CHAPTER 3

AREA OF STUDY

3.1 Introduction

The Himalayas lies at the convergence zone of two lithospheric plates. One is the Indian plate in the south, and the other is the Eurasian plate in the north (Siddique et al. 2015). After the final closure of the Neo-Tethys along the Shyok Suture Zone (SSZ) in the north and the Indus Tsangpo Suture Zones (ITSZ) towards the south, the continental India Plate with its Paleo-Mesozoic Tethyan sedimentary cover was remobilised into the Himalayan Metamorphic Belt (HMB). The Main Central Thrust (MCT) brought this belt over the Proterozoic-Paleozoic Lesser Himalayan sedimentary belt, which overrode the Cenozoic Sub-Himalayan belt along the Main Boundary Thrust (MBT). The latter is subsequently thrust over the Indo-Gangetic Plains along the Main Frontal Thrust (MFT) (Fig. 3.1) (Jain et al. 2020).

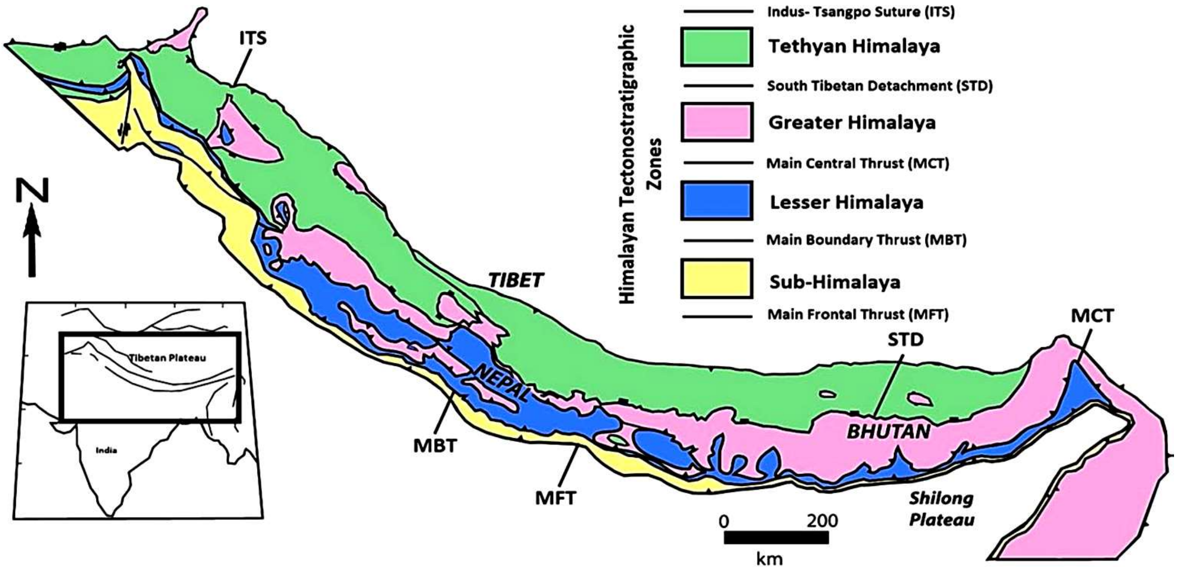

Fig. 3.1 Distribution of various stratigraphic zones of the Himalayas (McKenzie et al. 2011)

After late Mesozoic subduction of the Neo- Tethyan oceanic lithosphere along the SSZ and the ITSZ, Cenozoic convergence followed southward to evolve the Himalayan orogen. It produced (i) Tethyan Himalayan Sequence, (ii) Himalayan Metamorphic Belt containing Tso Morari Crystallines, Higher Himalayan Crystallines and Lesser Himalayan Crystallines, (iii) Lesser Himalaya Sedimentary Belt, and (iv) Sub-Himalayan Cenozoic belt (McKenzie et al. 2011).

