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Research Article

Geological contribution on landslide distribution in Siwaliks of parts of central and eastern Nepal

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Abstract

The Siwaliks is the youngest among all the geological units within the Nepal Himalaya, and it is inherently weak and fragile. Conservation of the Siwalik region in Nepal has become a national challenge, and the government is currently committed to bring breakthrough in controlling landslides. Therefore, a study was conducted in the Siwaliks of central and eastern Nepal to understand the spatial distribution of landslides in different geological formations. A geological formation distribution map is prepared by collecting lithological and structural geological data from the field, and the spatial distribution of the landslide is delineated from satellite images as well as field visits. It is found that the Siwaliks in the study area are divisible into Lower, Middle, and Upper Siwaliks. In terms of landslide distribution, the Middle Siwaliks is more hazardous in terms of landslide occurrence than the other two. In an average, 60% of the total landslides in the study area fall within the Middle Siwaliks, 22% fall within Upper Siwaliks, and 13% landslides have occurred in Lower Siwaliks. It is also found that highly weathered rock beds in Lower and Upper Siwaliks favor shallow failures, whereas the easily erodible mudstone layers interbedded with comparatively less erodible sandstone layers in the Middle Siwaliks make it unstable and more prone to rock slides and rock falls. It indicates the control of geology in landslide occurrences and their types. This study will provide insights into the possible geological controls for landslides throughout the Siwaliks and support for preparing a geohazard management strategy in the study area.

Keywords: *Geology, Siwaliks, landslide distribution, Nepal*

Introduction

Geology contributes largely to the hazards like earthquake, landslide, soil erosion, sedimentation and glacial lake outburst flood (GLOF) in the Himalaya. All these hazards shape the landscape and relief of the Himalaya (Dhakal, 2015) and control geomorphology. The Himalayan region consists of highly fractured, weathered, and tectonically disturbed rocks that possess low mechanical strength and are therefore highly susceptible to slope failures (Dahal & Hasegawa, 2008). Lithology plays a significant role, as weak rocks such as shale, mudstone, schist, and colluvial deposits are more vulnerable to weathering and erosion than competent rocks.

Recently, the impact of climate change has been largely contributing to the geo-hazards and geo-disaster in Nepal (Rai et al., 2017). Geo-hazard and land degradation of the Siwalik region of Nepal is collectively controlled by geology, topography, intense precipitation, human interference and climate change (Bhandari & Dhakal, 2021; Neupane & Dhakal, 2017), out of which geology is considered as most important factor for the occurrence of landslides. The rock types, discontinuities and their orientations, weathering conditions, presence or absence of deformation structures all contribute to landslides. Siwalik zone comprises of rocks of primarily four Geological Formations namely Lower Siwalik, Middle Siwalik, Upper Siwalik and Quaternary Deposits which are very young and fragile (TU-CDES, 2016). The upstream and downstream of the major river basins in these areas are highly interlinked and therefore such land degradation in the Siwalik region pose serious threat of flooding and inundation to the southern Terai (Dhakal, 2014).

In the recent years, the occurrences of cascading hazards have been increasing in the Himalaya and particularly in different watersheds of Nepal (Sharma et al., 2023), whereby the landslides and other mass movement processes typically occurring in the upstream and their impact causes flooding in the downstream. Therefore, it is imperative that the main causes of landslides in the source regions need to be identified to make better prevention and mitigation plans. As geology is one of the most persistent causative factors of landslide occurrences in Siwaliks (Bhandari & Dhakal, 2020; Sah et al., 2003), understanding the geological characteristics and their contribution in landslide occurrences is most important for managing landslide hazard and risk in the Siwalik area. The main objective of this study is to find the distribution of landslides with respect to geological formations in the parts of Siwaliks of Nepal Himalaya.

Materials and Methods

Methodology

The geological formation distribution map delineates the areas with similar geological characteristics in one group and the areas with different characteristics into other groups covering study areas. The map comprises of the rock types, major geological structures like faults, thrusts, unconformities and folds as well as geological boundaries. This map can be used as one of the main causative factor maps for the landslide hazard mapping

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and assessment. This map can also be used for erodibility assessment.

Two major steps are followed to meet the objectives of the study: one is the indirect method of data and map collection in the office; and the other is direct field visit for geological formation distribution mapping, landslide inventory mapping and validation. In this study, geological maps prepared by Department of Mines and Geology in 1994 are referred to, validated and updated. For geological formation mapping, measurement and documentation of rock types, weathering conditions and soil type assessment is carried out in the field and the geological boundaries are delineated. These data are digitized and processed in ArcGIS 9.3 to prepare the final geological formation distribution map. Some of the major landslides are studied in the field and their types, mechanics and major causes are identified. The landslide inventory prepared in the field and the inventory of landslide scars delineated from Satellite Image are combined to prepare the landslide inventory map of the study area. Distribution of landslides based on its distribution relative to different geological formations, types and causes is also analyzed to find the contribution of geology on landslide occurrence.

Study area

The study area is located in the central and eastern portion of southern part of Nepal comprising of three watersheds namely Lal Bakaiya Watershed, Ratu Watershed and Balan Watershed (Fig. 1). The study covers mainly the Siwalik area within these watersheds comprising of fluvial sedimentary rocks having age from 16 to 1 Ma based on paleomagnetic studies (Tokuoka et al., 1986). The fragile sedimentary rocks of the Siwaliks in this area are prone to different forms of mass wasting. Most of the area is occupied by the forest and the slopes are mostly facing southwest. The landslides within the study area are complex in type. They differ with the change of the terrain of different characteristics. The gravelly conglomerates of the Upper Siwaliks are prone to granular flow due to removal or washing away of the cementing materials while the massive sandstones of the Middle Siwaliks suffer rockslides due to differential weathering of the mudstones.

