Web-based Real Time Flood Forecasting Using SWAT Model

By
Narendra Kumar Tiwary
(Executive Engineer, Water Resource Department, Bihar, India
Ph.D Scholar, IIT Delhi)

Prof. A.K.Gosain, IIT Delhi

Prof. A.K. Keshari, IIT Delhi
Use of New Technologies & Softwares in Flood sector

Drainage Map of the Bagmati Basin

Legend
Drainage lines
Basin boundary
20 0 20 40 60
Km
Introduction

Flood is associated with a serious loss of life, property and damage to utilities.
Event-1 The man-made embankments of river Kosi failed and flooded north Bihar, India during 18 August 2008. 434 dead bodies were found until 27 November 2008.
Event-2

- In June 2013, a multi-day cloudburst centered on the North Indian state of Uttarakhand caused devastating floods and landslides in the country's worst natural disaster since the 2004 tsunami. More than 5,700 people were "presumed dead. Destruction of bridges and roads left about 100,000 pilgrims and tourists trapped in the valleys."
Event-2
Dehradun - Capital of Uttarakhand
Challenge for Water Resource Engineers and Scientists

- Today, with modern equipments and radars we should have been able to predict the floods and expected inundation much earlier and stopped these human disasters
Important Questions to be answered

- Where the floodplain and flood-prone areas are?
- How often the flood plain will be covered by water?
- How long the flood-plain will be covered by water?
- At what time of year flooding can be expected?
Objective of the study

- To modify SWAT model for real time flood forecasting and apply modified SWAT model for real time flood forecasting of river basins using web based data,
- To enhance the forecast lead time by incorporating the rainfall forecast issued by IMD and assess its accuracy.
- To map expected inundation, and flood zonation by integrating SWAT outputs into HEC GeoRAS and HEC-RAS models
The Real Time Flood Forecasting and Flood Plain Zoning System usually consists of one or more of the following components:

1. Rainfall Runoff Model.
2. Runoff Routing Model.
3. Error Analysis and Updating Technique
4. Hydrodynamic model for channel routing (HEC-RAS)
5. Generating TIN and delineating flood plain
1. Watershed delineation using SRTM DEM
2. Formation of HRUS
3. Writing input tables
4. Runoff generation using Green Ampt Method
5. Developing subroutines and modifying SWAT for real time flood forecasting application
Models for Forecasting

- Statistical/ Black box
  - Correlation
  - UH Based
  - Stochastic (ARMAX)
- Conceptual (Water Balance)
  - SWAT
  - HEC-HMS
Methods for Flood Forecasting

Simple correlations
- Use very little data
- Only gauge data is sufficient
- Work very well for reaches that have a small contribution from rain
Physically Based Models

To use the equations of mass, energy and momentum to describe the movement of water over the land surface and through the unsaturated and saturated zones.
Ways to enhance the forecasts

- Enhanced forecasts require data on rainfall
  - To incorporate the contribution of the catchment
  - To incorporate the impact of spatial variability
  - Forecast lead time increases on account of catchment lag
  - Addition to lead time is possible through precipitation forecasting
Typical flood forecasting situation

- Rain forecast
- Total Forecast Lead Time
- Effective Lead Time

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<th>Time used by observation and forecasting</th>
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<tr>
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<td>Time elapsed in observation</td>
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<td>Transmission time</td>
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<td>Data processing</td>
</tr>
<tr>
<td>Forecast formulation</td>
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<td>Transmission time</td>
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</table>

Rain begins | Rain ends | Forecast reaches user | Flood reaches outflow station
Surface runoff hydrograph generated by superimposing dimensionless triangular unit hydrographs
The gamma distribution UH method adapted from Aron and White (1982) defines unit flow as follows:

\[ q_{uh} = \left( \frac{t}{t_p} \right)^\alpha \cdot \exp \left( \left( 1 - \left( \frac{t}{t_p} \right) \right)^\alpha \right) \]

where \( \alpha \) is a dimensionless shape factor which is larger than zero.
**MUSKINGUM ROUTING METHOD**

The Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storages.

\[ \text{Wedge storage} = K X (q_{in} - q_{out}) \]
\[ V_{\text{stored}} = K \cdot (X \cdot q_{in} + (1 - X) \cdot q_{out}) \]

The weighting factor, \( X \), has a lower limit of 0.0 and an upper limit of 0.5. This factor is a function of the wedge storage. For reservoir-type storage, there is no wedge and \( X = 0.0 \). For a full-wedge, \( X = 0.5 \). For rivers, \( X \) will fall between 0.0 and 0.3 with a mean value near 0.2.

\[ q_{out,2} = C_1 \cdot q_{in,2} + C_2 \cdot q_{in,1} + C_3 \cdot q_{out,1} \]

where \( q_{in,1} \) is the inflow rate at the beginning of the time step \( (m^3/s) \), \( q_{in,2} \) is the inflow rate at the end of the time step \( (m^3/s) \), \( q_{out,1} \) is the outflow rate at the beginning of the time step \( (m^3/s) \), \( q_{out,2} \) is the outflow rate at the end of the time step \( (m^3/s) \).
START

If eventstatus = 1 Perform Hourly Simulations

If eventstatus = 2 Forecast hourly

Read Input Data

Initialize Parameters

Daily Loop

Yes

Last hr of Last Day Simulation

No

Hour loop

First Hour of First Day Of Simulation and want real time forecast

Routing Command loop

Import catchment characteristics saved in previous run

Route Command
Route water hourly through channel

Subbasin Command

Read Sub –daily Precipitation

Generate Max/Min Temperature

Compute and Print Final Basin Statistics

Capture Catchment Characteristics, Save values of Soil Water, Reach Storage, Base flow for next SWAT run

End Simulation

Write Outputs to File to be Read by Another SWAT Run

Add water

save Command

add Command

add water

Add water
Figure 4.1 Modified Operational Flow Chart of SWAT Model
4.1.2 Modifications in modelling architecture

All subroutines have been thoroughly studied and modelling architecture been reviewed. A new parameter “eventstatus” is defined. If “eventstatus” = 0, original SWAT is run without any modifications. It gives output on daily basis irrespective of weather data input being daily or sub-daily. This is the modelling design of the modified version of SWAT. The choices of eventstatus are given to the user during a program main.f. Next there are two options. The user can get subdaily output by providing subdaily input data by putting “eventstatus” = 1 or, he/she can use the conditions water in the reaches, soilwater content, baseflow, snow melt, hydraulic conductivity of soil, curve number, wetting front matric potential etc. from a previously saved file as initial conditions for the new run by putting “eventstatus” = 2 and go for real-time flood forecast for “eventstatus” = 3.

In the pre-modified SWAT, a model must run in daily loop starting with first hour of the first day and ending with 24th hour of the last day of declared simulation...
Two new subroutines forecasthourly.f and swatforecast.f have been developed and integrated into SWAT model and other related subroutines main.f, rout.f, rhourly.f, surq_greensampt.f for enabling it for hourly simulation and forecasting flows at outlet points of different sub-basins. The new subroutines forecasthourly.f and swatforecast.f are attached with Appendix I and other modified sub routines are attached with Appendix II. Modified version of SWAT takes in sub-hourly rainfall data as input and estimates infiltration and excess rainfall by GAML (Green and Ampt Mein Larson) excess rainfall method. A dimensionless synthetic unit hydrograph is used for overland routing to forecast flows at outlet points of different sub-basins. Evapotranspiration, soil water contents, base flow, lateral flow and snow melt are estimated on a daily basis and distributed equally for each time step. Subroutines have been modified to capture the final conditions of the catchment at any desired instant. Catchment station is updated on real-time basis after each time step. In modified SWAT, capability of event modelling has also been introduced. First of all the model is run in continuous mode to simulate the characteristics of the basin and validate the model using the historical flow data.
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it was compulsory to provide rainfall and other input data up to the 24th hour even if it was not available till the end of the last day. Simulation had to be done till 24th hour. This modelling structure did not support event modelling. Two new variables ‘starthour’ and ‘endhour’ have been introduced. Starthour is the starting hour of simulation in the first day. Endhour is the last hour of simulation in the last day. The intended values of these two variables should be saved in the file ‘simhour.dat’ before running the model. Likewise the starting day and ending day of simulation are controlled in file.cio as ‘idat’ and ‘idal’ respectively. The added advantage of this new provision is that simulation is made possible from one hour to another hour within the same day.

