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Morphological Characteristics and Vulnerability Assessment of Alaknanda, Bhagirathi, Mandakini and Kali Rivers, Uttarakhand (India)

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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. The main hazards in region related to the rivers are flooding, landslide, soil erosion, and river bank instability. 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. Erosion rendered many locations along the banks vulnerable to economic and human loss. 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 of the rivers. The shifts in reaches are calculated by digitizing the bank line using satellite imageries of year 2005, 2010 and 2015. Susceptibility of banks and damages by high discharge along bank line are also studied. A fuller understanding will enable decision makers towards more efficient resources management for prevention and mitigation of flood events.

Keywords

Vulnerability, Landslide, Flood, Bankline Changes, Himalaya, Disaster, Extreme Rainfall

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1. Introduction

The Himalayas are one of the youngest mountain ranges on earth due to high tectonic activities. The uncertain climatic conditions, varying geology, steep slopes, rivers, highly variable altitudes, glaciers make the region inherently vulnerable to numerous types of hazards [1]. Floods 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. 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, 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 [2-4].

Heavy downpour and subsequent devastating floods on 15th-17th June 2013 led to heavy loss of lives and property in Uttarakhand and neighbourhood. 4-weeks before, the unusual rapid snow cover around Chorabri lake and heavy rainfall due to early onset of 2013 monsoon elevated the stream flow, resulting in slope saturation and significant run-off [5-6]. The crucial hydrometeorological factor along with the glacial lake outburst flood (GLOF) and landslides killed more than 6000

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people [7]. Numerous roads and bridges were damaged and at least 30 hydropower plants were either destroyed or severely damaged [8]. The destruction of roads and trekking routes left around 100,000 pilgrims and tourists stranded until military and civic authorities could complete evacuation efforts [9]. Connectivity was disrupted across the state and vehicular traffic was disrupted along more than 2000 roads. About 150 bridges were damaged or washed off.

There are currently no documents [10], which explicitly details the hydro-meteorologically triggered glacial lake outburst floods (GLOFs). Even globally, such incidents are rarely recorded in detail [11-13]. 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 [14-17]. For developing the remedial measures few more useful studies have been carried out by [18-21]. 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 study area covers major river basins of Uttarakhand i.e. Alaknanda, Bhagirathi, Mandakini and Kali.

2. Study Area and Data

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 topographic characteristics of the study area. Figure 1 gives the topography of the area depicts panoramic view of the morphology. The same data has been used for slope mapping, drainage mapping, physiography and morphometric analysis [22]. The details of the data sources are shown in Table 1.

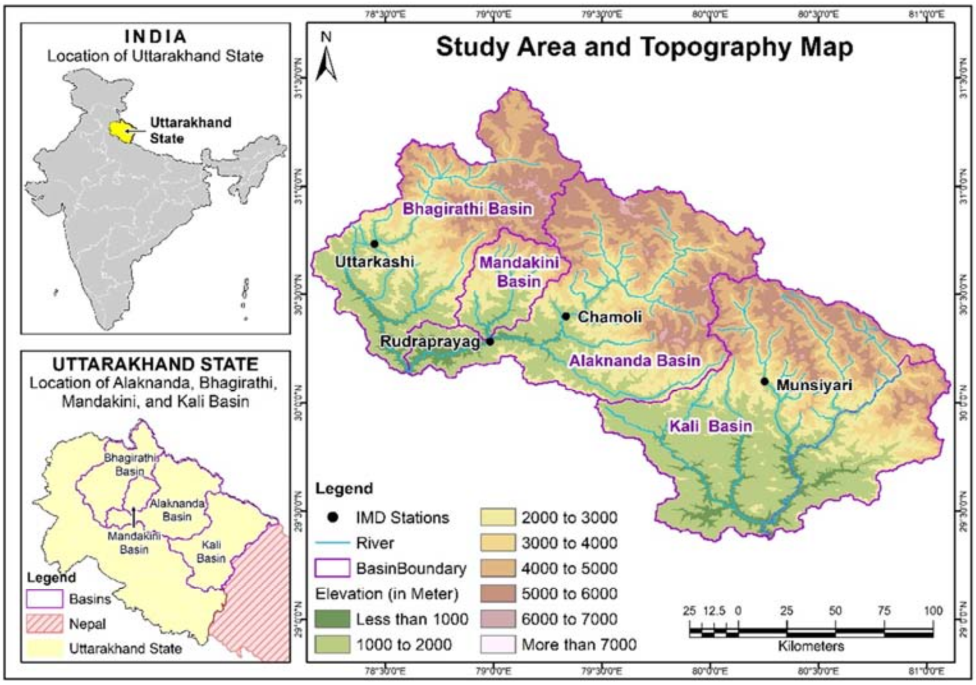


Figure 1. Study Area and Topography Map.

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 30m) acquired on 2nd December 2005 and on 26th September 2015 were used. Additionally, IRS-P6 data (spatial resolutions of 23.5m) captured on 5th November 2010 was also used. Geological sample data was gathered during the field assessments of vulnerable reaches.

Table 1. List of the Data and Sources.

S. No.	Data Layer/Maps	Sources
1.	Topographic Map	Series U502, U.S. 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 30.0m Global Land Cover Facility (GLCF), Earth Science Data Interface (ESDI), 2005. http://glcfapp.glcf.umd.edu:8080/esdi IRS-P6 LISS-III; spatial resolution 23.5m 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 15m U.S. Geological Survey (USGS), Earth Explorer, 2015& 2017. http://earthexplorer.usgs.gov
3.	Elevation Data	Shuttle Radar Topography Mission (SRTM), DEM Data; spatial resolution 30m NASA, & USGS EROS Data Centre, 2006. http://glcfapp.glcf.umd.edu:8080/esdi CartoSAT-1 Digital Elevation Model (CartoDEM) Data; spatial resolution 30m 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 has 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 has 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 have 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. Data Analysis

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

a) 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.

b) 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.

c) After mosaicking, the satellite imagery/DEM data was 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.

d) Ground control points (GCP's) were collected or found out using the satellite imagery/DEM data reference and actual DGPS survey.

e) Processed GPS acquired point data was used known as GCP's for referencing the satellite imagery and DEM data.

f) Using GCP's 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.

g) 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.

h) Nearest Neighbourhood method was used for the transformation of the raw satellite data to geo-referenced satellite data.

i) Automatically generated Root Mean Square Error (RMSE) less than 0.23 was maintained.

3.1. Topography

The area includes high mountains over 7184m above mean sea level (amsl) and low surfaces of about 362m 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 19km upstream from Gangotri town and ends at Devprayag. The river passes through Uttarkashi, Tehri and Pauri Garhwal district with total basin area of 7619Km^2. Maximum length of the river lies in Uttarkashi district with just about 2km in Pauri Garhwal district and merges with Alaknanda at Devprayag (~470m). The river basin is more like an elongated type, with straight length of about 205km. The basin has complex topography with high mountain chains and glaciered area in north. Within this stretch, the elevation of the basin ranges from ~412m amsl at Devprayag to ~7007m amsl at the higher region (northern side).

