Simulation of flows at Tehri dam during various storm events using HEC-HMS

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ABSTRACT

Reliable prediction of storm runoff from rainfall and snowmelt are important for flood hazard mitigation and resilience. In this study, the HEC-HMS software of U.S. Army Corps of engineers was used to simulate the flows at Tehri Dam during various storm events. The Tehri dam is the 4th highest dam in the world in earth and rock fill category. The catchment area of Tehri dam is 7293 km^2, out of which 2042 km^2 is covered with permanent snow. Eight storm events from monsoon of 2016-2017 and two events from monsoon of 2018 have been selected for calibration and validation respectively. Model parameters were calibrated and performance of the model was evaluated by comparing the six hourly flows at Tehri dam. Maximum and minimum Nash and Sutcliff efficiency (NSE) for 8 events during calibration were 90.7% and 72.6 % respectively. While during the validation of two monsoon events of 2018 the NSE were 85.3% and 85.1%. Model performs satisfactorily to reproduce the runoff induced from rainfall as well as snowmelt. The paper discusses delineation of sub-catchments, selection of storm events, sensitivity analysis, calibration of parameters and validation of six hourly flows at Tehri dam.

1. INTRODUCTION

The Hydrologic Modelling System (HEC-HMS) is a physically based, semi-distributed model developed by Hydrologic Engineering Centre of the United States Army Corps of Engineers HEC-HMS is very flexible application software that allows the user to select combinations of different models for runoff simulation of a watershed. Furthermore, a number of parameters required by different models can also be estimated automatically by optimization trials using observed input and output data. HEC-HMS software has been applied in watersheds as small as an elevated highway interchange to as large as 20,000 square miles. Hydrographs produced by HEC-HMS are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanisation impact, reservoir spillway design, flood damage reduction, floodplain regulation, and real-time systems operation. For Himalayan basins also, some studies have been reported in the literature, see, e.g. Gautam (2014), Prajapati (2015) and Khatri (2017).

However, for the Bhagirathi basin, only one study by Sah (2018) using gridded data has been carried out and reported in the literature. The main reason for the same has been the nonavailability of hydro-meteorological data for the basin. The present study is the first study for the application of the HEC-HMS model for the entire Bhagirathi basin at Tehri using the observed hydro-meteorological data of eleven stations.

2. STUDY AREA

Tehri dam is situated in the district Tehri of Uttarakhand state of India, Tehri dam catchment is bounded between longitude 78º9’15’’E to79º24’55’’E and latitude 30º20’20’’N to 31º27’30’’N (Fig. 1). The catchment area up to the dam axis is 7293 km^2. River Bhagirathi Bhilangana and Balganga are the three major rivers which contribute to Tehri reservoir. Bhagirathi River originates from Gangotri glacier near Gomukh at an elevation of 4255 m and traverses a distance of about 145 km to its confluence with river Bhilangana at 1.5 Km upstream of Tehri dam. River Bhilangana traverses a distance of 72 km before meeting with river Bhagirathi. Some minor tributaries like Mangad, Nilapani, Jadganga, Garunganga, Ganeshganga, Asiganga, Dharshugad, Jalkurgad also meet with river Bhagirathi. River Balganga is a major tributary of river Bhilangana, and it meets at Ghansali, 3 Km downstream of Sarasgaon at EL 818 m, falling directly into the reservoir. Different tributaries of Bhagirathi and Bhilangna are shown in Fig.2.

There are two run-of-the-river hydropower projects namely Maneri Bhali I and Maneri Bhali II situated in the upstream of Tehri Project on river Bhagirathi. The releases from these projects affect the inflows to the Tehri reservoir. These power schemes play a major role in the regulation of the inflows to the reservoir.

Tehri dam is 260.5 m high rockfill earthen dam. It is the fourth highest rock-fill earthen dam in the world after Rogun dam (335 m) in Russia, Nurek dam (300 m) in Tadzhikistan and Chicoasen dam (261 m) in Mexico. It is a multipurpose project. The first phase of the project was commissioned in 2006. In its first phase, four Francis turbines of 250 MW capacity each, have been installed. Another 1000 MW capacity is to be added after completing the third phase by 2020.

It is a major source of irrigation for Rabi crop to various canals of Uttar Pradesh and Uttarakhand State. Seven million peoples get drinking water from this dam. Dam’s FRL (Full Reservoir Level) is at 830.2 m above mean sea level, and MFL (Maximum Flood Level) is at 835m. The PMF (Probable Maximum Flood) for the dam is 15540 cumecs. To handle the PMF, a chute spillway, having 5500 Cumecss discharging capacity and four shaft spillways, each having 1900 cumecs discharging capacity have been provided. The gross and live storages of the reservoir are 3540 and 2615 MCM (Million Cubic Meters) respectively. Mean annual flow volume of river Bhagirathi is 8000 MCM. Dam and its reservoir are shown in Figure 3 and Figure 4 respectively.

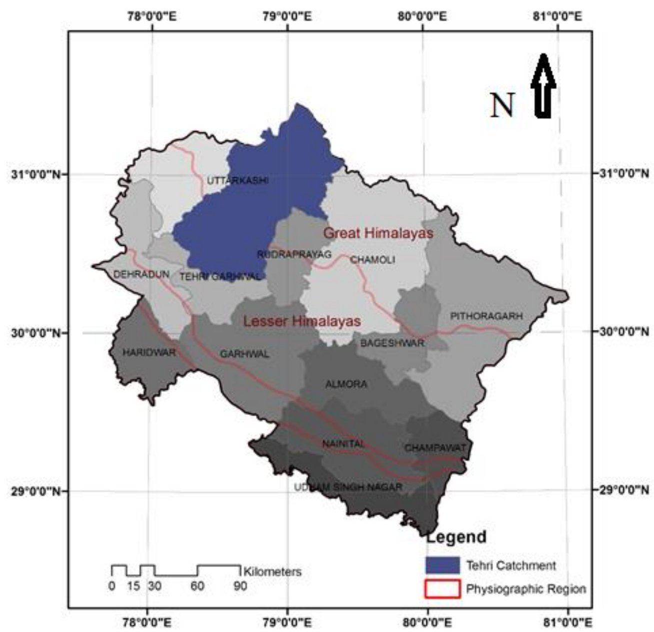


Figure 1. Showing location map.

