



Spatio-temporal evolution of landslides along transportation corridors of Muzaffarabad, Northern Pakistan

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Abstract

Landslide spatio-temporal distribution is an effective approach to understand the landslide mechanism and triggering factors. However, the quantitative characterization of the spatio-temporal distribution of landslides along with their causative factors remains a critical challenge for geoscientists due to limited historical landslide records. This study presents the landslide spatio-temporal distribution analysis by developing landslide inventories from World view-3, SPOT-5, Quick Bird and Google Earth imageries and verified in the field through extensive field visits along main road corridors (i.e., Neelum Road, Jhelum valley road and Kohala road) of the Muzaffarabad district. Past landslide records of 15 years were collected, and temporal inventories were prepared for 2005, 2007, 2012, 2015, and 2019 years. Based on the research activities, the landslide spatial variations were traced and analyzed to classify them into fall and slide types. The temporal analysis of the landslides was then compared with eleven causative factors, i.e., slope, aspect, surface relief, curvature, lithology, distance to roads, faults and streams, land use, Topographic Wetness Index (TWI) and Normalized Differential Vegetation Index (NDVI). The spatio-temporal analysis demonstrates that the total number of landslides along the selected road corridors are 107, 164, 169, 92, and 182 during the years 2005, 2007, 2012, 2015, and 2019, respectively. The analysis of the study area reveals that the landslide area and events depict an abrupt increase in 2005, 2007, 2012, and 2019 whereas a significant decrease in landslide area and events were recorded during 2015. The present research concluded that the combined effect of topographic factors (slope, aspect, elevation and curvature), lithology and distance to roads have found significant influence on the landslide phenomenon. This variation in landslide areas and events indicates the influence of causative factors with respect to time. The present work will be helpful to understand the spatial patterns, trends over the years and landslide triggering mechanisms.

Keywords Landslide · Spatio-temporal distribution analysis · Road corridors · Muzaffarabad · Causative factors

Introduction

Landslides are challenging natural hazards in mountainous terrains with diverse triggering mechanisms. Landslides are the downslope movement of rock, debris or earthen material, caused by gravitational pull, and generally triggered by a range of external factors such as severe rainfall, earthquake, pore water pressure, windstorms, and rapid erosional rate,

etc. (Dai et al. 2002). These triggering factors are responsible for enhancing the shear stress and reducing the shear strength of slope-forming materials beyond the factor of safety and causing slope failure. Landslides, the most hazardous natural calamities, cause human casualties and massive damages globally. Disastrous landslide events in mountainous regions are frequently initiated by extreme natural or anthropogenic events, like earthquakes (Ahmed et al. 2021; Riaz et al. 2018), heavy rainfall (Riaz et al. 2022a), or volcanic eruptions (Kerle et al. 2003), global warming, man-made activities, for instance, deforestation or road cuts, or both. Mortality rates and economic deficits due to landslides go beyond the reported statistics in most countries. These damages may exceed other natural calamities (Kjekstad and Highland 2009). On the other hand, landslide is a frequent

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phenomenon of active tectonic regimes such as the Himalayas in Northern Pakistan.

Spatio-temporal distribution of landslide events plays a vital role in evaluating and modelling the landslide hazard potential of the area (Witt et al. 2010). Assessing the landslide spatio-temporal distribution is challenging as the spatio-temporal properties of historical landslide events are hard to understand based on existing landslide classifications (Dikau and Schrott 1999). Comparatively, landslides besides other hazards are complex to categorize on a large scale because of the lack of available literature (Kirschbaum, et al. 2015). So, these shortcomings must be overcome through scientific and technical research (Pennington, et al. 2015). The development and analysis of a historical landslide database is also a significant tool for accurately predicting a landslide risk (Lin and Wang 2018). Landslides have proven to be the most challenging socio-economic disaster along the road corridors in the hilly landscapes, which led to massive losses of life, property and in particular environmental deterioration (Nanda et al. 2020). The landslide probability has escalated in the tectonically active regimes such as the Himalayas as a result of the extensive road cuts without the application of geological and geotechnical practices (Hadmoko et al. 2017). The consideration of landslide's spatio-temporal characteristics like intensity, frequency, recurrence, and human concerns have turned out to be the major attention for geoscientists, environmentalists as well as for public and private organizations and urban planners throughout the world (Devoli et al. 2007). These characteristics are necessary for quantifying landslide hazards, calibrating predictive models, and validating temporal predictions (Samia et al. 2017). Aslam et al. (2021) have adopted an integrated methodology using deep learning and ML algorithms for assessing landslide susceptibility and hazard potentials in the Muzaffarabad and Mansehra districts of Northern Pakistan. Aslam et al. (2021) have worked on landslide susceptibility through a feature extraction technique i.e., convolutional neural network (CNN) integrated with ML techniques, i.e., SVM, LR and RF in Mansehra and Muzaffarabad districts and found that the predictive ability can be enhanced by employing extracted features for the hybrid susceptibility models.

In mountainous terrains like Muzaffarabad, landslides are key threats to urban settlements, transportation routes, natural resource management and tourism developments. The road corridors (i.e., Neelum road, Jhelum Valley Road and Kohala road) of the Muzaffarabad district, Azad Jammu and Kashmir (AJ&K) experience numerous slope failures during monsoon seasons and after the devastating 2005 earthquake, which causes life-threatening risks to residents and tourists (Riaz et al. 2019). Road networks can be temporarily and permanently blocked due to landslides for at least a week up to a month, imparting significant influence on the economy

of the area. The present study has involved the landslide spatio-temporal distribution analysis to monitor the long-term evolution of the landslides and get an insight into the triggering and causative factors. Spatio-temporal landslide patterns in the study area for 2005, 2007, 2012, 2015, and 2019 were analyzed and compared with topographic factors like slope, aspect, curvature and elevation; geological factors like lithology and faults, hydrological attributes like distance to streams and Topographic Wetness Index (TWI), vegetation index like Normalized Differential Vegetation Index (NDVI) and anthropogenic attributes like landcover and distance to roads.

Spatio-temporal analysis particularly along road corridors is fundamental for land-use planners and decision-makers to plan and implement landslide mitigation measures at an effective cost. Hence, the present study provides the opportunity for all concerned agencies to adopt the appropriate decisions regarding future land use planning. In the current study, we investigated the relationship between landslide occurrences and their causative factors over 15 years along roadside sections of the Muzaffarabad district. On steep and unstable slopes, inappropriate road cuts and excavations within the physical environment are the sources of several landslide hazards.

The previous studies in the Muzaffarabad area like Saba et al. (2010), Shafique et al. (2016) and Shafique (2020), evaluated the spatio-temporal analysis for the co-seismic landslides only. Therefore, the present study is the first of its kind which includes the impacts of rehabilitation and reconstruction activities of road corridors on landslide occurrences. Considering the aforesaid facts, the present study aims to monitor the spatial distribution of landslides along the main transportation corridors of district of Muzaffarabad and their respective triggering and conditioning factors. Moreover, the present study also aims to monitor the landslide evolution along transportation corridors through temporal satellite imageries (i.e., 2005 to 2019) to categorize them based on landslide activities to correlate with LCF and their triggering mechanism. Systematic research work to evaluate the spatio-temporal dynamics of the landslide events is therefore of immense significance to reduce the economic and life losses in the Muzaffarabad district associated with roads. Therefore, the present study focuses on analyzing the landslide events which particularly disrupt the operation of the transportation routes in the study area. Once the most significant and influential landslide factors are determined in a specific area like Muzaffarabad, these results can be utilized to scale up the regional-level investigations through these LCFs.

Landslides have a recognized history in the Himalayas, though the statistics on these calamities are very inadequate and limited to the populated areas or along the main transportation routes. The primitive objectives of the present

research were three-fold: (1) to summarize and evaluate the spatial and temporal distribution of landslides along road corridors for the time interval of 2005 to 2019; (2) to evaluate the key landslide triggering factors, i.e., topographical, geological, natural, and anthropogenic, along these road corridors and (3) finally, the spatial association among landslide density and landslide causative factors were investigated. The study helps the decision and the policymakers for the development of these remote but tourism potentially attractive areas.

Study area

The study area road corridors are mainly located in the catchment of the Neelum and Jhelum River watersheds (Fig. 1). Neelum road connects Muzaffarabad with the Mansehra district of Khyber Pakhtunkhwa Province of Pakistan in the west and Neelum District in the northeast. The studied section along this road was 50 km long from Bararkot to the Nauseri area. Jhelum Valley Road connects Muzaffarabad with the Jhelum Valley District of AJ&K and

Srinagar of Indian-occupied Kashmir (IOK) in the southeast. The studied section along this road was 22 km long from Domel to Garhi Dupatta area. The Kohala road connects Muzaffarabad with Bagh District and Islamabad in the south and southwest, respectively. The studied section along this road was 35 km long from Domel to Kohala area.

Mostly the landslides are triggered by excavations either as construction materials for roads and buildings or mining-related jobs. Mostly the steep slopes are thickly populated which in turn increases the load on vulnerable slopes. The climate variations across the district of Muzaffarabad represent temperate, and subtropical monsoon climates from north to south. The climatic features are hot summers, dry to cold winters, and intense monsoon seasons. The annual average rainfall and atmospheric temperature of Muzaffarabad district are 1511 mm and 20 °C, respectively, whereas the maximum precipitation (70%) is observed in monsoon season and the maximum temperature (i.e. 45 °C) is observed in May to July of each year. The intensity of precipitation has been increasing due to changing weather incidents. During and after the earthquake in 2005, the affected areas suffered much from the blockages/damages of the roads which

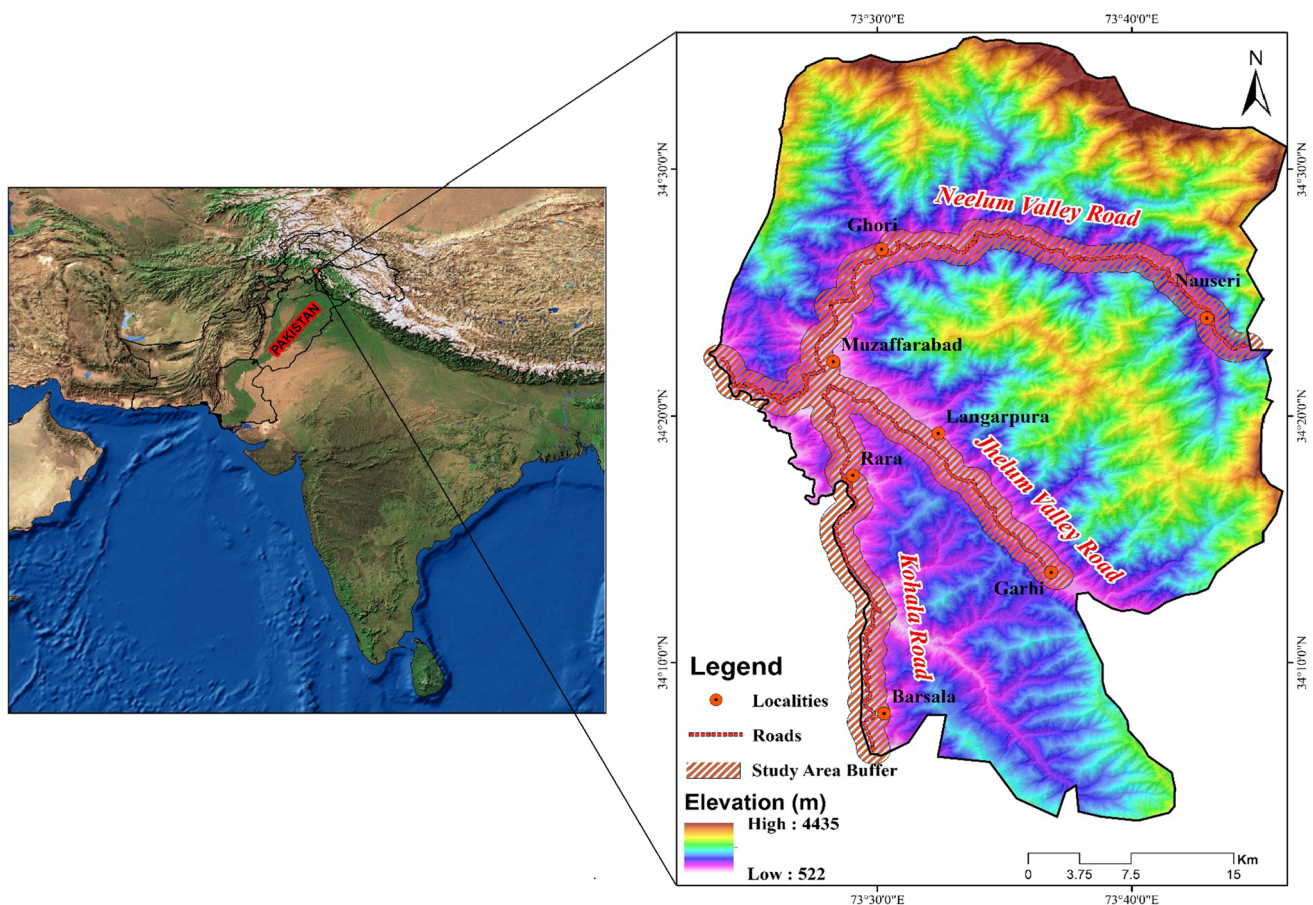


Fig. 1 The regional study area map with insight of the studied transportation corridors along with their buffers

contribute to the vulnerable conditions in the rehabilitation activities (Aslam et al. 2022a; Shafique 2020; Saba et al. 2010). After the rehabilitation, the widening and construction of new roads have increased the vulnerability of landslides due to improper slope excavations in the study area.

