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# Modelling of runoff response in a semi-arid coastal watershed using SWAT

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**ABSTRACT**
The GIS based hydrological model SWAT (Soil and Water Assessment Tool) is applied to a coastal watershed in the water scarce Saurashtra region of Gujarat, India, to understand the rainfall-runoff linkage. The study attempts to identify response of the coastal watershed for existing climatic conditions. The hydrological model is calibrated (2006-2009) and validated (2010-2012) at both daily and monthly scales. Performance of the model during calibration and validation period is evaluated through standard indices, NSE, $R^2$ and PBIAS that indicate an acceptable response. At monthly scale, model performance is good for both low and above average rainfall years.
***Keywords –*** coastal watershed, runoff, semi-arid, stream flow, SWAT

## I. Introduction

Arid and semi-arid regions around the world face acute shortage of water. Water resources in these regions are limited owing to insufficient rainfall and a heavy dependence on groundwater resources normally exists. However, groundwater in such regions is not replenished to the extent of its utilization. Problem further intensifies in arid and semi-arid regions with hard rock geology. The impervious hard rock formations hinder the rate of recharge and consequently the water table declines leading to water scarcity problems. Thus, proper management of water resources and quantification of available water is crucial in regions of low rainfall.

Management of water resources aided with hydrological modelling helps in quantification of hydrological components. Questions like how much water is available and how much can be stored or converted from other means are answered through modelling. Stream flow modelling involves estimation of runoff at catchment scale which is routed through stream network to the outlet.

Stream flow reflects the amount of water moving off the watershed and into the channel and the amount being removed from the stream. Stream flow is affected by both natural and human factors and can respond rapidly to changes in flow parameters. Seasonal variations in stream flow, coupled with increased and competing demands for water by a growing population, place considerable pressure upon efficient management of available water resources. Therefore, the assessment and prediction of stream flow is essential for watershed management as well as for the sustainable development of water resources.

One of the widely used tools in runoff estimation studies is the Soil and Water Assessment Tool (SWAT) developed by United States Department of Agriculture (USDA). In this study, SWAT is utilized to simulate hydrological processes in a semi-arid coastal watershed. From among the major hydrological processes occurring in a watershed such as runoff, percolation, evapotranspiration etc., this study focuses on runoff estimation. Runoff depends upon landuse, soil and slope characteristics of a watershed and significantly affects the stream flow. Quantification of runoff is very much important to effectively simulate the stream flow.

## II. Study Area

The Saurashtra peninsula is located on the Arabian sea coast of the western state of Gujarat in India. Districts located in this region are Rajkot, Porbandar, Bhavnagar, Junagadh, Somnath among others. Characterised by hot climate, the region falls under semi-arid zone with rainfall occurring during the monsoon period of June-September.

Many southwest flowing rivers flow in the coastal region of southern Saurashtra. Minsar river is southwest flowing river that originates in the village of Jamjodhpur district and drains into a low lying area near the coast in Porbandar district of Saurashtra region. Drainage pattern of this river is dendritic in appearance. The upper part of catchment of Minsar River upto the Rana-Kandorna gauging site is 542 $km^2$, and is selected as the study area, since the observed stream flow data is available only at this gauging site. Figure 1 shows the map of study area with locations of raingauges, reservoirs and other geographic details.