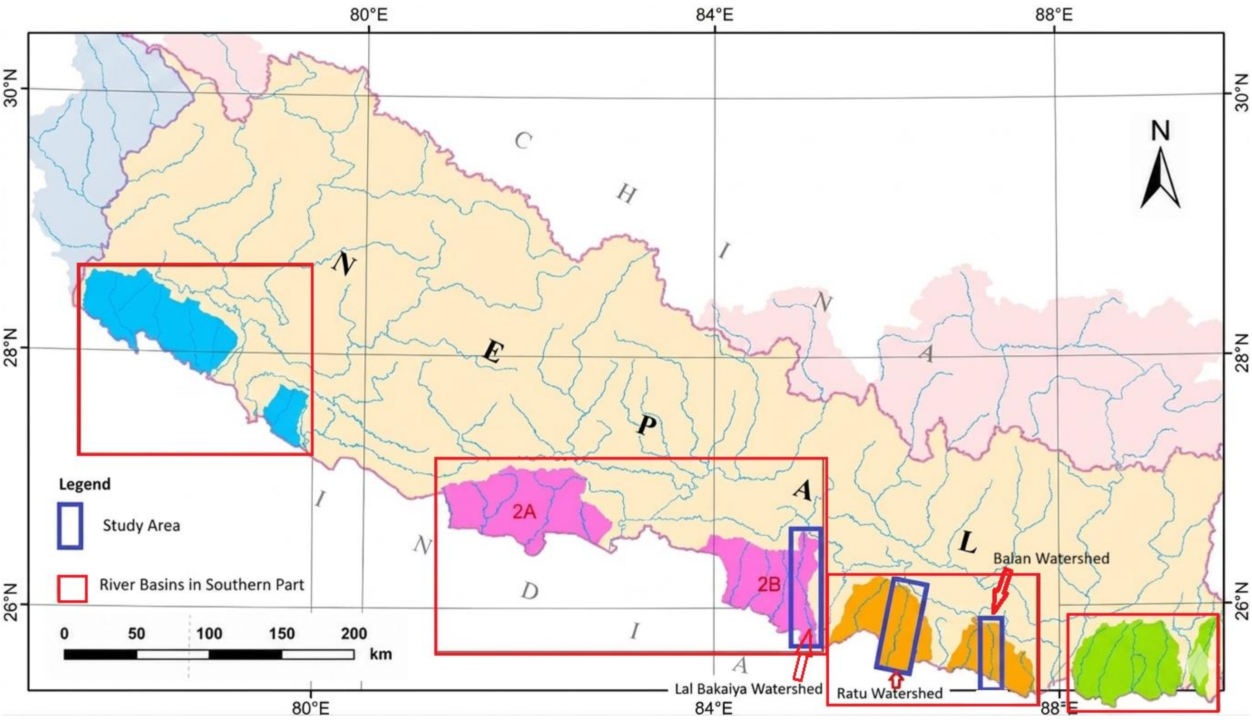

Figure 1 Location map of the study area, the red blocks in the figure indicate the river basins in the southern part that originate from Siwaliks (modified after GoN, 2024).

Geological setting

The Himalaya is originated due to the collision between the Eurasian and Indian plates which was initiated in Eocene period about 55 million years ago (Dhakal, 2015; Dewey et al., 1989; Searle et al., 1987; Powel & Conagan, 1973; Dewey & Bird, 1970) and the process is still continuing. Therefore, Himalaya is commonly known as the youngest mountain in the world. After the collision, the Indian crust was underthrusted beneath the Eurasian plate resulting in over riding of later along the series of north dipping thrust faults (Dhakal, 2015). These major thrusts run approximately parallel to each other and act as the boundaries of different litho-tectonic units in the Himalaya (Gansser, 1964; Le Fort, 1975). Like other Himalaya, Nepal Himalaya is also divided into the following units from south to north: The Terai, SubHimalaya (Siwaliks), Lesser Himalaya, Higher Himalaya and the Tibetan Tethys Himalaya (Fig. 2). Each unit is characterized by its own lithology, structure, weathering and geological history. Out of these geological zones, present study is focused only on the Siwalik area.

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As shown in Fig. 2, the Siwalik is bounded to the south by the Main Frontal Thrust (MFT) and to the north by the Main Boundary Thrust (MBT). This zone is also called Churia in Nepal. This zone consists of fluvial sedimentary rocks of Neogene to Quaternary period that are soft, loose and easily erodible; and are represented by sandstone, siltstone, mudstone and conglomerate (Dhakal & Tamang, 2025). Auden (1935) proposed the three fold classification, viz. the Lower Siwaliks consisting of fine-grained sandstones with a high proportion of mudstones, Middle Siwaliks comprising medium- to coarse-grained 'pepper and salt' sandstones with some mudstone and Upper Siwaliks containing boulder- cobble conglomerates. The sediments of this zone show coarsening upward sequence as a whole but show fining upward sequence in case of individual formation (Ulak & Nakayama, 2001).

