Evaluation of Surface Runoff Estimation in Ungauged Watersheds using SWAT and GIUH

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Abstract

Soil and Water Assessment Tool (SWAT) is a physically based distributed model that can estimate runoff, sediment and soil erosion from agricultural watersheds under different management conditions. The new SWAT has provision to simulate watershed process using sub daily rainfall. Though the model is generally meant for continuous modelling, the provision to make use of sub daily rainfall enables the model to be used for event modelling. GIUH is a methodology which can also be used for predicting the surface runoff from ungauged basins. On assessing the performance of these models in modeling of different events in Manali watershed, it is concluded that the GIUH method are marginally better than that from the SWAT model.

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1. Introduction

Geomorphological Instantaneous Unit Hydrographs (GIUH) has been considered as an effective tool to simulate runoff from rainfall for ungauged catchments. The GIUH can be interpreted as the probability density function of the travel time of a drop of water landing anywhere in the basin to the outlet. Horton’s geomorphic laws of stream order are used for deriving the same. Among complex hydrological models, the Soil and Water Assessment Tool (SWAT) with ArcGIS interface can also be used for estimating the surface runoff in ungauged basins.

Jeong et al. [1] studied the development and testing of a sub-hourly rainfall–runoff model in SWAT by using one minute sub-hourly time step. The SWAT model is modified to find infiltration, surface runoff, flow routing, impoundments, and lagging of surface runoff. Maharjan et al. [2] modified the SWAT model for sub-daily rainfall and predicted the flow from a watershed within the range of acceptable accuracy. Rodriguez-Iturbe and Valdes [3] developed the theory of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) which couples the hydrologic characteristics of a catchment with its geomorphologic parameters. Gupta et al. [4] linked the hydrologic response of watersheds to their geomorphologic parameters. Anju [5] developed a tool for the automatic generation of GIUH parameters from delineated watershed in ArcGIS.

As indicated in the literature, the GIUH is a potential tool for simulation of flood events in case of ungauged catchment. The SWAT model is generally used for continuous modelling. However, there is an option for running the model using hourly rainfall which could be utilised for event modelling.Accuracy of the SWAT model in simulating daily flow is less compared with that in simulating monthly flow and hence the accuracy at hourly time scale is to be assessed. In this study, it is attempted to compare the performance GIUH and the SWAT model in predicting the surface runoff in case of event modelling using sub daily rainfall and runoff.

2. Materials and methods

2.1. Study Area

For the comparison of GIUH and SWAT models, a watershed from Kerala, viz. Manali watershed is selected. The Manali watershed is located in the central region of Kerala state, lying between 10°10' and 10°46' north latitude and 75°57' and 76°54' east longitude. Annual rainfall of the state is about 3000 mm. The Manali tributary of Karuvanoor puzha originates from Vaniampara hills. This watershed covers an area of 148 km², with outlet located at latitude of 10°26’30.76’’ and longitude of 76°16’2.30’’. Fig.1 shows the Manali watershed. It also shows digitized stream network and location of gauging station for the selected watersheds. The catchment area upstream of the Peechi dam is removed from the analysis as the spill way discharge is zero during the period of events.

Fig.1.Manali watershed.
2.2. Model Description

The SWAT model is a physically based watershed model which is developed by Agricultural Research Service (ARS) of USDA. A complete information regarding weather, soil properties, topography, vegetation and land management practices occurring in the watershed are required for running the model [6]. The SWAT is a continuous time model and is not initially designed to simulate detailed, single event flood routing [7].

Water balance is the basic process which influences everything that happens in a watershed. The land phase of the hydrologic cycle can be represented by the water balance equation:

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

Where $SW_t$ is the final soil water content at the time $t$, $t$ is the time (days), $SW_o$ is the initial soil water content. $R_{day}$ is the amount of precipitation on day $i$, $Q_{surf}$ is the amount of surface runoff on day $i$ (mm H2O), $E_a$ is the amount of evapo-transpiration on day $i$, and $Q_{gw}$ is the amount of return flow on day $i$. All these quantities are expressed in mm of water [8].

