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Simulation of Rainfall Run off Process using HEC-HMS: A Case Study of Upper Godavari Basin (M.S., India)

Dr. Dattatray K. Rajmane[1], Mr. Shubham D. Ghungarde[2], Mr. Satyam B. Daule[3], Mr. Devidas G. Darandale[4], Mr. Dnyaneshwar D. Kashid[5]
[1]*Associate Professor,* [2, 3, 4, 5]*UG Students, Department of Civil Engineering, Sinhgad College of Engineering, Vadgaon bk., Pune*

Abstract: ***Runoff plays an important role in the hydrological cycle by returning excess precipitation to the oceans and controlling how much water flows into stream systems. "Modelling runoff can help to understand, control, and monitor the quality and quantity of water resources." (Jan Sitterson et. al.) Therefore, the present work entitled "Simulation of Rainfall Runoff process using HEC-HMS; A Case study of Upper Godavari Basin (M.S., India)"is undertaken for the present research work.***
The latest version Q-GIS 3.18 is used for numerous purposes such as Maps preparation, Implementation of Theisen polygon method and Delineation of watershed, sub-watersheds and inclusive streams while HEC-HMS 4.7.1 is used to simulate the complete hydrologic processes of the present dendritic watershed system. Estimation of all input parameters with their appropriate methods are discussed in detail in this study and Runoff is simulated at outlet of each sub-basin. The Model efficiency is assessed with the help of Coefficient of Inter Correlation, it gives values as 0.793 and 0.562 for year 2000 and 2010. It is concluded that the model shows High level of Coefficient of Inter Correlation. On the line of present study, it is concluded that, "The Hydrologic Engineering Centres Hydrologic Modelling System (HEC-HMS) watershed model can be effectively used to simulate Rainfall Runoff process to estimate basin's hydrological phenomenon caused due to precipitation." "The increase in Urbanization & change in Landuse pattern in the Upper Godavari basin have definitely increased the peak runoff significantly especially in Kham sub-basin."
Keywords: Climate change, Simulation, HEC-HMS, Rainfall - Runoff process, Upper Godavari basin

I. INTRODUCTION

WATER is scarce and there are millions of people across this globe who spend their entire day searching for it; so there is primary need to save water. "Runoff plays an important role in the hydrological cycle by returning excess precipitation to the oceans and controlling how much water flows into stream systems." "Modelling runoff can help to understand, control, and monitor the quality and quantity of water resources." (Jan Sitterson et. al., 2017) [1]
In the view of above discussion;

1) Watershed management is really an important subject which is helpful in future planning of Hydro projects & Natural resource management.
2) Extensive care should be given to the operation & management of river basins & dam reservoirs – no matter are they used for water supply or flood control or both.

Therefore, the present research paper entitled "Simulation of Rainfall Runoff process using HEC-HMS; A Case study of Upper Godavari Basin (M.S., India)" is undertaken for the study.

II. AIM AND OBJECTIVES

"The present study aims at finding out significance of Q-GIS and HEC-HMS in delineation and simulation of Rainfall-Runoff process in the Upper Godavari basin with outlet point at Jayakwadi (Nathsagar) dam." The following specific objectives can be useful to carry out the present study;

1) To Delineate the Watershed and Streams using open source Q-GIS software.
2) To use the HEC-HMS for estimating the basin's hydrological response to Precipitation.
3) To assess the change in Runoff with response to urbanisation within the basin.

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III. STUDY AREA

The Upper Godavari Watershed is selected as the study area in the state of Maharashtra, India. The catchment lies in the rain shadow zone of the western ghat. The catchment lies between $19^0 1' 54''$ to $20^0 26' 11''$ N Latitude and $73^0 27' 32''$ to $75^0 28' 21''$ E Longitude. The region with irregular shape has 1298.160 km perimeter spread over an area of 22118.443 sq. km.

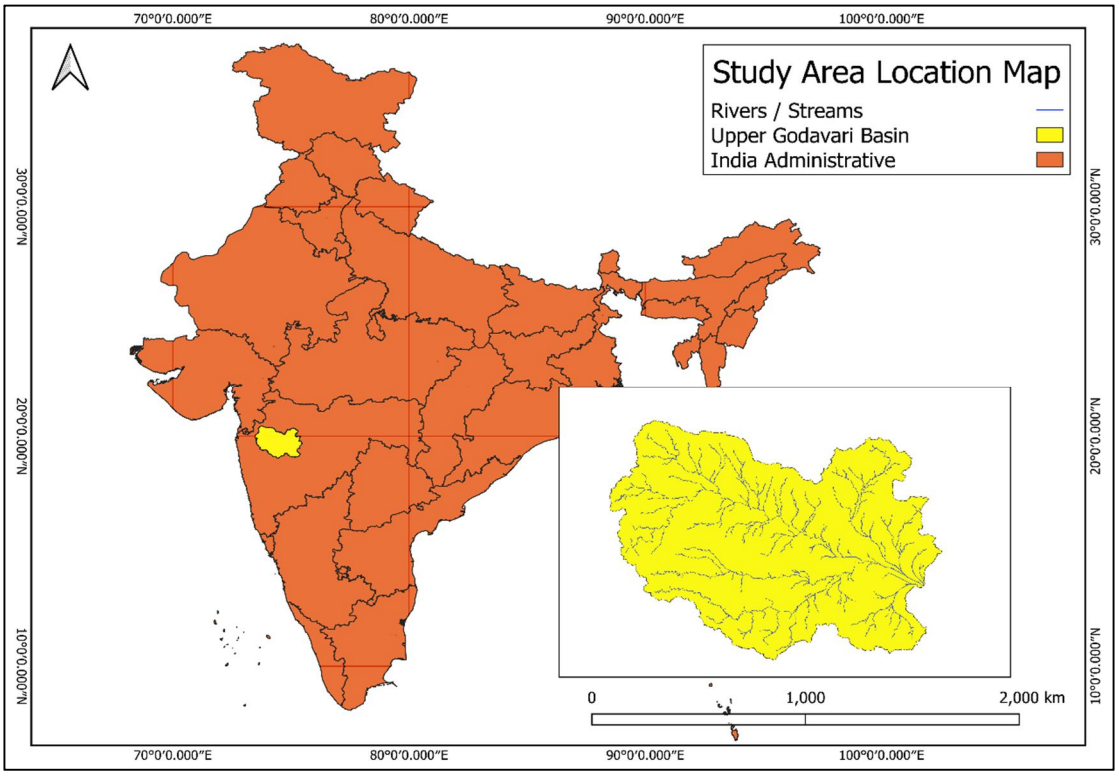


Figure No. 1: Location map of Study Area

The location of study area in India / Maharashtra is presented in location map (Fig. No. 1). The delineated Upper Godavari Basin is spread across three districts of Maharashtra viz., Nashik, Aurangabad and Ahmednagar.

