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

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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 Asiganga 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 6m 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.

Keywords - Cloudburst, 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. [1]. 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 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

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42   Sangamchetty to Joshiyara causing huge damage. The basic objective of this study is to prepare
43   the hydrodynamic simulation for a better understanding of cloudburst events.

44   Remote Sensing and geographic information system are the advanced computer based tools
45   and technique which are helpful in analysing the hydrological works related directly and
46   indirectly [2, 3]. Hydrological and Hydrodynamic research deals with the distribution and
47   circulation of water, and the interaction of water with environment [4, 5]. Distributed
48   hydrological model combine with the remote sensing information provides hazards
49   characteristic and their effects like water logging, soil erosion, flood height, velocity, inundated
50   area etc. along with calibration and validation of the model. The MIKE 11, a robust six point
51   distributed 1D model was used for Hydraulic analysis to calculate the gauge height at the cross-
52   section modelling [6, 7]. Early flood warning system for Langat river basin was developed
53   through the combination of remote sensing and GIS hydrodynamic modelling using MIKE11
54   model [8]. MIKE 11 was used for parameterization and validation of Bagmoti river, Sikkim
55   [9]. Hydrologic model integrate all the physical events leading to better simulation of physical
56   world using Geomatics techniques for hydrologic prediction and for understanding of
57   hydrologic processes. [10-12]. In this study, MIKE 11 model was used to simulate the 3rd
58   August 2012 cloudburst events of Asi Ganga valley. For cloudburst events, peak flood
59   discharge, storm runoff depth, flow velocity and flow width were estimated at catchments
60   outlets along the Asi Ganga, Bhagirathi main streams and its tributaries from Sangamchetty to
61   Joshiyara region and validated the result with field observation.

62   **2. Materials and Methodology**

63   **2.1 Study area**
64   The study area Asi Ganga region is in Uttarkashi district, Uttarakhand state. The spatial
65   location of the area varies from $30^0 57'56''$ to $30^0 43'14''$N latitude and $78^0 28'51''$to
66    $78^0 26'32''$E longitude. The total area of the district is about 8016 sq. km with a total population
67   of 329,686. The Asi Ganga valley exhibits characteristically distinct rugged mountainous
68   topography of the both lesser and higher Himalayan terrains. The location map of the probable
69   area of cloudburst in Asi Ganga valley is shown in Fig. 1. The area having several ridges and
70   the ground elevations vary from about 950 to 3045 meters above the mean sea level. The
71   monsoon begins in the first week of June and south west monsoon hits the region in the month
72   of July. Highest rainfall will be received in these months. While August also gets rain,
73   September witnesses the retreat of monsoon. The average amount of rainfall received in
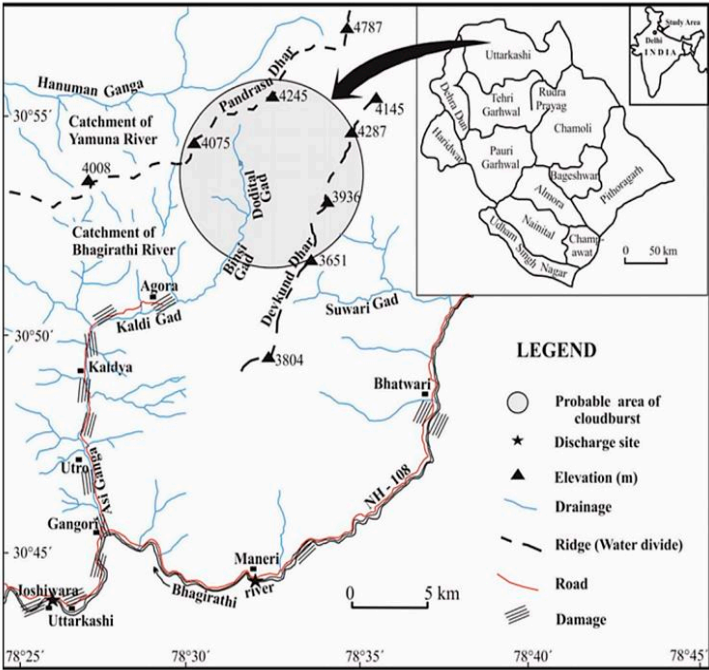74   southwest monsoon season will be around 1500-2000 mm.

Fig. 1: Location map of the study area depicting the probable area of cloudburst in Asi Ganga
        Valley (Source-[13])

