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Extreme rainfall and vulnerability assessment: case study of Uttarakhand rivers

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Abstract

The torrential rains in June 2013 combined with melting of snow caused voluminous floods in the rivers of Uttarakhand and subsequently triggered widespread mud, landslides and debris deposition. The event caused instability of the channel by shifting the banks. Erosion rendered many locations along the banks vulnerable to economic and human loss. The shifts in reaches are calculated by digitizing the bank line using satellite imageries of year 2005, 2010 and 2015. The extent and magnitude of risks have been assessed based on information of past events, rapid field assessments, current mitigation measures and interactions with the locals. The findings from these interactions, and secondary data based on geospatial analysis of bank line changes have been used in the identification of vulnerable reaches along the major rivers. Criteria to identify the vulnerable reaches are based on risk, exposure and hazards in that area. The magnitude of risks due to flood hazards on various exposures along the riverbank is calculated based on qualitatively derived scores. River basins focusing on rainfall, topography, drainage pattern, soil, landslide and exiting infrastructure in relation to vulnerability of the region using GIS data are discussed in details. A fuller understanding will enable decision makers towards more efficient resources management for prevention and protection of river banks due to flood events. In addition to this, an official online decision support system (www.urmis.dhi-india.com) with collaborating partners and organizations for relevant data, information and document has been created.

Keywords Vulnerability · Landslide · Flood · Bank line changes · Himalayas · Disaster · Extreme rainfall

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1 Introduction

The climate in the mid-Himalayas consists of four distinct seasons—winter, pre-monsoon, monsoon and post-monsoon. Most of the rainfall in the study area occurs during the summer monsoon from June through October due to tropical storms and depressions originating from Bay of Bengal. January is the coldest month after which the temperature begins to rise until June or July. The winter rains are brought by the western disturbances and summer rains by the summer monsoon winds. Upper parts of the Kedarnath area receives equal amounts of precipitation during summer and winter monsoon Vohra et al. (1981). The uncertain climatic conditions, varying geology, steep slopes, rivers, highly variable altitudes, glaciers make the region inherently vulnerable to numerous types of hazards (Nadim et al. 2006). At times, the rainfall may arrive at the expected time bearing considerably diminished rainfall throughout the season, and at times, there will be unusually heavy rain leading to disastrous floods Bharti 2015. Some of the major flash floods events that have occurred in the past years are Malpa flood and landslide of 1998 in Pithiragarh, Rudraprayag 2001 flood, Tehri 2002 flood and Varunavat 2003 flood. Landslides, debris flows, avalanches, flash floods, failure of high altitude natural and glacial lakes, extreme rainfall, earthquakes and rock falls cause widespread destruction in the area (Bajracharya and Mool 2009 and Immerzeel et al. 2010; Petley 2012).

Heavy downpour and subsequent devastating floods on 15–17 June 2013 led to heavy loss of lives and property in Uttarakhand and neighbourhood. Four weeks before, the unusual rapid snow cover around Chorabari lake and heavy rainfall due to early onset of 2013 monsoon elevated the stream flow, resulting in slope saturation and significant run-off (Dobhal et al. 2013a; Allen et al. 2016). The highest value quoted by was 370 mm on 17 June at Dehradun (Dube et al. 2013), which was said to be ‘a record not seen for five decades’. The crucial hydro-meteorological factor along with the glacial lake outburst flood (GLOF) and landslides killed more than 6000 people (Guha-Sapir et al. 2014). Numerous roads and bridges were damaged, and at least 30 hydropower plants were either destroyed or severely damaged (Sati and Gahalaut 2013). The destruction of roads and trekking routes left around 100,000 pilgrims and tourists stranded until military and civic authorities could complete evacuation efforts (Martha et al. 2014). Connectivity was disrupted across the state, and vehicular traffic was disrupted along more than 2000 roads. About 150 bridges were damaged or washed off (Thakkar et al. 2013).

There are currently no documents (ICIMOD 2011; Vilimek et al. 2013) which explicitly details the hydro-meteorologically triggered glacial lake outburst floods (GLOFs). Even globally, such incidents are rarely recorded in detail (Clague and Evans 2000; O’Connor et al. 2001; Worni et al. 2013; Vilimek et al. 2013). As a result, little attention has been given to the characteristics of the basin area that have contributed towards the enhanced run-off into catastrophe. Geotechnical and geophysical investigations to evaluate the failure are discussed by Pranab (2013); Dobhal et al. (2013b); Rao Durga et al. (2014) and Ravi et al. (2017). For developing the remedial measures, few more useful studies have been carried out by Bhambri et al. (2016), Martha et al. (2015), Cho et al. (2016), Bhatt et al. (2014), Vishwanath and Tomaszewski (2018) and Ahmed and Ilan (2018). The present study provides a comprehensive reference to the existing river systems and catchment, revealing the complex relationships between rivers, geomorphology, catchments and infrastructure along the basin. Hazards and exposure-based criteria have been used to identify the vulnerable reaches based on rapid assessments of the field observations, satellite images and consultations with government authorities and local people. The method of vulnerability assessment is based on post-disaster assessment due to flood, required for the decision maker to identify the critical riches for river protection works. The study area covers major river basins of Uttarakhand, i.e. Alaknanda, Bhagirathi, Mandakini and Kali.

2 Data

The remote sensing data collected by Indian satellites from National Remote Sensing Centre (NRSC) was used to extract the morphological analysis, land use/land cover, soil, geology and geomorphic characteristics of the area. In order to enhance the display of the study area, images of LandSAT-7 and LandSAT-8 with low cloud content (spatial resolutions of 30 m) acquired on 2 December 2005 and on 26 September 2015 were used. Additionally, IRS-P6 data (spatial resolutions of 23.5 m) captured on 5 November 2010 was also used. The same data have been used for slope mapping, drainage mapping, physiography and morphometric analysis. Geological sample data were gathered during the field assessments of vulnerable reaches. Details of the data sources are given in Table 1.

The original image data contained a combination of different types of information related to geographical elements. Due to differing coordinate projection systems, the data sets have been pre-processed to extract some geographical elements. The following steps were followed for processing the data:

- The study area was very large and the satellite imageries, and DEM data were available over many parts. So all the pieces were mosaicked into a single image for easy geo-referencing.
- Edge matching was done by bringing two adjoining images of same area into same map file and matching their edges into a "Seamless Map File".
- After mosaicking, the satellite imagery/DEM data were first been processed for removal of haze and noise, and then, image enhancement was carried out for better readability and analyses using the image processing software.
- Ground control points (GCPs) were collected or found out using the satellite imagery/DEM data reference and actual DGPS survey.
- Processed GPS acquired point data were used known as GCPs for referencing the satellite imagery and DEM data.
- Using GCPs from DGPS survey, the satellite imagery and DEM data was then geo-positioned/geo-referenced to the required projection and datum as per the standard process of the image processing software.
- The projection system Universal Transverse Mercator (UTM), with World Geodetic System 1984 (WGS-84) as datum was used for better calculation and verification of distances between utilities, area and the span length.
- Nearest neighbourhood method was used for the transformation of the raw satellite data to geo-referenced satellite data.
- Automatically generated root-mean-square error (RMSE) less than 0.2 was maintained.

