Kedarnath flash floods: a hydrological and hydraulic simulation study

K. H. V. Durga Rao*, V. Venkateshwar Rao, V. K. Dadhwal and P. G. Diwakar

National Remote Sensing Centre, Indian Space Research Organisation, Balanagar, Hyderabad 500 037, India

The recent floods in the Kedarnath area, Uttarakhand are a classic example of flash floods in the Mandakini River that devastated the country by killing thousands of people besides livestock. Though the duration of the event was small compared to other flood disasters in the country, it resulted in severe damage to property and life. Post-disaster satellite images depict that the river banks were eroded completely along the Kedarnath valley due to the flash floods and few new channels were visible. Extreme erosion took place in the upstream portion of Kedarnath, besides the breach of Chorabari Lake and deposition of debris/sediments in the valley. Hydrological and hydraulic simulation study was carried out in the Mandakini River using space-based inputs to quantify the causes of the flash floods and their impact. Chorabari Lake breach analysis was carried out using Froehlich theory. Flood inundation simulations were done using CARTO DEM of 10 m posting in which the combined effect of lake breach and high-intensity rainfall flood was examined. As the slopes are very steep in the upstream catchment area, lag-time of the peak flood was found to be less and washed-off the Kedarnath valley without any alert. The study reveals quantitative parameters of the disaster which was due to an integrated effect of high rainfall intensity, sudden breach of Chorabari Lake and very steep topography.

Keywords: Flash floods, flood inundation simulation, hydrological modelling, lake breach.

A major challenge associated with flash floods is the quantitative character of the forecast; the task is not just to forecast the occurrence of an event, which is difficult enough by itself, but to anticipate the magnitude of the event. It is the amount of precipitation that transforms an otherwise ordinary rainfall into an extraordinary, life-threatening situation. This challenge is exacerbated by the interaction of the meteorology with hydrology[1]. Advances in the flood forecasting beyond the present state-of-the-art are to be achieved, amongst others, on the basis of extending forecast lead-time. This can be done by weather forecasting at various temporal and spatial resolutions[2].

During 15–17 June 2013, incessant rainfall centred at Uttarakhand, caused devastating floods and landslides in the country's worst natural disaster since the 2004 tsunami[3,4]. Experts say that it is another alarm regarding the impact of rapid climate change on the environment[3,5]. Unprecedented destruction by the rainfall witnessed in Uttarakhand was attributed to a unique meteorological event by environmentalists due to unscientific developmental activities undertaken in recent decades contributing to loss of lives and property. The satellite imageries show that massive landslides occurred in the upstream northeast region of the Kedarnath valley due to high-intensity rainfall[6]. In the present work, hydrological and hydraulic simulation study was carried out on the Mandakini River to understand the events which took place in the Kedarnath valley during 10–18 June 2013. The disaster was due to an integrated effect of heavy rainfall intensity, sudden outburst of a lake (Chorabari), and very steep topographic conditions. The complete scenario was simulated in the Geographic Information System (GIS) environment using remote sensing data inputs through HEC–HMS and HEC–RAS hydrological modelling software and is discussed below.

Unprecedented rainfall between 10 and 18 June 2013 in the Alaknanda and Bhagirathi catchments was the main cause of the disaster in Uttarakhand. Mandakini River which is a tributary of the Alaknanda generally receives normal rainfall during June. Average June rainfall at Kedarnath during 2007–2012 was less than 200 mm (ref. 7). According to the India Meteorological Department, cumulative rainfall during 14–18 June 2013 at Tehri, Uttarkasi, Tharali and Jakoli was 381, 359, 326 and 390 mm respectively[8]. This high rainfall was due to strong interaction between an oncoming trough in the westerlies and the strong southeasterly monsoon wind flow in association with a monsoon low-pressure system over the North Indian region, resulting in the development of lower tropospheric wind convergence over Uttarakhand and neighbouring regions[8]. Various sources quoted that heavy rainfall occurred during the flood event, but data from very few stations were available as many rain gauge stations were washed-off[3,7]. Due to non-availability of sufficient rainfall field data, satellite-based rainfall data were used in the present study. Tropical Rainfall Measuring Mission (TRMM) 3 h rainfall data of 0.25° × 0.25° spatial resolution images were used in the study for the period 10–18 June 2013, covering the Alaknanda and Bhagirathi catchments. Daily accumulated rainfall was calculated. The daily rainfall distribution varies spatially from 50 to 200 mm during 15–17 June 2013, as shown in Figure 1. Accumulated rainfall computed in the Bhagirathi and Alaknanda catchments during 10–18 June 2013 was found to be 550 and 530 mm respectively. It was noticed that heavy rainfall occurred on 10 and 11 June 2013 as well; these antecedent heavy rainfall events raised the soil moisture to saturation level and the subsequent rainfall events resulted into full run-off in the catchments. Temporal distribution of rainfall in these two basins from 10 to 18 June 2013 is shown in Figure 2.