The study area has experienced maximum landslides yearly specifically after the 2005 Kashmir earthquake and during monsoon seasons (Kamp et al. 2008; Owen et al. 2008; Khattak et al. 2010). Geologically, the Muzaffarabad district lies in the sub-Himalayas region of Pakistan. The catastrophic 7.5 Mw earthquake in 2005 killed more than 75,000 inhabitants with thousands of injured people. Moreover, this catastrophic event also triggered multiple slope failures in the epicentre region (Kamp et al. 2008; Owen et al. 2008; Saba et al. 2010).

Hazara Kashmir Syntaxis (HKS) is the main tectonic scar in the study area. The rock units are folded and imbricated to form the HKS during the Tertiary Himalayan orogenic event (Calkins et al. 1975; Baig and Lawrence 1987; Bossart et al. 1988). Panjal thrust (PT) marks the tectonic boundary along the apex and eastern limb of HKS between the Carboniferous to Triassic Panjal Formation and the Pre-Cambrian Tanol Formation. Whereas along the western limb of HKS, PT demarcates the Tanol Formation from the Hazara Formation, Abbottabad Formation, and Paleocene-Eocene Sequence. The core of HKS generally comprises the Abbottabad Formation of the Cambrian age, Paleocene to Eocene sequence and Murree and Kamliyal formations of the Miocene age (Calkins et al. 1975). Generally, the area is tectonically active with a number of active thrust faults i.e., Muzaffarabad Fault (MzF), Main Boundary Thrust (MBT), Deolian Thrust (DT), Minhasa Fault (MF) and Jhelum Fault (JF). The rocks exposed in the study area are mainly Precambrian to Recent (Fig. 2). The Precambrian (Hazara Formation) and Cambrian (Abbottabad Formation) strata in the study area are mostly exposed along the hanging wall block of the MBT and MzF, respectively. The Paleocene to Eocene sequence (Hangu, Lockhart, Patala, Margalla Hill limestone, Chorgali and Kuldana formations) is exposed in the Yadgar section along the Neelum road whereas Miocene Murree Formation is covered the maximum area along these road corridors (Fig. 2). To assess the spatio-temporal analysis, the reliable data source, spatial overlap and time interval between landslide occurrences, are the proven key factors. The temporal analysis can be best performed on the availability of significant climatic, seismic, hydrological and remote sensing data to assess the actual reasons for the specific landslide activities. Therefore, based on the above-mentioned facts, the specific years, i.e. 2005, 2007, 2012, 2015 and 2019, were only selected from the 2005 to 2019 timeline. For the said timelines, the best satellite imageries were available to conduct the landslide spatio-temporal dynamics of the area. The year 2005 and 2007 were selected due to

the pre and post-earthquake 2005 impacts on the landslide intensity. During 2010, the intense rainfall triggers floods in the area and hence years 2012 and 2015 were selected to identify the rainfall impacts on landslide events. Moreover, the roads and other infrastructures were rehabilitated and reconstructed during these years after a catastrophic earthquake in 2005 which have an immense influence on landslide occurrences. The year 2019 was selected because of the re-alignment of roads and drastic climatic conditions in 2017 and 2018.

Data collection and methodology

The precise and accurate landslide inventory map is a crucial pre-requisite for landslide susceptibility mapping (Li et al. 2022; Tanyas and Lombardo 2020). Remote sensing data are a reliable data source with high-resolution observations over remote and rough mountainous terrains where landslides usually occur (Youssef and Pourghasemi 2021).

The multi-temporal landslide inventory maps allow to investigate their spatio-temporal patterns in five different timelines representing the areas with different landslide frequencies (Fiorucci et al. 2011; Guzzetti et al. 2005; Pisano et al. 2017). The spatial distribution of landslides is mainly influenced by several factors including lithology, hydrology, topography, land cover, seismicity, precipitation and soil cover (Lin et al. 2017). In the current study, we have selected eleven potential influencing factors i.e. slope, aspect, surface relief (Elevation), curvature, lithology, landcover, distance to streams, roads and faults, TWI and NDVI based on the previous literature and expert opinions (Aslam et al. 2022c; Khalil et al. 2022).

The landslide catalogue data is essential to be evaluated in contrast to the landslide influential factors to govern their significance and influence as well on the landslide event, as it is assumed that the similar conditions that were responsible to trigger the landslides in the past will be responsible for triggering the future landslides (Aslam et al. 2022a). At present, there is a lack of global standards regarding the landslide influencing factors assortment. Therefore, the selection of landslide influencing factors was selected by following the guidelines proposed by Aslam et al. (2022a) and hence the factors were selected based on the natural conditions, expert opinion and the past literature already discussed. Numerous reasons can be the causative factor for landslides and hence these reasons are distinguished for landslide influential factors (Sandric et al. 2019). Therefore, for a precise landslide spatial database, the selection of causative factors is a critical phase. Hence, the relevant factor selection is an essential component for drawing precise landslide spatial patterns. Moreover, Aslam et al. (2022b) have incorporated a broader range of landslide conditioning factors and distinguished

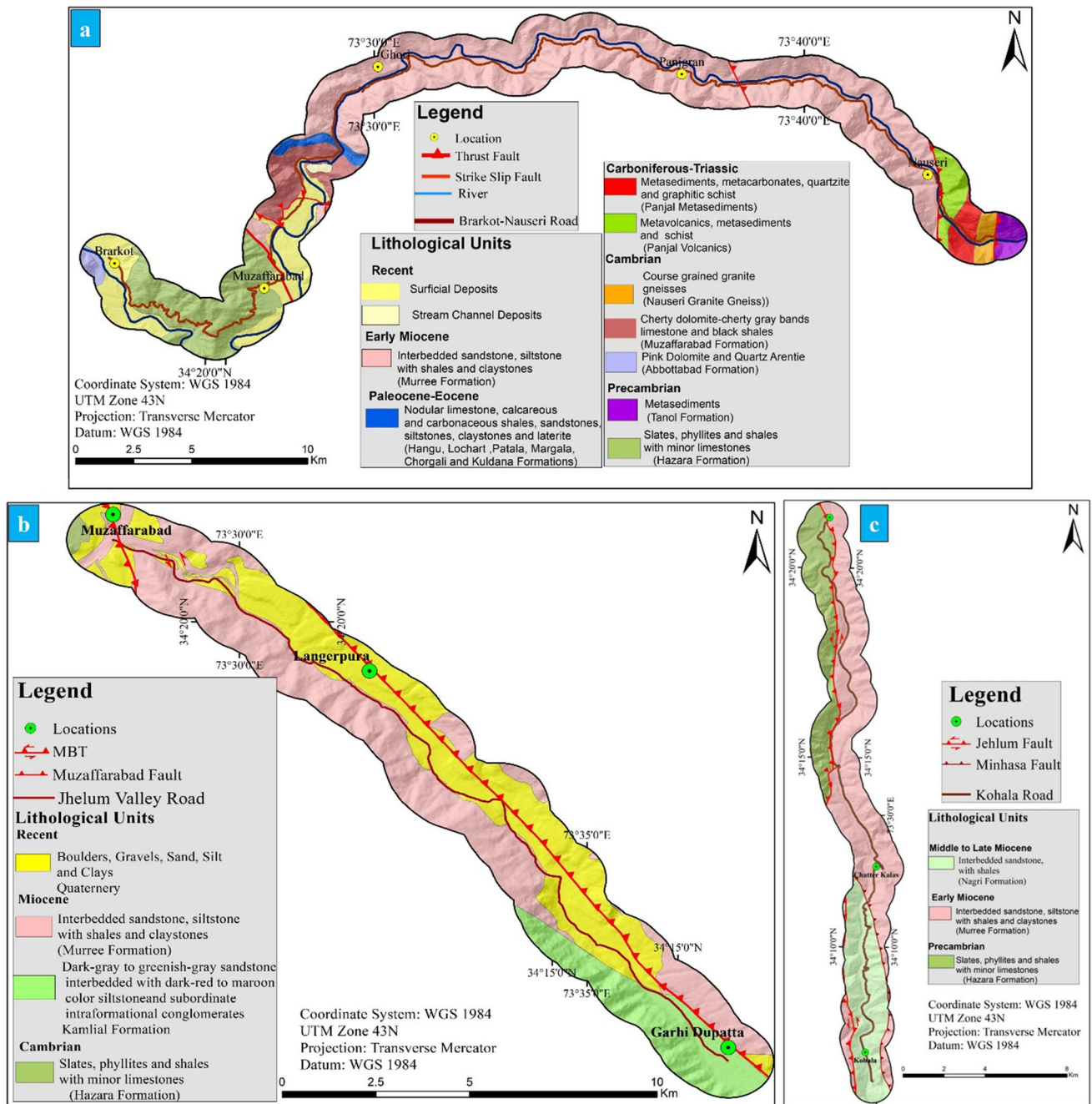


Fig. 2 Geological map of the study area

feature selection practices to opt for valuable features for evaluating landslide susceptibility. Therefore, based on the triggering mechanism involved, it is possible to prioritize the causative factors.

To classify the landslides and their causative factors, remote sensing techniques and comprehensive field visits have been carried out along the study area road corridors. This study focuses on the analysis of fatal landslides along these main road corridors during the period 2005–2019.

During this study, we compiled the landslide inventories along three (03) roads based on the interpretations of satellite imageries along with the field visits to verify the landslides (Fig. 3). Later on, the spatio-temporal patterns of these landslide events along these road corridors for each year (i.e., 2005, 2007, 2012, 2015 and 2019) were analyzed. In the end, the relationship among these landslide patterns and potential causative factors was evaluated. The ALOS PALSAR 12.5 m resolution digital elevation model (DEM)



Fig. 3 Field photographs of landslide events along the study area road corridors: **a** Lohargali landslide along Neelum road, **b** Panjgaran landslide along Neelum road, **c** Subri landslide along Jhelum Valley road, **d** Rara landslide along Kohala road

was acquired to study the topographic influence on the temporal changes of the landslides. The study area geological map was acquired from the Geological Survey of Pakistan (GSP) at a 1:50,000 scale to assess the impact of lithological units on the spatiotemporal changes of the study area landslide events. In the current study, we have marked the landslide events through the Worldview 3 (0.3 m resolution), Quick-bird Images, SPOT-5 and Google Earth imagery for different periods. Furthermore, field surveys were carried out to complete and verify landslide inventory. Locations and types of landslides, lithological units and faults were verified during the field surveys.

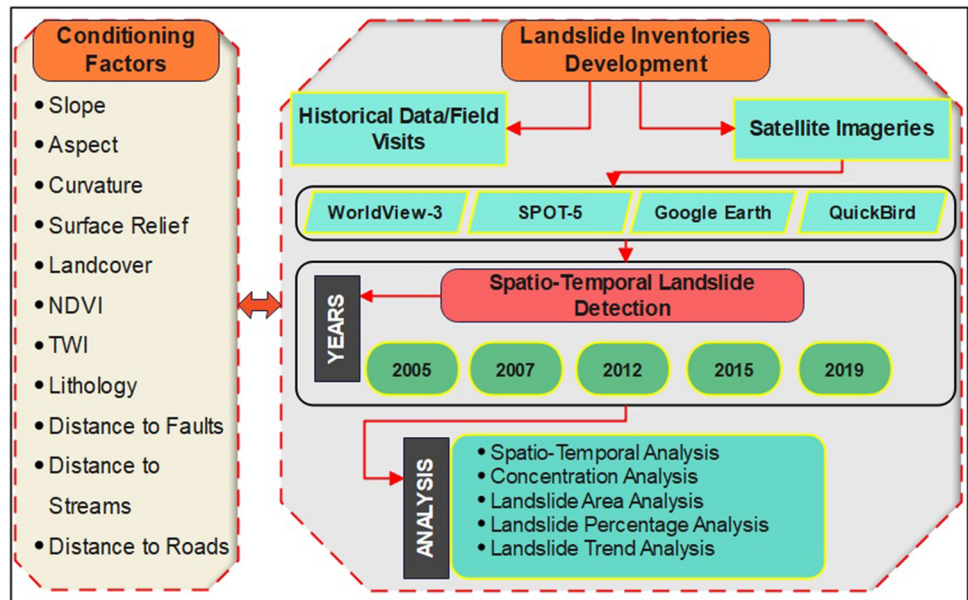
Moreover, the landslide classification and their triggering mechanism along with causative factors were also assessed during the visits. For the spatio-temporal distribution of landslides, the global positioning system (GPS) location is acquired which were then converted to the points. This conversion as landslide alternatives did not influence the conclusions of the present study. Primarily landslides were marked as polygons on Worldview 3, SPOT-5 and Google earth imageries and later on converted to points. Then ArcGIS software was used to process this compiled data for further analysis. One (01) km buffer zone was used on either

side of the studied road corridors for spatial patterns. The dataset comprised those landslide events only that has a significant impact or were located within the selected buffer zones along study area road corridors (i.e., Neelum road, Jhelum Valley Road and Kohala road) of the Muzaffarabad district. Therefore, landslide events that occurred outside the selected buffer zones along these roads were not included in this dataset. Methodological steps adopted in the research are illustrated in Fig. 4.