Mandakini Basin: The Mandakini River originates from the Chorabari Glacier (~5020m) located just 2km upstream of

Shri Kedarnath shrine and joins Alaknanda at Rudraprayag (~431m). 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 1645km^2. The average length of this river basin is 55km and average width is 35Km. Within this short stretch, the elevation of the basin ranges from ~6700m amsl at the higher region to ~400m amsl in the lower areas.

Alaknanda Basin: The Alaknanda basin has a complex topography having high mountain chains with glaciered basin in north and fluvial terrace in central and lower parts. There are huge changes in elevation within short stretches. The Alaknanda river basin area is 11070km^2. The river originates 6km upstream from Satopanth Glacier (~4350m amsl) and passes through Badrinath, Karnprayag, Rudraprayag and finally Devprayag (~475m 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 180km. Within this stretch the elevation of the basin ranges from ~412m amsl at Devprayag to ~7184m 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 was partially available for the study. In most of the result 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 (~5020m) and passes through Kalapani, Tawaght pass, Jauljibi and Jhulaghat before arriving at Pancheswar (~431m). Though the upper reach of river is steep, the overall slope of entire reach of the river is mild. 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 107km.

3.2. Climate and Extreme Rainfall

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 362m in south to more than 7,184m in the north of the study area. It has been observed that for every 1,000m ascent, there is a 6°C decrease in temperature [23]. Table 2 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). 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. January is the coldest month after which the temperature begins to rise until June or July.

Table 2. Climatic Zones in Uttarakhand [23].

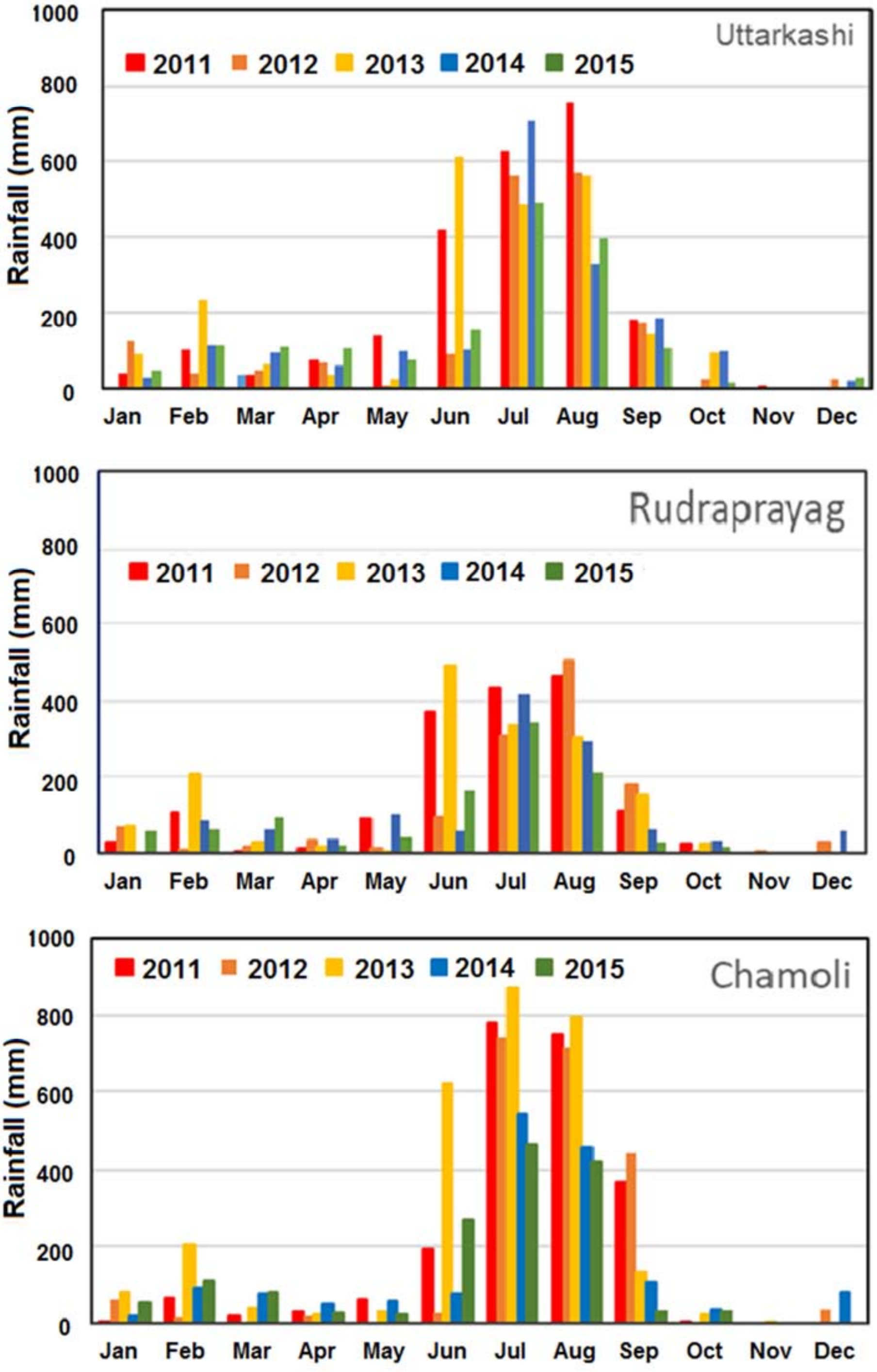
Climatic Zone	Altitude (m)	Average Temperature Range (°C)		
		Annual	June	January
Tropical	300-900	18.9-21.1	27.2-29.4	11.1-13.3
Warm (Sub Tropical)	900-1800	13.9-18.9	21.1-27.2	06.1-11.1
Cool	1800-2400	10.3-13.9	17.2-21.1	02.8-06.1
Cold	2400-3000	04.5-10.3	12.3-17.2	01.7-02.8
Alpine	3000-4000	03.0-04.5	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 2.2-3.9		

The climate in the mid-Himalayas consists of four distinct seasons - winter, pre-monsoon, monsoon and post-monsoon. 60% of the mean annual rainfall occurs during the summer 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. 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 [24]. For all the seasonal regularity of monsoon winds and rainfall, local climates (over much of the area) are quite variable. 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. Certain peculiar geomorphic features including cirque and funnel shaped valleys with high relative relief, dense forest cover, and average altitude exceeding 1500m are considered to provide favourable conditions for cloud burst.

Extremes rainfall at different locations in Uttarakhand since 1901 to 2013 has been obtained from various literature review and detail is shown in Table 3. The monthly variations of rainfall from 2011-2015 at four stations - Uttarkashi (Bhagirathi), Rudraprayag (Mandakini), Chamoli (Alkhananda) and Munsiyari (Kali) along the rivers are presented in Figure 2. The location of these IMD stations are marked in Figure 1. The highest rainfall recorded at all the stations was in 2013. According to the Indian Meteorological Department (IMD) June 2013 rainfall was over thrice the normal amount between June 1 and 21. The highest figure quoted by was 370mm on 17 June at Dehradun [25], which was said to be a record not seen for five decades. Figure 3 shows the normal versus observed rainfall from 13 - 19 June 2013. From the analysis it is clear that the June 2013 event was not the as intense as that of one in 100 years due to large special and temporal distribution of rain it was the most devastating in the history.

