



Geoenvironmental GIS development to investigate Landslides and Slope Instability along Frontal zone of Central Himalaya

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ABSTRACT

The Frontal Himalayan terrain comprises of Lesser Himalaya and Siwalik Hills; is highly susceptible to landslide disaster due to active tectonics, scrappy geology, steep slope, and reshaping geomorphology. Besides that, hydrological impacts of land use degradation and climate change enhancing the vulnerability of the terrain. Keep in view this; the Dabka watershed, falls in frontal zone of central Himalaya has been selected for case illustration. Geospatial analysis advocates that the areas of the most stressed geo-environment (comprises of very steep slopes above 30°, geology of Lower Krol and Lariakanta formation, geomorphology of moist areas and debris sites and land use of barren land) have high density (5–10 landslides km²) of landslides whereas the areas of least stressed geo-environment (comprises of gentle slopes below 10°, geology of Kailakhan and Siwalik formation, geomorphology of depositional terraces and land use of dense forest) have low density of landslides (2 landslides km²). Out of total 340 landslides in the region, 198 are active landslides whereas 51 and 91 are reactivated and old landslides respectively. Geospatial analysis of landslide areas reveals that across the region total 804.33 ha land has been degraded by landslides which account for 11.65% of the total area of the Dabka watershed. The wedge failure analysis suggests that there are 3–4 sets of rock joints across the region and most of the sites are unsafe as their safety factors are less than 1.

1. Introduction

Landslides and slope failure is one of the most threatening phenomena to loss of lives, socioeconomic development (buildings, roads, bridges, communication lines, etc) and natural environment such as land, vegetation cover, water resources, etc in hilly terrain across the world. (Wesnousky et al., 1999; Kamal et al., 2022). Therefore, to implement effective sustainable developmental planning in hilly terrain, geo-structural hazards (land subsidence, landslide and slope failure) susceptibility assessment is necessary. Numbers of methods have been developed for landslide susceptibility investigation which can be divided in four categories; physically-based models, statistical models, machine learning models and expert-based models (Huang et al., 2018; Vicente et al., 2021). Statistical models and machine learning are generally considered as data-driven techniques, both of which analyze landslide controlling factors using spatiotemporal datasets of landslide events (Zizheng et al., 2020). Expert-based model follows the judgment of experts to assemble the descriptive variables, whereas the most commonly used physically-based models consider geotechnical, geomorphological and geohydrological drivers of the landslides and slope instability

(Hurlimann et al., 2022). The proposed study of a Himalayan terrain was carried out by combining statistical and physically-based models.

The Himalaya region is among the most seismically active parts of the earth (Valdiya and Bartarya 1989; Rawat et al., 2017). The region straddles several parallel thrust that form the ranges of the Himalayas from south to north (Pant, 2007; Valdiya, 2010). These tectonically active regional thrusts are fragmented at several places by local faults and result in high frequency of landslides and slope failure along the areas associated with them (Pathak and Darmwal 2013). Beside that the climate change and its hydro-meteorological consequences (extreme rainfall events, excessive flood runoff and accelerated erosion) accelerated this frequency (Rawat et al., 2011; Rawat and Pant 2016). International Disaster Database (EM-Data) suggests that out of total annual disasters in Himalaya region 14% are landslide disasters which represents 6% geo-structural landslides and 8% geo-hydrological landslides. Geo-structural landslides occur due to earthquakes and other neotectonic activities along active thrusts and faults while geo-hydrological landslides take place due to extreme rainfall, excessive groundwater, river line floods and flash floods along the river valleys (Rawat et al., 2012, 2012a; Gerrard and Gardner, 2000; Tilahun et al., 2020). So the

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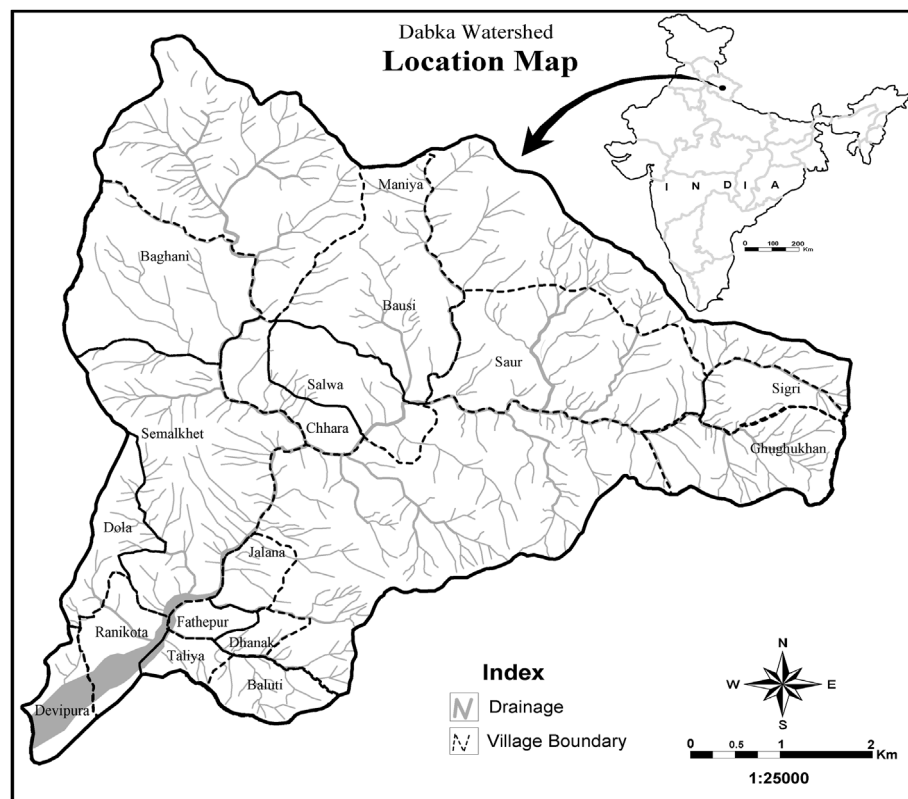


Fig. 1. Location map of the selected study area.

assessment and inventory on landslides and slope failure are essential for the formulation of successful disaster risk reduction (DRR) plan. Keeping this in view; the Dabka watershed one of the tectonically active Frontal Himalayan terrain (comprises of Lesser Himalaya and Siwalik Hills) along the Main Boundary Thrust (MBT) in district Nainital, Uttarakhand (India) has been selected for the case illustration (Fig. 1).