Results

The critical analysis of landslide inventory and landslide causative factors provides a base for hazard, vulnerability and risk assessment. Landslide inventory contains the landslide information like its location, type and damages which in turn play a significant role in evaluating the landslide spatio-temporal dynamics, landslide susceptibility and hazard of the area. Aerial photographs, field investigations and morphological surveys using high-resolution DEM and satellite imageries are significant tools to prepare landslide inventories (Guzzetti et al. 2012). The

Fig. 4 Methodological steps adopted for spatio-temporal distribution analysis



landslides classification comprises the rock/debris fall, rock/debris slide, and rock toppling. The satellite imagery for the corresponding years of 2005, 2007, 2012, 2015, and 2019 were analyzed to generate the respective inventories to identify the potential landslides and to detect the changes in the existing landslides and mapped the recently triggered events. These multiple inventories were generated to verify the spatiotemporal variations

in the landslide events. The generated temporal inventories are used to evaluate the impact of causative factors (i.e. slope, aspect, elevation, curvature, lithology, faults, streams, roads, NDVI, TWI and land cover) on landslide temporal distributions (Figs. 5, 6, 7). The landslides in the current study area have mostly shallow movements with an average thickness less than 1 m and comprise consolidated and unconsolidated debris materials, competent and

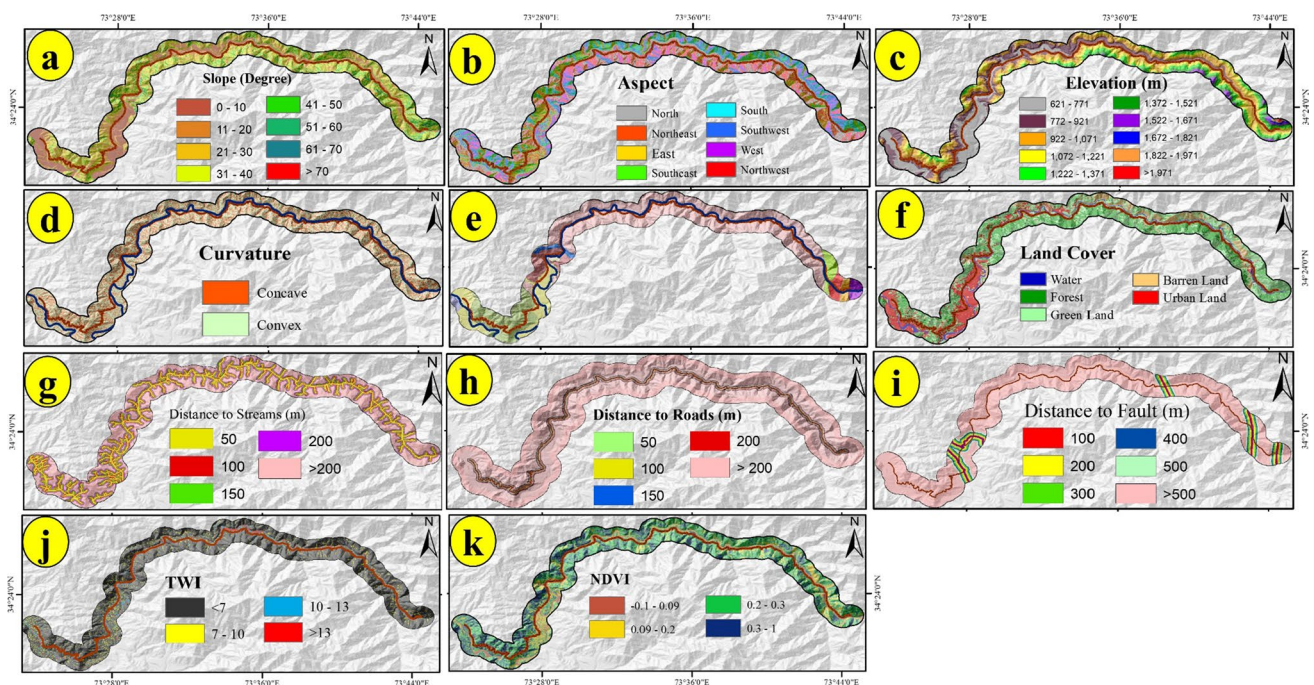


Fig. 5 Landslide Causative factors map along Neelum valley road: **a** slope, **b** aspect, **c** elevation, **d** curvature, **e** lithology, **f** landcover, **g** distance to streams, **h** distance to fault, **i** distance to roads, **j** TWI, **k** NDVI

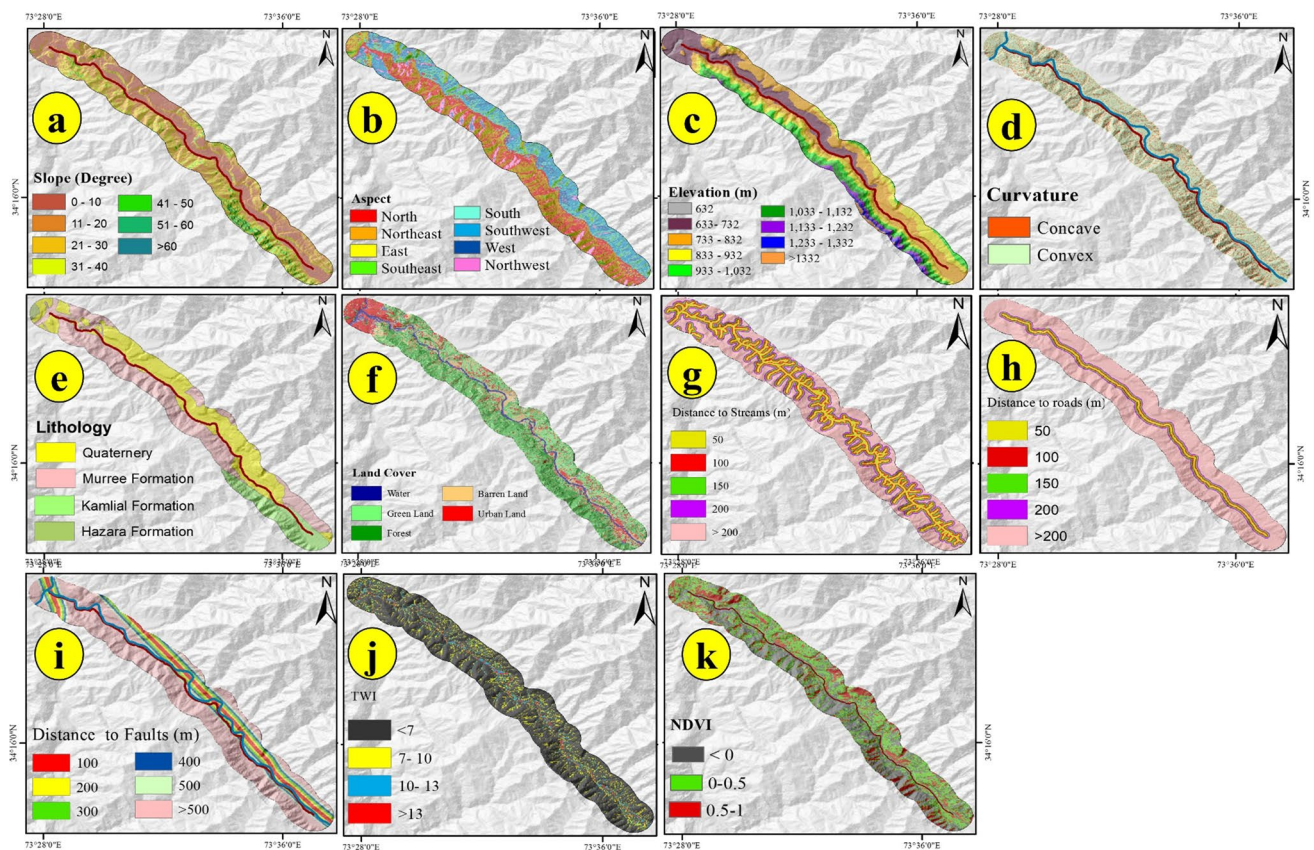


Fig. 6 Landslide Causative factors map along Jhelum valley road: **a** slope, **b** aspect, **c** elevation, **d** curvature, **e** lithology, **f** landcover, **g** distance to streams, **h** distance to fault, **i** distance to roads, **j** TWI, **k** NDVI

incompetent strata and fractured rock mass which posed serious threats to these road corridors. These shallow landslides have occurred on the steeper slopes along these road corridors. The translational and rotational slides were also identified and marked during the field investigations. Mostly, the translational slides are found in the sheared and crushed rocks exposed along these roadside sections. Rock or debris slides mostly occur along the discontinuity planes existed in the rock masses. Whereas few deep-seated landslides were also observed during field visits which are mostly the reactivation of the older mass movements in multiple phases.

Spatial analysis is applied to reveal the processes and patterns of landslide spatial distribution in an area. The temporal inventories were analyzed to evaluate topographic, geographic, hydrologic, geological, and anthropogenic parameters. Spatio-temporal landslide patterns in the study area for 2005, 2007, 2012, 2015, and 2019 years were analyzed from the interpretation of remote sensing imageries and extensive field work. The data acquired depicts that various triggering factor were responsible for

the landslide events along the study area road corridors during the inventoried years.

The landslide database along the study area road corridors was generated and evaluated regarding spatio-temporal distributions. Landslide variations were observed through respective time-based acquired satellite imageries and analyzed for selected years. Landslide numbers and types along each road were evaluated, including reactivated, old, and new ones and then quantitative analyses were performed from the selected years.

Spatio-temporal landslide inventory

The corresponding descriptive statistic for the selected years is given in Table 1 and Fig. 8. Landslide inventories for the selected years along the road corridors of Muzafarabad are shown in Fig. 9. The maximum landslide area along Neelum road is estimated as 6.102 km², with 70 landslides identified in 2005, whereas the minimum landslide area is 1.457 km² with 41 landslides in 2015. However, 82 landslides were observed in the year 2007, having a landslide area of about 4.201 km². In 2012 and 2019,

