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RESEARCH ARTICLE

Hydrological influences of the landslide mechanisms: insight into the Aakhu Khola Watershed, Dhading District, Nepal

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ABSTRACT

This study aims to determine the role of hydrological factors that influence landslides in the Aakhu Khola watershed in Dhading District, Nepal. The effort commenced by using satellite imagery and ArcGIS to create a spatial and temporal landslide inventory map. The four hydrological factors map was created using a 12.5 m digital elevation model, and a rainfall map was prepared using IDW interpolation of ten years of rainfall. The pixel size of the factors' subclasses and the pixel size of landslides within the subclasses were determined. The activity state landslide inventory map was used to ascertain the influence of rainfall on the occurrence of landslides. A regression study was performed to determine the significant relation between rainfall and landslides. The frequency ratio value was used to evaluate the correlation between landslides and the corresponding components. There is a significant positive correlation between the total annual rainfall and the total annual landslide from 2010 to 2023. The active and recent landslides exhibit a significant correlation with yearly precipitation. The linear regression analysis reveals a strong correlation between activity stages and rainfall, indicating a close relationship between the two variables. The frequency ratio value is greater at a distance of 100 meters from the drainage. The occurrence of landslides is inversely connected to the topographical wetness index but directly related to the stream power index. There is a positive association between the drainage density and landslides. All the results indicate hydrological control over the landslide mechanism in the study area.

Key words: ***Hydrological control, Landslide, stream power index, topographical wetness index***

INTRODUCTION

The rainfall-induced landslide is very common in the entire Himalayan region. Because most landslides in Nepal occur during the monsoon season, heavy rainfall is regarded as the primary cause of landslides (Dahal et al., 2009). The hills near drainage have more landslide events in Nepal (Regmi et al., 2014; Pokharel and Bhandari, 2019; Thapa and Bhandari, 2019). Toe cut and head erosion are major landslide-initiating factors in the Himalayas, ultimately caused by hydrological activities (Bhandari and Dhakal, 2020). Rainfall is the major cause to occur landslide and the long term rainfall in the Monsoon period play significant role to cause landslide in the Himalaya (Bhandari and Dhakal, 2021, Dahal et al., 2008). Rainfall pattern, geology, and geomorphology determine a rainfall-induced landslide's characteristics. According to Chen et al. (2019), rainfall-induced landslides tended to occur on a dip slope rather than a windward slope. The authors concluded that geological settings were a more effective control of the mass wasting processes on a hill slope scale than the rainfall condition. Chigira (2011) studied Japan's geological and geomorphological characteristics of rain and earthquake-induced landslides. According to that study, the responses of various geological materials to rain and ground shaking differ. The trigger of a landslide depends on material strength loss, precipitation through pore pressure, and water table height (Larsen et al., 2010; Guzzetti et al., 2008). The occurrence of landslides can be attributed to a combination of natural factors such as steep slopes, weak geology, and high rainfall, as well as human activities such as deforestation and unplanned human settlements. Human activities, such as inappropriate land use, encroachment on hazardous slopes, and unplanned development like road construction and irrigation canals without proper protective measures, worsen the danger of landslides in hilly places. The pore water pressure and hydrostatic pressure on the soil slope as well as rock-soil slope cause shallow to massive landslide. This study aims to access the hydrological action on the slope which ultimately trigger for landslide occurrence in the Aakhu Khola watershed of Dhading District Nepal. The study will also explain the combined role of flowing water, rain water and topographical wetness for landslide occurrence in the study area.

MATERIALS AND METHODS

Study Area

Aakhu Khola watershed has been proposed for this study. This area lies in the Dhading District of Bagmati province, Nepal (Fig.1). This consist of ward no 10 and 11 of Nilkantha municipality, and wards 1-6 of Ruby valley rural municipality, ward no.1-5 of Khaniyabas rural municipality, ward no. 1-5 of Gangajamuna Rural Municipality, ward no. 1-5 of Netrawati Rural Municipality, ward no 1, 2, 4, 5, 6, 7 of Tripurasundari Rural Municipality, and ward no.6 and 7 of Jwalamukhi Rural Municipality. It covers all the local level of north Dhading. This is one of the major Tributary of Budi Gandaki River.

