# *Stream Flow Prediction in Ungauged Basin: Calibration and Uncertainty Analysis Using SWATCUP*

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*Abstract*— **Predicting hydrologic quantities such as rainfall, runoff, sediment, nutrients etc is a major challenge for hydrologists in developing countries where a large number of watersheds are ungauged. This study is carried out to analyze the differences in stream flow predictions of ungauged watersheds using Soil and Water Assessment Tool (SWAT) by varying the threshold areas for sub-basin delineation and Hydrologically Response Unit (HRU) distributions. SWAT is implemented in hydrologically similar sub basins of Vamanapuram river basin located in Trivandrum District, Kerala. A coefficient of variation based homogeneity test is carried out to determine hydrologically homogenous catchments. Six models are developed by varying the threshold area of sub basin delineation and HRU definition. The result shows better agreement in bracketing the measured data for the model which uses half of the default area of sub-basin delineation and multiple HRU distribution. The differences of stream flow predictions in Valayinkil sub-basin of Vamanapuram watershed are also studied by varying the threshold levels of HRU distributions. Lower threshold level of HRU distribution gives better performance measures for stream flow predictions.**

***Keywords—SWAT, SUFI-2, ungauged, predictive uncertainty***

## I. INTRODUCTION

Stream flow is the main hydrological factor which influences the hydrological characteristics in many ways and shows their importance in balanced agricultural watersheds. Estimation of stream flow in ungauged catchments is an important issue in surface water hydrology. Ungauged basins are ones with inadequate records (in both data quantity and quality) of hydrological observations [5]. Hydrological models have large number of parameters that are estimated before the application to a specific watershed. Parameter uncertainty of the model can be minimized through model calibration by using observed data from the watershed. Calibration of the model for ungauged basins is not possible due to lack of observed data [6]. Model calibration reduces the parameter uncertainty, which in turn reduces the uncertainty in the simulated results. Hence in model calibration, selected parameters are allowed to vary within predefined bounds until a sufficient correspondence between the model outputs and actual measurements are obtained.

Schuol and Abbaspour [1] developed a method which used a sequential uncertainty fitting algorithm (SUFI-2) for calibration and uncertainty analysis of the Soil and Water Assessment Tool (SWAT) to model a four million km$^2$ area in West Africa. Migliaccio and Chaubey [2] conducted a study to identify the differences in annual predicted flow and sediment response of a watershed considering two sub-basin delineation with six different HRU distribution using SWAT. Abbaspour *et al*. [3] conducted a study describing SWAT-Calibration and Uncertainty Program and the three procedures such as Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), and SUFI-2. Peng *et al.* [4] also evaluated the performance of the SWAT for hydrologic modeling in the Xixian basin using SUFI-2, GLUE and ParaSol. Latin hypercube one-factor-at-a-time (LH-OAT) method implemented in SWAT is used for sensitivity analysis in this study. Cibin *et al.* [5] developed a method to quantify stream flow predictive uncertainty of SWAT for ungauged basins by deriving the probability distribution of the models sensitive parameters from a gauged basin and transferring the distribution to ungauged basin for stream flow prediction. Piman and Babel [6] presented a study to predict rainfall and runoff in an ungauged basin located in a mountainous region of Northern Thailand by using weather radar to estimate rainfall and a modelling approach to simulate rainfall-runoff processes. The calibrated rainfall- runoff relationship was used to estimate rainfall over a gauged basin and an assumed ungauged basin. Vishal *et al.* [7] conducted a study on calibration and parameter uncertainty analysis for a distributed model based on generalized likelihood measures such as SUFI-2 and GLUE.

