Indexed in
Scopus Compendex and Geobase Elsevier, Chemical Abstract Services-USA, Geo-Ref Information Services-USA

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume XX, No. XX

March XX, XX , P.P. X

# Hydrologic Modeling For The Gandak Basin Using SWAT With Sensitivity Considerations

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***Abstract:*** *The advances in computer technology have revolutionized the world of water resources management. One such development, ArcSWAT provides a GIS integrated user-friendly platform, which allows the effective use of spatial data to enhance the modelling capabilities. The objective of this study is to apply and validate the SWAT model on a river basin, Gandak, which originates from the Himalayan ranges in Nepal and flows into India forming a tributary of the Gangetic system.Two popular gridded observation precipitation datasets: (1) Asian Precipitation Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE), and (2) India Meteorological Department (IMD) were used to simulate runoff. The comparison of the outputs from both the data reveals that the APHRODITE data gives relatively better results. However, the model results show further improvement when run using an amalgam of both the data. The SWAT delineated model was run initially with default parametric values and the simulated river flow was compared with the observed runoff data at Triveni, which is the entry point of the river at the Indo - Nepal border. After performing sensitivity analysis of all the relevant model parameters, the model was calibrated both manually and automatically, using the SUFI2 method in SWAT-CUP. Comparative analysis of the influence of the subbasin, soil and aquifer properties, one at a time, was done by manually calibrating the corresponding parameters.Nash-Sutcliffe coefficient and Root Mean Square error are used to evaluate the efficiency of the model. The study reveals that the Temperature lapse rate (TLAPS) is the key governing factor in the sensitivity analysis as well as during calibration. From the results, it can be concluded that SWAT model has the capability to successfully capture and mimic the intricacies involved in the runoff generation process for the considered study area.*

***Keywords:*** *ArcSWAT, Sensitivity Analysis,Calibration, Validation, Rainfall, Gandak River Basin.*

## 1.Introduction:

The need to study and model the various hydrological processes came about from the requirement of the knowledge of various variables like peak flow, flood volume and time to flood peak for the design of hydraulic structures such as dams, spillways, culverts, urban stormwater systems, and other flood control structures. According to Dooge (1973), in the last part of the 19th century and the early 20th century, empirical formulas were used by most engineers. Then the rational method was introduced for estimation of peak flow and concentration time for small and mountainous catchments. The need to model rainfall-runoff for larger catchments was felt in the late 1920's and thus developments like the modified rational method came about. Later in 1932, Sherman proposed the unit hydrograph theory based on the superposition principle. In the next few decades, it took a tremendous amount of effort to make refinement and progressions in the unit hydrograph theory which led to the development of conceptual models. For further improvement in unit hydrograph shape, scientists used statistical procedures like moments, maximum likelihood etc., and later, methods based on time series analysis(Box and Jenkins, 1970). However, in this attempt to develop more advanced mathematical techniques, the hydrologic models seemed to lose their connection with reality(Todini, 1988). It was in the 1960's that various other alternatives were searched to physically represent the hydrologic processes more closely, that introduced the spatial variability of soil, landuse and topography into modeling. In this new framework, it was attempted to represent the behavior of the separate components of the hydrologic cycle in the form of a number of interconnected conceptual elements.

SWAT (Soil and Water Assessment Tool) is one such development (Arnold et al., 1998) which considers spatial variability of various hydrologic parameters, in a way that it divides the river basin into subcatchments which are further split into a number of HRUs based on the soil type, landuse and topography variations. The SWAT model consists of various modules, which contain various parameters like Ch_K2, Ch_N2, Cn2, Tlaps, Plaps etc., to compute the outputs like evapotranspiration, saturation excess runoff, etc. The accuracy of the model output depends on the values these parameters are assigned and is checked and refined through the process of sensitivity analysis, calibration and validation.