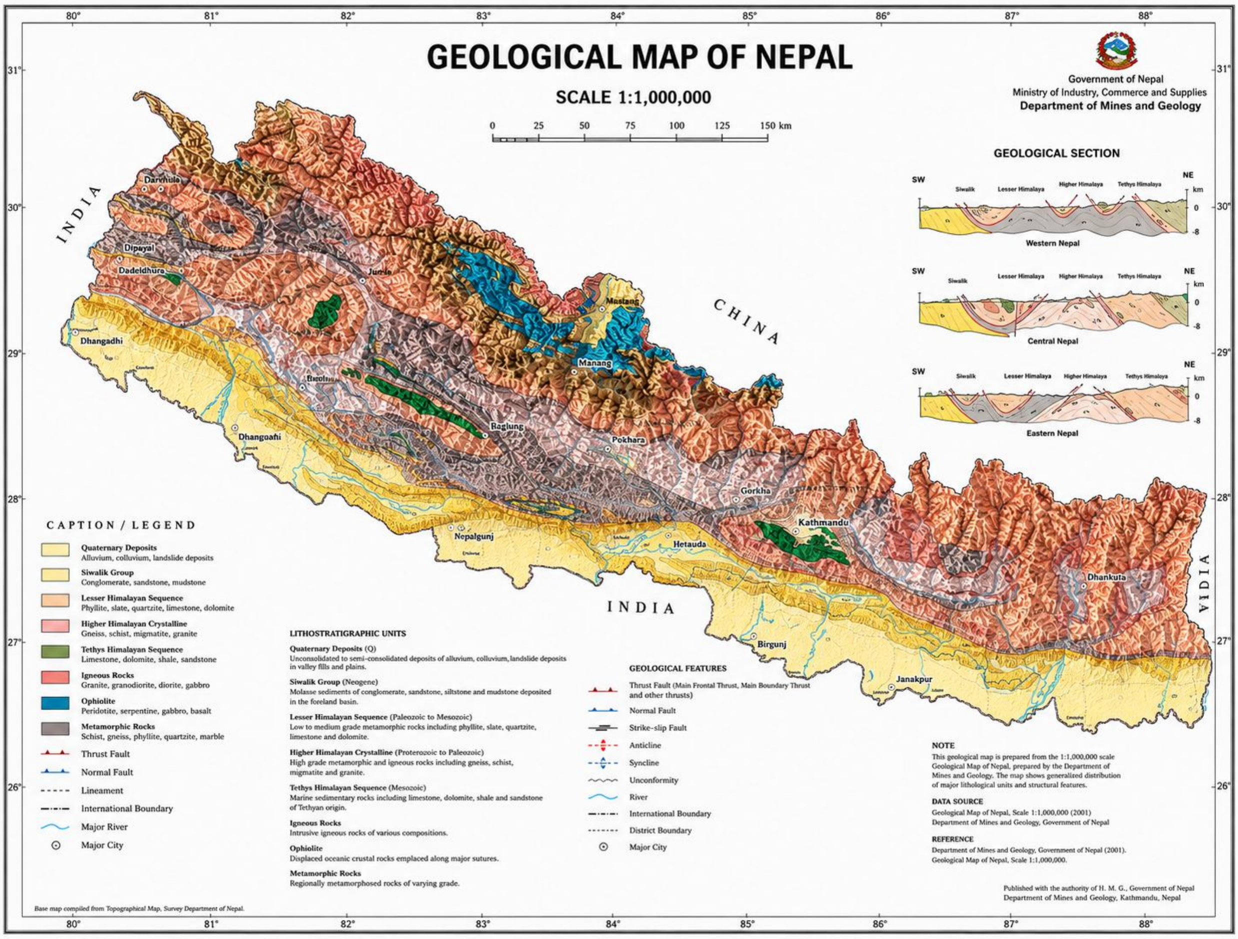

Figure 2 Generalized geological map of the Nepal Himalaya (source: DMG, 2023)

Results and Discussion

Geology of study area

Present study covers three watersheds namely Lal Bakaiya Watershed, Ratu Watershed and Balan Watershed that are located in central and eastern Nepal. Geologically, these watersheds consist mostly of Siwalik and Terai zones. Quaternary Deposits are also present in considerable amounts whereas Lesser Himalaya is present in only thin sequence of Lal Bakaiya Watershed. Ratu watershed and Balan watershed do not contain Lesser Himalaya. Balan watershed does not contain Quaternary deposits as well. In this study, the geological formations are delineated based on the distribution of typical lithology within the broad division of Siwalik area and the geological formation distribution maps of all three watersheds are separately prepared after the detailed field study utilizing the geological map prepared by the Department of Mines and Geology as reference maps (Figs. 3 to 5).

Terai is plain area consisting of recent alluvial deposits brought by the rivers from northern part and this area is free from landslides. Therefore, these areas are not elaborated here. The major parts of the Lal Bakaiya Watershed include a thick band of the Siwaliks which extends almost E-W and co-exists with a thin imbricate slice of the Pre-Siwalik Succession (Fig. 2). Rock composition varies rapidly from south to north and the rock older than the Siwaliks crops out within the Sub-Himalayan Zone associated with a local thrust. Siwaliks in this watershed can be divided into three units namely Lower Siwaliks, Middle Siwaliks and Upper Siwaliks.

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Lower Siwaliks consist of alternating beds of highly weathered green grey mudstones and green sandstone. The proportion of mudstone is greater than that of sandstone in this unit. The Lower Siwaliks represent the oldest unit of the Siwalik Group and cover the southernmost region of the Siwalik Hills in the study area. This unit is well exposed along the Dhansar Khola, Bakaiya Khola, Chisapani Khola, Lal Khola and many other streams, road cuts and foot trails around the Lal Bakaiya Watershed. Middle Siwaliks consist of alternating beds of thick bedded medium to coarse grained salt pepper sandstone with thin mudstone layers. Sandstone dominates mudstone in this unit. This unit is well exposed along the Bakaiya Khola, Pipal Danda, Thali, Chhap and adjacent places and foot trail. The Upper Siwaliks consist of pebbles to cobble conglomerates with various degrees of cementation. This is the typical composition of Siwaliks all over Nepal. This unit is well exposed at and around the Aredamar, north of Sripur village and many adjacent foot trails, stream distributed in the Lal Bakaiya Watershed. The clasts in conglomerates are dominantly quartzite and sandstone.

