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A Comparison Study of Streamflow with Satellite Derived and Point Measured Meteorological Data using QSWAT Modeling

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Abstract - Hydrologic cycle has a close relation with the earth surface and subsurface processes by its integration through its cycle, storage, and agricultural pattern. A hydrological modeling approach was used to predict rainfall-runoff/streamflow using Soil and Water Assessment Tool (SWAT) with 3-different meteorological data. The objective of this study is to predict Rainfall-Runoff based on satellite derived rainfall data and compare the runoff results with point measured rainfall data. The two satellite derived rainfall data agencies were Centre for Hydrometeorology and Remote Sensing (CHRS) PERSIANN-CDR, and National Aeronautics and Space Administration–Prediction of Worldwide Energy Resource (NASA-POWER) and point measured data from Indian Meteorological Department (IMD), India. To achieve this objective, a watershed selected namely 'Auranga' watershed, situated in Jharkhand state of India. In this study 2 point stations 'Balumath' and 'Latehar' were selected to get rainfall data. The QSWAT model simulation performed with the above meteorological data from 3 different agencies. The analysis of QSWAT model results carried in 2 scenarios, such as scenario-1: results of annual sum of stream flow considering entire 'Auranga' watershed. In this scenario from IMD rainfall data annual streamflow was 629 m3/s and with satellite derived rainfall data are 521 m3/s, 429 m3/s from NASA-POWER, PERSIAN-CDR agencies respectively. Scenario-2: simulation results, considering the largest sub-watershed no.27 only, the annual peak runoff delivered from point measured IMD rainfall data was 392 mm and 270 mm, 221 mm from satellite derived NASA-POWER and PERSIANN-CDR rainfall data consecutively. As nut-shell, the QSWAT model simulation results reveals, that the point measured IMD precipitation data predicts higher streamflow/runoff values to satellite derived rainfall data.

***Key Words*:** Streamflow, QSWAT, Hydrology, IMD, LU-LC

1.INTRODUCTION

Hydrologic models are more and more widely applied by hydrologists and resource managers as a tool to understand and manage natural and human activities that affect watershed systems. Hydrological models, even those physically based models, often contain parameters that cannot be measured directly due to measurement limits and scale issues [1]. There are many physically-based watershed models that have been successfully applied in practical hydrologic modelling problems, However, since running these models is time intensive, it is nearly impossible to test the optimization algorithms for the complex models. In this study one complex distributed hydrologic model–Soil and Water Assessment Tool (SWAT [2] was selected to predict rainfall-runoff for the 'Auranga' Watershed. The hydrologic and water quality models (H/WQ) are being used in the impact based analysis on water resources and its ecosystem services [3] and for assessing the influence of topography, landuse, and climate change on water resources using a distributed hydrological model is an effective tool [4]. Soil and Water Assessment Tool (SWAT) is a physical process based and distributed river basin model with spatial distributed parameters operating on a daily time step and it is widely accepted as robust inter-disciplinary watershed modeling tools [5]. Arnold and Fohrer (2005)[6] have shown that SWAT can be used in assessment based analysis like predicting long term impacts of land management measure on water, sediment and agricultural yield in large complex watershed with varying soils, and land management conditions. Borah and Bera (2004)[7] compared SWAT with Dynamic Watershed Simulation Model (DWSM), Hydrologic Simulation Program-Fortran (HSPF) model [8], and concluded that SWAT is useful in an agricultural watershed for monthly predictions except for extreme storm events and hydrologic conditions. A comparison was made between SWAT and HSPF for streamflow predictions and it was found that SWAT was more consistent in estimating streamflow for different climatic conditions and for investigating the long-term impacts of climate variability [9]. Discharge prediction using SWAT model has been done in most of the country in world [10],[11]. Schuol et al.[12] used SWAT for modeling blue and green water availability in Africa and freshwater availability [13] in the West African sub-continent using the SWAT model. With this background, the main objective of this study was to simulate rainfall-runoff of Auranga River watershed using SWAT model with 3-different rainfall data portals of CHRS, NASA and IMD. This modeling study also provides in effectively planning and managing agricultural water resources, soil erosion as well as natural disasters.

