



Spatio-temporal dynamics of landslides in the sedimentary terrain: a case of Siwalik zone of Babai watershed, Nepal

Bharat Prasad Bhandari¹ · Subodh Dhakal² Received: 21 January 2020 / Accepted: 30 March 2020 / Published online: 8 April 2020
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Abstract

Topographical, geological and hydrological attributes of mountainous region play significant role for landslide occurrence. In this study, the spatial and temporal behaviors of landslides in the Siwalik zone of Babai watershed are evaluated on the basis of topographical, geological and hydrological attributes. For this work, polygon based landslide spatial inventory and spatio-temporal inventory from the years 2010 to 2019 were prepared by using Santeniel-2, USGS and temporal series of Google earth images. Further analysis of landslides including the numbers, area and other geometrical parameters were carried out using Q-GIS. The geological map prepared by the Department of Mines and Geology of Nepal government was referred and validated from the field. The precipitation data was obtained from department of hydrology and meteorology, Government of Nepal. The state of activity of landslides was evaluated in different geological formations in temporal basis. The result shows that the landslides in study area are highly dynamic in nature showing reactivation, expansion and even self stabilization in some parts. The new and active landslides are identified every year in every geological formation since a decade. It is also found that the hanging wall of the thrust zone is more sensitive for the distribution of medium to large scale landslides. The total annual rainfall shows positive correlation with the landslide frequency. The study will be useful for the researchers and policy makers to understand landslide mechanics and to manage the safe settlements in the area.

Keywords Landslides · Spatio-temporal dynamics · Siwalik · State of activity

1 Introduction

Landslide is common geological hazard in the mountainous terrain like Nepal that causes long term threat to the people and properties. Lying on the convergent plate boundary between Tibetan plate and Indian plate, the Nepalese Mountain is considered as an active Mountain of the world and the geological structures are very common in the Nepalese hills. Topographical and hydrological attributes of mountainous region play significant role for landslide occurrence in the hills of Nepal [2]. Many people loose their life and property every year due to landslide

mostly in the monsoon period which is the great challenges in the entire Nepalese Himalaya.

Spatial and temporal dynamics of landslide give causes and evolution mechanism of landslide. The temporal study helps to understand the series of landslide initiation and development. For the spatial and temporal study, landslide inventory is essential. The number and area of landslide can be obtained from systematic and accurate landslide inventory map [18, 30].

The adverse topography, dynamic geomorphology, weak geology and presence of geological structures are the contributing factors for landslide occurrence in the Nepal Himalaya [16, 17]. TU-CDES [38] studied about the

✉ Subodh Dhakal, subodhdhakal@geology.edu.np | ¹Central Department of Environmental Science, Tribhuvan University, Kirtipur, Nepal. ²Department of Geology, Tri-Chandra Multiple Campus, Kathmandu, Nepal.



characterization of landslide of Siwaliks zone and prepared landslide susceptibility map. The research concluded that the major causes of landslide in Siwaliks zone is toe cutting of hillslopes, heavy soil erosion and geological composition. Bhandari and Dhakal [4] studied the landside of Babai River catchment of Siwaliks and reported that lithostratigraphy is the main cause for landslide occurrence in Siwaliks region of Nepal. Lithologically, the rocks may be strong but stratigraphy may adverse and cause the landslide. Most of the landslides of Siwalik zone are originated on the steep slope convert in to the debris flow and deposit huge amount of sediment in to the river channel [3]. Dahal et al. [13] studied the landslides of Eastern Siwaliks region and prepared the landslide hazard map in catchment scale. They concluded that the slopes of Siwaliks zone are prone to landslide during intense rainfall due to rugged and fragile topography. To reduce the future risk and to cope with them, the evolution mechanism of landslide should be identified. The landslide characters should be identified on spatial and temporal basis to judge the landslide dynamics.

The landslide evolution and dynamic has been studied by several researchers in the past globally. Carrara et al. [6], Crozier [11], Guzzetti et al. [21] discussed about the role of intrinsic (lithology, elevation and soil thickness) and extrinsic factors (extreme rainfall, earthquake and human interference) for landslide occurrence. Iverson [25], Msilimba and Holmes [28], Wang et al. [40], Sassa et al. [35], Guzzetti et al. [21] studied about the role of discontinuity, slope materials, rock weathering, nature of soil for landslide occurrence. Geomorphological characterization of landslide is important task for the study of landslide evolution.

The characteristics of rainfall induced landslide are controlled by rainfall pattern as well as geological and geomorphological conditions. According to Chen et al. [8], the rainfall induced landslide tended to occur on dip slope rather than windward slope and concluded that geological settings were a more effective control of the mass wasting processes on hill slope scale than the rainfall condition. Chigira et al. [9] studied the geological and geomorphological characters of rain and earthquake induced landslide of Japan. According to Chigira et al. [9], the response shown by different geological materials are different with rain and ground shaking. Triggering of landslide is majorly controlled by a stability or safety criterion, which depends on material strength loss [26], precipitation [13, 21, 25] through pore pressure and water table height. According to Densmore et al. [14], the landslides are supposed to occur along the steep slope. The threshold slope angle for sliding may be dependent on climate or on lithology [19, 24].

Despite so many studies globally, landslide dynamics and evolution process are still lacking in the important

geological zone of Nepal Himalaya. In this context, the main objective of this study is to identify the decadal evolution process and dynamic behaviors of landslide in catchment scale at the Siwaliks zone of Nepal. The study will be useful for the policy makers and different stake holders of Siwalik region to understand landslide and to manage the safe settlement in the days to come.

2 Materials and methods

2.1 Study area

The study area lies in the Babai River catchment, Mid-western Nepal which is extended into the three districts of Mid-Western Development region namely Dang, Salyan and Bardiya. The Babai River is east–west trending river originated from Siwalik hill and located between 27°57'59.03" N, 82°33'42.80" E at east, 28°28'30.14" N, 81°28'30.14" E at west, 28°12'47.90" N, 82°15'46.08" at north and 28°01'03.89" N, 82°12'39.61" E at south. Total area covered by whole watershed of Babai River is 1952 km² and perimeter is 316.640 km but the study area covered only 1157 km² (Fig. 1). The Babai catchment is characterized by various landscapes, from upper Dang valley to lower Babai valley with several ridges extended up to 1500 m from mean sea level. The large flat Dang valley is extruded for the study because the flat land is considered as landslide free area. The Siwaliks in the study area have altitudes ranging from 109 to 1500 m and exhibits a very rugged topography with highly dissected gullies and steep slopes.

Most of the hill ridges in the study area extend in the east–west direction, parallel to the main geological structures. The landforms of the study area are mainly controlled by the tectonic processes and subordinately by mass wasting and weathering. The erosional landforms predominate over the depositional ones. There are rugged hills, numerous deep gorges, steep slopes, cliffs, and active gullies representing the erosional landforms, whereas river terraces, alluvial fans, and talus cones are the examples of depositional landforms. Drainage density is higher toward North-East and lower towards South-West. As a whole, the climate of study area is sub tropical. The winter is very cold (0° to – 3 °C) and summer is very hot (40° to 45°). The rainfall is heavy and occasionally intense during rainy season. The average annual rainfall over the period 1990–2017 AD is in the range of 1800–3300 mm. More than 80% of rainfall occurs in rainy season.

2.2 Geological setting

The geological setting of the area is similar to the overall Siwalik region. The area lies between two major thrusts

