Development and Evaluation of a Near Real Time System for Assessing Hydrologic Response in Chenab River Catchment

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Abstract. Investigating the hydrologic response of a catchment to adverse climate changes is crucial for managing land and water resources and mitigating the natural hazards like floods. Limited availability of the in situ data, especially in case of transboundary rivers, further highlights the need to develop and evaluate decision support systems which may predict the flows in near real time using open source satellite rainfall data. Study was conducted in the Chenab river catchment to develop and evaluate a hydrologic model using HEC-HMS for predicting flows based on TRMM rainfall data. The catchment was analyzed regarding hydro-morphological properties using HEC-GeoHMS tools. Digital soil map of the world developed by FAO and global land cover map developed by European Space Agency were utilized to develop Curve Numbers for the sub-basins. The model was calibrated and validated for summer/rainy months (June-September) for 2006 and 2007, respectively. There was found consistency between simulated and observed flows with percent difference in volume to be 5.49% and 6.61% for calibration and validation periods, respectively. Values of Nash-Sutcliffe Efficiency were found relatively less (0.57 for calibration and 0.07 for validation) possibly due to continuous nature of simulations. Further refinement in calibrated parameters can be performed based on event-based simulations to better capture the effects of extreme rainfall events in terms of floods, and all this analysis may help as a mile stone in developing a near real time decision support system.

Keywords. Hydrologic modeling, Flood management, HEC-HMS, TRMM satellite data.

1. Introduction

Climate change impacts in terms of increased global temperatures and high spatio-temporal variations in rainfall can be seen worldwide. These climate change indicators have strong impacts on a river catchment regarding changes in the general water resource situation as well as in the form of natural disasters like floods. This demands the continuous investigation of updated water resource and flood situation in a river catchment, which becomes further challenging in case of limited or no availability of ground data, particularly in case of transboundary rivers.

Pakistan, a country lying in a region which is highly prone to climate change, possesses most of the rivers being shared by India as an upper riparian. River Chenab, being one of the three major western rivers, has an important contribution in water resources of Pakistan. However, major area of this river catchment upstream Marala Barrage lies either in the disputed territory of Jammu & Kashmir or in India; where the ground data availability is limited or its acquisition is difficult. This situation highlights the need for the development and evaluation of an independent system which may predict the flows in near real time using open source satellite rainfall data products.

Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) provides high temporal (3-hourly and daily) and reasonable spatial (0.25^o x 0.25^o) resolution products using combination of microwave and infrared sensing instruments. Many scientists have made efforts at global and regional scales for the evaluation of satellite rainfall products by comparing them with the field rainfall measurements as well as by testing their scope of use in hydrological studies. Adeyewa and Nakamura (2003)[1] tested TRMM 3B43 data product for 36 months over the major climatic regions in Africa and found it having close agreement with the rain gauge data, and even used it as a substitute of rain gauge data over the South Atlantic Ocean for the validation of other satellite products. Ji and Stocker (2003)[2] and Chokngamwong et al. (2005)[3] found correlations of 0.56 and 0.86 between the satellite and rain gauge measurements, respectively. Dinku et al. (2007)[4] estimated Nash–Sutcliffe efficiency of 0.81 and root mean square error of 25% between the satellite and rain gauge data averaged over 2.5^o grid boxes. Shahid et al. (2013)[5] evaluated the TRMM monthly product (3B43) for Pakistan using 15 years data from 1998 to 2012 in comparison to ground rainfall data for the same period. It was reported that TRMM data is quite reliable for its direct use with Nash-Sutcliffe Efficiency (NSE) values ranging from 0.73 to 0.92 for different months.

Hydrologic modeling is an important tool for the investigation of hydrological response of a river catchment based on the analysis of its geomorphologic and agro-ecological characteristics. Hydrologic models often provide a base for the traditional flood warning systems, where the objective is to provide timely alerts for the advance activation of flood mitigation measures to reduce the damages. Moreover, use of hydrologic models allows employing different open source datasets viz. digital soil map, global land cover and land use map, snow cover and other satellite imageries, satellite rainfall datasets, etc. to effectively address the deficiency of ground data and conduct sound hydrologic studies. Immerzeel et al. (2009)[6] conducted study in the Upper Indus Basin and reported that the stream flows can be predicted with a high degree of accuracy by developing and using a hydrological model and forcing it with remotely sensed precipitation and snow cover data.

HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) model, developed by the US Army Corps of Engineers[7], can be used for hydrological simulations in different studies viz. to analyze urban flooding, flood frequency, flood warning system planning, reservoir spillway capacity, stream restoration, etc. Chen et al. (2009)[8] used HEC-HMS model employing SCS Curve Number method to predict the impacts of land use change on surface runoff in a rapidly urbanizing Xitiaoxi Basin, China. Ali et al. (2011)[9] combined an empirical land use change model and an event based rainfall-runoff model using HEC-HMS to quantify the impacts of potential land use change on the storm-runoff generation in the Lai Nullah Basin in Islamabad, Pakistan. The model was calibrated and validated for 5 storm events in the study area, and the results showed good consistency between the simulated and measured hydrographs at the outlet of the basin with Nash–Sutcliffe efficiency ranging from 76 to 98%. Halwatura and Najim (2013)[10] conducted a study to calibrate and validate HEC-HMS model to Attanagalu Oya river catchment in Sri Lanka and generate long term flow data for the Oya River and tributaries and reported that the model can reliably be used for simulating flows. De Silva et al. (2014)[11] conducted a case study of event and continuous hydrologic modeling in the Kelani River basin in Sri Lanka using HEC–HMS model. The results depicted the capability of HEC–HMS to reproduce stream flows in the basin to a high accuracy with averaged computed Nash–Sutcliffe efficiencies of 0.91 for event–based simulations and 0.88 for continuous simulations. The study demonstrated the potential of HEC–HMS application for disaster management, flood control, and water management in medium-size river basins in tropical countries.

The current study was conducted for hydrological simulation of summer/rainy months' flows in Chenab river catchment upstream Marala Barrage using HEC-HMS model with TRMM rainfall data. The study is important in this respect that most of the catchment lies in India and Marala is the first rim station on River Chenab in Pakistan. Thus the use of open source rainfall datasets like

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TRMM in a hydrological modeling environment is very important for this area to independently predict peak flows in near real time and provide alerts for disaster management.

2. Methods

2.1. Study Area

The River Chenab originates in the Kulu and Kangra districts of the Himachal Pardesh province of India in the form of two main streams - the Chandra and the Bhaga, which arise from large snowfields on opposite sides of Baralcha pass and then join at Tandi in the state of Jammu and Kashmir, nearly 3000 m above mean sea level. The catchment of the river is elongate in shape and it covers an area of about 26,000 km^2 up to Marala Barrage (74.4636^{o}E, 32.6733^{o}N) near Sialkot in Pakistan (Figure 1). The elevation of the catchment varies widely from about 228 to 7100 m, with a very steep gradient in the upper part which gradually decreases towards downstream. Due to large variations in altitude, there is also high diversity in climatic conditions which range from hot and moist tropical in lower valleys to cool temperate at 1500-2000 m, and then become progressively colder reaching an extremely polar type at the highest altitudes, as reported by Singh et al. (1997)[12]. However, based on broad climatic conditions prevailing over the whole basin, a year can be divided into four major seasons viz. winter (December-March), pre-monsoon (April-June), monsoon (July-September) and post-monsoon (October-November).