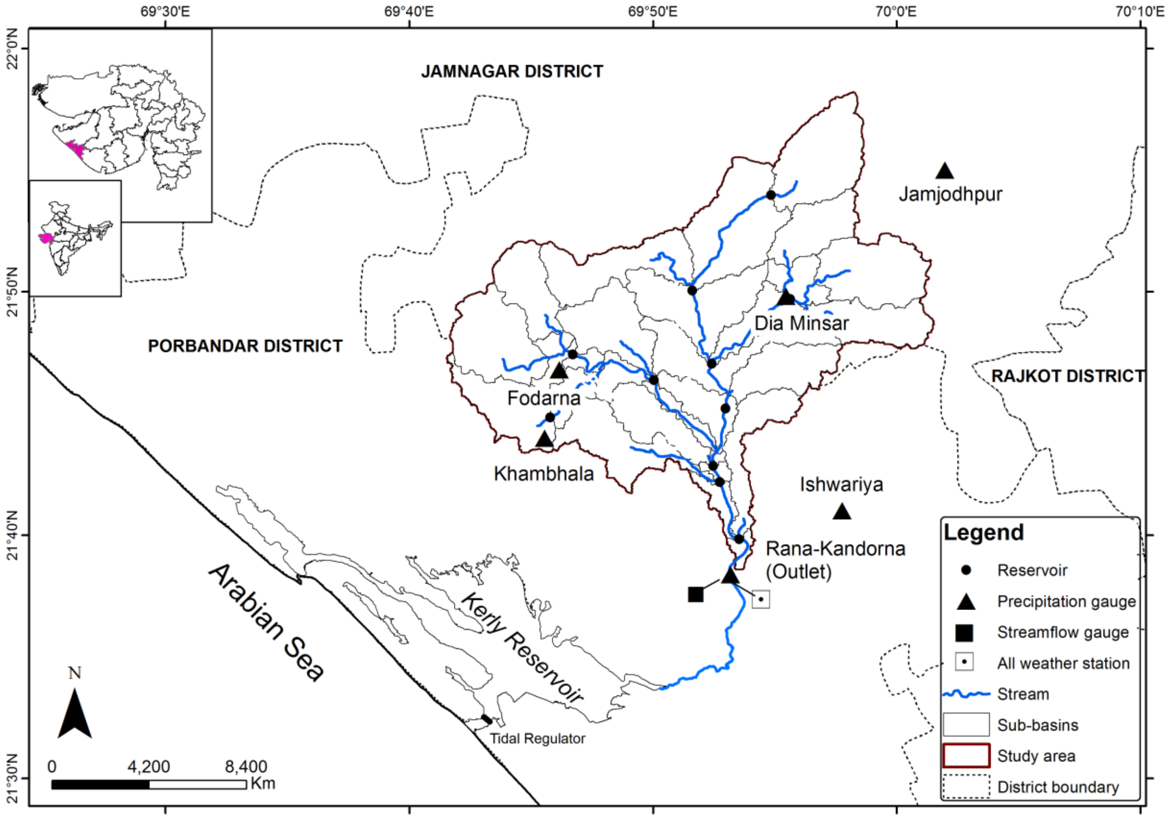


Fig. 1 Study area with weather and stream flow gauge stations, sub-basins and river layers (**i**nset shows location of study area in Gujarat district, India)

The hilly portions of the study area are underlain by hard rock geological formations. In hard rock hilly terrain, problems of deep groundwater table and low recharge during monsoon season persist. Therefore, in such areas, surface water bodies are an important resource for meeting daily water demands, augment groundwater recharge and thereby help in reducing pressure on groundwater resources.

Topography of study area is varying with elevation ranging from 16 to 623 meters above sea level (amsl). High altitude hills with rocky terrain are present on the eastern and western (Barda Hills) sides. The land use land cover in the study area is dominated by agriculture land followed by rocky terrain and forests. For irrigation, farmers practice row farming and are adopting modern methods like sprinkler irrigation technique to efficiently utilize the water and maximize the crop yields.

## III. Material and Methodology

### 3.1 Meteorological data

To model hydrologic response of the watershed, accurate and sufficient hydrological as well as meteorological data are required. Table 1 shows the list of hydrological and meteorological stations along with the period for which data were available. Fodarna, Khambhala, DiaMinsar, Rana-Kandorana, Ishwariya and Jamjodhpur are local stations in the watershed, of which datasets were used.