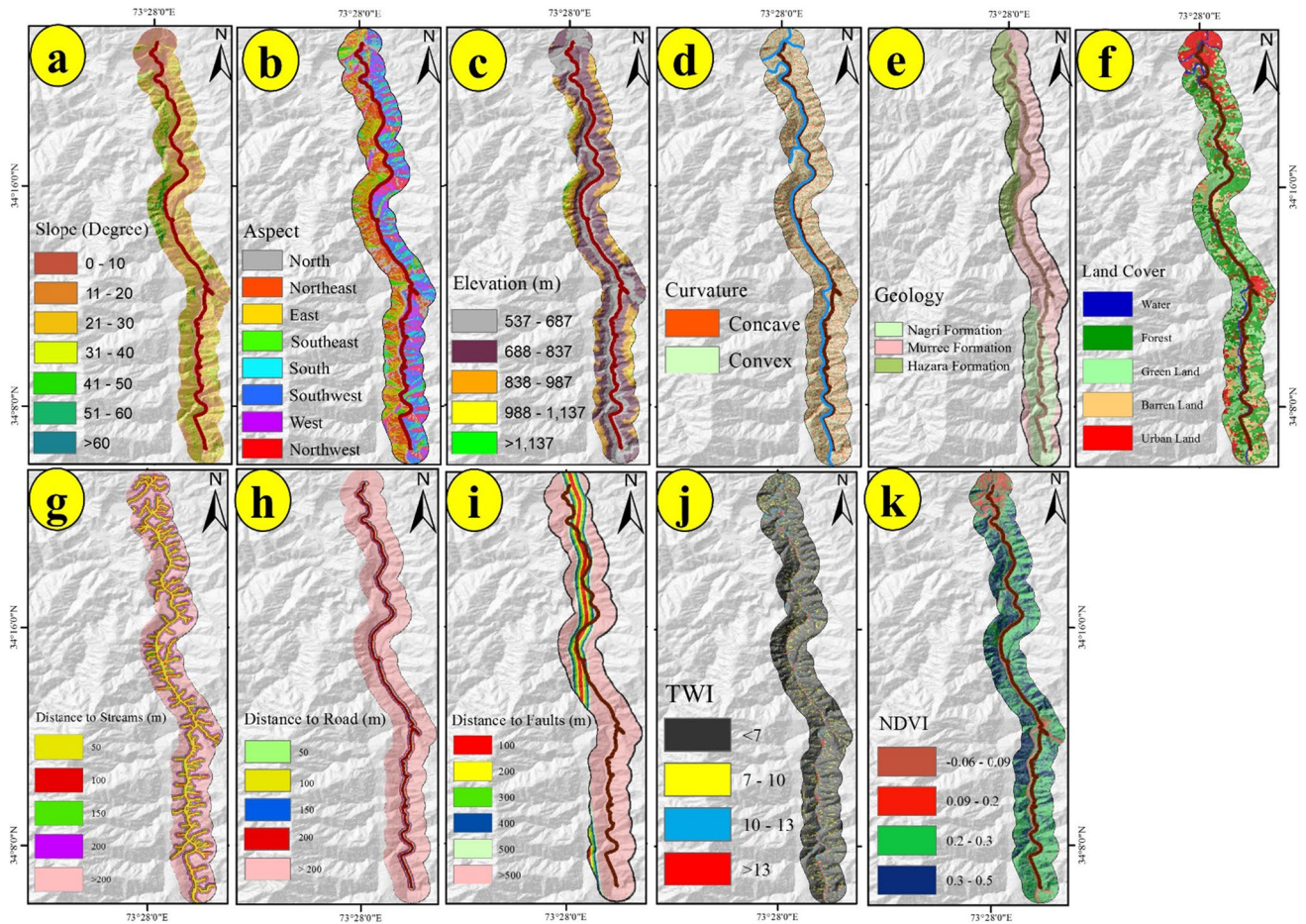


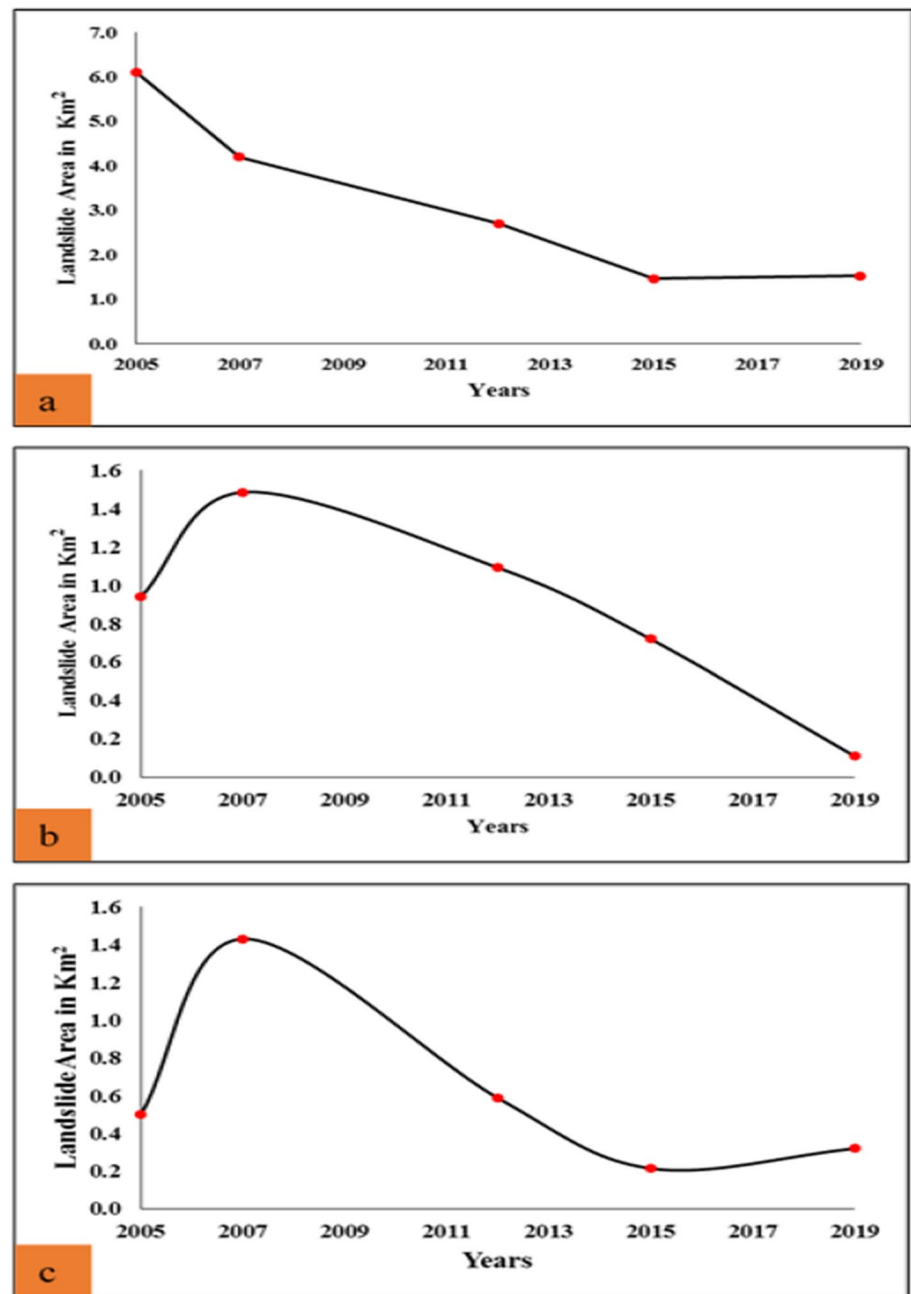
Fig. 7 Landslide Causative factors map along Kohala valley road: **a** slope, **b** aspect, **c** elevation, **d** curvature, **e** lithology, **f** landcover, **g** distance to streams, **h** distance to fault, **i** distance to roads, **j** TWI, **k** NDVI

Table 1 Temporal landslide inventories showing the number of landslides and the area covered by these landslides

Year	Roads	No. of landslides	Area (km ²)
2005	Neelum	70	6.102
	Jhelum	11	0.940
	Kohala	26	0.499
2007	Neelum	82	4.201
	Jhelum	31	1.487
	Kohala	51	1.432
2012	Neelum	88	2.702
	Jhelum	44	1.093
	Kohala	37	0.589
2015	Neelum	41	1.457
	Jhelum	31	0.720
	Kohala	20	0.215
2019	Neelum	91	1.518
	Jhelum	38	0.110
	Kohala	53	0.320

observed landslides in the Neelum Valley Road are 88 and 91, with a landslide area of 2.702 km² and 1.518 km², respectively. Along the Jhelum valley road, the maximum landslide area was calculated as 1.487 m² with 31 landslides during the year 2007, while the minimum landslide area was calculated as 0.110 m² with 38 landslides during the year 2019. However, 11 landslides were observed in 2005 and 44 landslides in 2012, having an area of 0.940 m² and 1.093 m² respectively. Moreover, with 31 landslides in 2015, the landslide area is 0.720 m². Along the Kohala road, the maximum landslide area was 1.432 m² with 51 landslides during 2007, while the minimum calculated landslide area was 0.215 m² with 20 landslides during the year 2015. However, during 2005, 2012 and 2019, the number of landslides observed are 26, 37 and 53, with the landslides area of 0.499 km², 0.589 Km² and 0.320 km² respectively.

Fig. 8 Dynamics in the total landslide area in the selected period: **a** Neelum Valley road, **b** Jhelum Valley road, **c** Kohala road



Spatio-temporal analysis

The spatio-temporal analysis revealed the impacts of various triggering factors and human interventions along these road corridors, for example, the 2005 Kashmir earthquake and 2010 monsoon significantly affected the stability of slopes along these roads. Moreover, the widening and construction of new roads after the earthquake have also influenced slope stability.

The 2005 Kashmir earthquake triggered several landslides in the area, the subsequent increase in landslides in 2007 was due to heavy rainfall in 2006. In 2010, massive

rainfall and floods in the rivers also triggered more landslides as all road corridors are throughout, followed by the Kunhar, Neelum and Jhelum rivers, along with many tributaries on their way. So, in the 2012 database, there is also a remarkable increase in landslide events along these road corridors. Due to the reconstruction and rehabilitation of these road corridors in 2016–2018, the landslide events reported in the 2019 database also increased. Lithology, tectonics, topography, hydrology, and land cover have a strong association with landslide events. Topographic attributes, i.e., slope angle, aspect, elevation and curvature, have a strong influence on the spatial variations of climatic intensity, which

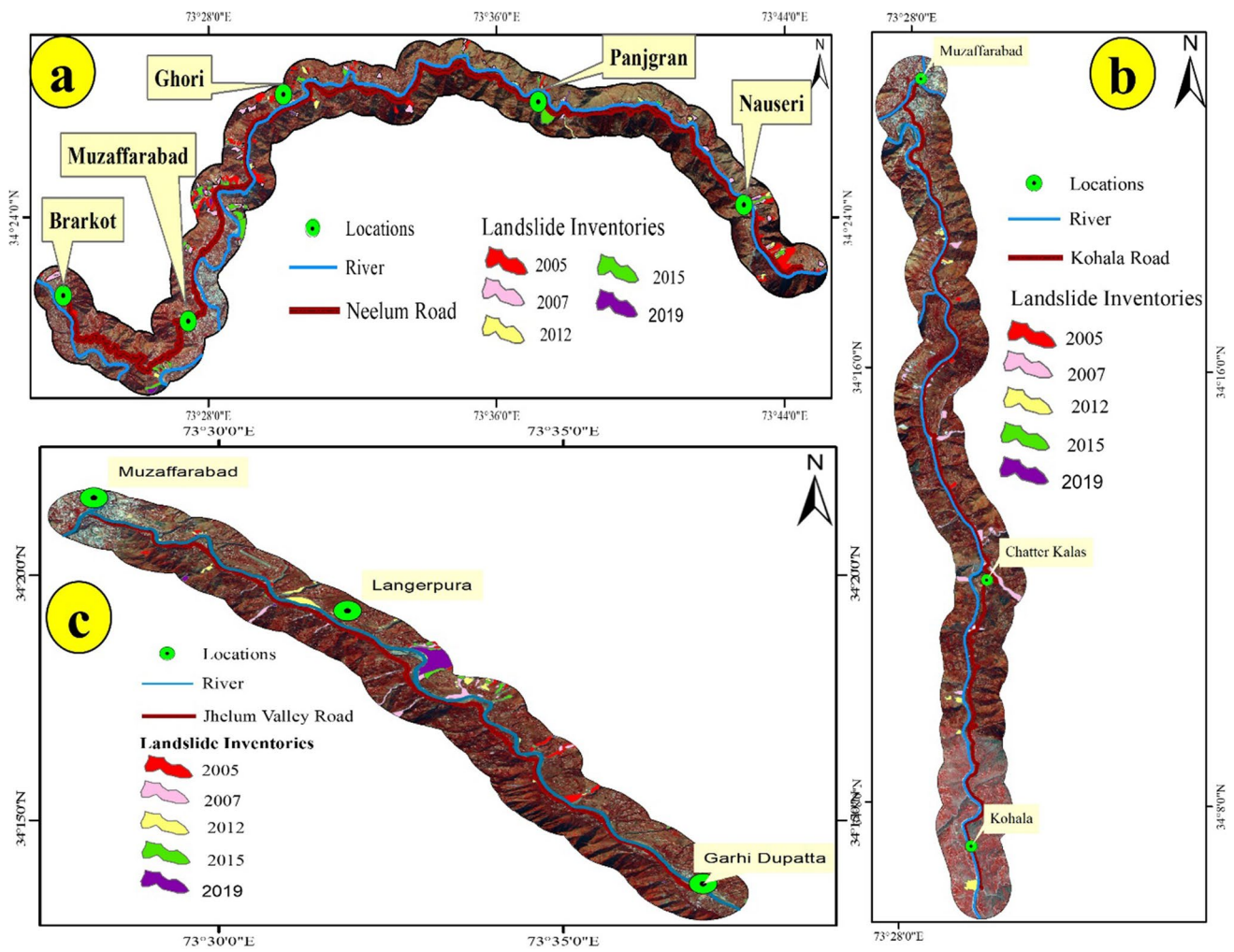


Fig. 9 Spatio-temporal landslide inventory map of the Neelum valley road, Jhelum valley road and Kohala road

may contribute to the spatial occurrence of landslide events. The temporal landslide inventories were compared with the DEM-derived topographic attributes of slope angle, slope aspect, elevation, curvature; lithology, distance to streams, faults and roads; TWI; NDVI and landcover. Spatio-temporal distribution analyses were analyzed for their distribution in the selected causative factors classes.

Slope

The slope angle is the most significant topographic factor responsible for the stability or failure of the slope. With the increase in the degree of slope, the weight of slope-forming materials also increased, making the slope more vulnerable to sliding and creating the potential for slip surfaces. The landslide area distribution, landslide number and landslide concentrations in various slope classes of the main road corridors have been investigated (Figs. 10a, 11a, 12a). The slope class of the area ranges from 0° to 70° which was grouped

into 08 classes with an interval of 10° along the Neelum Valley road and was plotted against the landslide area and landslide concentration, whereas along the Jhelum valley and the Kohala road, the slope ranges from 0° to 60°. Similar landslide distribution trends in different slope classes were observed in spatio-temporal landslide inventories along the selected road corridors. The terrain slopes range of 31°–40° has contributed to most of the landslides in all selected years along the Neelum Valley Road (Fig. 10a).