*For correspondence. (e-mail: khvdurgarao@yahoo.com)

Thus, it can be found that rainfall which occurred during 15–17 June 2013 was the main triggering force behind the disaster.

Remote sensing satellite images of 28 May and 21 June 2013 show that there was approximately 30% increase in snow cover in the Alaknanda/Mandakini catchment area[6]. It is a rare phenomenon to have snowfall of this extent during June. According to the energy balance theory, snowmelt during the snowfall period will be less. But, due to kinetic energy of high-intensity rainfall, melt could have accelerated from the fresh snow. The flow in the Mandakini River prior to the event, according to the Central Water Commission data, was of the order of 50–150 m^3/sec, which was a result of snowmelt as there was no significant rainfall prior to the event. Hence, considering the pre-event snowmelt run-off and increase in the fresh snow cover during the event, an assumed average snowmelt run-off of 150 m^3/sec was considered in the flood hydrograph computations.

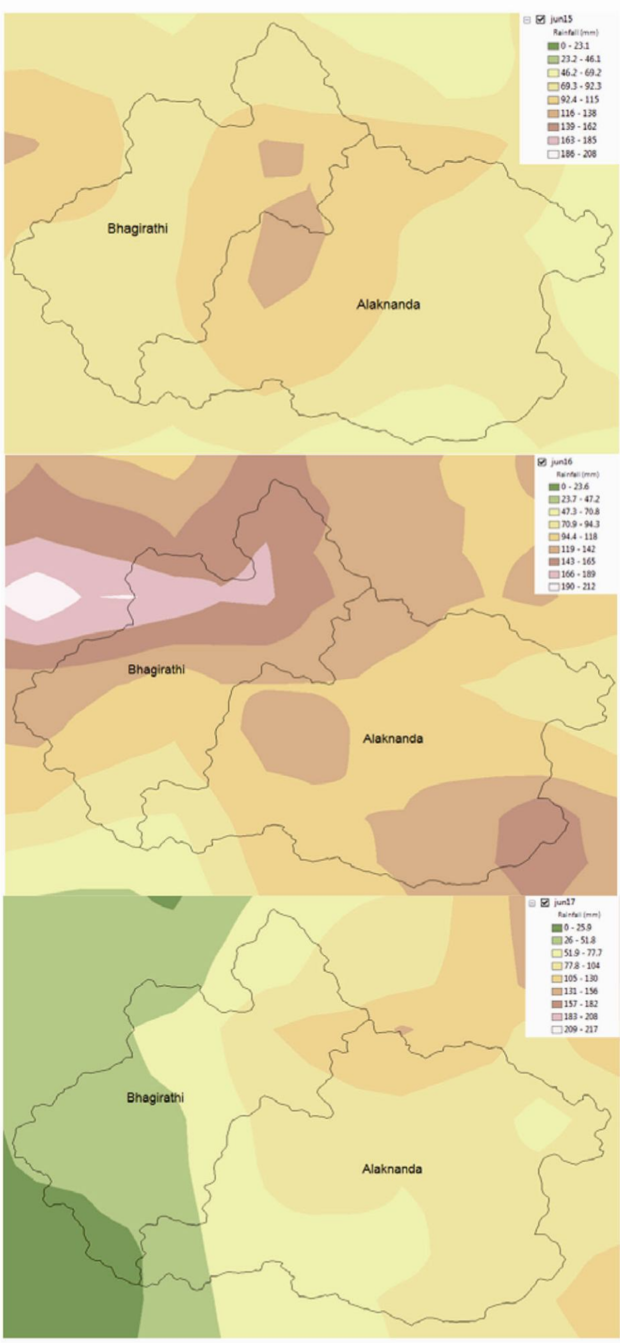

Figure 1. Spatial variation of rainfall in Bhagirathi and Alaknanda catchments as intercepted by TRMM on 15, 16 and 17 June 2013 (in mm).