IV. DATABASE

In the present study, the simulation of Rainfall-Runoff process has been carried out. The factors such as topography, climate, landuse and landcover, soil and evapotranspiration aspects are considered for this study. The secondary data is collected from various legal sources. The collected data have been compiled, processed and summarized with the help of suitable statistical, computer and GIS techniques. The collected data with respective sources is presented in table (Table 1).

Table No. 1: Data types and Sources

Sr. No.	Data Types	Data Sources
1	DEM (Digital Elevation Model)	Shuttle Radar Topography Mission (SRTM) by NASA
2	Landuse and Landcover	Quick Open street map (Quick OSM)
3	Soil	India – Water Resources Information System (India-WRIS)
4	Evapotranspiration	India – Water Resources Information System (India-WRIS)
5	Station wise Rainfall data (From 1 Jan 1979 to 30 Dec 2013)	Global Weather data for SWAT (www.globalweather.tamu.edu)

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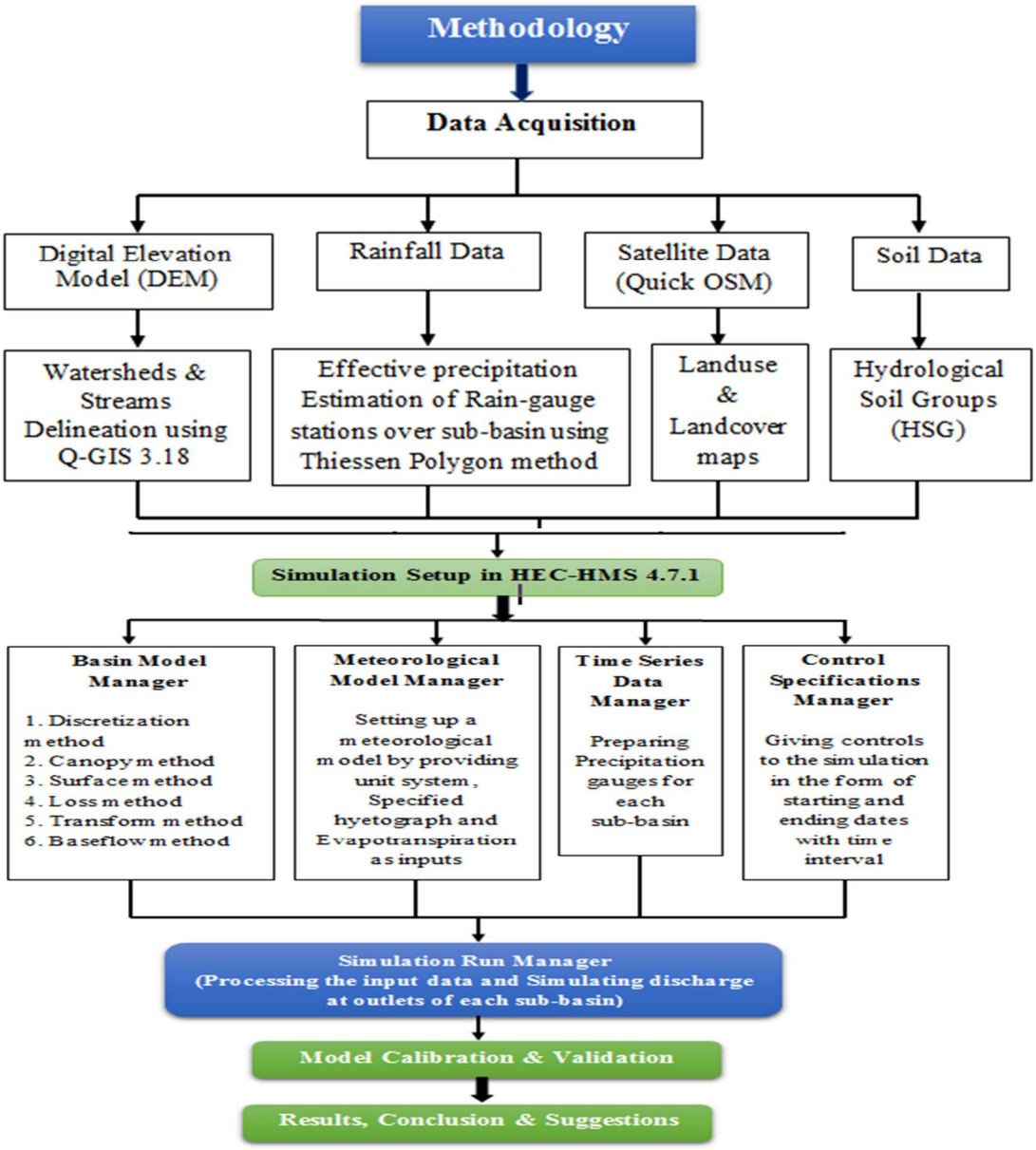
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V. METHODOLOGY

In the present research, the latest version Q-GIS 3.18 is used for numerous purposes such as Maps preparation, Implementation of Theissen polygon method and Delineation of watershed and streams while HEC-HMS 4.7.1 is used to simulate the complete hydrologic processes of the present dendritic watershed system.

The methodology includes various Model applications, Statistical techniques, Computer techniques, GIS techniques, several tools used in delineation of watershed and streams and Components of HEC-HMS etc. The methodology followed for the present research is given in the flowchart (Figure 2). The statistical techniques such as Average, Weighted Values, Correlation Analysis and Theissen Polygon Method are used to estimate input parameters as well as computing results. In the present study, the database has a matrix of number of Geographical, Hydrological and Meteorological parameters. For such a large sized quantitative data computer techniques are essential to obtain mean, standard deviation, correlation etc. Computer techniques are also essential for representation of data with tables, graphs, maps and diagrams.

A significant development and growth is observed in Population, Urban & Industrial sector during late 20th century and in 21st century. Therefore, it would be interesting to understand the change in Precipitation distribution, Landuse pattern and Resulting runoff pattern during this time period. Therefore, the study period of 35 years is considered for the present study dated from 1 January 1979 to 30 December 2013.



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A. Delineation of watershed using Q-GIS 3.18

In the present study, The Digital Elevation Model tiles (DEM) with 30 m resolution are downloaded from www.earthdata.nasa.gov using Shutter Radar Topography Mission (SRTM) plugin. Total six DEM tiles were required to cover the considered study area up to full extent. The un-necessary tiles covering other regions such as Arabian Sea etc., were removed. The steps followed in the delineation of the watershed is given in the flowchart (Figure No. 3).

