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Development of Rainfall-Runoff Model for Northeast Region of Bangladesh

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Abstract: ***Measuring discharge in a developing country like Bangladesh is very important to predict flood, land management and sustainable development. In this paper we are interested to investigate discharge estimation and to determine watershed parameters for northeast region of Bangladesh by using a semi-distributed model called Soil and Water Assessment Tool (Arc SWAT) after comparing simulated result with observed data. ArcGIS version 10.3 with extension software SWAT has been used to prepare a hydrological model for Meghna River catchment. For model calibration SWAT_CUP SUFI-2 algorithm has been used. The calibration and validation has been done at Bhairab Bazar station, outlet of Meghna River catchment. The paper also indicates a numerical modeling work performed in order to assess the feasibility of using freely available global weather, topography, and soil and land use datasets to simulate flow of the Meghna River catchment. The performance of the model indicates that such an approach can indeed produce an acceptable results. The NSE and R2 values for statistical evaluation of model efficiency for calibration period 2001-2006 and validation period 2007-2013 are 0.85, 0.88 and 0.76, 0.85 respectively.***

Keywords: SWAT, Meghna River Basin, Watershed, Ganges-Brahmaputra-Meghna (GBM), Temperature, Precipitation, Calibration and Validation

1. Introduction

Bangladesh is widely recognized as one of the country which is most susceptible to the adverse effects of climate change and has a tropical monsoon climate characterized by heavy seasonal rainfall, high temperatures and high humidity. South Asian country Bangladesh is located between 20°34´ to 26°38´ north latitude and 88°01´ to 92°42´ east longitude, with an area of 1,47,610 km^2. Bangladesh has many international and national rives. The Ganges-Brahmaputra-Meghna (GBM) River system (Fig. 1) plays an important role in China, Bhutan, India, Nepal and Bangladesh. The GBM basin is the third largest freshwater outlet to the world's ocean, being exceeded only by the Amazon and the Congo River systems [1]. The northeast region of Bangladesh is known for its many small streams and rivers. The Meghna river system is one of the major river systems in northeast region of Bangladesh. In Bangladesh the run off of Meghna river is primarily generated by the accumulation of basin-wide rainfall of the Meghna, the area of 65 000 km^2. In order to assess the water availability and predict floods in Bangladesh, it is necessary to establish a hydrologic model over the Meghna basin. There are some research on flow distribution and sediment transport of GBM basin [2], research on Brahmaputra basin are the established linear regression model between rainfall and stream flow for assessing change of future flow [3]-[4], impacts of climate changes on peak flow of Meghna river basin [5] but there are not so many studies to establish rainfall runoff relationship by using a semi distributed model like SWAT in Bangladeshi river basin. In this study, a physical based model SWAT has been set up over the Meghna basin. The main purpose of this paper is to develop a rainfall runoff model by using the discharge data of the Meghan river basin along with its land use, soil types and others hydrological and meteorological data corresponds with by using mentioned software and then compare the stimulated data with observed data to find out the watershed discharge parameters.

2. Study area and methods

2.1 Study area

The Ganges-Brahmaputra-Meghna (GBM) river basin is a transboundary river basin with a total area of just over 1.7 million km^2, distributed between India (64%), China (18%), Nepal (9%), Bangladesh (7%) and Bhutan (3%) [6] (Fig. 1). The Meghna River is one of the most important rivers in Bangladesh [7], one of the three that forms the Ganges Delta, the largest delta on earth, which fans out to the Bay of Bengal. Meghna River is formed inside Bangladesh above the town of Bhairab Bazar (Fig. 1) by the joining of the Surma and the Kushiyara, both of which originate in the hilly regions of eastern India as the Barak River. The Meghna meets its major tributary, the Ganges River (in Bangladesh it is known as Padma River) just a few hundred kilometers upstream of the mouth in the Bay of Bengal. The study area is shown in Figure 1 and Figure 2. The Meghna River catchment has been selected for the study area. The catchment of Meghna River is one of the most important alluvial basins of the world because of its size and location, density of population, catastrophic deposition of sediments, increased flooding and lower elevation above mean sea level [9]. The basin includes one of the largest delta of the world [10], the Bengal delta, and is situated at the confluence of the Ganges-Brahmaputra-Meghna (G-B-M) river system, the largest sediment dispersal system of the world [11]. Meghna basin comprises primarily of a large alluvial basin with quaternary sediments deposited by the Ganges and Brahmaputra rivers and their numerous associated streams and distributaries. The Meghna river system flows on the east of the Brahmaputra River through Bangladesh. The Meghna river basin is characterized by low precipitation in the northwest of its upper region and high precipitation in the areas along the coast. High precipitation zones and dry rain shadow areas are located in the Brahmaputra river basin; whereas the world's highest precipitation area is situated in the Meghna river basin [12]. Highest total average rainfall was observed in the Meghna river system area 52917 mm from 1985 to 1994 and lowest total average rainfall was in Brahmaputra river system 20185mm from 2005 to 2014 [13].