Two subroutines forcasthourly.f and swatforecast.f have been developed and integrated into SWAT for enabling it for hourly simulation and forecasting flows at outlet points of different subbasins. Modified version of SWAT takes in sub-hourly rainfall data as input and estimates infiltration and excess rainfall by GAML (Green and Ampt Meinke).
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If “eventstatus”=1 event modelling is done which acts as the first run of event modelling. This run is for a slightly longer duration which can help generate initial condition. Here modified subroutines `surgreenamptNKT.f`, `forcahourly.f`, `swatforecast.f`, `rhourlyNKT.f` are used for generating simulated/forcasted flows. Routing is carried out for the event flow and simulation of a slightly longer duration followed by the next event run.
points of different subbasins. Modified version of SWAT takes in sub-hourly rainfall data as input and estimates infiltration and excess rainfall by GAML (Green and Ampt Mein and Larson) excess rainfall method. A dimensionless time area diagram is used for overland routing to forecast flows at outlet points of different subbasins. Evapotranspiration, soil water contents, base flow, lateral flow and snow melt are estimated on a daily basis and distributed equally for each time step. This assumption is valid in view of the small contribution made by these components to the flood events.

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routing by variable storage routing method and \( \text{irte}=1 \) means channel routing using Muskingum river routing method). During this run some important parameters such as soil water, discharge values in the reaches at the endhour of last day, baseflows etc are stored in “StoreSoilWater.dat”, “EndWater.dat” and “baseflow.dat” respectively. This storing helps in quick generation of more realistic results in consecutive short runs.

Generally the values 1 and 24 can be entered in the simhour.dat file. In the rare case when the total data up to 24th hour is not available even for the first run, the endhour value can be put as desired specially in case of real time flood forecasting.

“eventstatus”=2 is given for the consecutive/following runs (i.e., 2nd, 3rd, 4th, ...), when the final situation has already been captured from a previous run. Here stored values of soilwater and endwater are imported from previously saved files. After the 2nd run (eg: 2nd) the files “StoreSoilWater.dat” and “EndWater.dat” are overwritten with final values generated from the present run. These values are again used as input.
Model Set up for study area

Data sets used

- The SWAT model requires data on terrain, land use, soil, and weather for assessment of inflows and outflows of reaches. Following datasets have been used for setting up of the SWAT model:
  1. DEM – SRTM (90 m resolution)
  2. Landuse – Global USGS (2 M)
  3. Soil – FAO Global soil (5 M)
  4. Rain gauges /Temperature gauges – IMD
  5. Stream Gauges – CWC
Study Area
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Division into subbasins
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GAUGE STATIONS

[Map showing various locations with markers and labels such as Kathmandu, Nagarkot, Dheng bridge, Janakpur, etc.]
Table 5.3 Daily Rainfall, Temperature and Wind speed of 13-14 Sept-12 of Hayaghat
(source: www.imdaws.com)

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</table>
Table 5.8 Real time hydrological data for year 2012 downloaded from websites (17July-4August)

<table>
<thead>
<tr>
<th>Date</th>
<th>Discharge (Hayaghat) (cumeecs)</th>
<th>WL (meters)</th>
<th>Rainfall (Nagarkot) (mm)</th>
</tr>
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<td>6.2</td>
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</table>
Analysis of web based real time hydrological data of year 2012

Rainfall and water levels of Havaghat gauge station for September 2012 were downloaded from websites www.imdaws, www.hydrology.gov.np, and www.fmis.bih.nic (Table 5 8-5 10). Discharge was calculated using stage discharge relationship of Havaghat. It can be concluded that rainfall of Nepal portion produces peak discharge at Havaghat after 10 days. Hence correlation between rainfalls of Nepal portion and runoff of Havaghat is very interesting. The lead time at Havaghat for rainfall of Nepal portion is very high 4-8 days.