Surface runoff is generated whenever the rate of rainfall exceeds the rate of infiltration and is computed either by SCS curve number or the Green-Ampt Infiltration methods. Surface runoff from the hourly rainfall is normally estimated using the Green-Ampt Infiltration method which estimates the infiltration, assuming excess water at the surface at all times. A modified form of Green-Ampt method, viz., the Green-Ampt Mein-Larson excess rainfall method is used in the SWAT model. This method requires sub-daily precipitation data supplied by the user [7].

The model setup involves following steps: (1) Watershed Delineation (2) HRU analysis (3) Write Input tables (4) Edit SWAT input table (5) SWAT Simulation. Automatic delineation tool in SWAT allows the user to delineate the watershed and its subbasins from the DEM.

2.3. Input Data

The data requirement for SWAT model includes DEM, soil type, land use, weather (temperature, solar radiation, relative humidity and wind speed) and river discharge data to establish the water balance. The DEM is used as the basic data for the watershed delineation in ArcGIS and that is downloaded from the site http://srtm.cgiar.org/index.asp. The rainfall and stream discharge data for the period 2005-2010 are used for the study.

2.4. GIUH

The concept of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) is introduced by Rodriguez Iturbe and Valdes [3] by means of which the hydrologic characteristics of a catchment are linked to the geomorphologic parameters. The GIUH is interpreted as the probability density function of the travel times of the rain drops, which is randomly and uniformly distributed over the catchment, to the outlet. The travel times on hill slope or along the streams are assumed to follow exponential distribution, and the initial and transitional probabilities are calculated based on Horton’s morphometric parameters. These parameters are area ratio, bifurcation ratio and length ratio.

1. Bifurcation ratio:

$$ R_B = \frac{N_i}{N_{i+1}} $$ (2)

Where $N_i$ and $N_{i+1}$ are the number of streams in order $i$ and $i+1$. Let $\Omega$ represent the highest stream order in the watershed, $i = 1, 2, ..., \Omega$.
2. Length ratio

\[ R_L = \frac{L_{i+1}}{L_i} \]  

Where \( L_i \) is average length of channels of order \( i \).

3. Area ratio

\[ R_A = \frac{A_{i+1}}{A_i} \]  

Where \( A_i \) is the mean area of the contributing watershed to streams of order \( i \).

4. Initial State Probabilities

The initial state probability accounts for rain drops falling on any hill slope areas and neglects rainfall on the channel network. The initial probabilities as well as the transition probabilities can be defined as functions of only geomorphologic and geometric parameters. The initial probability of a drop falling in an area of order \( i \) is equal to the percent contributing area for the given order.

5. Transitional State Probabilities

The transition probability accounts for the changing state of a drop from lower order stream to the higher order stream and are represented by \( P_{12}, P_{13}, P_{14}, P_{23}, P_{24} \) and \( P_{34} \). Here \( P_{23} \) represents the probability of the drop to move from 2\(^{nd}\) order stream to 3\(^{rd}\) order stream. Transition probabilities are the ratio of the number of streams of order \( i \) draining into streams of order \( j \), divided by the total number of streams of order \( i \). Thus, the transition probabilities are related to the average ratio of the number of streams of a given order to the number of streams of the next order (i.e., bifurcation ratio, \( RB \)).

6. Path Probabilities

Path probability is defined as the probability of a drop which will travel all possible paths \( S_i \) to the outlet. Path probability is denoted as \( \text{Prob} (S_i) \). The total number of possible paths can be calculated using \( N = 2^{\Omega} - 1 \) where, \( \Omega \) is the order of the stream.

7. GIUH

The IUH ordinates are the ordinates of the probability density function of travel time of rain drops and have the dimension of \( T^{-1} \). Hence it is converted into volume per second by multiplying with the area of the watershed and appropriate conversion factors. The IUH is then converted into unit hydrograph of 1 hour duration. All the computational steps in this methodology are available in [3].

3. Results and Discussion

As indicated earlier, the SWAT model is run using sub daily data and the results from such a run is compared with that from the GIUH computation.