A temporary lake, Chorabari, was formed just a few kilometres from Kedarnath towards northwest direction on high elevated terrain[6,7]. From the high-resolution satellite imagery of CARTOSAT, the impoundment area of the lake was found to be approximately 3 ha, which was due to rainfall and snowmelt run-off accumulation. Field reports indicate that the moraine dammed Chorabari Lake was busted on 17 June 2013 around 6:45 a.m. (ref. 7), abruptly releasing the impounded water.

Flood hydrograph due to outburst of the lake was computed using the popular Froehlich method after examining various earthen dam break analysis theories[9–11]. The dam breach parameters and peak flow prediction using the Froehlich method were computed using the following equations[12]

$$\text{Average breach width } (B_w) = 0.1803(V_w)^{0.32}(h_b)^{0.19}, \quad (1)$$

$$\text{Failure time } (T_f) = 0.00254(V_w)^{0.53}(h_b)^{-0.9}, \quad (2)$$

$$\text{Peak flow } (Q_p) = 0.607(V_w)^{0.295}(h_w)^{1.24}, \quad (3)$$

where V_w is the volume of water stored above the breach at the time of failure (m^3), h_b is the height of the breach (m) and h_w is the depth of water above the breach at the time of failure (m).

Average side slope of the breach was assumed at 1 : 0.9. As there is no field evidence on the lake depth, it was considered as 15 m in the present analysis from the cross-sectional profiles plotted across the lake at various locations using the high-resolution CARTO DEM of 10 m posting. Close view of the lake using CARTOSAT and the lake cross-sectional profile on CARTO DEM are shown in Figure 3.

Volume of water in the lake was estimated at 0.4 million cubic metres (MCM) through prismoidal formula using cross-section profiles and lake area as measured by CARTOSAT. Peak flow, failure time and breach parameters were calculated for the possible maximum water depth of 15 m. Breach width, time to peak and peak discharge computed using eqs (1)–(3) are found to be 18.7 m, 12.4 min and 783 m^3/sec respectively. Here, total failure time is assumed as the time to peak flow due to outburst of the lake. From the sensitivity analysis, peak flood computed assuming the lake depths as 10 and 12 m was found to be 474 and 594 m^3/sec respectively.

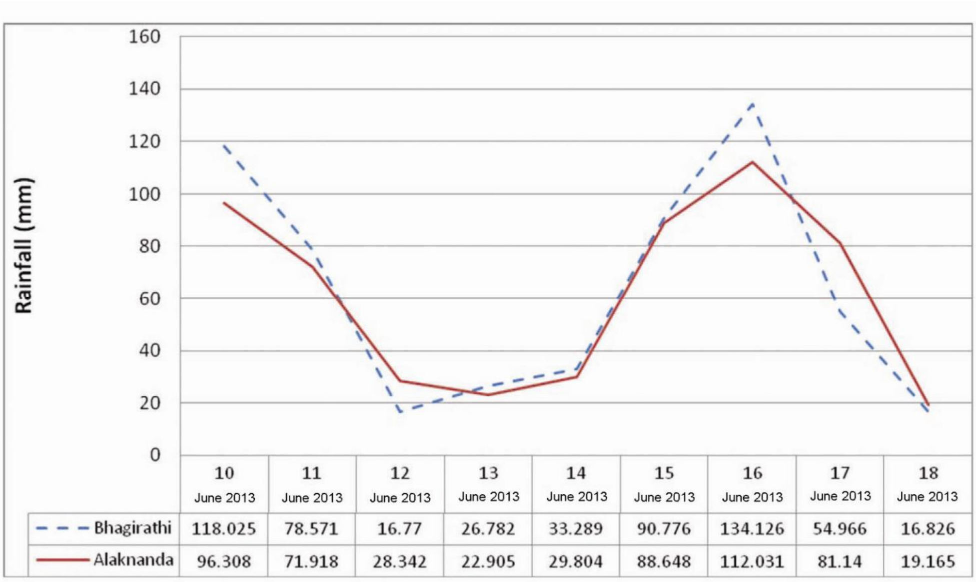

Figure 2. Temporal distribution of rainfall in the Bhagirathi and Alaknanda catchments during the flood event (source: TRMM data).

