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GEOLOGICAL AND SOCIO-ECONOMIC VULNERABILITY ASSESSMENT OF GILGIT AND SURROUNDING AREAS, GILGIT-BALTISTAN, PAKISTAN: AN INTEGRATED APPLICATION OF PARTICIPATORY VULNERABILITY ANALYSIS AND DIGITAL ELEVATION MODELING

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Abstract
This study examines the geological and socio-economic vulnerability to earthquakes in Gilgit and its surrounding areas within the Gilgit-Baltistan province. Geological vulnerability indicators include floods, landslides, avalanches, rockfalls, and debris flows, while socio-economic vulnerability is assessed through indicators such as population distribution, housing, educational institutions, industrial activity, tourism, and health facilities. A Participatory Vulnerability Analysis (PVA) approach was employed to conduct field surveys, with a particular focus on community-level and developed infrastructure. Geospatial datasets, including a 30-m resolution Digital Elevation Model (DEM), supervised land-use and land-cover classification derived from Sentinel satellite imagery with 10-m resolution, and administrative boundary maps, were utilized to support spatial analysis of the field data. Relative risk (RR) values were calculated to assess population and infrastructure exposure to earthquake hazards. The findings indicate that areas with high population and infrastructure density are predominantly located in close proximity to geologically hazard-prone mountainous zones associated with major seismic activity, thereby posing significant risks to human life and socio-economic activities. The most densely populated regions are situated in the central, northern, and southern parts of the study area, which also encompass some of the highest mountain ranges. Overall, the study concludes that both the population and infrastructure of the investigated area face a heightened level of risk from high-magnitude earthquakes (≥6.3), driven by persistent seismic activity in the region.

INTRODUCTION

The Gilgit-Baltistan (GB) province of Northern Pakistan lies among the mighty mountains of the Karakoram and Himalayas (Mehdi, 2019) (Figure 1)

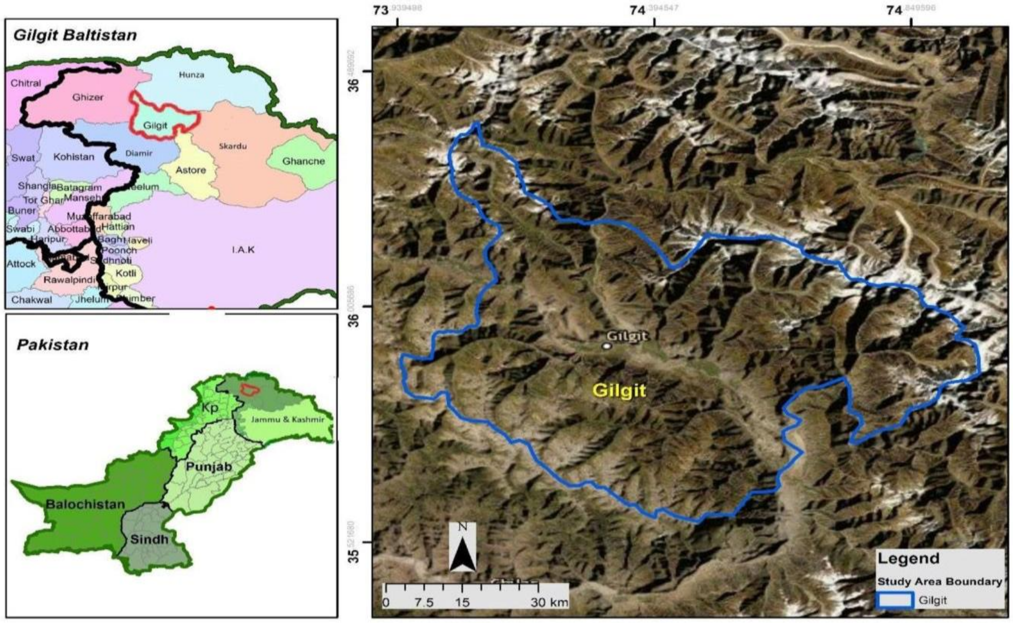

Figure 1. Location map of the study area. The Gilgit-Baltistan (GB) province of Northern Pakistan lies among the mighty mountains of the Karakoram and Himalayas. GB lies in the major earthquake zone, having a history of earthquakes with magnitudes ≥6.5 on the Richter scale (Mehdi, 2019).

GB lies in the major earthquake zone, having a history of earthquakes with magnitudes ≥6.5 on the Richter scale (Mehdi, 2019). Many fault lines are passing through GB, such as the Main Karakoram Thrust (MKT) (Mehdi, 2016) and the Main Mantle Thrust (Tahirkheli et al., 1979), originating in the Himalayan arc, making its population and infrastructure vulnerable to natural hazards. The Gilgit earthquake in 2002 of ≥ 6.2 magnitude, the Kashmir earthquake 2005 of ≥ 7.6 magnitude are the examples of recent seismic activities in Northern Pakistan (Owen et al., 2008; Mahmood et al., 2015; Bhattacharya, 2015). These earthquakes caused large-scale disasters in terms of human mortality, damage to infrastructure, landslides, debris flow, mountain displacement and riverbank erosion and so forth (Sato et al., 2007; Bhattacharya, 2015; Mahmood et al., 2015).

The Gilgit city is the provincial Headquarters providing high-quality services to the inhabitants like road network, infrastructure, housing, and health and education. High population density and extensive infrastructures make cities more vulnerable to natural hazards such as earthquakes (Armas, 2012). Gilgit has remained vulnerable to geological and socio-economic damage because of seismic activities in the past. As such, in the earthquake of 2002, they reported 40 fatalities, with 30 people injured and 1500 people being left homeless. In the Kashmir earthquake of 2005, with 978 aftershocks, 80,000 fatalities were reported, with 200,000 people injured and 4 million people being left homeless in Northern Pakistan, including Gilgit (Bhattacharya, 2015; Mahmood et al., 2015). Other notable earthquakes in Gilgit are the earthquakes of Astore (mb 6.1) in the year 2003 and Batgram (mb 5.3 and mb 5.5) in the year 2004, which caused considerable damage to infrastructure and loss of life.

