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Hydrodynamic simulation of a cloudburst event in Asi Ganga Valley of Indian Himalayan region using MIKE11 and GIS techniques

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सार – भारतीय हिमालयी क्षेत्र में बादलों का फटना सबसे विनाशकारी और अक्सर होने वाली खतरनाक प्राकृतिक घटनाओं में से एक है। स्थानीकृत सघन कपासी संवहनीय बादलों में समिति क्षैतिज क्षेत्र में बहुत अल्प समय में काफी अधिक मात्रा में वर्षा करने की क्षमता होती है। जब कभी इस प्रकार की घटनाएँ होती है, तो आकस्मिक बाढ़ आ जाती है जिससे भू-स्खलन होते हैं, मकान गिर जाते हैं, यातायात अव्यवस्थित हो जाता है तथा बड़े पैमाने पर लोग हताहत होते हैं। इसलिए यह आवश्यक है कि इससे होने वाले नुकसान से बचने के लिए बादल फटने से लेकर जलमग्न होने वाले क्षेत्रों के बारे में सटीक पूर्वानुमान दिया जाए। इसके लिए कार्टोसेट-1 (स्टीरियो जोड़ी) से उच्च विभेदन डिजिटल एलिवेशन मॉडल तैयार किया गया है और असी गंगा तथा भगीरथी नदी में भिन्न- भिन्न स्थानों से पहुँचने वाले जल स्तर तीव्र प्रवाह, प्रवाह वेग, प्रवाह की चौड़ाई का पता लगाने के लिए इसे एम आई के इ 11 हाइड्रोडायनेमिक 1 डी मॉडल के साथ जोड़ा गया है जिससे अध्ययन क्षेत्र का अनुदैर्ध्य प्रोफाइल तैयार किया जा सके और बादल फटने से बाढ़ आप्लावित परिदृश्य का पता लगाया जा सके। भारतीय हिमालयी क्षेत्र के असी गंगा घाटी में 3 अगस्त, 2012 को बादल फटने की एक बहुत बड़ी घटना हुई थी जिसे हाइड्रोडायनेमिक मॉडल का अनुकरण (सिम्युलेशन) माना जाता था। हाइड्रोडायनेमिक मॉडल के सिम्युलेशन के लिए 100 कि.मी/घंटा वर्षा होने पर बादल के फटने की घटना माना जाता है। ऐसा देखा गया है कि असी गंगा नदी के संगम चेट्टी में 1 घंटा में वर्षा 50 मी.^{3}/सेकेण्ड से बढ़कर 549.164 मी.^{3}/सेकेण्ड (लगभग 10 गुना अचानक वृद्धि) और भगीरथी नदी के जोशियारा क्षेत्र में 4 घंटे के भीतर वर्षा 600 मी.^{3}/सेकेण्ड से बढ़कर 3378.69 मी.^{3}/सेकेण्ड (लगभग 5 गुना अचानक वृद्धि) हो गई। इसी तरह से असी गंगा तथा भगीरथी नदियों का जल स्तर क्रमशः लगभग 3 मीटर और 6 मीटर तक बढ़ गया। 3 अगस्त, 2012 को बादल फटने के कारण तीव्र बाढ़ से जलमग्न हुए क्षेत्रों का सीमांकन जी आई सी पर्यावरण में सिम्युलेशन परिणामों से किया गया है।

ABSTRACT. Cloudburst is one of the most devastating and frequently occurring natural hazardous events in Indian Himalayan region. Localized deep cumulus convective clouds have a capability of giving enormous amount of rainfall over a limited horizontal area, within a short span of time. Whenever, such events occur, lead to flash floods causing landslides, house collapses, dislocation of traffic and human casualties on a large scale. Therefore, it is necessary to predict the cloudburst inundation zones accurately to avoid damage associated with them. For this, high resolution Digital Elevation Model generated from CartoSat-1 (Stereo pair) were integrated in MIKE 11 Hydrodynamic 1D model to generate longitudinal profile of the study area and to find water level, peak discharge, flow velocity, flow width at different reaches along the Asi ganga and Bhagirathi river, to know the Cloudburst flood inundation scenario. On 3rd August, 2012 one of the major Cloudburst event occurred in Asi Ganga Valley in Indian Himalayan region which was considered for simulation of hydrodynamic model. For a Cloudburst event, 100 mm/hr rainfall was considered for the simulation of the hydrodynamic model. It is observed that the discharge rise from 50 m^3/s to 549.164 m^3/s (an abrupt increase of about 10 times) within 1 hr at Sangamchetty in Asi Ganga river and at Joshiyara area rise from 600 m^3/s to 3378.69 m^3/s (an abrupt increase of about 5 times) within 4 hr in Bhagirathi river. Similarly, the water level rises around 3 m and 6 m in Asi Ganga and Bhagirathi rivers respectively. Flash Flood inundation areas due to Cloudburst on 3rd August, 2012 were demarcated from the simulation results in GIS environment.

Key words – Cloudburst, Geographic information system (GIS), MIKE11, DEM, Hydrodynamic model.

1. Introduction

Cloudburst is an extreme form of rainfall, sometimes mixed with hail and thunder, which normally lasts no longer than a few minutes but is capable of creating floods conditions. It is usually of shower type with a fall rate equal to or greater than 100 mm/hr (Sati and Maikhuri, 1992). It leads to flash floods/landslides, house collapse, dislocation of traffic and human casualties on large scale. It occurs very frequently in Himalayan region in Uttarkasi