The three major thrusts, namely the MCT, the MBT and the MFT, are formed during the isostatic adjustment, which divides the Himalaya into three reasonably recognisable lateral belts running approximately east to west. The Greater Himalaya form the northernmost unit, followed by the Lesser Himalaya and then the Shiwalik/Sub-Himalaya in the south (Bartarya and Valdiya 1989; Bhasin et al. 2002; Israil and Pachauri 2003). The MCT, a mylonitic zone on the scale of kilometres, divides the Greater Himalaya from the Lesser Himalaya. The MBT divides the Lesser Himalaya from the Shiwalik, and the MFT is the outer limit of the Himalayan range dividing the Shiwalik from the Indo-Gangetic/Tarai plane (Nandargi and Dhar 2011) (Fig. 3.2). The rocks occurring in the Himalayan Range vary from soft sedimentary rocks in the Shiwalik to highly weathered metamorphic rocks in Greater Himalaya (Table 3.1).

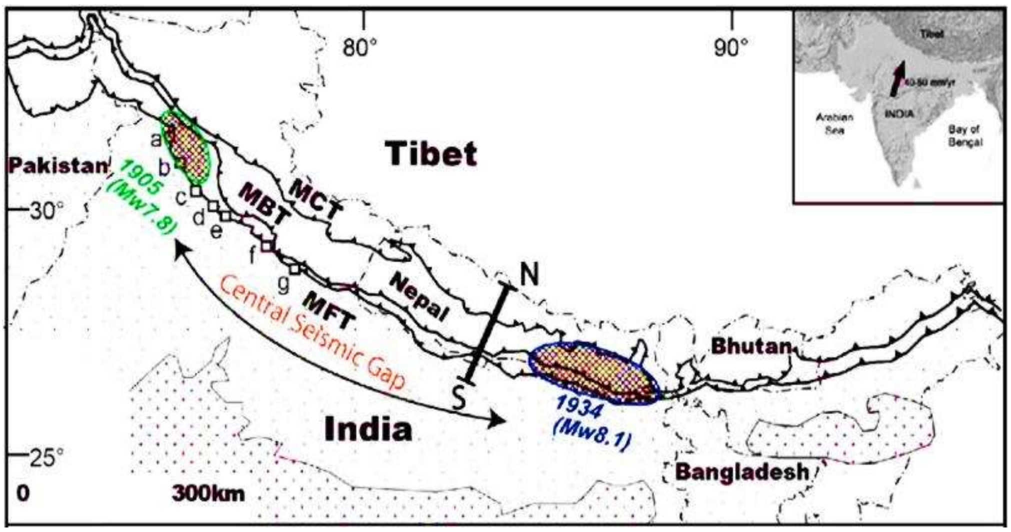

Fig. 3.2. Geological Formation of the Himalayas (Valdiya 2016)

Table 3.1: Major rock forms of Himalayas (Ray et al. 2021)

Zone	Major Rock Types
Greater Himalaya (The area between Lesser Himalaya and Tethys Himalaya. Metamorphic rocks are found at the base, and sedimentary rocks are found at the top.)	Sedimentary rocks: Marl, Dolomite, Greywacke, Siltstone, Shale, Limestone. Metamorphic rocks: Granite gneiss, Schists, Gneiss, Black schist, Augen gneiss, Mica schist, Kyanite schist, Kyanite gneiss, Biotite schist, Chlorite schist. Igneous rocks: Leucogranites, Granite, Diorite, Gabbro.
Lesser Himalaya (It is known for its metamorphic and sedimentary rocks; however, there are also some igneous rocks in this region.)	Sedimentary rocks: Chert, Dolomite, Conglomerate, Limestone, Diamictite. Metamorphic rocks: Metasandstone, Phyllite, Banded gneiss, Schist, Slate, Marble, White quartzite. Igneous rocks: Trachyte, Pegmatite.
Shiwalik/Sub-Himalaya (It is known for its sedimentary rocks.)	Sedimentary rocks: Marl, Siltstone, Mudstone, Sandstone, Shale, Conglomerate.

The current study focuses on the slope stability problem associated with the residual soil slopes produced by weathering carbonate lithologies (limestone, dolomite and dolomitic limestone) of the Lesser Himalayan Range in the Indian state of Himachal Pradesh and Uttarakhand.

