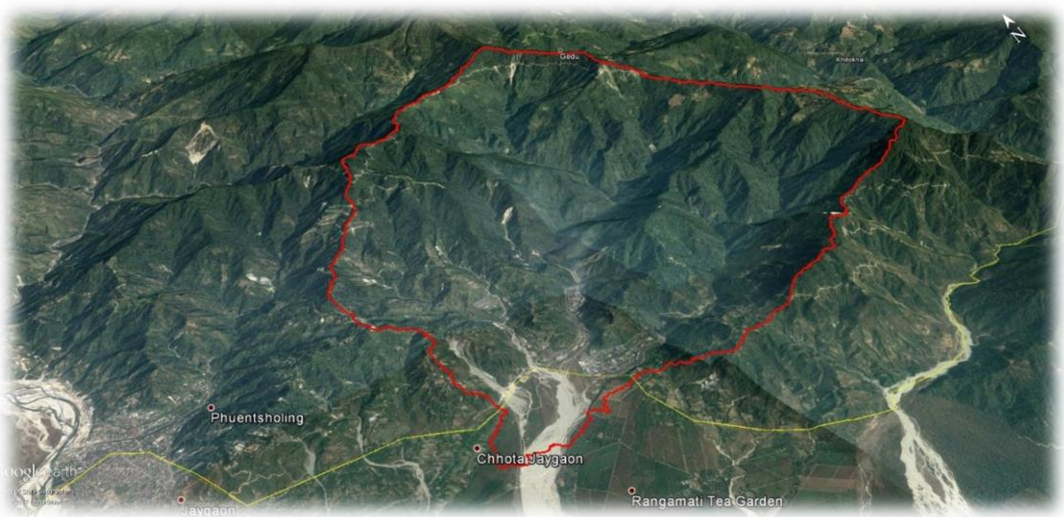
DEPARTMENT OF GEOLOGY AND MINES
MINISTRY OF ECONOMIC AFFAIRS

Integrated Geo-Hazard Risk Assessment of Critical Barsa Watershed under Chukha Dzonkhag



Department of Geology and Mines

Field Season: 2016-2017

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ABOUT DEPARTMENT OF GEOLOGY & MINES (DGM)

Established in 1981 as Division initially and upgraded later to department, Department of Geology and Mines under Ministry of Economic Affairs is the only geo-scientific institution in the Kingdom of Bhutan mandated to carry out and manage geo-scientific and mining activities. Currently, the mandates of the department are fulfilled through four divisions namely: (1) Geological Survey Division; (2) Earthquake and Geophysics Division; (3) Mineral Development Division; and (4) Mining Division.

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ABOUT THIS REPORT

This report is in accordance with the work plan of the Department of Geology and Mines, MoEA under the National Adaptation Programme of Action II (NAPA II) Project titled *'Addressing the Risks of Climate-Induced Disasters through Enhanced National and Local Capacity for Effective Actions*, funded by GEF-LDCF through UNDP and implemented by RGOB.

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Suggested citation: Department of Geology and Mines (2018). *Integrated Geo-Hazard Risk Assessment of Critical Barsa Watershed under Chukha Dzonkhag.* Thimphu

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Forward

Located in the eastern part of the Himalayas, the Kingdom of Bhutan is a small landlocked country between India and China. Being a part of young (ca. 55 million years) fold-thrust Himalayan mountain belt, more than 90 percent of the country's area is topographically rugged and geologically very fragile. In the foothills where rainfall is heavy during monsoon, the occurrence of landslides is significant. In recent years, landslide related risk to lives, livelihoods, infrastructures, properties and environment in the country is on rise because of intense and erratic rainfall pattern most likely induced by climate change and interactions of human activities with the nature.

Thus as an intervention to reduce risks associated with climate change induced landslide geohazard, the Department of Geology and Mines (DGM) under Ministry of Economic Affairs (MoEA), Royal Government of Bhutan (RGoB) has carried out the following two key activities under Outcome 1 and Output 1.3 of Second National Adaptation Programme of Action (NAPA-2) Project themed *'Addressing the Risks of Climate-Induced Disasters through Enhanced National and Local Capacity for Effective Actions*, funded by Least Developed Countries Fund (LDCF)-Global Environment Facility (GEF) through United Nations Development Programme (UNDP) and RGoB implementing partner National Environment Commission (NEC) between 2014 and 2017:

1. Integrated geohazard risk assessment and mapping of four critical landslide or landslide affected areas viz.: (1) Moshi landslides and (2) Arong/Lamsorong landslide on Samdrupjongkhar-Trashigang highway; (3) Box-cutting landslide on Gelephu-Zhemgang highway; and (4) Barsa watershed under Phuntsholing Dungkhag, Chukha Dzongkhag; and

2. Landslide monitoring and threshold development of six landslides namely: (1) Moshi landslide, (2) Arong/Lamsorong landslide, (3) Box-cutting landslide, (4) Tshimatsham

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on Phuentsholing-Thimphu highway under Chukha Dzongkhag, (5) Reldri landslide under Phuentsholing Thromdey, and (6) Lem landslide, Phongme Geog under Trashigang Dzongkhag.

The goal and objectives of these studies were to: (1) map and assess the four critical landslide affected areas using geo-scientific methods to provide findings and recommendations on suitable mitigation measures (both long term and short term); (2) monitor landslides using geoscientific methods to understand the movement behaviours and record landslide events; (3) develop rainfall thresholds for landslide initiation in the selected monitoring sites; (4) forecast or issue landslide warnings in regions with similar geological and topographical conditions through National Weather and Flood Forecasting and Warning Center (NWFFWC); and (5) share findings and recommendations of these studies with relevant users (national, district, local government, and others) for awareness and importantly for incorporation of the mitigation measures in their plans and implementations for reduction of risks associated with landslide geohazards.

In this regard, DGM on behalf of the Ministry and RGoB is pleased to publish the reports and maps for the four-critical landslide affected areas and six landslide monitoring sites in the country, whose findings and recommendations were shared to the relevant stakeholders during the two-day workshop held at Phuentsholing from 13-14, November 2017.

On behalf of the department, I acknowledge the effort put into publishing these reports and maps and I am hopeful that these documents will be useful to the relevant stakeholders who are responsible in dealing with risks associated with landslide in the study areas.

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Director General

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EXECUTIVE SUMMARY

The Barsa watershed under Chukha District in southwest Bhutan, with an area of ~ 58.33 km^2, is one of the most important watersheds in Bhutan that encompasses Bhutan's biggest industrial estate – Pasakha Industrial Estate and important infrastructures like Phuentsholing to Thimphu highway, the extended area of Phuntsholing Thromdey amongst others. This watershed, however, is severely affected by landslide and flood geohazards over several decades causing heavy losses to lives and properties. With global climate change, the watershed is more likely to be affected by landslide and flood hazards, thereby, increasing the risks to lives and properties. Thus, as an intervention to climate-induced geologic hazards, the Department of Geology and Mines (DGM) under Ministry of Economic Affairs (MoEA) has carried out integrated geohazard risk assessment and mapping of this watershed in fiscal year 2016-2017 as a part of second National Adaptation Program of Action (NAPA II) Project for climate-change, funded by Least Developed Countries Fund (LDCF) – Global Environment Facility (GEF), coordinated by Bhutan National Environment Commission (NEC) with support from United Nations Development Program (UNDP) under Outcome 1, Output 1.3 of the Project Document. The objectives of this study were (1) to assess landslide hazards and risks in Barsa Watershed; (2) identify critical landslide areas within this watershed for detailed study; and (3) propose sustainable mitigation measures or solutions to reduce the risks.

This study focused on geological and engineering geological mapping in 1:25000 scale with a detailed geotechnical study of critical landslides and collection of socio-economic data within the watershed. The field data collected from this study and spatial data collected from stakeholders were used for hazard, vulnerability and risk analysis using Logistic Regression multivariate technique in GIS.

Barsa watershed is characterized by rough topography with an elevation ranging between 220 m and 2000 m. The monthly rainfall data from 1996 to 2011 of

Phuentsholing station show that the area receives as high as 2320.9 mm of monthly rainfall (July 1998), where rainy months begin from April and lasts till September.

The major part of the watershed is occupied by rocks of Lesser Himalaya Sequence (LHS) with a minor part in the North occupied by rocks of Greater Himalayan Sequence (GHS). The geology of the watershed, in general, can be grouped into two litho-assemblage depending upon the sudden change in the grade of metamorphism above and below the Main Central Thrust (MCT). The area south of MCT comprises mainly of low-grade meta-sedimentary of LHS, overlying the high-grade metamorphic rocks of GHS. MCT is a narrow but persisting zone comprising of highly crushed coarse-grained, quartz-mica schist and forms the boundary between the two sequences. Phuentsholing Formation occupies the lowermost stratigraphic level in this watershed. It is then sequentially overlain by Shumar Formation, Jaishidanda Formation and Surey Formation towards the north. Phuentsholing Formation and Surey Formation have maximum thickness in this area whereas Jaishidanda Formation appears as a narrow zone with distinct shearing and regional persistence. The generalized trend of the rocks varies from N30˚ to 70˚W with dips 25˚ to 55˚ towards the north. The rocks of Phuentsholing and Shumar Formation are sandwiched between MCT and MBT and are highly disturbed. Surey gneiss overlying the Thimphu thrust is highly fractured and jointed. Several sets of closed spaced joint planes have weakened the rock surface where mass wastages in the form of rock falls are quite common.

In this watershed, 112 landslides were mapped, which included both active and inactive landslides. These Landslides are seen at different levels, irrespective of rock formations. In the lower part, landslides are associated with highly crushed, crenulated and incompetent dark phyllite and light pink calcareous quartzite of Phuentsholing Formation that are mostly concentrated around the shear zone. In the middle part, landslides occur along Shumar thrust and MCT and are dormant in nature with partial re-activation. In the upper part, the landslides are distributed mostly along Thimphu thrust, stream with high gradient, and along the faults.

The landslides are most likely caused because of weak or deformed underlying geology, steep topography, climatic condition, heavy precipitation and erosion, and land degradation, which are aggravated by human activities such as deforestation, overgrazing, constructions and infrastructural development, and agricultural practices.

The landslide hazard map or results indicate that the watershed is predominantly (~55 percent) occupied by moderately high landslide hazard, corresponding to 31.17 Km^2 of the watershed area; followed by ~30 percent indication of low hazard, which corresponds to 17.39 Km^2; and ~15 percent high hazard zone corresponding to 8.42 Km^2 of the watershed area. The south-west part of this watershed as compared to other parts is indicated as the highest concentration of high and moderately-high landslide hazard. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc.

Proper geotechnical or engineering geological studies are recommended before constructing any infrastructures in the medium and high hazard areas. For now, the low or no hazard areas seem safe for construction, but these areas are recommended to be monitored at least on yearly basis and verified by professionals before any developmental planning to ascertain that the geological, hydrological, topographical and other ground conditions have not varied significantly.

The vulnerability map results indicate that the majority (~90 percent) of socio-economic elements are located within low vulnerable areas to landslide hazard, corresponding to 52.63 Km^2 of the watershed area; followed by ~7 percent within moderately-low vulnerable areas, which corresponds to 4.08 Km^2 ; ~2.12 percent within moderately-high vulnerable areas, corresponding to 1.24 Km^2 ; and < 1 percent within highly vulnerable areas that correspond to 0.39 Km^2 of the watershed area. The south-west part of this watershed as compared to other parts is shown as more vulnerable to landslide hazard. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc.

The landslide risk map results indicate that ~96 percent of the watershed area is exposed to low or no risk of landslide hazard, corresponding to 56.27 Km^2; ~2.4 percent of the area to moderately-low risk corresponding to 1.41 Km^2 < 1 percent to moderately high corresponding to 0.48 Km^2; and 0.3 percent to high risk, which correspond to 0.17 Km^2 of the watershed area. The south-west part of this watershed as compared to other part is more exposed to landslide risks. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc. A cultivation land of 29.15 acres, 38 houses and 174 people (as counted during the socio-economic survey); a cultivation land of 44.06 acres, 57 houses, 1062 people, 1 BPC high tension pylon; 144.55 acres of cultivation land, 70 houses, 1546 people and 8 BPC high tension pylon are indicated to be located within high-risk area, moderately high-risk, and moderately low-risk area, respectively.

This study recommends for further detailed studies such as engineering geological or geotechnical and hydrological studies (along the Barsa river) to be carried out on a priority basis to assess the risk in areas designated as high-risk areas to come up with scientific-based sustainable remedial or mitigation measures to reduce risks.

This study also identified six critical landslides in locations such as Jumja, above BFAL Factory (about 500mNorth of BFAL industry), Opposite BFAL colony, Barsa/Gurungdara, BPC substation at Barsa, and Left bank of Barsa, BFAL Factory area and recommendations on mitigation measures are proposed separately for each landslide, aimed to reduce the risks. Detailed study of these six critical landslide areas to come up with better scientific based sustainable remedial or mitigation measures to reduce risks are recommended.

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1. INTRODUCTION

The southern region of Bhutan Himalaya is very vulnerable and prone to landslide hazards because of its weak geological setting and receive of higher precipitation during monsoons. In the month of August 1999, heavy rainfall-induced a massive flashflood from the Barsa watershed that damaged roads, residential buildings of the industrial colony, and bridges in Pasakha under Chukha District causing heavy losses to live and properties. The Phuentsholing-Thimphu highway - the only highway that connects an economic hub or Phuentsholing city to Capital city Thimphu, which passes through upper areas of this watershed also experiences landslides problems during monsoons, posing inconveniences and great risks to the commuters, transportation of goods, and overall economy of the country. Besides residents, this watershed is also encompassing Bhutan's biggest industrial estate (Pasakha Industrial Estate) and important infrastructures like roads, bridges, shops, colonies. The risks to geo-hazards such as landslide and flash flood within this watershed are likely to increase with global climate change.

Therefore, as an intervention to climate-induced geologic hazards, the Department of Geology and Mines (DGM) under Ministry of Economic Affairs (MoEA) has carried out integrated geohazard risk assessment and mapping of Barsa Watershed in fiscal year 2016-2017 as a part of second National Adaptation Program of Action (NAPA II) Project for climate-change, funded by Least Developed Countries Fund (LDCF) – Global Environment Facility (GEF), coordinated by Bhutan National Environment Commission (NEC) with support from United Nations Development Program (UNDP) under Outcome 1, Output 1.3 of the Project Document. The fieldwork was carried out for a duration of 90 days.

1.1 OBJECTIVES, OUTPUTS AND OUTCOME OF STUDY

1.1.1. Objectives

The objectives of this study were:

1. to assess landslide hazards and risks in Barsa Watershed;
2. identify critical landslide areas within this watershed for detailed study;
3. propose sustainable mitigation measures or solutions to reduce the risks.

1.1.2. Outputs

The study will generate maps and report that will: (1) help visualize and understand hazard and risks from landslides, and (2) encompass recommendations on mitigation measures or solutions to reduce risks.

1.1.3. Outcome

The end goal is to share findings and recommendations of this study both at a national and local level for: (1) awareness, and (2) mitigation and disaster response planning and implementation to reduce risks of landslide hazards.

1.2 LOCATION OF STUDY AREA

The Barsa watershed study area is located under Chukha District in the southwest Bhutan (Figure 1). The watershed is about 58.33 km^2 in area. The Phuentsholing-Thimphu highway passes from its northern part and Phuentsholing-Manitar road runs through its southern part. Pasakha Industrial Estate is located 15 km away from Phuentsholing and accessibility into the interior part of the Barsa watershed is by foot and it is mostly difficult to walk due to dense forest and steep slopes. Accessibility during monsoons becomes very difficult because of flooding from Barsa river and its tributaries.

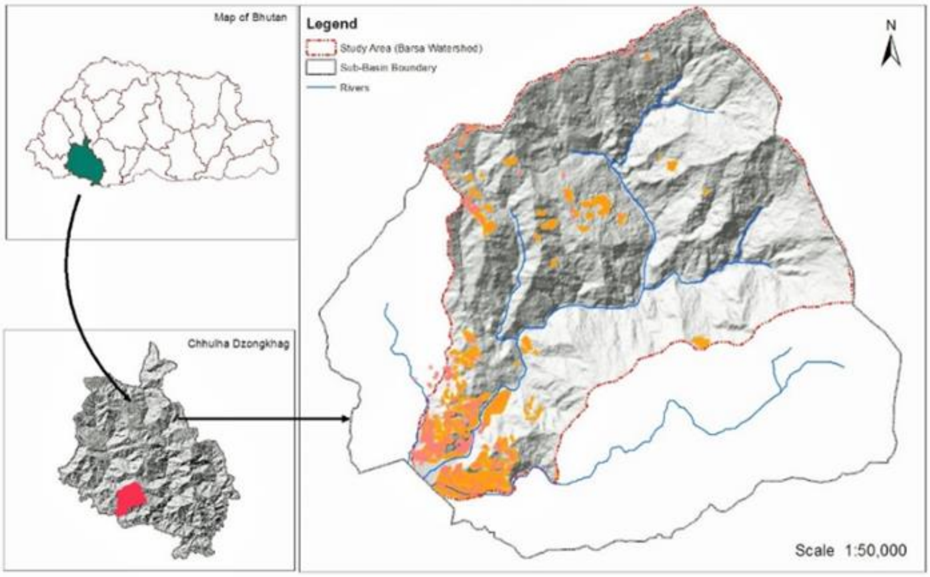


Figure 1. Location map of Barsa Watershed (Study Area).

1.3 FLORA AND FAUNA

Barsa watershed falls under sub-tropical zone and characterized by dense mixed vegetation mainly comprising of trees like Terminalia elliptica Saj, Semul, Uttis andSenegalia catechu (Khair), Bamboo and thick undergrowth of creepers, shrubs and bushes. Deer, stag, boars and monkeys are commonly seen in this area. Leopards and elephants are also seen occasionally.

1.4 GEOMORPHOLOGY AND DRAINAGE

The study area is characterized by rough topography with elevation ranging between 220 m (Singye-Barsa confluence) to about 2000 m at Jumja. The area is occupied by meta-sedimentary of Lesser Himalayan in the lower part and high-grade rock of crystalline complex in the upper part. The meta-sedimentary comprising of phyllite and quartzite sequence are mostly incompetent and semi-consolidated with deeply incised erosion forming narrow ridges with 'V' shaped valleys and steep escarpment.

The NE-SW trending Singyedara ridge is the prominent topographical feature that acts as main water divide into Barsa river and Singye river. Though several other minor NE-SW trending ridges are noticed during the study, they are situated mostly in north-eastern part above Main Central Thrust (MCT). The central part of the area is characterized by N-S trending ridges, which are in turn dissected by NW-SE minor ridges. Barsa river and Singye river flow from NE to SW whereas Thotney khola, Doyamara and Bhalujhora flow from north to south. The drainage exhibits a dendritic pattern in the upper part and sub-dendritic to sub-parallel in the lower part.

1.5 CLIMATE

Barsa watershed experiences hot summer and pleasant and cold winter. The rainy season begins from April and lasts till September. Thundershowers and hailstorms are quite common in this area. The monthly and annual rainfall data from 1996 to 2011 of Phuentsholing station obtained from National Center for Hydrology and Meteorology (NCHM) show that the area receives as high as 2320.9 mm of monthly rainfall (July 1998) and as low as 0.0 mm during the dry months (Table 1). The high amount of rainfall occurring in this area is most likely one of the main factors triggering landslides and floods.

Table 1. Monthly and Annual Rainfall at Phuentsholing Weather Station from 1996 to 2011 (Source: NCHM)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1996	30.7	12	49.1	166.6	289.2	612.3	1329.1	548.3	285.7	220.7	11.1	0	5550.8
1997	32.1	60.3	67.1	259.9	463.3	1282.6	750.8	745.6	586.3	82.9	27.1	18.6	6373.6
1998	69.6	18	120.2	232.6	252.4	2320.9	1596.4	1530.6	326.3	229.4	0	2.6	8697
1999	0	0	28.6	477.7	647.9	784	621.5	1213.9	597.9	175.7	0	0	6546.2
2000	35.4	16.5	22.2	326.7	597.7	1194.4	1192.7	1760.2	767.1	151.4	38.3	3.8	8106.4
2001	56.6	103.3	27.8	291.2	631.2	629.3	990.4	727.8	644.9	398	70	23.1	6594.6
2002	26.7	24.6	116.1	237	302.1	1074.3	1619.6	687.5	356.5	203.4	0.6	43	6693.4
2003	14.5	70.6	340.6	294.4	305.9	1031.2	915.5	675.2	617.2	292.7	30.7	44.7	6636.2
2004	30	73.2	38.2	279.8	697.5	1215	1364.3	559.2	407.6	342.8	0	27.2	7038.8
2005	22.2	3	59.3	78	163.7	125.9	1140.8	558.9	270.6	174.1	9.5	0	4611
2006	0	1.6	30.1	54.7	290.8	488.2	276.4	292.5	440.7	100.7	0.2	0	3981.9
2007	2.4	75.9	11.5	100.4	744.1	486.7	658.9	615.2	600.7	78.6	2.2	0	5383.6
2008	13.9	17.6	49.4	45.4	176.7	233.7	409.6	364.1	352	17.6	0	1.4	3689.4
2009	0	70	81	221.7	275	544.4	708.3	828.9	225.7	201.2	0	19.6	5184.8
2010	0	25	210.7	423.3	394.4	894.3	926	610.5	629.5	67.5	0.6	0	6191.8
2011	0	37.9	42.2	208.8	245.5	848.2	706.2	524.4	424.7	0	12	0	5060.9

2. REGIONAL GEOLOGICAL SETTING

Geology of Bhutan Himalaya has been grouped into four subdivisions by Nautiyal and Gansser (1964) as Sub-Himalaya, Lesser Himalaya, Higher Himalaya and Greater Himalaya. All these subdivisions were based on stratigraphical and structural aspects. The majority of Barsa watershed area is occupied by lesser Himalaya and partly by Higher Himalayan sequence in the north. The geology of Barsa watershed area, in general, can be grouped into two litho- assemblage depending upon the sudden change in the grade of metamorphism considering the Main Central Thrust (MCT) as a base line. The area south of MCT comprises mainly of low-grade meta-sedimentary of Lesser Himalayan Sequence and overlying high-grade metamorphic rock of Central Crystalline Complex. MCT is a narrow but persisting zone comprising of highly crushed coarse grain, quartz-mica schist and forms the boundary between the two sequences.

