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Hydrological Modelling of Small Gauged and Ungauged Mountainous Watersheds Using SWAT—A Case of Western Ghats in India

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Abstract

Mountainous forested watersheds are important hydrologic systems that are responsible for much of the water supply and run-of-the-river hydropower schemes in many parts of the world. In India, the Western Ghats are one of such important hydrologic systems located in southern peninsular region. Several of these watersheds are ungauged. The Soil and Water Assessment Tool (SWAT) has been used to model streamflows for two mountainous forested watersheds, namely, Gurupur (699 km^2) (a gauged watershed) and Upper Payaswini (44.6 km^2) (an ungauged watershed). Model calibration and validation are performed using monthly and daily streamflow data for the gauged watershed. Sample flow values obtained over a limited period were used for validation of ungauged watershed. Flow duration curves (FDCs) have been derived to assess percentile flow distributions. Model performance is evaluated using Nash-Sutcliffe coefficient (E_{NS}), percent bias (*PBIAS*), coefficient of determination (R^2) and comparison of percentile flow values obtained from observed and simulated FDCs. Sensitivity analysis with Latin Hypercube One-factor-At-a-Time (LH-OAT) indicates five soil-land use related parameters namely, soil available water capacity (*SOL_AWC*), soil evaporation compensation factor (*ESCO*), soil depth (*SOL_Z*) and layers, groundwater baseflow (*ALPHA_BF*), and curve number (*CN*2 (forest & agriculture)), to be sensitive for simulating both gauged and ungauged wet mountainous forested watersheds. Study shows that lateral flows from dynamic subsurface zones in such watersheds contribute substantially to the total water yield.

Keywords

SWAT, Hydrology, Ungauged, Mountainous, Sensitivity Analysis

1. Introduction

Mountainous forested watersheds are important hydrologic systems that are responsible for much of the water supply and run-of-the-river hydropower schemes in many parts of the world [1] [2] [3]. Western Ghats in India are responsible for more than 80 percent of the surface water of Peninsular India occupying an area of more than 400,000 km^2 supporting population of about 240 million. These mountainous ranges form a barrier to the monsoon winds originating in the Indian Ocean and moving north-east, thereby receive heavy rainfall during the south-west monsoon. More than 90 percent of the annual rainfall occurs during the monsoon months between June and October, with an average number of 120 - 140 rainy days per year. Rainfall intensities are relatively moderate, and rainfall occurs during most part of the day [4]. Soils are mostly red sandy loams, laterites, and coastal alluvial with thickness varying from 3 m on grassed slopes to about 20 m on well vegetated slopes. These are characterised by high infiltration rates. Forests vegetation is thick evergreen to semi-evergreen forests with large forest areas in the hinterland converted into plantations. The hydrologic regimes of these forested high-elevation headwaters of Western Ghats are linked to streamflow processes in low elevation stream reaches and serve as inputs to water supply schemes and run-of-the-river mini, micro and small hydropower plants. To better simulate these linkages in the mountainous watersheds of Western Ghats, most of which are ungauged watersheds, there is a need to understand spatial and temporal variations in water availability. Thus, the wet tropical Western Ghats mountain ranges in South India present an interesting combination of meteorological and physical characteristics that require an understanding of the catchment response and variability in water availability.

Various studies have indicated the possibility of the streamflows in Western Ghats being contributed by surface runoff from saturated source areas of the watershed, augmented by sub-surface lateral flows of the soil mantle [5] [6] [7] [8]. These lateral flows form very important part of streamflows and water availability in the region [4]. Hence, the spatial and temporal variations of these flows as well as their percentile distributions are critical to the understanding of the catchment response. This can be understood through the application of physically based and time continuous modelling approaches that can simulate various components of the land phase of the hydrological cycle in gauged or ungauged catchments [9].

Soil and Water Assessment Tool (SWAT) is one such model that can simulate various components of the land phase of the hydrological cycle in a spatially distributed, time continuous manner using physically based approach. Given its development philosophy and model architecture, SWAT has been applied on ungauged catchments and could be useful for simulating land phase of the hydrological cycle for forested rocky mountainous watersheds through incorporation of GIS and remotely sensed datasets [9]-[17]. This, however, needs to be further tested and applied to adequately estimate streamflow volume and timing from mountainous watersheds of Western Ghats characterised by deep soils, heavy rainfall of moderate to light intensity.

A sensitivity analysis can provide a better understanding of which particular input parameters have greater effect on model output. Benaman & Shoemaker [18] used the methodology of reducing input parameter ranges by performing a sensitivity analysis for input parameters throughout the entire range of values at regular intervals. When the difference in model output of the sensitivity analysis and model output of the base case exceeded a threshold value considered to be the limit for a reasonable outcome, the end of the range for the input parameter was established. They reported a reduction in model output uncertainty of an order of magnitude after applying the methodology. Several researches suggest that sensitivity analysis results have been mixed, indicating that different parameters are more sensitive for some regions than for others [19] [20]. Analysis is therefore needed of SWAT hydrologic parameter sensitivity applicable to the wet mountainous forested watersheds of Western Ghats.

The objectives of this study are: 1) to evaluate performance of SWAT model for a gauged and an ungauged watershed to simulate spatially-explicit watershed modelling of forested high-elevation headwater watersheds of wet tropical Western Ghats mountain ranges; 2) to derive daily streamflows and flow duration curves for assessing percentile distribution of available flows in the watersheds; and 3) to undertake sensitivity analysis that helps determine key parameters that influence streamflows in Western Ghats especially those contributing to surface runoff from saturated source areas of the watershed as well as sub-surface lateral flows of the soil mantle. The study makes an attempt to improve the understanding on physical parameters that are important determinants of run-off components of hydrological cycle for mountainous forested wet ungauged catchments of Western Ghats.

2. Material and Methods

2.1. Description of the Study Areas

The gauged *Gurupur* watershed, with an area of 699 km^2, is located in Dakshin Kannada district ("Dakshin" means "southern" in local language), Karnataka, India (**Figure 1**). The Gurupur stream originates from the Western Ghats (75˚10'42"E; 13˚09'31"N) and flows in the South West direction to join River Nethravathy which later drains into the Arabian Sea near Mangalore (at 74˚49'55"E; 12˚50'43"N).

ASTER 30 m resolution data was used to assess the watershed's topographical features (**Figure 2**). Elevation ranges from 2 m amsl (above mean sea level) at the outlet of the watershed to 1872 m amsl in Western Ghats mountains. The mean elevation is 169 m amsl. About 85 percent of the watershed area has elevation less than 200 m amsl; while 5 percent of the watershed area lies above 800 m amsl.

Land use characteristics for the watershed were derived from the Landsat (ETM+) image and updated from the Quick Bird (0.6 m) image (**Figure 3**).