2. MATERIALS AND METHODOLOGY

A. STUDY AREA

The present study was carried out in the ‘Auranga’ watershed (Watershed code: C2ASON01 to 83 as per India-WRIS watershed atlas) of son sub-basin of Ganga basin covered in Latehar district of Jharkhand state of India. The main river flows in this watershed is ‘Auranga’ river in Latehar and Palamu districts, therefore, the name of watershed titled as ‘Auranga’ watershed. The ‘Auranga’ river has two principle tributaries of Sukri, Ghaghri, till it flow into the ‘Koel’ near Kechki 16 km south of Daltonganj. The watershed covers a total geographical area of 1409 km^2 lies between 23^{0}39’4’’N latitude and 83^{0}39’20’’E longitude to 23^{0}23’43’’N latitude and 84^{0}46’32’’E longitude with an average elevation of 784m above mean sea level altitude as shown in Fig.1. The average annual rainfall in the ‘Auranga’ watershed was noted as 819 mm from 2004 to 2008. The ‘Auranga’ river rises near Saheda in pass leading down from the Chhtanagpur plateau. The riverbed is very rocky in some places and sandy above the junction with the North Koel. Like the North Koel it carries a large volume of water in rains but the summer dries up completely.

B. MODEL DESCRIPTION

The SWAT (Soil and Water Assessment Tool) distributed model was developed jointly by the Agricultural Research Service (ARS) of the united States Department of Agriculture (USDA-ARS) and Agricultural Experiment Station in Temple, Texas. It is a well recognized model for predicting water flows, sediment loss and nutrient balances in complex watershed, basin and even continental-scale assessment with varying soils, land use, and management conditions [14]. It is physically based, continuous time, long term simulation, lumped parameter, deterministic and originated from agricultural models. The model integrates the principal hydrological processes, soil and nutrient transport, and vegetative growth on a spatial and temporal frame, using a daily to an annual time scale. Regression based functions describe the relationship of input and output in SWAT, and a number of static and dynamic variables are created to represent the system boundary and its function/process.

Fig -1. Location Map of Study area - ‘Auranga’ Watershed

Large watersheds are divided into smaller units on stream network, soil and land use information. Rainfall is divided into different components, which include evaporation, surface runoff, infiltration, plant uptake, lateral flow, and groundwater recharge. Water in each sub-watershed is stored as: (1) snow at soil surface (not applicable here), (2) moisture content at various soil layers, (3) shallow aquifer and (4) deep aquifer [15]. Surface runoff from daily rainfall is estimated with a modification of the Soil Conservation Service (SCS) Curve Number (CN) method from United States Department of Agriculture-Soil Conservation Service (USDA-SCS) [16] and peak runoff rates using modified rational method. Water, soil, and nutrients are routed from sub-watershed outlet to stream channels [17].

In this present study the SCS-Curve Number was adopted to calculate surface runoff volume using the following equation

$$Q_{surf} = (R_{day}-I_a)/(R_{day}-I_a+S) \qquad (1)$$

Where, Q_{surf} is the accumulated runoff or rainfall excess (m), R_{day} is the rainfall depth for the day(mm), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm), and S is the retention parameter (m).

$$S = 25.4\ (1000/CN - 10) \qquad (2)$$

Where, CN is the Curve Number for the day.

The Initial Abstractions, I_a, is commonly approximated as 0.2 S and equation 1 becomes

$$Q_{surf} = (R_{day} - 0.2 * S)^2 / (R_{day} + 0.8 * S) \qquad (3)$$

Runoff will only occur when $R_{day} > I_a$

Where, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is retention parameter (mm). Runoff will occur when $R_{day} > 0.2*S$

The Hargreaves method was chosen for calculating Potential EvapoTranspiration (PET) in the present study. SWAT simulates plant growth by using the generic crop growth module from the EPIC (Erosion Productivity Impact Calculator) model [17].

C. INPUT DATA AND MODEL SETUP

Spatial Data

The spatial data used in QSWAT model for this study included a Digital Elevation Model (DEM) which describes the elevations of topography in digital media. This DEM useful to delineate stream network and subsequently sub-basins according streams. The other spatial data used was LandUse-LandCover (LU-LC) map. Another spatial data used as input for model was Soil map of the watershed. These spatial data sets were collected from different source/agencies and prepared to utilize as input data as shown in Table No.3. The detailed description of each spatial data as follows.

Digital elevation Model

The ASTER digital elevation data had a resolution of 30 m downloaded and used as an input in SWAT model for delineation watershed and for topographic parameterization of 'Auranga' watershed Fig.2. The watershed divided into 27-sub-watersheds with threshold area of 32 km^2. The total area of watershed bounded by 1409 km^2 and major area contributed by sub-watershed no.27 having an area of 121 km^2, which is nearer to outlet of the 'Auranga' watershed as shown in Fig. 2.