75   **2.2 Data used**
76   The high resolution Cartosat digital elevation model (DEM) procured from NRSC,
77   Resourcesat, Landsat 7 ETM+ data set and high resolution satellite images for better
78   visualization were used in this study. The continuous daily and monthly precipitation data was
79   collected from north Ganga Canal Division, Upper Ganga basin, Roorkee. However one hour
80   rainfall data around 100mm/hr was used for simulation of the model (for a cloudburst event).
81   For this purpose, Tropical Rainfall Measuring Mission (TRMM) rainfall data was used for
82   reference. The available discharge data (3rd to 5th August 2012) at Joshiyara barrage collected
83   from Uttarakhand Jal Vidyut Nigam Ltd. (UJVNL), Uttarkashi was used for validation of the
84   model. Peak flood data at Joshiyara barrage for the year 2013 on July 17th was used for
85   calibration and field visit data for validation of the model. Total 15 cross sections were
86   surveyed with in which 4 were situated at junction points of Asi Ganga tributaries. In the field
87   visit, monsoon and post monsoon discharge data, base flow, socio economic data, cross section
88   data, verification point data for LULC map, roughness of channel and floodplains, average
89   bottom width of the stream, side slope etc. were collected for MIKE11 model set up.
90
91   **2.3 Methodology**
92   Preparation of MIKE11 model for Asi Ganga valley cloudburst events started with generation
93   of high resolution Digital Elevation model using Cartosat stereo pair data. The collected data
94   was processed as an appropriate thematic map for their direct/indirect usage in hydrodynamic
95   model. The river network file created in HEC-GeoRAS was imported in MIKE11 and the cross
96   sections were extracted from high resolution Cartosat DEM. The boundaries parameters were
97   defined at upstream and downstream side for the river network. At upstream side hydrograph

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98   and downstream side water level were the input. Considering the channel material, amount and
99   type of vegetation cover, channel sinuosity, effect of obstruction etc. roughness values (N) were
100   determined [14, 15].

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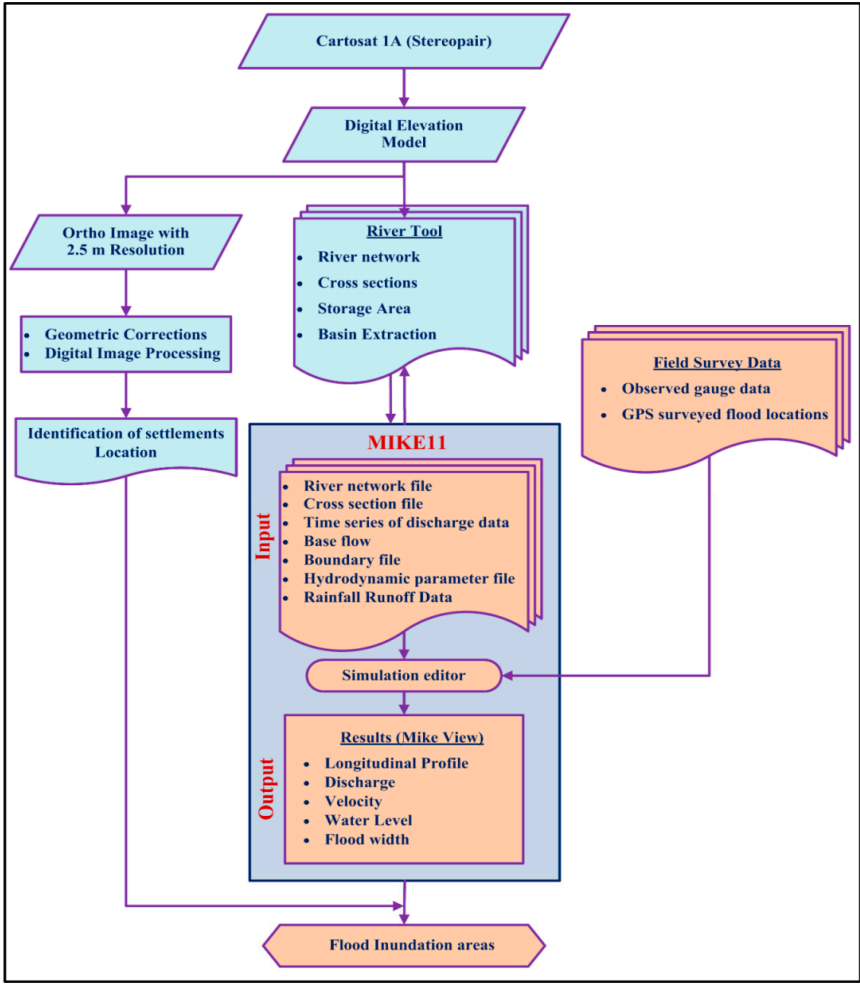
108   Fig. 2: Flow chart showing overall methodology