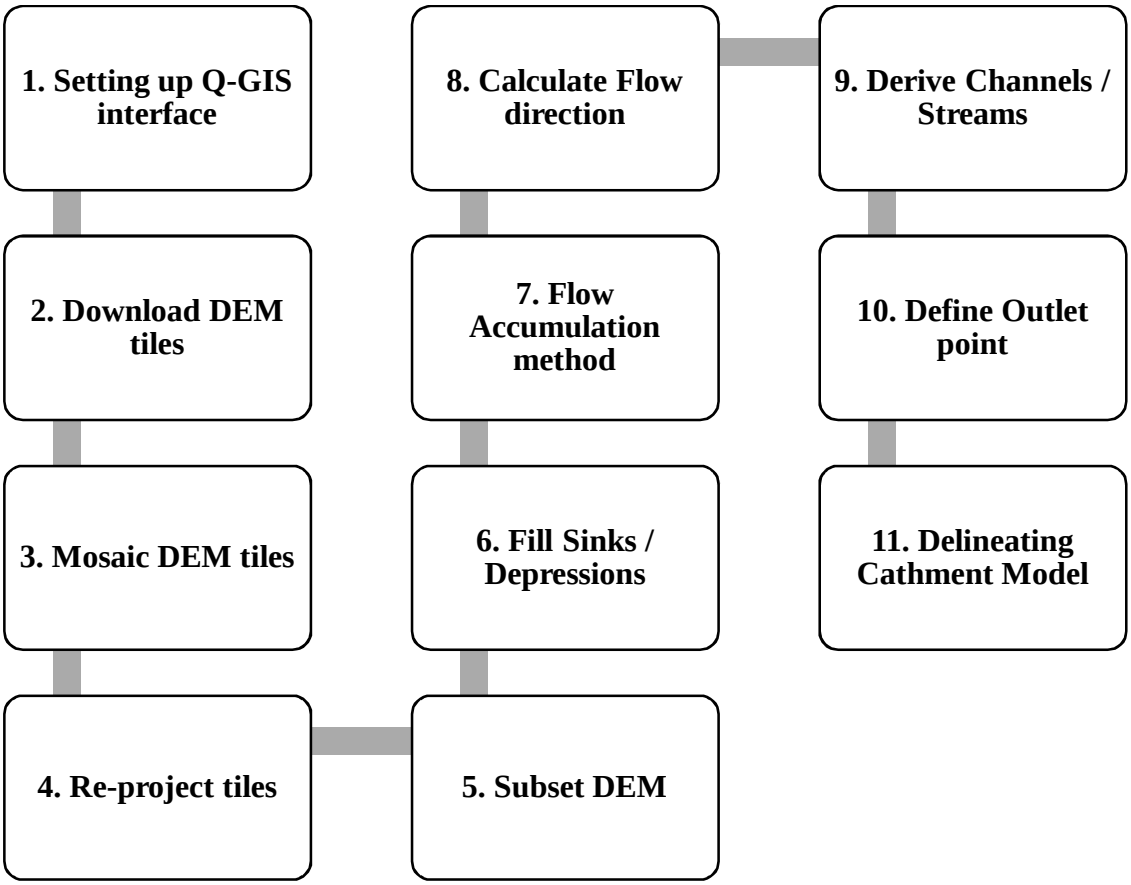


Figure No. 3: Flowchart for Watershed Delineation

Various tools and plugins such as Build Virtual Raster, r.fill.dir tool, r.stream.extract, r.water.outlet etc. are used in the delineation process in Q-GIS 3.18. The outlet point is specified manually by selecting the outlet cell at Jayakwadi Dam for the Delineation of Upper Godavari Basin. The similar process is followed for the delineation of Sub-catchments.

B. Setting up basin model in HEC-HMS

The Hydrologic Modelling System is designed to simulate the precipitation-runoff processes of dendritic watershed systems. Total seven components are present in HEC-HMS to give all the necessary input data for simulation of Rainfall Runoff process. These components are Basin Model Manager, Meteorological Model Manager, Control Specifications Manager, Time-series Data Manager, Paired Data Manager, Grid Data Manager and Terrain Data Manager. Each component has its own purpose in the simulation process. These components are presented in flowchart of methodology (Figure 2).

C. Effective Rainfall estimation by Thiessen Polygon Method

The Daily Station-wise Rainfall data is collected from India – Water Resource Information System (India WRIS) and Indian Meteorological Department Grid. Total 35 Rain gauge stations lie in the extent of Upper Godavari Basin (UGB). There is a need to find the weight of each Rain gauge station. This weight is nothing but the ratio of Area contributed by Each Station to Whole area of Sub-basin. This weight is further multiplied by Rainfall data of respective station. At the end, all the values contributed by each station were added to get a daily Average Rainfall value for each sub-basin. The Thiessen/Voronoi Polygons around each Rain Gauge stations are presented in figure (Figure 4).

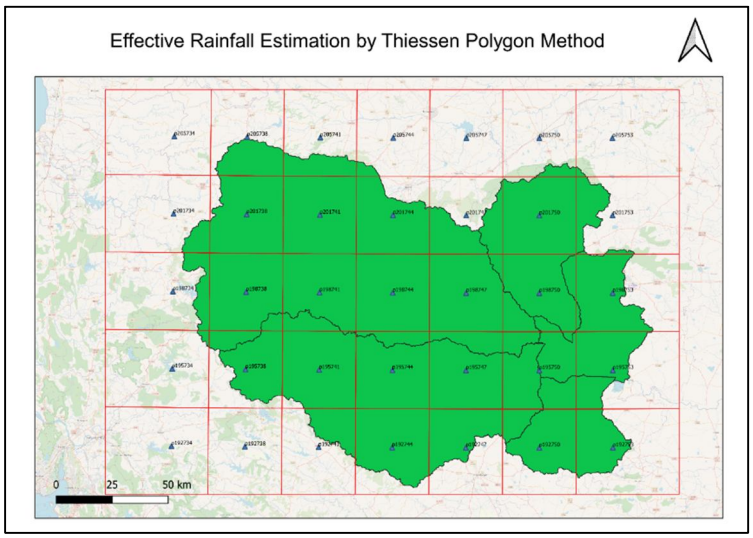


Figure No. 4: Thiessen Polygon Method

D. Structured Discretization Method

The discretization method defines how a sub-basin is discretized. Traditionally, the Mod Clark grid cell file has been used to define the spatially-discrete elements of a sub-basin. One limitation of the Mod Clark grid cell file is that it does not use absolute spatial references. Grid cell locations are referenced from an arbitrary lower left corner. *Structured* and *Unstructured* discretization provide spatial-awareness to spatially-discrete sub-basin elements. Advantages of the spatially-aware approach include the ability to view discrete elements, the ability to sample values from other geospatial data, and the ability to visualize results for discrete elements.
In the present study, the Structured Discretization method is used. Two inputs are required for this method. (Table 2)

Table No. 2: Input Parameters for Structured Discretization method

Sr. No.	Sub-basin	Input Parameters	
		Projection	Cell Size
1	MUG	UTM Zone 43 N	20
2	Kham	UTM Zone 43 N	
3	Dhora	UTM Zone 43 N	
4	Pravara	UTM Zone 43 N	
5	Shivna	UTM Zone 43 N	

The *Structured Discretization* creates a Cartesian grid within the bounds of the sub-basin. The *Structured Discretization* gives options for Standard Hydrologic Grid (SHG) or Universal Transverse Mercator (UTM) projection and 50, 100, 200, 500, 1000, 2000, 5000, or 10000-meter grid cell sizes. The present study area lies in UTM Zone 43 N with projection of 20 m cell size.