The Dabka Frontal Himalayan terrain is highly susceptible to geo-structural disasters (creeping, landslide, slope failure and earthquake) due to active tectonics, fragmented geology and reshaped geomorphology (Rawat et al., 2012b). Beside that rapid urbanization, climate change and dynamic upstream hydrological process, enhancing the vulnerability of the terrain (Rawat et al., 2012c). The study area lies between the latitude $29^{\circ}24'09''$ – $29^{\circ}30'19''$ E and longitude $79^{\circ}17'53''$ – $79^{\circ}25'38''$ N in the north west of Nainital town, adjacent to neotectonically active Main Boundary Thrust (MBT) of Himalaya. The region encompasses a geographical area of 69.06 km^2 between 700 m and 2623 m altitude above mean sea level (Fig. 1).

2. Methodology

The study was carried out through the amalgamation of GIS lab work and field mapping as discussed below.

2.1. Thematic mapping

Required geo-environmental thematic GIS maps (comprises of geology, geomorphology, slope, relief, drainage and land use pattern) carried out through digital and visual interpretation of Indian Remote Sensing Satellite and Panchromatic merged satellite data (IRS-1C LISS III + PAN) (Aditian et al., 2018; wachal and Hudak, 2000). The satellite images were registered in indigenous GIS software (Arc GIS-9 and Erdas Imagine-8.7) using Survey of India Topographical Sheets of the area at scale 1:25000. Comprehensive fieldwork was scheduled to carry out detailed geo-structural maps that included geology, geomorphology and its

associated lineaments (especially faults and thrusts). Beside that the digitally interpreted thematic GIS maps were validated during field study and the corrections have been incorporated through visual interpretation techniques (Liu, 1987; Kojima et al., 2000) during final mapping.

2.2. Landslide mapping

Landslide is a process of mass wasting which is also known as mass movement and down slope movement of earth forming materials. The earth has its gravitational force, which pulls downward all material on its surface. The methodology adopted for geo-environmental thematic mapping followed for landslide spatial distribution mapping. In order to do that a digitally interpreted landslide spatial distribution map was carried out using topographical Sheets and satellite data (LISS III + PAN and Google Earth data) in the GIS lab. Thereafter, geospatial characteristics of each landslide were verified through extensive fieldwork and corrections have been incorporated during final mapping through visual interpretation techniques (Farahmand and Aghakouchak, 2013; Rawat and Pant 2016). On the basis of mass movement and morphometric characteristics all the existing landslides are categorized as active landslides (heavy rock fall is occurred very often due to tectonic activity and underground water pressure inside the fractures and joints of the rocks along the dip slopes and steep or convex slopes), stable landslides (it refers to old landslide areas which are stabilized naturally since last some decades) and reactive landslides (unplanned developmental activities such as building, road canal, bridge, dam construction along the old landslide areas triggers landslide, is called reactivated landslides).

2.3. Geo-structural analysis and slope instability assessment

Through the landslide mapping, Dhiriya Pather landslide zone covered an area about 16 km^2 in the west part of Dabka watershed has been identified as one of the most potential landslide zones in the study area. This landslide zone includes seven major landslides which provide

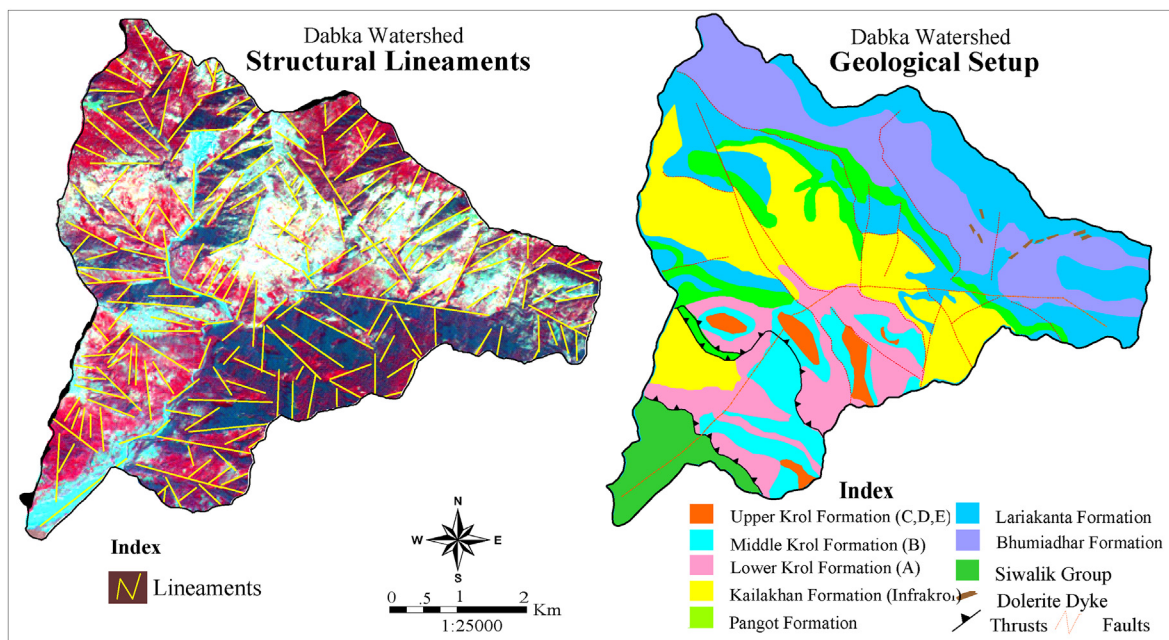


Fig. 2. Structural Lineaments (left side) and Geology (right side).