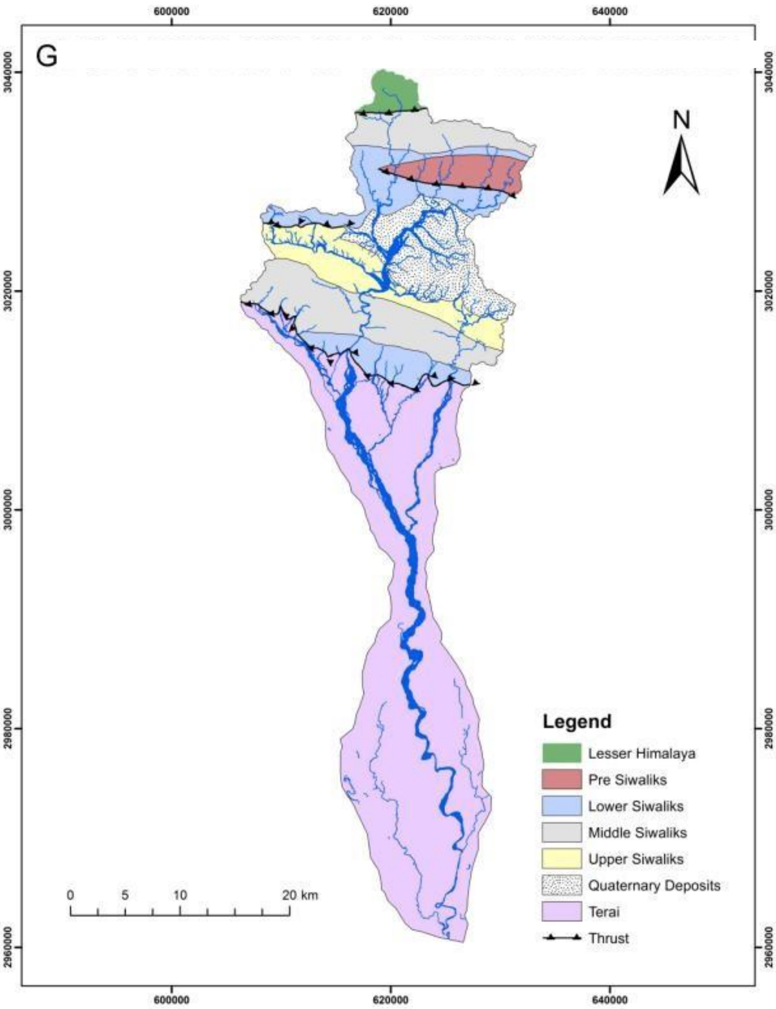

Figure 3 Geological formation distribution map of Lal Bakaiya Watershed

The Siwaliks in the Ratu Watershed are exposed in the northern section and can be subdivided into the Upper Siwaliks and Middle Siwaliks from top to bottom respectively (Fig. 4). The upper Siwaliks consist of matrix supported, highly weathered, pebbly to cobbly conglomerate whereas Middle Siwaliks are characterized by the interbedding of medium to coarse-grained, calcareous, "pepper and salt" sandstone and spheroidally weathered, often mottled, grey-green mudstone with some thin layers of purple shale. Lower Siwaliks are missing in Ratu Watershed.

The Lower Siwaliks form a thin band in the Balan Khola Watershed and are well exposed mostly in the northeastern part of the study area (Fig. 5). This formation can be well observed along the Rairaini Khola, Jhirari Khola, Rupani Khola, Hattidhuga Khola, Balan Khola and many small streams and foot trails around Rairaini, Solidhunga, Pidibas, Hattidhunga villages etc. Generally, the rocks of this formation extend from Northwest to Southeast and dip due northeast. Along the Balan Watershed, it forms the interbedding of medium- to thin-bedded, fine-grained, light grey sandstone and thick-bedded, green mudstone with thin layers of the red-purple shale.