E. Simple Surface Method

The depression storage of an impervious surface such as a parking lot is generally close to zero. However, the depression storage for an agricultural field can be quite large if conservation tillage practices are used. Precipitation through-fall from the canopy, or direct precipitation if there is no canopy, impacts on the surface. The net precipitation accumulates in the depression storage and infiltrates as the soil has capacity to accept water. Surface runoff will begin when the precipitation rate exceeds the infiltration rate, and the surface storage is filled. Precipitation residing in the surface storage can infiltrate after precipitation stops and is subject to potential evapo-transpiration.
In the present study, a Simple Surface method is selected. This method is a simple representation of the soil surface. All precipitation or precipitation through-fall that arrives on the soil surface is captured in storage until the storage capacity of the surface is filled. Water in surface storage infiltrates into the soil whenever it is present in storage.

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That is, water will infiltrate even when the storage capacity is not full. Surface runoff will be generated when the storage capacity is filled, and the precipitation through-fall rate exceeds the infiltration rate.

Table No. 3: Standard Parameters for Simple Surface method

Sr. No.	Surface Depression	Slope (%)	Maximum Surface Storage (mm)
1	Paved Impervious Area	NA	3.2 – 6.4
2	Steep, Smooth Slopes	> 30	1
3	Moderate to Gentle Slopes	5 - 30	12.7 – 6.4
4	Flat, Furrowed Land	0 - 5	50.8

(Source: According to T.H. Bennet et.al & M. Fleming et. al.)

The initial condition of the surface should be specified as the percentage of the surface storage that is full of water at the beginning of the simulation. In the present study it is assumed that before simulation, there is no surface storage. The maximum surface storage values depend upon the Surface Depression and Topographical slope (%). The standard values given by T.H. Bennet et.al & M. Fleming et. al. is given in table (Table 3).

Surface storage represents the maximum amount of water that can be held on the soil surface before surface runoff begins. The amount of storage is specified as an effective depth of water. The slope for each sub-basin has been computed using DEM tiles in Q-GIS 3.18 and four ranges were prepared and presented in table (Table 4).

Table No. 4: Estimated input Parameters for Simple Surface method

Sr. No.	Sub-basin	Input Parameters	
		Initial Storage	Weighted Maximum Storage (mm)
1	MUG	0	3
2	Kham	0	3
3	Dhora	0	1
4	Pravara	0	1
5	Shivna	0	3

F. SCS CN Loss Method

While a sub-basin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together, the actual infiltration calculations are performed by a loss method contained within the sub-basin. A total of twelve different loss methods are provided. Some of the methods are designed primarily for simulating events while others are intended for continuous simulation.

All methods work on mass conservation. That is, the sum of infiltration and precipitation left on the surface will always be equal to total incoming precipitation. In the present study, Soil Conservation Service (SCS) Curve Number method is implemented.

The Soil Conservation Service (SCS) Curve number method implements the curve number methodology for incremental losses (NRCS, 2007). Originally, the methodology was intended to calculate total infiltration during a storm. The program computes incremental precipitation during a storm by recalculating the infiltration volume at the end of each time interval. Infiltration during each time interval is the difference in volume at the end of two adjacent time intervals.

The Soil Conservation Service (SCS) Curve number requires three input parameters. The Curve Number (CN) can be considered as the most important parameter of the present study. The remaining two parameters are Initial Abstraction (Ia) and Impervious area (%). Their definitions are given below;

a) Initial abstraction (Ia): defines the amount of precipitation that must fall before surface excess results.

b) Curve Number (CN): It is composite curve number that represents all of the different soil group and land use combinations in the sub-basin.

c) Impervious (%): The composite curve number should not include any impervious area that will be specified separately as the percentage of impervious area.

- Initial abstraction (Ia): It can be calculated by the formula given by HEC-HMS technical reference manual as below;

$$Ia = 0.2 \times \frac{25400 - (254 \times CN)}{CN}$$

Where, Ia = Initial abstraction
CN = Curve Number

As the Initial abstraction is the dependent quantity; the CN should be estimated before.

- Curve Number (CN):

The Composite CN is calculated for each sub-basin based on Landuse-Landcover maps and Hydrological soil groups. The standard CN table from TR 55 is used for the estimation of weighted curve number. The weighted CN is calculated using following formula;

$$WCN = \frac{\sum_{i=1}^{n} CNi \times Ai}{\sum_{i=1}^{n} Ai}$$

Where, Ai = Area for ith Landuse Type, CNi = Curve Number for ith Landuse Type

The area under each landuse type is estimated using Landuse Landcover maps. These maps are also prepared with the help of Q-GIS 3.18. The area under Water bodies (Reservoirs) and Roads is taken as Impervious area and % area is Calculated for each sub-basin. The last column in the following figures gives the weighted CN values. (Table No. 5.1 to 5.5). The estimated input parameters are presented in table (Table No. 6). In the similar way, CN for different years have been found out and taken as a input parameter while setting up the basin model in HEC-HMS.

Table No. 6: Input Parameters for SCS Curve Number Loss method

Sr. No.	Sub-basin	Input Parameters		
		Initial Abstraction (mm)	Weighted CN	Impervious (%)
1	MUG	6.86	88	0.0010
2	Kham	8.79	85	0.0140
3	Dhora	6.91	88	0.0035
4	Pravara	6.85	88	0.0117
5	Shivna	8.97	85	0.0060

G. SCS Unit Hydrograph Transform Method

While a sub-basin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together, the actual surface runoff calculations are performed by a transform method contained within the sub-basin. A total of nine different transform methods are provided. The choices include various unit hydrograph methods, a kinematic wave implementation, a linear quasi-distributed method, and a two-dimensional (2D) diffusion wave method.

The SCS Unit Hydrograph method is selected as transform method. The Soil Conservation Service (SCS) unit hydrograph method defines a curvilinear unit hydrograph by first setting the percentage of the unit runoff that occurs before the peak flow (NRCS, 2007). A triangular unit hydrograph can then be fit to the curvilinear unit hydrograph so that the total time base of the unit hydrograph can be calculated. The standard unit hydrograph is defined with 37.5% of unit runoff occurring before the peak flow. This definition corresponds to a peak rate factor of 484 which incorporates the percentage of unit runoff before the peak, calculated total time base, and unit conversions when applying the equations within the US Customary unit system.