The GB has also remained vulnerable to several hydro-meteorological hazards (Shah et al., 2019). The geological evidence from the past shows that different landslides at different scales have been occurring frequently in the region because of seismic activities for thousands of years (Kausar et al., 2012. Multi-hazard analysis of Qurumber valley in GB shows the valley is at risk of glacial lake outburst floods, bank erosion, debris flows, ice avalanches and rockfall. It was found that earthquake was the major hazard in the Qurumber valley, while other hazards were found to be the consequences of seismic activities (Shah et al., 2019). Several researchers have discussed the vulnerability of GB from different perspectives (c.f., Jackson and Yielding, 1983; Usman et al., 2011; Kausar et al., 2012; Waseem et al., 2018; Shah et al., 2019). However, the geological and socio-economic vulnerability because of seismic activities in the Gilgit and the surrounding areas has not been discussed in the past. The present research addresses the grounded theory approach (c.f., Wegmann, 2020; Bahadori et al., 2017; Armas, 2012). It provides in-depth analysis of earthquake induced hazards in Gilgit and the surrounding areas. It also aims to cater susceptibility, adaptability and coping capacity and assessing relative risks to the population and infrastructure in relation to the disaster exposure.

SEISMOTECTONIC SETTING OF THE AREA

The Gilgit area comprises Kohistan-Ladakh magmatic arc sandwiched between the Karakoram-micro continental plate in the north and the Indian continental plate in the south (Tahirkheli et al., 1979). The area lies over seismically active fault lines, which makes the population susceptible to earthquakes hazards (Kazmi and Jan, 1997). Major faults from north to south include (1) Main Karakoram Thrust (MKT), (2) Main Mantle Thrust (MMT), (3) Main Central Thrust (MCT), (4) Main Boundary Thrust (MBT) and (5) Salt Range Thrust (SRT) (Kazmi and Jan, 1997). The Gilgit area lies in between MKT and MMT, which are seismically active (Kazmi and Jan, 1997). The MKT represents the suture zone between the Kohistan island arc with the Karakoram micro-continental plate (Tahirkheli et al., 1979). The suture zone comprises volcanic rocks, gabbros, mélanges, and ophiolites of the Neo-Tethyan oceanic crust. The MMT is a tectonic boundary between the Kohistan island arc and the Indian continental plate (Tahirkheli et al., 1979). It is a suture zone that comprises mélanges and ophiolites of the Neo-Tethyan crust. There are also two Syntaxial bends, viz., Kashmir-Hazara and the Nanga Parbat (e.g., Shahzad et al., 2009). The movements along these Syntaxial bends cause seismic activity in this region. The most active faults in Gilgit area are the Raikot-Sassi and Stak faults (Masek et al. 1994; Searle et al., 1999; Treloar et al. 2000; Shahzad et al., 2009).

GEOLOGY OF THE AREA

The Kohistan island arc in the Gilgit area contains variably metamorphosed volcanic and sedimentary rocks, intruded by the Kohistan batholith, which is the main magmatic unit of the arc (Tahirkheli et al., 1979; Bard, 1983; Jan et al., l98l; Jan and Asif, 1983; Petterson and Windley, 1985). The main units exposed from south to north in the area include, the Chilas complex (gabbros, diorites, and ultramafics), Jaglot group (Gilgit formation, Gashu-confluence volcanics and the Thelichi formation) and the Chalt volcanics (Coward et al., 1987; Khan et al., 1994). Structurally, the Kohistan island arc has been folded and faulted, fractured and highly sheared. The region is intensely denudated and rapidly uplifting (Burbank et al., 1996). Frost shattering, chemical weathering by growth of salt crystals, glacial erosions, mass movement and fluvial incision are the main denudation processes occurring in this region (Goudie, 1984). Because of these processes, the immense quantities of fine sediments have been produced and deposited in the lacustrine environments.

DATA AND ANALYSIS

The Ployvinyl Alcohol Fibre (PVA) method has been used to assess earthquake in the study area. PVA shares the community information about facilities and vulnerability for making policies and its implementation (Chiwaka and Yates, 2004). Here, the same method is being employed to diagnose the vulnerability induced by seismic activity and the emergency preparedness, responses, mitigation and development work for existing or new strategies (c.f., Chiwaka and Yates, 2004). Likewise, the participatory based approach in vulnerability analysis has also been widely used and discussed in several studies (c.f., McCubbin et al., 2015; Wisner and College, 2016; Butler et al., 2015; Bennett et al., 2016; Bunce et al., 2010a, b; Mangi et al., 2007; Suckall et al., 2014). The participatory mapping approach has been found valuable for the vulnerability study of urban region (Beichler, 2015).

PVA is a seven-step method involving i) preparations for primary data collection, such as selecting the community for survey and facilitation team, management, timing and logistics; ii) collection of secondary data, such as what we really need to know and what is already available information; iii) community work, such as demographic composition, gender roles, existing organizations, government and private institutions, livelihood strategies and physical and natural resources available; iv) analyzing hazards, impacts of changing climate, community's vulnerability and resilience; v) risk prioritizing, such as analyzing and prioritizing assets which are at greatest risk of potential hazard; vi) developing an action plan for risk reduction, addressing the most important risks and causes of vulnerability and informing the community about plan implementation; vii) plan implementation, involving short-term and immediate actions for mitigation and risk reduction (c.f., Chiwaka and Yates, 2004). Shuttle Radar Topography Mission (SRTM) 30 m spatial resolution DEM has been used to show the elevation and mountainous topography of the Gilgit area. The Sentinel 10 m spatial resolution satellite imageries were processed by using cloud based Google Earth Engine (GEE) for making composite of imageries from 15 June to 31 August 2020 (this period was considered for having least snow cover in satellite imagery, as it makes easy to identify the land features). The mean was calculated from the composite imageries. The mean imagery was used to identify the land features in the Gilgit area such as forest, grassland/agricultural land, built up land, water features, snow cover, and shrub land/barren land.