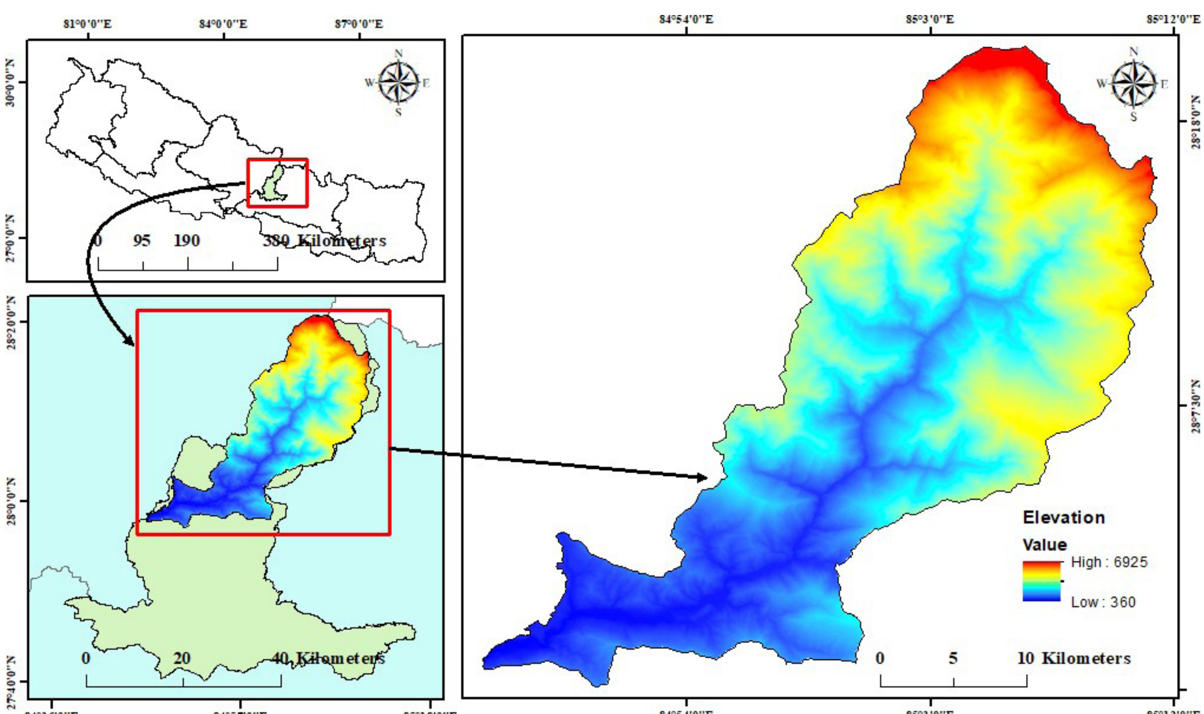


Fig. 1: Location map of the study area

The catchment area starts in GPS location (27°58'6.74"N ,84°46'19.57"E) near Budi Gandaki River and Northen most GPS location (28°20'38.86"N, 85° 4'52.17"E). The catchment area of the river is 701.04 km2. The watershed ranges from a Sub tropical climate in south to Alpine region in north with elevation range 6950 m north in Higher Himalaya range to 425m southern reaches. The study area starts from the alpine region to hilly and then to mountain. Average annual rainfall in the watershed is about 2213.22 mm.

METHODS OF DATA COLLECTION

This study focused on the spatial and temporal distribution of landslides and evaluated their probability using several methodologies. A combination of primary and secondary data sources, such as literature, satellite pictures, Google Earth, and field trips, are used to construct a landslide inventory map (LIM). To analyze the hydrological impacts for landslide, the landslide inventory map was prepared by using Landsat, Sentinel-2 and Google earth imageries from 2000 to 2023.

Primary data collection

The main data gathering method consisted of conducting field observations, which were supplemented by the use of tools such as GPS and a checklist. On field visits, certain landslide locations were chosen, and detailed images were taken for understanding landslides. After the first visit, a detailed inventory map of the landslides was created. Following that, a second phase of on-site verification was carried out, during which supplementary checklists were filled out. During the second field visit, Key Informant Interviews (KIIs) were performed regarding water resources and rainfall pattern in the study area. Similarly, the spring survey was conducted during field visit.