The SCS CN method requires two inputs, the one is Graph type and another is Lag time (T_L). The default Graph type standard PRF 484 is used. The Lag time is calculated using empirical equation given by HEC-HMS Technical Reference manual and other reputed journal publications. It is given below;

$$T_L = 0.6 \times Tc$$

Where, Tc = Time of Concentration

$$Tc = \frac{L^{0.8} \times (s+1)^{0.7}}{1140 \times Y^{0.5}}$$

Where,
L = Length of Longest Stream in Catchment (Feet)
Y = Avg. Watershed Land Slope in %
S = Maximum Potential Retention = $\frac{1000}{CN} - 10$

The Length of longest stream, Average watershed land slope is calculated using Q-GIS 3.18 and the required input parameters are presented in table (Table No. 7).

Table No. 7: Input Parameters for SCS Unit Hydrograph Transform method

Sr. No.	Sub-basin	Input Parameters						
		CN	Length of Longest Stream (L in feet)	Average Land Slope (Y in %)	S	Tc (hr.)	TL (hr.)	TL (min)
1	MUG	88	807378.61	142.3021	1.3636	7.14	4.284	257
2	Kham	85	265203.41	53.8533	1.7647	5.32	3.192	192
3	Dhora	88	204683.40	39.4416	1.3636	4.53	2.718	163
4	Pravara	88	735524.93	136.9737	1.3636	6.75	4.05	243
5	Shivna	85	403202.10	56.0988	1.7647	7.28	4.368	262

The standard lag is defined as the length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph.

VI. RESULTS & DISCUSSION

The details of the delineated watersheds / sub-basins are presented in table (Table 8). The Sub-basin maps showing Rivers / Streams, delineated boundary of the catchment, Tourist attractions, Towns and Cities were prepared using open source Q-GIS 3.18 software. These maps are presented in Figure 5 and final Upper Godavari Watershed is presented in Figure 6.

Table No. 8: Details of the Delineated Watersheds/Sub-basins

Sr. No.	Delineated Watershed / Sub-basin	Outlet Point	Area (Sq. Km)	Perimeter (Km)
1	Major Upper Godavari	Kaygaon Toka, Pravara-sangam	9669.433	827.400
2	Kham	Jayakwadi Dam, Paithan	6371.288	701.100
3	Dhora	Jayakwadi Dam, Paithan	2585.894	407.160
4	Pravara	Kaygaon Toka, Pravara-sangam	1612.331	303.120
5	Shivna	End point of Shivna river	1864.985	398.640
Upper Godavari Watershed		Jayakwadi Dam, Paithan	22103.931	1298.160

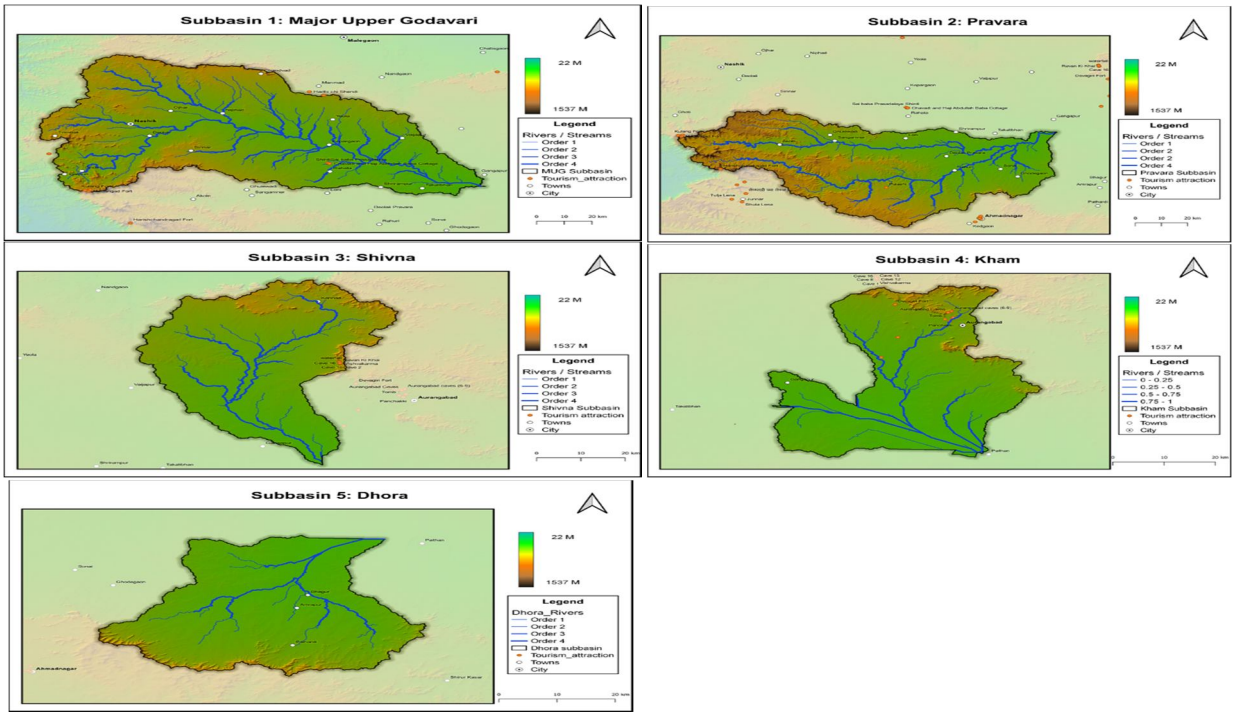


Figure No. 5: Delineated Sub-basins under Upper Godavari Basin

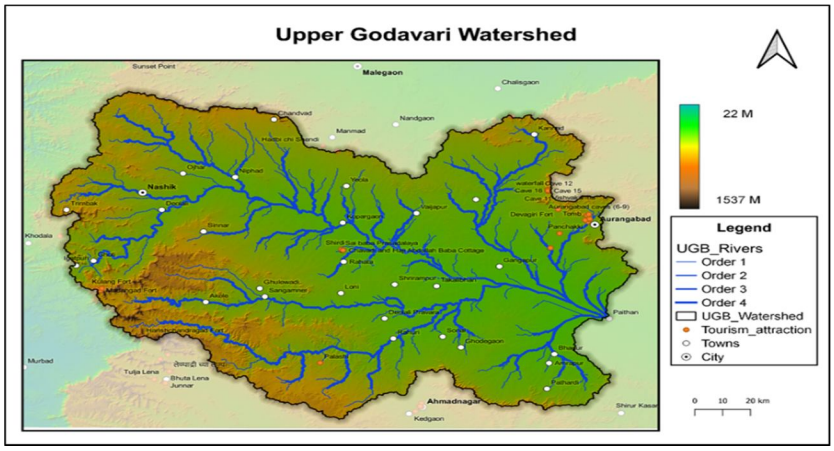


Figure No. 6: Delineated Upper Godavari Basin

After performing all the necessary steps and estimating required input parameters for the simulation of Rainfall Runoff process, the Simulation Run Manager is used for Processing the input data and Simulating discharge at outlets of each sub-basin.