Table 1 List of the data and data sources

S. no.	Data layer/maps	Sources
1.	Topographical map	Series U502, US Army Map Service, 1955; scale 1:250,000 http://www.lib.utexas.edu/maps/ams/india
2.	Satellite remote sensing data	LandSAT-7 ETM$^+$; spatial resolution 30.0 m Global Land Cover Facility (GLCF), Earth Science Data Interface (ESDI), 2005: http://glcfapp.glcf.umd.edu:8080/esdi
		IRS-P6 LISS-III; spatial resolution 23.5 m Indian Earth Observation, National Remote Sensing Centre (ISRO), 2010: http://bhuvan.nrsc.gov.in/data/download/index.php
		LandSAT-8 PAN + OLI merge data; spatial resolution 15 m US Geological Survey (USGS), Earth Explorer, 2015 and 2017 http://earthexplorer.usgs.gov
3.	Elevation data	Shuttle Radar Topography Mission (SRTM), DEM Data; spatial resolution 30 m NASA, and USGS EROS Data Center, 2006 http://glcfapp.glcf.umd.edu:8080/esdi
		CartoSAT-1 Digital Elevation Model (CartoDEM) Data; spatial resolution 30 m Indian Earth Observation, National Remote Sensing Centre (ISRO), 2010: http://bhuvan.nrsc.gov.in/data/download/index.php
4.	Land use/land cover map	Land use and land cover maps have been prepared at 1:50,000 scale by using ResourceSAT-2 LISS-III satellite imagery (2013), ResourceSAT-1 LISS-III satellite imagery (2001), LandSAT-5 TM satellite imagery (1990) and have verify through limited field check.
5.	Soil map	Soil map (1:250,000 Scale) data have been collected from Uttarakhand Soil Information System & National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) and updated through satellite data
6.	Geological map	District wise geological map (at 1:250,000 Scale) data have been collected from GSI and updated through IRS-P6 LISS-III & LandSAT-8 OLI satellite data with limited field check: http://www.portal.gsi.gov.in
7.	Geomorphological map	Geomorphological map at 1:50,000 scale along with geological structures has been prepared using the IRS-P6 LISS-III data, LandSAT-8 OLI data, CartoSAT-1 DEM/SRTM-DEM data and other ancillary data topographical map, geological map.
8.	Climatic data	Indian Meteorological Department (IMD) station data for varying time periods depending upon their availability with IMD

3 Methodology

The present method of vulnerability assessment focuses on providing a post-disaster location specific flood risk required for the bank protection works. The bank line changes have been obtained by comparing satellite images from 2005, 2010 and 2015. Based on this, a list of vulnerable reaches is prepared. The risk assessment at these locations is calculated based on qualitatively derived scores based on indicators, i.e. hazard, exposure and impact (Fig. 1). General risk assessment methods can lack sufficient data, leading to the selection of inappropriate indicators; hence, fieldwork and surveying activities were carried in context of more reliable primary data for the indicators. Based on scores assigned to the hazards, exposure and intensity, risk at vulnerable reaches is identified. List of critically vulnerable reaches is updated based on the final risk scores. Such relative data allow comparing the indicators from various administrative units carried out at different levels, ranging from local communities (Bollin and Hidajat 2006) cities (Greiving et al. 2006) to countries (Van Westen et al. 2010).

3.1 Hazards

The hazards considered in the present study are flood causing vulnerability along the rivers in the hilly region of Uttarakhand. Hazards due to extreme rainfall along the rivers in the hilly area are river morphological hazard, flood hazards and landslides. Description of geomorphology approached hazard analysis given in Table 2 and discussed in this section. Apart from this, location specific parameters obtained from GIS data sets such as topography, soil type, slope, drainage pattern and geomorphology (which contributes to the vulnerability) are discussed under Sect. 4.

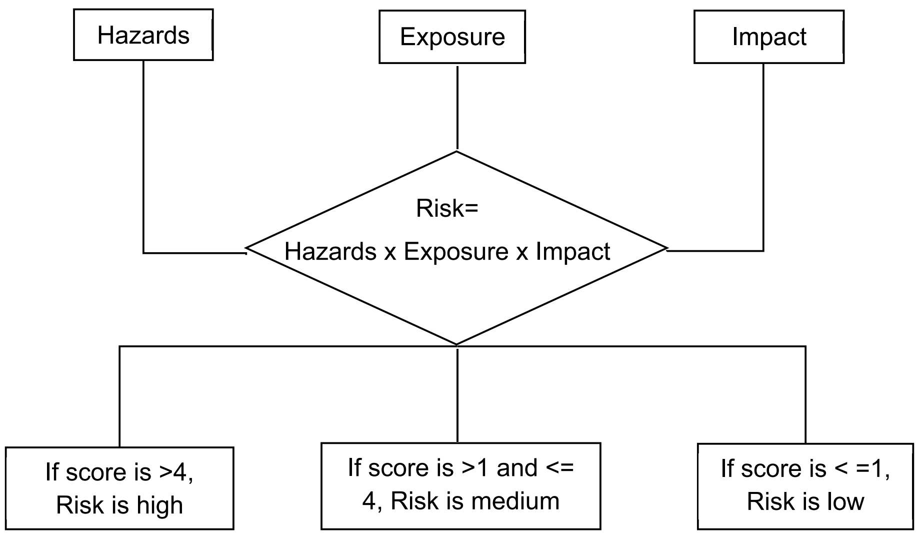

Fig. 1 Schematic of the methodology for identification of vulnerable riches

Table 2 Cause of river morphological hazard and flood hazard

Hazard	Cause
River morphological hazard	
Bank erosion	Increased hydraulic forces in the vicinity of the river bank
	Weaker bank materials properties or geotechnical characteristics of the banks
	Configuration of the bank
Bed scour	High flows with strong velocities
Aggradation of bed level	Higher sediments load than the sediment transport capacity of a river reach
Narrowing of waterways	Caused by blocking of channel due to landslides, unusual deposition, constrictions imposed due to occupation of land by human activities
Meandering of rivers	The meandering of rivers along a reach is the main cause of erosion of banks at high floods. Bed and bank scours occur at sharp meanders. Landslides depositing debris in the river bed aggravate the impacts of meandering rivers, causing sharp shifting of the river course and migration of rivers towards lands and settlements
Flood hazard	
	Flash floods generated due to sudden heavy rainfall, including cloudbursts in parts of the catchment Discharge higher than the conveyance capacity of a river reach Temporary blocking of river due to landslides Glacier lake outburst floods (GLOF) generated in catchments at higher elevations
Landslide	
	Landslides directly related to erosion of river banks, caused mainly by toe erosion Landslides due to construction of roads, with debris falling into the river Landslides away from the river above the road towards hillside terraces, but ultimately affecting the river flow due the falling debris

3.1.1 River morphological hazard

In general, there are three major causes of bank erosion which leads to morphological hazards.

Bank erosion due to increased hydraulic forces The hydraulic forces are the attacking forces, while the properties of the bank materials are defending forces. If attacking forces are stronger than the defending system, or the defending system is unable to sustain the changes in flow regimes, damages to the bank, i.e. bank erosion, occur.

Bank erosion due to bank properties Weaker bank materials properties that make the bank unable to sustain increased hydraulic forces. Such properties of the bank materials include engineering properties like size of the particles, gradation of bank materials, cohesion between the particles and wetness of the soil.

Bank erosion due to river bank configuration Configuration of the bank, such that the overall layout along or across the bank makes it unstable. The layout of a river bank would include mainly cross slope of the bank, height of the bank, bank alignment streamlined to the main river flow, growth of vegetation on the bank slope and existence of hard points located on the bank.

