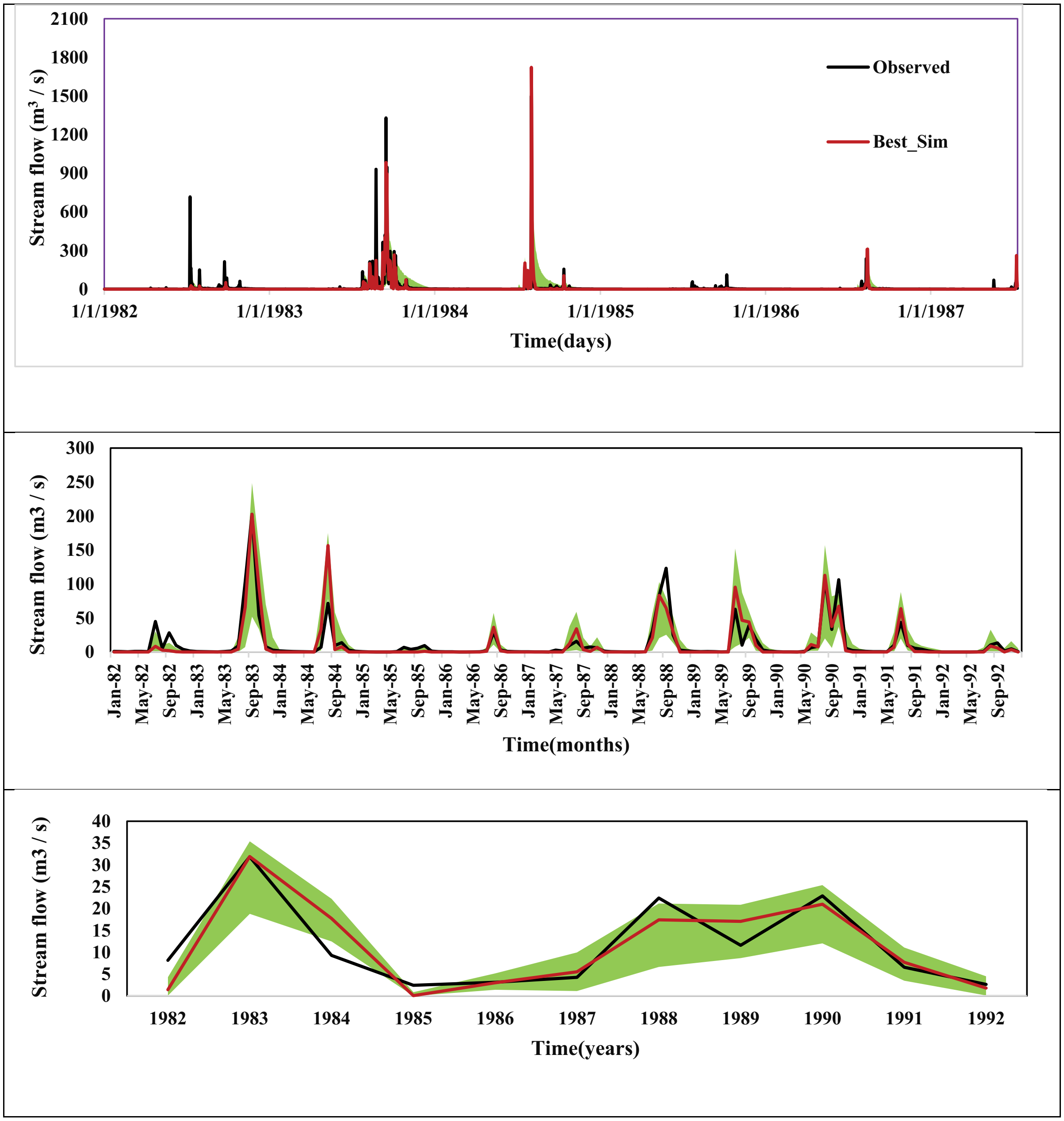

Figure 6. Streamflow simulation for Kagna watershed during the calibration period daily, monthly, and yearly time scales (top to bottom) using the best parameter compared with the observed flow and the 95-PPU bands shown in green. For clarity, the results at the daily scale are shown only for a small time window.