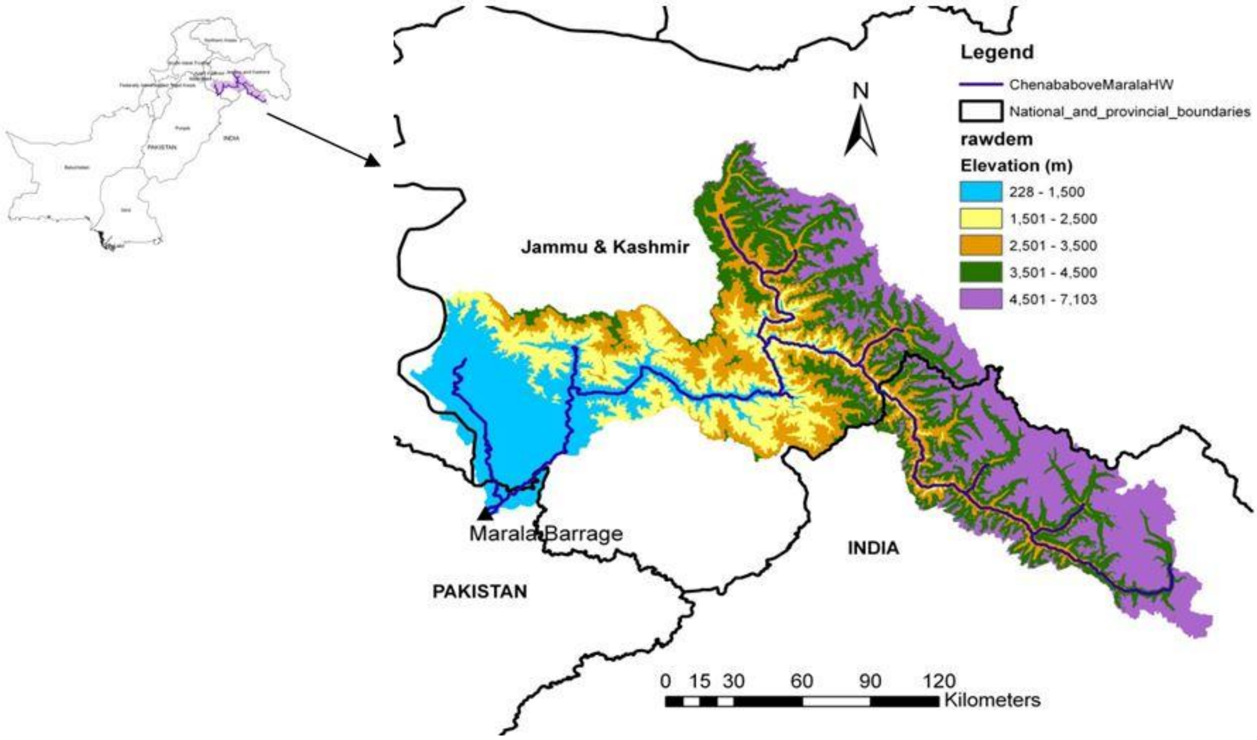

Figure 1: SRTM DEM of Chenab river catchment upstream Marala.

Singh et al. (1995)[13] described the spatial and seasonal variations in precipitation in Chenab river catchment in detail by dividing the area into three categories based on altitude. They reported that in Greater Himalaya ranges (higher altitudes), about 75% precipitation occurs in pre-monsoon and monsoon seasons, while about 15% precipitation occurs in winter in the form of snowfall. In Middle Himalaya ranges, about 65% precipitation occurs in pre-monsoon and monsoon periods and about 26% in winter. In Outer Himalaya ranges, about 36% precipitation occurs in winter, but most of it is not in the form of snow due to lower altitudes and tropical climate, and thus forms a major source of contribution to river flow during winter season in the form of seasonal winter rains.

Snowmelt runoff starts contributing to river flows in the mid or late summer season, while during monsoon season the flow is further enhanced by monsoon rains producing higher discharges and occasional peak floods. Due to combination of rain and snow and glacier-melt runoff, about 84% of annual river flows occur in pre-monsoon and monsoon seasons (April–September), particularly in the months of June-September[12]. Thus, it is highly important to predict and simulate flows for these months due to heavy rainfall events, which may enhance the normal flows and cause flooding.

2.2. Data Pre-processing using HEC-GeoHMS

For the hydro-morphologic analysis of the catchment, Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was used, which is necessary to simulate the stream network and delineate the watershed into a series of sub-basins. The SRTM DEM was first projected into UTM Zone 43 coordinates, and then different pre-processing operations like filling of sinks, simulation of flow direction, flow accumulation, stream definition and watershed and sub-basins delineation were performed using HEC-GeoHMS toolbar in ArcGIS 10.0. The project for the study area was generated which was to be used in HEC-HMS, and different input characteristics like river length, slope, basin slope, longest flowpath, sub-basins centroids and centroidal elevation, etc. were calculated. Other necessary steps like creation of background shape files for river and catchment were performed to be used in HEC-HMS.

Curve Number (CN) is an important hydrologic parameter used to assess the response of a basin in the form of runoff generation to a specific rainfall event. The Soil Conservation Services (SCS) CN grid was developed for the study area using soil and land use data and employing the methodology proposed by Merwade (2012)[14]. The soil information for the study area was analyzed by downloading and employing the Digital Soil Map of World, developed and updated by Food and Agriculture Organization of United Nations in 2007[15]. Based on the information of percent sand, silt and clay for different types of soils in the study area, a specific soil code or hydrologic soil group was assigned to each type following the guidelines provided in National Engineering Handbook of Hydrology (2007)[16]. The land use information was explored through global land cover map (GlobeCover 2009) developed and released by European Space Agency (ESA) in 2010[17]. There exist 22 different land cover classes which were reclassified into four broad classes for the study area[14]; Table 1 shows in detail the different land cover classes and their reclassification into four main classes. Finally, the developed CN grid was used to calculate the mean CN values for all sub-basins and export them to HEC-HMS for use in SCS CN loss method.

2.3. HEC-HMS Model Implementation

HEC-HMS model was implemented through different model components viz. basin model, meteorological model, control specifications and time series data managers. Background shape files for the river and catchment were loaded into the model and basin model representing the physical watershed was constructed, which consisted of 16 sub-basins, seven reaches and eight junctions with J8 representing the outlet at Marala Barrage (Figure 2). The SCS CN loss method was selected to calculate the losses and CN values of all sub-basins were input. The initial abstraction and percent impervious fields were kept blank, as these can be automatically set by the model based on CN values.