![Hayaghat discharge during 17 July-4-August'12](image)
Discharge at Hayaghat during 13 Sept-30 Sept'12

Discharge in cumecs

Rainfall (Kathmandu)
Discharge 13-30 Sept'12

13-sept time in days 30-sept

0 10 20 30 40 50 60 70 80 90 100

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31
discharge-stage for Hayaghat

\[ y = 108.73x - 4204.1 \]
\[ R^2 = 0.8808 \]
Stage-discharge for Hayaghat

\[ y = 4 \times 10^{-9}x^3 - 1 \times 10^{-5}x^2 + 0.0182x + 38.219 \]

\[ R^2 = 0.9605 \]
Stage-Discharge for Benibad

\[ y = 4 \times 10^{-7}x^3 - 0.0002x^2 + 0.0567x + 44.834 \]

\[ R^2 = 0.936 \]
Results
Calibration - Output

FLOW_OUT_18

Calibration Chart for Hayaghat

Discharge m³/s

Time in months of years 95-99
Calibration Results

Seventeen parameters were selected for sensitivity analysis, calibration, validation and uncertainty analysis to be carried out by SWAT-CUP4 using SUFI algorithm. On the basis of global sensitivity analysis it can be concluded that most sensitive parameter is CN2.mgt followed by GW_DELAY, CH_N2.rte,ESCO.hru, HRU_SLP.hru, GWQMN.gw, GW_REVAP.gw and SURLAG.bsn. P-factor and r-factor for calibration were found to be 0.74 and is 0.44 respectively, which are very much within the range recommended for a perfect model. Seventy four percent observed and simulated values lie in 95PPU. P-factor and r-factor for validation period are 0.63 and 0.55 respectively.
Validation for monthly flow

FLOW_OUT_18

Validation Chart for monthly simulation for Hayaghat

Time in months for years 2000-2001

Discharge in cumecs
The correlation statistics \((R^2)\) was determined to measure the linear correlation between the actual and the predicted values and it was found to be 0.93 which indicates the best performance of the model.

\[ R^2 = 0.96 \]

To estimate the efficiency of the fit, the Nash-Sutcliffe coefficient (Nash) (Nash and Sutcliffe, 1970) was used. It was found to be 0.96 which indicates the best performance of the model.
Daily Flow Validation

FLOW_OUT_18

Flow at Hayaghat

Discharge in cumecs

1-4-2004 to 31-12-2004

Time in days
Flow Hydrograph Daily Simulation

Flow Hydrograph of Hayaghat of July-04

Discharge in cumecs

Time in days

1-July 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32

31-July

RF at Simra
RF at Kathmandu
RF at Nagarkot
RF at Benibad
RF at Hayaghat
HayaOBS
HayaSim

05-08-2014
Valuation for daily flow 2010

FLOW_OUT_18

Validation Chart for daily simulation for year 2010 at Hayaghat

Discharge in cumecs

Time in months for years 2010

05-08-2014
Validation for hourly flow
NE = 0.72
Validation Graph

Discharge in cumecs at Hayaghat

- Blue line: Observed
- Red line: Simulated

2ndAugust-05 to 24thAugust-05

05-08-2014
ERROR ANALYSIS

- Time series analysis of errors in hourly simulations/forecasts has been performed. An ARIMA model developed for forecasting error has been deployed for correcting simulated/forecasted hourly flows. Integration of simulation capability of SWAT model and error forecasting capability by time series analysis has been done for solving the problem of real-time flood forecasting.
Error 2004 Simulation