From the above studies it is seen that model parameters are estimated and predictions of stream flow are assessed in gauged and ungauged watersheds. The present study is carried out to analyze the differences in stream flow predictions of ungauged watersheds using SWAT by varying the threshold areas for sub-basin delineation and HRU distributions. The major objectives of the study include the determination of hydrologically homogeneous basins using coefficient of variation (Cv) based homogeneity test. The differences of stream flow predictions are analyzed by varying the threshold areas of sub-basin delineation and Hydrologically Response Unit (HRU) distribution of Valayinkil sub-basin. Differences of monthly predicted flow are also analyzed by varying the threshold levels of HRU distributions. Finally the performance of SWAT in simulating stream-flow of ungauged basins is also evaluated.

## II. METHODOLOGY

In this study, two hydrologically independent sub basins of Vamanapuram river basin, Valayinkil and Mylamoodu sub basin are considered. Although both the basins are gauged, one of them is assumed as ungauged for the analysis. Mylamoodu basin is considered as gauged and Valayinkil as ungauged basin. The study develops six SWAT models by varying the threshold areas of sub-basin delineation and HRU distributions. Default area and half of the default area of SWAT interface is provided for sub-basin delineation. This default value of area depends on the project at hand. Three HRU distributions i.e. Dominant land use/ Soil/ Slope, Dominant HRU and Multiple HRU are selected for the study. SUFI-2 (Sequential Uncertainty Fitting Algorithm) program is used for calibration and uncertainty analysis. The differences in stream flow prediction of Valayinkil sub-basin is also evaluated by varying the threshold levels of HRU distribution in Mylamoodu sub-basin. Flowchart representing the detailed methodology is shown in Fig. 1.

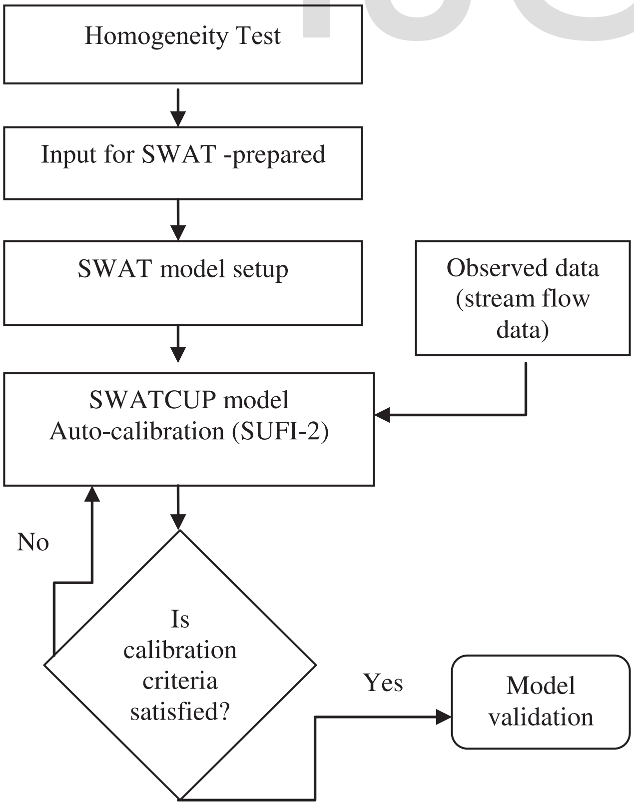

Fig. 1. Flow chart showing the detailed methodology

### *A. Homogeneity Test*

The preliminary identified regions were checked by Coefficient of variation based homogeneity test. Higher the values of mean coefficient of variation CV and site to site coefficient of variation of the coefficient variation CC, the lower the homogeneity for the region considered. The region is declared to be homogeneous if CC is less than 0.30.

### *B. SWAT Model*

The primary objective of Soil and Water Assessment Tool (SWAT) is to predict the impact of agricultural or land management on water, sediment, and agricultural chemical yields in ungauged basins. In SWAT, a watershed is divided into multiple sub basins, which are further discretized into units of unique soil/land use characteristics called hydrological response units (HRUs) [3]. HRUs are composed of a unique combination of homogeneous soil properties, land use, and slope. The runoff is estimated separately for each HRU and routed to obtain the total runoff for the watershed. Surface runoff from daily rainfall is estimated by using a soil conservation service (SCS) curve number method.