Table 5. R^2 and NSE for the self-validation and different transfer scenarios performed at the three catchments. For example, M to D (scenario MD) indicates that the calibration was performed at the monthly time scale and then validated at the daily scale.

Watershed	Statistic metrics	Self-validation (1993–2000)			Parameter values transferred from one time scale to another time scale					
		DD	MM	YY	DM	DY	MD	MY	YD	YM
Vamsadhara	R^2	0.63	0.77	0.74	0.78	0.65	0.47	0.64	0.49	0.67
	NSE	0.56	0.76	0.72	0.71	0.24	0.46	0.44	0.48	0.62
Kharkai	R^2	0.75	0.87	0.78	0.88	0.78	0.57	0.78	0.75	0.89
	NSE	0.65	0.75	0.74	0.74	0.23	0.5	0.16	0.69	0.75
Kagna	R^2	0.6	0.85	0.91	0.74	0.89	0.34	0.9	0.17	0.69
	NSE	0.55	0.76	0.72	0.58	0.44	0.31	0.72	0.15	0.6

time scale and 0.10 between the monthly and daily scale for Kharkai. Further, from Fig. 3, we observe that for CN2, ALPHA_BF, and GWQMN, the parameter ranges were closer between the daily and yearly scales than between the daily and monthly scales.

Figure 7 shows the hydrographs for the scenarios MD and YD for the Vamsadhara River Basin. MD underestimates the peak values, and there is a lag in the peak runoff. YD better captures the timing and magnitude of the peaks. Similar observations can be made for the other two basins from Figures S1 and S2. One possible reason for this difference might be drawn from the study by Kumarasamy and Belmont (2018), wherein the authors investigate the parameter sensitivity to the periods and scales using wavelet coherence analysis. In that study, they show that certain parameters influence only a specific scale, and except at that time scale, there is no impact of that parameter.