Several Geologists from Geological Survey of India had carried out geological studies on high-grade quartzite in the area at different stages. Chaturvedy and Reddy (1978), Lakshminaraya (1992-1993) and Mullick and Yadav (1999), carried out systematic geological mapping around the area and classified the meta-sedimentary sequences as Phuentsholing Formation (Buxa Group), Shumar Formation, Jaishidanda Formation and Surey Formation (Thimphu Group).

As observed during the fieldwork, Phuentsholing Formation occupies the lowermost stratigraphic level in Barsawatershed area. It is then sequentially overlain by Shumar Formation, Jaishidanda Formation and Surey Formation in the extreme north. Phuentsholing Formation and Surey Formation have a maximum thickness in this area whereas Jaishidanda Formation appears as a narrow zone with distinct shearing and regional persistence. The generalized trend of the rocks varies from N30˚ to 70˚W with dips 25˚ to 55˚ towards the north.

The tectonostratigraphic succession from north to south is shown below:

North

Formation	**Lithology**
Surey Formation	Granitic gneiss Coarse grain biotite schist and gneiss Augen Gneiss
…………………..Thimphu Thrust ………………..	
Jaishidanda Formation	Garnetiferous mica schist, quartzite and limestone.
………………….. Main Central Thrust (MCT)………………..	
Shumar Formation	greenish grey phyllite and quartzite White massive/flaggy quartzite. greenish grey phyllite and quartzite
………………….. Shumar Thrust …………………….	
Phuentsholing Formation	Green and grey phyllite and quartzite Grey phyllite/quartzite with cherty quartzite (Ironstone) Dark phyllite Calcareous purple/pink quartzite
Alluvium	Sand, Silt, Pebble, Cobble and Boulder

South

3. MATERIALS AND METHODS

3.1. MATERIALS USED FOR THE STUDY

The materials and instruments used during the fieldwork, data preparation and processing of datasets for final outputs are given below:

- Orthorectified SPOT satellite imagery from National Land Commission secretariat (NLC).
- Google maps and imageries from Google Earth Pro ^{Tm}.
- The topographical map on scale 1:50,000, published by Survey of India, NLC.
- Land cover map (national level) published by Ministry of Agriculture and Forests, Land Classes and Mapping Project (LCMP) 2010.
- ALOS Prism DEM, 10x10 m resolution, generated in DGM/JST/JICA project 2012.
- Existing hydrological data, National Center for Hydrology and Meteorology.
- Maps and reports from DGM Library.
- Published reports and information by Flood Engineering Management Division, Ministry of Works and Human Settlement.
- Digital data and publication prepared by Phuentsoling City Corporation.
- Internationally published technical papers, reports, and manuals.
- Total Station TS06, GPS and geological instruments, cameras, rangefinder and other accessories.
- ArcGIS 10.4.1 for spatial Analysis of the datasets.
- Statistical software R-Studio.
- Socio-Economic Survey Forms approved by National Statistical Bureau to collect socio-economic data.

3.2. METHODOLOGY

The outline of main methodologies used to carry out the integrated geohazard risk assessment and mapping of Barsa Watershed are provided below:

(1) Detailed topographical survey.

(2) Geological mapping and Engineering geological or geotechnical investigation.

(3) Application of GIS for hazard and risk assessment.

3.2.1. Topographical data and Landslide Survey

Detailed landslide survey, taking the measurement of the landslide crown on the study area was carried out using Total Station TS06 and GPS. The topography map was prepared in the scale of 1:25000 using existing data and provided as Plate-1. This map was used as a base map to prepare geological, DEM, hazard, vulnerability and risk map. Based on the desktop study, the occurrences of landslides and drainage system were validated on the ground.

3.2.2. Geological and Engineering Geological or Geotechnical Investigation

Geological mapping was carried out in 1:25000 scale covering the entire watershed area to map rock types and structures, and to understand and establish the geological setting of the area. Moderately-spaced traverses (<250 m) were undertaken; geological points were located using GPS and Total Station and structural data were recorded using Brunton compass.

Both active and inactive landslides were studied and mapped. Six random soil samples were collected from the landslide areas, which are located close to human settlements, river and infrastructures. These soil samples were tested in the Geotechnical Laboratory of Department of Geology and Mines to understand the grain size distribution of the materials.

3.2.3. Application of GIS for hazard and risk assessment

The spatial analysis of the hazard, vulnerability and risk of landslides in Barsa Watershed were carried out using Geographical Information System (GIS) and third-party software R. The main components of the processes are shown in Figure 2. The methodology used for GIS analysis are described in detail in this section.

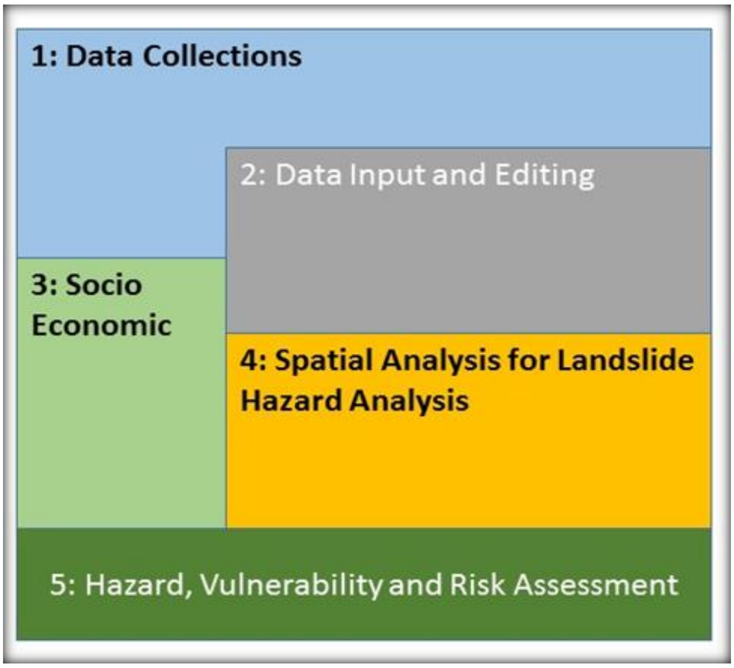


Figure 2. Main components of processes for integrated geo-hazard risk assessment of landslides in Barsa watershed.

3.2.3.1. *Approaches and Techniques*

During the desktop study, a conceptual workflow was developed taking into consideration the various techniques and approaches in using GIS technology in the field of spatial analysis. The use of computer-aided modelling is ideal for such type of work and has been gaining popularity all over the world in the field of landslide hazards or susceptibility, vulnerability and risk assessment mapping. Therefore, in this study, Logistic Regression (LR) applying multivariate approach technique under statistical methods was adopted. A conceptualized workflow was developed to maintain a smooth flow of the process (Figure 3).

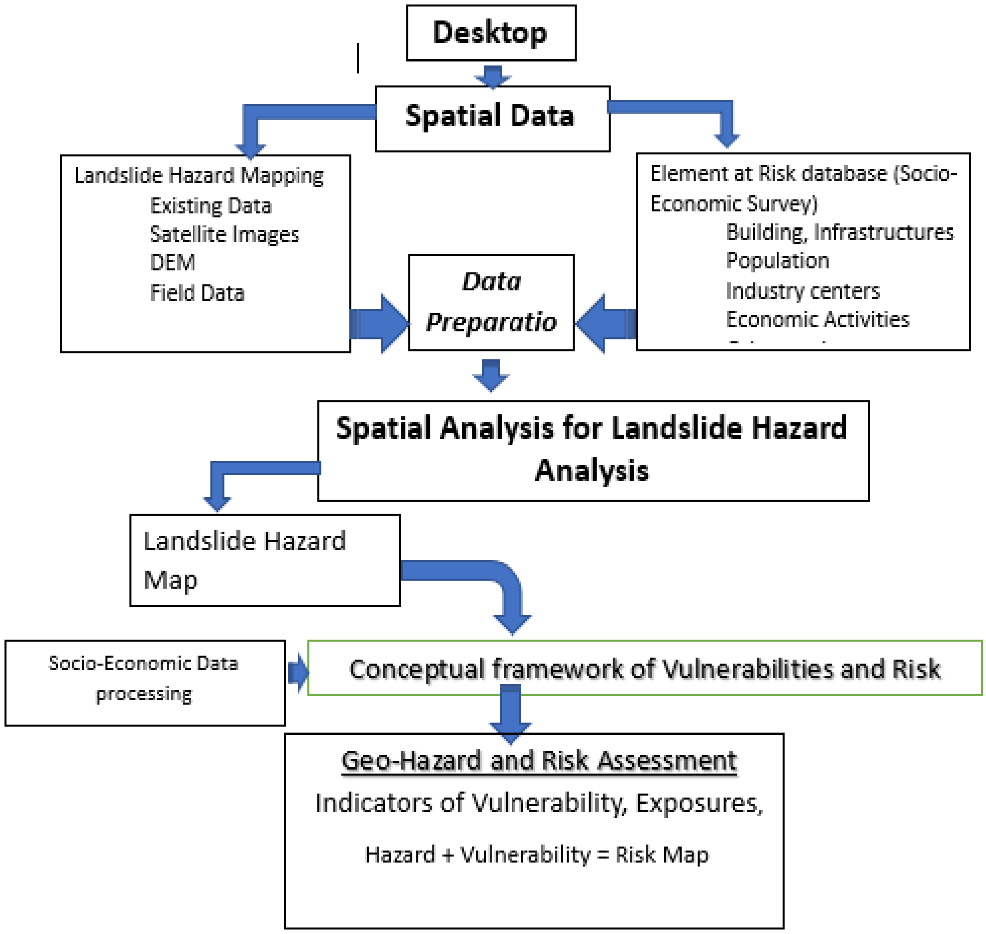


Figure 3. The Conceptual workflow or processes carried out for integrated geo-hazards risk assessment and mapping of Barsa Watershed.

3.2.3.2. *Data analytical process*

In computing hazard map, a systematic flow of the process was carried out as shown in Figure 4. The outline of the steps is given below:

- Data Collection.
- Data preparation.
- Methods and Approaches selection- Logistic Regression running multivariate analysis model.
- Training samples: out of 122 landslides 68% (76) for establishing the model and the remaining landslides (36 points) were used for validation as the test set.

- Raster conversion and Statistical Data preparation: Exported to .csv format for running with free OS statistical software.
- Process for Cramer' V coefficient values for the independent variables: Generalized Linear Model (GLM) function in R is used to process the data for intercepts and coefficients for all the parameter.
- Map mathematical calculation by ArcGIS tools.
- Probability calculation using equation.
- Reclassification.

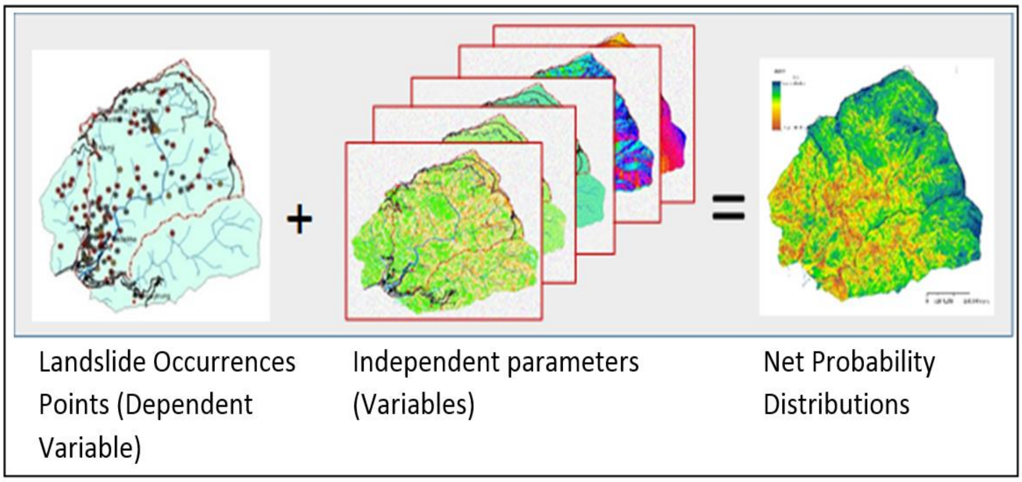


Figure 4. The Process of spatial analysis using Logistic Regression, Statistic multivariate model.

3.2.3.3. *Factors used for Spatial Data Analysis*

As the landslide hazard mapping depends on complicated mass movement and their controlling factors like slope, geological setting, water moisture content, soil etc., it is essential to identify the main physical factors contributing to the landslide occurrences and incorporating them in logistic multiple regression. In this context, each of the variables, independent and dependent are applied for GIS-based spatial analytical processes using a logistic regression model as shown in Table 2.

Table 2. The Independent factors used for the analysis process are given in the table, with sources and formats.

Nr.	Database	Parameters Name	Format	Sources
1	Landslide Inventory	lsdInvent	Vector/Raster	DGM fieldwork
2	Geology	geoPoly	Raster	DGM fieldwork
3	Structural Geology	GeoStruct	Raster	DGM fieldwork
4	Land Cover	Landcover	Raster	MoAF, LCMP 2010
5	Roads	RoadEu	Raster	DOR
6	Rivers	RivEu	Raster	DGM
7	Slope	Slope	Raster	Topo map 50K
8	Aspect	Aspect	Raster	Topo map 50K
9	Curvature	Curve	Raster	Topo map 50K

The importance of each variable (factors) triggering landslides used for determining landslide probability is explained below:

(1) Landslide inventory map: Preparing a landslide inventory for a certain region constitutes the first step in data production. The landslide inventory map with a total of 112 landslides was compiled based on desktop study and interpretation of satellite imageries, which was supported by field validation. Map of landslide inventory and the statistic information is provided as Plate 6. In the landslide data attributes, a standard numbering has been followed to provide unique IDs. This landslide data plays a crucial role in correlating with an intercept of coefficients of different thematic layers, that are used as factors.

(2) Lithology (Geology): It is significantly recognized as one of the important factors since geological behaviour greatly influences in landsliding, because of the lithological and structural variations often lead to a difference in strength and permeability of rocks and soils. The rock types, lithology and geological setting of the Barsa watershed are elaborately described in this report and the geological map is shown in Plate 2.

(3) Landcover map: Land cover data from Land Cover Mapping Project (LCMP 2010) published by Ministry of Agriculture and Forests was used. The area coverage for the various type of land cover is shown in Figure 5 and statistics are provided in Table 3.

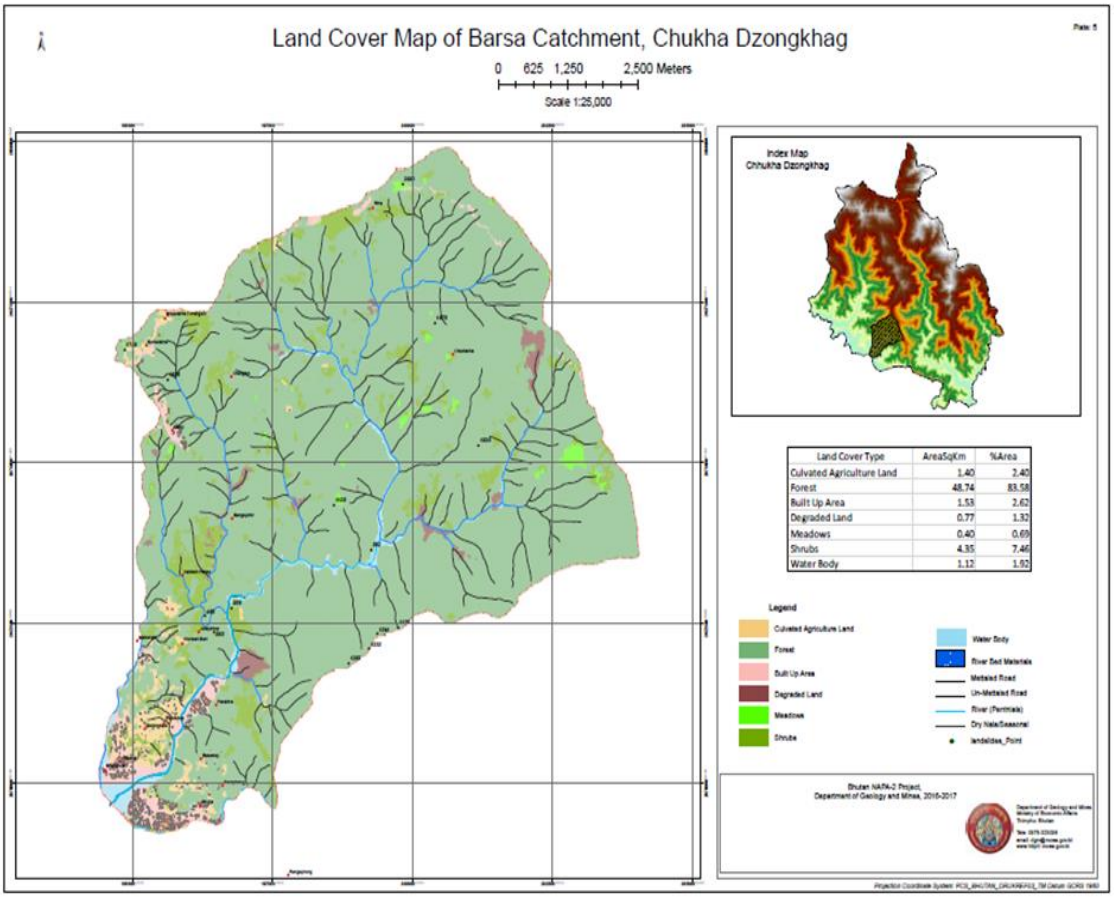


Figure 5. Land cover map of Barsa watershed.

Table 3. Different land cover types in Barsa watershed.

Land Cover Type	Area Km^2	Area %
Cultivated Agriculture Land	1.40	2.40
Forest	48.74	83.58
Built Up Area	1.53	2.62
Degraded Land	0.77	1.32
Meadows	0.40	0.69

(4) **Roads:** Road-cuts are usually the sites of anthropologically induced instability. The existing roadways act as barriers, a corridor for water flow especially when there is no proper drainage system along the road and depending on the location in the mountains, it usually serves as a source of landslides. It is quite clear that most of the landslides in our country are occurring along the road construction or cutting sites. For this reason, roadways are included in GIS-based landslide susceptibility analysis as one of the predisposing factors.

(5) **Drainage (River distance):** Slope saturation by water is the primary cause of landslides, this effect can occur in the form of intense rainfall, therefore drainage system in distance is considered as one of the key variables. In the process of analysis, it is defined as the buffered zone to the water flow at an equal interval distance in meters to landslide events. In this study Euclidean distance method is used to calculate the distance to the closest source using ArcGIS tools. The drainage density map of the study area is shown in Figure 6.

(6) **Digital Elevation Model (DEM):** Digital Elevation Model (DEM) is the most important data source as slope, elevation, aspect and curvature maps can be generated. The elevation map of the study area is shown in Figure 7. The DEM used in this study is from 1:50000 scale toposheet of 20 m contour interval which is converted to raster (10x10 m) resolution using ArcGIS interpolation tool, Topo to Raster. This is specifically designed for the creation of hydrologically correct digital elevation models. The advantage here using this method is the elevation has been corrected based on National Land Commission data.

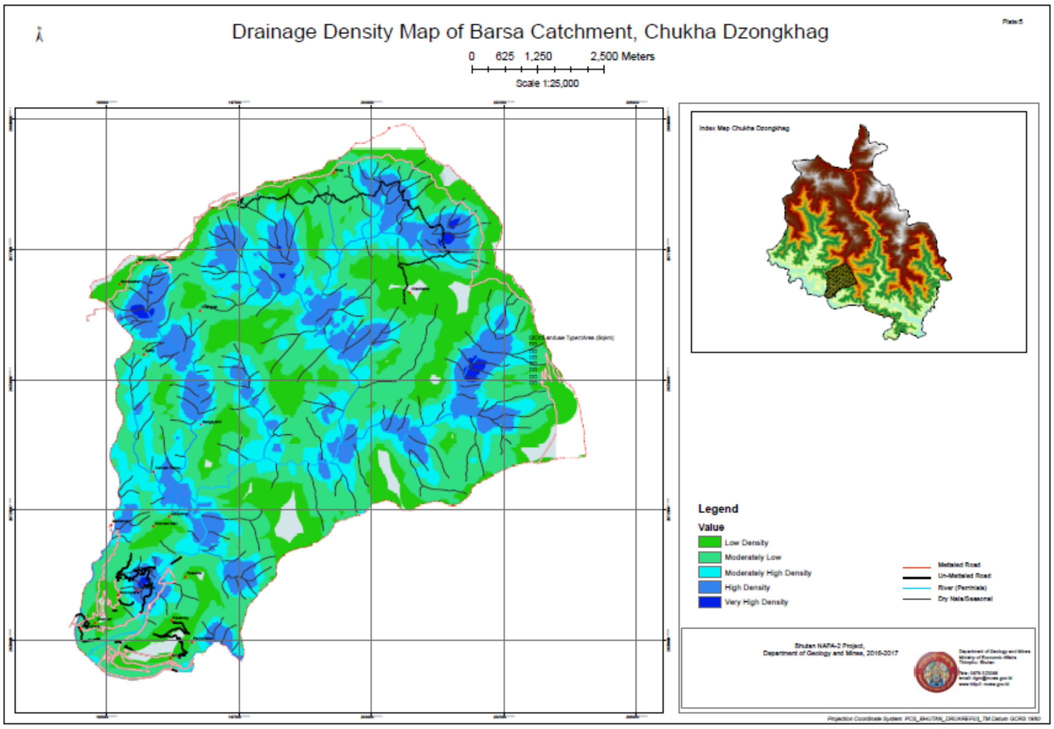


Figure 6. Drainage density map of Barsa watershed.