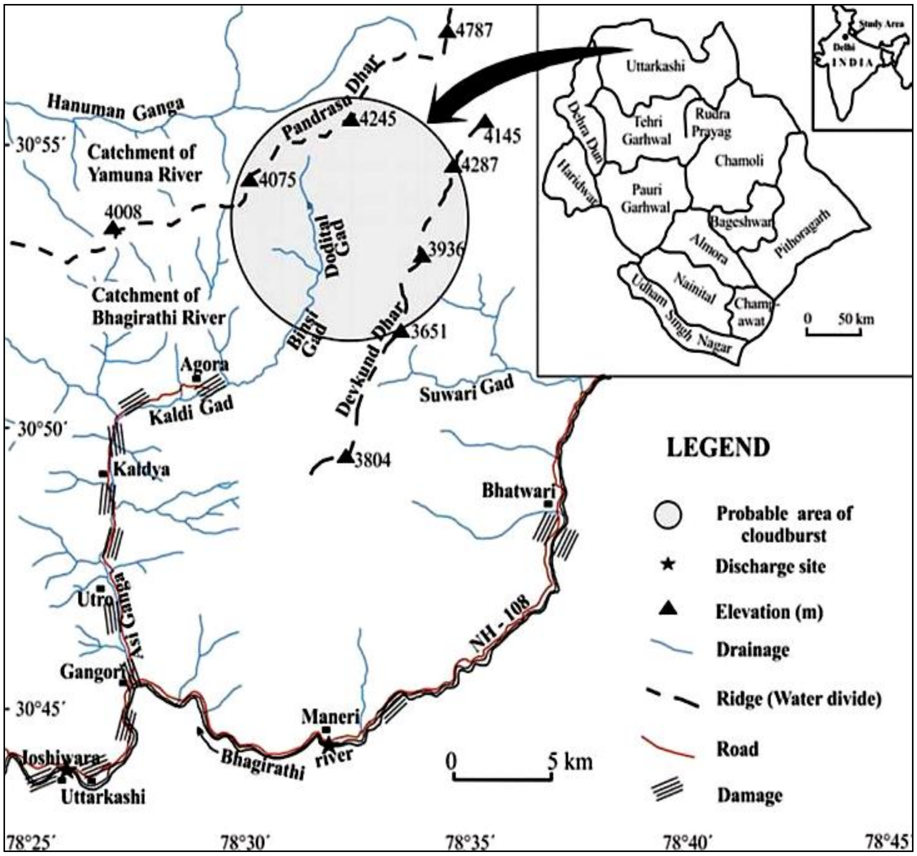


Fig. 1. Location map of the study area depicting the probable area of cloudburst in Asi Ganga Valley (Source - Gupta *et al*., 2013)

district. On 3rd August, 2012 there was cloudburst in Asi Ganga valley and heavy rainfall in upper catchment of Bhagirathi river system, which results peak discharge and overtopping of floods along the river from Sangamchetty to Joshiyara causing huge damage. The basic objective of this study is to prepare the hydrodynamic simulation for a better understanding of cloudburst events.

For prediction of such severe local events, an attempt has made to fidelity of MM5 model configured with multiple-nested domains (81, 27, 9 and 3 km grid resolution) are used to forecast the heavy rainfall 24 hr in advance with attention to horizontal resolution and the cloud Microphysics parameterization (DAS *et al*., 2006). Remote Sensing and geographic information system are the advanced computer based tools and technique which are helpful in analysing the hydrological works related directly and indirectly (Karimi and Houston, 1996; Walker, 1991). A high resolution non-hydrostatic Advanced Research WRF (ARW) mesoscale model developed at National Centre for Atmospheric Research (NCAR) is used to simulate the heavy rainfall on 16 June, 2013 with a resolution of 3 km, keeping Kedarnath and its adjoining areas as the center resulting rainfall associated with the event is well captured (Shekhar *et al*., 2015). Hydrological and Hydrodynamic research deals with the distribution and circulation of water and the interaction of water with environment (Chow, 1988; Subramanya, 2004). Distributed hydrological model combine with the remote sensing information provides hazards characteristic and their effects like water logging, soil erosion, flood height, velocity, inundated area etc. along with calibration and validation of the model. The MIKE 11, a robust six point distributed 1D model was used for Hydraulic analysis to calculate the gauge height at the cross-section modelling (Bates and De Roo, 2000; DHI user guide 2008). Early flood warning system for Langat river basin was developed through the combination of remote sensing and GIS hydrodynamic modelling using MIKE11 model (Billa *et al*., 2004). MIKE 11 was used for parameterization and validation of Bagmoti river, Sikkim (Agrawal *et al*., 2001). Hydrologic model integrate all the physical events leading to better simulation of physical world using Geomatics techniques for hydrologic prediction and for understanding of hydrologic processes. (Kusre *et al*., 2010; Rojanamon *et al*., 2009; Connolly *et al*., 2010). In this study, MIKE 11 model was used to simulate the 3rd August, 2012 cloudburst events of

