Assessing Causes and Impacts of Landslides in the Sikkim Himalaya, India

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Abstract

Landslide has been common phenomenon in Sikkim after earthquakes. The occurrence of landslides is ascribed to adverse geology, high rainfall, earthquakes, toe erosion, slope instability, vibrations, stone chips quarrying, poor drainage and lack of timely rim treatment at reservoirs sites at Dikchu, Rongli, Chungthang, Ranipul, Legship and Saagbari. The mean area (m^2) and failed volume (m^3) of the classified landslides is around 227176m^2 (cumulative area=10904044m^2) and 14884033m^3 (cumulative volume=714433604m^3), respectively. Among the four districts, East district has witnessed the highest number of landslides, followed by North, South and West districts of Sikkim because the state average annual rainfall has never gone down below 2,000mm in the last 10 years (2522.92mm) (2012-2022). The participants during PRA consultation ascribed the causes of the landslides to developmental activities (25%), catchment degradation/deforestation (21.43%), rainfall and drainage (17.86%), land use transformation (14.29%), cloudburst events (10.71%), adverse geology (7.14%), water impoundment (3.57%) and seismic events/earthquakes, respectively. The landslide events disrupt tourist movements, blockage of national and state highways, water supply pipeline causing shortage of drinking water in the municipal bodies of Sikkim.

Keywords: *Landslide, Rainfall, SSDMA, Earthquakes, Sikkim Himalaya*

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1. Introduction

Landslide has been a most common phenomenon in Sikkim after earthquakes. Owing to its location in the seismically active zone, this young state has been severally hit by landslides and earthquakes of varying magnitudes during 2006-2023. Further, its geographical location exposes it to geological, meteorological and hydrological disasters. In the contemporary era, landslides caught attention due to their considerable impact on the national highways/state highways, tourists movement, rural roads and riverine mega- infra structures (dams and barrages) etc. The earthquake-induced and rainfall-triggered landslides are common in Sikkim (Bhasin et al.2023). Recently, Uttarakhand High Court while addressing a PIL over the lack of compliance to the Doon Valley notification said that 'disasters in the Himalayan states are completely man-made'[1] .

According to IPCC's special report on "*Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*" there is a high likelihood that the frequency of shallow landslides would increase owing to rise in temperature and rainfall extremes (Sultana & Tan, 2021).In the contemporary era, mostly satellite-based interferometric synthetic aperture radar (InSAR) has been utilised for detecting and monitoring hill slope movements (Crosetto *et al.*, 2016; Lacroix *et al.*, 2020; Aslan et al., 2021).The review of literature and governments records showed that landslide in Sikkim is mostly caused by incessant rainfall, high magnitude earthquakes, fragile geology, and catchment degradation. Majority of the landslide in Sikkim is triggered by the average monsoon rainfall of 350mm/day which can reach upto 500 mm during cloudburst events (Gurung & Dar, 2023). Alternatively, the state has also experienced smaller Rock Slope Failures (RSF) after the major earthquake of 2011 (Bhasin *et al.* 2023). States rapid increase in population since 1991 census, higher rate of urbanisation (25.26%) (Census, 2011) and a rapid increase in the number of developmental projects and pharmaceuticals has led to greater stress on the fragile landscape of Sikkim. The study primarily focuses upon the classification and characterisation of the landslides with regard to area, depth and failed volume of the landslides individually. Besides, probable cause of the landslides and its impacts (damage) and *ex-gratia* provided to the landslide victims by the authority in 2020-2022 has been reported. Through this

[1] The Times of India, New Delhi, Thursday, September 7 2023

work, the researchers mainly address the following Research Questions (RQs) (i) What are the causes of increasing incidences of landslides in Sikkim? (ii) What is the extent of the failed volume and mean area of the landslides individually? (iii) Does the ex-gratia amount provided to the landslide victims economically sufficient during the occurrence of the landslides? The study can provide useful information to the citizens, especially to the line departments to frame specific strategies to cope up with increasing incidences of landslides in the era of contemporary climate change.

1.1. Description of Study Area

Sikkim, a small and unique land with diverse topography, climate, and vegetation is a NE state of the Indian union, its 7096 km^2 of the geographical area entirely lies in Eastern Himalaya between 27˚ 04'46" and 28˚ 07'45" North latitude and 88˚00'56" and 88˚ 55'25'East longitude (Census, 2011). The topography is rugged as most of its land area is occupied by greater and lesser Himalaya. It is a landlocked Indian state surrounded by Tibet in the North and NE, the Himalayan Kingdom of Bhutan in the SE, Nepal in the West, and the Darjeeling district of West Bengal in the South (GSI, 2012). The state is characterized by mountainous terrain. Almost, the entire state is hilly, with an elevation ranging from 284m at the confluence of Teesta and Rangit near Chitrey, Kalimpong district, West Bengal to 8,598m at the summit of Mt. Kanchenjunga (8,598m). For the administrative purpose, Sikkim has been reorganized into six districts (Mangan, Gangtok, Geyzing, Namchi, Pakyong, and Soreng) and 18 sub-sub-districts by the authority. The states geology is too young, as it is surrounded by young fold mountains. The formation is still ongoing with strongly folded and faulted strata in various locations. The entire state of Sikkim lies in zone IV of the seismic zonation map of India, the seismic zone IV is broadly associated with seismic intensity VIII on the Modified Mercalli Intensity[2]. The average annual normal rainfall of the state is 2544.40 mm (CISM&HE, 2005). Throughout the year, precipitation in Sikkim Himalaya varies greatly. Periods of heavy rain in Sikkim contributes to rapid erosion and weathering of the rock mass, and raise groundwater levels, reducing the stability of natural slopes (Bhasin et al. 2002) (Figure 1). Sikkim is the least populated state in India, with a population of around 610577 persons with a population density of only 86/km^2 (Census, 2011).