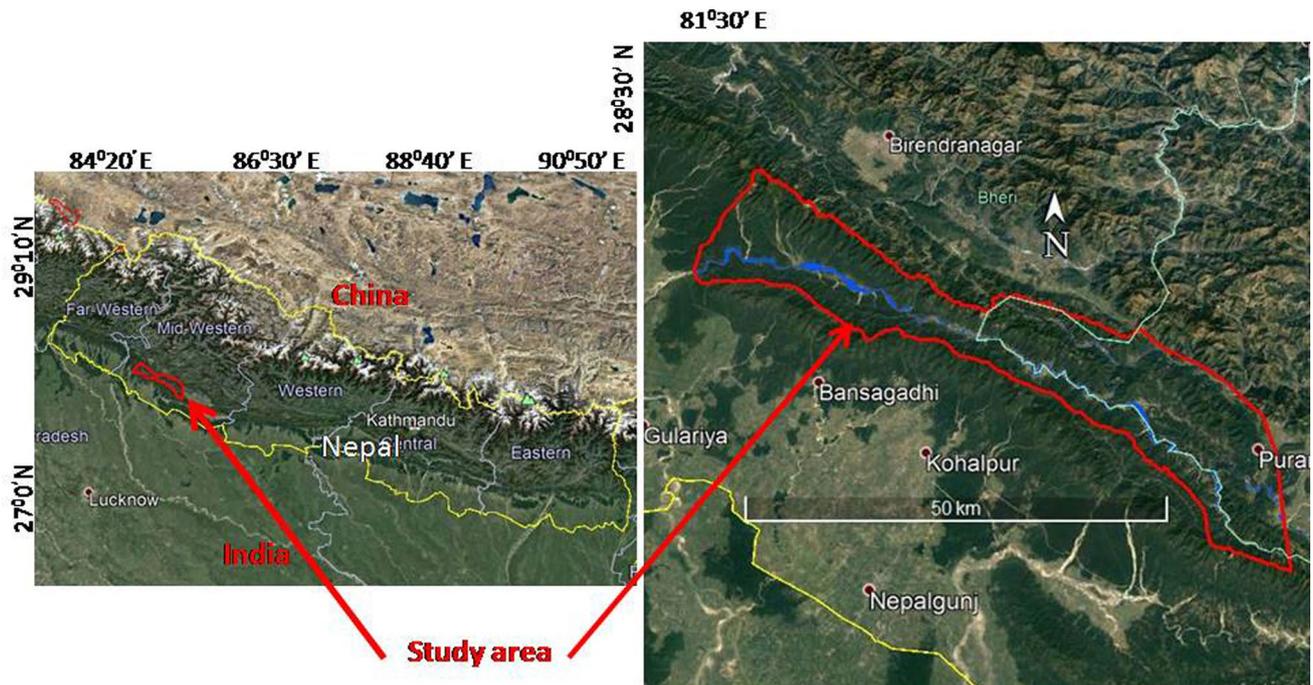


Fig. 1 Location map of study area. Source Google Earth

namely Himalayan Frontal Thrust (MFT) and Main Boundary Thrust (MBT) that is bounded by Indogangetic plain in the south and the Lesser Himalayan rocks in the north. The bed rock geology of study area is dominated by younger (Neogene) sedimentary rocks. The study area has three major thrust and one minor thrust [3, 4]. Main Boundary Thrust, Babai Back Thrust and Bheri Thrust are major thrust where as Malai Thrust is one minor thrust. All the Thrust are E-W trending and north dipping (Fig. 2).

The sedimentary rocks of the study area divided in three geological formations [1, 3, 4, 7, 23]. From bottom to top they are Lower Siwaliks, Middle Siwaliks and Upper Siwaliks, respectively. The Lower Siwalik consists of interbedding of fine to very fine grained grey-green sandstone and red–purple, brown mudstone. Mudstone bed is medium to thick, highly fractured and highly weathered. Sandstone bed is of thinly bedded and spheroidically weathered [4]. Thin layer of sandstone lies between thick layers of mudstone in the overall Lower Siwalik zone. The characteristics feature of Middle Siwaliks is of medium to coarse grained thickly bedded salt and pepper as well as pebbly sandstone and variegated mudstone. Sandstone beds are massive, less compact and weathered due to poor intergranular bonding [3, 4]. The sandstone of Middle Siwaliks consists of minerals like quartz, feldspar, muscovite and biotite. The bed of sandstone is thicker than mudstone. The thickness of

sandstone bed varies from 0.3 to 3.4 m whereas thickness of mudstone bed varies from 7 to 92 cm [3, 4].

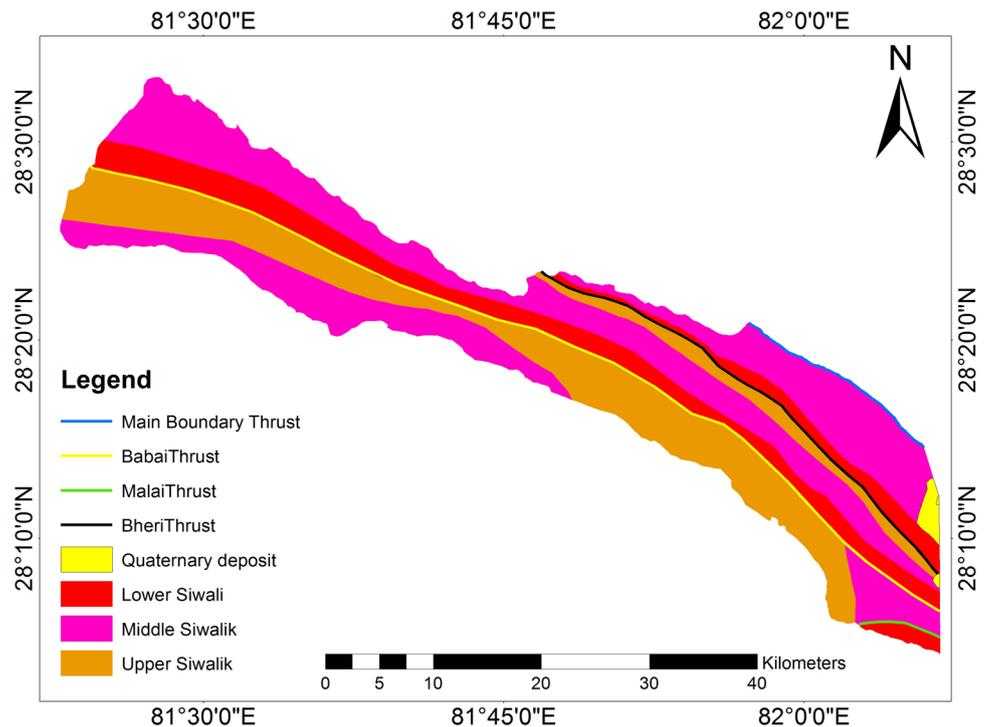
Upper Siwaliks consists of cobble and pebble bearing conglomerate interbedding with yellow to brown mudstone. The cementing material of conglomerate is calcite and mostly clay. The size of clast in conglomerate varies from 5 to 100 mm. Most of the flat lying area is covered by superficial quaternary deposits.

The colluviums of hilly terrain include debris-flow and other slope debris deposits and landslide deposit mostly of late-quaternary period [3]. Colluviums occur as relatively thick deposits filling drainage courses. However, there are deposits which are considerably thinner and of greater areal extent on some hill slopes in the study area. The colluviums derived from erosion and landslide typically consists of sub angular cobbles and boulders of sandstone and mudstone with some conglomeratic fragments. Huge amount of alluvial deposits occur in river terrace and valley fill.

2.3 Methods

The remote sensing data and satellite images are essential to identify the landslide evolution process but field investigation is very important to understand the mechanism of land sliding. Morphological analysis is another important factor for the landslide study. Varnes [39], Guzzetti et al.

Fig. 2 Stratigraphical map of study area. Source Bhandari and Dhakal [3]



[22], Bucci et al. [5] proposed several geomorphological characters to identify landslide probable area. By the study of surficial process such as rock weathering, soil erosion, deposition and status of vegetation, the morphological features of old landslide can be identified. For the early stage of landslide investigation, various factors such as aerial photography, remote sensing images and mostly field observation are considered the necessary task [33, 34]. For the study of landslide mechanism, the land surface condition before and after the land sliding are identified. Detail methodology is described in the following section.

2.4 Landslide inventory

The polygon based landslide inventory of study area was prepared on spatial and temporal basis by using 12.5 m resolution satellite images and 952 landslides were identified in images (Fig. 3). The temporal inventory of landslide from 2010 to 2019 AD (Fig. 4) was prepared on the basis of state of activity (Fig. 5), slope (Fig. 6) and size by using USGS images, Santeniel-2 and time series data of Google earth of resolution 12.5 m. The acquisition dates of imagery used to map landslides ranged from August to December and April to Jun of each year from 2010 to 2019 AD. Some imagery as badly affected by cloud but the multiple set of imagery from different dates helped to avoid the problems. Some area badly disturbed due to cloud and steep terrain has been excluded for analysis but has been included in map after field verification. The scar

to toe area of each landslide was identified in the image. The landslides were recognized by the color variation and topographical differences. We were able to identify the scar area and deposit area of landslide due to that the polygon based landslide inventory was possible. The landslide boundaries in the satellite images were identified based on attributes such as headwall scarps, chutes representing material movement pathways, and lobes of transferred materials [20]. The prepared inventory map was updated by using topographical map of 1:25,000, geological map [3] and Digital Elevation Model (DEM) of 12.5 m resolution. The slope and elevation maps were obtained from DEM. The perimeter, length and area of landslides were obtained on temporal basis by using polygon in images. The polygons were obtained in a GIS framework to analyzed topographical, hydrological and geological factors.

2.5 Field study

All the mapped landslides using remote sensing techniques were verified in the field by visual observation in the landslide site. Among 952 landslides, 100 landslides were selected randomly for field study. The landslide having area greater than 100 m² were taken for detailed field study. The length of landslide, slip surfaces, tow length, distance travelled by slide materials, slope, aspect and elevation of 100 landslides were measured manually. The area and length of landslide measured in the polygon were compared to each other.