3.1.2 Flood hazard

The reasons for flood hazards are high flows due to sudden heavy rainfall, including cloudbursts in parts of the catchment, temporary blocking of river flows due to landslides and GLOF in the catchments at higher elevations. In June 2013, first and last reason occurred simultaneously. Flood hazard is mainly related to submergence of land and property located on the floodplains of the river. Cases of submergence of villages and cities are limited along the rivers in hilly areas. However, small settlements like commercial, religious places, tourist spots and agricultural lands that are vulnerable to flooding have been considered. Hence, flood hazards are caused by peak floods rather than prolonged inundation of the areas. One of the main effects of flood hazard is the high velocity of the rivers during high flows, which causes erosion of banks and other structures.

3.1.3 Landslide hazard

The landslide hazards along the rivers are due to erosion of river banks caused mainly by toe erosion, or construction of roads with debris falling into the river. If the landslides are away from the river above the road towards hillside terraces, they may ultimately affect the river flow due the falling of debris. The major infrastructures landslide area and glaciers existing along the rivers are depicted in the composite Fig. 2.

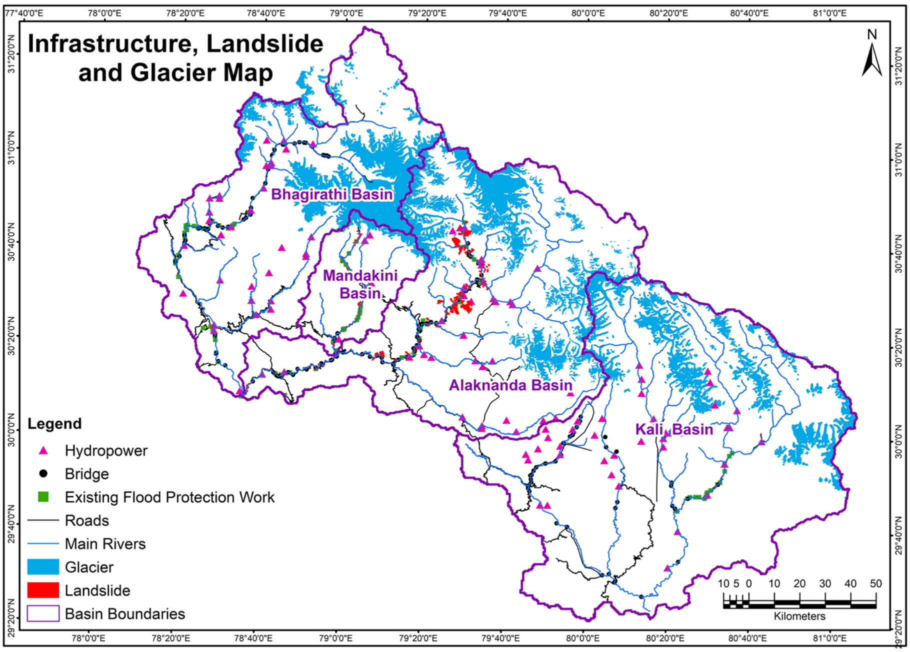

Fig. 2 Generalized overburden map of river basins

3.2 Exposure

Exposure indicates the degree to which the elements at risk are exposed to a particular hazard. The exposures considered are human population (rural as well as urban) residing near the river bank, infrastructure includes roads, bridges, hydropower stations, irrigation systems, human settlements, healthcare facilities, places of religious importance, agricultural land, tourism spots and defence establishments.

3.3 Vulnerability and risk analysis

Level of risks at the vulnerable reaches along the rivers is assessed based on direct and indirect impacts of the hazards to the exposed elements given in Table 3. Impact is estimated based on exposure to human losses, socio-economic losses and environmental losses. If the hazard is due to the river, score is one and if hazard is not due to the river then the score is zero. Risk is calculated by multiplication of hazard, exposure and impacts. If score is more the four risk will be high, and if score is one or less than one then risk will be low.Risk = Hazard × Exposure × Impact

If score is > 4, risk is high
If score is > 1 and ≤ 4, risk is medium
If score is ≤ 1, risk is low.

Besides affecting the local population quite adversely, such disaster severely disrupts the habitations, agricultural lands, forest and other infrastructures along the rivers.

Table 3 Vulnerability indicators with scores for computation of risk associated with river floods in hilly area

	Score	Descriptions
Hazard		
If multi-hazard	3	If hazard is due to river
If single hazard	2	If hazard is due to river
If single hazard	1	If hazard is due to landslide or other than river
Exposure		
If exposure is more than one	3	If road, agricultural land associated with settlement or only settlement
If settlement	3	
If road	2	
If agricultural land	1	
Impact due to		
If due to river	1	
If not due to river	0	
Special case	Populated town: Uttarkashi, Srinagar and Dharchula Kasba	Populated and important towns

4 Study area and analysis

The study area covers major river of Alaknanda, Bhagirathi, Mandakini and Kali in Uttarakhand, India. The region predominantly falls under the category of hilly terrain with huge variation in lowest and highest elevation. Satellite remote sensing data, elevation data and hydro-meteorological data were used to assess the vulnerability in the river due to floods. Shuttle Radar Topography Mission (SRTM) and CartoSAT-1 Digital Elevation Model (CartoDEM) available at spatial resolution of 30 m has been used to derive the general topographical characteristics of the study area.

4.1 Topography

Figure 3 gives the topography of the area depicts panoramic view of the morphology. The area includes high mountains over 7184 m above mean sea level (amsl) and low surfaces of about 362 m amsl. The topography of the basin is rugged with high mountains and deep valleys dissected by the river and its tributaries.

Bhagirathi basin The Bhagirathi River originates around 19 km upstream from Gangotri town and ends at Devprayag. The river passes through Uttarkashi, Tehri and Pauri Garhwal district with total basin area of 7619 Km^2. The river basin is more like an elongated type, with straight length of about 205 km. The basin has complex topography with high mountain chains and glaciered area in north. Within this stretch, the elevation of the basin ranges from ~ 412 m amsl at Devprayag to ~ 7007 m amsl at the higher region (northern side).

Mandakini basin The Mandakini River originates from the Chorabari Glacier (~ 5020 m) located just 2 km upstream of Shri Kedarnath shrine and joins Alaknanda at

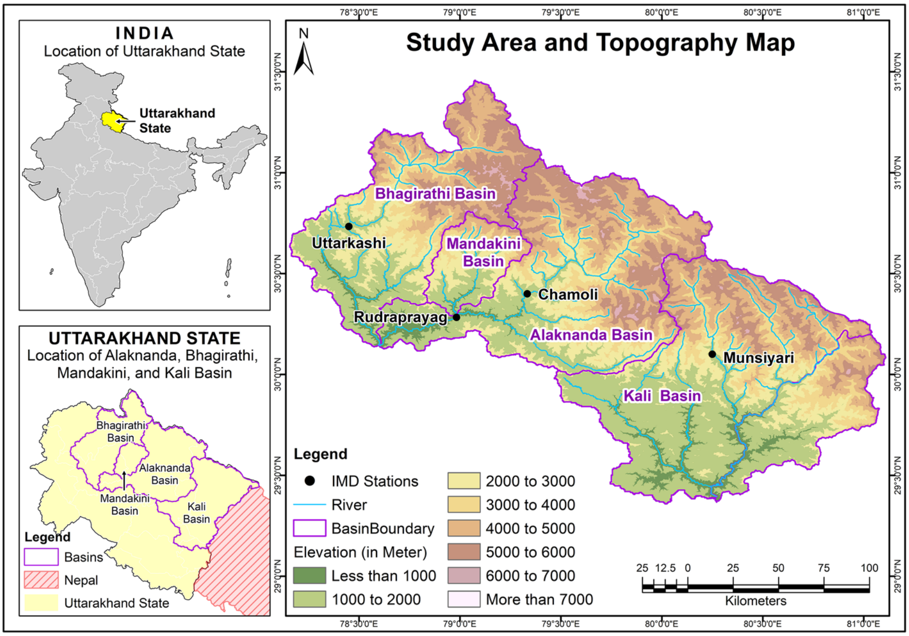

Fig. 3 Study area and topography map

Rudraprayag (~431 m). On the way, it passes through Kedarnath, Chunni and Sumari, covering major hydropower projects Kund and Tilwara. The area of the Mandakini River basin is 1645 km^2. The average length of this river basin is 55 km, and average width is 35 km. Within this short stretch, the elevation of the basin ranges from ~6700 m amsl at the higher region to ~400 m amsl in the lower areas.