Table 3. Extremes Rainfall in Uttarakhand since 1901 to 2013.

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



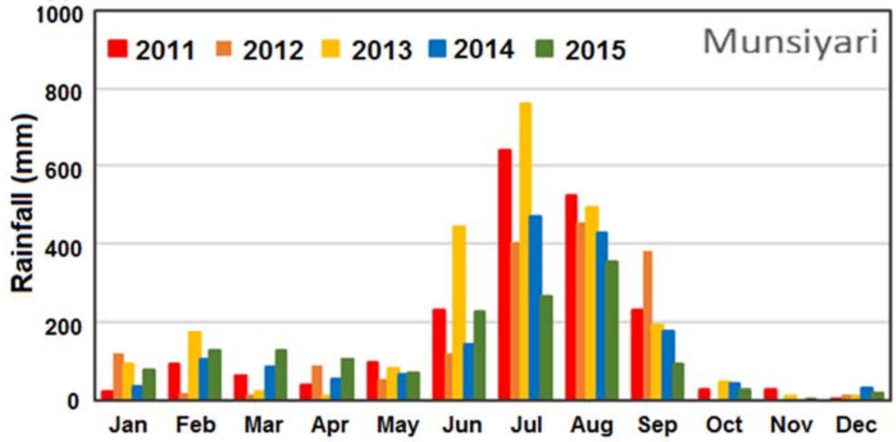


Figure 2. Monthly Rainfall Variations during 2011-2015 at Uttarkashi (Bhagirathi), Rudraprayag (Mandakini), Chamoli (Alkhananda) and Munsiyari (Kali).

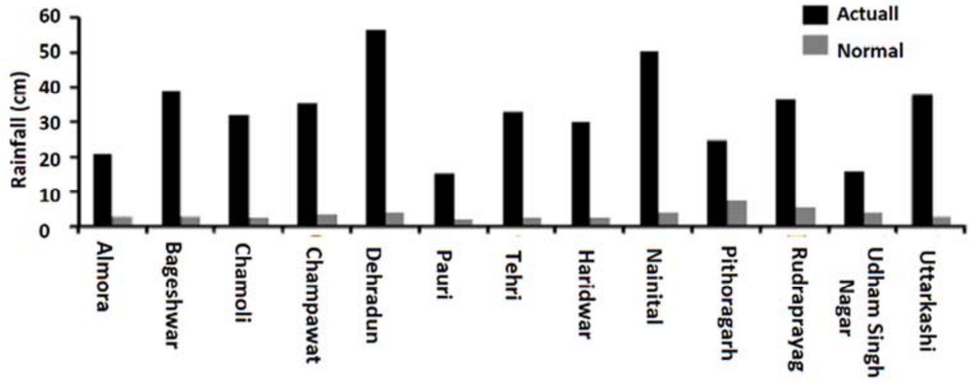


Figure 3. District-wise Rainfall Distribution bar of Uttarakhand from 13 June to 19 June 2013.

3.3. 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 such as: [26-32] and many more.

On-Site Geological Mapping: The field operation essentially geologic mapping of the study area determines the underlying lithological units. The geologic 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 [33]. 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., topographic maps and 3D Images from Google-Earth, and Carto-DEM. The results of the remote sensing interpretation were integrated into a GIS allowing to produce the geological map.

On site geological mapping combined with satellite remote sensing based geological data have been used. Recorded principal rock formations of the region are described in Table 4. Figure 4 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 geologic event is recognized in recent years. Therefore, geologic 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 Fromation has been recorded.

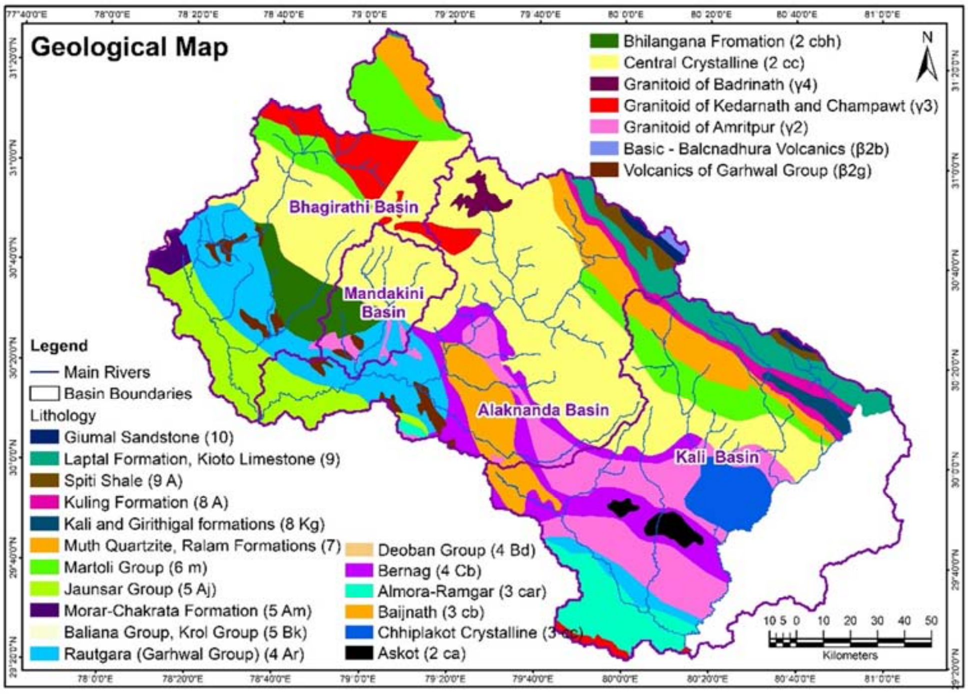


Figure 4. Geological Map of River Basins in Uttarakhand.

Table 4. Stratigraphy of the Study Are.

Map Symbol	Group/Formation/Lithology	Age
10	Giumal Sandstone	Cretaceous
9	Laptal Formation, Kioto Limestone, Kuti Shale, Kalapani Limestone; Chocolate Formation	Triassic-Jurassic
9A	Spiti Shale	
8A	Kuling Formation	Carboniferous-Permian
8kg	Kali and Girithigal Formations	
7	Muth Quartzite, Variegated Shale, Sniala, Garbyang, Ralam Formation	Ordovician-Devonian
6m	Martoli Group	Neoproterozoic-Cambrian
5Aj	Jaunsar Group	
5Am	Morar-Chakrata Formation	Neoproterozoic
5Bk	Baliana Group, Krol Group	
4Ar	Rautgara (Formations of Garhwal Group)	
4Bd	Deoban Group	Mesoproterozoic
4Cb	Bernag	
3car	Almora-Ramgar	
3cb	Baijnath	
3cc	Chhiplakot Crystalline	
2ca	Askot	Palaeoproterozoic
2cbh	Bhilangana Formation	
2cc	Central Crystalline	
	Igneous Rocks - Plutonic Rocks	
γ4	Granitoid of Badrinath	Mesozoic-Tertiary
γ3	Granitoid of Kedarnath and Champawt	Neoproterozoic-Palaeozoic
γ2	Granitoid of Amritpur, Almora, Chamoli and Chandrapuri	Proterozoic
	Igneous Rocks - Volcanic Rocks	
β2b	Basic - BalcnadhuraVolcanics	Cretaceous-Palaeogene
β2g	Volcanics of Garhwal Group	Proterozoic

3.4. Soil Types

The soil map was generated in GIS environment using soil map collected from Uttarakhand Soil Information System NBSS&LUP and was updated using ResourceSAT-1 LISS-IIII (23.5m), and Landsat-7 ETM$^+$ (30m) multi-spectral satellite imageries (Figure 5). 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. Most of the study area has steep slopes (with slope gradients ranging between 32% and 55%) making the region erosion prone.