Fig. 3 Landslide inventory map of Siwalik hill of Babai catchment

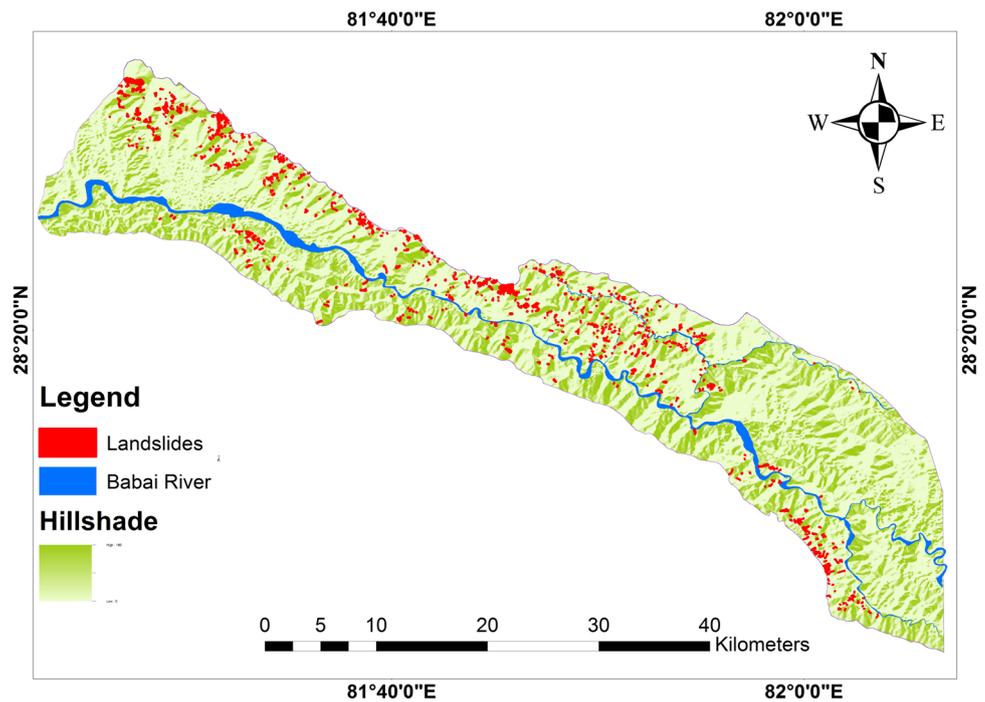
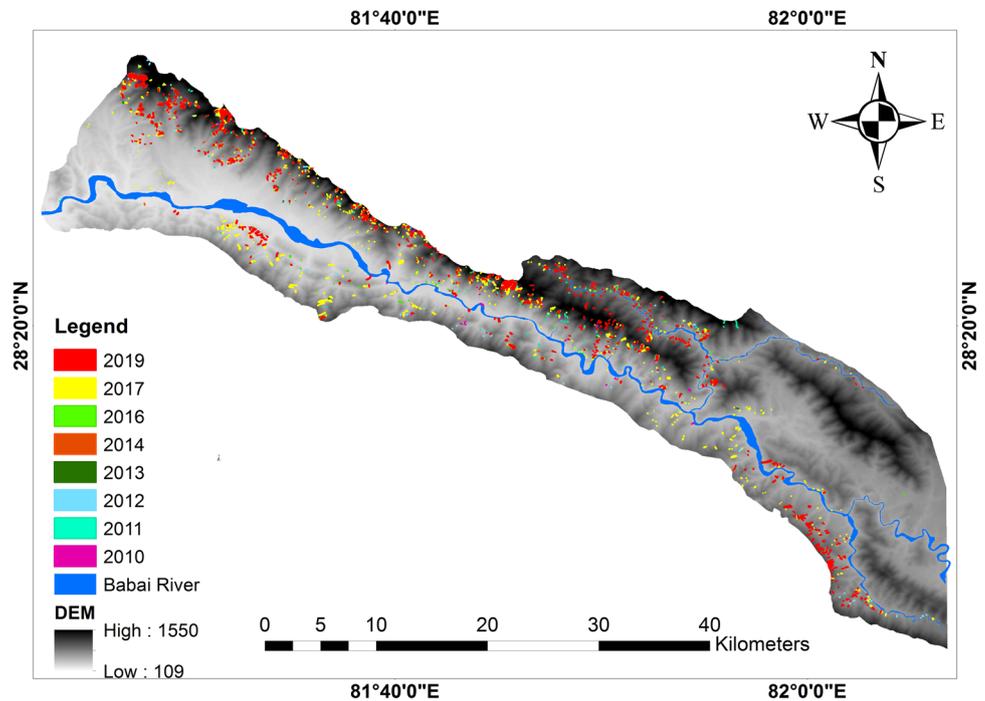


Fig. 4 Multi temporal inventory map of Siwalik zone of Babai watershed



The geological structures, formations and their impacts on landslide occurrence were also studied in the field. Physical characteristics of landslides, including landslide description, the physical parameters contributing to the initiation of landslides were analyzed. The landslide initiation mechanisms were studied and analyzed based on the field observation.

2.6 Data analysis

The landslides in the inventory map were compared with the field data for the validation of landslide distribution in the study area. This is followed by the characterization and analysis of landslides. Major four landslide probable factors: geology, slope, fault and rainfall were selected

Fig. 5 Inventory of state of activity of landslides

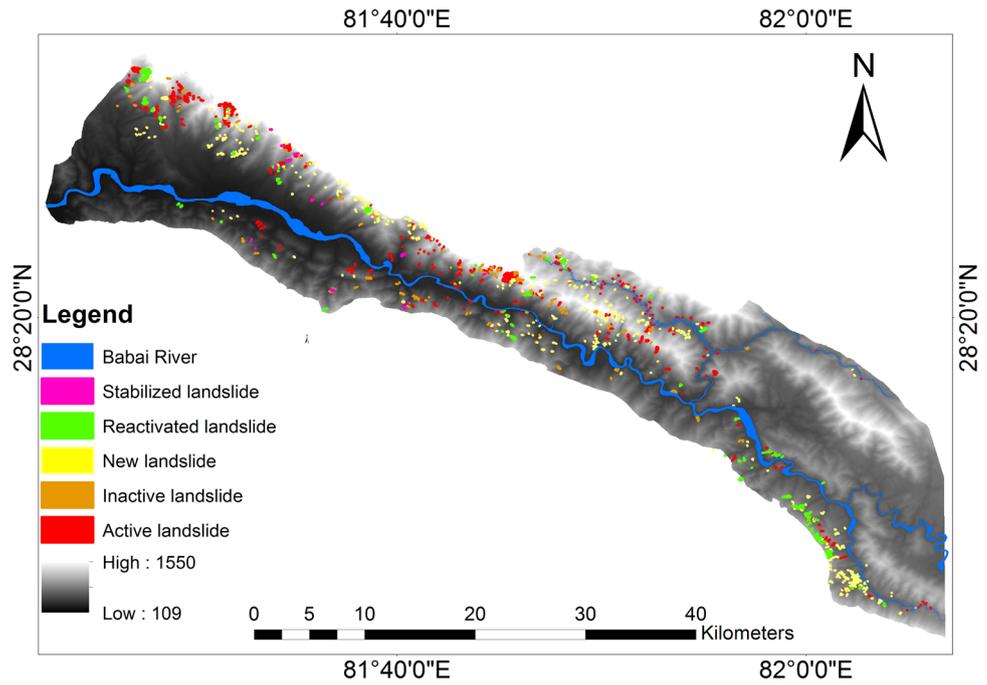
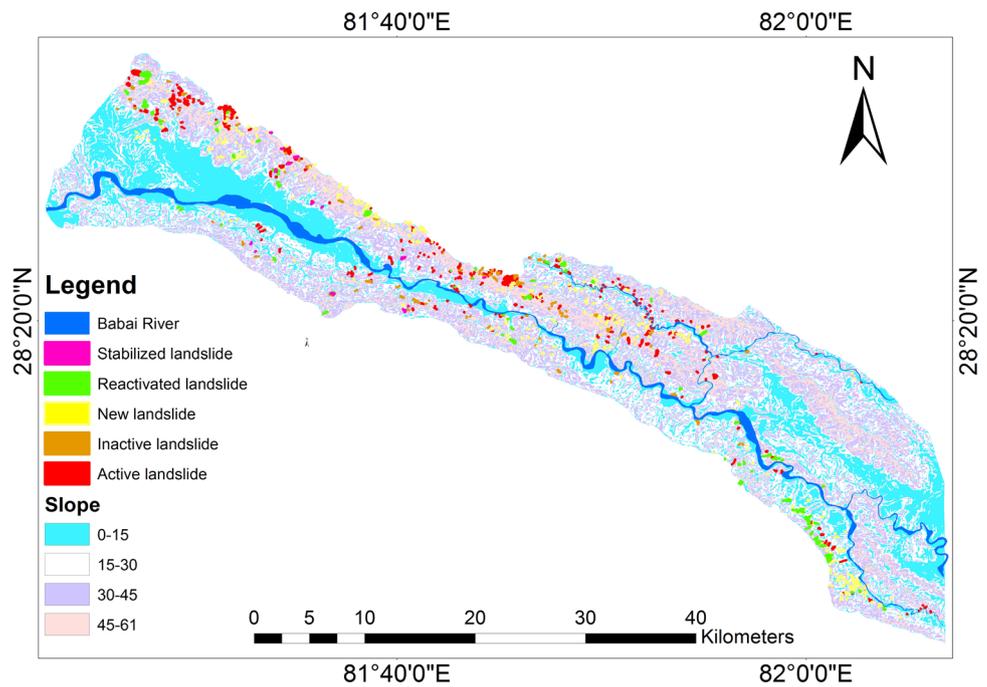


Fig. 6 State of activity of landslides in different slopes



for the evaluation of landslide dynamics. The geological formation and thrusts were taken for geological attribute, slope was taken for topographical attribute and rainfall data was taken for hydrological attribute. The pre existing landslides were used to analyze the different attributes. MS excel and R-software was used for data analysis. More than thousand landslides were encountered but only 952 are of size having area greater than 100 m².