huge amount of debris flow to downstream of Dabka River and resultant to rising river beds and subsequent river line floods during rainy season. These landslides are caused by natural factors such as local topography, lithology, river toe cutting and neotectonic movements. These all seven landslides have been further studied in detailed for their wedge failure models and Markland stereographic projection test (Markland, 1972) to find out the factors of severity and geo-structural dynamics. Markland stereographic projection test is based on the geometrical relationship of three parameters: (i) slope angle and direction (ii) dip amount and direction of discontinuities (iii) friction angle along gentler discontinuity.

3. Results

3.1. Geoenvironmental setup

The key geoenvironmental drivers of the landslides are geology, structural lineaments, relief of the terrain, geomorphology and land use pattern. Keep in view this all those parameters have been investigated as discussed below.

3.1.1. Geology and structural lineaments

The geology of the study area is highly controlled by several regional and local structural lineaments such as faults, thrusts, strike ridges and

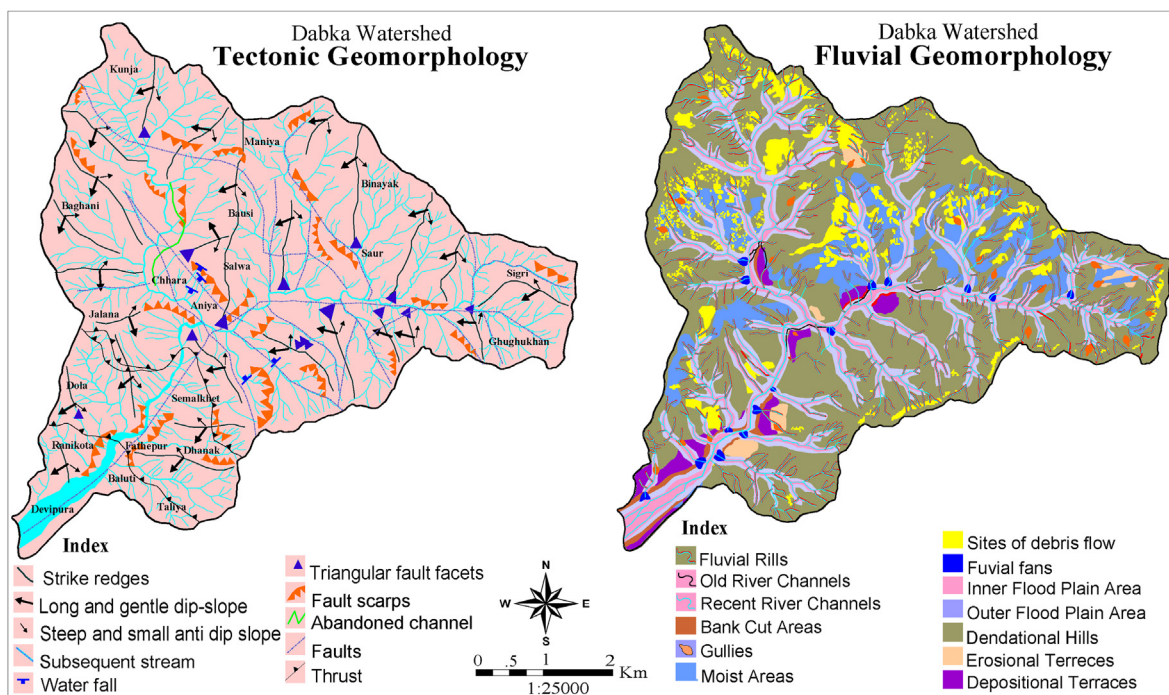


Fig. 3. Tectonic Geomorphology (left side) and Fluvial Geomorphology (right side).

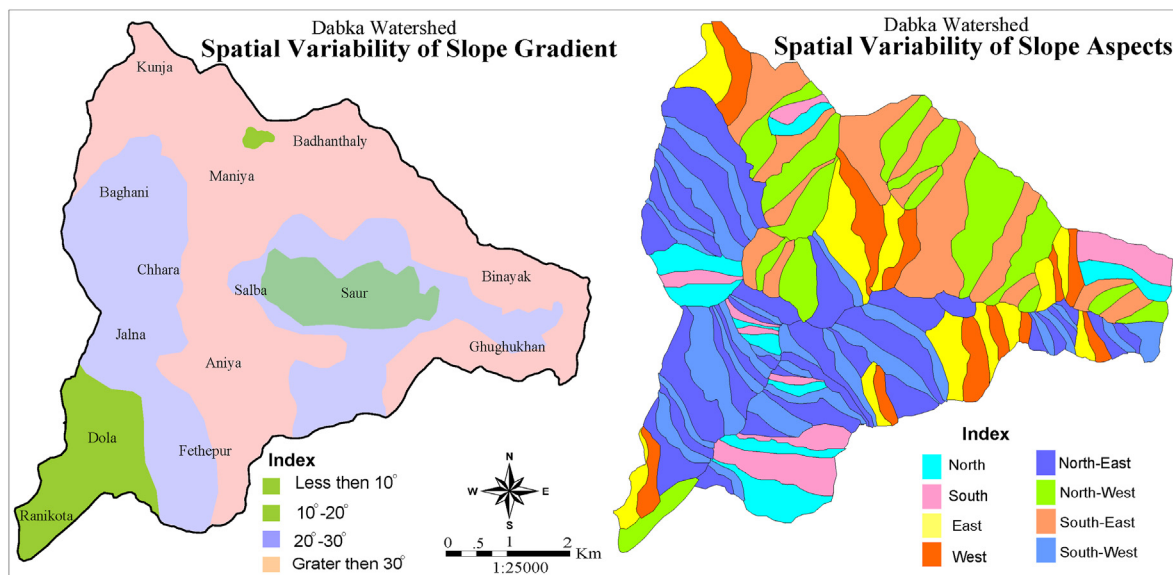


Fig. 4. Slope Gradient (left side) and Slope Aspects (right side).

