

Continuous Hydrological Modeling using Soil Moisture Accounting Algorithm in Vamsadhara River Basin, India

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Abstract-In this study, a continuous soil moisture accounting (SMA) algorithm was used in a Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) to model stream flow in the Vamsadhara River Basin in India. The spatial domain of the catchment was discretised into smaller sub-basins to account for catchment heterogeneity in terms of topography, land use and soil. The SMA algorithm in HEC-HMS was calibrated using data from 1984 to 1989, and has been validated for the period from 1990 to 1993 on a continuous time scale. Statistical and visual evaluation was conducted to determine the performance of the HEC-HMS model in the Vamsadhara River Basin. For the calibration period, the performance of the model ranges from good to very good with a coefficient of determination $R^2=0.71$, Nash-Sutcliffe Efficiency $EFF=0.701$, percentage error in volume $PEV=2.64\%$, percentage error in peak $PEP=0.21\%$, and index of agreement $d=0.94$. Similarly, the model performance for the validation period ranges from good to very good with $R^2=0.78$, $EFF=0.762$, $PEV=12.33\%$, $PEP = -15.2\%$, and $d=0.93$. Sensitivity analysis of model parameters has also been conducted and the ranking of different parameters have been assigned based on their sensitivity in terms of percent change in simulated runoff volume. Sensitivity analysis helps to understand the behaviour of the model. Overall, the SMA procedure in the HEC-HMS conceptual model performed satisfactorily and can be used for long-term runoff modeling in the Vamsadhara River Basin.

Keywords- Continuous Hydrologic Simulation; SMA; HEC-HMS; Nash-Sutcliffe Efficiency; Sensitivity Analysis

I. INTRODUCTION

The assessment of the water resources includes building comprehensive insight and knowledge about water inflows, storage, outflows, sediment yield and their relationships over time. Long-term simulation of runoff response from a watershed helps the water resources assessment and planning for the development of the watershed. The long-term runoff response from a watershed can be simulated with a properly chosen and calibrated hydrological model. A dependable calibration procedure is required to predict runoff response realistically for situations in which the data is limited [18]. Obtaining accurate and reliable results through a models is one of the challenges faced by many researchers. Many researchers agree that appropriate model choice and selection of the modeling methods is one of the most viable solutions [8]. Modeling requires several input parameters such as rainfall characteristics, soil characteristics, topography, vegetation, etc., which are distributed in both space and time. Therefore a distributed rainfall runoff model is more applicable than a lumped model. A distributed model differs from a lumped model according to use of domain. Dividing the watershed into various smaller sub-watersheds will provide a semi-distributed model by treating each sub-basin as a lumped model, joining it with certain river reaches. Though this type of modeling is very common and easy to understand, there are always certain limitations. For example, the model does not follow the laws of physics and the lumping of sub-basins result in extremely cumbersome data [24]. A semi-distributed model framework can be developed in the HEC-GeoHMS interface, an extension of ArcGIS developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) [23]. This allows for the easy creation of the basic basin parameters of a hydrologic model based on topographic data.

The Hydrologic Modeling System (HEC-HMS) is one of the most widely used simulation tools developed by the U. S. Army Corps of Engineers Hydrologic Engineering Center (HEC), and is designed to simulate the rainfall-runoff processes of dendritic drainage basins [22]. A soil moisture accounting (SMA) algorithm has been used to evaluate the performance of the HEC-HMS model for the Subarnekha River Basin. The results revealed high model efficiency, though it was reported that the use of the semi-annual model parameter sets improves the model efficiency as it accounts for varying hydrologic conditions [18]. Many studies have reported the use of the HEC-HMS model to simulate runoff response successfully in different basins worldwide [6, 10, 9, 25, 2]. However, very few studies have reported long-term hydrological simulation using HEC-HMS in Indian basins. Anticipating the importance of rainfall-runoff modeling for future water resource management, a study has been conducted to model stream flow using a continuous SMA algorithm in the HEC-HMS conceptual model for a mid-size river basin in India. Continuous hydrologic modeling obtained the hydrographs at its outlet as a result of a series of storms of long duration, also involving the rainless periods between storms [7]. Alternatively, event-based hydrologic modeling can be used to obtain the flood hydrographs at the outlet of the catchment in response to a storm.

II. STUDY AREA AND DATA ACQUISITION

The present study was conducted on Vamsadhara River Basin (Fig. 1), situated between the Godavari and Mahanadi River basins in India. The Vamsadhara River originates from the outermost boundary of the district of Kalahandi, a well-known drought-prone district of Orissa, and extends up to the Bay of Bengal over a distance of 254 km. The total catchment area of the basin, upstream to the point where it joins the Bay of Bengal, is 10,830 km² and lies within the geographical coordinates of 18° 15' to 19° 55' N latitudes and 83° 20' to 84° 20' E longitudes. The catchment upstream to the last gauging and discharge measurement station on the river at Kashinagar, comprised of 7,921 km², has been selected for the present study. The Vamsadhara River basin witnesses a tropical hot climate which is influenced by the southwest monsoons during the months of June through October. Occasionally, cyclones strike the basin due to the formation of depression in the Bay of Bengal. Due to its narrow shape, undulated terrain and other characteristics of the catchment, the runoff time is limited and flash floods frequently affect the area. The temperature variation in the plains of the basin is between 10°C to 43°C. The mean annual rainfalls of the Phulabani, Koraput and Ganjam districts in which the basin lies are 1280 mm, 1700 mm and 1500 mm, respectively. The area which falls in the districts of Phulabani and Koraput is primarily forest. The soil types in the basin are: mixed red and black, yellow, red sandy soils, coastal soils and some forest soils.