Landuse-landcover

LU-LC data set of the study area was downloaded from GlobCover web portal. A brief description of each class are given in Table 1. The mixed crop cover area was most dominant class (64%) in the study area. The LU/LC has forest mixed, barren land, forest deciduous, shrubland, mixed crop and very less percentage of waterbody as shown in Fig.3

Soil map

The soil map downloaded from UNESCO-FAO web portal. Soil map contained six soil classes. The SWAT soil classes are 'Lf-1bc-3785'(sandy-loam) has an area of 97 km^2 and major portion of soil class 'Lf92-1a-3791' having an area of 964 km^2, 'I-Lc-2bc-3721' soil type occupied an area of 347 km^2. The 'Auranga' watershed covered with 75% of area having sandy-loam. Manually soil attributes were added into the SWAT user soil database. The classified soil map used in SWAT model shown in Fig.4. The detail description of soil classes used in this study as shown in Table No.2

D. TEMPORAL DATA

Whether information is one of the vital input data to the hydrological processes in SWAT modeling. Rainfall and Maximum, Minimum temperature data at Balumath and Latehar rain gauge stations were collected and used as shown in Fig.5. The rainfall data and maximum/minimum temperature data used in a span of 28 years from 1987 to 2014. Relative humidity, solar radiation, and wind speed data were simulated using SWAT's built-in weather generator [18] based on the weather data. The weather generator was also used to fill data gaps in the rainfall and maximum/minimum temperature data. The main objective of this study is to avail rainfall data from 3–different agencies namely PERSIAN-CDR (CHRS), NASA-POWER and IMD. The detail description of each organization as follows. The brief description of spatial and temporal data as illustrated in Table No.3