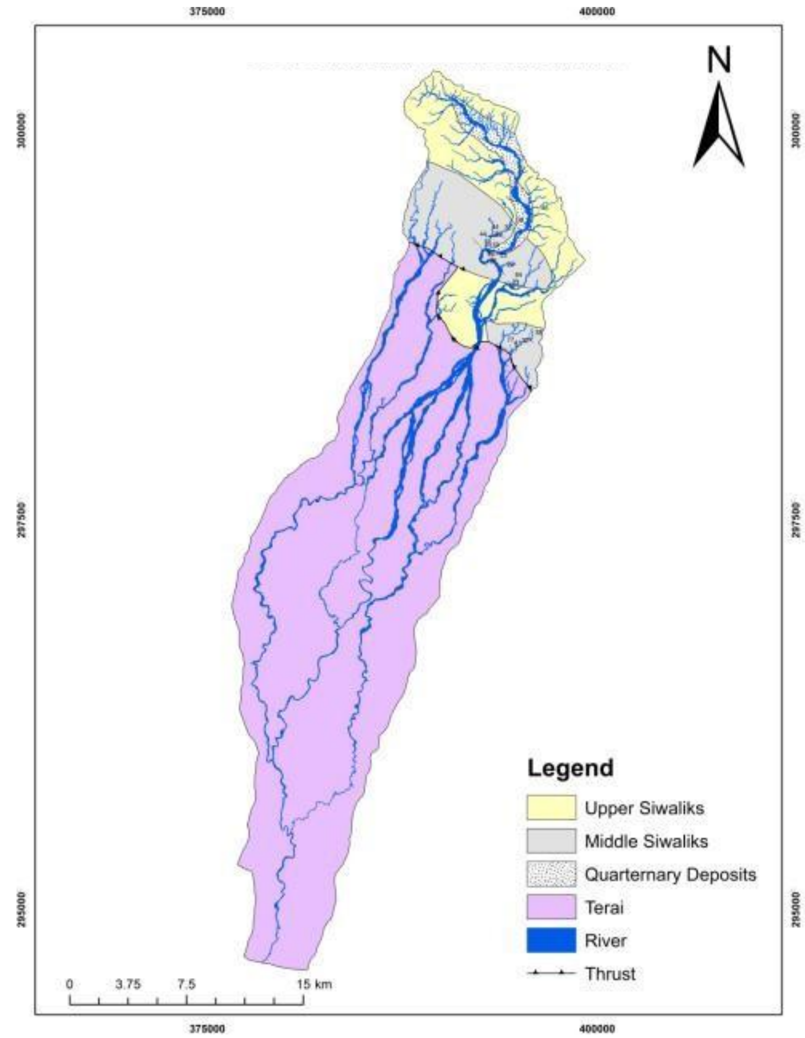

Figure 4 Geological formation distribution map in Ratu Watershed

The Middle Siwaliks in Balan Watershed are represented by the cyclic deposition of thick-bedded 'pepper and salt' sandstone, variegated, mottled, sometimes green mudstone and few red purple shale partings. This unit is well exposed along the Jhirari Khola, Rupani Khola, Satyawati Khola, Mahajani Khola, Balan Khola and Madyan Khola. Similarly, this unit is distributed around the Aredamar, Ahale, Dhabre, Saraswatitar, Mahajani villages and further to the east of the Balan Khola. The Upper Siwaliks in this watershed can be observed in the northwestern part. This unit is well exposed along the Rairaini Khola around Rairaini village, Dalame Khola, Khutti Khola, Mainamaini Khola and many other streams and foot trails in the northern part of the area. This unit consists of matrix supported pebbles to cobble conglomerate interbedded with some coarse-grained, grey sandstone. A thin sequence of the Lesser Himalaya is exposed on the northern part of Lal Bakaiya Watershed and is separated by a thrust called Main Boundary Thrust (MBT) from the underlying Siwaliks and Pre-Siwalik Rocks. However, this is not the dominant feature of this watershed. Lesser Himalaya is absent in Ratu and Balan Watershed.

Landslide distribution in study area

Landslide inventory maps are prepared separately for all the three watersheds. A landslide inventory map shows the spatial distribution of the existing landslides in the study area and is the simplest output of direct landslide mapping. In the present study, landslide scars delineated from the google earth images and verified from the field visit. The same process is applied in all the three watersheds to prepare the landslide inventory maps. In the Lal Bakaiya Watershed, a total of 594 landslide scars are delineated, whereas 41 landslide scars are delineated in Ratu Watershed and in the Balan Khola Watershed, a total of 223 landslide scars are delineated (Table 1). Within the Lal Bakaiya watershed, more than 70% landslides are found in Bakaiya Rural Municipality comprising Shreepur Chhatiwan (Fig. 6).

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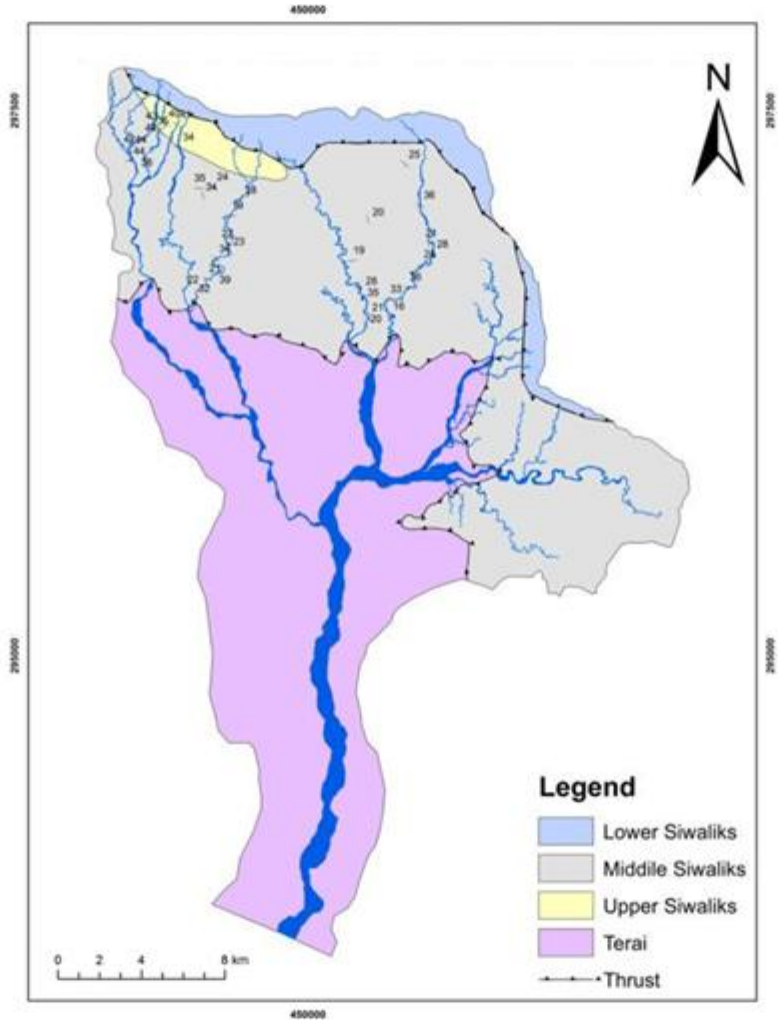

Figure 5 Geological formation distribution map in Balan Watershed

Correlation of the landslide inventory maps (Figs. 6 to 8) with the geological map depict that in an average 60 % of the landslide scars in the study area have been occurred in Middle Siwaliks. Similarly, about 22% of the landslide scars have been found in Upper Siwalik and 13% in Lower Siwalik. This correlation indicates that Middle Siwalik is most vulnerable for landslides followed by Upper Siwalik and Lower Siwalik, which is similar to the findings of TU-CDES (2016) in Central and Eastern Nepal and that of Bhandari & Dhakal (2021) in Siwaliks of Babai watershed. In Lal Bakaiya Watershed Quaternary Deposit also constitutes considerable landslides. Maisthan, Tulsichauda and Gauribas area comprises of more than 70% of landslides in Ratu watershed (Fig. 7). Similarly, Bishnupurkatti area comprises nearly 40% of landslides in Balan watershed (Fig. 8).

