SWAT hydrological modelling for non-Himalayan catchment of Sone River in India

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Abstract

This paper reports a study on simulation of rainfall-runoff for the Sone river catchment extending from Bansagar to Indrapuri Barrage in India using the Soil and Water Assessment Tool over a period of three years (2011-2013) to assess basin water availability. The model includes a hydrologic model coupled with a simplified flow routing model. The study area is delineated using GIS tools with implementation of SWAT model using Arc-SWAT software. The river basin is sub-divided into smaller catchments. Each catchment is further divided into several hydrological response units (HRUs), based on similarity with respect to terrain slope, land use/land cover and soil characteristics. The developed model was calibrated and validated with observed data with certain statistical parameters. Observed data and model computed data were compared and found to be quite good in agreement. It is indicative of that the model is suitable with realistic assessment of its parameters in the study area (Sone River Basin) with certain known limitations.

Keywords: Distributed model; Land use and land cover maps; Rainfall-runoff modelling; Soil Water Assessment Tool; Validation

1. Introduction

Sone River is an important Ganga River's southern tributary, which originates in the central Indian state of Madhya Pradesh. After passing through Manpur, it flows north before turning northeast. The river paves its ways through the Kaimur Hill Range and outfalls Ganga at upstream of Patna. It has approximately 784-km river course. The catchment of Sone River lies within the territories of the major states of India namely Uttar Pradesh (U.P.), Madhya Pradesh (M.P.) and Bihar.

The Bansagar Dam on Sone River was situated near Deoland in the district of Shahdol district under Madhya Pradesh. The geographic location of Bansagar Dam is 24° 11´ 30´´ N and 81° 17´ 15´´ E. At present Bansagar project has necessitated creation of another reservoir near kadwhan downstream of Bansagar Dam to maintain on assured discharge of the Indrapuri Barrage across the Sone River. In light of the tripartite agreement amongst three states namely U.P., M.P., Bihar, total availability of Sone River Basin at Indrapuri Barrage was worked out to be 14.25 M.A. F (Million Acre Feet) in 1973. However, the impasse regarding actual availability of Sone Water at Indrapuri Barrage has been persisting due to apparent absence of adequate scientific investigation with state-of-the-art hydrological modelling of Sone River Basin to facilitate realistic estimation of actual Sone water availability [1]-[4].

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In view of the above, a semi distributed river catchment model [5] namely SWAT was deployed to develop annual discharge hydrograph of Sone River Basin (SRB) at Indrapuri Barrage gauge site to facilitate realistic assessment of basin water availability.

The semi distributed and temporal based runoff-rainfall model namely SWAT was developed in the early 1990s [5]. Srinivasan and Arnold [6] and Arnold et al. [7] reported river basin model using SWAT in junction with the geographic information system (GIS) with of the model [5]. Further description of SWAT was reported by Gassman et al. [8]. They also gave an in-depth overview of over 250 SWAT-related applications from around the world. Krysanova and Arnold [9], Douglas-Mankin et al. [10], and Tuppad et al. [11] reported further development on SWAT application, and the last two study provided detailed deliberation of SWAT version 2009, of the model.

Although several satellite data based hydrological semi distributed model studies and more [12]-[16] have been reported on Ganga Basin. However exclusive effort on model study on Sone River, a non-Himalayan southern tributary of Ganga with its associated catchment can rarely be found in literature resulting in prevailed inadequacy of proper scientific findings for possible resolution of water share issues amongst its co-basin states.

In light of the above, the following are the goals of the current study,

a) To develop a river basin model of Sone River Basin (From Bansagar Dam site to Indrapuri Barrage site at Dehri in Rohtas district of the State of Bihar) using Soil and Water Assessment Tool. The monthly and seasonal rainfall and discharge data (time span of five years that is 2011-2016) of SRB are to be considered for the development of SWAT model.

b) To simulate historical data within the Sone Basin by calibrating the Arc SWAT version 2012 model with Arc GIS version 10.3 interface for the study basin and validate it with available observed data along with statistical analysis.

This research deals with effect of changes of hydrological parameters between Bansagar in M.P and Indrapuri barrage in Bihar using ArcSWAT.

2. Study Area and Data Processing

Sone river catchment comprising many groups of rivers falling inside Indian regions is spread under Katni, Dindori, Sahdol, Anuppur, Rewa, Sidhi, Singrauli in three states namely U.P., M.P. and Bihar of India. Significant locations of Madhya Pradesh and Robertganj of Uttar Pradesh and Sasaram, Aurangabad, Dehri of Bihar falling in the drainage area of Sone River. The total catchment area of SRB is 380906 km² with 178880 km², 69546 km² and 132480 km² lies in M.P., U.P. and Bihar respectively. Sone is the largest river of Madhya Pradesh which is also tributaries of Ganga River. The details of tributaries of Sone River are presented here as Table 1 and study are map is presented in Fig. 1.[1]-[4]

![Fig. 1: Study Area Map (source: India-IRIS)](3)

2.1. Physiographic Features

The river paves its ways through the Kaimur Hill Range and outfall at Ganga River ahead of Patna, traversing 784-km course. The Son valley is a geographical extension of the Narmada River valley to the southwest. It is mostly forested and has a small population. Between the Kaimur Hill Range and the plateau area of Chhotanagpur in Central
Bihar, India, the valley stretches. The river flow is largely seasonal based; hence it is not used for navigational purpose. Quite a few small dams have been constructed on some of its tributaries.