Alaknanda basin The Alaknanda River basin area is 11070 km^2. The river originates 6 km upstream from Satopanth Glacier (~4350 m amsl) and passes through Badrinath, Karnaprayag, Rudraprayag and finally Devprayag (~475 m amsl) where it merges with the Bhagirathi. The merged river downstream of Devprayag is called the river Ganga. The length of the Alaknanda River is 180 km. Within this stretch, the elevation of the basin ranges from ~412 m amsl at Devprayag to ~7184 m amsl at the higher region (northern side).

Kali basin Kali River serves as a border between Nepal and India, and the data for the basin were partially available for the study. In most of the results, analysis concerns the portion of the basin within the Indian border. This river is also called Kali Gad or Kali Ganga or Mahakali. It originates at the Lipulekh pass (~5020 m) and passes through Kalapani, Tawaghat pass, Jauljibi and Jhulaghat before arriving at Pancheshwar (~431 m). The river then flows down and later enters Uttar Pradesh where it is called Sharda. The total length of the river in the present study area is nearly 107 km.

4.2 Climate and extreme rainfalls

The climatic conditions in the study area are not uniform and vary according to the location, altitude, aspect and morphology. There is a large variation of relief from 362 m in south to more than 7,184 m in the north of the study area. It has been observed that for every 1,000 m ascent, there is a 6 °C decrease in temperature (AHEC 2011). Table 4 has demonstrated the details of temperature recorded at meteorological observation stations in the study area which are ranging from 34 °C (highest) to 0 °C (lowest). Certain peculiar geomorphic features including cirque and funnel-shaped valleys with high relative relief, dense forest cover and average altitude exceeding 1500 m are considered to provide favourable conditions for cloud burst.

Floods due to extreme rainfall in the Himalayas have influenced the behaviour of rivers in Uttarakhand by changing the bank line, bed level and flow pattern of rivers in various stretches. The monthly variations of rainfall from 2011 to 2015 at four stations—Uttarkashi

Table 4 Climatic zones in Uttarakhand. (*Source*: AHEC 2011)

Climatic zone	Altitude (m)	Average temperature range (°C)		
		Annual	June	January
Tropical	300–900	18.9–21.1	27.2–29.4	11.1–13.3
Warm (subtropical)	900–1800	13.9–18.9	21.1–27.2	06.1–11.1
Cool	1800–2400	10.3–13.9	17.2–21.1	02.8–06.1
Cold	2400–3000	04.5–10.3	12.3–17.2	01.7–02.8
Alpine	3000–4000	03.0–04.5	05.6–13.3	Below zero
Glacial: perpetually frozen zone (cold desert, no vegetation)	4000–4800 Above 4800	For 10 months, below zero and in July and August between 2.2 and 3.9		

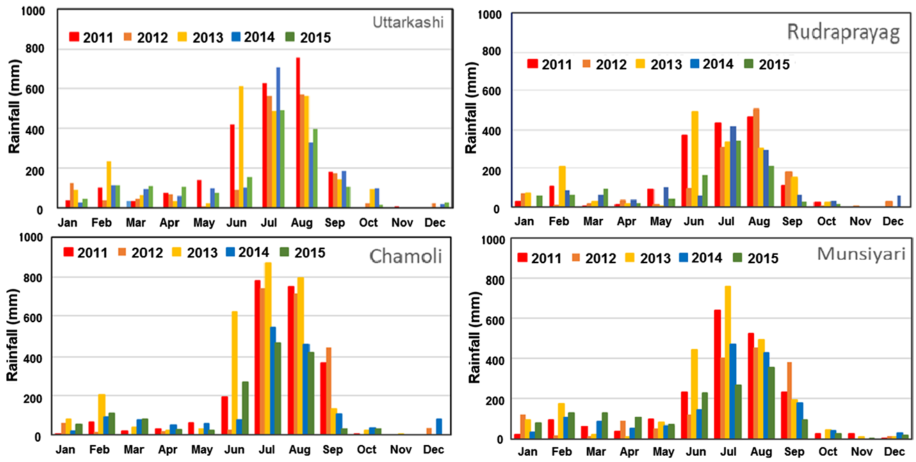

Fig. 4 Monthly rainfall variations during 2011–2015 at Uttarkashi (Bhagirathi), Rudraprayag (Mandakini), Chamoli (Alkhananda) and Munsiyari (Kali)

Table 5 District wise rainfall distribution in Uttarakhand. (*Source*: Thakkar and Dandekar 2013)

District (name)	13.06.2013–19.06.2013 actual (mm)	June month normal (mm)	% Dep
Almora	208.7	26.3	694
Bageshwar	391.2	26.3	1387
Chamoli	316.9	22.6	1302
Champawat	351	33.5	948
Dehradun	565.4	36.8	1436
Garhwal Pauri	149.7	15.8	847
Garhwal Tehri	327.7	22	1390
Hardwar	298.8	21.6	1283
Nainital	506.5	38.8	1205
Pithoragarh	246.9	73	238
Rudraprayag	366.3	53.9	580
Udham Singh Nagar	157.7	40.2	292
Uttarkashi	375.6	25.8	1356

(Bhagirathi), Rudraprayag (Mandakini), Chamoli (Alkhananda) and Munsiyari (Kali) along the rivers are presented in Fig. 4. The locations of these IMD stations are marked in Fig. 3. The highest rainfall recorded at all the stations was in 2013. Table 5 shows the normal versus observed rainfall from 13 to 19 June 2013. Further daily extreme rainfall observed at different stations in the state since 1901–2013 is given in Table 6 (*Source*: Damodar and Parineeta 2013). The highest quoted values in 2013 can be said as highest recorded in the last five decades. The June 2013 rainfall event was not the as intense as that of one in 100 years, but due to large temporal and special coverage of rain it was the most devastating in the Uttarakhand history.

Table 6 Extremes rainfall in Uttarakhand since 1901 to 2013. (*Source*: Damodar and Parineeta 2013)

Station name	Maximum rainfall in last 100 years	Minimum rainfall in last 100 years	Maximum rainfall in 2013
Uttarkashi	800.8 mm in August 1963	36.8 mm in June 1987	529.9 mm in June
Dehradun	1271 mm in August 1943	20.4 mm in June 1965	676.7 mm in August
Tehri Garhwal	1097 mm in September 1995	0 mm in September 1997	453.4 mm in June
Rudraprayag	914.6 mm in August 1925	0 mm, in September 1971	664 mm in June
Chamoli	860.7 mm in September 1924	0 mm in 1998	537.9 mm in July
Haridwar	848.2 mm in September 1924	0 mm in September 1971	426 mm in August
Pithoragarh	1057 mm in August 2000	22 mm in June 1901	471.9 mm in July

4.3 Geology

The geological mapping consists of a sequence of activities executed on the field, with the purpose of collecting the maximum information about the geological constitution of a specific area. Several scientific papers concerning different geological aspects, like structural geology, lithostratigraphy, geomorphology, slope instability, seismic hazard of the area, have been collected and critically reviewed and relevant information incorporated into the final map. Notable studies which have contributed to diverse geological aspects of the study area are Auden (1934), Gansser (1964), Verma et al. (1970), Krishnaswamy and Shanker (1982), Dhingra and Chakrapani (2004), Celerier et al. (2009) and many more.