[2] Disaster Mitigation and Management Centre Report Uttarakhand Secretariat, 2011

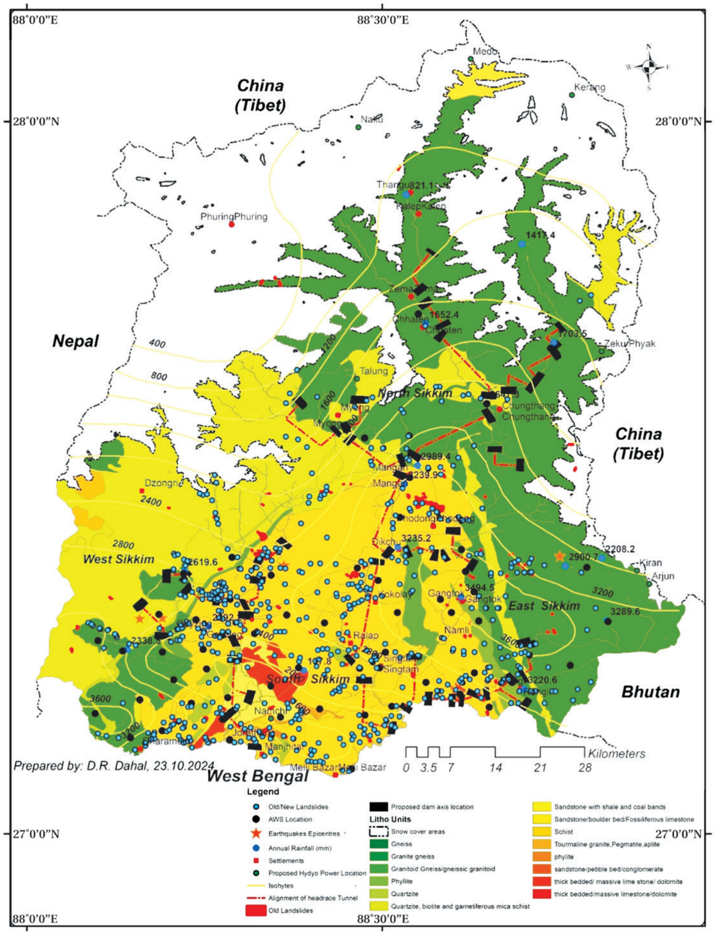

Figure 1: Relative location of landslides points/polygons, past earthquakes epicentres, and a concise overview of the proposed dam axis location and tunnel alignment on the geological map of Sikkim, India

2. Database and Methodology

This study is based on primary and secondary sets. The study is based on transect/ field work carried out in the landslide affected areas in North, East and West districts of Sikkim. Tabulated data on the major landslides of Sikkim (old and new) were analysed to find out the area, failed volume, causes and impacts of the landslides. Before going to the field, a list of geological/ non-geological factors causing landslides has been prepared and the list were shared with the respondents (about 40 participants) for pair wise ranking on a scale 1-8. Secondary datasets were mainly derived from the SSDMA web portal, Government of Sikkim, local newspapers (Sikkim Express, Summit Times and Face Book etc). LULC retrieved from Copernicus web portal and Isohyet map of Tejwani (1981) has been used to superimpose landslide points/polygons over the rainfall zones receiving high, medium and low rainfall and the geological map of the state. Structural framework of the study has been divided into pre-field stage, field stage and *post-field* stage and the steps followed are described below in a flow chart (Figure 2) and the list of datasets/tools utilised in the present study is mentioned below (Table 1).

Pre-Field Stage

- Initial thought for the preparation of concept note on the landslides and causative factors and map-based inquiry though Swiss maps, Google Earth, Landsat imagery and government reports
- Selection and delineation of the reported landslides, desk work on the reported/seasonal landslides (newspaper/ media) of Sikkim ad causative factors through google scholar (Scopus / UGC Care/ peer-review journals, government reports, newspaper and media etc.)

Field Stage

- Field work regarding spatial attributes of the landslides
- Setting of the research objectives and research questions
- Compilation of the secondary data sets and primary data from the field
- Spatial layer of landslide/past earthquakes epicentres (points and polygons). roads using QGIS/ArcGIS software and attributes generation (type of landslide, area and failed volumes etc.)
- PRA consultation regarding causative factors of the landslide
- Ranking of the causative factors as per PRA consultation.