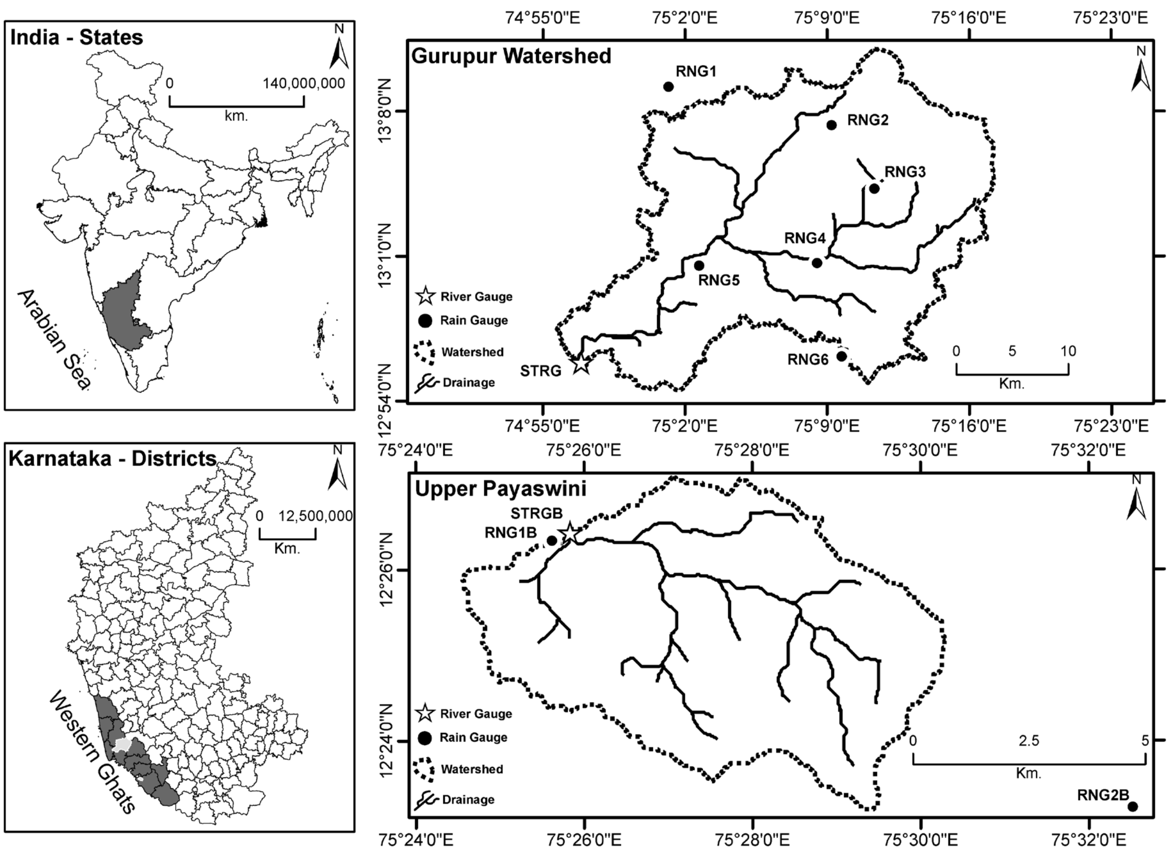


Figure 1. Extent and location of the Gurupur and Upper Payaswini watersheds (including location of raingauges).

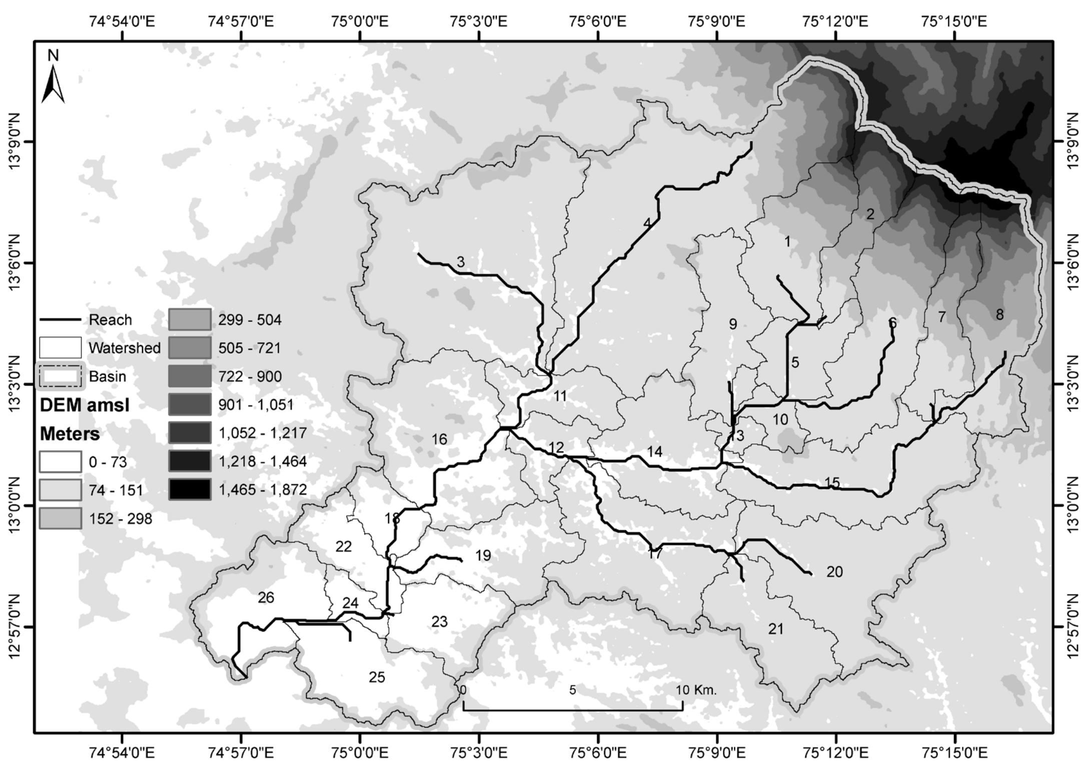


Figure 2. Elevation Map (ASTER 30 m) for Gurupur watershed.

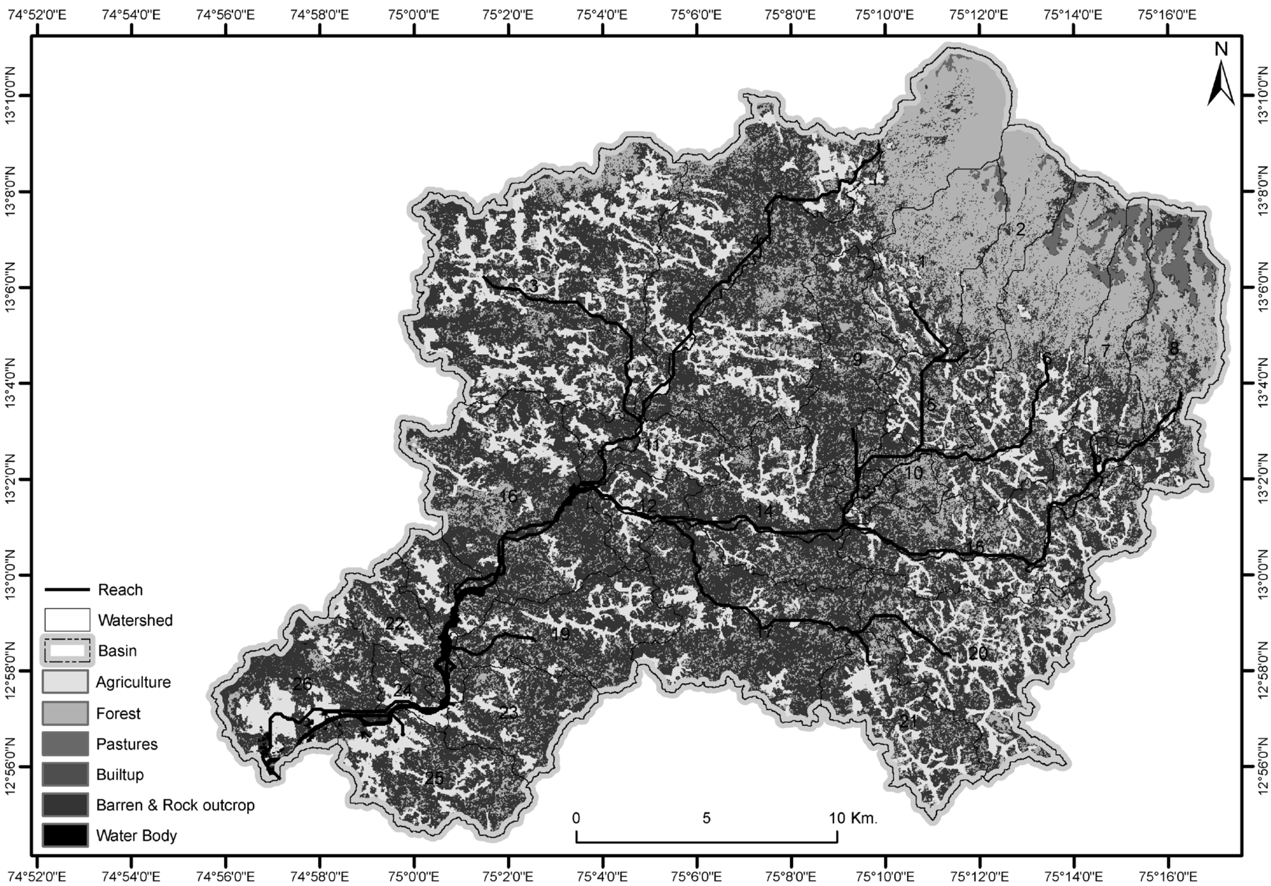


Figure 3. Land use map for Gurupur watershed.