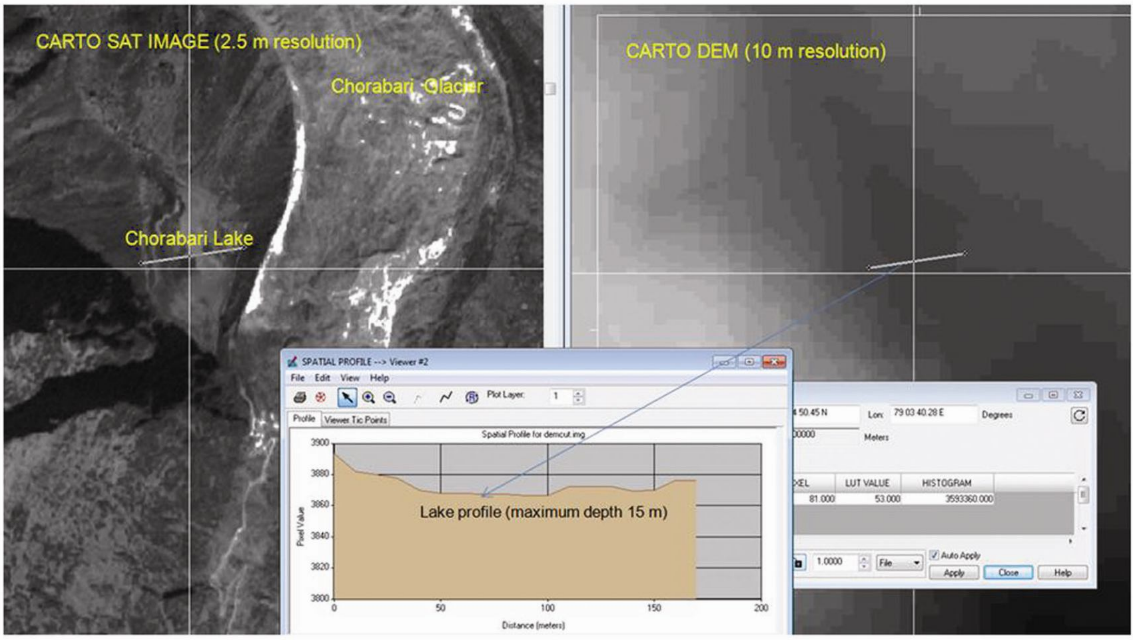

Figure 3. Cross-sectional profile of Chorabari Lake (source: CARTO DEM, NRSC).

However, peak discharge of 783 m^3/sec was considered in flood hydrograph computation using dimensionless hydrograph technique and used in the hydrological model while computing run-off of the Mandakini River.

Mandakini River that flows through the Kedarnath valley has a catchment area of approximately 1614 sq. km (up to Rudraprayag and before joining the Alaknanda River). From CARTO DEM, it was found that the average side slopes (terrain slopes) of tributaries of the Mandakini vary from 45% to 68% and longitudinal slopes of the river vary from 1% to 6%.

Hydrological model was developed for the Mandakini River using remote sensing and geo-spatial inputs in the HEC–HMS software environment. HMS adopts distributed/semi-distributed approach in hydrological modelling which is more accurate than the lumped approach[13]. The approach includes the rainfall run-off modelling, hydrodynamic flow routing and computation of flood hydrograph. Topographic and hydraulic parameters of each sub-basin and channel were computed using the land-use/land-cover grid that was derived from the Indian Remote Sensing Satellite (IRSP6) AWiFS sensor data, CARTO