Table 1 Numbers of landslides according to geological Formations in all the three watersheds

Formations	**Lal Bakaiya Watershed**		**Ratu Watershed**		**Balan Watershed**	
	No. of landslide scars	*% of total*	*No. of landslide scars*	*% of total*	*No. of landslide scars*	*% of total*
Lesser Himalaya	6	1.01	Formation do not exist		Formation do not exist	
Lower Siwaliks	92	15.49	Formation do not exist		27	12.11
Middle Siwaliks	242	40.74	24	58.54	182	81.61
Pre Siwaliks	1	0.17	Formation do not exist		Formation do not exist	
Quaternary Deposit	140	23.57	-	-	-	-
Upper Siwaliks	113	19.02	17	41.46	14	6.28
Total	**594**	**100**	**41**	**100**	**223**	**100**

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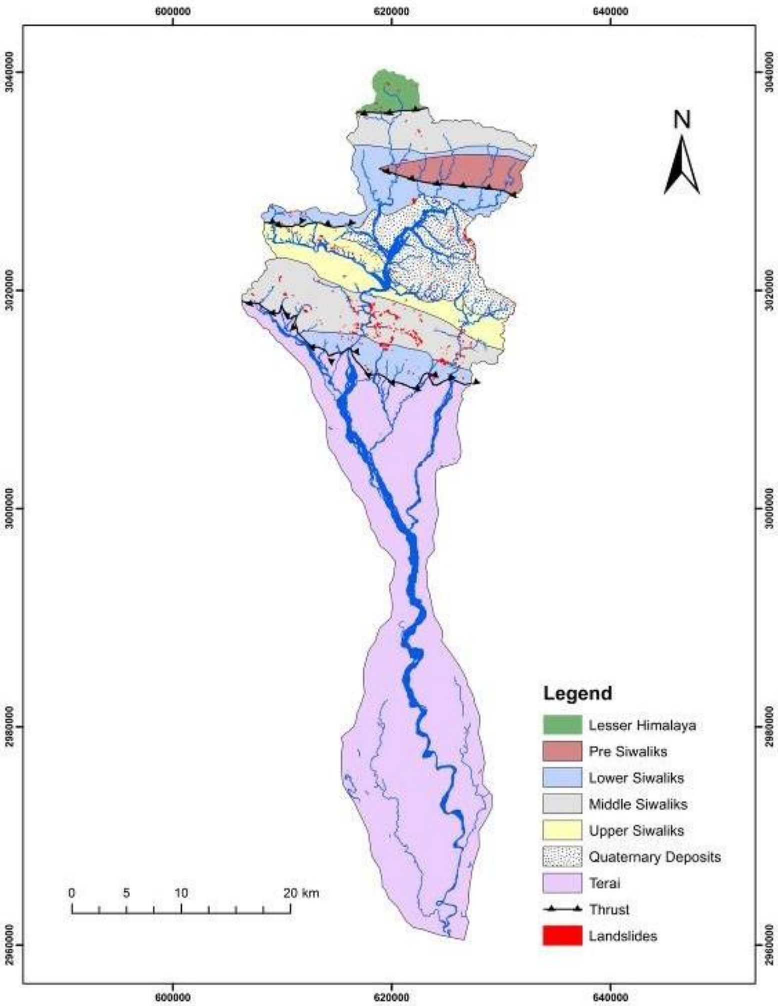

Figure 6 Landslide inventory map of the Lal Bakaiya Watershed superimposed over geological map

It is to note that the Upper Siwaliks in many places of Ratu Watershed resemble Quaternary Deposits because of the loss of cementing materials and loose compaction. Numbers of landslides studied in the field have provided insight into the causes and mechanism of landslides in the study area. The type of landslide and the mechanism vary according to the variation in geological Formations.

The Middle Siwalik consists of dominant numbers of landslides. This is because of the fact that this zone consists of thickly bedded medium to coarse grained sandstone that are relatively strong alternating with thinly bedded mudstones which are very weak and highly susceptible to physical weathering. This provides differential weathering conditions within the same area. High grade of weathering followed by erosion of the weak mudstone layers provide plenty of opportunity for the strong sandstone beds to move down slope as the support given by weak mudstone layers is lost (Fig. 9a). Further, the permeability difference between the sandstone and mudstone enhances the activity of water to create extra load in the slopes that helps to move the slope. In addition, thick sandstone beds have provided relatively steep slopes in the Middle Siwalik which have contributed to the increase in driving force, indicating the decreased safety factor in the slopes. Major mode of mass movements in this Formation is rock slide, rock fall and complex movements.

The causes and mechanisms of landslides in other Geological Formations are different. Lower Siwalik consists dominantly of weak and thin beds of mudstones which are highly weathered. In general, these rocks have already been converted to residual soil after the complete weathering of rocks (Fig. 9b). These materials can easily move down slope especially when the intensity of rainfall is high. Since the permeability of the rocks or the residual soils obtained from these rocks is low, water cannot easily infiltrate to the great depths, remain within the soil mass and put extra load of pore water pressure. This pressure also triggers the landslides in Lower Siwalik. Earth Slide is very common in this Formation; debris slide and rock slides are also present. Dominantly shallow landslides and surface erosion are common feature in this Formation. In the Upper Siwalik, conglomerate rocks are present which are made by the consolidation and cementation of the different sized rock fragments (clasts) and matrixes (Fig. 9c).