2.2. Topography

The Sone River basin has steep gradient in Madhya Pradesh nearby the source of the primary river, is 16 km northeast of Amarkantak, in Shivpuri hill range. It is located at an altitude of 1.2 km. The Sone River is one the largest rivers in Madhya Pradesh. The bed gradient of Sone varies between 35-55 cm per km. At Dehri-on-Sone, the Sone River is about 5 km wide, but the floodplain is very small, varying between 3-5 km. Topography of the region is developed using Shuttle Radar Topography Mission (SRTM) data as shown in Fig.2.

| SN | Name of Tributary | L/R | Origination | Outfall | River condition |
|----|-------------------|-----|-------------|---------|-----------------|
| 1  | Gopad             | R   | Sonhat Plateau | Bardi   | Perennial tributary |
| 2  | Rihand            | L   | Matiranga hills | Singrauli district | During peak flood it spills on both banks |
| 3  | Kanhar            | R   | Gidha-Dhodha on the Khudia plateau in Chhattisgarh | In Sone river at a village Kota | It carries the local discharge of countryside drainage |
| 4  | North Koel        | R   | -            | -       | -               |

3. Methodology

In this section, methodology adopted for using a commercially available software namely Arc SWAT for SWAT hydrological modelling are discussed in detail with data processing in the subsequent section. ArcGIS is a spatial mapping software that offers contextual methods for exploring data and sharing location-based perspectives. It provides just a collection of compatibilities for using location-based analysis. There are many features and additional tools under the Arc Toolbox such as 3D Analyst tools, ArcView, ArcMap, Spatial Analyst tools, Geostatistical Analyst tool etc. Spatial Analyst tools have used extensively in this study.

3.1. Arc-SWAT

The modelling deployed in this study includes a hydrologic model attached with a simplified hydrodynamic model for river-flow. The one-way pairing is implemented that is, when the runoff enters the river channel, it is not possible for water to return to the land process of the hydrological cycle. Version 2009 of SWAT model, [17][18] is implemented for this study. SWAT is a hydrological model that operates on a regular time step and is semi-distributed. The river system is split into sub-basins or divisions. Each segment is further sub-divided into hydrological response units (HRUs). HRUs are said to be portions of the sub-basin with equivalent terrain gradient, land-use, and soil type. The SWAT hydrological model, in this study contains 12 sub-basins with outfall located at the outfalls of major tributaries with main channel, or at on site discharge measurement locations (Fig 1). The routing model used in this research is a basic Muskingum routing scheme [19], which is used outside of the SWAT simulator to allow for efficient data updating. Muskingum parametric indicators are computed taking consideration of channel widths, presumed cross-section geometry and channel Manning’s n for calibration. The river is subdivided into 12 distinct river divisions or reaches. If necessary, the main reaches are subdivided further to satisfy the Muskingum routing scheme's numerical stability requirements [19]. In the Muskingum routing scheme [19], the model operator propagating the discharge forward in time is linear; the simulated discharge at time step \( t \) is presented in Eq. (1).

\[
q^{t+1} = Aq^t + B r^t + C r^{t+1}
\]

The superscripts denote time measures, and \( q \) is the vector of simulated discharge and \( r \) is the vector of runoff forcing in this equation. A, B, and C are linear operators that depend on the configuration of the river channel and
network connection. The reader is advised to refer Chow et al. [19] and Michailovsky et al. [20] for information on the application of the Muskingum routing scheme.

4. Input Data Processing for SWAT Model

SWAT requires several input data sets such as elevation, land cover, land use, soil type and climatic data. The elevation data set is required for delineation of watershed and river network along with determination of terrain gradient. The ACE2 (Altimeter Corrected Elevation, version 2) global elevation data collection [21] is used in this analysis with a resolution of 30 acres. The ground cover land use (LCU) input data was used to evaluate the parameterization of vegetation processes within the SWAT hydrological model. The data set used for this study is the USGS Global Land Cover Characterization (GLCC) data set, version 2.0, with a spatial resolution of 1 km [22] is used. The soil data set obtained through soil hydraulic process parametrization in SWAT model. For this analysis, authors used the FAO-UNESCO [23] digital soil map of the world and derived soil products, revision 1, with a spatial resolution of 5 arcmin [23]. The Water Base Project [24] has worked out and developed lookup tables that translate GLCC ground cover groups and FAO-UNESCO soil types into SWAT parameters. This model uses data from the National Oceanic and Atmospheric Administration's Global Forecast System (NOAA-GFS) for daily precipitation and daily minimum and maximum temperatures. At a 6-hourly temporal resolution and 0.5 spatial resolution, it can forecast for up to seven days [25].