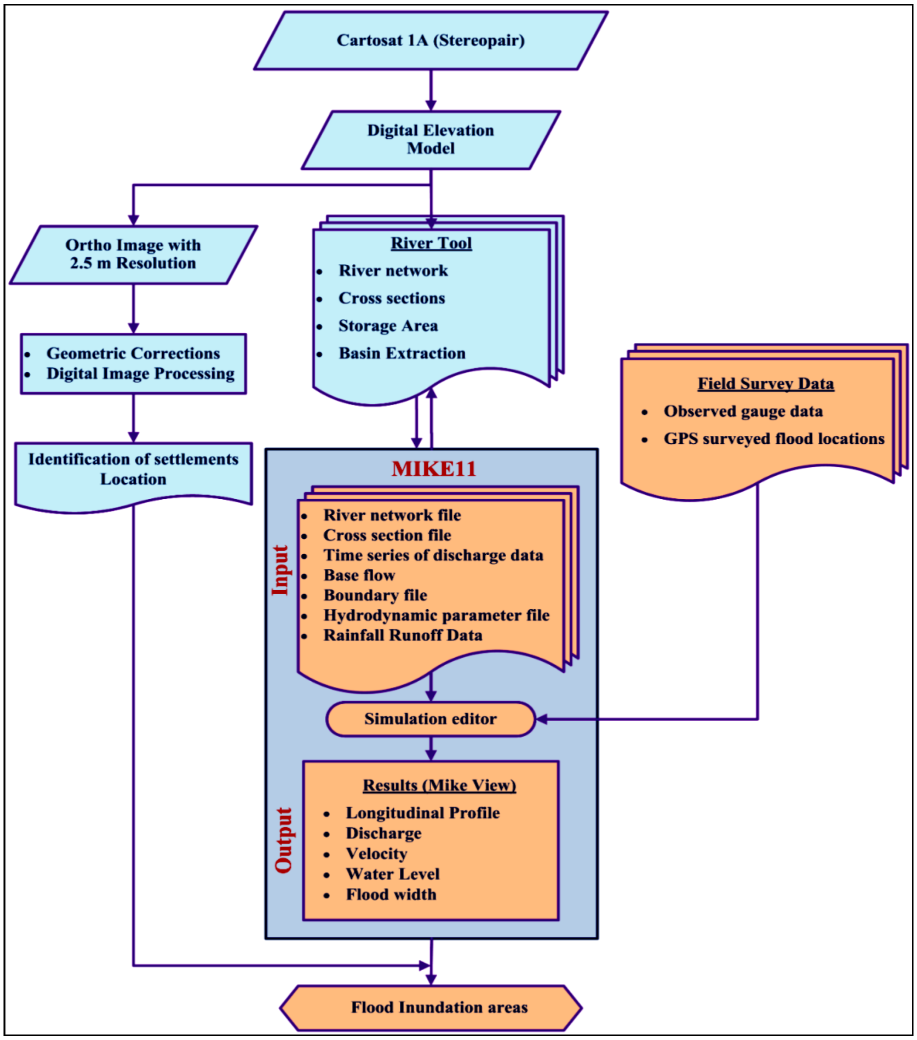


Fig. 2. Flow chart showing overall methodology

Asi Ganga valley. For cloudburst events, peak flood discharge, storm runoff depth, flow velocity and flow width were estimated at catchments outlets along the Asi Ganga, Bhagirathi main streams and its tributaries from Sangamchetty to Joshiyara region and validated the result with field observation.

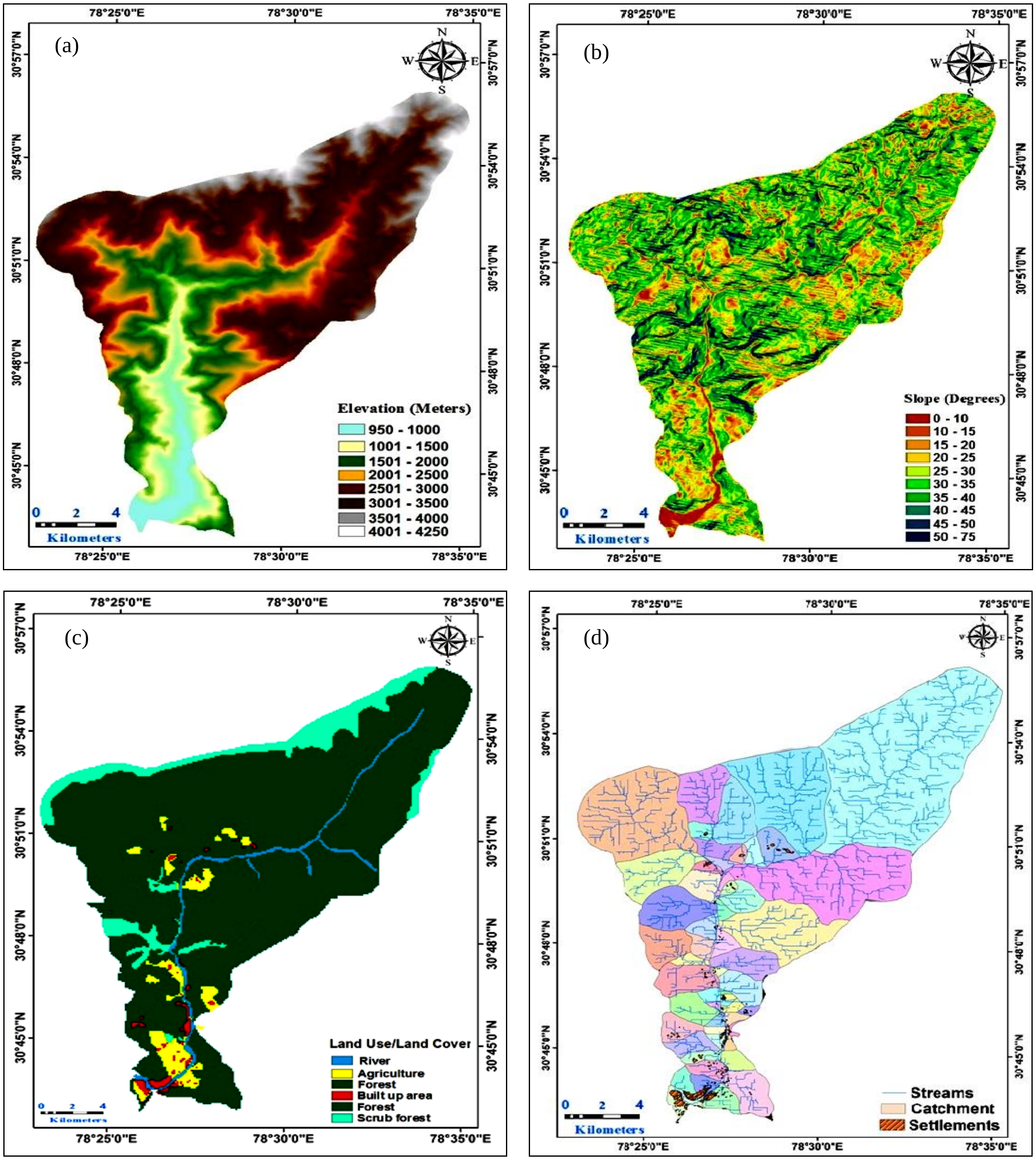
2. Materials and methodology

2.1. *Study area*

The study area Asi Ganga region is in Uttarkashi district, Uttarakhand state. The spatial location of the area varies from 30°57′56″ to 30°43′14″ N latitude and 78°28′51″ to 78°26′32″ E longitude. The total area of the district is about 8016 sq. km with a total population of 329,686. The Asi Ganga valley exhibits characteristically distinct rugged mountainous topography of the both lesser and higher Himalayan terrains. The location map of the probable area of cloudburst in Asi Ganga valley is shown in Fig. 1. The area having several ridges and the ground elevations vary from about 950 to 3045 meters above the mean sea level. The monsoon begins in the first week of June and south west monsoon hits the region in the month of July. Highest rainfall will be received in these months. While August also gets rain, September witnesses the retreat of monsoon. The average amount of rainfall received in southwest monsoon season will be around 1500-2000 mm.