Secondary data collection

A variety of methodologies and data sources were used in the comprehensive assessment of landslide in the study area. The assessment process utilized ArcGIS 10.8, Google Earth, USGS data, meteorological data, and geological information. The field verification of landslide locations was crucial in ensuring accuracy and generating a detailed inventory map. In order to create a map that identifies the factors that contribute to landslides, a digital elevation model (DEM) with a resolution of 12.5 meters was obtained from the ALOSPALSAR website. The thematic maps related to water and playing role to cause landslide were prepared with the help of DEM. The geological map was obtained from the Department of Mines and Geology, Nepal. The rainfall data of twenty-three years was obtained from four different stations and the rainfall map was created.

HYDROLOGICAL FACTORS

Stream power index (SPI)

SPI map is prepared by using the DEM and determined using GIS software. ALOSPALSAR DEM with (12.5*12.5 m) resolution is used as data for the preparation of SPI map. The SPI is grouped into five categories (-45.696 to -9.5668, -9.5668 to -5.243619, -5.243619 to -1.53811, -1.53811 to 1.5498, 1.5498 to 33.0472) using the natural perk classification method (Fig.2a).

Rainfall

Rainfall map is prepared by using interpolation, IDW in Arc GIS. For this process, the rainfall data of twenty year was obtained from the department of hydrology and meteorology (DHM) of Nepal. Rainfall is sorted into five groups based on the obtained values. These categories include rainfall ranges from 1574.119141 to 1990.4233, 1990.4233 to 2255.344, 2255.344 to 2507.6497, 2507.6497 to 2772.570, and 2772.570 to 3182.56 (Fig. 2b).

Distance to drainage

Distance to river map is prepared by using GIS software. ALOSPALSAR DEM (12.5*12.5 m) resolution is used as data for the preparation of distance to river map. The distance to the river is divided into five groups, each representing a specific range. These classes are 400-800, 800-1200, 1200-1600, 1600-2000 and >2000 (Fig.2c).

Topographic wetness index (TWI)

TWI map is prepared by using the DEM and determined using GIS software and formula TWI= ln (α/tanβ). Where α is the local upslope area draining through a certain point per unit contour length and tanβ is the local slope in radians. ALOSPALSAR DEM with (12.5*12.5 m) resolution is used as data for the preparation of TWI map. The TWI is separated into five groups (0.9242-4.2873, 4.2873-5.9688, 5.9688-8.2109, 8.2109-11.9476, 11.9476-24.74) using the natural break classification method (Fig.2d).

DATA ANALYSIS

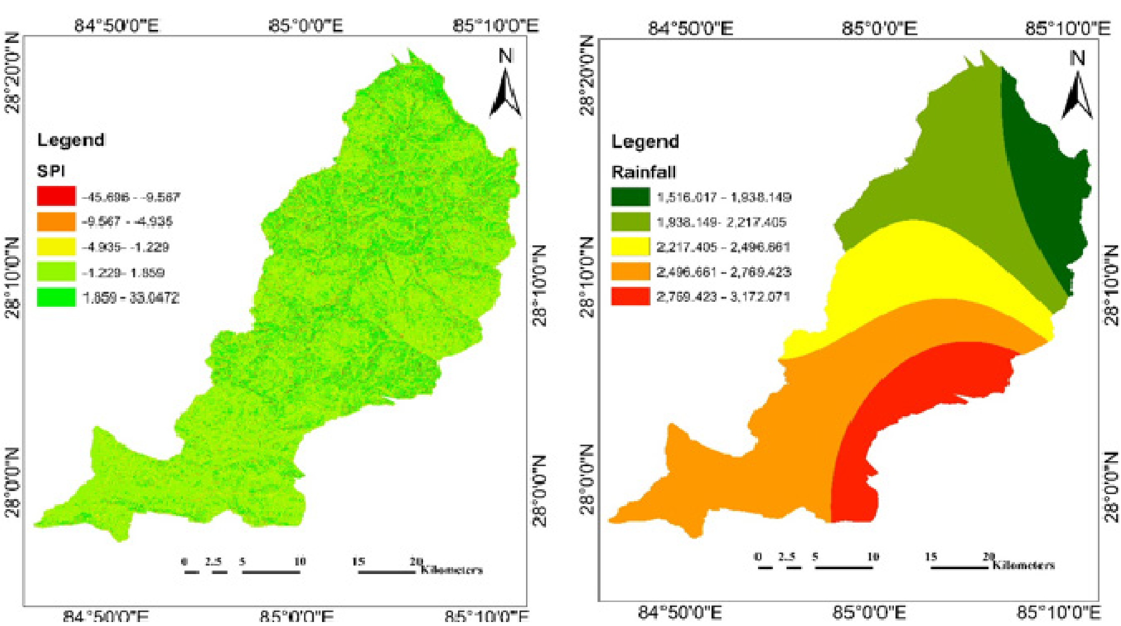
Simple linear regression

A simple linear regression model consists of a single independent variable and a single dependent variable. The model calculates the gradient and y-intercept of the regression line, which symbolizes the correlation between the variables. The slope of a line in a regression model indicates the rate of change in the dependent variable for each unit increase in the independent variable. On the other hand, the intercept shows the estimated value of the dependent variable when the independent variable is zero.