Table 1. Reclassification of different land cover classes.

Original GlobeCover Classification		Revised Classification	
Number	Description	Number	Description
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water	1	Water and Wetlands

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180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water		
210	Water bodies		
220	Permanent snow and ice		
190	Artificial surfaces and associated areas (Urban areas >50%)	2	Urban/ Residential Areas
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	3	Forest
50	Closed (>40%) broadleaved deciduous forest (>5m)		
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)		
70	Closed (>40%) needleleaved evergreen forest (>5m)		
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)		
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)		
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)		
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)		
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water		
11	Post-flooding or irrigated croplands (or aquatic)	4	Agricultural Lands
14	Rainfed croplands		
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)		
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)		
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)		
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)		
150	Sparse (<15%) vegetation		
200	Bare areas		

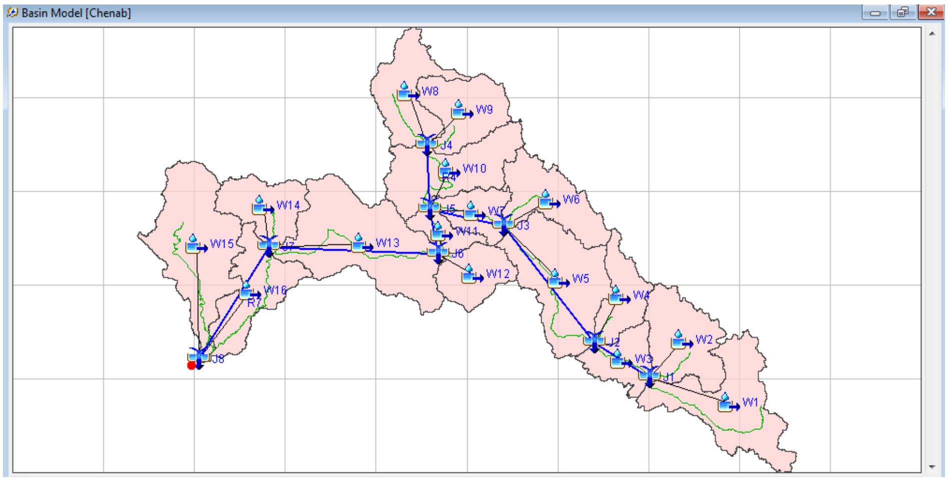

Figure 2: Basin model of Chenab river catchment

The SCS Unit Hydrograph transform method was chosen to calculate the direct runoff; lag times for this purpose were calculated and averaged using different empirical equations viz. Kirpich, Chow, NERC, Watt & Chow, and SCS Lag, as described by Loukas and Quick (1996)[18]. Constant monthly values of base flow were input; while for reaches, Lag method of routing was chosen and lag times for all reaches were calculated and input.

The meteorological model determines the way to calculate the precipitation input for the sub-basin elements. In this study, TRMM daily rainfall product (3B42) averaged over the sub-basins level was utilized. For this purpose, specified hyetograph meteorological model was selected and a hypothetical rain gauge was defined for each sub-basin to input daily time series rainfall data for all sub-basins. Evapotranspiration is the combination of evaporation from ground surface and transpiration by vegetation, and is not a required input in case of SCS CN loss method. Moreover, as the objective in this study was to capture and simulate the peak flows due to monsoon rains, no snowmelt mechanism was studied separately in addition to giving constant monthly base flows. Daily time series data of TRMM 3B42 rainfall product for all sub-basins and the daily observed flow data of Marala Barrage at the outlet (J8) of the basin model, collected from Water and Power Development Authority (WAPDA) of Pakistan, were input. The model was initially run from June 1 to September 30, 2006 for having continuous simulation of peak season flows in Chenab river catchment.

2.4. Calibration and Validation

Watershed parameters such as CN, initial abstraction and lag time need calibration to produce a best fit between the observed and simulated flows. For this purpose, the model was calibrated using optimization trail tool based on simulation run for the year 2006 from June 1 to September 30.

Table 2. Optimized parameters based on the peak weighted RMSE objective function.