2.7 Activity classes

Most of the landslides that were unclear in the images were confirmed in the field by visual observations and different social survey. The term to define activity classes were adopted from some of the past researches. The multilingual landslide glossary [41], distinguishing the following four classes of states of activity:

Table 1 Landslide classification based on its activities

Name	Characters
New (N)	Landslides that has occurred in last 36 months
Active (A)	Landslides that has been moving every year/ Movement has occurred in last 12 months
Inactive (I)	No movement has occurred since three years and having no prior probability to reactivate in near future
Reactivated (R)	Landslide reoccurred in the inactive or stabilized landslide
Stabilized (S)	The landslide mitigated naturally or structurally and seems stable at present

Table 2 Landslide size on the basis of area

SN	Area (m ²)	Size class
1	< 100	Very small
2	100–1000	Small
3	1000–10,000	Medium
4	10,000–100,000	Large
5	100,000–1,000,000	Very large

Stabilized (S): not affected by their original causes anymore.

Dormant (D): potentially being reactivated.

Active (A): currently moving.

Reactivated (R): moving after being inactive.

Cigna et al. (2013) proposed three classes of activity of landslide on the basis of VACT (Distinguishing moving from non moving area) and Vp (Present velocity) namely; stabilized, Dormant and Active. We proposed five activity classes and established for this study namely: new, active, inactive, reactivated and stabilized. The basis of classification of landslides based on activities is as given in Table 1.

2.8 Size of landslide

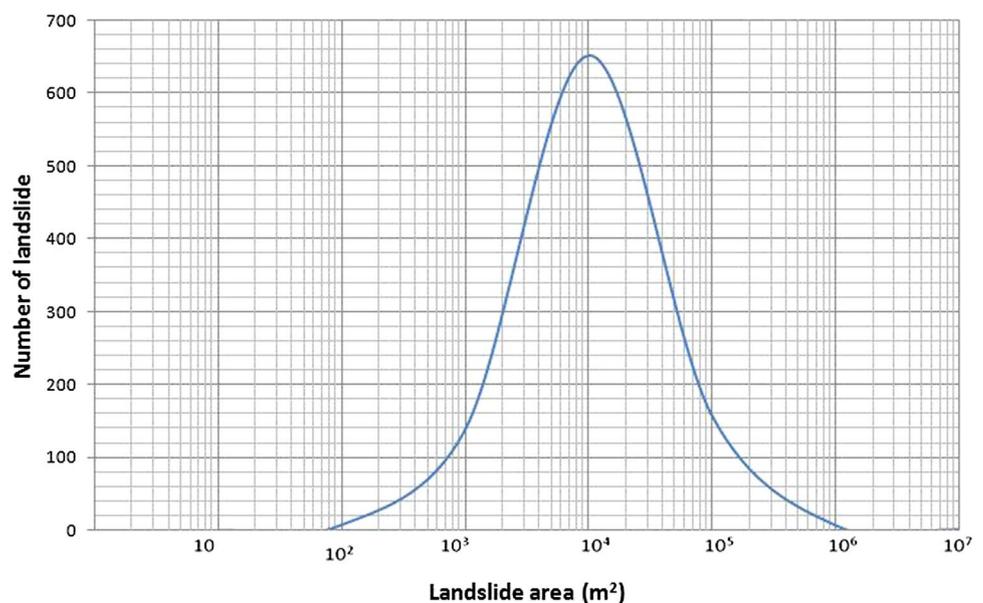
Five landslide size classes are proposed on the basis of logarithmic scale. The proposed landslide size classes are adopted on the basis of area for the size based classification (Table 2).

3 Results

3.1 Landslide inventory

Altogether 952 landslides (old and new) were identified in the image and from the field verification. The landslide area and frequency has been investigated and the result showed that the area of landslides are log-normally distributed (Fig. 7). The five different sizes of landslide were adopted for size based classification namely very small, small, medium, large and very large on the basis of area. The medium sized landslide covered 67.7% whereas the large and small sized landslide covered only 16.5% and 14.7% respectively. The result indicates that the landslides

Fig. 7 Figure showing the landslide size and number relationship



having area between 1000 m² to 10,000 m² (medium sized) are dominant in the study area.

3.2 State of activity

After the study of state of activity of landslides, five major states of activities are taken namely new, active, inactive, reactivated and stabilized. The maximum, minimum and total area of different states is given in Fig. 8. In the study area, 40% of area is covered by active landslide whereas 26% area is covered by reactivated landslide. Area covered by new landslide is 18.45%. The stabilized landslide is only 3.3% and inactive landslide is 11.63% (Fig. 8), thus the result showed that the most of the landslides are being active every year since a decade. The occurrence of new landslides is less than active landslide. Similarly, the rate of reactivation of landslide is 26% which is second highest rate of landslide occurrence. Most of the past landslide deposits are reactivated.

3.3 Geological distribution

The geological distribution of landslide was found on the basis of geological formation. The area is divided in to three formations namely Lower Siwalik, Middle Siwalik and Upper Siwalik [3, 4]. Figure 9a shows that every state of landslides is dominant in Middle Siwalik whereas the active and new landslides are majorly found in Middle Siwalik but new landslides are major in Lower Siwalik. The landslides having area 1000–100,000 m² is dominant in all the geological formations (Fig. 9b). There is no significant difference in the size-frequency of landslide in all the geological formation. Less number of very large sized landslides was encountered in the decade from 2010 to 2019 AD. The size distribution of landslide in every geological formations of study area is normal distribution. The result shows that the landslide size distribution in all the

geological formations is same. The total length of landslide is significantly different in all geological formations. The landslides having total length < 200 m is dominant in every formation (Fig. 9c). The landslides distributions in the structure of different thrust zone are given in Fig. 9d. Among the three major thrusts of the study area, Babai thrust is more potential for landslide. Hanging wall of thrust zone has higher number of landslides. Most of the landslides lie on the fault zone either in hanging wall or on foot wall. The rock of hanging wall are crumbling, highly jointed and crushed and due to that hanging wall consists of large number of landslides in comparison with foot wall.

3.4 Temporal dynamics of landslide

The landslide distribution from 2010 to 2019 AD was performed (Fig. 10a). During the period of 2010 to 2019 AD, the annual landslide frequency varies significantly. In 2010 AD, there were only 198 landslide events but in 2011 AD, the landslide number increased significantly and reached 398. But in 2012, again the landslide number decreased. The landslide events increased significantly from 2013 to 2019 AD. In case of geological formation, the landslide trend can be described in three patterns. Firstly, the landslides number increased significantly from 2010 to 2011 AD. Secondly, the landslide number decreased in 2012 AD and again increased from 2013 to 2019 AD. These trends are similar for every geological formation. The annual change in area of landslide in geological formations is not in positive trend. The area has fluctuated annually. In case of Lower Siwalik, area increased from 2010 to 2011 AD but decreased in 2012 AD. Again the area increased from 2013 to 2017 AD. The area decreased in 2018 AD and again increased in 2019 AD. Similar result is found in Middle Siwalik but the result is slightly different in Upper Siwalik. The area decreased from 2011 to 2013 AD and increased up to 2017 AD. The result shows that the number of landslide event decreased significantly in 2018 AD and increased in 2019 AD. The number of landslide is found highest in 2019 AD in all the geological formations since 2010 AD. It is also found that the area and number of landslide is higher in Middle Siwalik every year (Fig. 10b). The result concluded that the Middle Siwalik is potential for landslide occurrence.