Linear regression is a statistical method that demonstrates the linear association between the independent variable (also known as the predictor variable) on the X-axis and the dependent variable (also known as the output variable) on the Y-axis. In this research, simple linear regression is used to find the relation between the total annual landslides and total annual rainfall from 2000 to 2023. So, landslide is taken as dependent variable and rainfall is taken as predictive variable.

Frequency ratio

The frequency ratio is a quantitative tool for evaluating the landslide possibility in the particular region based on the correlation between landslides and causative factors using the spatial analyst tool of Arc GIS (Thapa and Bhandari, 2019). The Frequency Ratio indicates the correlation between several factors that influence landslides and the specific places where landslides occur.



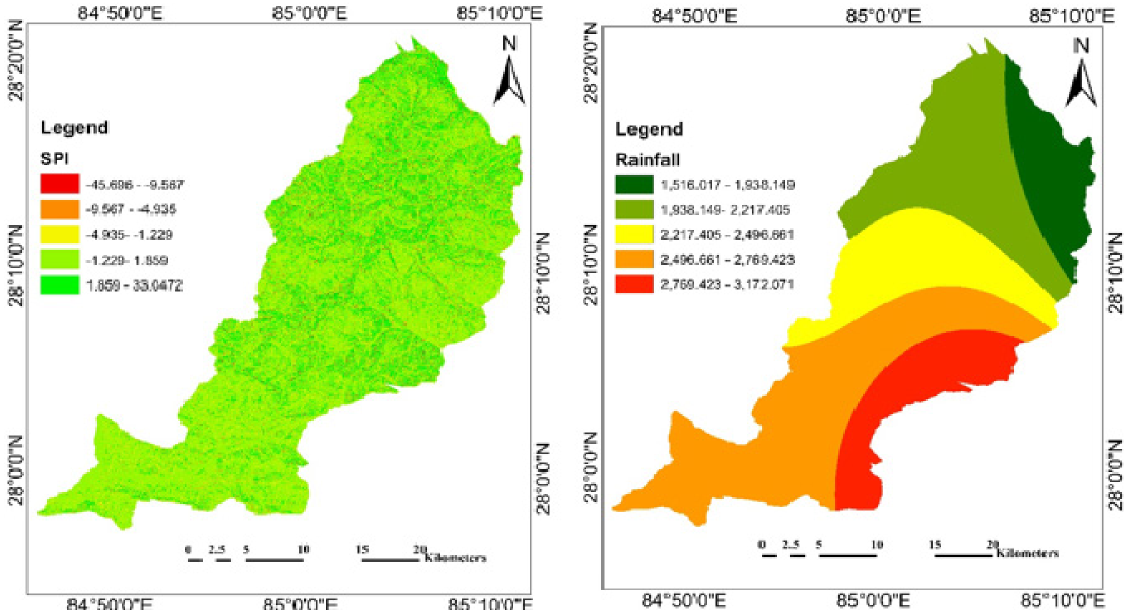


Fig. 2: Hydrological factors map a) Stream power index b) Rainfall c) Distance to stream d) Topographical wetness index.

Due to its mathematical simplicity and quick evaluation time, it is chosen for this study as the fundamental analysis for an initial probabilistic assessment. It is reasonable to expect that the factors that caused past landslides will probably result in future landslides as well. According to this assumption, a correlation can be identified between the occurrence of landslides and the lack of landslides in a region where landslides are influenced by specific causes (Gyawali et al. 2021). The following relation provides the frequency ratio value.

$$FR = \frac{N_a\ /N}{N_b\ /N^l}$$

Where,

N_a = number of pixels in each landslide conditioning factor class

N = number of all pixels in total the study area

N_b = number of landslide pixels in each landslide conditioning factor class

N^l= number of all landslide pixels in total the study area

RESULTS

Landslide inventory

The research focused on studying landslides in a specific area using satellite images and on-site visits, identifying a total of 807 landslides. These landslides varied in size, with the smallest being 55.31 square meters, the largest measuring 1,551,345 square meters, and an average size of 10864.96 square meters. The combined area of all the landslides was calculated to be 8749795.8638 square meters. This area represents 1.24% of the total study area. The Darcha landslide and Jharlang landslides are the largest landslide in the study area. Similarly, the Dhunigaun landslide is also a remarkable landslide in the study area. The Dapcha landslide killed 16 people and destroy seven houses in the year 2019.

