EVENT BASED RAINFALL-RUNOFF SIMULATION USING HEC-HMS MODEL

A Thesis submitted to the

DR. BALASAHEB SAWANT KONKAN KRISHI VIDYAPEETH
DAPOLI - 415 712
Maharashtra State (India)

In the partial fulfillment of the requirements for the degree

of
MASTER OF TECHNOLOGY
(AGRICULTURAL ENGINEERING)

In
SOIL AND WATER CONSERVATION ENGINEERING

By
Jaybhaye Pradeep Udhavrao

DEPARTMENT OF SOIL AND WATER CONSERVATION ENGINEERING
COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY
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DAPOLI- 415 712, DIST. RATNAGIRI, M. S. (INDIA)
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CANDIDATE'S DECLARATION

I hereby declare that this thesis or part thereof has not been submitted
by me or any other person to any other
University or Institute
for a Degree or
Diploma.

Place: Dapoli

Date: / /2014 **(Jaybhaye Pradeep Udhavrao)**

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CERTIFICATE

This is to certify that the thesis entitled **"EVENT BASED RAINFALL-RUNOFF SIMULATION USING HEC-HMS MODEL"** submitted to the Faculty of Agricultural Engineering, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Dist. Ratnagiri (Maharashtra State) in the partial fulfillment of the requirements for the award of the degree of **Master of Technology (Agricultural Engineering)** in **Soil and Water Conservation Engineering,** embodies the record of a piece of bonafied research work carried out by **Mr. Jaybhaye Pradeep Udhavrao** under my guidance and supervision. No part of the thesis has been submitted for any other degree, diploma or publication in any other form.

The assistance and help received during the course of this investigation and source of the literature have been duly acknowledged.

Place: Dapoli

Date: / /2014 **(dilip MAHALE)**

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Place: Dapoli

Date: / /2014 **(N. J. Thakor)**

Dedicated

To

My Beloved Parents

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Lastly, I would like to thank all those who are involved directly or indirectly in completion of the present project work.

Place : Dapoli

Date : / /2014 **(Jaybhaye Pradeep Udhavrao)**

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations		Meanings
%	:	Percent
<	:	Less than
>	:	Greater than
Agril.	:	Agricultural
AMC	:	Antecedent Moisture Condition
C.A.E.T	:	College of Agricultural Engineering and Technology
CN	:	Curve Number
CWMS	:	Corps Water Management System
Dd	:	Drainage Density
Dv	:	Percent Deviation
Dept.	:	Department
DEM	:	Digital Elevation Model
Dr. B.S.K.K.V	:	Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth
DSPM	:	Distributed Snow Process Model
DSRO	:	Direct Surface Runoff
DSS	:	Data Storage System
E	:	East
e.g.	:	For Example
et.al	:	And others
Etc	:	Etcetera
Fig.	:	Figure
GIS	:	Geographical Information System
Govt.	:	Government
GUI	:	Graphical User Interface
Ha	:	Hectare
HEC-HMS	:	Hydrologic Engineering Center’s Hydrologic Modeling System
HSG	:	Hydrologic Soil Group
i.e	:	That is

IUH	:	Instantaneous Unit Hydrograph
J	:	Journal
Km	:	kilo meter
km^2	:	Square kilo meter
M	:	Meter
m^3	:	Cubic meter
MM5	:	Mesoscale Model
ModClark	:	Modified Clark
MS	:	Maharashtra State
N	:	North
No.	:	Number
Qt	:	Threshold Flow
R	:	Storage Coefficient
R^2	:	Coefficient of Determination
RMSE	:	Root Mean Square Error
SCS	:	Soil Conservation Service
SDR	:	Standard Deviation Ratio
SMA Methods	:	Soil Moisture Accounting Methods
SWM	:	Stanford Watershed Model
Tc	:	Time of Concentration
UH	:	Unit Hydrograph
US	:	United State
USACE-HEC	:	US Army Corps of Engineers Hydrologic Engineering Center
V 3.5.0	:	Version 3.5.0

ABSTRACT

EVENT BASED RAINFALL-RUNOFF SIMULATION USING HEC-HMS MODEL

By

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2014

Research Guide	**:**	**Prof. dilip MAHALE**
Department	**:**	**Soil and Water Conservation Engineering**

Flood is a natural demolishing phenomenon, forecast of which is of high importance. Estimation of rainfall-runoff and flood is a difficult task due to influence of different factors. So estimation of surface runoff in a watershed based on the rate of received precipitation and quantifying discharge at outlet is important in hydrologic studies. Improper estimation of runoff in basins causes some problems in optimum management of water resources and reservoir dams. Therefore, simulation of rainfall-runoff is a proper solution for runoff estimation.

Considering all these facts, the present study was carried out with the specific objectives. So for fulfillment of the objectives, HEC-HMS hydrological model version 3.5 was used to simulate rainfall-runoff process in Priyadarshini watershed

located in C.A.E.T. campus of Dr B.S.K.K.V. Dapoli, which is located at 17-^{0}45'N and 73^{0}20'E. The total area of watershed is 50.29 ha

HEC-HMS is used for the simulation of stream flow from the Priyadarshini watershed. The rainfall runoff data was collected for three years 2008, 2010 and 2013 and fifteen rainfall-runoff events were selected randomly for the study, out of these ten was selected for the calibration and the rest of five events were selected for validation. By using these event data Clark's unit hydrograph parameters (Time of concentration (Tc) and Storage coefficient, (R) and SCS curve number model parameters (Curve number, CN and initial abstraction, Ia) are calibrated as Tc = 0.261 hr, R = 0.020 hr, CN = 62.19 and Ia = 25.76 mm, respectively. The base flow parameters i.e. recession constant (Rc), initial base flow (Qo), and threshold flow (Qt) in exponential recession model were calibrated as Rc = 0.690, Qo = 0.018 m^3/sec, and Qt = 0.121 m^3/sec respectively. Total surface runoff hydrographs were computed for these rainfall-runoff events using Clark's unit hydrograph model which were compared with the observed hydrographs. The surface runoff hydrographs thus computed using the Clark's UH and SCS curve number model were compared employing error functions viz. sum of absolute errors, sum of squared residuals, percentage error in peak, peak weighted root mean square error, root mean square error, percentage change in peak discharge and percentage change in outflow volume.

Rainfall-runoff simulation results show that there is clear difference between observed and simulated peak flows. Therefore, model calibration with optimization method and sensitivity error analysis has been done. Model validation using optimized parameter values showed reasonable difference in peak discharge and outflow volume. Finely it is concluded that calibrated model performs satisfactorily in Priyadarshini watershed.

Comparison of the computed peak discharge and outflow volume using Clark's UH model, SCS curve number model, Exponential recession model and Muskingum model shows that in spite of limited data availability, the HEC-HMS model prove to be good for runoff estimation.

INTRODUCTION

Climate change and global warming is the most significant threat to the living beings on this planet at the twenty-first century. Recent seasons have shown the effects of climate change and global warming in the form of extreme temperatures and weather patterns. Extremities in weather conditions cause droughts and floods that can have significant impacts on agriculture, natural resources, overall ecosystem and livelihood (Yener *et al*, 2008). As compare to the global scenario, the situation in India is very poor. The rampant growth of population, changing life style and associated multiplication of needs have tremendously increased the demands for food and water. These growing demands are putting the resilience of the natural resource base under threat. This has led to erosion in the quality and quantity of basic resources of land and water. Thus, India is facing a serious problem of natural resources scarcity.

To overcome the water related problems, extensive care should be given to the operation and management of reservoirs and watersheds. But in many cases, poor land-use planning and land management practices during rapid development have adversely impacted the surface runoff quantities and quality through the reduction of land cover, loss of plant nutrients, deterioration of river water quality and an increase of impervious surface area. Therefore, a major challenge still remaining is the accurate prediction of catchment runoff responses to rainfall events (McColl and Aggett, 2006 and Yener, 2006). Numerous researchers have used many methods to simulate, assess, and predict the effects of urbanization on hydrological response of the watersheds (Du *et al*., 2012). Watershed management is an integration of technologies within the natural boundaries of a drainage area for optimum development of lands, water, and plant resources to meet basic minimum needs of the human in a sustainable manner. Simply, watershed management implies the judicious use of all land and water resources. Decision support tools can help in better development options for people to manage water, land and labor resources. One viable answer and approach to this challenge is the use of suitable hydrologic models for the efficient management of watersheds and ecosystems.

The quantitative understanding and prediction of the processes of runoff generation and its transmission to the outlet represent an active area of research through the evaluation of hydrology. Hydrological modeling is a commonly used tool to estimate the basin's hydrological response due to precipitation. It is simplified representations of actual hydrologic systems that allow us to study the functioning of watersheds and their response to various inputs, and thereby gain a better understanding of hydrologic processes. Hydrologic models also allow us to predict the hydrologic response to various watershed management practices and to have a better understanding of the impacts of these practices (Srinivas, *et al.*, 1999).

Experience has shown that quantitative description of the land phase of the hydrologic cycle may become very complicated and are subject to a great deal of uncertainty. Region to region climate, geography and physical properties of watershed changes and it is because; basin response to the rainfall event accordingly changes. Due to lack of rainfall runoff data, it has not been able to understand hydrological condition of the basin. Thus, it has become inevitable to determine rainfall-runoff model and the model parameters for a particular watershed (Halwatura and Najim, 2013).

It is evident from the extensive review of the literature that the studies on comparative assessment of watershed models for hydrologic simulations are very much limited in developing countries, including India. There is bare necessity to undertake study on hydrologic simulation through development of a suitable watershed model.

Hydrological Model is a simplified representation of natural system. We can say that "A model is a collection of symbols, which represents the system in a concise form that works as a representation of natural system or some aspect of it". The rainfall runoff model is one of the most frequently used events in hydrology (Kumar and Bhattacharjya, 2011).

HEC-HMS is hydrologic modeling software developed by the US Army Corps of Engineers, Hydrologic Engineering Centre (HEC). It is designed to simulate the precipitation runoff processes of watershed systems in a wide range of geographic areas such as large river basins and small urban or natural watersheds. The system encompasses losses, runoff transform, open-channel routing, and analysis of meteorological data, rainfall-runoff simulation, and parameter estimation. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow. Each model run combines a basin model, meteorological model and control specifications with run options to obtain results. The system connectivity and physical data describing the watershed are stored in the basin model. The precipitation data necessary to simulate watershed processes are stored in the meteorological model (USACE-HEC, 2008). Currently used HEC-HMS (v 3.5.0) is updated version of earlier version HEC-1 that contains many improvements over the predecessor and includes many additional capabilities.

The models flexible structure and ability to employ physical laws in the interpretation of hydrological processes, provides significant advantage over existing hydrological models. It has wide spread use in the Corps, other Federal agencies, local government, and private sector.

So from the view of easy availability, easy handling and operating, better technical advantage and support from its developers, the HEC-HMS model is selected for the present study entitled **"Event Based Rainfall-Runoff Simulation Using HEC-HMS Model"**. The Priyadarshini watershed with the mixed agricultural use located at the Dapoli is the proposed experimental site.

Keeping this in view the study is undertaken with following specific objectives,

1. To calibrate the HEC-HMS model for micro watershed for runoff prediction.
2. To estimate Clark's Unit Hydrograph and loss rate parameters of HEC-HMS model for micro watershed.

II. REVIEW OF LITERATURE

The following paragraphs of this chapter heighted a brief review of some the significant contributions made by various researchers in the field of rainfall runoff processes.

2.1. Conceptual Models

Usually analysts have some kind of a perception in their mind about the behavior of the hydrological system under study. The rationale for incorporating such concepts into the structure of a hydrological model can be an attempt to reproduce stream flow more accurately at the point of interest, or the need to include representations of various hydrological fluxes and runoff pathways into the model.

One of the first conceptual, hydrological models for continuous stream flow simulation was that of Linsley and Crawford (1960), which was developed to assess increase of the capacity of one of the water supply reservoirs of the Stanford University.

2.1.1 Zoch model

Zoch (1934) presented a runoff model which consists of a linear storage that was fed by a rectangular block input of uniform excess rain. He also presented solution for triangular and elliptic input. These inputs can be considered as the efforts of translation in particular basins on an instantaneous excess rainfall. In that case input diagrams represent the respective time area curves.

2.1.2 Clark model

Clark (1945) used the idea given by Zoch and presented an Instantaneous Unit Hydrograph (IUH) that was obtained by routing the time-area curve through a linear storage. He first calculated translation lines and drew the time contour lines by a bar diagram and successive flow rates of this diagram can be routed through the linear storage by the use of the routing equation.

2.1.3 O'Kelly model

O'Kelly (1955) concluded from his study of a number of Irish drainage basins that the smoothing effect of storage on the time area curve was so great that the latter could be replaced by an isosceles triangle without loss of accuracy. The base of this time-area diagram was the time of concentration, Tc and its area represented the unit depth of input.

2.1.4 Nash model

Nash (1957) developed a model based on a cascade of equal linear reservoirs for derivation of the IUH for a natural watershed. He derived the IUH by routing the unit impulse input through *n* linear reservoirs of equal storage coefficient and the impulse response.

2.1.5 HEC-HMS model

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was designed as a part of the U.S. Army Corps of Engineers Hydrologic engineering Centers "Next Generation Software Development Project". The system models are precipitation based and intended to replace the commonly used HEC-1 program with an advanced technical capability.

Increased computing power advanced the development of conceptual models and since the early efforts in the 1960's plethora of alternative structures for conceptual hydrological models have been suggested worldwide.

2.2. Clark's Unit Hydrograph Related Studies

The regional unit hydrograph related studies have been carried out for some of the sub zones by various research and academic organizations.

Singh and Seth (1984) developed regional unit hydrograph relationship for lower Godavari sub–zones relating the parameters of Nash IUH and Clark IUH models with the physiographic characteristics of five gauged catchments in the sub-zones.

Jain and Ramashastri (1990) used HEC-1 model for modeling rainfall runoff response of Hemavati river basin up to Sakleshpur within the constraints of data availability. The simulation results showed good reproduction of storm flow volumes, peak and hydrographs.

Daniel and Feldman (1998) used the original Clark's Unit Hydrograph theory in spatially distributed runoff generation. They effectively utilized the effect in grid areas along with NEXRAD data to develop a new method called as ModClark method which was incorporated in HEC-HMS later.

Srinivas *et al.* (1999) modeled the Ajay river basin upto Sarath using HEC-1 package. They calibrated and validated the model; and evaluated the model using Nash-Suctcliffe's coefficient.

Chatterjee *et al*. (2001) compared the responces of HEC-1 package and Nash model in Lower Godavari basin. They concluded that in general, the performance of the HEC-1 package and the Nash IUH model for estimation of the DSRO hydrograph for the catchment under study was comparable.

2.3. Hydrologic Engineering Center's Hydrologic Modeling System

Hammouri and Naqa (2007) modeled the rainfall-runoff process using HEC-HMS and GIS in a selected ungauged basin for the purpose of groundwater artificial recharge at Zarqa catchment, Jordan. Two model runs were carried out using precipitation data of the Intensity-Duration-Frequency (IDF) curves for 10 years and 50 years return periods. The total direct runoff volume and the peak discharge for 10 years return period were estimated to be 151,000 m^3 and 5.43 m^3/s respectively and for 50 years return period, it was 280,000 m^3 and 12.77 m^3/s, respectively. The model was optimized against observed runoff data measured during a storm event that occurred between 2nd and the 4th of April, 2006. This calibration was performed by applying different curve numbers in the simulated model. The flow comparison graph for calibrated model fits well with the observed runoff data with a peak-weighted root mean square error (RMSE) of less than 2 percent.

Parag (2008) used HEC-HMS model for rainfall–runoff modeling for Maheshgad watershed of 45.03 ha in semi-arid region of Maharashtra with sub-basins named as W1, W2, W3 and W4. The hydrological event recorded on 27th July 1998 was considered for rainfall-runoff simulation. The model was calibrated manually for two parameters such as initial loss (14 to 24 mm) and constant rate of infiltration (1.0 to 4.2 mm/hr) for the given watershed. Result of the study indicated better agreement between calibrated and observed runoff hydrographs for all sub-watersheds for their peak rate, its timing of occurrence and lag time.

Chu and Steinman (2009) discussed the application of joint event and continuous hydrologic modeling with the HEC-HMS to the Mona Lake watershed in West Michigan. Four rainfall events were selected specially for calibration and verification of event model and identified the model parameters. The calibrated parameters were then used in the continuous hydrograph model. The SCS-CN and SMA methods in HEC-HMS were used for simulating surface runoff in the event and continuous models, respectively, and the relationship between the two rainfall-runoff models was analyzed. The model output suggest that the fine scale event hydrological modeling, support by intensive field data, was found useful for improving the coarse-scale continuous modeling by providing more accurate and well-calibrated parameters.

Verma *et al.* (2009) carried out rainfall runoff modeling using HEC-HMS and WEPP hydrologic models, and remote sensing and GIS (Geographical Information System) techniques in the Upper Baitarani River basin of Eastern India. They used daily monsoon season (June–October) rainfall and the corresponding stream flow data of 6 years (1999–2005) together with the soil map, topographic maps, digital elevation model (DEM) and Land Sat images. The modeling results revealed that both the models under predicted stream flow for 1999, 2002, 2004, and 2005 and over predicted for 2001 and 2003, whereas HEC-HMS under predicted and WEPP over predicted stream flow for the year 2000. However, the lower values of root mean square error (RMSE) and standard deviation ratio (SDR) coupled with the higher values of Nash–Sutcliffe efficiency, percent deviation (D_V) and coefficient of determination (R^2) for HEC-HMS during calibration and validation periods indicated its better reliability than WEPP.

Kumar and Bhattacharjya (2011) simulate the rainfall-runoff process using of HEC-HMS (with both Distributed and Lumped modeling), remote sensing and GIS techniques for estimating infiltration parameters in the Ranganadi river basin of North-Eastern India. The required precipitation and stream flow data were collected for 3 years (2006–2008) together with topographic maps, and DEM images of the study area. The input file for the proposed hydrologic models was prepared using remote sensing and GIS techniques. For simulating stream flow by the HEC-HMS model, the SCS unit hydrograph transform method was used to compute direct surface runoff hydrograph, the SCS curve number loss method was used to compute runoff volumes and the constant monthly method was used for base flow separation. Lumped and Distributed modeling was simulated and validated using the rainfall-stream flow data of May 2006 to May 2007, and rainfall-stream flow data of 2008 respectively. Finally, the performance of HEC-HMS model was assessed using various statistical and graphical indicators. It was shown that the HEC-HMS Distributed approach simulated daily stream flow better than the Lumped simulatedparameters and for simulating daily stream flow in the Ranganadi river basin of North- Eastern India.

2.4. Applications of HEC-HMS Model

Putty and Prasad (2000) presented the result of lumped parameters conceptual watershed model SAHYADRI to understand the catchment response and the relative importance of different runoff process in Western Ghat region in South India. The model is a modified version of variable source area model, developed by Moore (1985). A lumped parameter model simulating saturated source area runoff, lateral flow through pipes and the saturated zone ground water flow, has been developed assuming that source area runoff is the only quick flow component. The model has been calibrated on seven catchments using sufficient long records of daily data. A wide range of tests showed the reliable performance of model. The groundwater flow forms a dominant component of runoff and the catchments response is strongly dependant on the rainfall magnitude. Two major implications of study are that (i) Flow through pipes from dynamic subsurface saturated zones may contribute substantial quantities of quick flow, and (ii) Field work necessary for further research must concentrate on pipe flow responses and the influence of rainfall on the nature of pipe nets. A modified model incorporating quick flow through is now under development.

Anderson *et al*. (2002) used HEC-HMS watershed model for runoff prediction. The process can be automated, yielding a valuable tool for reservoir management. The methodology was demonstrated for a 48-h forecast period in January 1999 in the Calaveras watershed in Northern California. The HEC-HMS model was calibrated by means of point gauge precipitation data. The timing and magnitude of the forecast peak in the runoff hydrograph were underestimated when the point gauge calibrated HEC-HMS model was driven by spatially distributed MM5 rainfall forecasts. However, when the point gauge calibrated HEC-HMS used point gauge rainfall for the same storm, the magnitude and timing of the peak runoff were matched. This would indicate that it is necessary to calibrate the HEC-HMS model with spatially distributed rainfall when using the model in the forecasting framework. Improved accuracy in terms of matching the timing and magnitude of the peak inflow and total volume of runoff would provide more information to reservoir operators for flood control releases. Initial results indicated that: (i).Model parameterization choice in MM5 was necessary to refine the precipitation forecasts; (ii).The method could show promise for generating 48-h-ahead forecasts of reservoir inflows and (iii).