The landslides show a minimum presence in terrain slopes steeper than the 50°. Along the Jhelum valley road, slope class 21°–40° has the highest number of landslide events in all the selected landslide inventories while minimum landslide numbers were observed in class > 50° (Fig. 11a). The landslide numbers were maximum in the class 31°–40° in 2005, 2012 and 2015 years while a minimum number of landslides along Kohala road were observed in the class 21°–30° slope class in the landslide inventories of 2007 and 2019 (Fig. 12a). Along all the studied road corridors, about

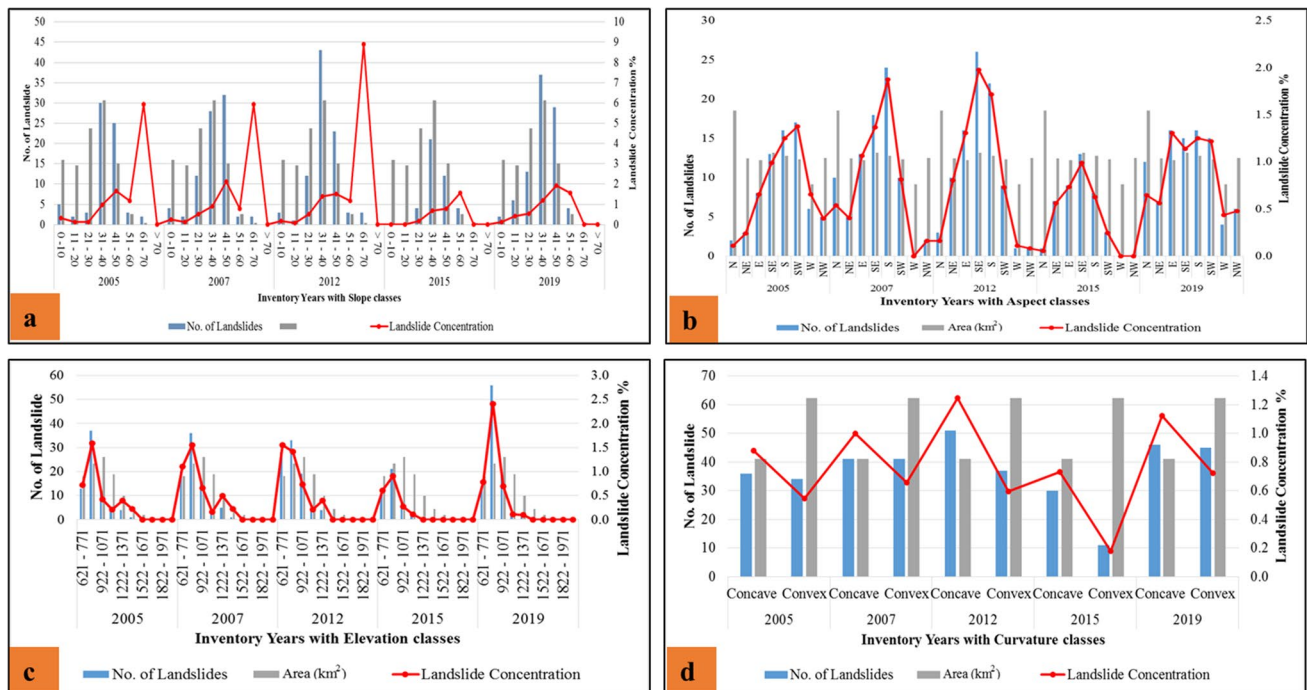


Fig. 10 Spatio-temporal (2005–2019) landslide dynamics (landslide area, landslide numbers and landslide concentration) correlation with different classes of causative factors along Neelum Valley road: **a** cor-

relation with slope gradient, **b** correlation with aspect, **c** correlation with elevation and **d** correlation with curvature

50% of the area containing a slope angle between 21° and 40° with a maximum number of landslide events revealing a strong relationship between the slope angle class and landslide incidents.

Aspect

The slope aspect is generally the face of the landscape surface, which is in the plane's direction (tangent) at a certain point on the earth's surface. The aspect map of these roads was categorized into eight (08) classes, namely north (N), north-east (NE), east (E), south-east (SE), south (S), south-west (SW), west (W) and north-west (NW). The comparison of developed inventories and categorized landslides with terrain aspect (Fig. 10b) reveals that the majority of the landslides are facing SW in the year 2005; S in the year 2007; SE in 2012 and 2015; E and S in the year 2019 along the Neelum Valley Road. While minimum landslides were observed in N facing slope in 2005; W facing slope in 2007; 2012; 2015 and 2019. The comparison of developed inventories and categorized landslides with terrain aspect along the Jhelum Valley Road (Fig. 11b) reveals that most of the landslides are facing southwest in the year 2005; NE in the year 2007 and 2019; N in 2012 and S in 2015. Along the Kohala road, the maximum number of landslides was observed in SW during the years 2005 and 2019 in 2007,

2012 and 2015, whereas maximum numbers were observed in E facing slope (Fig. 12b).

Elevation

The area's elevation can define the slope breaks, as the biological elements and natural or artificial agents vary with the increase of the altitude. In the present study, the elevation values acquired through the DEMs were divided into ten (10) and five (05) classes along the Neelum and Kohala roads, respectively, whereas into nine (09) classes with intervals of 100 m along the Jhelum valley road. The maximum landslide events were observed in the elevation class of 772–921 m along the Neelum valley road in all the landslide inventories, while the elevation > 1071 m has a minimum number of landslides events (Fig. 10c). Along the Jhelum valley road, the maximum number of landslides were observed in elevation class 733–832 m in the years 2005, 2007, 2015 and 2019. In 2012, the maximum number of landslides was observed in the elevation class of 633–732 m (Fig. 11c). Landslides are largely absent in the elevation > 932 m. Along the Kohala road, the maximum number of landslides were observed in elevation class 537–687 m in 2005, 2007, 2012 and 2019, while in the year 2015, the maximum number of landslides was observed in elevation class of 688–837 m (Fig. 12c). Landslides are largely absent in elevation greater than 987 m.

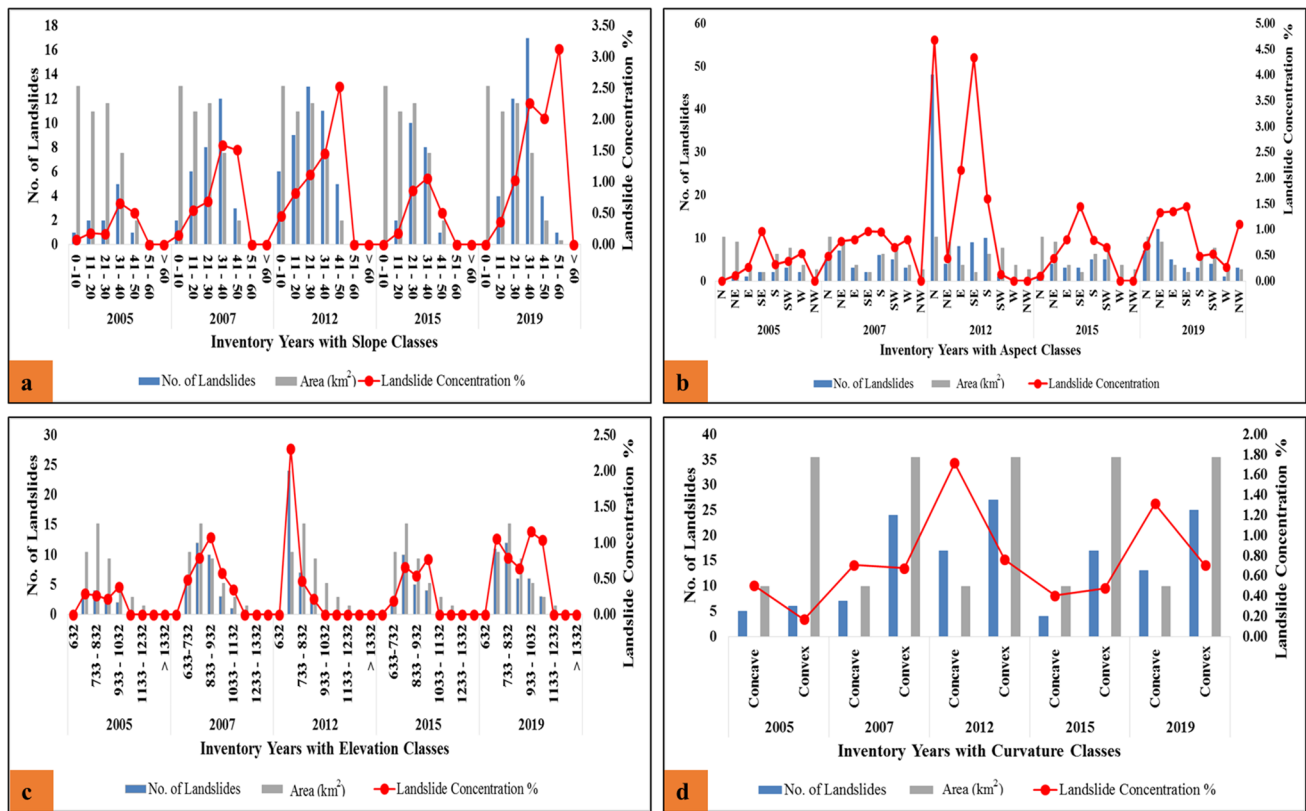


Fig. 11 Spatio-temporal (2005–2019) landslide dynamics (landslide area, landslide numbers and landslide concentration) correlation with different classes of causative factors along Jhelum Valley road: **a** cor-

relation with slope gradient, **b** correlation with aspect, **c** correlation with elevation and **d** correlation with curvature

Curvature

Slope curvature is also among the key geomorphic factors of topographic attributes. Slope curvature is categorized into two (02) classes, i.e., convex and concave. The landslide events were maximum in concave curvature and minimum in convex curvature in all the landslide inventory years along Neelum valley road (Fig. 10d). On the contrary, the landslide events were minimum in concave curvature and maximum in convex curvature in all the landslide inventory years along the Jhelum valley road (Fig. 11d). Along the Kohala road, the maximum landslide events are in the convex curvature class except for the year 2015, which is the concave class and vice versa for the concave class (Fig. 12d).

Lithology

The lithology is considered the most influential causative factor in slope failures. Due to the variety of material characteristics, i.e., shear parameters and incompetent strata, the behavior of the lithological units possess a significant role in slope instabilities and landslide frequencies (Merghadi et al. 2018).

Spatio-temporal landslide distribution analysis of lithological units along the Neelum valley road (Fig. 13a) reveals that the highest number of landslides were observed in the Murree Formation in the years 2005, 2007, 2012 and 2019, which covers a greater fraction of the study area while the maximum landslide concentrations in all the inventory years were observed in the Muzaffarabad Formation which is in line with the results from Shafique (2020). The lowest number of landslides were observed in the Abbottabad Formation and Nauseri Granit Gneiss. Maximum landslide events and their concentration were found in the Murree Formation along Jhelum valley road, indicating its high proneness for slope instability due to the alteration of competent and incompetent layers, including moisture-sensitive clays and shales (Fig. 14a). Along Kohala road, the maximum number of landslides were observed in the Murree Formation in the years 2005, 2007 and 2019, whereas in 2012 and 2015, the maximum landslide events were observed in the Hazara Formation (Fig. 15a). The spatial analysis of the studied sections inferred that the highly fractured and deformed Muzaffarabad and Hazara formations and incompetent strata, i.e., shales of Murree and Nagri formations, showed a higher frequency of landslides.

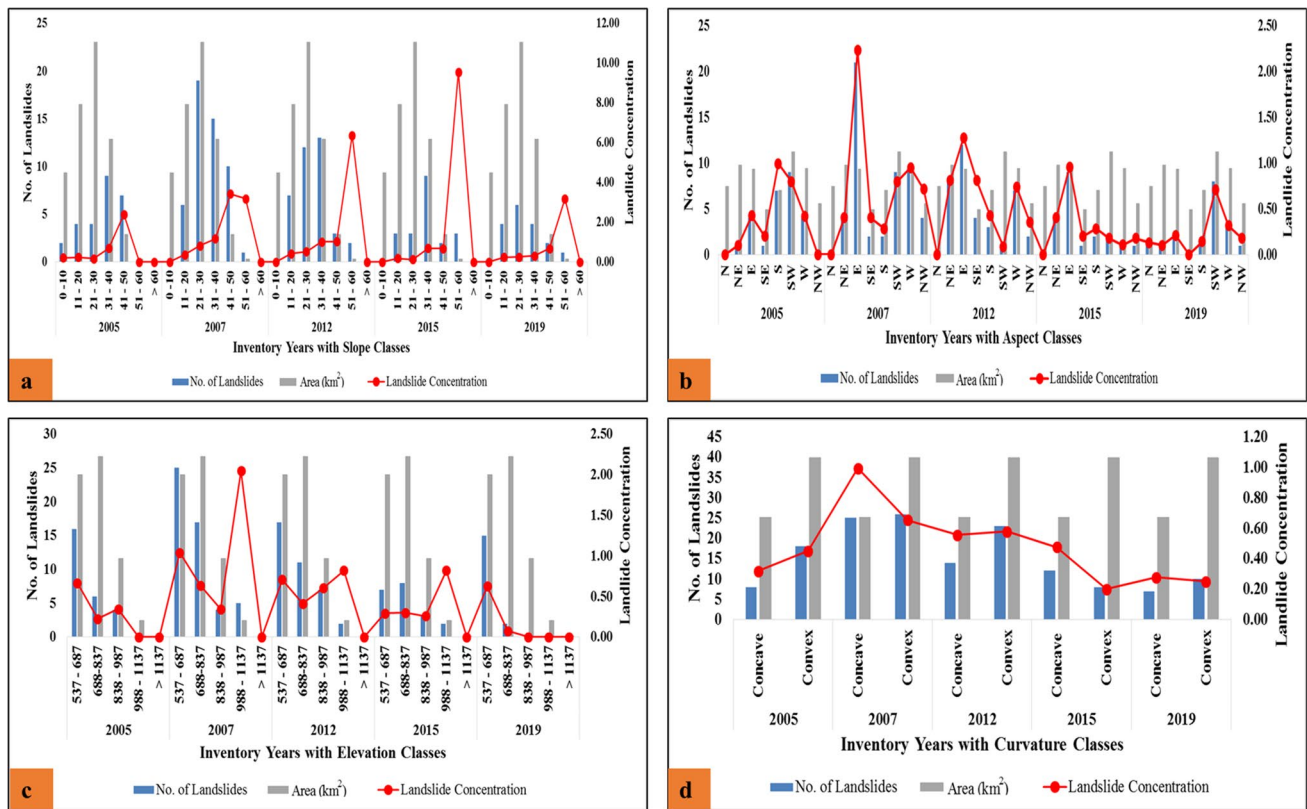


Fig. 12 Spatio-temporal (2005–2019) landslide dynamics (landslide area, landslide numbers and landslide concentration) correlation with different classes of causative factors along Kohala Valley road: **a** cor-

relation with slope gradient, **b** correlation with aspect, **c** correlation with elevation and **d** correlation with curvature