To implement the HEC-HMS model in the study area, spatial data such as a digital elevation model, soil map and land use land cover map are required in order to define the catchment boundary and the various physiological characteristics of the study area. The digital elevation model (DEM) was acquired from Shuttle Radar Tropical Meteorology (SRTM, 2008) with a spatial resolution of 90 m. The land use land cover map of the area was obtained from the National Remote Sensing Center (NRSC), ISRO on a scale of 1:50,000 and published under Bhuvan Thematic Services. The original land use land cover has been reclassified into seven different simpler classifications for the present study: built up/urban areas, agricultural lands, grasslands, forested land, water bodies, shifting cultivation and wastelands. The soil map of the study area was obtained from the National Bureau of Soil Science & Land Use Planning (NBSS&LUP).

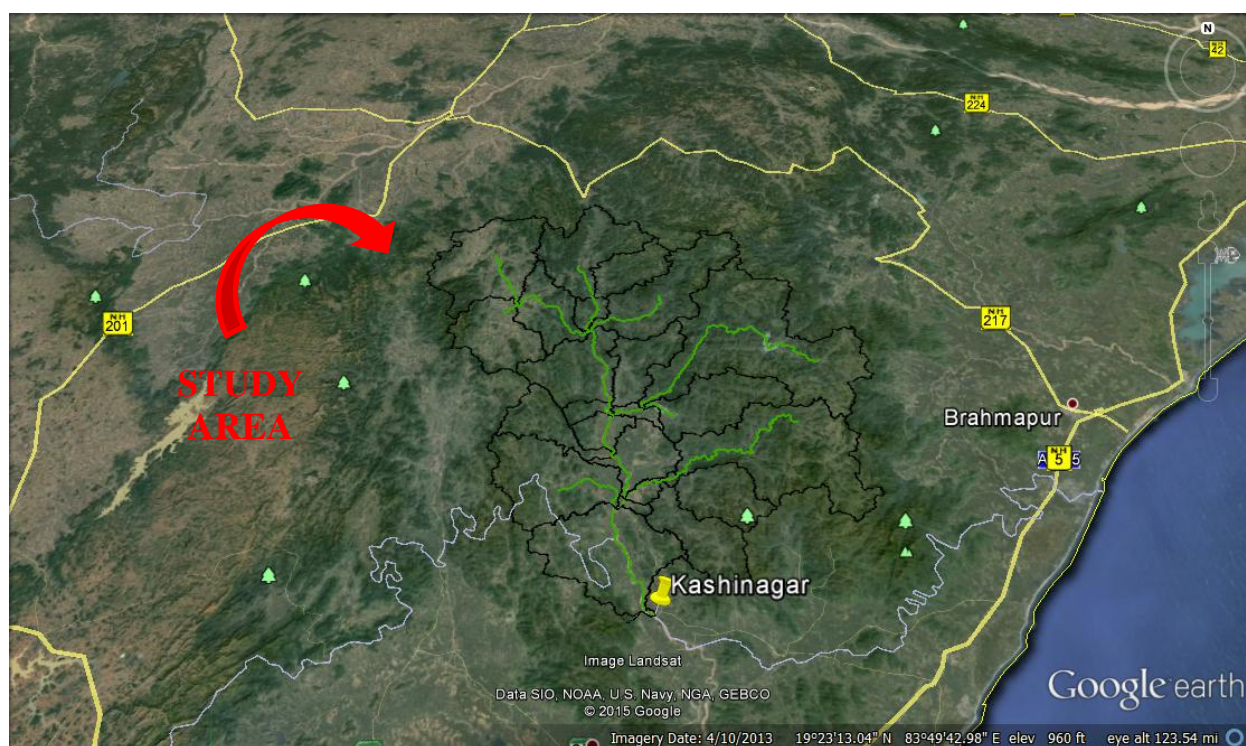


Fig. 1 Vamsadhara River Basin

Gridded rainfall data with a resolution of 0.5 X 0.5 degrees from the years 1984 to 1993 was obtained from the National Climatic Centre, India Meteorological Department, Pune. The stream flow data for the Kashinagar station for June through October from the years 1984-1993 was obtained from the Central Water Commission (CWC), Godavari Mahanadi Circle Division, South-Eastern Region, Bhubaneswar, Orissa. Due to the discontinuity of the dataset, stream flow data for the years 1984 to 1993 was acquired from the website of India-WRIS (Water Resource Information System of India), as developed by a joint effort between the Central Water Commission (CWC), Ministry of Water Resources, Govt. of India, New Delhi and Indian Space Research Organization (ISRO), Department of Space, Govt. of India, Bangalore. Daily temperature data was acquired from Aphrodite 2013 to calculate potential evapotranspiration (ET). Sunshine hour data was acquired as reported in the *Solar Radiation Handbook* by Solar Energy Centre, Ministry of Non-Renewable Energy and Indian Meteorological Department. The runoff coefficient value of an area reveals some of the characteristics under investigation. A summary of the annual hydrological data of the Vamsadhara River Basin is given in Table 1, below.