On-site geological mapping The field operation essentially geological mapping of the study area determines the underlying lithological units. The geological mapping was carried out at a scale of 1:25,000 using sampling method. The rock samples were collected from different localities in the study area, after which they were labelled accordingly to avoid mix-ups. The geographical location of each outcrop was determined with the aid of a GPS, and the lithologic and field description and features characteristic to each sample were correctly recorded in the field notebook. Thorough general geology of the area has been mapped by the GIS expert in the usual way.

Satellite remote sensing-based geological study The methodology is based on observations and analysis of data from satellite images. In order to optimize the results, these digital graphics were combined with other digital data, i.e. topographical maps and 3D images from Google Earth, and CartoDEM. The results of the remote sensing interpretation were integrated into a GIS allowing producing the geological map.

On-site geological mapping combined with satellite remote sensing-based geological data has been used. Recorded principal rock formations of the region are described in Table 7. Figure 5 shows the geological map of the study area, with the maximum information about the geological constitution. The area is mostly composed of banded central crystalline; Martoli group; granitoid of Amritpur, Almora, Chamoli and Chandrapuri; Rautgara (formations of Garhwal group). The bedrock outcrops are severely weathered on the ground surface. No geological event is recognized in recent years. Therefore, geological features are divided into two parts: hard part and soft part. Erosion due to river and landslide in soft rock parts at Rautgara (formations of Garhwal group), granitoid of Amritpur, Almora, Chamoli and Chandrapuri, and Bhilangana formation has been recorded.

Table 7 Stratigraphy of the study area *Source*: Geological Survey of India, Misc. Pub. No. 30(XIII) (2002)

Map symbol	Group/formation/lithology	Age
10	Giumal sandstone	Cretaceous
9	Laptal formation, Kioto limestone, Kuti shale, Kalapani limestone; Chocolate formation	Triassic–Jurassic
9 A	Spiti shale	
8 A	Kuling formation	Carboniferous–Permian
8 kg	Kali and Girithigal formations	
7	Muth quartzite, Variegated shale, Sniala, Garbyang, Ralam formation	Ordovician–Devonian
6 m	Martoli group	Neoproterozoic–Cambrian
5 Aj	Jaunsar group	Neoproterozoic
5 Am	Morar–Chakrata formation	
5 Bk	Baliana group, Krol group	
4 Ar	Rautgara (formations of Garhwal group)	Mesoproterozoic
4 Bd	Deoban group	
4 Cb	Bernag	
3 car	Almora–Ramgarh	Palaeoproterozoic
3 cb	Baijnath	
3 cc	Chhiplakot crystalline	
2 ca	Askot	
2 cbh	Bhilangana formation	
2 cc	Central crystalline	
	Igneous rocks–Plutonic rocks	
γ4	Granitoid of Badrinath	Mesozoic–Tertiary
γ3	Granitoid of Kedarnath and Champawat	Neoproterozoic–Palaeozoic
γ2	Granitoid of Amritpur, Almora, Chamoli and Chandrapuri	Proterozoic
	Igneous rocks–Volcanic rocks	
β2b	Basic – Ballndura volcanics	Cretaceous–Palaeogene
β2g	Volcanics of Garhwal group	Proterozoic

4.4 Geomorphology

Geomorphology is the science of evolution of landforms in terms of its lithology, structure, basin geometry and other morphometric factors. Figure 6 presents the geomorphology of the river basins, presenting an intricate mosaic of mountain ranges, hills and valleys. Physiographically, the area is a part of the great Himalayas with high peaks. It is a region of complex folding, which has gone under many orogenesis. The entire analysis area is highly dissected into numerous ridges and spurs, wide U-shaped to narrow V-shaped valleys, deep gorges to wide outwash plains with a variety of slopes. "U-", "V-" and "S-" shaped meanders are present all along the valley. In the upstream sections, the valley is narrow and deep, while in the downstream sections, it becomes wide and sinuous.