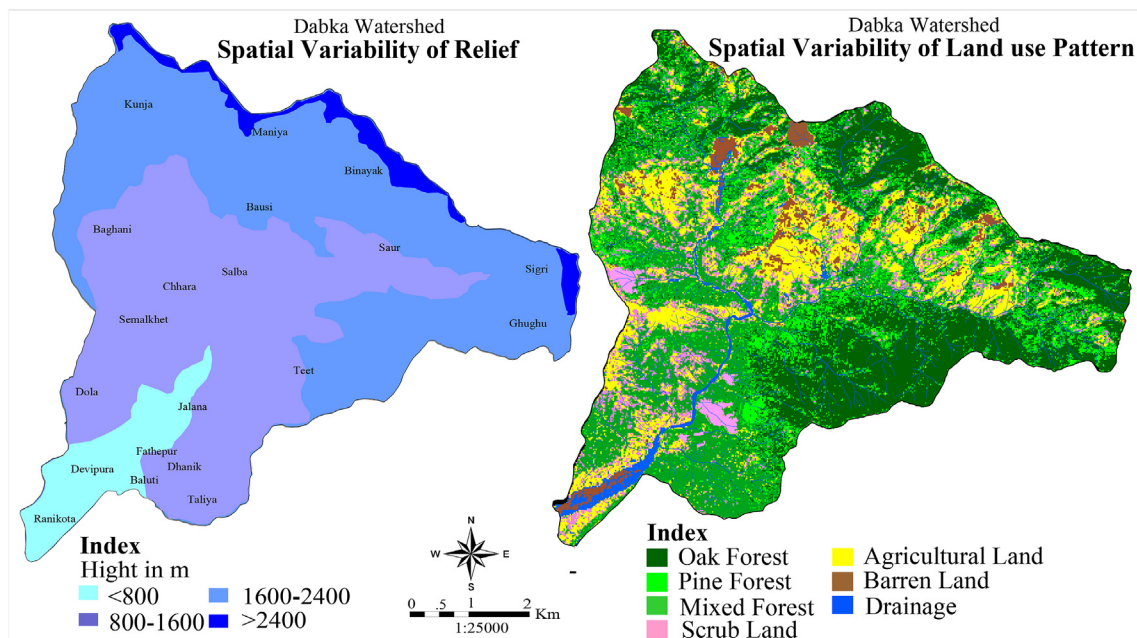


Fig. 5. Relief Pattern (left side) and Land use Pattern (right side).

inclined valleys (Fig. 2). These structural lineaments discriminate different types of rocks which are categorized as Blaini, Krol and Siwalik groups from north to south (Fig. 2). Blaini groups represent rocks of Bhumiadhar formation (comprise diamictite, siltstone and shale), Lariakantha formation (quartzwacke and quartzarenite), Pangot formation (comprises diamictites, purple grey slates, siltstone and lenticular pink siliceous dolomitic limestone) and Kailakhan formations (comprises dark grey carbonaceous pyritous slate and siltstone) in an ascending order of succession). Krol group represents rocks of Lower Krol formation (argillaceous marly sequence), Middle Krol formation (purple green slates and yellow weathered dolomites with pockets of gypsum) and Upper Krol formation (an assemblage of dolomitic limestone at the base followed by carbonaceous shales, fenestral dolomite showing cross bedding, brecciation and oolites and cryptalgal laminites) which are thrust over the

autochthonous Siwalik Group (quartzitic rock blocks, massive sandstones and boulders) along the Main Boundary Thrust (MBT) of Himalaya.

3.1.2.2. Geomorphology

The watershed is constituted multiple landforms of tectonic and fluvial genetics. The fluvial landforms are multilevel terraces, high level bedrock erosional terraces, small alluvial cones and fans, bank cut, narrow floodplains, sites of debris flow, moist areas, rills and gullies on alluvial terraces, unchannelled concave valleys or hollows, knolls, cols, convex hill spurs, and sheetwash cones and fans (Fig. 2). Apart from these fluvial landforms, the watershed is characterized by tectonic landforms; are vertical rock and terrace scarps, triangular facet, abandoned valleys, waterfalls, rapids, soil and rock creeping zones, slumping zones, debris fall, rock fall and block gliding (Fig. 3).