TABLE 1 SUMMARY OF ANNUAL HYDROLOGICAL DATA OF VAMSADHARA RIVER BASIN

Year	Annual Rainfall (mm)	Annual Observed Runoff (mm)	Runoff coefficients	Rainy Days
1984	1088.8	152.68	0.14	86
1985	1200.5	187.74	0.15	112
1986	1332.8	236.47	0.17	103
1987	1143.8	107.64	0.09	97
1988	1378.7	257.67	0.18	121
1989	1138.2	198.82	0.17	100
1990	2017.6	438.89	0.22	141
1991	1513.5	303.25	0.2	113
1992	1493.1	479.14	0.32	93
1993	1160.2	178.44	0.15	103

III. METHODOLOGY

A. Preparation of Precipitation and Evaporation Inputs

This work involved the conversion of the 0.5 X 0.5 degree gridded rainfall into station rainfall. Using the VBA program available in the Microsoft Office 10, the data was extracted for every grid that falls within the study area. The gridded rainfall was then converted into station rainfall for the sake of uniformity of the rainfall data for six stations which actually existed within the catchment, using a weighted inverse distance method [19].

Consideration of the ET loss may be neglected with event-based modelling, but cannot be neglected with the continuous SMA model as this model also considers the rainless periods. The evapotranspiration data was estimated based on monthly average values for the entire catchment using Thornwaite's method [1]. First, the gridded data acquired from the Aphrodite 2013 update was first processed in Matlab 2013(a) to obtain average monthly temperatures for various years. Then, using the relations given below, the monthly average ETs were estimated in the Microsoft Excel interface.

$$ET_o = 16 \times \left(\frac{10T_f}{5}\right)^a \left(\frac{N}{12}\right)\left(\frac{1}{30}\right) \quad (1)$$

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514} \quad (2)$$

$$a = (492390 + 17920I - 77.1I^2 + 0.675I^3) \quad (3)$$

where T_i is the mean monthly temperature ($^{\circ}\text{C}$), and N is the mean monthly sunshine hour. Monthly average ET values were entered manually in the HEC-HMS model with a coefficient value of 0.7 to compute the actual ET. Due to the lack of meteorological data, Thornwaite's method was adopted to estimate monthly average ET values. This method estimates ET based on daily temperature data and sunshine hours. This is advantageous for areas with limited data where only temperature data is available.

B. Catchment Delineation

The catchment area was delineated using HEC-GeoHMS 10.1 in ArcGIS 10.1, and different sub-basins and river networks have been created. Before a watershed boundary is formed, the raw DEM was pre-processed so that a well-defined watershed and river network could be delineated. It uses advanced GIS functions to segment watersheds into several hydrologically connected sub-watersheds. The number of sub-watersheds and the stream network that will be created depends upon the threshold value of the area provided by the user during watershed delineation. Once the delineation is complete, the basin has been divided into 15 sub-basins with a well-defined river network.

C. Soil Moisture Accounting (SMA) Method

The soil moisture accounting loss method uses five layers to represent the dynamics of water movement above and in the soil. The layers include canopy interception, surface depression storage, soil, upper groundwater, and lower groundwater, as shown in Fig. 2. Initial conditions for the five storage layers must be specified as the percentage of water in the respective storage layers prior to the start of the simulation. Maximum canopy storage represents the maximum amount of water that can be held on leaves before through fall to the surface begins. These values were obtained from GIS analysis of the LULC map. Surface storage represents the maximum amount of water that can pond on the soil surface before surface runoff begins. Surface runoff occurs when the storage is at full capacity and there is excess precipitation. These parameter values were obtained from GIS analysis of the soil map as derived from Table 2.

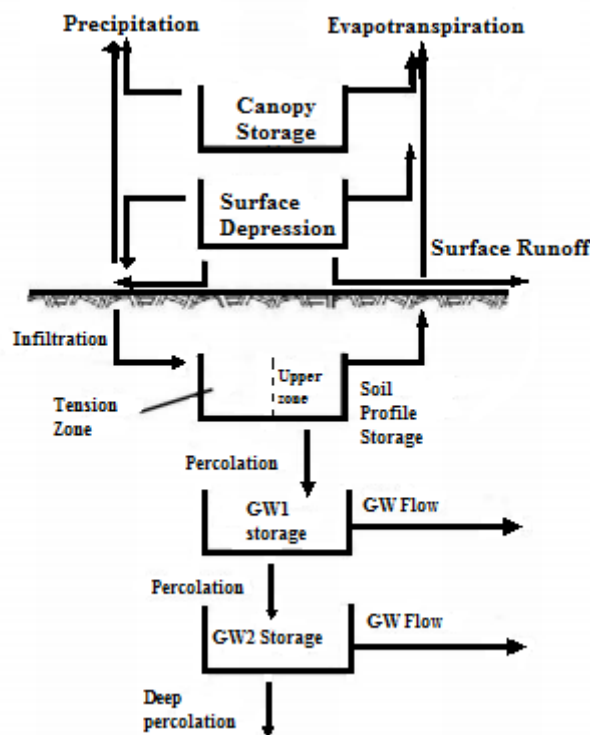


Fig. 2 Soil Moisture Accounting Model (HEC, 2000).