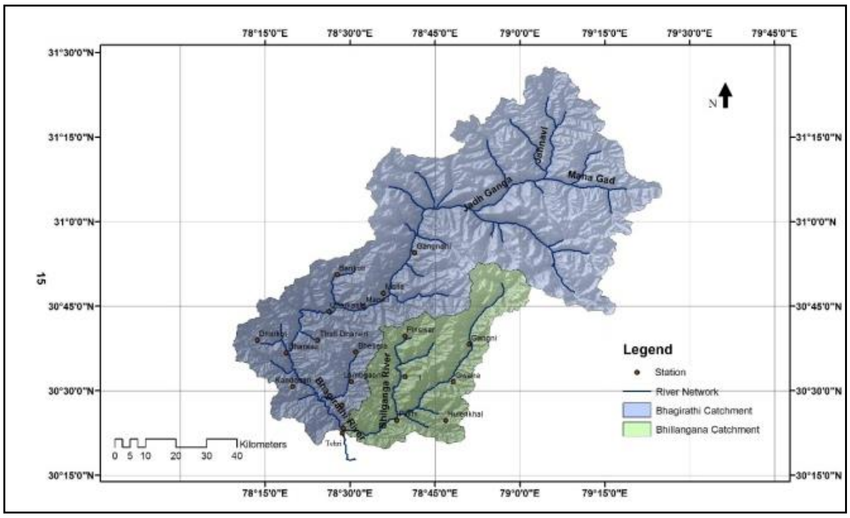


Figure 2. Showing location map and major rivers and tributaries of Tehri catchment.

Fig. 3

Fig.4

Figure 3&4. View of Tehri dam, its Chute Spillway & Tehri Reservoir.

3. METHODOLOGY

Digital Elevation Model (DEM) is used as input for partitioning of the basin into some sub-basins. HEC-HMS can be used to simulate an individual storm event or can be used in continuous simulation mode. The model has three components viz. basin model, meteorological model and control specifications. The basin model deals with the physical characteristics of the watershed. The inputs like precipitation, temperature, evaporation are handled by the meteorological model. The control specifications are used to provide the simulation time of a process.

The HEC-HMS software models overland flow and interflow, base-flow and channel flow separately. In the HEC-HMS model, six different models can be used to model the runoff volume. There are six models for estimating the temporal distribution of runoff, three different models for modelling of base- flow and eight different models for channel routing.

However, keeping in view the data availability, the following combinations were selected, Initial and constant loss rate method, SCS-UH for the time distribution of run-off, Constant monthly base flow, and Muskingum-Cunge for channel routing. For the meteorological setup, different rain gauges were used, and the gauge weights were setup. The snowmelt runoffs from different catchments have been computed using the Temperature Index method. Thiessen weights for different gauges have been computed using the ARC-GIS. The temperature index method is used to calculate the snowmelt contribution to the basin. Snow generally occurs when the temperature is below the freezing point over the land surface, and the snow will accumulate on the land surface as long as the temperature remains below the freezing point. In some basins, snow accumulates to the snowpacks during the winter season. The snowpack melting starts when the atmospheric condition transfers sufficient energy to raise the temperature above the freezing point of the snowpack. The most common means of measuring the water content from the snowpack is the snow water equivalent (SWE).

The snowmelt method is only required when the temperature of the basin is going below the freezing point during the simulation, or if there is already available snowpack within the basin at the beginning of the simulation. The temperature index method is generally an extension of the degree day method used for modelling snowmelt in the study. Hourly temperature data of Dhopardhar and Bishan have been used for snowmelt modelling for Bhilangana and Balganga catchments respectively. Hourly rainfall data of Ghansali, Bishan and Dhopardhar have been used to model the runoff of these sub-catchments. For computation of snow melt contribution, Bhilangana and Balganga catchment have been divided into six and five elevation bands respectively. Model parameters such as lag time, temperature index, critical temperature, base temperature, initial snow water equivalent and time weight of automatic weather stations have been calibrated.

The flow of Bhilangana at Ghansali, Balganga at Sarasgaon, regulated flow, i.e. spill, flush and turbine discharge of Maneri Bhali II and DSRO of all the sixteen ungauged tributaries were routed up to Tehri dam through twenty-one reaches using Muskingum-Cunge method. Bhagirathi River from Joshiyara barrage to Tehri dam has been divided into twelve reaches, Bhilangana River from Ghansali to Tehri dam has been divided into 8 reaches. For Balganga at Sarasgaon, there is one additional reach. Cross-section of each reach has been obtained from the hydrographic survey of Tehri reservoir, which was done by THDCIL in 2013. Dimensions like bottom width, top width, side slopes and invert levels of each cross-section were used. The flow of each tributary and MB II outflows are taken as a source. Every reach is connected with a junction and Bhilangana at Ghansali and Balganga at Sarasgaon are taken as sub-catchments. The flow chart of the intermediate catchments from Bhagirathi side and Bhilangana side is presented in Fig 5 and Fig 6 respectively. For validation of the flows, Tehri reservoir levels and turbine discharges were used to calculate the inflow at the dam site.