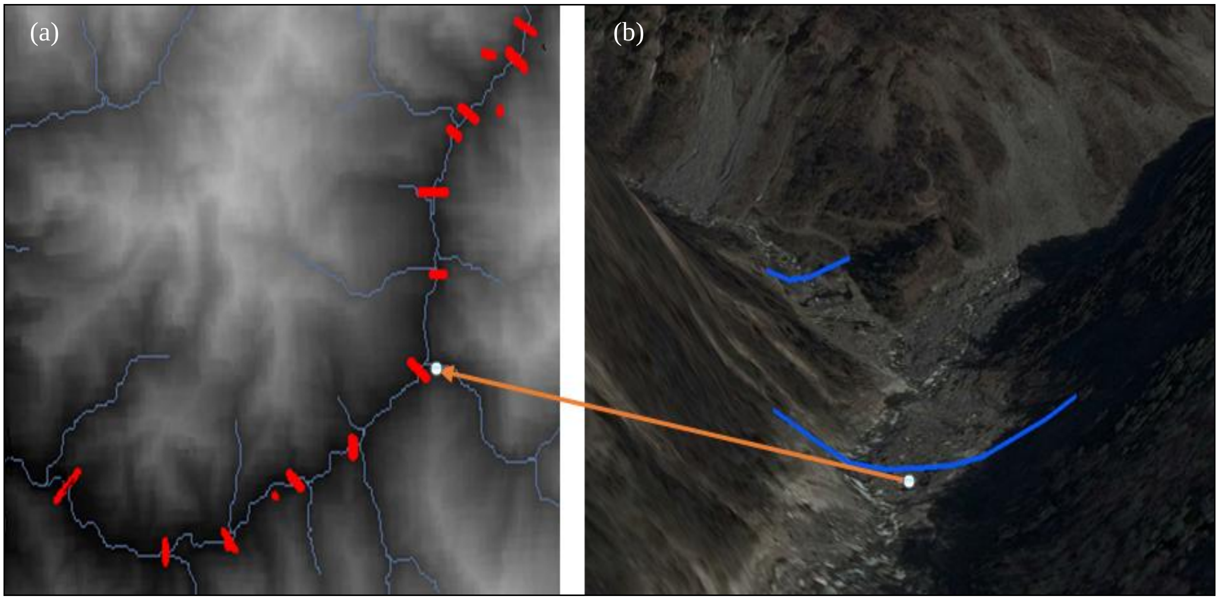
2.2. *Data used*

The high resolution Cartosat digital elevation model (DEM) procured from NRSC, Resourcesat, Landsat 7 ETM+ data set and high resolution satellite images for better visualization were used in this study. The continuous daily and monthly precipitation data was collected from north Ganga Canal Division, Upper Ganga



Figs. 3(a-d). (a) Elevation map, (b) Slope map, (c) Land use/land cover map and (d) Sub catchment area showing with Inhabitations

basin, Roorkee. However one hour rainfall data around 100 mm/hr was used for simulation of the model (for a cloudburst event). For this purpose, Tropical Rainfall Measuring Mission (TRMM) rainfall data was used for reference. The available discharge data (3rd to 5th August, 2012) at Joshiyara barrage collected from Uttarakhand Jal Vidyut Nigam Ltd. (UJVNL), Uttarkashi was used for validation of the model. Peak flood data at Joshiyara barrage for the year 2013 on July 17th was used for calibration and field visit data for validation of the model. Total 15 cross sections were surveyed with in which 4 were situated at junction points of Asi Ganga tributaries. In the field visit, monsoon and post monsoon discharge data, base flow, socio economic data, cross section data,



Figs. 4(a&b). (a) Cross sections extracted from Cartosat DEM; (b) Cross sections overlayed on high resolution satellite image

verification point data for LULC map, roughness of channel and floodplains, average bottom width of the stream, side slope etc. were collected for MIKE11 model set up.

2.3. *Methodology*

Preparation of MIKE11 model for Asi Ganga valley cloudburst events started with generation of high resolution Digital Elevation model using Cartosat stereo pair data. The collected data was processed as an appropriate thematic map for their direct/indirect usage in hydrodynamic model. The river network file created in HEC-GeoRAS was imported in MIKE11 and the cross sections were extracted from high resolution Cartosat DEM. The boundaries parameters were defined at upstream and downstream side for the river network. At upstream side hydrograph and downstream side water level were the input. Considering the channel material, amount and type of vegetation cover, channel sinuosity, effect of obstruction etc. roughness values (N) were determined (Arcement and Schneider, 1989; Chow *et al*., 1995).

The MIKE 11 model was simulated as unsteady flow for 12 hr time duration (cloudburst event) from 3/8/2012 (12:00:00 hour) to 4/8/2012 (12:00:00 hour). The time step for calculation was taken as 2 seconds. Field visit data and photographs at major locations were used for validation. The peak discharge at Gangori and Joshiyara barrage were used for validation of the simulation model. In field visit, photographs of the flood width and water levels marks on the banks and settlements were considered for validation of simulation model results. The overall methodology of the study is shown in Fig. 2.

3. Results and discussion

3.1. *Preparation of thematic layers*

The data was processed as an appropriate thematic map for their direct/indirect usage in hydrodynamic model. A high resolution DEM generated by using Cartosat stereo pair data was used as input to derive various layers and preparation of the database. The area elevation range of the study area varies from 950 m to 4250 m as shown in Fig. 3(a). The cloudburst happened at an elevation of 3500 m. The settlements deposited along the Asi Ganga main channel from Sangamchetty with an elevation 1660 m. Slope is an important factor in understanding the surface water movement (Saraf and Choudhury, 1998; Ghayoumian *et al*., 2005). Slope map of study area was generated using the quadratic surface algorithm developed by Srinivasan and Engel, the maximum elevation changes over the distance between the cells and its eight neighbours were slope (Srinivasan and Engel, 1991; Esri, 2014). The slope of the area varies from flat to very steep slope 0-75 degrees is shown in Fig. 3(b). Some settlements are locating where the slope is greater than 35° which indicates very steep sloping. River in the Asi Ganga valley flowing between ~3400-1200 m at an average gradient of ~90 m/km. Form the slope map, it was observed that the slope patterns in the catchment shows steep slopes towards upper catchment along the northeast to southwest trending. The higher discharge at the catchment outlet raises the height of water of the flash