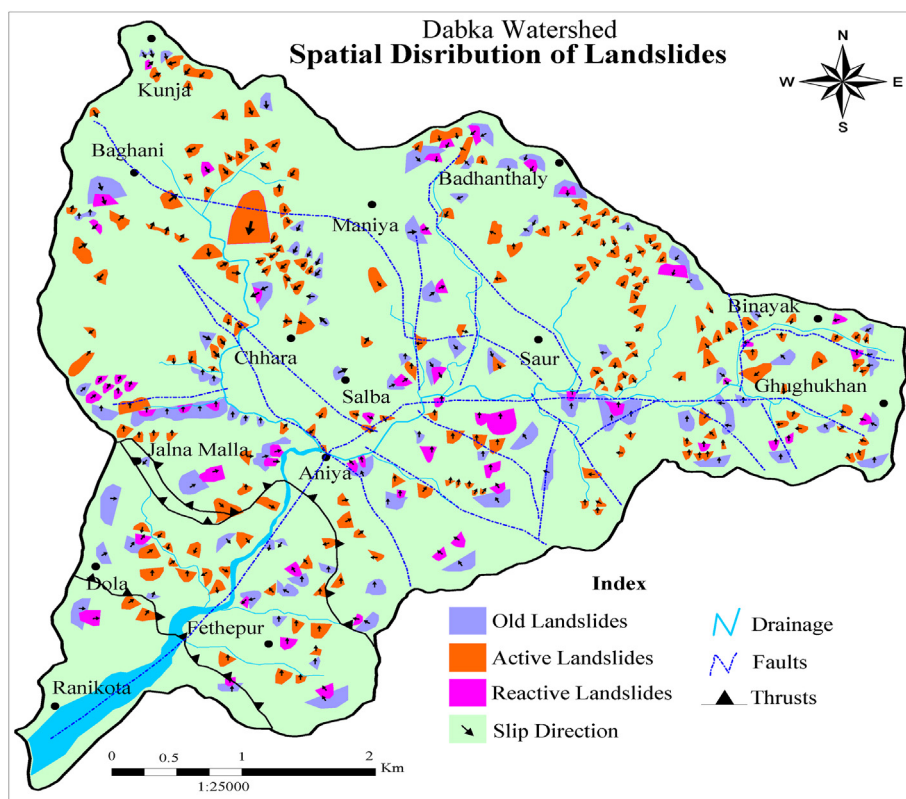


Fig. 6. Spatial distribution of landslides.

Table 1
Types and spatial distribution of landslides.

Types of landslides	Attributes of Landslides	Distribution of landslides with area covered by them			
		East Dabka Microwatershed	West Dabka Microwatershed	Lower Dabka Microwatershed	Total Dabka Watershed
Active Landslides	Number of landslides	72	68	58	198
	Area in hectare	162.00	158.00	139.27	459.27
	% of total Landslide area	20.14	19.64	17.32	57.09
Reactive Landslides	Number of landslides	29	12	10	51
	Area in hectare	63.93	39.00	21.00	123.93
	% of total Landslide area	7.95	4.85	2.61	15.41
Old Landslides	Number of landslides	37	28	26	91
	Area in hectare	84.10	70.00	67.03	221.13
	% of total Landslide area	10.46	8.70	8.33	27.49
Total Landslides	Number of landslides	134	112	94	340
	Area in hectare	310.03	267.00	227.30	804.33
	% of total Landslide area	4.49	3.87	3.29	11.65

3.1.3. Relief morphometry

Four morphometric parameters were investigated as the study required, these are spatial variability of slope gradient, slope aspects, absolute relative and relative relief. The slope gradient varies from less than 10° to more than 30° across the region and highly controlled by geo-structural lineaments and geological sections; subsequently shows eight facets; are north, south, east, west, northeast, southeast, southwest, and northwest (Fig. 4). The absolute relief map demonstrates that the elevation varies less than 600 m in the south to above 2600 m from mean sea level in the north whereas the relative relief varies less than 200 m in the south to more than 600m in the north (Fig. 5).

3.1.4. Land use pattern

The existing land use pattern suggested that the forest emerged as the major land use category in the study area (Fig. 5). About 53% area of the study region is classified as dense forest. This dense forest area represents Oak (16%), Pine (9%) and mixed species (28%) respectively from hill

tops to deep downstream valleys. Remaining 47% area is under agricultural land and settlements (30%), Shrubs land (9%), Barren land (5%) and river bed with water bodies (3%).

3.2. Spatial distribution of landslides

The occurrence of landslides is related to a number of geo-environmental parameters as discussed previous section. Total 340 landslides have been investigated in the region. These are broadly classified as active slides, reactivated slides, and stable slides (Fig. 6). Table 1 illustrates that out of the total landslide area (804.33 ha), account for 11.65% of the total area of the Dabka watershed. Active slide, reactivated slide and old or stable slide respectively account for 459.27 ha (57.09% of total landslide area), 123.93 ha (15.41% of total landslide area), and 221.13 ha (27.49% of total landslide area). A detailed description of all three types of landslides in the study area is given below.