Rainfall induced landslides

The temporal inventory map from 2000 to 2023 was prepared using satellite imagery and real-ground surveys. We verified some of the landslides through community surveys and focus group discussions. The total annual rainfall was obtained after synthesizing the raw daily rainfall data obtained from the Department of Hydrology and Meteorology, Nepal. The Figure 3 displays the distribution of total annual landslides and rainfall. Similarly, the regression between temporal landslide inventory data and temporal rainfall distribution data was obtained (Fig.4). The result shows that the coefficient of determination between rainfall and landslides is 0.8196, which indicates that the model is close to the prediction. In the Figure 4, the majority of the points are close to the best fit line. The model predicts a proportion of variance in the landslides that is close to one simple mean high value. This implies that the amount of rainfall can predict the landslides. The significant test results confirm the significance of the result, demonstrating a p value of 0.00015 and F value of 54.32. This implies that the amount of rainfall significantly influences the occurrence of landslides.

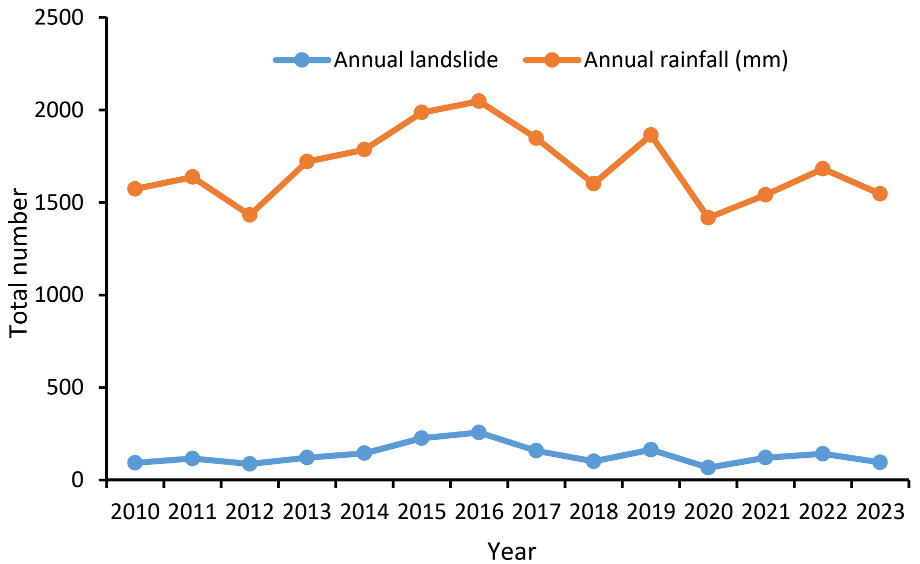


Fig. 3: Distribution of annual rainfall and annual landslide in the study area

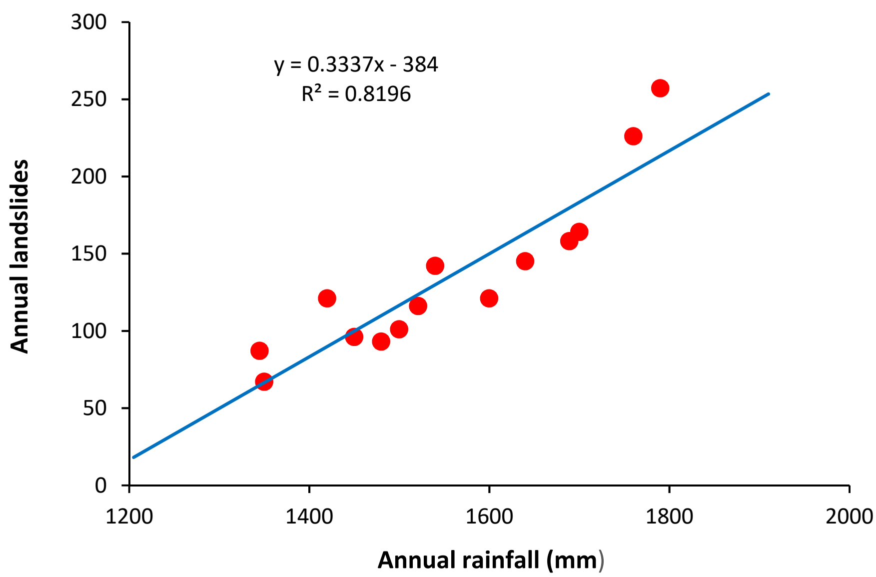


Fig. 4: Relation between annual landslides and annual rainfall from 2010 to 2023.

State of activity

The activity state of landslide was studied based on the five major classes namely active, new, inactive, reactivated and stabilized. The relationship between activity state of landslides and total annual rainfall is obtained. The regression between rainfall and activity state of landslides (reactivated, inactive, active and new) is shown in the Figure 5 a, b, c, d) respectively. The points are closer with the fit line and coefficient of determinations in each curve is greater than 80%. The result indicates that there is strong association between annual rainfall and activity of state. The new, active and reactivated landslide increased with increasing rainfall amount whereas the inactive landslides increased with decreasing rainfall amount. The result shows that the activity state of landslide depends on the total rainfall of the area.