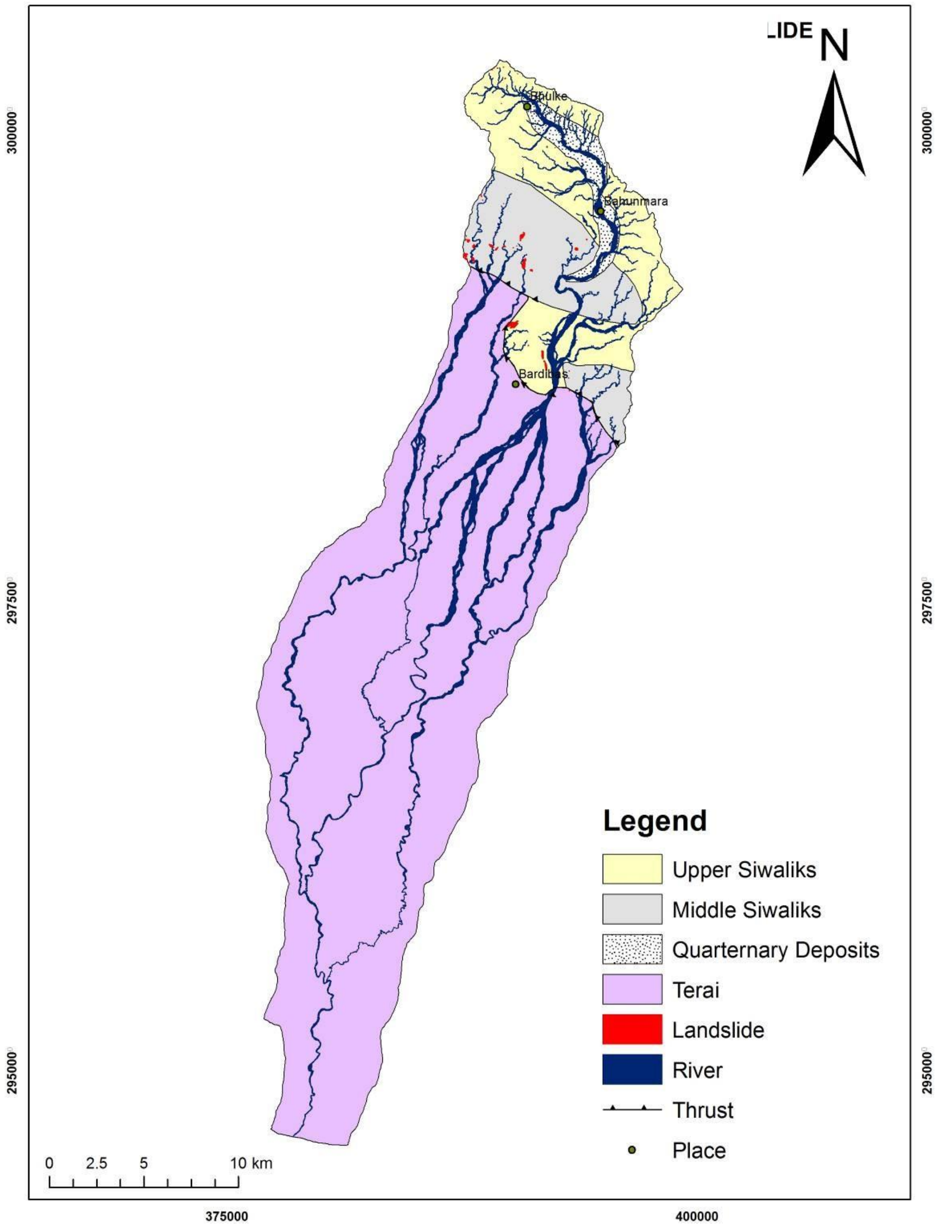

Figure 7 Landslide inventory map of the Ratu Watershed superimposed over geological map

However, in many places the cementation is so weak that the rock is converted to soil. The hills made by these types of materials easily got slided or flow in the presence of rainwater or sometimes even in the absence of rainwater as a result of discrete particle collisions. This phenomenon is especially prevalent in the Upper Siwalik of Ratu Khola watershed. Further, this zone is also characterized by differential weathering due to the different degree of cementation within the same rock mass. After the cementing material is eroded, matrix and clasts become loose and easily get eroded, slided, or fall in the form of debris or boulders. The study results in terms of spatial distribution of landslides in different geological formations of Siwaliks are in accordance with the results of Bhandari and Dhakal (2018).

The Quaternary Deposits that have been piled up at the side of river channels making small scale hills have faced mass movement problems caused by river undercutting and surface erosion. Because of the lack of cementation and consolidation of sediments, the hills are very fragile, and sediments of these hills can easily move down slope in the form of debris fall, debris flow, granular flow or debris slide. Pre-Siwaliks constitute relatively uniform and strong beds of sandstone with only slight physical weathering and therefore this unit is relatively safe for landslides. Big landslides are also found near the boundary between Lower Siwaliks and Middle Siwaliks as it can be seen near Aapdamar in Lal Bakaiya Watershed (Fig. 9d).

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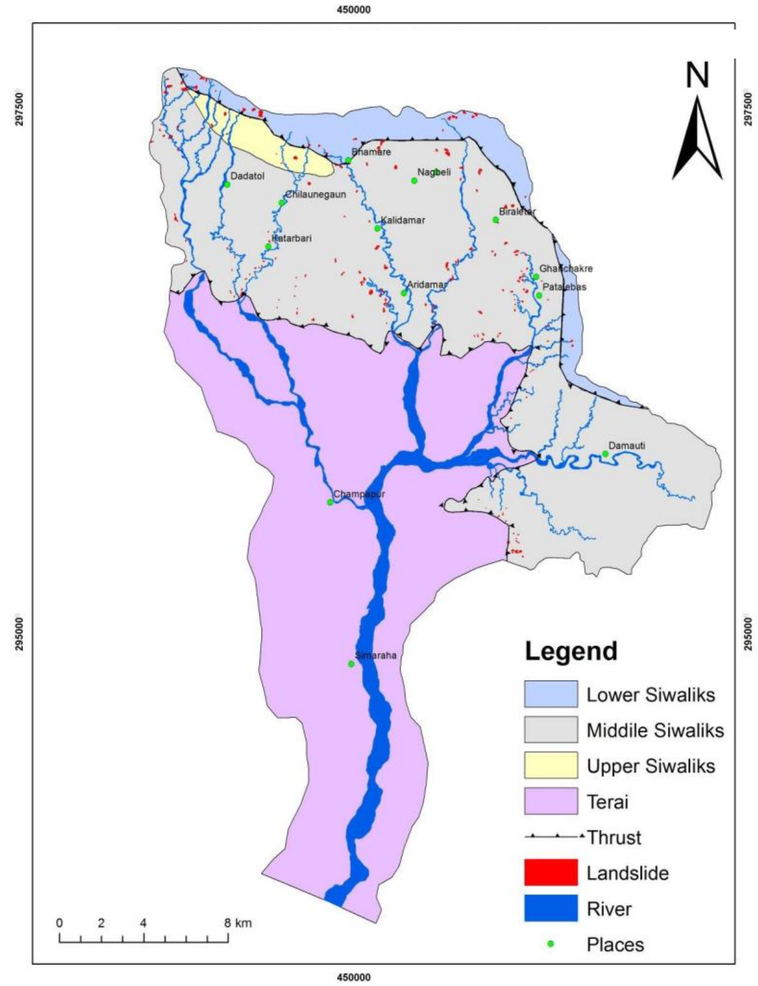