Sub-basins	Curve Number	Initial Abstraction (mm)	Lag Time (min)	Reaches	Lag Time (min)
W1	40.282	16.77	671.21	R1	410.93
W2	48.033	21.299	378.16	R2	896.97
W3	47.65	22.85	275.54	R3	525.06
W4	40.231	17.956	391.3	R4	840.61
W5	47.477	23.557	493.76	R5	426.8
W6	40.193	14.343	402.64	R6	1320
W7	45.722	31.042	272.85	R7	803.14
W8	46.742	26.621	488.79		
W9	40.329	17.496	338.54		
W10	46.289	28.562	433.69		
W11	42.611	45.823	238.28		
W12	42.363	47.097	276.62		
W13	42.892	44.4	635.19		
W14	43.61	40.846	383.52		
W15	41.672	33.983	1239.2		
W16	44.96	34.471	694.38		

The Peak-Weighted RMS Error function was selected as objective function, which is used to determine the goodness of fit and is a modification of standard RMS error giving increased weight to flows above average and less weight to flows below average. The Univariate Gradient method was chosen to run optimization trail with maximum iterations set as 165 and tolerance value to be 0.01. Table 2 shows the optimized parameters values, which were then taken as input along with other known parameters and rainfall and discharge data of 2007 to validate the model by running simulation from June 1 to September 30, 2007.

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2.5. *Statistical Assessment of Model Performance*

Model performance was assessed statistically using two evaluation parameters, i.e. Nash–Sutcliffe Efficiency (NSE), and the % deviation in runoff volumes (D_v) using following equations[9]:

$$NSE = 1.0 - \frac{\sum_{i=1}^{N}(Qsi - Qoi)^2}{\sum_{i=1}^{N}(Qsi - <Qo>)^2}$$

$$D_v\,(\%) = \frac{\sum_{i=1}^{N} Qsi - \sum_{i=1}^{N} Qoi}{\sum_{i=1}^{N} Qoi} \times 100$$

Where Q_{si} and Q_{oi} are the simulated and observed stream flows at time step i, and $<Q_o>$ is the mean observed stream flow over the simulation period. These parameters were estimated for both calibration and validation periods.

3. Results

Figure 3 highlights the hydrologic response of some sub-basins as simulated by the model. Three sub-basins namely W1, W8 and W15 are presented here, which basically describe three different categories based on elevation and climate. W1 represents the south-east side of the catchment where average elevation is more than 4500 m and glacier and snow-melt have major contribution to flows, whereas W8 represents the northern side with elevation in the range of 3500-4500 m in most of the area. W15 represents the western downstream side of catchment with elevations less than 1500 m, which has high contributions to flows in the form of heavy monsoon rainfalls.

The collective response of whole catchment along with observed flows at upstream Marala Barrage is presented in Figure 4. It can be seen that model simulated the flows with reasonable accuracy especially regarding time of the peaks, but highly overestimated some peak flows in the later part of the season, which is also evident from Figure 3 as there can be seen significant decrease in precipitation losses after about one month for all sub-basins. Calibrated and observed flows by running the optimization trail have been shown in Figure 5, where the difference between simulated and observed flows was reduced considerably. Average absolute residual was decreased from 787.09 m^3/s to 554.10 m^3/s, while total residual was decreased from 217.00 mm to 38.85 mm after calibration.

Model validation was performed by running it for 2007 based on the calibrated parameters; Figure 6 shows the simulated and observed flows for 2007. From the figure, it can be seen that the model could not perform well during first month of June to capture the peaks. However, the model performed quite well for rest of the period; average absolute residual and total residual were recorded as 502.15 m^3/s and 34.25 mm, both even less than the respective values for the calibration period (Table 3).