Dense vegetation cover (evergreen forests) comprises 12 percent of the watershed area and is largely towards its northern part. About 54 percent of watershed area is barren rocky with low and scattered vegetation, 18 percent covered by mixed forests and grasslands, and 15 percent is moderately cultivated with coconut plantations and mixed agriculture.

The soils are predominantly lateritic (84 percent), 11 percent is coastal alluvial soil and 5 percent red sandy soils.

Watershed has elevation-adjusted mean annual rainfall close to 4700 mm. About 90 percent of the total annual rainfall occurs during the period from June-October with coefficient of variation being 18 percent. The probability of the wet day following a wet day ranges from 0.7 to >0.9 during the months of June-October. Minimum and the maximum temperature ranges from 21.8˚C (January) to 32.7˚C (April).

The second watershed, *i.e.*, "ungauged" Upper Payaswini watershed, with an area of about 44.6 km^2, lies in Kodagu district of Karnataka, which forms a part of Western Ghats with high mountain ranges running north-south as also shown in Figure 1 in sections above. The watershed is drained by Upper Payaswini River, a perennial west flowing stream originating in Brahmagiri hill ranges (75˚30'E; 12˚24'30"N) of the Western Ghats. It traverses through the states of Karnataka and Kerala to eventually join the Arabian Sea near Kasargod (74˚59'5.36"E; 12˚28'49.59"N). The toposheet for the watershed was unavailable and Satellite information (ASTER 30 m resolution) was used to derive the elevation map (Figure 4).

The entire watershed is mountainous with high peaks situated on the southern side. The elevation ranges from 174 m amsl to 1322 m amsl. The mean elevation for the watershed is 771 m amsl. The land use characteristics for the watershed were derived from the Landsat (ETM+) image and updated from the Quick Bird (0.6 m) image (Figure 5). Considerable part of the watershed (85 percent) is covered by evergreen forests, followed by barren rocky land area spread over 14 percent of total watershed area. The built up and habitation area is very less and spread in small clusters. Red sandy soils are predominant and small areas in south western part of the watershed have lateritic soils.

Average annual rainfall is close to 5600 mm. The area receives about 90 percent of rainfall during June to October with coefficient of variation (CoV) being 20 percent. The probability of the wet day following a wet day ranges between 0.7 to >0.9 from June to October. Minimum and the maximum temperature ranges from 14˚C (January) to 29˚C (March).

2.2. Description of Soil and Water Assessment Tool (SWAT)

Soil and Water Assessment Tool (SWAT) is a physically based, computationally efficient, continuous time model with spatially explicit parameterization applicable

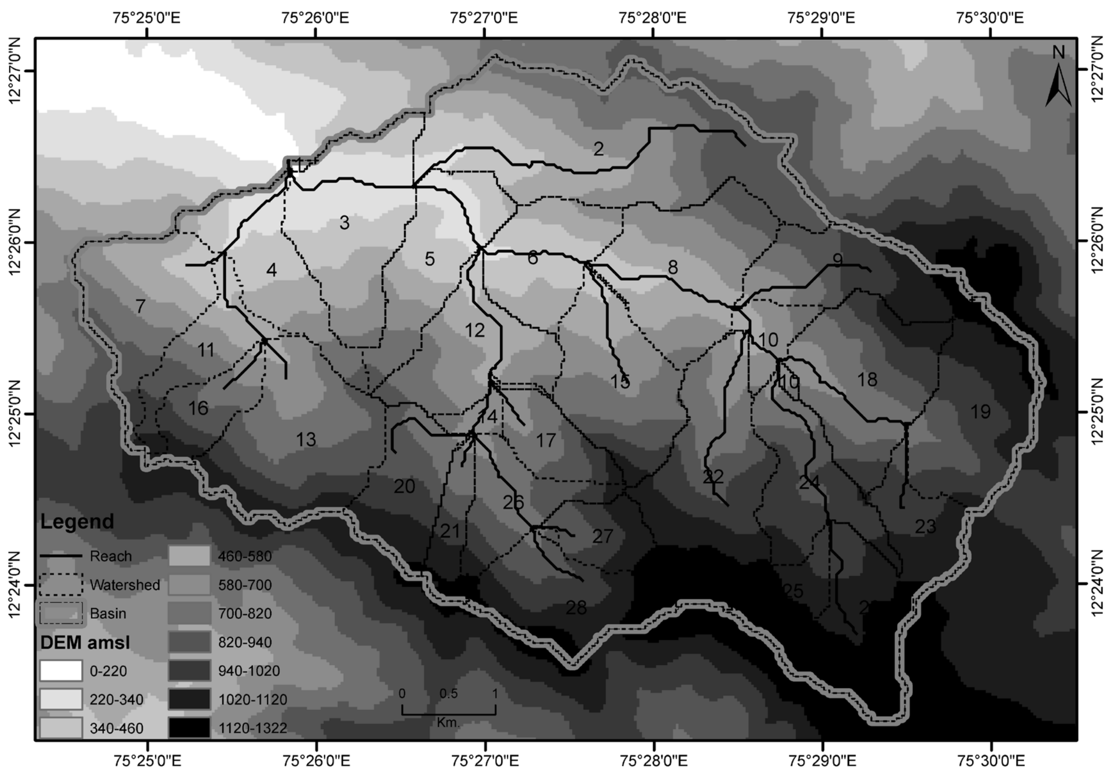


Figure 4. Elevation map (ASTER 30 m) for Upper Payaswini watershed.

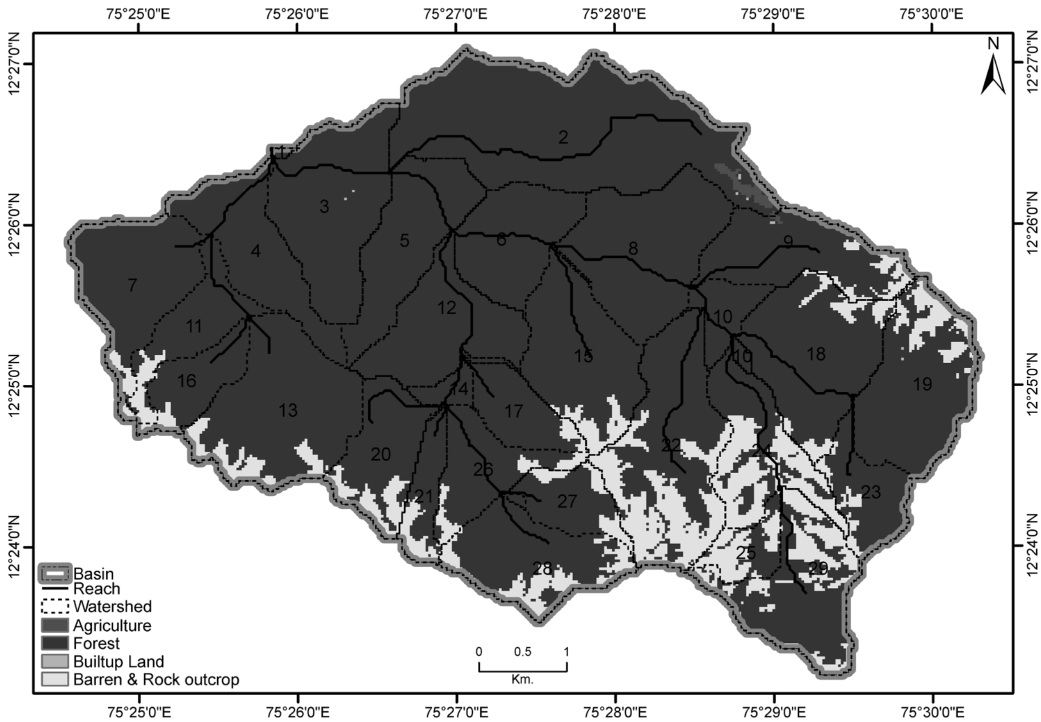


Figure 5. Land use map for Upper Payaswini watershed.

to ungauged watersheds [21]. In SWAT, watersheds could be sub-divided into multiple sub-basins connected by a stream network. The model discretization of a sub-basin is according to Hydrologic Response Units (HRUs) consisting of unique soil, slope and land cover combinations. The local HRU water balance is presented by four storage volumes: snow, soil profile (0 - 2 m), shallow aquifer (2 - 20 m), and deep aquifer (>20 m), including canopy interception of precipitation, partitioning of precipitation, snowmelt water, and irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, and return flow from shallow aquifers. Soil profile can be subdivided into multiple layers. Soil water processes include infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. Percolation from the bottom of the soil profile and root zone recharges the shallow aquifer (groundwater recharge), which is conceptualized as an unconfined aquifer that contributes to flow in the main channel or reach of the sub-basin [22]. Deep percolation from the shallow aquifer recharges the deep aquifer (deep groundwater recharge).