Discussing the state of activity of landslide, the area of new landslide decreased in 2011, increased in 2012 and 2013 and again decreased in the year 2014 but increased from the year 2016 to 2019 (Fig. 11). The active landslide rate is increasing trend from 2010 to 2016 but slightly decreased in 2017 and increased in 2018 and 2019. The reactivation rate decreased in 2011 and 2012 but increased from the year 2013 to 2019. The result shows that the number and area of landslides decreased mostly

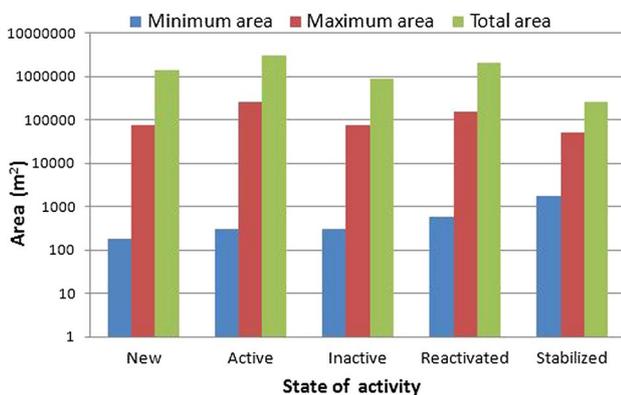


Fig. 8 The area of different state of activity of landslides

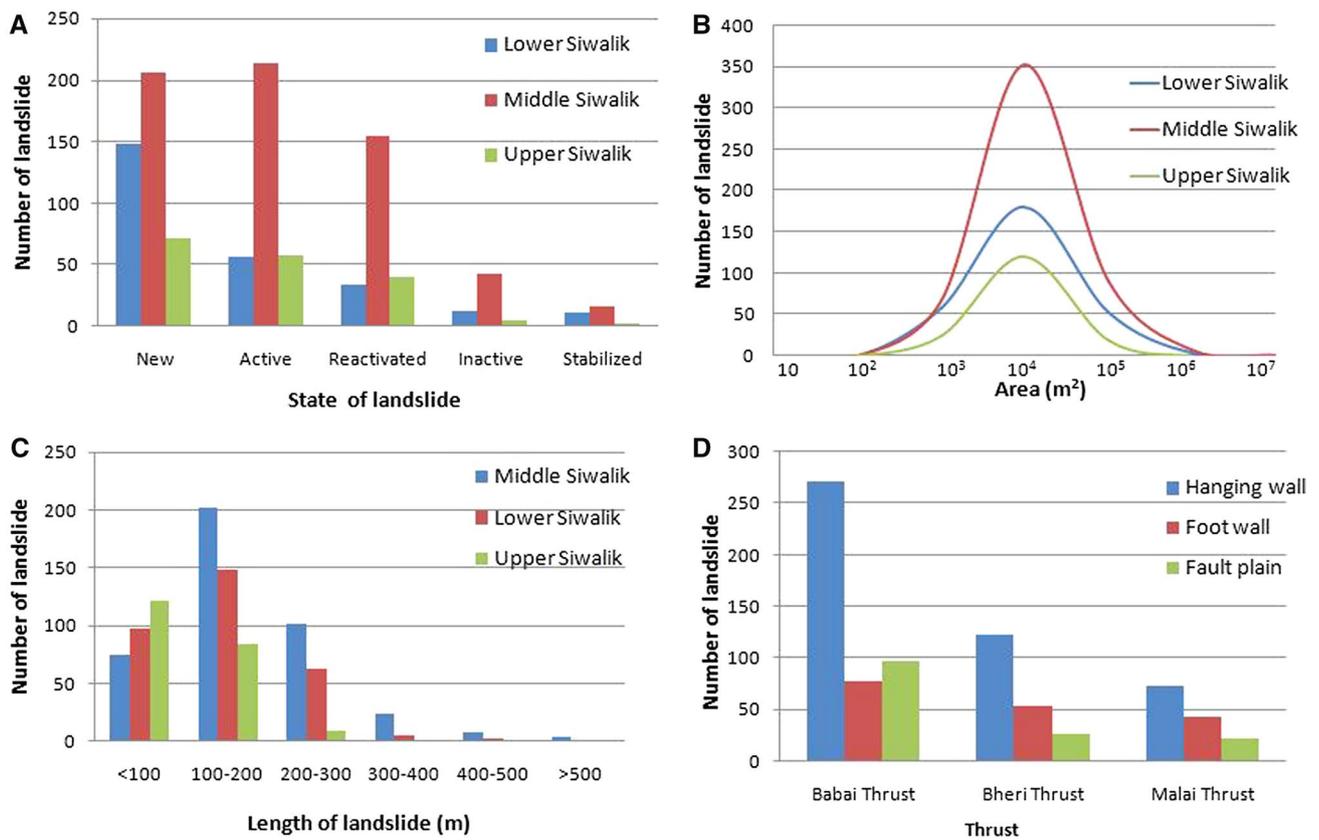


Fig. 9 **a** Figure shows the number of state of landslide activity in different geological formations, **b** area and number relation of landslides in the geological formations, **c** length and number dis-

tribution of landslide in different geological formations, **d** landslide distribution into different thrust zone

in two years; that is 2012 and 2018. In other years, the landslides area and frequency has increased. Since the decade, the area and number relation is in normal distribution. The medium sized landslide (having area 10,000 m²–100,000 m²) is dominant every year. The trend of landslide area and number curve is same in every year since the years 2010–2019 (Fig. 12). It indicates that the landslide size is not significantly difference in every year. The landslide number has been increasing every year since 2010.

3.5 Slope angle

The landslide number distribution in different slope angles with geological formation is given in the Fig. 13a. In every geological formations, the landslide number is higher above the slope angle > 45°. Middle Siwalik has higher number of landslide in every slope greater than 15°. New and active landslides are predominant at the slope > 30° (Fig. 13b).

3.6 Rainfall and landslide

Rainfall is considered as one of the major cause of landslide. We compared the maximum 24 h rainfall and total number of landslide, total annual rainfall with total annual landslide from 2010 to 2019 AD. There is no exact correlation between maximum 24 h rainfall and landslide (Fig. 14a, b). But the total annual rainfall and number of landslides are relatively correlated. Comparatively, the maximum 24 h rainfall amount is less in 2016, 2017 and 2019 AD but the landslide events are higher in these years. Figure 14a and b shows that maximum 24 h rainfall is not major cause of landslide. In Fig. 14c and d, the total landslide and total annual rainfall give the more a less same trend line. It can be said that landslide occurrence depends upon the total annual rainfall. The magnitude of rainfall, events of landslide and landslide intensity are summarized in Table 3.

Fig. 10 a Temporal landslide and number in different geological formations, **b** temporal distribution of area of landslides in geological formations

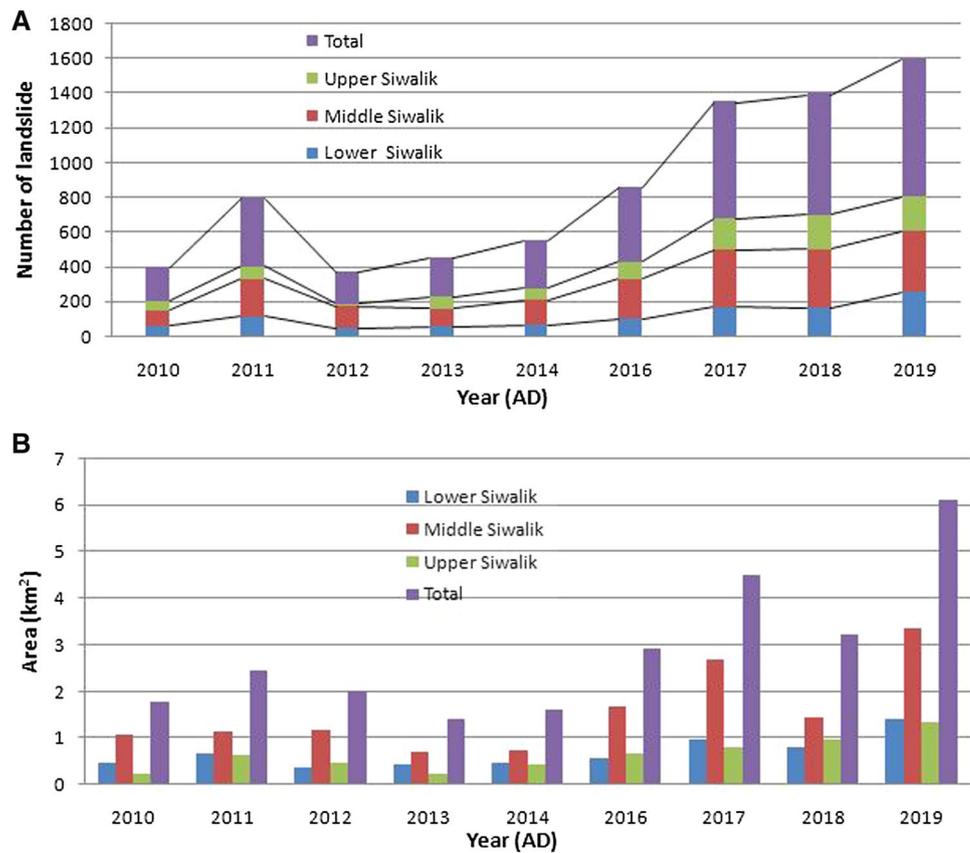
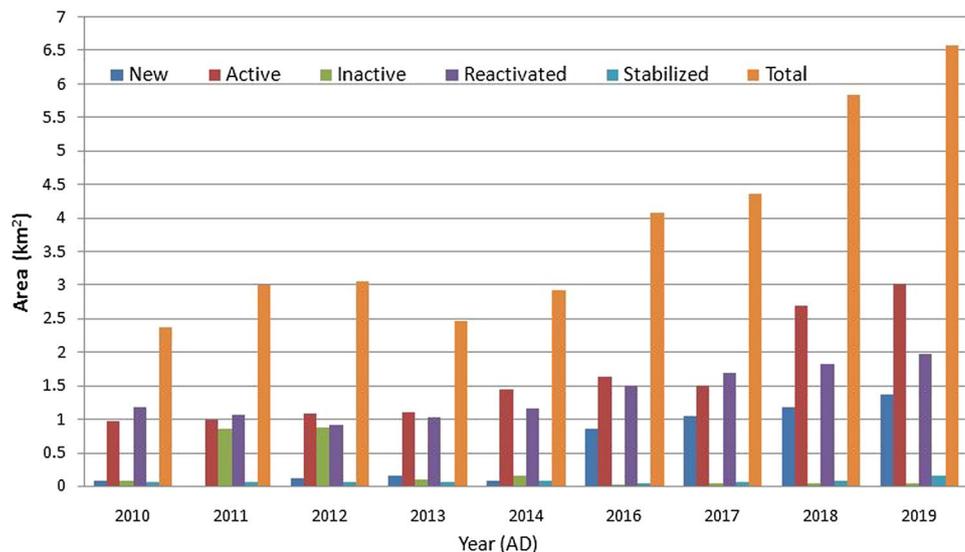