Land cover

Land cover is a crucial causative factor that has a critical role in stabilizing or destabilizing slopes (Zhu et al. 2018). The highest landslide events along the Neelum valley, Jhelum valley and Kohala roads were observed in the barren land class in all inventory years except in 2007 along Jhelum valley road, the forest class bears the most landslide events. The lowest events were found in the water bodies’ class except for the year 2012, which is forest class along Neelum valley road (Fig. 13b). The lowest events found along Jhelum valley road for the years 2005, 2012 and 2019 were in urban land class while during the years 2007 and 2015 in the water bodies class (Fig. 14b). The lowest landslide events found along Kohala road were in forest class for all the inventory years (Fig. 15b). In the present research, the spatio-temporal analysis concluded that along the Neelum and Kohala roads, most of the area and landslide events fall in the barren land. This analysis showed that the slope excavations and irregular urban planning aided the slope instability conditions.

Distance to streams

The spatio-temporal analysis of streams depicts that the most landslide incidents along the Neelum valley road were recorded during the years 2005 and 2015 in the class of 150 m, during years 2007 and 2019 in the class of 100 m, whereas during the year 2012, the stream class > 200 m bears the most landslide events. The analysis showed that during the years 2005 and 2007 received the minimum landslide events in the class of 200 m, during the years 2012 and 2019 in the class of 150 m, whereas during the year 2015, the class of 50 m has recorded the minimum landslide events (Fig. 13c). Along the Jhelum valley road, the maximum and minimum landslide events were recorded against the classes of > 200 m and 200 m, respectively (Fig. 14c). Along the Kohala road, during the years 2005, 2007 and 2015, most landslide events were recorded against the class of 100 m, the class > 200 m during the year 2012 and the class of 50 m during the year 2019. The analysis showed that the class of 200 m has minimum landslide events during the years 2005, 2007 and

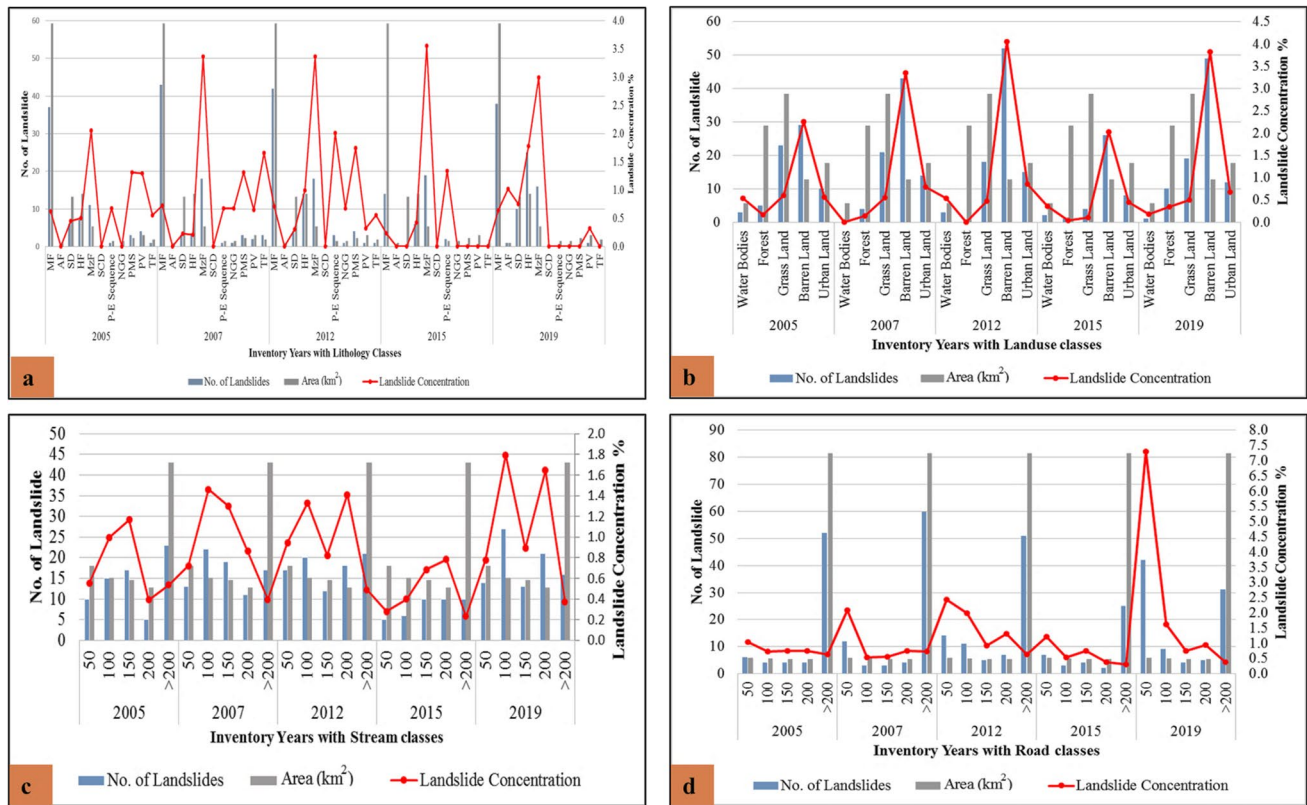


Fig. 13 Spatio-temporal (2005–2019) landslide dynamics (landslide area, landslide numbers and landslide concentration) correlation with different classes of causative factors along Neelum Valley road: **a** correlation with lithology (Murree Formation (MF), Abbottabad Formation (AF), Surficial Deposits (SD), Hazara Formation (HF),

Muzaffarabad Formation (MzF), Stream Channel Deposits (SCD), Paleocene-Eocene (P-E) sequence, Nauseri Granite Gneiss (NGG), Panjal Metasediments (PMS), Panjal Volcanics (PV) and Tanol Formation (TF)). **b** Correlation with landcover, **c** correlation with distance to streams and **d** correlation with distance to roads

2012, a class of 50 m during the year 2015 and the class of 100 m during the year 2019 (Fig. 15c).

Distance to roads

Distance to roads increases the probability of landslide events, consequently, has been one of the triggering factors in slope failures (Lai and Tsai 2019). During the current study, spatio-temporal patterns showed that the maximum landslides occurrences along all the studied road corridors are found in the > 200 m class of distance to roads in all inventoried years except in the year 2019 along Neelum valley road where the 50 m class holds the maximum landslide events. The pattern showed that the classes that faced the least number of landslide areas are 150 m and 200 m along each studied area roads (Figs. 13d, 14d, 15d). Poor excavation techniques and a lack of geotechnical approaches have led the slopes more vulnerable to landslides. The improper cut slopes along the roads enhance the tensions, toe disturbance and slope angle variations that may result in slope failures. This spatio-temporal study along the main road

corridors concluded that the closer the road’s distance (< 500 m) to the slopes higher will be the landslide events.

Distance to faults

Faults usually play a significant role in the landslide occurrence in the region, which influences the surficial lithology and terrain permeability which in turn enhances the slope instability (Chen et al. 2019). The spatial analysis of the distance to fault map reveals that the maximum area and landslide events reported in the class are > 500 m along each studied road corridor. While along Neelum valley road, the minimum landslide incidences are found in the 200 m class in all the selected years except 2019, where the 500 m class bears the minimum incidences (Fig. 16a). Along Jhelum valley road, the least number of landslides are found in the 200 m class in all the inventoried years except 2012, where the class 300 m bears the minimum events (Fig. 17a). During the inventoried years 2005, 2007 and 2015 along Kohala road, the 400 m class of fault distance hold the minimum landslides but during the years 2012 and 2019, the 200 m class encounters

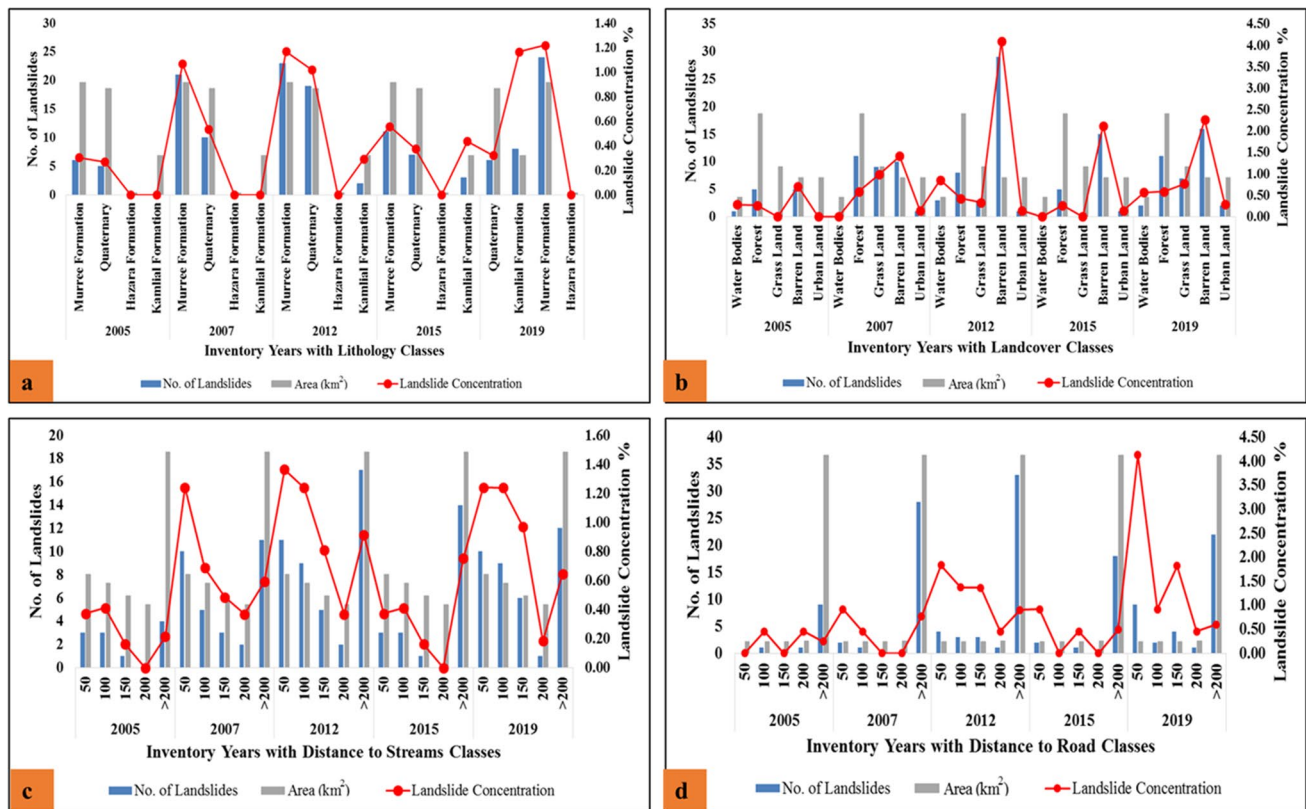


Fig. 14 Spatio-temporal (2005–2019) landslide dynamics (landslide area, landslide numbers and landslide concentration) correlation with different classes of causative factors along Jhelum Valley road: **a** cor-

relation with lithology, **b** correlation with landcover, **c** correlation with distance to streams and **d** correlation with distance to roads

the least landslide occurrences (Fig. 18a). This analysis concludes that landslide intensity decreased with the increase in the distance to the faults and, most landslides (i.e., 70%) were clustered within the 500 m fault radius. Therefore, the areas closer to the faults possess maximum landslide events.

TWI

Based on the values, the TWI map has been classified into four classes, with the higher values indicating the wet conditions and vice versa. The analysis depicts that along all the road corridors, the maximum landslide events occurred within the class of < 7 along all the roads excluding the 2019 year, along Jhelum valley road, which corresponds to the class of 7 to 10, which bears a maximum landslide frequency. The spatio-temporal analysis of TWI indicates that more than 50% of the total area along each road lies in moderate wetter conditions and hence faces more landslide occurrences (Figs. 16b, 17b, 18b).