3.2 Lithology

The Lesser Himalaya lies between the Shiwalik in the south and the Greater Himalaya in the north and runs almost parallel to both ranges. It is around 60-80 km wide and about 2400 km in length. In the north, the MCT has brought up high-grade metamorphics of the basement and uplifted to soaring heights of the Great Himalaya. The MBT in the south seems to be geodynamically still active, being the plane of underthrusting of the Indian plate under the Himalayan. The primary rock type occurring in this region includes sedimentary carbonate rock (dolomite and limestone) and metamorphic rocks (phyllite, gneiss, schist and quartzite). These rocks are highly fractured and jointed due to the brittle deformation during the movement along the MCT, MBT, and MFT, making the rocks highly susceptible to physical as well as chemical weathering (Bartarya and Valdiya 1989; Kumar et al. 2017; Panikkar and Subramanyan 1997; Paul and Mahajan 1999). The prevalence of a large number of discontinuities makes this region geologically very fragile and susceptible to frequent landslides (Mukherjee and Mitra 2001). A slight imbalance in elements of shear stress and strength factors might trigger landslides. The Lesser Himalaya is under enormous pressure from human activity, which has accelerated the amount of weathering of the bedrock, thereby increasing the incidence of landslides (Gerrard 1994).

Limestones, Dolomitic limestone and Dolomite are collectively referred to as carbonate rocks because they consist predominantly of the carbonate minerals like calcite ($CaCO_3$) and dolomite ($CaMg[CO_3]_2$). Though Limestone and dolomite are considered strong, they are highly reactive to water. The hydrological regime of the area primarily affects the bedrock and results in variable rate and spatial distribution of chemical weathering. Most of the sites in the study area are highly degraded by weathering and anthropogenic activities, which has resulted in a varying depth of residual soil cover over the bedrock (Fig. 3.3). The soils are generally very fine grain to coarse grain and are loose, rendering the slopes vulnerable to failure.

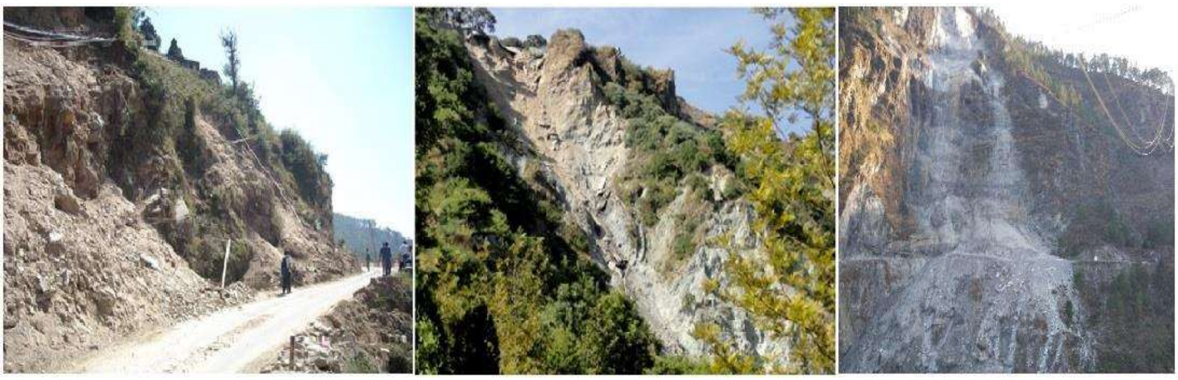

Fig. 3.3. Highly degraded slopes observed in the study area

Fig. 3.4 shows various locations of carbonate lithologies in the Indian state of Himachal Pradesh and Uttarakhand. The major lithological formations possessing carbonate rocks include Dehradun (Barkot-Nutiya Deposit, Lambidhar-Hatipaon Deposit, Song Valley Deposit, Deoban-Bajmara area), Chakrata (Deoban formation), Pithoragarh (Dharchula Deposit, Gangolihat Deposit, Rorgaon Deposit), Mussoorie and Nainital (Krol formation), and Tehri Garhwal (Nagni) are some of the areas in Uttarakhand where primary calcite bearing rocks are found. Similarly, in Himachal Pradesh, Dharamkot, Bilaspur and Shimla (Shali Group), Kullu (Largi Group), Sirmaur and Manal (Krol Group), Gumma and Rohana (Deoban Group) and Nauran (Jutog Group).

