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Climate change-induced landslide vulnerability: Empirical evidence from Shimla district, Himachal Pradesh, India

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ABSTRACT

Landslides as dynamic geological hazard have caused socio-economic and environmental vulnerabilities at various scales. Thus, landslide vulnerability assessment is essential for understanding the implications for society and the environment. The present study attempts to examine landslide vulnerability in Shimla District, Himachal Pradesh, India. It constructed a composite landslide vulnerability index (CLVI) by integrating 57 indicators of 7 different domains (social vulnerability index, physical vulnerability index, economic vulnerability index, climate change and environmental vulnerability index, early warning system index, emergency response system, and adaptation strategies index) at the household level. CLVI serves as a most effective tool for the quantification of complex domains of disaster vulnerability and identification of thematic areas for disaster risk reduction. The data on various indicators were derived through a field survey of 450 households from 30 villages. The relationship between CLVI and its domains was ascertained using multiple linear regression. The CLVI analysis revealed that nine villages were highly vulnerable to landslides, while six villages experienced moderate vulnerability. Climate change and environmental vulnerability, physical fragility, and low adaptation strategies induced high to moderate vulnerability. The regression analysis showed that the degree of vulnerability was mostly influenced by the physical domain, followed by the economic and environmental domains. Effective policy, institutional setups, provision of landslide-resistant buildings, and livelihood diversification may enhance adaptive capacity among the communities. Thus, CLVI has not only helped in identifying thematic areas for reducing vulnerability but has also been instrumental in recognizing priority areas.

1. Introduction

Climate change-induced landslides are occurring more frequently in mountainous ecosystems, distressing both the natural environment and human settlement [1–5]. Variability in rainfall patterns, increased soil erosion rates, temperature extremes, and land use changes have altered the mountain landscapes considerably over the decades [6]. It is projected that more landslides would occur with an unprecedented rise in extreme precipitation and average surface temperature in the high mountains of Asia [7]. The frequent occurrence of landslides has greatly impacted the inhabitants of mountainous areas living in and surrounding lowlands. Various studies have evinced that people with limited resources have been more sensitive to calamities and vulnerable to disasters [8–10]. Climate variability and weather extremes have become distinct worldwide, including the region of the Indian Himalayas with the Indian Himalayan region being no exception. Nearly 12 % of India's land area is vulnerable to landslides [5]. North-western Himalayas in India

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are more vulnerable to landslides due to high population density and developmental activities [11,12]. This region experiences several rainfall-induced landslides every year which cause severe ecological and socio-economic implications [5,13]. Thus, the scientific community has raised concerns about disaster-induced impacts on the socio-economic characteristics of the communities.

The term vulnerability has been used in many contexts and examined at the individual, household, regional, and national levels [3,9,14,15]. Intergovernmental Panel on Climate Change (IPCC) has initially examined climate change vulnerability involving exposure, sensitivity and adaptation components [10,14,16–18]. Later, many studies have examined vulnerability by integrating ecological, social, and biophysical dimensions [19–21]. Vulnerability assessment in response to climate change has become a dynamic concept in environmental research and policy frameworks. Many studies have utilized the IPCC approach for assessing flood vulnerability [10,22,23], coastal disaster vulnerability [24–27], drought vulnerability [16,18,28], and livelihood vulnerability [8,9,29,30]. Vulnerability assessment to landslides is multi-dimensional phenomena that result from the interaction of dynamic drivers and indicators [4,21,31]. The United Nations Office for Disaster Risk Reduction (2017) defines vulnerability as the function of various dimensions namely physical, environmental, economic and social [32–34]. Physical vulnerability to landslide is associated with the 'the degree of loss to a given element, or set of elements, within the area affected by a hazard, expressed on a scale of 0 (no loss) to 1 (total loss)' [35–38]. It determines the functional relationship between the intensity of disaster and its impacts on exposed values and elements-at-risk [37,39,40]. Economic vulnerability is the extent to which people and economies are exposed to financial challenges and disruptions [10,41]. The environmental dimension is the damage incurred to natural resources, topographical features and alteration in the land use pattern [17,42]. Social vulnerability refers to the capacity of persons, institutions, and non-institutional systems to manage and combat the consequences of disasters [23,32,43,44]. Factors such as social disparities, demographic attributes, housing characteristics, accessibility of basic services, institutional facilities, level of awareness, and communication system have significantly influenced social landslide vulnerability [9,29,45]. Further, housing insurance, livelihood diversity, dependency on natural resources, social networks, and communication are directly or indirectly associated with landslide vulnerability [8,10,46]. Thus, disaster vulnerability can differ significantly from region to region, with factors influencing vulnerability in a developing country potentially varying markedly from those in a developed nation [47].

In recent years, scientists, academics, and policymakers have paid significant attention to the conceptualization of landslide vulnerability assessment. It depends on the choice of technique, the nature of the available data, the specific objectives of the assessment, and the complexity of the landslide-prone environment being studied. Various scholars have attempted to bridge the gap through the inclusion of innovative parameters and methods for analyzing different dimensions of landslide vulnerability [43,48]. Papathoma-Köhle et al. [37] utilized vulnerability curve method for analyzing the debris flow intensity and degree of loss to assess physical vulnerability in South Tyrol, Italy. To assess the future economic loss, they estimated the deposition height and process impact of the built environment. Kang & Kim [49] used physical vulnerability curves to understand the impact pressure, debris flow velocity, and depth for different structural buildings affected during the debris flow events that occurred in South Korea. Their study revealed that non-reinforced concrete structures had more extensive damage and were more susceptible to harm compared to reinforced concrete buildings. Chen et al. [35] employed a similar method to examine the potential impact of slow-moving landslide on buildings in different rainfall scenarios in China. They emphasized the specific measurements and characteristics of masonry structures, including their length, width, depth, inclination, foundation, horizontal force of landslide residual thrust, and response system of buildings.

While the physical aspects of vulnerability are critical to understanding and mitigating disaster risks, it is imperative to recognize that the socio-economic fabric and demographic characteristics of a population play an equally significant role in shaping vulnerability profiles [2,50,51]. Guillard-Gonçalves & Zêzere et al. [39] assessed landslide vulnerability in terms of physical and social dimensions in Loures municipality, Portugal, using a matrix approach. They have also reported the significance of combining the social attributes and physical and economic value of the buildings to prevent future losses and improve preparedness. Murillo-García et al. [31] developed a Spatial Approach to Vulnerability Assessment (SAVE) model to analyze landslide vulnerability in Pahuatlán, Mexico. They combined exposure, sensitivity, and resilience indicators and determined the degree of vulnerability based on slope units on a geospatial platform. Ullah [52] utilized weighted overlay technique to create a landslide vulnerability map in Bandarban District, Bangladesh. Wijaya and Hong [32] compared geospatial models to determine social vulnerability to landslide by integrating datasets on demography, health, poverty, and education in Central Java, Indonesia. Xiao et al. [44] used the order reference by similarity to the ideal solution (TOPIS) and the entropy weight method to assess social vulnerability to landslide in the towns of the Qinghai Tibet Plateau, China. For effective disaster risk reduction, they compared, classified, and ranked the demographic attributes, social structure, hazard risk perception, and disaster prediction. Sharma et al. [53] utilized statistical indicators, namely average density, highest density, and co-efficient of variation, for ranking the causative factors. They also demonstrated high efficacy in performing landslide vulnerability zonation in the east district of Sikkim, India.

These methods have been instrumental in assessing the landslide vulnerability of various communities and nations in diverse geographical locations. However, an approach based on site-specific indicators to assess vulnerability has received significant academic interest for identifying areas at risk and prioritizing suitable adaptation measures [16,46,47,51]. Indicator-based approaches have been particularly useful in identifying key aspects of vulnerability for constructing a vulnerability index [20]. The index-based approach has enabled an extensive analysis of a wide range of biophysical and social factors at varied scales [9,10]. For instance, Masroor et al. [47] developed a composite drought vulnerability index by integrating social, environmental, economic, ecological, climate change, an early warning system, and adaptation aspects from the farmer community in Godavari Middle Sub-basin, India. The authors employed an equal-weighted method instead of assigning different weights to the sub-components. Ullah et al. [51] quantitatively measured social, economic, physical, attitudinal, and institutional aspects for constructing a composite index for flood disaster in Khyber Pakhtunkhwa province, Pakistan. The study also highlighted the need to prioritize areas for flood mitigation efforts by better understanding early warning systems, formulating emergency management plans, and developing risk reduction strategies. Another study by Rehman et al. [46] examined the effectiveness of the composite vulnerability index (CVI) using socio-economic and ecological parameters for climate change-induced floods in the Bhagirathi sub-basin in India. To ascertain the relationship between the parameters and vulnerability, the authors also conducted cross-tabulation and regression analyses.

The composite vulnerability index provides a scientific and robust framework to quantitatively measure specific hazard or disaster vulnerability in the era of climate change [8,10,16,17]. Bera et al. [38] developed a physical vulnerability index by integrating construction material, state of maintenance, and building typology across different houses for analyzing landslide vulnerability in Kalimpong District, India. The study used data collected from the local communities (on the basis of active landslide prone sites) on varied exposure and resistance levels through interview techniques. Dias et al. [43] expanded to include physical exposure to houses, societal response, and the Brazilian early warning system to construct an Operational Index for Vulnerability Analysis on a national scale. Kumar & Bhattacharya [42] evaluated the social landslide vulnerability index (SLVI) based on site-specific physical, economic, social, and environmental indicators in Uttarakhand district, India. Eidsvig et al. [4] utilized an indicator-based approach for ranking socio-economic vulnerability to landslide in Europe. They employed fourteen indicators related to demographic conditions, degree of preparedness, response, and adaptive capacity. They also emphasized that population density, urbanization and social cohesion substantially determine the societal ability to prepare for, respond to, and recover from landslide events. Disaster vulnerability is centered around people, and thus, assessing the interconnected nature of physical, social, environmental, and economic dimensions, the early warning system, emergency preparedness, and adaptive capacity is essential for comprehending the damages and losses associated with landslide [43,51,54]. Addressing landslide vulnerability requires a holistic approach that considers the unique characteristics and needs of a region and its inhabitants.

The present study was undertaken with two specific objectives. Firstly, Shimla district is susceptible to geological disasters, fragile topographic terrain, and past occurrences of landslides. The district is experiencing frequent rainfall-induced landslides during the monsoon season [55]. Consequently, the communities of the district are increasingly becoming vulnerable to landslides. Secondly, most of the past studies on landslide vulnerability have either focused on one dimension of vulnerability or rarely considered integration of all dimensions in a landslide vulnerability assessment. The composite vulnerability index has been utilized for many disasters [16,17,46,47,51,56]. Despite the growing body of literature on vulnerability assessment to natural disasters, the integrated approach to assess landslide vulnerability is relatively rare, particularly the response capability, emergency preparedness, and early warning mechanism in mountainous landscape. Our study has proposed a novel approach using the composite vulnerability index for examining landslide vulnerability. This study also added new indicators of early warning system and emergency response system in landslide vulnerability assessment which were lacking in the previous studies. Early warning and emergency response systems may be regarded as a significant dimensions in the process of improving the capacity to lessen and mitigate the risks of disaster in the era of climate change [57]. We argue that the composite vulnerability assessment utilized in this work may be helpful for effective decision-making processes and for creating communities resilient to landslide disasters. The composite landslide vulnerability index (CLVI) as an effective quantitative measure may also help in preparing bottom-up approaches to policy formation to target vulnerability reduction [16,46,57]. It addresses the grass-roots concern and especially for socially disadvantaged people (i.e., marginalized communities, women, children, and the unemployed population) impacted by climate change induced landslide disasters. The adaptations and mitigation strategies encompassed agroforestry practices, the installation of vegetated gabions, geotextiles, check dams, proper drainage system, retrofitting building and land-use planning. On the other hand, community-based preparedness planning could be more effective in empowering local communities to mitigate the impact of climate change-induced landslide vulnerability in Shimla district. The preparedness strategies involved raising awareness through education, training and drills to disseminate information to the community. By involving community members in the decision-making process, these policies are more likely to be effective and sustainable in the long term. The findings from this research may provide policymakers and local communities with insights and recommendations for making informed decisions and improved adaptation capabilities [8,14,17,46,47,54]. The methodological framework of the study may help future studies to analyze landslide vulnerability at different spatial scales using various site-specific indicators.

2. Study area

Shimla district located in the Himachal Pradesh state of India stretches between 30°45′ and 31°44′ N latitudes and 77°0′ and 78°19’ E longitudes (Fig. 1). The district is comprised of 10 blocks (administrative division), namely *Nankhari, Mashobra, Chhohara, Theog, Rampur, Jubbal-Kotkhai, Narkanda, Rohru, Chopal,* and *Basantpur*. The study area is characterized by highly dissected steep slopes, undulating terrain, and narrow and deep valleys [58]. The *Sutlej* River flows through the district. Drainage density is moderate to high and is not uniform across the district. Pangi, Nichar, Powari, Jhakri, Urni, Sholdan, Thangi, Khadra Dhank, and Barua are the some of the devastating landslide events that have affected the National Highway 22 in the *Satluj* valley of the district [59]. Orthents-Ochrepts, Udalfs-Orchepts, and Orchepts-Orthents are the major soil types of the district.