109   **3. Result and Discussion**

110   **3.1 Preparation of Thematic layers**

111   The data was processed as an appropriate thematic map for their direct/indirect usage in
112   hydrodynamic model. A high resolution DEM generated by using Cartosat stereo pair data was
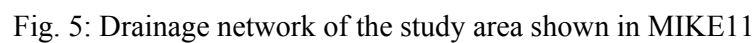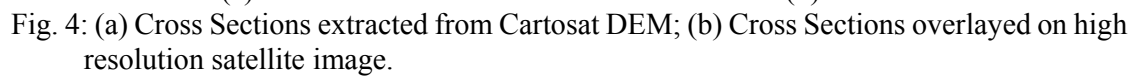
113   used as input to derive various layers and preparation of the database. The area elevation range
114   of the study area varies from 950 m to 4250 m as shown in Fig. 3(a). The cloudburst happened
115   at an elevation of 3500 m. The settlements deposited along the Asi Ganga main channel from
116   Sangamchetty with an elevation 1660 m. Slope is an important factor in understanding the
117   surface water movement [16,17]. Slope map of study area was generated using the quadratic
118   surface algorithm developed by Srinivasan and Engel (1991) [18, 19], the maximum elevation
119   changes over the distance between the cells and its eight neighbours were slope. The slope of
120   the area varies from flat to very steep slope 0- 75^0 degrees is shown in Fig. 3(b). Some
121   settlements are locating where the slope is greater than 35^0 which indicates very steep sloping.
122   River in the Asi Ganga valley flowing between ~3400–1200 m at an average gradient of ~90
123   m/km. Form the slope map, it was observed that the slope patterns in the catchment shows
124   steep slopes towards upper catchment along the northeast to southwest trending. The higher
125   discharge at the catchment outlet raises the height of water of the flash flood and affected a
126   broader area of the slope causing damage to life and property [13, 20]. Although the catchment
127   is small but the high rainfall on a steep slope with very high watercourse triggered widespread
128   runoff that smashed houses, road network and bridges along the channels [20].The land
129   use/land cover is an important characteristic of the runoff process that affects the infiltration,
130   erosion and evapotranspiration. Cartosat-1, Resourcesat- 2 data from LISS III sensor of 3
131   seasons pertaining to 2011-12 and high resolution satellite imageries were visually interpreted
132   and ground truth information during field work was used to demarcate the land use/land cover
133   features in the Uttarkashi–Gangori–Dodi Tal area. Various image interpretation elements such
134   as colour, shape, size patterns association etc. were taken into consideration to identify various
135   land use/land cover categories. Subsequently field checks were conducted in key areas to
136   checks the veracity of remote sensing data and to incorporate the field knowledge on the map.
137   Five major features were identified to assess their contribution towards runoff are shown in
138   Fig. 3(c). From satellite image interpretation the area has appreciable forest cover up to 80
139   percent, Scrub forest is about 10 percent, agriculture is restricted to just 5 percent of the total
140   area. This is attributed to the fact that the area is sparsely populated around 5 percent. Streams
141   in the study area are seasonal except river Bhagirathi and Asi Ganga which are perennial.
142   LULC map was used for determining the roughness coefficient along the surveyed cross-
143   section with the help of literature [14]. Streams with micro basins map prepared by HEC-
144   GeoHMS are shown in Fig. 3(d).

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

156 resistance ratio (observed manning's N / Global manning's N) was given as 1 as per the
157 channel/flood plain material [21].

(a)

(b)

(c)

(d)
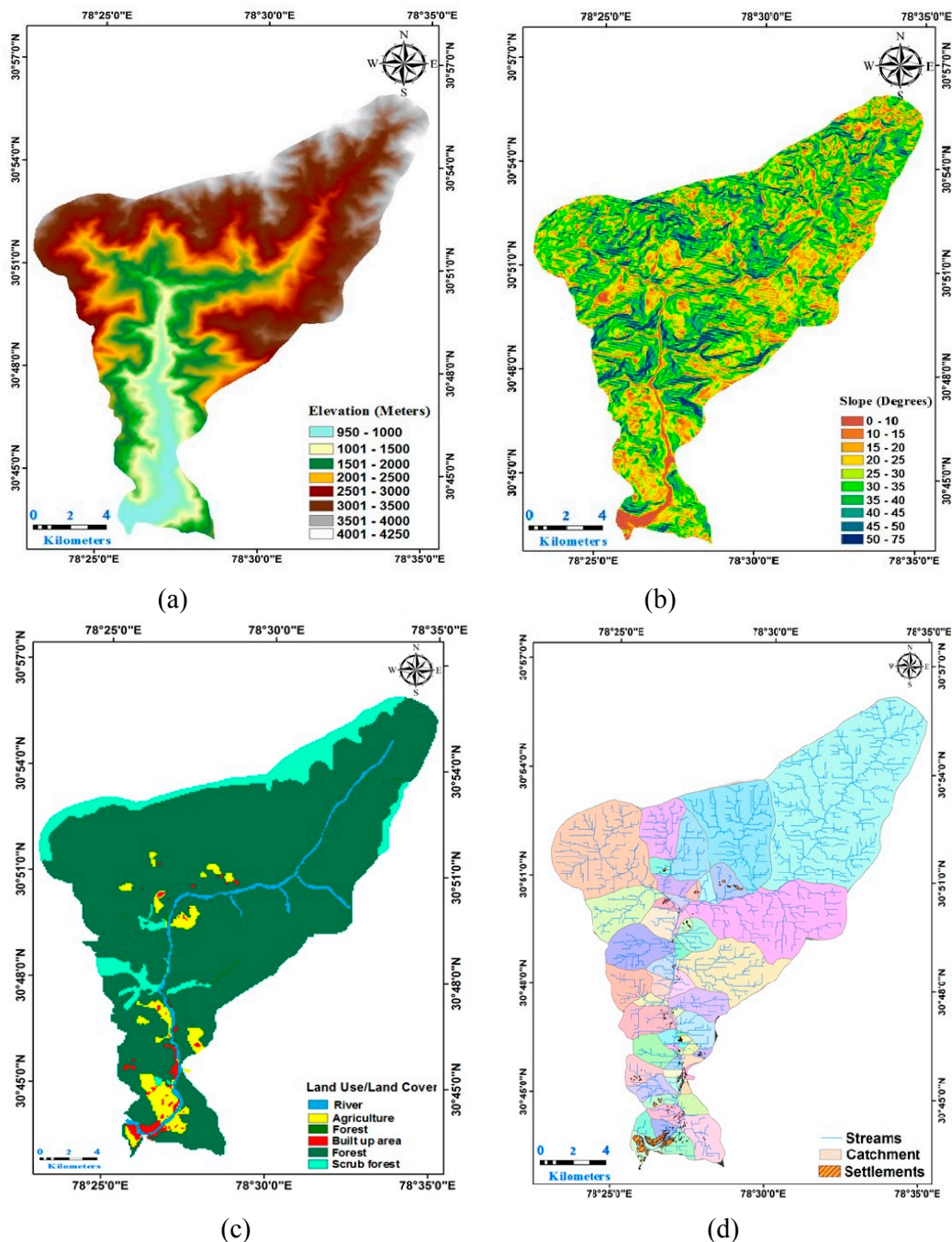
158
159 Fig.3: (a) Elevation Map; (b) Slope map; (c) Land Use / Land Cover map; and (d) Sub
160 catchment area showing with Inhabitations