Figure1: Ganges-Brahmaputra-Meghna basin [8]

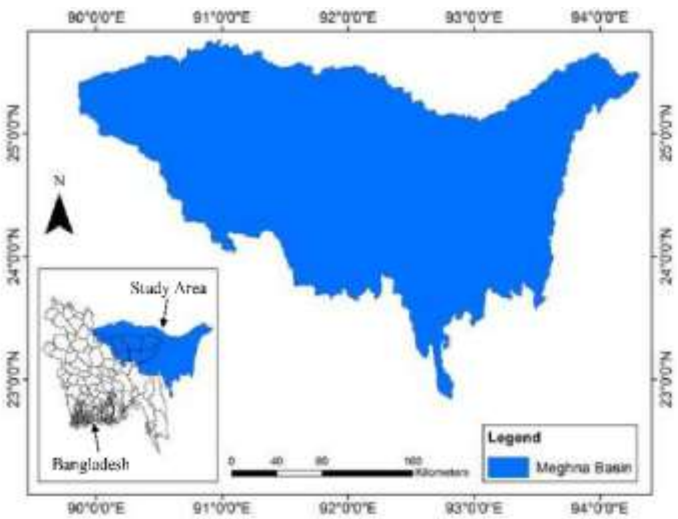


Figure 2: Study area, Meghna basin with distinct boundary

2.2 Methods

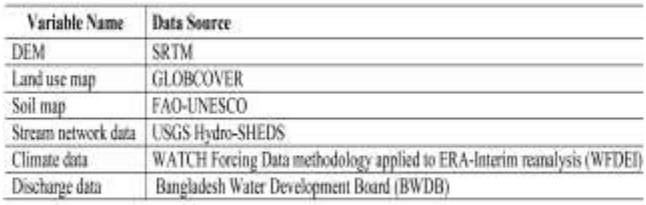
Soil Water and Assessment Tool (SWAT) is a semi distributed public domain hydrologic model developed by United States Department of Agriculture (USDA) to simulate runoff, sediment and nutrients from catchment. SWAT is a physical process based model to simulate continuous-time landscape processes at a catchment scale. The catchment is divided into different hydrological response units (HRUs). The major model components include hydrology, weather, soil erosion, nutrients, soil temperature, crop growth, pesticides agricultural management and stream routing. The model predicts the hydrology at each HRU using the water balance equation, which includes daily precipitation, runoff, evapotranspiration, percolation and return flow components. The surface runoff is estimated in the model using two options (i) the Natural Resources Conservation Service Curve Number (CN) method (USDA-SCS, 1972) and (ii) the Green and Ampt method (Green and Ampt, 1911). The percolation through each soil layer is predicted using storage routing techniques combined with crack-flow model. The evapotranspiration is estimated in SWAT using three options (i) Priestley-Taylor, (ii) Penman-Monteith and (iii) Hargreaves. The flow routing in the river channels is computed using the variable storage coefficient method, or Muskingum method. In a conservative environment, the total water entering channels every day from each HRU in the SWAT model can be derived from