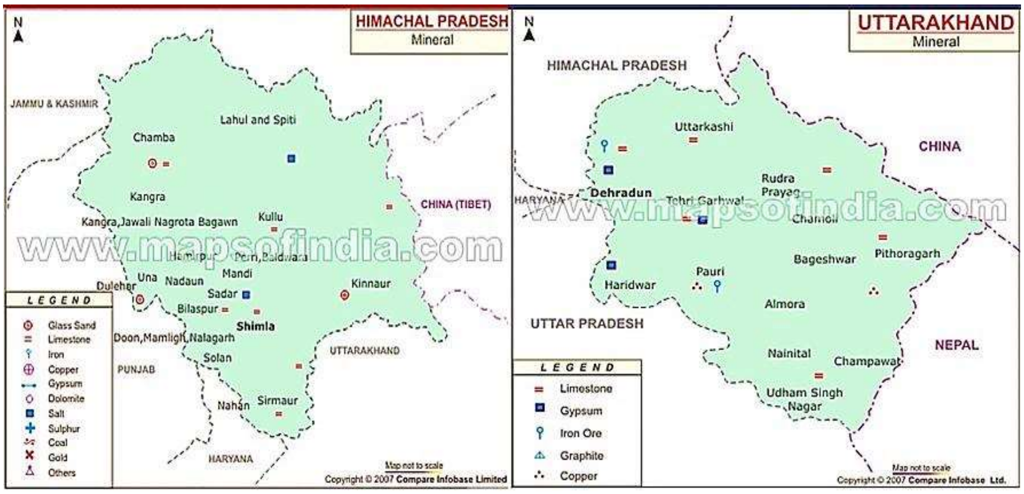

Fig. 3.4. Mineral Map of Himachal Pradesh and Uttarakhand
(Source: https://www.mapsofindia.com/)

3.3 Slope Morphology

Moderate to steep slopes are the general features of the Lesser Himalayan geomorphology. The hillslopes lie at an average angle of 45^0-50^0, steepening locally to 70^0-80^0 and sometimes can be of nearly vertical rock slope (Bartarya and Valdiya 1989; Gupta et al. 1999; Mahanta et al. 2016; Mehrotra et al. 1996). The average elevation varies from 3500 m to 5000 m above mean sea level. Many peaks are more than 5,050 m above sea level and are snow-covered throughout the year. Lesser Himalayas generally have sparsely-covered forested southern slopes and denselycovered forested northern slopes. The south-facing slopes receive more solar radiation that leads to more freeze/thaw cycles which reduce the strength of the residual soil and makes the area more susceptible to weathering and landslides. About half of the new slope failures occur on the south-facing slopes (including southeast and southwest) (Bhambri et al. 2017).

The gentle to moderate Lesser Himalayan slopes generally comprises three stratigraphic layers, i.e., a residual soil layer at the top, which is underlain by a highly weathered layer of rock and finally the parent bedrock (Anbalagan et al. 2008; Chaudhary et al. 2010; Gupta et al. 2016b; Kanungo et al. 2013; Kumar et al. 2017). The depth of all three layers varies considerably from region to region based on weathering pattern, but overall, the stratigraphy remains the same up to 50^0-60^0 slope inclination (Fig. 3.5). Steep slopes (>60^0) are mostly devoid of the residual soil cover and have a rocky nature having the inner two-layer, i.e., weathered layer and the bedrock (Bartarya and Valdiya 1989; Mehrotra et al. 1996; Sati and Sundiyal 2007). The majority of the slopes in the Lesser Himalayan region falls under the moderate slope profile hence have residual soil cover.