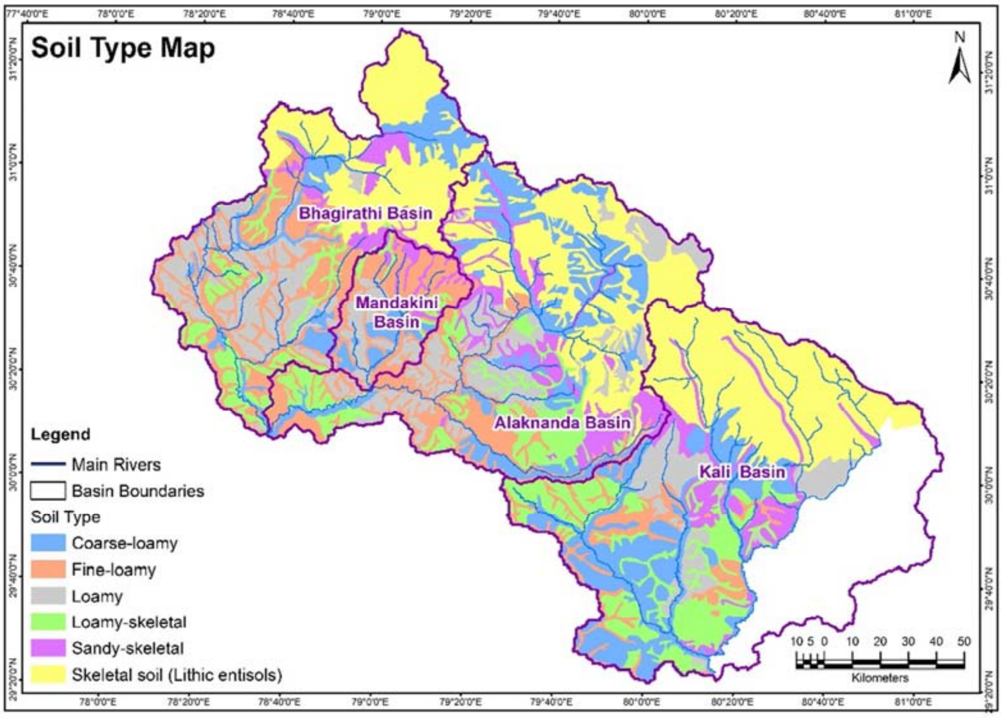


Figure 5. Soil Map of River Basins in Uttarakhand.

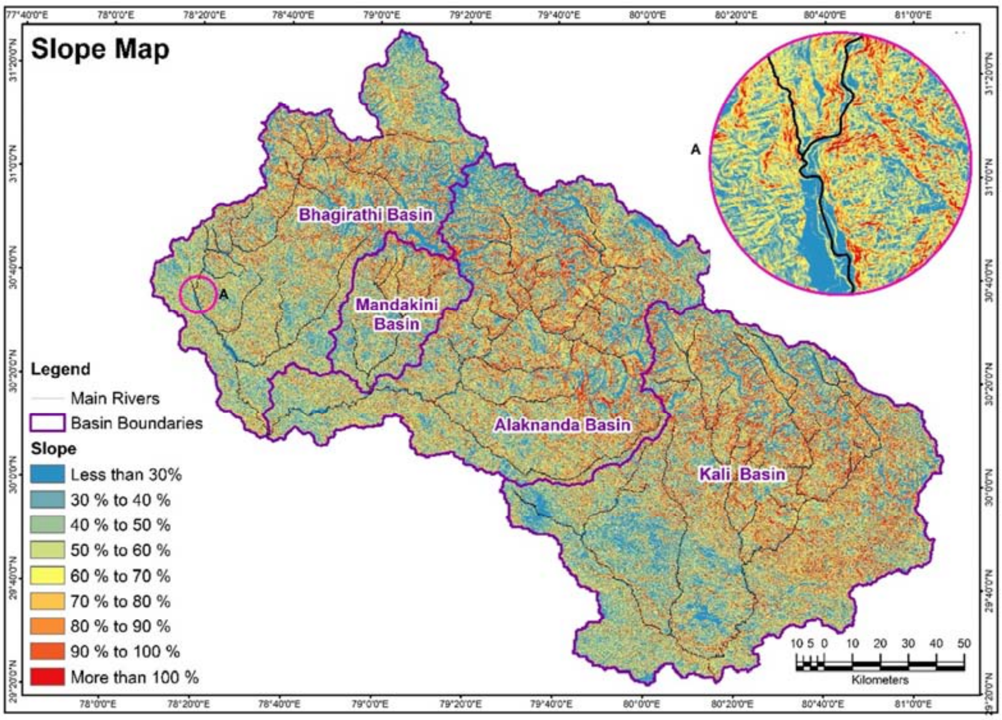


Figure 6. Slope of the River Basins.

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.

3.5. Slope

Slope is the most important and specific feature of the earth's surface form. 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 to flood plains, river terraces and other local depositional landforms. The average side slopes (Figure 6) 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 another 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.

3.6. Drainage Pattern

Drainage texture reflects climate, permeability of rocks, vegetation, and relief ratio. Figure 7 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 geologic 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 [34]. 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 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 sub-soil and thick vegetative cover.

3.7. Existing Infrastructure, Landslide and Glacier

Figure 8 is a composite image of the analysis area depicting the infrastructures, landslides and glaciers. The major infrastructure within the study area which are vulnerable to river disasters are given in Table 5. 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 [35]. 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 et al 2008) Gangotri system is a cluster of glaciers comprising the main Gangotri glacier (length: 30.2 Km, width: 0.20-2.35 Km, area: 86.32Sq. Km) as a trunk part of the system. Other major glaciers of the system are: Raktvarm (55.30Sq. Km), Chaturangi (67.70Sq. Km), Kirti (33.14Sq. Km), Swachand (16.71Sq. Km), Ghanohim (12.97Sq. Km) and a few others (13.00Sq. Km). Depths of these glaciers are about 200m and the elevations vary from 4000-7000m.