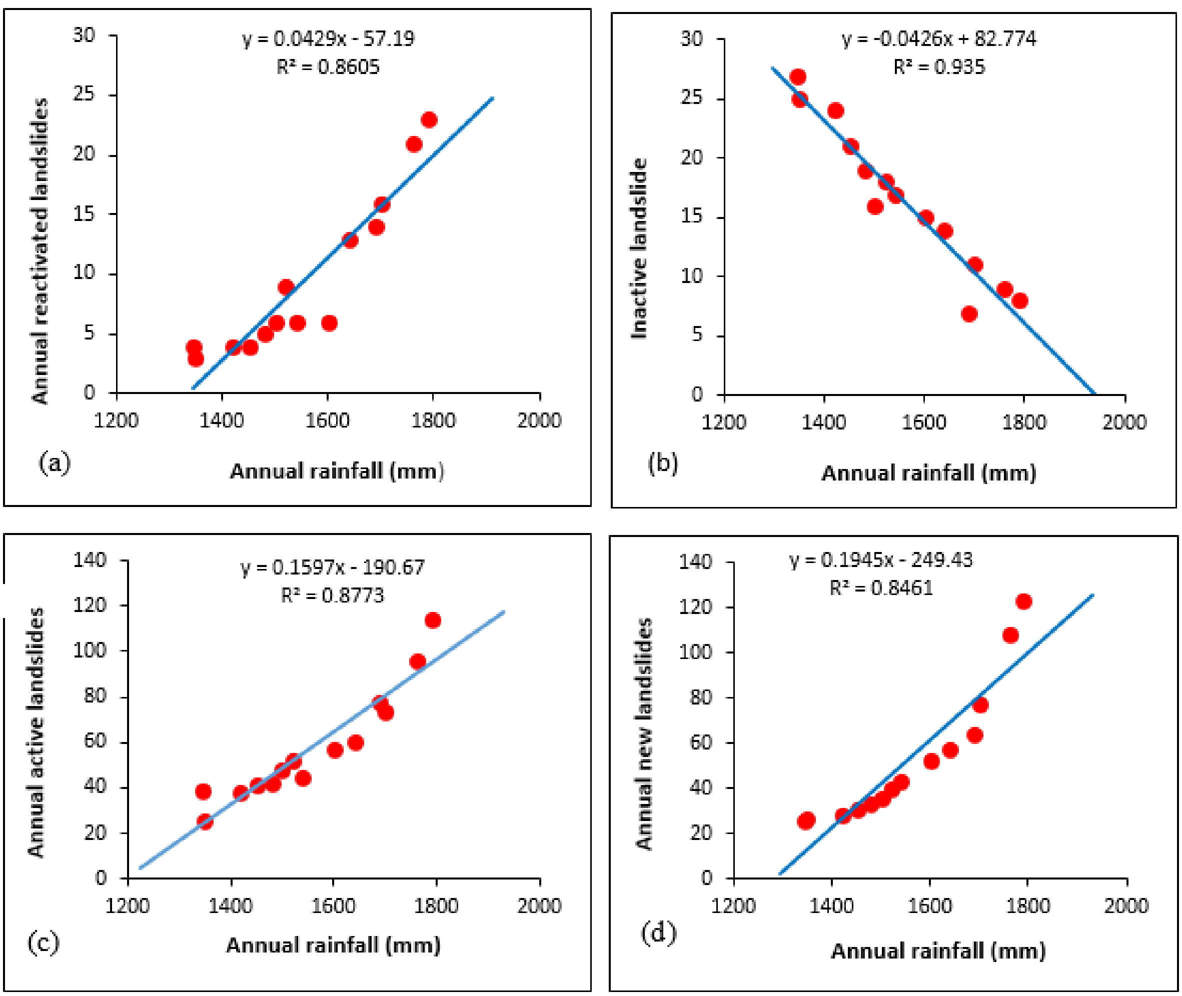


Fig. 5: The regression between annual rainfall and a) annual reactivated landslide b) inactive landslide c) annual active landslide d) annual new landslide.

Landslide size distribution

The size of the landslides (very small, small, medium, large and very large) based on Bhandari and Dhakal (2019) was obtained from 2010 to 2023. The landslide size distribution was correlated with the total annual rainfall. Year wise landslide distribution and total rainfall is shown in the table 1. Total annual rainfall is maximum in 2016. In the same year small and medium landslide is higher in number. Similarly, very large landslide was also occurred during the heavy rain time. The number of very large landslides increased in 2015, 2016 and 2019. The total annual rainfall exceeded more than 1700 mm. The small sized and shallow landslides are mostly controlled by rainfall amount. The medium sized landslides are dominant in the year having rainfall maximum. The size of landslide and rainfall amount also show that landslides are mostly controlled by rainfall in the study region.

Table 1: Annual rainfall and size distribution of landslide.

		Size of landslide				
Year	Annual rainfall (mm)	Very small	Small	Medium	Large	Very large
2010	1480	12	20	38	5	5
2011	1521	18	40	52	9	3
2012	1345	26	27	39	4	3
2013	1600	52	57	15	6	2
2014	1640	57	60	14	13	5
2015	1760	32	96	108	21	8
2016	1790	32	123	114	23	9
2017	1689	7	64	78	14	2
2018	1500	16	36	48	6	3
2019	1700	11	74	77	16	8
2020	1350	21	26	27	6	5
2021	1420	18	24	38	9	3
2022	1540	17	43	45	9	6
2023	1450	31	41	21	4	6

Frequency ratio analysis