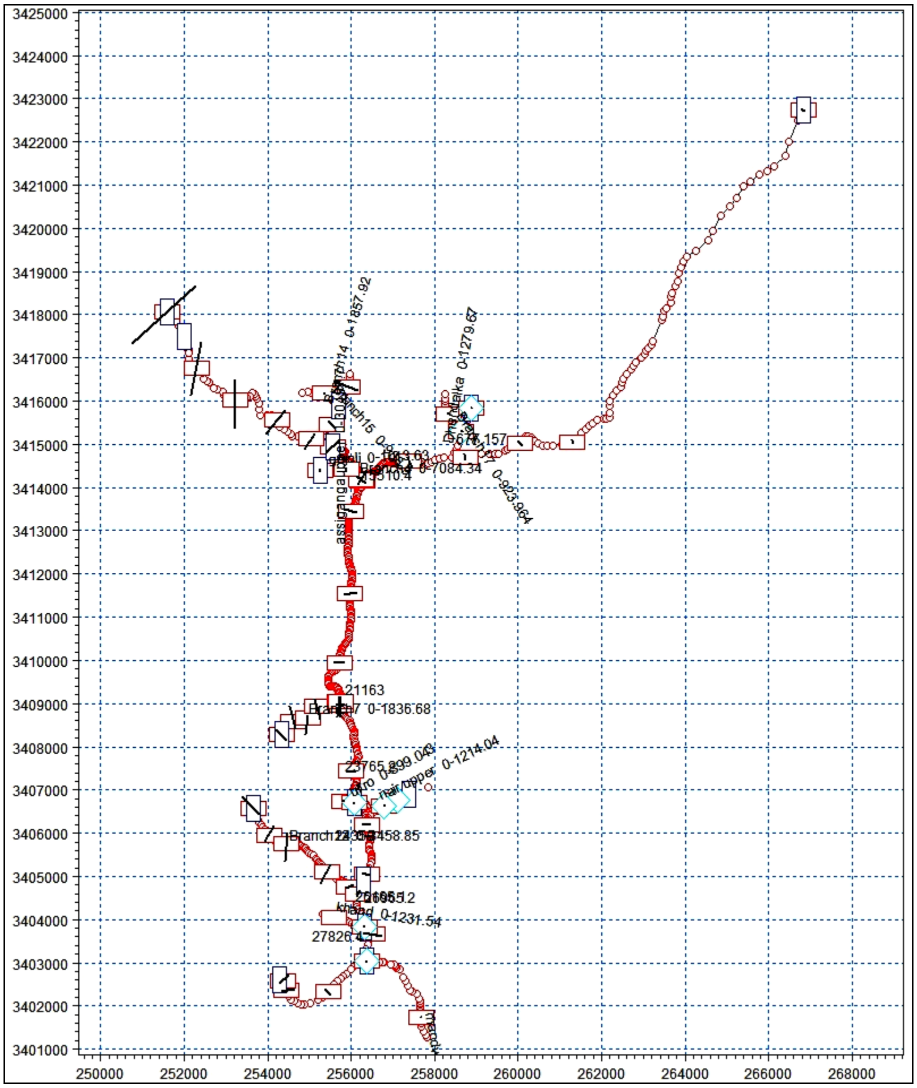


Fig. 5. Drainage network of the study area shown in MIKE11

flood and affected a broader area of the slope causing damage to life and property (Gupta *et al.*, 2013; Dimri *et al.*, 2017). Although the catchment is small but the high rainfall on a steep slope with very high watercourse triggered widespread runoff that smashed houses, road network and bridges along the channels (Dimri *et al.*, 2017). The land use/land cover is an important characteristic of the runoff process that affects the infiltration, erosion and evapotranspiration. Cartosat-1, Resourcesat-2 data from LISS III sensor of 3 seasons pertaining to 2011-12 and high resolution satellite imageries were visually interpreted and ground truth information during field work was used to demarcate the land use/land cover features in the Uttarkashi-Gangori-Dodi Tal area. Various image interpretation elements such as colour, shape, size patterns association etc. were taken into consideration to identify various land use/ land cover categories. Subsequently field checks were conducted in key areas to checks the veracity of remote sensing data and to incorporate the field knowledge on the map. Five major features were identified to assess their contribution towards runoff are shown in Fig. 3(c). From satellite image interpretation the area has appreciable forest cover up to 80 per cent, Scrub forest is about 10 per cent, agriculture is restricted to just 5 per cent of the total area. This is attributed to the fact that the area is sparsely populated around 5 per cent. Streams in the study area are seasonal except river Bhagirathi and Asi Ganga which are perennial. LULC map was used for determining the roughness coefficient along the surveyed cross-section with the help of literature (Arcement and Schneider, 1989). Streams with micro basins map prepared by HEC-GeoHMS are shown in Fig. 3(d).

TABLE 1

Cross section locations according to reach and chainage

S. No.	Reach Name	Chainage	S. No.	Reach Name	Chainage
1.	Asi Ganga	0	23.	Asi Ganga Tributary 1	0
2.	Asi Ganga	9929	24.	Asi Ganga Tributary 1	1575
3.	Asi Ganga	11337	25.	Asi Ganga Tributary 1	2886
4.	Asi Ganga	12711	26.	Asi Ganga Tributary 1	4378
5.	Asi Ganga	14112	27.	Asi Ganga Tributary 1	5386
6.	Asi Ganga (Sangamchetty)	15528	28.	Naugon	0
7.	Asi Ganga (Kaldya School)	16337	29.	Naugon	437
8.	Asi Ganga (Asi Ganga Power House)	18281	30.	Naugon	1052
9.	Asi Ganga	19940	31.	Gajoli	0
10.	Asi Ganga	21238	32.	Gajoli	450
11.	Ultro	22943	33.	Gajoli	625
12.	Gangori	24436	34.	Gajoli	960
13.	Bhagirathi (Gegat)	25660	35.	Ultro	0
14.	Bhagirathi (Tilot)	27226	36.	Ultro	244
15.	Bhagirathi (Uttarkashi)	28963	37.	Nair	0
16.	Bhagirathi (Joshiyara)	30182	38.	Nair	330
17.	Bhagirathi (Joshiyara)	30433	39.	Nair	660
18.	Dhandalka	0	40.	Khand	0
19.	Dhandalka	485	41.	Khand	300
20.	Dhandalka	642	42.	Khand	800
21.	Dhandalka	1071	43.	Mandwa	0
22.	Dhandalka	1500	44.	Mandwa	300

TABLE 2

Catchment detail of each zone in Assi Ganga basin

S. No.	Name	No of settlements	Area (km^2)	Time of concentration (min)	Base flow in monsoon (m^3/s)	Runoff coefficient
1.	Zone 1	00	73.667	81.7	10	0.234
2.	Zone 2	20	11.212	9.45	10	0.264
3.	Zone 3	07	39.730	29.21	10	0.298
4.	Zone 4	83	32.008	30.46	10	0.398
5.	Zone 5	103	16.495	16.59	10	0.25
6.	Zone 6	213	16.823	20.45	10	0.402