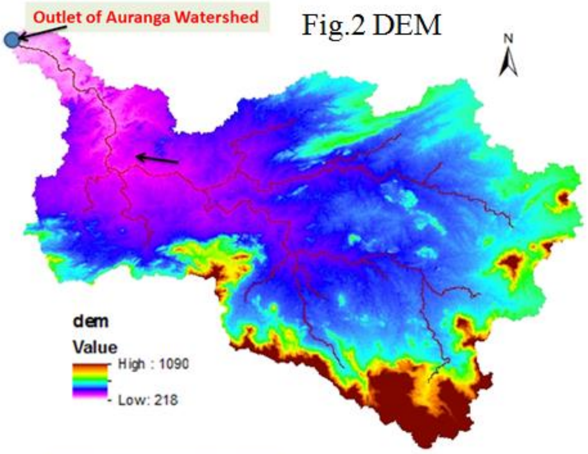

Fig.2 DEM

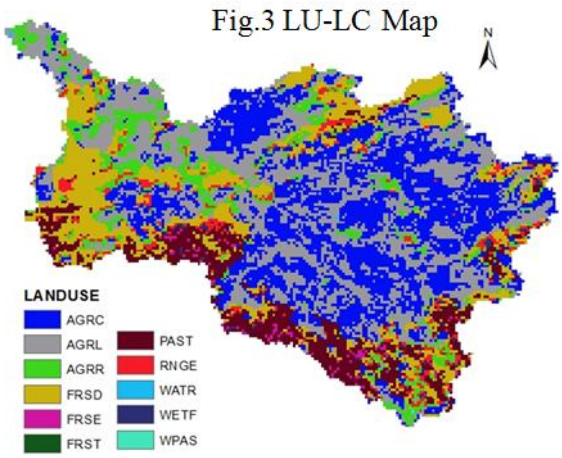

Fig.3 LU-LC Map

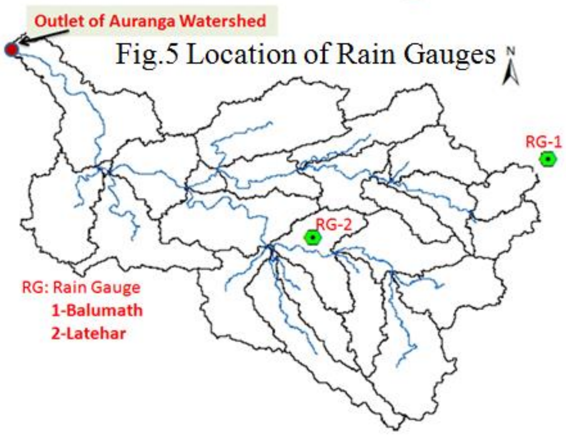

Fig.5 Location of Rain Gauges

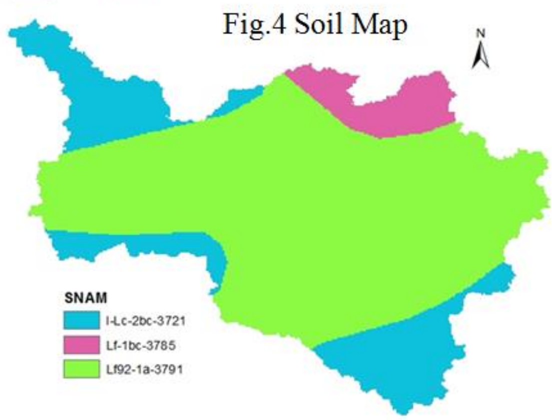

Fig.4 Soil Map

Table -1. Land use-Landcover types and their description

SWAT class	Description	Area km^2	% of area
AGRL	Irrigated crop land	445.76	31.63
AGRC	Rainfed crop land	331.25	23.51
AGRR	Mosaic crop land	142.83	10.13
RNGE	Mosaic Vegetation	62.59	4.44
FRSE	Evergreen Forest	11.03	0.78
FRSD	Deciduous Forest	244.59	17.36
WETF	Closed needled evergreen forest	6.87	0.48
FRST	Mixed Forest	0.18	0.01
PAST	Shrubland	162.82	11.55
WPAS	Grassland	0.18	0.012
WATR	Water bodies	0.81	0.057

PERSIANN-CDR

Precipitation Estimation from Remote Sensed Information using Artificial Neural Networks- Climate Data Record (PERSIANN-CDR) developed by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI) provides daily rainfall estimates at 0.25 deg. For the latitude band 60N-60S over the period of 01/01/1983 to 12/31/2015 (delayed present). PERSIANN-CDR is aimed at addressing the need for a consistent, long term, high-resolution and global precipitation dataset for studying the changes and trends in daily precipitation, especially extreme precipitation events, due to climate change and natural variability [19]. PERSIANN_CDR is generated from the PERSIANN algorithm using GridSat-B1 infrared and adjusted using the Global Precipitation Climatology Project (GPCP) monthly product to maintain consistency of the two datasets at 2.5 deg. monthly scale throughout the entire record. The PERSIANN-CDR product is available to the public as an operational climate data record via the NOAA NCDC CDR program website under the Atmospheric CDRs category.

Table -2. SWAT soil classes and soil texture

S.no.	SWAT class	Texture	Area (km^2)	Percentage (%)
1	3785 (Lf-1bc-3785)	Sandy-Loam	97.07	6.89
2	3791 (Lf92-1a-3721)	Sandy-Loam	964.03	68.44
3	3721 (I-Lc-2bc-3721)	Loam	140	9.94
4	3721 (I-Lc-2bc-3721)	Loam	148.14	10.52
5	3721 (I-Lc-2bc-3721)	Loam	59.24	4.2

NASA-POWER

National Aeronautics and Space Administration (NASA)–Prediction of Worldwide Energy Resource (POWER) through its Earth Science research program, has long supported satellite systems and research providing data important to the study of climate and climate processes. These data include long-term climatologically averaged estimates of meteorological quantities and surface solar energy fluxes. Additionally, mean daily values of the base meteorological and solar data area provided in time series format. These satellite and model-based products have been shown to be sufficiently accurate to provide reliable solar and meteorological resource data over regions where surface measurements are sparse or nonexistent. The products offer two unique features the data is global and generally contiguous in time.

The meteorological data/parameters in POWER were based upon the Goddard's Global Modeling and Assimilation (GMAO), Modern Era Retrospective-Analysis for Research and Applications (MERA-2) assimilation model products and GMAO forward Processing-Instrument Teams (FP-IT) near real time products. Recent upgrades to the component of POWER were initiated to include Geographic Information System (GIS) functionality as an option to the data ordering/access process [20]. The POWER solar data is based upon satellite observations from which surface insulation values are inferred. The meteorological parameters are based upon the MERRA-2 assimilation model.

IMD-India

Indian Meteorological Department-Ministry of Earth Science Government of India supply meteorological data of rainfall and temperature for a period of 28 years from 1987 to 2014. In this study, Auranga watershed has two point stations selected namely 'Balumath' and 'Latehar' as shown in figure 5 for collection of rainfall and temperature data.

Table 3 - Description of Spatial & Weather data for 'Auranga' watershed

S.no	Spatial & Weather Data	Description	Source
1	Digital Elevation Model (DEM)	30m X30m grid DEM for delineation of watershed and analyzed the drainage pattern of the terrain	ASTER-GDM (https://earthdata.nasa.gov)
2	LandUse/LandCover	This data obtained from European space agency - GlobCover	European Space Agency (http://due.esrin.esa.int/page_globcover.php)
3	Soil data	The soil data has been obtained from UNESCO-FAO	Food and Agricultural Organization (FAO) Digital Soil Map (https://www.fao.org/soils-portal/data-hub)
4	Weather data	Rainfall & Temperature	PERSIANN-CDR (https://chrsdata.eng.uci.edu/) NASA-POWER (https://power.larc.nasa.gov/data-access-viewer/) Indian Meteorological Department (IMD)-India

3. METHODOLOGY-QSWAT Model

The objective of this study is to demonstrate with a case study, a new open source interface for SWAT using QGIS, named as QSWAT. Besides all the scientific merits of being open source software, QSWAT has added capabilities of merging small subbasins and has static and dynamic visualization outputs. QSWAT is installed as a plug-in to QGIS, and the main components to perform modeling are 1) watershed delineation 2) Hydrological Response Units (HRU) creation 3) opening the SWAT editor to complete input preparation and execute SWAT and 4) visualization of results.