Post-Field Stage

- Tabulation of the landslide attributes (failed volume, width, length, age etc.) and ancillary data in MS excel spreadsheets)
- Generation of the thematic maps (superimposition of landslides points/polygons, past earthquakes epicentre location, dam axis on the geological, LULC and isohyet map of Sikkim
- Visualisation of the landslids points/polygons on Google Earth Image/LULC image
- Descriptive analysis of the data and interpretation of the results
- Export of the visualised data in the form of graphs/maps

Figure 2: Flow chart showing the structural framework of the study

Table 1: Datasets/tools used for the study

Thematic maps/data/reports/ software	Sources
Swiss map of Sikkim	Department of Geography, Visva Bharati Santiniketan-731235
Google Earth Pro *Ver.* 7.3.4.8642	http://www.googleearth.com;accessed on 17.05.2022
QGIS Desktop *Ver*. 3.22/ArcGIS	http://www.qgis.com;installed on 12.04.2020
Global Positioning System	Garmin Etrex
Past Earthquakes epicentre location	Gazetteer of Sikkim (2013), Indian Metro-logical Department, Government of India
Average annual rainfall (mm) at district /state level 2011-2022	Hydrome Division, India Meteorological Department, New Delhi
Old landslides points (1962-63)	Survey of India topographical maps at 1:50K
New landslides points	Landsat satellite imageries and google earth
Geological map of Sikkim	GSI, 2012
Isohyte map of Sikkim	Tejwani, 1981

Global Land cover, 2019 Landcover classification (*discrete classification*)	*https://land.copernicus.eu/global/products/lc, accessed on 03/03/ 2022*
List of the factors causing landslide were identified during PRA consultation by landslide affected people	Respondents from East, West and North districts of Sikkim

3. Results and Discussion

(i) District Wise Classification and Characterisation of Landslides

In this study, attempt has been made by the researchers to locate and map the occurrence of major and reported landslides in Sikkim along with their area (m^2) and the failed volume (m^3) individually. The Sikkim Himalaya is characterised by a mountainous topography and it is susceptible to various kinds of hazard which often turn into disaster. About 1,569 landslide occurrences in the state has been reported (NRSC, 2023). Conversely, 141 landslides have been reported in the NE states including Sikkim in 2020 based on newspapers, online media, SDMA reports, GSI reports and field visits (NESAC, 2020). The forms of landslide vary from literature to literature. The incidence of the landslides in the districts/state has increased because the state average annual rainfall has never gone down below 2,000 mm in the last 10 years (2522.92 mm (2012-2022) (Figure 3).

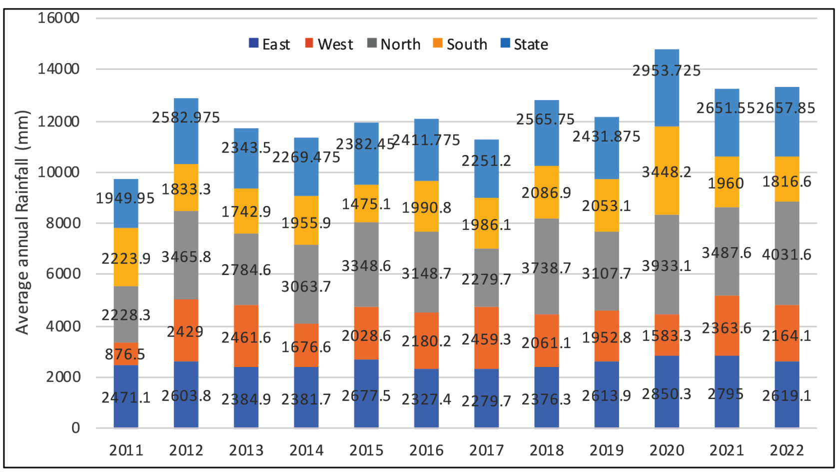

Figure 3: State vs. districts average annual rainfall (2011-2022)

During monsoon season, heavy rainfall increases the possibility of landslides and flashfloods (SSDMA, 2012). The study by Singh (2014) reported occurrence of 552 landslides in Sikkim with an average occurrence of 138 landslides per districts. Database of the landslides occurred between 1999-2014 and some of the major landslides occurred during 2014-2022 reported by newspaper and media such as Sikkim Express, Sikkim Chronicle, Summit Times and landslide victims in the social media platforms has been discussed (Figure 4A, 4B & 4C) (Table 2). The district wise characterisation of the landslides is in (Table 3A, 3B & 3C).

Table 2: District wise distribution of landslides in Sikkim vis a'- vis rainfall

District	No. of Landslides (SSDMA, 2012)	No. of Landslides (Singh, 1999- 2014)	Only seasonal landslides reported by newspaper and Media (2014-2020)	District average rainfall (mm) of 11 years * (2011-2022)	Annual average rainfall(mm) of 11 years* (2011-2022)
West	32	91	17	2019.72	2454.34mm
South	23	77	16	2047.73	
East	36	227	42	2531.72	
North	17	157	11	3218.17	
Total	108	552	89	2454.34	

Source: Compiled by the researcher through literature review and filed work[3]
* computed by the author based on the rainfall database retrieved from http://hydro.imd.gov.in/hydrometweb/(S(uw4ptqehyw3huc452eqfpi55))/DistrictRaifall.aspx

[3] Sources include SSDMA (2012), Singh (2014), field work, Sikkim Now, Sikkim Express, Sikkim Chronicle, Summit Times and landslide victims in the social media platforms