The various thematic maps of the catchment were utilized for further processing in MIKE 11. The river network file created in HEC-GeoRAS was imported in MIKE 11 network. After generation of river network, cross section were extracted from Cartosat DEM in ArcGIS is shown in Fig. 4(a) and overlaid on Google earth imagery for better visualization shown in Fig. 4(b). The drainage network in MIKE 11 network editor is shown in Fig. 5. The total length of Asi Ganga River was 33 km from upstream Dodital lake to downstream location at Joshiyara and cross section collected at an interval of 500 m then those were interpolated by using natural neighbour method. Some cross sections were validated with field visit data. Eight reaches-were identified according to the location of settlements and named as Dhandalka, Naugon, Gajoli, Seku, Ultru, Nair, Mandwa and Khand. The name of reaches, their chainage-wise length in UTM coordinate system and junction hydrodynamic flow are mentioned in Table 1. The resistance ratio (observed manning's N/Global manning's N) was given as 1 as per the channel/flood plain material (Walker, 1991).

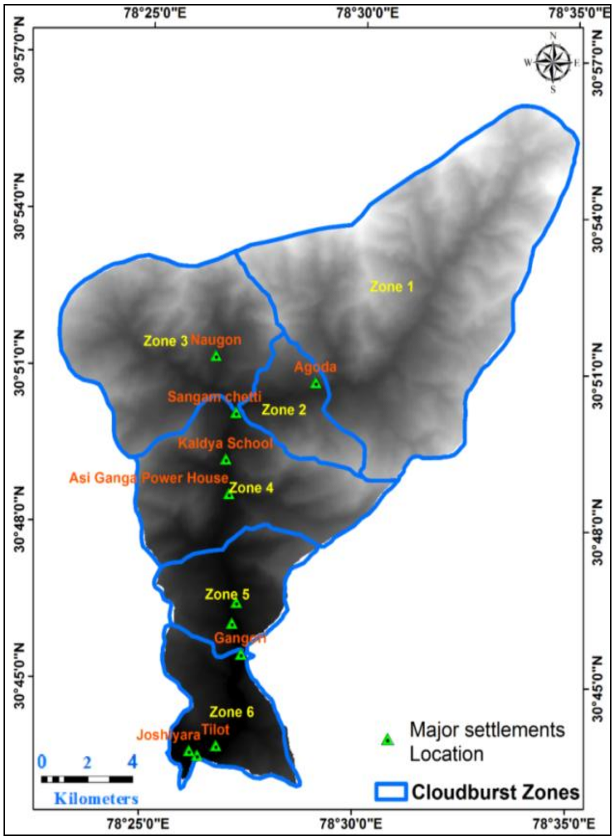


Fig. 6. Clouburst zonation with settlements location

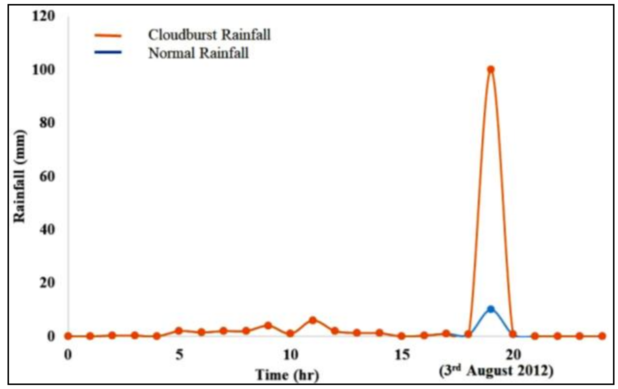


Fig. 7. Rainfall intensity in zone 1 and rest of the zones

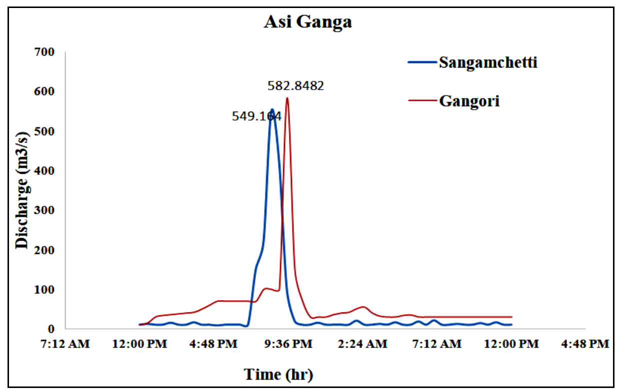


Fig. 8. Discharge in Asi Ganga river

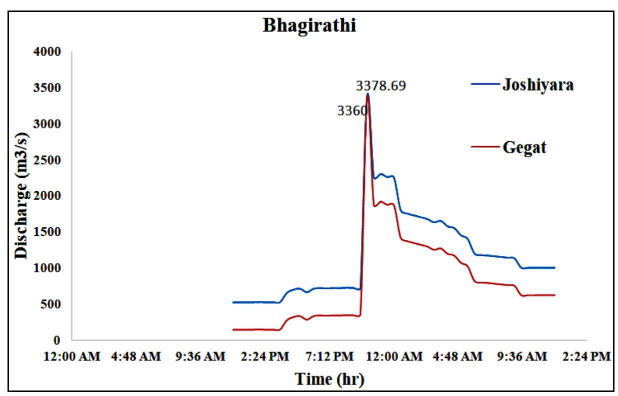


Fig. 9. Discharge in Bhagirathi river

For rainfall runoff modelling, detail of catchments and rainfall distribution file was used as input. The unit Hydrograph model was used for hydrograph generation and Kripich formula was used for time of concentration. Rational method was used for computation of runoff hydrograph for each sub catchment. For simulation of model, the discharge from Bhagirathi river was added as a base flow at Gangori after Asi Ganga meets. Due to heavy rainfall in Bhagirathi upper catchment on 2nd and 3rd August, 2012, the discharge around 2700 m^3/s was added as constant flow to Asi Ganga basin. Cloudburst zone wise map is shown in Fig. 6 and area of each catchment is given in Table 2. The boundary parameters were defined at upstream and downstream side for the river network. At upstream side hydrograph and downstream side water level were the inputs.