The socio-economic (infrastructure)/geological (land) survey has been conducted for the Gilgit and the adjacent areas. Avalanches, debris flow, flood, rockfall, and landslide are considered as geological (land) indicators. The PVA survey focused on socio-economic indicators (community and developed infrastructure) such as population, houses, educational facilities, industry, tourism, and health facilities. The vulnerable regions/hot-spots having hazard exposure (i.e., earthquake) based on land characteristics (geological based) is shown on the boundary map of 43 villages of Gilgit and the surrounding areas. Mapping of the Gilgit city shows the vulnerability exposure/risk (i.e., earthquake). The data from the socio-economic vulnerability survey is used for calculating the Relative Risk Ratios (RR). The RR is the ratio of probability of absolute risk of events occurring in the treatment group (ART) to the probability of absolute risk of events in the control group (ARC) (Stare and Boulch, 2016), that is:

$$RR = \frac{ART}{ARC} \ldots (1)$$

The RR=1 denotes there is no vulnerability of the population/infrastructure due to hazard exposure (i.e., no noteworthy difference between ART and ARC), RR>1 denotes the high vulnerability of the population/infrastructure due to hazard exposure, and RR<1 denotes the low vulnerability of the population/infrastructure due to hazard exposure. The RR

as been widely used in the scientific studies of natural hazards (c.f., Zhou et al., 2015; Khalid et al., 2015; Liu et al., 2013; Hy and Pascal, 2004). The relative risk level provides quantitative evidence for decision making and planning for management and risk reduction (Hy and Pascal, 2004).

RESULTS

The fault lines in Northern Pakistan have been analyzed to show the geological vulnerability of Gilgit and the surrounding areas (Figure 2).

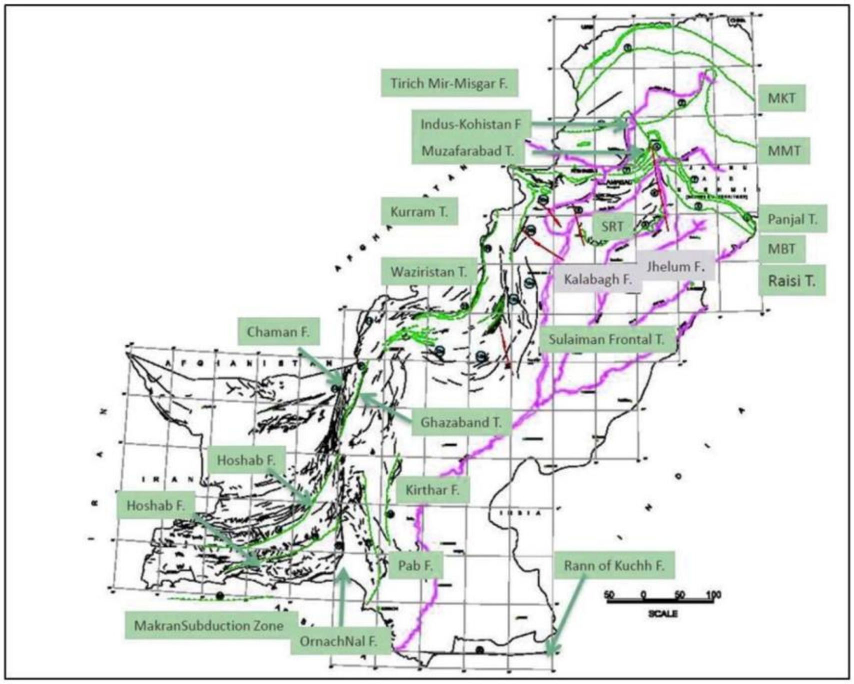

Figure 2. The fault lines in Northern Pakistan showing the geological vulnerability of Gilgit and the surrounding areas.

The GB region in the north can be seen as highlighted in green colors showing high vulnerability and severe damages because of earthquakes (Figure 3).

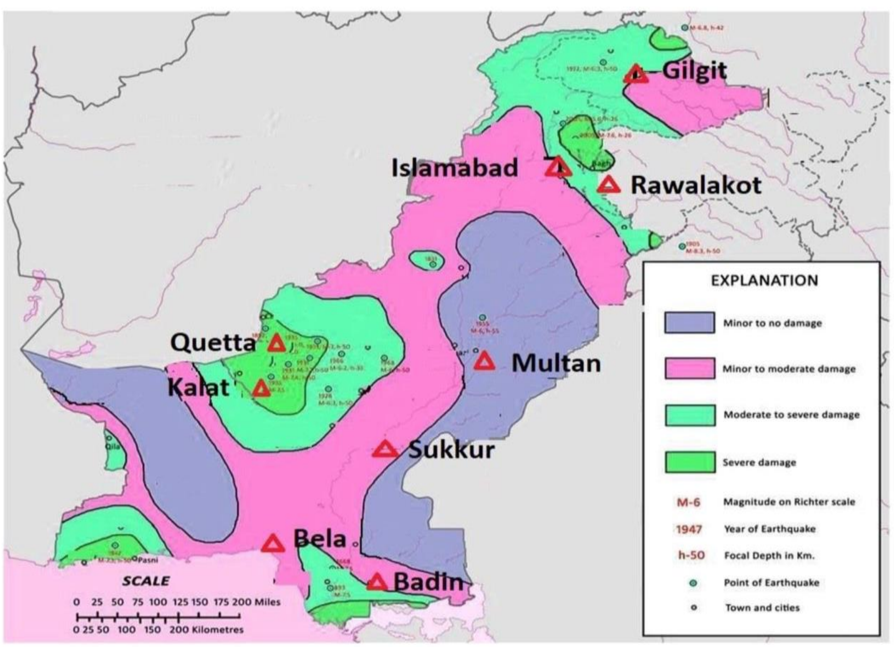

Figure 3. The GB region is showing high vulnerability and severe damage because of earthquakes in the north as highlighted in green color.

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The elevation and topography of Gilgit has been analyzed by processing DEM. The Gilgit area is shown in blue color lying in the middle of high mountain ranges (Figure 4)