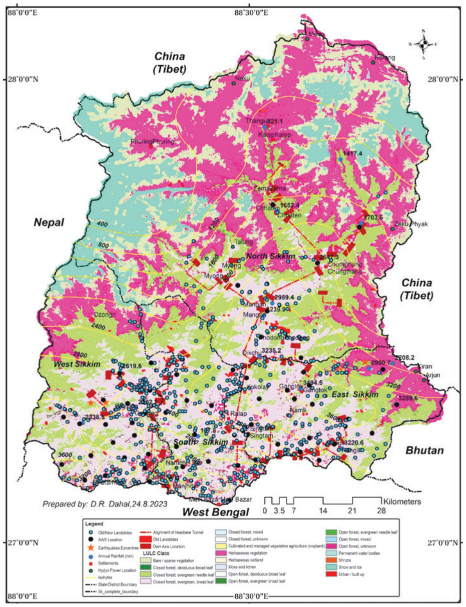

Figure 4A: Landslides points superimposed over different land use and land cover class along with isohyets

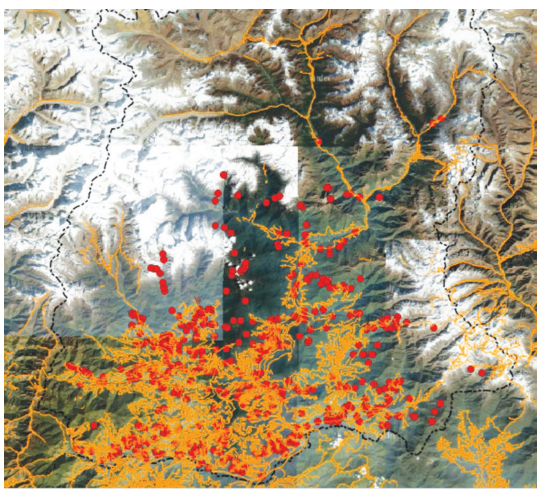

Figure 4B: Point cloud of the landslides superimposed on the road network of Sikkim

Image: *Yandex satellite image*

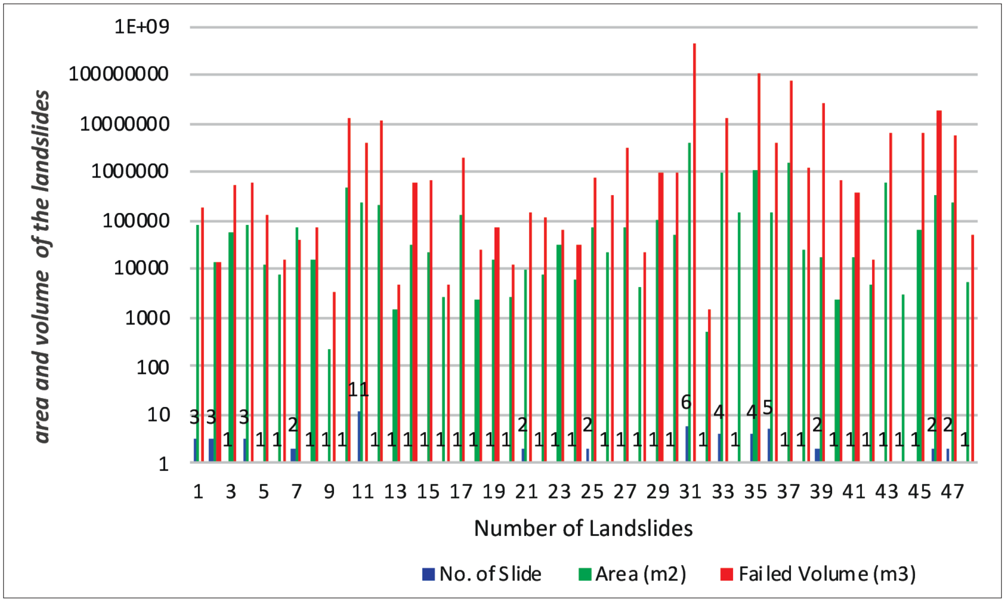

Figure 4C: Number of landslides vs. area and the vozlume of the landslides

(ii) Scenario of Landslides in East Sikkim (Gangtok & Pakyong District)

In East Sikkim mostly complex, planner, debris, translational, massive subsidence and rotational, subsidence, rotational, active subsidence, wedge type failure, rotational controlled by wedge failure, rock topple and complex: translational type mainly rock fall, debris fall wedge type dominates, complex-translational type dominating, mainly wedge type, block and wedge failure type of landslides are pre-dominant. They are classified and their failed volume, area, damage and causative factors has been presented in a tabular form.

Mostly complex type of slide occurred in East district due to failure start suddenly in a small area and spread rapidly. Often the initial failure is a slump, but in some material, movement occurs for no clear reason. The causes of this type of landslide are due to adverse geology, rainfall, toe erosion, steep slope, surface runoff, sheared rock, toe cutting and high-water regime. Secondly, rotational types of slides are dominant due to sheared rocks, ground water, toe erosion, rock floor, adverse geology, wet agriculture proactive, vibrations due to developmental activities, stone chips quarrying, steep slope and poor drainage. Thirdly, occurrence of subsidence type of slide is ascribed to steep slope, weak geology, excessive water runoff, slope, vibrations due to developmental activities, unstable slope with deposits of boulders, untimely treatment of landslides in the periphery of the water pondage created by public and private hydro-power developers at Dikchu (area of pondage:43.1ha), Rongli, Chungthang (area of pondage:1.31ha), Ranipul (near Namli), Rangti near Saagbari and Legship (area of pondage: 20.4 ha) etc. As medium to large sized water pondage (water impoundment) exists in the mid and lower stretch of Tista and Rangit river and its tributaries in Sikkim, Kalimpong and Darjeeling district, West Bengal.