Shimla district lying in the north-west Indian Himalayan region, is geologically fragile due to geodynamics and is devastated by severe landslides. Nearly 51 % of landslides have occurred along the north-west Himalayas and caused 49 % of human fatalities during 1800–2017 [60]. Landslides of varying magnitudes are triggered by the topographical, meteorological, and geological changes [61]. Rampur-Leori on NH-22, Theog-Sainj, Sungri-Narkanda, and Rohroo-Chirgaon are four vulnerable landslide stretches on highways in Shimla district [62]. Of the total population of the district (0.81) million, nearly 75 percent of people live in rural areas. The study area has a population density of 159 persons/km^2. Agriculture and horticulture are the dominant economic activities of the study area. The cultivation of the crops in the district predominantly relies on rainfall. Animal husbandry, beekeeping, fishing, and tourism are other sources of livelihood in the district [63]. From a tourist destination point of view, the area has immense economic advantages, making it an ecotourism spot. However, deforestation, unscientific road construction, environmental degradation, inten-

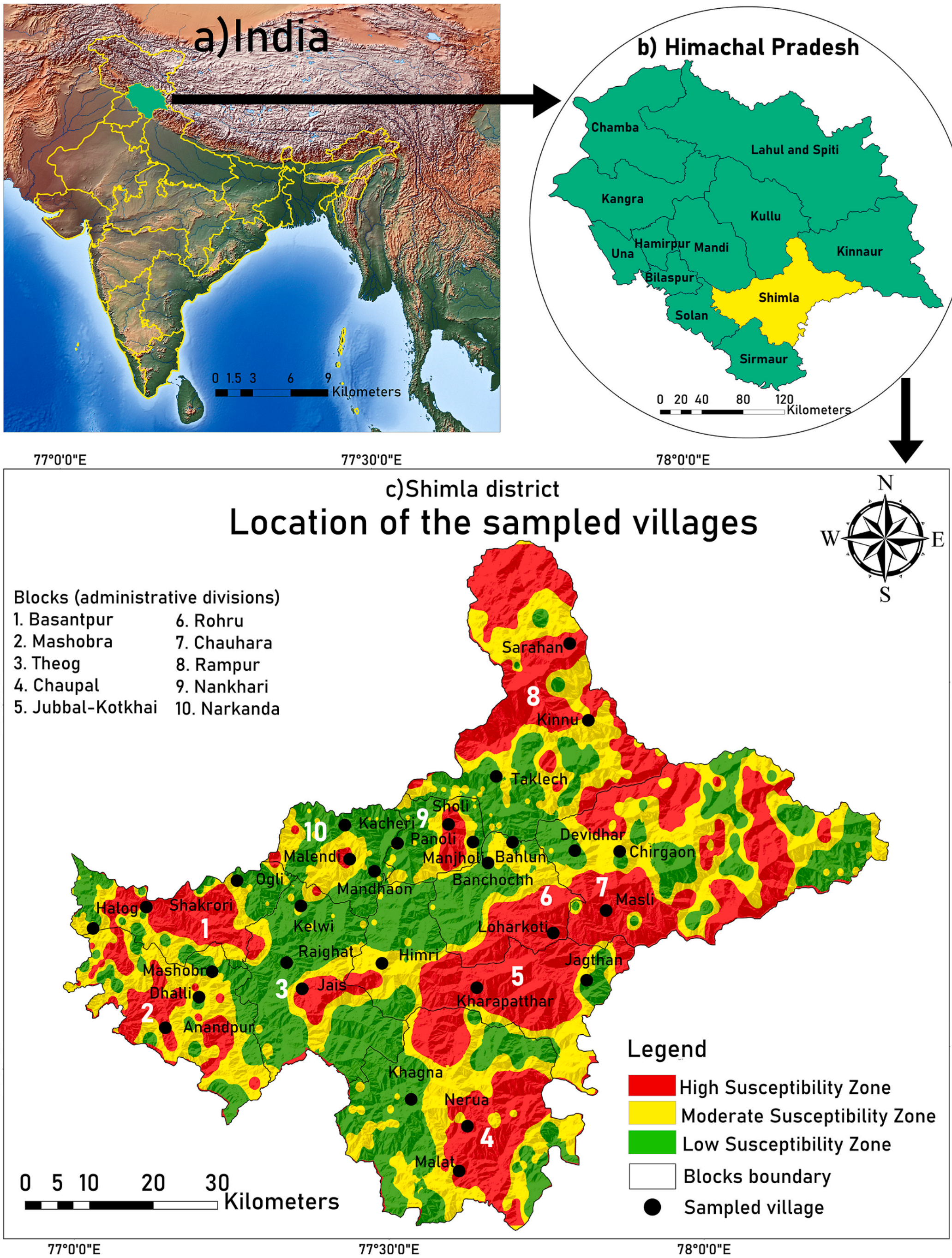

Fig. 1. (a) Location of Himachal Pradesh in India (b) Shimla district in Himachal Pradesh (c) Location of the surveyed villages in Shimla district. Source: Adapted from District Disaster Management Authority of Shimla district, Himachal Pradesh and created in ArcGIS 10.8 software.

sive agricultural practices, and terracing on steep hill slopes have increased the vulnerability to landslides [64]. Thus, examining the vulnerability to landslides assumes greater significance for devising effective landslide mitigating strategies in Shimla district.

3. Database and methodology

The methodology employed for this work involved five stages (Fig. 2). The first stage consists of selecting the site-specific indicators for landslide vulnerability assessment using existing literature and expert knowledge. The selection of villages was made in the second stage. Households from the chosen villages were selected during the third stage. The composite vulnerability index was constructed to examine the vulnerability of the surveyed households in the study area in the fourth stage. Lastly, in the fifth stage, multi-

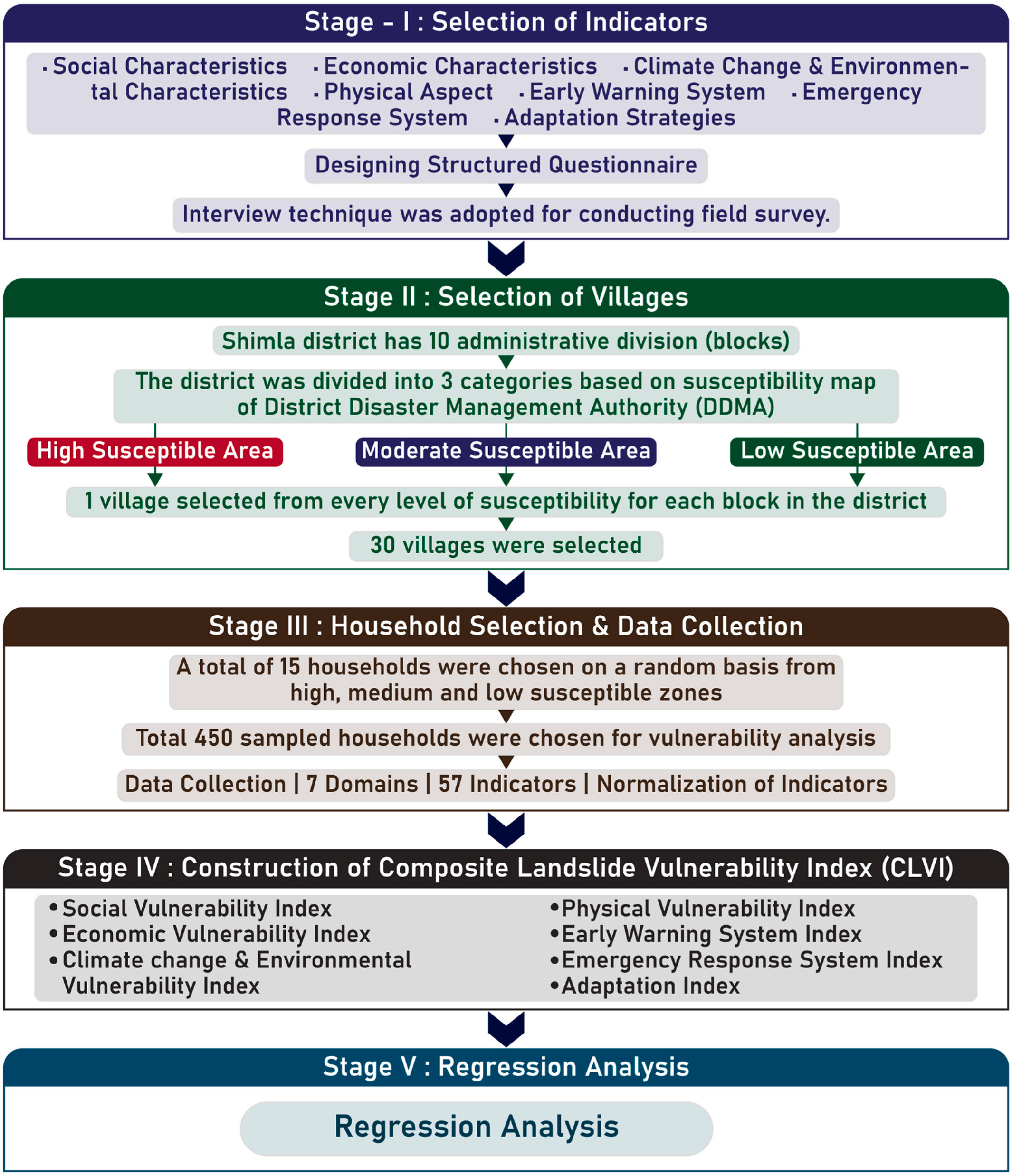

Fig. 2. Methodological framework for the study. Source: Prepared by author

ple linear regression was performed to analyze the relationship between vulnerability and its components. The methodology adopted for this study has been explained in the following subsections.

3.1. Rationale for indicator selection

Vulnerability is a complex concept that encompasses several domains, involving social, economic, physical, climate change and environmental, early warning systems, emergency response systems, and adaptation strategies. By incorporating these seven core domains for measuring composite vulnerability, the evaluation becomes comprehensive for climate change induced landslide vulnerability. Site-specific and relevant indicators for these domains were selected through literature mining and prior knowledge. These indicators provide a holistic way to assess landslide vulnerability. A total of 57 key indicators were chosen to examine vulnerability that could aid in the identification of effective strategies for lessening landslide vulnerability (Table 1). The rationale for expanding these dimensions is grounded in the need to address the complex and dynamic nature of both the pre and post disaster management strategies to effectively mitigate climate change induced landslide disasters. The dissemination of warnings and institutional mechanisms in the Indian Himalayan region have not received much attention in past studies. By integrating a wider array of indicators, our framework addresses this gap and provides innovative dimensions for analyzing landslide vulnerability. This approach not only aligns

Table 1
List of composite vulnerability domain and indicators.

Domains	Indicators	Rationale	Source	Relation to vulnerability
Social	Ratio of female population to total population	A higher female ratio is generally considered more vulnerable to calamities due to biological constraints and inferior social status.	[8,9,65]	+
	Ratio of disabled population to total population	Individuals with severe illnesses and impairments experience the most significant hardships during the evacuation and recovery phase.	[1,10,33]	+
	Marginalized communities	Marginalized communities are disproportionately affected by socio-economic challenges leading to the unequal distribution of aid and resources.	[8,13,47]	+
	No. of years living in the area (<10 years)	Households that have resided for longer periods of time show greater awareness of evacuation routes and emergency systems.	[51]	+
	Ratio of illiterate population to total population	Low literacy can hinder people's ability to access and comprehend information on landslide risks and safety measures.	[10,34,66]	+
	Injuries incurred due to landslide	Evaluating injuries from landslides is an essential indicator for long-term planning and community preparedness.	[29,39,65]	+
	Human deaths incurred due to landslide	High human fatalities examine the severity and exposure of climate change induced landslide disasters in a particular area.	[43,45,65]	+
	Damages to the material asset	The extent of direct and indirect damage disrupts the functioning of local economies. It provides a comprehensive view for planning economic support and recovery programs.	[33,39,48]	+
	Joint and extended family	Families with strong support systems demonstrate less vulnerability to disasters due to social capital and human resources.	[4,51,56]	–
	Accessibility to medical facilities	Well-equipped medical facilities can provide immediate care and life-saving interventions during disasters. It is a fundamental factor in preventing outbreaks of communicable diseases that may emerge post-disaster.	[9,38,67]	–
Economic	Ratio of dependent population to total population	Children and the elderly need special care and support and are particularly more vulnerable to disasters. Their limited mobility and dependence may be hindered during emergency situations.	[8,43,66]	+
	Monthly average income (US$ = Indian rupees <15,000)	Low-income households may struggle to rebuild and recover after a disaster, potentially leading to long-term economic challenges.	[29,33,68]	+
	Debt	The financial burden and increased indebtedness may have a detrimental effect on households' ability to invest in preventive measures for landslides.	[29,46,68]	+
	Ratio of unemployed population	High unemployment might affect social networks and community linkages needed for post-landslide support and action.	[10,39,66]	+
	Persons working in primary sector of economy	Communities dependent on primary sector activities may be forced to relocate due to landslide damage, leading to the loss of homes and disruption of livelihood activities.	[4,15,42]	+
Physical	House located on steep slope	Households residing on a steep slope are more vulnerable to soil erosion and landslides.	[1,35,40]	+
	House made up of mud	Mud house structures have inherent structural fragility when compared to houses made of concrete or brick.	[41,48,50]	+
	Age of the building (>30 years)	Older houses and buildings often lack reinforcement when subjected to the dynamic forces of landslides lateral and vertical stresses.	[2,13,51]	+
	Presence of cracks in the house	Large fractures imply structural weakness and slow land movement.	[13,33,38]	+
	Multiple floors of the house	In ecologically sensitive areas, multi-story buildings increase the risk of collapse to withstand landslide forces.	[2,37,51]	+
	Non-resistant roof of the house	Tin roofs are weaker and less resistant to disasters than concrete roofs in landslide susceptible areas.	[37,38]	+
	Narrow opening of the house entrance	A narrow entrance may impede rapid evacuation routes and hinder the degree of resistance during landslides.	[13,37,38]	+
	Door/window opening towards slope	Households where doors and windows that open towards a slope act as entry points for debris to enter the building.	[14,17,69]	+
	Unpaved road connectivity in the area	Unpaved roads pose significant challenges for navigating emergency vehicles. This can delay the arrival of rescue teams, medical aid and other critical services during landslides.	[17]	+
	Extraction of firewood	Lack of vegetative cover increases surface runoff during rains, leading to soil erosion and proneness to slope failure.	[3,6]	+
Climate Change and Environmental	Increasing temperature during summer	Rising temperatures can lead to dry soil conditions that are less cohesive and more susceptible to cracks and fragmentation. This reduces slopes' frictional resistance and increases the likelihood of shallow landslides.	[14,17,69]	+

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Table 1 (*continued*)

