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Research Paper

Hydrological Modelling Studies of Paravar River Basin, a Tributary of River Godavariusing HEC-HMS Model

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ABSTRACT

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing. The model is applied to the Pravara River Basin, which is a tributary of the Godavari River in the Ahmednagar district of Maharashtra (India). For the simulation of runoff, the daily precipitation data and daily observed streamflow data from 1999 to 2012 was collected and ten years of data from 1999 to 2008 was used for the calibration of the model and 4 years of data from 2009 to 2012 was used for the validation of the model. The calibration of the HEC-HMS 4.0 model for the study area is carried out by comparing the simulated daily streamflow with the observed flow at the outlet of the basin. For this particular study, the deficit and constant loss model is used to compute the losses from the watershed. Under prediction of high flows is an inherent problem seen in hydrological modeling of the basin in the present study. This is due to the lack of extreme event modeling capability of the hydrological model. The daily flows except extreme flows are better simulated. The ability of HEC–HMS to simulate the magnitude of the peaks in extreme floods in the river basin underscores the significance of the model application as a flood prediction tool. The HEC–HMS successfully reproduced low flows and thus the model is a useful tool to estimate low flows in advance based on drought forecasts.

Keywords – Hydrological Modelling, HEC model, Streamflow analysis, watershed losses, flood prediction.

INTRODUCTION

The rainfall-runoff relationship is an important issue in hydrology and a common challenge for hydrologists. In India, the impact of rainfall on runoff becomes more intensive and a reliable estimate is essential for flood management. Since the middle of the 19th century, different methods have been demonstrated by hydrologists to assess the impact of rainfall on runoff whereupon many models have attempted to describe the physical processes involved in it. The majority of these rainfall-runoff models generally fall into a black box or system theoretical models, conceptual models and physically-based models. Black box models normally contain no physically based input and output transfer functions and therefore, are considered to be purely empirical models. Conceptual rainfall-runoff models usually incorporate interconnected physical elements with simplified forms, and each element is used to represent a significant or dominant constituent hydrologic process of the rainfall-runoff transformation (Xia et al., 1997; Sanaga and Jain, 2009). Physically-based model are distributed models consists a large number of parameters as input to the model.

Hydrological models are tools used for studying hydrologic processes in a river basin for estimation of its resource. A hydrological model is the mathematical representation of the response of a catchments system to hydrologic events during the period under consideration. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is designed to simulate the complete hydrologic processes of dendritic watershed systems. HEC-HMS also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting (Fleming, 2004; Asadi and Boostani, 2013; Chatterjee et al, 2014). A supplemental analysis tool is provided for model optimization. This paper presents the results of Rainfall-Runoff modeling using HEC-HMS for Pravara River Basin, a tributary of River Godavari.

Study area and Data collection

Study area

Pravara River Basin is in the Ahmednagar district of Maharashtra (India). The area under review falls in a semi-arid tract of the Western Upland Maharashtra which is a part of the Deccan Trap Region, in India. The location of the study area is indicated in Fig.1. The total catchment area of the basin is 5800 km^2 and the location of the basin lies between 73°38'- 74°50' East and 19°02'- 19°45' North. Paravara river is the smallest of the major tributaries of the Godavari river located in Maharashtra, India. Among the 7 major tributaries, it is the only tributary that originates in the Western Ghats. Paravara river flows from west to east direction with more tributaries from northern portion. The river acquires water from two main tributaries Mahalungi and Mula on the left bank. There are also tributaries coming from other sides in the form of Nalas. Some tributaries flow from the southern side i.e., to the right bank of the Paravara River. These tributaries flow from the north to south direction and nearly in the right angle to Paravara River. Also, it is the only major tributary of Godavari to have both its source and confluence located within the Ahmednagar district.