The key water balance equation used in SWAT is as follows;

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

where $SW_t$ = final soil water content (mm of water); $SW_0$ = initial soil water content on day i (mm of water); t = time (days); $R_{day}$ = amount of precipitation on day i (mm of water); $Q_{surf}$ = amount of surface runoff on day i (mm of water); $E_a$ = amount of evapotranspiration on day i (mm of water); $w_{seep}$ = amount of water entering the vadose zone from the soil profile on day i (mm of water); $Q_{lat}$ = lateral flow from soil to channel; and $Q_{gw}$ = amount of return flow on day i (mm of water) [2].

Threshold based stream definition is used to define the minimum size of the sub-basin during watershed delineation. Smaller the sub-basin size, more detailed is the drainage network delineated. Default area and half of default area of SWAT interface is used for sub-basin delineation. SWAT requires land use and soil data to determine the area and the hydrologic parameters of each land soil category simulated within each watershed. HRU distribution involves three optional operations such as Dominant Land use/soil/slope, Dominant HRU and Multiple HRU. In Dominant Land Use/ Soil/ Slope Classification, the dominant land use, dominant soil, and dominant slope classes in the sub basin are simulated in the HRU. Each sub basin is provided with only one HRU. In the case of Dominant HRU definition, dominant unique combination of land use, soil, and slope class in the sub basin are used to simulate the HRU. And Multiple HRU distribution creates multiple HRUs in each sub basin.

### *C. Calibration and Validation of SWAT*

Calibration of the model is performed using SUFI-2 Program incorporated in SWATCUP (SWAT Calibration and Uncertainty Program). In SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. The degree to which all uncertainties are accounted for is quantified by a measure referred to as the P-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU) [7]. The percentage of data captured (bracketed) by the prediction uncertainty is a good measure to assess the strength of our uncertainty analysis. The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling, disallowing 5% of the very bad simulations [1]. Another measure quantifying the strength of a calibration/uncertainty analysis is the R-factor, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. In each step, previous parameter ranges are updated by calculating the sensitivity matrix, equivalent of a Hessian matrix, followed by the calculation of covariance matrix, 95% confidence intervals of the parameters, and correlation matrix. Parameters are then updated in such a way that the new ranges are always smaller than the previous ranges. The goodness of fit and the degree to which the calibrated model accounts for the uncertainties are assessed by the above two measures. Theoretically, the value for P-factor ranges between 0 and 100%, while that of R-factor ranges between 0 and infinity.

The SUFI-2 algorithm consists of the following procedures:

1) In the first iteration, an objective function g and the physically meaningful ranges of parameters to be optimized are defined. The objective function formulated in this study is the Nash-Sutcliff (NS) coefficient between the measured and simulated discharges.

2) Latin hypercube sampling is conducted and the corresponding objective function is calculated. In each sampling round, the sensitivity matrix, J, of g and the parameter covariance matrix, C,are calculated from

$$J_{ij} = \frac{\Delta g_i}{\Delta b_j} \qquad (2)$$

$$i=1, 2....C_2^n, \quad j = 1,...m$$

$$C = s^2_g (J^T J)^{-1} \qquad (3)$$

where $C_n^2$ is the number of rows in the sensitivity matrix (equal to all possible combinations of two simulations), and j is the number of columns (number of parameters), $s^2_g$ is the variance of the objective function values resulting from the n runs. The estimated standard deviation and 95% confidence interval of a parameter $b_j$ is calculated from the diagonal elements of C.

$$s_j = \sqrt{C_{jj}} \qquad (4)$$

$$b_{j,\ lower} = b_j^* - t_{v,0.025}\, s_j \qquad (5)$$

$$b_{j,\ upper} = b_j^* + t_{v,0.025}\, s_j \qquad (6)$$

3) In this step, the 95PPU is calculated for all of the variables and the average distance between the upper and the lower 95PPU and the R-factor are calculated.