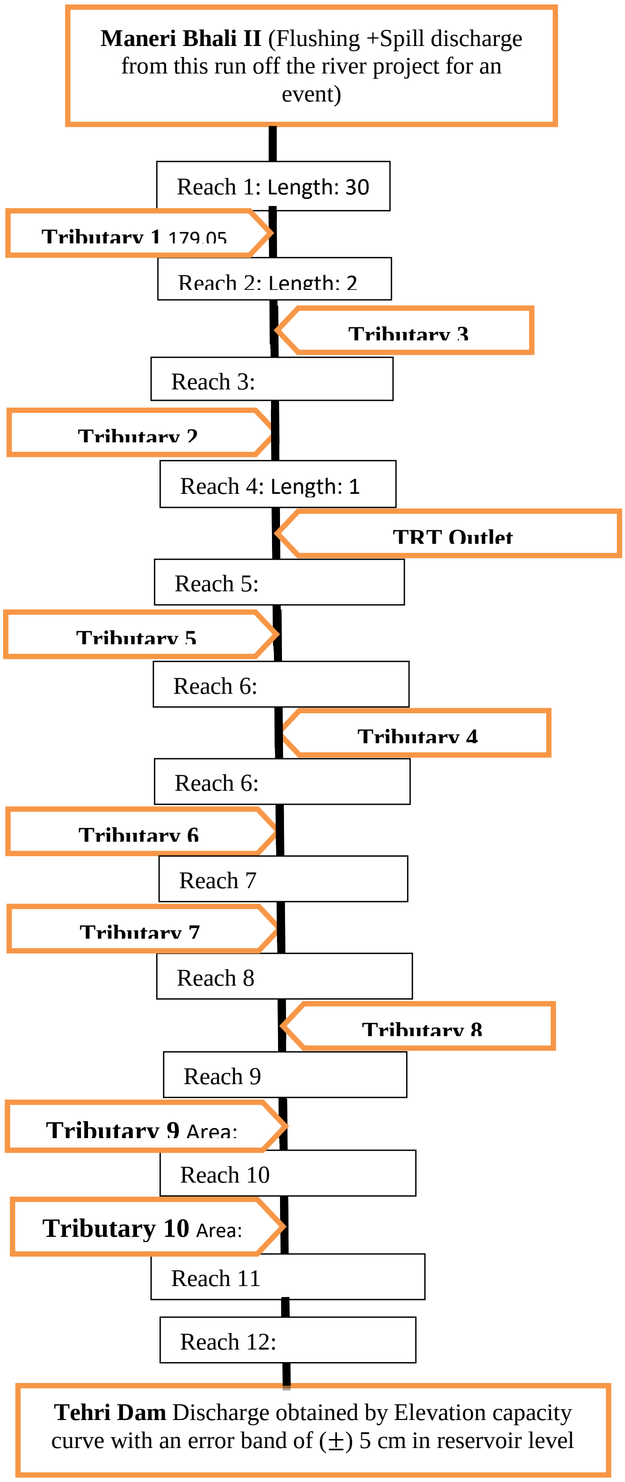


Figure 5.

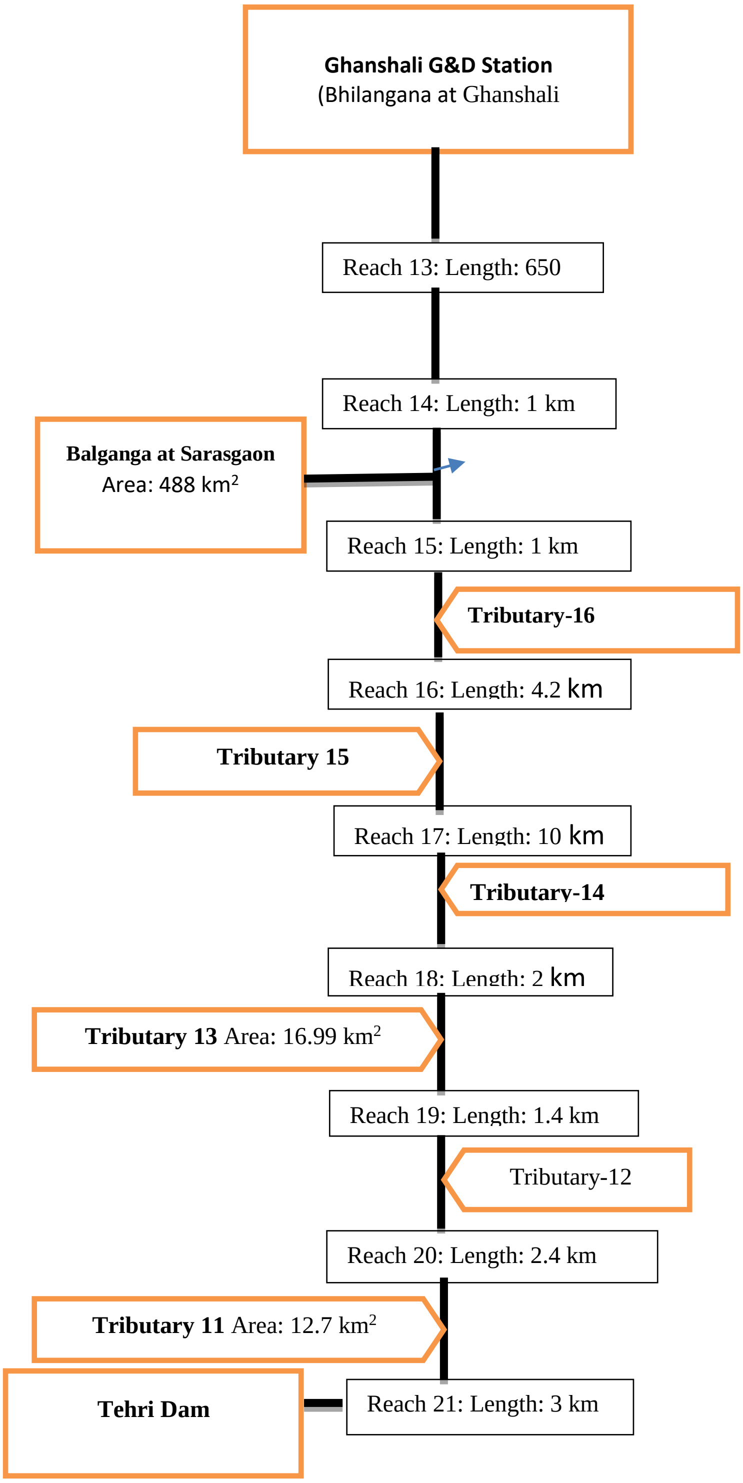


Figure 6.