Table 1 Meteorological and hydrological stations locations in the study area.

| Station | Longitude | Latitude | Data Period |
|---|---|---|---|
| *For Precipitation* | | | |
| Fodarna | 69$^0$46'10.53" | 21$^0$46'47.42" | 2001-2012 |
| Khambhala | 69$^0$45'33.79" | 21$^0$43'59.05" | 2001-2012 |
| Ishwariya | 69$^0$57'47.08" | 21$^0$41'0.27" | 2001-2012 |
| Jamjodhpur | 70$^0$20'0.00" | 21$^0$55'0.00" | 2001-2012 |
| Dia Minsar | 69$^0$55'28.79" | 21$^0$49'49.22" | 2001-2012 |
| Rana-Kandorna | 69$^0$53'12.00" | 21$^0$38'23.00" | 2001-2012 |
| *Temperature, RH*, SS,WS* | | | |
| Rana Kandorna | 69$^0$53'12.00" | 21$^0$38'23.00" | 2001-2012 |
| *Stream flow* | | | |
| Rana Kandorna | 69$^0$53'12.00" | 21$^0$38'23.00" | 2001-2012 |

**RH-Relative humidity, SS- Sunshine hours, WS- Wind speed*

### 3.2 Hydrological data

#### 3.2.1 Stream flow

Minsar river is monitored four times a day at the gauging site Rana-Kandorna during the months (June-October). The data records were available for the years 2006-2012 in which the period 2006-2009 was considered for calibration and the period 2010-2012 was considered for validation of the hydrologic model while 2001-2005 was used as a warm up period.

### 3.3 Thematic maps

#### 3.3.1 Landuse

Landuse map of the study area was prepared by interpretation of satellite images followed by ground truthing. Satellite data were used for classifying different land use land cover classes. Details of satellite data used for classification are listed in Table 2.

Table 2 Satellite data details used for classification

| S.No. | Satellite | Sensor | Resolution | DOP | Path | Row |
|---|---|---|---|---|---|---|
| 1. | IRS-P6 | LISS-III | 24 m | 16-01-2010 | 90 | 57 |
| 2. | IRS-P6 | LISS-III | 24 m | 21-01-2010 | 91 | 57 |

IRS-P6 satellite data of LISS-III sensor was visually interpreted for land use classification. Identified land use classes are given in Table 3 and shown in Fig. 2(a).

Table 3 Identified land use classes of the study area and their geographical area.

| Class | Code | Area (km$^2$) | Area (%) |
|---|---|---|---|
| Cropland | CROP | 183.64 | 33.9 |
| Rock Terrain | ROCK | 215.63 | 39.8 |
| Open land | OPEN | 23.34 | 4.3 |
| Waterbodies | WATR | 9.78 | 1.8 |
| Settlement | SETT | 4.27 | 0.8 |
| Fallow land | FALL | 68.25 | 12.6 |
| Forest | FRSD | 37.44 | 6.9 |
| | Total | 542.45 | 100.0 |

#### 3.3.2 Soil

Study of soil properties is essential for any area to understand the hydrologic response. Soil samples were collected from field followed by analysis for texture classification in the laboratory. Three major soil classes were identified in the study area as given in Table 4 and shown in Fig. 2(b).

Table 4 Identified soil group classes of the study area and their geographical area.

| Class | Area (km$^2$) | Area (%) |
|---|---|---|
| LOAM | 443.20 | 81.7 |
| SILTLOAM | 92.72 | 17.1 |
| SILTCLAYLOAM | 6.54 | 1.2 |
| Total | 542.45 | 100.0 |

### 3.4 DEM

The Shuttle Radar Topography Missions (SRTM) 90m DEM is used as DEM (Digital Elevation Model). It was downloaded from the Consultative Group for International Agriculture Research - Consortium for Spatial Information (CGIAR-CSI) website (http://srtm.csi.cgiar.org). DEM is used for terrain processing, delineation of sub-basins and deriving slope classes (Table 5).