Table 3A: Classification and characterisation of landslide: East Sikkim

Types of Slide	No. of slide	Area (m^2)	Failed Volume (m^3)	Damaged Done	Causes
Complex	6	3899000	418350000	Road, agriculture, Forest, Habitation, NH 31A, Trees, Road cut off since 1997	Toe erosion, adverse geology, steep slope, Surface runoff, Sheared rock, Toe cutting, high water regime
Planner-debris slide	1	500	1500	forest/ agricultural land	Surface water, adverse geology-toe cutting
Translational	4	974000	12030000	Road, forest, Pachak village, Pache-Samsing road, Agricultural land	Steep slope, toe erosion, ground water, sheared slope farming materials, Down slope dipping foliation, toe cutting, Down slope dipping Daling group of rocks, Water, adverse geology

Types of Slide	No. of slide	Area (m^2)	Failed Volume (m^3)	Damaged Done	Causes
massive subsidence and rotational	1	150000	0	Pache-Samsing road, Agricultural land	Excessive Ground water thick slope material
Subsidence	4	1088000	102415000	Road, Agriculture, Trees, Forest,	Steep slope, weak geology, Excessive water runoff, Slope, Vibration, Unstable slope with deposit of boulders and debris ground water, lack of rim treatment at reservoir of Dikchu Dam
Rotational	5	139250	4000000	Road, agricultural land, forest, habitation, Damage to Houses and Housing site, Road between Rongli and Rorathang/ Rhenock forest	Sheared rocks ground water, Toe erosion, rock floor, adverse geology, wet agriculture proactive, vibrations, quarrying, steep slope, poor drainage, high ground water,
Complex, wedge type dominating	1	1500000	75000000	Thekabong road, houses, fields, Forest, Cardamom	Jointed, blocky nature of bedrock

Types of Slide	No. of slide	Area (m^2)	Failed Volume (m^3)	Damaged Done	Causes
Rotational, active subsidence	1	24000	1200000	Road	Ground water seepage, adverse geology (wedge failure in brittle country rock)
Wedge type failure	2	17250	25225000	Road, agriculture land, health quarters, Pakyong-Linkey Road, forest	Adverse geology, ground water, Joint failures, water (underground) Steep slope,
Rotational controlled by wedge failure	1	2250	675000	Road, agriculture land	Wedge failure, toe cutting by Diking khola
Rock topple and complex failure	1	18000	360000	Roads, Trees, Agriculture	Water, Adverse geology, Steep slope
Debris avalanche	1	5000	15000	Road, house, (9 houses) buried, Agriculture land	Weak geology, excusive rainfall (unmanaged drain) upside is wet farming paddy field
Complex: Translational type mainly	1	630000	6300000	Agriculture land, houses, forest, road	Bedrock dipping down slope, high ground water, Steep sloppy
Rock fall	1	3000	0	Forest	Weak geology, Steep slope, Rainfall
Debris fall wedge type dominates	1	60000	6300000	Road	Steep slope, sheared rocks, water

Types of Slide	No. of slide	Area (m^2)	Failed Volume (m^3)	Damaged Done	Causes
Complex, translational type dominating	2	350000	17500000	Rongli-Dalapchand Road, Forest, Cardamom, J.N. Road	Steep slope, down slope dipping rock foliation freeze and thaw, rain water, high ground water
Mainly wedge type	2	233000	5330000	J.N. Road, Rongli-Rhenock road	Steep slope, jointed nature of rock, vibration, fractured nature of rocks
Block and wedge failure type	1	5200	52000	JN Road	Steep slope, jointed / sheared rock vibrations

Source: Cf. SSDMA, 2012

East district of Sikkim is a part of lesser Himalaya; altitude naturally range from 350m to 4630m; terrain is heavily dissected, with steep gorges, large valleys and ridges. Since the landslide is meticulously associated with the rain precipitation and East district receives considerably high rainfall during monsoon (district 11 years (2011-2022) annual average rainfall = 2531.72 mm). Thus, weak geology and the presence of sedimentary rocks such as phyllites, quartzite, gneiss, sandstone and high surface runoff have triggered some of the large landslides in East district of Sikkim (SSDMA, 2012). Other anthropogenic factor includes developmental activities including road construction, hydro-power development, road widening and high rate of urbanization (25.15%) led to higher construction activities which have resulted into different forms of mass wasting in the district.

iii. Landslides Scenario in West Sikkim (Geyzing and Soreng)

West district is dominated by Daling group of rocks, which is fully within the Lesser Himalaya and has undergone multiple periods of loading, unloading and uplift during the time of orogeny (SSDMA, 2012). Triggering factors of these slides are attributed to adverse geology, steep slope, highly jointed rock, high rainfall (district 11 years

(2011-2022) annual average rainfall =2019.72mm), vibration, road construction, seasonal surface runoff, fault zone and toe cutting by Rangit river and vibrations caused due to high magnitude earthquakes in the past (e.g. earthquake of 18th sept. 2011) and on-going developmental activities such as construction, hydro power development and widening of the roads etc.