4.1. Digital Elevation Model (DEM)

A digital elevation model (DEM) is a digitized 3D image of the surface of terrain gradients generated from elevation data. When representing height, a DEM can be represented as a raster, which is a grid of squares. Photogrammetry, Lidar, IFSAR, land surveying, and other techniques may be used to build the DEM [26]. DEMs are often created using data obtained by remote sensing techniques, but they can also be created using basic land surveying techniques and Total Station survey equipment. Digital elevation model from SRTM, resolution obtained by averaging the grid wise elevation using nearest neighborhood method in land cover coordinate (LCC) is deployed as an input data set into the model. Digital elevation model for the study area is as shown in Fig. 3.

4.2. Land Cover

The land use is normally horticultural and agricultural in the study area. Almost 20% of the study area is under non-agricultural uses such as roads, railways, waterbodies, buildings etc. Forest cover constitutes a considerable part of the study area. The upper part in Madhya Pradesh. The forest cover in the upper portion of the study basin is around 17.27 percent of the total basin area. While developing land use/land cover classification for at 1:50,000 scale imageries, various categories having exhibited similar tones in the fringes leading to difficulties in delineation and extraction. Furthermore, data for the month of February did not reflected mixtures distinctly. Due to this, classification of some of the units based on percentages of mixtures has become very difficult and tedious task. Hence care has been taken to minimize the human error as far as possible. Below are descriptions of the different land use/land cover types.

- Forest
  Area under forest cover is subdivided into 5 different categories. They are (a) Very Dense Forest where vegetation density (crown cover) is 60 percent or above. This category encompassed approximately 25.85% of the overall geographical area. (b) Dense Forests are described as forest land with a potential tree density of 40 to 60% of the total area. It is projected to occupy 295 km², or 7.01 percent of the total land area. (c) Open Forest is described as forest land with a tree density (crown cover) of 20-40% of the total area. It contains thick vegetation that has been destroyed as a result of unabated human activity. This category encompasses 220 km², or around 5.23 percent of the total sample area. (d) Open Forest with Blanks consists of forest land with a tree density of 20–40%, as well as gaps amidst the forest that are blanks of various shapes and sizes as seen on images. About 20-30% of the blanks are thought to be suitable for agriculture. This category encompasses about 292 km², or 6.94 percent of the overall geographical area under investigation.
Agriculture

As stated earlier, the land use in the study area is complex with varieties of uses. A coherent portrayal of current differences in the research field has been attempted [27]. Watersheds, ponds, and reservoirs are substantial variations of agricultural land that are classified and separated into distinct units depending on the magnitude of different types of land uses. By analyzing multi-temporal data of a chosen portion of the sample area and standardizing tonal characteristics, ‘wastelands’ is distinguished from ‘agricultural land without crop’ in this study. To keep it simple, wasteland has not been split into sub-categories. Area covered with wasteland worked out to be 170 km². That is around 4.04 percent of the total basin area under study. Also, as result, the main channels of major rivers such as the Son, Rihand, and Kanhar, as well as a part of the G.B. Pant Sagar Reservoir, are included in the ‘rivers and reservoirs’ group. This category is estimated to be covering an area of 409 km². That worked out to be around 9.72 percent of the geographical area under study. It's noteworthy that multi-temporal satellite datasets are used as primary inputs for creating spatial databases for LULC (Land Use and Land Cover) groups that are temporally variable. As the LULC groups exhibit varying spatial/temporal characteristics across larger geographic gradients, this becomes more relevant when developing regional and national level datasets. The processed land cover map for the study area is presented as in Fig. 4.
4.3. Soil Map

There are thousands of different varieties of soil around the world, which is not unexpected given the variations. Many global organizations are gathering and analyzing soil data for various research domains such as geography, atmosphere geology, vegetation, and so on. The soil map has been developed and classified as per Food and Agriculture Organization (FAO) of United Nations. As per FAO classification, there are six types of soil spatially distributed in the study basin. The associated soil map is presented herein as Fig.5 [28]-[30].

4.4. Weather Input

Daily rainfall, extreme temperature, humidity, wind speed, solar radiation might be used as input for the model. All are put in specified input format. In SWAT model format of input is very important. All these weather input used to weather generation parameter for the model in the form of extension file namely **.wgn. In this study, monthly rainfall data with minimum and maximum temperature as input were considered. Depending on the data availability and degree of accuracy required, model simulation for runoff can be performed using daily, weekly, or yearly rainfall data. The location of rain gauge stations installed in study basin is presented in Table 2.