Surface runoff from daily rainfall is estimated with a modification of the SCS curve number (CN) method and Green-Ampt infiltration method. Lateral subsurface flow in the soil profile (0 - 2 m) is calculated simultaneously with percolation. A kinematic storage routing technique is used. Groundwater flow condition to total streamflow is simulated by creating shallow aquifer storage [23]. Other components include pumping, withdrawals, and seepage to the deep aquifer. The Muskingum method is used for channel flood routing. Outflow from a channel is adjusted for transmission losses, evaporation, diversions and return flow. The model offers three options for estimating potential evapotranspiration, including Hargreaves, Priestley-Taylor, and Penman-Monteith method. The SWAT model computes evaporation from soil and plants separately. Srinivasan & Arnold [24] describe integration of SWAT into a GIS system for input dataset development and model output visualization.

The hydrologic cycle, as simulated by SWAT, is based on the water balance Equation (1):

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{lat} - Q_{gw}\right) \quad (1)$$

where SW_t is the final soil water content (mm water), SW_0 is the initial soil water content on day I (mm water), t is the time (days), R_{day} is the amount of precipitation on day I (mm water), Q_{surf} is the amount of surface runoff on day I (mm water), E_a is the amount of evapotranspiration on day I (mm water), w_{seep} is the amount of water entering the vadose zone from the soil profile on day I (mm water), Q_{lat} is lateral flow from soil to channel and Q_{gw} is the amount of return flow on day I (mm water).

2.3. Input Data and Model Setup

Major inputs for simulating land phase of the hydrological cycle can be categorized into spatial and non-spatial data. Spatial datasets pertain to topography, land use, and soil type. Non-spatial includes data on weather, soil properties, land use/cover characteristics, and crops. **Table 1** provides various input data used for model set up.

The following datasets were prepared for the two watersheds: 1) a Digital Elevation Model (DEM) with a spatial resolution of 30 m (derived from ASTER), 2) land-use map from Landsat (ETM+) image and updated from the Quick Bird (0.6 m resolution), 3) soil map at a scale of 1:100,000 in which the physical soil layer properties (including texture, bulk density, available water capacity, saturated conductivity, soil albedo and organic carbon) were collected mainly from National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) Handbook

Table 1. Various sources of information for the required datasets.

Theme	Databases	Source and map scale
Topography	Digital Elevation Map (DEM)	ASTER 30 m resolution
Climatic data	Mean monthly and daily precipitation, maximum and minimum temperature, solar radiation, wind speed, relative humidity, potential evaporation	Indian Meteorological Department (IMD) Climatological tables (1951-1980); Daily rainfall data available for raingauges in the watershed (1990-2010) from Water Resource Development Organisation, Government of Karnataka.
Soil-physical data	Soil characteristics (% silt, sand, clay, rocks), field capacity, wilting point, hydraulic conductivity, depth to water table, properties for different soil layers varying with depth	National Bureau of Soil Survey and Land use planning (NBSS & LUP); NATMO, and Department of Science and Technology 1981, West India Soil Maps, USDA Soil Taxonomy, 1:100,000
Land use data	Ground cover	Landsat (ETM+) image and updated from Quick Bird (0.6 m resolution) images
Gauge data	Daily river flows	State Water Resource Department, Karnataka

and field data, 4) climate data provided from IMD Climatological tables (1951-1980) (mean monthly rainfall, maximum and minimum mean monthly air temperature, mean monthly wind speed, solar radiation, and relative humidity) and rain gauges in Western Ghats (daily precipitation from 6 rain gauges (RNG 1 - 6) in and around Gurupur watershed; 2 rain gauges (RNG1B-2B) in and around Upper Payaswini watershed) provided by the Water Resources Development Organisation, Government of Karnataka (as shown in **Figure 1** in sections above and **Table 2**).

The ArcView Interface for SWAT 2000, was used to delineate the boundaries of the entire watershed and its sub-basins, along with their drainage channel from ASTER 30 m resolution DEM [25]. The boundary of the watershed was superimposed on Google Earth to ensure that delineated watershed boundary and drainage channels closely matched the mountain and hill ridges and drainage network on Google Earth imagery. The Gurupur watershed was finally divided into 26 sub-basins, with sizes varying from 470 hectare to 10,160 hectare (see **Figure 2**), and the Upper Payaswini watershed into 29 sub-basins with sizes varying from 2.5 to 479.5 hectares (see **Figure 4**). Further, land use and soil map were used to define multiple HRUs for each of the sub-basins.

The land cover/use map was processed as raster data and included 6 categories consisting of 1) forest (evergreen/mixed), 2) barren and rock outcrop, 3) agriculture, 4) low density habitation/built up, 5) water bodies, 6) grassland/pastures, derived from Landsat (ETM+) image and Quick Bird (0.6 m resolution). These remotely sensed data accounted for the spatial variability in forest and other vegetation characteristics. The vegetation map was finalized after field verification in each of the delineated sub-basins. The barren landcover category, which includes

Table 2. Details of the raingauges and river gauge in Gurupur and Upper Payaswini watersheds.

Watershed	Raingauge/Stream gauge		Location		
	Number as shown in Figure 1	Name	Latitude	Longitude	Avg. Annual rainfall (mm)
Gurupur	RNG 1	Irvattur	13˚09'09"N	75˚01'11"E	4430
	RNG 2	Naravi	13˚07'19"N	75˚09'14"E	5570
	RNG 3	Sulkeri	13˚04'17"N	75˚11'20"E	4975
	RNG 4	Venur	13˚00'39"N	75˚08'30"E	4300
	RNG 5	Sangabettu	13˚00'31"N	75˚02'43"E	4260
	RNG 6	Kukkala	12˚56'10"N	75˚09'43"E	4070
	STRG	Polali	12˚55'48"N	74˚57'13"E	-
Upper Payaswini	RNG 1B	Karike	12˚26'23"N	75˚25'39"E	5840
	RNG 2B	Bhagmandala	12˚23'12"N	75˚32'31"E	5340
	STRGB	Mini hydel	12˚26'24"N	75˚25'53"E	-

*RNG refers to raingauge station; STRG refers to stream gauge station.

bare ground, and rock outcrops, was parameterised by modifying the dirt road transportation parameter set in SWAT [10]. The soil database consisting of soil map and attributing databases developed by NBSS&LUP was used to characterize soils in the study areas. Finally, the values for the standard soil and land use parameters used to configure the model were extracted and/or estimated from datasets by the SWAT interface. In SWAT, these parameters are grouped at the levels of watershed, sub-basin, and HRU, and are described in detail by Neitsch *et al.* [25]. The number and diversity of HRUs can influence model output, and to ensure a high level of resolution, multiple HRUs were defined for each watershed.

Rainfall in mountainous watersheds is influenced by changes in elevation. Fontaine *et al.* [9] showed that definition of elevation bands within the model's sub-basins can enhance simulation performance in watersheds with topography having large elevation gradients. To account for a high elevation gain (around 1800 m in Gurupur and around 1000 m in Upper Payaswini watershed), two elevation bands were defined. The data from six raingauge stations has record on daily rainfall from 1991-2009 for Gurupur watershed. Data from these raingauges and from the National Weather Station maintained by Indian Meteorological Department (IMD) located approximately 15 straight line kilometres south west of the south western watershed boundary were used to estimate the local precipitation lapse rate of 25 m/km applicable to elevation range of 1050 - 1800 m amsl and 12 m/km applicable to range of 500 - 1050 m amsl (estimated from rainfall data provided by the Water Resources Development Organisation, State Government of Karnataka, India). Once established, these values were used to parameterize SWAT and then maintained throughout the calibration.