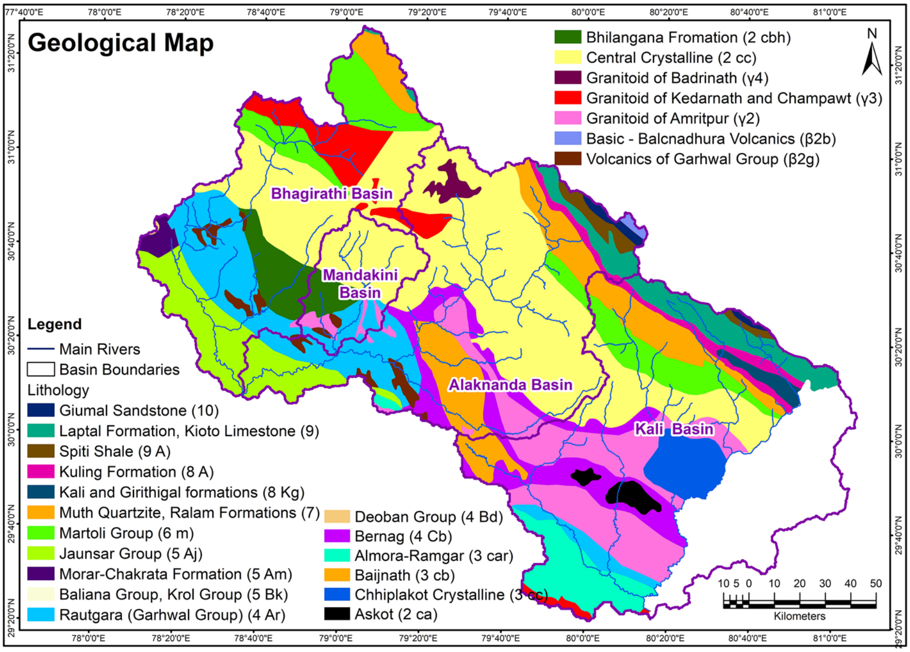

Fig. 5 Geological map of river basin in Uttarakhand

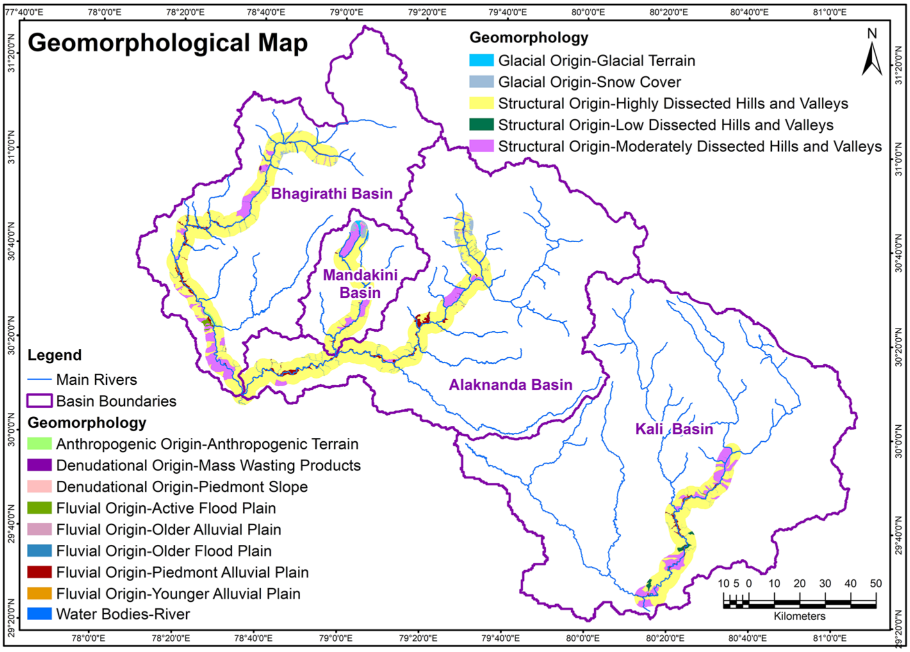

Fig. 6 Geomorphology map of river basins

4.5 Slope

The slope aspect also plays an important role in determining the climate, as north facing slopes are much cooler and more damp when compared with south facing slope due to insolation effect. Maximum slope line is well marked in the direction of a channel reaching downwards on the ground surface. In any region, valley slopes occupy most of the area of erosional relief in greater extent in comparison with flood plains, river terraces and other local depositional landforms. The average side slopes (Fig. 7) of the study area vary from 30 to 100%. An aspect-slope map simultaneously shows the aspect (direction) and degree (steepness) of slope for a terrain (or other continuous surface). The inland image in the circle presents zoomed view of the slope. Most of the area shows less slopes along river (between 32 and 40%) making the region erosion and flood prone.

4.6 Drainage pattern

Drainage texture reflects climate, permeability of rocks, vegetation and relief ratio. Figure 8 presents some characteristics of study area through drainage texture. The patterns observed in the study area are mostly dendritic and radial. Dendritic pattern occurs when there is fairly homogeneous rock without control by the underlying geological structure. Another element of drainage analysis is drainage density which is stream length per unit area in study area. Drainage density is a better quantitative expression of the dissection and analysis of landform. Although it is a function of climate, lithology and structures, and relief history of the region, it can be used as an indirect indicator to explain the morphogenesis of

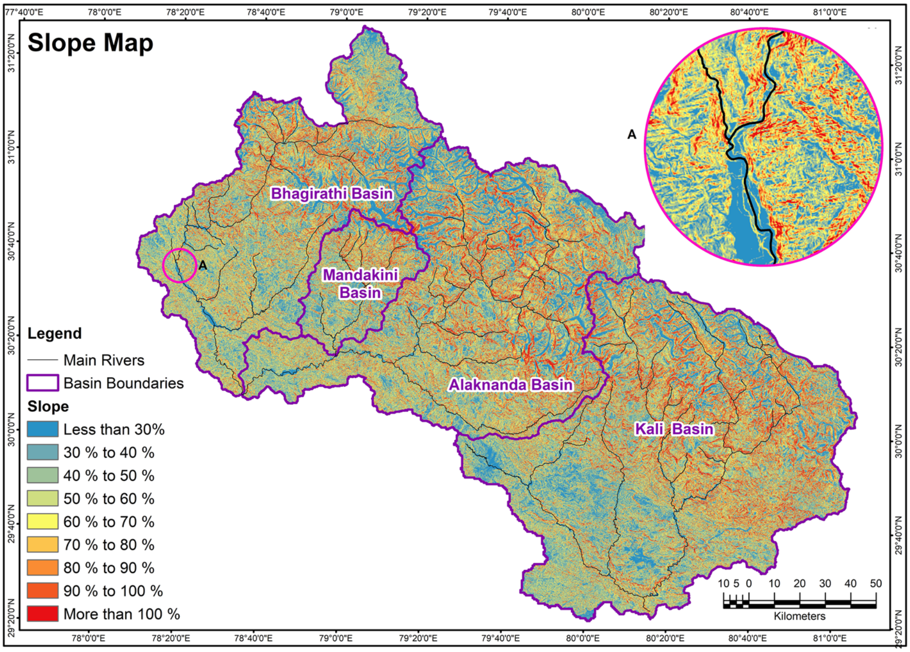

Fig. 7 Slope of the river basin

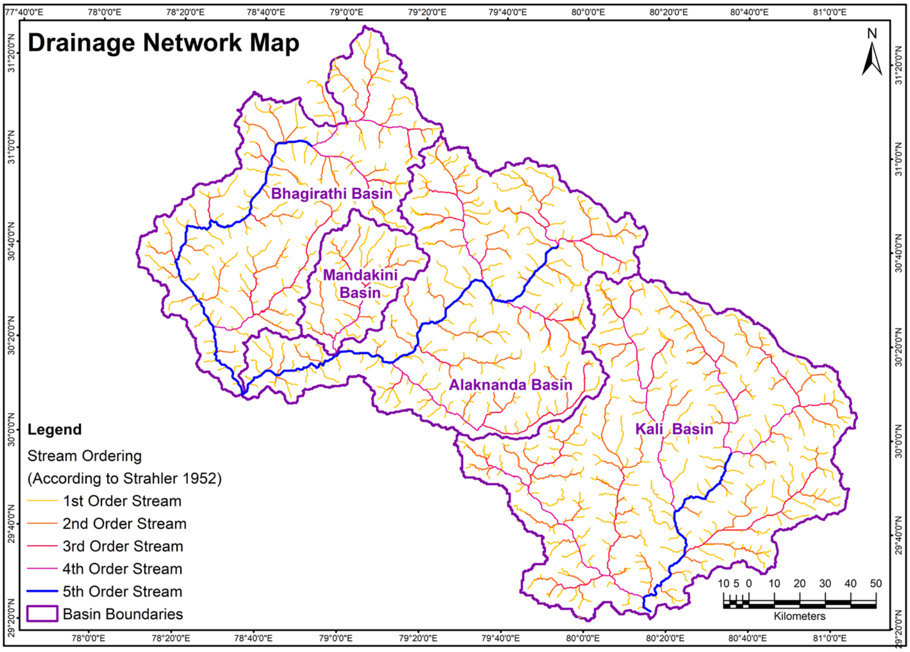

Fig. 8 Generalized drainage map for 1st to 5th order streams in the river basins

a landform. The drainage density value for study area is calculated as 0.96 km/km^2 indicating moderate to high density. The moderate drainage density indicates the study area has moderately permeable subsoil and thick vegetative cover.

4.7 Soil types

The soil map was generated in GIS environment using soil map collected from Uttarakhand Soil Information System NBSS and LUP and was updated using Resource SAT-1 LISS-IIII (23.5 m), and LandSAT-7 ETM$^+$ (30 m) multi-spectral satellite imageries (Fig. 9). The soil map obtained from Uttarakhand Soil Information System was geometrically registered to the base data to match LandSAT & IRS satellite imageries. The geo-referenced soil map was used to assist in visual classification of satellite imagery for obtaining soil categories. The final vector map was stored in a geodatabase which is amenable to spatial analysis. Major soil types of the study area are: coarse loamy soils, fine loamy soils, loamy soils, loamy skeletal soils, sandy-skeletal soils, skeletal soil (lithic entisols) and rock outcrops. It is noted that the steep relief predictably causes soil materials to be eroded downslope during or after a rainfall event. This leads to truncation of the soils on the upper slope and accumulation of soil materials at the foot slopes where deposition takes place. The rate of truncation at the upper slope and the subsequent deposition at the foot slope entirely depended on the type of erosion, i.e. whether geological (also called natural erosion) or accelerated erosion. The latter removes a considerable amount of soil at a rate way above which it is replenished.