Figure 5&6. Flow Charts of the intermediate catchment, Bhagirathi and Bhilangana side.

4. RESULT AND DISCUSSIONS

Ten storm events during 2016, 2017 and 2018 were selected for event-based modelling. The catchment area has been divided into four parts, i.e. (i) Bhagirathi up to MBII, (ii) Balganga up to Sarasgaon; (iii) Bhilangana up to Ghansali and (iv) intermediate catchment area. The outflows from MB II, being regulated flows, are taken as source and Bhilangana, and Balganga flows are modelled using HEC-HMS as snowfed catchments. The contributions of the intermediate catchment are obtained using HEC-HMS considering these catchments as ungauged and rainfed.

4.1 Modelling of Balganga at Sarasgaon

For this catchment hourly rainfall data of three stations namely Bishan, Dhopardhar and Ghansali were used. Thiessen weights of Bishan, Dhopardhar and Ghansali are 0.45, 0.3 and 0.25 respectively. Hourly temperature data of Bishan AWS were used for snowmelt modelling. Before the calibration of the model sensitivity analysis was performed for Event-1

4.2 Sensitivity Analysis

Sensitivity analysis is performed to understand how the model results react to change in model parameters. Some of the parameters have more impact on model results than others. The knowledge of sensitive parameters is useful in model calibration. To perform the sensitivity analyses the parameters whose sensitivity is to be analysed are changed and other parameters are kept constant. It is found that unmeasured parameters like ATI melt rate coefficient, wet melt rate, lapse rate, and constant loss rate are highly sensitive. Other parameters such as initial loss, critical (PX) temperature, rain rate limit and cold limit do not have much effect on the results.

4.3 Calibration and validation

The calibration of the parameters in HEC-HMS, i.e. initial loss rate, constant loss rate, lag time, temperature lapse rate and parameters of different elevation bands etc. has been done These calibrated parameters have been obtained after a number of iterations to maximize the efficiency. Based on these calibrated parameters of eight events, the average parameters of July and August separately were obtained and using these average parameters, same eight events of 2016 and 2017 were validated. The plots of one typical event in calibration and validation are shown in Fig. 7 to 10 It can be seen from these figures that during calibration and validation the peak flows are matching quite closely. The NSE of eight events of 2016 and 2017 during calibration and validation with averaged parameters are given in Table1. It may be seen from this table, that average, maximum and minimum NSE of all the eight events during calibration are 81.4%, 94.2% and 61.2% respectively. During validation, using the averaged parameters, the same get deteriorated to 72.8%, 90.8% and 50.5% respectively. The validation of the model has also been done for two events of July 2018. The results of validation of two new events no. 9 and 10 shows that NSE of the model is 88% and 89.4% respectively. From Fig 7&8 and 9&10, it can be seen that peeks of the flows are matching. The model is predicting the runoff generated due to rainfall quite effectively.

Table 1. Nash-Sutcliffe efficiency for Balganga sub-catchment using HEC-HMS event based modelling.

Event no.	Efficiency	
	Calibration	Validation
1	75.8	75.1
2	87.6	86.8
3	75.7	69.8
4	94.2	90.8
5	87.2	86.6
6	61.2	48.5
7	88.5	67.6
8	81.2	57.5
9	-	88.0
10	-	89.4

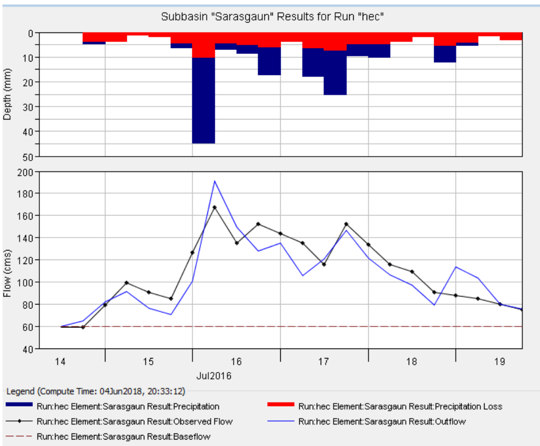


Figure 7.

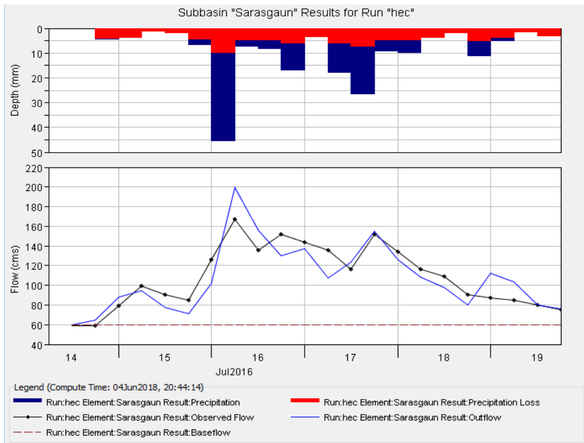


Figure. 8.

Figure 7&8. Hydrographs for event-1, during calibration and validation.

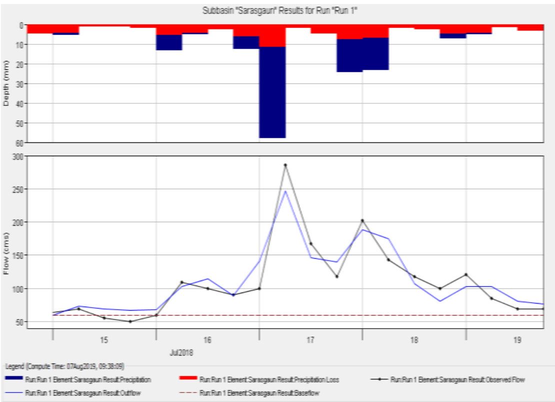


Figure 9.