Table 3B: Classification of landslide and its characterisation: West Sikkim

Types of slides	No. of slides	Area (m^2)	Failed Vol-ume(m^3)	Damaged Done	Causes
Rotational	11	219210	3964000	Agricultural land, Cardamom field, Forest, Road, Road disruption, cultivated land, Frequent blocking of road traffic, Forest trees etc., Simithang under impact, Cardamom field	Strike slip faulting, Weak geology, Ground water/ rain water, vibration, Water movement, highly jointed rocks, soil cover, toe cutting, disturbed rock sequence, steep slope, Water seepage, Toe cutting by Bhutey *Khola*, poor drainage, Weathered nature of slope material, foliation down dip, ground water, Adverse geology, water, road construction, Loose crushed materials, surface/subsurface water runoff, Thrusting, toe cutting, vehicular vibration, sheared nature of slope material, poor drainage.

Types of slides	No. of slides	Area (m^2)	Failed Volume(m^3)	Damaged Done	Causes
Mainly planner	1	216000	10800000	Road, forest	Adverse geology, slope parallel to foliation plane, steep slope poor drainage, vibration
Wedge failure-Planner	1	1500	4500	Road	Sheared rock with immature soil cover/ surface run off
Rotational (creep)	1	30000	600000	Sinking of road, Tilted trees	Degraded slope materials, seasonal water runoff, Toe cutting
Wedge failure controlled by an active fault	1	22500	675000	Agricultural land	Strike slip faulting, Weak geology, Ground water/ rain water, vibration
Planner, rock toppling	1	2500	5000	Road traffic period disruption for long period during monsoon	High degree slope, toe cutting by Rangit river
Complex with displaced rock f ormations in the slide body	1	132000	1980000	Road, Forest	Adverse geology, steep slope, high rainfall, vibration
Planner due to ailure of joint plane	1	2400	24000	Agricultural land, Forest	Steep slope, brittle rocks

Types of slides	No. of slides	Area (m^2)	Failed Volume(m^3)	Damaged Done	Causes
Rock slide failure along joint	1	15000	75000	Forest, Road	Highly jointed rocks, steep slope
A unique case of rock toppling or fall	1	2500	12500	Road disruption, trees	Highly jointed rock
Planner	2	10000	137500	Agriculture land, Trees, Road (Bermoik - Legship Road	Toe cutting, Seasonal surface run off, Soil collapse above the rock bed during rainfall
Complex	1	7500	112500	Road destabilization, forest cover	Weak geological highly jointed rocks
Translational	1	30000	60000	Road destabilization	Water seepage/runoff, rock slip along foliation
Fault controlled complex	1	6000	30000	Road, Cardamom	Soil collapse above the rock bed during rainfall
Rotational and Complex	2	75000	750000	Road disruption, Agriculture land, trees, Road sinking	Adverse geo setting, toe cutting by Rangit river, road construction, Geological formation, water runoff,
Rotational as well as wedge failure	1	21000	315000	Forest	Surface/ sub-surface water movement, slide materials, Brittle rock, Toe cutting, vibration

Types of slides	No. of slides	Area (m^2)	Failed Volume(m^3)	Damaged Done	Causes
Complex and rotational rock toppling	1	75000	3000000	Road disruption, Forest cover and agriculture land	Weak geology, surface/ subsurface runoff, Toe cutting
Rock failure and planner	1	4375	21875	Vehicles and traffic disruption	Highly jointed rock, steep slope, surface runoff
Planner as well as Rotational	1	100000	1000000	Habitation, cultivation, road	Adverse geology, high ground, road construction, Toe cutting
Rotational S65E- 15SE	1	50000	1000000	Road, Forest, agriculture	Fault Zone, Surface/ subsurface water movement, steep slope

Sou†rce: Cf. SSDMA, 2012

In West Sikkim planner, rotational and complex types of slides are pre-dominant. It is known for wedge failure-planner, rotational (creep), wedge failure controlled by an active fault, planner, rock toppling, complex with displaced rock formations in slide body, planner due to failure of joint plane, rock slide failure along joint, planner, complex, translational, fault controlled complex, rotational and complex rotational as well as wedge failure, complex and rotational rock toppling, rock failure and planner form of slides had occurred in the past.

(iii) Landslides Scenario in North Sikkim (Mangan district)

North Sikkim is the least populous district (population density 10/km^2) of the state and largest in terms of geographical area (4,226 km^2). The landscape is mountainous with lush vegetation that reaches alpine altitude before thinning out to the cold desert scrub as it approaches the northern tundra. Landslides are frequently seen as a result of steepness of the valleys reworked by fluvio-glacial action in the past. The region consists of rock from the inner, axial, and trans-axial belts in the super-positional flow order. Sandstones, limestone, and fossil bearing shales formed the Tsho-Lahmu series. Latchi series are made by slates, pebble beds, carbonate shells, and sandstone. Chhubakha series formed by granite with fine grains that has granet tourmaline, and pegmatite, lime silicates, hornblende inclusion, etc. (SSDMA, 2012).