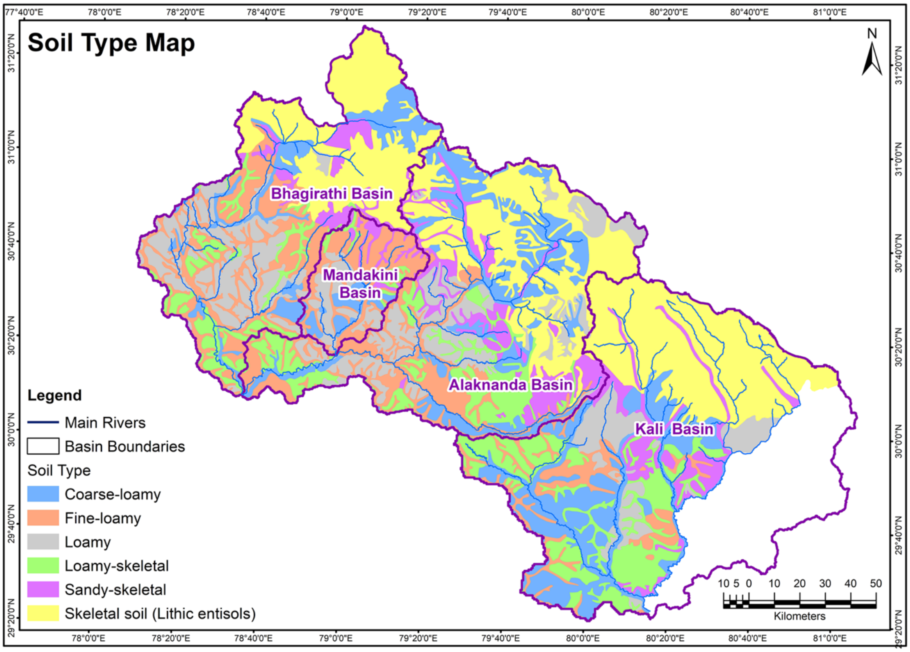

Fig. 9 Soil map of river basin in Uttarakhand

4.8 Existing infrastructure, landslide and glacier

Figure 2 is a composite image of the analysis area depicting the infrastructures, landslides and glaciers. The major infrastructures within the study area which are vulnerable to river disasters are given in Table 8. The high relief snow clad ranges of all river basins are located along the northern periphery of the basin. About 2276 Himalayan glacial lakes exist above the snow line (Fujita et al. 2013). The factors controlling the glacierization of an area include the height of ridges, the orientation of slopes and amount & type of precipitation in the area. According to Alternate Hydro Energy Center (Jain 2008), Gangotri

Table 8 Summary of existing infrastructure along the major river basin

Major infrastructure	Bhagirathi	Mandakini	Alkhananda	Kali
Hydropower stations	√	√	√	√
Bridge	√	√	√	√
Roads	√	√	√	√
Spiritual infrastructure	√	√	√	√
Existing flood protection works	√	√	√	√
CWC hydrological site	√	√	√	√
Meteorological sites	√	√	√	√
Parking area	√	√	√	√
Agriculture land	√	√	√	√

system is a cluster of glaciers comprising the main Gangotri glacier (length: 30.2 km, width: 0.20–2.35 km, area: 86.32 Sq. Km) as a trunk part of the system. Other major glaciers of the system are: Raktvarm (55.30 Sq. Km), Chaturangi (67.70 Sq. Km), Kirti (33.14 Sq. Km), Swachand (16.71 Sq. Km), Ghanohim (12.97 Sq. Km) and a few others (13.00 Sq. Km). Depths of these glaciers are about 200 m, and the elevations vary from 4000 to 7000 m.

Landslides are mass wasting due to slope failures. It is downslope movement of rocks, soil and debris by the action of gravity. Several features of the basin make landslides a common occurrence such as the relationship between the rocks, characterized by multiple structural discontinuities, and the high relief slopes. Landslides on the roads disrupt communication routes. Similarly, landslides into the streams also pose major threats. The slid land masses cause blockades of river courses, and subsequent breach of landslide dams increases the flooding potential of downstream reaches. Landslides also induce higher sediment loads into the rivers which can also have adverse impacts.

5 Result and discussion

5.1 Morphological and bank line changes

The trends of channel migration have been established by comparing satellite images from 2005, 2010 and 2015 and post-flood field visits. The approach is based on geospatial analysis of bank line changes along the river. To calculate the bank line shifts of the river, bank lines from 2005, 2010 and 2015 are digitized manually using LandSAT-7 ETM^+, IRS-P6 LISS-III data, LandSAT-8 PAN + OLI merge data and Google Earth Pro satellite images to delineate the river courses for the respective years (Fig. 10). The bank line changes (stations 1–8 given in Table 9) are given in the inland circles.

Bhagirathi River In general, Bhagirathi is a mountainous river. The river bed up to Gangotri is filled with debris left behind due to recession of glaciers. Further downstream of Gangotri, the evidence of broad U-shaped valley of glacial origin is seen only at the higher elevation and the river has cut a narrow V-shaped fluvial at the lower elevation. The bed slope variation in the upper reaches is in the order of 50 m/km to 3 m/km. The extreme flood event of 2010 and 2013 in Bhagirathi River caused instability of the channel and the banks. Associated bank line changes along the river are presented in Fig. 10 at two locations marked as station 1 and 2 for stations Jyoti and Uttarkashi, respectively.

Alaknanda River Two types of bank materials exist along the course of Alaknanda River. In the first type, the bank materials are igneous, metamorphic and sedimentary rocks of various types as mentioned above. The erodability of these rocks is generally low. However, presence of fractures, joints and faults in these rocks makes them prone to erosion. Particularly, certain types of sedimentary and metamorphic rocks such as slates, shales and phyllites are more erodible than the other rock types such as granites, dolomites and amphibolites. In the second type, the bank materials are constituted of poorly sorted and unconsolidated sediments and soils such as moraine deposits. These materials are highly erodible. The extreme flood event of 2013 in Alaknanda River caused instability of the channel and the banks. Upstream of Gangotri, the river is very steep and passes through gorges which in a shadow of the mountains being cast on the river, making it difficult to digitize river bank polylines. Examination of the bank line shifts of the Alaknanda River

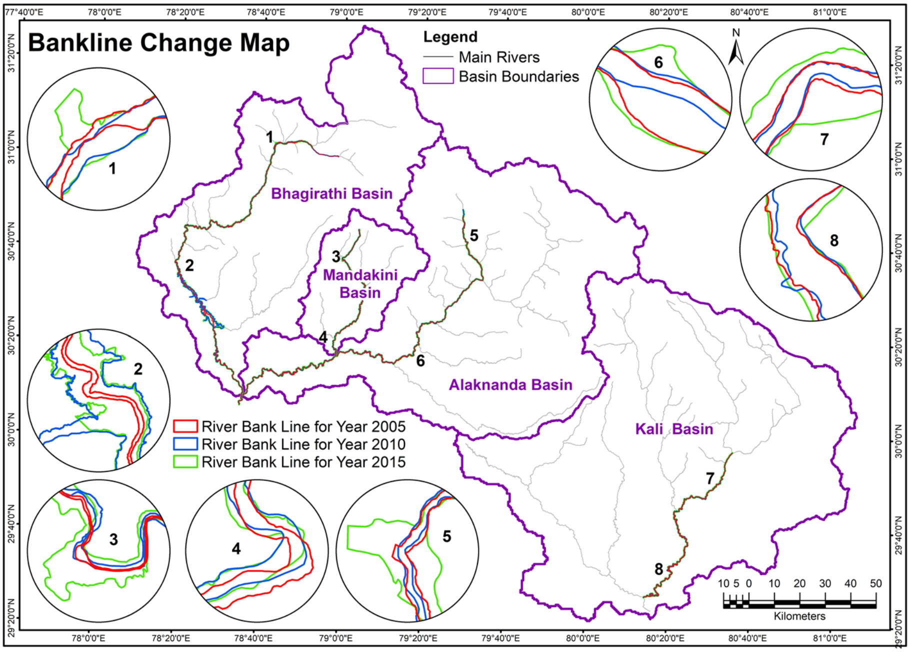

Fig. 10 Bank line changes along Bhagirathi, Mandakini, Alaknanda, and Kali Rivers