Each iteration is carried out with 50 simulations. The procedure is repeated with different iterations until the P-factor approaches to 100% and R-factor to zero. The results obtained from the SWAT model was tested against the measured data using statistical measures such as Correlation coefficient (R), Nash Sutcliffe Efficiency (NSE), Mean Square Error (MSE), Root Mean Square Error (RMSE), Observation standard deviation ratio (RSR) and Percent Bias (PBIAS).

## III. STUDY AREA

The study is carried out in the Valayinkil and Mylammodu sub basins of Vamanapuram River basin located in Trivandrum District. Valayinkil and Mylamoodu lies at the upstream portion of the river basin with an area of 49 sq km and 88.67 sq km respectively. Map showing the study area is shown in Fig. 2. Land use map and Soil map were collected from Kerala State Land use Board, Trivandrum. Climate data such as daily temperature data, solar radiation data, relative humidity data and wind speed data for the year 2000 to 2007 were collected from India Meteorological Department (IMD) Trivandrum and Pune. Daily rainfall and runoff data of Valayinkil and Mylamoodu stations were collected from Jalabhavan, Trivandrum. The model was set up for 8 years from 2000 to 2007, out of which the first 2 years were considered as model's warm up period. Data from 2002 to 2004 is used for calibrating the model and 2005 to 2007 data is used for validation.

## IV. RESULTS AND DISCUSSIONS

The similarity in hydrological response of the Valayinkil and Mylamoodu sub-basins is analysed using Cv based homogeneity test and the value obtained is 0.23 which is less than 0.3. The spatial inputs needed for SWAT simulation were prepared using Arc-GIS 10.1. Digital Elevation Model (DEM), land use map and soil map of Mylamoodu sub-basin were prepared.

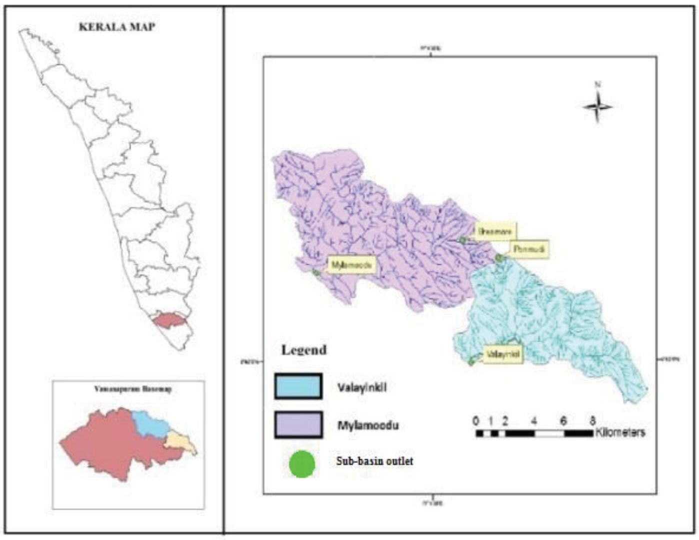

Fig. 2. Map showing the study area.

### *A. Varying the Threshold Areas of Sub-Basin Delineation and HRU Distribution of Valayinkil Sub-Basin*

SWAT model was prepared for different cases by varying the default area of SWAT interface for sub-basin delineation and HRU definition and the details are shown in Table 1. Model 1 denotes SWAT model with default area of sub-basin delineation and Dominant land use/ Soil/ Slope classification for HRU definition. Model 2 represents SWAT model with default area of sub-basin delineation and Dominant HRU classification for HRU definition. Model 3 represents default area of sub-basin delineation and Multiple HRU classification for HRU definition. Model 4 denotes half of default area of sub-basin delineation and Dominant land use/ Soil/ Slope classification for HRU definition. Model 5 represents half of default area of sub-basin delineation and Dominant HRU classification for HRU definition. Model 6 indicates half of default area of sub-basin delineation and Multiple HRU classification for HRU definition.