The data on daily rainfall from rainfall gauges were pre-processed into database files within the SWAT required format for a simulation period extending from 1st January 1991 to 31st December 2009 in case of Gurupur watershed and 1st January 1990 to 31st December 2010 in case of Upper Payaswini. The long term (1951-1980) mean monthly values on rainfall, solar radiation, wind speed, relative humidity, and number of precipitation days in a month obtained from IMD Climatological tables (Station Mangalore in case of Gurupur–12˚52'N; 74˚51'E and station Madikeri in case of Upper Payaswini–12˚25'N; 75˚44'E) were used as inputs into the weather generator (a stochastic engine incorporated in the deterministic SWAT software package). The missing values on daily rainfall were simulated by the calibrated and validated weather generator using the procedures described by Neitsch *et al.* [25]. Further, during the simulation period records on daily streamflows were available in gauged Gurupur watershed for Polali gauge station STRG (refer to **Table 2** and **Figure 1**) from 1991 to 1999 years and intermittent data for select days in the months of June and July 2009 and 2010 were available from a mini hydropower project STRGB (refer to **Table 2** and **Figure 1**) in the ungauged Upper Payaswini watershed, which makes the model evaluation possible.

2.4. Model Calibration and Validation

The original design objective of the SWAT model was to operate in large-scale, ungauged basins with little or no calibration efforts [26]. Studies have demonstrated that SWAT input parameter values can be successfully estimated without or with minimum calibration in a wide variety of hydrologic systems and geographic locations using readily available GIS databases that have been developed based on prior knowledge [27] [28].

The calibration has been undertaken by conducting a sensitivity analysis to identify the surface runoff and lateral flow related parameters that are sensitive for simulation. Guidance for identifying input parameters for the calibration and sensitivity analysis was provided by prior research in mountainous forested catchments [29] [30] [31]. Research indicated that watershed runoff generation should incorporate rapid lateral flow from soils in wet humid regions as a preferential mechanism of total flow generation, which increases as the degree of wetness of the soil increases. They identified three parameters to reflect local environmental conditions to improve streamflow predictions: the soil infiltration capacity (permeability), soil profile, and soil saturated conductivity.

The sensitivity analysis method implemented in SWAT is Latin Hypercube One-factor-At-a-Time (LH-OAT) [32] [33]. Latin Hypercube (LH) sampling is computationally efficient, and One-At-a-Time (OAT) procedures ensure that a change in model output is unambiguously attributed to the change in an input parameter [10]. LH-OAT starts with taking N Latin Hypercube sample points for N intervals, it then varies each LH sample point P times by changing each of the parameters one at a time. The method operates by loops and each loop starts with a Latin Hypercube point. Around each Latin Hypercube point j, a partial effect S_{ij}, for each parameter e_i is calculated as in Equation (2):

$$S_{ij} = \left| \frac{100 * \left(\dfrac{M\left(e_1, \cdots, e_i * (1+f_1), \cdots, e_p\right) - M\left(e_1, \cdots, e_i, \cdots, e_p\right)}{\left[M\left(e_1, \cdots, e_i * (1+f_1), \cdots, e_p\right) + M\left(e_1, \cdots, e_i, \cdots, e_p\right)\right]^2} \right)}{f_i} \right| \tag{2}$$

where $M(\ldots)$ refers to model functions, f_i is the fraction by which the parameter e_i is changed (a predefined constant) and j refers to a LH point. A final effect is calculated by averaging the partial effects of each loop for all LH points. The final effects can be ranked with the largest effect being given rank 1 and the smallest effect given rank equal to the number of the parameters. Thus, the impact of each parameter on the model results can be quantified and the most sensitive parameters can be identified [34].

For this study the daily measured streamflow datasets were available for the period 1991 to 1999 years (for gauged Gurupur watershed). The period from January 1, 1991 to December 31, 1991 served as a warm-up period for the model, allowing state variables to assume realistic initial values for the calibration period. Data from 1992 to 1995 has been used for calibration and 1996 to 1999 has been used for validation purposes.

Evaluation of model performance during the calibration and validation periods has been done following the methods, namely percent bias (***PBIAS***), coefficient of determination (R^2), and Nash-Sutcliffe efficiency (E_{NS}) [35].

PBIAS is calculated according to Equation (3):

$$PBIAS = \left(\sum_{t=1}^{T} \left(Q_{s,t} - Q_{m,t} \right) \middle/ \sum_{t=1}^{T} Q_{m,t} \right) 100 \tag{3}$$

where $Q_{s,t}$ is the model simulated value at time unit t. $Q_{m,t}$ is the observed data value at time unit t, and $t = 1, 2, \ldots, T$. ***PBAIS*** measures the average tendency of the simulated data to be larger or smaller than their observed data. Values with small magnitude are preferred, positive values indicate model overestimation bias while negative values indicate underestimation. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. In short, PBAIS reflects the goodness of model's simulation in respect of the observed data.

R^2 is calculated according to Equation (4).

$$R^2 = \left\{ \sum_{t=1}^{T} \left(Q_{m,t} - \bar{Q}_m \right) \left(Q_{s,t} - \bar{Q}_s \right) \middle/ \left[\sum_{t=1}^{T} \left(Q_{m,t} - \bar{Q}_m \right)^2 \right]^{0.5} \left[\sum_{t=1}^{T} \left(Q_{s,t} - \bar{Q}_s \right)^2 \right]^{0.5} \right\}^2 \tag{4}$$

where $\bar{Q}_m$ is the mean observed data value, $\bar{Q}_s$ is the mean simulated data value for the entire evaluation time period. R^2 is equal to the square of Pearson's product-moment correlation coefficient. It represents the proportion of the total variance in the observed data that can be explained by the model. R^2 ranges between 0.0 and 1.0. Higher values mean better performance.

E_{NS} is calculated according to Equation (5).

$$E_{NS} = 1.0 - \sum_{t=1}^{T} \left(Q_{m,t} - Q_{s,t} \right)^2 \middle/ \sum_{t=1}^{T} \left(Q_{m,t} - \bar{Q}_m \right)^2 \tag{5}$$

E_{NS} indicates how well the plot of the observed values versus simulated values fits the 1:1 line and ranges from $-\infty$ to 1 [36]. Larger E_{NS} values (close to 1) are equivalent with better model performance.

Additionally, flow duration curves (FDCs) depicting percentile flow availability have been derived and compared both for observed and simulated flows, summarizing relationship between the magnitude and frequency of streamflows [37].

3. Results and Discussion

Two watersheds, namely Gurupur (699 km^2) and Upper Payaswini (44.6 km^2), located in Dakshin Kannada and Kodagu districts respectively of Western Ghats have been modelled using SWAT. Model calibration is performed using daily streamflow data of 3 years in case of Gurupur gauged site.

3.1. Parameter Sensitivity Analysis for SWAT Applicable to Western Ghats

Sensitivity analysis is implemented to identify sensitive parameters for model calibration using LH-OAT. The selected parameters were adjusted over a range of values through a stepwise process that utilized both automated methods, and manual refinement until an acceptable parameter set was obtained [38]. The sensitivity analysis resulted in a list of parameters from most to least sensitive (Table 3) that includes soil, land use and groundwater parameters as discussed in subsequent sections.

CN curve number, which is related to both soil and vegetation, is found to be an important sensitive parameter in the model. It is a function of the soil's permeability, land use and antecedent soil water conditions. A moderate to low initial value of CN2 number for such highly forested sub-basins is desirable. Another important parameter is Soil Available Water Content (AWC) [26]. With increasing AWC, the soil storage increases resulting in decrease of surface runoff, and or percolation and water available for soil evapotranspiration increases. In addition to AWC, other parameters that were found to be sensitive include Soil Evaporation Compensation factor (ESCO), soil depth (Z) and soil texture including silt (SILT), sand (SAND), and clay (CLAY) content. ESCO adjusts depth distribution for evaporation from the soil to account for capillary action, crusting and cracking. As the value of ESCO is decreased it enables lower layers of soil matrix to compensate for the water deficit. Percentage decrease in ESCO values to match the flows is mostly felt in sub-basin characterized by cultivable area and trees and presence of good soils. Alpha factor for groundwater, ALPHA_BF, is a function of the overall topography, drainage pattern, soil, and geology of the watershed [13]. It is a direct index of the intensity with which the groundwater outflow responds to changes in recharge [39]. Increases in alpha factor cause the simulated recession curve to be much faster. Varying this parameter does the adjustment of recession curves. Variations in values of various other parameters such as CH_K2, GW_DELAY, and SURLAG did not further improve the results and showed low sensitivity in terms of adjusting flows in this study area. Table 3 shows the results of sensitivity analysis of parameters.