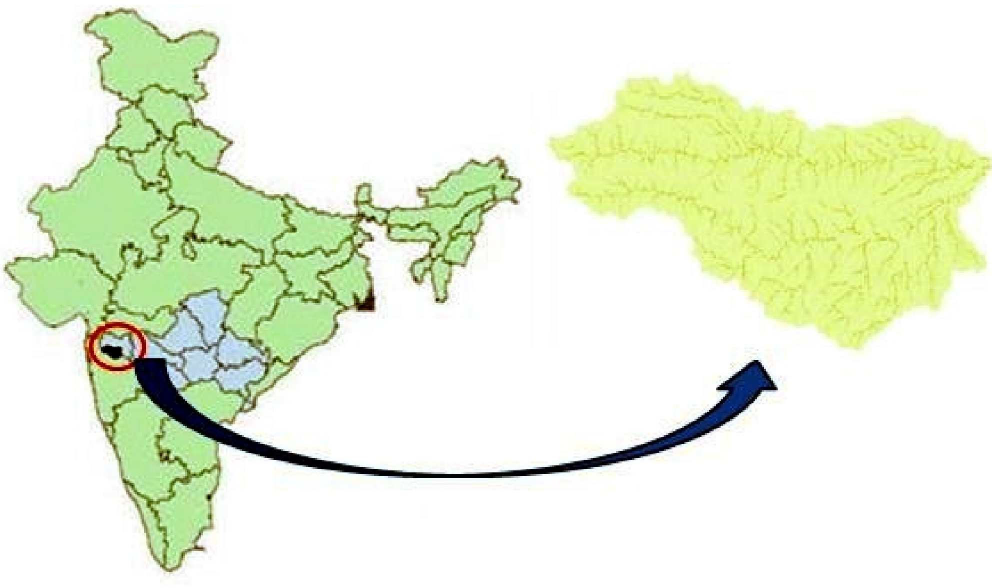

Fig. 1 Location of Paravara river basin

This region is hot in summer and generally dry during a major part of the year except during the rainy season. Rainy Season normally starts in the second week of June and continues till the end of September. October and November constitute the post-monsoon or retreating southwest monsoon season. The average annual rainfall is 501.8 mm. Though the area is near the Western Ghats and the rain is plentiful in the hilly parts of Sangamner and Rahuri it is unevenly distributed most of the time. The Winter season is from December to February. The hottest month of the year is May in which the mean maximum temperature is 39.9^{0}C (maximum - 43^{0}C or 44^{0}C) and the mean minimum temperature is about 25.4^{0}C. As the characteristic feature of semiarid climate region dryness prevails throughout the year except in the south-west monsoon season.

Data Collection and Analysis

The basic data required for the hydrologic model are rainfall information, discharge data, Digital Elevation Model (DEM), Soil types, Land use/Land-cover data of the study area and dam data. Pachegaon discharge gauging station is the outlet of the catchment which is located in the Ahmednagar district of Maharashtra. The observed streamflow data is collected from the Central Water Commission (CWC), Govt of India. Collected streamflow data at the Pachegaon gauging station is used for the comparison with the simulated stream flows. Rainfall data of six rain gauge stations falling under the catchment area are collected. Rain gauge stations present only point sampling of the areal distribution of a storm. The Thiessen polygon method is used to convert the point rainfall values at various stations into an average value over a catchment. Evapotranspiration data is downloaded from the website. Dam release data is collected from the Water Resources and Irrigation Department of Ahmednagar district, Maharashtra.

Methodology

Watershed Delineation

The first step in the study is to delineate watershed polygons using DEM tiles and several tools from the Hydrology section of the Spatial Analyst toolbox. All of the tools or functions used throughout the procedure can be found using the search function located on the ArcMap toolbar. The delineated watershed image is shown in Fig. 2.

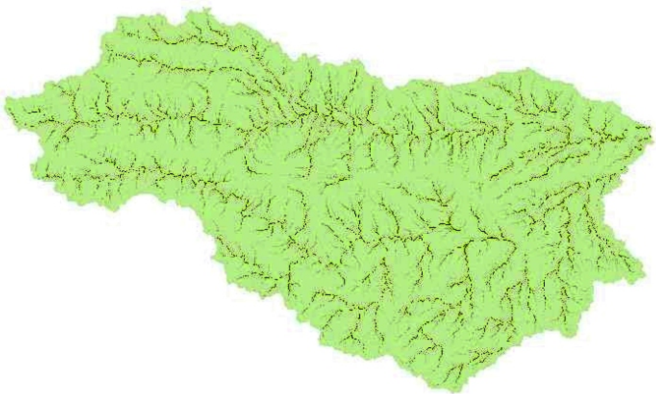

Fig. 2 Delineated watershed image of the study area

HEC-HMS Model Development

In HEC-HMS, a project is created which contains separate "models": the Basin Model, the Precipitation Model, and the Control Model. The user may specify different data sets for each model and then the hydrologic simulation is completed by using of data set for the Basin Model, the Precipitation Model, and the Control Model. The Basin Model contains the basin and routing parameters of the model, as well as connectivity data for the basin. The Precipitation Model contains the rainfall data, either historical or and the easy input of basin characteristics. The model has an extensive array of capabilities for conducting hydrologic simulation. Many of the most common methods in hydrologic engineering are included in such a way that they are easy to use. The program does the difficult work and leaves the user free to concentrate on how best to represent the watershed environment.