As the Simulation is carried out for 35 years, the Daily Runoff values has been obtained. It is difficult to express results in the form of statistical values, therefore, the Graphical interpretation is done. Therefore, the Runoff obtained at three junctions (Figure 7) i.e. Kaygaon Toka, Outlet point of Shivna Sub-basin and the main Outlet point at Jayakwadi dam are presented in graphs (Figure 8.1 to 8.3).

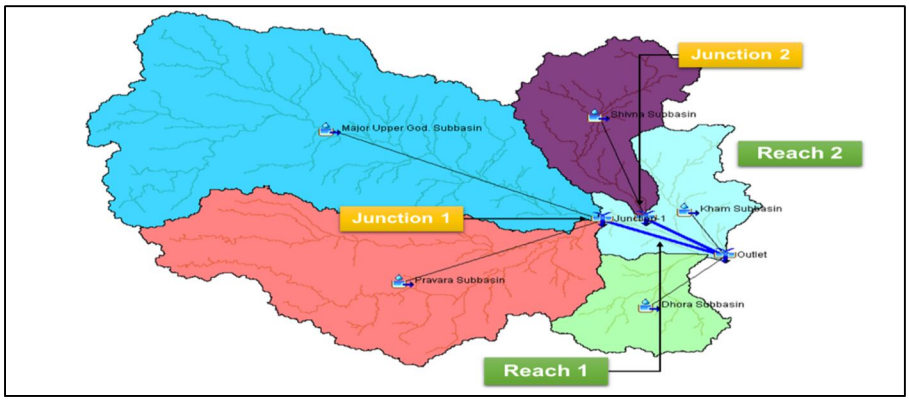


Figure No. 7: Locations of Junctions & Reaches in the Upper Godavari Watershed

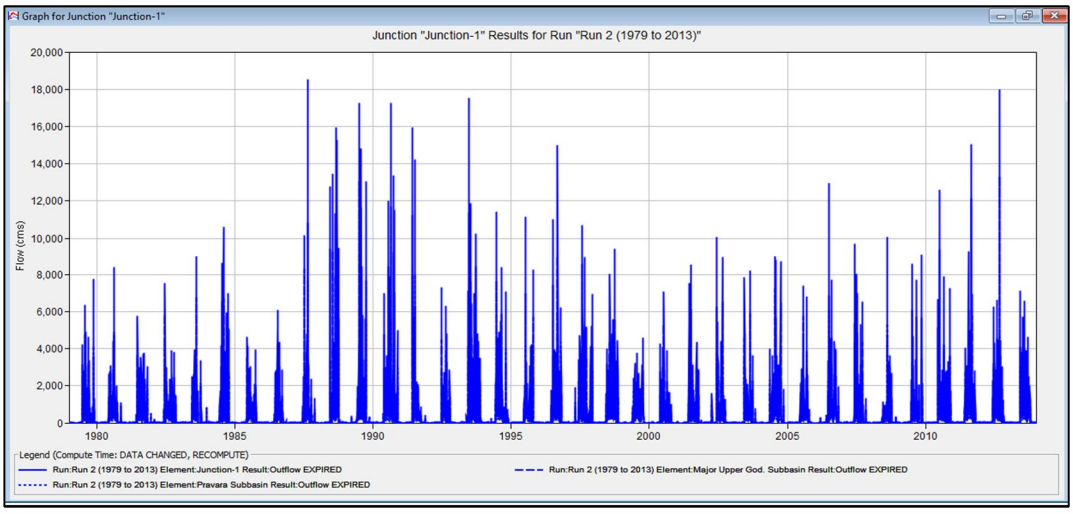


Figure No. 8.1: Simulated Runoff at Kaygaon Toka (Junction 1)

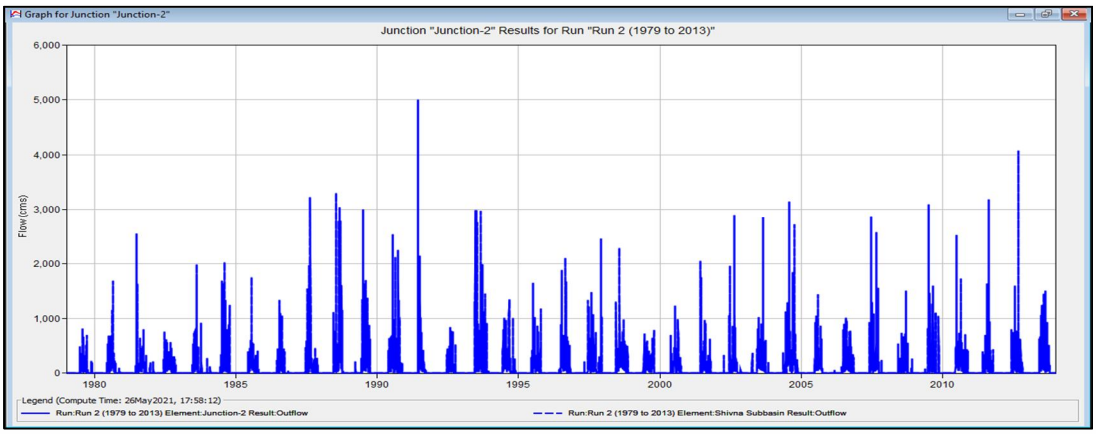


Figure No. 8.2: Simulated Runoff at Shivna Outlet (Junction 2)

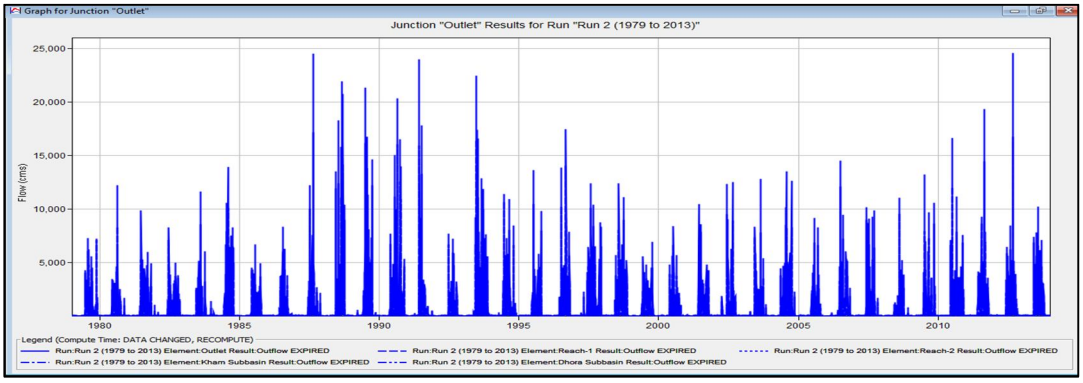


Figure No. 8.3: Simulated Runoff at Jayakwadi Dam (Outlet)

As discussed earlier, the Reach 1 carries the runoff from Junction 1 to Outlet and Reach 2 carries from Junction 2 to Outlet. The Results obtained can be summarized with the help of table (Table 9).