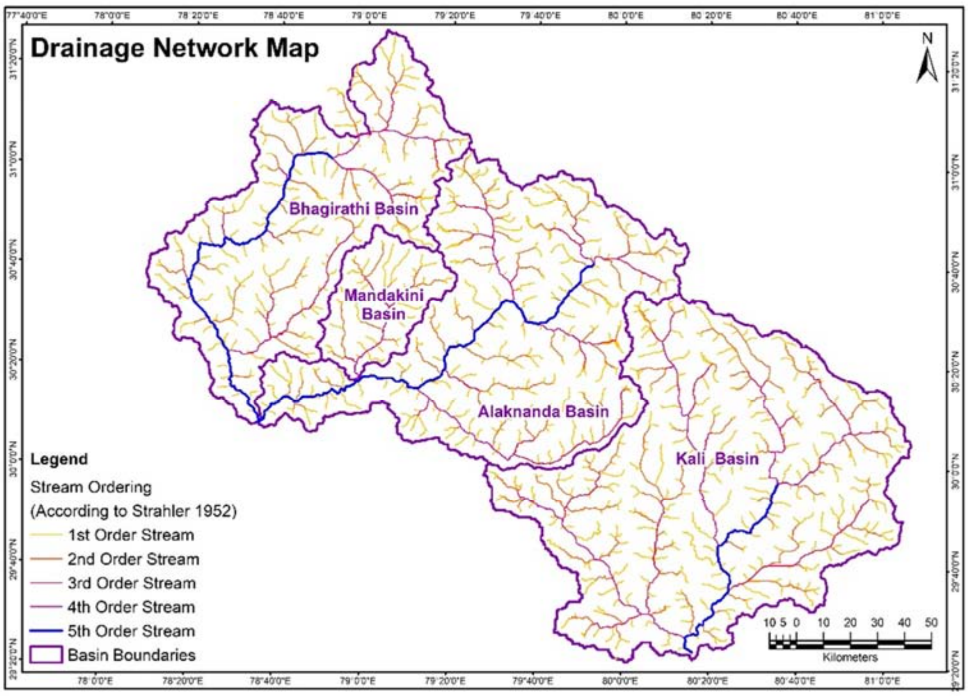


Figure 7. Generalized Drainage Map for 1st to 5th Order Streams in the River Basins.

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, characterised 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 [36].

Table 5. Summary of Existing Infrastructure along the Major River Basins.

0	Bhagirathi	Mandakini	Alaknanda	Kali
Hydropower Stations	√	√	√	√
Bridge, Parking Area	√	√	√	√
Roads, Agriculture Land	√	√	√	√
Spiritual Infrastructure	√	√	√	√
Existing Flood Protection Works	√	√	√	√
CWC Hydrological Site, Meteorological Sites	√	√	√	√

3.8. Geomorphology

Geomorphology is the science of evolution of landforms in terms of its lithology, structure, basin geometry and other morphometric factors. Figure 9 presents the geomorphology of the river basins, presenting an intricate mosaic of mountain ranges, hills and valleys. Physio-graphically, the area is a part of the great Himalayas with high peaks [37]. 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.

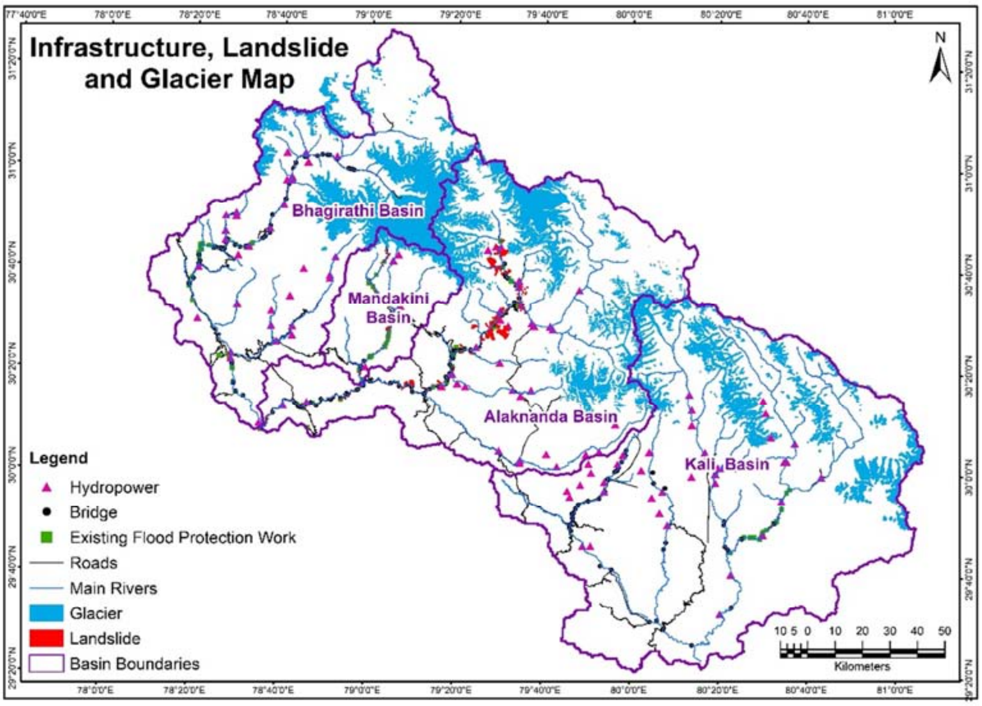


Figure 8. Generalized Overburden Map of River Basins.

4. Result and Discussion

4.1. Bankline 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 (Figure 10). The bank line changes (stations 1 to 8 given in Table 6) 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 50m/km to 3m/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 Figure 10 at two locations marked as station 1 and 2 for stations Jyoti and Uttarkashi respectively.

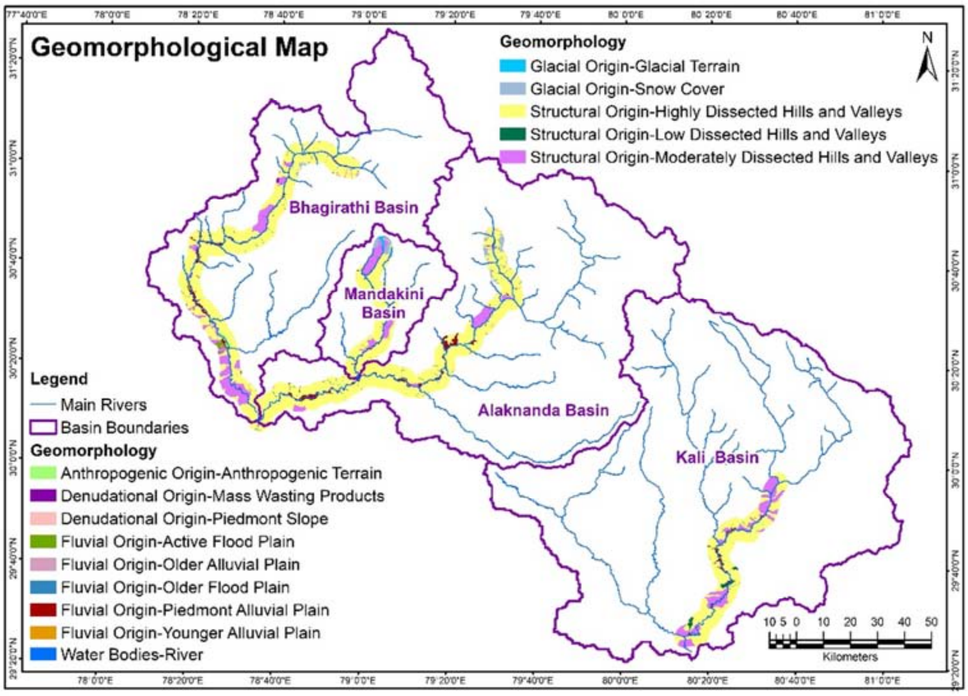


Figure 9. Geomorphology Map of River Basins.