The global average value was given for bed roughness as 0.045. The roughness along main Asi Ganga River and other streams, used here were almost same because of the presence of medium and large size boulders without vegetation cover from channel bottoms to banks for each channels. The Manning's 'N' values, used in this study for all the reaches vary from 0.030 to 0.070 among all cross-sections. The simulation model was run as unsteady flow for 12 hr time duration (cloudburst event) from 3/8/2012 (12:00 hour) to 4/8/2012 (12:00 hour). The time step for calculation was taken as 2 seconds.

3.2. *Preparation of hydrodynamic model*

Initial assumption was that cloudburst happened within a range of 1-5 km. In this study, the model simulated for the case in which Cloudburst happens in Zone 1 and rest of zones are normal rainfall (Actual case).

TABLE 3

Comparison of hydrological parameters in monsoon season with cloudbusrt

S. No.	Location	Discharge (m^3/sec)		Flow velocity (m/s)		Flow width (m)		Water level (m)	
		Monsoon	Cloudburst	Monsoon	Cloudburst	Monsoon	Cloudburst	Monsoon	Cloudburst
1.	Sangam chetty	50	549.164	6.0	12.54	25	65.23	1.5	4
2.	Asi Ganga powerhouse	52	559.384	6.0	10.4	25	92.12	1.5	4
3.	Gangori	76	582.848	6.5	10.18	40	75.85	1.25	5.1
4.	Tilot	655	3363.05	5.0	8.36	70	134	1.25	7.05
5.	Joshiyara	662	3378.69	5.0	7.4	120	162.35	1.25	6.9

TABLE 4

N values and discharge (m^3/s)

S. No.	Location	Discharge (m^3/s)			
		N_0.045	N_0.08	N_0.015	Observed
1.	Sangam chetti	180.425	180.4	180.38	270.125
2.	Gegat	874.23	874.205	874.19	905.608
3.	Tilot	1174.65	1174.85	1174.5	1195.6
4.	Joshiyara	1174.7	1174.65	1174.455	1195.608

Cloudburst happened in Zone 1 near Dodital on 3rd August, 2012 around 7 PM. The amount of rainfall used for simulation was 100 mm/hr in Zone 1 and 10 mm/hr for Z2, Z3, Z4 and Z5 respectively as shown in Fig. 7. The peak flood occurred in Asi Ganga due to Cloudburst from 3rd August, 2012 at 20:00:00 hr to 4th August, 2012 at 6:00:00 hr. Therefore above time was selected as the simulation period for the respective cloudburst flood event.

It was observed from results that there was an unusual high discharge on 3rd August, 2012 in Asi Ganga valley and the discharge at Sangamchetty abruptly increased at 20:30 Hrs. The discharge rise from 50 m^3/s to 549.164 m^3/s (an increase about 11 times) within 1 hr. The discharge at Joshiyara rose from 600 m^3/s to 3378.69 m^3/s (an increase of about more than 5 times) within 4 hr. Similarly the peak discharges observed at Gangori (21:40 hrs), Tilot (22:00 hrs) and Joshiyara (22:05 hrs) are 582.848 m^3/sec, 3363.05 m^3/sec and 3378 m^3/sec respectively. The water level at different locations rose from 3 to 5 meters in Asi Ganga basin and up to 7.5 m in Bhagirathi river. Water level at Uttarkashi locations thus rises as much as 4 meters above the danger level. The velocity of flow in the river channel observed to increase from 2 to 12 m/s and the flood width increase from 5 to 10 m from river banks. The time series profile of discharge at Sangamchetty and Gangori in Asi basin is shown in Fig. 8. The time series profile of Gegat and Joshiyara in Bhagirathi River is shown in Fig. 9.

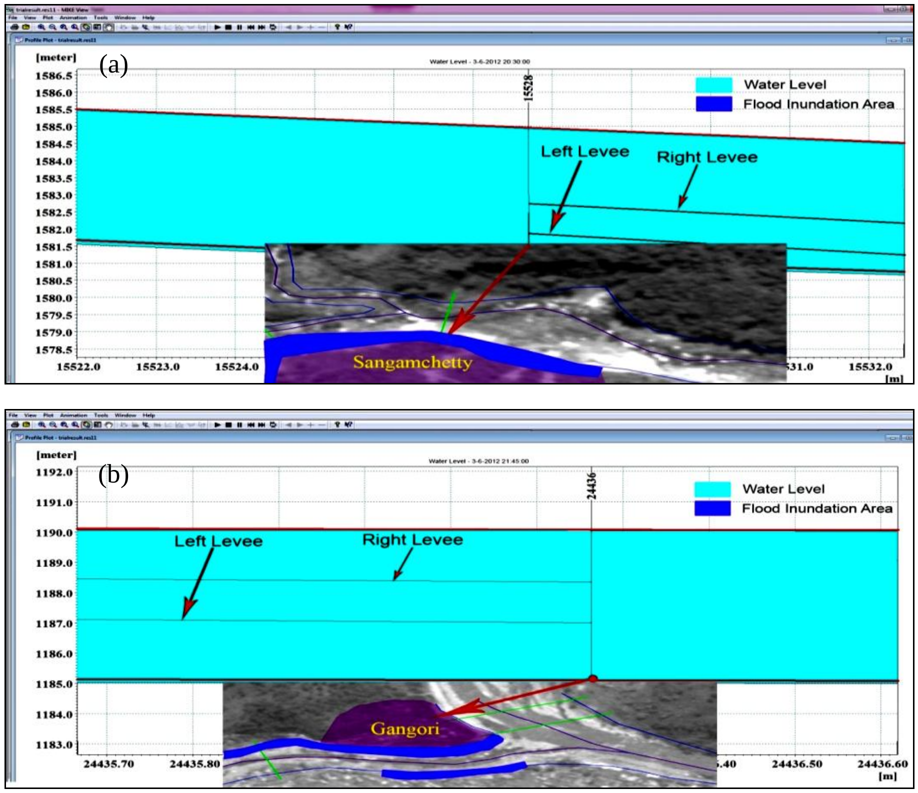
Comparison of Hydrological parameters in normal days of South west monsoon season and in case of cloudburst is shown in Table 3. The longitudinal profile of overtopping water level at Sangamchetty, Gangori in Asi ganga Basin and Tilot, Joshiyara in Bhagirathi river are shown in Figs.10 (a&b) and Figs. 11(a&b) respectively.