Table 3. Sensitivity analysis for the mountainous watersheds of Western Ghats.

Parameter	Description	Range used		Sensitivity	Rank
		Min	Max		LH-OAT
Curve Number (CN2)	Curve number for moisture condition II	25	52.65	High	5
ESCO	Soil Evaporation Compensation Factor	0.74	0.95	High	2
AWC ($mm \cdot mm^{-1}$) varying with depth	Soil Available Water Capacity	0.07	0.165	High	1
SOL_K ($mm \cdot h^{-1}$) varying with depth	Soil Hydraulic Conductivity	10	300	Moderate/Low	6
SOL_Z (mm)	Soil depth and number of layers (SOL_LY)	2100* (2)	4500 (6)	High	3
ALPHA_BF	Baseflow Alpha factor	0.039	0.048	High	4
CH_K2 ($mm \cdot h^{-1}$)	Channel Conductivity	0	75	Low	
GW_DELAY (days)	Groundwater delay time	1	50	Low	7
SURLAG	Surface lag coefficient	1	4	Low	8

*Figures in brackets refer to number of soil layers.

Calibration indicates five soil-land use related parameters to be sensitive for simulation namely, soil evaporation compensation factor (*ESCO*), soil available water capacity (*SOL_AWC*), soil depth (*SOL_Z*) and soil layers, groundwater baseflow (*ALPHA_BF*) and curve number (*CN*2).

3.2. Streamflows and Runoff Components Simulated by SWAT

The measured and simulated daily streamflow for calibration and validation periods are presented. Scatter plots that compare observed and simulated flows are shown. Model performance is evaluated using Nash-Sutcliffe coefficient (E_{NS}), percent bias (*PBIAS*) and coefficient of determination (R^2). R^2, and E_{NS} values above 0.6 are generally acceptable and values near unity indicate a close relationship between predicted and measured yields [40]. After the calibration of several parameters (sensitivity analysis), it was also estimated if SWAT successfully captured the study area's hydrologic characteristics and reproduced acceptable daily runoff simulations during validation period.

Model validation is conducted using an additional 3 years of data for gauged watershed. FDCs have been derived both for observed and simulated flows in gauged watershed. For ungauged watershed, FDC has been derived based on the simulated flows obtained from SWAT for the watershed. Finally, different runoff components simulated by SWAT are represented for capturing the hydrologic cycle.

3.2.1. Gurupur (Gauged) Watershed

Results of model calibration and validation for the Polali gauge station in Gurupur watershed are presented in **Figure 6**. Scatter plot that shows a comparison of

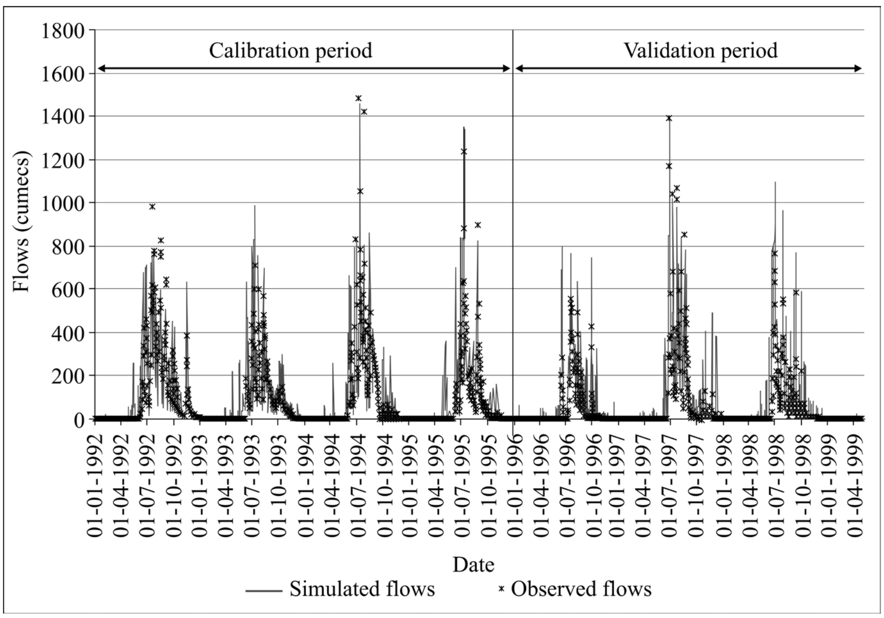


Figure 6. Daily hydrograph for Gurupur watershed: Comparison of daily flows (cumecs) at the gauge station (Polali) for calibration period (1992-1995) and validation period (1996-1999).

observed and simulated flows is presented in Figure 7. The FDCs both for observed and simulated flows are shown in Figure 8(a) and Figure 8(b) with corresponding percentile flow values detailed out in Table 4.

Figure 8(c) and Figure 8(d) depict the FDCs for observed and simulated flows in semi-logarithmic scale to capture the lean flow series in the watershed. The model performance values have been shown in Table 5. A good performance is considered to be obtained [40].

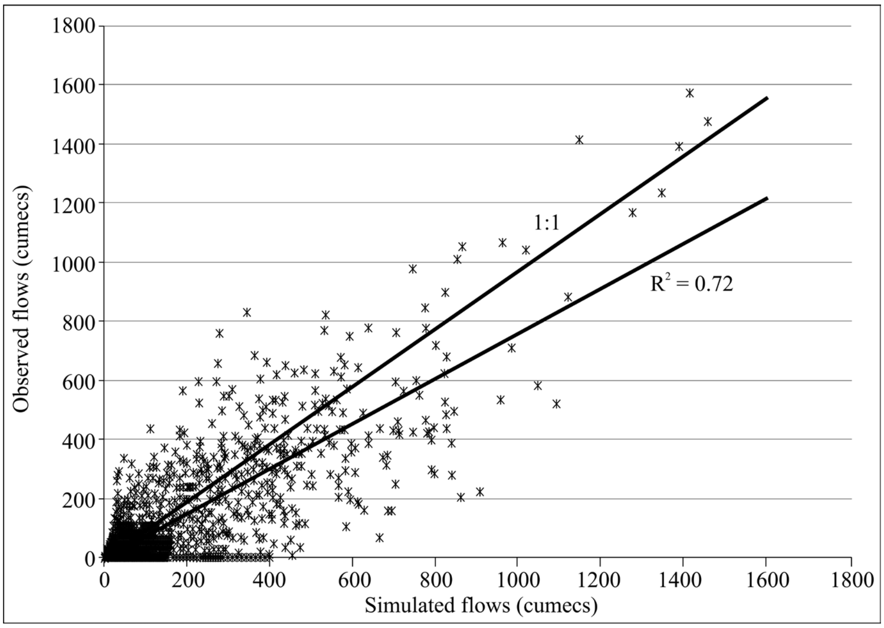
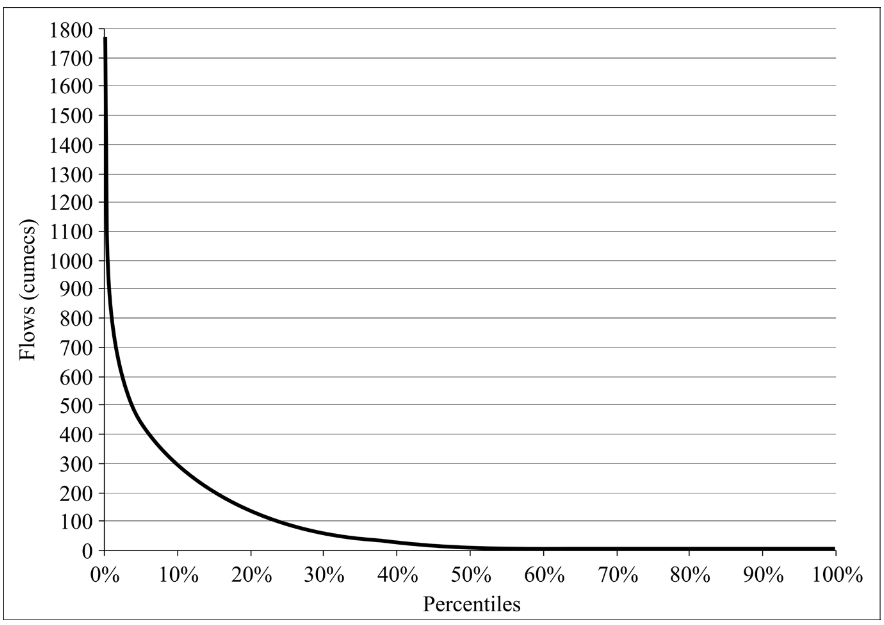
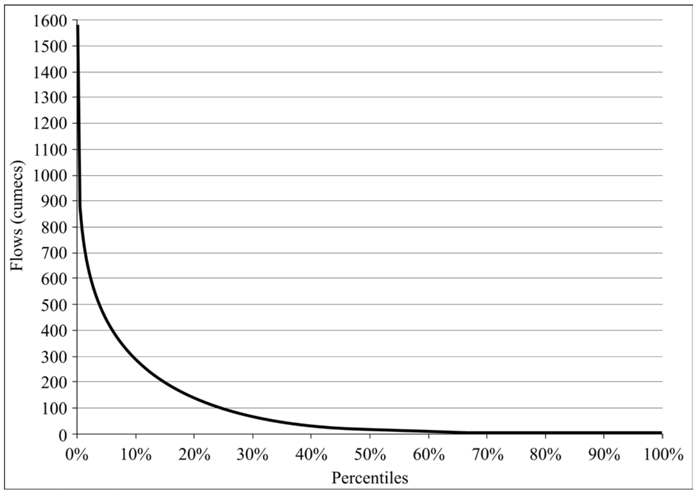