Table 3C: Classification of landslide and its characterisation: North Sikkim

Type of slide	No. of slide	Area (m^2)	Failed Volumye (m^3)	Damaged Done	Causes
Subsidence	3	80000	192500	Forest, Agricultural field, Settlement, Agricultural land, Road highways	Adverse Geology, high ground/rain water, Bad geology, High water regime, ground water and vehicular vibration
Debris slide	3	13000	13000	Agricultural land, Forest, houses, road	Bad geology, high ground/ rain water, steep slope, water, Adverse geology, slope, rainfall
Debris Fall	1	55380	553800	Forest	Adverse geology, slope, rainfall
Debris Flow	3	82000	595000	Forest, Road, forest cover	Adverse geology, steep slope, rainfall, ground water activities, rain water, scouring by nala, vehicular traffic vibration
Complex	1	12500	125000	Road	Highly jointed rocks, debris overburden of rock and soil on both abutment and scouring by active water

Type of slide	No. of slide	Area (m^2)	Failed Volumye (m^3)	Damaged Done	Causes
Wedge Failure	1	7500	15000	Road distance	Steep slope, highly jointed and fractured rocks, excess water, vibration
Complex, Fault controlled	2	67500	40500	Road, forest, agricultural land	Weak geology, excess water, Weak geology (Jointed rock/sheared), steep slope, vibration
Complex, Debris Flow or Fall dominating	1	15000	75000	casualties at GREF Camp 10/11 September, 1983	Weak geology (Jointed rock/sheared) excess water, steep slope, vibration
Rotational	1	228.6	3429	Road strike, Overburden material, boulders	Hydrology, weak geology, slope failure
Planner on the catchment of Nalas main tributary	1	450000	13500000	Forest	Hydrology, weak geology, forest load

Source: *Cf. SSDMA, 2012*

In North district, subsidence, debris slide, debris fall, debris flow, complex, wedge failure, complex fault controlled, complex debris flow or fall dominating, rotational and planner on the catchment of nalas are very common. Frequently occurring slides includes subsidence, debris slide, debris flow and complex fault controlled. The frequent occurrence of these slides has been ascribed to adverse geology, high ground or rain water, high water regime, vehicular vibration, high rainfall (district 11 years annual average rainfall = 3218.17 mm), developmental activities, steep slope, catchment degradation and dam construction (hydrology). All these triggers affected settlement, tourism movement, agricultural land, forest retaining walls and road ways which has created inconvenience in road transportation throughout the year. Similarly, to get insights regarding the factors causing landslides in Sikkim, fourty (40) experienced participants from the villages who have been affected by large and medium sized landslides in the last 5-15 years have been prepared through PRA consultation. The views of the participants (respondents) regarding triggering factors of the landslides have been analysed and tabulated. On the basis of the pairwise ranking, factors triggering landslides during monsoon and non-monsoon months in Sikkim have been categorized into high, medium and low on a scale of 1-8. (Table 4).

Table 4: Major factors causing landslides in Sikkim (Respondents) PRA consultation

Factors triggering Landslides in Sikkim	1. Rainfall, drainage	2. Adverse geology	3. Seismic events	4. Developmental Activities	5. Cloud Burst	6. Catchment Degradation/ deforestation	7. Water pondage	8. Land Use Transformation	Total points	Rank	Percentage
1. Rainfall, drainage		1	1	4	1	6	1	1	5	3	17.86
2. Adverse geology	1		2	4	5	6	2	8	2	6	7.14
3. Seismic events/ Earthquakes	1	2		4	5	6	7	8	0	8	0
4. Developmental Activities (Road construction Tunnelling/ blasting/	4	4	4		4	4	4	4	7	1	25

vibration, toe erosion)											
5. Cloud Burst	1	5	5	4		6	5	8	3	5	10.71
6. Catchment Degradation/ deforestation	6	6	6	4	6		6	6	6	2	21.43
7. Water Impound-ment by hydro projects	1	2	7	4	5	6		8	1	7	3.57
8. Land Use Transforma-tion	1	8	8	4	8	6	8		4	4	14.29

The respondents argued that developmental activities (road construction tunnelling/blasting/vibration, toe erosion) (25%) and catchment degradation/ deforestation (21.43%) are the most important factor triggering landslides in Sikkim followed by rainfall and drainage (17.86%), land use transformation (14.29%), cloud burst (10.71%), adverse geology (7.14%). The respondents had given less importance to the seismic events/earthquakes as they firmly believed that they mostly cause rock blocks/boulders to slide from the steep slopes, collapse of the buildings and triggers landslides only in case of their high intensity/magnitude. They further alleged that huge water impoundments (pondage) of about 81.23 ha by the hydro projects in the mid-stream of the river Tista and Rangit has triggered landslides and subsidence in and around the rim of the reservoirs in the recent past. As the past landslides in Sikkim have caused enormous damage to the community and individual assets. Thus, to sustain the loss, District Disaster Management Offices (DDMO) provides ex- gratia to the landslides victims. The ex- gratia relief according to degree of damage for the landslides victims during 2020-2022 is highlighted below:

Table 5: Ex-gratia to the landslide victims of South Sikkim (2020-2022)