Domains	Indicators	Rationale	Source	Relation to vulnerability
	Changes in rainfall pattern	Alterations in rainfall patterns might affect soil moisture and shear stress on slope stability.	[70,67]	+
	Increase in rainfall intensity	Intense rainfall may accelerate soil saturation and erosive power, causing mass wasting along the hillslopes.	[1,70,69]	+
	Increased frequency of landslide in last 10 years	Landslide frequency is an important indicator for understanding temporal trends and determining high-risk areas.	[1,43,69]	+
Domains	Indicators	Rationale	Source	Relation to vulnerability
Climate Change and Environmental	Landslide caused due to heavy rainfall	Heavy rainfall influences climate change and environmental vulnerability, exposing human communities to significant risk.	[3,6]	+
	Landslide caused due to developmental activities	The detrimental impact of poor engineering practices, widespread deforestation, extensive excavation, and intensive mining activities will have adverse impact on mountain ecology and landscapes.	[3,6]	+
	Landslide caused due to earthquake	Landslides induced by earthquakes are crucial for assessing the complex interaction between the seismic forces and the geology of the affected area.	[8,46]	+
	Land use/land cover changes	The dynamics of land use and land cover changes provide insights into man-made alterations over time that have significant implications for local communities and ecosystems.	[14,17,70]	+
	Soil erosion and contamination	Areas with high soil degradation will be more susceptible to landslides due to the increased gravitational forces acting on the soil mass.	[48,67]	+
	Depletion of surface water quality	Households that encounter deteriorated surface water quality during landslides are directly subjected to gauge climate change and environmental vulnerability.	[13,21,43]	+
Early warning system	Local authority	Local authorities and agencies are essential for effectively mitigating landslides through timely alerts and warnings.	[46,51,68]	–
	News (TV, Radio, Print)	Households with access to broadcast and print media can play an important role in reaching a large audience and monitoring the environment.	[4,21,41]	–
	Detailed Inventory maps	Comprehensive data on past landslide events aids in understanding occurrence patterns and frequencies. It serves as a tool for raising awareness and increasing community preparedness.	[1,4,21]	–
	Basic hazard maps	Basic hazard maps guide zoning regulations and land use planning to prevent construction in highly landslide-prone areas, thereby mitigating future risks.	[4,41,65]	–
Emergency response system	Permanent coordination between responders in communities with specialized equipment and well-trained rescue services	Households agreeing to permanent coordination between responders in communities and rescue services demonstrate an effective emergency response system.	[4,21,41]	-
	Clear definition of roles and responsibilities at local level and proportionate allocation of resources	Community cohesion and coordination represent the level of response systems required to cope with landslides. Well-defined roles and responsibilities at the local level contribute to a more transparent response process.	[13,23,51]	-
	First aid and probable health facilities availed during the disaster	Adequate supply of first aid services and access to health facilities during a disaster is a critical aspect of examining the effectiveness of an emergency response system.	[48,66]	-
	Basic facilities availed during the disaster (food, water, transport, and emergency shelter)	During a disaster, households with access to basic facilities are more likely to have access to emergency response systems, which will reduce their vulnerability to landslides.	[14,51]	-
Adaptation strategies	Housing Insurance	Housing insurance scheme provides landslide-affected homeowners with financial security and compensation for property damage during the recovery process.	[29,48]	-
	Health Insurance	Health insurance covers unexpected injuries and sudden emergency illnesses, promoting timely recovery for people affected by disasters.	[1,17,69]	-
	Diversification in livelihood practices	Multiple livelihood practices reduce dependency on a single livelihood activity, making households better able to cope with and recover from disasters.	[29,50,51]	-

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Table 1 (*continued*)

Domains	Indicators	Rationale	Source	Relation to vulnerability
	Monthly savings	Saving monetary resources for future use helps to prepare for future emergencies and calamities.	[48]	-
	Other home outside the community	Other homes outside of the affected areas provide protection for displaced individuals and families from disasters and adverse weather conditions.	[17,51]	-
	Strong social network or intracommunity cooperation	Strong social bonding serves as an effective adaptation measure during environmental challenges. It helps reduce vulnerability by pooling resources, knowledge and skills to prepare for and respond to extreme weather events.	[1,4,65]	-
	Access to disaster funds from stakeholders	Proper allocation of disaster funds will safeguard and address the immediate needs of landslide-affected communities.	[13,52]	-
	Non-structural assistance from government	Public awareness campaigns, workshops and community-centered approaches are cost effective measures for making landslide resilient society.	[8,17,48]	-
	Saving foodgrains during a different time of year	Foodgrain storage is crucial for ensuring food security and preventing malnutrition in the aftermath of a disaster.	[1,4,21]	-
Domains	**Indicators**	**Rationale**	**Source**	**Relation to vulnerability**
Adaptation strategies	Stringent guidelines for constructions and land-use activities	Households that follow the land use guidelines reduce the exposure of people and property to potential hazards.	[4,41,45]	-
	Fairly effective regulations for new developments, however, potential problems with older constructions	This indicator outlines the disparity between older and new construction, highlighting the need for stricter regulations and inspections for older buildings.	[3]	-
	Retrofit buildings	Buildings that are retrofitted are likely to suffer less damage and enhance structural resilience and safety.	[46,47,50]	-
	Soil management and agroforestry	Effective soil management practices are important for improving soil stability, erosion control and maintaining slope stability.	[29]	-
	Participation in awareness and training program me	A high participation rate in awareness and training programs may be attributed to better adaptive capacity.	[45,48]	-

with contemporary trends in vulnerability research but also enhances the practical relevance of our findings for policymakers and practitioners.

3.1.1. Social vulnerability

Social vulnerability shows how prone a social group is to disaster [20,32,34]. The ratio of the female population, marginalized communities, family type, education, the person with a disability, number of years residing in the area, and health status are significant social indicators for analyzing social vulnerability [1,10,34]. Women, elderly and children are considered to be more vulnerable to disasters [8,9,65]. Households with physically and mentally disabled persons are likely to suffer more from disasters. The persons who are not able to move and receive services deepen the state of social vulnerability during the occurrence of landslide [1]. Marginalized communities, namely ethnic minorities and lower socio-economic groups who already face social and economic disparities become more vulnerable in the event of disaster. Higher education levels represent skillfulness, a good communication system, and a higher awareness rate [34,66]. However, low educational status increases social vulnerability and reduces resilience during disasters. Number of years residing in the area reflects a profound connection to awareness of emergency routes and evacuation plans [51]. Experience, knowledge, and learning from past occurrences will contribute to making more informed decisions in managing future calamities. Joint and extended families often have broader social networks and are better equipped with community support during disasters [4,56]. Larger family size represents greater access to resources, workforce availability, and assistance during recovery efforts. Thus, the large number of members in the family can help individuals cope with stress and trauma more effectively. Accessibility to healthcare facilities was chosen to determine the health status. The landslide occurrences have caused immediate and long-term psychological impairments among individuals and households [34]. Losses reflect the potential impact of landslides on the affected communities. Human injuries and deaths due to landslides are important indicators to ascertain vulnerability [4,39]. Indirect losses are considered to have consequential impacts on utilitarian services, environmental degradation, and material assets to the environment and society from landslides. Bicycles, motorcycles, radio, agricultural land, and home appliances were considered for assessing asset losses. Compared with the direct losses of landslides, the indirect losses are more complex and extend beyond the physical damages [1].

3.1.2. Economic vulnerability

Economic vulnerability arises when the economic conditions of the population are affected due to external shocks [10,41]. Dependency ratio (the persons below 15 and above 65 years of age to total population), monthly income, households with debt, unemployment ratio and persons working in the primary sector were selected for analyzing economic vulnerability. Monthly income determines the economic condition of a household [29,33,68]. Households with low income may be more sensitive to disasters [42,66].

The burden of debt and limited financial resources have a strong relationship with landslide vulnerability. Households under debt are unable to effectively cope with the severity of catastrophes and their repercussions [46,68]. Studies have demonstrated that dependent populations are vulnerable to health risks [8,48,66]. A highly dependent population in the economy is an important indicator of the strain on adaptative capacity during a disaster. Among the working-age population, households with many working members will tend to have better income stability and lower vulnerability to disasters. However, the high unemployment ratio in the area would intensify the household's vulnerability due to limited resources to meet their daily needs. The communities that rely on natural resources are highly vulnerable to disruptions, food shortages, and climate change-induced disasters [4,15]. It can distress economic well-being and livelihood systems during disasters.

3.1.3. Physical vulnerability

Physical vulnerability establishes the relationship between the magnitude of processes and their impacts on house structures [2]. The nature of loss is influenced by the intensity of landslides and the resilience of the house structures that are frequently exposed to landslides [13]. Slope, construction material, age, degree of cracks, number of floors, roof material, window of the building towards the slope, road connectivity and extraction of firewood were considered as important indicators for assessing physical vulnerability [37,38,49]. Poorly designed buildings on steeper and undulating slopes are susceptible to landslide [35,40]. Houses built with landslide-resistant such as reinforced concrete (RCC) material is less subjected to deformation than the houses built with local raw materials (i.e., timber, mud, unburnt bricks, and thatch material) during a landslide [41,48,50]. Multiple flooring systems and large windows could strain the structural integrity and are more subjected to instability, fissures, and collapse [2,37,51]. The houses with the presence of significant cracks would have a higher possibility of getting damaged than the ones built with resistant materials [38]. The accessibility to all-weather roads plays a crucial role in safe evacuation to emergency shelters during landslide. However, unpaved road connectivity and road blockage hinder crucial access to emergency shelters and increase the threat to individual safety. Moreover, the narrow house entrances cause considerable obstacles during evacuations and emergency services, which can impede the efficient movement of people and emergency responders. A major proportion of people in mountainous ecosystems are dependent on firewood for cooking. The practice of reckless cutting of trees for this purpose has contributed to the loss of vegetation cover, making the slopes even more susceptible to erosion and landslides.

3.1.4. Climate change and environmental vulnerability

Environmental vulnerability is expressed in terms of the adverse changes the environment undergoes, especially impacted by climate change [3,14,46]. Changes in rainfall, temperature, vegetation and ecology are analyzed to gauge environmental vulnerability [42]. The study area, being an ecologically and climatically sensitive zone, has witnessed an increased magnitude of extreme disasters [5,13]. The changes in the climatic variables may have severe consequences on nature and the means of sustenance of communities. Understanding the environmental severity of mountainous communities and their surroundings is crucial for disaster management and decision-making. The perception of the respondents on rainfall and temperature variability can help in understanding microclimate [70]. Precipitation and temperature changes are regarded as important meteorological variables affecting slope stability and causing deep-seated landslides [6,7]. Rainfall patterns are shifting due to climate change, with some regions witnessing increased precipitation because of increasing temperatures. Increased evaporation and transpiration may cause cracks to get wider above a certain temperature level [18]. The topographical characteristic of an area is affected by deforestation, urbanization and improper land management practices [46]. Monitoring changes in land use/land cover (LULC) patterns, degradation of surface water quality, soil erosion and contamination will provide valuable insights into landscape alterations. An increase in vulnerability has been observed due to LULC changes, thus making it an important indicator for analyzing environmental vulnerability.

3.1.5. Early warning system

Early warning system outlines the interaction between technological and social elements, inclusive of awareness, response, and education [10,43]. This might require local authorities and media (i.e., television, radio, and print) to transmit the information to every person for preparedness and response mechanisms. Information systems included timely forecasts and warning systems for efficient and reliable systems in mitigating landslides. Detailed inventory and basic hazard maps provide information regarding the topography, geology, and land-use patterns of an area. These maps are crucial for identifying susceptible zones and planning preventive measures [4,21]. With proper knowledge of landslide susceptible areas, households can be alerted in advance, enabling them to make timely response efforts and evacuation. The respondents who were not intimated about the impending disaster through warning systems are considered one of the important indicators because they reflect the level of preparedness of the households during a climate-related emergency, especially in the absence of a proper disaster management system.

3.1.6. Emergency response system

Emergency response systems are determined by the timely assistance and coordinated process that helps the communities during the occurrence of disaster [4,46]. For instance, an emergency shelter is a form of emergency response system which is essential to provide disaster-affected people shelter during evacuation [38]. The system helps to take immediate action for addressing the severity of a landslide disaster. Its effectiveness depends upon the roles and responsibilities, medical assistance, shelter provision, and meeting urgent needs during a disaster [3,4]. The primary amenities like food, water, and transport during disaster ensure effective response system. This helps in reducing vulnerability.

3.1.7. Adaptation

Adaptation is the ability to reduce vulnerability and exposure by securing long term sustainability of ecosystem goods, services, and functions [8,10]. Formal adaptation entails infrastructural, capital, and governmental aid to landslide vulnerability, while informal adaptation examines the techniques devised by the households themselves [51]. Diversification of the livelihood system helps communities recover from economic losses caused by landslides. It reduces vulnerability by ensuring income from various sources [13]. Strengthening social networking, community cohesion, soil management, and agroforestry are of paramount importance to ensure better-coping strategies, timely warnings, and evacuation measures in the event of an impending landslide. Implementation of insurance schemes and savings against landslide risks undoubtedly helps households mitigate the negative consequences of landslides. Receiving help in the form of monetary aid and structural assistance (retaining walls, rebuilding homes, repairing roads, and reinforcing structures) helped the landside-affected communities to recover both financially and morally [46]. A well-documented zoning regulation scheme and building codes can provide systematic guidelines to adapt to landslide disasters [4,21]. Retrofitting buildings with landslide resistant designs can enhance adaptive capacity in the area. These are safer and would require less repair expenses in comparison to muddy and semi-muddy houses during natural catastrophes [8]. Accessibility to medical facilities has a positive relationship with adaptive capacity [39]. It can effectively provide timely emergency response and long-term health recovery efforts in landslide-susceptible areas. Similarly, training to cope with climate change-induced disasters can help households to be better prepared for future changes. Thus, it is important to consider households that do not receive any training and participate in awareness programs to determine the overall vulnerability to landslides.

3.2. Data collection

A household-based survey was carried out to analyze vulnerability to landslides in Shimla district. Data regarding the various site-specific indicators was collected through a structured questionnaire during July and August 2023. The months of July and August experienced intense storms and were, thus, selected as the data collection period for acquiring information on landslides. A stratified random sampling technique was adopted for the selection of villages and households. The district has ten blocks (administrative divisions of the district). In the first stage, the blocks were divided into 3 strata (i.e., high, moderate, and low) on the basis of landslide susceptibility zones provided by the District Disaster Management Authority. From each category of susceptibility, one village was chosen randomly. Likewise, three villages from each block were selected. Therefore, a total of 30 villages were selected from the study area. In the second stage, the number of households was selected. The households were sampled using the random sampling technique. From each category of susceptible villages, 15 households were chosen, and altogether 450 were sampled for the study. The data on the number of active landslide sites in the villages was obtained from the Geological Survey of India. Every sampled household provided affirmative responses to the questionnaire, resulting in a survey response rate of 100 %.