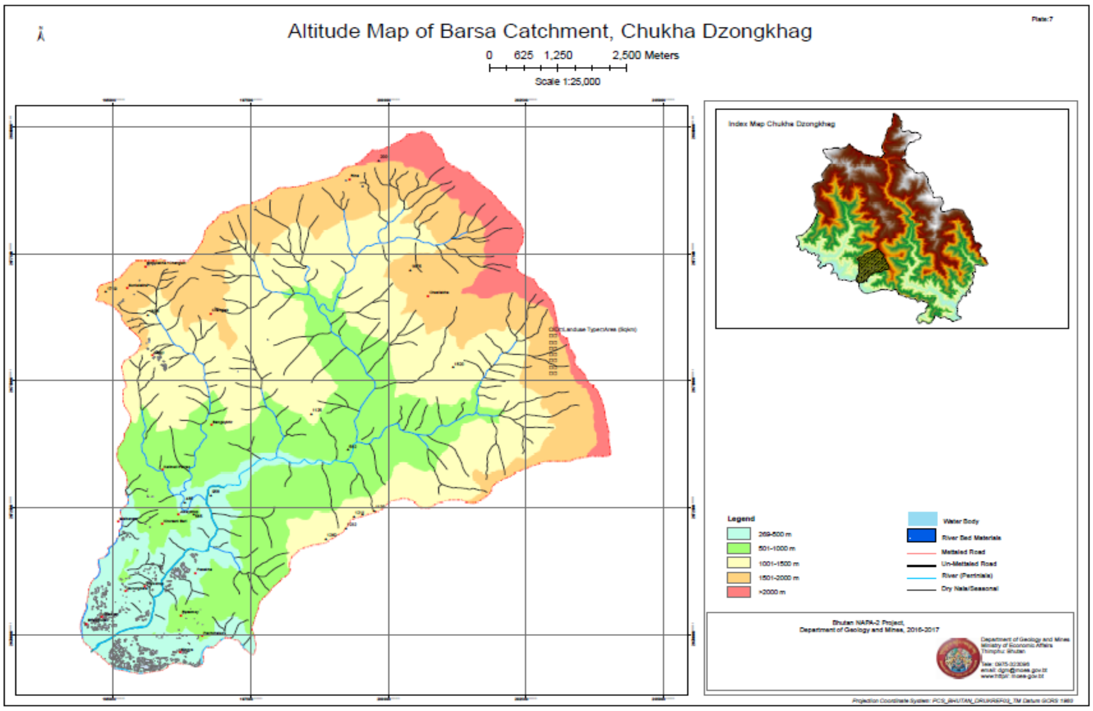


Figure 7. Elevation map of Barsa watershed.

(7) Slope: Slope is an area of land that makes a definite angle to the horizontal landscape. Slope plays a crucial role in mass wasting for inducing small to major landslides. In this study, slopes are classified into 5 types as given in Table 4 and shown in Figure 8.

Table 4. Slope gradient, area and percentage of slope area in the Barsa watershed study area.

Slope Type	Slope Angle	Area Km^2	Slope %
Escarpment/Cliff	> 45	6.27	10.75
Steep Slope	36-45 deg	15.26	26.14
Moderately Steep Slope	26-35 deg	19.99	34.24
Gentle Slope	16-25 deg	12.09	20.72
Very Gentle Slope	<15 deg	4.75	8.15

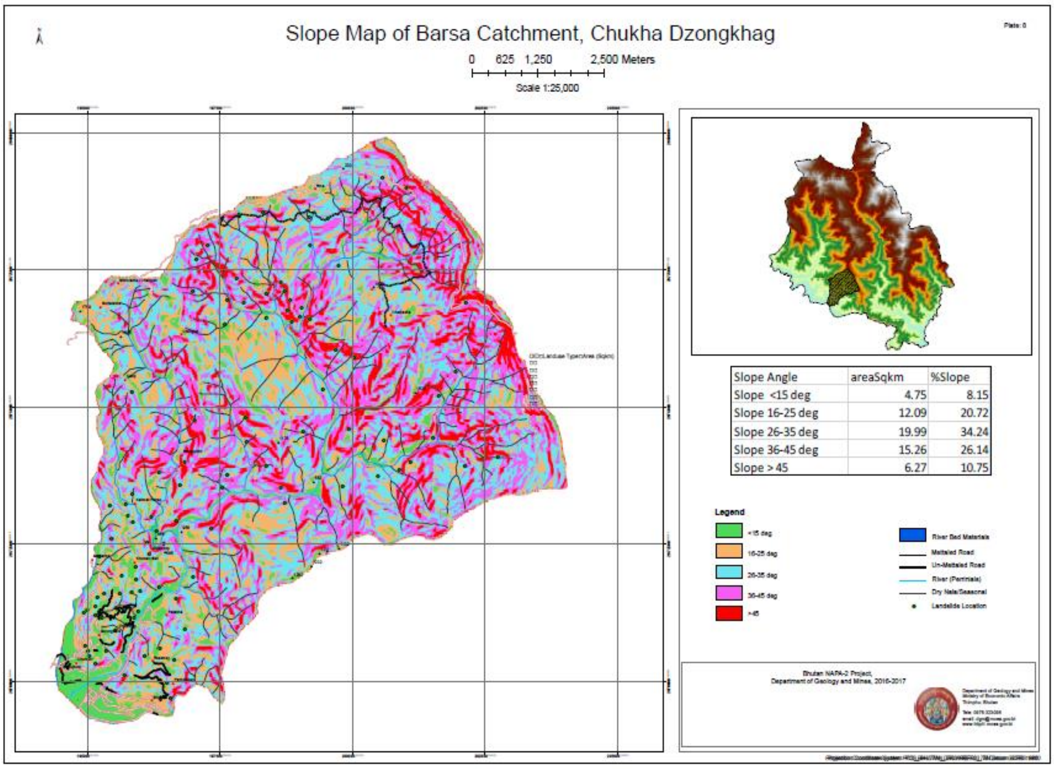


Figure 8. Slope classification map of Barsa watershed.

(8) Aspect: Aspect map shows slope faces at different directions, e.g. Flat area, North, Northeast, South, Southeast, etc. In context to landslide hazard mapping, slope aspect is one of the indispensable internal factors besides lithology and shown in Figure 9.

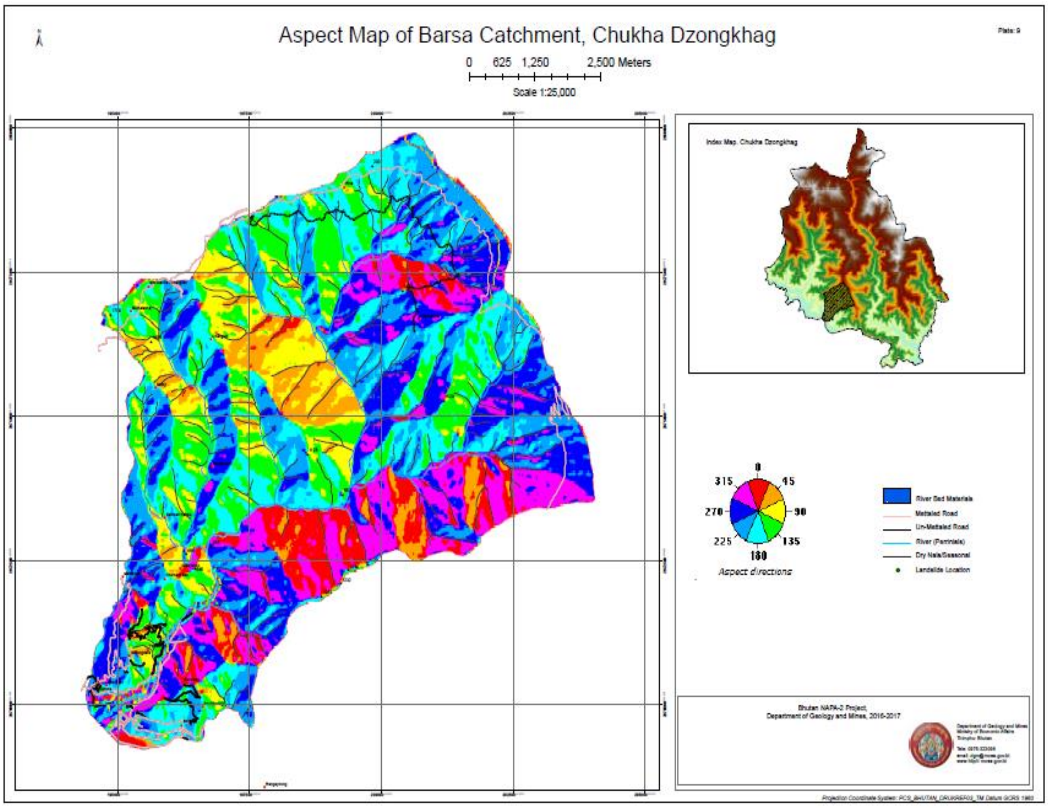


Figure 9. Aspect map of Barsa watershed. **Landslides and Slope Aspect in the Three Gorges Reservoir Area Based on GIS and Information Value Model, WU Caiyan, QIAO Jianping it, WANG Meng.*

(9) Curvature: The Curvature raster layer is derived from DEM and delineates the shape or curvature of the slope in convex or concave shape. This is also one of the critical factors that triggering landslides.

3.3. VULNERABILITY AND RISK ASSESSMENT

For vulnerability and Risk assessment on the hazardous area, socio-economic survey was vital to understand the livelihood of the communities, type of houses, infrastructures and capacity to cope up with the natural calamities. To carry out the survey, a format was designed and with prior approval from National Statistical Bureau and the team visited more than 300 houses with survey questionnaires in places like Kamji, Ganglakha, Gurungdara, Resamey and Pasakha, which falls within the Barsa Watershed area.

The process of risk analysis and evaluation is the measure of the probability and severity of an adverse effect on people, property or the environment. Therefore, the process of *risk estimation* integrates the behaviour of the hazard (hazard Map) with elements at risk and their vulnerability (*conceptual frameworks of consequences/indicators*) to allow risk calculation, usually in the form of basic hazard-risk calculation equation shown below:

Risk= hazard x vulnerability x elements at risk (Exposures)

A conceptual framework was developed to estimate the vulnerability to the infrastructures, people and other economic activities, as per the guidelines for standardized vulnerability assessments, BMZ, Published by GIZ (Figure 10).

- Sex ratio - proportion of female to male in %.
- Dependency Ratio- The dependency ratio relates to the number of children (0-14 years old) and older persons (60 years or over) to the working-age population (15-59 years old).
- Differently abled- Physically challenged population.
- Infrastructure and Environment.
- Awareness to a natural disaster.

Based on the above 5 indicators, a calculation was carried out in Excel and later applied point risk assessment in ArcGIS software for visualization as shown in Figure 11.

Main Factor	Indicator Name	Indicator Explanation
Exposures		
Infrastructures	(E1) Number of infrastructures	Location of household (residential, Industry, Institutional etc.)
Population	(E2) Total Household Population	Total Household Population, Male, Female, Senior Citizen, Differently abled, Child with Location
Economy	(E3) Number of Economic Activities	Number of Economic Activities, Cottage industry, Farms, Moveable Property
Vulnerability		
Physical/ Demographic	(V1) Sex Ratio	% of female on number of male
	(V2) Dependency Ratio	% of dependent child <=14 years
	(V3) Senior Citizen	Number of senior citizen (old age) >60 years
	(V4) Differently Abled	Number of Differently abled person
	(V5) Infrastructure CC	Infrastructure category (see on table,,,)
	(V6) Age of the House	Number of years old, based on Socio Economic study
Economic	(V5) Income Sources	Number of Income sources, Economic Activities, Employments, etc. (Implies to only Livelihood)
Awareness	(V7) Societal Awareness	Number of person who are aware of natural disaster

*Figure 10. Standardized vulnerability assessments of BMZ, Published by GIZ. *Definition from: Guidelines for landslide susceptibility, hazard and risk zoning, Journal and News of the Australian Geomechanics Society Volume 42 No. 1, March 2007.*

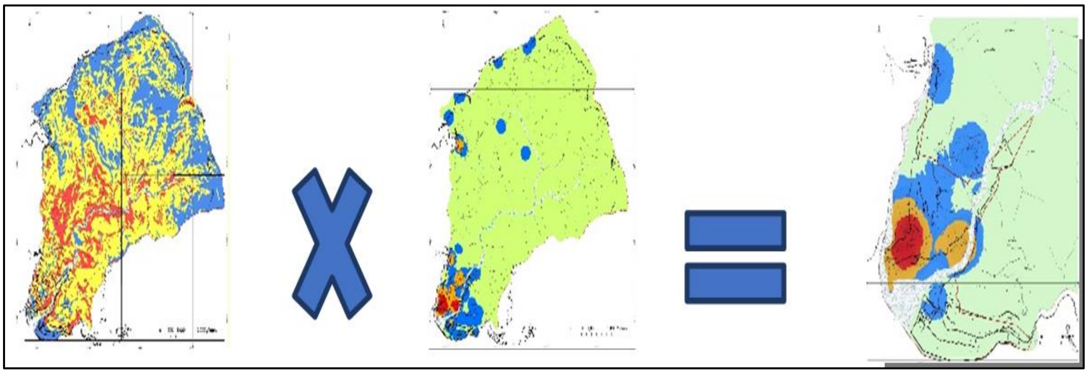


Figure 11. The process of computing risk assessment map of Barsa watershed area.

4. RESULTS AND DISCUSSIONS

4.1. GEOLOGY OF THE AREA

Different geological Formations were observed during the field traverse from south to north of Barsa watershed. The Formations with different types of litho-units are shown in (Plate-2) and each formation is described in detail below.

4.1.1. Phuentsholing Formation

Phuentsholing Formation is well exposed in the southern part of Barsa watershed and it is represented by an alternating sequence of dark phyllite and calcareous purple to light pink quartzite in the lower part followed by grey phyllite and quartzite with ironstone and green to grey quartzite and phyllite towards the north.

Dark phyllite is highly crushed and crenulated in nature and found to be the most incompetent unit. The crushed carbonaceous part when dissolved in rainwater during monsoon adds volume and flows along the downslope leaving deep gully erosions. The dark phyllite is also intensely intruded by vein quartz mostly along the foliation. The light pink quartzite is fine-grained, resinous texture, mylonitised and calcareous in nature.

At Bhalujhora and Resamey sections, it is exposed as prominent outcrops but, in most cases, slumped or dislocated blocks with highly jointed and fractured surface are seen. Grey phyllite and quartzite unit is thinly laminated and looks more competent in nature. Several impersistent ferruginous cherty quartzite (ironstone) lenses occur within this unit. It is fine, hard and compact in nature. Greenish grey quartzite/phyllite unit has the maximum thickness and occupies the top part of Phuentsholing Formation. The quartzite is medium grain, thickly bedded and fractured and jointed on the surface. The greenish grey phyllite is arenaceous in nature and well laminated. It is frequently traversed by vein quartz along the foliation. At places, the vein quartz has been highly sheared/shattered forming minor fold and boudins.

Meta-basic sills ranging in thickness from 0.5 m to 8 m occurs at a different level within Phuentsholing Formation. The above litho-units has a gradational contact with each other but the contact with overlying Shumar Formation is delimited by greenschist facies of metamorphism. Thrust and have attained a normal set up of

4.1.2. Shumar Formation

Shumar Formation comprises of an alternating unit of greyish white quartzite, greenish grey and carbonaceous phyllite. Thin parting of mica schist is also observed towards the upper part. The fine grain partially foliated greenish grey phyllite with grey quartzite lenses forms the dominant sequence. The greyish white, thickly bedded quartzite occurring at a different level is the subordinate unit. The quartzite is commonly fine grain and hard and compact in nature but due to the presence of close spaced joint sets, the surface has a fractured/fragmented look. At places, fine intercalation of phyllitic layers in quartzite exhibits a flaggy nature. Basic sills are seen commonly within Shumar Formation, but the concentration is more around the contact points. Shumar Formation is well exposed in the study area and both the upper and lower contact is thrust.

4.1.3. Jaishidanda Formation

Jaishidanda Formation overlying the Shumar Formation occurs as highly crushed zone mainly comprising of garnetiferous mica schist with intercalations of micaceous and recrystallized quartzite, rare carbonaceous schist and carbonate bands. Past studies (Bhargava, 1995) consider this litho-assemblage as the lower part of Surey Formation as this garnetiferous mica schist resembles the schist of Surey Formation. But schist in Jaishidanda Formation forms the main bulk of the sequence with profuse intrusions of vein quartz, granite-pegmatite lenses. In Barsa area, schist is coarse grain and light grey to silvery white in colour with well develop schistosity plane. Greyish white, medium bedded, recrystallized quartzite occurs as thin impersistent beds at a various level within schist. Garnet is seen in almost all the litho-units of Jaishidanda Formation. The bigger size reddish brown garnets which are fractured and weathered are seen in schist mostly along the Main Central Thrust.

Whereas smaller size pink garnet with clear crystal faces are seen in quartzite and calc-silicate rocks.

Due to narrow but regional persistence occurring at a particular tectonostratigraphic level with distinct metamorphism and deformation, schist of Jaishidanda has been designated as a different formation. This zone is highly sheared with thin lenses of augen gneiss and has a sharp/thrust contact with the overlying Surey Formation.

4.1.4. Surey Formation

Surey Formation occurring at the highest stratigraphic level overlying the Jaishidanda Formation has a maximum thickness and forms the major part of Barsa watershed area. Major rock type comprises of medium grain granitic gneiss, an inter-layered unit of coarse-grained biotite schist/gneiss and augen gneiss.

The augen gneiss occurs in the lower part overlying the Jaishidanda Formation defining a sharp contact. It is thinly to medium bedded and exhibits fine bands with well-developed augen structures. The augens is of various sizes (0.5 * 0.7 to 5 * 7 cm) and mostly formed by quartz and feldspar. At some places, the augens are highly shattered and elongated whereas at other places it is boudinaged.

The inter-layered unit of coarse-grained biotite schist/gneiss overlies the augen gneiss. The different minerals observed under megascopic studies are quartz-felspar and biotite with garnet as accessories. The gneissic banding is defined by quartzo-felspathic and biotite laminae. The biotite-rich layer forms prominent foliation where quartzo-felspathic layer is porphyritic in nature.

The upper part of Surey Formation is occupied by greyish white, medium to coarse-grained and massive granitic gneiss. This unit is well exposed along Thimphu-Phuentsholing Highway between Jumja and Ganglakha. Thin lenses and patches of migmatite gneiss and leucogranites are commonly seen within this gneiss. Impersistent bands of weathered mica schist are found at various tectonic levels. Small intrusions of aplite, tourmaline bearing leucogranite and pegmatite are present in massive gneiss whereas vein quartz is concentrated mostly in schist. The degree of weathering is more in felspathic gneiss and coarse grain schist.

4.1.5. Structural Geology

The regional trend of the rocks in the area ranges from N30˚W to N70˚W with varying dips 25˚ to 55˚ towards northeast. Both primary and secondary structures are observed during the fieldwork. Primary structures like bedding and cross-stratification are represented by alternating light grey and greyish white colour laminated quartzite of Phuentsholing and Shumar Formations. At places, light grey and green coloured phyllite exhibits a weak developed bedding.

The secondary structures like schistosity and gneissosity are the most developed planar features found in garnetiferous mica schist of Jaishidanda Formation and gneiss of Surey Formation respectively. They are parallel or subparallel to bedding and represented by parallel alignment of flaky minerals. Several sets of joints have been developed in almost all the rocks of the area. The prominently developed joints are found in quartzite and gneiss giving a highly fractured/ fragmented appearance. Some of the joint sets measured in the field are E-W/60°-80°N, N30°-40°W/30°-50°NE, N30°-50°E/50°-70°SE and N-S/60°-75°W. The former two sets are more prominent than the later.

Tentatively four fault lines namely F1, F2, F3 & F4 (Plate III) and two shear zones, SZ1 & SZ2 were deduced during the fieldwork based on structural data and topographical features. F1, F2 and F3 are trending N-S whereas F4 occurs along the Thimphu thrust and is trending NW to SE. Fault scarp, highly disturbed and slumped outcrop or topography, landslides with an accumulation of debris and boulders at the base and straight drainage pattern are some of the evidence of faulting. Along F4, thinning or thickening and abrupt ending of minor units are commonly seen. Two E-W trending major shear zones (SZ1 & SZ2) are also noted within phyllite and quartzite sequence of Phuentsholing Formation. SZ1 is traced from west of Bhalujhora that passes between two identical hillocks shattering apart at Malbase and continue through Gurungdara to north of Resamey village. The phyllite along the shear zone is highly crushed and crenulated and easily eroded during monsoon forming deep gully erosions, whereas quartzite is highly fractured and fragmented and slumpy in nature. SZ2 is about 150m north of SZ1 and passes parallel to it. Presences of dormant as well as active landslides along this zone are some of the evidence.