Fig. 11 The temporal distribution of landslide area with state of activity

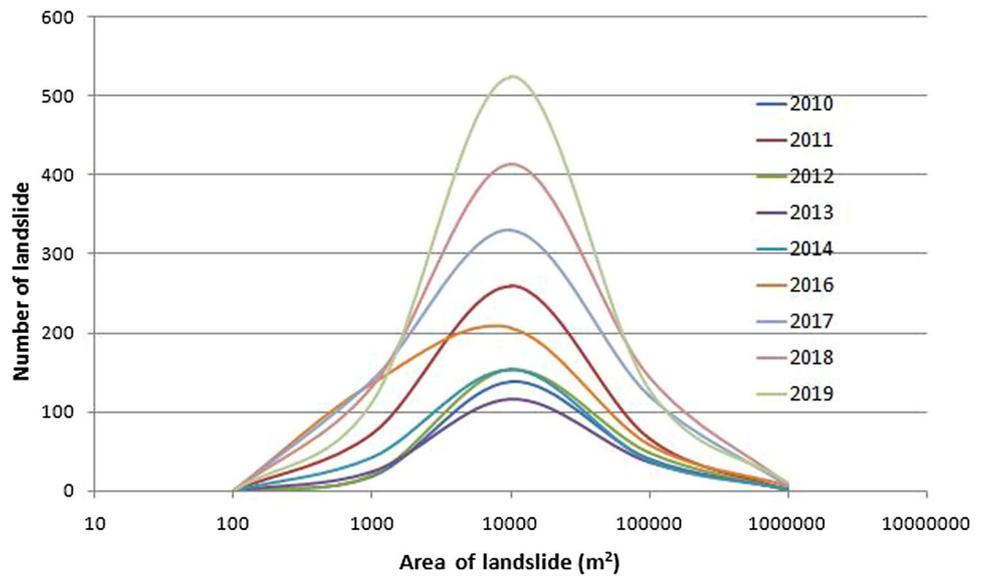


3.7 Initiation of landslide

Field study indicates that the failures generally occurred along the colluviums, bedrock contact, colluviums-bedrock contact, geological contact, and the fault zone. Landslides of sandstones start from slides or fall and

quickly convert to flows (debris flow) because of the water involved and the steep terrain below the landslide sources. From our analysis, the landslide distribution can be summarized in the five types based on their initiation as discussed in the following section.

Fig. 12 The area and number relationship of landslides since 2010 to 2019



Type 1 Thin layer of shale is present between the massive sandstone beds of Middle Siwalik (Fig. 15). The shale is permeable in nature. In the saturation state, the shale weathers and erodes out. It reduces the friction angle and weakens the support of sandstone beds, causing massive sandstone beds slide or fall from the steep slope.

Type 2 Landslides in mudstone begin from erosion with small channel and rill. The thick layers of mudstones are

highly jointed, highly weathered and concretionary in nature. The landslide with short scar begins from slope erosion. Landslides of mudstone have short scar and longer toe (Fig. 16). Landslides of mudstone resulted alluvial fan at bottom after transporting huge amount of landslide mass (debris) during heavy rain. Slope has played vital role to transport such huge landslide debris towards bottom of hill through the channel.

Type 3 Conglomerate beds of study area are basically two types. One is calcite binding and another is clay binding [4]. Due to environmental alteration, the loose binding of cementing material gets weak. The detached rock fragments and clay rich soil layer flow with water during heavy rain fall. Similarly, the mud/clay vein present on conglomerate beds weathers and jointed to the rock bed. The large block separated from intact rock.

Type 4 The rocks and soils of the fault zone are crumble and fragile. The tension cracks and joints are common in fault zone. Seismic wave or any active stress applying on the area causes the rock/soil to slide or fall. When the water enters from the cracks and joints, there exist pore water pressure and also reduces the friction and ultimately caused landslide.

Type 5 The colluvium deposit of old landslide has been covered by thin layer of soil causing devolvement of forest. The density of soil increased in saturated state in rainy season. The colluvium loses the bedrock-colluvium contact. The trees and forest increased the soil density and causing landslide.

The major initiation models of type 1 to type 5 are shown in Fig. 17. In Fig. 17a, the type 1 model is shown. After eroding the thin layer of shale, the thick layer of sandstone loses the support on the steep slope. The thick and massive sandstone beds fall or slide due to this

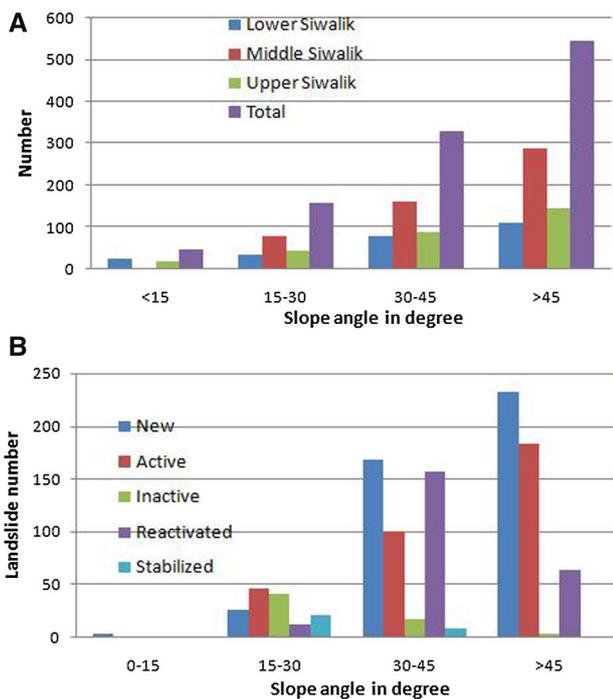


Fig. 13 a Slope and landslide number relation in different geological formations, b slope and landslide number relationship with state of activity