3.3. Construction of composite vulnerability index

In the present study, composite vulnerability index was utilized to evaluate climate change induced landslide vulnerability. A plethora of site-specific indicators of various domains have been integrated for constructing composite vulnerability index [19,51,56]. These indicators have touched upon the multi-dimensional aspects of changing climatic conditions and their impact on socio-economic vulnerability to landslides. Suitable indicators help in the process for reducing vulnerability and contribute to effective decision-making process. Methodology from past literature was adopted for constructing the composite vulnerability index [17,46,47,51,56]. A total of 57 indicators related to social, physical, economic, climate change and environmental, early warning systems, emergency response systems and adaptation strategies were identified and grouped into the respective domains at household-based scale. These domains are social vulnerability index (SVI), economic vulnerability index (EVI), physical vulnerability index (PVI), climate change and environmental vulnerability index (CEnVI), early warning system index (EWSI), emergency response system (ERSI) and adaptation strategies index (ASI). The chosen indicators were standardized by implementing the equal weightage approach for their comparative evaluation. This approach was first employed by the Human Development Index during 1990. Since then, scientists and policy makers worldwide have extensively utilized this approach for assessing vulnerability [8–10,14,16]. Assigning equal weights also ensures uniformity by eliminating redundancies and missing observations in indicator-based assessments [46,47]. The arithmetic mean of each indicator was obtained after normalization. These indicators were standardized on a scale of 0 and 1 utilizing minimum and maximum values approach. We integrated the relative scores of the seven domains to determine the composite landslide vulnerability index. The CLVI values range from 0 to 1, where 0 and 1 represent the least and most vulnerable [9,10]. The indicators were normalized following eq. (1):

$$\mathbf{X} = \frac{\mathrm{Xi} - \mathrm{Xmin}}{\mathrm{Xmax} - \mathrm{Xmin}} \tag{1}$$

Where X represents the standardized value of indicators, Xi represents the value of the relevant indicator, X min is the lowest value of the indicator, and X max is the maximum value of each indicator.

$$\textbf{Sub Domain Score (SDS)}\,v = \sum_{i=1}^{n} \frac{IS\mathrm{iv}}{SNiv} \tag{2}$$

Where SDS denotes the subdomain score, '*i*' and 'v' are the indicators within the subdomain, *IS* refers to the sum of all indicators while *SN* is the total number of indicators within a subcomponent. Thus, different domains were calculated by combining different indicators to compose the index.

$$\textbf{Social Vulnerability Index} = \left\{ \frac{((S1 + S2 + S3 + S4 + S5 + S6 + S7 + S8)) - (S9 + S10)}{N} \right\} \quad (3)$$

SVI is the social vulnerability index, where S1, S2, S3 … …. S8 are the aggregate of indicators (which increase the vulnerability) while S9 and S10 decrease the vulnerability for each household. These are divided by the total number of indicators *N*. Following the above-mentioned method of calculating the social vulnerability index, different indices, namely EVI, PVI, CEnVI, EWSI, ERSI and ASI were calculated.

Each indicator contributes differently to the overall vulnerability, and the specific weights assigned to them in the calculation of the composite landslide vulnerability index that would determine their relative importance. After the calculation, the final composite landslide vulnerability index was calculated as:

$$\textbf{Composite Landslide Vulnerability Index (CLVI)} = \left\{ \frac{((SVI + EVI + PVI + CEnVI) - (EWSI + ERSI + ASI))}{N} \right\} \quad (4)$$

3.4. Regression analysis

A multiple linear regression test is a statistical technique that employs several independent variables to predict the value of a dependent variable by fitting a linear equation to observed data [2]. Such an estimation can be used to determine how a change in one or, in some instances, many independent variables will affect a dependent variable. The R^2 (goodness-of-fit) measures the proportion of the variance in the dependent variable that is predictable from the independent variable. An R^2 value closer to 1 indicates a strong relationship, while a value closer to 0 indicates a weak relationship. The beta coefficient (β) indicates the strength and direction of the relationship between the index and the dependent variable. A positive β value suggests a positive relationship, meaning as the index increases, the dependent variable also increases. A negative β value suggests a negative relationship, meaning as the index increases, the dependent variable decreases. Thus, the multiple regression analysis helped in identifying the most critical aspects of vulnerability that contributed to the overall composite vulnerability.

4. Results

4.1. A brief of demographic status of the sampled households

This section presents the general attributes of the surveyed households, namely gender, social group, age, religion, type of family, educational status, and annual income. Of the total respondents, 52 percent were males, and the remaining 48 percent were females. The average age of the respondents was 58.33 years. About 78 % of the households practiced Hinduism, followed by Islam (18 percent) and Sikhism (4 percent). Most of the sampled households (59 percent) belonged to the general caste, followed by other backward castes (19 percent), scheduled castes (16 percent), and scheduled tribes (7 percent). About 41 percent of the heads of households have completed higher secondary education, followed by secondary (23 percent) and primary (18 percent). While only 2 % were graduates. Most of the sampled households (57 percent) had a joint family, followed by a nucleated family (43 percent). The monthly income of most of the respondents (37 percent) was less than 15,000 Indian rupees (1 US $ = 82.90 Indian rupee), followed by ₹15001-30,000 (29 percent), ₹30,001–45,000 (20 percent), and more than ₹45000 (13 percent). Out of the total households, 46 percent were engaged in the agricultural sector, followed by petty business (22 percent), labour (18 percent), livestock rearing (7 percent), service (4 percent), and fishing (3 percent). Most of the respondents live in muddy houses (58 percent), followed by cemented houses (24 percent), and semi-cemented houses (19 percent).

4.2. Relative performance of different domains

The values of the social vulnerability index varied from 0.03 to 0.45 (Table 2). The values were further categorized into three classes (SVI) low (0.03–0.17), moderate (0.17–0.31), and high (0.31–0.45) using equal interval classification scheme (Fig. 3a). The analysis of SVI revealed that of the total surveyed villages, ten villages namely Shakrori, Anandpur, Loharkoti, Sarahan, Kelwi, Mashobra, Masli, Ogli, Bahlun and Halog displayed high social vulnerability. High social vulnerability of these villages was attributed to the high ratio of illiterate population, significant proportion of marginalized communities, and inaccessibility to medical facilities. The low educational status of the respondents has led to increased vulnerability. The respondents of these villages disclosed high incidence of landslide-induced death, and injuries. Households with shorter duration of stay in landslide susceptible areas have limited knowledge about past disasters and cope with landslides during emergencies have made the villages moderately vulnerable. Less number of marginalized communities, low disability rates, and an extended family type contributed to low social vulnerability in these villages. The presence of joint family has rendered low social vulnerability due to support networks and community connections. These findings highlight that gender dynamics, educational disparities, and persons with disability increase social vulnerability.

The values of the economic vulnerability index (EVI) varied between 0.14 and 0.75 (Fig. 3b). The values were further grouped as low (0.14–0.34), moderate (0.34–0.54), and high (0.54–0.75) economic vulnerability. The EVI analysis revealed that Sarahan, Taklech, Shakrori, and Malendi villages scored high values in the economic vulnerability index (Table 3). Low monthly income, high de-

Table 2
Indices of indicators used for assessing social vulnerability.

Village	Ratio of female population	Ratio of disabled population	Marginalized communities	Ratio of illiterate population	No. of years of living in the area (<10 years)	Joint and extended family	Accessibility to medical facilities	No. of injuries due to landslide	No. of human deaths due to landslide	Damage to the material asset due to landslides	Social Vulnerability Index
Shakrori	0.74	0.41	0.85	0.77	0.62	0.69	0.00	0.60	0.22	1.00	0.45
Ogli	0.58	0.16	0.77	0.70	0.46	0.46	0.10	0.20	0.33	0.75	0.34
Halog	0.74	0.07	0.92	0.67	0.23	0.54	0.10	0.10	0.44	0.67	0.32
Anandpur	0.64	0.14	0.23	0.64	0.46	0.46	0.00	0.80	1.00	0.58	0.40
Dhalli	0.57	0.00	0.15	0.80	0.54	0.46	0.80	0.60	0.89	0.50	0.28
Mashobra	0.51	0.17	0.31	0.49	0.15	0.08	0.10	1.00	0.67	0.67	0.38
Malat	0.57	0.02	0.85	0.29	0.31	0.54	0.40	0.20	0.33	0.33	0.20
Nerua	0.67	0.07	1.00	0.43	0.54	0.00	1.00	0.80	0.22	0.25	0.30
Khagna	0.75	0.18	0.69	0.63	0.15	0.46	0.50	0.00	0.00	0.42	0.19
Jais	0.36	0.00	0.15	0.70	0.69	0.38	0.00	0.10	0.11	0.83	0.26
Kelwi	0.68	0.18	0.31	0.57	1.00	0.46	0.40	0.60	0.44	0.92	0.38
Raighat	0.53	0.00	0.23	0.66	0.38	0.54	0.80	0.20	0.00	1.00	0.17
Masli	0.65	0.31	0.69	0.58	0.15	0.62	0.20	0.90	1.00	0.25	0.37
Chirgaon	0.53	0.08	0.38	0.47	0.00	0.54	0.10	0.00	0.22	0.08	0.11
Devidhar	0.58	0.09	0.23	0.33	0.54	0.23	0.70	0.00	0.00	0.17	0.10
Sarahan	0.57	0.28	1.00	0.36	0.54	0.46	0.40	0.30	0.67	1.00	0.39
Kinnu	0.72	0.19	0.54	0.44	0.38	1.00	0.50	0.80	0.44	0.83	0.28
Taklech	0.66	0.39	0.69	0.59	0.23	0.85	0.30	0.40	0.33	0.67	0.28
Malendi	0.36	0.02	0.31	0.47	0.69	0.54	0.90	0.10	0.67	0.67	0.18
Kacheri	0.63	0.02	0.62	0.33	0.23	0.77	0.00	0.20	0.00	0.08	0.13
Mandhaon	0.46	0.08	0.46	0.30	0.15	0.69	0.00	0.20	0.00	0.17	0.11
Sholi	0.45	0.08	0.92	0.55	0.62	0.62	0.00	0.30	0.22	0.08	0.26
Manjholi	0.67	0.05	0.54	0.07	0.38	0.00	0.60	0.00	0.56	0.50	0.22
Panoli	0.61	0.07	0.08	0.13	0.77	0.62	0.20	0.00	0.00	0.67	0.15
Kharapatthar	0.36	0.00	0.85	0.45	0.38	0.46	0.60	0.10	0.56	0.00	0.16
Himri	0.73	0.02	0.00	0.19	0.23	0.54	0.10	0.00	0.44	0.33	0.13
Jagthan	0.67	0.05	0.54	0.49	0.23	0.92	0.90	0.00	0.00	0.17	0.03
Loharkoti	0.31	0.06	0.08	0.66	0.46	0.23	0.20	0.90	1.00	0.83	0.39
Bahlun	0.34	0.06	0.23	0.78	0.31	0.15	0.10	0.70	0.22	0.92	0.33
Banchochh	0.26	0.02	0.38	0.57	0.46	0.69	0.30	0.30	0.44	0.75	0.22

Sources: Based on field survey and authors own calculation

pendency ratio and dependence on the primary sector for sustenance were identified as the contributing factors for economic instability in these villages. High unemployment rates and debt have made the respondents of the villages moderately economically vulnerable. The relatively stable economic status and less-dependency population were influencing factors that helped in reducing the vulnerability of respondents to the severity of landslides.

Marked variations were found that constituted physical vulnerability in the study area (Fig. 3c). High physical vulnerability (0.60–0.81) was found in Malendi village, followed by Bahlun, Loharkoti, Nerua, Shakrori, Malat, and Manjholi (Table 4). The houses in these villages were located on a steep slope and constructed approximately thirty years ago without adhering to the building codes. The absence of the execution of building codes and laws has led to an increase in landslide vulnerability. The use of wood, stone, and mud to construct homes, non-resistant roofs, and narrow house entrances provided little resistance to the forces of nature, making the houses more fragile to collapse during rainfall-induced landslides. Narrow entrances impeded the evacuation during emergencies, increasing the risk to occupants' safety. The respondents in these villages become physically highly vulnerable due to unpaved road connectivity and non-engineered houses on steep slopes. Moderate physical vulnerability is attributed due to numerous cracks and the orientation of doors and windows towards the slope. The number of floors in the house is another factor in the observed damage. The villages are marked by intensive exploitation of firewood for conventional cooking methods and varied purposes that led to slope failure and instability. Wider house entrances, landslide-resistant construction materials, minimal cracks, and single-flooring structures have minimized the potential for damage and led to low physical vulnerability.

Anandpur, Loharkoti, Jais, Sarahan, Mashobra, Nerua, Devidhar, Kacheri, and Masli villages have experienced high climate change and environmental vulnerability (Fig. 3d). High rainfall intensity, temperature variability, and increased frequency of landslides within the last decade are the dominant factors for high climate change and environmental vulnerability to landslides (Table 5). Most households were exposed to the high landslide-prone area and perceived rainfall as the principal trigger of landslides. Changes in land use/land cover dynamics and increased developmental activities have influenced environmental stressors, leading to moderate environmental vulnerability. Low landslide frequency and less temperature variability are attributed to low climate change and environmental vulnerability.