Calibration of the HEC-HMS model with distributed precipitation was necessary for this methodology.

Abed *et al.* (2005) modeled the Zarqa river basin in north of Jorden Valley using HEC-HMS and SWBM model. They compared the results from both the models and carried out the sensitivity for the parameters used in HEC-HMS . They found the imperviousness, curve number and base flow had strong effect on output except other parameters and HEC-HMS gave better result than SWBM model.

Clay *et al.* (2005) used HEC-HMS for rainfall-runoff simulation to evaluate the effectiveness of storm water detention basins in Valley Creek watershed, Chester Country. They had used the model in accessing the effects of alternate management practices in the watershed. They concluded that a runoff volume based plan was the most effective means of attenuating watershed peak flow rates.

Knebl *et al.* (2005) developed a framework for regional scale flood modeling that integrated NEXRAD Level III rainfall, GIS and a hydrological model (HEC-HMS/RAS). The San Antonio river basin (about 4000 square miles) in Central Texas, USA, was the domain of the study because it was a region subjected to frequent occurrences of severe flash flooding. A major flood in the summer of 2002 was chosen as a case to examine the modeling framework. The model consisted of a rainfall–runoff model (HEC-HMS) that converted precipitation excess to overland flow and channel runoff, as well as a hydraulic model (HEC-RAS) that modeled unsteady state flow through the river channel network based on the HEC-HMS-derived hydrographs. HEC-HMS was run on a 4 × 4 km grid in the domain, a resolution consistent with the resolution of NEXRAD rainfall taken from the local river authority. Watershed parameters were calibrated manually to produce a good simulation of discharge at 12 sub basins with the calibrated discharge; HEC-RAS was capable of producing floodplain polygons that were comparable to the satellite imagery. The modeling framework presented in that study incorporated a portion of the recently developed GIS tool named Map to Map that had been created on a local scale and extended it to a regional scale. The results of this research would benefit future modeling efforts by providing a tool for hydrological forecasts of flooding on a regional scale. While designed for the San Antonio River Basin, this regional scale model may be used as a prototype for model applications in other areas of the country.

Hu *et al.* (2006) applied the distributed snow process model (DSPM) and the (HEC-HMS) in gridded snowmelt and rainfall-runoff modeling for reservoir operational forecasting to reduce future flood damage in the Red river of the North Basin. The reservoir operational forecasting is an essential component of the Corps Water Management System (CWMS) model. The authors described information requirements of DSPM and HEC-HMS for model setup/calibration and continuous forecast operations The CWMS operational forecasting were found important in both cold and warm regions.

McColl and Aggett (2006) developed a methodology to integrate a land use forecasting model and a rainfall-runoff simulation model i.e. HEC-HMS to improve land use planning.

Yenar *et al*. (2008) applied HEC-HMS model (v 3.1.0) to Yuvacık Basin, which is located in southeastern part of Marmara Region of Türkiye with the drainage area of 257.86 km^2 for hydrologic modeling studies. A study on event based hourly simulation and runoff scenarios using intensity-duration-frequency curves was carried out for three sub-basins: Kirazdere, Kazandere and Serindere to obtain seasonal (spring, summer and fall) average values. The infiltration loss and base flow parameters of each sub-basin were calibrated with hourly simulations for each sub-basin. Kirazdere sub-basin simulations gave better results than the other two sub-basins (Kazandere and Serinder). The calibrated model parameters can be used as a decision support tool in the Yuvacık Dam reservoir operation and management such as: domestic and industrial water supply, floodplain management and flood damage estimation studies. Runoff generated from frequency storm method will be useful for future flood hazard and risk assessment studies.

Paudel *et al.* (2009) developed modified Clark (ModClark) method or quasi-distributed model for HEC-HMS. The ModClark method was initially developed to use the national network of WSR-88D radar (NEXRAD) rainfall data in specific format. This study explored the possibility of using any real or synthetic rainfall data whether it is spatially distributed or not.

Arekhi (2012) used HEC-HMS model to compare the results of Green and Ampt, initial and constant loss rate and deficit and constant loss methods for estimation of runoff losses. He considered percent error in peaks and volumes objective functions for selection of the best method. Results showed for six events. In Initial and constant loss rate method, four events fitted with percent error in peak and five events fitted with percent error in volume. And in Green and Ampt method, three

events fitted with percent error in peak and in one event fitted with percent error in volume. The Initial and constant loss rate method had better results than
Green and Ampt method. In deficit and constant loss rate method, three events fitted with percent error in volume and in two events fitted with percent error in peak. It had less changes rather than Green and Ampt method. For two objective functions, initial and constant loss rate method had less changes percent of simulated to observed discharges and it selected as optimum method for simulation of surface runoff . Green and Ampt and constant loss rate methods took place in next preferences.

Majidi and Shahedi (2012) simulated the rainfall-runoff process using HEC-HMS hydrological model version 3.4 in Abnama watershed located in south of Iran. Rainfall-runoff simulation was con-ducted with five events. The model validation with optimized lag time values showed 9.1% difference between the observed and simulated discharges and their coefficient of determination was 0.86. The results showed that the lag time was sensitive parameter. Finally it was concluded that model can be used with reasonable approximation in hydrologic simulation in Abnama watershed.

Sardoii *et al*. (2012) compared the different methods i.e. initial and constant, Green and Ampt, SCS curve number with regard to various purpose functions (percent error in peak, peak-weighted root mean square) in HEC-HMS model. Results of simulation of seven events were compared with observed hydrographs. Based on each objective function, the method gave preference as compared to other methods. Finally, result showed that for two objective functions, Green and Ampt., SCS and initial and constant method placed in first to three preferences, respectively. So, Green and Ampt method was suggested for use in similar area and conditions.

Halwatura and Najim (2013) calibrated and validated the HEC-HMS model to Attanagalu Oya (river) catchment in Sri Lanka. They used twenty year daily rainfall data from five rain gauging stations scattered within Attanagalu Oya catchment and monthly evaporation data from agro meteorological station, Henarathgoda, together with daily flow data at Dunamale from 2005 to 2010. GIS input data for the flow simulation were prepared using Arc GIS 9.2. The model was calibrated adjusting three different methods; the SCS CN method and the deficit constant loss method (the Snyder unit hydrograph method and the Clark unit hydrograph method) in order to determine the most suitable simulation method to the study catchment. The calibrated model was validated with a new set of rainfall and flow data (2008 to 2010). The flows simulated from each method were tested statistically employing the coefficient of performance, the relative error and the residual method. The study concluded that the Snyder unit hydrograph method simulated flows more reliably than the Clark unit hydrograph method.

Majidi and Vagharfard (2013) calibrated and validated HEC-HMS hydrological model for simulation of surface run-off in Abnama watershed, south east of Iran. For choosing appropriate method between Green-Ampt and Soil Conservation Service (SCS), HEC-HMS model was separately run for four events. A result of the model calibration and validation showed that Green-Ampt method estimated peak discharge with lower difference and it’s time to peak was less than SCS method. Also comparison of simulated and observed hydrographs and correlation between their values in Minitab software showed that results based on the Green-Ampt method which had a higher coefficient of determination (R^2 = 0.71) and Pearson correlation = 0.84 than the SCS method R^2 = 0.46 and Pearson correlation = 0.7. Thus it could be concluded that simulation using Green-Ampt method was more precise than SCS method.

III. MATERIALS AND METHODS

This chapter deals with the brief description of the study area, data acquisition and methodologies used for data processing. Overview and brief description of the model operation, model calibration, model validation and its limitations, along with the description of the hydrological components of the model are also discussed in this chapter.

3.1 Study Area

'Priyadarshini' watershed of Dr. B.S.K.K.V. Dapoli, (50.20 ha) which is a typical representative of the Konkan region of Maharashtra state, was selected for the study. It has an area of 50.29 hectares and hence, it comes under the category of micro-watershed. It is situated at the tri-junction of Dapoli, Gimhavane and Chandranagar villages of Dapoli Tahasil, in Ratnagiri district. The watershed is situated at latitude of 17° 45' N, longitude of 73° 20' E and altitude of 250 m above the M.S.L. It has hilly undulating topography and shallow and stony lateritic soils. The watershed is having majority of land under agriculture with undulating topography. It is having one major stream connecting other small streams.

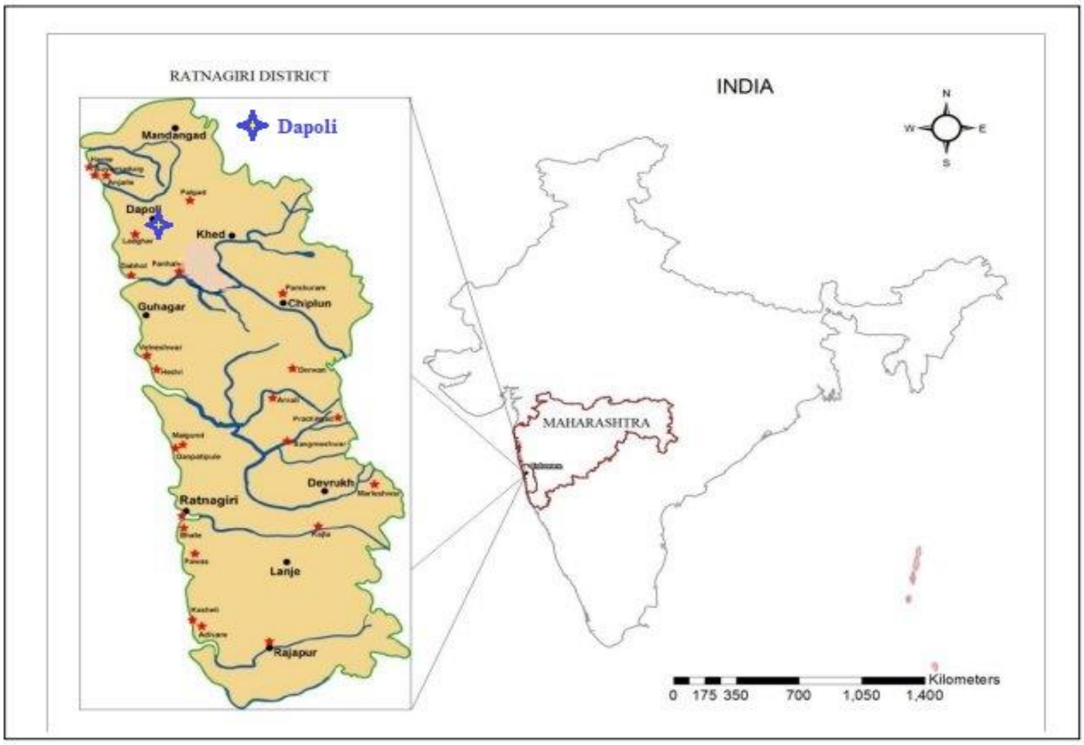


Fig. 3.1: Location map of study area

3.2 Data Acquisition

3.2.1 Meteorological Data

Daily rainfall and other meteorological data for the three years 2008, 2010 and 2013 was collected from the Department of Agronomy, College of Agriculture, Dr. B.S.K.K.V. Dapoli and Runoff data was collected from the department of SWCE, CAET, Dapoli.

The data was analyzed for rainfall depth at one day interval for event based simulation of selected rainfall-runoff events.

3.2.2 Hydrological Data

Besides rainfall and other meteorological data, the daily runoff data for the three years 2008, 2010, and 2013 recorded at watershed outlet using automatic water level stage recorded was collected. The flood hydrographs recorded were analyzed for water stages at one day interval which was required for event based rainfall-runoff simulation.

3.2.3 Topographic and Soil Data

The GIS model used to create the basin model for HEC-HMS is based solely on topography. It drives watershed network from the topographic information and calculate their relevant characteristics. With this topographical map, other maps like soil type, land slope, land use/pattern, drainage network, curve number, watershed boundary map etc. were extracted. Table 3.1 represents the data acquisition from different source.

Table 3.1: Data acquisition

Sr.No.	Item	Type	Source
1.	Rainfall data	Daily rainfall	Agronomy Department Dr.B.S. K.K.V. Dapoli
2.	Hydrological Data	Daily runoff recorded at watershed outlet	Dept. of SWCE, CAET Dapoli
3.	Contour map/ Soil map	Polygon/line	Dept. of SWCE, CAET Dapoli
4.	Hardware and Software	HEC-HMS set up to Microsoft windows	USACE website http:www.hec.usace.army.mil/ software/hec-hms

3.4 Hardware and Software

3.4.1 Operating System Requirements

The program has been created using Java programming Language. Programs written in the language can run almost any operating system.

The program is available for,

- ✓ Windows XP and Windows Vista.
- ✓ Solaris 10 Ultra SPARC.
- ✓ Modern Linux X86 distributions.

3.3.2 Hardware Requirements

The minimum hardware requirement for installation of HEC-HMS set up to Microsoft Windows is detailed as below

- ✓ Intel 3 processor/800 MHz or higher (or compatible)
- ✓ 512 MB of memory minimum
- ✓ 1 GB of memory available for the sole use of program
- ✓ 120 MB of available hard disk space for installation
- ✓ 1024×768 minimum screen revaluation

Significantly more resources may be needed depending on the scope of the study. The minimum requirement of operating system will be suitable for event simulation of basin models containing only 20 or 30 hydrological elements. For intense application a faster processor with 1 GB or more physical memory required.

3.3.3 The Software Requirement

The software requirement for the present study is HEC-HMS (v 3.5.0) (USACE, 2010) downloaded from following website

- ✓ http:www.hec.usace.army.mil/software/hec-hms

3.4 Watershed Characteristics

Morphometry is the measurement and mathematical analysis of the configuration of the Earth's surface, shape and dimensions of its landforms (Clark, 1966). This analysis can be archived through measurement of linear, aerial and relief aspects of basin and slope contributions.

The linear aspect of the drainage network morphometry incorporates stream order, stream length, drainage density, drainage frequency and bifurcation ratio. The aerial aspect of the drainage network morphometry incorporates basin area, stream frequency, constant of channel maintenance, texture ratio, elongation ratio, circulatory ratio and form factor. The relief aspect of drainage network morphometry incorporates basin relief (H) relief ratio (Rh) and ruggedness number (Rn). Various important morphometric parameters used in the study for analysis are described below.

3.4.1 Linear Aspects of the Basin

Stream Order (u):- The designation of stream orders is the first step in drainage analysis and is based on hierarchic ranking of streams. In the present study, ranking of the streams is carried out based on the method proposed by Strahler (1964). The order of the basin is the order of the highest stream.

Stream Number (N_u):- Stream number is the number of stream segments of various orders. It is inversely proportional to the stream order.

Stream Length (L_u):- Total stream length is the length of all the streams having order u. It is indicative of the contributing area of the basin of that order.

Mean Stream Length (L_W):- The total stream length divided by the number of stream segments of that order gives the mean stream length of that order.

Length of Overland Flow (L_O):- It is the largest length of the flow stream from the starting point of runoff water up to that point of the catchment where runoff is not available to flow the outlet.

Maximum Basin Length (L_b):- It is the distance between watershed outlet and the farthest point of the watershed.

Stream Length Ratio (R_L):- It is defined as the total stream length of one order to the next lower order of stream segment.

$$R_l = \frac{L_u}{L_{u-1}}$$

Horton's law (1945) of stream length states that mean stream length segments of each of the successive orders of a basin tends to appropriate a direct geometric series with streams length increasing towards higher order streams.

Bifurcation Ratio (R_b):- It is the ratio of the number of stream of a given order (Nu) to the number of streams of the next higher order (Nu+1).

$$R_b = \frac{N_u}{N_{u+1}}$$

Horton (1945) considered the bifurcation ratio as an index of relief and directions. Lower value of the Rb is characteristics of basin which have suffered less structural disturbances (Strahler, 1964).

3.4.2 Aerial Aspects of Drainage Basin

Basin Area (A):- Basin area is the direct outcome of the drainage development in a particular basin. The area of the Priyadarshini basin is about 50.29 ha, which indicates that rainwater will reach the main channel more rapidly where water has not much further distance to travel.

Shape Index (S_w):- It is the length of watershed along the mean stream from the outlet to the most distant ridge of watershed divided average width of watershed.

Slope (S):- For very small watershed, the average slope can be taken as the ratio of difference in elevation between the watershed outlet and the most distinct ridge to the approximate average length of the watershed.

It can also be determined by following formula;

$$S = \frac{(M \times N)}{A} \times 100$$

Where,

M= total length of contours within the watershed (m)

N= contour interval (m)

A= area of watershed (m^2)

Drainage Density (D_d):- Drainage density is defined as a ratio of total length of all streams to the total area of the basin. Horton (1945) introduced drainage density into literature as an expression to indicate the closeness of spacing of channels.

Stream Frequency (F_s):- The stream frequency is the number of streams per unit area of the basin. It mainly depends upon the litho-logy of the basin and reflects the texture of the drainage network. It is a good indicator of drainage pattern.

Elongation Ratio (R_e):- Elongation ratio is defined as the ratio of diameter of a circle of the same area as the basin to the maximum basin length.

$$R_e = \frac{2R}{L_b}$$

Values close to 1.0 are typical of very low relief, where as in the range 0.6-0.8 are usually associated with the high relief and steep ground slope (Schumm, 1964).

Circulatory Ratio (R_c):- It is the ratio of area of the basin to the area of circle having the same circumference as the perimeter (P) of the basin (Miller, 1953).

$$R_c = \frac{A}{4\pi \times P}$$

It is influenced more by the length, frequency and gradient of streams of various orders than slope condition and drainage pattern of the basin (Strahler, 1964).

Form Factor (F):- It is the dimensionless ratio of the basin area to the square of basin length (Horton, 1945).

$$F = \frac{A}{L_{b^2}}$$

3.4.3 Relief Aspects of Drainage Basin

Maximum Watershed Relief (H):- It is the maximum vertical distance between the lowest and highest points of watershed. It is also known as total relief.

Relief ratio (R_h):- It is the total relief (H) of watershed divided by maximum basin length (Lb). It is an indicator of potential energy available to move water and sediment down the slope.

$$R_h = \frac{H}{L_b}$$

Ruggedness Number (R_n):- Ruggedness number is the product relief of basin (H) and drainage density (Dd). It gives an idea of overall roughness of watershed.

$$R_n = H \times D_d$$

Relative relief (Rr):- It is the ratio of the maximum watershed relief to the perimeter of the watershed.

$$R_r = \frac{H}{P}$$

Morphological characteristic of a catchment were derived manually from topographic map of the watershed and Geographical Information System (GIS).

3.5 HEC-HMS Model

3.5.1 Overview of Model

HEC-HMS is hydrologic modeling software developed by the US Army Corps of Engineers-Hydrologic Engineering Center (HEC). It is the physically based and conceptual semi distributed model designed to simulate the precipitation-runoff processes in a wide range of geographic areas such as large river basin water supply and flood hydrology to small urban and natural watershed runoff. Hydrographs produced by the program can be used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, wetlands hydrology and systems operation.

It is an earlier version of HEC-1 that contains many improvements over its predecessor and includes many additional capabilities such as continuous hydrograph simulation over longer periods, distributed runoff computation using a grid cell, graphical user interface (GUI), integrated hydrograph analysis tools, data storage and management tools, graphics and reporting packages. The system encompasses losses, runoff transform, open-channel routing, and analysis of meteorological data, rainfall-runoff simulation and parameter estimation.

The Hydrologic Modeling System is designed to simulate the precipitation-runoff processes of dendritic watershed systems. Its design allows applicability in a wide range of geographic areas for solving diverse problems including large river basin water supply and flood hydrology, and small urban or natural watershed runoff. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow. Each model run combines a basin model, meteorological model and control specifications with run options to obtain results.

3.5.2 Representation of Runoff Process HEC-HMS model

The appropriate representation of the hydrologic system as shown in Fig. 3.2 depends upon the information needs of a hydrologic-engineering study. The HEC-HMS hydrologic process can be somewhat simpler. This model only computes and reports the peak or the volume or the hydrograph of watershed runoff. In this model only those components necessary to predict runoff are represented in detail and the other components are omitted or lumped.