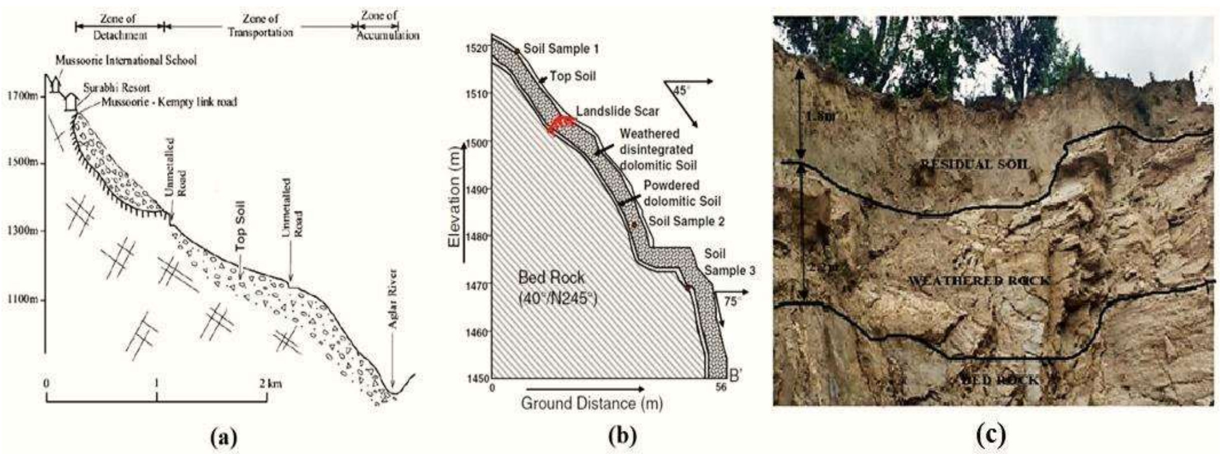

Fig. 3.5 Cross-section of Lesser Himalayan slope (a) Mussoorie (Pal et al. 2012), (b) Pipalkoti (Kanungo et al. 2013) and (c) Field observation at Uttarkashi, Uttarakhand

The natural virgin slopes are observed to be in a state of equilibrium with the strength of the slope and stress on the slope. However, change in slope gradient and profile by natural or anthropogenic activity disturb the equilibrium condition of the mountain system by changing the internal stress of the soil or rock mass and lead to the formation of cracks along the weak zones. The developed cracks get saturated with water during and after precipitation, thereby initiating the failure (Miščević and Vlastelica 2014).

3.4 Hydrology

Precipitation is one of the major factors which control the extent of weathering and the frequency of landslides (Chatterjee and Krishna 2019). The magnitude and rate of chemical weathering depend upon the intensity of precipitation, the porosity and the permeability of the soil and rock (Bartarya 1993; Goswami and Singh 2008). Owing to the highly water-soluble nature of the carbonate lithologies, the groundwater movement washes out soluble minerals. This reduces the mechanical strength of the bedrock by weakening the inter-granular bonds and development of intragranular porosity, facilitating further weathering (Calcaterra and Parise 2005; Ollier 2010; Sajinkumar et al. 2011). The infiltration under gravity tends to accumulate at the highly permeable boundary between the residual soil and weathered/fractured rock profile, increasing the pore water pressure in the overlying soil mass, leading to its failure (Fig. 3.6). Also, the continuous freeze-thaw action in which water continually seeps into cracks freezes and expands, eventually breaking the rock apart, making the bedrock vulnerable to further weathering and finally, the formation of residual soil (Chansarkar 1975; Sajinkumar et al. 2011). The increase in anthropogenic activities has significantly affected the drainage network. Heavy sediment outflow from the civil and mining sites has chocked the hydrological regime; thereby, the granulometric composition of the soil also gets altered (Mehrotra et al. 1996).

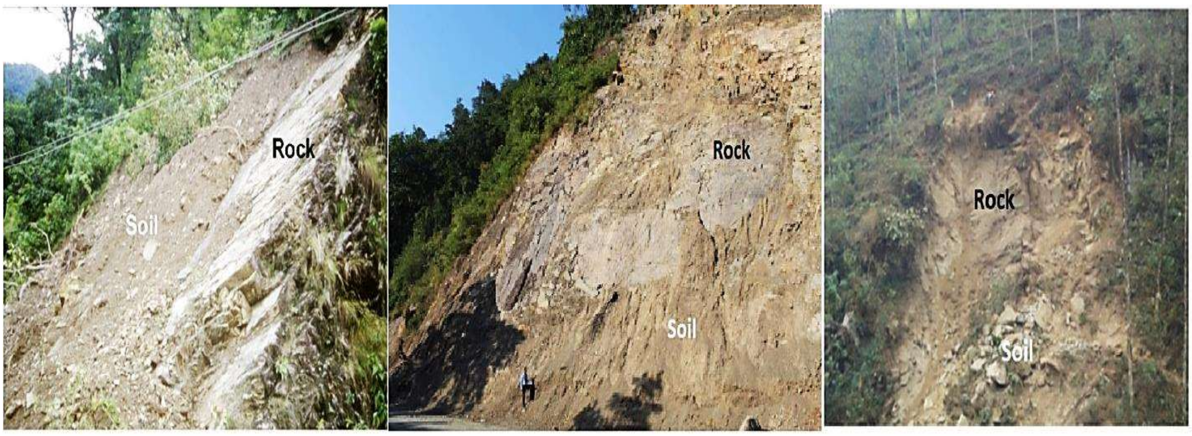

Fig. 3.6. Failure of the entire residual soil layer observed at various sites in the study area