**2.Study Area:**

The Gandak basin lies between latitude 25.6° N and 29.4° N and longitude 82.8° E and 85.82° E, parts of the basin lying in Tibet, Nepal and India. The Gandak River is said to originate near the Nepal – Tibet border at an altitude of 7620 m to the north-east of Dhaulagiri(Jain et al., 2008). After that it enters the plains of Champaran district of Bihar at Triveni. For the present study the catchment outlet has been taken a little north of its confluence with the Ganga, with the catchment area amounting to 40,713 km$^2$. The elevation ranges from 18 m above mean sea level to 7745 m as per the SRTM based DEM shown in figure 1.

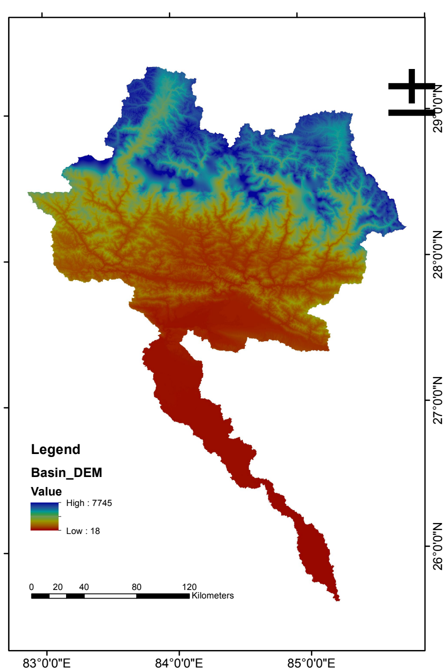


***Figure 1***: *Elevation map of Gandak basin form SRTM based DEM*

The Gandak basin occupies most of the western Nepal and a part of the Central Nepal. The Gandak originated from the Himalaya Mountain and flows through the Shivalik. Pokhara is one of the main cities in the country that lies in the Gandak basin, lying in the western Nepal. Temperature in the region has ranged from -6.5°C to 30.8°C in the years 1979-2000. Another striking feature about the basin is that three of the world's 10 highest peaks lie in the basin – Annapurna I, Manaslu and Dhaulagiri I. Parts of the basin experiences snowfall in the months of December to February.

**3.Materials and Methods:**

SWAT is a physically – based, continuous time hydrological model developed by USDA Agricultural Research Services, widely used to simulate quality and quantity of surface and ground water and predict the environmental impact of landuse, land management practices, and climate change.
An integral part of SWAT is the general water balance equation

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

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

The present study is concentrated on the rainfall-runoff modelling of the Gandak watershed taking into account the sensitivity considerations of the SWAT model parameters. To estimate surface runoff an empirical model, SCS curve number procedure (USDA Soil Conservation Service, 1972) was used. This method provides a consistent basis for the estimation of runoff under varying land use and soil types.The curve number equation is:

$$Q_{surf} = \frac{\left( R_{day} - I_a \right)^2}{\left( R_{day} - I_a + S \right)}$$

where$Q_{surf}$ is the accumulated runoff or rainfall excess (mm H2O),$R_{day}$is the rainfall depth for the day (mm H2O), $I_a$ is the initial abstraction which include surface storage, interception and infiltration prior to runoff (mm H2O), and $S$ is the retention parameter (mm H2O defined as:

$$S = 25.4 \left( \frac{1000}{CN} - 10 \right)$$

where$CN$ is the curve number for the day and is a function of the soil's permeability, land use and antecedent soil moisture conditions. The initial abstractions, $I_a$ is commonly approximated as 0.2 $S$. Runoff will only occur when $R_{day}>I_a$.

### 3.1. Input data used:

The spatially distributed data (GIS input) needed for the ArcSWAT interface include the DEM, soil cover data, land use and stream network layers. Data on rainfall, temperature, weather and river discharge were also used for prediction of streamflow in the calibration and validation process.