$$Q_{flow} = \left(Q_{surf} + Q_{lat} + Q_{gw}\right) \times HRU_{area}$$

where Q_{flow} is the total water entering the channel of the sub-basin where the HRU is located (mm^3), Q_{surf} is surface runoff yield (mm), Q_{lat} is lateral flow yield (mm), Q_{gw} is groundwater yield (mm) and HRU_{area} is the HRU area (mm^2). The simulation of the water balance of a catchment by SWAT model requires a large amount of special and time series datasets in order to establish the water balance [14]. For developing hydrological model different types of data are used such as:

i. DEM (Digital Elevation Model)
ii. Land-use data
iii. Soil data
iv. Climate data (precipitation, temperature, solar radiation, humidity, wind speed)

Hydrological data such as river discharge, water level, water temperature pressure and air temperature. These data are required for developing SWAT model which are collected from different sources as Watch Forcing Data methodology applied to ERA-Interim reanalysis data (WFDEI), Bangladesh water development board (BWDB), United States of Geological Survey (USGS) and Food and Agriculture Organization (FAO) etc. Data used for SWAT model development and the data sources are given in the following table.



Variable Name	Data Source
DEM	SRTM
Land use map	GLOBCOVER
Soil map	FAO-UNESCO
Stream network data	USGS Hydro-SHEDS
Climate data	WATCH Forcing Data methodology applied to ERA-Interim reanalysis (WFDEI)
Discharge data	Bangladesh Water Development Board (BWDB)

Table 1: Data used and their sources for SWAT model

2.2.1 Digital Elevation Model

For this study the Shuttle Radar Topography Mission (STRM) 90m resolution Digital Elevation Model (DEM) were used (Fig. 3). It has been downloaded from open source of (http://srtm.csi.cgiar.org/). DEM was processed according to study area for input and then by using DEM and river shape extracted the flow direction, flow accumulation, stream network generation and delineation of the watershed and sub-basins. There are 29 sub-basins were produce and DEM elevation ranges from 2m to 2961m above the mean sea level.

Figure 3: Digital Elevation Model of Meghna Catchment

2.2.2 Stream Network

For watershed delineation the digital stream network was required. The digital stream network data is available from United States Geological Survey (USGS) Hydro-SHEDS at http://hydrosheds.cr.usgs.gov/index.php. Hydro-SHEDS deliver data in various regional extents, types, and resolutions. For this study the used data resolution was 15s. The watershed is delineated using watershed delineation tool in SWAT with using DEM and Digital stream Network. Meghna River is divided into 29 sub-basins as sub-basin into 90 hydrological response unit (HRU) based on soil type, land use and slope classes that allows a high level of spatial detail simulation. The stream networks, sub basin and outlet of Meghna River basin is shown in Figure 4. Here we have taken the basin out at Bhairab Bazar to measure the water level which is used for measuring river flow.