4.1.6. Metamorphism

The rock types in the area have attained a reverse grade of metamorphism**.** The Phuentsholing Formation of Buxa Group is composed of an argillaceous and arenaceous unit of low-grade metamorphism. The constituent minerals are chlorite, muscovite or sericite, quartz and clay. In Shumar Formation, the grade of metamorphism increases from south to north. The greyish white quartzite occurring at various levels are finely grained with the presence of primary structures (colour banding and cross-bedding) in the lower part. The upper part is coarse and massive with devoid of such structures. The quartzite and phyllite are coarse with weakly developed schistosity. The Jaishidanda and Surey Formations are composed of high-grade metamorphic rocks like garnetiferous biotite schist, biotite gneiss, augen gneiss with well-developed schistosity and gneissosity respectively, with presence of metamorphic index minerals like staurolite, silliminite and kyanite.

4.2. ENGINEERING GEOLOGICAL OR GEOTECHNICAL INVESTIGATION

Landslide is superficial instability caused by loose unconsolidated rock and soil which moves abruptly or slowly downwards from its in-situ position. Such movement caused along the surface of failure is known as a mass movement.

Landslides in Barsa watershed are seen at different levels irrespective of rock formations. At Gurungdara and north of BFAL factory, landslides are associated with dark phyllite and light pink calcareous quartzite of Phuentsholing Formation and mostly concentrated around the shear zone. The phyllite is highly crushed, crenulated and incompetent. Moreover, lots of quartz veins and basic rock intrusion have rendered the rock mostly fragile. In the middle part of the area, landslides occur along Shumar thrust and Main Central Thrust and are dormant in nature with partial re-activation. Landslides along Barsa tributary coming from the west are fresh and active. In the upper part of the watershed area the landslides are distributed mostly along Thimphu thrust, stream with high gradient and along the faults. The landslides above Barsa-Padzechu confluence and south of Ganglakha are dormant but the slide along Jumjachu and north of Changling are active in nature.

The main causes of landslide could be initial upliftment, climatic condition, heavy precipitation and erosion, geological conditions or structures and land degradation. The rocks of Phuentsholing and Shumar Formation are sandwiched between MCT and MBT and are highly disturbed. Surey gneiss overlying the Thimphu thrust is highly fractured and jointed. Several sets of closed spaced joint planes have weakened the rock surface where mass wastages in the form of rock falls are quite common. The constituent minerals of gneiss are feldspar (60%) and quartz (40%). Felspar is prone to chemical weathering and disintegration. Beside this, forest degradation, soil erosion, human intervention, overgrazing and developmental activities are some of the factors related to landslides.

4.2.1. Observations on the prominent landslides in Barsa Watershed area

112 landslides have been studied using satellite images and physically verifying in the field. Settlements and infrastructures are mostly along the upper reach and lower reach of the Barsa watershed. The middle portion of the watershed is mostly inaccessible with thick vegetation and steep slopes which are not suitable for settlement. Most of the landslides located in the middle part of the watershed area are far away from settlements and roads and do not pose any direct threat. But few landslides prone areas, which are located near to roads and settlements were studied in detail as they pose a direct threat during natural disasters like flood and landslides and explained in detail below.

(1) **Jumja landslide:** The Jumja landslide is located at N26°54’8.7” and E89°31’3.4” at an elevation of around 2164 m above main sea level. It is mainly made up of massive gneiss with wide spaced open joints filled by infills like gauge and pebbles. The joints have spacing ranging from 5cm to 15cm. Most of the outcrops are jointed and fractured and as much as three joints were observed and measured as follows: (i) N65°W/65°SW (ii) N45°E/70°SE and (iii) EW/80°S. Due to several joint sets, wedge failures were also observed.

A grab soil sample was collected from the base of the slide to test in the Geo-tech laboratory to understand the particle size distribution of the material. From the grain size graph in Figure 18, the soil distribution curve is not flat nor slightly concave, which could mean that it is a gap graded soil. Moreover, the coefficient of curvature of 0.028, which is less than 0.1 further indicates a possible gap graded soil. Usually poorly graded or gap-graded soils have good drainage property, but in a place like Jumja slide, where the rocks are highly fractured and soil particles are loosely packed, mass movement is quite high during rainfall and vibrations from heavy vehicles.

The slope angle of slide ranges from 50° to 80° and the loosely composed materials are seen hanging on the slope face which is protected by retaining wall at the base (Figure 12). A bulging of retaining wall was observed, which indicates that the area is not stable and there is constant movement of mass over the period.

Figure 12. Jumja slide with bulging retaining wall as shown in the picture. Inventory ID: lsd02100141.

(2) Landslide ID: lsd02150055 (about 500m North of BFAL industry): This slide lies on the left bank of main Barsa river at N26° 51’25.3” and E89°27’55.6” with an elevation of about 382 m above msl. Material type in this site is highly weathered and banded phyllite with basic rock intrusion. Presence of thin lenses of quartz sills intrusion were also observed within the phyllite rocks. The landslide type is dominantly debris flow which is mainly caused by heavy rainfall on the weathered and loose phyllitic materials. The slope angle of the slide ranges from 50° to 70°and the strike direction of phyllite outcrop is N60°W and dipping 25° NE. As seen in the Figure 13, the top portion of the slide has higher growth of vegetation and is slightly stable as compared to the toe part of the slide. The toe part of the slide is quite active due to undercutting action of the swollen Barsa river during monsoon season. Although this slide is about 500m away from BFAL industrial area, proper monitoring of slide around the toe area is necessary.

Two grab soil samples namely, LS-2(a) and LS-2(b) were collected from the middle and base of the slide respectively, to test their particle size distribution in the Geo-tech laboratory. From the grain size graph in Figs. 19 and 20, the soil distribution curves are slightly smooth and concave which could mean that it is a well-graded soil. Moreover, the coefficient of curvatures of these two soil samples of 0.245 and 0.99 are greater than 0.1 means they are well-graded soils. The well-graded soils have higher resistance to erosion than a poorly-graded soil. As seen in Figure 13, the slide is slightly stable due to the presence of vegetation growth as compared to Jumja slide, which has gap graded soil with less vegetation.

Figure 13. Landslide located about 500m North of BFAL industry, at the left bank of Barsa River. (Inventory ID: lsd02150055).

(3) **Landslide No. 3 (lsd02150230), Opposite BFAL Housing colony:** This slide is located at an elevation of 398.79 m msl at N26°31'.7" and E89°27'13.5".

From the local source, this slide has occurred in the year 2000, after the course of a flash flood in Pasakha. The slide area is composed mostly of phyllite with about 40 m thick calcareous quartzite on the top section of the slide. The crown of the slide is made up of quartzite and has a steep slope angle of about 80^{o} whereby, some signs of minor tension cracks are visible. The landslide is dormant for almost 14 years since its last major slide in 2000. Except for a small reactivation of slide at the south-east part of the slide slope as seen from Figure 14, the remaining part of the slide surface have a thick growth of bushes.

Figure 14. Landslide (Inventory ID: lsd02150230) seen from the BFAL colony.

Just below this landslide or the road as seen from Figure 14, there is an active toe cutting erosion by Barsa river. Some part of the retaining wall that was constructed to resist the slope failure is also damaged, which has led to further mass wastage below the road. There is an ongoing flood protection wall being constructed on the right bank of Barsa river/river beside BFAL housing colony, which is financially supported by NAPA-II project. Although this wall will benefit and protect the BFAL colony from the future flood, care must be taken on the left bank of Barsa river where the Pasakha-Manitar road passes through (Figures 14 and 15). The present flood protection wall construction might alter the course direction of Barsa river towards the left bank and this will increase water current force along the slopes below the road. This force could further increase toe cutting erosion and destabilize the slope which will reduce the stability of the road.

Figure 15. Disturbance in Barsa river course due to ongoing river protection wall.

Therefore, construction of river protection wall along the slopes on the left bank of Barsa river is important to avoid undercutting erosion from the river which otherwise could damage the road passing above.

A grab soil sample, LS-3, was collected from this slide to test the particle size distribution in the Geo-tech laboratory. From the grain size graph in Figure 21, the soil distribution curve is not that smooth and concave which could mean that it is a poorly-graded soil. Moreover, the coefficient of curvature value of 0.03 calculated from the grain size distribution graph indicates a possible gap graded soil.

(4) **Landslide ID: lsd02150253, Gurungdara/Barsa:** This landslide is located at 26^{o}51'13.2" and E89^{o}27'23.6" at an elevation of 320.32 m above msl. The slide area is thickly vegetated with sub-tropical trees, bettle nuts and does not seem to be an active slide at present. The crown of the landslide consists

of highly weathered phyllite. Full grown trees show signs of bending at the bottom part of the trunk and straight growth at the upper part of the trunk. This indicates there was creep movement in past years and has remained dormant in later years as shown in Figure 16. The presence of residual soils in this area also indicates that there was not much mass wastage taken place. However, in the southern crown part of the landslide, a mass subsidence length of about 4m and a depth ranging from 10 to 40 cm was observed. Therefore, there are chances of landslide reactivation from heavy rainfall and toe cutting erosion as it lies close to the right bank of Barsa river. It may not be advisable to construct any structure nearby the crown of the slide or within the dormant slide as there are indications of subsidence and creep movement as seen in Figure 16.

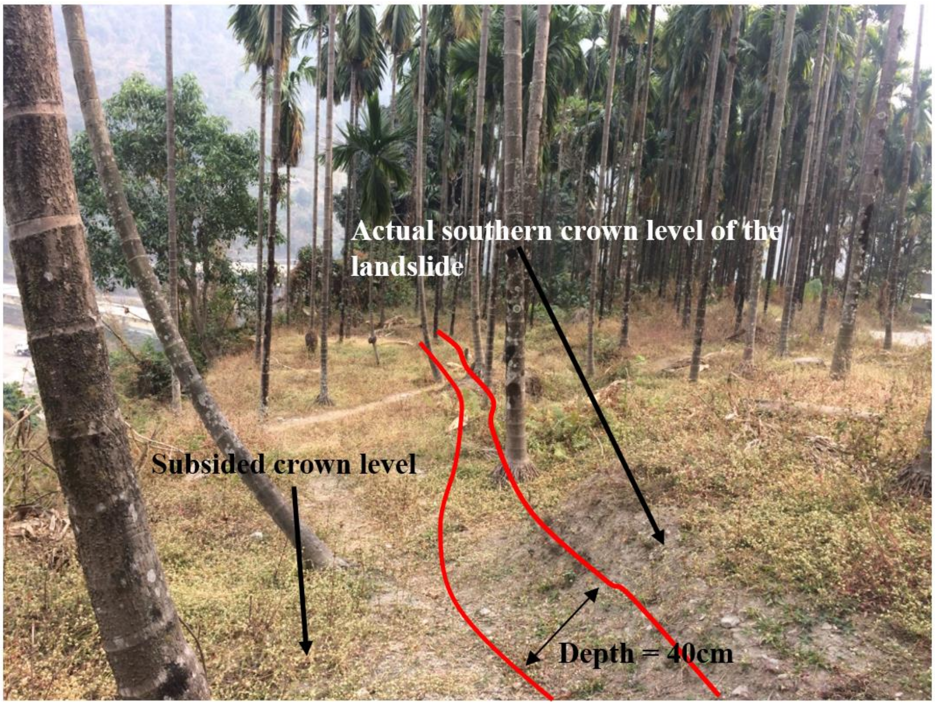


Figure 16. Subsidence at the crest of the slide and slanting trees due to movement of the ground.

(5) Landslide ID: lsd02100061, ThuloKhop: This slide is located at N26° 51’14.5” and E89°26’56.6” with an elevation of about 446 m above msl. The slide is a rotational type and is dormant with a thick growth of vegetation. Outcrops and scarps are not visible in this area as it is covered by colluvial and residual soils with vegetation. The body of the landslide slope angle is gentle with angles ranging from 20° to 45°. This slide will not have any direct impact from the river as it is about 50 to 100 m away from the river.

A grab soil sample was collected from this slide at N26°51'8.7" and E89°26'52.0" and tested in the Geo-tech laboratory to understand the particle size distribution. From the grain size graph in Figure 22, the soil distribution curve is not that flat and smooth which could mean that it is a gap graded soil. Moreover, the coefficient of curvature of 0.03, which is less than 0.1 further indicates a possible gap graded soil. Poorly graded or gap-graded soils have good drainage property and with a thick growth of vegetation, there will be less erosion from precipitation. Therefore, this dormant slide seems to be slightly stable from the field and laboratory observations. However, periodic monitoring of this slide is necessary.

(6) **Landslide ID: lsd02150299, SirukhapPakha:** This slide is located at an elevation of about 440m above sea level with N26°51'7.1" and E89°26'56.5". From the local source, this landslide occurred in the year 1994. It is a translational type of slide and has remained dormant until now with a thick growth of vegetation. The outcrop is highly weathered and thinly banded phyllite with thin quartz intrusions and has a strike of N30°W and dipping 25° NE. The length and width of the slide are approximately 165 m and 86 m respectively.

A road connecting Bhutan Power Corporation housing colony and Power Sub-station to Pasakha-Manitar road passes through the lower part of this slide. Due to road cutting, the stability of the landslide slope strength has been disturbed and this is mitigated by constructing about a 100 m length of retaining wall at the base of the slide along the road. But the retaining wall is quite old as there are grasses and small plants growing out from the wall. Creep is observed just above the road and there is a slight bulge on the retaining wall which has damaged and pushed a part of the wall by 20 cm as seen in Figure 17. Improperly maintained water drainage canal was also observed along the base of retaining wall, which could lead to water clogging and overflowing on the road surface that will further deteriorate road and slope conditions.

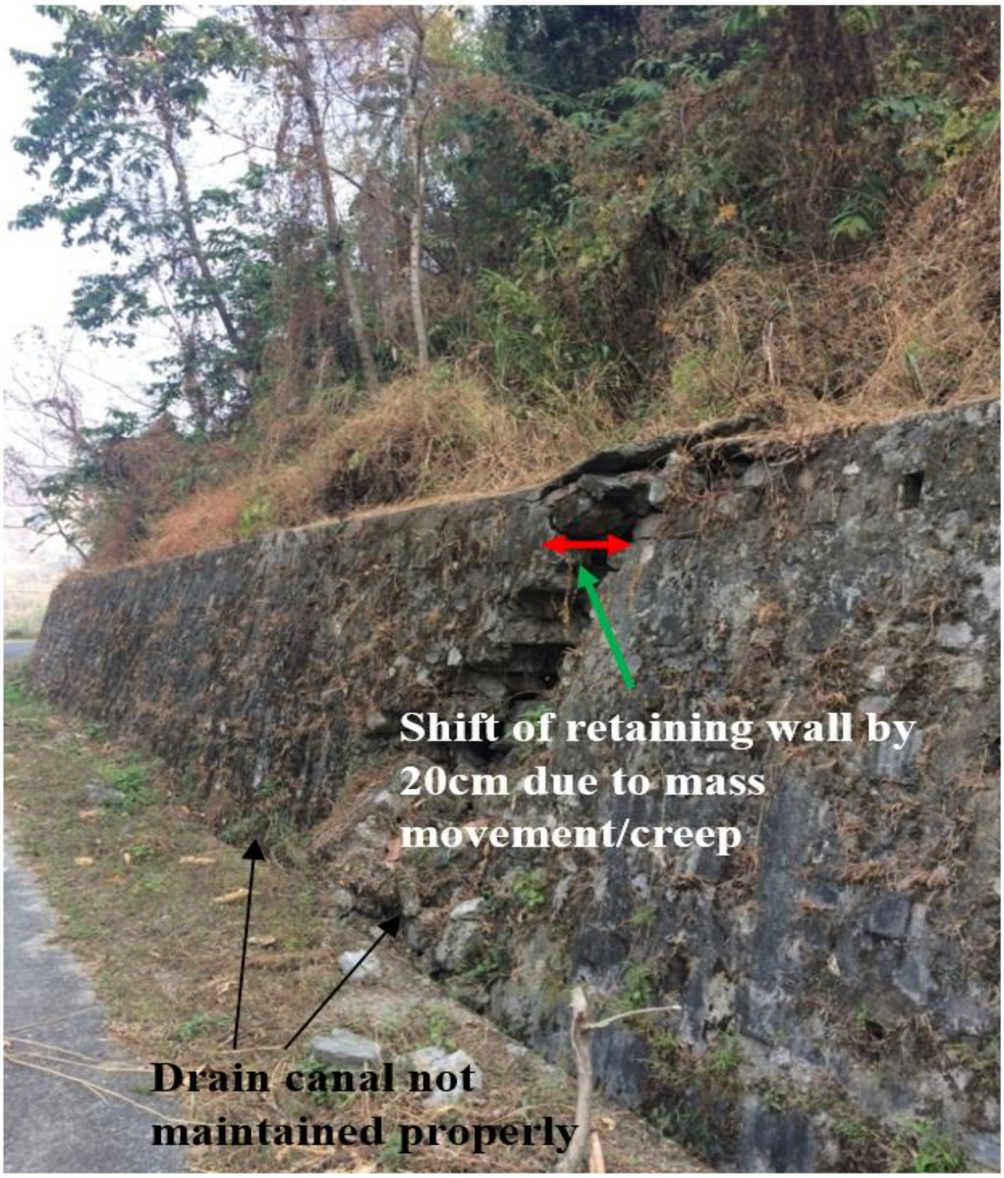


Figure 17. Displacement of retaining wall due to a mass movement.

A grab soil sample was collected from this slide at N26°51’13.5” and E89°26’50.8” and tested in the Geo-tech laboratory to understand the particle size distribution. From the grain size graph in Figure 23, the coefficient of uniformity and curvature were calculated as 24.28 and 0.16 respectively, which meets the conditions of a well-graded soil. Usually, well-graded soils have poorer drainage as compared to poorly graded soil, therefore, as explained above proper care should be taken to keep the drainage system free of obstruction.

4.3. GEOTECHNICAL LABORATORY ANALYSIS

To know the grain size distribution of materials from the prominent landslides, which are near river, roads and other infrastructures, six random soil samples namely JLS, LS-2(a), LS-2(b), LS-3, LS-6 and LS-7 were collected from different landslide locations. The test results of these samples are described below.

(1) **Grain size distribution:** Sieve analysis is a simple but proven method of separating bulk materials of all kinds into size fractions and to ascertain the particle size and distribution by weighing the single fractions. The grain size distribution graphs of the six soil samples collected from various landslides located close to river, roads and settlements in the study area are shown in Figs. 18 to 23.

From the grain size distribution graphs, respective Coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c) are calculated as shown in Table 5. These results are important to classify whether the soil samples collected are well graded, poorly graded or gap graded. A well-graded soil has particles of different sizes and has a good representation of all sizes, a poorly-graded soil does not have a good representation of all sizes of particles and a gap graded soil has an excess of deficiency of certain soil particle sizes. The soil gradation or classification is an important aspect in geotechnical engineering because it is an indicator of other engineering properties such as hydraulic conductivity.

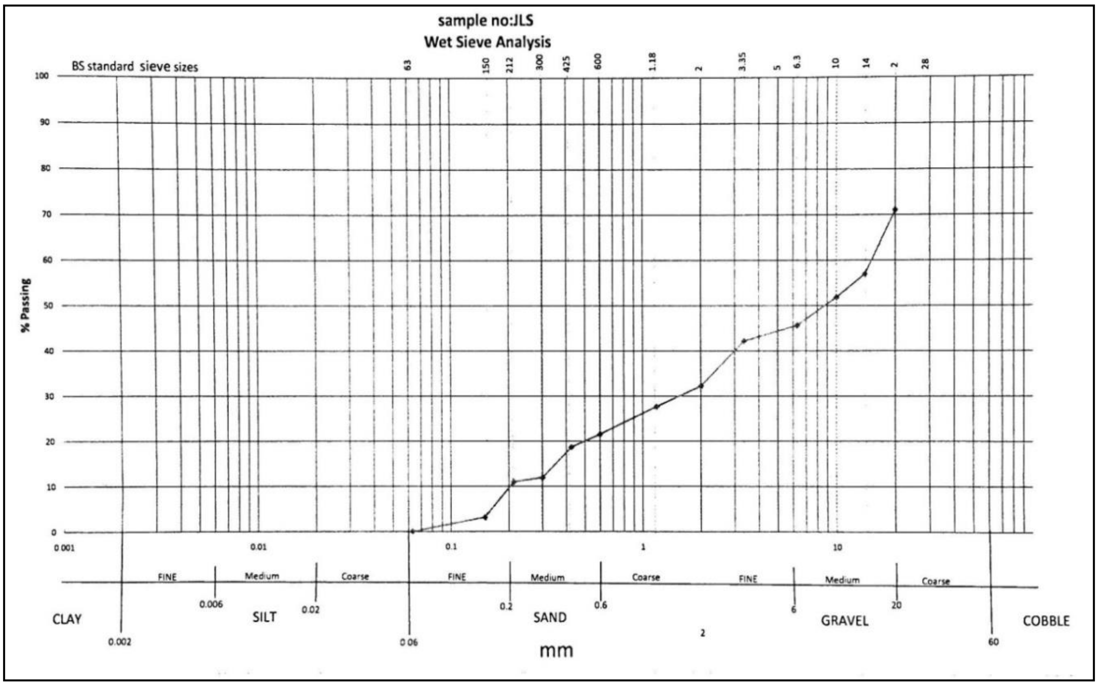


Figure 18. Grain size distribution of JLS soil sample collected from Jumja Slide.