Table No. 9: Summary table of Simulated Parameters

Hydrologic Element	Simulated Parameters			
	Drainage Area (Km2)	Peak Discharge (M^3 per Sec)	Time of Peak	Volume (1000 M^3)
Major Upper God. Sub-basin	9674.951	13328.7	04Sep2012, 00:00	335052058.2
Pravara Sub-basin	6375.486	7984.7	11Jul1991, 00:00	203965707.4
Junction-1	16050.437	18518.6	20Aug1987, 00:00	539017765.6
Reach-1	16050.437	17161.1	20Aug1987, 00:00	539017765.6
Shivna Sub-basin	2587.953	5002.2	09Jun1991, 00:00	104555119.8
Junction-2	2587.953	5002.2	09Jun1991, 00:00	104555119.8
Reach-2	2587.953	4818.9	09Jun1991, 00:00	104555119.8
Kham Sub-basin	1866.445	2807.4	20Aug1987, 00:00	58029321.8
Dhora Sub-basin	1613.608	2073.7	11Jul1991, 00:00	47199976.3
Outlet	22118.443	24562.0	04Sep2012, 00:00	748802183.5

It is observed from the table (Table 9) that, HEC-HMS gives the result in the form of Drainage Area (Km^2), Peak Discharge (M^3 per Sec), Time of Peak and volume (1000 m^3). The Major Upper Godavari and Pravara sub-basins are the larger sub-basins compared with the other sub-basins. Therefore, the Peak Runoff generated by these two basins at junction 1 (20 Aug.1987) largely affect the runoff at Jayakwadi basin.

It is recorded that, during the study period of 35 years, Peak discharge of volume 24562.0 m^3 per sec on day 04 Sep 2012 is observed at Jayakwadi Dam.

The flows which were simulated from the various methods were tested using Statistical techniques. In the present study, to assess the model efficiency, Pearson's Correlation method (Coefficient of Inter Correlation, r) is used. The daily river flow data at Jayakwadi Dam were obtained from Central Water Commission (CWC) through online portal of India – Water Resource Information system (INDIA WRIS). The model's efficiency is assessed for 2 years, i.e. for 2000 and 2010 and the Area graphs were Prepared. The Coefficient of Inter Correlation (r) is computed using following empirical formula given by Pearson,

$$r = \frac{\sum(xi - \bar{x})\,(yi - \bar{y})}{\sqrt{\sum(xi - \bar{x})^2\,(yi - \bar{y})^2}}$$

Where,

$\boldsymbol{r}$ = Correlation Coefficient

$\boldsymbol{xi}$ = Values of x variables in a sample (Simulated Flows)

$\bar{\boldsymbol{x}}$ = Mean of the values of x variables in a sample

$\boldsymbol{yi}$ = Values of y variables in a sample (Observed Flows)

$\bar{\boldsymbol{y}}$ = Mean of the values of y variables in a sample

Therefore, by using computer techniques, Correlation Coefficient has been computed for two variables namely Observed and Simulated flows. The correlation values have been given on the respective area graphs (Figure 8.1 and 8.2) Various researchers have given the range of inter correlation as below (Table 10);

Table No. 10: Levels of Coefficient of Inter Correlation

Sr. No.	Coefficient of Inter correlation	Level of Correlation
1	Below 0.3	Low
2	0.3 to 0.5	Moderate
3	Above 0.5	High

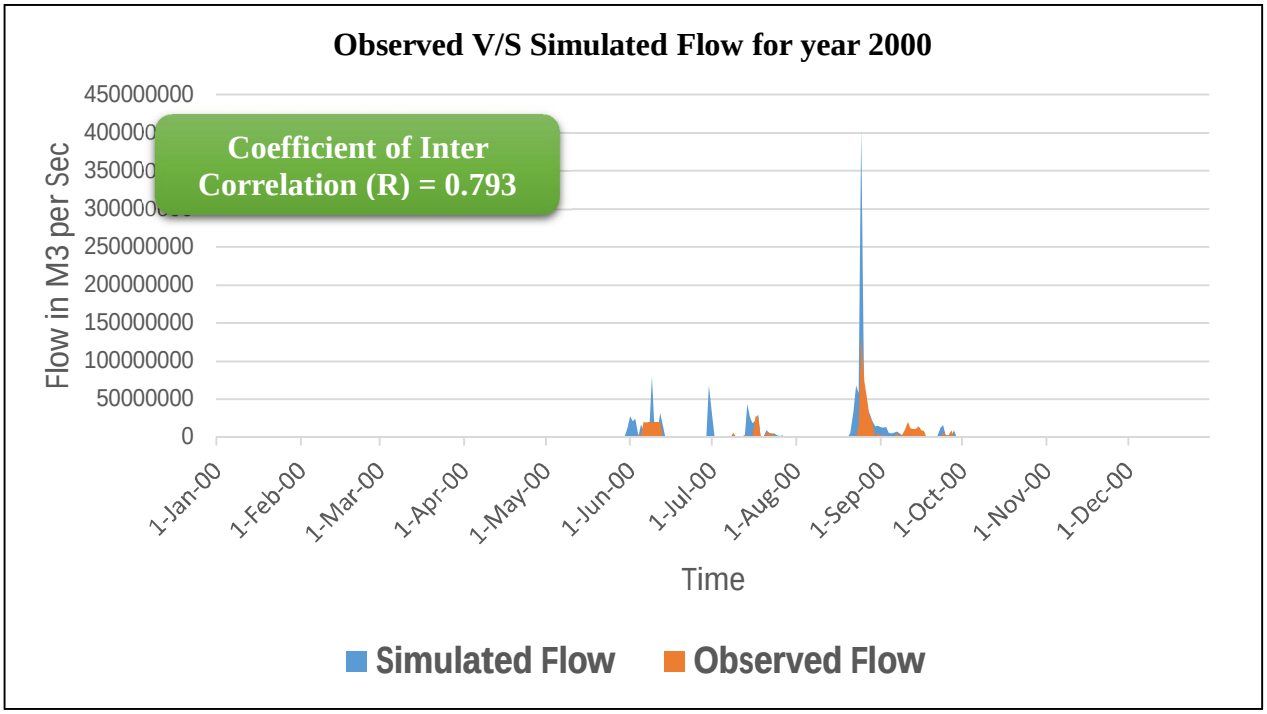


Figure No. 8.1: Observed v/s Simulated Flow for year 2000

The graphs (Figure 8.1 and 8.2) clearly shows that the Correlation coefficient of Inter correlation for year 0.793 and 0.562 for year 2000 and 2010. According to the standard ranges given by various researchers, therefore, it is concluded that the model shows High level of Levels of Coefficient of Inter Correlation.