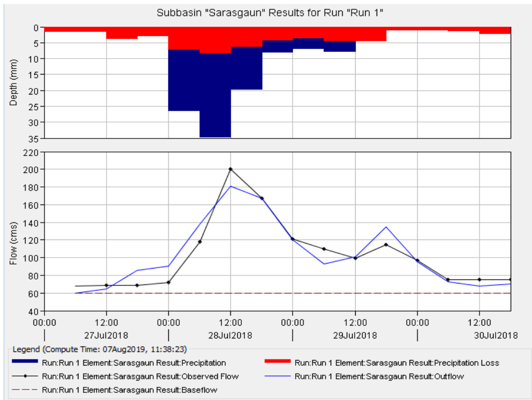


Figure. 10.

Figure 9&10. Hydrographs for event-9 and 10 during validation.

4.4 Modelling of runoff of bhilangana at ghansali

For this catchment hourly rainfall data of three stations namely Bishan, Dhopardhar and Ghansali were used. Thiessen weights of Bishan, Dhopardhar and Ghansali are 0.3, 0.45 and 0.25 respectively. Hourly temperature data of Dhopardhar AWS were used for snowmelt modelling.

The calibration of the parameters in HEC-HMS, i.e. initial loss rate, constant loss rate, lag time, temperature lapse rate and parameters of different elevation bands etc. has been done These calibrated parameters have been obtained after a number of iterations to maximize the efficiency. Based on these calibrated parameters, separate average parameters of July and August were obtained and using these averaged parameters different events of 2016 and 2017 were validated. The plots of two typical events in calibration and validation are shown in Fig. 11 to 14. It can be seen from these figures that during calibration and validation the peak flows are matching quite closely. The NSE of eight events of 2016 and 2017 during calibration and validation are given in Table 2. It may be seen from this table that average, maximum and minimum NSE of all the eight events during calibration are 83.8%, 93.2% and 56.4% respectively. During validation, using the average parameters the same get deteriorated to 70.5%, 90.4% and 45.1% respectively. The validation of the model has also been done for two new storms of July 2018. The NSE of these two events no. 9 and 10 are 83.6% and 79.2% respectively. From Fig 11&12 and 13&14, it can be seen that peeks of the flows are matching closely.

Table 2. Nash-Sutcliffe efficiency for Bhilangana sub-catchment using HEC-HMS event-based modelling.

EVENT NO	EFFICIENCY	
	Calibration	Validation
1	81.9	76.6
2	91.4	89.5
3	88.2	49.2
4	91.0	90.4
5	81.8	78.6
6	93.2	49.4
7	56.4	45.1
8	86.3	85.2
9	-	83.6
10	-	79.2

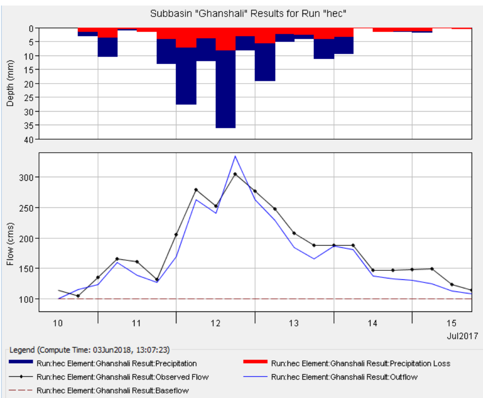


Figure 11.

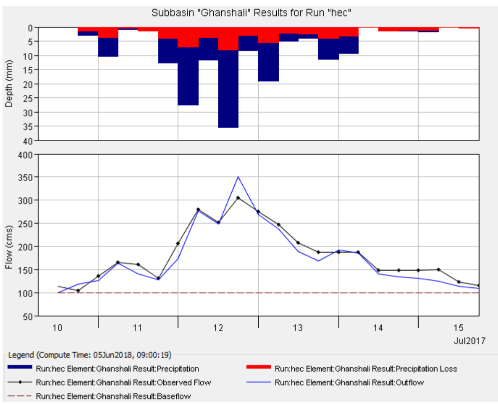
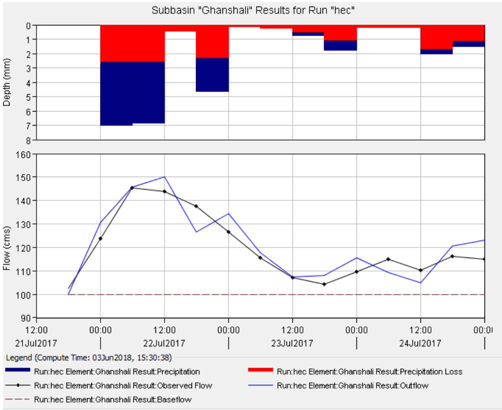


Figure 12.

Figure 11&12. Hydrographs for event-4 during calibration and validation.



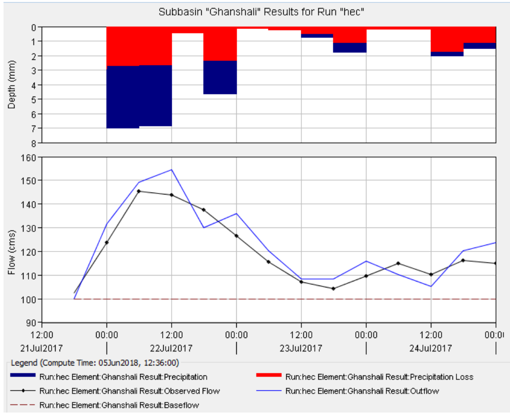
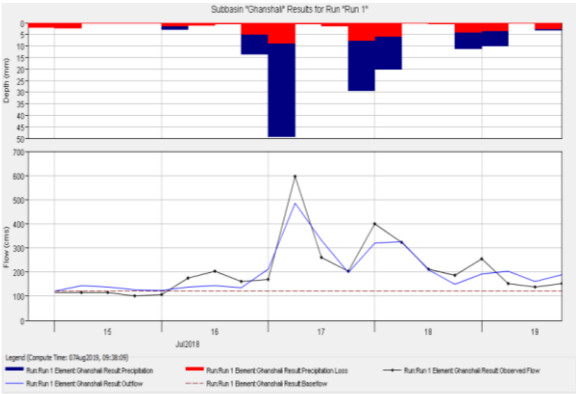


Figure 13. Figure 14.