NDVI

The normalized difference vegetation index (NDVI) values obtained at selected years can be helpful in determining the multi-temporal characteristics of the vegetation along these roads. During all the selected inventory years, along Neelum valley road highest number of landslides occurred in the class of 0.09–0.2 while the least landslide events were recorded against the class of 0.3–1 during all inventoried years (Fig. 16c). Along Jhelum valley road, the 0.5–1 class is more prone to landslides throughout the selected years and class < 0 has the minimum landslide events in the selected studied years except the year 2019, which has more landslide incidences in NDVI class of 0–0.5 (Fig. 17c). Similarly, along the Kohala road, the NDVI class of 0.2–0.3 bears maximum landslides occurrences except in the year 2019, in which the class 0.09–0.2 has maximum landslide numbers and the class of –0.06 to 0.09 holds the minimum landslide events throughout the studied inventoried years (Fig. 18c). The spatial pattern of the NDVI factor in the present study incorporates the conclusion that with the expansion of the

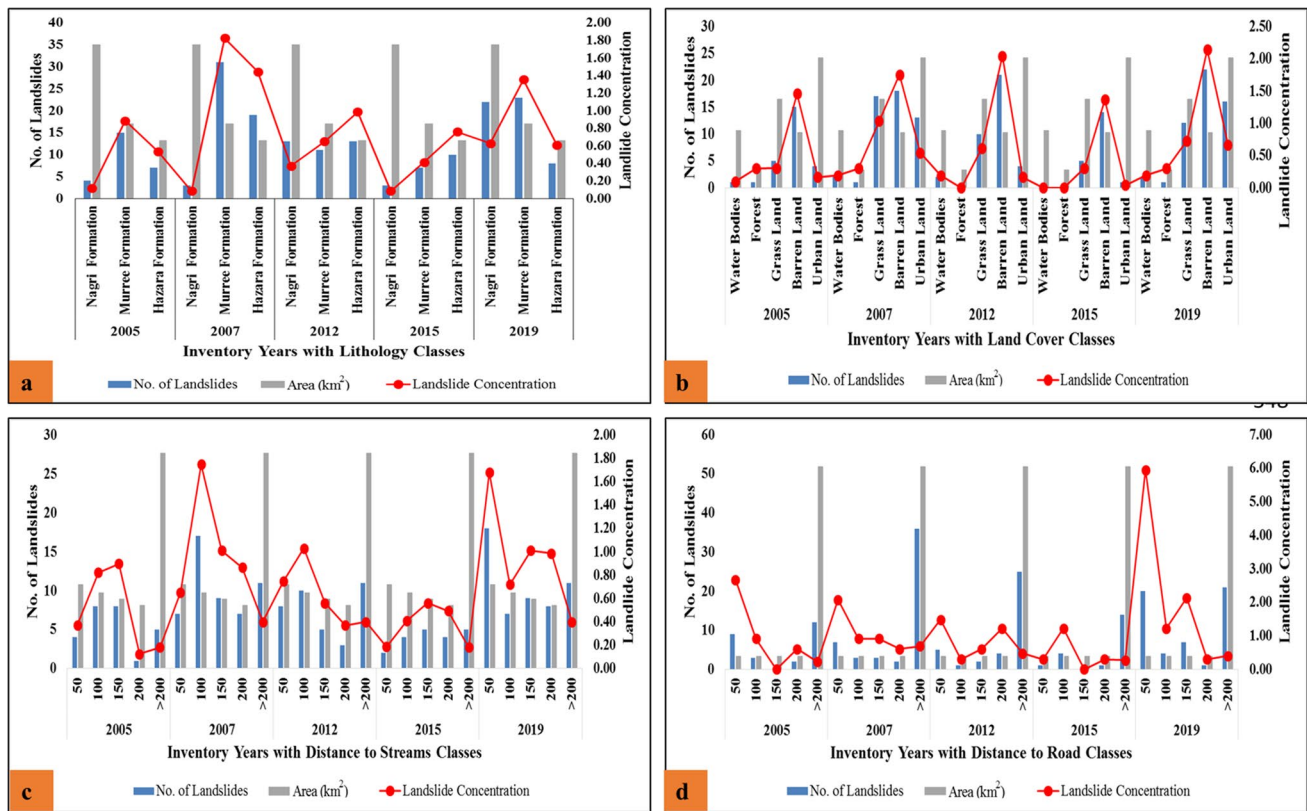


Fig. 15 Spatio-temporal (2005–2019) landslide dynamics (landslide area, landslide numbers and landslide concentration) correlation with different classes of causative factors along Kohala road: **a** correlation

with lithology, **b** correlation with landcover, **c** correlation with distance to streams and **d** correlation with distance to roads

population and road excavations, the vegetation index has been badly affected and hence the landslide events have also increased.

Discussion

A landslide is a complex natural calamity that poses serious threats and hazards to the environment and is influenced by a number of triggering factors like seismicity, extended rainfall, volcanic activities, and tsunamis (Guzzetti et al. 2009). To predict future landslides, the landslide causative factors must be evaluated. Though numerous factors are responsible for landslide occurrences, intense rainfall and seismicity are thought to be the most influential (Khattak et al. 2010). The multi-temporal inventories prepared in the current study include all landslide events reported in the respective years of 2005 (pre-earthquake), 2007, 2012, 2015 and 2019. These events are then utilized to extract the related landslide causative factors to generate multi-temporal datasets along the studied road corridors. Shafique (2020) has worked on the spatio-temporal evolution of seismically induced landslides after the 2005 Kashmir earthquake

from 2004 to 2018, categorizing the landslides based on landslide events and associating them with their causative factors. However, this study concluded that the landslide area of the seismically induced landslides is decreasing with time. Basharat et al. (2014) and Riaz et al. (2018) have also worked in the same area and observed that the continuous landslide events in the Muzaffarabad area are generally affected by the intense rainfall during monsoon, river cutting, and anthropogenic activities. The present research provides the temporal changes and spatial distributions of massive landslides along the road corridors of Muzaffarabad district. The landslide area decreases slowly between 2005 and 2010, however, it accelerated from 2010 to 2018. After the earthquake, a gradual decrease in unconsolidated material, natural restoration, confinement along cracks and fractures produced; compaction of debris, regrowth of the vegetation cover, and geotechnical measures, are the reason to stabilize the seismically induced landslides (Domènech et al. 2019). The present study concludes that in the respective years the number of landslide events and landslide areas decreases within the study area. According to Khattak et al. (2010), the area received the most annual rainfall from 2008 to 2010 which as result, slightly enhances the landslide

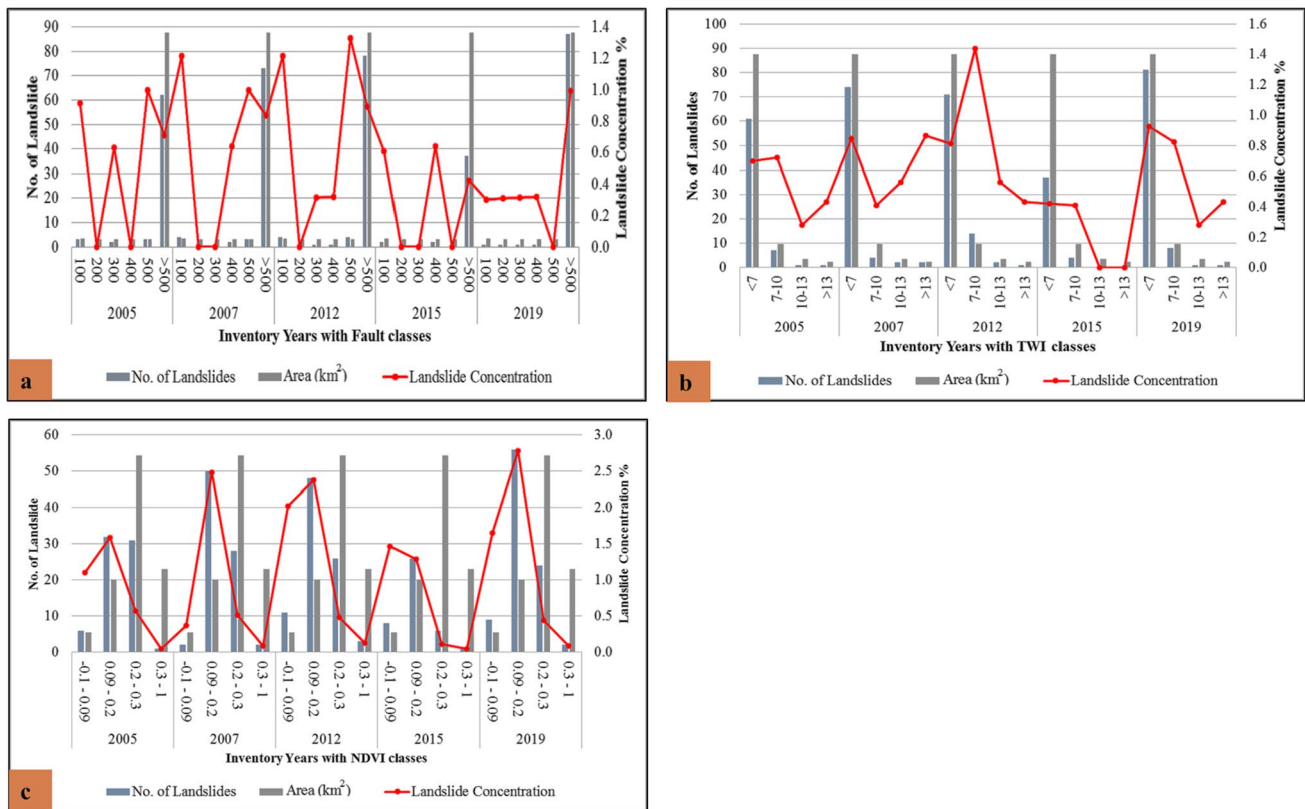


Fig. 16 Spatio-temporal (2005–2019) landslide dynamics and correlation with different classes of causative factors along Neelum Valley road: **a** correlation with distance to faults, **b** correlation with TWI and **c** correlation with NDVI

probability within the area but in contrast, the present study is mainly along the main road corridors with 1 km buffer on both sides showed the slopes which are already disturbed through natural or anthropogenic factors have become more vulnerable during rainfalls in the inventoried years. The present results are aligned with the results of Khattak et al. (2010) and Saba et al. (2010) that the area is marginally stabilized due to various factors (i.e. re-vegetation, change of slope morphology, removal of loose material, etc.) after activated during 2005 Kashmir earthquake. Khattak et al. (2010) investigated the landslide variations from November 2005 to August 2007 including 2006 which received maximum precipitation in the study area and observed 68 similar landslide locations of the 164 landslide locations inventoried by Owen et al. (2008) and concluded that 80% of the localities showed no significant change, 11% revealed the vegetation growth on the landslide geometry whereas only 9% indicated a significant rise in the landslide area. Khattak et al. (2010) concluded that pore water pressure in the soil is significantly responsible for triggering the landslides as soil on the slopes is relatively dry in pre-earthquake conditions. Due to low pore water pressure during the 2005 earthquake, therefore, the co-seismic landslide events were lower than the expected numbers after the 7.6 magnitude earthquake.

The temporal changes in slope angle in the area is recorded due to the road cuts during reconstruction and rehabilitation activities along roads. Therefore, in most cases, the road cuts makes the slope more vulnerable to landslides. Moreover, during 2005 earthquake, the shaking destabilize the slope forming materials due to intense stresses. The higher ground acceleration produces due to local tectonic activity caused collapsed in the hilly terrain and hence the curvature may plays significant role in enhancing landslide activities. The NDVI factor experienced the change due to the deforestation activities in the area with respect to the time. Although, NDVI deteriorates because of the developments of urban land in the area along slopes. As for as lithology is concerned, the parent material of the slope forming materials varied with the passage of time due to the anthropogenic attributes, i.e. road cuts, building construction at slopes, drainage diversion along slopes. Earthquake 2005 also contributes to the vulnerability of slope materials and fragile rock units in the study area. The wetness index varies with the extreme climatic variations specifically during monsoon periods and hence trigger landslides in the area.