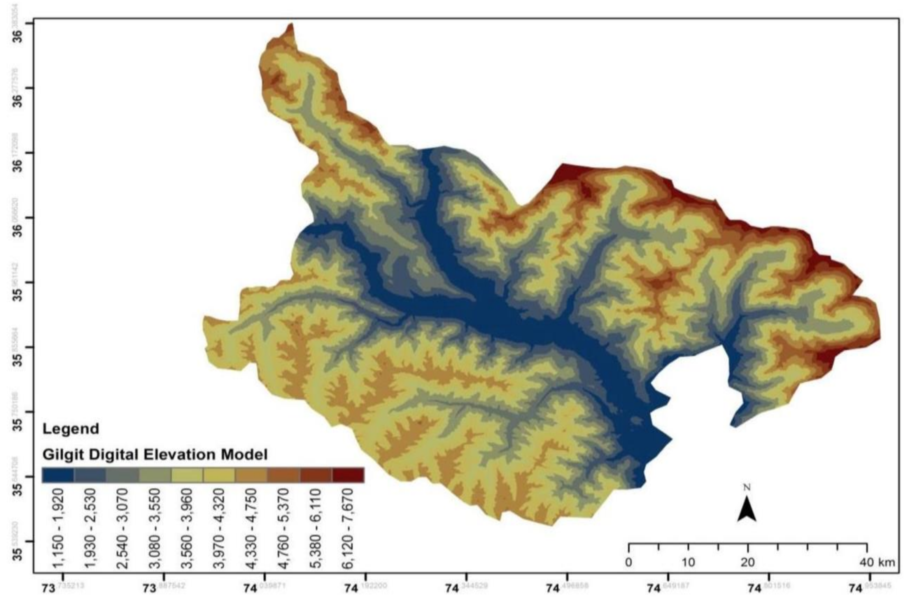


Figure 4. The DEM showing elevation and topography of the Gilgit and the surrounding areas. and the identified land features in figure 5. The forest cover is shown as dark green,grassland/agricultural area light green, brown color shows the built up area comprising urbanization and infrastructure which can be seen in the Gilgit valley lying in the middle of high mountains and the snow cover is shown in red, and shrub land/barren land as pink (Figure 5).

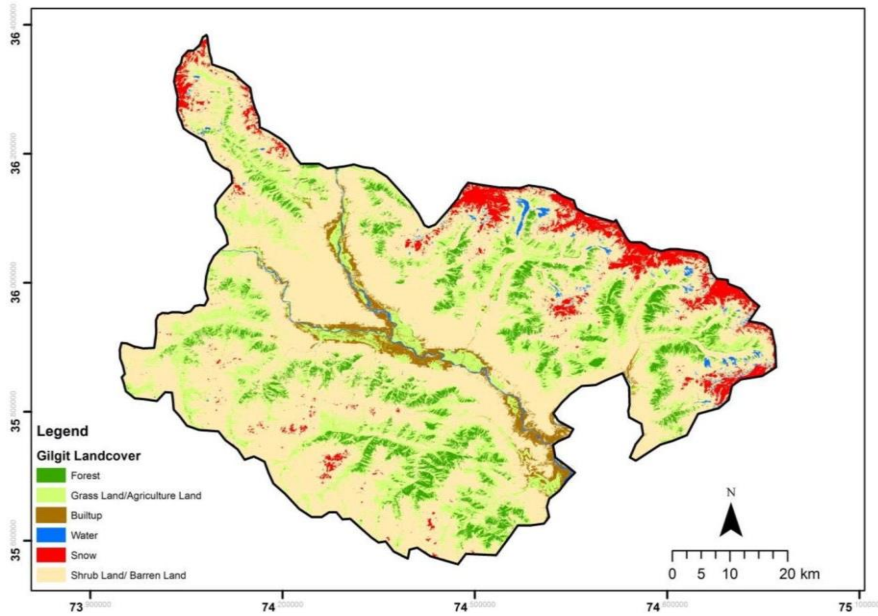


Figure 5. Land features of the Gilgit and the surrounding areas. The forest cover is shown as dark green, grassland/agricultural area light green, brown color shows the built up area comprising urbanization and infrastructure which can be seen in the Gilgit valley lying in the middle of high mountains and the snow cover is shown in red, and shrub land/barren land as pink.

Geological (land) vulnerability survey was conducted in the area of investigation. 43 villages were visited and found vulnerable to different disasters because of earthquakes. The villages of Gilgit area are shown in different colors highlighted according to the vulnerability to different hazards because of earthquakes (Figure 6). many villages are vulnerable to debris flow, floods, and rockfall, as shown in blue color; villages vulnerable to avalanches, debris flow, floods, and rock fall are light green; pink color shows the vulnerability to debris flow, flood, rockfall, and landslide; dark green shows the vulnerability to debris flow and rock fall; orange color shows the vulnerability to debris flow, rockfall, and landslide; yellow shows the vulnerability to floods only; and purple color shows the vulnerability to the rock fall only (Figure 6).

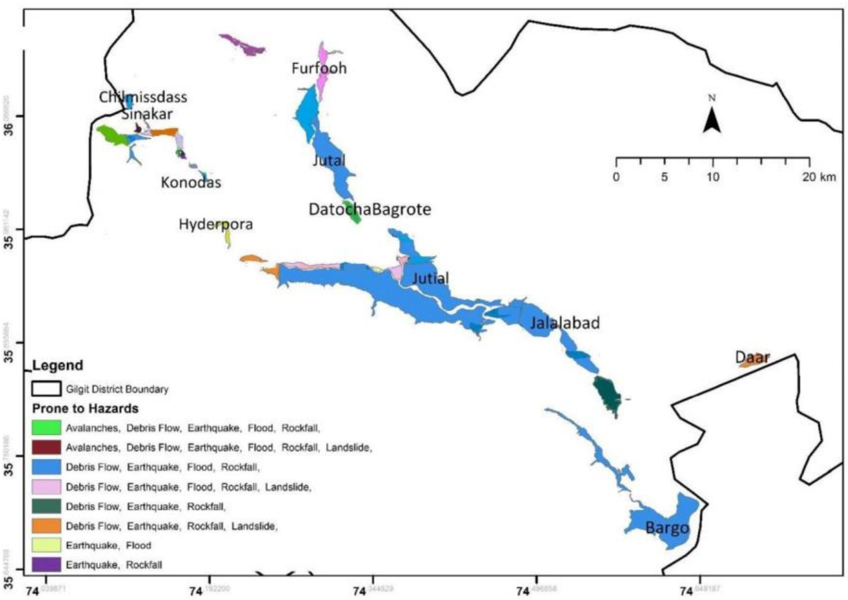


Figure 6. Geological vulnerability due to earthquake hazards. The villages of Gilgit area are shown in different colors highlighted according to the vulnerability to different hazards because of earthquakes The socio-economic vulnerability of infrastructure and population in the Gilgit area has also been analyzed. The human population density of the Gilgit is concentrated in the southern and western parts of the region (Figure 7 (a)).