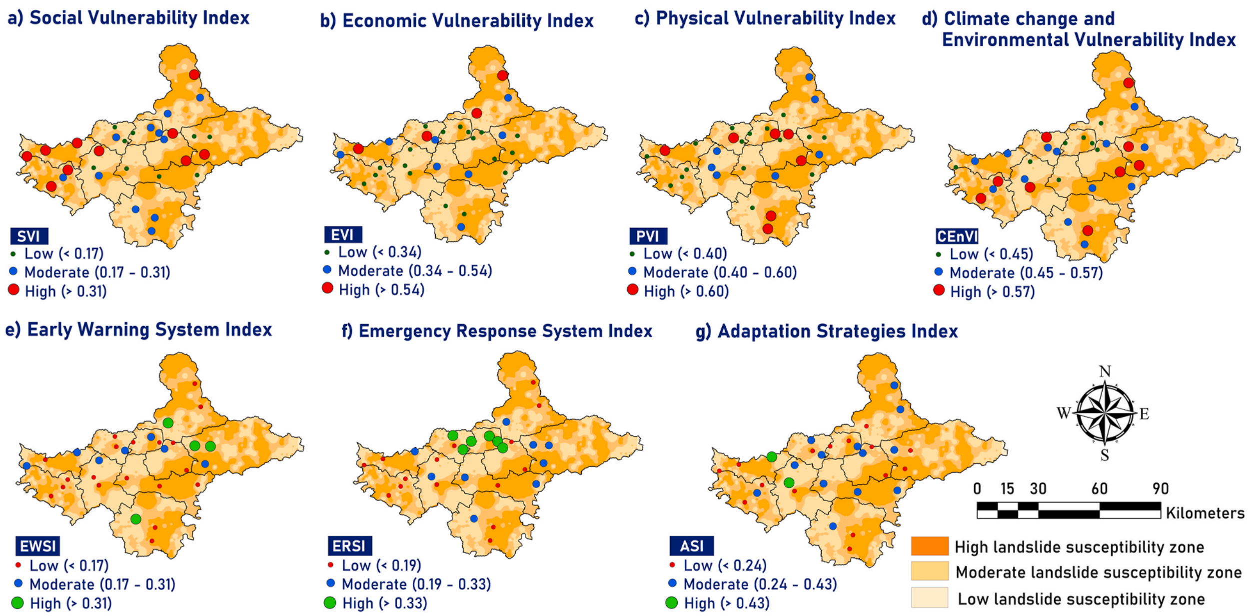

Fig. 3. Different domains of vulnerability and adaptation: (a) Social Vulnerability Index (b) Economic Vulnerability Index (c) Physical Vulnerability Index (d) Climate change and Environmental Vulnerability Index (e) Early Warning System Index (f) Emergency Response System Index and (g) Adaptation Strategies Index. Source: Prepared by author

Table 3
Indices of indicators used for assessing economic vulnerability.

Villages	Ratio of dependent population	Monthly average income (<Indian Rupees 15,000)	Debt	Ratio of unemployed population	Persons working in primary sector of the economy	Economic Vulnerability Index
Shakrori	0.49	0.91	0.33	0.46	0.64	0.57
Ogli	0.30	0.55	0.67	0.26	0.21	0.40
Halog	0.38	0.18	0.78	0.12	0.36	0.36
Anandpur	0.48	0.18	0.44	0.09	0.01	0.24
Dhalli	0.38	0.64	0.00	0.17	0.14	0.27
Mashobra	0.32	0.09	0.22	0.22	0.07	0.19
Malat	0.39	0.45	0.67	0.14	0.50	0.43
Nerua	0.22	0.27	0.00	0.22	0.36	0.21
Khagna	0.35	0.09	0.22	0.28	0.43	0.27
Jais	0.17	0.09	0.33	0.13	0.43	0.23
Kelwi	0.42	0.27	0.22	0.15	0.57	0.33
Raighat	0.15	0.09	0.11	0.12	0.86	0.27
Masli	0.19	0.36	0.22	0.32	0.50	0.32
Chirgaon	0.14	0.09	0.89	0.15	0.14	0.28
Devidhar	0.18	0.91	0.44	0.16	0.43	0.43
Sarahan	0.43	1.00	0.89	0.43	1.00	0.75
Kinnu	0.37	0.82	0.33	0.37	0.71	0.52
Taklech	0.46	0.73	1.00	0.46	0.64	0.66
Malendi	0.53	0.64	1.00	0.24	0.43	0.57
Kacheri	0.13	0.18	0.11	0.33	0.43	0.24
Mandhaon	0.26	0.55	0.89	0.24	0.14	0.41
Sholi	0.10	0.18	0.22	0.33	0.29	0.22
Manjholi	0.16	0.09	0.11	0.33	0.50	0.24
Panoli	0.13	0.27	0.11	0.16	0.36	0.21
Kharapatthar	0.30	0.36	0.67	0.43	0.50	0.45
Himri	0.22	0.18	0.78	0.29	0.50	0.39
Jagthan	0.26	0.18	0.11	0.33	0.36	0.25
Loharkoti	0.10	0.18	0.22	0.29	0.50	0.26
Bahlun	0.18	0.27	0.00	0.18	0.07	0.14
Banchochh	0.13	0.00	0.33	0.11	0.50	0.22

Sources: Based on field survey and authors own calculation

Table 4
Indices of indicators used for assessing physical vulnerability.

Villages	Steep slope	House made of mud	Age of the building (>30 years)	Presence of cracks in the house	Multiple floors of the house	Non-resistant roof of the house	Narrow opening of the house entrance	Door/window opening towards slope	Unpaved road connectivity in the area	Extraction of firewood	Physical Vulnerability Index
Shakrori	0.73	0.93	1.00	0.86	0.09	0.90	0.22	0.36	1.00	0.85	0.69
Ogli	0.40	0.47	0.38	0.29	0.00	0.70	0.00	0.36	0.62	0.38	0.36
Halog	0.47	0.47	0.38	0.00	0.00	0.40	0.22	0.36	0.38	0.15	0.28
Anandpur	0.67	0.80	0.13	0.14	0.36	0.40	0.56	0.27	0.15	0.23	0.37
Dhalli	1.00	0.67	0.50	0.14	0.27	0.50	0.11	0.27	0.08	0.23	0.38
Mashobra	0.73	0.87	0.13	0.43	0.27	0.10	0.33	0.55	0.00	0.00	0.34
Malat	1.00	0.60	0.25	0.14	0.73	0.60	0.22	1.00	0.85	0.92	0.63
Nerua	0.87	0.80	1.00	1.00	0.45	1.00	0.22	0.73	0.15	0.77	0.70
Khagna	0.67	0.27	0.38	0.14	0.27	0.50	0.33	0.18	0.31	0.54	0.36
Jais	0.87	0.67	0.75	0.00	0.55	0.40	1.00	0.45	0.46	0.38	0.55
Kelwi	0.67	0.40	0.50	0.14	0.55	0.50	0.11	0.64	0.77	0.69	0.50
Raighat	0.20	0.60	0.38	0.00	0.00	0.80	0.22	0.36	0.92	0.85	0.43
Masli	0.53	0.40	0.50	0.29	0.36	0.90	0.22	0.36	0.38	0.23	0.42
Chirgaon	0.40	0.13	0.13	0.29	0.27	0.60	0.33	0.18	0.31	0.31	0.29
Devidhar	0.20	0.07	0.50	0.14	0.36	0.50	0.11	0.45	0.15	0.54	0.30
Sarahan	1.00	0.73	0.25	0.14	0.27	0.60	0.33	0.45	0.85	1.00	0.56
Kinnu	1.00	0.93	0.13	0.14	0.36	0.60	0.22	0.64	0.85	0.92	0.58
Taklech	0.07	0.13	0.25	0.00	0.27	0.50	0.33	0.00	0.31	0.23	0.21
Malendi	0.93	0.86	0.63	1.00	0.45	1.00	0.78	1.00	0.69	0.77	0.81
Kacheri	0.33	0.67	0.13	0.29	0.18	0.30	0.00	0.27	0.15	0.38	0.27
Mandhaon	0.13	0.47	0.38	0.14	0.45	0.00	0.11	0.36	0.23	0.00	0.23
Sholi	0.20	0.40	0.50	0.29	0.36	0.70	0.33	0.18	0.31	0.08	0.33
Manjholi	1.00	0.60	0.25	0.14	0.73	0.60	0.22	1.00	0.85	0.92	0.63
Panoli	0.27	0.07	0.00	0.00	0.18	0.40	0.33	0.55	0.08	0.08	0.19
Kharapatthar	0.67	0.87	0.25	0.00	0.55	0.40	0.44	0.55	0.77	0.85	0.53
Himri	0.00	0.00	0.25	0.29	0.27	0.20	0.11	0.45	0.15	0.46	0.22
Jagthan	0.13	0.07	0.25	0.00	0.36	0.30	0.22	0.18	0.31	0.15	0.20
Loharkoti	0.80	0.93	0.75	0.57	0.55	0.90	0.56	1.00	0.38	0.62	0.71
Bahlun	0.73	0.67	0.63	0.71	1.00	0.70	0.78	0.82	0.85	0.54	0.74
Banchochh	0.60	0.33	0.38	0.29	0.00	0.70	0.00	0.36	0.08	0.38	0.31

Sources: Based on field survey and authors own calculation

The values of the early warning system index varied from 0.03 to 0.46, with higher values representing a more effective early warning system (Fig. 3e). The findings revealed that of the total surveyed villages, four, namely Chirgaon, Taklech, Devidhar, and Khagna, have an effective early warning system (Table 6). Highly responsive local authorities, regular updates on landslides, and quick dissemination of information have aided in enhancing early warning capacities. Basic hazard maps have also served as a dynamic tool for increased awareness, community preparedness, and resource allocation for targeted mitigation measures in these villages. High reliability of the landslide inventory map and moderate diurnal daily updates on landslides were responsible for the moderate early warning system. Low early warning systems have been identified in areas with relatively limited media coverage, incomplete landslide hazard mapping, and ineffective response mechanisms. Thus, timely actions are necessary to improve the affected communities' access to crucial information to ensure their safety and carry out evacuation in times of future landslide events.

High emergency response system was found among the households of Sholi, Manjholi, Panoli, Banchochh, Kacheri, and Mandhaon villages (Fig. 3f). The effective and timely coordinated assistance between trained rescue services and responders in communities contributed to a high emergency response system (Table 7). Households disclosed that the local stakeholders had designated schools and colleges as emergency centers for mitigating landslide risk. Relatively good access to medical services, food, and transportation services made the respondents of these villages less sensitive. Lack of training and coordination among responders indicated some gaps with resource allocation. It implies the roles and responsibilities at the local level are disproportionately distributed, that could influence effectiveness of emergency response system in villages that had moderate emergency response system. However, efforts are being made to address these issues through awareness programs and training sessions aimed at increasing coordination and communication among local responders in the villages. With continued focus on improving emergency response systems in these villages, it is expected that their adaptation to landslides will continue to increase. Low emergency response system was observed in villages where the absence of specialized equipment such as rescue gear, medical supplies, and communication systems have hampered the capacity to cope with the aftermath of disasters and emergencies.

High adaptive capacity was observed in Ogli and Raighat villages (Fig. 3g). These villages performed relatively better in terms of social network, livelihood strategies, housing insurance, medical facilities, and access to disaster funds from stakeholders (Table 8). Effective coordination and social ties have greatly reduced vulnerability in these villages. The respondents of these villages have received assistance for repair of houses from the state government to combat the severity of landslides. The livelihood strategies adopted by the respondents, included diversification of livelihood and migration in urban areas for better income and job opportuni-

Table 5
Indices of indicators used for assessing climate change and environmental vulnerability.

Villages	Increasing temperature during summer	Changes in rainfall pattern	Increase in rainfall intensity	Increased frequency of landslide in last 10 years	Landslide caused due to developmental activities	Landslide caused due to heavy rainfall	Landslide caused due to earthquake	Land use/land cover changes	Soil erosion and contamination	Depletion of surface water quality	Climate and Environmental Vulnerability Index
Shakrori	0.67	0.50	0.77	1.00	0.09	0.45	0.00	0.15	0.45	0.69	0.48
Ogli	0.67	0.67	0.62	0.67	0.27	0.73	0.64	0.08	0.18	0.08	0.46
Halog	0.58	0.42	0.69	0.33	0.27	0.64	0.27	0.15	0.00	0.00	0.34
Anandpur	0.58	0.83	0.54	0.67	0.55	0.91	0.64	0.69	0.91	0.62	0.69
Dhalli	0.42	0.58	0.62	0.00	0.27	0.36	0.91	0.85	0.64	0.08	0.47
Mashobra	0.17	1.00	0.54	0.50	0.45	0.64	0.82	0.69	1.00	0.46	0.63
Malat	0.50	0.67	0.85	0.00	0.64	0.64	0.36	0.38	0.55	0.62	0.52
Nerua	1.00	0.00	0.62	0.67	0.09	0.55	1.00	0.69	0.64	0.92	0.62
Khagna	0.67	0.33	0.62	0.67	0.73	0.64	0.64	0.69	0.18	0.15	0.53
Jais	0.75	0.25	1.00	0.75	0.64	0.82	0.64	0.08	0.64	0.92	0.65
Kelwi	0.58	0.50	0.54	0.25	0.18	0.64	0.00	0.46	0.27	0.00	0.34
Raighat	0.58	0.42	0.54	0.58	0.64	0.64	0.73	0.31	0.09	0.15	0.47
Masli	0.58	0.83	0.69	0.42	0.82	0.27	0.73	0.00	0.64	0.77	0.57
Chirgaon	0.58	0.67	0.69	0.58	0.73	0.18	0.64	0.85	0.36	0.31	0.56
Devidhar	0.67	0.92	0.62	0.25	0.91	0.73	0.64	0.15	0.64	0.54	0.61
Sarahan	0.75	0.67	0.46	0.58	0.45	1.00	0.82	0.46	0.64	0.69	0.65
Kinnu	0.17	0.50	0.23	0.67	0.64	0.64	0.73	0.54	0.73	0.46	0.53
Taklech	0.42	0.67	0.46	0.67	0.18	0.82	0.27	0.23	0.55	0.23	0.45
Malendi	0.42	0.42	0.23	0.67	0.36	0.36	0.45	1.00	0.64	0.46	0.50
Kacheri	1.00	0.50	0.77	0.58	0.45	0.55	0.82	0.62	0.64	0.15	0.61
Mandhaon	0.42	0.67	0.85	0.33	0.00	0.73	0.36	0.69	0.64	0.92	0.56
Sholi	0.42	0.50	0.46	0.42	0.82	0.00	0.18	0.54	0.64	0.31	0.43
Manjholi	0.50	0.08	0.54	0.50	0.64	0.18	0.55	0.08	0.64	0.23	0.39
Panoli	0.00	0.58	0.00	0.42	0.27	0.45	0.82	0.62	0.64	0.54	0.43
Kharapatthar	0.83	0.42	0.15	0.00	0.18	0.82	0.27	0.62	0.73	0.62	0.46
Himri	0.42	0.75	0.54	0.25	0.09	0.64	0.64	0.15	0.64	0.38	0.45
Jagthan	0.25	0.58	0.54	0.42	1.00	0.64	0.18	0.62	0.27	0.31	0.48
Loharkoti	0.58	0.67	0.54	0.42	0.73	0.73	0.64	0.77	0.64	1.00	0.67
Bahlun	0.50	0.67	0.69	0.58	0.09	0.45	0.73	0.62	0.55	0.77	0.56
Banchochh	0.50	0.50	0.46	0.25	0.64	0.18	0.45	0.62	0.82	0.08	0.45

Sources: Based on field survey and authors own calculation

ties. Contour farming, mulching, crop rotation, and intercropping, have helped soil conservation and maintaining soil fertility in these villages. High health insurance coverage, saving of foodgrains during crisis, fair regulations on new constructions and land use activities were found to be the contributing indicators for moderate adaptation in these villages. Low coverage of housing and health insurance, ineffective implementation of standardized building codes and low participation in awareness and training initiatives on disaster preparedness were attributed to low adaptation in these villages. The affected population primarily relied on loans for financial assistance during emergencies and disasters. It was also found that without insurance in susceptible areas, the residents face challenges in paying for health-related costs. Lack of knowledge and awareness have caused ineffective response mechanisms to environmental challenges.