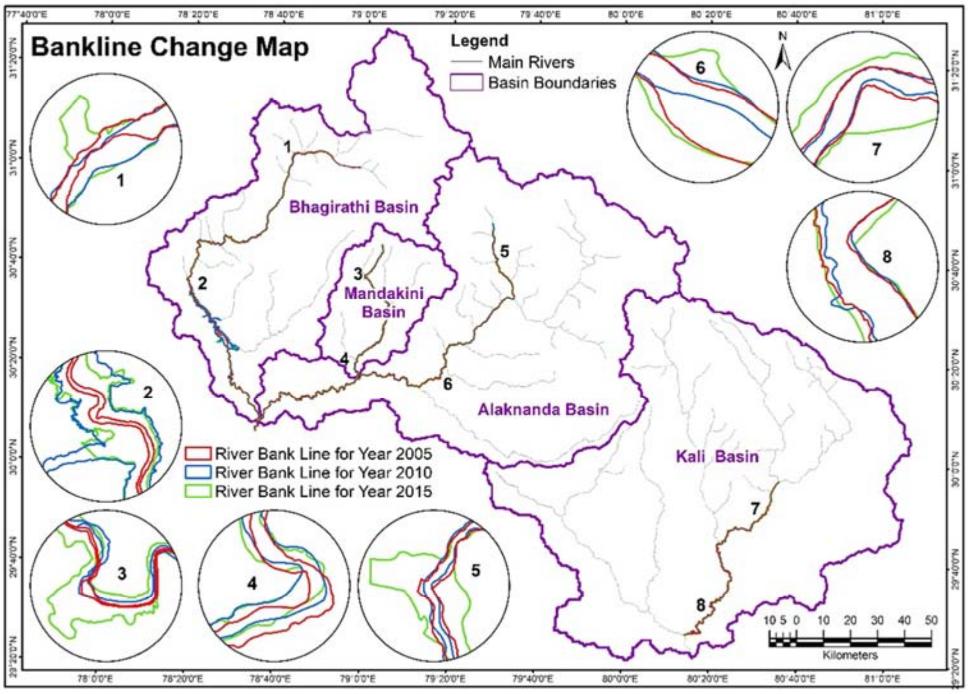


Figure 10. Bankline Changes along Bhagirathi, Mandakini, Alaknanda, and Kali Rivers.

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 erodibility of these rocks is generally low. However, presence of fractures, joints, and faults in these rocks make 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, amphibolite's, etc. 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 has been carried out along several stretches. Two such locations are presented in the inland circle 3 and 4 for stations Sitapur and Rudraprayag respectively in Figure 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. Bankline shifting at two such locations are presented in the inland circle 5 and 6 for the stations Sitapur and Rudraprayag respectively in Figure 10. The bankline along Sitapur has shifted 12m 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, Vjaynagar (at left bank) has occurred.

Kali River: In general, Kali River is a mountainous river. The reach from Tawaghat to Pancheswar 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. 50km downstream of Pancheswar, 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 are shown in Figure 10. The average shift in bankline change along the zones covering these locations along river is given in Table 6. 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.

Table 6. 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	+21M	0	+45.96M	+39.27M
2		Near to Uttarkashi	-11.4M	+11.7M	+20.40M	-37.02M
3	Mandakini	Sitapur	-24.92M	+28.23M	+41.0M	+53.40M
4		Tehsil area Rudraprayag	-19.59M	+30.35M	+9.0M	+10.15M
5	Alaknanda	Khiru Village	-29.84M	+33.23M	+67.84M	+124.35M
6		Deolibagad	-19.89M	+42.97M	-12.49M	-8.62M
7	Kali	Downstream of Gothi	+26.66M	-40.47M	-16.92M	+107.90M
8		Near to Jhulagat	-4.9M	+11.8M	-10.54M	+34.22M

4.2. Hazards

The screening process for identification of vulnerable reaches is based on the hazards present along a river reach, the level of risk of those hazards, and the level of exposure of the population and the infrastructure to the hazards. Hazards due to extreme rainfall along the rivers in the hilly area are River Morphological Hazard, Flood Hazards, and Landslides.

4.2.1. River Morphological Hazard

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

a) 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 occurs. The increase in hydraulic forces can be due to the following factors:

i. Steeper longitudinal slopes.

ii. Increased flood discharge.

iii. Shifting of channel closer to the river bank, caused by the morphological changes, or forced by accumulation of muck due to landslide, or by development of shoals/islands within the river channel.

iv. Changes in the direction of flow with reference to the alignment of river bank, caused by uneven sediment deposition/removal from a river reach.

b) 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:

i. Engineering properties like size of the particles, larger the size, higher is the resistance to its displacement from the bank.

ii. Gradation of bank materials - wider range of particles help to resist the displacement of smaller particles by armouring effects.

iii. Cohesion between the particles - existence of suitable percentage of clay in the bank materials can have cementing effect which increases the resistance to the erosive forces.

iv. Wetness of the soil - this is an important factor in bank failures at many places; wet soil has less resistance to withstand the slope.

c) 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 the following aspects:

i. Cross slope of the bank - a steeper bank increases instability and consequently it collapses.

ii. Height of the bank - the height of bank has very high influence on its stability - higher the bank greater is the chance of failure.

iii. A bank alignment streamlined to the main river flow results in less turbulence close to the bank during floods, and consequently results into lesser bed scours.

iv. Growth of vegetation on the bank slope can provide high resistance to bank erosion.

v. Existence of hard points located on the bank, like rock outcrops can help to arrest overall bank line migration over long stretches of a river.

4.2.2. Flood Hazard

Flood hazard is mainly related to submergence of land and property located on the floodplains of the river. Submergence is caused by high flows that result in the rise of the water levels and spilling of water over the banks. Cases of submergence of villages and cities are limited in the river reaches considered in this study. However, there are small settlements (commercial, religious places such as temples, tourist spots etc.) along the rivers that are vulnerable to flooding. Submergence of agricultural lands along the rivers is also an example of flood hazard. Most floods in the river basins under consideration are of flashy in nature. 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. Apart from inundation resulting from high flows, the types of flood hazard include following

a) Flash floods generated by sudden heavy rainfall, including cloudbursts in parts of the catchment.

b) Temporary blocking of river flows due to landslides.

c) Glacier lake outburst floods (GLOF) generated in the catchments at higher elevations.

4.2.3. Landslide Hazard

Description of Fluvial geomorphology approached hazard analysis is detailed in Table 7. The landslide hazards along the rivers in Uttarakhand are categorized in the following types:

a) Landslides directly related to erosion of river banks, caused mainly by toe erosion.

b) Landslides due to construction of roads, with debris falling into the river.

c) Landslides away from the river above the road towards hillside terraces, but ultimately affecting the river flow due the falling debris.

Table 7. 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.

Hazard	Cause
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.