Default area (160 Ha) of sub-basin delineation of SWAT interface in Mylamoodu watershed resulted in 33 sub-basins and half of the default area (80 Ha) resulted in 55 sub-basins. Sensitivity analysis was carried out using 26 parameters. It is observed that the sensitive parameters were mostly responsible for the model calibration and parameter changes during model iteration processes. The remaining parameters had no significant effect on stream-flow simulations. Changes in their values do not cause significant changes in the model output [4]. Hence after the first iteration, only four parameters were varied within the ranges, keeping all other parameters with a fixed range of values. Calibration is performed using SUFI-2 program. In SUFI-2 procedure, a threshold value for the objective function (NSE) is used to reduce the range of parameter for each iteration. From different literature reviews, a threshold value 0.3 is assigned for the objective function. Hence a value of 0.3 is used for all the six models. The progressive improvement in uncertainty with likelihood value plotted against their frequency for model 6 is shown in Fig. 3. For each iteration, 50 simulations were done. From Fig. 3, NSE values increased considerably after each iteration. This is because the initial parameter ranges were updated after every iteration and the new ranges were used for the next iteration. Several iterations were performed until the parameter ranges converged. The iteration at which the parameter ranges converged was noted, and these ranges were used for validation. Validation of the model was done using Valayinkil data (2005-2007).

The results obtained from the calibration and validation process was tested against the measured data using statistical measures, and the values are shown in Table 2.

TABLE 1: MINIMUM THRESHOLD AREA AND HRU DEFINITION

| Model | Minimum Threshold area | HRU Definition | No of Sub basins | No of HRU |
|---|---|---|---|---|
| Model 1 | Default area | Dominant Land Use/ Soil/ Slope | 33 | 33 |
| Model 2 | Default area | Dominant HRU | 33 | 33 |
| Model 3 | Default area | Multiple HRUs | 33 | 86 |
| Model 4 | Default area /2 | Dominant Land Use/ Soil/ Slope | 55 | 55 |
| Model 5 | Default area /2 | Dominant HRU | 55 | 55 |
| Model 6 | Default area /2 | Multiple HRUs | 55 | 117 |

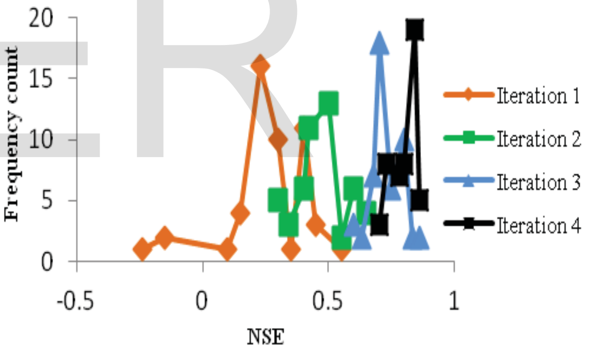

Fig. 3. Frequency plot of Nash Sutcliffe Efficiency for different iterations in Model 6 of Mylamoodu basin.

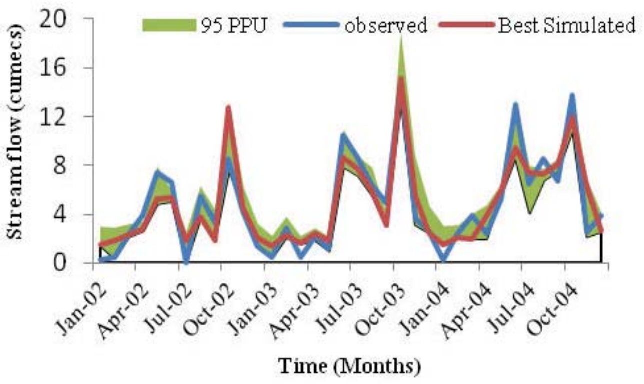

Fig. 4. Time series plot of the measured and predicted stream flow after calibration for Model 6.