Table 5 Identified slope group classes of the study area and their geographical area

| Class (degree) | Area (km$^2$) | Area (%) |
|---|---|---|
| 0-1 | 134.78 | 24.9 |
| 1-3 | 211.33 | 39.0 |
| 3-5 | 63.09 | 11.6 |
| >5 | 133.25 | 24.6 |
| Total | 542.45 | 100.0 |

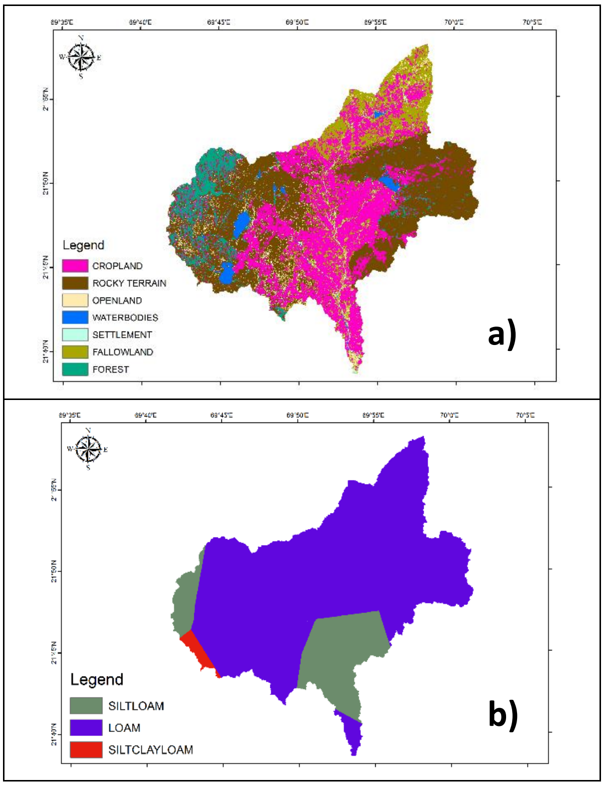


Fig. 2 a) Land use map b) Soil texture map

3.5 SWAT (Soil and Water Assessment Tool)

SWAT is a physical process based model used to simulate hydrological processes such as infiltration, runoff generation and evapotranspiration for a single or multiple rainfall events at catchment scale. All these responses are simulated at the smallest Hydrologic Response Units (HRU). The catchment is divided into several HRUs. These HRUs are based on land use, soil, and slope characteristics of the watershed. Overland flow is computed at HRUs scale and routed through channels to the outlet of the catchment. SWAT uses water balance equation to compute hydrological components such as runoff, percolation, baseflow, evapotranspiration and return flow [1].

The runoff is computed using Natural Resources Conservation Service Curve Number method [2] incorporated in SWAT.The percolation through each soil layer is predicted using storage routing techniques combined with crack-flow model [1]. 1998). The evapotranspiration is estimated using Penman-Monteith method [3]. The flow is routed through the river channels using either the variable storage coefficient method [4] or Muskingum method [5]. The data handling is made easier by ARCSWAT which is a public domain graphical user interface program, designed to link SWAT and geographical information system (GIS) (ARC/INFO) package.

The present study was undertaken using ArcSWAT hydrological model version 9.0 interfaced with ESRI Arc GIS 9.3. The investigated study area was divided into 901 HRUs for analysis.

## IV. Calibration and Validation

Model was calibrated for runoff estimation. Prior to calibration, sensitivity analysis was carried out to identify the most sensitive parameters using the One-factor-At-a-Time (LH-OAT) tool, which is an automatic sensitivity analysis tool implemented and available in SWAT [6]. In case of models with a large number of parameters on account of many sub-processes being considered or because of the defined model structure, the calibration process becomes complex and computationally extensive [7, 8]. In such instances, sensitivity analysis aids in identification and ranking of parameters that have substantial impact on model outputs of interest [9]. In the present study, rankings were established for 26 sensitive parameters affecting the runoff.

In Table 6, all the flow parameters which were tested for sensitivity analysis are listed. Their rankings suggest that the most sensitive parameter is the base flow alpha factor.

Daily observed stream flow data series for 2001-2012 was divided into three groups: Warm up (2001-2005), calibration (2006-2009) and validation (2010-2012).