161   (a)   (b)
162   Fig. 4: (a) Cross Sections extracted from Cartosat DEM; (b) Cross Sections overlayed on high
163   resolution satellite image.

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

165   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

166   For Rainfall Runoff Modelling, detail of catchments and rainfall distribution file was used as
167   input. The unit Hydrograph model was used for hydrograph generation and Kripich formula
168   was used for Time of concentration. Rational method was used for computation of runoff

169 hydrograph for each sub catchment. For simulation of model, the discharge from Bhagirathi
170 River was added as a base flow at Gangori after Asi Ganga meets. Due to heavy rainfall in
171 Bhagirathi upper catchment on 2nd and 3rd August 2012, the discharge around 2700 m^3/s was
172 added as constant flow to Asi Ganga basin. Cloudburst zone wise map is shown in Fig. 6 and
173 area of each catchment is given in Table 2. The boundary parameters were defined at upstream
174 and downstream side for the river network. At upstream side hydrograph and downstream side
175 water level were the inputs.
176 The global average value was given for bed roughness as 0.045. The roughness along main Asi
177 Ganga River and other streams, used here were almost same because of the presence of medium
178 and large size boulders without vegetation cover from channel bottoms to banks for each
179 channels. The Manning's 'N' values, used in this study for all the reaches vary from 0.030 to
180 0.070 among all cross–sections. The simulation model was run as unsteady flow for 12 hr time
181 duration (cloudburst event) from 3/8/2012 (12:00 hour) to 4/8/2012 (12:00 hour). The time step
182 for calculation was taken as 2 seconds.

183 **3.2 Preparation of Hydrodynamic Model**

184 Initial assumption was that cloudburst happened within a range of 1-5 km. In this study, the
185 model simulated for the case in which Cloudburst happens in Zone 1 and rest of zones are
186 normal rainfall (Actual case). Cloudburst happened in Zone 1 near Dodital on 3rd August 2012
187 around 7 PM. The amount of rainfall used for simulation was 100mm/hr in Zone 1 and
188 10mm/hr for Z2, Z3, Z4 and Z5 respectively as shown in Fig. 7. The peak flood occurred in
189 Asi Ganga due to Cloudburst from 3rd August 2012 at 20:00:00 hr to 4th August 2012 at 6:00:00
190 hr. Therefore above time was selected as the simulation period for the respective cloudburst
191 flood event.
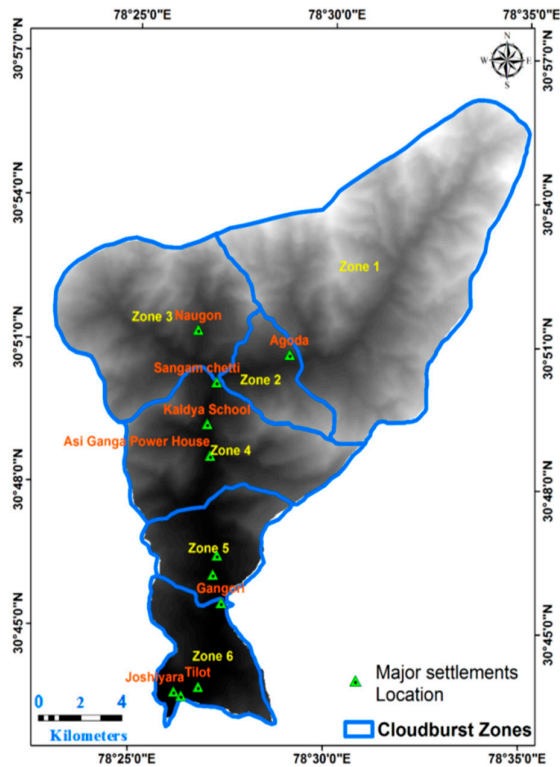
192   Fig. 6: Clouburst zonation with settlements location.