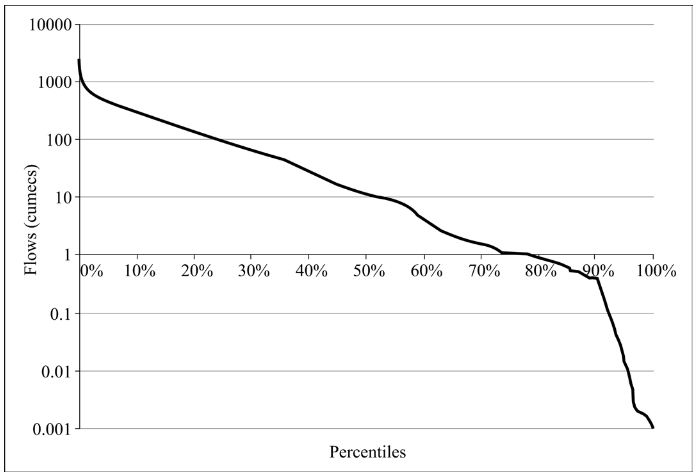
Figure 7. Scatterplot of observed and simulated daily flows (cumecs) for Gurupur watershed at Polali gauge station (graph also shows comparison of regression line with 1:1 line; ideally, the two lines would coincide).



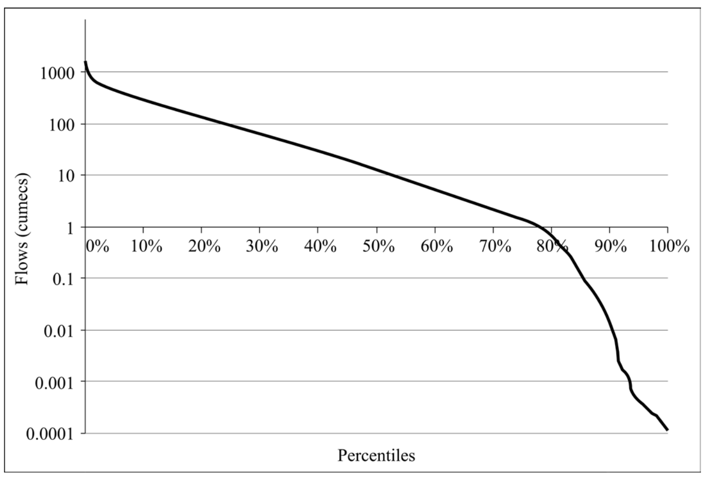
(a)



(b)



(c)



(d)

Figure 8. (a) Flow Duration Curve (based on observed flows) for Gurupur watershed; (b) Flow Duration Curve (based on simulated flows) for Gurupur watershed; (c) Flow Duration Curve (based on observed flows in semi-logarithmic scale) for Gurupur watershed; (d) Flow Duration Curve (based on simulated flows in semi-logarithmic scale) for Gurupur watershed.

Table 4. Percentile values of flow comparison of observed and simulated FDCs for Gurupur watershed.

Percentile duration	FDC (observed flow) (cumecs)	FDC (simulated flow) (cumecs)
25 percentile	92.5	94.0
50 percentile	11.3	12.7
75 percentile	1.0	1.4

Table 5. Model performance of monthly and daily flows: Polali gauge station.

Sub-basin	Polali gauge station	
	Daily	Monthly
Calibration period		
Coefficient of Determination (R^2)	0.74	0.81
Nash and Sutcliffe coefficient (E_{NS})	0.71	0.80
Percent bias (*PBIAS*)	1.87	0.97
Validation period		
Coefficient of Determination (R^2)	0.72	0.79
Nash and Sutcliffe coefficient (E_{NS})	0.69	0.76
Percent bias (*PBIAS*)	-7.21	-1.82

Watershed runoff components simulated by SWAT indicate that surface runoff contributions to the water yield during calibration and validation periods are 61 percent and 66 percent, respectively, and lateral soil and shallow groundwater contributes 39 percent and 34 percent to the water yield for calibration and validation periods, respectively.

3.2.2. Upper Payaswini (Ungauged) Watershed

Time continuous discharge data was not available for any station in the Upper Payaswini watershed or in close vicinity of the watershed. Intermittent and instantaneous flow data maintained by run-of-the-river hydro power plant operating in the area was available for a very short period and was used for comparison of observed and simulated streamflows. The results of validation for the Upper Payaswini gauge station are presented in **Figure 9** in terms of comparisons of simulated and observed flows. The percentile flow values corresponding to FDC based on simulated flows in the watershed are detailed out in **Table 6**. Scatter plot that shows a comparison of observed and simulated flows is presented in **Figure 10**, while **Figure 11** shows FDC for simulated flows. The model performance criteria values have been depicted in **Table 7**.

Watershed runoff components simulated by SWAT indicate that surface runoff contributions to the water yield is about 31 percent, and lateral soil release and shallow groundwater contributes 69 percent to the water yield. This is mainly attributable to large areas of watershed being covered by evergreen forests and deep soils with good infiltration rates.

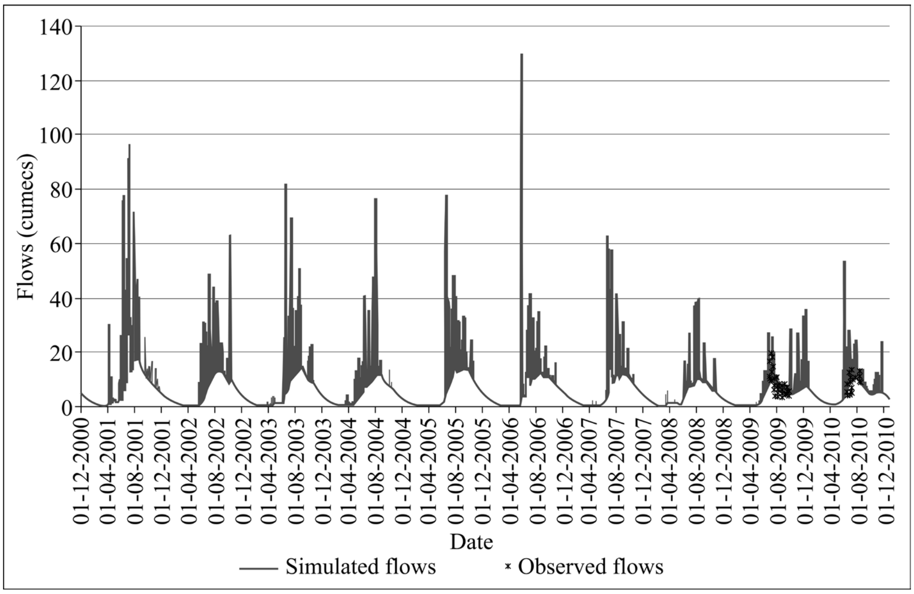


Figure 9. Daily hydrograph for Upper Payaswini watershed: Comparison of daily flows (cumecs) for limited instantaneous data.