The highly fractured rock near the slope surface collects the run-off water, which penetrates along the fractures/joints during monsoon. This initiates the weathering process along the fracture/joint planes, which initially becomes loaded with secondary minerals produced from the disintegration of the least stable parent mineral (Saunders and Fookes 1970). During winters, the water present in the fractures/joints freezes, resulting in volume expansion, thereby inducing extra stress on the slope. Weathering gradually attacks the bedrock having discontinuities to isolate them into blocks with kernels of fresh material within a cover of decomposed rock. With the further continuation of attack, the isolated blocks become spheroidal after losing their corners until complete decomposition results in the formation of residual soil. However, the original texture may still be recognisable (Saunders and Fookes 1970).

3.5 Climate

The prevalence of subtropical climate, along with the most characteristic feature of the southwest monsoon, expedite the chemical weathering process and assist in triggering landslides in this area (Bartarya and Valdiya 1989; Vyshnavi et al. 2015). Due to the presence of favourable climatic conditions and increase in various anthropogenic activities, extensive chemical weathering extends to enormous depth resulted in the formation of thick columns of residual soil over the bedrock. The deep and varying weathering is not the outcome of the present climate; instead, it is a continuous process occurring at a different rate under different climatic conditions in the past. The time scale may be attributed to 'Tertiary' times or even dated back to 'Mesozoic' times (Ollier 2010).

Table 3.2 shows the report of the India Meteorological Department (IMD) on mean rainfall (mm) and coefficient of variation for the monsoon months (June, July, August and September), southwest monsoon season (JJAS) and annual during the period 1989-2018 for the state of Uttarakhand (Source: IMD, Met Monograph No.: ESSO/IMD/HS/Rainfall Variability/28(2020)/52) and Himachal Pradesh (Source: IMD, Met Monograph No.: ESSO/IMD/HS/Rainfall Variability/10(2020)/34). It was observed that Himachal Pradesh and Uttarakhand receives more than 61% and 79% of annual rainfall, respectively, during the southwest monsoon season only. The variability of monsoon and annual rainfall is 19.6% and 15.5%, respectively, for Himachal Pradesh and 21% and 19%, respectively, for Uttarakhand. Fig. 3.7 show the time series of rainfall in mm for the months of June, July, August, September and southwest monsoon season, annual respectively for both the states. The trend lines are also displayed for each series, which indicates an increase in precipitation over the years in Uttarakhand and a decrease in precipitation over the years in Himachal Pradesh. However, the yearly and monsoonal precipitation shows marked variations every successive year. The highly erratic nature of the monsoonal and annual precipitation coupled with increased anthropogenic activities severely affect the hydrology and geotechnical aspects of the residual soil slopes of the area. Both the factors i.e., hydrology (gets altered naturally and human-induced) and geotechnical (gets altered naturally and human-induced), act in tandem and are responsible for the increase in the number of slope failure incidents in the past few decades.

Table 3.2: Mean rainfall (mm) and coefficient of variation of the state for the monsoon months, southwest monsoon season and annual (Source: Climate Research and Services, IMD)

Himachal Pradesh						
	June	July	August	September	Monsoon (JJAS)	Annual
Mean	101.4	236.0	248.7	124.1	710.3	1163.3
CV	48.4	29.7	33.0	48.9	19.6	15.5
Uttarakhand						
	June	July	August	September	Monsoon (JJAS)	Annual
Mean	162.1	382.0	360.2	189.7	1093.8	1385.5
CV	57.5	23.6	28.5	56.3	21.2	18.5