TABLE 2: PERFORMANCE EVALUATION OF DIFFERENT MODELS

| Model | | R | NSE | RSR | PBIAS | MSE | RMSE |
|---|---|---|---|---|---|---|---|
| Model 1 | Calibration | 0.92 | 0.857 | 0.437 | -5.6 | 2.9 | 1.7 |
| | Validation | 0.76 | 0.47 | 0.78 | -26.06 | 8.99 | 2.99 |
| Model 2 | Calibration | 0.932 | 0.854 | 0.44 | -9.81 | 2.95 | 1.72 |
| | Validation | 0.82 | 0.60 | 0.677 | -33.41 | 6.77 | 2.6 |
| Model 3 | Calibration | 0.935 | 0.863 | 0.42 | -7.95 | 2.76 | 1.66 |
| | Validation | 0.826 | 0.66 | 0.62 | -13.51 | 5.69 | 2.38 |
| Model 4 | Calibration | 0.925 | 0.853 | 0.44 | -6.65 | 2.97 | 1.72 |
| | Validation | 0.826 | 0.585 | 0.70 | -36.74 | 7.04 | 2.65 |
| Model 5 | Calibration | 0.928 | 0.853 | 0.44 | -9.15 | 2.98 | 1.727 |
| | Validation | 0.72 | -0.9 | 1.49 | -122.7 | 32.2 | 5.69 |
| Model 6 | Calibration | 0.94 | 0.868 | 0.42 | -0.466 | 2.66 | 1.63 |
| | Validation | 0.913 | 0.683 | 0.632 | -22.94 | 5.89 | 2.42 |

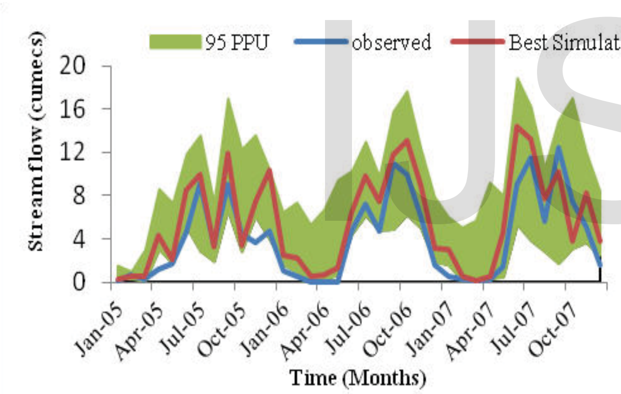

Fig. 5. Time series plot of the measured and predicted stream flow after validation for Model 6.

The time series plot of the measured and predicted stream flow after calibration and validation for the model 6 is shown in Fig. 4 and Fig. 5. In these figures green shaded line represents the 95 PPU, blue line indicates the observed data and red line indicates the best simulated data. The 95 PPU brackets most of the measured data during calibration and validation indicating that model with half of default area of sub-basin delineation and multiple HRU distribution predicts the stream flow accurately in ungauged watersheds. From the Table 2, model with half of default area of sub-basin delineation and multiple HRU distribution gives better performance measures during calibration and validation.

### *B. Varying the Threshold Levels of HRU Distributions*

Stream flow was also predicted in Valayinkil basin by varying threshold levels of land use, soil and slope in Multiple HRU Distribution. In HRU definition, SWAT interface consists of three slider bars in which the land use slider bar controls the threshold level used to eliminate minor land uses in each sub-basin. Land uses that cover a percentage (or area) of the sub-basin area less than the threshold level are eliminated. After the elimination process, the area of the remaining land use is reapportioned so that 100% of the corresponding area in the sub-basin is modeled. The soil slider bar controls the creation of additional HRU's based on the distribution of the selected land uses over different soil types. This scale is used to eliminate minor soils within a land use area. The slope slider bar controls the creation of additional HRUs based on the distribution of the selected soil types over different slope classes. This scale is used to eliminate minor slope classes within a soil on a specific land use area.