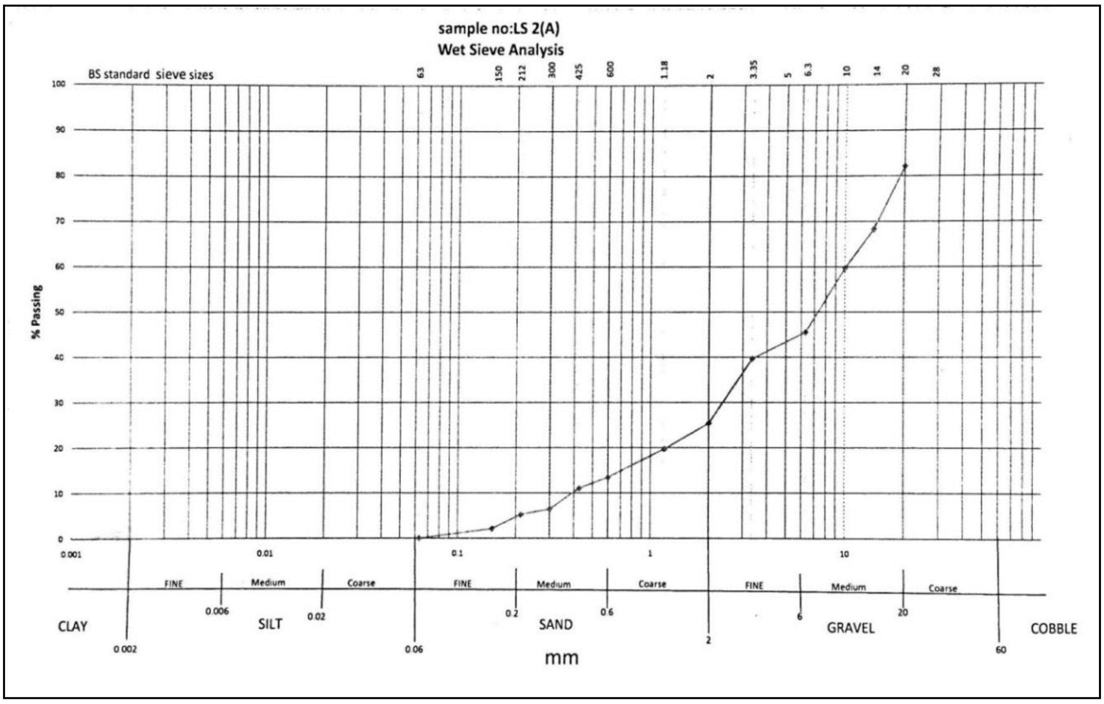


Figure 19. Grain size distribution of LS-2(a) sample collected from a Slide located about 500m north of BFAL industrial site.

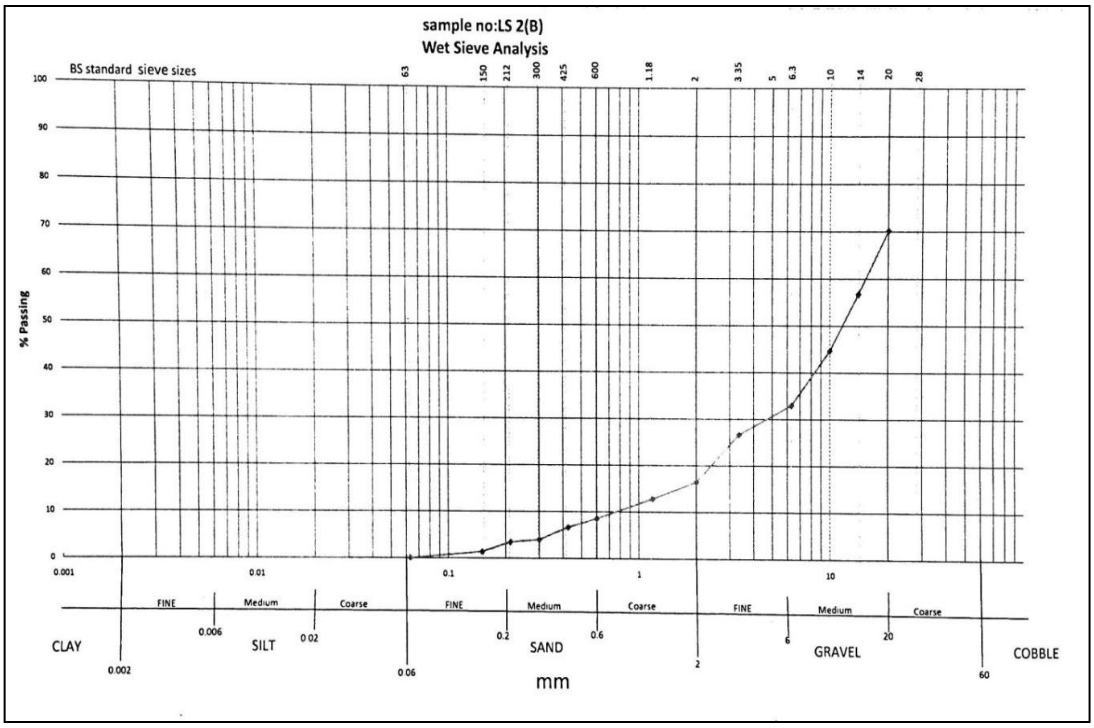


Figure 20. Grain size distribution of LS-2(b) sample collected from a Slide located about 500m north of BFAL industrial site.

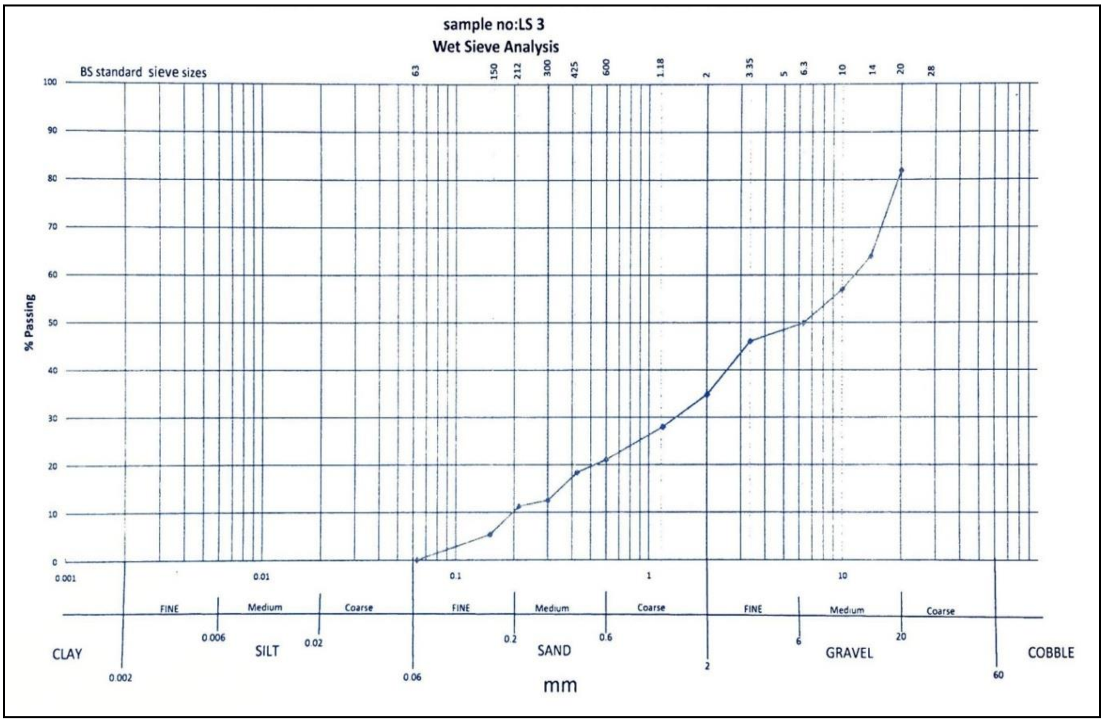


Figure 21. Grain size distribution of LS-3 sample collected from a Slide located opposite to BFAL Colony.

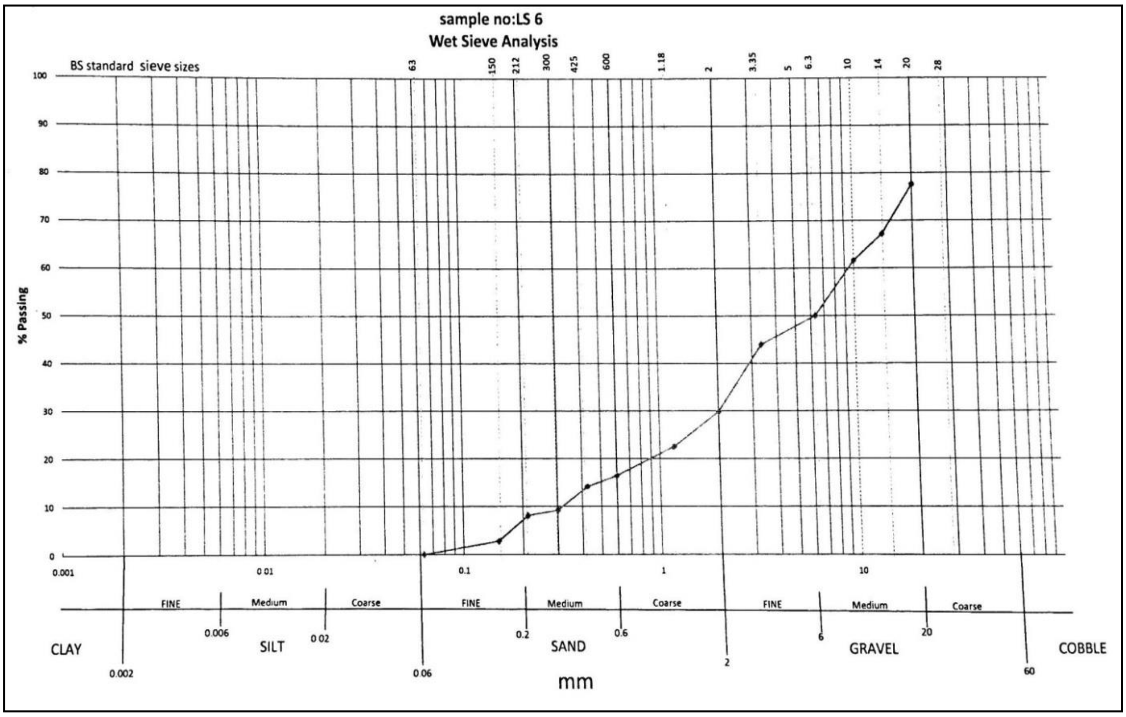


Figure 22. Grain size distribution of LS-6 sample collected from a Slide located at ThuloKhap.

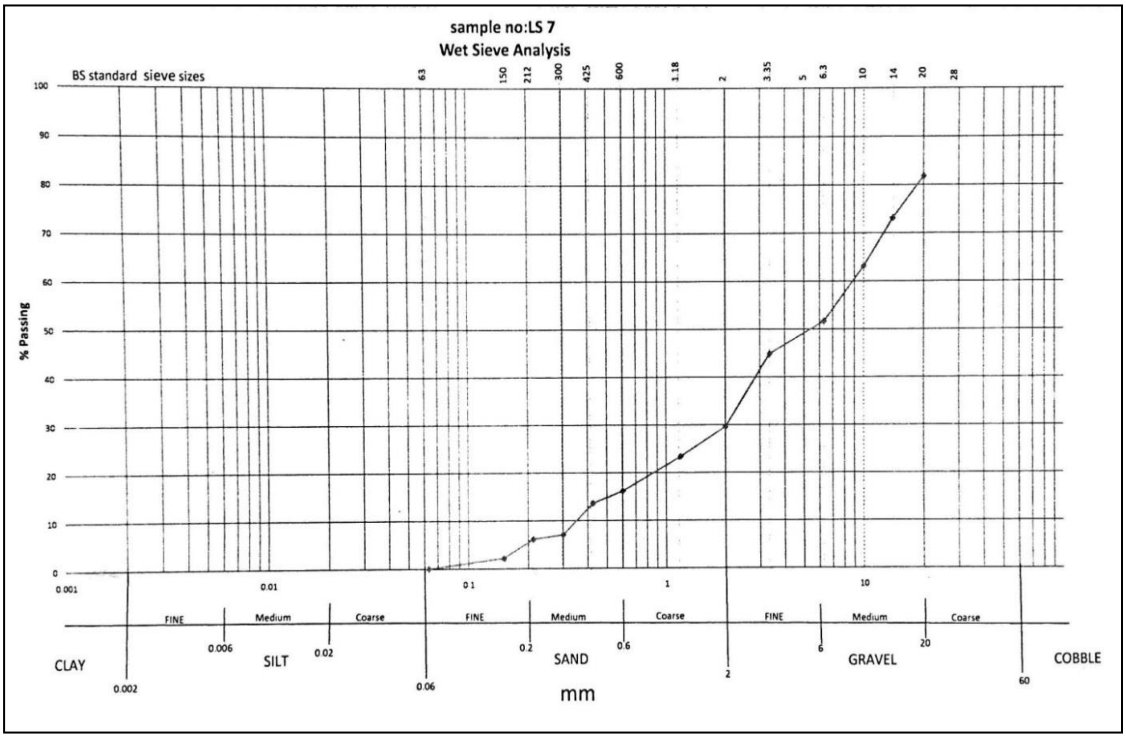


Figure 23. Grain size distribution of LS-7 sample collected from a Slide located in SerikhapPakha.

(2) The Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cc): The C_u and C_c values of the 6 soil sample results were deduced from the grain size distribution graphs (Figs. 18 to 23) and these results and soil gradation types are given in Table 5. The Coefficient of Uniformity value of less than 3 indicates uniform or poorly graded soil and the C_u value more than 5 means the soil is well graded. The Coefficient of Curvature value between 0.5 to 2 also means the soil is a well graded. Furthermore, the most well-graded soil will have grading curves that are mainly flat or slightly concave. When the value of C_c happens to be less than 0.1 it could possibly mean a gap graded soil.

Table 5. The coefficient of uniformity and curvatures of the 6 samples collected from different parts of Barsa watershed.

Sl No.	**Soil Sample name**	**Coefficient of uniformity $C_u = D_{60}/D_{10}$**	**Coefficient of curvature $C_c = (D_{30})^2/D_{60}*D_{10}$**	**Remarks on material**
1	JLS-Jumja Slide	80	0.028	Gap graded gravel with lesser fine materials
2	LS-2(a) (lsd02150055)	23.53	0.245	Well graded gravel with less fine materials
3	LS-2(b) (lsd02150055	21.3	0.99	Well graded gravel with less fine materials
4	LS-3 (lsd02150230)	55	0.03	Gap graded gravel with lesser fine materials
5	LS-6 (lsd02100061)	30.3	0.03	Gap graded gravel with lesser fine materials
6	LS-7 (lsd02150299)	24.28	0.16	Well graded gravel with less fine materials

4.4. APPLICATION OF GIS FOR INTEGRATED-GEO-HAZARDS AND RISK ASSESSMENT OF BARSA WATERSHED.

4.4.1. Landslide Hazards in Barsa watershed

In this stage, the Spatial Analysis of Landslide Hazards is generally expressed as likelihood or probability of occurrence of a given event of magnitude and computed using the above-mentioned techniques. Technically, we refer to this adverse condition as “the hazard”. Thus, this level of probabilistic in continues integers in raster format are reclassified into 3 main hazard levels (High, Moderate and Low) as shown in Plate-3 and Table 6.

The final compiled map showing different hazard zones was delineated by adapting standard colouring system. This system was created based on methodology developed by Garcia et al. (2003, 2005). In this study, three primary colors are chosen for delineating the different level of hazard zones: Red, Yellow and Blue as described below.

Table 6. Levels of hazard zones calculated based on output probabilistic and reclassified using standard methods.

Colour	Hazard Level	Explanation
(Red)	High	These colour represents the property, people are in potentially in high danger.
(Yellow)	Moderate	The properties are in the moderately high hazard but can be mitigated and improved.
(Blue)	Low	The infrastructures located in this area is in the safe zone or no hazard.

The Integrated Landslide Hazard Zonation Map of Barsa watershed is provided as Plate-3. The area coverage details by different hazard levels are shown in Table 7. The hazard level results indicate that the watershed is predominantly (~55 percent) exposed to moderately-high landslides hazard corresponding to 31.17 Km^2 of the watershed area; followed by ~30 percent indication of low hazard, which corresponds to 17.39 Km^2; and ~15 percent high hazard zone corresponding to 8.42 Km^{2}of the watershed area. The south-west part of this watershed as compared to other parts is shown as the highest concentration of high and moderately-high landslide hazard. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc. The socio-economic elements falling under different hazard levels in this watershed is provided in Table 8.

Table 7. Area coverage by different hazard levels in Barsa watershed.

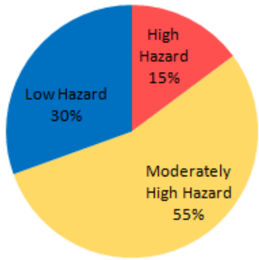
Hazard Level	Area Km^2	Area %	Graph in Area
High Hazard	8.42	14.52	
Moderately High Hazard	31.17	54.70	
Low Hazard	17.39	30.51	

Table 8. Socio-economic elements falling under different levels of landslide hazards in the Barsa watershed.

Hazard Level	Cultivation Land (Acres)	*Infrastructure (No.)	Population (No.)	BPC-High Tension Pilon
High	95.468	40	115	6
Medium	418.914	149	1990	27
Low	303.28	125	1778	35

**Number of houses taken in socio-economic survey.*

The NW part of the watershed hosts villages like Kamji, Suntolakha, Gogkhalaka, Rina, and Tsangling. The area is shown as low hazard area along the tributaries of Barsachu but indicated by high hazard around 300 m away from the Changlep village, as this place falls under grazing area of the communities (Figure 24).

However, most NW part of the watershed is indicated as a low hazard and therefore seems safe.

The SW part of the Barsa watershed, which is predominantly indicated as high and moderately high hazard zone (Figure 25) is occupied by several landslides along ThuloThotney (Kamji Watershed), locally called KalimatiPairo, a tributary of Barsa Chu/river. Several active landslides were also observed in this part. For example, some of the active landslides were found at Pasakha area, above the BFAL colony and at the left side of the Barsa river.

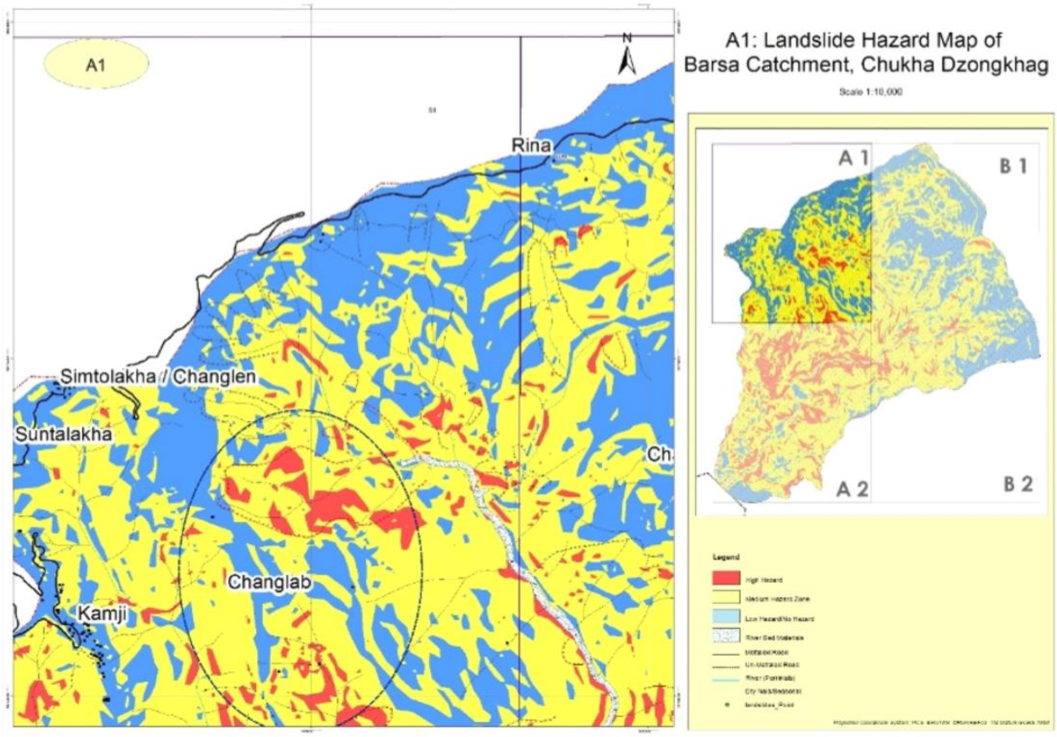


Figure 24. Hazard levels of NW part of Barsa watershed.

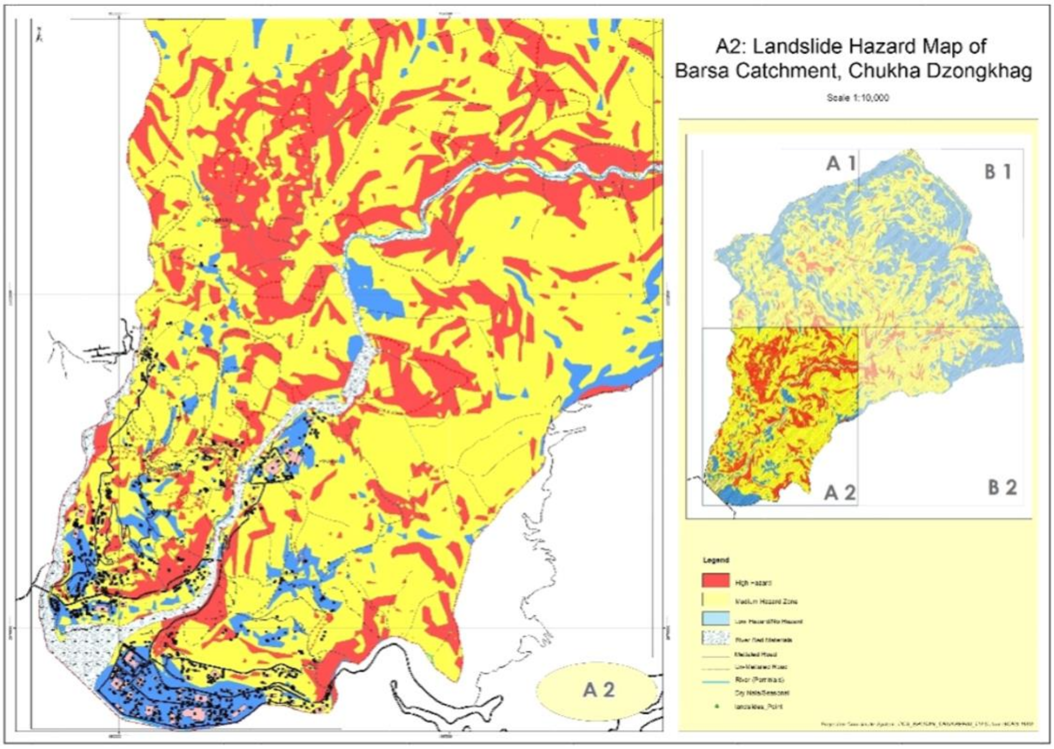


Figure 25. Hazard levels in the SW part of the Barsa watershed.