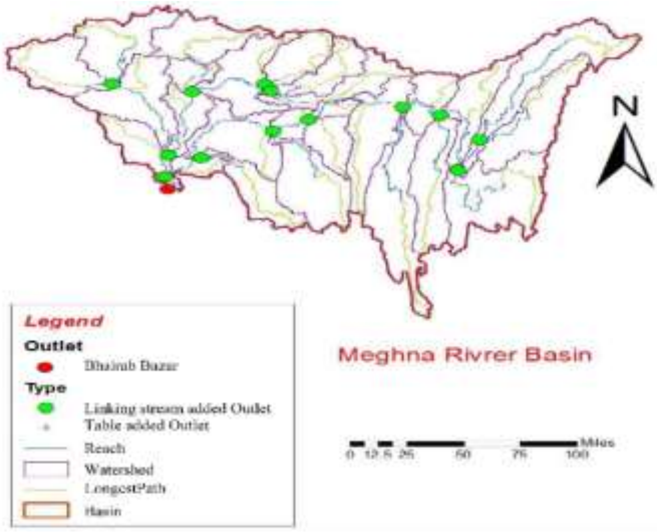


Figure 4: River network, sub basin and outlet of Meghna basin

2.2.3 Land Use

Land use changes has a great impact on flooding and water cycle. Land cover data was taken from European Space Agency (ESA) Glob-Cover project with resolution of 300 m. The data is available at http://due.esrin.esa.int/page_globcover.php. Table 2 represents the value and label of the land use classification in this study area. The data input as raster file and also define as lookup table. In the Meghna River basin there are ten types of different land use (Table 2). Most of the land (32.97%) is covered by Range-Grasses (RNGE) followed by Agricultural Land Generic (AGRL) (24.65%), Forest-Mixed (FRST) (20.29%) and so on. The lowest portion of land is used for residential purpose (URBN). Land use has a great role for infiltration, surface flow, river flow and climate change also. More precipitation occurs in forest land area instead of barren land. Forested area has less runoff because rainfall speed is interrupted by leaves and trees before it reach to ground. Some water is absorbed by plant root and some water go back to atmosphere by transpiration. If the land is paved for parking, road or for residential purpose then surface flow occur very quickly. If the forested and other area are replaced by houses, farms, roads, street then it has great effect on surface runoff. In a barren land surface soil is easy eroded and fertility of soil is reduced easily where is soil erosion is less in forest land. We can see in southeast part of Bangladesh in rainy season frequently land slide occur in mountainous area which causes may causality. So land use are very important for surface flow, river discharge, river bank collapse, mountain flood. The land use patterns of this study area are shown in Table 2 and Figure 5.

Land use type (Code)	Percentage of area (%)
Agricultural Land Generic (AGRL)	24.65
Agricultural Land- Row Crops (AGRR)	5.22
Agricultural Land Close-grown (AGRC)	5.59
Indian grass (INDN)	6.02
Forest-Mixed (FRST)	20.29
Forest-Deciduous (FRSD)	1.97
Forest-Evergreen (FRSE)	2.59
Range-Grasses (RNGE)	32.97
Residential (URBN)	0.05
Water (WATR)	0.65

Table 2: Land use of Meghna River basin

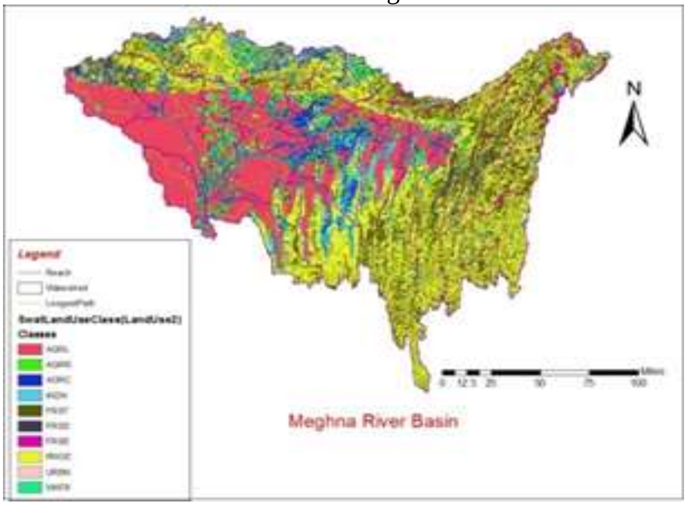
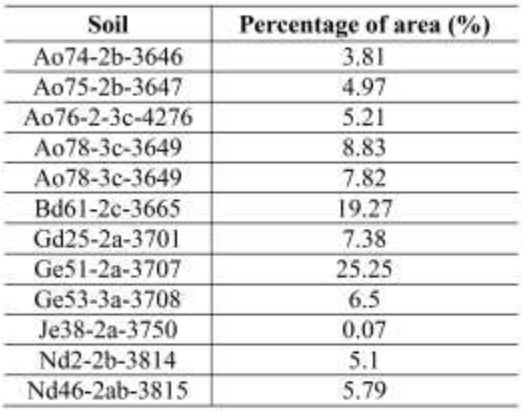