In this study thresholds for land use percentage over sub-basin area, soil percentage over land use area and slope percentage over soil area were individually assigned as 10%, 15%, 20% and 25% respectively and four scenarios were created as shown in Table 3. Default area of SWAT interface was selected for sub-basin delineation. Scenario 1 represents SWAT model with threshold level of 10/10/10, indicating land use type with percentage of area less than 10% of sub-basin area, soil type with percentage of area less than 10% of remaining reapportioned land use type and slope classes having percentage of area less than 10% of reapportioned soil type is neglected for modeling. Similarly Scenario 2 represents model with threshold level of 15/15/15, Scenario 3 with threshold level of 20/20/20 and Scenario 4 with 25/25/25 respectively.

Objective function (NSE) for Scenario 1 is plotted against the frequency count and is shown in Fig. 6. The NSE value ranged from -0.2 to 0.7 for iteration 1. In iteration 2, as the parameter ranges were modified NSE converged from 0.3 to 0.75 and finally for iteration 5, NSE ranged from 0.7 to 0.86. This clearly indicates that as the range of parameter values were modified for each iteration, the NSE values successively converged and attained an optimum value. i.e for the last two iterations the highest value of NSE obtained was 0.863 from the 50 simulations.

Time series plot of the measured and predicted stream flow after calibration for Scenario 1 is shown in Fig. 7 and for validation is shown in Fig. 8. Validation of the model was carried out using Valayinkil discharge data from 2005 to 2007. From the time series plot, it can be observed that 47% and 50% of the measured data is bracketed by 95 PPU during calibration and validation.

The performance evaluation of the scenarios is shown in Table 4. From the table, lower threshold levels of 10/10/10 gave better predictions compared to higher threshold levels of HRU distributions. As the threshold levels of HRU distribution in Mylamoodu sub-basin (gauged) is increased, the predicted values in Valayinkil sub-basin (pseudo-ungauged) deviated from the measured values, indicating poor performance measures.

TABLE 3: THRESHOLDS FOR LAND USE/ SOIL/ SLOPE FOR DIFFERENT SCENARIOS

| Scenario | % land cover/ % soil/ %slope | No of Sub-basins (Default area) | No of HRU |
|---|---|---|---|
| Scenario 1 | 10/10/10 | 33 | 86 |
| Scenario 2 | 15/15/15 | 33 | 68 |
| Scenario 3 | 20/20/20 | 33 | 57 |
| Scenario 4 | 25/25/25 | 33 | 55 |

The performance measures of the Scenario 1 (10/10/10 threshold level) accurately predicts the results during calibration and validation, compared to other scenarios, indicating good correlation between predicted and measured stream flow values.

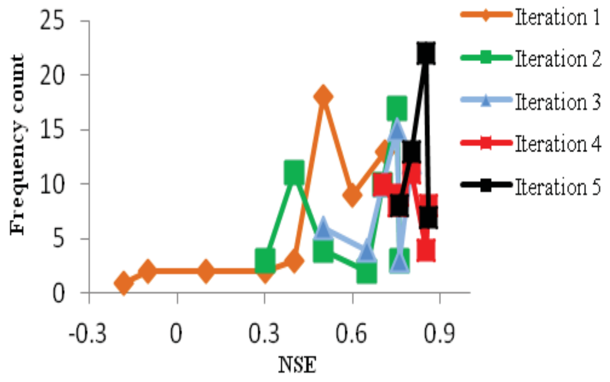

Fig. 6. Frequency plot of Nash Sutcliffe Efficiency for different iterations in Scenario 1 of Valayinkil basin.