4.4.2. Vulnerability and Risks in Barsa watershed.

The different levels of vulnerability of socio-economic elements to landslide hazard, and risk from landslide hazard to socio-economic elements in Barsa watershed are shown in Vulnerability and Risk Map in Plate-4 and Plate-5, respectively. The area coverage details by different vulnerability classes are shown in Table 9. The vulnerability class results indicate that the majority (~99 percent) of socio-economic elements are located with low vulnerable areas to landslide hazard, corresponding to 52.63 Km^2 of the watershed area; followed by ~7 percent within moderately low vulnerable areas, which corresponds to 4.08 Km^2; ~2.5 percent within moderately high vulnerable areas, corresponding to 1.24 Km^2; and < 1 percent within high vulnerable areas that correspond to 0.39 $Km^2$of the watershed area (Figure 26). The south-west part of this watershed as compared to other parts is shown as more vulnerable to landslide hazard. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc. The socio-economic elements falling under different vulnerability classes in this watershed is provided in Table 10.

Table 9. Area coverage by different vulnerability classes in Barsa watershed

Vulnerable Class	Area (Sq.Km)	Area (%)
Low Vulnerable Area	52.63	90.22
Moderately Low Vulnerable	4.08	6.99
Moderately High Vulnerable	1.24	2.12
High Vulnerable Area	0.39	0.67

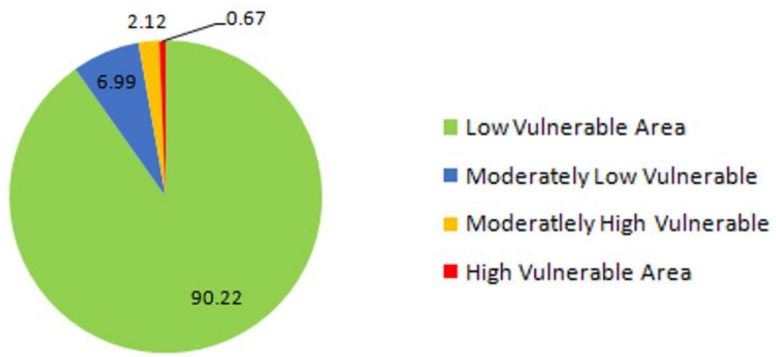


Figure 26. Vulnerable areas (in percent) to landslide hazard within Barsa watershed.

Table 10. Socio-economic elements falling under different vulnerability classes in the Barsa watershed.

	Cultivation Land (Acres)	*Infrastructure (No.)	Population (No.)	BPC-High Tension PL
1. Low Vulnerable Area	277.89	21	402	1
2. Moderately Low Vulnerable	348.58	87	1282	7
3. Moderately High Vulnerable	131.48	68	1223	7
4. High Vulnerable Area	54.76	84	967	1

**Number of houses taken in socio-economic survey.*

The area coverage details by different risk levels are shown in Table 11. The risks results (Figure 27) indicate that ~96 percent of the watershed area is exposed to low or no risk of landslide hazard, corresponding to 56.27 Km^2, ~2 percent of the area to moderately low risk corresponding to 1.41 $Km^2$of the area, 2.41 percent to moderately high corresponding to 1.41 $Km^2$of the area, and <1 percent to high risk, which correspond to <1 $Km^2$of the area. The south-west part of this watershed as compared to other part is more exposed to landslide risks. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc. The socio-economic elements falling under different risk levels in this watershed is provided in Table 12. A cultivation land of 29.15 acres, 38 houses and 174 people (as counted during the socio-economic survey); a cultivation land of 44.06 acres, 57 houses, 1062 people, 1 BPC high tension pylon; 144.55 acres of cultivation land, 70 houses, 1546 people and 8 BPC high tension pylon are indicated to be located within high-risk area, moderately high risk, and moderately low-risk area, respectively.

Table 11. Area coverage by different risk levels in Barsa watershed.

Risk Class	Area (Sq. Km)	Risk (%)
Low/ No Risk Area	56.27	96.46
Moderately Low Risk	1.41	2.41
Moderately High Risk	0.48	0.82
High Risk	0.17	0.30

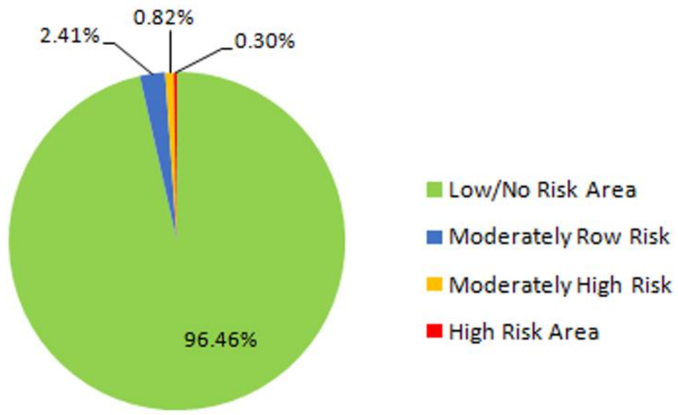


Figure 27. Risk areas (in percent) to landslide hazard within Barsa watershed.

Table 12. Socio-economic elements falling under different risk levels in the Barsa watershed.

Risk Level	Cultivation Land (Acres)	*Infrastructure (No.)	Population (No.)	BPC-High Tension Pylon
Low/No Risk Area	595.39	95	1101	7
Moderately Low Risk	144.55	70	1546	8
Moderately High Risk	44.06	57	1062	1
High Risk	29.15	38	174	0

**Number of houses taken in socio-economic survey.*

4.4.3. Validation

GIGO (**garbage** in, **garbage out**) is a concept common to computer science and mathematics: the outputs must be authenticated and check the level accuracy. In the process, the result is evaluated using receiver operating characteristic (ROC) analysis. The prediction availability was found to be 80.00 % indicating an acceptable susceptibility map obtained from GIS-based bivariate statistical model (Figure 28).

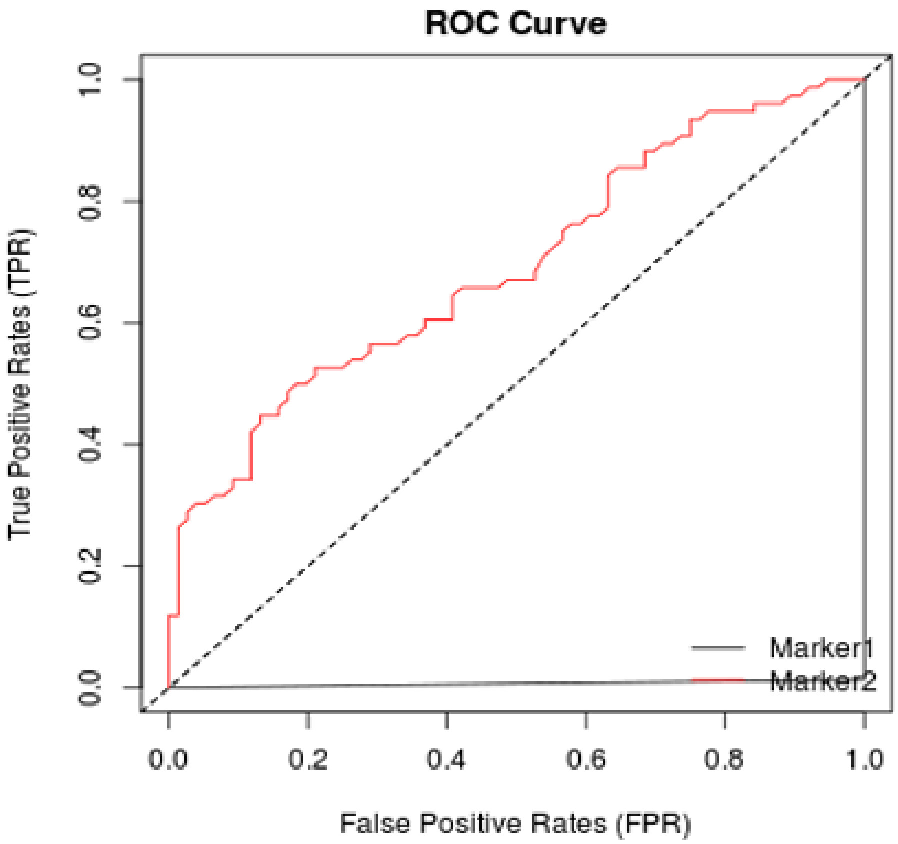


Figure 28. Showing a receiver operating characteristic analysis curve in red colour, which represents the accuracy level of analysis and the output is 80.00 % accurate.

5. CONCLUSIONS AND RECOMMENDATIONS

Generally, mass movement control tends to be both expensive and far from simple. It is not possible to come out with any method to prevent mass movement in a very large place like Barsa Watershed area. However, in many situations, there are actions that we can be taken to reduce or mitigate its damaging effects on people and infrastructures. In slope failures of smaller dimensions, some geotechnical methods like constructing retaining walls, drainage, bio-engineering and rock bolting could be useful to strengthen the slope stability.

Rather, some intellectual arrangement can be made, by setting up landslide monitoring system, an early warning system to alert people, that facilitate the timely and accurate prediction of mass wasting and produce more accurate integrated-geo hazards maps. But, setting up monitoring and early warning system has a limitation in mountainous and thick vegetated area like Barsa watershed. Therefore, its applicability must be properly studied before its implementation.

The following conclusions and recommendations are made based on this study in Barsa watershed:

5.1. RECOMMENDATIONS FOR SIX CRITICAL LANDSLIDES

Six critical landslides are identified and remedial or mitigation measures to reduce risks are proposed as under:

(1) Jumja Slide- Inventory ID: lsd02100141

As per the observation made, the probability of causing this slide is from heavy rainfall, steep slope angle with highly fractured and jointed outcrops, planer failure. Based upon these causative factor's observations, the following remedial measures are proposed:

a. Construct drainage from the upper portion of the slide to divert water runoff from the rain.
b. There is a slight bulge on the existing retaining wall due to pressure exerted by the debris flow. Therefore, there is a need to build a better retaining

wall along the road to contain the increasing pressure from debris movement.

(2) Landslide above BFAL Factory (about 500mNorth of BFAL industry)- Inventory ID: lsd02100055

This slide is caused by heavy rainfall and toe cutting action from the flooded Barsa river. Though this slide is quite far away from the BFAL industrial area, it is quite massive and active and will contribute a significant quantity of debris downstream during the flood. The remedial measures proposed for this slide are:

a. Construct retaining wall along the toe of the slide to contain debris and strengthen the slope toe.
b. Plantation of plants and trees on the slide face will be good to hold and prevent soil erosion.

(3) Landslide Inventory ID: lsd02150230 (LS-3), Opposite BFAL colony

This slide is caused by heavy precipitation, road cutting and toe erosion from the flooded Barsa river. This slide is located close and opposite to the BFAL housing colony and Barsa river runs through them. The proposed remedial measures for this landslide are:

a. A section of existing flood protection wall along the base of the landslide is badly damaged and may not be effective enough to protect the slope from the future flood (Figure 14). A substantial amount of mass has been removed from that damaged wall due to toe cutting by the river. Moreover, there are disturbances along the gabion wall too. Therefore, a better and stronger flood protection wall should be built along the existing wall.

b. The ongoing flood protection wall construction on the right bank of Barsa river/river beside BFAL housing colony might alter the course of Barsa river towards the left bank and this will increase water pressure along the slope below the road (Figure 15). This force could further increase toe cutting erosion and destabilize the slope which will reduce the stability of the road. Construction of river protection wall along this stretch of slope on the left bank of Barsa river would prove useful.

(4) lsd02100290 and lsd02150253- Barsa/Gurungdara

About 200 m NE of Pasakha Power Substation, below the house of Buddhi Man Rai, on the right bank of Barsa river, a fresh toe cut by river Barsa is observed (Figure 29). River protection wall along the base of this toe cut area is necessary to prevent further aggravation of toe cutting and to counter re-activation of dormant landslide above. And, a BPS tower located on the top of the landslide crown. Just below the toe cut area, there exists a stretch of river protection wall, of which some sections are badly damaged, and these disturbed parts need to be replaced by new protection walls.

Figure 29. Showing the fresh toe cutting by Barsa river.

The landslide-lsd02150253 seems to indicate there was creep movement in past years and has remained dormant in later years (Figure 16). Therefore, there are chances of landslide reactivation from heavy rainfall and toe cutting erosion as it lies close to the right bank of Barsa river. It is not advisable to construct any structure nearby the crown of the slide or within the dormant slide as there are indications of subsidence and creep movement.

(5) BPC substation at Barsa

The BPC transmission station in Pasakha is located quite close to the right bank of Barsa river. There exists a long stretch of old and badly damaged gabion wall built along the base of the power substation to countermeasure flooding from Barsa river (Figure 30). This existing damaged wall might not be effective enough to protect the substation from the flood. Therefore, a better river training wall is required over the existing wall to protect the station from flood and stabilize the slope as well.

Figure 30. Pasakha transmission station with disturbed gabion wall along the right bank of the river.

(6) Left bank of Barsa, BFAL Factory area

Along the left bank of river Barsa, there exist a long gabion wall, which was built to protect the industrial area from Barsa river flood (Figure 31). These old lengthy walls are now badly damaged through the passage of time as seen in the inset photo below and might not be too effective flood protection in the future. Therefore, new and better flood protection structures along the existing damaged walls are necessary to prevent toe erosion from Barsa river.

Figure 31. Photo shows damaged gabion walls along the left bank of Barsa river below the industries.

5.2. RECOMMENDATIONS ON LANDSLIDE HAZARD AND RISK ASSESSMENT USING GIS

(1) The landslide hazard map or results indicate that the watershed is predominantly (~55 percent) occupied by moderately high landslide hazard, corresponding to 31.17 Km^2 of the watershed area; followed by ~30 percent indication of low hazard, which corresponds to 17.39 Km^2; and ~15 percent high hazard zone corresponding to 8.42 Km^2 of the watershed area. The south-west part of this watershed as compared to other parts is indicated as the highest concentration of high and moderately-high landslide hazard. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc.

(2) Proper geotechnical or engineering geological studies are recommended before constructing any infrastructures in the medium and high hazard areas. For now, the low or no hazard areas seem safe for construction, but these areas are recommended to be monitored at least on yearly basis and verified by professionals before any developmental planning to ascertain that the geological, hydrological, topographical and other ground conditions have not

varied significantly.

(3) The vulnerability map results indicate that the majority (~90 percent) of socio-economic elements are located within low vulnerable areas to landslide hazard, corresponding to 52.63 Km^2 of the watershed area; followed by ~7 percent within moderately-low vulnerable areas, which corresponds to 4.08 Km^2; ~2.12 percent within moderately-high vulnerable areas, corresponding to 1.24 Km^2 ; and < 1 percent within highly vulnerable areas that correspond to 0.39 Km^2 of the watershed area. The southwest part of this watershed as compared to other parts is shown as more vulnerable to landslide hazard. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc.

(4) The landslide risk map results indicate that ~96 percent of the watershed area is exposed to low or no risk of landslide hazard, corresponding to 56.27 Km^2; ~2.4 percent of the area to moderately-low risk corresponding to 1.41 Km^2 < 1 percent to moderately high corresponding to 0.48 Km^2; and 0.3 percent to high risk, which correspond to 0.17 Km^2 of the watershed area. The south-west part of this watershed as compared to other part is more exposed to landslide risks. This coincides with the highest concentration of the socio-economic elements such as the Pasakha Industrial estate and industrial colonies etc. A cultivation land of 29.15 acres, 38 houses and 174 people (as counted during the socio-economic survey); a cultivation land of 44.06 acres, 57 houses, 1062 people, 1 BPC high tension pylon; 144.55 acres of cultivation land, 70 houses, 1546 people and 8 BPC high tension pylon are indicated to be located within high-risk area, moderately high risk, and moderately low-risk area, respectively.

(5) This study recommends for further detailed studies such as engineering geological or geotechnical and hydrological studies (along the Barsa river) to be carried out on priority a basis to assess the risk in areas designated as high-risk areas to come up with scientific-based sustainable remedial or mitigation measures to reduce risks.

(6) Finally, this study also recommends carrying out a detailed study of the six critical landslide areas identified in this study to come up with scientific-based sustainable remedial or mitigation measures to reduce risks.

6. ACKNOWLEDGEMENT

The authors are very grateful to Mr Phuntsho Tobgay, Director General; Mr Ugyen Wangda, Chief Geologist of Geological Survey Division; and Mr Tashi Tenzin, Project Manager of DGM for their leadership, support, guidance and feedback provided during fieldwork and report and map preparation. The support and guidance rendered by NAPA-II Project Manager Ms Sonam Lhaden Khandu; current Project Support Officer Mr Netra Sharma and all previous Project Support Officers; Mr Ugyen Dorji; NAPA-II focal person from UNDP; current and past Project Directors from NEC; Board Chair and Members; and all other people who were directly or indirectly involved in this project are well appreciated. Our gratitude also goes to Mr Netra Sharma for improving this report by proof-reading the final draft and providing valuable comments. We also thank Phuntsholing Thromdey, Watershed Management Division (WMD), Local Government, National Land Commission, National Center for Hydrology and Meteorology, Management of Pasakha industrial estate, and all government agencies, NGOs, private firms and people who have provided help during fieldwork and feedback during the National Workshop held on this project at Phuentsholing from 13-14 November 2017. Lastly, on behalf of DGM, we sincerely extend our gratitude to LDCF-GEF and UNDP for providing funding and technical support, without which, this study would not have been achieved.

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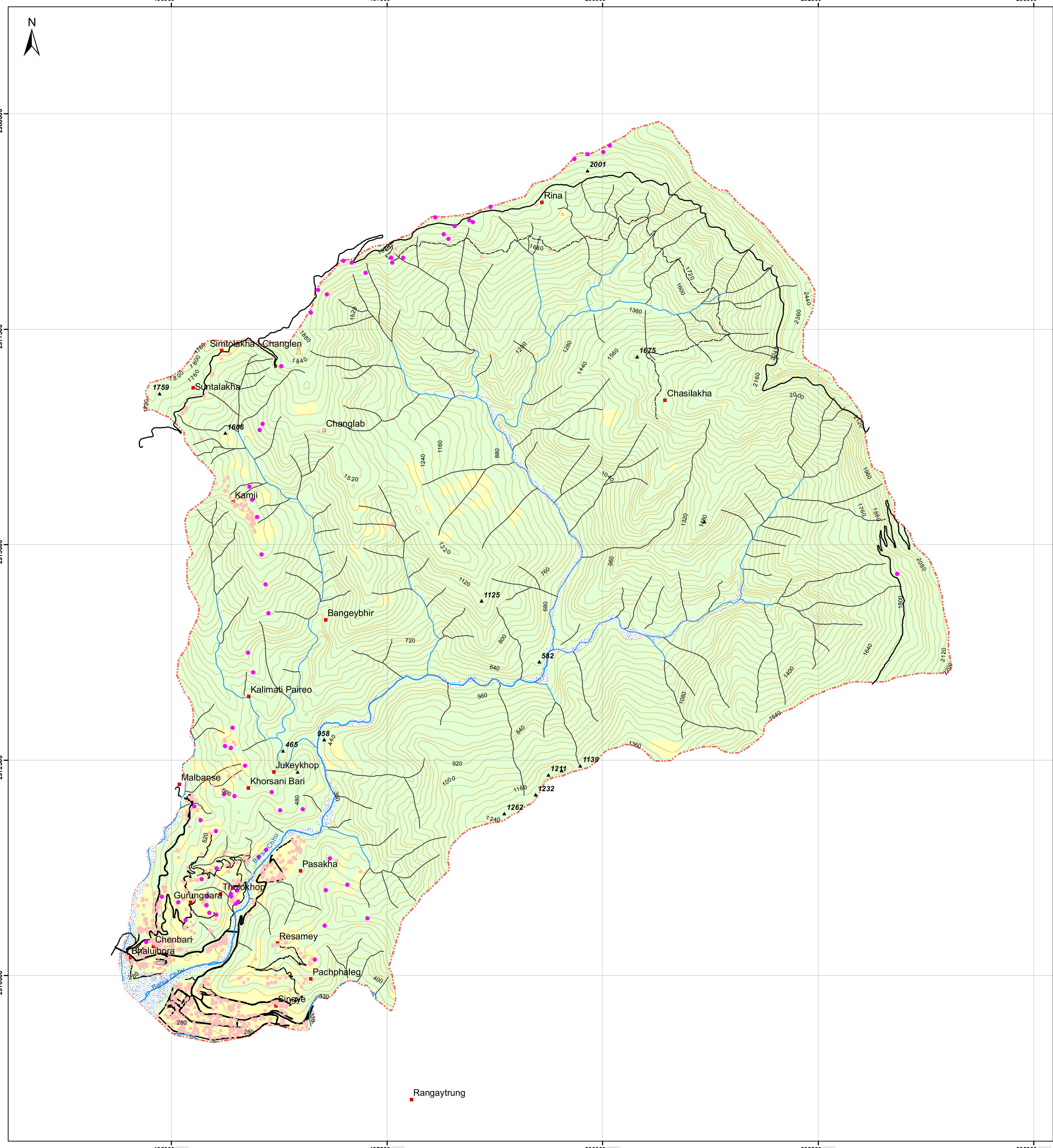
Report printed at Kuensel Corporation Ltd., Thimphu: Bhutan