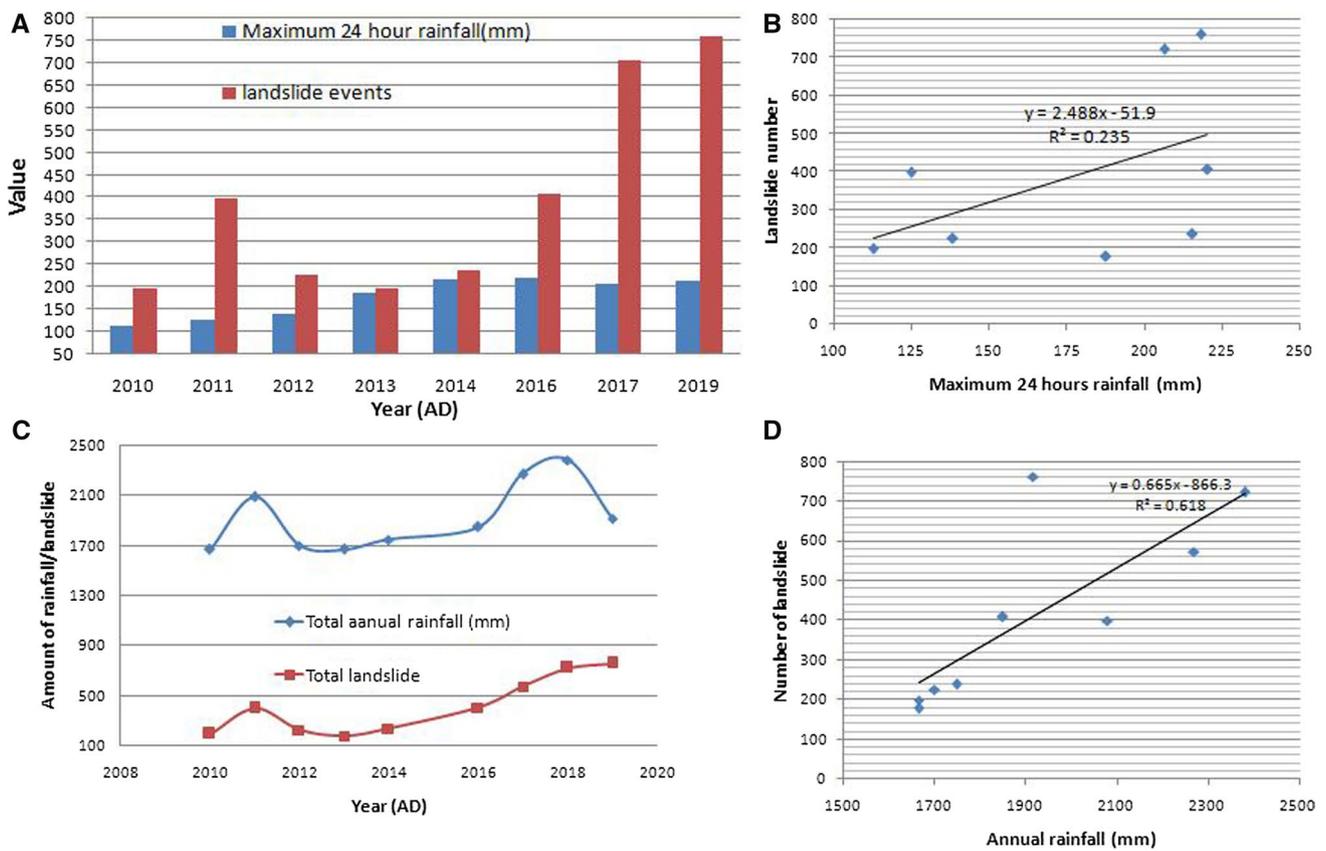


Fig. 14 **a** Landslide and rainfall events of Babai River catchment from 2010 to 2019. **b** Regression of maximum 24 h rainfall and landslide frequency. **c** Trend analysis of landslide and total annual rainfall. **d** Regression of total annual rainfall and landslide frequency

mechanism. The type 2 model is shown in Fig. 17b. The gully erosion is the initiation in this type model. The landslide begins from erosion with small and narrow scar. After continuous erosion process, huge amount of debris transported from hill slope and covers large area on the down slope. This type of landslide causes huge fan deposit at the gentle slope. The type 3 model is shown in Fig. 17c. In this model, the landslide initiation in conglomerate bed is shown. The cementing material erodes out due to its loose binding mechanism. After eroding the binding materials, the large block of conglomerate bed dissociate into granular debris masses and flows down like granular flow [15] with or without rain water. This type of landslide also creates debris flow and results debris fan deposits. The type 4 model is related to thrusting and faulting mechanism. The hanging wall of thrusts is found fragile and weak. The rocks are highly jointed and weathered. Due to this process, landslide activities are very common on thrust zone (Fig. 17d). The type 5 model is shown in Fig. 17e. This model explains about the landslide initiation on the slope comprising of old colluvium. Most of the Siwalik hills are affected by landslides in the past. Later on, the hill slopes made this way and comprised of colluvium are covered

by vegetation. The tall trees are very common on these colluvium deposits. At many places, these colluvium become unstable due to the overload at saturation state. As a result, landslides are very common even in the forest area of the entire study area.

4 Discussions

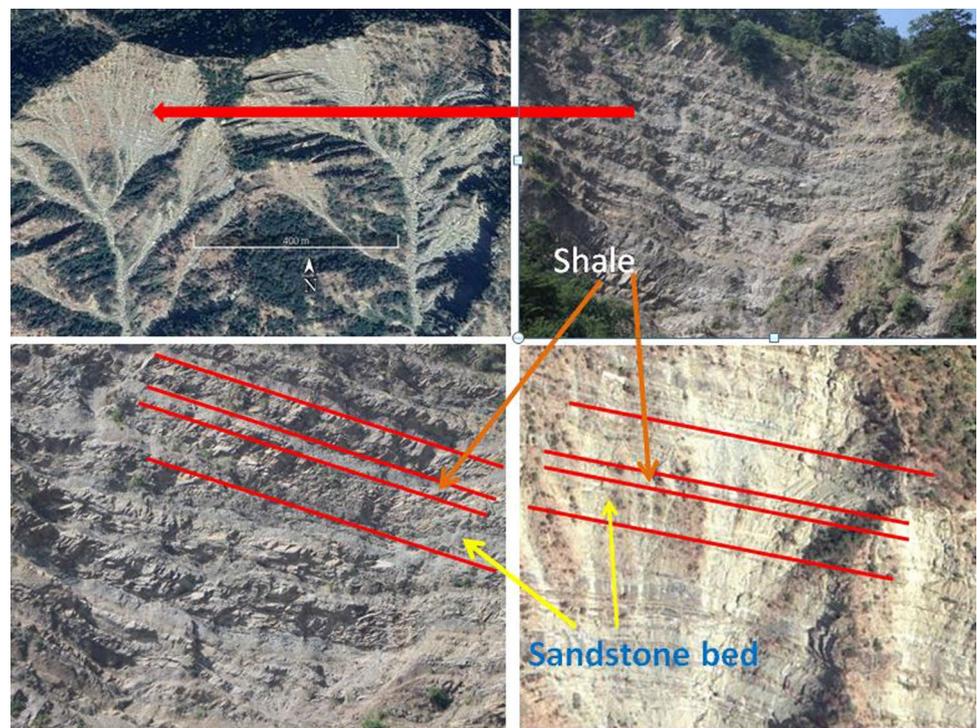
Geologically, the Siwalik zone of study area has been divided into three formations on the basis of lithology and stratigraphy by various researchers [2, 3, 4, 16, 38]. This threefold classification is the most followed classification system dividing the Siwalik zone into three formations namely: Lower Siwalik, Middle Siwalik and Upper Siwalik. The Siwalik zone consists of Quaternary fluvial sedimentary succession. There is typical lithology and stratigraphy in the sedimentary sequence. The rocks are north dipping sequence in general trend except some folding and faulting cases. Both Middle and Lower Siwalik consists of sandstone and mudstone bed but the proportion of rocks are different. Lower Siwalik consists of thick layer of mudstone alternated by thin layer of

Table 3 Rainfall amount, landslide events and intensity in temporal series of representative landslides

SN	Rainfall date	Rainfall amount (mm)	Rainfall duration (h)	Landslide date	Size (m ²)	Location
1	7-2-2010	100.6	3.0	7-6-2010	14,678	Babai village
2	8-30-2010	39.4	1.5	9-06-2010	1,34,342	Ban gaun
3	7-23-2011	96.6	6.0	7-26-2011	45,231	Mulkharka
4	8-23-2011	120.2	4.3	8-23-2011	53,125	Khahare
5	7-02-2012	77.5	3.2	7-04-2012	45,567	Purandanda
6	9-04-2012	40.6	1.2	9-04-2012	1,23,187	Guhiyachaur
7	7-02-1013	56.78	1.2	7-05-2013	24,156	Sarada Khola
8	8-09-2013	86.21	1.6	8-09-2013	9,786	Damdawali
9	6-28-2014	116.5	1.4	7-04-2014	96,176	Gidde Khola
10	7-16-2014	154.0	6.0	7-17-2014	1,56,342	Gidde Khola
11	7-17-2014	215.0	8.0	7-17-2014	2,77,879	Gidde Khola
12	6-02-2015	175.2	2.5	6-04-2015	1,34,456	Harre
13	6-21-2015	263.3	5.0	6-26-2015	39,213	Lekhparajul
15	7-06-2016	95.6	1.5	7-11-2016	6,22,362	Lekhparajul
16	7-28-2016	120.5	2.5	8-06-2016	9,62,409	Babai Village
17	8-09-2017	157.5	4.3	8-09-2017	4,34,980	Bardia National park
18	8-18-2017	125.0	3.2	8-19-2017	2,13,435	Bardia
19	7-22-2018	122.5	1.2	7-22-2018	99,876	Salyantari
20	8-17-2019	178.5	3.5	8-22-2019	3,66,178	Bardia

Data from Department of Meteorology, Nepal government and field study

Fig. 15 Landslide (rock slide) in sandstone bed of Middle Siwaliks. Landslide occurred in the alternate layer of sandstone and shale of Middle Siwaliks due to erosion of shale. Photo taken at Gidde Khola landslide of Bardiya district



sandstone. The mudstone of lower Siwalik consist clay rick mud that is soft and easily breakable. The mudstone gets weathered after continuous interface with water.

The concretions are developed in the mudstone in dry condition. Both dry and wet conditions make the mudstone bed easy to slide, erode or fall. The Lower Siwalik



Fig. 16 Landslide caused by weathered mudstone in between the alternate layer of Mudstone and Sandstone of Lower Siwaliks (Photo taken at Upper Damdawali of Salyan district)

is in the range of 900 m elevation in the study area. Only 8% area of Lower Siwalik consists of slope greater than 45°. The distance to travel by landslide mass is less and slopes to increase flow velocity also less in Lower Siwalik. So that, the area and length of landslides in Lower Siwalik is significantly less than Middle Siwalik. New and active but small landslides are most common every year but possibility to stabilize is seem less in Lower Siwalik

because the scar erosion and lateral movement occurs in every monsoon period. In the Middle Siwalik, there consist alternate layer of thickly bedded sandstone and thinly bedded mudstone or shale. The sandstone consists of Feldspar and Mica (Muscovite and Biotite) with little Quartz [32]. The sandstone beds are loosely bonded and less compacted [4].