Figure 5: Major Land-Use in Meghna river Basin area

2.2.4 Soil data

Soil is a one of the most important element of SWAT model setup. SWAT model requires different soil properties of all different soil layers such as soil textures, hydraulic conductivity, available water content, bulk density etc. Soil data input as a shape file and collected from FAO-UNESCO Soil Map of the world at http://www.fao.org/soils-portal/. The scale of digitized soil map is 1:5 scale ranges. After input soil shape file then by lookup table use SNUM- a sequential code number that ranges from 1 to 6,997, unique for each soil mapping. Depending on hydraulic conductivity soil are divided into four hydrologic groups. They are Hydrologic group A having high infiltration rates even when thoroughly wetted, Hydrologic group B having moderate infiltration rates even when thoroughly wetted, Hydrologic group C having slow infiltration rates when thoroughly wetted and Hydrologic group D having very slow infiltration rates when thoroughly wetted. Also soils are divided into four groups based on their grain sized, clay, silt, sand and rock. Hydraulic conductivity and grain size of soil are very important elements for surface flow. Surface flow depends on soil initial condition o and soil texture. Twelve types of soil are found in the Meghna River basin area as, Ao74-2b-3646, Ao75-2b-3647, Ao76-2-3c-4276, Ao78-3c-3649, Bd61-2c-3665, Gd25-2a-3701, Ge51-2a-3707, Ge53-3a-3708, Je38-2a-3750, Nd2-2b-3814, and Bh16-2-3c-4301. Soil in Meghna River basin and its percentage are given in Table 3. Figure 6 reveals the FAO soil types in the Meghna river basin. Here we see that the dominating soil is Ge51-2a-3707 occupied 25.25% of soil followed by Bd61-2c-3665 (19.27%) and Ao78-3c-3649 (8.83%) respectively.

Table 3: Land use of Meghna River basin



Soil	Percentage of area (%)
Ao74-2b-3646	3.81
Ao75-2b-3647	4.97
Ao76-2-3c-4276	5.21
Ao78-3c-3649	8.83
Ao78-3c-3649	7.82
Bd61-2c-3665	19.27
Gd25-2a-3701	7.38
Ge51-2a-3707	25.25
Ge53-3a-3708	6.5
Je38-2a-3750	0.07
Nd2-2b-3814	5.1
Nd46-2ab-3815	5.79

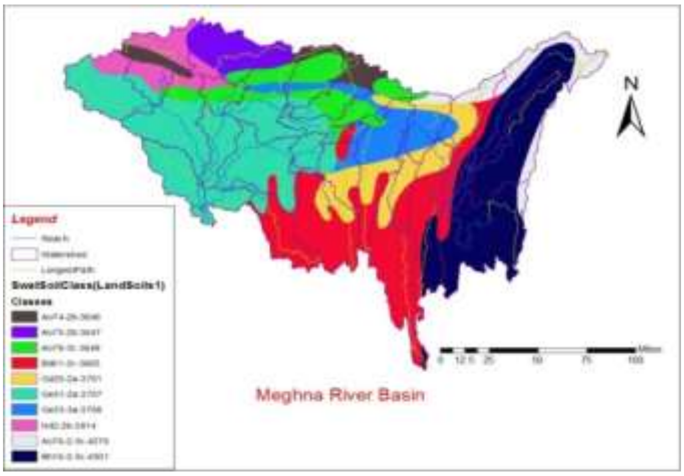


Figure 6: Soil types in the Meghna River basin

2.2.5 Meteorological Data

SWAT model require a large amount of meteorological data for model run. The meteorological data (temperature and precipitation) has been collected from WATCH Forcing Data methodology applied to ERA-Interim reanalysis data (WFDEI). The meteorological data then prepare for the input into the SWAT model according to study area geographical location with meteorological station location. For SWAT model the records of precipitation and temperature are the minimum mandatory inputs and the other parameters are optional [15]. Meteorological data were used from 1998 to 2013 for model simulation. Here we have used 3 years a warm-up period for model simulation. Meteorological data used for simulation performed for the watershed in a short listed below:

i. Input data time series: Daily data
ii. Simulation period: (2001-2013)
iii. Precipitation distribution: Daily (mm)
iv. Temperature: Maximum and Minimum (Daily)

2.2.6 Hydrological Data

For SWAT model it is very important to input the hydrological data. Hydrological data were collected from Bangladesh Water Development Board [16]. Hydrological data that used in this study mainly the water level data for calibration and validation in the period 2001 to 2013. For calibration the Bhairab bazar bridge station (Fig. 1) water level data were used. The water level data used in this study mainly 24 hour data for the calibration and validation.