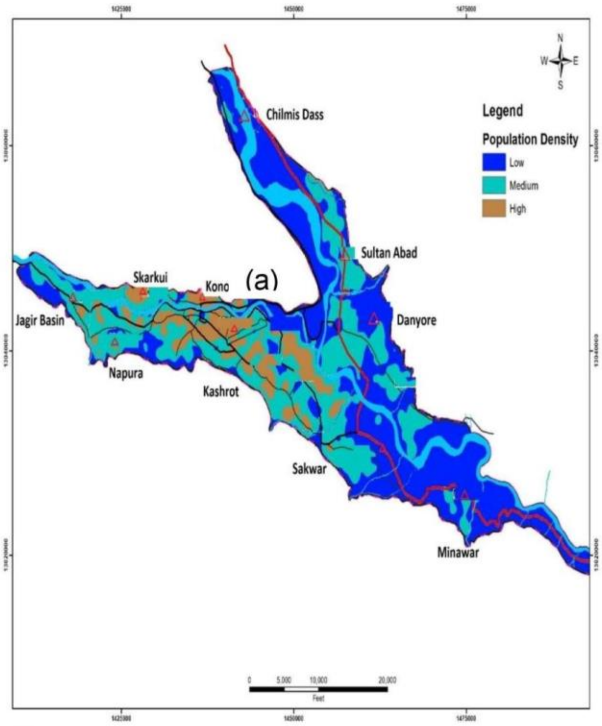


Figure 7a. Naseer et al., 2022

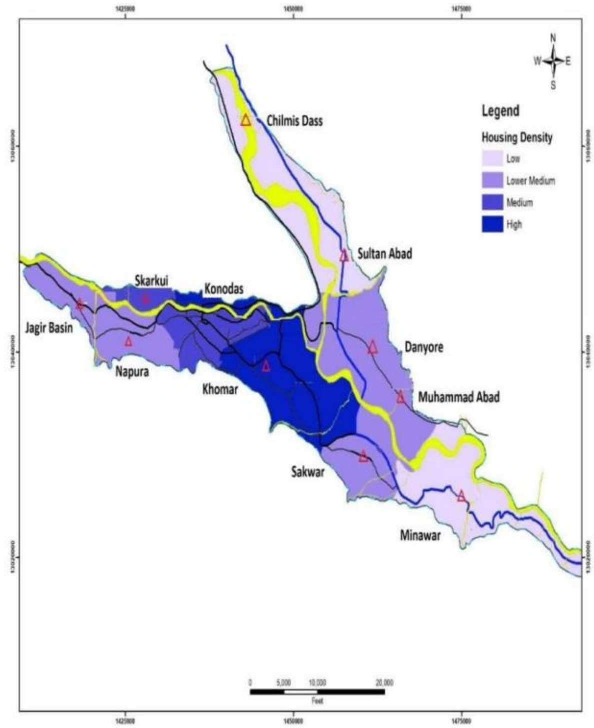


Figure 7b. Naseer et al., 2022

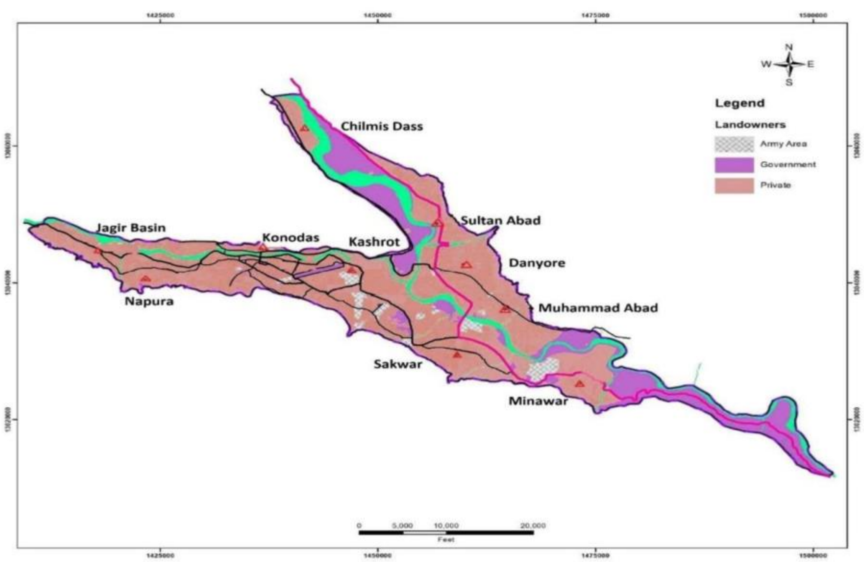


Figure 7. The maps showing a) population density. The human population density of the Gilgit is concentrated in the southern and western parts of the region. b) Housing density is concentrated in the southern and western part of the Gilgit as validating the human population density c) Land owners. The areas concentrated with human population and housing mostly maintained by private owners as shown in brown color, government-owned property areas are shown in purple color whereas they show military owned areas in black and white check.

Housing density is concentrated in the southern and western part of the Gilgit as validating the human population density (Figure 7 (a, b)). The areas concentrated with human population and housing mostly maintained by private owners as shown in brown color, government-owned property areas are shown in purple color whereas they show military owned areas in black and white check (Figure 7c). The land use map of the Gilgit area shows most of the urban/built up area (infrastructure) lies in the central northern, southern, and western regions (Figure 8a).