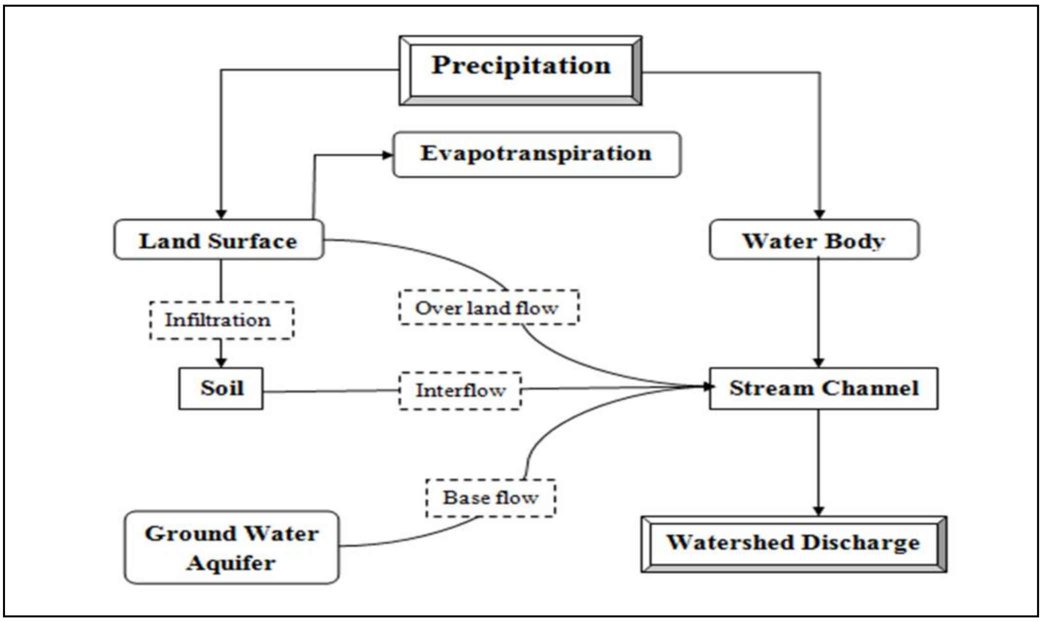


Fig. 3.2: Typical HEC-HMS hydrological representation of watershed runoff

For example, in a common application, HEC-HMS omits any detailed accounting of movement of water within the soil. In this “reductionist” mode, HEC-HMS includes models of infiltration from the land surface, but it does not model storage and movement of water vertically within the soil layer. It implicitly combines the near surface flow and overland flow and models this as direct runoff. It does not include a detailed model of interflow or flow in the groundwater aquifer, instead representing only the combined outflow as base flow.

HEC-HMS uses a separate model to represent each component of the runoff process that is illustrated in Fig. 3.2 including:

- ✓ Models that compute runoff volume;
- ✓ Models of direct runoff (overland flow and interflow);
- ✓ Models of base flow;
- ✓ Models of channel flow.

3.6 HEC-HMS Model Components

HEC-HMS model components are used to simulate the hydrologic response in a watershed. It includes basin models, meteorological models, control specifications, and input data. A simulation calculates the precipitation-runoff response in the basin model which is given input from the meteorological model. The control specifications define the time period and time step of the simulation run. Input data components, such as time-series data, paired data, and gridded data are often required as parameter or boundary conditions in basin and meteorological models (USACE-HEC, 2010).

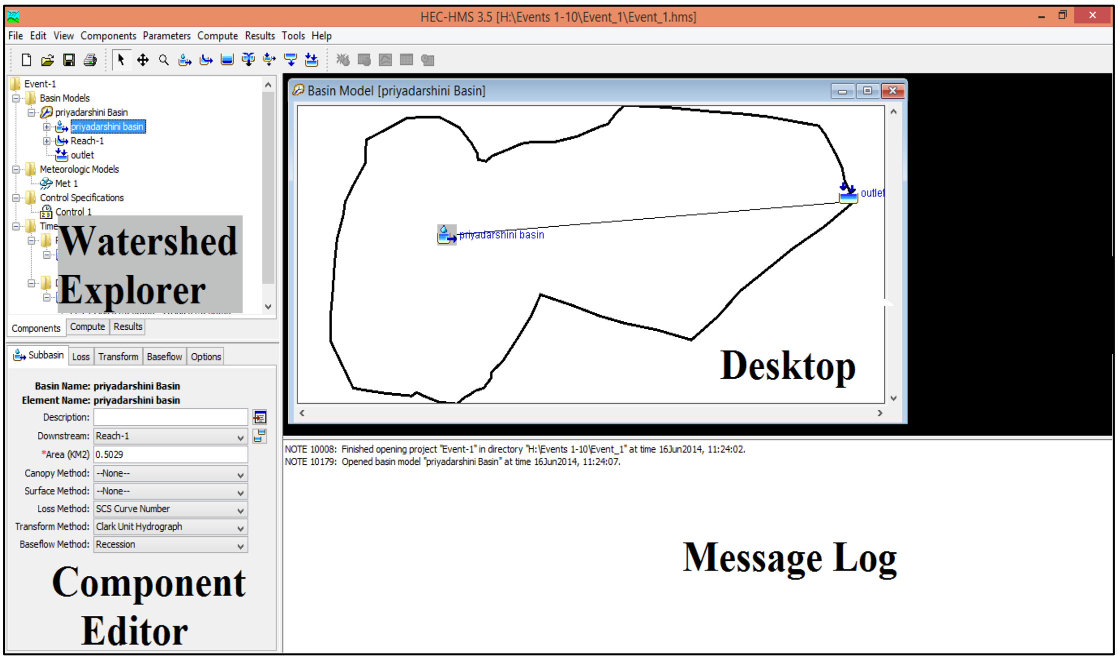


Fig. 3.3: Snapshot showing different hydrologic elements of HEC-HMS window.

Catchment Explorer:

The catchment explorer was developed to provide quick access to all components in HEC-HMS project like basin model, meteorologic model, control specification model and time-series data. The catchment explorer is divided into three parts: Components, Compute and Results.

Component Editor:

When a component or sub-component in the Catchment Explorer is active, a specific Component Editor will open. All data that can be specified in the model component is entered in the Component Editor. Any data required will be indicated with a red asterisk.

Message Log:

Note, warming, and errors are shown in the Message Log**.** These messages are useful for identifying why a simulation run failed or why a requested action like opening a project was not completed.

Desktop:

The desktop represent the physical drainage network of the study area. The basin model map is used to develop elements like sub-basin, river reach, reservoir, junction, source, diversion, sink from the toolbar. Background maps can be imported to help visualize the catchment. The variety of windows, including summary tables, time-series tables, graphs, and the basin model map shown in desktop component.

3.6.1 Basin Model Component

Basin model represents the physical watershed. The user develops a basin model by adding and connecting hydrologic elements. Hydrologic elements use mathematical models to describe physical processes in the watershed. It is based on Graphical user interface (GUI) and can import map files from GIS program to use as background.

Hydrologic Elements:

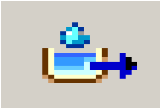
The hydrologic elements are those which are used during the calibration and validation process of HEC-HMS model for selected basin. The following description gives brief information on each symbol that is used to represent individual hydrologic element.

Sub-basin:

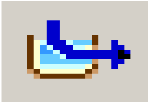
Sub basin represents the physical watershed. It calculates precipitation losses, transforming excess precipitation to stream flow at the sub basin outlet, and base flow. Symbol of sub-basin and reach are shown in figure below.

Reach:

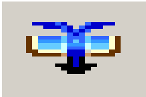
Reach connects other elements together and convey stream flow from upstream to downstream in the basin model. Inflow into the reach element can come from one or many upstream hydrologic elements. Outflow from the reach is calculated by accounting for translation and attenuation of the inflow hydrograph.



Symbol of sub-basin



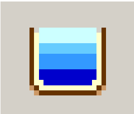
Symbol of reach



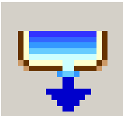
Symbol of junction

Junction:

The junction element is used to combine stream flow from hydrologic elements located upstream of the junction element. Inflow into the junction element can come from one or many upstream elements. Outflow is simply calculated by summing all inflows and assuming no storage at the junction. Symbol of Junction is shown in figure below.



Symbol of reservoir



Symbol of source

Reservoir:

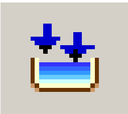
It stores runoff and releases runoff at a specific rate. Inflow into the reservoir element can come from one or many upstream hydrologic elements. Symbol of reservoir and source are shown in figure below.

Source:

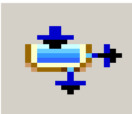
The source element is used to introduce flow into the basin model. It has no inflow. Outflow from this element is defined by the user. Symbol of source and sink are shown in figure below.

Sink:

The sink element represents the outlet of the physical watershed. It has an inflow but no outflow. Inflow into the sink element can come from one or many upstream hydrologic elements. Symbol of sink and diversion are shown in figure below.



Symbol of sink



Symbol of diversion

Diversion:-

This element is used to represent diversion of specified amount of runoff to an outlet. It is based on a rating curve-used detention storage element or outflows. Outflow from the diversion element consists of diverted flow and non-diverted flow.

Following are the methods which are used in the basin model component (Table 3.2). The bold methods have been used in present study of Priyadarshini watershed.

Table 3.2: Sub-basin and reach calculation methods.

Hydrologic Element	**Calculation Type**	**Method**
Sub-basin	Runoff-volume	Deficit and constant rate (DC), Exponential, Green and Ampt, Gridded DC, Gridded SCS CN, Gridded SMA, Initial and constant rate, **SCS curve number (CN),** Smith Parlange, Soil moisture accounting (SMA)
	Direct-runoff	**Clark's UH,** Kinematic wave, Mod Clark, SCS UH, Snyder's UH, User-specified s-graph, User-specified unit hydrograph (UH)
	Base flow	Bounded recession, Constant monthly, Linear reservoir, Nonlinear Boussinesq, **Recession**
Reach	Routing	Kinematic wave, Lag, Modified Puls, **Muskingum**, Muskingum-Cunge

3.6.2 Meteorologic Model Component

The precipitation and evapotranspiration data necessary to simulate watershed processes are stored in the meteorological model. The meteorologic model calculates the precipitation input required by a sub-basin element. This model can utilize both point and gridded precipitation and has the capability to model frozen and liquid precipitation along with evapotranspiration. The newly added snowmelt method uses a temperature index algorithm to calculate the accumulation and melt of the snow pack. The evapotranspiration methods include the monthly average method and the new Priestly Taylor and gridded Priestly Taylor methods. An evapotranspiration method is only required when simulating the continuous or long term hydrologic response in a watershed.

A brief description of the methods available for calculating basin average precipitation or grid cell precipitation is included in Table 3.3.

Table 3.3: Description of meteorologic model methods

Precipitation Methods	Description
Frequency Storm	It is used to develop a precipitation event where precipitation depths for various durations within the storm have a consistent exceedance probability.
Gage Weights	**This method applies user specified weights to user defined precipitation gages.**
Gridded Precipitation	This method allows the use of gridded precipitation products, such as RADAR.
Inverse Distance	This method calculates sub-basin average precipitation by applying an inverse distance squared weighting to user defined precipitation gages.
SCS Storm	This method applies a user specified SCS time distribution to a 24-hour total storm depth.
Specified Hyetograph	This method applies a user defined hyetograph to a specified sub-basin element.
Standard Project Storm	This method applies a time distribution to an index precipitation depth.

3.6.3 Control Specifications Component

The control specifications set the time span of a simulation run. Information in the control specifications includes a starting date and time, ending date and time, and computation time interval.

3.6.4 Input Data Components

Time-series data, paired data and gridded data are often required as parameter or boundary conditions in basin and meteorologic models. A complete list of input data is included in Table 3.4. Input data can be entered manually or referenced to an existing record in a HEC-DSS file. All gridded data must be referenced to an existing HEC-DSS record.

Table 3.4: Input data components.

Time-Series Data	**Paired Data**	**Gridded Data**
Precipitation gages	Storage-discharge functions	Precipitation grid sets
Discharge gages	Elevation-storage functions	Temperature grid sets
Stage gages	Elevation-area functions	Solar radiation grid sets
Temperature gages	Elevation-discharge functions	Crop coefficient grid sets
Solar radiation gages	Inflow-diversion functions	Storage capacity grids
Crop coefficient gages	Cross sections	Percolation rate grids
	Unit hydrograph curves	Storage coefficients grids
	Percentage curves	Moisture deficit grids
	ATI-melt rate functions	Impervious area grids
	ATI-cold rate functions	SCS curve number grids
	Ground melt patterns	Elevation grids
	Melt rate patterns	Cold content grids
		Cold content ATI grids
		Melt rate ATI grids
		Liquid water content grids
		Snow water equivalent grids

3.7 Watershed Delineation and Hydrological Structure

Following step-by-step procedure is adapted for the watershed delineation and identification of hydrological structure they are:

i. Delineation of watershed area from available top sheet
ii. Identification of drainage network in the watershed
iii. Determination of all geometric parameters such as sub basin area, overland flow length, basin slope, and stream channel length and slope etc.
iv. Determination of composite curve number based on hydrologic soil group, land use/land cover and hydrologic condition etc. of watershed area and
v. Formulation of hydrological setup with sub-basin, reach, junction sink and reservoir etc.

3.8 Event Based Hydrological Modeling

An event model simulates a single storm. The duration of the storm may range from a few hours to a few days. This distinction applies primarily to models of watershed-runoff processes. Event hydrological modeling reveals the how a basin responds to an individual rainfall event (e. g. quantity of surface runoff, peak, timing of peak, detention etc.). Fine-scale event hydrological modeling is particularly useful for understanding detailed hydrologic processes and identifying the relevant parameter that can be further used for coarse-scale continuous modeling, especially when long-term intensive monitoring data are not available or the data are incomplete.

3.8.1 Selection of Rainfall-Runoff Events

Selection of rainfall-runoff events is a critical step for event hydrologic modeling and model calibration/validation (Chu and Steinman, 2009). Selection depends on many factors, such as rainfall characteristics (magnitude, duration, intensity, temporal and spatial variability etc.), watershed properties (size, land use/covers, soil types etc.) and availability and completeness of rainfall and stream monitoring data.

The following criteria were applied for selecting individual rainfall-runoff events suitable for the calibration and verification of the HEC-HMS model according to the recommendations given in USACE-HEC (2010) manual:

- ✓ Maximum spatio-temporal data density of the observed daily stream flow and rainfall records.

- ✓ Uniform rainfall distribution throughout the period of effective precipitation over the entire watershed.
- ✓ Rainfall-runoff events generated by the same rainfall event.
- ✓ Stream flow peaks representing all runoff due to the selected rainfall event.
- ✓ The duration of rainfall events exceeding the time of concentration of the basin.
- ✓ The magnitude of rainfall events selected for calibration approximately equal the magnitude of rainfall events the model is intended to analyze.

3.8.2 Selection of Modeling Methods

Following methods were selected for each component of runoff process such as runoff volume, direct runoff, base-flow and channel routing in event based hydrological modeling as given in Table 3.5.

Table 3.5: Selected methods for runoff components in event based hydrological modeling.

Hydrological Element	Calculation Type	Method
Sub-basin	Runoff volume	SCS curve number (CN)
	Direct runoff	Clark's Unit hydrograph method
	Base flow	Exponential recession method
Reach	Routing	Muskingum method

These methods are selected on the basis of applicability and limitations of each method, availability of data, suitability for same hydrologic condition, well established, stable, widely acceptable, researcher recommendation, etc. The application and limitation of all methods are given after description of each method.

3.8.2.1 SCS Curve Number (CN) Method

It is simple, predictable and stable method used for estimating precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture. The equation is (Singh and Seth, 1984):

$$P_e = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (3.1)$$

Where,

P_e = Accumulated precipitation excess at time t;

P = Accumulated rainfall depth at time t;

I_a = The initial abstraction (initial loss through interception, evaporation, detention, infiltration before runoff starts) and

S = Potential maximum retention (ability of a watershed to abstract and retain storm precipitation).

From analysis of results from many small experimental watersheds, the SCS developed an empirical relationship of I_a and S as:

$$I_a = 0.2S \tag{3.2}$$

Therefore, the cumulative excess precipitation at time *t* is:

$$P_e = \frac{(P-0.2S)^2}{(P+0.8S)} \quad \text{(Subject to } P \geq 0.2S\text{, otherwise } P_e = 0) \tag{3.3}$$

Incremental excess for a time interval is computed as the difference between the accumulated excess at the end of and beginning of the period. The maximum potential retention (S) and watershed characteristics are related through an intermediate parameter, called curve number (CN). It is an index that represents the combination of hydrological soil group, land treatment classes, and antecedent moisture conditions and is expressed as:

$$S = \frac{25400}{CN} - 254 \tag{3.4}$$

Value of CN is ranges from a minimum of zero to a maximum of hundred. However it can be zero for permeable impervious surface.

Estimation of CN

The CN for a watershed can be estimated as a function of land use, soil type, and antecedent watershed moisture and using tables published by the SCS-USDA. For a watershed that consists of several soil types and land uses, a composite CN is calculated as,

$$CN_{composite} = \frac{\sum(A \times CNi)}{\sum Ai} \tag{3.5}$$

Where,

$CN_{composite}$ = the composite CN used for runoff volume computations

i = an index of watersheds subdivisions of uniform land use and soil type

CNi = Curve number for subdivision i and

Ai = the drainage area of subdivision i

Selection of the SCS CN Runoff-Volume Method:

Curve Number model contains two parameters the curve number and the initial abstraction. As typically used, however, the initial abstraction is made to be a function of the curve number. So in reality, it is a one parameter model. The reasons for the use of curve number include its simplicity, ease of use, widespread acceptance and the significant infrastructure and institutional momentum. Curve Number (CN) method is very simple, widely used method for estimating infiltration characteristics of the watershed and is based on the land use property and soil property. Cowan (1975) stated that the SCS CN method is comfortably used for estimation of runoff in a watershed where soils, vegetation and other characteristics affecting runoff have not been evaluated experimentally. Proper estimation of CN or infiltration parameters is necessary for estimation of runoff from rainfall data (Bhatt *et al*., 2012).

3.8.2.2 Clark's Unit hydrograph model for direct runoff

Clark's model derives a watershed UH by explicitly representing two critical processes in the transformation of excess precipitation to runoff:

• **Translation** or movement of the excess from its origin throughout the drainage to the watershed outlet; and

• **Attenuation** or reduction of the magnitude of the discharge as the excess is stored throughout the watershed.

Estimating the Clark's UH Model Parameters

Clark's Unit hydrograph model will be used to derive watershed UH. It explicitly represents two processes in transformation of excess precipitation to runoff. The processes are: (a) Translation or movement of excess runoff from its origin throughout the watershed outlet and (b) Attenuation or reduction of magnitude of discharge as the excess stored throughout the watershed. Short term storage in soil, on the surface and in the channel plays an important role in transformation of precipitation excess to runoff. The linear reservoir is a common representation of this storage. Model begins with continuity equation as

$$\frac{ds}{dt} = It - Ot \tag{3.6}$$

Where,

$\frac{ds}{dt}$ = Time rate of change of water in storage at time, t;

It = Average inflow to storage at time, t;

Ot = Outflow from the storage at time, t;

$$St = R.Ot \tag{3.7}$$

R = A constant linear reservoir parameter known as storage coefficient.

After combining and solving the equations using a simple finite difference approximation

$$Ot = C_A\, It + C_B + Ot\text{-}1 \tag{3.8}$$

$$C_B = \frac{Ot-1+Ot}{2} \tag{3.9}$$

Estimation of Clark's UH model parameters

Application of Clark's UH model requires properties of time-area histogram and storage coefficient (R). Linear routing model properties are defined implicitly by a time area histogram. Studies at HEC have shown that even though a watershed specific relationship can be developed, a smooth function fitted to a typical time area relationship represents temporal distribution adequately for UH derivation for most watersheds.

$$\frac{At}{A} = 1.414\left(\frac{t}{tc}\right)^2 \text{For t} \leq \frac{tc}{2} \tag{3.10}$$

$$\frac{At}{A} = 1 - 1.414\left(1 - \frac{t}{tc}\right)^{1.5} \text{For t} \geq \frac{tc}{2} \tag{3.11}$$

Where,

At = Cumulative area contributing at time t;

A = Total watershed area;

tc = time of concentration;

Time of Concentration (T_c) is the time required for water to travel from the most hydraulically remote point in the basin to the basin outlet. Many empirical and physically-based equations have been proposed in the literature by many scientists for basin time lag. Kirpitch (1940) has given the following empirical formula to compute the time of concentration is:

$$T_c = 0.02\, L^{0.77}\, S^{-0.385} \tag{3.12}$$

Where,

L = Main channel length (m),

S = Average slope of the channel reach, m/m

T_c = Time of concentration (min).