TABLE 2 STANDARD DEPRESSION STORAGE FROM BENNET (1998)

Description	Slope, %	Surface Storage, mm
Paved impervious	NA	3.2 - 6.4
Steep	> 30	1
Moderate to gentle	5-30	12.7 - 6.4
Flat, furrow	0-5	50.8

The maximum infiltration rate has been specified as the upper limit of the rate of water entry from surface storage into the soil. These values have been obtained from Table 3, and the saturation hydraulic conductivity is considered to be the maximum infiltration rate. The percentage of impervious areas was specified as the percentage of the area under urban civilization for each sub-basin using Google Earth with the aid of the LULC map. Soil storage was specified as the total storage of water available in the soil profile. These parameters have been derived from Table 3. Tension storage, another component of the upper soil layer parameter values, was derived from SPAW software by determining the field capacity of the soil based on different soil texture values. The soil percolation rate and the GW1 percolation rate have been obtained as the average hydraulic conductivity of all the sub-basins as obtained from SPAW software based on the soil texture. The GW1 and GW2 storage coefficient and storage depths were obtained from stream flow recession analysis of the historical stream flow data, described later in this paper. GW2 percolation rate parameter values were obtained during the calibration process.

D. Base Flow Computation

The inflection point on the receding limb of a hydrograph marks where the surface flow has stopped contributing to runoff [12]. After this point, the receding limb represents contributions from both interflow and groundwater flow. Recession analysis of the historical stream flow data provides the recession constant value of the stream flow [19].

$$Q_t = Q_0 K_r^t \quad (4)$$

where Q_t is the discharge at time t ; Q_0 is the initial discharge; and K_r is the recession constant of values less than unity.

The recession constant K_r consists of three components to account for the three types of storages as follows:

$$K_r = K_{rs} \cdot K_{ri} \cdot K_{rb} \quad (5)$$

where K_{rs} is the recession constant for surface storage; K_{ri} is the recession constant for interflow; and K_{rb} is the recession constant for base flow.

When plotted on a semi-log paper with discharge on the log scale, Eq. (4) will plot as a straight line and is reduced to Eq.

(6) for two different stages of storage.

$$\frac{Q_1}{Q_2} = K_r^{(t_1 - t_2)} \quad (6)$$

Using this equation, the recession constant can be determined from the stream flow historical data. The storage S_t remaining at any time t is obtained as follows:

$$S_t = \int_t^\infty Q_t dt = \int_t^\infty Q_0 e^{-at} = \frac{Q_t}{a} \quad (7)$$

Where

$$a = -\ln K_r \quad (8)$$

Hydrographs were chosen from different seasons and from storm events where no rain occurred for some time after the peak flow, and recession constant and storage parameters were determined [19].

TABLE 3 SOIL TEXTURE AND PROPERTIES [17]

Soil Texture	Porosity, cm ³ /cm ³	Saturated hydraulic conductivity (cm/hr)
Sandy	0.437	21
Loamy sand	0.437	6.11
Sandy loam	0.453	2.59
Loam	0.463	1.32
Silt loam	0.501	0.68
Sandy clay loam	0.398	0.43
Clay loam	0.464	0.23
Silty clay loam	0.471	0.15
Sandy clay	0.43	0.12
Silty clay	0.479	0.09
Clay	0.475	0.06

E. Modeling Framework

For the current study, an SMA algorithm was adopted for modeling the loss method base on a continuous time scale while the Clark UH method, exponential recession method and Muskingum routing method have been selected to model rainfall excess transform, baseflow and reach routing methods, respectively. The Clark Unit Hydrograph Method explicitly represents two critical processes of translation of excess rainfall and attenuation due to effects of storage in the sub-basins. The parameters required for the Clark UH transform method are concentration time and the storage coefficient. While time of concentration is obtained from the GIS processing of the basin, the storage coefficient was evaluated by calibration. The Muskingum routing method uses the principle of conservation of mass to route the flow along the river reach. It assumes a linear water surface with a non-level surface to account for increases in storage during flood rise and decreases in storage during flood fall. Travel time of the flood waves and a weighting factor is also added to achieve attenuation. It models the flood routing in a channel by accounting for prism and wedge storage. During flood rising, a positive wedge is incorporated into the model while a negative wedge is incorporated during the recession stage. The Muskingum routing parameters were calibrated and evaluated for simulation of the runoff hydrograph. The base flow in the basins is computed using the base flow exponential recession method, as previously described.

F. Sensitivity Analysis

Some model parameters are very sensitive, so that a small change in their value may result in huge differences between the observed and simulated volumes. Therefore, the most sensitive parameters of the model need to be precisely estimated in order to make accurate predictions. Thus, determination and discovery of the sensitive parameters is one of the most important tasks in rainfall-runoff modeling. Initially, the model is run with the base data, i.e. the initial estimates obtained using the methods explained in earlier sections. Thereafter, out of the various soil moisture accounting parameters, one parameter at a time was varied and analysed from -50% to 50% with increments of 10%, keeping all other parameters constant. The model was used again and the output values were analysed to determine variation with respect to the initial estimates of the parameters. Greater percentage change in the simulated volumes represents greater variable sensitivity. In this manner, the sensitivity of each parameter of the SMA model was evaluated and parameters were ranked from most to least sensitive.

G. Calibration and Validation

A model is considered credible only when it can reliably estimate stream flow as compared to observed stream flow. The model was calibrated for the identified sensitive parameters to achieve good agreement between the simulated and observed data. Optimization trials available with the HEC-HMS model have been used for optimizing the initial estimates of the model parameters. For the present study, the sum of square residual method was used as an objective function with the Nelder-Mead method as the search method for optimization. The auto-calibration process in the HEC-HMS may not converge to desired

optimum results, so the model was calibrated with both manual and auto calibration. Generally, manual calibration provides the range of the parameters while the auto-calibration process optimized the result. After the model is calibrated, the model must be validated for another dataset so as to estimate the accuracy of the model.