Nature of damage	No. of damage/ area (hectare)	Amount (Rs.)
Land damage with crops	1 hectare	37500/
Barren land	1 hectare	65500/
Kutcha House damage	190	3200/
Pucca House partially damage	-	5200/
Pucca house severely damaged	317	101900/
Lives	-	400000/
Death of milching cow	1	30000/
Cowshed/Goat shed/Pig shed	1	2100/
Chickens	1	50/
Protection wall	-	Approx. 5000 – 200000/
Toilet with septic tank damaged	-	7000/

Source: DDMO, Namchi, South Sikkim, 2020-2022

The authority has provided ex-gratia according to the nature of damage, area and number of damages caused by the landslides. Loss of life during the landslide events have been compensated with the amount of Rs.4 lakhs individually. For the damage of the land (about1 hectare) with crops are compensated with the amount of Rs. 37,500/ and for the damage of barren land (about1 hectare) compensation amount was around Rs.65,500/. For damage of kutcha house compensation amount was Rs. 3,200/ and for pucca house partially damaged by landslides had been given Rs. 5,200/ and severely damaged pucca house had been given Rs. 10,1900. For damage of toilet with septic tank ex-gratia amount was Rs.7,000; similarly, compensation amount for the protection wall was approximately Rs. 5,000-2,00000.

4. Conclusion

State of Sikkim is extremely susceptible to natural hazards like landslides (1,569 incidences), earthquakes, snow avalanche, GLOFs, forest fires (1,050 incidences), and cloudburst events. The mean depth (m) and failed volume (m^3) of the major landslides in Sikkim is around 57m (cumulative depth=4,718m) and 8518488.94m^3 (cumulative volume = 689997604m^3). The incidence of the landslides in the state has increased mainly because the state average annual rainfall has never gone down below 2,000 mm in the last 10 years (2454.34mm) (2012-2022). Respondents ascribed the causes of the landslides to developmental activities (25%), catchment degradation/ deforestation (21.43%), rainfall and drainage (17.86%), land use transformation (14.29%), cloudburst events (10.71%), adverse geology (7.14%), water impoundment (3.57%) and seismic events/earthquakes during PRA consultation.

As a hilly area, it lies in seismic zone IV of the seismic map of India. Natural hazards affect a staggering number of people annually, with landslides being the most common phenomenon in the state. In Sikkim, long-term rainfall and other anthropogenic influences, such as construction of buildings in the prone areas, rapid road widening, and vibration caused by developmental projects are the most common landslide triggers in Sikkim. Additionally, it affects the denizens who reside very close to the major national (NH-10) and state highways (NH-10, NH -710, NH- 510, NH -710A) of the state. Sikkim is extremely affected by landslides as they led to the loss of lives and property, tourists movements due to blockage of national and state highways. The landslides often swept away water supply pipelines or pollute and destroy water sources, urban dwellers occasionally have to deal with water shortages during monsoon seasons. In order to prevent the loss of life and property in the event of a natural disaster, an intervention from the authority is required. The Sikkim State Disaster Management Authority, NDMA, NIDM and UNDP have all initiated several research projects, trainings, workshops/seminars and mock drills in this regard for the communities, students and institutions etc. Ex-gratia is provided by the district authority as per the extent of damage by the landslides. The study is delimited to the major and the seasonal landslides of East, North and West districts of Sikkim as the legacy data of the landslides are very limited and due to unavailability of the rainfall datasets at the GPU level, precipitation threshold could be calculated even for the major landslides. Though, this study has identified, characterized and mapped the landslides, still a comprehensive inventory of the landslides using Sentinel datasets (Sentinel-B/Landsast/Google hybrid/ Yandex) can be done. The present study will assist the concerned authority in making further assessments of landslides and the damages arising out of them.

Further, the findings can help policymakers and authority to formulate effective strategies and policies in reducing disaster risks and mitigating plans to minimize the threat of landslides in the state. Besides, disaster management frameworks such as Sendai, Hyogo/GSI guidelines and national/state disaster management frameworks can be followed for such studies. The following recommendations are suggested to the authorities concerned:

1. Regularly training programme, workshops/seminars and mock drill should be organised for the capacity building of the youths and senior citizens and women in specific.
2. Involvement of the grassroot level community including old age/differently abled people in participatory planning and disaster management plans.
3. Inclusion of landslides and its mitigation techniques in the Sikkim State Disaster Management Plans and Climate Change Action Plan and such other policy documents of the state incorporating five major pillars viz; NDM Act 2005, NPDM 2009, participating proactively in realizing the global goals focusing upon Sendai Framework for DRR, Sustainable Development Goals (SDGs) and Hon'ble Prime Minister Ten Point Agenda for DRR, Social inclusion and mainstreaming DRR.
4. Appropriate database development of landslides at Village Administrate Centre (VAC) as their catchment area is large as compared to ward panchayats.
5. Vulnerability assessment at GPU level based on physical and bio-physical methods using tier-III approach.
6. Landslide hazard zonation at GPU level.
7. Geo-hydrological assessment/geo-technical assessment should be made compulsory for the construction's sites.
8. Use of UAVs and SAR technology in landslide monitoring and prediction/deformation studies.
9. Use of advanced Early Warning System for the prediction of the landslides.
10. Geotagging of the landslides by the authority concerned.

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6. Conflict of Interest

The authors declare no potential conflict of interest.

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Nil

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