3.8.2.3 Exponential Recession Model for Base Flow

Exponential Recession Model in HEC-HMS is used to represent watershed base flow (Chow *et al.*, 1988). It is used to explain the drainage from natural storage in a watershed (Linsley *et al.*, 1982). It defines the relationship of *Qt* (the base flow at any time *t*), to an initial value as:

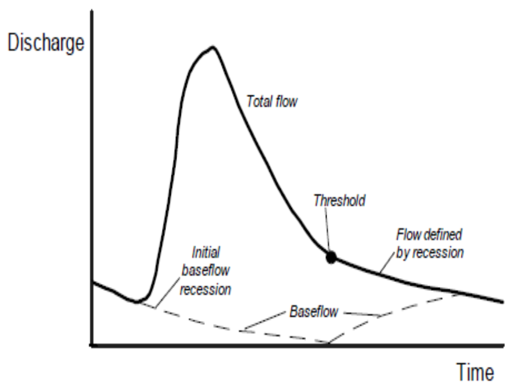
$$Q_t = Q_o^{kt} \tag{3.13}$$

Where,

Q_0 = Initial base flow at time t = 0 (User specified value); and

k = An exponential decay constant.

As implemented in HEC-HMS, k is defined as the ratio of the base flow at time *t* to the base flow one day earlier. The starting base flow value, Q_0, is an initial condition of the model. The base flow thus computed is illustrated in Fig. 3.4. The shaded region represents base flow in this figure; the contribution decays exponentially from the starting flow. Total flow is the sum of the base flow and the direct surface runoff.



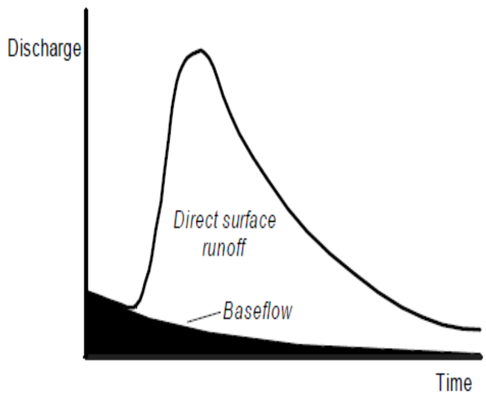


Fig. 3.4: Initial base flow recession. **Fig. 3.5: Base flow model illustration**

In HEC-HMS, the base flow model is applied both at the start of simulation of a storm event, and later in the event as the delayed subsurface flow reaches the watershed channels, as shown in Fig 3.5. A user-specified threshold flow defines the time at which the recession model (Eq. 3.13) defines the total flow. That threshold may be specified as a flow rate or as a ratio to the computed peak flow.

At the threshold flow, base flow is defined by the initial base flow recession. Thereafter base flow is not computed directly, but is defined as the recession flow less the direct-surface-runoff. When the direct-surface runoff eventually reaches zero, the total flow and base flow are identical.

Estimation of Base Flow Model Parameters:

Initial base flow (Q_o), recession constant (k) and threshold flow (Q_t) are the parameters of exponential recession model. Initial base flow (Q_o) is estimated by field inspection. For analysis of hypothetical storm runoff, initial flow should be selected as a likely average flow that would occur at the start of the storm runoff.

The recession constant (k) is estimated from observed flow hydrograph which depends upon the source of base flow. Pilgrim and Cordery (1992) gives typical value for different flow constants (Table 3.6). If k = 1.00, the base flow contribution is constant with $Q_t = Q_0$. Thus k must be less than 1.00 for natural watershed.

Table 3.6: Typical recession constant values

Flow component	Recession constant, daily
Groundwater	0.95
Interflow	0.8 - 0.9
Surface runoff	0.3 - 0.8

The threshold flow (Q_t) is estimated from observed flows hydrograph, wherein the flow at which recession limb approximated well by a straight line.

3.8.2.4 Muskingum Model For Channel Routing

It uses a simple finite difference approximation of the continuity equation as like modified puls model. The model is:

$$\left(\frac{I_{t-1}+I_t}{2}\right) - \left(\frac{O_{t-1}\ O_t}{2}\right) = \left(\frac{S_t - S_{t-1}}{\Delta t}\right) \tag{3.14}$$

Storage in the reach is modeled as the sum of prism storage and wedge storage. Prism storage is the volume defined by a steady-flow water surface profile, while wedge storage is the additional volume under the profile of the flood wave (Linsley *et al*., 1982). During rising stages of the flood, wedge storage is positive and is added to the prism storage whereas during the falling stages of a flood, the wedge storage is negative and is subtracted from the prism storage. The volume of prism storage is the outflow rate (O) multiplied by the travel time through the reach (K). The volume of wedge storage is a weighted difference between inflow and outflow multiplied by the travel time K. Thus, the Muskingum model defines the storage as:

$$S_t = K\,Q_t + K\,X\,(It - Q_t) = K\,[X\,It + (1 - X)\,Q_t] \qquad (3.15)$$

Where,

K = Travel time of the flood wave through routing reach; and

X = Dimensionless weight ($0 \leq X \leq 0.5$).

If Eq. (3.13) is substituted into Eq. (3.15) and the result is rearranged to isolate the unknown values at time *t*, the result is:

$$O_t = \left(\frac{\Delta t - 2KX}{2K(1-X)+\Delta t}\right)I_t + \left(\frac{\Delta t + 2KX}{2K(1-X)+\Delta t}\right)I_{t-1} + \left(\frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t}\right)O_{t-1} \qquad (3.16)$$

HEC-HMS solves Eq. (3.16) recursively to compute ordinates of the outflow hydrograph given the inflow hydrograph ordinates (It for all t), an initial condition ($O_t = 0$), and the parameters, K and X.

Estimating the Muskingum Model Parameters:

If observed inflow and outflow hydrographs are available, parameter *K* can be estimated as the interval between similar points on the inflow and outflow hydrographs. Once *K* is estimated, *X* can be estimated by trial and error.

The value of parameter X ranges from 0 to 0.5. Experience has shown that for channels with mild slopes and over-bank flow, the parameter X will approach 0.0. For steeper streams, with well-defined channels that do not have flows going out of bank, X will be closer to 0.5. Most natural channels lie somewhere in between these two limits. X is estimated as (Majidi and Shahedi, 2012):

$$\mathrm{X} = \frac{I^{1/2}}{n \times P^{2/3}} \qquad 3.17$$

Where,

I = River slope, m/m

n = Manning’s coefficient

P = Wetter perimeter, m

Selection of HEC-HMS Routing Methods:

Each routing model that is included in HEC-HMS solves the momentum and continuity equations. However, each omits or simplifies certain terms of those equations to arrive at a solution. To select an appropriate routing model, assumptions include the followings:

- ✓ Backwater effects:-The Muskingum models cannot account for the influences of backwater on the flood wave, because this is based on uniform-flow assumptions. This method is not suitable for river basin model while this method is suitable for small watershed runoff where backwater effect is negligible.
- ✓ Floodplain storage**:-** The Muskingum model can be calibrated to match the peak flow and timing of a specific flood magnitude.
- ✓ Configuration of flow networks:- In a dendritic stream system, if the tributary flows or the main channel flows do not cause significant backwater at the confluence of the two streams, any of the hydraulic or hydrologic routing methods can be applied.
- ✓ Interaction of channel slope and hydrograph characteristics.
- ✓ Occurrence of subcritical and supercritical flow.
- ✓ Availability of data for calibration.

3.9 Model Calibration

3.9.1 HEC-HMS Calibration Procedure

Followings are the HEC-HMS calibration procedure to obtain the best (optimal) parameter values:

1. The first procedure begins with data collection in which for rainfall-runoff models, the required data are rainfall and flow time series and for routing models, observations of both inflow to outflow from the routing reach are collected.
2. The next step is to select initial estimates of the parameters.
3. Given these initial estimates of the parameters, simulate the HEC-HMS models for observed boundary conditions to compute the output, either the watershed runoff hydrograph or a channel outflow hydrograph.
4. Then compare the computed hydrograph to the observed hydrograph to judge how well the model "fits" the real hydrologic system.
5. If the fit is not satisfactory, then do parameter optimization trails to adjust the parameters systematically.

6. When the fit is satisfactory, HEC-HMS will report the optimal parameter values. The presumption is that these parameter values then can be used for runoff or routing computations that are the goal of the flood runoff analyses.

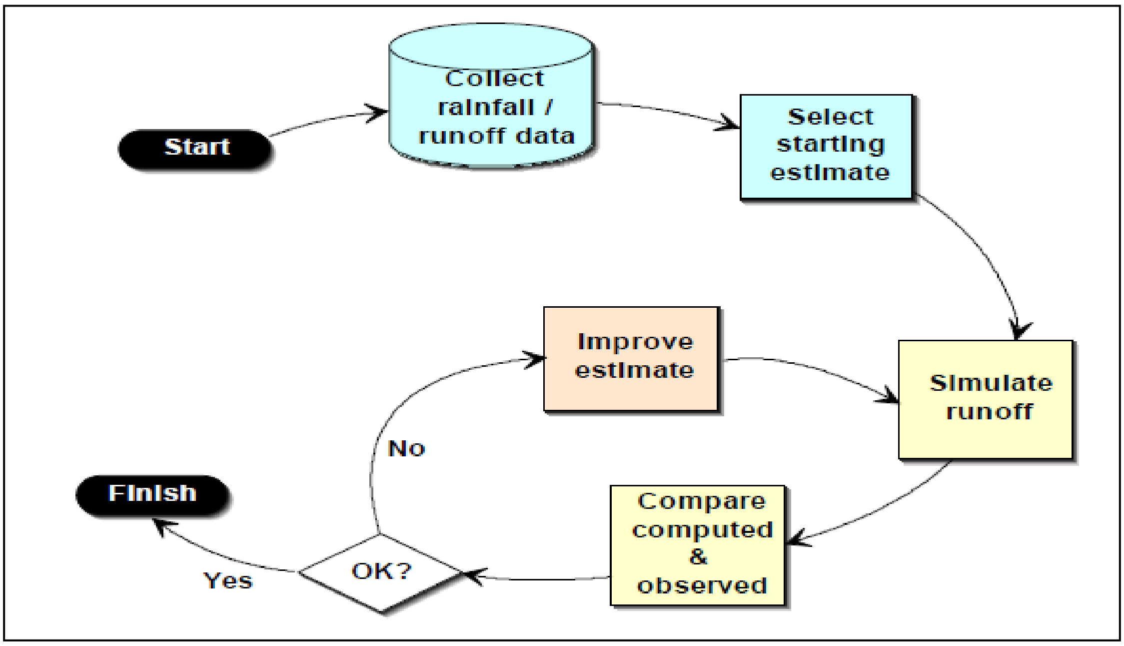


Fig. 3.6: Schematic view of calibration procedure

3.9.2 Calibration of the Model

The successful application of the hydrologic watershed model depends upon how well the model is calibrated which in turn depends on the technical capability of the hydrological model as well as the quality of the input data. HEC-HMS watershed model is calibrated for the event based simulation. The objective of the model calibration is to match simulated volumes, peaks, and timing of hydrographs with the observed ones.

The available hydro-meteorological data in the year of 2008, 2010, and 2013 is split up in two parts for model calibration and model validation. For event based simulation, the SCS curve number loss is used to compute runoff volume, Clark's UH to direct runoff, Recession base flow to base flow and Muskingum method to routing. Curve number (CN), initial abstraction (I_a), time of concentration (T_c), storage coefficient (R), initial base flow (Q_o), recession constant (R_c), and threshold flow (Q_t) are considered as calibration parameters. These model parameters will be estimated using trial and error method until a reasonable match between observed and simulation hydrograph in event based simulation is obtained.

Muskingum model parameter K can be estimated as the elapsed time between the centroid of areas of two hydrograph as the time between the hydrograph peaks, or as the between midpoints of the rising limbs. Once K is estimated, X can be estimated by trial and error. If gauged data are not available, K and X can be estimated from channel characteristics.

3.10 Validation of the Model

The available hydro-meteorological data in the year of 2008, 2010, and 2013 is split up in two parts for model calibration and model validation. Using parameters fine-tuned in the calibration process, the model will be validated from the available data. Like calibration, the first year run will be taken as model initiation and exclude from model performance evaluation. Using different watershed parameters in the calibration process, the model is validated from available data.

3.11 Limitations of HEC-HMS Model

Every simulation system has limitations due to the choices made in the design and development of the software. The limitations that arise in this program are due to two aspects of the design: simplified model formulation and simplified flow representation. Simplifying the model formulation allows the program to complete simulations very quickly while producing accurate and precise results. Simplifying the flow representation aids in keeping the compute process efficient and reduces duplication of capability in the HEC software suite.

3.11.1 Model Formulation

All of the mathematical models included in the program are deterministic. This means that the boundary conditions, initial conditions, and parameters of the models are assumed to be exactly known. This guarantees that every time a simulation is computed, it will yield exactly the same results as all previous times it was computed. During long periods of time, it is possible for parameters describing a watershed to change as the result of human or other processes at work in the watershed. There is a limited capability to break a long simulation into smaller segments and manually change parameters between segments.

All of the mathematical models included in the program are uncoupled. The program first computes evapotranspiration and then computes infiltration. In the physical word, the amount of evapotranspiration depends on the amount of soil water. The amount of infiltration also depends on the amount of soil water. However, evapotranspiration removes water from the soil at the same time infiltration adds water to the soil. To solve the problem properly, the evapotranspiration and infiltration processes must be simulated simultaneously with the mathematical equations for both processes numerically linked. This program does not currently include such coupling of the process models. Errors due to the use of uncoupled models are minimized as much as possible by using a small time interval for calculations. While preparations have been made to support the inclusion of coupled plant-surface-soil models, none have been added at this software.

3.11.2 The Minimum and Maximum Parameter Values

In simulation of rainfall-runoff models the range of feasible, acceptable parameters is limited. The assumed maximum and minimum range between parameter values is given in the following Table 3.7.

Table 3.7: Maximum and minimum parameter values

Model	Parameter	Minimum Value	Maximum Value
SCS Loss	Initial Abstraction, I_a	0 mm	500 mm
	Curve Number, CN	1	100
Clark's UH	Storage Coefficient (R)	0 hr	150 hr
	Time of Concentration (Tc)	0.1 hr	500 hr
Base Flow	Initial Base Flow, Q_o	0 m^3/s	100000 m^3/s
	Recession Factor, R_c	0.000011	-
Muskingum Routing	K	0.1 hr	150 hr
	X	0	0.5
	Number of Steps	1	100

3.11.3 Limitations of Model Components

The design of the basin model only allows for dendritic stream networks. The best way to visualize a dendritic network is to imagine a tree. The main tree trunk, branches and twigs correspond to the Main River, tributaries, and headwater streams in a watershed. The basin model allows each hydrologic element to have only one downstream connection. So it is not possible to split the outflow from an element into two different downstream elements. The diversion element provides a limited capability to remove some of the flow from a stream and divert it to a different location downstream in the network. Likewise, a reservoir element may have an auxiliary outlet. The design of the process for computing a simulation does not allow for backwater in the stream network. The computer process begins at headwater sub-basins and proceeds down through the network. Each element is computed for the entire simulation time window before proceeding to the next element. There is no iteration or looping between elements. Therefore, it is not possible for an upstream element to have knowledge of downstream flow conditions which is the essence of backwater effects. There is a limited capability to represent backwater if it is contained within a reach element. However, in general, the presence of backwater within the stream network will require a separate hydraulic model.

3.12 Error Function Used for Evaluation of Computed Runoff Hydrographs

The error function employed for evaluation of the runoff hydrograph estimated by the HEC-HMS model in comparison with the observed runoff hydrographs for both calibration and validation are as follows:

i. **Root Menu Square Error (RMSE)**

Root mean square error is computed as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{m}(Qoi - Qci)^2}{m}} \quad 3.18$$

ii. **Sum of Absolute Errors (SAE)**

Sum of absolute errors is computed as follows:

$$SAE = \sum_{i=1}^{n} |(Qoi - Qci)| \quad 3.19$$

iii. **Sum of Squared Residuals (SSR)**

Percentage error in volume is computed as follows:

$$SSR = \sum_{i=1}^{n} [Qoi - Qci]^2 \quad 3.20$$

Where,

Qoi = Observed outflow volume and

Qci = Computed outflow volume

iv. Percentage Error in Peak (PEP)

Percentage error in peak is computed as follows:

$$\text{PEP} = 100 \left| \frac{\text{Qc(peak)} - \text{Qo(peak)}}{\text{Qo(peak)}} \right| \qquad 3.21$$

Where,

Qo (peak) = Observed peak discharge and

Qc (peak) = Computed peak discharge

v. Peak Weighted Root Mean Square Error (PWRMSE)

It is computed as follows:

$$\text{PWRMSE} = \left\{ \frac{1}{n} \left[\sum_{i=1}^{n} (Qoi - Qci)^2 \left(\frac{Qoi + Qo(mean)}{2Qo(mean)} \right) \right] \right\}^{\frac{1}{2}} \qquad 3.22$$

Where,

Qo (mean) = Mean of observed flows

Qci = Computed outflow volume

Qoi = Observed outflow volume and

n = Number of Computed hydrograph ordinates.

IV. RESULTS AND DISCUSSION

This chapter embodies all the result obtained during the course of study for the selected catchment.

4.1 Analysis of Geo Morphologic Parameters of Watershed

The geographic parameters of the watershed have significant effects on runoff, sediment loss and erosion occurring in the watershed. It is common in hydrologic design to assume a constant depth of rainfall occurring uniformly over the watershed. The watershed area reflects the volume of water that can be generated from the rainfall. The morphologic parameters of Priyadarshini watershed under study were extracted using Arc GIS 10.2 and also derived manually and are given in Table 4.1. The morphologic parameters of watershed such as area of watershed (A), perimeter of watershed (P), total stream length (L), mean stream length (L_w), maximum basin length (L_b), maximum basin width (W_b) etc., are extracted using Arc GIS 10.2 software.

Area and perimeter of Priyadarshini watershed are 50.29 ha and 3.56 km, respectively. The total stream length of watershed is the sum of lengths of all streams of all orders in arable and non arable area of Priyadarshini watershed. The Longest Flow Path (L) and Stream Length Ratio (Rl) of Priyadarshini watershed are 1.12 km and 0.65 respectively. The maximum basin length and basin width of the watershed are 1200 m and 625 m, respectively.

The remaining geomorphologic parameter of watershed such as, form factor (F_f), circulatory ratio (R_c), elongation ratio (R_e), drainage density (D_d), length of overland flow (L_o), bi-furication ratio (R_b), maximum basin relief (H), relief ratio (R_h), relative relief (R_{hp}), ruggedness number (RN) etc. are calculated manually. The shape of watershed is generally expressed by three factors i. e. form factor, circulatory ratio and elongation ratio and these values for Priyadarshini watershed are 0.36, 0.50, and 0.67, respectively. These factors are dimensionless and refer to the shape of outline of the watershed.

Table 4.1 Morphologic parameter of Priyadarshini watershed

Sr. No.	Parameter	Value
1	Stream Number (Nu)	32
2	Longest Flow Path (L)	1.12 km
3	Stream Length Ratio (Rl)	0.65
4	Perimeter of Watershed (P)	3.56 km
5	Area of Watershed (A)	50.29 Ha (0.5029 km^2)
6	Bifurcation Ratio (Rb)	1.285
7	Drainage Density (Dd)	14.30
8	Stream Frequency (Df)	63.63 / km^2
9	Form Factor (F)	0.36
10	Elongation Ratio (Re)	0.67
11	Circulatory Ratio (Rc)	0.50
12	Max.Watershed Relief (H)	43
13	Relief Ratio (Rc)	2.4
14	Ruggedness Number (RN)	0.602
15	Relative Relief (Rr)	1.24
16	Length of overland flow (Lo)	0.07 km/km^2
17	Stream Channel Slope (S)	4.1 %
18	Max. Length of Watershed (Lb)	1.20 km

4.2 Processing of Rainfall Data

All the rainfall events were methodically scrutinized and the events were selected randomly from the collected data. Flood events of various durations and different peak flows were selected to cover a wide spectrum of duration and peaks. For the final study 15 events were selected. Among these 15 events, 10 events were used for calibration and remaining 5 events were used for validation.