A. WATERSHED DELINEATION

QSWAT uses TauDEM for watershed delineation. TauDEM provides a suit of programs to perform various geoprocessing functions [21],[22]. QSWAT uses some of capabilities of TauDEM such as pit removal using the flooding approach, calculation of flow paths and slopes, calculation of contributing areas using single and multiple flow direction methods, delineation of stream networks using contributing area threshold, delineation of watersheds and subbasins, areas draining to stream segments, and the association between subbasins and stream segment attributes.

B. HRU CREATION

The SWAT model works by modelling assumed homogeneous areas called Hydrological Response Units (HRUs). An HRU has a particular subbasin it belongs to and has a particular combination of landuse, soil and slope range. The HRUs in QSWAT are created using landuse and soil data layers and associated lookup tables. These data layers are used to identify land use and soil values for each DEM raster cell, since slopes are already available from watershed delineation. Each HRU will belong to a particular subbasin, and each cell within it will have the same landuse, soil and slope range. Beyond belonging to a subbasin, an HRU is not spatially explicit. The creation of HRUs is therefore based on counting cells, since the count multiplied by the grid cell area gives the HRU area. QSWAT has also the capability of exempting certain landuse from possible elimination during HRU selection.

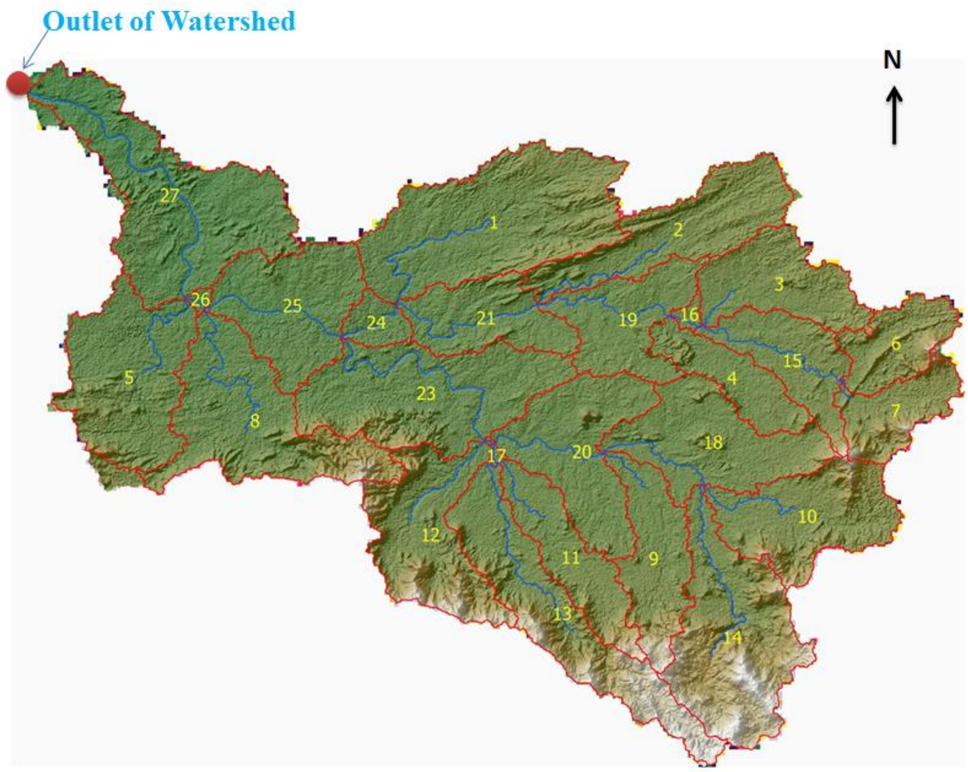

Fig – 6. QSWAT Model Delineation of 27 sub-watersheds from DEM

C. LINKING WITH SWAT EDITOR

QSWAT creates a number of database tables from the watershed delineation and HRU creation steps. These databases will be used as input to the SWAT Editor. The SWAT Editor thereafter creates SWAT readable text files from the database. Moreover, it helps to create text files for weather data and edits various databases. It also executes the SWAT model and reads and exports SWAT outputs. The SWAT Editor is also used to manually change model parameters in the model calibration process.