Topography was defined by SRTM based DEM (Jarvis et al., 2008) that contains the gridded elevation information of a given area at a 90m spatial resolution. Subbasin parameters such as slope gradient and slope length of the terrain are derived from the DEM. The stream network to be worked upon was also derived from the same DEM after delineation.Landuse is one of the most important factors that affects surface erosion, runoff, and evapotranspiration in a watershed. The land use map obtained from the open-source Global Land Cover Facility (GLCF)(Tucker et al., 2004) was used to estimate vegetation and other parameters for input into the SWAT model. Soil data was obtained chiefly from the published dataset by Food and Agriculture Organisation of the United Nations(Batjes, 1997). It holds more than 5000 soil types.

Two sources of gridded rainfall data available for the study zone have been taken into consideration. The first that is provided by the India Meteorological Department, is available only for the area lying within the Indian subcontinent. The second dataset is the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) which is available for the whole region of the basin.Discharge gauge data is available at Triveni, lying at the Nepal-India border region for the period 1971-1980. For the present study 1971-75 has been taken as the calibration period and 1976-80 as the validation period.The stations input data for both weather and temperature were taken from the IMD for the whole Gandak basin. Though the stations were found to lie only in the region of Gandak lying in India.

### 3.2. Sensitivity analysis:

Sensitivity analysis is helpful to identify and rank parameters that have significant impact on specific model outputs of interest(Saltelli et al., 2000). It demonstrates the impact that change to an individual input parameter has on the model response and can be performed using a number of different methods (Veith and Ghebremichael, 2009). The method in the ArcSWAT Interface combines the Latin Hypercube (LH) and One-factor-At-a-Time (OAT) sampling(Van Griensven, 2006). Sensitivity analysis was conducted to determine the parameters that influence the flow for the subbasin outlet at Triveni. Parameters were selected for sensitivity analysis by reviewing previously used calibration parameters and documentation from the SWAT manuals.

### 3.3. Calibration and validation process:

Model calibration is the process of choosing suitable values of model parameters such that the hydrological behavior of the catchment can be simulated closely(Wagener et al., 2005; Moore and Doherty, 2005). In the subsequent processes, the parameter values, especially the ones which occupy a higher rank in the sensitivity analysis, are progressively refined and altered one by one or as a combination of few, based on their influence on the desired output, so as to obtain results as close to the observed data. Calibration can be carried out in two ways– manually and automatically, with automatic being less tedious and, when a judicious range for varying the parameter values is specified by the user, is more efficient.

Validation is performed after calibration to check the validity of the model in a different time frame, than the period for which calibration was done. Like calibration, predicted model outputs results are compared against the observed data which helps determine how well the model has been calibrated and how far do the selected values for the various parameters hold true in the model.

### 3.4. Model Setup:

The model setup involved five steps: (1) data preparation; (2) subbasin discretization: (3) HRU definition; (4) parameter sensitivity analysis; (5) calibration and validation. In the current study, for better watershed delineation a predefined digital stream network layer digitized from Google Earth was imported and superimposed onto the DEM to accurately delineate the location of the streams. The Land use/Land cover and soil cover spatial data were reclassified into SWAT land cover/plant types. User look up tables were created to identify the SWAT code for the different categories of land cover/land use and soil cover on the map as per the required format. These datasets were imported, overlaid and linked with the SWAT2009 databases.

The basin was then discretized spatially into sub basins based on the topographic features of the basin which were further divided into HRUs. It depends on the size of the watershed, spatial detail of the available input data and the amount of detail required to meet the goals of the study.Figure 2 shows the subbasins formed in the Gandak basin.