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193   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
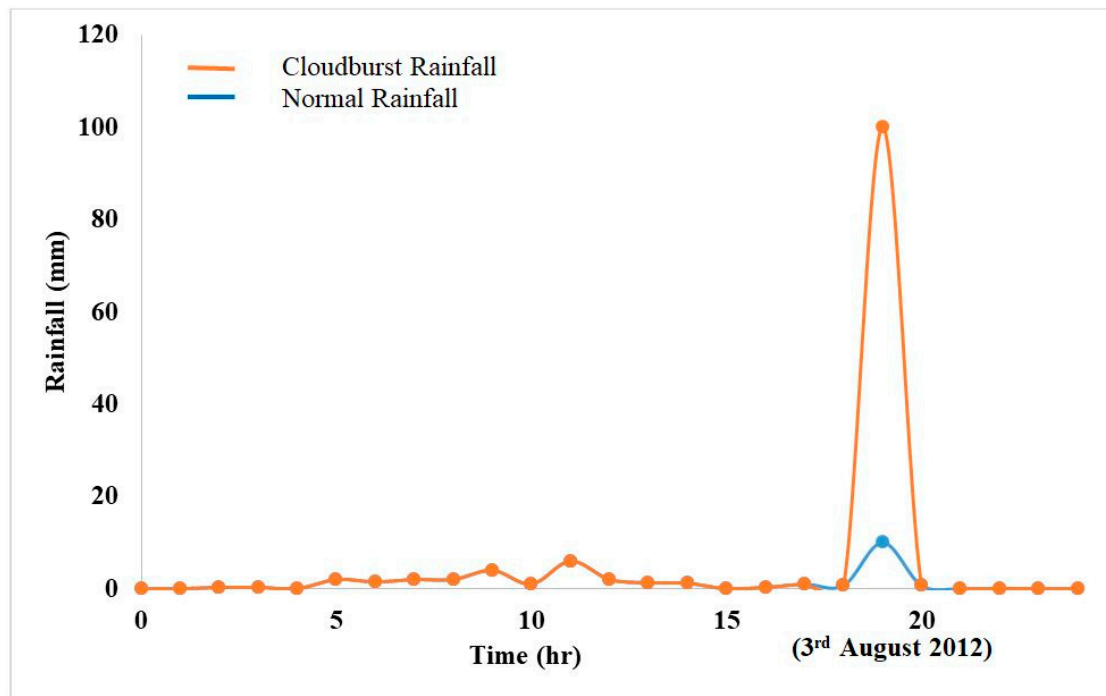
194   Fig. 7: Rainfall intensity in Zone 1 and rest of the zones

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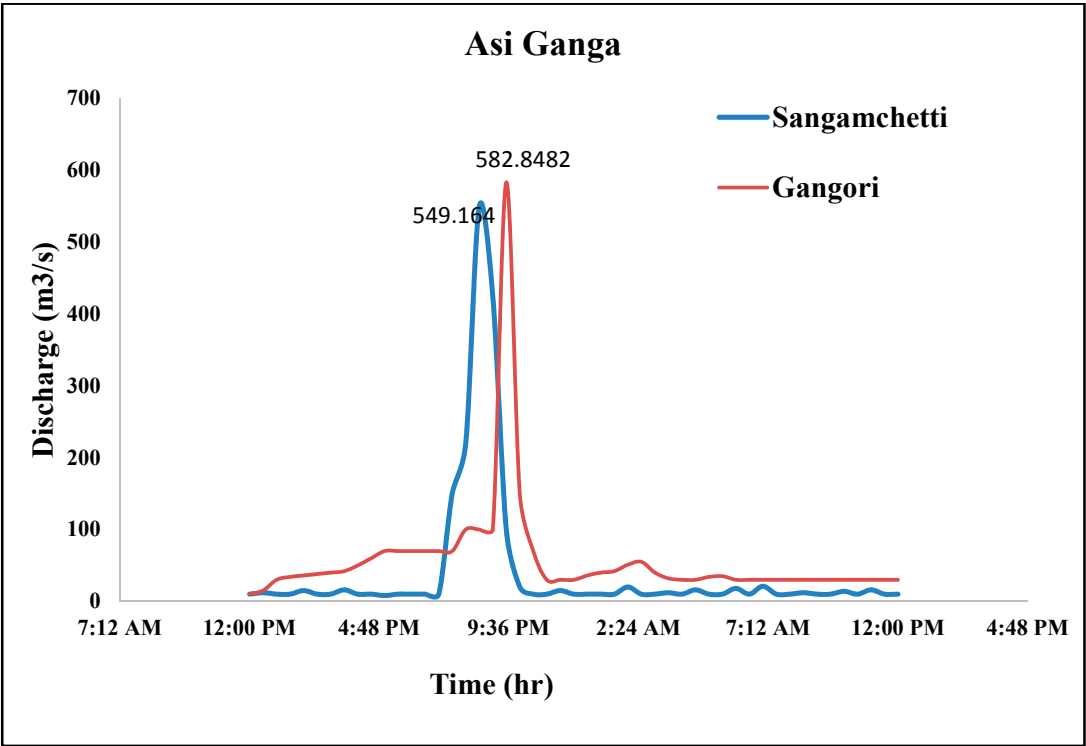
207   Fig. 8: Discharge in Asi Ganga River
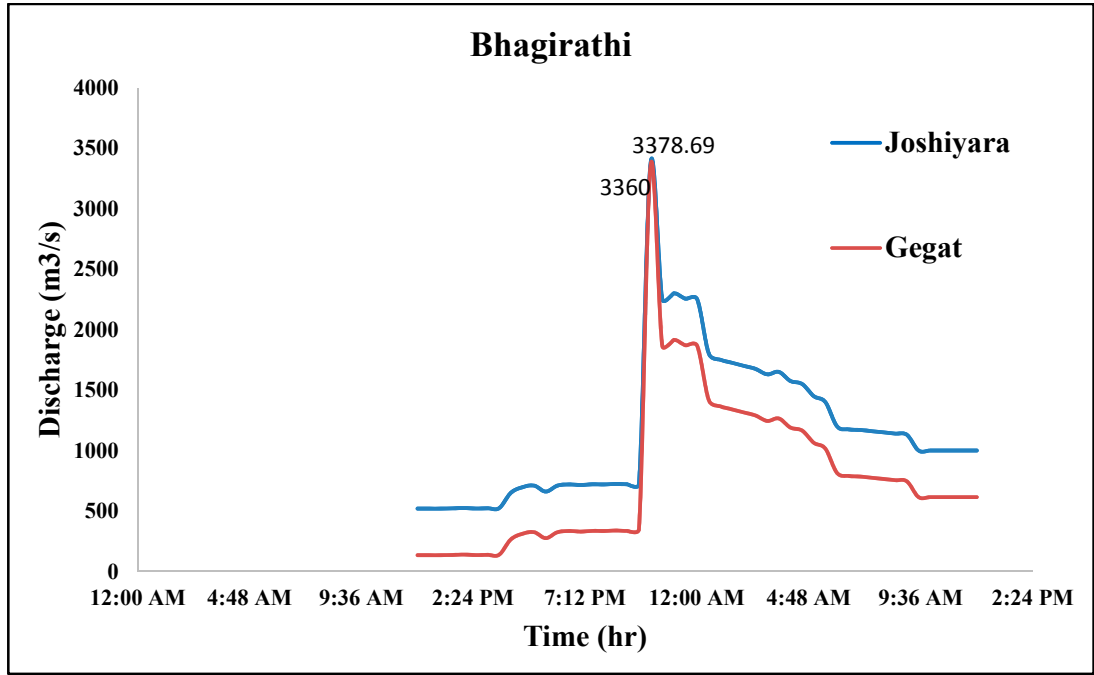