D. VISUALISATION OUTPUTS

Visualizations are required for quickly discovering issues of interest in the data that warrant further investigation and analysis. QSWAT has three types of visualizations. The first two are static and dynamic visualizations. They are designed to show spatially distributed data and use the map canvas and legend panel of QGIS. The third visualization is the plot function that shows graphs of outputs and is mostly intended for comparison between different subbasins, model simulations or simulated and observed results.

E. QSWAT MODEL APPLICATION

Watershed discritization, using a threshold area of 32 km^2, created 27 subbasins. Four slope classes were defined in the watershed: 0-10%, 10-20%, 20-30% and > 30%. The HRUs were created using the multiple HRU option of filtering by landuse, soil and slope. A 10% threshold area was used to define HRUs-applying a 10% threshold means that landuses, soils and slope ranges whose areas are less than 10% of the subbasin area are eliminated from HRU formation within each subbasin. Since the mixed forest, grassland, and water bodies were very small, the concerned LandUse were exempted from 10% threshold rejection criteria. This is to avoid elimination of these LandUse types from HRU creation and maintain diversity in the landuse types. Altogether, a total of 428 HRUs were created during the HRU creation process. Incorporating land management practices in the SWAT model significantly improves representation of real world conditions and further improves hydrological budget simulations. SWAT model has different options for calculating the hydrological components in a watershed. In this study, the Hargreaves method was used to determine Potential EvapoTranspiration (PET). Surface runoff is estimated separately for each HRU using SCS-CN method and routed to obtain the total runoff for the subbasin. A 'variable storage' routing method was used for routing the flow of water in the channel to reach at outlet of the 'Auranga' watershed.

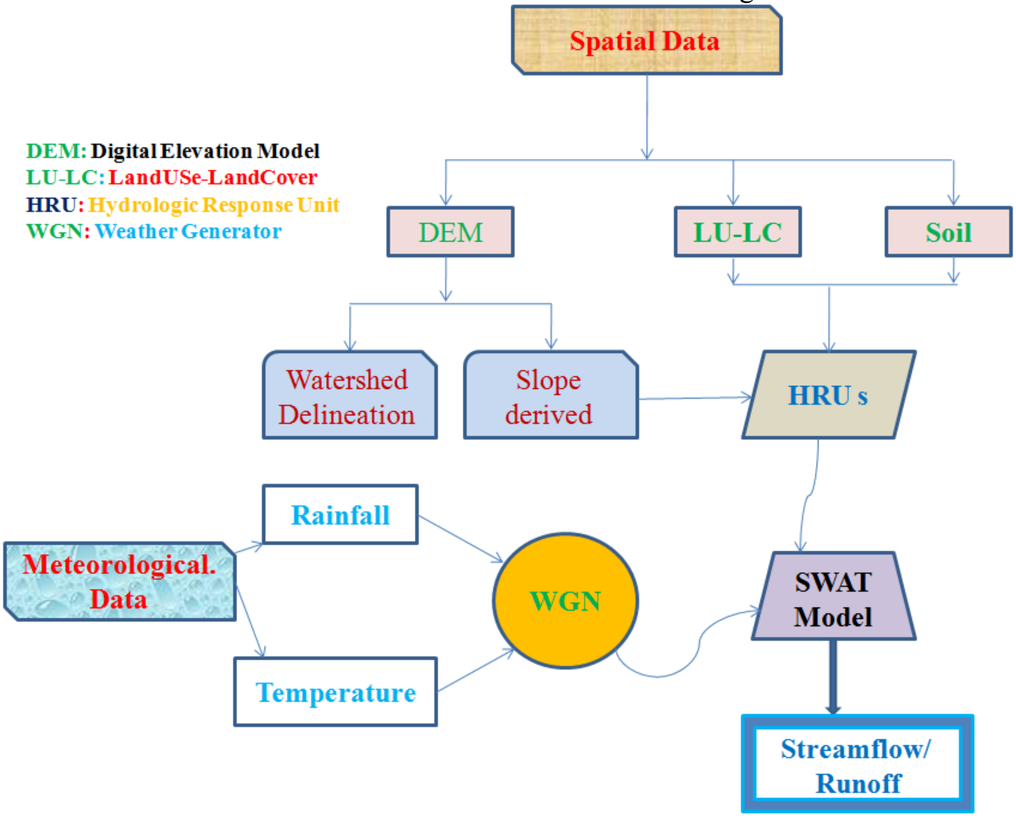

Fig -7. Schematic diagram of Methodology

4. RESULTS AND DISCUSSIONS

The QSWAT model utilized 28 years of rainfall and temperature data for computation of evapotranspiration using Hargreaves method. 5 years of data used as warm up period and the results for 23 years of streamflow plotted as graph shown in Fig.8. In this study the simulation performed based on 3 verities of meteorological data from agencies like PERSIANN-CDR, NASA-POWER and point measured data from IMD. The first analysis made as scenario-1 considering entire 'Aunranga' watershed. The results reveals that the annual stream flow obtained from point rainfall (IMD) data predicts higher than satellite derived rainfall data (PERSIANN-CDR, NASA-POWER) considering the entire 'Auranga' watershed.