The physical representation of a watershed is accomplished with a basin model. Hydrologic elements are connected in a dendritic network to simulate runoff processes. Available elements are sub-basin, reach, junction, reservoir, diversion, source, and sink. Computation proceeds from upstream elements in a downstream direction. An assortment of different methods is available to simulate infiltration losses. Meteorological data analysis is performed by the meteorological model and includes shortwave radiation, precipitation, evapotranspiration, and snowmelt. Not all of these components are required for all simulations. Simple event simulations require only precipitation, while continuous simulation additionally requires evapotranspiration. The period of a simulation is controlled by control specifications. Control specifications include a starting date and time, ending date and time, and a time interval. A simulation run is created by combining a basin model, meteorological model, and control specifications. Run options include a precipitation or flow ratio, the capability to save all basin state information at a point in time, and the ability to begin a simulation run from previously saved state information. Simulation results can be viewed from the basin map. Global and element summary tables include information on peak flow, total volume, and other variables. Fig. 3 shows a screenshot of typical simulated flow using the HEC-HMS model.

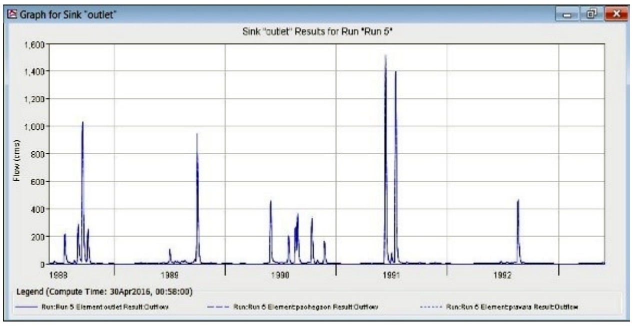

Fig. 3 Output from the HEC-HMS simulation

Most parameters for methods included in sub-basin and reach elements can be estimated automatically using optimization trials. Observed discharge must be available for at least one element before optimization can begin. Parameters at any element upstream of the observed flow location can be estimated. Seven different objective functions are available to estimate the goodness-of-fit between the computed results and observed discharge. Two different search methods can be used to minimize the objective function. Constraints can be imposed to restrict the parameter space of the search method. Analysis tools are designed to work with simulation runs to provide additional information or processing. Currently, the only tool is the depth-area analysis tool. It works with simulation runs that have a meteorological model using the frequency storm method. Given a selection of elements, the tool automatically adjusts the storm area and generates peak flows represented by the correct storm areas.

In this particular study, the deficit and constant loss model is used to compute the losses from the watershed. The deficit and constant loss model use a single soil layer to account for continuous changes in moisture content. It is a quasi-continuous model and has to be used in conjunction with a meteorological model that computes evapotranspiration (US Army Corps of Engineers, 2008). The parameters for this model include the initial deficit, maximum deficit, constant rate, and impervious percentage. To compute direct runoff from excess precipitation. The initial deficit is the initial condition for the method. It indicates the amount of water that is required to saturate the soil layer to the maximum storage and it is assumed to be zero. The maximum storage specifies the amount of water the soil layer can hold, specified as a depth and for the type of soil of this study area initially, it is estimated to be 100 to 235 mm. The constant rate defines the infiltration rate when the soil layer is saturated and for the type of soil of this study area, it is estimated to be 0.0016 to 2.1 mm per hour. The percentage of the sub-basin which is directly connected impervious area can be specified. No loss calculations are carried out on the impervious area, all precipitation on that portion of the sub-basin becomes excess precipitation and subject to surface storage and direct runoff and for the selected study area it is 8 per cent and the evapotranspiration data is also given as an input to the software that is monthly average evapotranspiration data is used for monsoon season that is 6.61, 5.30, 5.01 and 5.67 for June, July, August and September, respectively.