4.3. Exposure

Exposure refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses. While the literature and common usage often mistakenly combine exposure and vulnerability, they are distinct. Exposure is a necessary, but not sufficient, determinant of risk. The major infrastructures present along the rivers are depicted in the composite Figure 8. Following exposures are considered under the present study.

a) Human population (rural as well as urban) residing near the river bank, which is exposed to a hazard or affected earlier.

b) Infrastructure includes roads, bridges, hydropower stations, irrigation systems, human settlements, health care facilities and places of religious importance.

c) Agricultural land.

d) Tourism spots.

e) Defence establishments.

4.4. Vulnerability and Risk Analysis

Level of risks at the vulnerable reaches along the river is assessed based on direct and indirect impacts of the hazards to the exposed elements given in Table 8. 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 x 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. Hence a vulnerability study is important for protection of the region.

Table 8. Calculation of the Risk.

	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 etc.	Populated and important towns

4.4.1. Problems Encountered in the Vulnerable Reaches

The changes brought to the rivers have made identification of vulnerable reaches problematic at many locations. It developed adverse conditions for river hydraulics and sediments transportation. Following morphological changes at various river reaches occurred.

a) Straightening of river meanders.

b) Accentuation of meanders at their apex points.

c) Shifting of channels.

d) Due to thorough saturation of soils, the stability of the slopes of river banks had been seriously disturbed and severe bank erosions took place at numerous locations.

e) High sediment loads deposited by the rivers at every probable place of comparatively slack flows, resulting in high HFL and high pressure on banks.

4.4.2. Critically Vulnerable Reaches

Settlements, roads, forests, agricultural lands and other infrastructure are exposed to river hazards. Based on the analysis given in Tables 7 & 8, the vulnerability has been identified through field visits and interaction with local people. Risks on vulnerable reaches along the rivers are assessed based on hazard, exposure and impacts due to hazard. Such eight locations have been listed in Table 9 detailing the vulnerability and associated risks.

Table 9. 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 Alkananda from the heavy silt laden flow of Khiru Nala which hits the Alaknanda almost perpendicularly on the right bank. This can divert the Alkanada flow toward 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

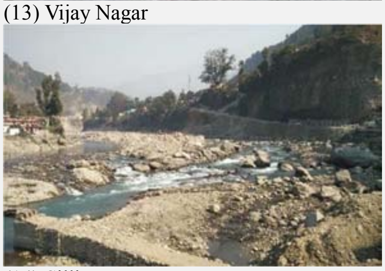
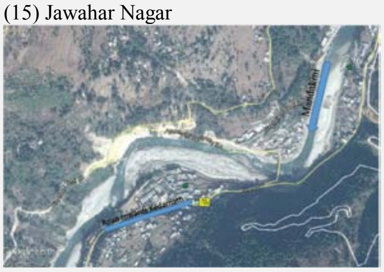
4.4.3. Critically Vulnerable Reaches Along Mandakini River

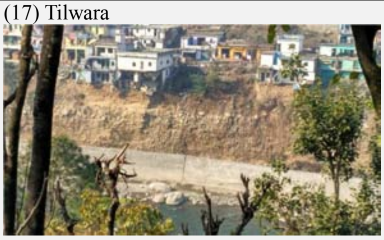
Out of 4 study rivers, we have brief described the vulnerable reaches only for one river i.e. Mandakini river. Locations along the Mandakini River suffered major disaster during the June 2013 catastrophic flood event. Thousands of human and cattle lives and properties worth billions were lost during the disaster. Based on field investigations and input from the local administrations, vulnerable reaches were identified and shown in Figure 11. The reaches are grouped into two categories namely, "where new protection works are to be planned and designed" and "reaches where protections works are already in place and hence only needs to be reviewed". From Tilwara to Rudraprayag, out of 18 reaches along Mandakini River, 13 vulnerable reaches need to be reviewed. These 13 reaches fall within 27km along the river stretch. Out of these, 3 critical vulnerable reaches are identified (Sonprayag, Sitapur and Tehsil area Rudraprayag). Brief description of these vulnerable reaches is given in Table 10.

Table 10. Brief Description of Vulnerable Reaches along Mandakini River.

Vulnerable Reaches	Brief Description
(1) Kedarnath 	The main problem at this location is excessive toe erosion on both banks of Mandakini and Saraswati, shooting boulders/stones from the north of temple. The famous Kedarnath Temple, human lives, live stocks and properties are at high risk. The local administration has provided 3-tier Protection work viz. Gabion wall, wired mesh & RCC counterfort wall towards the north of the town. Also, the left bank of Saraswati river has been provided with gabion walls. The bank of Mandakini river towards the southern part of town is eroded up to high relief, thereby rendering the strategic assets vulnerable. It is evident from the photographs that stretch downstream of Kedarnath up to Rambara is highly susceptible to landslides.
(2) Gauri Kund 	It was one of the worst affected areas during the 2013 flood. At this location, river flows through narrow channel; it enters on a slight bend and flows through a generally straight channel along the town. There is extensive erosion and deposition along both banks with huge boulders lying within the river channel, thereby constricting its width (Photograph). The slope is vertical along right bank with loose soil-gravel matrix and rocky exposures occur intermittently. The left bank is steep with extremely loose-soil gravel matrix along the town.

Vulnerable Reaches	Brief Description
(3) Sonprayag 	Mandakini River enters Sonprayag on a bend and is flowing through a generally straight channel along the town. There is extensive erosion and deposition along both banks with huge boulders lying within the river channel, thereby constricting its width (Photograph). The slopes are vertical along both banks with right bank made of loose soil-gravel and left bank essentially rocky. Due to the proximity of the Sonprayag market to the river course and the low bank area at this location there remains the potential of flooding of the commercial area during high flows.
(4) Sitapur 	Sitapur is located around 2km downstream of Sonprayag. It has several commercial establishments as well as huge vehicle parking area constructed in the middle of the Khadir. River at this location is on a U-shaped bend and hugging the right bank. Extensive erosion can be seen on the right bank. The river Khadir is very wide with heavy debris deposited in the Khadir. A small nala is flowing through the heart of the village and joining the river on its left (Photograph). Left bank is commercially and residentially active and is on a moderately steep slope whereas left bank is vertical with exposed rocky banks and firm overburden. The main problem at Sitapur is the probable shifting of the channel towards left. Human lives, live stocks, properties, road to Kedarnath, vehicle parking area and small agricultural area are at high risk.
(5) Semi 	Semi is a small village located at higher elevation on the right bank of Mandakini. Though the village is at higher elevation, it has suffered severe damage due to Mandakini. River is generally flowing in a straight profile.
(6) Bhiri 	This village is situated on the banks of Mandakini. River at this village flows through somewhat narrow channel and has a generally straight profile. The river is mostly hugging the right bank. Debris, including huge boulders can be seen deposited on both banks; mainly on left bank. Left bank has important assets viz. agriculture land, residential, school, etc. whereas right bank has some habitations at an elevation from river. The main problem at this location is the extensive toe erosion of both banks (Photograph).
(7) Bansbada 	The village is situated on the left bank of river. Mandakini enters the village on a bend & flows under the bridge obliquely. Vertical slopes on both banks can be seen made of loose soil-gravel 38 River Morphology Report with rocks exposed intermittently. Left bank is important as residential & commercial establishments are located on it whereas right bank only has a road. River section at this village is moderately wide. The main problem at this location is also the bank erosion (Photograph).
(8) Monika Lodge 	Mandakini River at this section is slightly turning right. River section is wide with debris deposited mainly along left bank (Photograph). Commercial establishments are on the left bank whereas right bank essentially consists of agriculture land. The main problem at this location is the extensive toe erosion of both banks as the banks are composed of loose soil-gravel.
(9) Chandrapuri 	Chandrapuri town is mainly situated on left of river while mostly agriculture lands are on right. The river while entering the town turns left. A small nala joins the river further downstream through the heart of the town. River section is moderately wide with heavy debris on both banks. The main problem at this location is the extensive toe erosion of both banks as the banks.