3.3. *Calibration of the model*

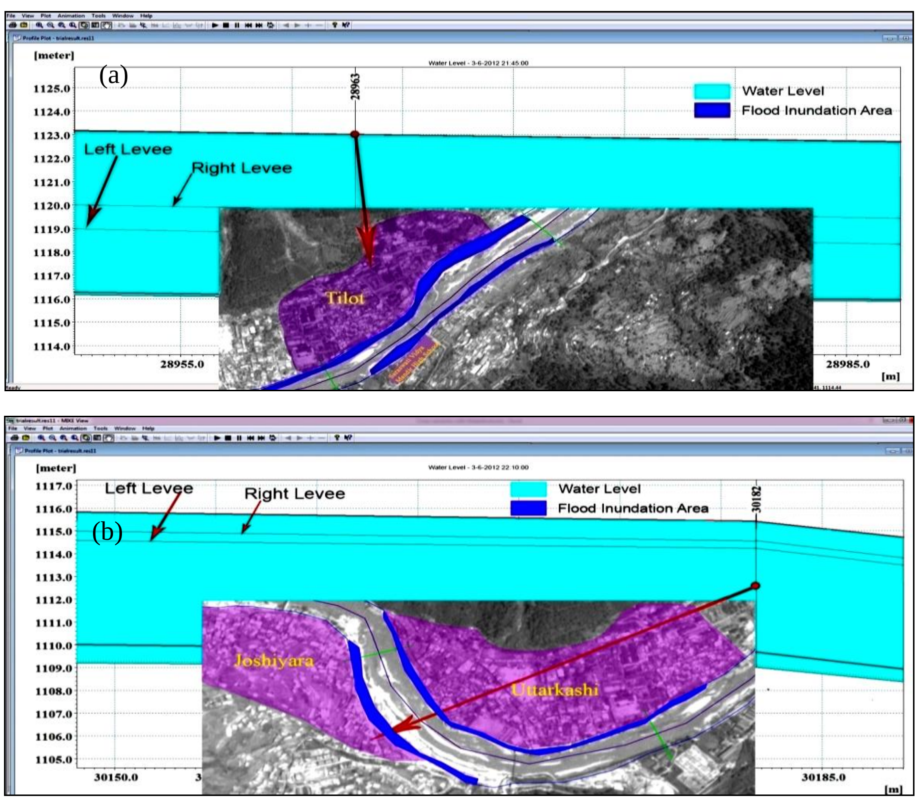
The roughness co-efficient value 'N' was used to observe the relationship between the roughness of channel and discharge amount for 2013 datasets. Three values 0.015, 0.08 and 0.45 are used globally for this purpose. No such change in peak discharges was found as given in Table 4. Among these values, 0.045 gave most suitable output as shown in the validation part. The values were taken globally in the model because the channel morphology was almost similar throughout the reaches. The fully dynamic energy (momentum) was distributed and so, no such changes in simulated discharges were observed after a dramatic change in roughness.

3.4. *Validation of MIKE 11 result*

In Cloudburst condition, it was difficult to get the data for validation because most of the areas were washed out in Asi Ganga region. For present condition, field visit data and photographs at major locations were used for validation. Few stations were available for validation of simulation data in Asi Ganga basin. Remaining data was



Figs. 10(a&b). Map showing location of flood overtopping at (a) Sangamchetty (b) Gangori of Asi Ganga river



Figs. 11(a&b). Map showing location of flood overtopping at (a) Tilot (b) Joshiyara of Bhagirathi river

Figs. 12(a-d). Field observations measured at (a) School entrance of Kaldya village; and water level marks observed at (b) Asi Ganga power house; (c) Gangori bridge and (d) Saraswathi Vidya mandir near Tilot

Fig. 13(a&b). Field observation of washed-out areas at (a) Joshiyara market and (b) Joshiya bridge

TABLE 5

Validation of simulation model with 2012 cloudburst data

S. No.	Location	Discharge (m^3/s)	
		Simulated	Observed
1.	Gangori	582.848	595
2.	Joshiyara	3378.69	3390

validated with the aid of field visit photographs. The peak discharge at Gangori and Joshiyara barrage were used for validation of the simulation model. The validation results are listed in Table 5. In field visit photographs the flood width and water levels marks on the banks and settlements were considered for validation of simulation model results. The field visit data along the main stream channel in Ai Ganga valley and Bhagirath river collected for validation of the model at School entrance of Kaldya village, Asi Ganga power house, settlements near Gangori bridge, Saraswathi vidya mandir near Tilot are shown in Figs. 12(a-d) and field observations of washed-out areas at Joshiyara market and Joshiyara bridge near Joshiyara barrage are shown in Figs. 13(a&b) respectively.

4. Conclusions

Future peak discharges due to cloudburst event indicate the possibility of more serious flash floods in Northern Himalayan region, India. Flood-prone areas in Uttarkashi district, Uttarakhand would be more vulnerable in terms of spatial extent and depth of flooding, due to sudden hitting of Cloudburst leads to increases in peak discharge of the Asi Ganga and Bhagirathi rivers.

Due to cloudburst event in Asi Ganga basin and heavy rainfall in upper Himalayan region, increase of peak discharge in two rivers (Asi Ganga and Bhagirathi) indicate there is an unusual high discharge on 3rd August, 2012 in Asi Ganga valley. It is observed that the discharge rise from 50 m^3/s to 549.164 m^3/s (an abrupt increase of about 10 times) within 1 hr at Sangamchetty in Asi Ganga river and at Joshiyara area rise from 600 m^3/s to 3378.69 m^3/s (an abrupt increase of about 5 times) within 4 hr in Bhagirathi river. Similarly the peak discharges observed at Gangori (21:40 PM), Tilot (22:00 PM) are 582.848 m^3/sec, 3363.05 m^3/sec respectively. The water level at different locations rise from 3 to 5 meters in Asi Ganga basin and upto 7.5 m in Bhagirathi river. Water level at Uttarkashi locations rise around 4 meters above the danger level. The velocity of flow in the river channel observed from 2 to 12 m/s and the flood width increase from 5 to 10 m from river banks.

Due to the recent developments in Uttarkashi district, in terms of population and Land use changes more people will be vulnerable for flooding in future, if the intensity of the Cloudburst is maximum. More infrastructure and houses will be exposed to flooding and the likelihood of increased damage is high. This underscores the need for strengthening flood management policies and adaptation measures in the state Uttarakhand, India to reduce increased flood hazard due to cloudburst.

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