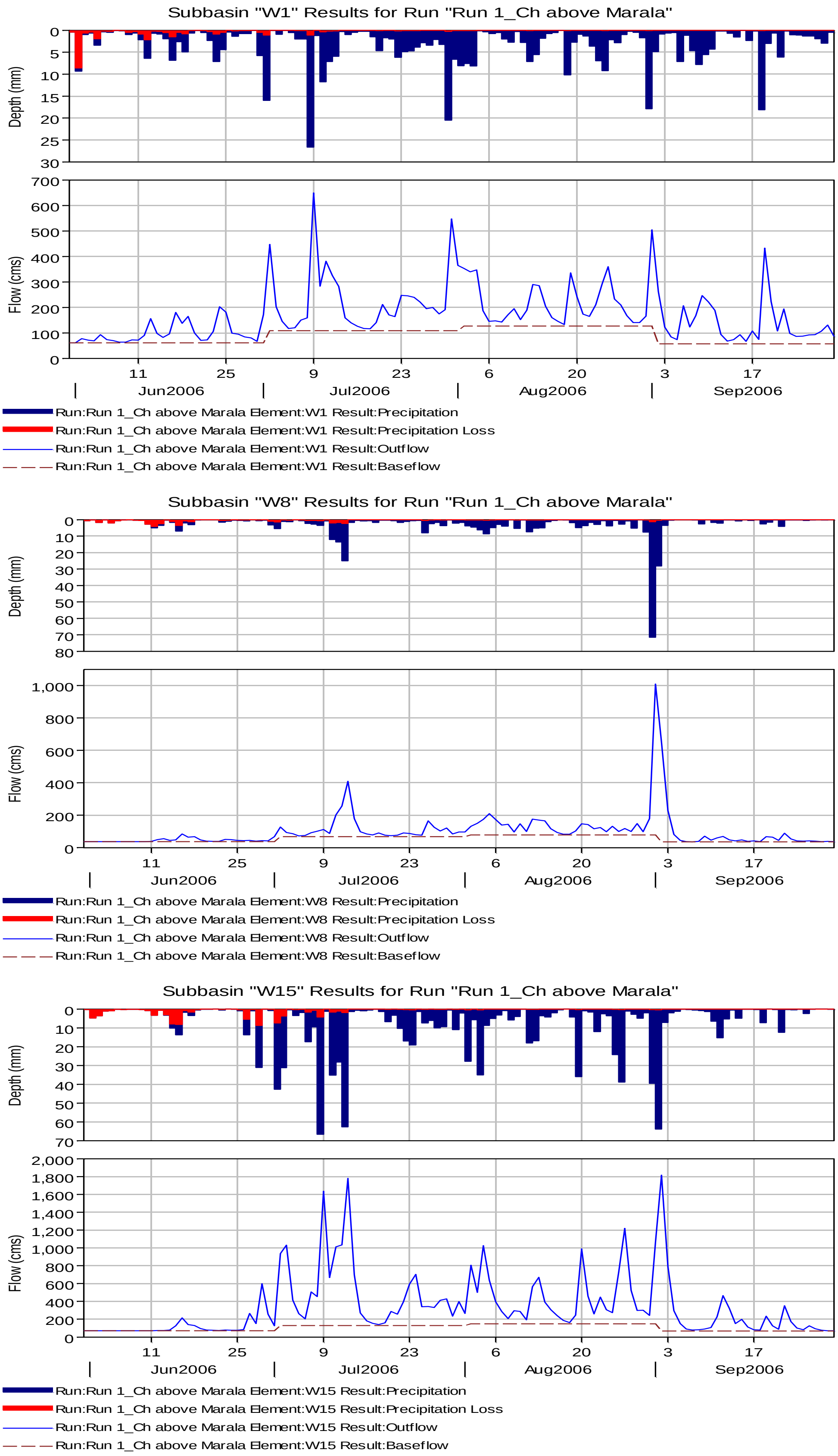

Figure 3: Hydrologic response of (a) W1, (b) W8, and (c) W15 sub-basins.

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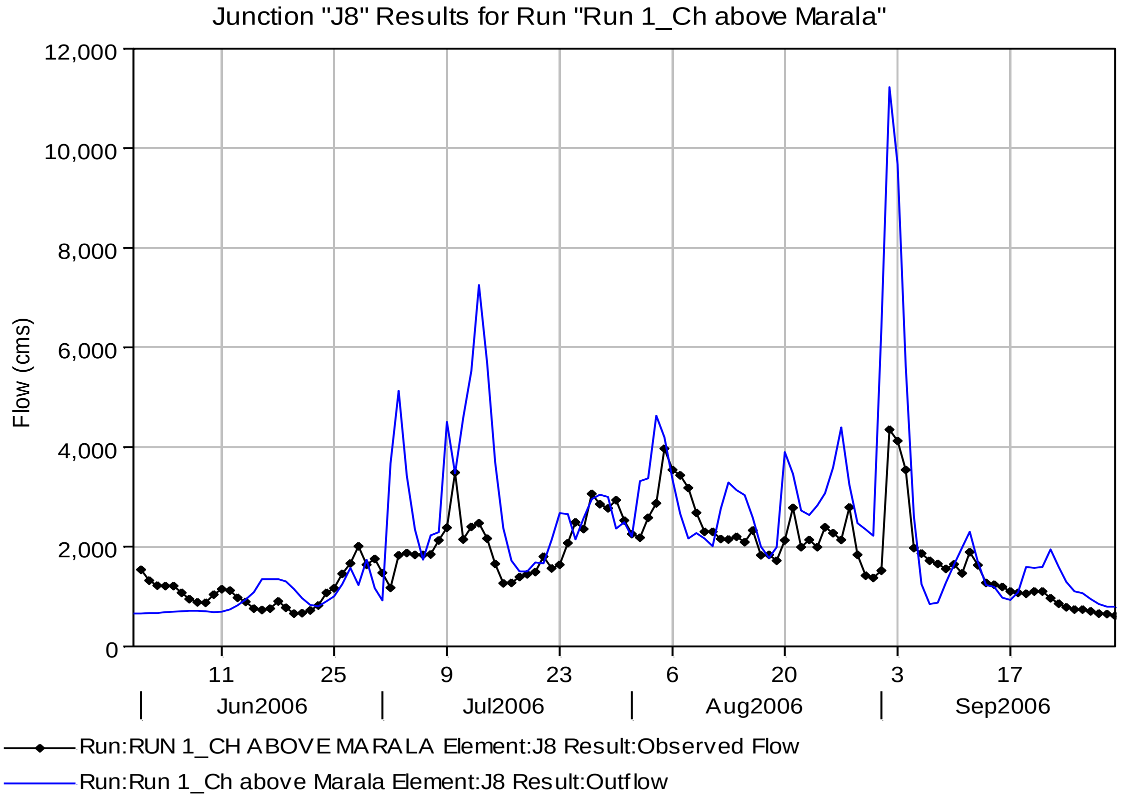