H. Model Evaluation

Model evaluation can be achieved by analyzing the efficiency index, i.e. the goodness of fit. The criteria for model evaluation adopted in this study include the following:

1. Percentage Error in simulated volume (PEV)

$$PEV = \frac{Vol_o - Vol_c}{Vol_o} \times 100 \quad (9)$$

2. Percentage error in simulated peak (PEP)

$$PEP = \frac{Q_{po} - Q_{pc}}{Q_{po}} \times 100 \quad (10)$$

3. Coefficient of determination (iR²)

$$R^2 = \left[\frac{\sum_{i=1}^n (y_i^{obs} - y_{mean}^{obs})(y_i^{stm} - y_{mean}^{stm})}{\sqrt{\sum_{i=1}^n (y_i^{obs} - y_{mean}^{obs})^2} \sqrt{\sum_{i=1}^n (y_i^{stm} - y_{mean}^{stm})^2}} \right]^2 \quad (11)$$

4. Index of agreement (id)

$$d = 1 - \frac{\sum_{i=1}^n (y_i^{obs} - y_i^{stm})^2}{\sum_{i=1}^n (|y_i^{stm} - y_{mean}^{obs}| + |y_i^{obs} - y_{mean}^{obs}|)^2} \quad (12)$$

where Vol_o and Vol_c are the observed and computed volumes, respectively, in mm or cubic meters; Q_{po} and Q_{pc} are the observed and computed peak flow rates, respectively, in cubic meter per second; y_i^{obs} and y_i^{stm} are the flow rate values for observed and simulated stream flow, respectively, at the i^{th} time step; and y_{mean}^{obs} and y_{mean}^{stm} are the average flow rate values of observed and simulated stream flows, respectively. The overall model performance of HEC-HMS has been assessed by Nash-Sutcliffe model efficiency (EFF) criterion recommended by ASCE Task Committee in 1993. It is given as follows:

$$EFF = \frac{\sum_{i=1}^n (Q_{oi} - \bar{Q}_o)^2 - \sum_{i=1}^n (Q_{ci} - \bar{Q}_o)^2}{\sum_{i=1}^n (Q_{oi} - \bar{Q}_o)^2} \quad (13)$$

where Q_{oi} is the i^{th} ordinate of the observed discharge (m³/s); Q_{ci} is the i^{th} ordinate of the computed discharge (m³/s) and \bar{Q}_o is the mean of the observed discharge (m³/s). Table 4 was [13] used to determine the performance evaluation of the HEC-HMS model in the study area. The range adopted for performance rating using other statistical criteria is listed in Table 5.

TABLE 4 GENERAL PERFORMANCE RATINGS FOR RECOMMENDED STATISTICS [13]

Sl. No.	Performance Rating	EFF	PEV (%)
1	Very good	0.75 to Unity	< ± 10
2	Good	0.65-0.75	± 10-± 15
3	Satisfactory	0.50-0.65	± 15-± 25
4	Unsatisfactory	< 0.50	> ± 25

TABLE 5 GENERAL PERFORMANCE RATINGS FOR RECOMMENDED STATISTICS (MORIASI, 2007)

Sl. No.	Performance Rating	PEP (%)	R ²	d
1	Very Good	<15%	0.75 to 1.00	0.90 to 1.00
2	Good	15% to 30%	0.65 to 0.75	0.75 to 0.90
3	Satisfactory	30% to 40%	0.50 to 0.65	0.50 to 0.75
4	Unsatisfactory	>40%	<0.50	<0.5

IV. RESULTS

A. Sensitivity Analysis

Sensitivity analysis of the HEC-HMS model with respect to the soil moisture accounting SMA parameters is one of the objectives of this study. All SMA parameters (except the five initial conditions for the five storage layers in the SMA model) were analyzed within -50% to +50% variation in increments of 10%. Each parameter was varied individually while keeping all

other parameters constant. The percentage changes in simulated volume were then plotted against the percentage variation of each parameter, as shown in Fig. 3. From this analysis, it was determined that soil storage is the most sensitive parameter for simulated stream flow during the calibration period, and the GW2 percolation rate was the least sensitive parameter. Each parameter was ranked according to their sensitivity according to the change in simulated volume, as shown in Table 6. In some of the studies for the Dale Hollow basin [9], Cumberland River basin in USA [3] and for the Blue Nile, Kulfo and Bilate catchments in the Abaya-Chamo sub-basin, soil storage was reported as the most sensitive parameter. Tension zone storage and soil percolation parameters were also identified as sensitive parameters in previous studies. As illustrated by Fig. 3 and Table 6, impervious area is one of the most sensitive parameters, which must be accurately determined for successful modeling. However, evaluation of this parameter requires close observation and field surveys for accurate determination, which could not be obtained in this study due to fund constraints.