Table 6 Flow parameters tested for sensitivity analysis and their rankings (most sensitive to least sensitive)

| Parameter | Parameter code | Ranking | Mean |
|---|---|---|---|
| Base flow alpha factor [days] | Alpha_Bf | 1 | 0.762 |
| Threshold water depth in the shallow aquifer for flow [mm] | Gwqmn | 2 | 0.431 |
| Initial SCS CN II value | Cn2 | 3 | 0.415 |
| Channel effective hydraulic conductivity [mm/hr] | Ch_K2 | 4 | 0.261 |
| Manning's n value for main channel | Ch_N2 | 5 | 0.089 |
| Groundwater delay [days] | Gw_Delay | 6 | 0.040 |
| Soil evaporation compensation factor | Esco | 7 | 0.036 |
| Available water capacity [mm H20/mm soil] | Sol_Awc | 8 | 0.022 |
| Soil depth [mm] | Sol_Z | 9 | 0.017 |
| Saturated hydraulic conductivity [mm/hr] | Sol_K | 10 | 0.011 |
| Surface runoff lag time [days] | Surlag | 11 | 0.008 |
| Average slope steepness [m/m] | Slope | 12 | 0.005 |
| Average slope length [m] | Slsubbsn | 13 | 0.003 |
| Threshold water depth in the shallow aquifer for "revap" [mm] | Revapmn | 14 | 0.001 |
| Groundwater "revap" coefficient | Gw_Revap | 15 | 0.001 |

4.1 Warm up period

The data period 2001-2005 was used as a warm up period for the SWAT model. Warm up of the model before calibration helps in calibrating the parameters effectively and accurately by way of activating all the model hydrologic components depending on the initial conditions.

4.2 Calibration

The model was calibrated for four years from 2006-2009. Flow parameters which were found to be more sensitive were chosen for calibration. From Table 6, parameters with ranking from 1-11 were selected for calibration

ArcSWAT includes a multiobjective, automated calibration procedure based on a Shuffled Complex Evolution Algorithm (SCE-UA; [10,11]) and a single objective function that is to be minimized [12]. The objective function is an indicator of the deviation between a measured and a simulated series. Available objective function options in the auto-calibration tool include the sum of squares of residuals and the sum of squares of residuals ranked. The former represents the classical mean square error method that aims at matching a simulated time series to a measured series while the latter represents the fitting of the frequency distributions of the observed and simulated series. In the present study, sum of squares residuals objective function was used in the auto-calibration tool of ArcSWAT. Optimal values of calibrated parameters are given in Table 7.

Table 7 Optimal values for calibrated parameters.

| Parameter | Optimal value |
|---|---|
| Alpha_Bf | 0.78167 |
| Ch_K2 | 32.569 |
| Ch_N2 | 0.44708 |
| Cn2 (%) | -0.1749 |
| Epco | 0.13223 |
| Esco | 0.36786 |
| Gw_Delay | 17.8225 |
| Gwqmn | 475.83 |
| Sol_Awc(%) | 5.805 |
| Sol_K(%) | 12.801 |
| Surlag | 9.4208 |

4.3 Validation

Calibrated model is validated by comparing simulated stream flow with observed stream flow for the period 2010-2012. Different performance indicators like Nash Sutcliffe Efficiency (NSE), Coefficient of determination ($R^2$) and Root Mean Square Error (RMSE) were used to evaluate the performance of the model.

## V. Results and Discussions

SWAT model was calibrated over four years and validated over three years. Model performance was tested through standard indices. Figure 3 shows the monthly observed and simulated stream flow at outlet of the basin. Model performs fairly well during validation period at monthly scale. Both flow peak and volume is reproduced satisfactorily. Even for year 2012 which is a low rainfall year, model performance is found to be good. This distinguishes the ability of model to perform well in low and high rainfall years.