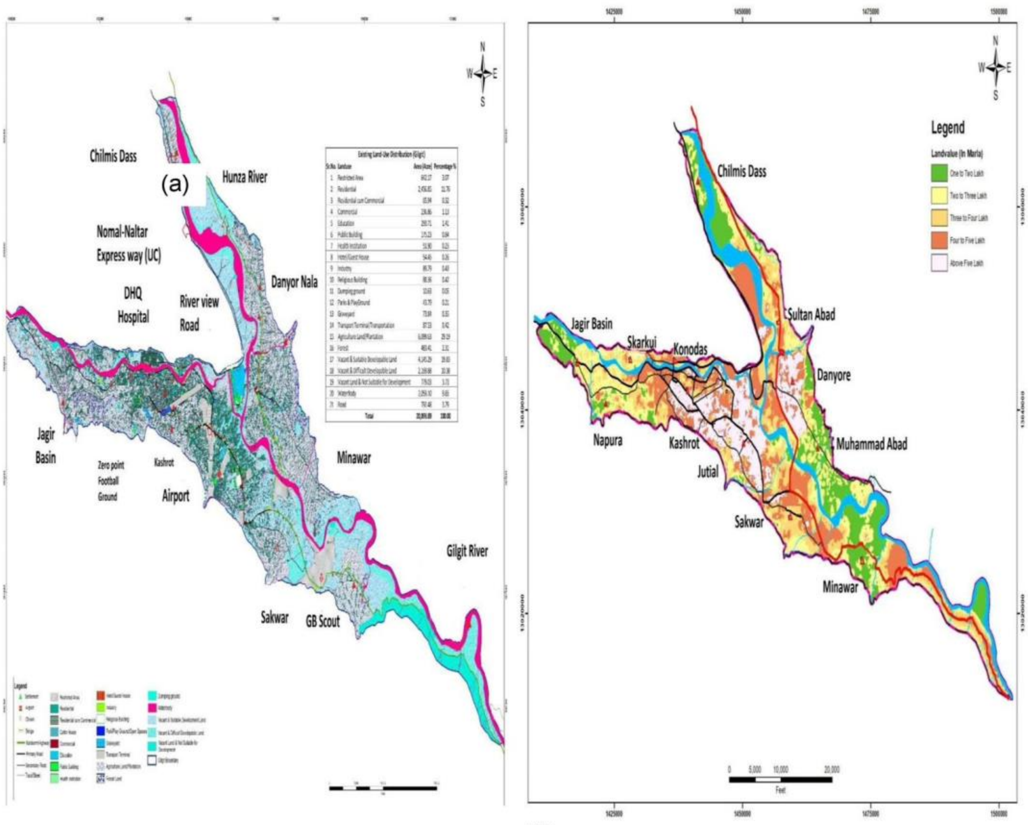


Figure 8. The maps showing a) The land use map of the Gilgit area shows most of the urban/built up area (infrastructure) lies in the central northern, southern, and western regions b) The land values in Gilgit are shown in Marla (a traditional standardized unit set by British rulers in the subcontinent to measure land) 1 Marla equals to 272.25 square feet) in Pakistani Rupee (PKR).

The land values in Gilgit are shown in Marla (a traditional standardized unit set by British rulers in the subcontinent to measure land) 1 Marla equals to 272.25 square feet) in Pakistani Rupee (PKR) are shown in figure 8b. The highest land value in PKR for 1 Marla is shown in white color, whereas variations in price are shown in different colors. The analysis of age, height and condition of buildings/infrastructures in Gilgit area are shown in the Figure 9 (a-c). The buildings/infrastructures aged since 1981-to date (including newly build infrastructure) are mostly concentrated in the central northern areas and are shown in shades of green. However, some of them can also be seen in the central southern to western parts. The height of the buildings shows infrastructure in figure 9b, illustrating that the construction is mostly single story throughout the area with a few double story buildings lying within the infrastructure. The condition of infrastructure is mostly good with sound structure and is shown in blue color in the Figure 9c.

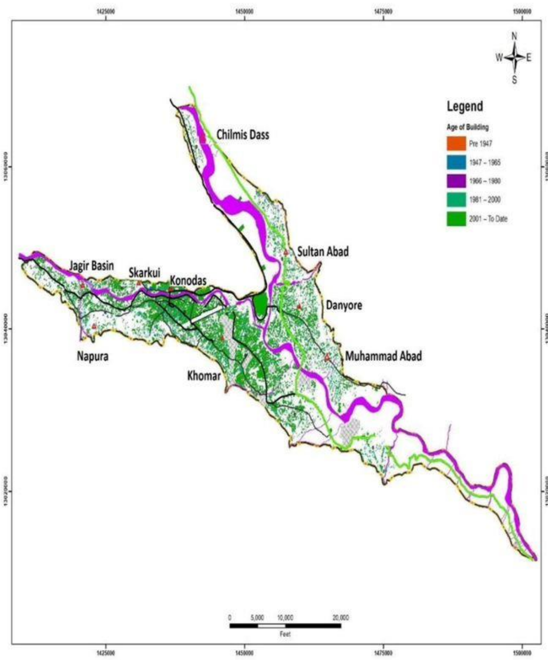


Figure 9a. Naseer et al., 2022

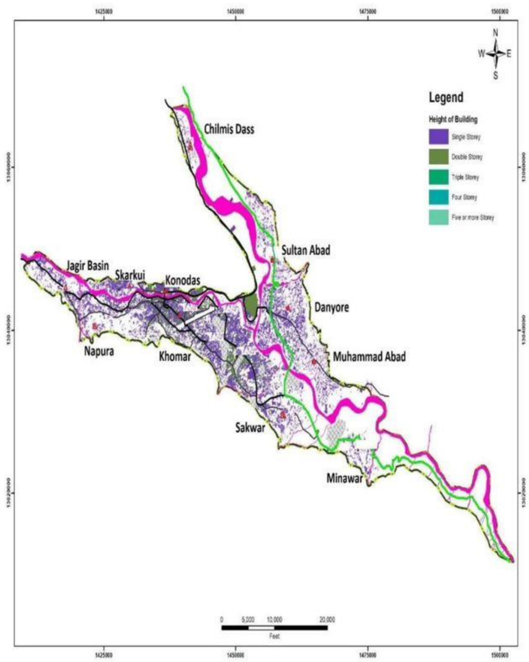


Figure 9b. Naseer et al., 2022

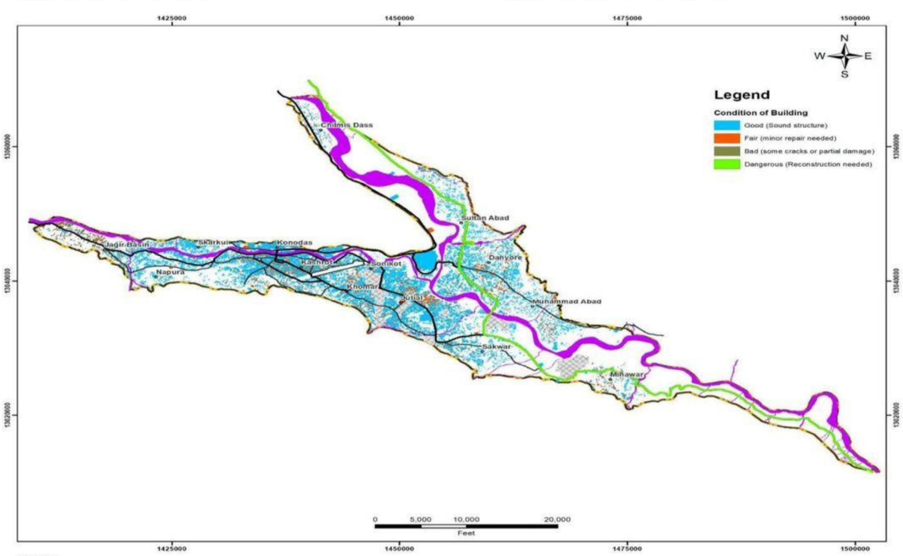


Figure 9. The maps showing a) age of buildings, b) height of buildings, and c) condition of buildings. The educational facilities, health facilities and industries are shown in Figure 10 (a-c).