3.1. Runoff estimation using GIUH tool

In this study, the python scripts [5], are utilized for finding the surface runoff. The different tools that are needed for the GIUH computation are created [1] by adding python script in ArcGIS. They are tools for Bifurcation ratio, Length ratio, Area ratio, Travel time parameters, Path probability, Unit Hydrograph and Runoff. The effective rainfall is computed following the manual [9] and based on constant Loss rate /hour of 0.19 cm/hr. The watershed is
delineated with a threshold of 100 pixels for this basin and the stream order is obtained as 4th order. Fig. 2 shows the stream network obtained from watershed delineation process. The instantaneous unit hydrograph represents the response of the catchment to an instantaneous rainfall of 1 cm. The GIUH tool is used for finding out the ordinates of instantaneous unit hydrograph. Number of hours of simulation is also given as the input. Then it is converted to one hour unit hydrograph. The generated unit hydrograph is shown in Fig. 3.

As could be seen, the peak is located at 16 hours which is less than 1 day and hence daily flow recording is insufficient for the catchment. If it is recorded once in a day, there are chances that the some peak values of flow may get missed.

For finding out the runoff, unit hydrograph ordinates and effective rainfall values are required. Unit hydrograph text file obtained from the previous tool is used as one input. Effective rainfall values are entered into a text file. These two text files are given as the input to runoff tool. The direct runoff hydrograph ordinates for each hour are obtained using this tool.

3.2. Runoff estimation using SWAT

Sub-daily precipitation data are used for hourly runoff simulation for the study area using the SWAT. The SWAT identifies the sub daily or sub hourly computation by means of a variable IDT. This variable is set to a value of 60 for hourly simulation. i.e., it can accept minute wise data, if available.

Four events of Manali watersheds are considered for the comparison of runoff. The outputs from the GIUH model and the SWAT model for the four flood events in the Manali watershed are given in Fig. 4. All these selections are based on the availability of flood event and availability of rainfall data. There are many stretches of period during which the rainfall data is not available. While selecting the events, such periods are omitted.

Fig. 4a shows the computed hydrograph from the SWAT and the GIUH models for an event in 2005. The hourly hydrographs from both the models follow the same pattern. However, the generated output from GIUH model is slightly better than that from the SWAT.
Further, the simulation is done for the periods from 28th June to 16th August, 2007, from 20th June to 20th August, 2008, in 5th Aug - 4th Oct, 2009 (Fig. 4b to d). Here, the computed flows are better in all cases. These are evident from the RMSE error (Table no.1).

The following points may be noted while comparing the results. (a) The runoff using GIUH ordinates will be obtained at hourly time step and the observed runoff data are measured thrice a day. (b) Hourly rainfall is available at only one station and no other rainfall is available for the study. Distributed rainfall data is needed for the computation of the GIUH to have better representation and hence to get more accurate results. (c) For the computation of GIUH, hourly rainfall data from more stations are required for getting accurate results, but are not available. (d) Green-Ampt method is used in the SWAT for the computation of effective rainfall while the method specified by CWC [8] is used in GIUH for the computation of the same.

Table 1. RMSE value comparison

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Manali</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE of results from GIUH model</td>
<td>10.75</td>
</tr>
<tr>
<td>RMSE of results from SWAT</td>
<td>10.645</td>
</tr>
<tr>
<td>Average Observed Discharge</td>
<td>13.905</td>
</tr>
</tbody>
</table>
It is seen that the RMSE error of runoff from the GIUH model is better in all the four cases. However, further refinement in the model is required as there is large discrepancy between observed flow and computed flow. This could be done by running the model with distributed rainfall and hourly runoff data, using Green Ampt method for evaluating effective rainfall for both the methods, and deriving GIUH at sub basin level.

4. Conclusion

The main aim of the study is to compare the performance of GIUH and SWAT models in simulating the flood events by using sub daily rainfall. To compare the efficiency of these models, four events in Manali watersheds from Kerala are selected. On comparing the performance of the models, it is found that consistently better results are obtained for the GIUH models. However, refinements in the results are required as there is large discrepancy between the simulated flow and the actual flow. There are several external reasons for the less accurate performance of the model for watersheds such as lack of hourly rainfall and runoff data.

References