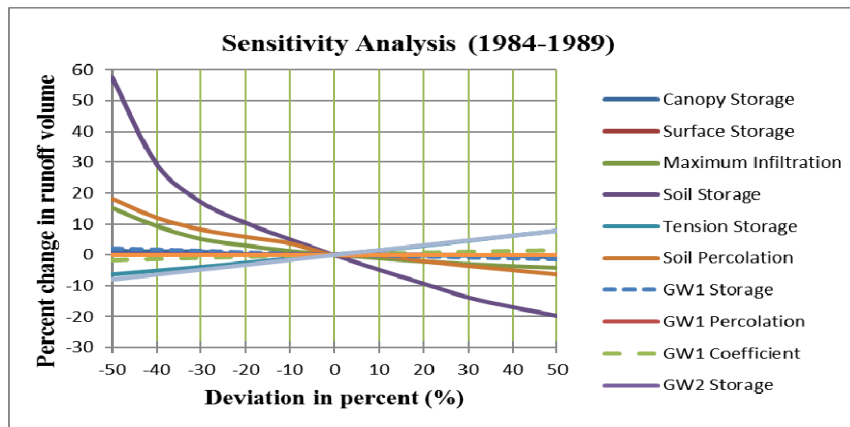


Fig. 3 Sensitivity analysis of the HEC-HMS model for the calibration period

B. Calibration and Validation of the Model

The calibration of the parameters of the model was conducted using stream flow data from the Kashinagar site from 1984 to 1989. The parameters were first calibrated using auto-calibration methods available in the HEC-HMS model; fine-tuning of parameters was conducted using manual calibration as well. Twelve model parameters were calibrated using stream flow data at the last gaging site, Kashinagar. GW1 and GW2 storage depths and coefficients were obtained from the base flow computation analysis as reported earlier. Some of the parameters have been calibrated individually for different years, and the most accurate optimized value were obtained and used for all other years. The optimized values of the model parameters obtained from calibration for the year 1984 have been found to be the most accurate, and thus was adopted for the remaining years. Comparison of hydrographs representing simulated and observed stream flow for the calibration period (1984 to 1989) is shown in Fig. 4. The comparison illustrates close agreement between the simulated stream flow and observed stream flow in terms of timing of peak and peak value, as well as rising and recession of stream flow. During calibration, various parameters were optimized to obtain a closer agreement between the simulated and observed stream flow. Table 7 shows the various optimized parameters for the study area.

TABLE 6 SENSITIVITY RANKING OF SMA MODEL PARAMETERS

Model Parameter	Definition	Model Sensitivity Ranking
Soil Storage	Max. amount of water that could held by the soil profile, mm	1
Soil Percolation	Average rate of the percolation of water from soil into the GW1 layer, mm/hr	2
Maximum Infiltration	Maximum rate at which water can enter the soil profile, mm/hr	3
Impervious Area	Built up area which directly converts rainfall into runoff without any loss, %	4
Tension Storage	Portion of the soil storage from which water in this storage is lost through evapotranspiration only, mm	5
GW1 Storage	Storage volume in mm in GW1 layer	6
GW1 Coefficient	GW1 delayed time, hr	7
Canopy Storage	Max. storage that can be intercepted by canopy, mm	8
GW1 Percolation	Percolation rate to GW2 layer, mm/hr	9
Surface Storage	Maximum storage in depression storages before runoff starts, mm	10
GW2 Storage	Storage volume in mm in GW2 layer, mm	11
GW2 Coefficient	GW2 delayed time, hr	12
GW2 Percolation	Deep percolation from GW2 layer, mm/hr	13

TABLE 7 OPTIMIZED MODEL PARAMETERS

Sub basin	Max. canopy, mm	Max. surface, mm	Max. infiltration, mm/hr	Soil storage, mm	Tension storage, mm	Soil percolation, mm/hr	GW1 percolation, mm/hr	GW2 percolation, mm/hr	Storage coefficient, hr	K _r
W300	5.23	3.39	8.5	459.85	164.97	2.432	1.63	1.2	9.66	0.923

W290	3.09	3.88	4.58	514.95	175.07	0.21	0.2	0.15	2.04	0.946
W280	1.67	1.60	8.09	416.22	162.23	1.6	1.6	1.56	8.08	0.946
W270	1.5	1.32	15.55	450.66	138.89	1.8	1.8	1.71	12.3	0.946
W260	1.14	0.65	6.626	449.16	151.81	0.1	0.1	0.113	27.5	0.946
W250	1.09	1.89	40.27	450	89.571	1.9	1.95	1.95	7.8	0.946
W240	1.99	1.02	18.99	439.74	124.61	1.95	1.9	1.25	9.86	0.946
W230	1.97	0.80	22.76	439.6	119.06	1.52	1.23	1.65	10.73	0.946
W220	2.54	0.56	73.01	457	60.571	1.23	1.52	1.28	1.79	0.946
W210	2.12	0.68	14.65	455.28	144.96	0.87	1.18	0.5	15.55	0.946
W200	1.59	0.59	26.39	440.04	118.25	1.15	0.29	0.5	7.39	0.946
W190	1.92	1.98	61.41	454.24	76.181	1.36	1.5	0.56	13.54	0.946
W180	2.13	1.50	23.74	440.5	116.76	1.65	1.9	1.26	14.58	0.946
W170	2.07	1.68	26.99	441.76	115.97	1.26	1.6	1.36	13.51	0.946
W160	1.75	1.20	37.65	457.48	114.54	1.64	1.34	1.36	12.34	0.946
Reach	K hr	X	-	-	-	-	-	-	-	-
R40	2.63	0.25	-	-	-	-	-	-	-	-
R60	28.055	0.48	-	-	-	-	-	-	-	-
R90	29.986	0.29	-	-	-	-	-	-	-	-
R100	27.236	0.44	-	-	-	-	-	-	-	-
R110	21.041	0.38	-	-	-	-	-	-	-	-
R140	1.37	0.28	-	-	-	-	-	-	-	-
R150	10.486	0.48	-	-	-	-	-	-	-	-