Figure 4: Simulated and observed flows at Marala for 2006.

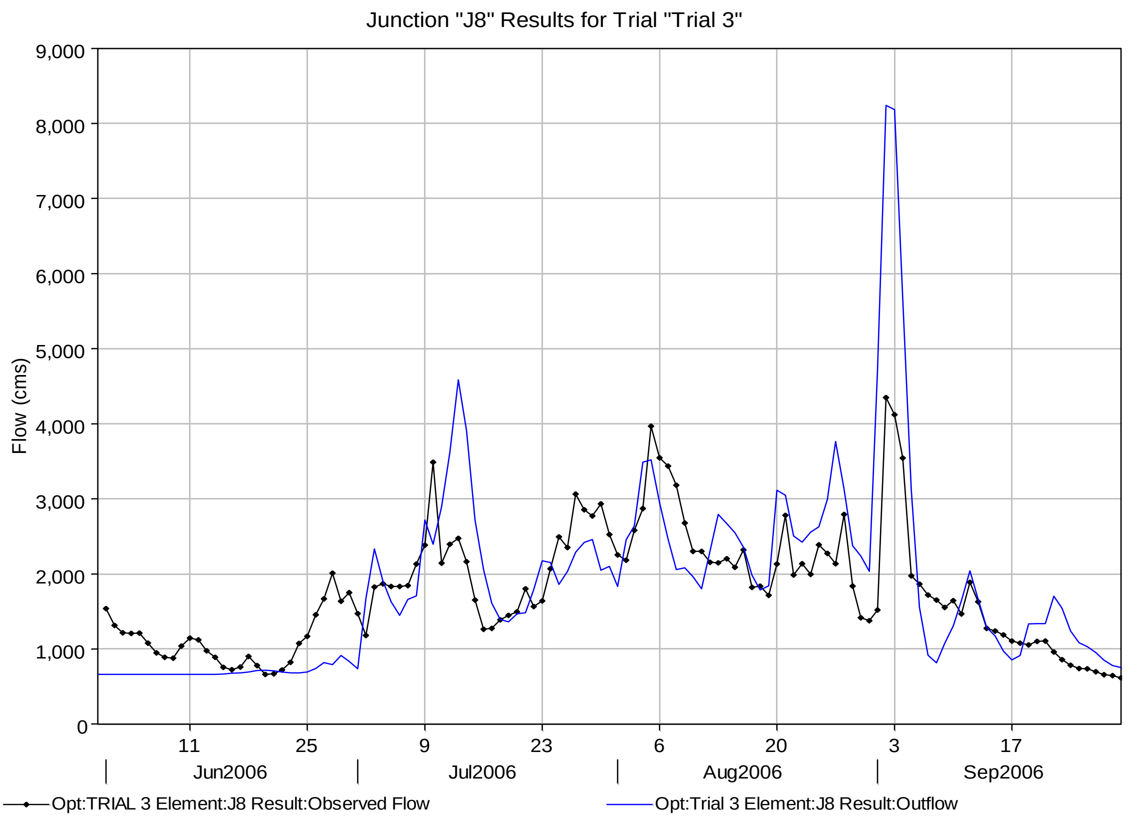

Figure 5: Calibrated and observed flows at Marala for 2006.