208   Fig. 9: Discharge in Bhagirathi River

209   Comparison of Hydrological parameters in normal days of South west monsoon season and in
210   case of cloudburst is shown in Table 3. The Longitudinal profile of overtopping water level at

211   Sangamchetty, Gangori in Asi ganga Basin and Tilot, Joshiyara in Bhagirathi river are shown
212   in Fig.10 (a) & (b) and Fig. 11(a) & (b) respectively.

213   Table 3: Comparison of Hydrological parameters in Monsoon season with Cloudbusrt

S.No.	Location	Discharge (m³/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
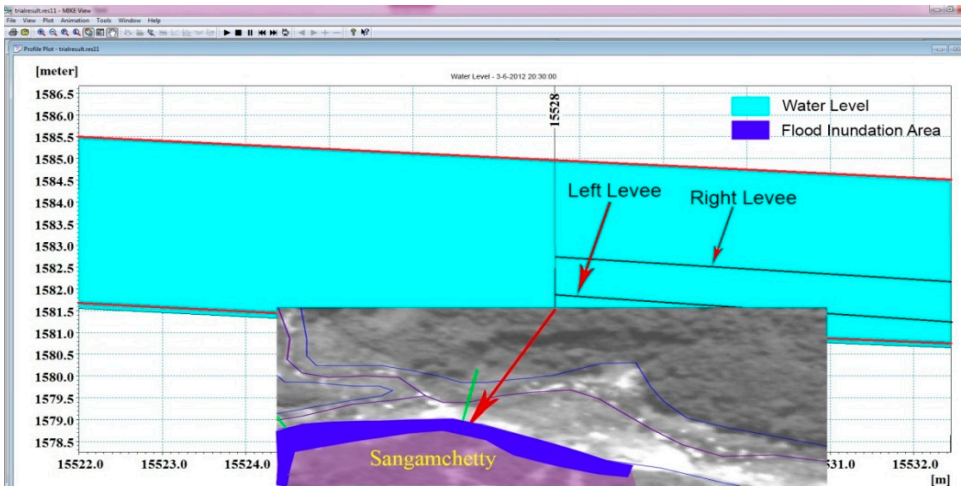
214   Fig.10 (a) : Map showing location of flood Overtopping at Sangamchetty of Asi Ganga River
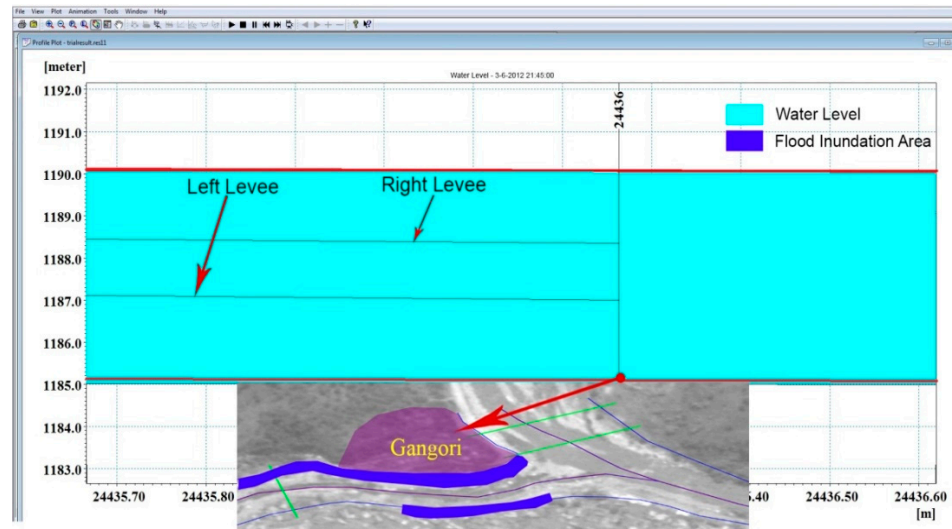
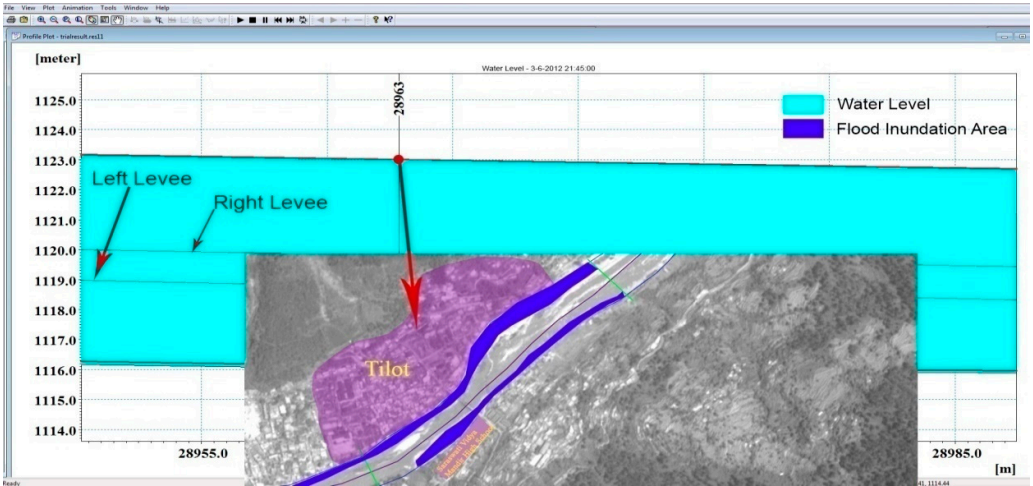215   Fig.10 (b) : Map showing location of flood Overtopping at Gangori of Asi Ganga River