Model validation involves running a model using the same input parameters as determined by the calibration process. With the calibrated parameters as listed in Table 7, the model was executed for the validation period (1990 to 1993) to check the ability of the model to accurately predict runoff at the Kashinagar gaging station. Similarly, for the validation period (1990 to 1993) comparison of hydrographs between simulated and observed stream flow is shown in Fig. 5. The comparison illustrated close agreement between the simulated stream flow and observed stream flow in terms of timing of peak and peak value, as well as the rising and recession of the stream flow. The model performed very well when the entire data period was considered, while the model runs for individual years displayed some discrepancies such as recession of the hydrographs and initial hydrographs at the start of the post-monsoon season (June), clearly visible in the years 1992 and 1993. Such discrepancies revealed the need to parameterize the model according to the varying seasons. All the model parameters do not remain constant throughout the year; instead, some vary as the season changes. Thus, seasonal parameterization, which is out of the scope of this study, might improve the performance of the model.

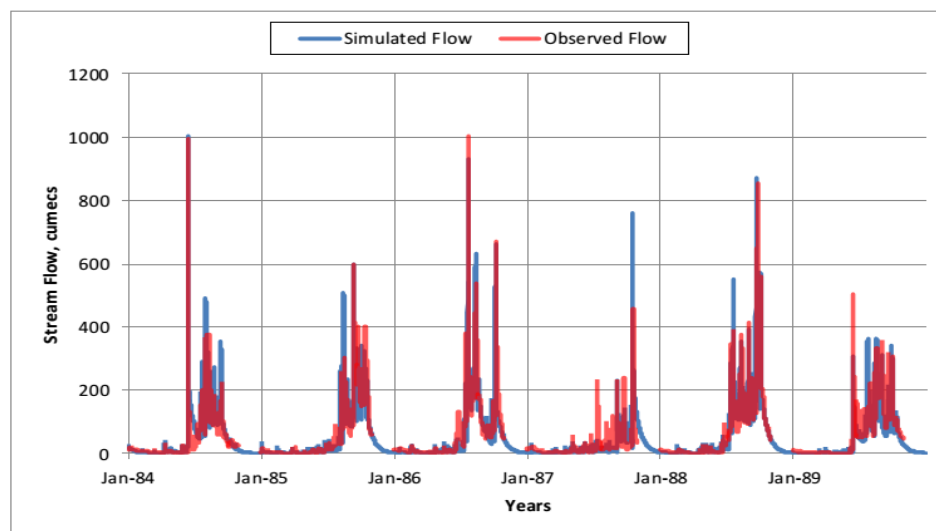


Fig. 4 Daily observed and simulated discharge for entire calibration period (1984-1989)

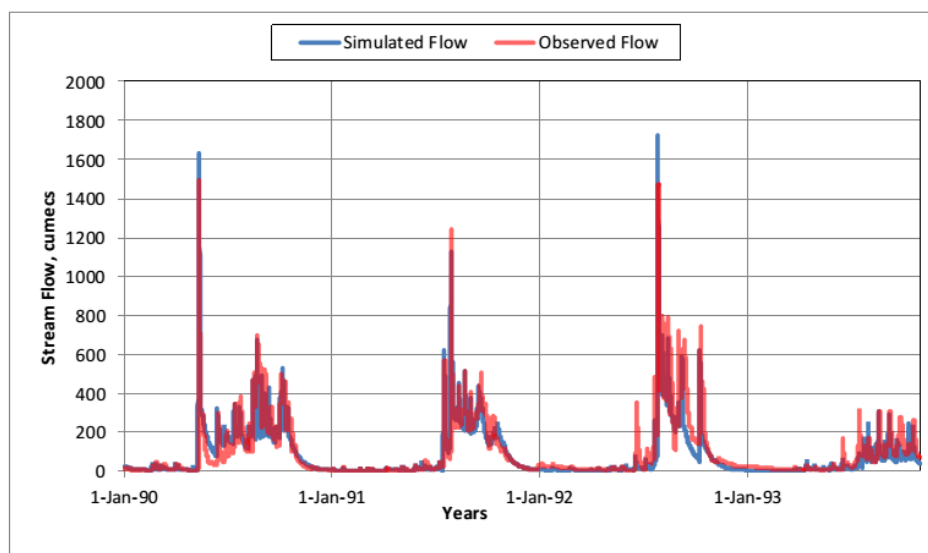


Fig. 5 Daily observed and simulated discharge for entire validation period (1990-1993)

C. Evaluation of the Model

Evaluation of the model performance was undertaken on the basis of individual years as well as the calibration and validation periods in their entirety. Time series of simulated and observed flows were taken from the results of simulation run of the soil moisture accounting HEC-HMS model of the Vamsadhara River basin, and were then analyzed in Excel to evaluate the model performance. The evaluation was undertaken based on various statistical parameters such as the Nash-Sutcliffe Efficiency (EFF), percentage error in volume (PEV), percentage error in simulated peak (PEP), coefficient of determination (R^2), and index of agreement. The first evaluation criteria used is the Nash-Sutcliffe Efficiency (EFF), (Nash and Sutcliffe, 1970), found to be one of the most widely-used criteria for indicating the overall fit of a hydrograph. EFF expresses the fraction of the measured stream flow variance that is reproduced by the model. The value of EFF varies from very high negative values to unity; unity is the optimal value. Coefficient of determination R^2 is also a frequently used criterion for model evaluation. It is a statistical measure of how well the regression line approximates the real data points, i.e. how well the model simulates as compared to the observed flow. It varies from 0 to 1 with higher values indicating good fit. The values of PEV, PEP, d, R^2 and EFF obtained during calibration are 2.64%, 0.21%, 0.94, 0.71 and 0.701, respectively. Similarly during validation of the model, the model evaluation criteria for PEV, PEP, d, R^2 and EFF were found to be 12.33%, -15.2%, 0.93, 0.78 and 0.762, respectively. The model was evaluated using the criteria given in Tables 4 and 5. Various statistical evaluations of the model obtained from the calibration and validation of the continuous SMA algorithm in HEC-HMS conceptual model is illustrated in Table 8. Table 8 includes the performance evaluation of the SMA HEC-HMS model for the calibration and validation periods, as well as the model performances for individual years. According to Tables 4 and 5, the model performance ranges from good to very good model, except for the year 1987, which may be credited to various uncertainties in the datasets. Based on the EFF, PEP, PEV and R^2 values of the model, the model performance is satisfactory. The index of agreement (d) ranges from 0.81 to 0.95, which also indicate good model performance.