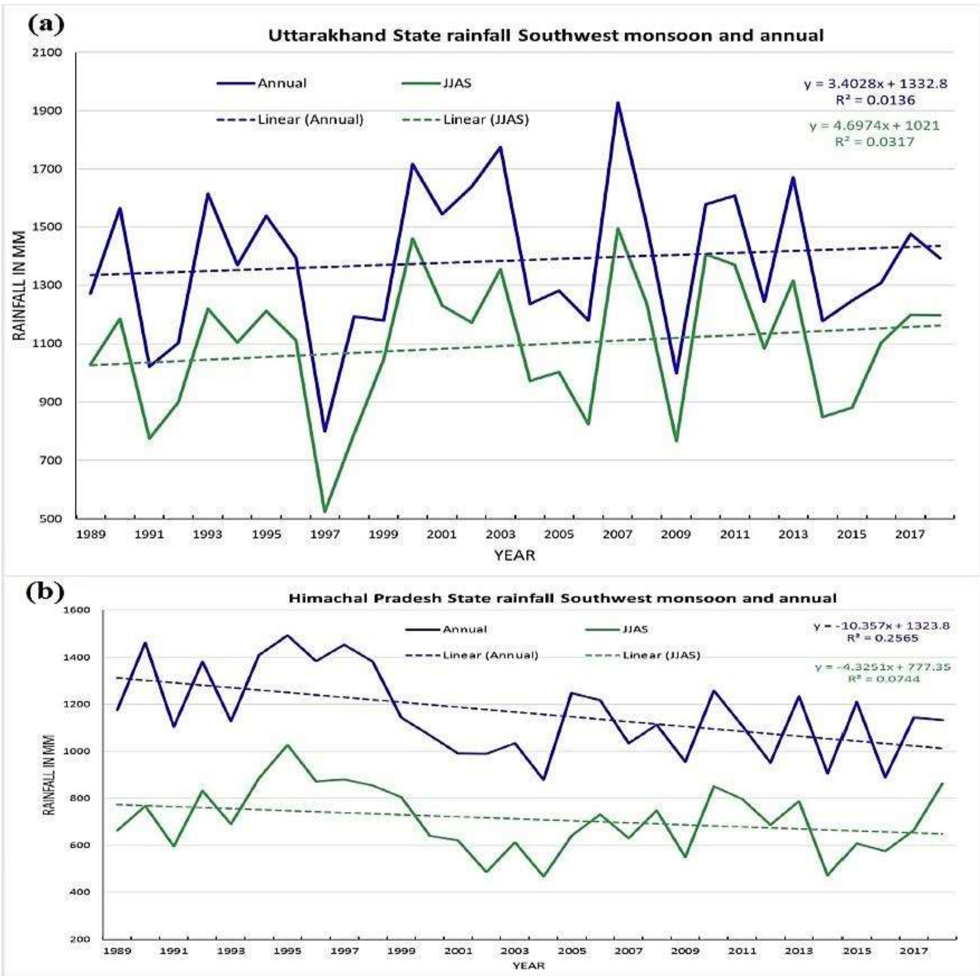

Fig. 3.7. The time series of rainfall in mm for the months of June, July, August, September and southwest monsoon season, annual respectively for (a) Uttarakhand and (b) Himachal Pradesh (Source: Climate Research and Services, IMD)

3.6 Discussion

The Himalayan Mountain range is divided into Higher, Lesser and Shiwalik/Sub Himalayan ranges by various thrust planes. The Lesser Himalayan region is highly susceptible to landslides owing to huge population density, slope profile (high and steep slopes), extreme climate and increased anthropogenic activities. Among major lithological units, the carbonate lithologies such as the limestone, dolomite and dolomitic limestones are widely distributed in this region. Due to various natural (climate, hydrology, slope morphology) and anthropogenic factors, this region has undergone prominent weathering of the bedrock resulting in the formation of residual soil layer of varying thickness. The geotechnical characteristics and engineering behaviour of residual soil depend primarily on the coupled interaction between the geotechnical properties of the soil (which in turn depends on weathering pattern) and water content. Thus, the residual soil slopes of the Lesser Himalayan region formed from weathering of carbonate lithologies have been selected for detailed investigation and predicting its behaviour under varying geotechnical and water content.

After selecting the area for investigation, the next step is to identify specific sites for data collection, including field and laboratory data collection. The detail about site selections and in-situ & laboratory tests performed to gather the geotechnical parameters of the slope is given in the next chapter.