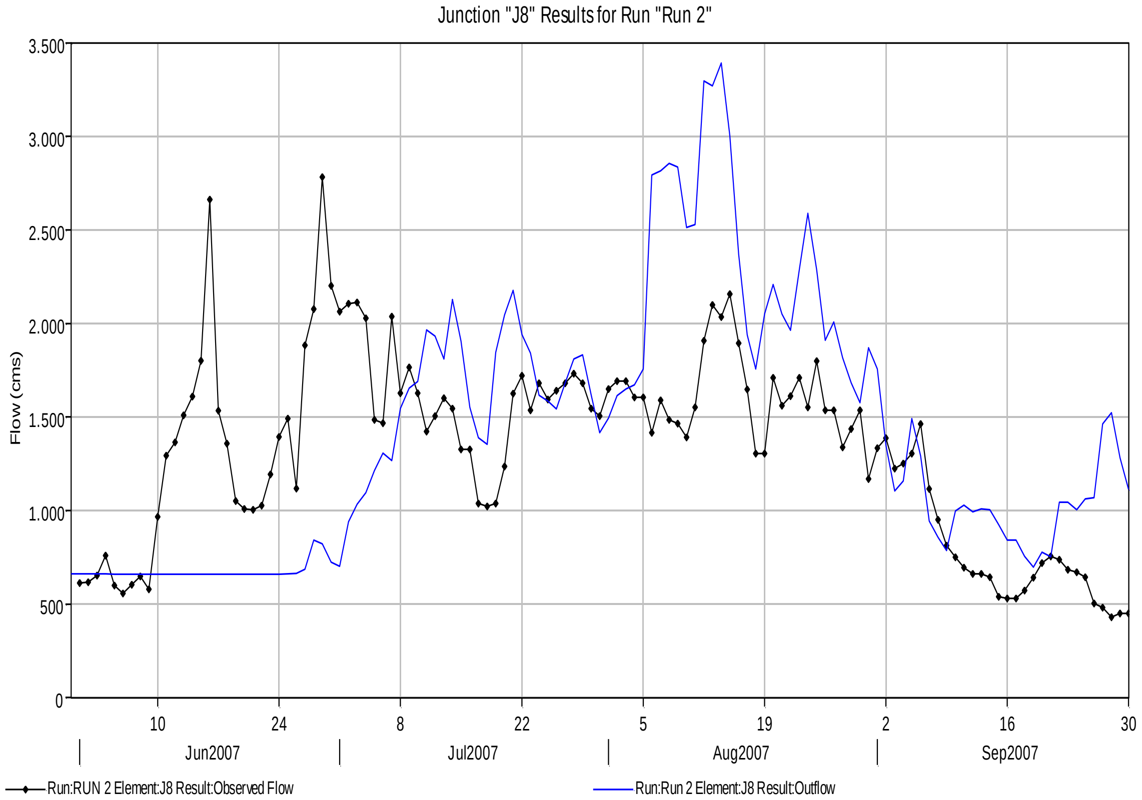

Figure 6: Model validation – simulated and observed flows at Marala for 2007.

Reasons for the inability of model to capture the peak flows in June might be the snowmelt effect, which was not considered in this study but may have significant impact during the high temperature month of June as can be seen from two distinct and extra ordinary peaks of more than 2500 m^3/s in this year. Another possible reason might be the use of SCS CN loss method which was basically developed for event-based simulation and results in high losses at initial stage, but almost negligible losses in the later stages, which is not well suited to continuous simulation scenario.

Other statistical parameters like NSE and D_v (%) are also presented in Table 3 for both calibration and validation runs. A very low value of NSE (0.07) for the validation period may be referred to almost constant flows during this year with no major peaks in rainy season, which made the difference between simulated values and the average observed value quite less, and thus resulted in low NSE value. However, percent difference in volume was found less than 10% for both simulation runs.

Table 3. Summary of model performance during calibration and validation.

Parameters	Calibration (2006)	Validation (2007)
Avg. Absolute Residual (m^3/s)	554.10	502.15
Total Residual (mm)	38.85	34.25
NSE	0.57	0.07
Percent Difference in Volume, D_v (%)	5.49	6.61

4. Conclusions

This study presented a methodology to assess hydrologic response of a transboundary river catchment by integrating HEC-HMS model with open source land cover, soil and rainfall datasets.

The model performed well to simulate the flows with percent difference in volume to be less than 10%; however, some peak flows in the month of June were not captured well due to the starting month of simulation with high losses in case of SCS CN loss method as well as possibly due to the snowmelt effects. The main objective in this study was to calibrate and evaluate the model for runoff simulations due to heavy rains being occurred in these months. The model was found quite suitable; however, further refinement in the optimization of parameters can be performed by selecting significant rainfall events and running it for event based simulations as well as by investigating the use of other loss methods. Such validated hydrologic model may be used as an effective tool for a near real time decision support system.

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