The selected events from the collected data were used to calibrate the loss rate parameters by optimization trial. These calibrated parameters were further used for validation. The details of the selected flood events are given in the Table 4.2.

Table 4.2 Period of selected storm events

Sr. No.	Events	Start Date	Start Time	End Date	End Time	Calibration/ Validation
1	Event 1	22 Jun 2008	08:00	28 Jun 2008	08:00	Calibration
2	Event 2	29 Jun 2008	08:00	05 July 2008	08:00	Calibration
3	Event 3	13 Sept.2008	08:00	19 Sept. 2008	08:00	Calibration
4	Event 4	18 July 2010	08:00	24 July 2010	08:00	Calibration
5	Event 5	01 August 2010	08:00	07 August 2010	08:00	Calibration
6	Event 6	29 August 2010	08:00	04 Sept. 2010	08:00	Calibration
7	Event 7	16 June 2013	08:00	22 June 2013	08:00	Calibration
8	Event 8	30 June 2013	08:00	06 July 2013	08:00	Calibration
9	Event 9	07 July 2013	08:00	13 July 2013	08:00	Calibration
10	Event 10	14 July 2013	08:00	20 July 2013	08:00	Calibration
11	Event 11	10 August 2008	08:00	16 Aug 2008	08:00	Validation
12	Event 12	25 July 2010	08:00	31 July 2010	08:00	Validation
13	Event 13	05 Sept. 2010	08:00	11 Sept. 2010	08:00	Validation
14	Event 14	23 June 2013	08:00	29 June 2013	08:00	Validation
15	Event 15	21 July 2013	08:00	27 July 2013	08:00	Validation

4.3 Calculated Parameter

The parameter values required for calibration were calculated and given as initial values at the time of calibration to the selected model. These values of parameters are presented in Table 4.3.

Table 4.3 Calculated parameters for the watershed

Sr.No.		Parameter	Value
1	**Loss Rate Parameter**	Initial abstraction (Ia), mm	24.850
2		Curve Number (CN)	67.153
3		Impervious Area (%)	10.930
4	**Transform Parameter**	Time of Concentration, (Tc) Hr	0.2611
5		Storage Coefficient, (R) Hr	0.0200
6	**Base flow Parameters**	Initial discharge (Qo), m3/sec	0.0222
7		Recession constant (Rc)	0.750
8		Threshold flow (Qt), m3/sec	0.531
9	**Routing Method Constants**	Muskingum (K), Hr	0.660
10		Muskingum (X)	0.200

4.4 Model Application

4.4.1 Parameter Estimation from Optimization Trial

An objective functions is a mathematical tool to measure the goodness of fit between the observed and generated hydrographs. The main objective behind optimization trial is to find out optimum parameter values with lowest objective function. The Univariate gradient method computes and adjusts one parameter at a time while locking other parameters. Alternatively, the Nelder and Mead method evaluates all parameters simultaneously and determines which parameter to adjust. The search algorithms are also known as optimization methods. The optimal objective function value is closed to zero.

The rainfall and runoff data are used to estimate the parameter of all methods used in the HEC-HMS model by optimization trial. The optimized values will be used in validation process for entire Priyadarshini watershed considering as a single unit. All parameters were estimated for each calibrated event. The parameters for all the individual events, along with mean values are presented in Table 4.4.

It is observed from Table 4.4 that loss rate parameters i.e. initial abstraction (I_a) varies from 24.04 mm to 27.18 mm and curve number (CN) from 56.98 to 68.19 for different storm events. The mean value of I_a is 25.76 mm and that of CN is 62.19.

Table 4.4 Optimized parameter values for each events

Parameters / Events	I_a (mm)	CN	T_c (Hr)	R	Q_o (m^3/s)	R_c	Q_t (m^3/s)	K (hr)	X
Event 1	25.48	65.68	0.261	0.020	0.019	0.759	0.123	0.133	0.039
Event 2	26.40	60.73	0.261	0.020	0.017	0.720	0.122	0.456	0.147
Event 3	25.77	61.55	0.261	0.020	0.017	0.692	0.119	0.133	0.500
Event 4	27.18	62.94	0.261	0.020	0.017	0.470	0.123	0.133	0.185
Event 5	24.04	65.93	0.261	0.020	0.019	0.748	0.122	0.147	0.185
Event 6	27.11	56.98	0.261	0.020	0.018	0.720	0.125	0.133	0.040
Event 7	24.53	63.58	0.261	0.020	0.019	0.692	0.113	0.133	0.185
Event 8	24.53	68.19	0.261	0.020	0.019	0.737	0.113	0.147	0.500
Event 9	27.09	56.98	0.261	0.020	0.017	0.692	0.123	0.137	0.185
Event 10	25.73	60.37	0.261	0.020	0.018	0.727	0.123	0.028	0.058
Mean Value	**25.76**	**62.19**	**0.261**	**0.020**	**0.018**	**0.690**	**0.121**	**0.131**	**0.205**

The transform parameter time of concentration (Tc) and storage coefficient (R) are constant having values 0.261 hr and 0.020, respectively.

The initial discharge (Q_o), threshold flow (Q_t), and recession constant (R_c) are the base flow method parameters which varies from 0.017 m^3/s to 0.019 m^3/s, 0.113 m^3/s to 0.125 m^3/s and 0.470 to 0.759 respectively. Mean value computed from ten events for initial base flow (Q_o), threshold flow (Q_t), and recession constant (R_c) parameters are 0.018 m^3/s, 0.121 m^3/s, and 0.690 respectively.

Muskingum method parameter K varies from 0.028 hr to 0.456 hr which gives mean value of 0.131 hr. Parameter X varies from 0.039 to 0.500 and gives 0.205 as average value. The value of X is dimension less and generally varies from 0 to 0.5.

4.5 Model Calibration

Ten events (Event-1, Event-2, Event-3, Event-4, Event-5, Event-6, Event-7, Event-8, Event-9, and Event-10) are randomly selected for calibration of the HEC-HMS model parameters where as the remaining five events (Event-11, Event-12, Event-13, Event-14 and Event-15) were used for validation. The list of the rainfall-runoff events selected for calibration and validation presented in Table 4.2.

The observed direct surface runoff hydrographs were compared with the hydrographs computed by the model (both before optimization and after optimization trial) for the selected events used for calibration. The values of peak discharge and total outflow volume of the observed direct surface runoff hydrograph were compared with the simulated values (both before optimization and after optimization trial) for individual calibration events and are presented in Table 4.5.

The model was simulated for initial parameter values given in Table 4.3 and done parameter optimization trial for obtaining optimum parameter values. These optimized parameter values were used again for simulation. Thus there were two simulated results given in Table 4.5 i.e. first one as initial value designated in the table as before optimization and the second as optimized value designated in the table as after optimization.

The data presented in Table 4.5 reveals that peak discharge and total outflow volume simulated with optimized value are close to the observed values compared to that of before optimization. The observed peak discharge was minimum for the Event-

Table 4.5 Comparison of simulated and observed peak discharge and total outflow volume

Events	Peak Discharge (m^3/s)			Total Outflow Volume (1000 m^3)		
	Simulated		Observed	Simulated		Observed
	Before Optimi-Zation	After Optimi-Zation		Before Optimi-Zation	After Optimi-zation	
Event 1	0.063	0.067	0.069	20.090	20.610	21.130
Event 2	0.241	0.230	0.245	102.640	96.050	96.350
Event 3	0.300	0.282	0.287	95.790	88.570	87.730
Event 4	0.851	0.830	0.901	259.130	250.980	246.150
Event 5	0.142	0.145	0.130	60.340	61.620	62.220
Event 6	0.341	0.291	0.298	86.180	76.600	83.530
Event 7	0.660	0.650	0.620	210.950	206.710	202.950
Event 8	0.250	0.260	0.270	72.990	74.540	74.850
Event 9	0.590	0.560	0.540	217.930	201.210	202.190
Event 10	0.379	0.350	0.375	100.290	94.050	97.300

1 with a value 0.069 m^3/sec and for the same event the peak discharge simulated before optimization was 0.063 m^3/sec and after optimization it is 0.067 m^3/sec.

Observed peak discharge was maximum for Event-4 which is 0.901 m^3/sec. For the same event, the simulated peak discharge before optimization was 0.851m^3/sec and that of after optimization it is 0.830m^3/sec.

The observed outflow volumes and computed outflow volume for these ten events are given in Table 4.6 and these values are used to calculate the percentage change in the computed outflow volume with respect to observed outflow volume. Similarly peak discharges calculated after optimization in the runoff events also used to calculate the percent changes in it with respect to the observed once. These percentage changes in outflow volumes and the peak discharges are listed in Table 4.6.

Table 4.6 Comparison of simulated and observed peak discharge and total outflow volume with percent change

Events	**Peak Discharge (m^3/s)**			**Total Outflow Volume (1000 m^3)**		
	After Optimi - Zation	**Observed**	**Peak Discharge Changes (%)**	**After Optimi-zation**	**Observed**	**Total Volume Changes (%)**
Event 1	0.067	0.069	2.899	20.610	21.130	2.461
Event 2	0.230	0.245	6.122	96.050	96.350	0.311
Event 3	0.282	0.287	1.742	88.570	87.730	0.957
Event 4	0.830	0.901	7.880	250.980	246.150	1.962
Event 5	0.145	0.130	11.538	61.620	62.220	0.964
Event 6	0.291	0.298	2.349	76.600	83.530	8.296
Event 7	0.650	0.620	4.839	206.710	202.950	1.853
Event 8	0.260	0.270	3.704	74.540	74.850	0.414
Event 9	0.560	0.540	3.704	201.210	202.190	0.485
Event 10	0.350	0.375	6.667	94.050	97.300	3.340

4.5.1 Graphs Obtained After Calibration of Individual Events

The observed runoff hydrographs and the simulated runoff hydrographs (both before optimization trial and after optimization trial) for selected 10 events are shown in Fig. 4.1 to Fig. 4.10.

A perusal of the Fig. 4.1 to Fig. 4.10 shows that the peaks both in terms of magnitude and time to peak are best simulated by HEC-HMS model after parameter optimization for Event-1, Event-3, Event-7, Event-8, and Event-9. For the Event-2, Event-4, and Event-10 although there is a lag in time to peak, yet the discharge is simulated well and the shape of the hydrograph is symmetric with the observed hydrograph. However the calibrated results are not that encouraging for the Event-5 and Event-6. This may be due to erroneous rainfall-runoff records.