$R^2$ or coefficient of determination values was estimated to test the performance of the model on both daily and monthly scales. On daily scale, $R^2$ value is 0.69 in calibration stage and 0.55 in validation stage. Values are relatively higher on monthly scale, 0.80 and 0.88 in calibration and validation stages, respectively.

NSE of the SWAT model was calculated on both daily and monthly scales. On daily scale, values are 0.62 and 0.53 in calibration and validation stages, respectively. These values improve to 0.74 and 0.84, respectively, on monthly scale during calibration and validation.

PBIAS or Percent Bias tests the model performance for its biased nature. A positive value indicates output is underestimated and negative value indicates output is overestimated with respect to observed values. PBIAS value is 20.99 for calibration and 13.97 for validation, reflecting underestimation of discharge by the model.

According to performance ratings for recommended statistics for a monthly time step [13], the model performance can be taken under good to satisfactory category (Table 8 and 9).

Performance of the model is better for monthly scale values compared to daily scale values. This defines the ability of the model to simulate stream flow at monthly scale more accurately than the peak flows. In Fig. 4 simulated stream flow is shown at daily time step. During the calibration period, extreme high rainfall events occurred in years 2007 and 2009. Model could not simulate these high rainfall events properly. In Fig. 5, scatter plots between observed and simulated values at both daily and monthly scale during calibration and validation stages are shown.

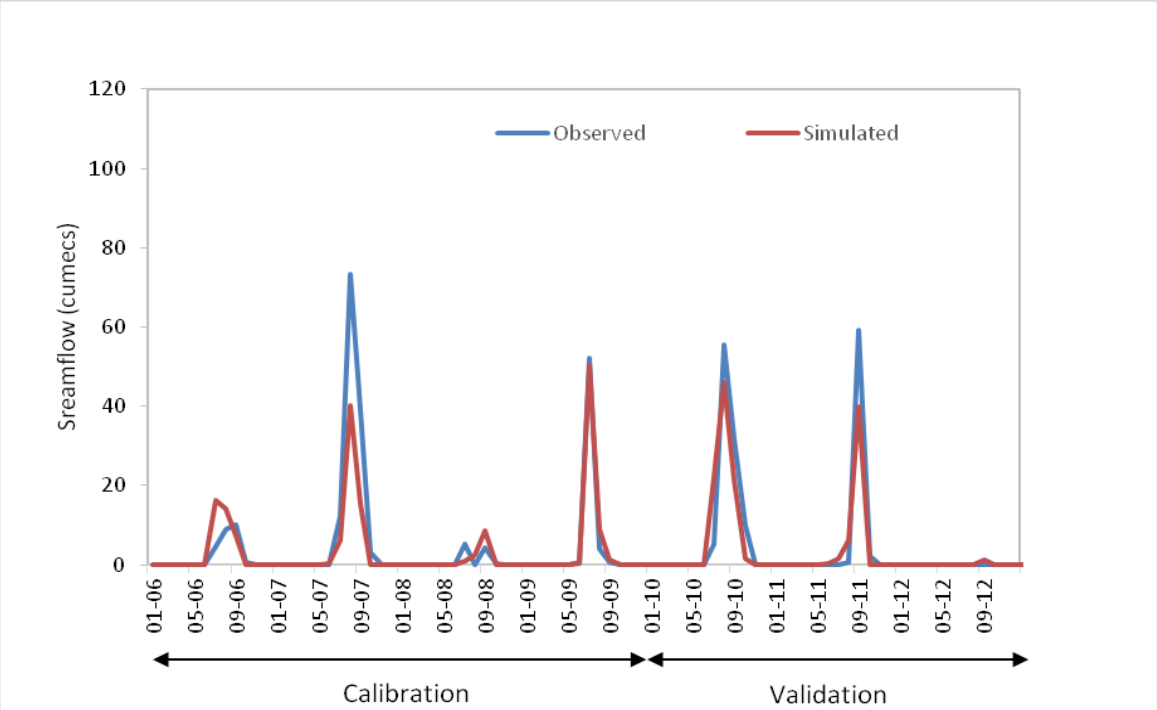


Fig. 3 Observed and simulated monthly stream flows for study area at Rana-Kandorna gauging site.