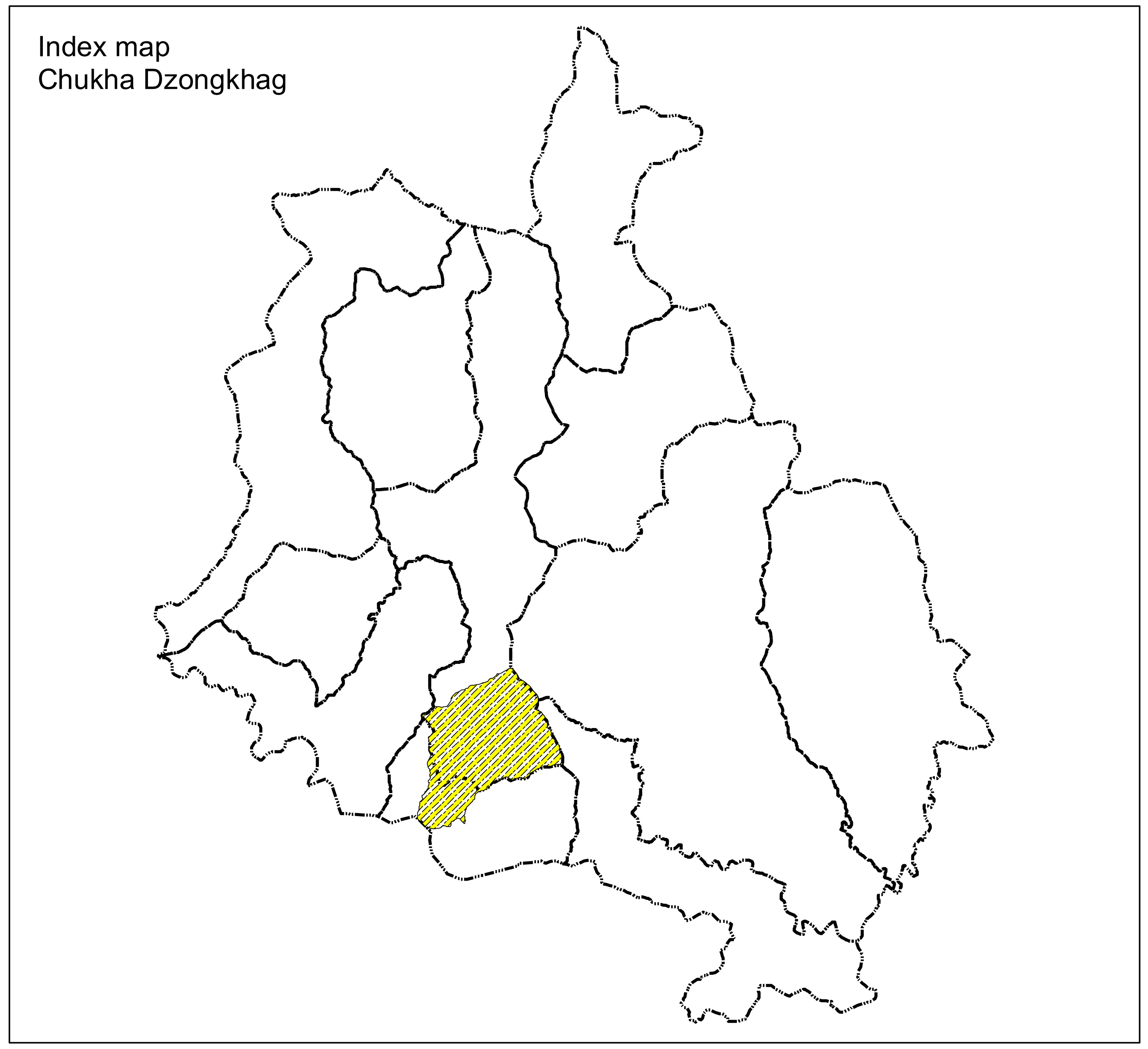
Plate -1

Plate:1 Topographical Map of Barsa Catchment, Chukha Dzongkhag

Scale 1:25,000

0 600 1,200 2,400 Meters





Legend

River Bed Materials	Spot Height (M)
Culvated Land	Houses
Forest	Important Place Names
Metalled Road	BPC Tower/Pylon
Un-Metalled Road	Telecom-Tower
Contour Interval 20 m	
River (Perennial)	
River (Perennial Tributaries)	
Dry Nala/Seasonal	

Bhutan NAPA-2 Project,
Department of Geology and Mines, 2016-2017

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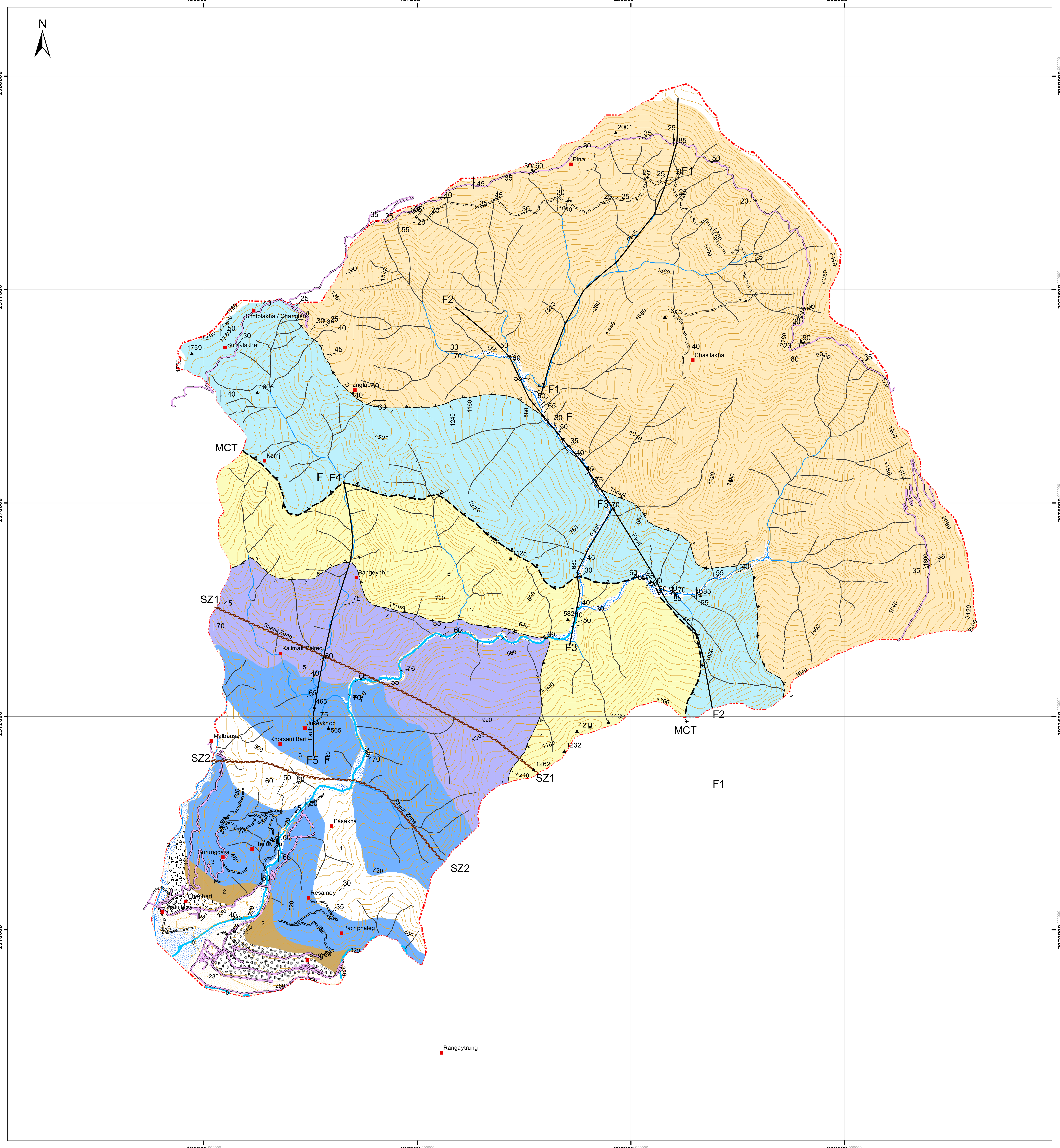
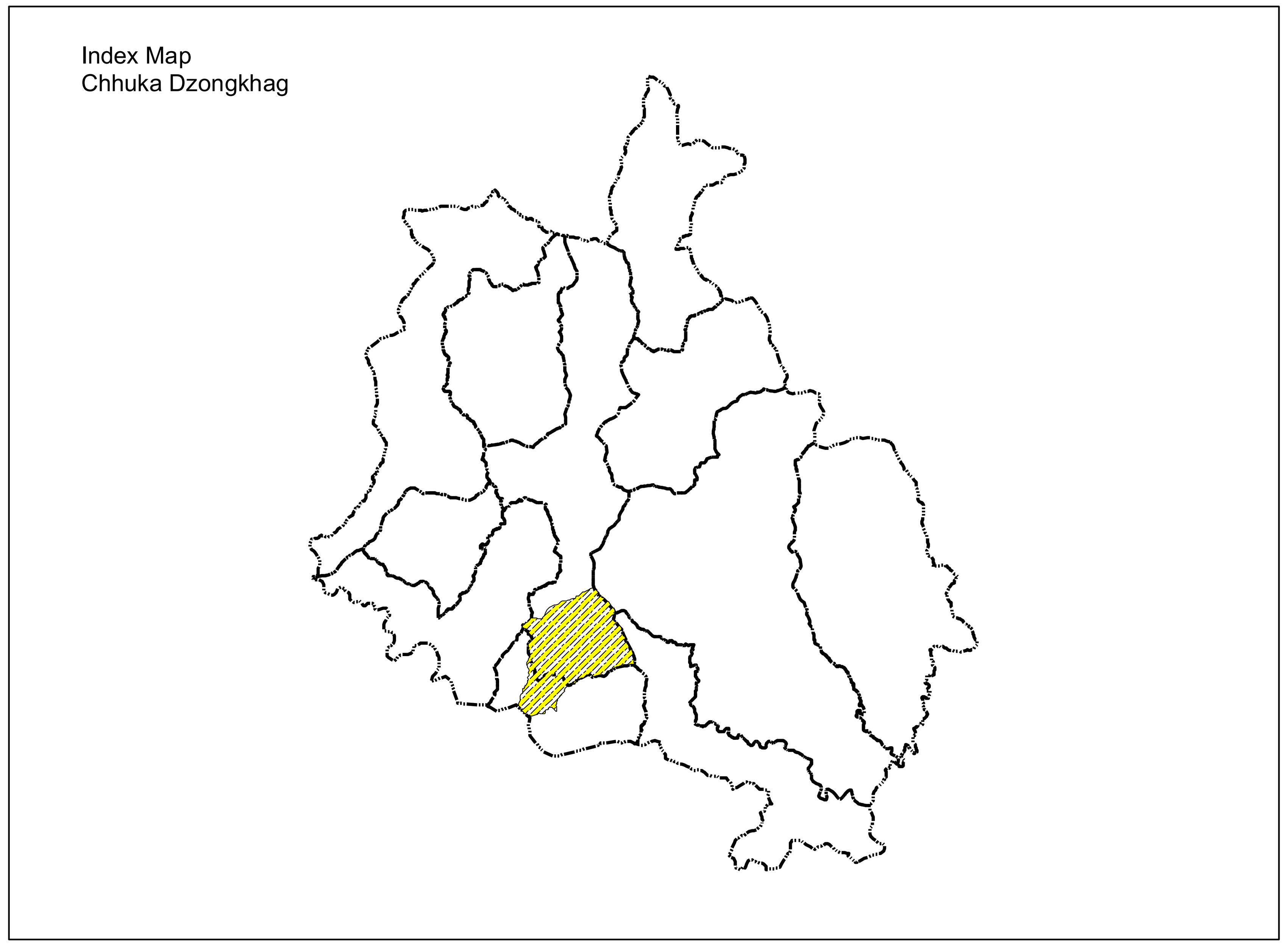
Projection Coordinate System: PCS_BHUTAN_DRUKREF03_TM Datum GCRS 1980

Plate:2 Geological and Structural Map of Barsa Catchment, Chukha Dzongkhag



Scale 1:25,000

0 625 1,250 2,500 Meters



Legend

Lithology

- 8, Biotite gneiss migmatite and Augen gneiss
- 7, Garnetiferous mica Schist
- 6, Massive white quartzite with lenses of grey quartzite and phyllite
- 5, Light grey quartzite and phyllite
- 4, Greenish grey phyllite with lenses of ironstone
- 3, Light pink calcarious quartzite
- 2, Dark grey phyllite
- 1, Alluvium
- 0, River Materials

- Strike and Dip of Bedding
- Strike and Dip of Foliation
- Joint

- Fault (F1, F2, F3, F4)
- Main Central Thrust (MCT)
- Shear Zone (SZ1, SZ2)
- Thrust
- Mettaled Road
- Un-Mettaled Road
- River (Perrinials)
- Dry Nala/Seasonal

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Department of Geology and Mines, 2016-2017

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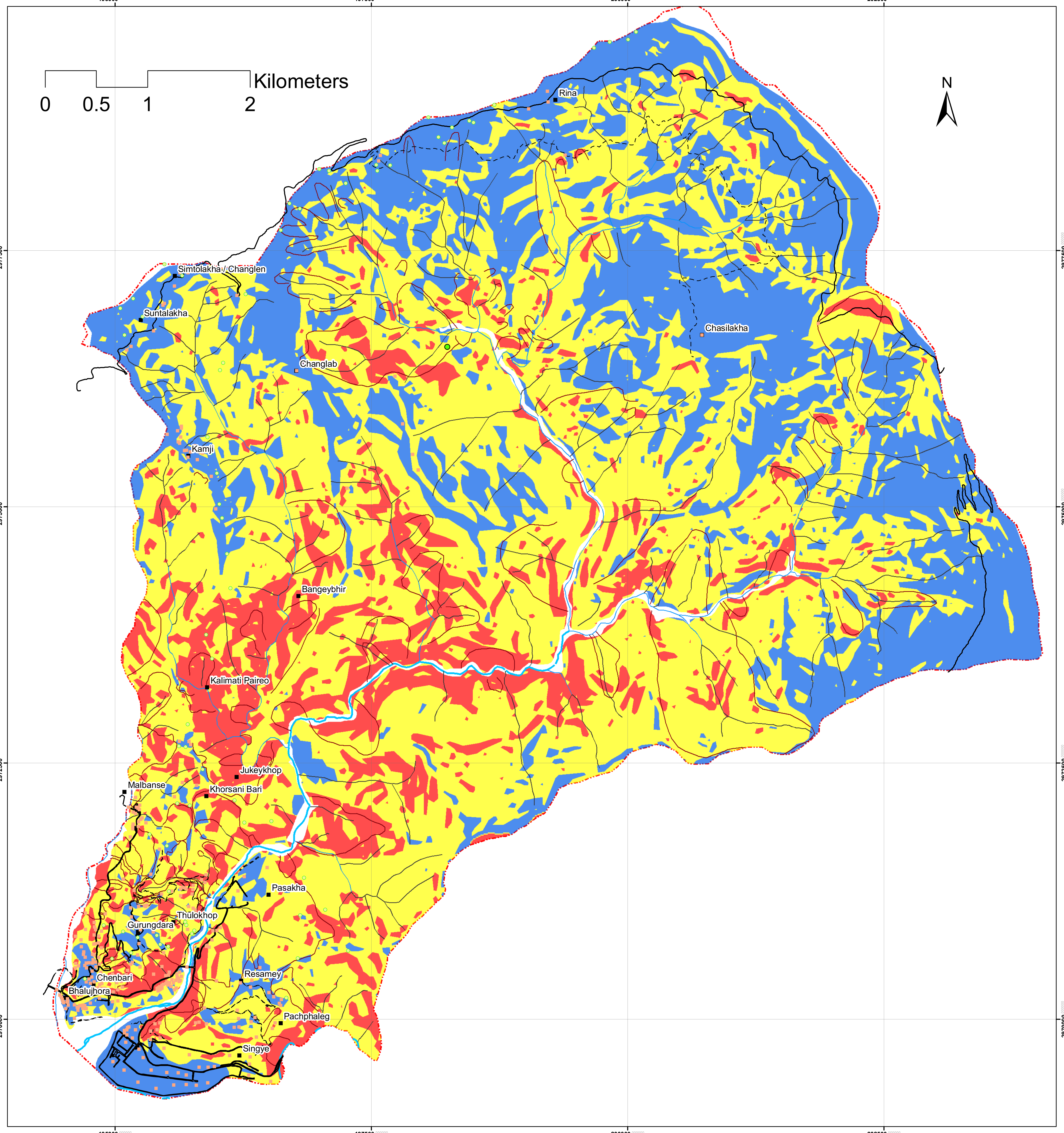
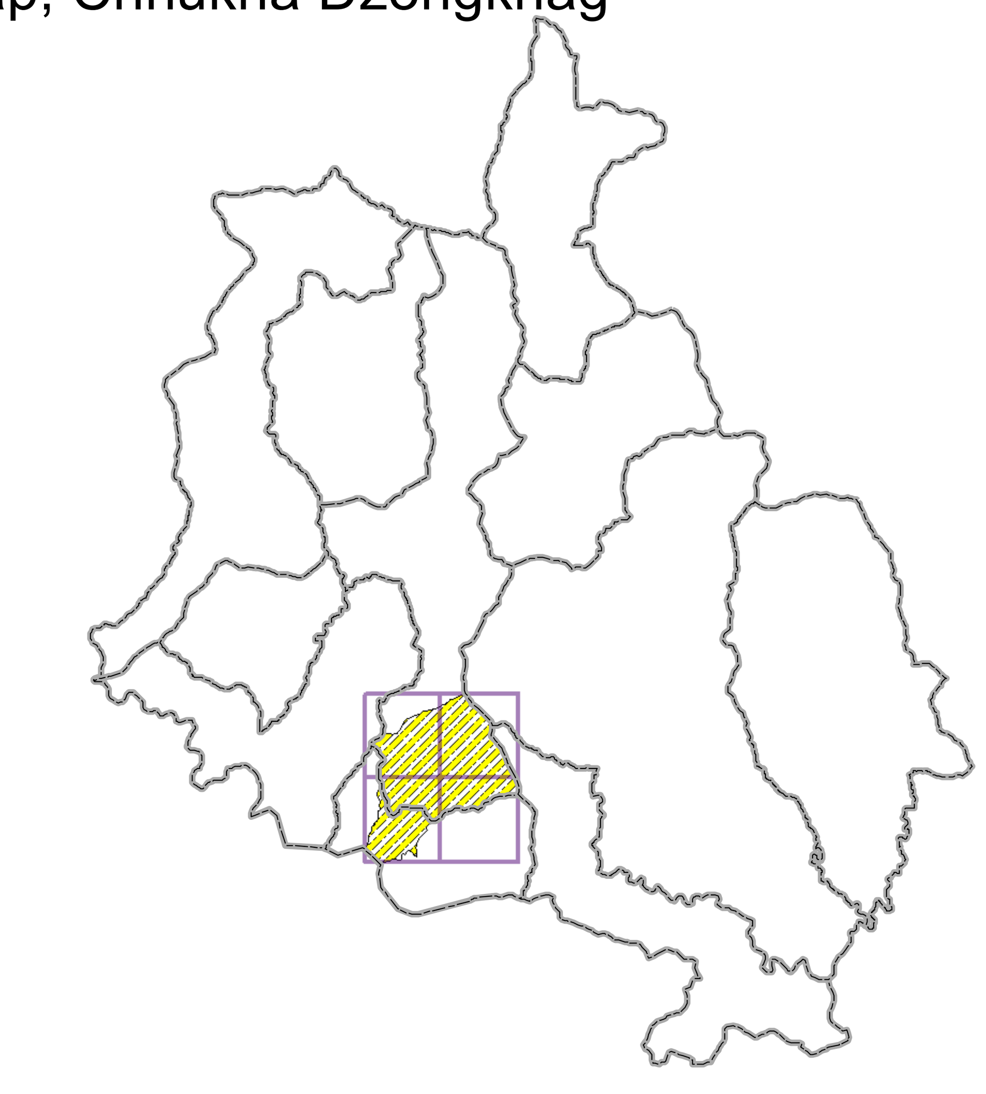


Plate:3 Integrated Hazard Zonation Map of Barsa Catchment, Chhukha Dzongkhag

Scale 1:20,000

Index Map, Chhukha Dzongkhag



Summary of Hazard Levels with area

Hazard level	Area_SqKm	Area%
High Hazard Zone	8.42	14.78
Moderately High Hazard Zone	31.17	54.70
Low Hazard/ No Hazard Zone	17.39	30.51

Legend

- **High Hazard**
- **Moderatly Hazard Zone**
- **Low Hazard/No Hazard**
- River Bed Materials
- Mettaled Road
- Un-Mettaled Road
- River (Perrinials)
- Dry Nala/Seasonal
- Socio Economic Study Location
- BPC-Electric High Tension Power Lines