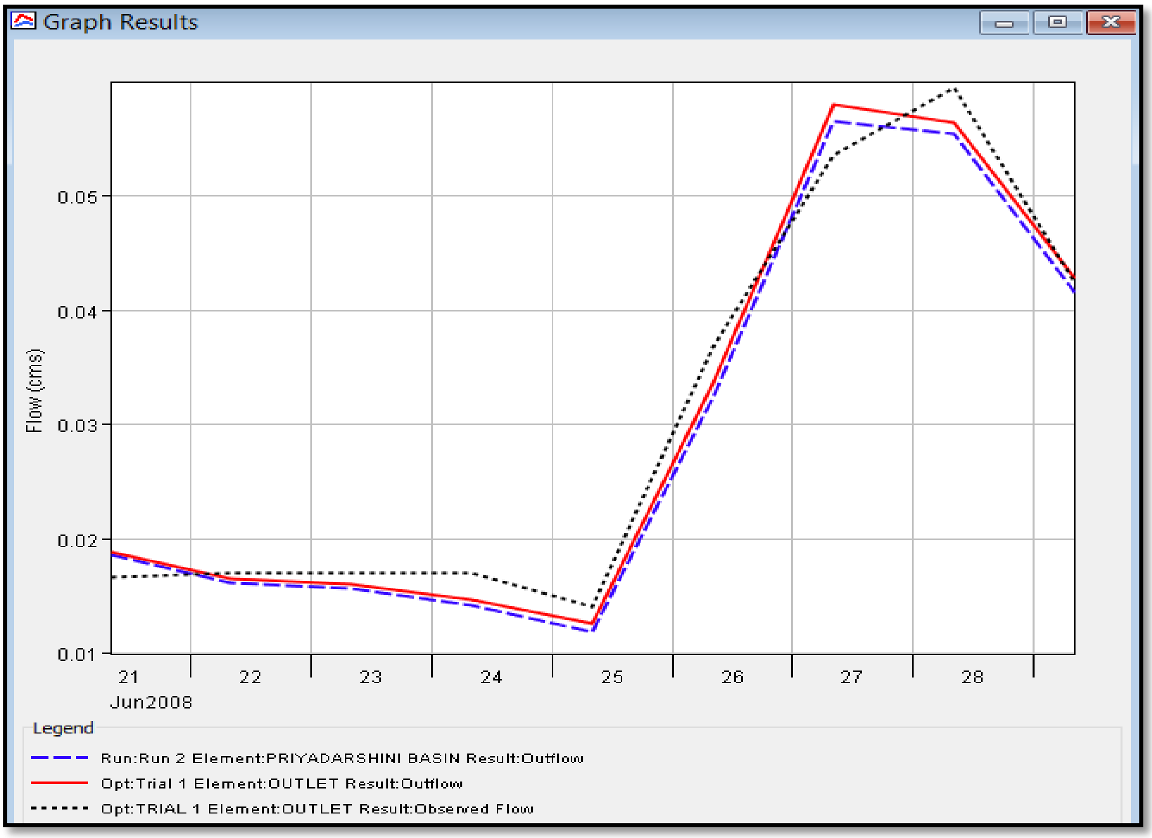


Fig. 4.1: Comparison of runoff hydrograph for Event 1

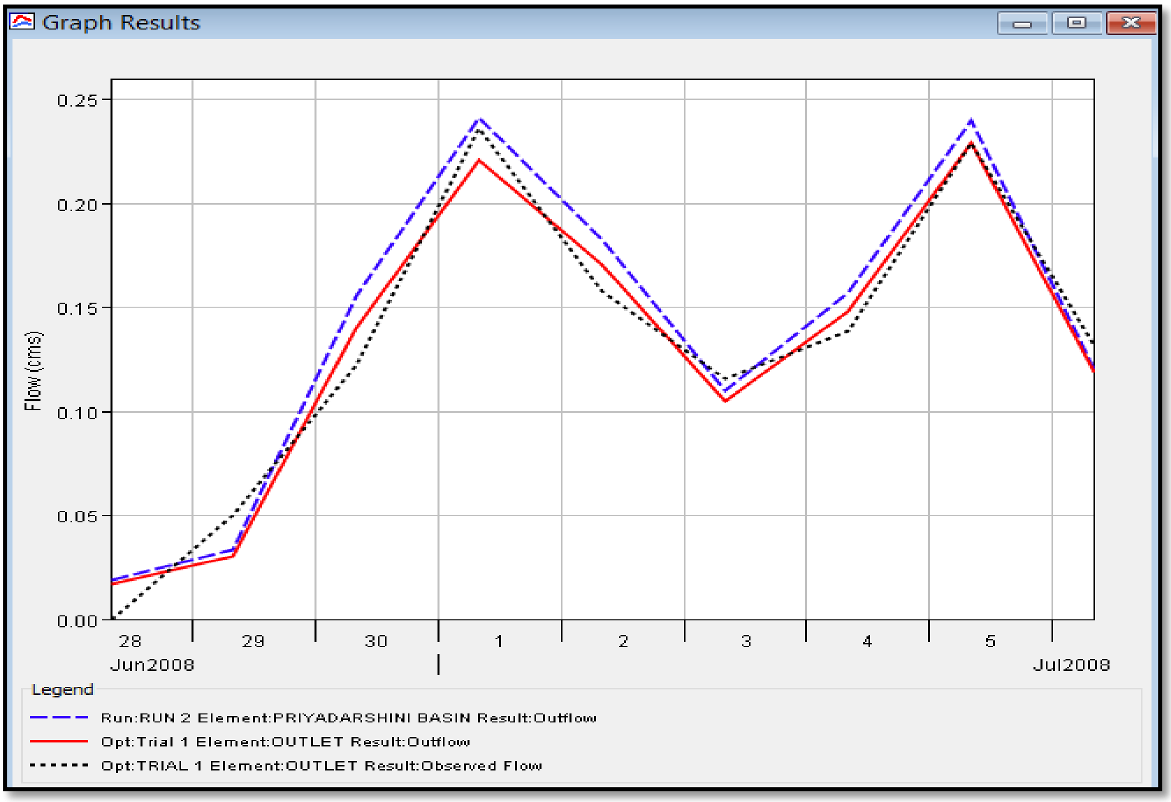


Fig. 4.2: Comparison of runoff hydrograph for Event 2

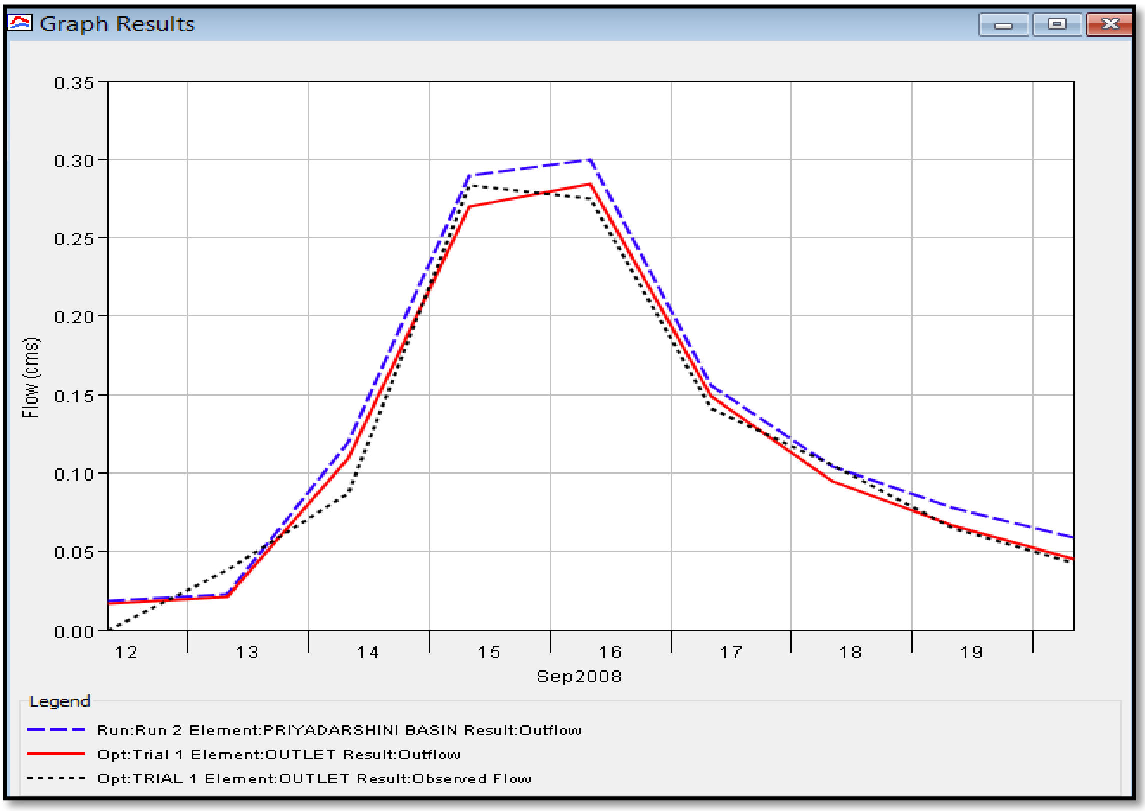


Fig. 4.3: Comparison of runoff hydrograph for Event 3

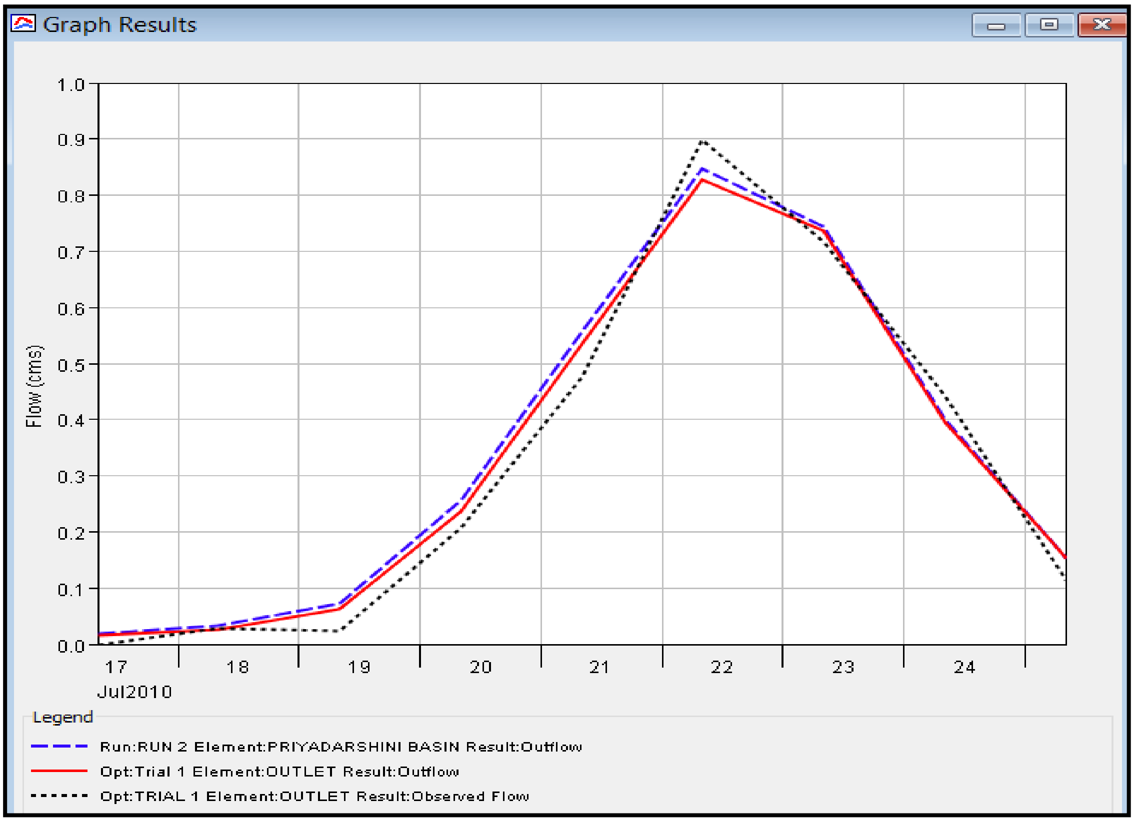


Fig. 4.4: Comparison of runoff hydrograph for Event 4

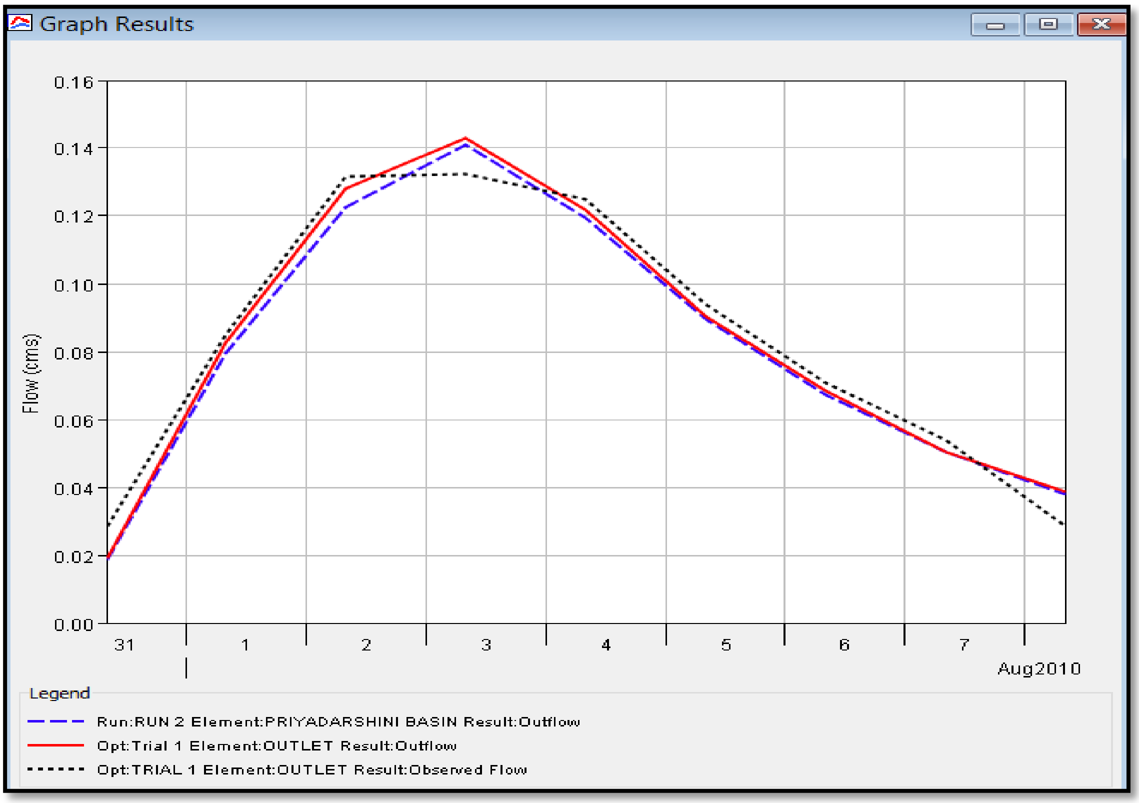


Fig. 4.5: Comparison of runoff hydrograph for Event 5

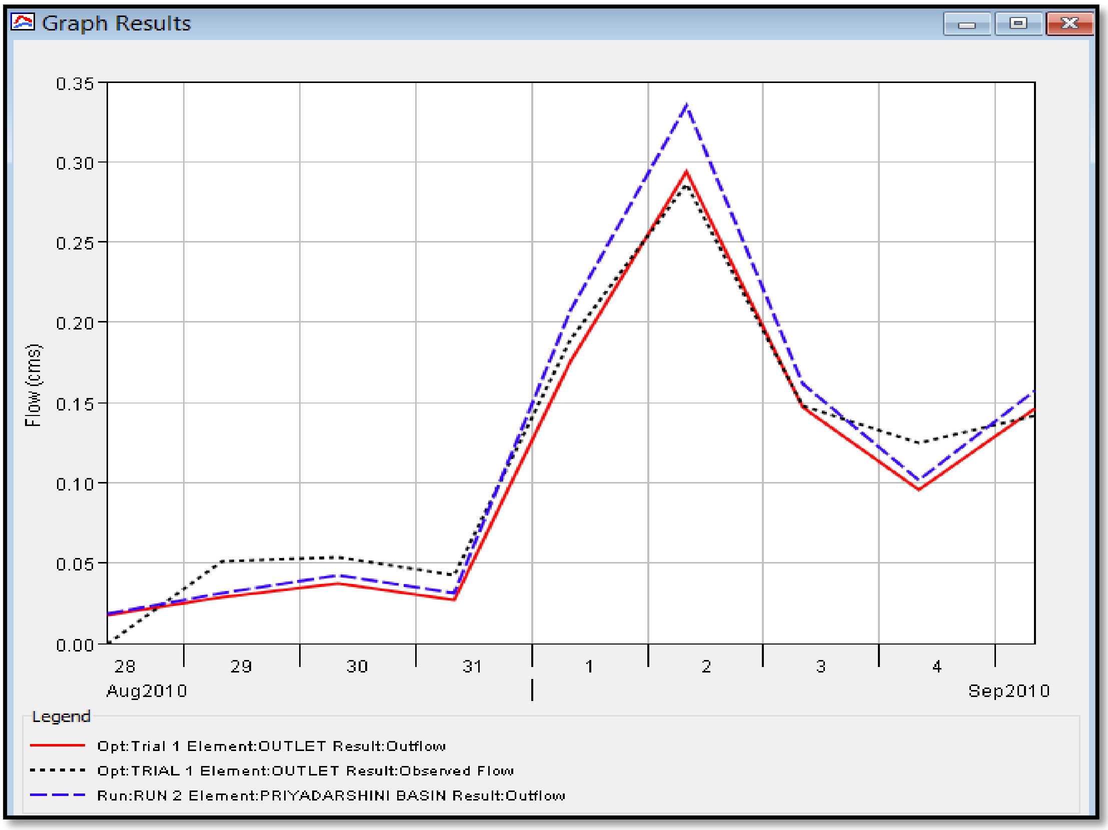


Fig. 4.6: Comparison of runoff hydrograph for Event 6

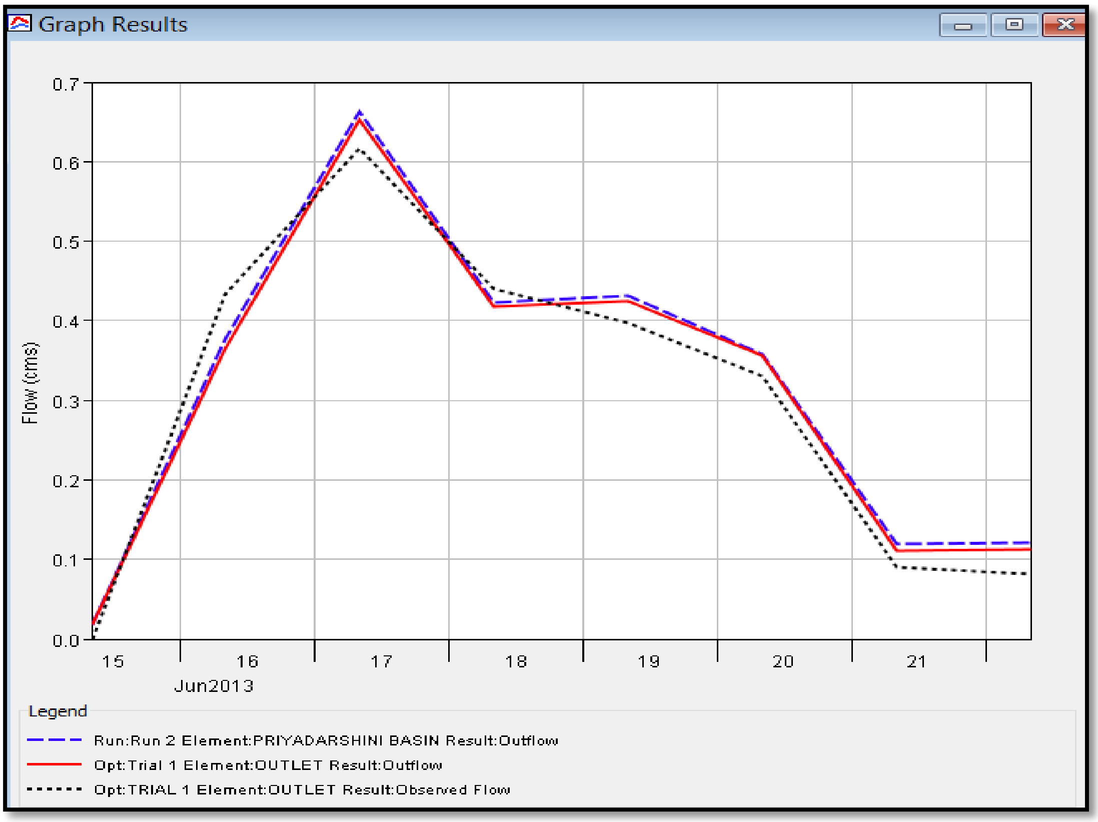


Fig. 4.7: Comparison of runoff hydrograph for Event 7

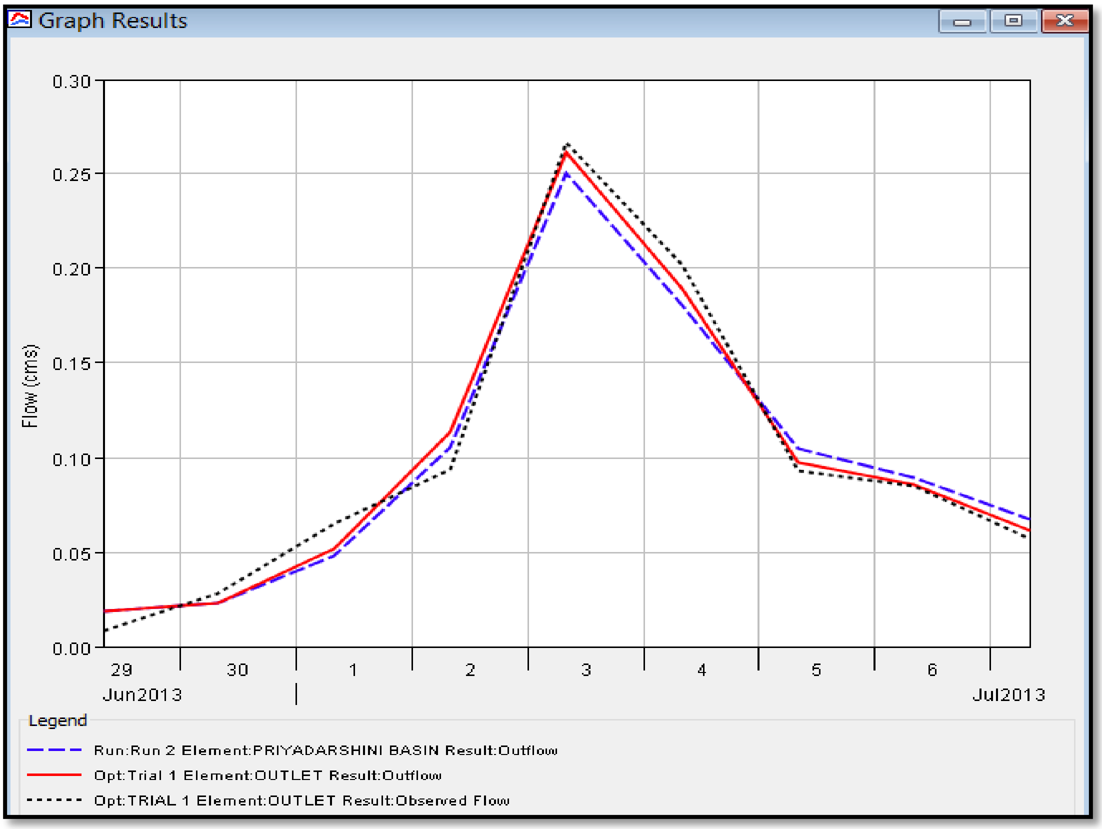


Fig. 4.8: Comparison of runoff hydrograph for Event 8

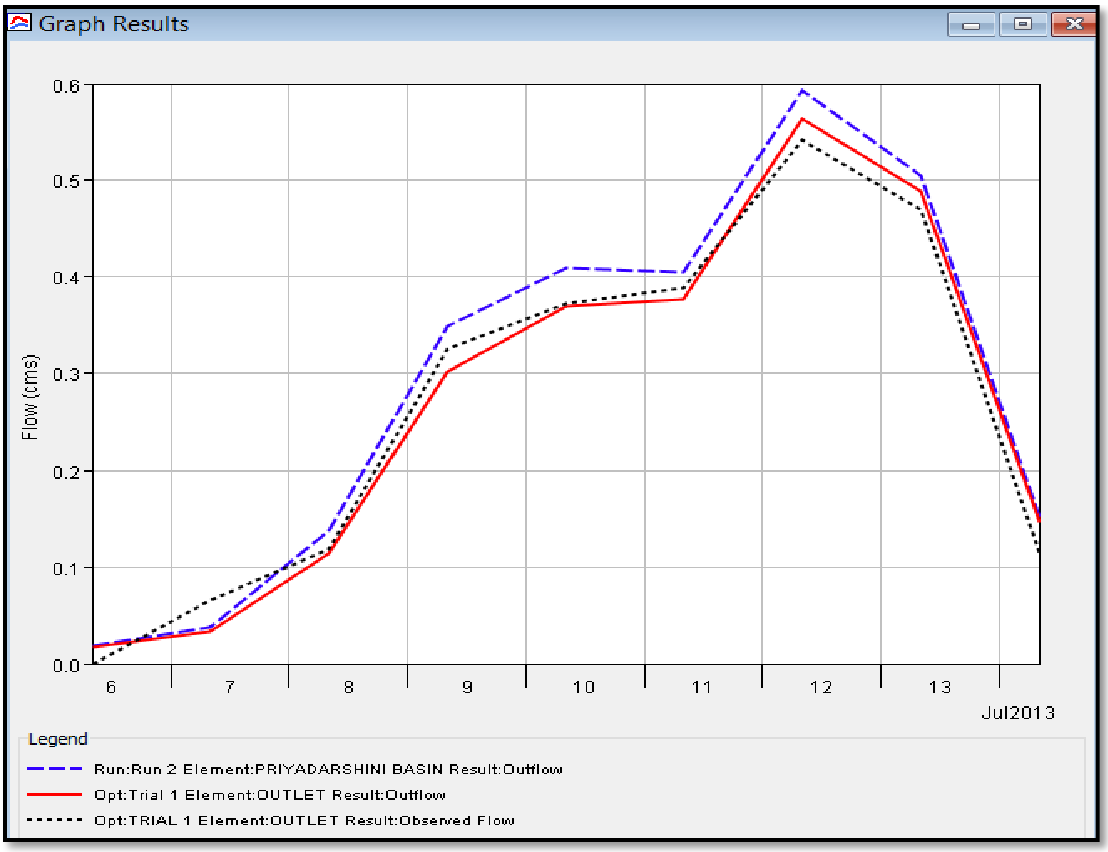


Fig. 4.9: Comparison of runoff hydrograph for Event 9

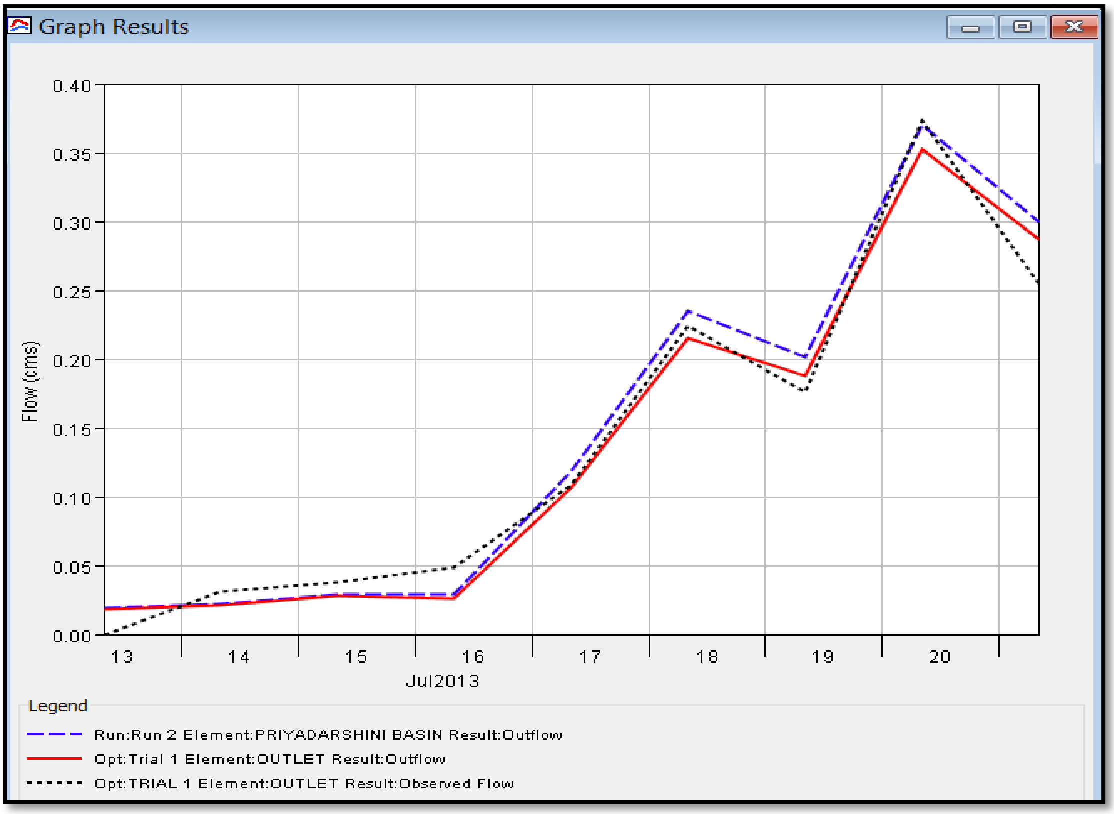


Fig. 4.10: Comparison of runoff hydrograph for Event 10

4.5.2 Error Function for Calibration Events

The error functions of calibration events were computed on the observed and computed direct surface runoff hydrographs for the calibration events as discussed in chapter 3. Values of these error function with optimized and non-optimizes values are shown in Table 4.7.