4.3. Composite landslide vulnerability index-based performance

The composite landslide vulnerability index (CLVI) was determined by integrating SVI, EVI, PVI, CEnVI, EWSI, ERSI, and ASI using Eq. (10). The CLVI index ranged from 0.04 to 0.28 (Fig. 4). This is further divided into three classes of vulnerability: low (0.04–0.11), moderate (0.11–0.19), and high (0.19–0.28). The relative performance of CLVI and its various domains is presented in Table 9. A close perusal of the table shows that high landslide vulnerability was found in Shakrori village, Sarahan, Loharkoti, Nerua, Malendi, Malat, Anandpur, Jais, and Bahlun villages. Low early warning system, low implementation of adaptation strategies, high climate and environmental vulnerability, and high physical led to high composite vulnerability in these villages. Residents of these villages reported that the poor construction of buildings, inadequate infrastructure, and prevalence of muddy structures emanated high physical vulnerability to landslides. Most houses were built by local masons and constructors with limited awareness of the fundamental building codes and principles. Variability in meteorological variables, increased landslide frequency, and rainfall-induced landslides were identified for the high climate change and environmental vulnerability in these villages. The disparities in housing conditions directly reflected the economic status of households, thereby exposing them to the risk of landslides. The villages namely Shakrori, Sarahan, and Malendi villages had experienced high composite vulnerability due to high economic vulnerability.

Economic, physical, climate, and environmental vulnerability, and emergency system have made moderate composite vulnerability in Kinnu village. Mashobra, and Kharapatthar demonstrated moderate vulnerability, attributed primarily to economic challenges coupled with varying degrees of physical and environmental vulnerability. Kelwi, Masli, and Dhalli villages have high economic con-

Table 6
Indices of indicators used for assessing early warning system.

Villages	Local authority	News (TV, Radio, Print)	Detailed Inventory maps	Basic hazard maps	Early Warning System Index
Shakrori	0.13	0.00	0.00	0.00	0.03
Ogli	0.13	0.17	0.88	0.08	0.31
Halog	0.07	0.33	0.25	0.33	0.25
Anandpur	0.13	0.17	0.00	0.08	0.10
Dhalli	0.00	0.17	0.13	0.00	0.07
Mashobra	0.07	0.08	0.13	0.00	0.07
Malat	0.00	0.08	0.13	0.08	0.07
Nerua	0.13	0.00	0.25	0.08	0.12
Khagna	0.07	0.25	0.88	0.25	0.36
Jais	0.07	0.17	0.13	0.00	0.09
Kelwi	0.00	0.17	0.38	0.17	0.18
Raighat	0.07	0.08	0.13	0.00	0.07
Masli	0.13	1.00	0.00	0.00	0.28
Chirgaon	1.00	0.17	0.50	0.17	0.46
Devidhar	0.07	0.17	0.25	1.00	0.37
Sarahan	0.00	0.17	0.00	0.08	0.06
Kinnu	0.00	0.17	0.13	0.00	0.07
Taklech	0.13	0.42	1.00	0.17	0.43
Malendi	0.13	0.17	0.13	0.25	0.17
Kacheri	0.00	0.42	0.00	0.17	0.15
Mandhaon	0.07	0.17	0.38	0.33	0.24
Sholi	0.13	0.17	0.25	0.17	0.18
Manjholi	0.13	0.42	0.13	0.00	0.17
Panoli	0.07	0.25	0.13	0.08	0.13
Kharapatthar	0.00	0.08	0.25	0.08	0.10
Himri	0.20	0.25	0.13	0.08	0.16
Jagthan	0.07	0.00	0.00	0.08	0.04
Loharkoti	0.07	0.08	0.13	0.00	0.07
Bahlun	0.07	0.17	0.00	0.25	0.12
Banchochh	0.20	0.33	0.25	0.17	0.24

Sources: Based on field survey and authors own calculation

straints, poor understanding of early warning system and infrastructure vulnerabilities. Halog, Taklech, Raighat, Chirgaon, Sholi, Manjholi, Himri, Khagna, Ogli, Devidhar, Mandhaon, Panoli, Jagthan, Kacheri, and Banchochh experienced low vulnerability. These villages are vulnerable due to climate change and environmental vulnerability. However, the high adaptation strategies reduce the composite vulnerability in Ogli and Raighat. The coordinated emergency response efforts supported by responsive local authorities and designated evacuation centers have helped in reducing vulnerability in Sholi, Panoli, and Banchochh villages.

4.4. Relationship between vulnerability and its domains

A multiple linear regression test was carried out to regress one dependent variable on several independent variables (Table 10). The regression analysis found that physical vulnerability ($R^2 = 0.899$) had a significant impact on the degree of vulnerability. It indicates that 89 % of the variance in the dependent variable is due to physical vulnerability. This is followed by the social ($R^2 = 0.838$), climate change and environment ($R^2 = 0.805$), and economic ($R^2 = 0.709$) vulnerabilities. On the other hand, indices related to adaptation ($R^2 = 0.180$), emergency response ($R^2 = 0.155$), and early warning systems ($R^2 = 0.037$) had the least impact on landslide vulnerability. The test also demonstrated that beta coefficients of social ($\beta = 0.166$), economic ($\beta = 0.241$), physical ($\beta = 0.316$), climate change and environmental vulnerabilities ($\beta = 0.153$) came out to be positive and statistically significant at the 0.01 level of significance. However, the early warning system ($\beta = -0.237$), emergency response system ($\beta = -0.237$), and adaptation ($\beta = -0.244$) were found to have a negative association with vulnerability.

Of the total indicators, houses located on steep slopes ($R^2 = 0.542$), houses made up of mud ($R^2 = 0.539$), and narrow housing entrances ($R^2 = 0.352$) in terms of physical vulnerability were found to be statistically significant at the 0.01 level of significance. When the composite landslide vulnerability index regressed against the indicators of economic vulnerability, the dependent population ($R^2 = 0.208$) and low monthly average income ($R^2 = 0.163$) proved to be statistically significant. Within the social domain, indicators such as injuries ($R^2 = 0.330$) and deaths ($R^2 = 0.320$) incurred due to landslides had a substantial impact on landslide vulnerability. In terms of climate change and environmental factors, an increase in rainfall intensity ($R^2 = 0.514$), increased frequency of landslides in the last 10 years ($R^2 = 0.412$), and changes in rainfall pattern ($R^2 = 0.412$) emerged as significant indicators. While the indicators signifying early warning system, emergency response system, and adaptation strategies had relatively insignificant outcomes and negatively influenced composite vulnerability. Thus, it can be inferred that both physical and social factors have affected the level of vulnerability and played a dominant role in determining the degree of vulnerability. An improvement in these domains would have a positive impact on landslide vulnerability.

Table 7
Indices of indicators used for assessing emergency response system.

Villages	Permanent coordination between responders in communities with specialized equipment and well-trained rescue services	Clear definition of roles and responsibilities at local level and proportionate allocation of resources	First aid and probable health facilities availed during the disaster	Basic facilities availed during the disaster (food, water, transport, and emergency shelter)	Emergency Response System Index
Shakrori	0.00	0.13	0.10	0.20	0.11
Ogli	0.50	0.25	0.20	0.20	0.29
Halog	0.25	0.00	0.30	0.20	0.19
Anandpur	0.25	0.00	0.10	0.00	0.09
Dhalli	0.00	0.13	0.20	0.10	0.11
Mashobra	0.13	0.13	0.10	0.10	0.11
Malat	0.38	0.00	0.00	0.20	0.14
Nerua	0.00	0.00	0.10	0.20	0.08
Khagna	0.38	0.13	0.30	0.20	0.25
Jais	0.13	0.00	0.00	0.10	0.06
Kelwi	0.00	0.25	0.20	0.00	0.11
Raighat	0.38	0.25	0.20	0.10	0.23
Masli	1.00	0.00	0.10	0.00	0.28
Chirgaon	0.88	0.00	0.00	0.00	0.22
Devidhar	0.25	0.00	1.00	0.00	0.31
Sarahan	0.25	0.13	0.00	0.10	0.12
Kinnu	0.00	0.13	0.10	0.20	0.11
Taklech	0.38	0.00	0.40	0.50	0.32
Malendi	0.00	0.25	0.30	0.20	0.19
Kacheri	0.75	0.13	0.10	0.60	0.39
Mandhaon	0.63	0.13	0.20	0.40	0.34
Sholi	0.63	0.25	0.40	0.60	0.47
Manjholi	0.63	0.50	0.10	0.50	0.43
Panoli	0.63	0.38	0.20	0.50	0.43
Kharapatthar	0.13	0.00	0.10	0.20	0.11
Himri	0.13	0.00	0.30	0.50	0.23
Jagthan	0.38	0.00	0.40	0.00	0.19
Loharkoti	0.00	0.13	0.20	0.20	0.13
Bahlun	0.00	0.13	0.10	0.10	0.08
Banchochh	0.38	0.13	0.20	1.00	0.43

Sources: Based on field survey and authors own calculation

5. Discussion

A large body of literature has touched upon the efficacy of an indicator-based approach on the themes of disaster resilience, climate change vulnerability assessment, and risk management studies [4,8,9,15,41,47]. These studies have integrated biophysical and social dimensions of vulnerability by employing a weighted sum approach and constructed vulnerability index. It serves as a valuable tool for predicting future vulnerability and has given edge over conventional techniques. Natural disaster induced vulnerability is multi-faceted, spatiotemporally dynamic, and is based on site-specific parameters. It could be examined at varied scales ranging from micro to macro level [39]. Due to the distinct and localized nature of landslides, vulnerability assessment using various site-specific indicators holds immense significance [19]. Referring to studies such as [13,21,31,43,50,69], scholars have tried to explore a wide range of indicators for analyzing landslide vulnerability at both local and regional scales. However, the integrated and comprehensive framework for formulating landslide adaptation and mitigation strategies at the household level was less explored. It requires meaningful consideration of their relevance, reliability, and sensitivity to changes in the socio-economic context. Thus, the study makes an embryonic attempt to quantify social, economic, physical, environmental vulnerability, early warning systems, emergency response systems, and adaptation strategies in Shimla district of the north-west Indian Himalaya. Various thematic areas have been identified at the household level that helped in composite vulnerability mapping and individual representation of its indicators. Such analyses have helped in identifying thematic areas that require immediate policies intervention to make a landslide resilient society.

The mountainous landscape of Shimla district has been significantly influenced by an interplay of complex lithology, continuous downpours, active tectonics, and steep slopes. The rapid expansion of settlements and developmental activities have affected the dynamics of landslides and have become a major concern for safety purposes [55,61,64]. However, the severity of its implications has become more pronounced, particularly during the monsoon season (June–September). This is due to the frequent landslide occurrences in response to climate variability and weather extremes [12,71]. The study conducted by Perera et al. [50] found an increasing trend in fatal landslides in the Kegalle district of Sri Lanka. These landslides were attributed to changing climatic conditions and improper land use practices. A similar situation was observed in the Mae Chaem basin in northern Thailand, where an increasing amount of rainfall, deforestation, and terrace farming were identified as the principal triggering factors for devastating several households as well as the functioning of the livelihood system [70]. Uncertainties in climate have jeopardized rural communities due to the possession of limited assets and their low capacity to cope with shocks, risks, and challenges. Pham et al. [48] assessed household vulnerability to flash floods and landslides and found smallholder farmers to be highly sensitive groups due to their high exposure and fi-

Table 8
Indices of indicators used for assessing adaptation strategies.