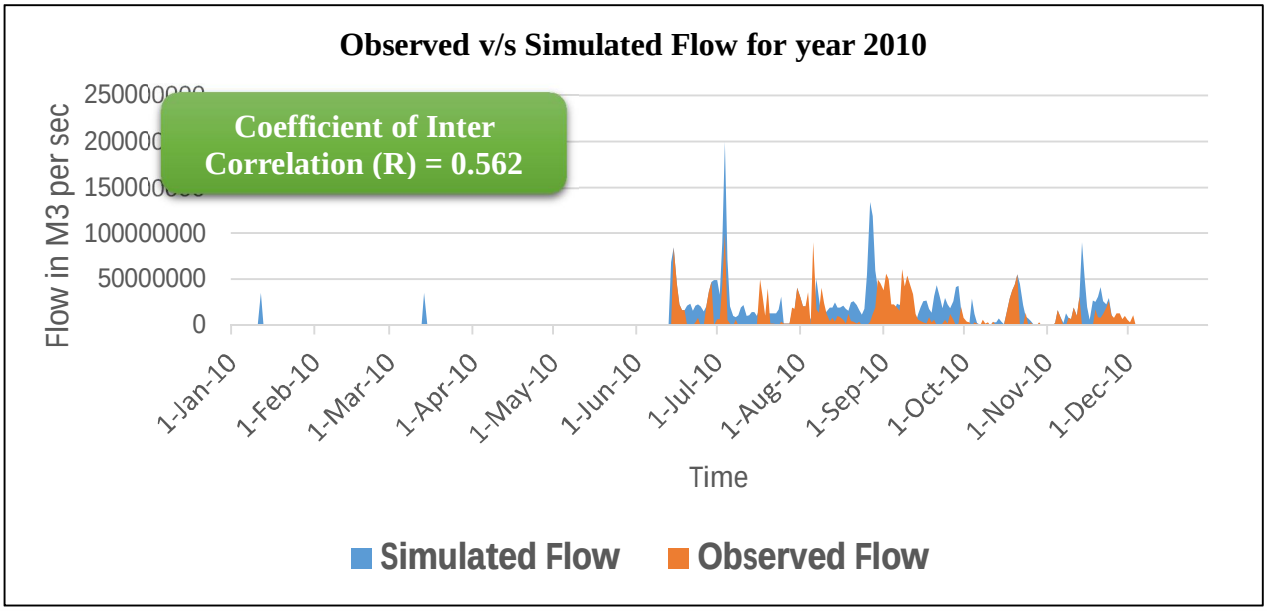


Figure No. 8.2: Observed v/s Simulated Flow for year 2010

VII. CONCLUSION

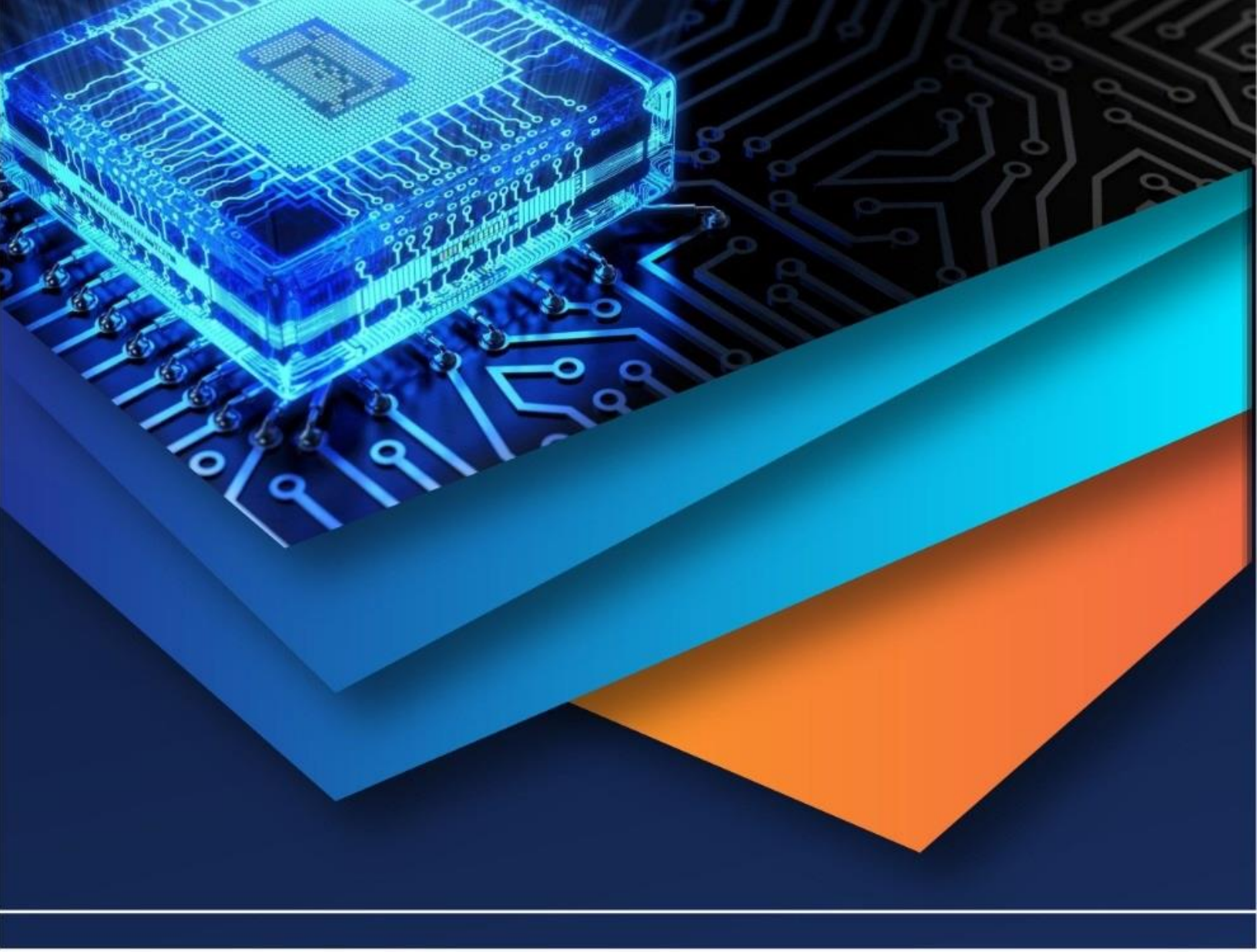
It is concluded that,

"The Hydrologic Engineering Centres Hydrologic Modelling System (HEC-HMS) watershed model can be effectively used to simulate Rainfall Runoff process to estimate basin's hydrological phenomenon caused due to precipitation."

"The increase in Urbanization & change in Landuse pattern in the Upper Godavari watershed have definitely increased the peak runoff significantly especially in Kham sub-basin."

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