Data presented in Table 4.7 shows that value of errors for the HEC-HMS model calibration considering these 10 events Event-1, Event-2, Event-3, Event-4, Event-5, Event-6, Event-7, Event-8, Event-9, and Event-10 gives good results. The values of sum of absolute errors (SAE), Sum of squared residuals (SSR), percentage errors in peak (PEP), Peak-weighted root mean square errors (PWRMSE), and RMSE are minimum for Event-1, Event-2, Event-3, Event-4, Event-6, Event-8 and Event-9 shows the best result for comparison of direct surface runoff hydrograph and computed hydrograph. As stated earlier error percentage is higher for Event-5, Event-7, and Event-10. Event-5 shows the highest percentage error in peak i.e. 11.538 %. However the overall result of the calibration parameters is quite satisfactory for the other events.

Table 4.7: Error function computed for calibration events

Event	Sum of Absolute Errors (SAE)	Sum of Squared Residuals (SSR)	Percentage Error in Peak (PEP)	Peak-Weighted Root Mean Square Error (PWRMSE)	RMSE	R^2 Value
Event 1	0.008	0.0003	02.899	0.008	0.007	0.888
Event 2	0.024	0.0018	06.122	0.016	0.016	0.939
Event 3	0.010	0.0013	01.742	0.013	0.014	0.978
Event 4	0.041	0.0130	07.880	0.059	0.043	0.984
Event 5	0.013	0.0001	11.538	0.005	0.005	0.983
Event 6	0.073	0.0012	02.349	0.012	0.013	0.995
Event 7	0.050	0.0075	04.839	0.036	0.033	0.968
Event 8	0.010	0.0013	03.704	0.014	0.014	0.970
Event 9	0.051	0.0035	03.704	0.022	0.022	0.994
Event 10	0.053	0.0011	06.667	0.015	0.013	0.992

Computed values of error function of calibration events are within acceptable limit (near to zero) when optimization values are used. Hence the HEC-HMS model calibrated with consideration of various events and considering optimized values are suitable for use in the study area.

Table 4.8: Calibrated parameter values used for validation

Sr.No.		Parameter	Value
1	**Loss Rate Parameter**	Initial abstraction (Ia), mm	25.76
2		Curve Number (CN)	62.19
3		Impervious Area (%)	10.93
4	**Transform Parameter**	Time of Concentration, (Tc) Hr	0.261
5		Storage Coefficient, (R) Hr	0.020
6	**Base flow Parameters**	Initial discharge (Q), m^3/sec	0.018
7		Recession constant (Rc)	0.690
8		Threshold flow (Qt), m^3/sec	0.121
9	**Routing Method Constants**	Muskingum (K), Hr	0.131
10		Muskingum (X)	0.205

The final avarage values of calibrated parameter are shown in Table 4.8. All these parameter have been taken considering avareage estimated value from all selected events. The obtained values of loss rate parameter from the calibration process are I_a = 25.76 mm, CN = 62.19, Transform parameter Tc = 0.261 hr, R= 0.02, the base flow parameters, Q_o = 0.018 m^3/s, R_c = 0.690, and Q_t = 0.121 m^3/s. The Muskingum parameters K = 0.131 hr and X = 0.205. All these calibrated values are used for the validations of the model.

4.6 Model Validation

The calibrated model parameter values i.e. time of concentration, Tc = 0.261 hr, R= 0.02, I_a = 25.76 mm, CN = 62.19, Q_o = 0.018 m^3/s, R_c = 0.690, Q_t = 0.121 m^3/s, K = 0.131 hr and X = 0.205 (shown in table 4.8) are tested for validity.

Simulated and observed total ouflow volume and peak discharge are shown in Table 4.9.

Table 4.9: Comparison of Simulated and Observed Total Outflow Volume and Peak Discharge

Events	Peak Discharge (m^3/s)		Peak Discharge Changes (%)	Total Outflow Volume (1000 m^3)		Outflow Volume Changes (%)
	Simulated	Observed		Simulated	Observed	
Event 11	0.190	0.20	5.000	82.083	83.43	1.615
Event 12	0.521	0.50	4.200	227.46	221.59	2.649
Event 13	0.573	0.55	4.182	169.70	172.38	1.555
Event 14	0.138	0.14	1.429	55.19	54.76	0.785
Event 15	0.488	0.47	3.830	173.74	172.29	0.842

The maximum peak dischagarge and volume of runoff occurred from event 13 i.e. 0.573 m^3/s, 227.46 (1000 m^3) respectively, and mimmum from event 14 i.e. 0.138 m^3/s and 173.74 (1000 m^3) respectively.

4.6.1 Graphs Obtained After Simulation of Individual Validation Events

For validation of the model the ramaining five floodevents (Event-11, Event-12, Event-13, Event-14 and Event-15) are used. Computed and observed hydrographs for five events selected for validation are presented in Fig. 4.11 to Fig. 4.15.

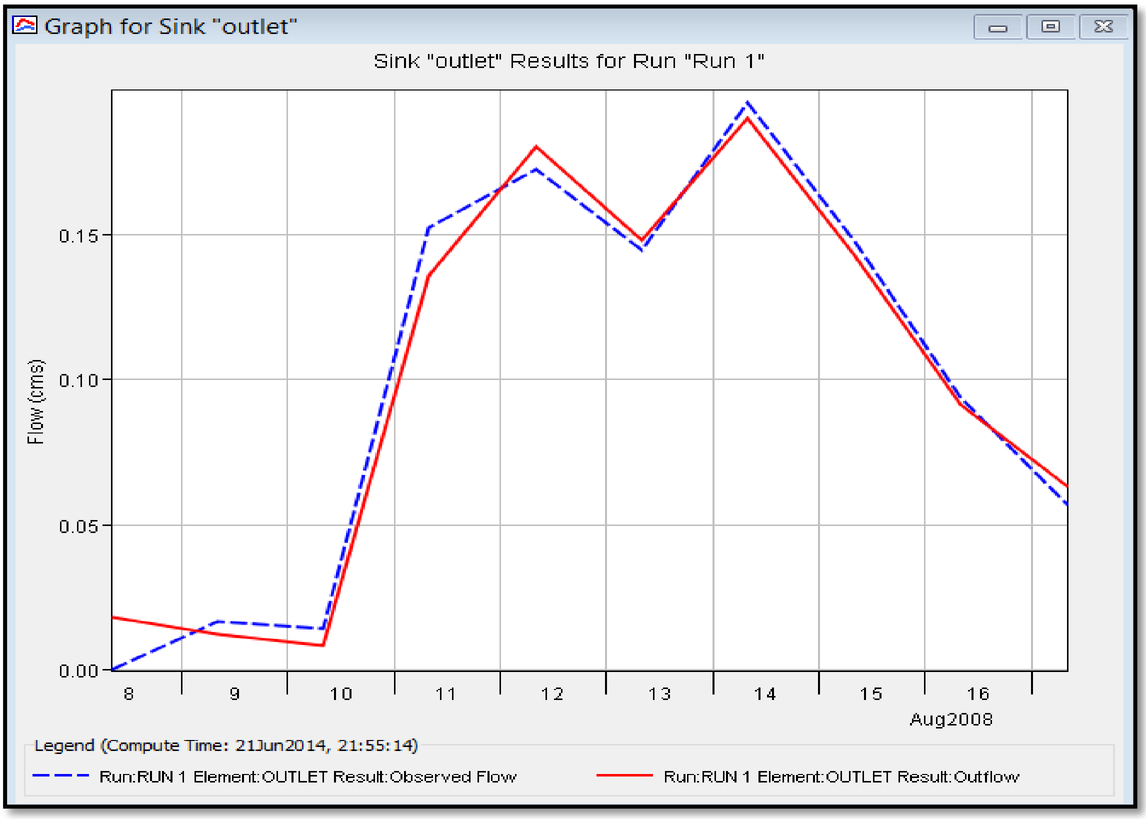


Fig. 4.11: Comparison of validated runoff hydrograph for Event 11

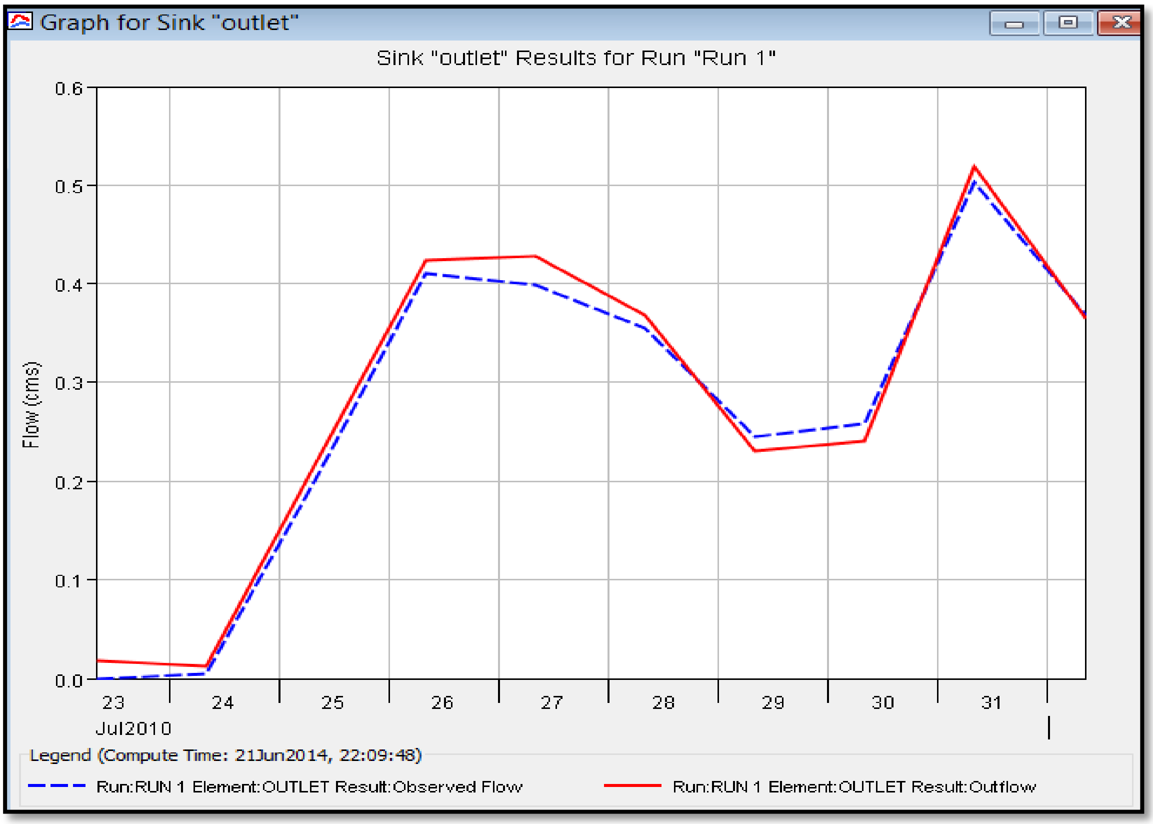


Fig. 4.12: Comparison of validated runoff hydrograph for Event 12

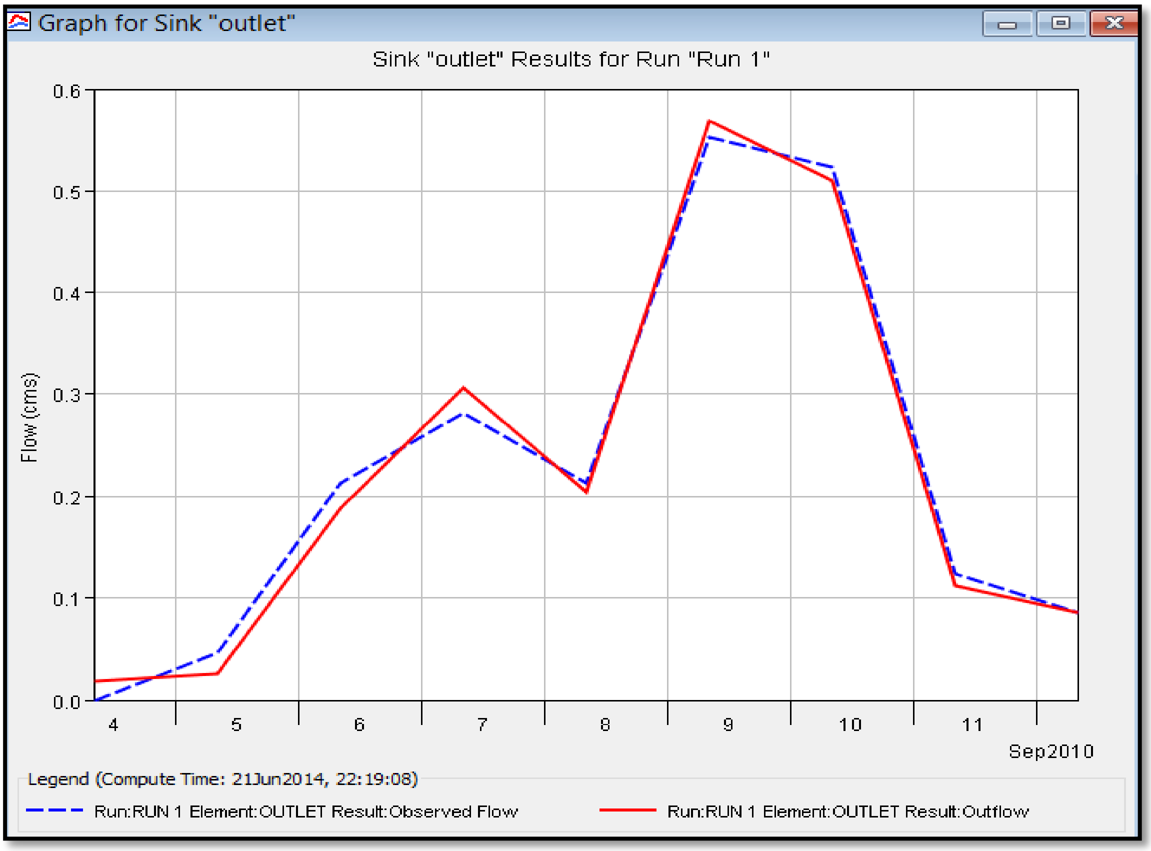


Fig. 4.13: Comparison of validated runoff hydrograph for Event 13

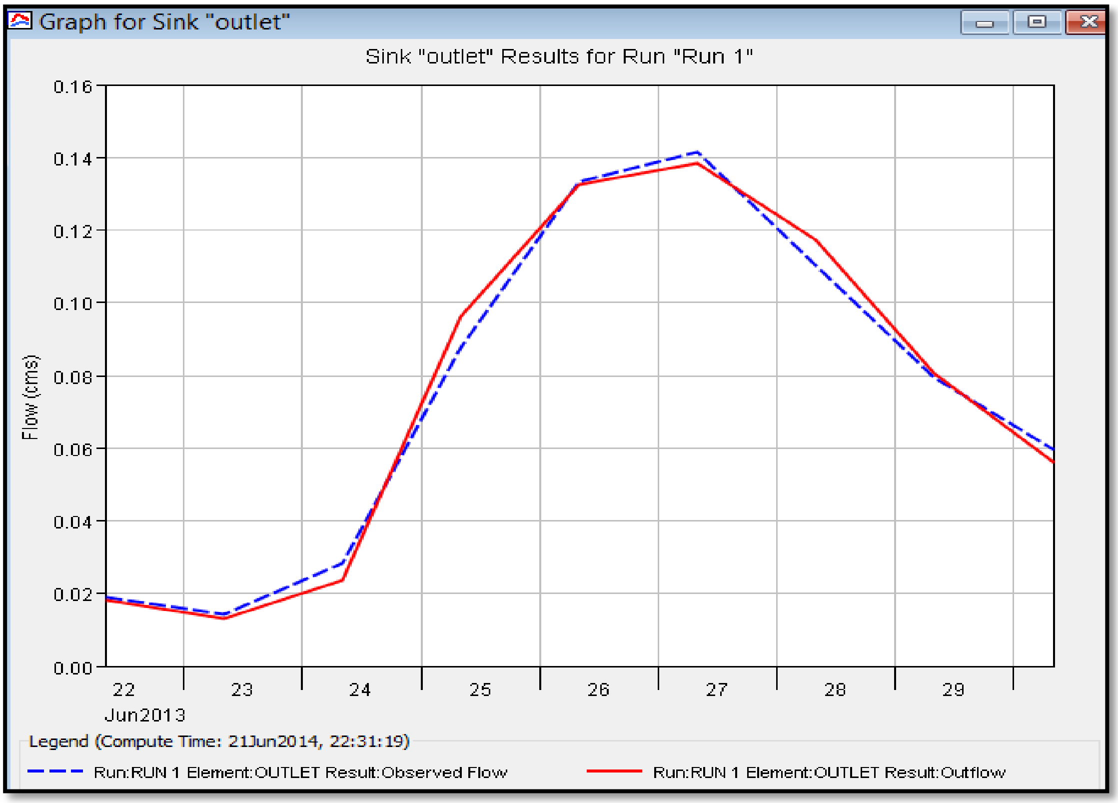


Fig. 4.14: Comparison of validated runoff hydrograph for Event 14

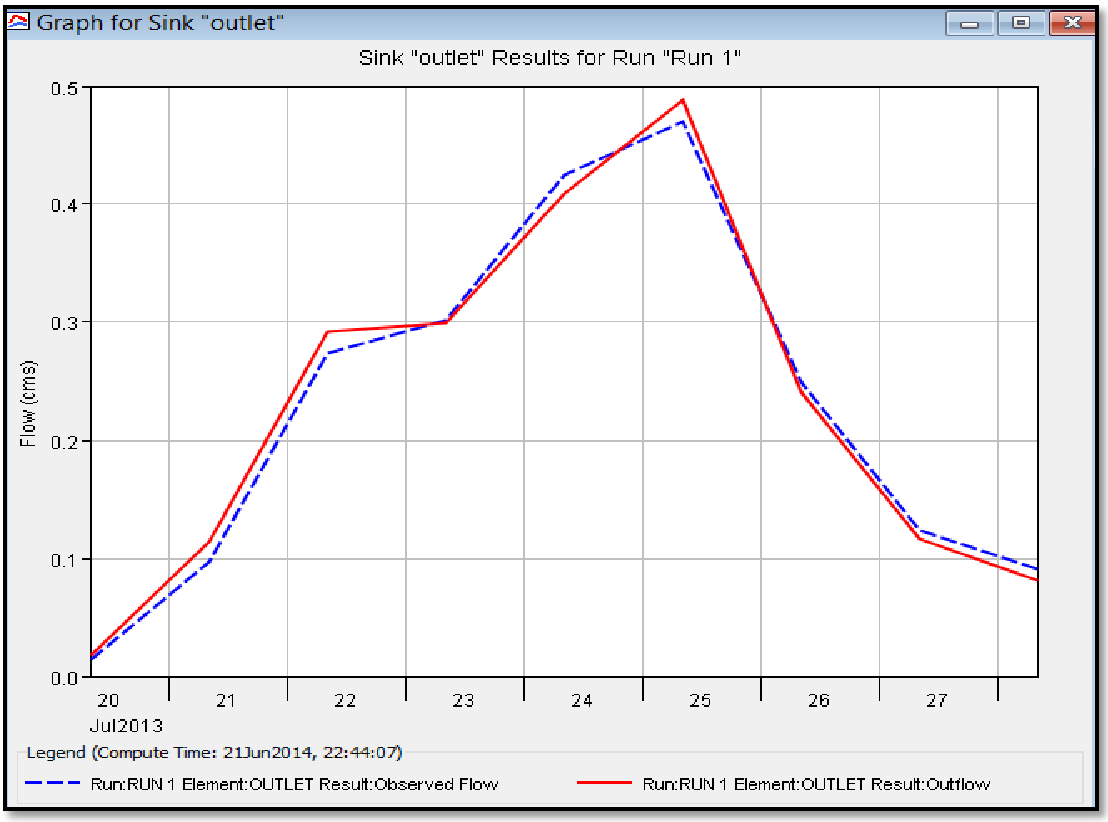


Fig. 4.15: Comparison of validated runoff hydrograph for Event 15

Figure 4.14 shows that for Event-14 , the computed hydrograph follows the trend of the observed hydrograph. The peak discharge is slightly over predicted in case of Event-11 but the time to peak coincides with the observed hydrographs.

4.6.2 Error Function for Validated Event

Error function values are computed and given in Table 4.10. Which shows the HEC-HMS model is applicable for selected watershed with error function approching to thre zero.