3. Observed Results

3.1 Temperature and precipitation

We have already mentioned that in this research work we have used precipitation and maximum, minimum temperature of this Meghna River catchment and discharge at Bhairab bazar, out let of this catchment. In SWAT model temperature and precipitation data has been used as weather data from period: 1998-2013.The model can read this inputs directly from the file or generate the value using daily averaged data analyzed for a numbers of years. It includes the WXGEN weather generator model [17] to generate climate data or to fill in gaps in measured records. The weather generator first independently generates precipitation for the day, followed by generation of maximum and minimum temperature. The daily averaged maximum-minimum temperature is shown in Figure 7. The maximum temperature occur in the month of April to August sometimes in September also whereas minimum temperature in the month November to January. Daily average precipitation has been shown in the Figure 8. Usually the maximum rainfall is seen in the month of June in every year.

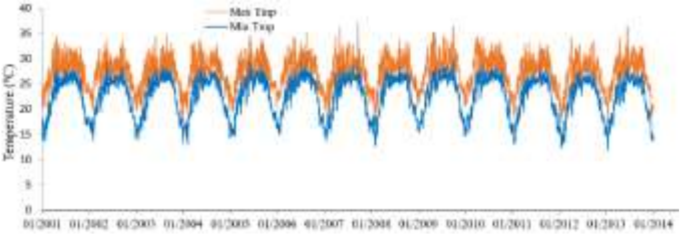


Figure 7: Daily average maximum–minimum temperature

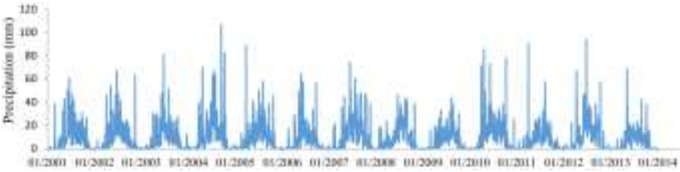


Figure 8: Daily average precipitation

3.2 Observed discharge with precipitation

We know that precipitation is the one of the main factor for discharge. There are some similarities between discharge and precipitation. We have used precipitation in the period of 2001 to 2013 and measured the discharged in the same period at Bhairab Bazar (Fig. 1), out let of Meghna River basin. The precipitation and observed discharge are shown in Figure 9. Here can easily see that peak discharge is occurred at the time of high precipitation and vice versa. In addition we observed that there is some lag between peak precipitation and peak discharge, it is because there is need some time to occur surface or river flow after precipitation, and it is called lag time.

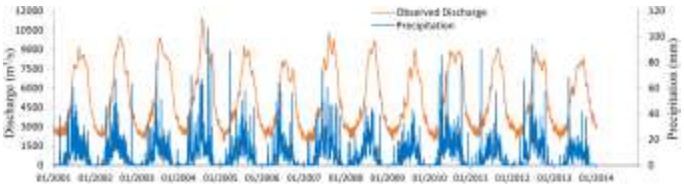


Figure 9: Comparison between observed discharge and precipitation of Meghan basin

4. SWAT-CUP for Calibration and Validation

After getting the simulated result from SWAT model we need to compare our simulated result with observed result. Usually simulated result will not coincide with observed result because there are many physiographic parameters use in SWAT which influence discharge cannot measure directly. So we need to calibrate our model by changing the model input parameters values to produce simulated result that are within in a certain range of observed result [18]. Calibration can be done manually or using auto calibration by SWAT-CUP [19]. SWAT-CUP is a computer program for calibration of SWAT model that include Sequential Uncertainty Fitting (SUFI2) algorithm, GLUE, Parasol, procedures to SWAT. SWAT cup is additional software that is used to manually and automated calibrate the parameters and analysis the sensitivity and uncertainty. A semi-automated approach (SUFI2) is incorporated in SWAT-CUP where we can manually adjust parameters and ranges iteratively between auto calibration and incorporating sensitivity and uncertainty analysis [20]. Completing calibration we need validation our model by using the calibrated parameters values from calibration. In this study calibration and validation in SWAT model were done by SUFI2. The calibration and validation periods have been selected for 2001 to 2006 and 2007 to 2013 respectively.