- Rainfall
  
  Rainfall for our study area recorded by automatic rain gauge installed under surveillance of the Central Water Commission, Government of India, and state governments. The input file essentially contains data for the entire
simulation period, however, the record does not have to start on the first simulation day. Data may be in the daily or sub-daily format. The data availability at Shahdol, Sidhi, Katni and Rohtas (Dehri) are considered and used as model input. The rainfall data for four rain gauges namely shahdol, katni, Sidhi and Rohtas for the period 2011-2016 is depicted in Fig. 6 in chart form. Regular or sub-daily time intervals may be used to read precipitation data into the model.

*Table 2: Location of Rain-gauges in Study Area*

| Place     | Latitude | Longitude | Elevation in meters |
|-----------|----------|-----------|---------------------|
| Shahdol   | 23.30ºN  | 81.35ºE   | 464                 |
| Sidhi     | 24.39ºN  | 81.88ºE   | 272                 |
| Katni     | 23.83ºN  | 80.40ºE   | 304                 |
| Dehri     | 24.92ºN  | 83.19ºE   | 52                  |
| Singrauli | 24.14ºN  | 82.38ºE   | 382                 |
| Obra      | 24.47ºN  | 82.98ºE   | 205                 |
| Surajpur  | 23.21ºN  | 82.86ºE   | 528                 |

*Temperature*

Temperature measurements in sub-basins are adjusted for elevation using the recording gauge's elevation. The daily maximum and minimum air temperatures are required by SWAT. Temperature data may be produced or read from records of observed data. The temperature (Minimum and Maximum monthly temperatures) data for four rain gauges namely shahdol, katni, Sidhi and Rohtas for the period 2011-2016 is depicted in Fig. 7 in chart form.

*Fig. 6: Monthly Rainfall Data for 2011-2016*

*Fig. 7: Monthly Max/Min. Temperature Data for 2011-2016*
5. Result and Discussion.

The effect of the model with reliable input parameters and stress is usually similar to observed results. In the event of a mismatch, either the input parameters or the stresses become unstable. Thus, calibration of model parameters make model reliable. The model was calibrated by simulating the input values and stresses. The output water table elevation is then compared to observation well water table elevation data, and the parameters are adjusted based on the mismatch. Simulated values of runoff at outlet of the basin along with the observed runoff have been presented in Table 3 and graphically in Fig. 8.

| Month | Simulated Runoff (m³/s) | Observed Runoff (m³/s) |
|-------|-------------------------|------------------------|
| Jan   | 7601.50                 | 6593.20                |
| Feb   | 9031.60                 | 9214.70                |
| Mar   | 9829.00                 | 9861.00                |
| Apr   | 12481.50                | 13854.40               |
| May   | 13036.30                | 14284.00               |
| Jun   | 14875.30                | 15574.80               |
| Jul   | 19271.50                | 17245.60               |
| Aug   | 21280.70                | 24654.10               |
| Sep   | 18072.20                | 21543.70               |
| Oct   | 16039.80                | 15490.00               |
| Nov   | 10918.70                | 11214.20               |
| Dec   | 11524.30                | 12312.40               |

The calibrated model is evaluated with Nash-Sutcliffe efficiency [31]. The Nash-Sutcliffe Efficiency (NSE) is a normalized statistic that computes the residual variance's relative magnitude in comparison to the estimated data variance [31]. NSE is a measure of how well the observed and simulated data plot suits the one-to-one rows. The correlation formula for computing NSE is given in Eq. (2).

$$E = 1 - \frac{\sum_{t=1}^{n}(Q_{m}^{t} - Q_{o}^{t})^2}{\sum_{t=1}^{n}(Q_{m}^{t} - \bar{Q}_{o})^2}$$  \hspace{1cm} (2)

Where $Q_{m}^{t}$= model computed value, $Q_{o}$= Observed value; $n$=number of data points. In this case $n=12$. The computed value of NSE for the values in Table 2 is worked out to be 0.9785 and it is closer to 1. That shows that simulated runoff is good agreement with the observed data.

![Fig. 8: Model validation for the Year 2012](image-url)
6. Conclusion

Hydrological modelling using SWAT for the Sone River Basin lying between Bansagar Dam to Indrapiur barrage have been developed. This model can be used to assess Sone River discharge at the out fall point namely Indrapiur Barrage site. Model result showed good agreement with the observed discharge data of the year 2012. This study strongly suggests that semi distributed model such as SWAT can be used in Sone Basin for predicting river discharge with reliable accuracy provided hydrological data with sufficient time span are made available. The predicted data may be further utilised for realistic assessment of water availability in the study basin.

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