ERROR 4-July-28-July-04

Discharge in cumecs

4-July-04  Time in hours  28-July-04
Error 2004 hourly simulation

FIRST DIFF OF ERROR 4-July-28-July on y-axis and time in hrs on X-axis
Error analysis of 2004 flood event

ARIMA Model Parameters for error analysis for hourly simulation of year 2004

- **ARIMA Parameters**
- $B_1(\text{LAG}_1) = 1.3153$
- $B_2(\text{LAG}_2) = -0.0162$
- $B_3(\text{LAG}_3) = -0.3013$
Error Analysis

- There are 600 observed and simulated values. Four hundred data have been used for determining ARIMA model parameter and two hundred forecasted errors have been determined. Nash Sutcliffe coefficient before correction for forecasted period of error was 0.64 and after error correction it is 0.795. ARIMA model parameters are given below.

\[ b = 1.3153, -0.0162, -0.3013 \]
\[ Z(t)= 1.3153*Z(t-1) - 0.0162*Z(t-2) - 0.3013*Z(t-3) \]
Hourly Simulation 2nd August-22nd August-05

Discharge in cumecs

- OBS
- SIMCorrected
- SimOld
Hourly 2005

- ARIMA Model Parameters for error analysis for hourly simulation of year 2005
- ARIMA Parameters
- $B_1(\text{LAG}_1) = 0.6056$
- $B_2(\text{LAG}_2) = 0.1792$
- $B_3(\text{LAG}_3) = 0.0988$
Real time flood forecasting graph

Direct Surface Runoff Hydrograph at Khagaria for 10july-11july-04

Discharge in cumecs

Rainfall in mm

10july

Time in hours

11july

05-08-2014
Real time forecasting graphs

Real time forecasts issued on 20th July and 23rd July '04

05-08-2014
Real time forecast

![Graph showing discharge in cumecs over time from 25-8-2010 to 6-9-2010]
Forecast generated at Benibad for July 2004 event

Real Time Flood Forecasting of Subbasin 32 (Day-192-194), 2004
Forecast generated at Benibad for July 2004 event

Flood Forecasting of Sub-basin no.32 of days 192-194
Real time flood forecasting Graph

Discharge in cumecs at Khagaria

- **Forecast issued at 10hr on 18July-05**
- **Forecast issued at 10hr on 19July-05**
- **Forecast issued at 22hr on 19July-05**

18July-05  time in hours  30July-05

05-08-2014
Real time flood forecasting of Haya

25/7-26-7HAYAfLOW-04
Hourly Discharge

![Graph showing hourly discharge for Benibad, Hayaghat, and Khagaria on 14 July and 10 August 2005.](image)

**Discharge in cumecs**

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<td>56</td>
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- Blue line: Benibad
- Red line: Hayaghat
- Green line: Khagaria
SUMMARY AND CONCLUSIONS

(1) Increase in lead time (cathment response delay + travel time in channel)
(2) Application possible in ungauged cathments also
(3) Sediments, water quality and land use can be modelled on real time basis simultaneously
(4) Physically based
(5) Easy in adaptability
(6) Capable of modelling snow melt, percolation, lateral flow and base flow
(7) Parsimonious
(8) GIS based
(9) Inundation mapping and flood zonation easily possible
(10) Easy updating of catchment characteristics
(11) Capable to incorporate rain fall forecast of IMD and increase lead time
(12) Increase in accuracy
(13) Capable of generating synthetic sub-hourly hydrographs
CONCLUSIONS

As outcome of the present research work it can be concluded that Modified SWAT model combined with time series error forecasting ARIMA model and HEC-RAS hydraulic model can be used as an efficient tool for real-time flood forecasting and inundation mapping. Modified SWAT model reproduces stream flow hydrographs reasonably under multiple storm events and can be used as a real-time flood forecasting tool with enhanced lead time. Rainfall forecast can further increase the forecast lead time.
Thank You