Vulnerable Reaches	Brief Description
(10) Gabni Gaon 	The residential and commercial establishments in the Gabni Gaon are mostly situated on the left bank of the river. The river is flowing almost straight at this location with relatively wider section. Debris deposition can be observed on both the banks of the river. The main problem at this location is the extensive toe erosion of both banks as the banks are mainly composed of loose sand and gravel materials (Photograph).
(11) Saudi 	The settlement all commercial establishments are on left bank; the right bank is mostly agriculture land. The river enters the town with right turn and leaves the town with left bend. The river section at this location is wide but full of debris and gravel boulders. Banks slope is very steep to vertical. The main problem at this location is the extensive toe erosion of both banks as the banks are mainly composed of loose sand and gravel materials (Photograph).
(12) Bedu Bagad 	The town is completely situated on the left bank and a HEP is under construction on the right bank by L&T. The river enters the town with left turn and runs almost straight all along the town. The river section is wide but full of debris and boulders. The main problem at this location is the extensive toe erosion of both banks as the banks are mainly composed of loose sand and gravel materials.
(13) Vijay Nagar 	The Vijay Nagar town is located on both banks of Mandakini, however, mostly populated on the left bank. The river flows along the town with minor left turn. The river width is moderate all along the town. The main problem at this location is the extensive toe erosion of both banks as the banks are mainly composed of loose sand and gravel materials.
(14) Silli 	Commercial and residential assets are on both the banks of the river. River enters & exits the city on a bend while following a straight profile through it. Bank slopes are generally vertical to very steep and made up of loose soil-gravel with exposed rocks at some stretches. Debris deposition can be observed on both banks. The main problem at this location is the extensive toe erosion of both banks. RRM walls have been constructed on both banks.
(15) Jawahar Nagar 	The entire residential and commercial establishments in the Jawahar Nagar are situated on the curvilinear left bank of river. The river is hugging the right bank in the heart of the town. Just down of the town the river is hitting the road on left bank (Figure). The river section along the town is wide but full of debris and boulders. The main problem at this location is the extensive toe erosion of both banks as the banks are mainly composed of loose sand and gravel materials.
(16) Chaka Phalati 	River is flowing almost straight all along the town. Wide spread residential buildings are on the left bank whereas the right bank is mostly agriculture land and few houses at higher level (Photograph). Both banks are visibly eroded. The main problem at this location is the extensive toe erosion of both banks as the banks are mainly composed of loose sand and gravel materials.

Vulnerable Reaches	Brief Description
(17) Tilwara 	The town is spread on both sides of the river. The river enters the town almost straight but takes right turn in the heart of the town and again turns left at exist. The river section is moderately wide with boulders on its bed. The main problem at this section is the toe erosion on both banks with right bank mostly affected (Photograph).
(18) Tehsil Building 	This location is close to the Rudraprayag town and Tehsil administrative building is situated here. The river is flowing though this location in a straight channel. The left bank has couple of tehsil administrative blocks and right bank is completely deserted. The main problem at this section is the left bank toe erosion which is threatening the safety of the tehsil blocks. The slope of left bank is vertical with loose soil-stone-gravel mix whereas the right bank has rocky exposure (Photograph). To stabilize the slope of the left bank, RRM wall has been constructed in a small stretch which doesn't seem to be adequately protecting the buildings. Looking at the problems and resulting risks, it can be summarized that banks erosion due to the flow in Mandakini is the main problem and resulting threats are the endangered human lives, live stocks, properties & infrastructures, road to Kedarnath, means of communication etc.

5. Conclusions

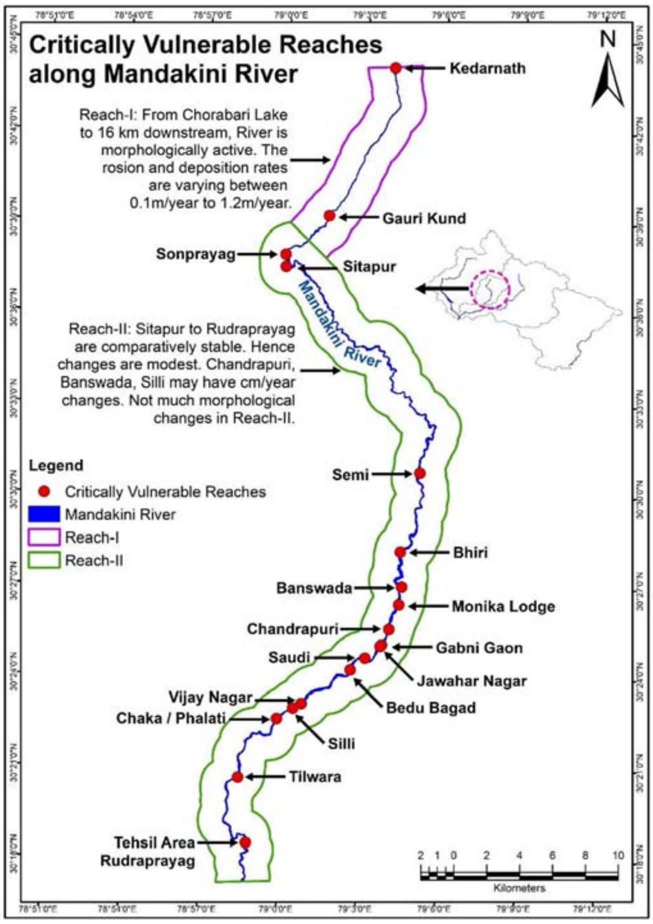


Figure 11. Critically Vulnerable Reaches along Mandakini River.

The torrential rain on 15-17 June ravaged the state that had already been subjected to high snowfall a few days before. The significant run-off that soon ensued was not only because of pre-saturated soil, but also from rapid snowmelt. 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. This will give detailed knowledge of the basin and behaviour of the rivers. All data collected, onsite detailed work combined with satellite information and knowledge acquired from the available literature contributes to understanding the geology and geomorphology of the study area. River basins focusing on rainfall, topography, drainage pattern, soil, landslide, and exiting infrastructure in relation to vulnerability of the region are discussed in detail.

Vulnerability assessment method 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. A detailed description to identify the critical vulnerable reaches along the river which are associated with the river morphology in the region is given. Bank line changes and river bar delineation have been obtained using high resolution satellite data through GIS for the years 2005, 2010 and 2015. This manual will be of great use to 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. The manual 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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