Landslide preventive measures control the relationship between landslides and land urbanization. Improper land urbanization increases the landslide probability of the area

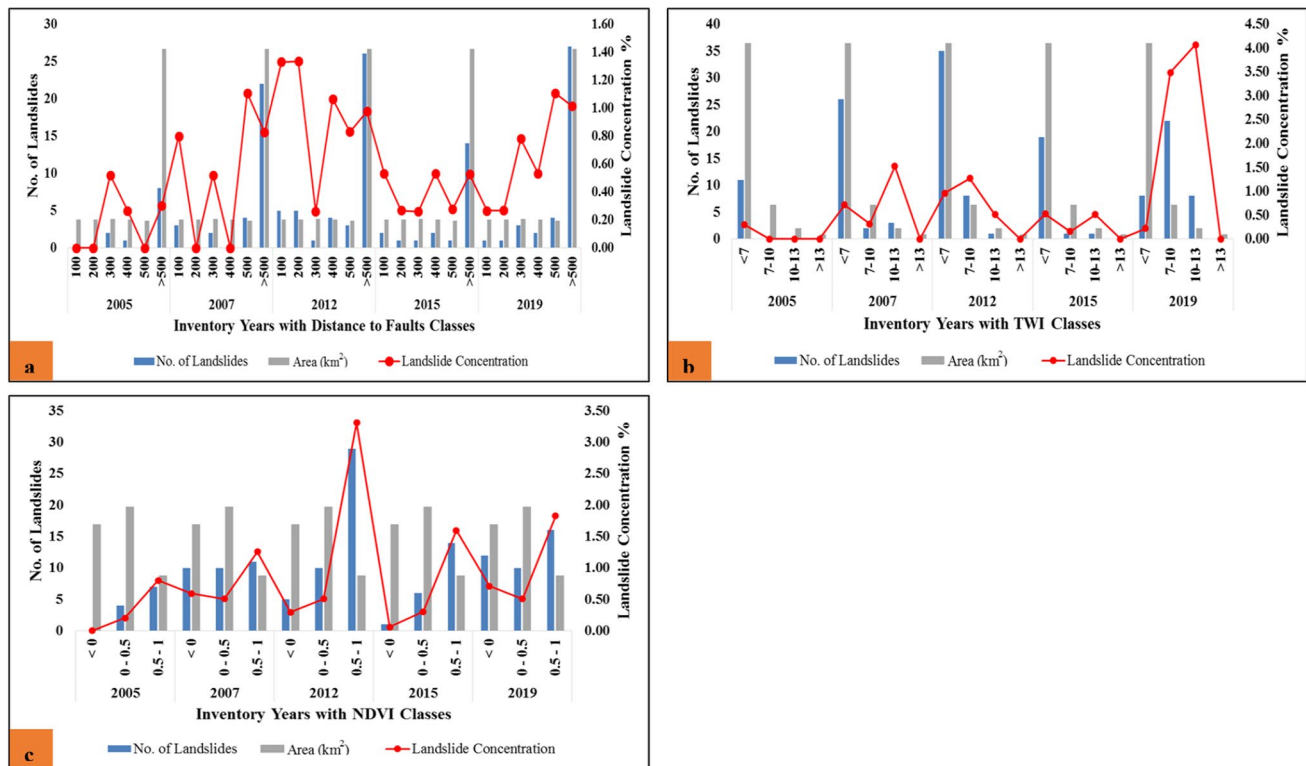


Fig. 17 Spatio-temporal (2005–2019) landslide dynamics and correlation with different classes of causative factors along Jhelum Valley road: **a** correlation with distance to faults, **b** correlation with TWI and **c** correlation with NDVI

due to inadequate and non-professional landslide mitigation measures (Alcántara-Ayala 2002; Holcombe and Anderson 2010). Road corridors are the most significant civil infrastructures of human society that are highly influenced by the recurrence of landslides, emphasizing the importance of road construction at places with minimum destruction risk due to landslides (Yousefi et al. 2022). In the study area, along roads, most of the landslide events occurred either due to improper road cuts in the presence of soft rocks like shales, clays and fractured rock units or due to the selection of improper route design. Therefore, road construction techniques play a major role to reduce slope stability and thus increasing landslide events. Especially all the studied transportation corridors were reconstructed and rehabilitated after the 2005 earthquake and no significant geotechnical investigations were performed during these constructions which causes most of the slopes prone to failure.

According to Aslam et al. (2022b), lithology provides the material support for landslide incidents and hence develops the foundation for landslide activation. Moreover, they found that the weaker the lithologies higher will be the landslide frequency as weaker lithologies possess low strength to withstand the higher rainfalls and slip away easily. The fragile lithology and weaker units which act as detachment planes are responsible for the deep-seated landslides while

semi-permeable and impermeable rock units and soil are responsible for shallow landslides (Borgomeo et al. 2014).

The current elevation analysis of the study area reflects the results of Aslam et al. (2022b), that the 575 to 2000 m or higher elevations are more susceptible to landslides. The outcomes of the current analysis are following the former investigations as Yang et al. (2017) also identified that anthropogenic activities like road construction, and loading and unloading of slopes, are responsible for triggering landslides in an area of fragile geological conditions. The results of the present study are following Khalil et al. (2022) who worked on the comparative analysis of ML and MCDA for LSM in the Muzaffarabad area. They have marked the slope, elevation, lithology, rainfall, flow direction and NDVI as the most influential landslide factors.

The present study showed similar trends as discussed by Shafique (2020) which revealed that after the 2005 earthquake, the landslide area decreased with time at a slow rate. Moreover, the study also concluded that extremely active landslides within the area demonstrated the persistent landslide events are mainly due to the extensive monsoon rainfalls, the river undercutting, roads rehabilitation and reconstruction, and other anthropogenic factors as also discussed by Basharat et al. (2014) and Riaz et al. (2018, 2022a, b). The temporal decline of landslide area results is the same as

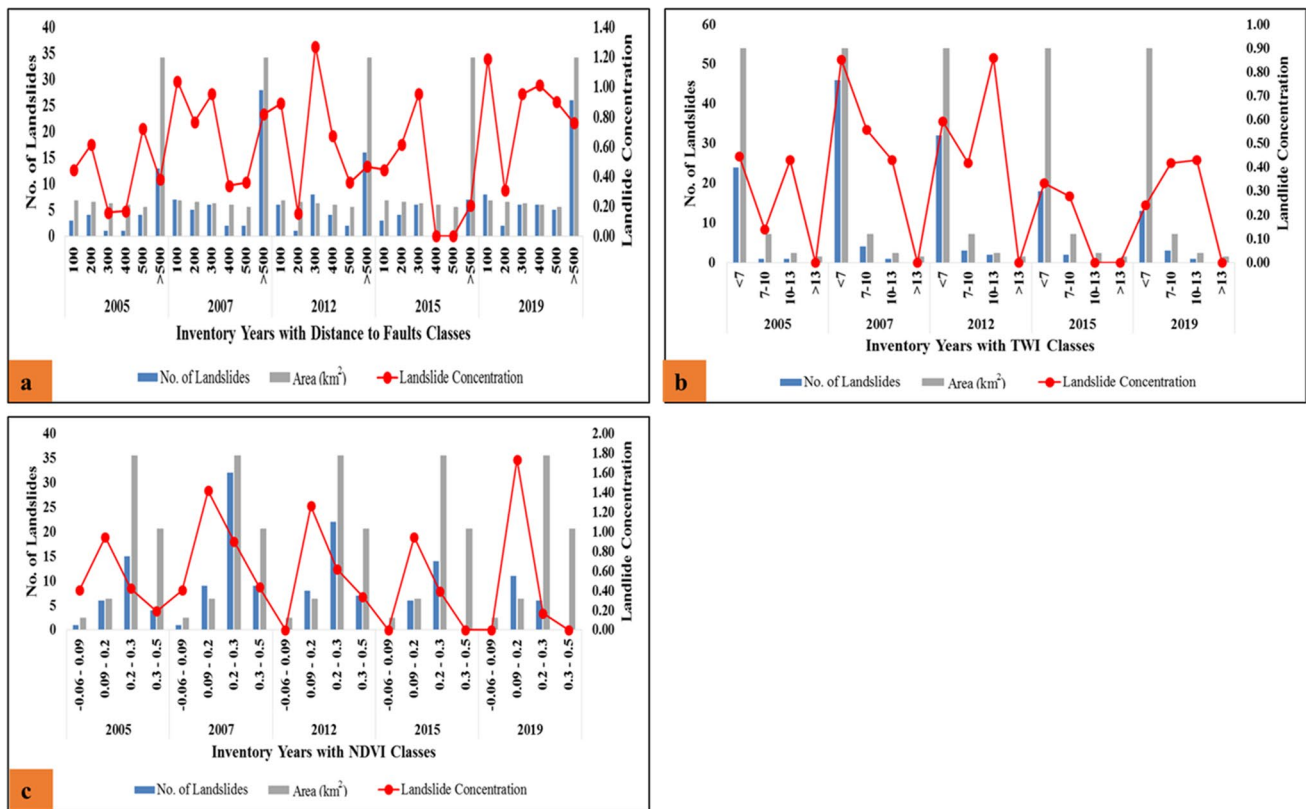


Fig. 18 Spatio-temporal (2005–2019) landslide dynamics and correlation with different classes of causative factors along Kohala Valley road: **a** correlation with distance to faults, **b** correlation with TWI and **c** correlation with NDVI

the conclusions of Saba et al. (2010) and Khan et al. (2013) with varying rates of decline in landslide area due to the difference in the study area extent, data acquired and temporal variations. Moreover, the present study area is along the main road corridors which are highly disturbed after the rehabilitation and reconstruction of road projects. Furthermore, the present study provides a better insight analysis for the temporal evolution of landslides associated with the slope/ road cuts. Hence, the landslides mapped during this study are different as compared to the previous ones, like Basharat et al. (2014, 2015), Kamp et al. (2008), Owen et al. (2008), Saba et al. (2010) and Shafique (2020).

The present study is in line with the conclusions of Basharat et al. (2014) that landslide concentration increases within the buffer zones of the Muzaffarabad Fault and MBT, drainage networks, incompetent rock units and disturbed rock masses. However, the present study also incorporates the re-alignment of the existing road networks also contributed to the landslide concentrations. The NDVI temporal analysis in the present study reveals that the vegetation cover increased from 2006 to 2010 but gradually decreases afterwards which indicates that the rehabilitation works along roads degraded the grassland and forests which in turn enhanced the landslide activities in the area.

The findings of the present study also align with the conclusions of Aslam et al. (2022a) who worked in the same area and evaluated that slope, seismicity, aspect, road density and lithology are more influential factors for landslide events whereas curvature, NDVI, TWI and SPI possess less impact on landslide events in the area. This result also aligns with the findings of Shafique (2020) that relatively younger vegetation growth with shallower roots from 2005 to 2010 which in turn possessed scarcely impact on the stabilization of slopes with a slower landslide decay rate during the period. The elevation ranges between 600 and 1350 m are experiencing the most landslide events consistently along these road corridors which supports the study revealed by Shafique (2020). The Murree Formation is more prone to landslides due to its fragile lithology variations, hence present study concluded that the landslide area is maximum covered by the Murree Formation followed by Muzaffarabad and Nagri formations. Therefore, the combined influence of these topographic attributes, lithology and proximity to roads marked the elevation ranges of 600 to 1350 m as the landslide-prone regions. The present study also concluded that the highest landslide concentration of southwest (SW) and south (S) trending slope aspects is partly because of the predominant presence of MBT and vulnerable elevation and

slope ranges. In contrast to the above-mentioned research, this study investigates the landslide spatio-temporal dynamics along the main transportation routes of Muzaffarabad focusing on identifying the critical zones of extremely concentrated landslide events. At last, based on temporal data, the spatial relationship between landslide density and their possible conditioning factors was determined to predict the future hazard potential. The landslide concentration along these road corridors still poses serious threats to land use along with the local communities and infrastructures. Therefore, real-time monitoring systems should be installed at critical landslide sites to evaluate the triggering mechanism and mitigation measures to reduce the risk associated with these events.

Conclusions

The present study involves the landslide's spatio-temporal evolution for the years 2005, 2007, 2012, 2015 and 2019. Along each studied road corridor, the inventories have been generated based on the collected information through field investigations, interpretation of imageries and review of published sources. Eleven landslide conditioning factors derived from different data sources were utilized in the analysis to assess the spatial and temporal dynamics of the landslides in the study area. The spatio-temporal analysis demonstrates that the total number of landslides along selected road corridors are 107, 164, 169, 92 and 182 during 2005, 2007, 2012, 2015 and 2019, respectively. Over time after the 2005 Kashmir earthquake, landslide events have shown an increasing trend till 2012. The landslide area showed a considerable decline trend in 2015, indicating that the number of landslide events decreases, hence stability increases. But the heavy monsoon rainfalls after 2015, and road reconstruction caused an increase in landslide events in 2019. The current study identified the topographical, lithological and hydrological parameters that are influencing the proneness of landslides for a particular area, whereas it also reconstructed the temporal landslide probability concerning the triggering factors. The landslide spatio-temporal investigation showed that the landslide activities in the study area are significantly controlled by the road construction in slopy areas along with fragile lithological units in the vicinity of faults. By employing these outputs, proper planning can be done to prevent, mitigate or reduce the occurrence of future landslide disasters along the roads of this territory. Hence, this awareness regarding the risk of landslide events will help the locals to save and mitigate their lives and properties, as well as the government, and works department to plan their future road projects concerning the current findings. The spatio-temporal analyses of landslides will provide support to various departments for categorizing the

priorities for appropriate mitigation measures. Moreover, due to landslides, the total length of roads remained unstable and blocked so, the technical countermeasures, regulatory measures or both should be planned.

Author contributions Yasir Sarfraz and Muhammad Basharat designed the study. Yasir Sarfraz and Muhammad Tayyib Riaz collected and analyzed the data. Yasir Sarfraz and Muhammad Tayyib Riaz drafted the manuscript. Yasir Sarfraz, Muhammad Basharat, Muhammad Tayyib Riaz and Mian Sohail Akram interpreted the results. Khawaja Shoaib Ahmed and Amir Shahzad revised the manuscript. All authors reviewed and edited the manuscript.

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Declarations

Conflict of interest The authors declare no any conflict of interest/competing interests.

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