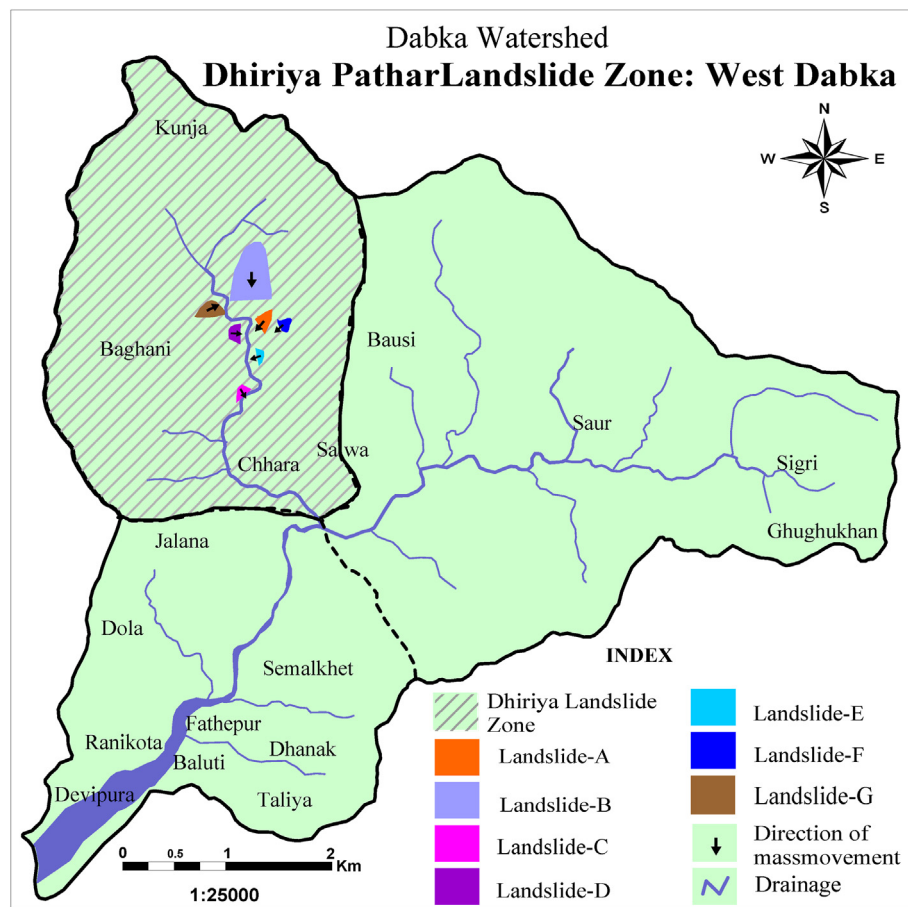


Fig. 7. Selected area for Slope instability Analysis (Dhiriya Pather active landslide zone).

3.2.1. Active landslide

A total of 97 active slides have been identified in the study area. Most of the active slides are associated with tectonic planes. Both translational and planar slides have been encountered but frequency of wedge failure process is common. Out of the total identified landslides in affected area, 459.27 ha or 57.09% is under active landslide (Fig. 6 and Table 1). East Dabka microwatershed zone has the highest proportion (20.14%) of active slides followed by West Dabka and Lower Dabka microwatershed zone which respectively covers 19.64% and 17.32% of total active landslides of the study area. It has been observed during the field surveys that the highest numbers of landslides were found in areas occupied by Lariakanta Formation. The major rock units of Krol Formation, which are exposed in the vicinity of Main Boundary Thrust (MBT), are highly affected by active landslides. Along the MBT the rocks are sheared, shattered, and therefore it is considered as a potential zone for slope failure especially during rainy season.

3.2.2. Reactive landslides

These are the slope failure processes of the past where reactivation by triggering cannot be excluded. Such landslides have been identified in similar geomorphic settings as that of stable/old slides but because of human interference, such as road and building construction, deforestation, extension of agricultural land, mining, etc. these slides have reactivated. There are 51 reactivated slides observed in the entire study area (Fig. 6 and Table 1). Out of the total landslide affected area of the Dabka watershed zone 123.93 ha or 15.41% is under reactivated landslide (Fig. 6 and Table 1). East Dabka Headwater zone has the highest proportion (7.95%) of reactivated slides followed by West Dabka and Lower Dabka microwatershed zone which respectively cover 4.85% and 2.61% of the area affected by all types of landslides (Fig. 6 and Table 1).

3.2.3. Old or stable landslide

There are a number of old landslides which have been stabilized due to natural processes like growth of thick vegetation, and where the reactivation of slope failure processes may not be by normal triggering events as a consequence of geomorphic setting, in the study area. Such zones are recognisable on aerospace data by their characteristics, such as presence of scraps, hummocky terrain condition and deviation in the drainage pattern. Old slide zones have a moderate frequency in the study area. Out of total 340 landslides only 91 have been characterized as stable landslides, which account for 221.13 ha or 27.49% of the area under landslides (Fig. 6 and Table 1). East Dabka microwatershed has the highest proportion (10.46%) of stable slides followed by West Dabka and Lower Dabka microwatershed, which respectively cover 8.70% and 8.33% of the area degraded by all landslides in the region.

4. Discussions

The spatial distribution of landslides shows that there is very high frequency of active landslides across the region due to frizzle geo-environment. These active landslides have been affecting natural resources (forests, agricultural land, water resources, etc.) and socio-economic development (roads, canals, buildings etc.) of the region. Keep in view this; it is an urgent need to investigate geo-structural dynamics of landslides and their associated vulnerable slopes before any developmental activities. In order to that the present study selected a most landslide affected zone (Dhiriya Pather active landslide zone) for slope stability analysis (Fig. 7).

The Dhiriya Pather active landslide zone covered an area about 16 km² in West Dabka headwater, is one of the most potential landslide zone in the study area, which includes seven major landslides which provide