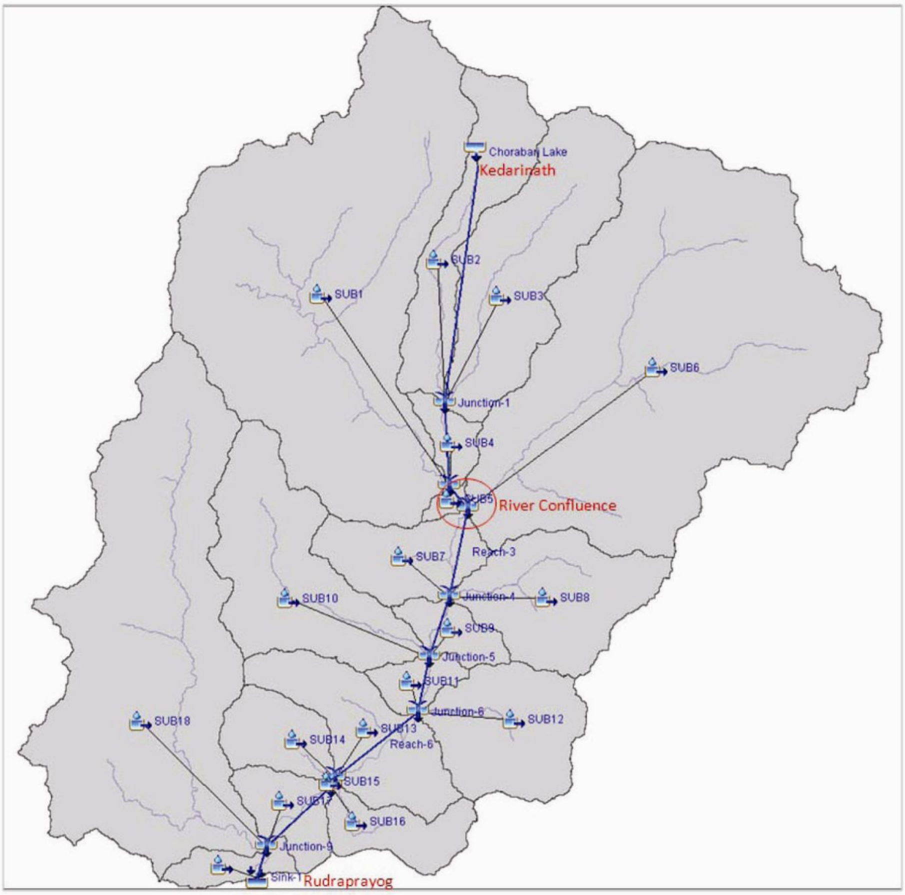

Figure 4. Hydrological model set-up of the Mandakini River.

Digital Elevation Model and the soil textural grid. Flow direction, flow accumulation and stream network grids were computed through automated process using HEC–GeoHMS software. The Mandakini watershed was divided into many sub-watersheds considering the flow direction pattern to improve the accuracy in model calculations. TRMM rainfall data were extracted for each sub-watershed and used in the model. The basin model set-up is shown in Figure 4.

Flood hydrograph computed for Chorabari Lake using earthen dam break analysis theory was integrated with the hydrological model to study the combined effect of rainfall and lake breach. It is interesting to note that the simulated peak flow due to lake breach was accrued within 12 min of the breach time and flow receded within 37 min. Hence, the time interval adopted in the lake breach analysis was one minute. But, this was not the case with the flood discharge due to rainfall during the event, as it was continuous for a few days. As the maximum impact was noticed on 17 June 2013, combined simulated flood hydrograph at the river confluence (as marked in Figure 4) due to lake breach and rainfall flood is shown in Figure 5. As no field discharge gauge site is available at the marked river confluence, model calibration could not be done. Peak discharge simulated by the model at the mentioned river confluence was found to be approximately 1800 m^3/sec, which is the result of lake breach and rainfall run-off. It was also found that the peak flood discharge of the Mandakini at Rudraprayag (before confluence with Alaknanda River) was more than 2800 m^3/sec. This flash flood washed-off many villages in its course and caused severe erosion in the river banks[5,6]. From the satellite images, it was observed that in Kedarnath about 64 buildings were completely washed away and 47 buildings were partially damaged. Images also revealed that Rambara village was totally washed away and damage to structures in Gaurikund was noticed. From Gaurikund to Rudraprayag, five bridges were partly damaged and two bridges were completely damaged. Road breaches were also observed in this stretch[6].