Figure 12&13. Hydrographs for event-5, during calibration and validation



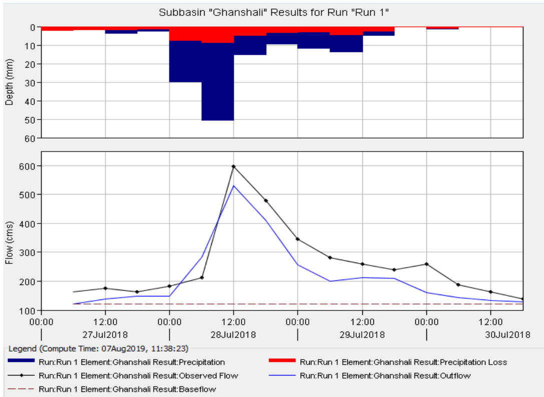


Figure 15. Figure 16.

Figure 15&16. Hydrographs for event-9 and 10 during validation.

4.5 Modelling of ten events of intermediate catchment using HEC-HMS

For this sub-catchment hourly rainfall data of Dharasu, Lambgaon, Tehri and Ghansali have been used. Thiessen weights of Dharasu, Lambgaon, Tehri and Ghansali, are 0.25, 0.35, .25 and 0.15 respectively. The maximum elevation of this sub-catchment is 2826m hence there is no snowmelt contribution in runoff from this sub-catchment. There is no G&D site is available in this part of catchment, therefore, validation of the flows was done at Tehri dam itself.

4.6 Results of event-based modelling of flows at Tehri dam

The runoff contribution of different segments is routed up to the Tehri dam and added together to compute the Tehri flows. The observed and simulated flows at Tehri using HEC-HMS model for the eight events in calibration and validation are plotted in Fig 17 to 32 are compared on the basis of NSE, the percentage difference in peak discharge and percentage difference in flow volumes entering into the reservoir. The results are presented in Table 3 to 5.

The maximum NSE is for the event no 2 during calibration and validation as 90.7% and 89.5% respectively. During calibration the minimum NSE for the event no. 5 is 72.6%. During validation, the minimum efficiency is for event no.7 as 56%. It may be seen from Table 4 that the percentage difference in observed and simulated peak flows varies from -11.6% to +9.6%, which is considered to be satisfactory. Table 5 shows that the percentage differences in flood volumes vary from -4.34% to +7.4%, which may also be considered as satisfactory. However, NSE's are not satisfactory for some of the events.

The validation of the model has also been done for two new storm events of July 2018. The NSE of these two events no. 9 are 10 during validation are 85.3% and 85.1% respectively. The percentage volume entered in to the reservoir for these two events are 0.31% and -8.89% respectively. Fig 31 shows that peaks of simulated flows are under estimated by the model in the event no 9, while the overall flows were under predicted by the model during the validation of the event no 10 as shown in Fig 32.

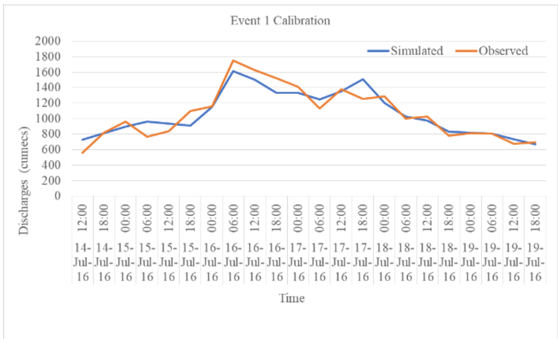


Figure 17.

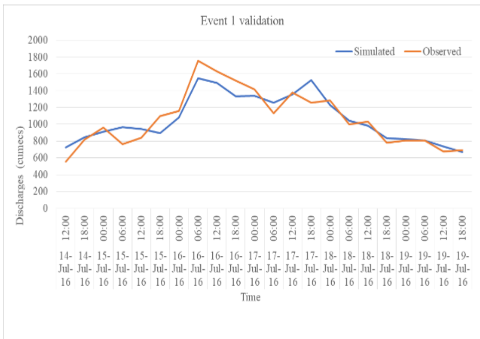


Figure 18.

Figure 17&18. Observed and simulated flows of Bhagirathi at Tehri for event no.1 from July 14, 2016, to July 19, 2016, during calibration and validation.

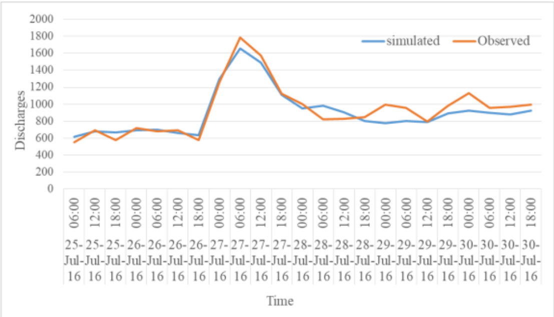


Figure 19.