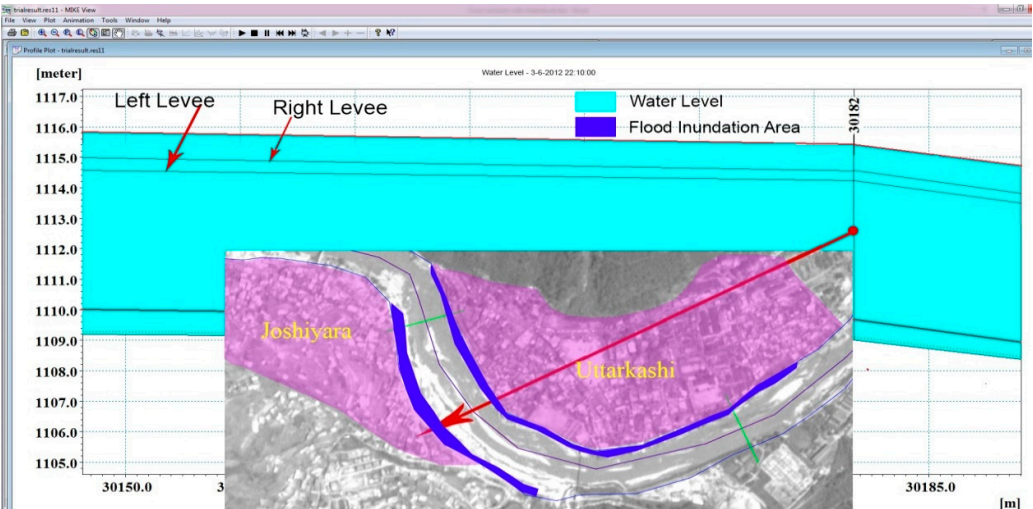216 Fig.11 (a) : Map showing location of flood Overtopping at Tilot of Bhagirathi River

217 Fig.11 (b) : Map showing location of flood Overtopping at Joshiyara of Bhagirathi River

218 **3.3 Calibration of the Model**

219 The roughness co-efficient value 'N' was used to observe the relationship between the
220 roughness of channel and discharge amount for 2013 datasets. Three values 0.015, 0.08 and
221 0.45 are used globally for this purpose. No such change in peak discharges was found as given
222 in Table 4. Among these values, 0.045 gave most suitable output as shown in the validation
223 part. The values were taken globally in the model because the channel morphology was almost
224 similar throughout the reaches. The fully dynamic energy (momentum) was distributed and so,
225 no such changes in simulated discharges were observed after a dramatic change in roughness.