In this study, the SCS unit hydrograph model is used to transform the flows. The SCS unit hydrograph method was originally developed from observed data collected in small, agricultural watersheds. The data were generalized as dimensionless hydrographs and a best-approximate hydrograph was developed for general application. The general hydrograph is scaled by the time lag to produce the unit hydrograph for use. It is interesting to note that 37.5% of the runoff volume occurs before the peak flow and the time base of the hydrograph is five times the lag.

The standard lag is defined as the length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph. Studies by the SCS (Now the Natural Resources Conservation Service) found that in general the lag time can be approximated by taking 60% of the time of concentration. For the selected study area, the time of concentration is calculated using the Kirpich formula which uses travel length and slope. The travel length for the basin is 170km and the slope calculated is 0.000723. The obtained time of concentration is 3358 minutes and the basin lag is 0.6 times of time of concentration that is 2015 minutes.

Model Optimization

The optimization process begins with initial parameter estimates and adjusts them so that the simulated results match the observed streamflow as closely as possible. Two different search algorithms are provided that move from the initial parameter estimates to the final best parameter estimates. A variety of objective functions are provided to measure the goodness of fit between the simulated and observed streamflow in different ways. While parameter estimation using optimization does not produce perfect results, it can be a valuable aid when calibrating models.

The simulation and calibration are done using ten years of daily precipitation data from 1999 to 2008 and for the same period daily observed streamflow data is used for comparison and calibration. Then four years of daily precipitation data from 2009 to 2012 is used for validation of the model with optimized parameter values and error statistics are used to evaluate the performance of the model.

Simulated Flows

Initially, the daily stream flows are simulated for the period 1999 to 2008 using the model and simulated flows. The screenshot of the model output indicating observed and simulated daily stream flows at the outlet of the basin for the period 1999-2008 is shown in Fig. 4. The plot shown in Fig. 4 indicates good simulation for daily flows but most of the high flows are slightly under-predicted by the model and the peak flow is underestimated. The observed peak flow value is 3932 m^3/s on August 9, 2006, and the simulated peak value is 3841 m^3/s on the same day.

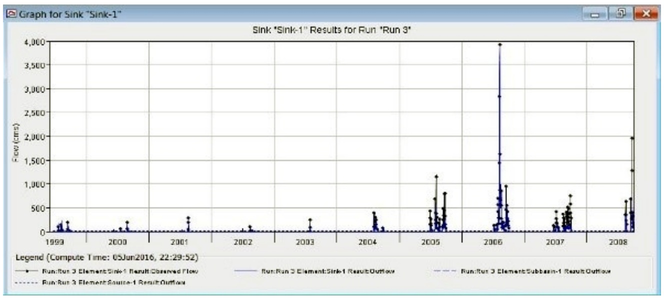

Fig. 4 Observed Vs Simulated daily stream flows at the outlet of the basin (1999-2008).

Model Calibration

For the results obtained in the simulation period the optimization trial is created in the software and all the four parameters initial deficit (mm), maximum deficit, constant rate (mm/hr) and lag time (min) is added in the optimization trial and the optimization trial is run using univariate search method and based on the sensitivity suggested by the software only two parameters constant rate (mm/hr) and lag time (min) is used for calibrating the model. During model calibration, the peak flow was overestimated. The simulated peak flow was 4161.3 m^3/s on August 9, 2006, while the observed peak flow was 3932 m^3/s on the same day. Other high flows are underestimated by the model. Similar trends are reported in previous studies of hydrological modelling (Meenu et al., 2012). The results of the model calibration are presented in Table 1.

Table 1 Initial and calibrated estimates of the model parameters

Parameter	Initial value	Optimized value	Sensitivity
Lag time (min)	2015	1896.5	0.29
Constant rate (mm/hr)	1.5	1.32	-0.06
Initial deficit (mm)	0	0	0
Maximum deficit (mm)	100	100	0

As indicated in Table 1, parameters are optimized and sensitivity is during the calibration of the model was determined. It is found that the model is not sensitive to the parameters initial deficit and maximum deficit and the model is more sensitive to lag time and constant rate. Hence, these two parameters values are optimized to match observed and simulated stream flows. The performance of the model is evaluated using error statistics and the results are presented in Table 2.