Table 8 Calibration and validation statistics of SWAT Model.

| Parameter | Daily | | Monthly | |
|---|---|---|---|---|
| | Calibration | Validation | Calibration | Validation |
| R | 0.83 | 0.74 | 0.90 | 0.94 |
| $R^2$ | 0.69 | 0.55 | 0.80 | 0.88 |
| NSE | 0.62 | 0.53 | 0.74 | 0.84 |
| PBIAS | 20.99 | 13.97 | 21.14 | 14.26 |

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Table 9 General performance ratings for recommended statistics for a monthly time step [13]

| Performance rating | NSE | PBIAS (%) |
|---|---|---|
| Very good | $0.75 < NSE \leq 1.00$ | PBIAS < $\pm$10 |
| Good | $0.65 < NSE \leq 0.75$ | $\pm$10 ≤ PBIAS < $\pm$15 |
| Satisfactory | $0.50 < NSE \leq 0.65$ | $\pm$15 ≤ PBIAS < $\pm$25 |
| Unsatisfactory | $NSE \leq 0.50$ | PBIAS > $\pm$25 |

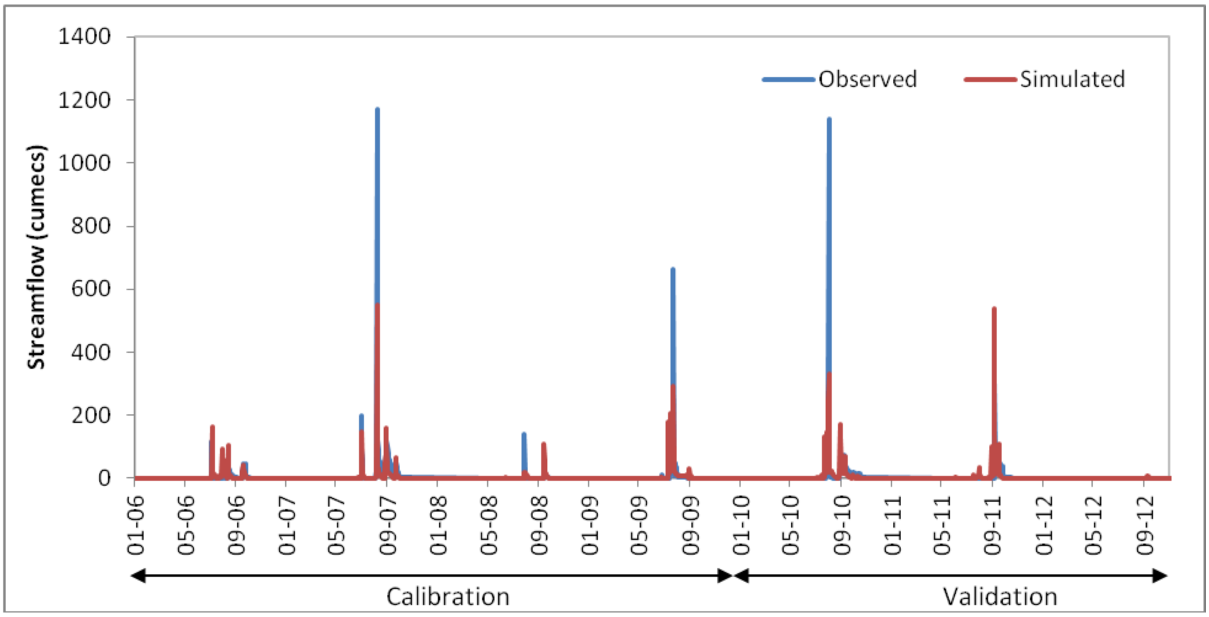


Fig. 4 Observed and simulated discharge at daily scale for study area at Rana-Kandorna gauging site