226   Table 4 N values and discharge (m^3/s)

227

S.No.	Location	Discharge (m^3/s)			
		N_0.045	N_0.08	N_0.015	Observed
1	Sangamchetti	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

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 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 Fig. 12 (a), (b), (c) & (d) and field observations of washed-out areas at Joshiyara market and Joshiyara bridge near Joshiyara barrage are shown in Fig. 13 (e) & (f) respectively.

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

(a)   (b)

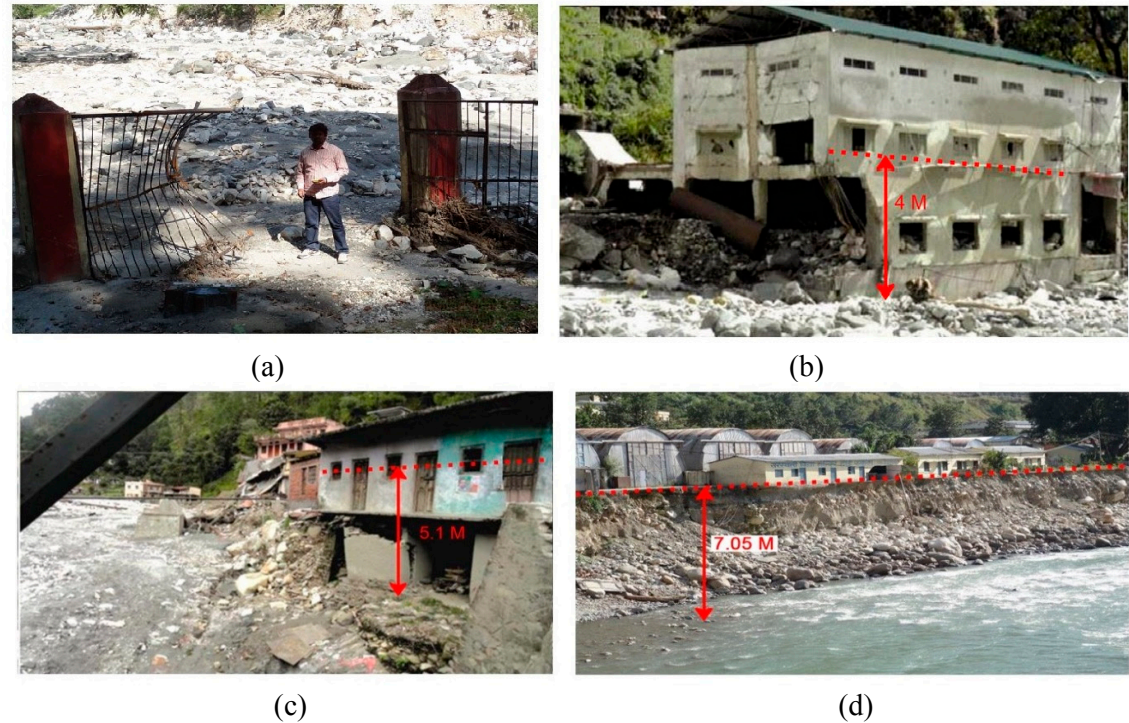(c)   (d)

Fig. 12: 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

248   Fig. 13: Field observation of washed-out areas at (e) Joshiyara Market and (f) Joshiya bridge

249   **4. Conclusions**

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

255

256   Due to Clousburst event in Asi Ganga basin and heavy rainfall in upper Himalayan region,
257   increase of peak discharge in two rivers (Asi ganga and Bhagirathi) indicate there is an unusual
258   high discharge on 3rd August 2012 in Asi Ganga valley.It is observed that the discharge rise
259   from 50 m³/s to 549.164 m³/s (an abrupt increase of about 10 times) within 1 hr at
260   Sangamchetty in Asiganga river and at Joshiyara area rise from 600 m³/s to 3378.69 m³/s (an
261   abrupt increase of about 5 times) within 4 hr in Bhagirathi river. Similarly the peak discharges
262   observed at Gangori (21:40 PM), Tilot (22:00 PM) are 582.848 m³/sec, 3363.05 m³/sec
263   respectively. The water level at different locations rise from 3 to 5 meters in Asi Ganga basin
264   and upto 7.5 m in Bhagirathi river. Water level at Uttarkashi locations rise around 4 meters
265   above the danger level. The velocity of flow in the river channel observed from 2 to 12 m/s and
266   the flood width increase from 5 to 10 m from river banks.

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

Author Contributions:

Vasanta Govind Kumar Villuri, Kamal Jain and Ajay Gairola have got major contributions in this work in conceiving the research, analysing DEM and in preparation of hydrodynamic model. All authors involved in summarizing the results and findings. Vasanta Govind Kumar Villuri, Kamal Jain, Ajay Gairola and Srinivas Pasupuleti are involved in preparing the manuscript.

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