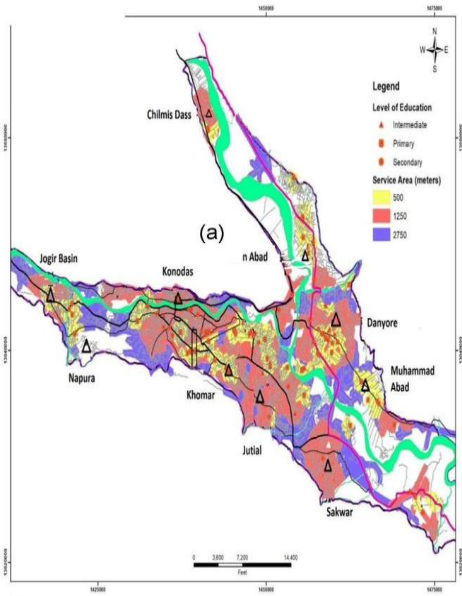


Figure 10a. Naseer et al., 2022

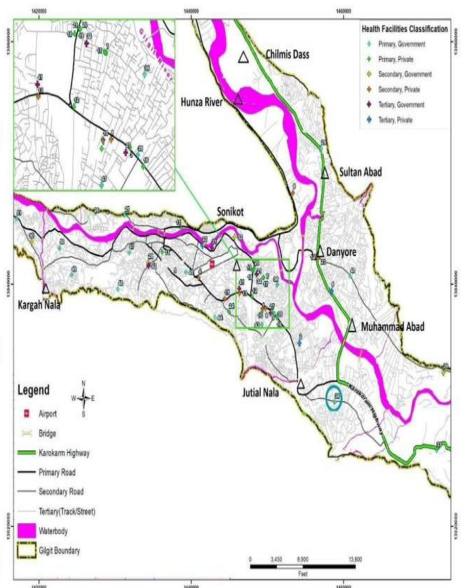
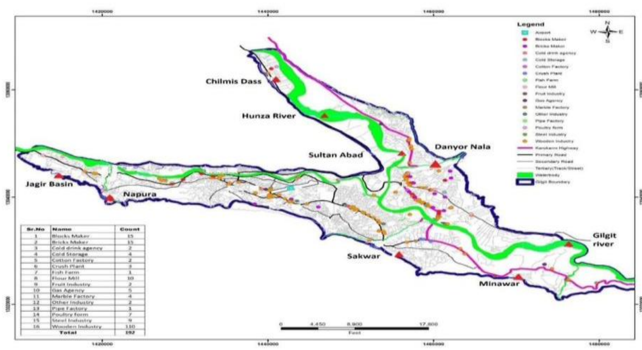


Figure 10b. Naseer et al., 2022



Sr.No	Name	Count
1	Blocks Maker	15
2	Bricks Maker	15
3	Cold drink agency	2
4	Cold Storage	4
5	Cotton Factory	2
6	Crush Plant	3
7	Fish Farm	1
8	Flour Mill	10
9	Fruit Industry	2
10	Gas Agency	5
11	Marble Factory	4
12	Other Industry	2
13	Pipe Factory	1
14	Poultry form	7
15	Steel Industry	9
16	Wooden Industry	110
	Total	192

Figure 10. The maps showing a) educational facilities b) health facilities, and c) Industries.

Most of these facilities lie with in the central southern to western parts. The recreational resorts are also in the high population density areas of southern and western parts area (Figure 11).

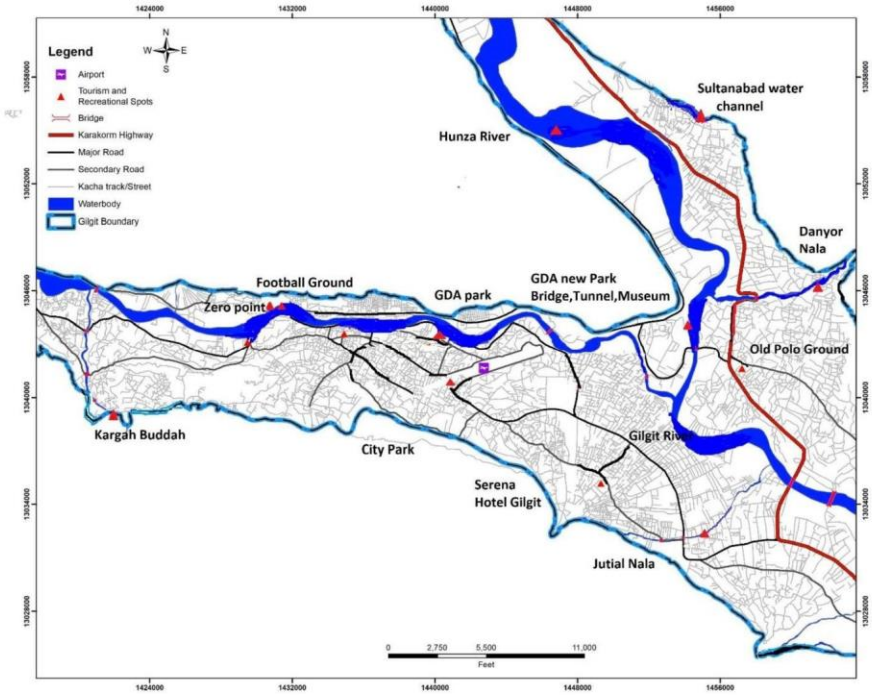


Figure 11. The recreational and touristic facilities in the study area. The recreational resorts are also in the high population density areas of southern and western parts area. For the population at risk to the geological/socio-economic hazards because of earthquakes in the Gilgit area, RR>1 (RR>1 particularly for children affected); whereas RR<1 for infrastructure at risk.