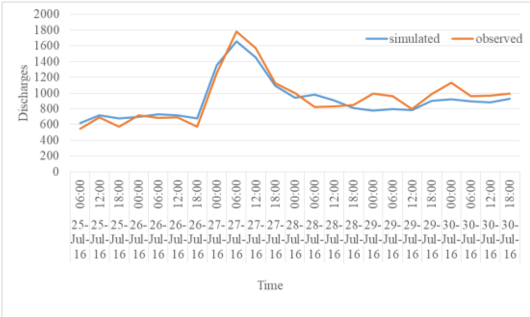
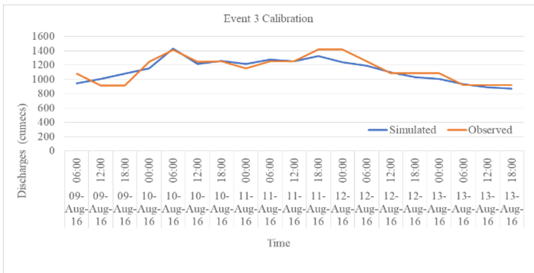


Figure 20.

Figure 19&20. Observed and simulated flows of Bhagirathi at Tehri for event no 2 from July 25, 2016, to July 30, 2016, during calibration and validation.



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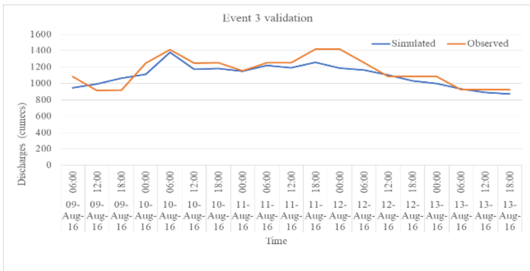

Figure 20.

Figure 19&20. Observed and simulated flows of Bhagirathi at Tehri for event no.3 from Aug 09, 2016 to Aug 13, 2016, during calibration and validation.

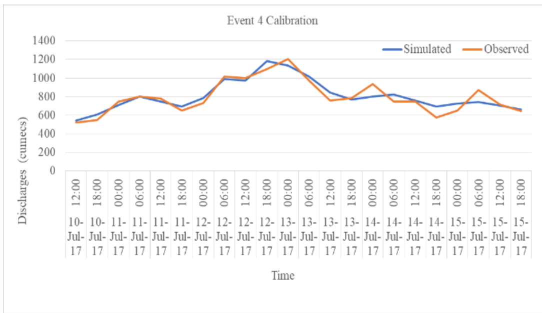

Figure 21.

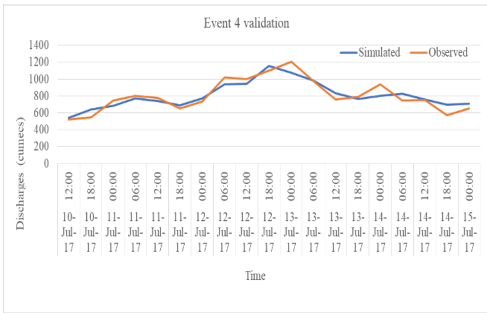

Figure 22.

Figure 21&22. Observed and simulated flows of Bhagirathi at Tehri for event no. 4 from July 10, 2017, to July 15, 2017, during calibration and validation.

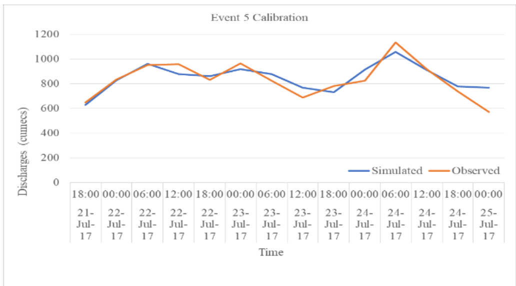

Figure 23.

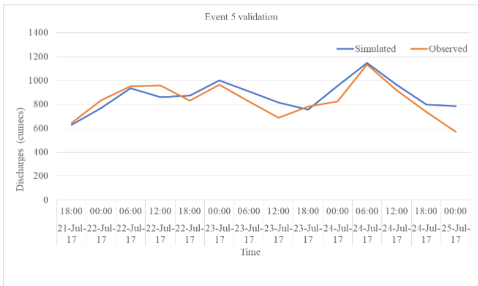

Figure 24.

Figure 23&24. Observed and simulated flows of Bhagirathi at Tehri for event no. 5 from July 22, 2017, to July 25, 2017, during calibration and validation.

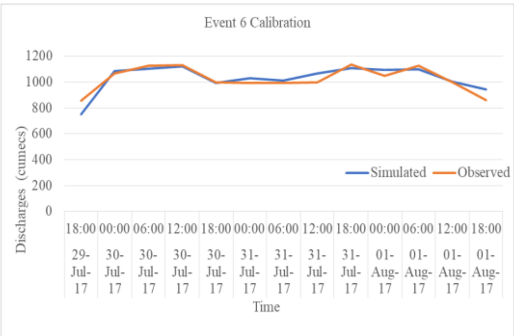

Figure 25.

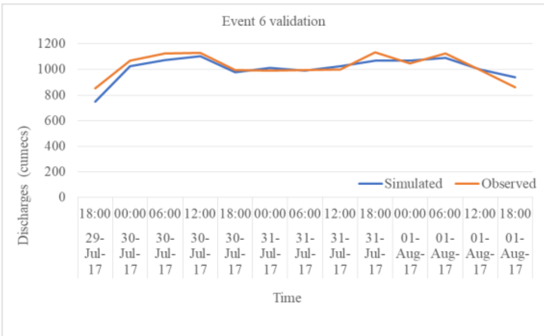

Figure 26.

Figure 25&26. Observed and simulated flows of Bhagirathi at Tehri for event no. 6 from July 29, 2017, to Aug 01, 2017 during calibration and validation.

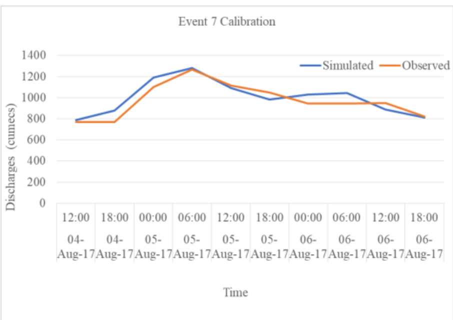

Figure 27.