Villages	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Adaptation Strategies index
Shakrori	0.07	0.00	0.13	0.11	0.00	0.00	0.20	0.00	0.22	0.20	0.00	0.09	0.27	0.00	0.09
Ogli	0.00	0.57	0.00	0.56	1.00	0.73	0.90	0.00	0.89	0.60	0.89	0.55	1.00	1.00	0.62
Halog	0.07	0.14	0.27	0.11	0.00	0.00	0.90	0.20	0.56	0.40	0.00	0.55	0.00	0.00	0.23
Anandpur	0.50	0.00	0.00	0.00	0.22	0.09	0.10	0.00	0.00	0.10	0.11	0.00	0.27	0.00	0.10
Dhalli	0.00	0.29	0.13	0.33	0.23	0.18	0.10	0.20	0.44	0.90	0.44	0.82	0.27	0.00	0.31
Mashobra	0.00	0.14	0.13	0.11	0.00	0.27	0.00	0.11	0.11	0.20	0.00	0.00	0.13	0.22	0.10
Malat	0.36	0.00	0.07	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.11	0.07
Nerua	0.00	0.00	0.08	0.13	0.00	0.18	0.20	0.20	0.00	0.08	0.10	0.18	0.40	0.00	0.11
Khagna	0.21	0.29	0.47	0.00	0.11	0.82	0.40	0.00	0.44	0.50	0.00	0.82	0.47	0.00	0.32
Jais	0.29	0.14	0.00	0.11	0.22	0.09	0.50	0.00	0.11	0.00	0.11	0.00	0.13	0.00	0.12
Kelwi	0.14	0.00	0.00	0.00	0.00	0.18	0.00	0.67	1.00	0.80	1.00	0.00	0.00	0.00	0.27
Raighat	0.43	0.29	0.07	1.00	0.00	0.73	0.80	1.00	0.89	0.50	0.89	0.64	0.60	0.00	0.56
Masli	0.14	0.14	0.13	0.00	0.11	0.09	0.20	0.22	0.22	0.40	0.22	0.09	0.13	0.00	0.15
Chirgaon	0.14	0.00	0.13	0.00	0.22	0.09	0.10	0.11	0.11	0.20	0.11	0.00	0.20	0.00	0.10
Devidhar	0.21	0.43	0.67	0.33	0.22	0.00	0.80	0.44	0.22	0.70	0.33	0.00	0.40	0.89	0.40
Sarahan	0.00	0.00	0.53	0.33	0.00	0.18	0.60	0.00	0.00	0.50	0.56	0.45	0.47	0.00	0.26
Kinnu	0.00	0.14	0.00	0.56	0.89	0.45	0.50	0.89	0.44	0.60	0.44	0.55	0.27	0.00	0.41
Taklech	0.13	0.14	0.08	0.50	0.00	0.00	0.00	0.90	0.89	0.33	0.00	0.00	0.00	0.00	0.21
Malendi	0.07	0.00	0.33	0.11	0.78	0.00	0.00	0.11	0.00	0.10	0.00	0.00	0.60	0.00	0.15
Kacheri	0.36	0.00	0.00	0.00	0.00	0.36	0.80	0.89	0.89	1.00	0.00	1.00	0.47	0.00	0.41
Mandhaon	0.29	0.00	0.00	0.00	0.67	0.82	0.00	0.67	0.78	0.40	0.78	0.00	0.00	0.89	0.38
Sholi	0.00	0.29	0.13	0.00	0.00	0.18	0.10	0.00	0.11	0.00	0.22	0.09	0.07	0.22	0.10
Manjholi	0.00	0.14	0.08	0.25	0.23	0.64	0.00	0.90	0.44	0.33	0.40	0.00	0.80	0.78	0.36
Panoli	0.00	0.00	0.07	0.11	0.00	0.00	0.10	0.22	0.00	0.10	0.11	0.09	0.00	0.00	0.06
Kharapatthar	0.14	0.43	0.00	0.00	0.00	0.45	0.00	0.44	0.00	0.50	0.22	0.64	0.33	0.44	0.26
Himri	0.00	0.00	0.08	0.13	0.00	0.36	0.80	0.00	0.89	0.00	0.00	1.00	0.70	0.00	0.28
Jagthan	0.00	0.21	0.17	0.00	0.46	0.00	1.00	0.60	0.78	0.00	0.00	0.00	0.90	0.89	0.36
Loharkoti	0.13	0.14	0.00	0.00	0.08	0.00	0.10	0.00	0.00	0.08	0.30	0.00	0.00	0.33	0.08
Bahlun	0.00	0.14	0.17	0.00	0.00	0.18	0.20	0.30	0.11	0.00	0.20	0.09	0.50	0.22	0.15
Banchochh	0.00	0.00	0.00	0.56	1.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.53	0.89	0.28

nancially deprived state in the Van Yen district of Vietnam. These climate change-induced catastrophes have further caused disturbances in daily activities, decreased crop production, significant food shortages, and deterioration in the quality of food items. Masroor et al. [47] identified a cyclical pattern of vulnerability induced by climate change-related disasters. This cycle is characterized by loss of income, depletion of assets, and a heavy reliance on bank loans for adaptation, which collectively exacerbate individuals' and communities' vulnerability to resist shocks and stresses [1,34]. Insufficient resources and support systems have threatened the farmers in China's Three Gorges Reservoir Area to recover and rebuild after each landslide event [68]. Yang et al. [29] emphasized that farmers are increasingly adopting non-farming livelihood activities in landslide-threatened areas of Sichuan Province, China, to effectively reduce their livelihood vulnerabilities. Rural households in developing countries, particularly those living in mountainous areas, are highly dependent on natural resources. The agrarian economy tends to experience more intensive exploitation of natural resources and direct losses from climate change-induced disasters than the other sectors of the economy [8,16,48].Bera et al. [38] and Kumar &Bhattacharya [42] deduced from their investigations that landslide vulnerability was more pronounced in Indian Himalayas owing to high concentration of population among all mountain areas of the globe. The intensity and magnitude of landslides have caused ecological, socio-economic, and political implications for local communities. Every year, the district suffers enormous losses of life, economy, infrastructure, resources, and utilities, rendering it one of the most vulnerable landslide areas in the north-west Indian Himalayan region. This finding is in line with Central Ground Water Board [58] and SDMA [63].

The analysis of composite vulnerability to landslide in the study area revealed that the villages are highly impacted by landslides and the effects are magnified due to the prevalence of poor housing conditions, climate change induced environmental vulnerability and negligible adaptation (Table 11). Most of the sampled households located along the unpaved road connectivity posed serious challenges for transportation to nearby healthcare services and emergency centers. The respondents also disclosed that they were primarily dependent on their own agricultural produce to meet their daily meal requirements. However, despite experiencing recurrent landslides, a considerable number of households in Shakrori, Sarahan, and Bahlun villages preferred not to relinquish their lands due to their cultural roots and deprived socio-economic status. Other respondents expressed their desire to relocate to a different area while maintaining their ancestral property for agricultural and horticultural activities. It is evident that the strong sense of community and cultural ties in these villages play a significant role in the residents' decision-making process. Their commitment to maintaining their agricultural traditions and way of life outweighs the potential benefits of relocating to a safer area. We also observed that those who were willing to relocate have insufficient resources and land elsewhere, rendering staying in their present community the most practical option for them. Without access to adequate resources and opportunities for relocation, inhabitants are left with limited opportunities for improving their situation. This increased vulnerability to natural disasters and economic hardships has created a cycle of poverty and insecurity within the community. These findings are in tune with Subasinghe & Kawasaki [2] and Pham et al. [48] who found that climate change-induced disasters such as landslides have adversely impacted the socio-economic status of moun-

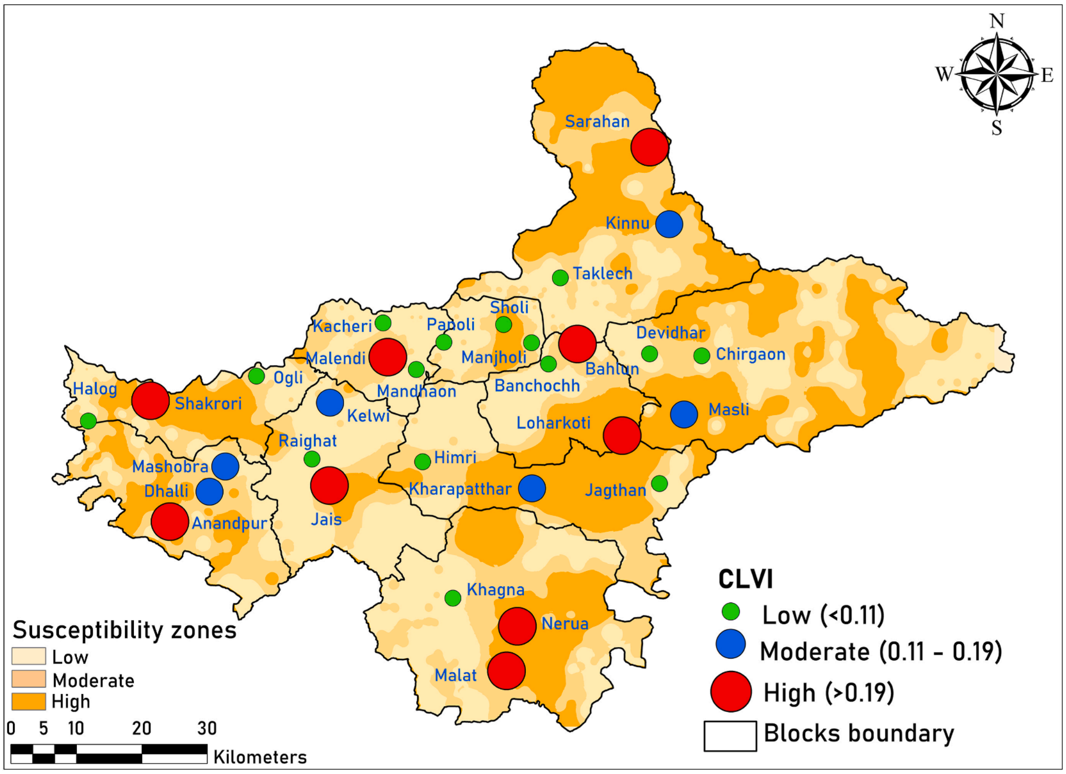

Fig. 4. Composite landslide vulnerability in sampled villages. Source: Prepared by author

tainous communities in Vietnam. Bera et al. [33] highlighted the necessity of addressing socio-economic disparities in disaster risk reduction efforts to improve society's resilience to landslide disasters. The domain-wise analysis indicated that the economic conditions need to be improved in Shakrori, Halog, Sarahan, Kinnu, Taklech, and Malendi villages. Provisions should be made to strengthen the education sector, microfinance services, electrification, and road connectivity to stimulate economic growth [4,13]. Since the average income of the respondents is meagre and their earnings are primarily agriculture-based, promoting livelihood diversification becomes of paramount importance for social welfare. The focus should be laid on providing vocational training, technology, and infrastructure support to enhance productivity in primary sector activities. This could help in preventing excessive debt accumulation.

Inadequate financial resources hindered the ability to implement necessary infrastructure improvements and disaster preparedness measures in terms of stability. Recent literature has found the negative relationship between income and physical vulnerability, with those of lower income implying increased vulnerability to landslides [2,15,39]. Fig. 5 shows the physical exposure of the sampled households to different landslide susceptible villages located in the study area. The majority of houses in the sampled households were built on steep slopes and used mortar and burnt bricks as walls and pathal (baked clay) for the roof construction in the fragile Himalayan areas. In the study area, frequent landslides and earthquakes have occurred in the past, leading to large cracks in the houses made up of mud and non-resistant roofs that require urgent repairs. Many residents in Sarahan, Kinnu, Taklech, and Shakrori villages have reported devastation to farmlands, uprooted apple trees on hillsides, and regular land sinking during rains. Besides the asset loss and damage, the rapid growth of hydropower projects has further disrupted the natural equilibrium of mountainous areas, leading to increased occurrences of landslides. Extensive excavation, blasting, and drilling activities have disturbed the geological structure, created loose debris, and weakened the slopes in already vulnerable areas [28,60]. The unscientific faulty house designs and lack of proper land-use planning have threatened safety and livelihoods as they grapple with the impacts of destabilized terrain and increased landslide risks [2,35,36,38,49,72]. A reduction in physical vulnerability is required in the villages of Shakrori, Malat, Nerua, Jais, Kelwi, Sarahan, Kinnu, Malendi, Manjholi, Kharapatthar, Loharkoti, and Bahlun. The Himalayas are a young, new fold mountain orogeny not suitable for non-engineered house structures and excessive developmental activities. It requires site-specific slope restoration techniques for mitigating soil erosion and landslides.

Nasiri & Hajiazizi [73] recommended that sandy soils, geotextile-encased stone columns, and concrete piles are the most appropriate strategies to improve slope stability. Maerz et al. [67] explored how cable and mesh, dowels, benches, anchors, catch ditches, scaling and trimming, shotcrete, bolts, and controlled blasting can effectively mitigate the landslide hazard. A study by Sharma et al. [74] on Kotropi Landslide in Himachal Pradesh, India, found that helical soil nails, retaining walls, and rock bolts would prevent the movement of soil and debris effectively for mitigating landslides. Shukla et al. [75] examined the stability-enhancing characteristics of geosynthetic-reinforced slopes for holding the soil mass on the failure surface and thereby increasing slope safety. However, this would require heavy capital investment, manpower, and technical knowledge [3]. Implementing cost-effective measures such as con-

Table 9
Indices of indicators used for assessing composite landslide vulnerability.

Village	Social Vulnerability Index	Economic Vulnerability Index	Physical Vulnerability Index	Climate and Environmental Vulnerability Index	Early Warning System Index	Emergency Response System Index	Adaptation Strategies index	Composite landslide Vulnerability Index
Shakrori	0.45	0.57	0.69	0.48	0.03	0.11	0.09	0.28
Ogli	0.34	0.40	0.36	0.46	0.31	0.29	0.62	0.05
Halog	0.32	0.36	0.28	0.34	0.25	0.19	0.23	0.09
Anandpur	0.40	0.24	0.37	0.69	0.10	0.09	0.10	0.20
Dhalli	0.28	0.27	0.38	0.47	0.07	0.11	0.31	0.13
Mashobra	0.38	0.19	0.34	0.63	0.07	0.11	0.10	0.18
Malat	0.20	0.43	0.63	0.52	0.07	0.14	0.07	0.21
Nerua	0.30	0.21	0.70	0.62	0.12	0.08	0.11	0.22
Khagna	0.19	0.27	0.36	0.53	0.36	0.25	0.32	0.06
Jais	0.26	0.23	0.55	0.65	0.09	0.06	0.12	0.20
Kelwi	0.38	0.33	0.50	0.34	0.18	0.11	0.27	0.14
Raighat	0.17	0.27	0.43	0.47	0.07	0.23	0.56	0.07
Masli	0.37	0.32	0.42	0.57	0.28	0.28	0.15	0.14
Chirgaon	0.11	0.28	0.29	0.56	0.46	0.22	0.10	0.07
Devidhar	0.10	0.43	0.30	0.61	0.37	0.31	0.40	0.05
Sarahan	0.39	0.75	0.56	0.65	0.06	0.12	0.26	0.27
Kinnu	0.28	0.52	0.58	0.53	0.07	0.11	0.41	0.19
Taklech	0.28	0.66	0.21	0.45	0.43	0.32	0.21	0.09
Malendi	0.18	0.57	0.81	0.50	0.17	0.19	0.15	0.22
Kacheri	0.13	0.24	0.27	0.61	0.15	0.39	0.41	0.04
Mandhaon	0.11	0.41	0.23	0.56	0.24	0.34	0.38	0.05
Sholi	0.26	0.22	0.33	0.43	0.18	0.47	0.10	0.07
Manjholi	0.22	0.24	0.63	0.39	0.17	0.43	0.36	0.07
Panoli	0.15	0.21	0.19	0.43	0.13	0.43	0.06	0.05
Kharapatthar	0.16	0.45	0.53	0.46	0.10	0.11	0.26	0.16
Himri	0.13	0.39	0.22	0.45	0.16	0.23	0.28	0.07
Jagthan	0.03	0.25	0.20	0.48	0.04	0.19	0.36	0.05
Loharkoti	0.39	0.26	0.71	0.67	0.07	0.13	0.08	0.25
Bahlun	0.33	0.14	0.74	0.56	0.12	0.08	0.15	0.20
Banchochh	0.22	0.22	0.31	0.45	0.24	0.43	0.28	0.04

Sources: Based on field survey and authors own calculation

Table 10
Multiple linear regression analysis between composite vulnerability index and its domains.