TABLE 4: PERFORMANCE EVALUATION OF DIFFERENT SCENARIOS

| Scenarios | | R | NSE | RSR | PBIAS | MSE | RMSE |
|---|---|---|---|---|---|---|---|
| Scenario 1 | Calibration | 0.93 | 0.863 | 0.42 | -7.95 | 2.76 | 1.66 |
| | Validation | 0.826 | 0.66 | 0.62 | -13.51 | 5.69 | 2.38 |
| Scenario 2 | Calibration | 0.92 | 0.839 | 0.46 | 0.839 | 3.5 | 1.8 |
| | Validation | 0.811 | 0.591 | 0.68 | -23.27 | 6.94 | 2.63 |
| Scenario 3 | Calibration | 0.90 | 0.829 | 0.48 | -3.85 | 3.46 | 1.86 |
| | Validation | 0.71 | 0.45 | 0.79 | -21.4 | 9.27 | 3.04 |
| Scenario 4 | Calibration | 0.91 | 0.83 | 0.46 | -2.14 | 3.29 | 1.81 |
| | Validation | 0.65 | -0.22 | 1.09 | -79.49 | 8.23 | 2.86 |

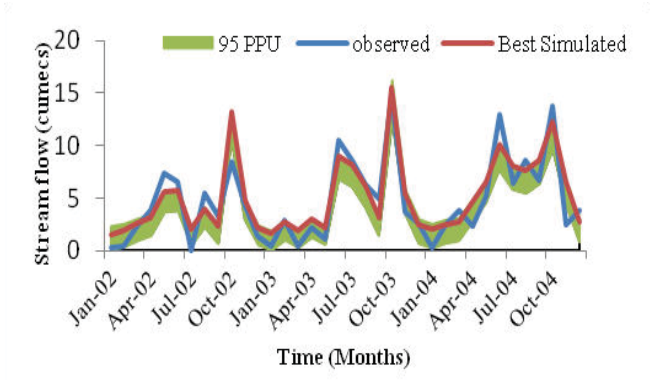

Fig. 7. Time series plot of the measured and predicted stream flow after calibration for Scenario 1

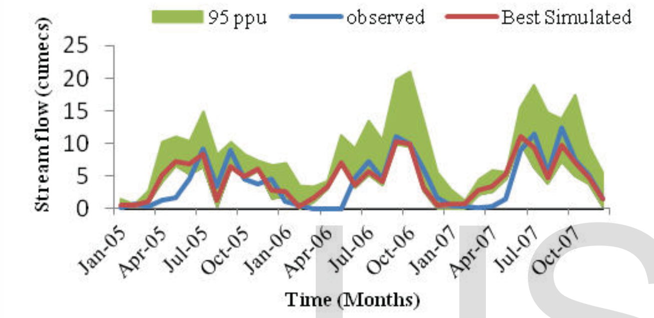

Fig. 8. Time series plot of the measured and predicted stream flow after validation for Scenario 1

## V. CONCLUSIONS

Hydrological model such as SWAT can be used to accurately simulate runoff at different spatial scales. Coefficient of variation based homogeneity test indicated that Valayinkil and Mylamoodu sub basins were hydrologically similar. As the range of parameter values were modified for each iteration, the NSE values successively converged and attained an optimum value. SWAT model having half of default area for sub-basin delineation and multiple HRU distribution within each watershed accurately predicts stream flow in Valayinkil sub-basin and gives better performance measures which lies within the acceptable ranges

As the threshold levels of HRU distribution in Mylamoodu sub-basin (gauged) is increased, the predicted values in Valayinkil sub-basin (pseudo-ungauged) deviated from the measured values, indicating poor performance measures. The performance measures of the Scenario 1 (10/10/10 threshold level) accurately predicts the results during calibration and validation, compared to other scenarios, indicating good correlation between predicted and measured stream flow values.

Hence discretization of the watershed into sub basins with smaller drainage area and with multiple HRU's within each sub basins can improve the stream flow predictions in ungauged basins.

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