The various performance evaluation measures computed for the daily stream flow in the calibration period are given in Table 2. The R^2 and E values for the calibration period are 0.84 and 0.83, respectively and the peak flow is overestimated and the difference in the peak flow of observed and simulated streamflow is 229.2 m^3/s and the root mean square error value and mean absolute error value is 50.0 m^3/s and 9.8 m^3/s, respectively.

Table 2 Model Performance during calibration.

Performance statistic	Value
Simulated peak flow (m^3/s)	4161.3
Observed peak flow (m^3/s)	3932.1
Difference in peak flow	229.2
Percentage difference in peak flow	5.82
Mean absolute error (m^3/s)	9.8
RMS error (m^3/s)	50.0
R^2	0.84
Nash-Sutcliffe efficiency (E)	0.83

Model Validation

The optimized parameter values for the calibration period are used for the validation of the model. That is the constant rate and time lag as in Table 1 and four years from 2009 to 2012 are used for validation of the model. The same steps are followed as mentioned in the methodology for the simulation of stream flows during this period. The results presented in Fig. 5 show that daily flows are well simulated but the majority of high flows are underpredicted by the model. On August 30, 2011, the simulated peak flow was 324.2 m^3/s whereas the observed peak flow was 407.6 m^3/s indicating under prediction. The other performance evaluation parameters computed for the daily stream flow for the validation period are given in Table 3. The R^2 and E values for the validation period are 0.73 and 0.72 respectively and the peak flow is underestimated and the difference in the observed and simulated peak low is 83.4 m^3/s.

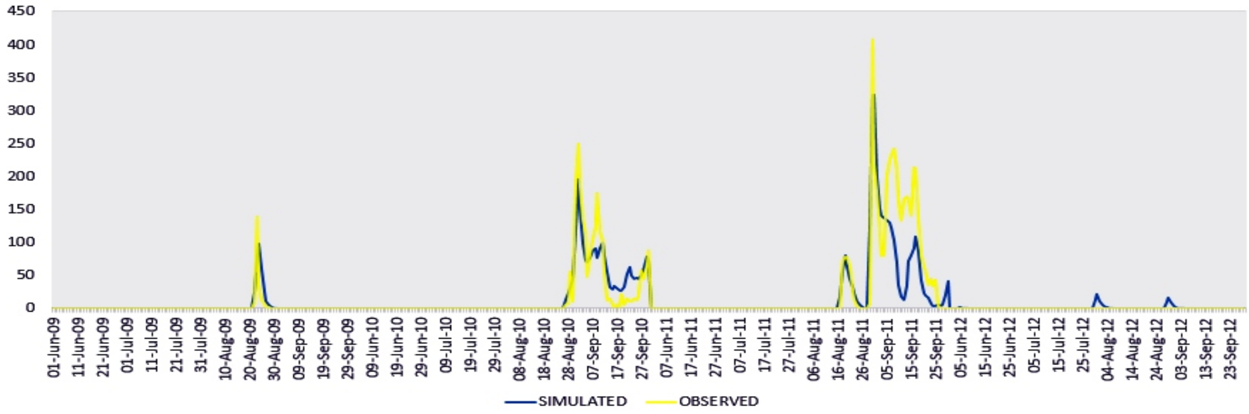

Fig. 5 Simulated Vs observed flows

Table 3 Model Performance during Validation

Performance Statistic	Value
Simulated Peak flow (m^3/s)	324.2
Observed peak flow (m^3/s)	407.6
Difference in peak flow	83.4
Percentage difference in peak flow	20.46
Mean absolute error (m^3/s)	3.2
RMS error(m^3/sec)	15.3
R^2	0.73
Nash-Sutcliffe efficiency(E)	0.72

Conclusions

The present case study aimed to create a hydrological model for the catchment area of the Pravara river basin. The hydrology of the basin is modeled quite well by the HEC-HMS 4.0 hydrological model except for the high flows. Under-prediction of high flows is an inherent problem with the model for hydrological modeling of the basin under study. This may be due to the lack of extreme event modeling capability of the hydrological model. The daily flows except extreme flows are better simulated. The ability of HEC–HMS to simulate the magnitude of the peaks underscores the significance of the model application as a flood prediction tool. However, the HEC–HMS model can successfully reproduce low flows and thus the model is a useful tool to estimate low flows in advance for drought forecasts. In the model, the parameters are assumed to be time stationery, and it is a limitation of the study. For want of time and date, event hydrologic modeling was not attempted in the present study.

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