The Babai thrust, Tui Khola thrust, Bheri thrust caused the sandstone beds crumble and highly jointed. The feldspar has higher weathering rate causing the sandstone weathered both physically and chemically. The thin layered, weak and fragile mudstone/shale when get weathered, it erodes out time by time. 39% area of Middle Siwalik consists of slope greater than 30° and this slope class is potential for landslide occurrence in this area. The Middle Siwalik lies in the range of elevation 1100 m to 1500 m in the study area. When thickly bedded sandstone bed slide or fall, the block crumbled and crushed resulting fragments into cobble, pebble and boulder size. The fragmented rocks flow down with flowing water during or after rainfall through the gully or valley and reaches to the longer distance as debris flow. The landslide mass of Middle Siwalik travels longer because there exists steep slope on higher elevation to increase flow velocity and to travel longer distance. Both new and active landslide having medium to large size is very common in this formation.

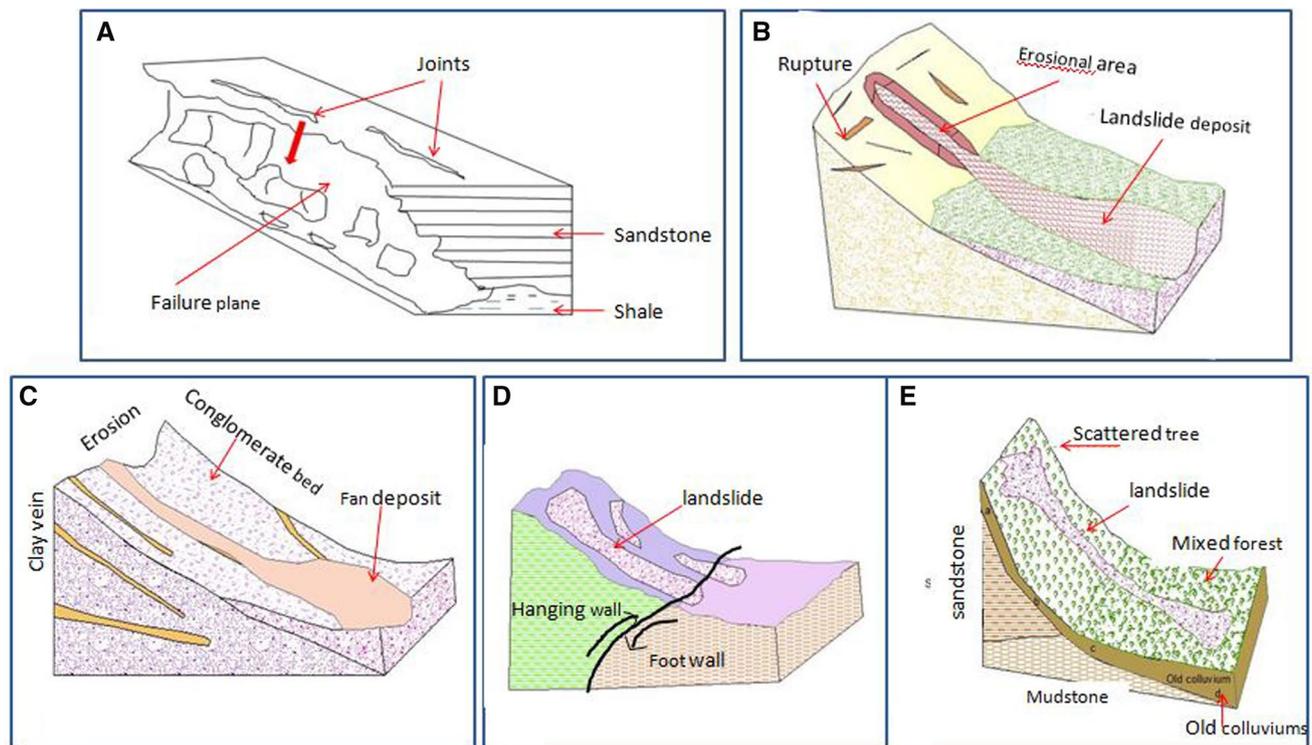


Fig. 17 Landslide models at different geological conditions, **a** alteration of sandstone and shale followed by weathering of shale, **b** lower Siwalik having alternate layer of sandstone and mudstone, **c** conglomerate bed, **d** in the thrust zone, **e** in the colluvium deposit

In the Upper Siwalik, clay bonded conglomerate alternately found with thin layer of shale. The quaternary fluvial conglomerate belts are weakly bonded and loose in nature. At the saturation condition, the beds weather and erode out after losing inter particular bonding. The eroded rock fragments and materials flow with running water resulting debris flow and gravel flow. If the conglomerate is in steep slope, the large blocks separate and slide/fall down and remain as the boulder conglomerate. The Upper Siwalik rocks are found in the elevation of 400 m to 700 m. Only 7% area of Upper Siwalik lies in the slope $> 40^\circ$.

The landslide size shows log-normal distribution in the study area. Medium to large scale landslides are commonly found. The result is similar in every year since 2010. The area distribution in all three formations is in the similar trend. The area and frequency of medium to large sized landslides are higher in every formation. The Middle Siwalik consists of larger area as well as number of landslide than Lower and Upper Siwalik since 2010. The decadal data shows that Middle Siwalik is landslide prone area in the Siwalik zone. Bhandari and Dhakal [4] and TU-CDES [38] reported the similar result of this area.

The activity classes proposed by previous researchers are not sufficient to classify the state of activity in Siwalik zone. So, we proposed the states of activity into five classes on the basis of activity time and processes. The active and landslides are very common in the study area. Most of the landslides move every year. The landslides nearby thrust zone and the landslides of the colluviums bedrock contact are active landslide. The new landslides are found in the contact between two formations, colluvium deposit as well as hanging wall area of thrust zone. The hanging wall of thrusts is more sensitive for landslide and debris flow than the foot wall. The active landslides are dominant in the Middle Siwalik. Both in spatial and temporal cases, number of landslides are higher in Middle Siwalik.

Thrust zones are found highly susceptible for landslide occurrence. Most of the large sized landslides are found concentrated on the hanging wall of the thrust. Bucci et al. [5] tested the landscape evolution model in the Peloritani range of Italy and concluded that large landslides and their cumulated volume are sensitive to local rates of tectonic deformation, and the large sized landslides are controlled by the active faults.

Among the 9 rainfall stations, the average rainfall for 24 h and total average annual rainfall was calculated. There is very weak correlation between 24 h rainfall and landslide occurrence but total annual rainfall and landslide frequency has positive correlation. Dahal and Hasewaga [12] found that 140 mm maximum 24 h rainfall

is the threshold for landslide in Nepalese hill. However, our result shows that only 24 h rainfall cannot cause the landslide in every formations but average rainfall in rainy season may cause medium to large scale landslides.

Regarding the seismic activities, catastrophic Gorkha Earthquake of 7.8 MW was occurred in Nepal on 25th of April 2015. Several aftershocks were occurred after the major earthquake. The major earthquakes and several aftershocks caused the surface potential for landslide occurrence. Continuing rainfall after earthquakes and strong aftershock shaking are key factors affecting continued landslides in the earthquake-affected areas [27, 29, 31, 36]. Our result shows that the landslide number has increased in 2016 and 2017 after 7.8 MW Gorkha Earthquake. Several aftershocks were occurred within a year. Tsou et al. [37] mapped 13,847 earthquake induced landslides in most affected parts of Central Nepal due to 7.8 MW Gorka Earthquake. Among them 750 were enlarged preexisting landslide and 13,097 landslides were new. Although, the data on the landslides triggered by Gorkha Earthquake 2015 in our study area was not found and the precise differentiation of earthquake induced landslides was beyond the scope of this study, this earthquake and its major aftershocks may have triggered landslides as indicated by the increased numbers of landslides in 2016 and 2017 in this study area.

5 Conclusions

The study concludes that landslides of Siwalik region are highly dynamic in nature. There are spatial differences of landslide on the basis of geology and structures. The Middle Siwalik is the major geological Formation which is comprised of large number of landslides. The hanging wall of thrust zone is more sensitive for landslide. The result shows that total annual rainfall has positive role for landslide occurrence rather than maximum 24 h rainfall. The typical sizes of the landslides in the area are between 10,000 m² and 100,000 m². The landslides are potentially found larger in number at the hanging wall of thrust. In terms of landslide activity, 40% of area is covered by the active landslides. The rapid increment of landslides is found after 2015, which can be due to the effect of Mw 7.8 Gorkha earthquake in Nepal.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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