DISCUSSION

The GB experiences several natural and human induced hazards and risks endangering its population, land and economy and faces multiple hazards, threatening the livelihoods, ecosystems and infrastructure. Therefore, different geological hazards have been analyzed in this study in connection with the socio-economic vulnerability of population and infrastructure of the area. The geological hazards coupled with the tough terrain reduces the development potential of infrastructure and residential construction. According to Building Code of Pakistan (Seismic Provision 2007), Gilgit lies in a hyper active seismic zone and is regarded as Zone III of seismic danger with 0.24-0.32 g acceleration values. It lies in the immediate north and north-west of the Zone IV of seismic danger, having ≥0.32 g acceleration values (Figures 1-3). This area is divided in to nine seismic zones. All zones are active with the highest earthquake potential of Mw 7.5-8.0. The fault line MKT (shown in red line in the Northern Pakistan region) and also the MMT are passing through the GB region, categorized as zone 3 seismic area having peaked ground acceleration (PGA) of >0.24g that poses a great threat of earthquakes. The development potential and construction in this region is restricted by the seismic activity. However, most of the infrastructure is developed without seismic provisions for design of buildings (PEC and AKBSP, 2012). The topography and elevation map shows that high mountainous region surrounds the valley of Gilgit from all sides with elevation from 3000m to 5000m. The Gilgit city lies in the middle of the area and is shown in dark blue color having highest built up/urbanized cover of the land shown in the brown color (Figures 4-5). Grass and forest cover can be seen in the shades of green color however, most of the mountain region does not have any vegetation cover and are comprised of shrub/barren land. The villages with infrastructure and population are vulnerable to the geological hazards. The region shown in blue color is vulnerable to debris flow, flood, and rock fall because of earthquakes which covers a large area of the Gilgit area (Figure 6). The high population density and most of the infrastructure is in the central, southern, and western parts of the study area, near the mountainous region, posing a geological risk due to earthquakes. All private, government and army owned properties are equally prone to the socio-economic disasters because of geological hazard (caused by earthquakes) including debris flow, flood, and rock fall, landslides, and avalanches. Hence, the geological activities in the study region are exposing and endangering the population. Social vulnerability was found to be a consequence of the important exposure to the natural hazard, which is amplified by the risk levels in China (Zhou et al., 2015). Over one-third of the landslide activities because of earthquakes in the Himalayas have been observed occurring within 1 km from the active fault lines (Sato et al., 2007). The landslide has been reported because of earthquakes in several studies, especially due to devastating earthquakes of Mw 7.6 or higher (c.f., Mahmood et al., 2015; Ray et al., 2009; Sato et al., 2007). The complex terrain such as slope gradient, curvature, relief, and slope aspect were identified, contributing to the largest landslide because of HK earthquake of 2005 (Ray et al., 2009). Private owners are the residents of Gilgit area and are vulnerable to different geological/socio-economic hazards. The government owned property is in the south-eastern and north-western part of the study region is comparatively less vulnerable to the disasters (Figure 7 (a-c), 8 (a, b)).

The KKH passing through the Gilgit area is shown in pink colored line in (Figure 7c), highlights the importance of the study region being part of the China Pakistan Economic Corridor. The highest land values are also shown in the central and southern parts of the Gilgit area in orange and white colors. The southern parts shown in white color are having highest land value in terms of PKR but because of lying in the proximity to the mountainous region which is vulnerable to geological hazards because of earthquakes, this high value land is consequently prone to the socio-economic hazards. Most of the infrastructure/building were built after the year 2001 hence are in good condition and sound in structure, somehow preventing the high level of destruction due to earthquakes of low to medium magnitude. Similarly, the industries, education, health, and tourism facilities, as part of the bigger infrastructure of the area, the locations of these facilities are marked and presented. These facilities are concentrated in the high population density areas, i.e., central and southern parts of the Gilgit area, hence equally prone to the geological/socio-economic hazards because of earthquakes (Figures 9 (a-c), 10 (a-c), 11). The quality of the construction, level of maintenance and renewal, level of protection and adaptability (Eidsvig et al., 2017) quantifies the risk to the infrastructure due. The aged buildings and their proximity to the hazard prone areas were found to be highly vulnerable to the earthquake disasters in Bucharest, Romania. The spatial patterns of the city designed by the socio-economic conditions shape the vulnerability profile of the region (Armas, 2012).

5.1. Regional tectonics significance and future implications for regional natural hazards activities due to major earth quake events

Based on the exploratory research notes, our study reveals the geological and socio-economic vulnerability in the GB because of earthquakes of medium to high magnitude. Gilgit city and the surrounding areas are highly prone to the disasters because of earthquakes, since its complex topography limits the accessibility from the mainland. The complex topography also limits the adaptive capacity due to the location of the study region over the seismically active fault lines and earthquake zones, hence limiting the coping capacity as well. The vulnerability may result from the interaction between adaptive capacity, exposure, and sensitivity (Bennett et al., 2016). The RR shows that the population because of earthquake hazard is at higher risk as compared to the infrastructure in the Gilgit area.

CONCLUSIONS

The vulnerability emphasizes and focuses on the current characteristics or the historical factors of communities, individuals, households or infrastructure and so forth, which determines their differential exposure to the hazard. In this study, the geological and socio-economic indicators have been analyzed for the vulnerability exposure because of earthquakes in the Gilgit and surrounding areas of GB province. It was found that the geological and socio-economic indicators are connected with each other. Both indicators are affecting the population and infrastructure because of earthquakes in the area. The geological hazards encountered in the area are due to earthquakes, including debris flow, rock fall, avalanches, landslide, and floods. The population and infrastructure of the study area is in the proximity to the geological hazard prone mountainous region, causing a serious threat to the life and socio-economic activities.

The population, housing and infrastructure density (including population, education, health, industry and tourism facilities) is highest in the central, southern, and western parts of the study region, with the highest land values. Something may unevenly distribute the impacts of the exposure among exposed groups (government, private, military) based on differential sensitivities. The location of concentration of infrastructure and population density suggests the resource distribution among land owners to mediate sensitivity to the exposure. The professionals working at local level need to bring the concern in order to knowledge of the residents, local governments, and environmental groups to help and organize them to cooperate with each other to mitigate the impacts of the exposure to the earthquake hazard. The governmental focus on risk and resilience based approach with a concern of the local vulnerable community. Deliberative engagement in adaptation planning is needed to address the issue and bring the policy in to practice.

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AUTHORS' CONTRIBUTION

A.N. and T.K. derived the idea and wrote the manuscript; A.N. conducted the field survey and collected the data; N.M. and interpreted the data. Z.F. provided his expert guidance in performing the analysis. T.N critically review the manuscript.

DECLARATION OF COMPETING INTEREST

The authors declare no competing interest.

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