5. Model performance evaluation

The acceptance of SWAT simulation results is determined by examining the coefficient of determination (R^2), the Nash and Sutcliffe efficiency (NSE). The R^2 value is an indicator of the strength of the linear relationship between the observed and simulated values. The NSE simulation coefficient indicates how well the plot of observed values versus simulated values fits the 1:1 line. If the R^2 and NSE values are less than or very close to zero, the model prediction is unacceptable or poor. If the values are one, then the model prediction is perfect [21]. In general, model simulation can be judged as satisfactory if R^2 >0.75 [22] and NSE > 0.50 for stream flow [23]. R^2 and NSE are statistically defined as follows

$$R^2 = \frac{\sum_{i=1}^{n}(x_{oi} - \bar{x}_{oi})(x_{si} - \bar{x}_{si})}{\left[\sum_{i=1}^{n}(x_{oi} - \bar{x}_{oi})\right]^{0.5}\left[\sum_{i=1}^{n}(x_{si} - \bar{x}_{si})\right]^{0.5}}$$

and

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x_{oi} - x_{si})^2}{\sum_{i=1}^{n}(x_{oi} - \bar{x}_{oi})^2}$$

where x_{oi} is the observed data on day i, x_{si} is the simulated output on day i, $\bar{x}_{oi}$ is the average measured value during the study period, $\bar{x}_{si}$ is the average simulated value during the study period and n is the total number of the observed data.

6. Results and Discussions

6.1 Calibration and Validation result

The main aim of calibration are to provide the best possible fit values amongst the observed and simulated stream flows for a particular calibration period. Here we calibrated our model by manual and automated changing the parameter values within their range. The fitted values of calibrated sensitive parameters are given in table 4. Using the same calibrated values of parameter we have done the validation. The calibration period has been selected for 2001-2006 and validation period for 2007-2013.The calibration and validation graph of discharge along with observed discharge has been shown in the following Figure 10 and Figure 11 respectively. In the calibration period in the years 2001-2006 the values of statistical tools R^2 and NSE are 0.88, 0.85 whereas in the validation period 2007-2013 these are 0.85, 0.76, respectively.

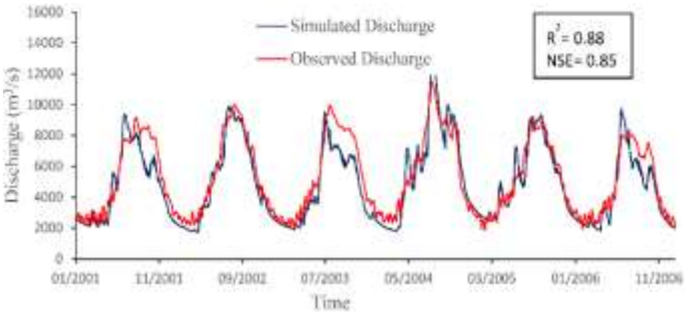


Figure 10: Daily flow calibration (2001-2006)

The R^2values were 0.88 and 0.85 for calibration and validation respectively. It indicates that model results produced for the flow were acceptable for both periods. In SWAT model R^2 value for calibration 0.88 is good and for validation period R^2 value 0.85 is also good. During the calibration period, the NSE value was 0.85 which was acceptable. For SWAT model, NSE value (>0.65) is very good for calibration period. For validation NSE value is 0.76 which is also satisfactory. Model performance test values indicate that the model results are very good that we can use this calibrated model to predict or measure the discharge by using climate data (precipitation, temperature, solar radiation, humidity, wind speed)