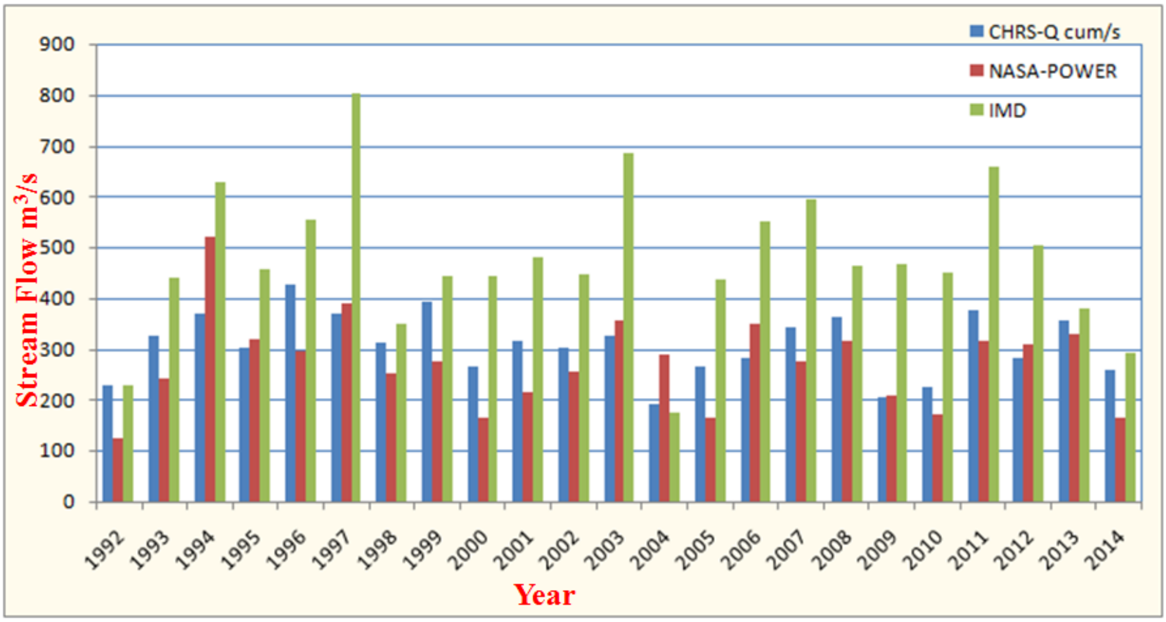

Fig -8. Annual sum of stream flow of 'Auranga' watershed

From the graph (Fig 8), it shows that the simulation of annual streamflow of 628.92 m^3/s from IMD data. The other high runoff predicted from NASA-POWER data in the year 1994 as 521.36 m^3/s and the lower runoff of 428.82 m^3/s from PERSIANN-CDR data. Considering the average stream flow predicted higher by IMD rainfall data and 2nd higher stream flow obtained from PERSIANN-CDR and low prediction from NASA-POWER data.

The Rainfall-Runoff analysis has been made by considering results obtained from sub-watershed no.27 as scenario-2. This sub-watershed is closer to outlet of 'Auranga' watershed and is larger area than other 26 numbers of sub-watersheds. Considering average annual runoff of 28 years, the highest runoff of 222 mm, 148 mm and 131mm from IMD, PERSIANN-CDR and NASA-POWER consecutively.