Table 9 Risks on selected vulnerable reaches during 2015 flood

Station no.	River	Station name	2005–2010		2010–2015	
			Left bank	Right bank	Left bank	right bank
1	Bhagirathi	Near to Jyoti	+21 M	0	+45.96 M	+39.27 M
2		Near to Uttarkashi	−11.4 M	+11.7 M	+20.40 M	−37.02 M
3	Mandakini	Sitapur	−24.92 M	+28.23 M	+41.0 M	+53.40 M
4		Tehsil area Rudraprayag	−19.59 M	+30.35 M	+9.0 M	+10.15 M
5	Alaknanda	Khiru village	−29.84 M	+33.23 M	+67.84 M	+124.35 M
6		Deolibagad	−19.89 M	+42.97 M	−12.49 M	−8.62 M
7	Kali	Downstream of Gothi	+26.66 M	−40.47 M	−16.92 M	+107.90 M
8		Near to Jhulaghat	−4.9 M	+11.8 M	−10.54 M	+34.22 M

has been carried out along several stretches. Two such locations are presented in the inland circles 3 and 4 for stations Sitapur and Rudraprayag, respectively, in Fig. 10.

Mandakini River The extreme flood event of 2013 in Mandakini River caused instability of the channel and the banks. Upstream of Sonprayag, the river is very steep, passes through gorges, and hence due to the shadowing effects of the mountains, it is difficult to digitize river bank polylines. Bank line shifting at two such locations is presented in the inland circles 5 and 6 for the stations Sitapur and Rudraprayag, respectively, in Fig. 10. The bank line along Sitapur has shifted 12 m from the year 2010 to 2015, mainly due to heavy flood in June 2013. At Rudraprayag from downstream of Kund hydropower project, due to bank erosion, slight bank line shifting at Sumari (at right bank) and Banswada, Chandrapuri, Vijaynagar (at left bank) has occurred.

Kali River In general, Kali River is a mountainous river. The reach from Tawaghat to Pancheshwar has mostly steep banks with intermittent rocky and loose materials in its bank. The river bed is mostly constituted of boulders. Within this reach, the river shows only meandering and partly straight planform. 50 km downstream of Pancheshwar, the river is alluvial in nature. Beyond this location, the river pattern becomes wide and braided. Based on the limited available years (2005, 2010 and 2015) of satellite imageries, the most recognizable migration of the channel has been traced along the Kali River and is shown in Fig. 10. The average shift in bank line change along the zones covering these locations along river is given in Table 9. In this analysis, calculations are made to determine shifting of the bank lines from 2005 to 2015 and from 2010 to 2015. A positive number indicates outward movement of the bank, and a negative number indicates inward movement of the bank.

5.2 Critically vulnerable reaches and major issues identified

Settlements, roads, forests, agricultural lands and other infrastructure are exposed to river hazards. Based on the analysis given in Tables 2 and 3, the vulnerability has been identified through field visits and interaction with local people. Saturation of soils changes the stability of the slopes of river banks causing severe bank erosions; high sediment loads deposited by the rivers causing comparatively slack flows resulting in high HFL and high pressure on banks. Risks on vulnerable reaches along the rivers are assessed based on hazard, exposure and impacts due to hazard. Such eight locations are listed in Table 10 detailing the vulnerability and associated risks. Observed morphological changes at various river reaches are straightening of river meanders; accentuation of meanders at their apex points; shifting of channels; and sediment loads deposition. These changes developed adverse conditions for river hydraulics and sediments transportation.

6 Conclusions

This paper describes the meteorological and morphological characteristics of Uttarakhand river basins (Alaknanda, Bhagirathi, Mandakini and Kali), which influenced the river morphology during 2013 disaster. The main hazards in region related to the rivers are flooding, landslide, soil erosion and river bank instability. River basins focusing on rainfall, topography, drainage pattern, soil, landslide and exiting infrastructure in relation to vulnerability of the region are discussed in details. Most of the study area has steep slopes making the region erosion prone. All data collected, on-site detailed work combined with satellite information and knowledge acquired from the available literature contributes to understanding the geology and geomorphology of the study area. Online database with collaborating organizations has been created as (www.urmis.dhi-india.com).

Bank line changes and river bar delineation have been obtained using high-resolution satellite data through GIS for the years 2005, 2010 and 2015. To assess the risk along critical vulnerable reaches, indicator-based approach is used. The various indicators are hazards present along a river, level of risk to those hazards, and the level of exposure of the population and the infrastructure to the hazards. Various geological and geomorphological data sets along the river basins also have been analysed. This paper will be of great use to

Table 10 Risks on vulnerable reaches before emplacement of protection work

S. no.	River basin	Location	Exposure and description of hazard	Vulnerability	Risk
1	Bhagirathi	Jyoti	Agriculture land: Landslide above the road and toe erosion below the road may affect the vehicular traffic and obstruct the pilgrimage	Landslide and toe erosion	Medium
2		Uttarkashi	Settlement: Debris deposition, flooding due to the barrage situated within the town, toe cutting on both banks are main hazards	Debris deposition, flooding	High
3	Mandakini	Sitapur	Agriculture land: Toe erosion and direct cutting of the right bank led the loss of agricultural land	Toe erosion and debris deposition	Medium
4		Tehsil area Rudraprayag	Settlement: Slope failure and bank erosion at the bend is the main hazard to Tehsil area	Bank erosion	High
5	Alaknanda	Khiru village	Settlement: Toe cutting by high shear stress is the major cause of bank failure. There is the possibility of sediment deposition to block the flow of Alkhananda from the heavy silt laden flow of Khiru Nala which hits the Alaknanda almost perpendicularly on the right bank. This can divert the Alkhananda flow towards the village by shifting of the bank	Flow from tributary is directly hitting the settlement	High
6		Deolibagad	Settlement: The hazards are flooding of the low-lying village on the left bank and gravity failure of bank associated with toe erosion	Settlement existing on the flood plain	High
7	Kali river	Gothi village	Settlement: The hazard is bank failure due to by toe erosion, removal of material from bank	Settlement endangered due to toe erosion	High
8		Jhulaghat	Settlement: Major hazard at this location is bank erosion at right bank and landslide at left bank	Settlement is on the eroding bank of river	High

policy makers and rural or villages planners in preparing proper village plans, slope stability plan, disaster management plan and in prevention of natural hazards and manmade hazards. It will also be useful to drainage designers to plan the layout of drains and potential hydro projects and in planning of other infrastructure facilities like roads, national parks, reserve forest and government plans.

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