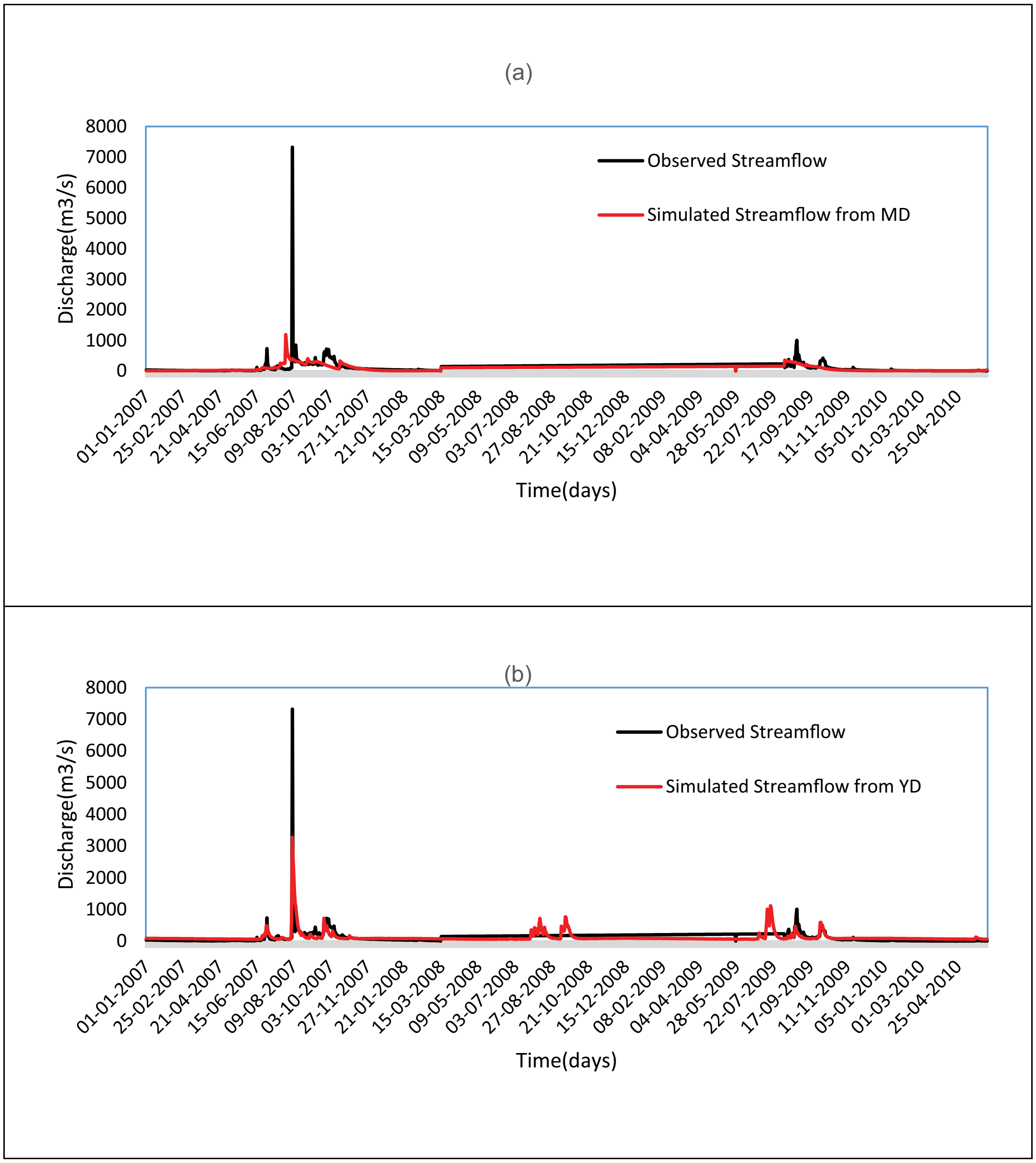

Figure 7. Comparison of the daily runoff generated from (a) monthly to daily scale (MD) and (b) yearly to daily scale (YD) parameter transfer scenarios with the observed runoff for the Vamsadhara River basin.

The transfer of parameters from finer to coarser scales and from from coarser to finer scales mostly aggravated model performance. The lower performance of the coarser scale model at finer scales could be attributed to its inability to capture the variability in the streamflow. When the monthly scale calibrated models were used for simulating the flow at a daily time step, the results in terms of NSE were lower or similar compared to daily time scale calibration for all three basins. When yearly scale models were used to generate the daily flow, the results were better than the MD (monthly–daily) transfer but were closer to the daily calibration results.

It is important to note that a large percentage of SWAT modelling studies do not report the model performance on a daily scale when they have calibrated at monthly or yearly scales. Our results suggest that a good model performance at a coarse time scale may not ensure good performance at smaller time scales, and therefore, caution must be exercised in such cases. The results of this study strengthen the understanding provided by Adla *et al.* (2019) based on one river basin. Since our study is limited to three catchments and the SWAT model, further studies can be directed towards understanding the transferability of parameters from one scale to another as a function of several factors such as the size and complexity of the catchment, spatial variability of rainfall, model complexity, and the objective function used for calibration. For a more generalized understanding of the transferability of parameters across time scales, particularly for detailed distributed models like SWAT, studies along similar lines must be conducted for hundreds of catchments of varying sizes and characteristics.

4 Conclusions

This paper investigated the effect of the time scale of calibration on hydrological model calibration results, sensitivity analysis, and parameter uncertainty using the SWAT model for three catchments, Vamshadara, Kharkai, and Kagna, in India. The sensitivity of the model parameters and the best parameter range varies for different calibration time scales. Therefore, the decision about the time scale of calibration has implications for the sensitivity analysis stage in the hydrological model calibration. Finally, the model performance was higher for the coarser scale models than the finer scale models.

A SWAT model that has been calibrated at a finer time scale achieves lower model performance at coarser time scales when compared to a model calibrated directly at the coarse scales. However, the reduction in performance seems to be modest, with a mean NSE reduction of 0.04 for our catchments. In contrast, when the parameters were transferred from the coarser to the finer time scales, the performance declined in almost all cases. The decline was particularly substantial for the Kagna River Basin, i.e. the smallest catchment. To understand whether there are systematic influences of catchment size and other characteristics on the gain or loss of performance during the parameter transfer would require similar studies to be carried out with hundreds of catchments.

Overall, these observations indicate that careful attention must be exercised when assuming the validity of coarser scale parameters for fine-scale simulation. The implicit assumption that such models mimic the process dynamics even at a smaller time step than the one they have been calibrated for may not be valid. Instead, our results suggest that the SWAT model should be calibrated at the time scale at which model results are required.

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Disclosure statement

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