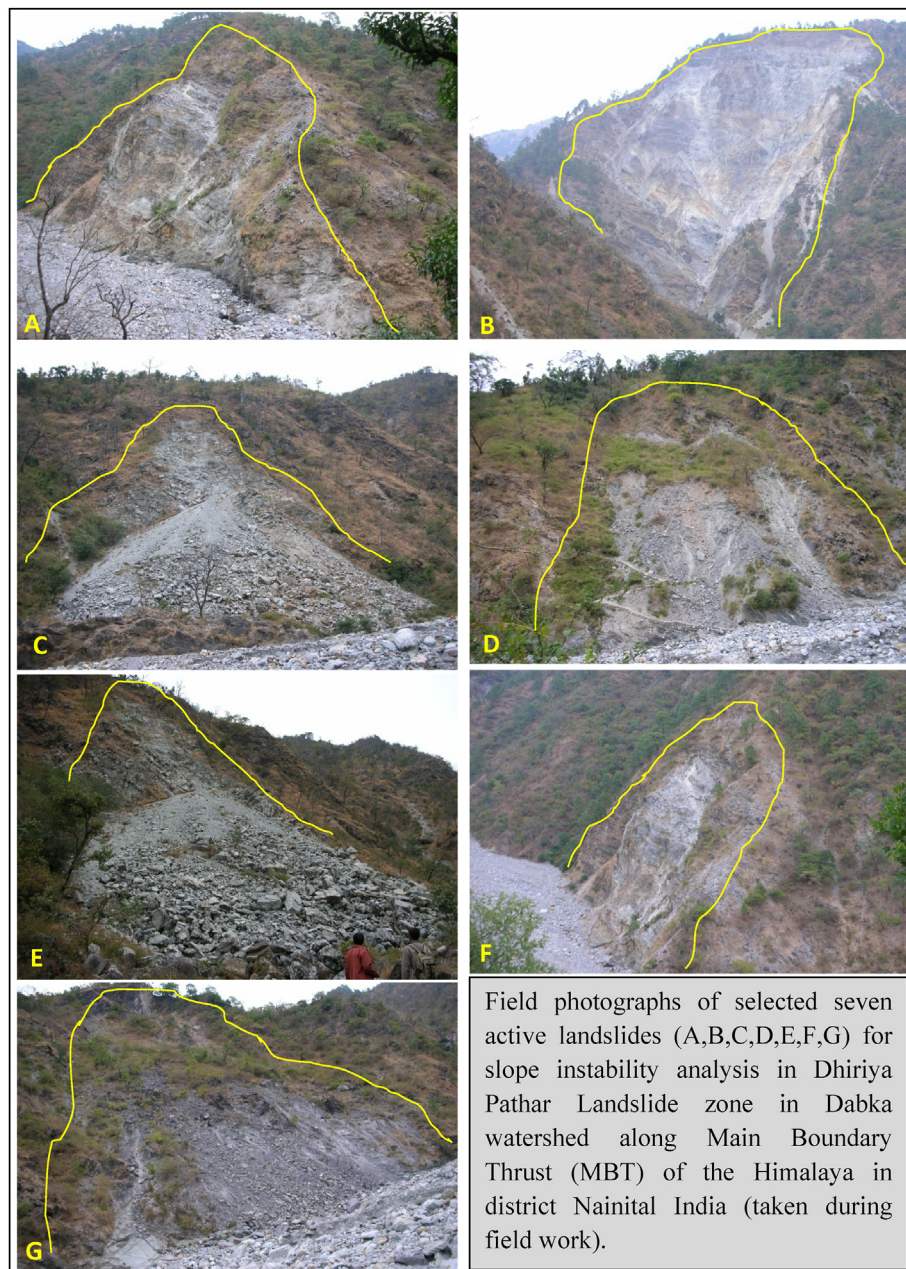


Fig. 8. Filed site view of selected active landslides for slope instability analysis.

huge amount of debris flow to downstream of Dabka River and resultant to rising river beds and subsequent river line floods during rainy season (Figs. 7 and 8). These seven landslides have been further studied in detailed for their wedge failure models and Markland test to find out the factors of severity and geo-structural dynamics (Fig. 9). The outcomes of this analysis are discussed below.

4.1. Landslide A

This rock fall has been observed in the quartzites of Nagthard Formation near Baghni village (Figs. 7–9). The rock slope design (ψ) is 50° in $N80^\circ W$. Two prominent or dominant steeply dipping joints set occur at this side. The potential wedge failures are against the natural slope at an angle 42° in SE (Fig. 9A). A simple Markland Test shows, that the safety factor of the rock mass is 0.5934 which is moderate value, so the wedge failure at a higher angle to friction angle and natural slope. The wedge geometry shows natural slope and friction angle played major role than the wedge failure geometry.

4.2. Landslide B

This rock fall is also observed in quartzites of Nagthard Formation near Baghni village (Figs. 7–9). The rock mass model in topographic projection has been shown in Fig. 9B, including moderately oriented two joints sets, natural slope (ψ) is 50° to $N 80^\circ W$ and slip direction is 50° in $N 60^\circ W$. The safety factor of the rockmass is 0.7727 which is moderately high and wedge failure (wf) is at 30° to SE (against the slope).

4.3. Landslide C

This rock fall is observed in quartzite and carbonaceous slates of Kailakhan member (Figs. 7–9). The wedge failure modal is shown in Fig. 9C including steeply dipping two joint sets, the natural slope (ψ) is $52^\circ N 80^\circ W$ and slip direction is $63^\circ W$. Wedge failure (wf) is 63° in SW. The safety factor for the rockmass in the present existing natural slope is .7012 which is less than unit i.e. unsafe. The angle of wedge failure is