The frequency ratio value of each subclass was obtained by using pixel number of landslide, class and sub-class. The frequency ratio value increased with increasing stream power index. The erosive capacity of River increases with increasing stream power index and cause toe cut and foothill erosion so that the number of landslides increases. Similarly, the frequency ratio (FR) value is higher in the area having higher drainage density. Drainage density has positive correlation with landslide. The FR value increased with increasing rainfall amount as shown in the table 2. Similarly, distance to drainage has positive association with landslide because, the FR value increased with decreasing distance to drainage. The topographical wetness index and landslide has negative association. The FR value decreased with increasing topographical wetness index.

Table 2: Frequency ratio distribution of five hydrological factors

Factors	Sub class	FR
Stream Power Index(SPI	-45.69 to -9.56	1.071
	-9.56 to -5.24	1.045
	-5.24 to -1.53	1.019
	-1.53 to 1.54	1.137
	1.54 to 33.047	2.676
Drainage Density(DD)	0 - 0.6461	0.36705
	0.646199 - 1.06	0.755855
	1.0650 - 1.44	1.17229
	1.4479 - 1.87	1.269799
	1.878 - 3.051	1.628132
Rainfall	1574.11 - 1990.42	0.599933
	1990.42-2255.344	0.670908
	2255.344 - 2507.649	0.725309
	2507.649 - 2772.570	1.070411
	2772.570 - 3182.56	1.197803
Distance to River	0 - 100	1.314859
	100 - 200	0.936945
	200 - 300	0.776706
	300 - 400	0.690032
	>400	1.129667
Topographic Witness Index	0.9242 - 4.2873	1.037844
	4.2873 - 5.9688	0.982469
	5.9688 - 8.2109	0.646215
	8.2109 - 11.9476	0.428743
	11.9476 - 24.74	0.156439