Index	β (Regression Coefficient)	R^2
Social Vulnerability Index	0.166[a]	0.838
Economic Vulnerability Index	0.241[a]	0.709
Physical Vulnerability Index	0.316[a]	0.899
Climate Change and Environmental Vulnerability Index	0.153[a]	0.805
Early Warning System	−0.237	0.037
Emergency Response System	−0.237	0.155
Adaptation Index	−0.244	0.180

[a] ** Significant at 0.01 level of significance, *Significant at 0.05 level of significance.

struction on stable ground, using durable designs, and reinforced concrete construction can significantly improve the structural strength of dwellings. Though several guidelines have been promulgated by the government for sustainable construction, the availability of skilled construction workers continues to be an issue. Thus, formal training of construction workers, retrofitting construction that meets seismic safety protocols, and re-construction work need to be implemented.

The evolving trends in climate and weather conditions have significantly impacted vulnerability by introducing new and heterogeneous challenges to socio-economic systems. Discussion with the respondents revealed that the increasing rainfall intensity, frequent landslides in the last 10 years, and increasing temperature during the summer season have exacerbated climate and environmental vulnerability. Rainfall induced landslides have triggered ecological disturbances in the form of soil degradation and depletion of surface water quality. This problem is acute in Anandpur, Jais, Sarahan, and Loharkoti villages. The findings are in line with those of Manandhar et al. [70]. Their vulnerability analysis found that rainfall was the most significant triggering factor for landslides and urgent measures should be implemented to mitigate the impacts of climate change and environmental degradation on the landslide-affected communities. During the survey, it became evident that the immediate neighborhood, local panchayat (local governance body), and self-help groups are major sources for disseminating meaningful and timely information in Chirgaon, Taklech, Devidhar, and Khagna villages. However, in some villages located at higher elevations, the people's understanding of an early warning system

Table 11
Prioritization of thematic areas for vulnerability reduction in Shimla district.

Village	Social Vulnerability Index	Economic Vulnerability Index	Physical Vulnerability Index	Climate change and Environmental Vulnerability Index	Early warning system Index	Emergency Response System Index	Adaptation Strategies Index
Shakrori	–	✓	✓	✓	✓	✓	✓
Ogli	–	–	–	✓	–	–	–
Halog	–	✓	–	–	–	✓	–
Anandpur	–	–	–	✓	✓	✓	✓
Dhalli	–	–	–	✓	✓	✓	–
Mashobra	–	–	–	✓	✓	✓	✓
Malat	–	–	✓	✓	✓	✓	✓
Nerua	–	–	✓	✓	✓	✓	✓
Khagna	–	–	–	✓	–	–	–
Jais	–	–	✓	✓	✓	✓	✓
Kelwi	–	–	✓	–	✓	✓	–
Raighat	–	–	–	✓	✓	–	–
Masli	–	–	–	✓	–	–	✓
Chirgaon	–	–	–	✓	–	–	✓
Devidhar	–	–	–	✓	–	–	–
Sarahan	–	✓	✓	✓	✓	✓	–
Kinnu	–	✓	✓	✓	✓	✓	–
Taklech	–	✓	–	–	–	–	–
Malendi	–	✓	✓	✓	✓	✓	✓
Kacheri	–	–	–	✓	✓	–	–
Mandhaon	–	–	–	✓	–	–	–
Sholi	–	–	–	✓	✓	–	✓
Manjholi	–	–	✓	–	✓	–	–
Panoli	–	–	–	✓	✓	–	✓
Kharapatthar	–	–	✓	✓	✓	✓	–
Himri	–	–	–	✓	✓	–	–
Jagthan	–	–	–	✓	✓	✓	–
Loharkoti	–	–	✓	✓	✓	✓	✓
Bahlun	–	–	✓	✓	✓	✓	✓
Banchochh	–	–	–	✓	–	–	–

Sources: Based on field survey and authors own calculation

seems lacking due to the absence of responsible authorities. Level of early warning system and emergency response system must be enhanced in Shakrori, Anandpur, Mashobra, Malat, Nerua, Jais, Malendi, Loharkoti, and Bahlun villages. Reliable weather forecasting, automated alert systems, placement and maintenance of warning symbol hoarding are of paramount importance for enhancing early warning systems. Detailed inventory maps and comprehensive evaluation of hazard can effectively contribute in landslide preparedness planning and newer constructions. It is apparent that the existing early warning and emergency response systems are in the developing stage and require more attention and resources in these remote areas to ensure that all communities are adequately prepared for natural disasters. Dias et al. [43] and Mohanty et al. [54] discussed the importance of effective early warning systems and community engagement in making landslide resilient society. Research emphasizes the significance of telecommunication technologies in advancing communication and dissemination systems for better early warning [51,57].

In this complex human-environment system, villages are often intertwined not only in terms of their social, economic, physical, climate change and environmental vulnerability but also in their adaptation strategies. The adaptative capacity of the sampled households were based on their structural, social, and institutional strategies to mitigate landslide risk. In the study area, low adoption of insurance schemes, limited livelihood opportunities, absence of retrofit buildings, and less participation in soil management techniques were found major challenges in highly vulnerable villages. The finding is in line with the studies which have also reported social capital and single livelihood strategy as major driver of low adaptation [13,48,68]. The local administration and non-government organizations (NGOs) need to focus on capacity building and training about impending disasters among the masses. The gap found in the adaptation strategies outlined the necessity for saving money, adequate insurance coverage, first aid training, well-documented community contingency plans, reforestation, and storing foodgrains to cope with climate change induced landslides. Strong intracommunity cooperation can significantly aid in awareness-raising programs, emergency situations and planning purposes. Similar findings were reported by Rana et al. [56] and Ullah et al. [51]. Thus, the formulation of a comprehensive vulnerability reduction framework necessitates a bottom-up approach for mitigating landslides. It may enable local authorities and disaster management experts to gain comprehensive understanding into the socio-economic vulnerabilities of the households, thereby empowering them to devise more effective solutions. This methodology is not simply restricted to the study of landslide vulnerability but can be broadened to encompass a wide variety of catastrophes.

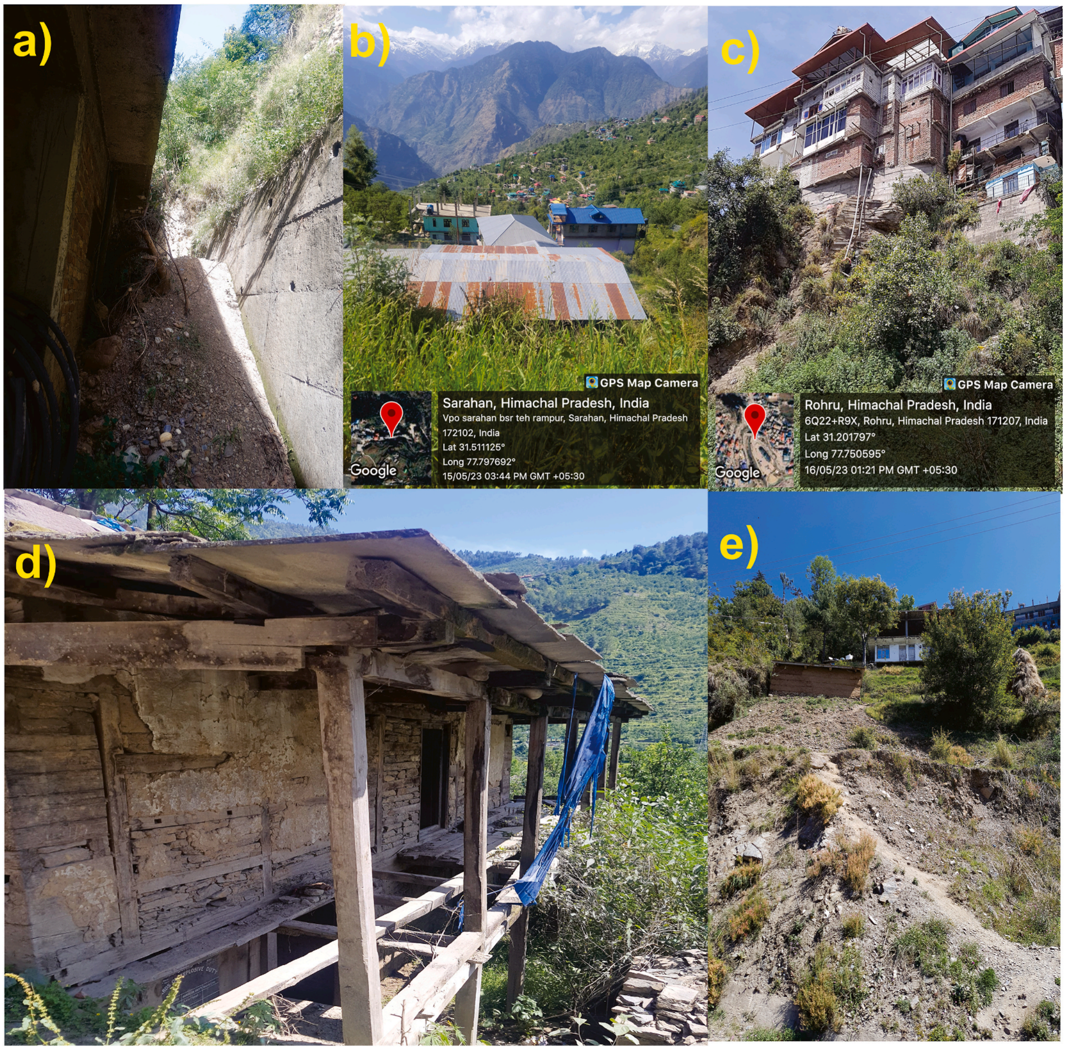

Fig. 5. Physical vulnerability of surveyed households: (a) significant damage at the backyard of a house in Shakrori village (b) metal sheet roof corrosion in Sarahan village (c) multiple flooring systems in the highly susceptible village of Loharkoti (d) poor housing structure in Dhalli (e) houses located on steep terrain in Banchochh village. Source: Photographs clicked during the field visit

6. Conclusion

Household-level assessment on landslide vulnerability worked effectively for making a holistic perspective of social, economic, climate change and environmental, and physical dimensions of the local communities. An improvement in the vulnerability analysis was made by integrating additional dimensions, namely early warning systems and emergency response systems to construct composite index. It elucidated the complex drivers to examine preparedness and response mechanism of local authorities and communities. There have been wide variations in the level of vulnerability and its domains of the sampled households. Overall, the sampled households experienced high and moderate vulnerability. Of the total sampled villages, Shakrori, Sarahan, Loharkoti, Nerua, Malendi, Malat, Anandpur, Jais, and Bahlun villages had high landslide vulnerability. These villages were identified at a higher risk of being negatively impacted by climate variability, physical dimension, economic vulnerability, and low adaptation. Moderate vulnerability was found in Kinnu Mashobra, Kharapatthar, Kelwi, Masli and Dhalli villages. Comparatively, these villages had high social vulnerability, low early warning system, and low emergency response system. Low vulnerability was found in Halog, Taklech, Raighat, Chirgaon, Sholi, Manjholi, Himri, Khagna, Ogli, Devidhar, Mandhaon, Panoli, Jagthan, Kacheri, and Banchochh villages due to better performance of domains and adaptation capacity. Regression analysis between composite landslide vulnerability index and its domains demonstrated that physical and economic vulnerability were the most influential domains affecting landslide vulnerability. The evolution of the methodology utilized for vulnerability assessment is limited to the index method, geospatial techniques and regression analysis. The index-based approach is widely embraced due to its ability to visualize and simplify complex indicators. However, the study has few limitations. One of the major limitations of the study was the lack of past damaged data of the houses and fatalities. This has hindered the ability to understand the severity of past landslide events and accurately examine vulnerability. While there are indicators concerned with housing conditions (e.g., "house located on a steep slope," "house made up of mud"), vulnerabilities specific to temporary houses of seasonal migrants could not be included.

Thus, the study calls for timely interventions for reducing vulnerability and enhancing adaptation strategies. This study revealed that household-based adaptation measures have yet to be implemented to lessen the impact of landslide vulnerability effectively. Provision of regular structural safety should be given higher priority and should be covered under the Indian Standard code of practice for resilient house design. It is imperative for the government to promote sustainable land management practices, retaining wall support and infrastructural development in slope failure areas. Raising awareness, conducting drills, and access to reliable communication channels for receiving timely alerts along the active sites and at remote locations can help to reduce landslide vulnerability. The CLVI, as a powerful tool, has not only identified the vulnerable villages but also recognized thematic areas where efforts could be made to reduce vulnerability. CLVI has proved an effective policy tool for assessing relative landslide vulnerability among communities. Thus, the methodology used in this study may assist in the future progression of vulnerability analysis for different mountainous environments at varied scales. In continuation of the research carried out a more effective quantitative model can be constructed by including past damaged data of the houses and fatalities. Slope stability analysis should also be work on vulnerability assessment. Future studies should also be focused on multi-hazards perception for effective vulnerability management.

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CRediT authorship contribution statement

Aastha Sharma: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haroon Sajjad:** Writing – review & editing, Supervision, Conceptualization. **Nirsobha Bhuyan:** Investigation, Formal analysis. **Md Hibjur Rahaman:** Visualization. **Rayees Ali:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2024.104657.

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