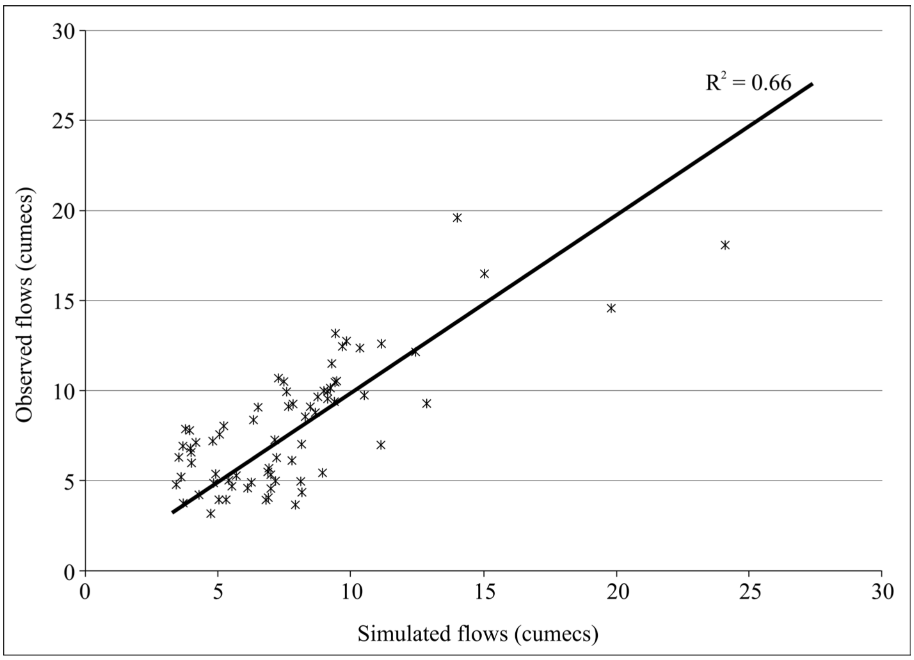


Figure 10. Scatterplot of intermittent observed and simulated daily flows (cumecs) for Upper Payaswini watershed.

Table 6. Percentile values of flow –simulated FDC for Upper Payaswini watershed (in cumecs).

Percentile duration	FDC (simulated flow)
25 percentile	9.3
50 percentile	2.6
75 percentile	0.5

Table 7. Model performance for simulation of daily flows: ungauged Upper Payaswini.

Sub-basin	Upper Payaswini
Coefficient of Determination (R^2)	0.66
Nash and Sutcliffe coefficient (E_{NS})	0.61
Percent Bias (PBIAS)	−9.12

Note: based on instantaneous flow data available from run-of-the-river mini hydropower scheme in the watershed.

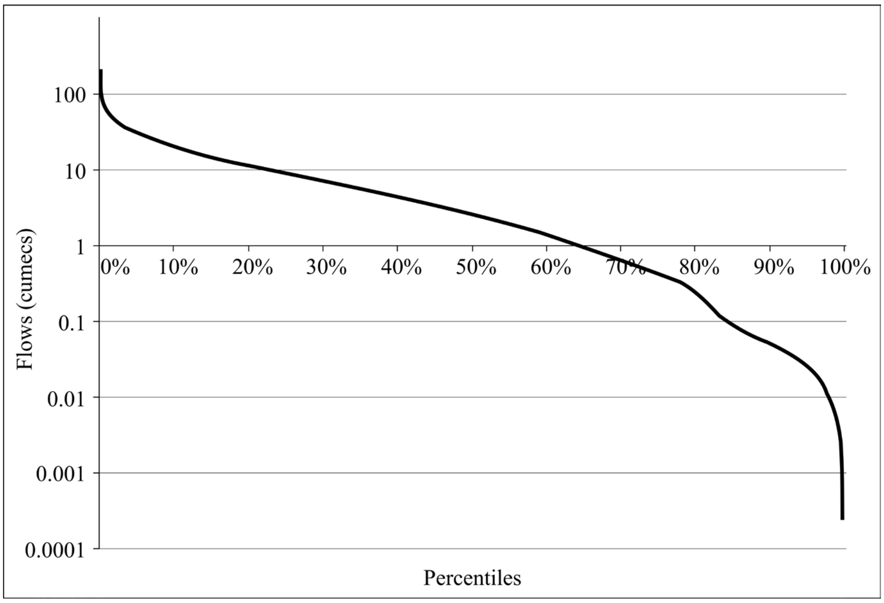


Figure 11. Flow Duration Curve (simulated flows in semi-logarithmic scale) for Upper Payaswini watershed.

4. Conclusions

The study focused on mountainous forested watersheds that form important hydrologic systems responsible for much of the water supply and run-of-the-river hydropower schemes in many parts of the world. It compared the runoff simulation performance of two watersheds (a gauged and ungauged) located in the mountainous Western Ghats in southern peninsular India. Soil and Water Assessment Tool (SWAT), a physically based model that can simulate various components of the land phase of the hydrological cycle and applicable to ungauged catchments was successfully used. This required an extensive use of remote sensing and geographical information system (GIS). The results show that SWAT model simulates the land phase of the hydrological cycle satisfactorily and generates daily runoff series as well as percentile flow series (flow duration curves) comparable to observed values. Comparing simulated and observed daily flows for the two watersheds produced R^2, and E_{NS} values larger than 0.6 and *PBIAS* values lower than 15 percent for both calibration and validation periods.

Flow duration curves were used as a graphical representation of the magnitude and frequency of the observed streamflows. Simulated daily FDC was found to be in good agreement with observed daily FDC.

Sensitivity analysis with Latin Hypercube One-factor-At-a-Time (LH-OAT) was carried out in order to identify parameters with a high impact on simulated streamflows especially applicable to mountainous forested watersheds. The analysis and watershed evaluation results indicate five soil-land use related parameters to be sensitive for simulation of the components of the land phase of the hydrological cycle in the gauged Gurupur mountainous forested watershed. These are soil available water capacity *SOL_AWC*, soil evaporation compensation factor *ESCO*, soil depth *SOL_Z* and soil layers, groundwater baseflow *ALPHA_BF* and curve number *CN*2. The same parameters are also found to be key determinants of run-off components of hydrological cycle in case of ungauged Upper Payaswini mountainous watershed of the Western Ghats. It is observed that contributions from dynamic sub-surface zones that appear as slow and consistent release of water from soil matrix and shallow groundwater aquifers in the Western Ghats are responsible for considerable quantities of available water throughout the year. It is concluded that in the wet forested mountainous areas like the Western Ghats, the catchment response is shaped more by the sub-surface flow pattern, than by surface flow lengths and channel properties. The prevalence of a combination of evergreen forests towards the extreme north headwater and combination of lateritic and red loamy soil types with good infiltration rates in Gurupur watershed is a key factor for slow and consistent lateral flows that lead to constant releases in non-monsoon months. Similarly, a combination of dense evergreen forests with existence of deep red loamy soil with good infiltration rates in most of the Upper Payaswini watershed remains a key determinant for lateral flows. Model validation reveals that successful simulation of the land phase of the hydrological cycle using SWAT can provide precise estimates of streamflow in mountainous watersheds. Application of SWAT to mountainous gauged and ungauged watersheds of Western Ghats is found to be a useful tool for evaluation of water resources.

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Conflicts of Interest

The authors declare no conflict of interest with this publication. Also, the funders had no role in the design of the study; in the analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. As Corresponding Author, I confirm that the manuscript has been read and approved for submission by my named co-author.

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