Table 4.10: Error function computed for direct surface runoff hydrographs estimated by HEC-HMS for validation events

Event	Sum of Absolute Errors (SAE)	Sum of Squared Residuals (SSR)	Percentage Error in Peak (PEP)	Peak-Weighted Root Mean Square Error (PWRMSE)	RMSE	R^2 Value
Event 11	0.0240	0.0005	5.0000	0.0089	0.0081	0.983
Event 12	0.0540	0.0022	4.2000	0.0182	0.0179	0.984
Event 13	0.0410	0.0024	4.1818	0.0194	0.0186	0.993
Event 14	0.0080	0.0002	1.4286	0.0051	0.0046	0.991
Event 15	0.0200	0.0014	3.8298	0.0147	0.0139	0.988

Thus from the analysis of data, computation and calibration it is observed that the model performs well for study area. Hence, the model parameter values optimized in this study can be confudently for studing the rain-fall process in the Priyadarshini watershed.

V. SUMMARY AND CONCLUSIONS

Flood is a natural demolishing phenomenon, forecast of which is of high importance. Estimation of rainfall-runoff and flood is a difficult task due to influence of different factors. So estimation of surface runoff in a watershed based on the rate of received precipitation and quantifying discharge at outlet is important in hydrologic studies. Improper estimation of runoff in basins causes some problems in optimum management of water resources and reservoir dams. Therefore, simulation of rainfall-runoff is a proper solution for runoff estimation.

Considering all these facts, the present study was carried out, HEC-HMS hydrological model version 3.5 was used to simulate rainfall-runoff process in Priyadarshini watershed located in CAET campus of Dr B.S.K.K.V. Dapoli, which is located at $17^0$45'N and $73^0$20'E. The total area of watershed is 50.29 ha. First task performed during this study was delineation of watershed and calculation of catchment characteristics.

HEC-HMS is used for the simulation of stream flow from the Priyadarshini watershed. Fifteen rainfall-runoff events are selected for this study. Out of these ten was selected for the calibration and the rest of five events were selected for validation. The total surface runoff hydrographs were computed for these rainfall-runoff events using Clark's unit hydrograph model which were compared with the observed hydrographs. The surface runoff hydrographs thus computed using the Clark's UH and SCS curve number model were compared employing error functions viz. sum of absolute errors, sum of squared residuals, percentage error in peak, peak weighted root mean square error, root mean square error, percentage change in peak discharge and percentage change in outflow volume.

Rainfall-runoff simulation has been conducted using fifteen rainstorm events. Initial results showed that there is clear difference between observed and simulated peak flows. Therefore model calibration with optimization method and sensitivity analysis has been undertaken. Model validation using optimized parameter values showed reasonable difference in peak discharge and outflow volume. Finally it can be concluded that model can be used with reasonable approximation in hydrologic simulation in Priyadarshini watershed.

The salient conclusions drawn from the present study are as follows:

- The Clark's model parameters time of concentration (Tc) and storage coefficient (R) are calibrated as Tc = 0.261 hr and R = 0.020 respectively for Priyadarshini watershed. The validation results obtained showed that the Clark's UH model of HEC-HMS performs well for study area.
- The loss rate parameters i.e. curve number (CN) and initial abstraction (Ia) are calibrated using SCS curve number model and the values obtained are 62.19 and 27.76 respectively.
- The base flow parameters that is recession constant, initial discharge (Q) and threshold flow (Qt) in exponential recession model was calibrated as Rc=0.690, Q = 0.018 m^3/sec, and Qt = 0.121 m^3/sec respectively.
- Comparison of the computed peak discharge and outflow volume using Clark's UH model, SCS curve number model, Exponential recession model and Muskingum model shows that in spite of limited data availability, the HEC-HMS model prove to be good for runoff estimation.

VI. BIBLIOGRAPHY

Abed, N. A., Abdulla, F. and A. A. Khayarah. (2005). GIS-hydrologic models for managing water resources in the Zarqa river basin. Environmental Geology. 47, 405-411.

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E. and J. Ramsmussen. (1986). An Introduction to the European Hydrological System- Systeme Hydrologique Europeen," SHE",1: History and Philosophy of a physically based, distributed modeling system. Journal of Hydrology, Vol. 87 (1) : 45.

Anderson, M. L., Chen, Z. Q., Kavvas, M. L. and A. Feldman. (2002). Coupling HEC-HMS with atmospheric models for prediction of watershed runoff. Journal of Hydrologic Engineering, ASCE, Vol.7 (4) : 312-318.

Arekhi, S. (2012). Runoff modeling by HEC-HMS Model (case study: Kan watershed, Iran). International Journal of Agri. and Crop Sciences. 4(23): 1807-1811.

Bennett, T., Donner, P. E., Eggers, D. and K. Puhn. (2003). Challenges of Developing a Rain-on-Snow Grid –Based hydrologic model with HEC-HMS for the Willow Creek Watershed, Oregon.Proc. of World Water and Environmental Resources Congress-2003.

Bhatt, A., Yadav, H. L., and D. Kumar. (2012) Estimation of infiltration parameter of Tehri Garhwal Catchment. Int. Journal of Engg. Res. and Tech. IJERT. Vol. 1(7).

Chatterjee, C., Kumar, S., Jain, S. K., Lohani, A. K., and R. D. Singh. (2001). Intercomparison of Responses of HEC-1 package and Nash model. Hydrology Journal, 24(3) : 13-24.

Chow, V. T., D. K. Maidment and L. W. Mays. (1988). Applied Hydrology. McGraw-Hill Book Company, New York, USA. Edition-1.

Chow, V. T., D. K. Maidment and L. W. Mays. (2002). Applied Hydrology. McGraw-Hill Book Company, New York, USA. Edition-2.

Chu, X. and A.Steinman. (2009). Event and continuous hydrologic modeling with HEC-HMS.J. Irrig. And Drain. Engg. Vol. 135 (1): 119-124

Clark, C. O. (1945). Storage and the unit hydrograph. Trans. Am. Soc. Civ. Eng., 110(2261):1419-1446

Clarke, J. I. (1966). Morphometry from maps. Essays in geomorphology. Elsevier Publications, New York, 235-274.

Clay, H. E., Claire, W. and R. G. Travere. (2005). Watershed scale evaluation of a system of storm water detention basin. Journal of Hydrologic Engineering. 3, 237-242.

Daniel, K. W. and A. D. Feldman. (1998). Evoluation of Clark's unit graph method to spatially distributed runoff. Juornal of Hydrologic Engineering. 3, 9-19.

Dooge, J. C. I. (1959). "A general theory of the unit hydrograph." Journal of Geophysical Research , 64(2):241-256.

Du, J., L. Qian, H. Rui, T. Zuo, D. Zheng, Y. Xu, and Xu, C.-Y. (2012). Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Quihuai River basin, China. Journal of Hydrology. 464-465.

Feldman, A.D. (2000). Hydrologic Modelling System HEC-HMS Technical Reference Maual.U.S. Army Corps of Engineers Hydrologic Engineering Center's, Davis, CA.

Halwatura, D. and M. M. M. Najim. (2013). Application of the HEC_HMS model for runoff simulation in a tropical catchment. Journal of Environmental Modeling and Software. Vol 46 : 155-162.

Hammouri, N. and A. E. Naqa. (2007). Hydrological modeling of unguaged wadis in arid environments using GIS. Revista Mexicana de Geologicas. Vol. 24(2). pp. 185-196.

Horton, R. E. (1945). Erosion development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bulletin of The Geological Society of America. 56:275-370.

Hu, H. H., Kreymborg, L. R., Doeing, B. J., baron, K. S. and S. A. Jutila. (2006). Gridded Snowmelt and Rainfall-Runoff CWMS Hydrologic Modeling of the Red River of the North Basin. Journal of Hydrological Engineering. Vol 11 (2): 91-100.

Jain, M.K. and K. S. Ramshastri. (1990). Application of HEC-1 to Hemavati river basin upto Sakleshpur. NIH Report No.CS-55.

James, V. and P. E. Bonta, (1997). Determination of watershed curve number using derived distributions. Journal of Irrigation and Drainage Engineering. 128:28-36.

Knebl, M. R., Yang, Z-L., Hutchison, K. and D. R. Maidment. (2005). Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS- A case study for the San Antorio River Basin Summer 2002 Storm event. J. of Environ. Manag. 75 pp: 325-336.

Kumar, D. and R. K. Bhattacharjya.(2011). Distributed rainfall runoff modelling. International journal of Earth Science and Engineering. Vol 04. No. 06. pp. 270-275.

Linsley, R. K. and C. H. Crawford.(1960). Computing of a synthetic steam flow record on a digital computer. Publication 51, International Association of Scientific Hydrology, Stanford, 526-538.

Linsley, R. K., Kohler, M. A., and J. L. H. Paulhus. (1982). Hydrology for engineers. McGraw-Hill, New York.

Majidi, A. and K. Shahedi. (2012). Simulation of rainfall-runoff process using Green-Ampt Method and HEC-HMS Model (case study: Abnama Watershed, Iran). International Journal of Hydraulic Engineering. 1(1): 5-9.

Majidi, A. and H. Vagharfard (2013). Surface runoff simulation with two methods using HEC-HMS model. Current Advantages in Environmental Science. Vol. 1(1). pp: 7-11.

McColl, C. and G. Aggett. (2006). Land use forecasting and hydrologic model intregation for improved land use decision support. Journal of Environmental Management, 84(4), 494-512.

Miller, V.C. (1953). A quantitative geomorphologic study of drainage basin characteristics in The Clinch mountain area, Virginia and Tennessee, Proj. NR 389-402, Tech Rep 3, Columbia University Department of Geology, ONR New York.

Moore, R. J. (1985). The probability- distributed principle and runoff production at point and basin scales. Hydrol. Sci. J., 30, 273-297.

Nash, J. E. (1957). "The form of instantaneous unit hydrograph." International association of Science Hydrology Publication. 45(3):114-121.

O'Kelly, J.J. (1955). "The employment of unit hydrograph to determine the flows of Irrish arterial drainage channels." Proceedings of the institution of Civil Engineers. 4(3): 365-412, Dublin, Ireland.

Parag, S. (2008). Rainfall-runoff modeling using HEC-HMS model. Unpublished B.Tech. thesis submitted to Deptt. of Irrig. and Drain. Engg., MPKV., Rahuri.

Paudel, M., Nelson, E. J. and W. Scharffenberg. (2009). Comparison of Lumped and Quasi-Distributed Clark Runoff Models Using the SCS curve Number Equation. Journal of Hydrological Engineering, Vol. 14(10):1098-1106.

Perrone, J. and C. A. Madramootoo. (1998). Improved curve number selection for runoff prediction Canadian Journal of Civil Engineering, 25: 728–734.

Putty, M. R. Y. and R. Prasad. (2000). Understanding runoff processes using a watershed model: A case study in the Western Ghats in South India. Journal of Hydrology. Vol.228: 215-227.

Sardoii, E. R., Rostami, N., Sigaroudi, S. K., and S. Taheri. (2012). Calibration of loss estimation methods in HEC-HMS for simulation of surface runoff. Journal of Advances in Environmental Biology. 6(1): 343-348.

Schumm, A. (1964). A quantitative geomorphologic study of drainage basin characteristics and channel network characteristics. In handbook of Applied hydrology, edited by V. T. Chow, McGraw Hill, New York.

Singh, R. D. and S. M. Seth. (1984). Comparison of Unit Hydrograph, CS 7, Technical Report, National Institute of Hydrlogy.

Singh, V.P. (1992). Elementary Hydrology. Prentice-Hall of India Private Limited, New Delhi, India, 474 – 482.

Singh, V. P. (1995). Computer models of watershed hydrology, Water Resource Pub., P.O.B. 260026, Highland Ranch, Litton, Colorado, 1-22.80126-0026, USA.

Soil Conservation Service (1964). National Engineering Handbook, Section 4, Hydrology. Department of Agriculture, Washington, 450.

Soil Conservation Service (1972). National Engineering Handbook, Section 4, Hydrology. Department of Agriculture, Washington, 762.

Srinivas, B., Singh, R. and A. K. Lohani. (1999). Optimization of Clark's hydrograph and loss rate parameters using HEC-1, Unpublished M.Tech. thesis. IIT Karagpur.

Strahler, A. N. (1964). Quantitative geomorphology of drainage basins and channel networks. Section 4-11: In handbook of Applied hydrology, McGraw Hill, New York.

Subramanya, K. (2008). Engineering Hydrology. Tata McGraw-Hill Publishing Company Limited, New Delhi, India.

Suresh, R. (1996). Soil and Water Conservation Engineering. Standard Publisher Distribution.

USACE-HEC (2006). Hydrologic Modelling System, HEC-HMS (3.0.1). User's Manual, U. S. Army Corps of Engrs.Hydrol.Engg. Center (HEC), Davis, USA.

USACE-HEC (2006). Hydrologic Modelling System, HEC-HMS (3.0.1). Technical reference manual (2006). Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA.

USACE-HEC (2010).Hydrologic Modelling System, HEC-HMS (3.0.1). User's Manual, U. S. Army Corps of Engrs.Hydrol.Engg. Center (HEC), Davis, USA.

USACE-HEC (2010).Hydrologic Modelling System, HEC-HMS (3.0.1). Technical reference manual (2010). Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA.

Veeranna, B., Muralikrishna, I.V., Bhavani, N. L. and E. G. Rajan. (2004). Investigation of Rainfall-Runoff modeling of the Ashti catchment by SCS Curve Number using Remote sensing and GIS.

Verma, A. K., madan, K. J. and R. K. Mahana. (2010). Evaluation of HEC-HMS and WEPP for simulating watershed runoff using remote sensing and geographical information system. Paddy and Water Environment, 8(2): 131-144.

Yener, M. K. (2006). Semi distributed Hydrologic Modeling Studies in Yuvacik Basin, Unpublished M.Sc. Thesis, Civil Engineering Department, Middle East Technical University, September, 2006.

Yener, M. K., Sorman, A. U., Sorman A. A., Sensoy, A. and T. Gezgin. (2008). Modeling studies with HEC-HMS and runoff scenarios in Yuvacik basin, Turkiye. International Congress on River Basin Management. pp. 621-634.

Zoch, R.T. (1934). “On the relation between rainfall and stream flow (part-1)”. Monthly Weather Review. 62(9) : 315-322.

VII. APPENDICES

APPENDIX I (A)

Selection of Hydrological Soil Group

On the basis of following information, the hydrological soil group ‘B’ was selected for the Priyadarshini watershed.

Information about the soils of given watershed:

1.	Type	: Lateritic
2.	Colour	: Reddish brown to grayish black
3.	Texture	: Sandy clay loam
4.	Depth	: Very shallow to medium (7.5 to 45.0 cms)
5.	Infiltration Rate	: 6 to 6.5 cm/hr
6.	Drainage	: Well
7.	Hydrologic Soil Group	: B

APPENDIX I (B)

CNs for given hydrologic soil cover complex

Sr. No.	Land use / Plant Cover	Area	Poor Hydrologic condition	Good Hydrologic Condition
1.	Agriculture Area	3.30	81	78
2.	Buildings + Roads	5.50	74	74
3.	Cashew Plantation	2.30	66	55
4.	Mango Plantation	3.25	73	58
5.	Kokum + Mango	2.50	73	58
6.	Roads	0.29	98	98
7.	Other	33.06	61	61
	Total Area	50.29		

APPENDIX I (C)

Determination of weighted CN for poor as well as good hydrologic conditions

CNp = Weighted CN for poor hydrologic condition

CNg= Weighted CN for good hydrologic condition

$$CNp = \frac{(CNp1 \times A1) + (CNp2 \times A2) + ... + (CNp7 \times A7)}{A1 + A2 + ...An}$$

$$= \frac{(81 \text{ x } 3.3) + (74 \text{ x } 5.5) + (73 \text{ x } 3.25) + (73 \text{ x } 2.5) + (98 \text{ x } 0.29) + (61 \text{ x } 33.06)}{50.29}$$

= 65.43

$$CNg = \frac{(CNg1 \times A1) + (CNg2 \times A2) + ... + (CNg7 \times A7)}{A1 + A2 + ...An}$$

$$= \frac{(78 \text{ x } 3.3) + (74 \text{ x } 5.5) + (55 \text{ x } 3.25) + (58 \text{ x } 2.5) + (98 \text{ x } 0.29) + (61 \text{ x } 33.06)}{50.29}$$

= 63.024

APPENDIX I (D)

Determination of CN for corresponding values of AMC I and AMC II

Hydrologic Condition	AMC I	AMC II	AMC III
Poor	47.76	65.43	79.17
Good	42.22	63.02	81.93

Event	AMC Condition	Poor Hydrologic Condition	Good Hydrologic Condition
Event 1	AMC I	47.76	42.22
Event 2	AMC III	79.17	81.93
Event 3	AMC III	79.17	81.93
Event 4	AMC III	79.17	81.93
Event 5	AMC I	47.76	42.22
Event 6	AMC III	79.17	81.93
Event 7	AMC III	79.17	81.93
Event 8	AMC III	79.17	81.93
Event 9	AMC III	79.17	81.93
Event 10	AMC I	47.76	42.22
Geometric Mean		**68.03177**	**67.15302**

APPENDIX I (E)

Transformation of weighted CN value to corresponding maximum potential retention (S) and initial abstraction

The curve number were transformed to corresponding maximum potential retention using following expression suggested by SCS (1972)

$$S = \frac{25{,}400}{CN} - 254$$

$$= \frac{25400}{67.15} - 254$$

S = 124.25 mm

Initial Abstraction = 0.2 S

= 0.2 x 124.25

Ia = 24.85 mm

APPENDIX II

Calculation of time of concentration (Tc)

$$Tc = 0.01947\ L^{0.77}\ S^{-0.385}$$

Where,

L = Main channel length (m),

S = Average slope of the channel reach, m/m

T_c = Time of concentration (min).

$$Tc = 0.02\ L^{0.77}\ S^{-0.385}$$

$$= 0.02 \times 1120^{0.77} \times 0.004^{-0.385}$$

$$= 16.072 \text{ min}$$

Tc = 0.2611 hr

APPENDIX III

Calculation of Muskingum parameters X and X

ne rs)	**Inflow**	**C_0I_2**	**C_1I_1**	**C_2O_1**	**Outflow**	$\frac{I_1+I_2}{2}$	$\frac{O_1+O_2}{2}$	**Storage**	**X=0.20**			**X=0.**	
									xI	**(1-x)O**	**xI+ (1-x)O**	**xI**	**(1-x)O**
	1.096	-	-	-	1.096				0.225	0.871	1.096	0.329	0.767
	0.597	0.589	1.087	-1.07	0.604	0.846	0.85	-0.004	0.122	0.480	0.603	0.179	0.423
	0.597	0.589	0.592	-0.59	0.59	0.597	0.597	-0.004	0.122	0.469	0.591	0.179	0.413
	0.597	0.589	0.592	-0.57	0.604	0.597	0.597	-0.004	0.122	0.480	0.603	0.179	0.423
	1.686	1.663	0.592	-0.59	1.665	1.141	1.134	0.007	0.346	1.324	1.669	0.506	1.166
	1.686	1.663	1.673	-1.62	1.708	1.686	1.686	0.006	0.346	1.358	1.703	0.506	1.196
	2.355	2.323	1.673	-1.67	2.326	2.020	2.017	0.010	0.483	1.849	2.332	0.707	1.628
	4.759	4.693	2.336	-2.27	4.754	3.557	3.54	0.017	0.976	3.779	4.755	1.428	3.328
	3.094	3.052	4.72	-4.65	3.121	3.926	3.937	0.006	0.635	2.481	3.115	0.928	2.185
	1.103	1.088	3.069	-3.05	1.104	2.098	2.112	-0.008	0.226	0.878	1.104	0.331	0.773
	1.28	1.262	1.094	-1.08	1.276	1.191	1.19	-0.006	0.263	1.014	1.277	0.384	0.893
	3.094	3.052	1.27	-1.24	3.073	2.187	2.174	0.006	0.635	2.443	3.077	0.928	2.151
	0.597	0.589	3.069	-3.00	0.653	1.845	1.863	-0.011	0.122	0.519	0.642	0.179	0.457
	1.096	1.081	0.592	-0.63	1.035	0.846	0.844	-0.009	0.225	0.823	1.048	0.329	0.725

Therefore, $k = \frac{a}{b} = \frac{0.2 \text{ x } 10^6}{1.52 \text{ x } 60 \text{ x } 60 \text{ x } 24} = 0.66$

and x = 0.2