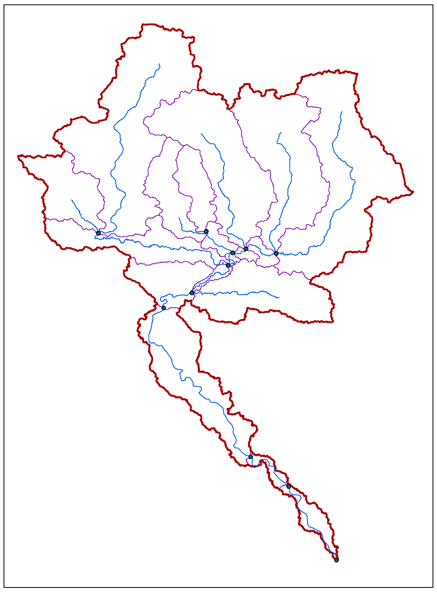

***Figure 2****: Division of basin area into various subbasins*

To define the HRU distribution, the multiple HRU definition option was selected with a threshold value of 2% land use, 2% soil and 2% slope. This percentage signifies that only soils that occupy more than the specified % of a subwatershed area are considered in HRU distributions. Land uses, soils or slope that cover a percentage of the subbasin area less than the threshold level were eliminated. After the elimination processes the area of the land use, soil or slope is reallocated so that 100 percent of the land area, soil or slope in the subbasin is included in the simulation. This was followed by sensitivity analysis of the various parameters used in SWAT which was further used for calibration and validation of the model outputs.

## 4.Results and Discussion:

### 4.1. Simulation Scenarios:

The default simulation of stream flow, using the default parameter values, was run for the basin for the calibration period (1971-1975) for three possible input data scenarios:

(i) Only using IMD rainfall data, which hence leaves the rainfall in a major part of the basin to be extrapolated from the available data.

(ii) Only using APHRODITE rainfall data, which has full areal coverage

(iii) Using IMD rainfall for the area lying in India and APHRODITE rainfall data for the portion of the basin lying beyond the Indian part.

The period 1969 to 1970 was considered as warm up period. This allows the model to get its hydrologic cycle fully operational. The output was compared with the observed streamflow data of Triveni basin. Figures 3 to 5show the comparison of the three scenarios.

***Figure3****: Plot of Observed Discharge against SWAT generated results for case (i)*

***Figure4***: *Plot of Observed Discharge against SWAT generated results for case (ii)*

***Figure5***: *Plot of Observed Discharge against SWAT generated results for case (iii)*

However, the third case was found to give the best result. Therefore, the further work of sensitivity analysis, calibration and validation was done for the case (iii).

**4.2. Sensitivity Analysis:**

Following the above process, the parameter sensitivity analysis was carried out for the whole catchment area using the twenty six hydrological parameters selected for the undertaken study area, the results of which were used for calibrating the model. Here, we used the default lower and upper bound parameter values, the details of which are found in the SWAT user's manual. Out of the 26 parameters, 21 parameters were found to be significantly influencing the results of the simulation. Table 1 shows the list of sensitive parameters with the ranks indicating the order in which they influence the result.

**4.3. Calibration and Validation:**

Then the model was calibrated both manually and automatically to reach the best match between observed and simulated flows. The goodness of calibration is judged on the basis of the goodness of fit that is generally quantified by the coefficient of determination ($R^2$), Nash- Sutcliff efficiency (NSE), PBIAS (percent – bias), etc. Figure 6 and 7 show the comparison of observed and simulated series after manual calibration was done. In the process, the best results were obtained with a precipitation lapse rate (PLAPS) value of 275 and temperature lapse rate (TLAPS) value of -2.25. Any change made in the other parameters was found to make negligible improvement in the results. The various performance ratings for the calibration and validation results are shown in table 2. These ratings were found to be lying in good to very good classification according to Moriasi et al., 2007.