DISCUSSION

This study examined the hydrological control of landslides at a catchment scale. We correlated various hydrological factors with the landslide data. The work began with landslide spatial and temporal inventory mapping. We prepared the temporal inventory annually from 2010 to 2023 using Google Earth, Sentinel, and Landsat images of various years. Similarly, the size-based landslide inventory, ranging from tiny to very large was prepared by following the classification guidelines provided by Bhandari and Dhakal (2020). The activity-state-based landslide inventory was also prepared and classified into five classes: new, active, reactivated, inactive, and stabilized. The Nepal Government's Department of Hydrology and Meteorology provided rainfall data from 2010 to 2023. Using the ArcGIS spatial analyst tool, we prepared the rainfall map and other related factors. The regression analysis between the number of annual landslides and the amount of rainfall was conducted. The correlation between the activity state and the amount of rainfall was also obtained. The frequency ratio value for each class also obtained to determine the correlation between landslides and hydrological factors such as drainage distance, topographical wetness index, stream power index, and drainage density. The higher FR value indicates a better correlation between the class and landslides.

The regression of annual landslides and annual rainfall shows that the landslides and rainfall are positively significant. The coefficient of determination shows that there is a closer relationship between landslides and rainfall amounts. Many researchers studied rainfall-induced landslides in the Nepal Himalaya (Dahal and Hasewaga, 2008; Dhakal, 2014; Bhandari and Dhakal, 2020) and around the world (Iverson, 2000; Guzzetti et al., 2008). Similarly, the FR value increased with increasing annual rainfall, indicating that there is a good relationship between landslides and rainfall. As drainage density increased, the FR value increased. A higher number of drainages makes the slope unstable, either due to increasing hydraulic pressure or continuous erosion. We observe landslides near drainages in the study area. Numerous drainages in the Kanniyabas area contribute to the distribution of small to large landslides. Similarly, water flows at high speed into several dry streams during the rainy season, causing Meghan landslides, Galche landslides, and Seuri landslides. These three landslides are active and move every year in the monsoon period, so people have been facing challenges for a long time. The Jharlang landslide is the study area's mega (very large) landslide, which has been active for 20 years and is still creating problems in the rainy season. The Jharlang landslide consists of three major natural drainages and several gullies. The landslide becomes active from the early to late monsoon period but remains inactive for the rest of the time. The 24-hour maximum rainfall recorded in the Khaniyabas area is 350 mm, and the maximum total rainfall only in the monsoon period is 1600 mm from 2010 to 2023, indicating that the rainfall occurs mostly in the monsoon period and the winter rain is negligible. The topographic wetness index is the function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. We primarily design and use the index for hillside soil conditions. Soil thickness, soil composition, and organic matter content correlate with the topographical index. We have used the TWI to study spatial-scale effects on hydrological processes and to identify hydrological flow paths for geochemical modeling. It also provides information on the hydrological flow's impact on the unit area. The topographic wetness index is a tool to indicate areas accumulating water flow, often with seasonally and permanently waterlogged ground. As such, it is very useful to show the geomorphic complexity of a landslide terrain, including the pattern of dry areas and wet areas. On a steep slope, the TWI value decreases, whereas on a gentle slope, it increases. The results show that the FR value decreased as TWI increased. Previous researchers used the TWI value to correlate with landslides (Schmidt et al., 2008; Wang et al., 2020; Bhandari et al., 2024) and found that the landslide has a negative correlation with TWI. The stream power index represents the erosive power of flowing water. The higher the stream power index, the more erosion capacity there is. There is a positive correlation between the stream power index and landslides. Erosion and bank cutting are the primary causes of landslides in weak geological areas.

CONCLUSION

The main objective of this study was to evaluate the hydrological control on the landslide in the Aakhu Khola watershed of Dhading District, Nepal. The study begun from the preparation of the landslide inventory map of the study area by using Landsat and Google Earth imageries. The hydrological factors map such as precipitation, drainage to distance, topographical wetness index and drainage density were prepared by using Arc. GIS. Landslides events are correlated with the selected hydrological factors. The results indicate that rainfall is primarily responsible for landslides, and the total number of landslides closely matches the total annual rainfall. As drainage density values rose, landslide events increased. Similarly, near the drainage, the number of landslides is higher. The topographical wetness index and landslides are highly correlated. The number of landslides decreased in the area with a higher topographical wetness index. The landslides show a positive relationship with the stream power index. The number of new and active landslides are increasing every year also signifies that the landslides are hydrologically controlled in the study area.

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