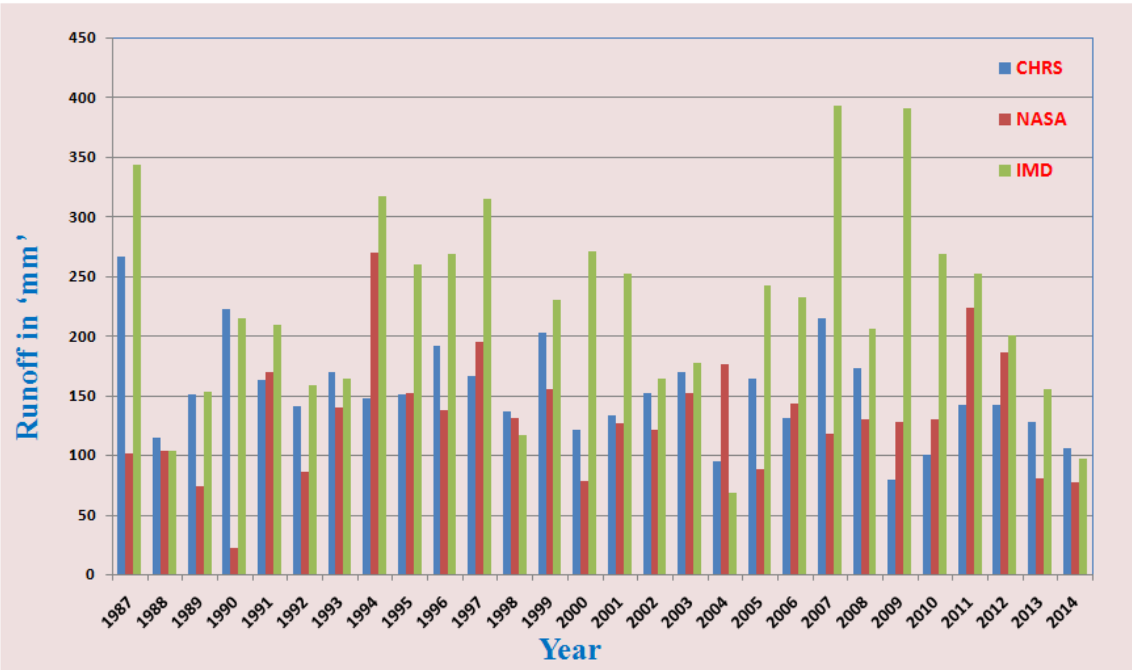

Fig -9. Annual peak runoff for sub-watershed No.27

The Figure 9 shows a graphical representation of average annual runoff comparison between IMD, NASA-POWER and PERSIANN-CDR data results. The highest runoff of 392 mm occurred from IMD rainfall data, 270 mm from NASA-POWER and 221 mm from PERSIANN-CDR rainfall data respectively.

5. CONCLUSIONS

QSWAT an open source GIS interface for the SWAT model was developed on the QGIS platform. In this paper core input data of Hydro-meteorological data from satellite derived agencies like PERSIANN-CDR and NASA-POWER and point measured agency of IMD rainfall data applied for simulation of Rainfall-Runoff with QSWAT model. Visualization of outputs both statically and dynamically can be helpful for interpreting the large amounts of SWAT model outputs. The analysis of results were made in 2 scenarios comparison of streamflow between satellites derived rainfall data with point measured data. Considering the entire ‘Auranga’ watershed as cenario-1 and largest sub-watershed no.27 for comparison analysis as scenario-2. In scenario-1, the comparison of annual sum of stream flow was considered and annual peak runoff was considered as scenario-2.

The following conclusions were made from this heuristic study of Rainfall-Runoff using QSWAT model.

i. The highest runoff predicted from IMD rainfall data considering the whole ‘Auranga’watershed and the largest sub-watershed no.27.
ii. The highest average annual runoff and peak runoff obtained from IMD data in both scenarios.
iii. The satellite derived rainfall data used from PERSIANN-CDR and NASA-POWER simulated lower runoff than IMD rainfall data.
iv. In case of average annual runoff computation, the PERSIANN-CDR simulation results shows higher than NASA-POWER runoff values.
v. Considering higher runoff values within the period of 28 years NASA-POWER delivered higher runoff than PERSIANN-CDR runoff values as shown in figure.9.
vi. IMD-point measured data enable to predict a higher percentage of runoff by 35% and 42% from PERSIANN-CDR and NASA-POWER rainfall data.
vii. The PERSIANN-CDR precipitation data predict 11% of higher average annual runoff to NASA-POWER data. Interestingly, the peak runoff value occurred from NASA-POWER data.

Indian Metrological Department (IMD) point measured rainfall data simulation results delivered higher runoff from simulation QSWAT model. It is concluded that, QSWAT is a credible tool in working with SWAT model considering different meteorological data from satellite derived and point measured data sets of various agencies. This study successfully attempted to estimate the effects of streamflow/runoff changes based on historical rainfall events from satellite derived and point measured rainfall data. The application of semi-distributed modeling approach may help in detailing the streamflow/runoff characteristics within the vulnerable floodplains. Future studies aimed at investigating landuse-landcover change scenarios and their impacts on the streamflow/runoff with different meteorological information through satellite derived and point measured data.

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