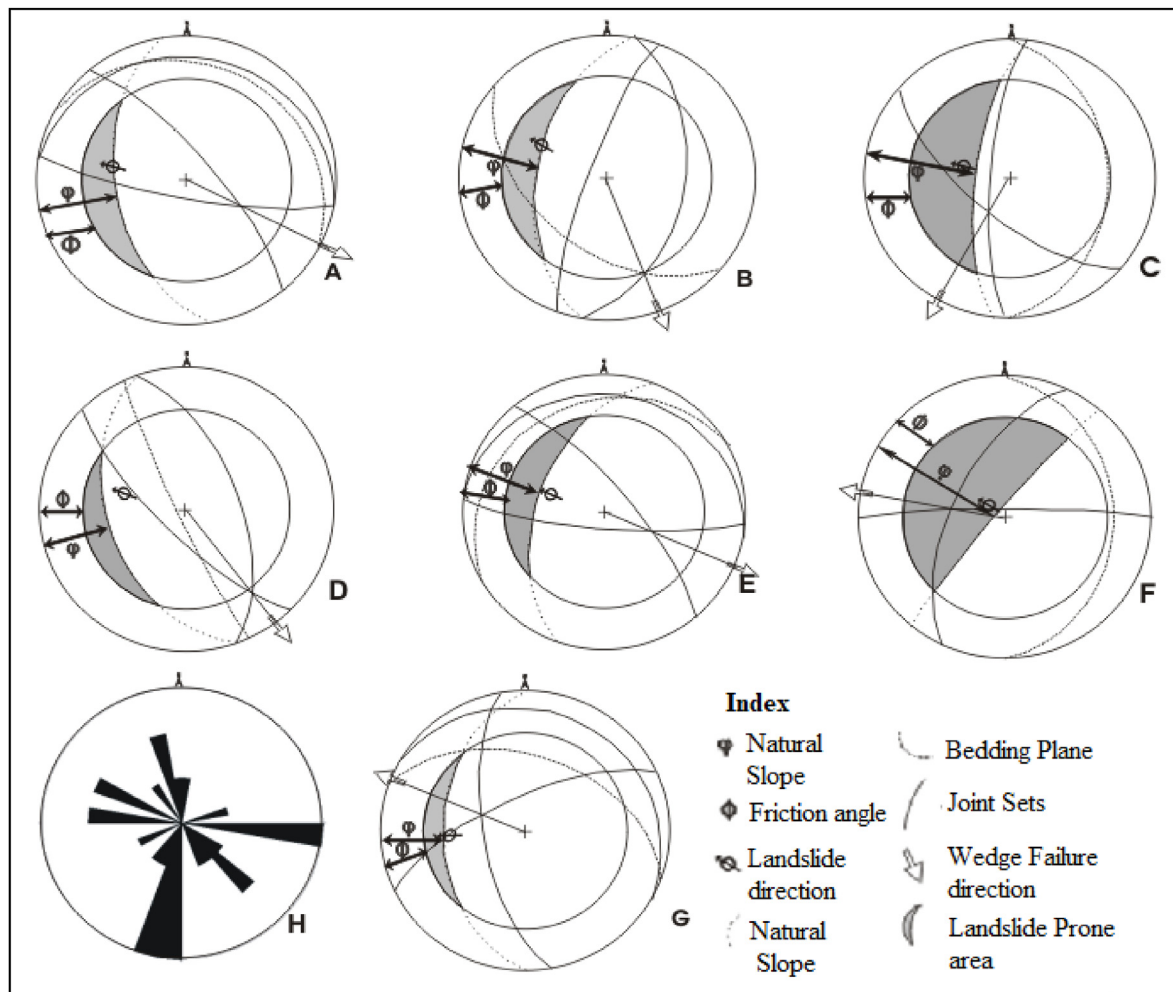


Fig. 9. Stereographic projection for Slope Instability Analysis at different Landslide locations.

more than the friction angle and the natural slope. Therefore the landslide side is unsafe.

4.4. Landslide D

This rock fall has been observed in dark colour Khilakhan slates (Figs. 7–9). Rockmass model of wedge failure is shown in Fig. 9D. Two moderately dipping joint sets and steeply dipping bedding planes are shown in Fig. 9. The natural slope (ψ) is $45^{\circ}\text{S } 70^{\circ}\text{W}$, slip direction is at an angle of 40° in W and friction angle is 30° . The potential wedge failure (wf) is at an angle of 30° in SE that is against the natural slope. The safety factors for the rock mass in the present existing natural slope is .2709 which is very less i.e. unsafe.

4.5. Landslide E

This rock fall has also been observed in dark colour slates of Kailakhan members (Figs. 7–9). The wedge failure (wf) model of rock mass is given in Fig. 9E. The natural slope (ψ) is $30^{\circ}\text{N } 70^{\circ}\text{W}$. this slide show two steep joint sets with low angle dip bedding an enlarged fracture. Fiction angle is 30° and the potential wedge failure is measured at 50°E . The Markland Test shows the average value of 0.0716 for the factors of safety of rock mass which is very less.

4.6. Landslide F

This landslide is observed in slates and phylites of Kailakhan member,

which are dipping by 26°E . Two sets of steeply dipping joints are observed (Figs. 7–9). Natural slope (ψ) is $85^{\circ}\text{N } 50^{\circ}\text{W}$ and landslide slip direction is 80° in same direction. The wedge failure model (wf) is shown as Fig. 9F, which is at 58°W which is in the slope direction. The safety factors for the rock mass with present existing nature slope is .5715 which is very less than the safe model. Since the wedge failure angle and natural slope are higher than the friction angle; therefore it is the most unstable rock mass.

4.7. Landslide G

This rock fall is observed in slates and interbedded limestone of Blaini Formation (Figs. 7–9). The rockmass model in topographic projection is shown in Fig. 9G. The model has shown moderately inclined joints sets, bedding plane and enlarged joints. Natural slope (ψ) is 42° in W, landslide slip direction is also in the same direction at 40° , wedge failure (wf) is at 62° in W. The safety factor for the rock mass in the present existing natural slope is .7107, which is much less than unity, i.e. unsafe.

Overall joints-sets, observed in the West Dabka landslide zone are shown as rose diagram in Fig. 8, which suggest three significant joints-sets exposed in the study area. The wedge failure models of all above mentioned landslides show that all the sites are unsafe as their safety factors are less than 1. All the landslides are not caused by wedge failures. Other natural factors such as geology, topography, river toe cutting and wind action may be responsible for these slope failures.

5. Conclusion

Results concluded that the areas of the most stressed geo-environment (comprises of very steep slopes above 30°, geology of Lower Krol and Lariakanta formation, geomorphology of moist areas and debris sites and land use of barren land) have high density (5–10 landslides km²) of landslides whereas the areas of least stressed geo-environment (comprises of gentle slopes below 10°, geology of Kailashan and Siwalik formation, geomorphology of depositional terraces and land use of dense forest) have low density of landslides (2 landslides km²). In the wake of landslide hazard, the terrain of the region is highly unstable and poses very threatening view as maximum 58% landslides are found active and often fall down from time to time whereas 27% landslides are reactivated landslides, remaining 15% landslides are old landslides which are stabilized since last some decades. Across the region, about 12% (804.33 ha) land is badly affected by landslides which comprise of 7% (459.27 ha) under active landslides, 2% (123.93 ha) under reactive landslides whereas 27% (221.13 ha) under old or stable landslides. The wedge failure analysis also concluded that most of the sites are unsafe for any socioeconomic development as their safety factors are found less than 1.

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