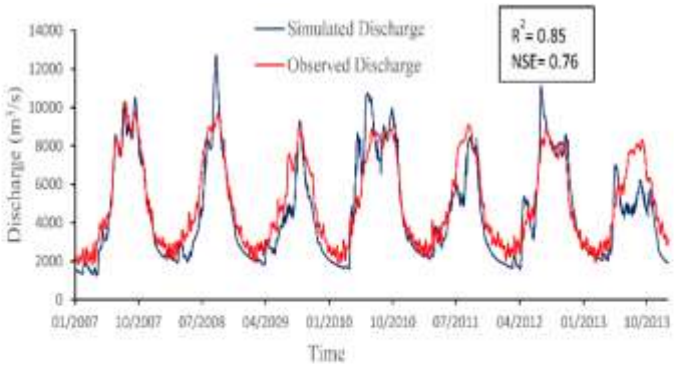
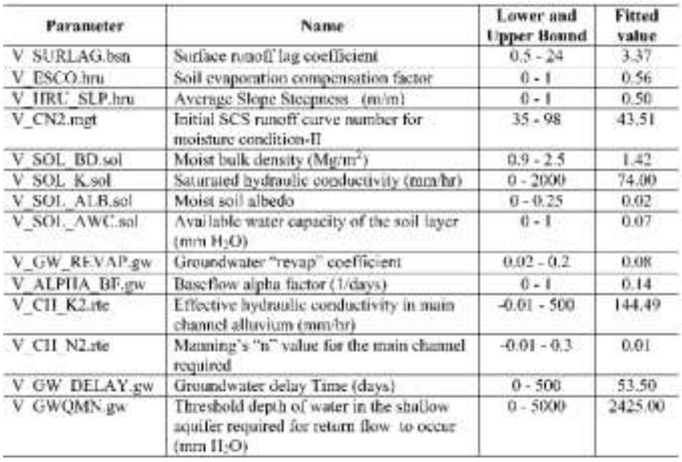


Figure 11: Daily flow validation period (2007-2013)

Table 4: Fitted value of calibrated parameters



Parameter	Name	Lower and Upper Bound	Fitted value
V_SURLAG.bsn	Surface runoff lag coefficient	0.5 - 24	3.37
V_ESCO.hru	Soil evaporation compensation factor	0 - 1	0.56
V_HRU_SLP.hru	Average Slope Steepness (m/m)	0 - 1	0.50
V_CN2.mgt	Initial SCS runoff curve number for moisture condition-II	35 - 98	43.51
V_SOL_BD.sol	Moist bulk density (Mg/m^3)	0.9 - 2.5	1.42
V_SOL_K.sol	Saturated hydraulic conductivity (mm/hr)	0 - 2000	74.00
V_SOL_ALB.sol	Moist soil albedo	0 - 0.25	0.02
V_SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O)	0 - 1	0.07
V_GW_REVAP.gw	Groundwater "revap" coefficient	0.02 - 0.2	0.08
V_ALPHA_BF.gw	Baseflow alpha factor (1/days)	0 - 1	0.14
V_CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	-0.01 - 500	144.49
V_CH_N2.rte	Manning's "n" value for the main channel required	-0.01 - 0.3	0.01
V_GW_DELAY.gw	Groundwater delay Time (days)	0 - 500	53.50
V_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	0 - 5000	2425.00

7. Conclusions

Meghna river basin is most important basin as a flash flood-prone basin. This research exercises the use of hydrological data with Arc-SWAT in combination of SWAT-CUP software to indicate model performance which produced acceptable results. The results presented in this paper are based on the identifying simulated data using a SWAT model. It also indicates flood frequency analysis which enabled us to predict future flood. In this research, different satellite based data and organization open source data were used. Besides, there are many different parameters of the governing equation were used for adjust value. Most of the time the model agrees with observed value and some time it over estimates the value. The statistical fitting values were well matched every time but sometime it deviated from the best fit value. We can also extend our research to simulate sediment load of this flash flood-prone basin when suspended sediment concentration data are available.

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