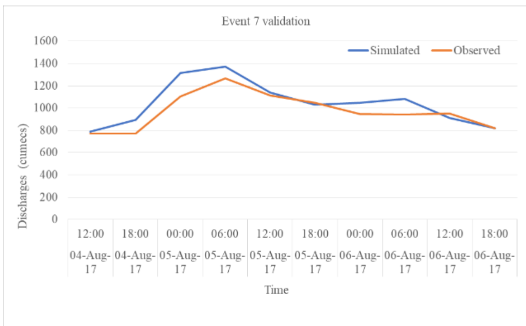

Figure 28.

Figure 27&28. Observed and simulated flows of Bhagirathi at Tehri for event no. 7 from Aug 04, 2017 to Aug 06, 2017 during calibration and validation

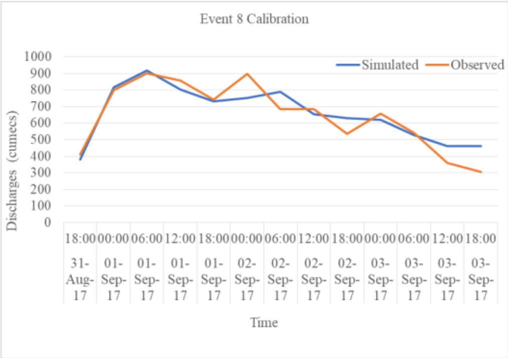

Figure 29.

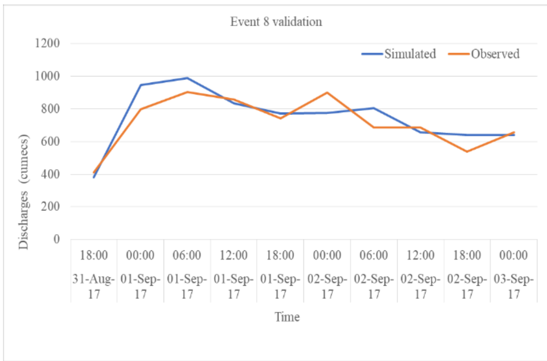

Figure 30.

Figure 29&30. Observed and simulated flows of Bhagirathi at Tehri for event no.8 from Aug 31, 2017, to Sep 03, 2017 during calibration and validation.

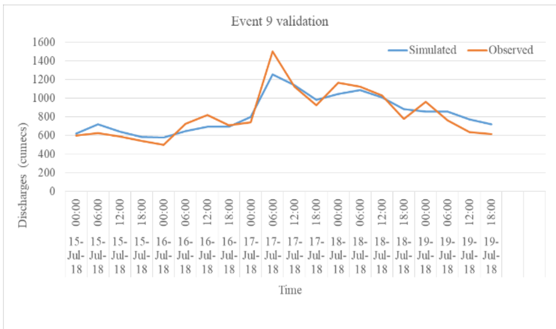

Figure 31.

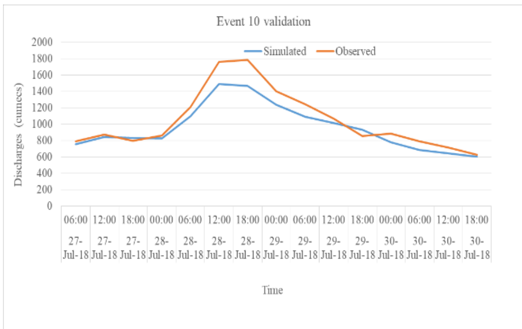

Figure 32.

Figure 31&32. Observed and simulated flows of Bhagirathi at Tehri for event no.9 and 10 from July 15, 2018, to July 20, 2018 during validation.

Table 3. Nash-Sutcliffe efficiency for Tehri catchment during event-based modelling.

Event no.	Efficiency in %	
	Calibration	Validation
1	87.7	85.3
2	90.7	89.5
3	77.1	67.0
4	85.8	82.8
5	72.6	60.5
6	73.4	72.3
7	80.4	56.0
8	83.1	77.9
9	-	85.3
10	-	85.1

Table 4. Observed and computed peak discharges at Tehri.

Event no.	Peak Discharge observed (cumecs)	Peak Discharge computed (cumecs)	Difference in peak discharge (cumecs)	Percentage difference
1	1753.6	1550.6	-203	-11.6
2	1783.0	1634.0	149.0	8.36
3	1420.6	1378.9	-41.7	-2.9
4	1206.8	1155.5	-51.3	-4.3
5	1136	1147.1	11.1	1.0
6	1132.4	1104.8	-27.6	-2.4
7	1267.3	1371.6	104.3	8.2
8	902.7	989.3	86.6	9.6

9	1501.2	1253.6	-247.6	-16.49
10	1786.9	1490.3	-296.6	-16.60

Table 5. Observed and computed volume entered in to the reservoir.

Event no	Observed volume entered in Tehri reservoir (MCM)	Modelled volume entered in Tehri reservoir (MCM)	Difference in volume (MCM)	Percentage difference
1	491.23	489.42	-1.81	-0.37
2	452.8	439.16	-13.64	-3.01
3	450.64	431.08	-19.56	-4.34
4	365.77	363.07	-2.7	-0.74
5	239.15	248.46	9.31	3.89
6	269.25	265.4	-3.85	-1.43
7	192.9	207.17	14.27	7.40
8	173.28	182.71	9.43	5.44
9	342.652	343.698	1.046	0.31
10	322.96	294.237	-28.723	-8.89

5. CONCLUSIONS AND RECOMMENDATIONS

ATI Cold/Melt rate functions and Index (mm) value are highly sensitive to the model. While, the first one is important to run the model the second one is important to simulate the model. Runoff estimation is mandatory to sustain the water resources. Event-based rainfall-runoff modelling using HEC-HMS model gives good result for Tehri dam catchment. Sufficient warning time may be available by using this event based model to evacuate the flood prone area of Rishikesh and Haridwar.

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