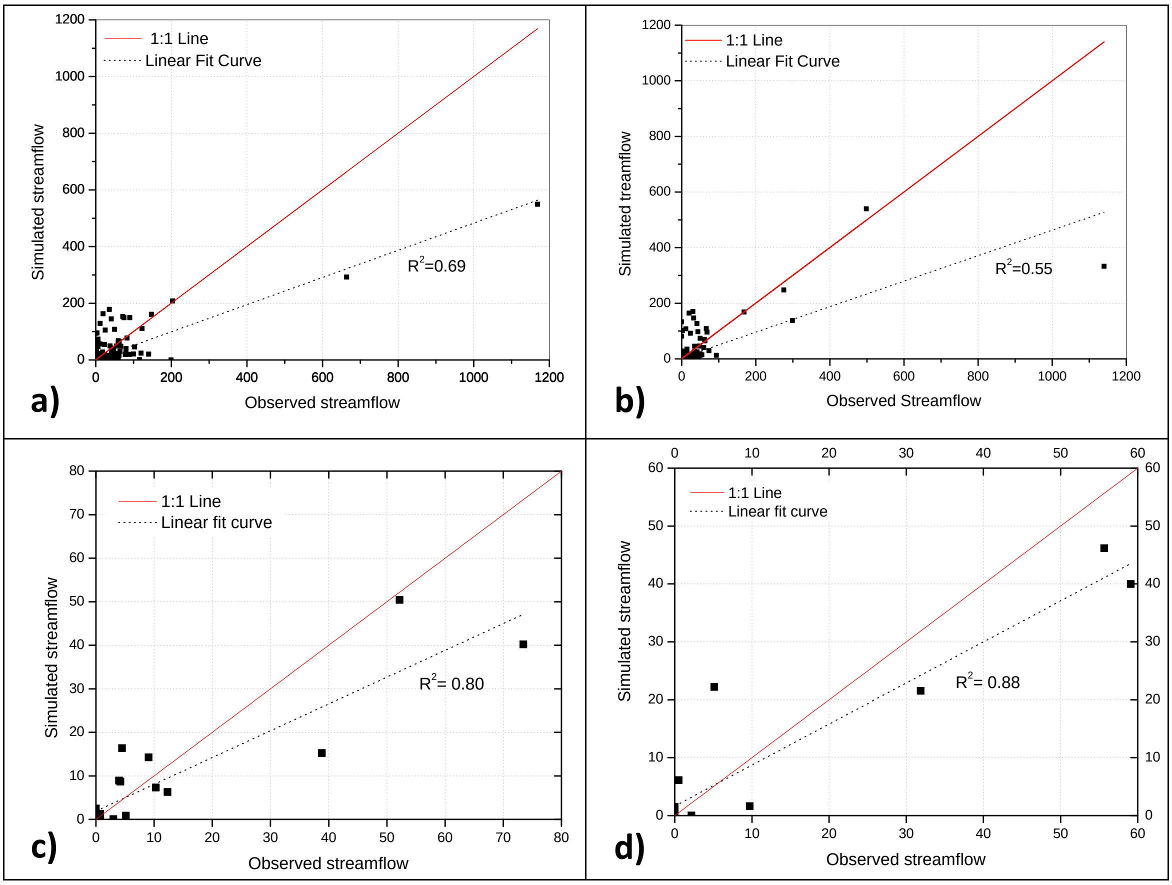


Fig. 5 Scatter plot between observed and simulated stream flow at daily and monthly scale during calibration and validation periods. a) Daily calibration b) Daily validation c) Monthly Calibration d) Monthly validation.

## VI. Conclusions

In the present study, applicability of SWAT model was tested in an upland hilly coastal watershed for simulating runoff response of the watershed for existing climatic conditions. Simulation was carried out at both daily and monthly scales. Performance of the model is evaluated through standard indices, NSE, $R^2$ and PBIAS. Performance of SWAT model for simulating runoff response is better at monthly scale than at daily scale. At monthly scale, model performance is good for both low and above average rainfall years.

## VII. Acknowledgements

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