***Table 1****: Parameter ranks obtained from sensitivity analysis*

| PARAMETER | RANK | PARAMETER | RANK |
|---|---|---|---|
| Alpha_Bf | 17 | Sftmp | 24 |
| Biomix | 19 | Slope | 7 |
| Blai | 11 | Slsubbsn | 21 |
| Canmx | 6 | Smfmn | 24 |
| Ch_K2 | 4 | Smfmx | 24 |
| Ch_N2 | 15 | Smtmp | 24 |
| Cn2 | 2 | Sol_Alb | 20 |
| Epco | 14 | Sol_Awc | 10 |
| Esco | 3 | Sol_K | 5 |
| Gw_Delay | 18 | Sol_Z | 8 |
| Gw_Revap | 12 | Surlag | 16 |
| Gwqmn | 13 | Timp | 24 |
| Revapmn | 9 | Tlaps | 1 |

***Figure6****: Plot of Observed Discharge against SWAT generated results from calibrated model*

***Figure**7: Plot of Observed Discharge against SWAT generated results for validation period*

***Table 2**: Performance ratings for the calibration and validation results*

| | $R^2$ | PBIAS (%) | NS |
|---|---|---|---|
| Calibration | 0.916 | -5.40 | 0.8875 |
| Validation | 0.873 | -21.68 | 0.8239 |

The results of the automatic calibration in SUFI2 with all the 21 parameters obtained from the previous process of sensitivity analysis is shown in the figure below in a graphical manner comparing the simulated flow after calibration and the observed flow. The calibration was given 2000 runs and the input data file was obtained from the default simulation run in ArcSWAT. The flow values at the outlet of subbasin no. 15 were compared against the observed values at Triveni for the calibration period (1971-1975). The result from the autocalibration process has been shown in figure 8 and its performance statistics have been shown in table 3. The optimum values of the two parameters TLAPS and PLAPS were -2.28 and 224.25 in this case.

***Figure8**: Plot of Observed Discharge against SWAT generated results from auto calibration for 1971-75*

*__Table 3__: Performance ratings for the autocalibration results*

| $R^2$ | PBIAS (%) | NS |
|---|---|---|
| 0.94 | -22.38 | 0.8875 |

The statistics show that both the manual and automatic calibrations show similar results with the shape of the graphs of both being nearly equal and very close performance ratings of the two. It was also noted during the study that using different version of SWAT programs produced slightly different results although same input data was used. This could be a possible reason why similar values of model parameters are giving different results when run on SWAT and using SWATCUP.

## 5. Conclusion:

From use of different rainfall datasets: the two gridded rainfall datasets: between IMD and APHRODITE the latter gave better simulation results in the present model signifying the importance of the precipitation and snowfall occurring in the Nepal region of the basin which otherwise is left unaccounted for. Further the combination of both the said data helped achieve the best match for the observed and simulated model output concluding that the IMD data has lesser uncertainties when compared to APHRODITE over the same area.

From sensitivity analysis: According to the Latin Hypercube method of sensitivity analysis it was found out that Tlaps and CN2 were the two major parameters that significantly affected the model output. This process significantly helps reduce the work and effort involved in manual calibration by helping the user know which parameters to change to obtain the desired results.

From manual calibration and validation: After various runs with varying parameter values on a monthly basis for the years 1971-1975, it was finally concluded that for value of Tlaps= -2.25 and Plaps= 275, the best calibration output was achieved justifying itself with a Nash Sutciffe efficiency coefficient of 0.8875. Further when the same parametric values were used for the validation of the model outputs for the years 1976-1980, it was found that the calibration results were quite optimized and accurate in the sense that they presented a very close match to the observed values for those years too with a Nash Sutcliffe coefficient not falling beyond 0.8239. The NSE value obtained from the flow output as computed in automatic calibration which has the advantage of being quicker and less tedious, also shows sufficiently good results. But the lower performance ratings than that obtained manually declares human judgment as the best way to reach at the most optimized results with a greater objectivity and irreplaceable by any automated format of the same.

## 6. Acknowledgement:

We would like to thank Ms. Jayshri Patel, Research Scholar, Civil Department, IIT Delhi and Mr. JatinAnand, Project Scientist, Civil Department, IIT Delhi for their valuable help.

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