To study the dynamics of flood in the river, flood inundation simulations were carried out in the Mandakini River using CARTO DEM of 10 m posting. Land-use land-cover grid (derived from IRS P6 satellite, AWiFS data; source: Bhuvan; www.bhuvan.nrsc.gov.in) of the study area was used in deriving Manning's roughness parameters. River cross-section profiles and Manning's roughness parameters were extracted at regular intervals. The above computed flood hydrograph was used in simulating the approximate flood inundation and in computing

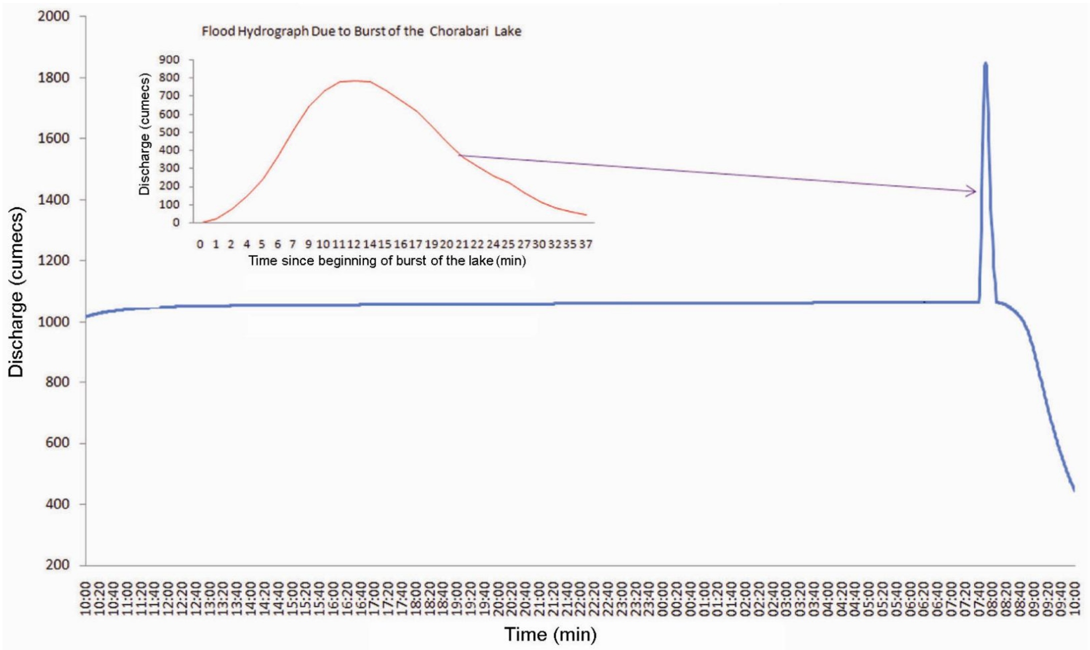

Figure 5. Combined flood hydrograph at river confluence (as marked in Figure 3) due to rainfall run-off and lake outburst (10 a.m. of 16 to 10 a.m. of 17 June 2013).