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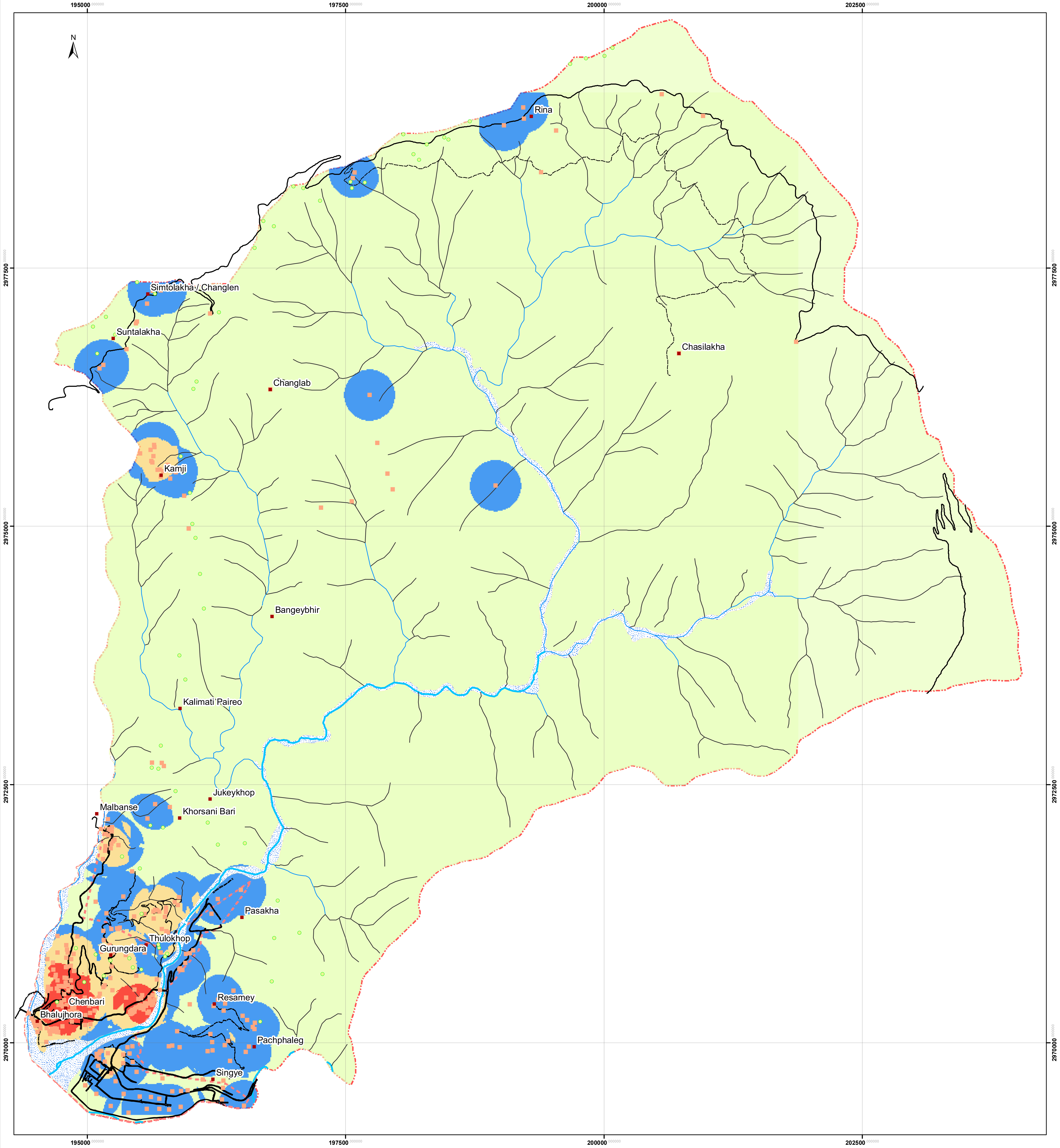
Plate:4 Vulnerability Map of Barsa Catchment, Chhukha Dzongkhag

Scale 1:20,000



Index Map, Chhukha Dzongkhag

Vulnerable Class	Area_ Sq.Km	Area %
Low Vulnerable Area	52.63	90.22
Moderately Low Vulnerable	4.08	6.99
Moderately High Vulnerable	1.24	2.12
High Vulnerable Area	0.39	0.67

Legend

- Very Low Vulnerable Area
- Low Vulnerable Area
- Moderatly High Vulnerable Area
- High Vulnerable Area
- River Bed Materials
- Mettaled Road
- Un-Mettaled Road
- River (Perrinials)
- Dry Nala/Seasonal
- Socio Economic Study Location
- BPC-Electric High Tension Power Lines

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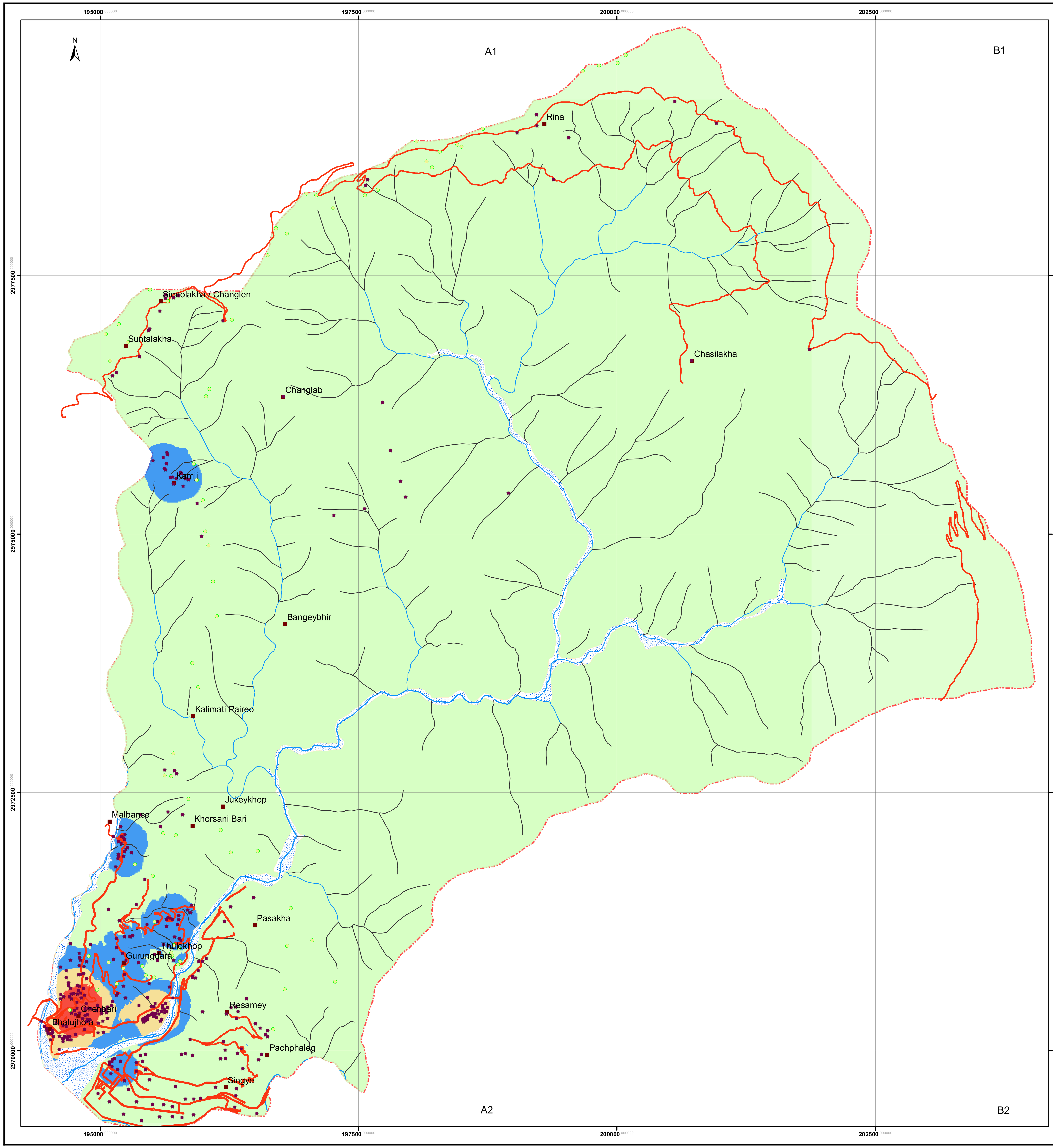
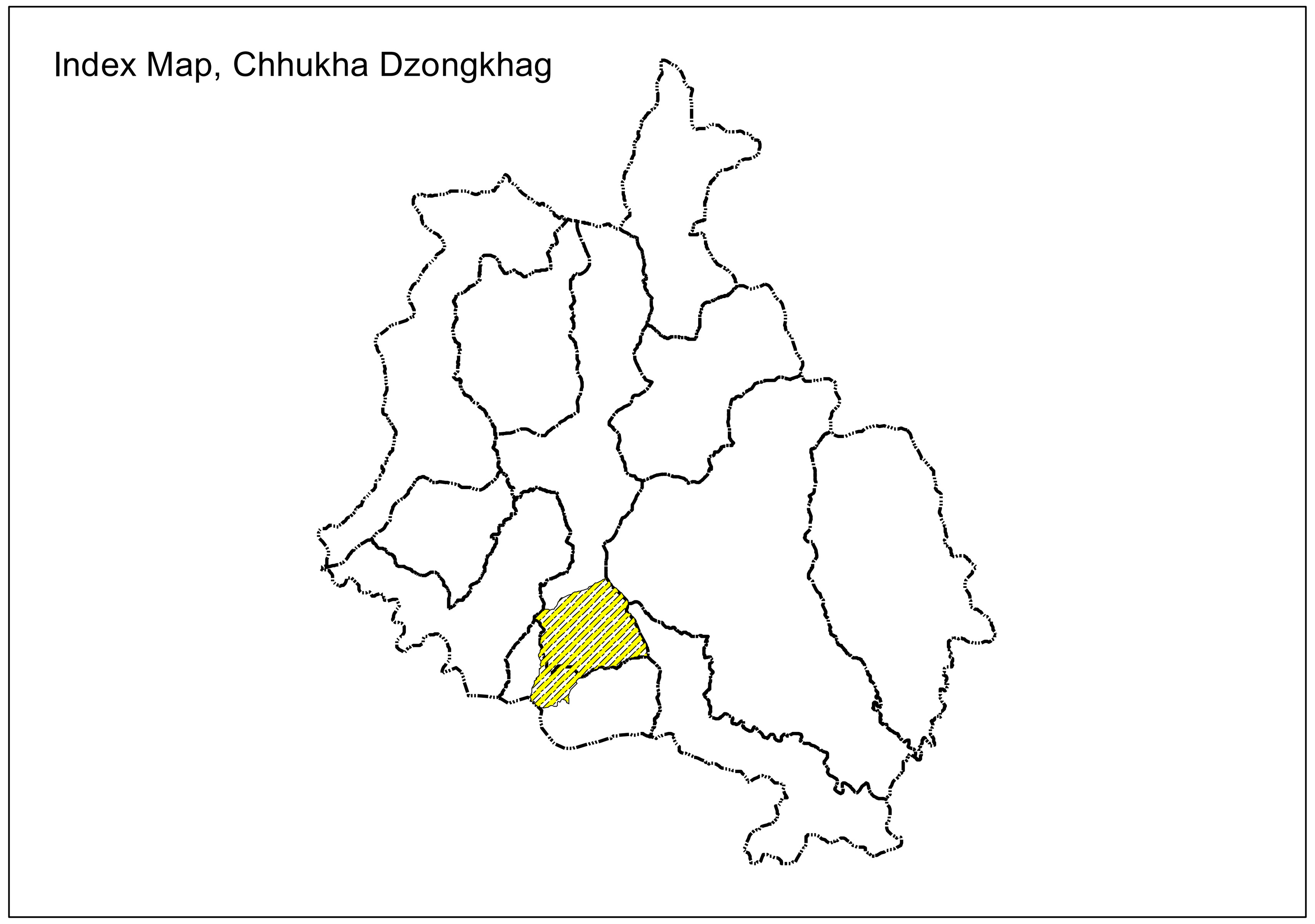
Plate:5 Risk Assessment Map of Barsa Catchment, Chukha Dzongkhag

Scale 1:20,000





Risk Class	Area Sq.Km	Risk %
Low/No Risk Area	56.27	96.46
Moderately Low Risk	1.41	2.41
Moderately High Risk	0.48	0.82
High Risk	0.17	0.30

Legend

- **Low/No Risk Area**
- **Moderately Low Risk**
- **Moderately High Risk**
- **High Risk**
- River Bed Materials
- Mettaled Road
- Un-Mettaled Road
- River (Perrinials)
- Dry Nala/Seasonal
- Socio Economic Study Location
- BPC-Electric High Tension Power Lines

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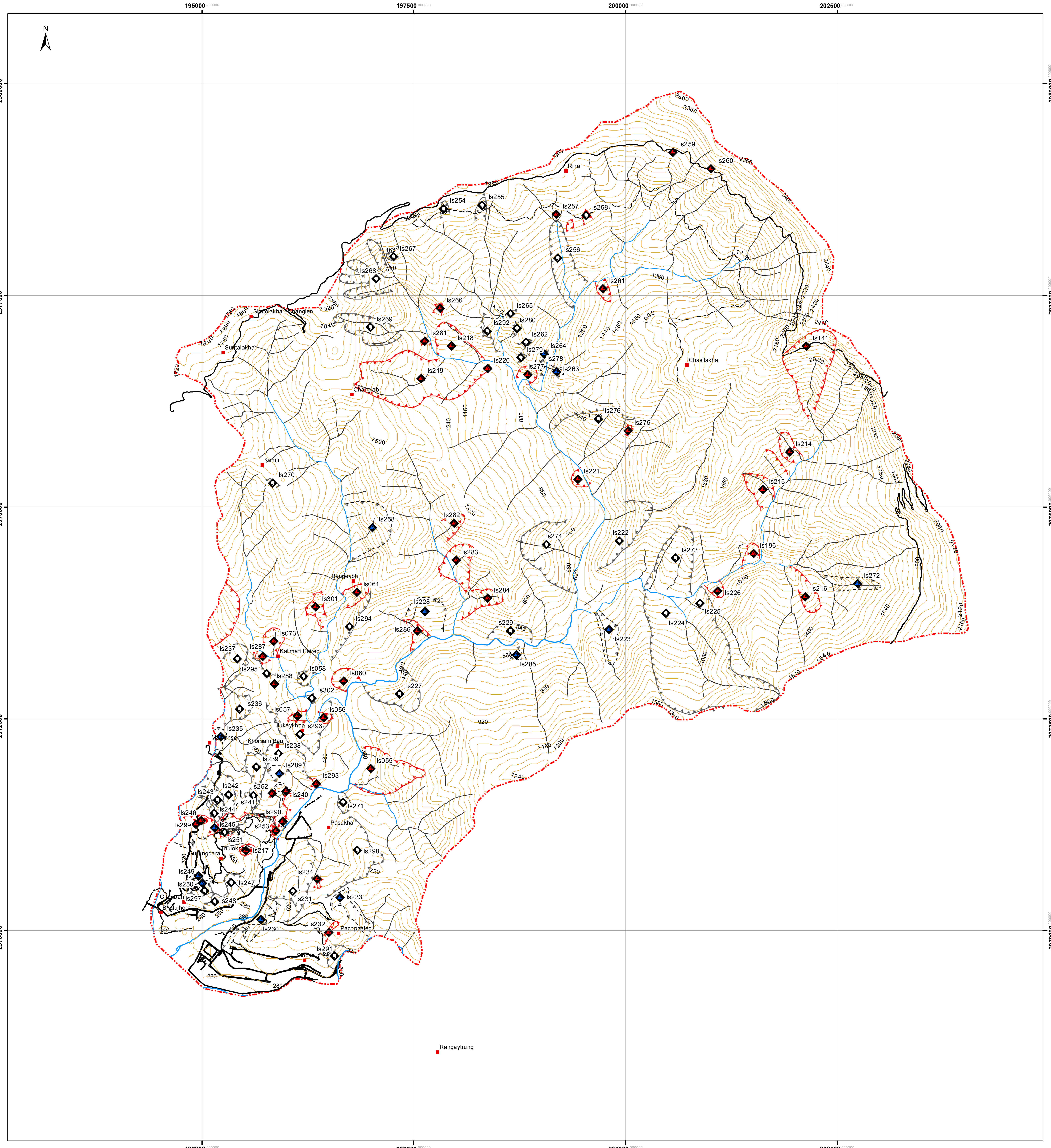
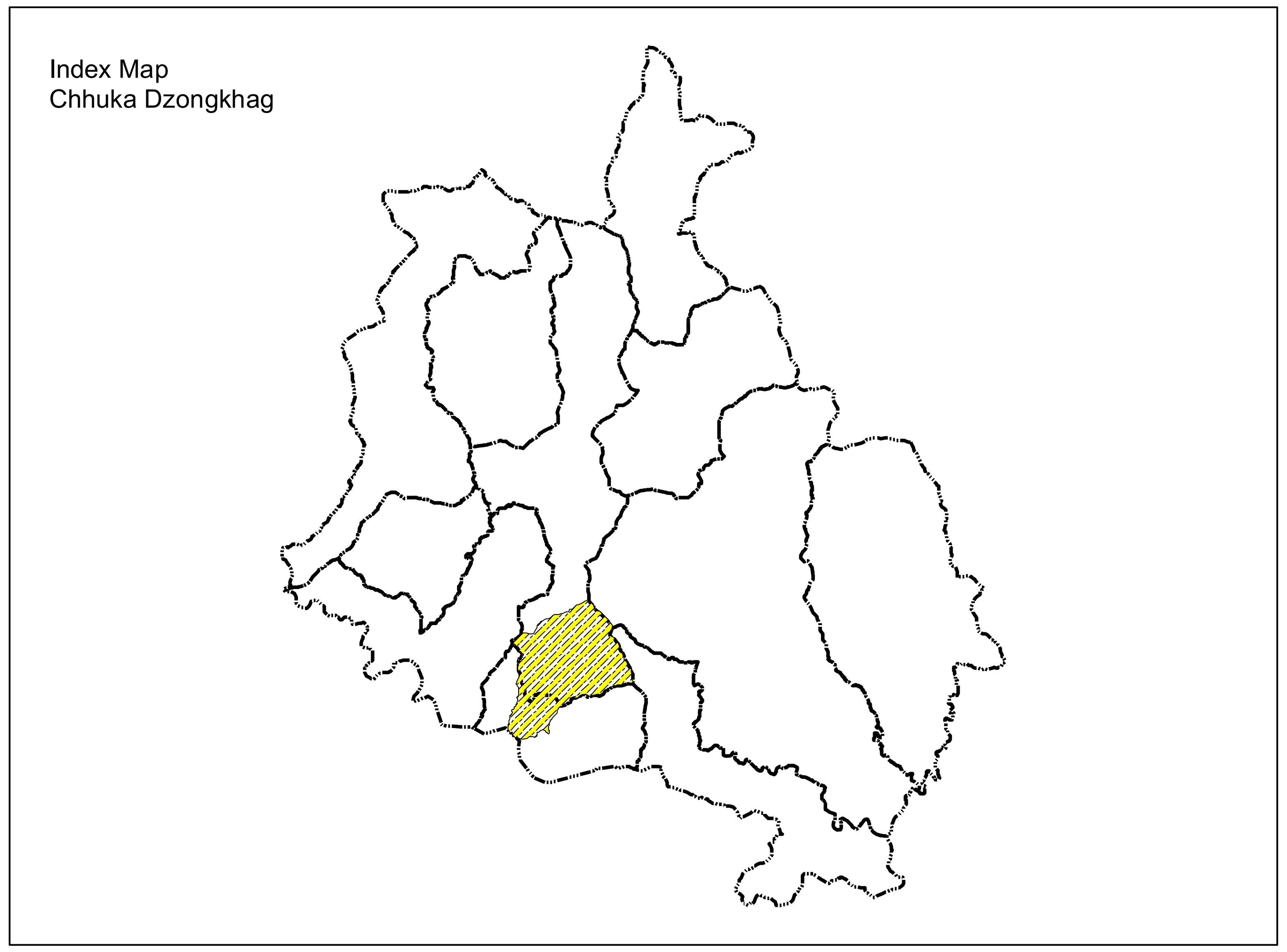
Plate:6 Landslide Inventory Map of Barsa Catchment,Chukha Dzongkhag

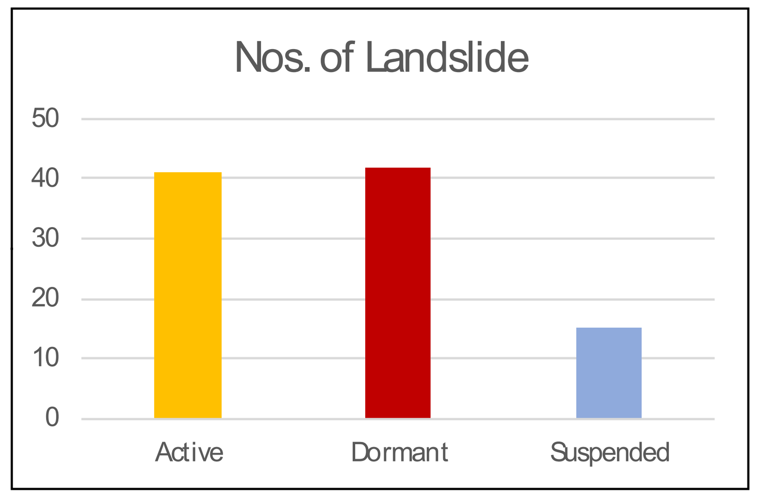
Scale 1:25,000

0 625 1,250 2,500 Meters





Activity	Nos. of Landslide
Active	41
Dormant	42
Suspended	15



Legend

Activity

- Active Landslide
- Dormant Landslide
- Suspended Landslide

- River Bed Materials
- Mettaled Road
- Un-Mettaled Road
- River (Perrinials)
- Dry Nala/Seasonal
- landslides_Point

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