Figure 8 Landslide inventory map of the Balan Watershed superimposed over geological map

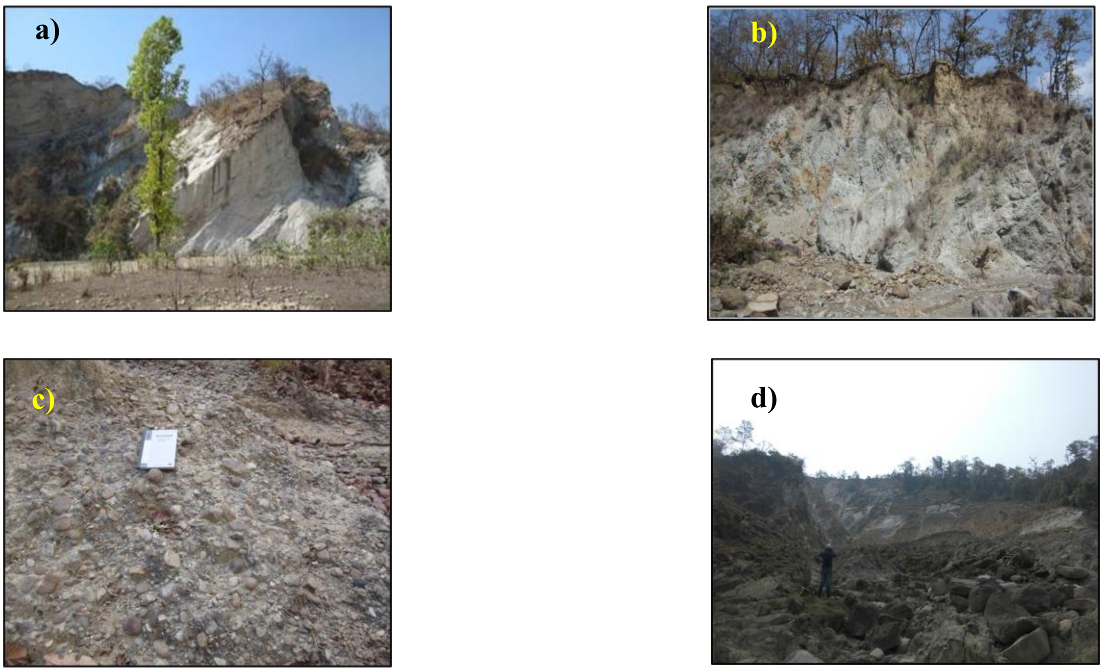

Figure 9 a) Rockslide in Middle Siwaliks exposed at the bank of the Khokasi Khola in Ratu Khola Watershed, b) Typical Lower Siwalik rock exposure in Lal Bakaiya watershed, near Hattisude, c) Matrix supported conglomerate bed exposed at Rairaini village in Balan Watershed, d) Large landslide at Lal Bakaiya Khola near the contact between Lower Siwalik and Middle Siwalik in Aapdamar

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Conclusions

It has been reported that the landslides and land degradation of the Siwaliks region in Nepal is primarily controlled by geology as the area is made up of young, weak and fragile sedimentary rocks. However, the relation of geology with landslide distribution is not well established in these areas. Present study identified it by establishing geological sequences in three watersheds of the central and eastern Nepal namely Lal Bakaiya, Ratu and Balan Watersheds. The common in all the watersheds is the presence of Terai with recent alluvium deposits in southernmost part. It is concluded that Lal Bakaiya watershed is geologically most diverse consisting of Lower Siwaliks, Middle Siwaliks, Upper Siwaliks, Quaternary Deposits, Pre-Siwaliks and Lesser Himalayan rocks. Ratu Watershed does not contain Lesser Himalaya, PreSiwaliks and Lower Siwaliks sequences. Balan Watershed also lacks Lesser Himalaya, Pre-Siwaliks and Quaternary Deposits.

It is found that on average 60% of the total landslides in study area fall within Middle Siwaliks, 22% falls within Upper Siwaliks and 13 % landslides have occurred in Lower Siwaliks indicating that Middle Siwaliks is most prone for landslide process. It is found that the diverse rock types present within this unit represented by the presence of alternating layers of thinly bedded weak mudstones with thickly bedded strong sandstone layers is the main reason for more landslides in Middle Siwaliks. This variation in lithology provides differential weathering in these two rock types and the strong sandstone layers lose support from underlying mudstone layers after the latter got washed away due to intense weathering and subsequent erosion. This contributes to the sliding of thick sandstone layers within Middle Siwaliks. In Lower Siwaliks, alternating beds of thin sandstone and mudstone have been completely weathered in most of the area providing shallow failures. The Upper Siwaliks consist of pebble to cobble conglomerate layers which have been converted to unconsolidated alluvial deposits after washing away of calcitic cementing materials. This process has led to slope failure and shallow landslides in the hills within this unit in the form of granular flow and debris slide or debris flow. The occurrence of landslides is therefore controlled highly by the geology in the Siwaliks of Nepal.

Conflict of Interest: The authors declare no conflicts of interest while publishing this paper.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

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