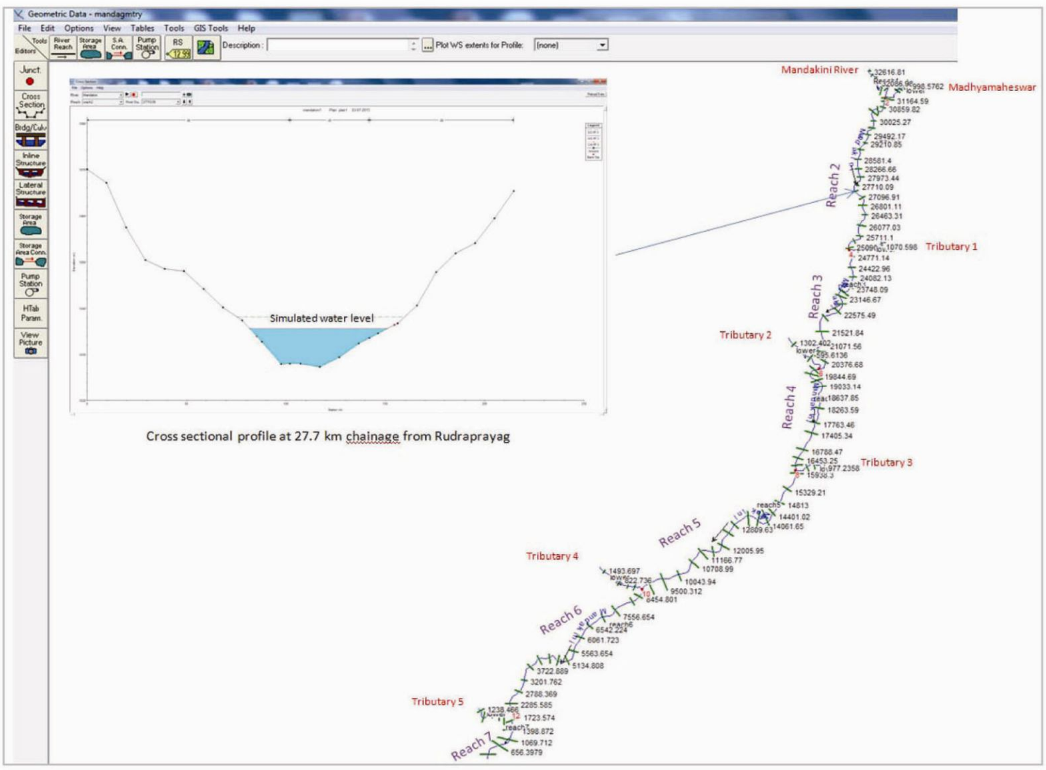

Figure 6. Cross-sections and simulated water level at 27.7 km chainage from Rudraprayag.

the dynamics of the flood. Run-off in each tributary of the Mandakini River was computed and used in the model. Flood inundation simulations were done in the HEC–RAS software (open-source software) environment using unsteady state conditions of flow. It was found that the velocity of flow in the river channel varied from 2 to 8 m/s. Also flash floods occurred due to narrow cross-sections of the river and high velocity of flow. From the inundation simulations, maximum depth of flow at different cross-sections was found to vary from a couple of metres to 12 m. Cross-sectional profiles and simulated water level at 27.7 km chainage are shown in Figure 6.

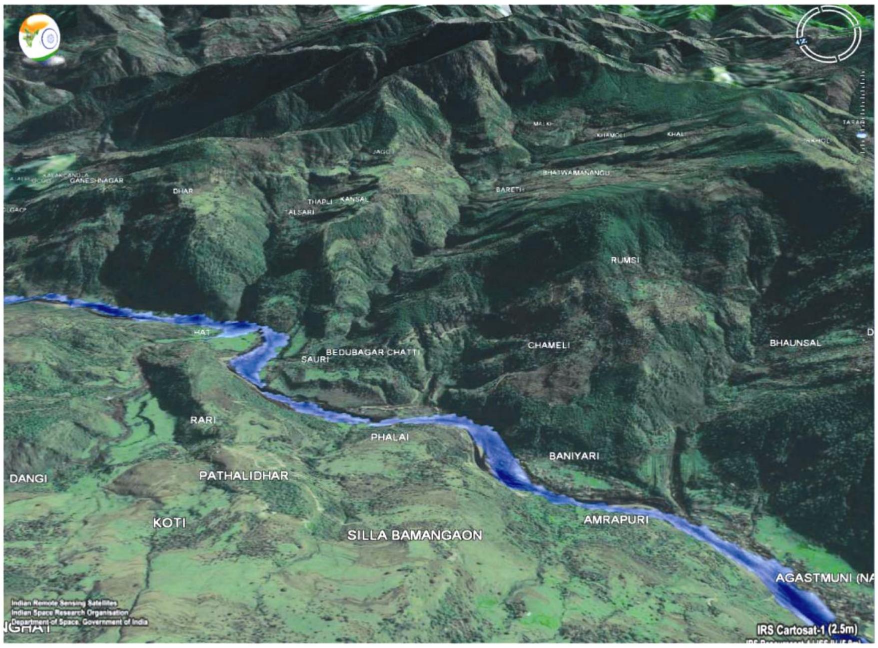

Figure 7. Approximate simulated flood inundations during peak discharge in the Mandakini River (image source: http://www.bhuvan.nrsc.gov.in).

Figure 7 depicts a perspective view of the simulated flood inundation in Mandakini River. These simulations could be helpful in identifying flood-vulnerable areas prior to the event and planning for risk reduction activities.

The present study highlights the urgent need to develop flash flood forecast models to help in improved preparedness for flood damage mitigation in hilly terrains. As the flood forecast lead time in such terrains is short, there is a need to improve spatial and temporal resolution rainfall forecast data in such flood forecast models. In recent times, under climate change scenario, glacier lakes are an increasing threat in the hilly regions. Outbursts of such lakes individually or in combination with rainfall run-off will cause severe damage to the downstream environment. Development of flood forecast models in conjunction with the flood inundation simulation models can provide flood alarms in the floodplains, which is an effective non-structural method of flood damage mitigation.

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