TABLE 8 PERFORMANCE EVALUATION OF THE HEC-HMS MODEL

Year	PEV (%)	PEP (%)	R^2	d	EFF
1984	-2.18	-0.98	0.80	0.94	0.745
1985	11.06	8.28	0.74	0.89	0.732
1986	10.44	8.42	0.83	0.95	0.819
1987	0.028	-65.2	0.44	0.81	0.01
1988	14.5	-1.29	0.72	0.91	0.709
1989	+13.79	27.70	0.75	0.92	0.729
1990	-3.92	-9.22	0.71	0.92	0.692
1991	-7.39	11.30	0.84	0.95	0.810
1992	32.50	-16.02	0.85	0.94	0.797
1993	33.44	1.04	0.58	0.82	0.508
Calibration	2.64	0.21	0.71	0.94	0.701
Validation	12.33	-15.2	0.78	0.93	0.762

D. Discussion

The soil moisture accounting (SMA) method adopted for rainfall-runoff modeling of the Vamsadhara River basin is a data intensive conceptual model which must be calibrated well for accurate prediction of runoff. Various data involved in SMA modeling requires careful observation and field surveys to achieve a high level of accuracy. However, no such observations

and surveys have been conducted for the present study; instead all data was obtained from secondary sources acquired from various organizations. With such data being used in the modeling of the watershed, the results obtained are highly satisfactory. Representing a continuous modeling, evapotranspiration plays an important role which can typically be neglected with event-based modeling assuming zero evapotranspiration during rainfall. Due to the unavailability of data such as humidity, wind speed, etc., evapotranspiration was estimated by Thornthwaite's method. A limitation cited in Alkaeed (2006) for Thornthwaite's method apparently provide underestimations in arid areas while the overestimating in humid areas might also affect study results. During the sensitivity analysis of the soil moisture accounting (SMA) parameters, percentage of impervious area was found to be one of the most sensitive parameters for accurate prediction of runoff at the basin outlet. However, in the absence of data on imperviousness in different discretized sub-basins, a rough estimate was obtained using high resolution google earth images. The percentage error in volume (PEV) for the developed HEC-HMS model for the Vamsadhara River basin in this study ranges from -2.18% to +33.4% with satisfactory model performance. In some years, simulated volume and peak are underestimated while some years show overestimation of the peak and volume with average values of 2.64% and 12.33% errors in volume and 0.21% and -15.2% errors in peak, indicating very good and good model performance, respectively. The Nash-Sutcliffe efficiencies of the model range from 0.692 to 0.819, which indicates good to very good model performances. However, the years 1987 and 1993 depict very low model efficiencies, which could be attributed to various uncertainties in the datasets involving both precipitation and stream flow. The model can be further improved by using multiple stream flow gauging stations. This will enhance the model calibration inside the catchment leading to more accurate estimation of the model parameters for each sub-basin. The modeling study was conducted according to daily rainfall and discharge, which is again the maximum limit for the HEC-HMS model. The time of concentration for most of the sub-basins was less than 24 hours, and a computational time less than 24 hours improves the model performance. Therefore, it is recommended to check the modeling of the Vamsadhara River basin using the HEC-HMS conceptual model by incorporating hourly rainfall and discharge data.

V. CONCLUSIONS

The HEC-HMS conceptual model was successfully calibrated and validated for the Vamsadhara River basin on a continuous time scale. Sensitivity analysis of the model reveals that soil storage, soil percolation rate, maximum infiltration rate, percentage impervious area and tension soil storage were found to be the most sensitive parameters, with soil storage being the most sensitive and GW2 percolation rate be the least sensitive. The overall model efficiencies (EFF) given by Nash-Sutcliffe Efficiency criteria are 0.701 and 0.762 for the calibration and validation periods, respectively, indicating a good model fit. Percentage error in volume (PEV) for the calibration and validation periods were found to be 2.64% and 12.33%, respectively, which indicates good model fit. On the basis of percentage error in peak (PEP) criteria, which gives an error of 0.21% and -15.2% for the calibration and validation periods, respectively, the performance of the model can be rated as good. The coefficient of determination (R^2) for the calibration period was found to be 0.71 and 0.78 for the validation period, indicating good model fit. Similarly, the index of agreement (d) has been found to be 0.94 and 0.93 during the calibration and validation periods, respectively, indicating good model fit. Based on overall evaluation, it could be concluded that the SMA algorithm available in the HEC-HMS model can be used to model stream flow in the Vamsadhara River basin.

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